Alushta-2012
International Conference-School on Plasma Physics and Controlled Fusion
and
The Adjoint Workshop
"Nano- and micro-sized structures in plasmas"

Alushta (Crimea), Ukraine, September 17-22, 2012

BOOK OF ABSTRACTS

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International Conference and School on Plasma Physics and Controlled Fusion ALUSHTA-2012 combined with Adjoint Workshop "Nano- and micro-sized structures in plasmas" follows the previous International Conferences , which were held in Alushta in 1998, 2000, 2002, 2004, 2006, 2008, 2010 and were organized by the National Science Center “Kharkov Institute of Physics and Technology” and Bogolyubov Institute for Theoretical Physics . More than 100 Ukrainian scientists and 70 foreign participants (from 16 countries) presented about 200 reports during previous Alushta-2010 Conference.

Alushta-2012 is sponsored by the National Academy of Science of Ukraine, National Science Center “Kharkov Institute of Physics and Technology”, Bogolyubov Institute for Theoretical Physics, European Physical Society (EPS) and Science and Technology Center in Ukraine (STCU). More than 220 abstracts were submitted by Ukrainian and foreign authors and selected by the Program Committee for presentation at the Alushta-2012 Conference. All the abstracts have been divided into 9 groups according to the topics of the Conference Program.

The Adjoint Workshop "Nano- and micro-sized structures in plasmas" is supported in part by the Alexander von Humboldt Foundation. 16 abstracts have been submitted by Ukrainian and foreign authors and selected by the Program Committee for presentation at the Adjoint Workshop sesions.

Since the abstracts presented in this volume were prepared in camera-ready form, and the time for the technical editing was very limited, the Editors and the Publishing Office do not take responsibility for eventual errors. Hence, all the questions referring to the context or numerical data should be addressed to the authors directly.

We hope that the contributed papers and invited talks, to be given at the Conference and Adjoint Workshop, will supply new valuable information about the present status of plasma physics and controlled fusion research. We also hope that the Conference will promote further development of plasma physics and fusion oriented research as well as the scientific collaboration among different plasma research groups in Ukraine and abroad.

Program and Local Organizing
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I-01

MODELLING OF MATERIAL DAMAGE AND HIGH ENERGY IMPACTS ON TOKAMAK PFCs DURING TRANSIENT LOADS

B. Bazylev[1], I. Landman[1], S. Pestchanyi[1], Yu. Igitkhanov[1], R.A. Pitts[2], S. Putvinski[2], S. Brezinsek[3], M. Lehnen[3], J.W. Coenen[3], V. Philipps[3]

[1]Karlsruhe Institute of Technology, IHM, P.O. Box 3640, 76021 Karlsruhe, Germany

[2] ITER Organization, Route de Vinon sur Verdon, 13115 Saint Paul Lez Durance, France

[3] Institute of Energy and Climate Research – Plasma Physics, Forschungzentrum Jülich EURATOM-FZJ, Partner of Trilateral Euregio Cluster, 52425 Jülich, Germany

Tungsten (W) is planned in the nuclear phases (and even now possibly from the beginning of non-active operations) as the armour material for plasma-facing components (PFCs) in the ITER divertor and as the main PFC material of future tokamak reactors. Beryllium (Be) will be used as first wall (FW) plasma-facing material on ITER [1] and is currently being used as FW in the new JET ITER-like Wall (ILW) configuration. Uncontrolled off-normal and transient events, such as ELMs (Edge Localized Modes), VDEs (Vertical Displacement Events) and disruptions on ITER have the potential to drive significant erosion of PFC surfaces by vaporization and melting [2]. In particular, melt motion followed by melt splashing of metallic armour components can be very serious, leading to deterioration of PFC surface topology (and possible consequences for subsequent plasma operation), a decrease in PFC lifetime production of Be and W dust in the form of re-solidified droplets.

Scaling from today's experiments to ITER predicts [1-2] that due to the high thermal energy of the confined burning plasma (>0.3 GJ), uncontrolled transient heat fluxes on the PFCs could reach values in the following range: I) Divertor target: Type I ELMs: 0.5 – 4 MJ/m^2 on the timescale of 0.3-0.6 ms; disruption thermal quench (TQ): 2-25 MJ/m^2 (1-5 ms). II) FW: Type I ELMs 0.5 – 2 MJ/m^2 (0.3-0.6 ms); TQ: up to 13 MJ/m^2 for major disruptions and up to 30 MJ/m^2 for upward and downward VDEs (few ms). During disruptions mitigated with massive gas injection (MGI), photon fluxes in the range 0.1 – 2 MJ/m^2 (2-5 ms) can be deposited on the FW. The runaway electron fluxes, which are expected to be generated during the current quench (CQ) of mitigated and unmitigated disruptions, can exceed 35-70 MJ/m^2 (1-100 ms). The anticipated impact of these powerful ITER transients cannot be reproduced in existing tokamaks. Alternative devices, such as powerful plasma guns are thus used for armour testing under extreme conditions. However, the transients created in these facilities cannot simultaneously match all characteristics of ITER transients and estimates of the damage to be expected on ITER must be supported by numerical simulations with using the codes, benchmarked against experiments.

The 2D version of the melt motion code MEMOS has been successfully benchmarked against experiments on the plasma guns for the ELM-like heat loads (QSPA-T, QSPA-Kh50) and on TEXTOR tokamak for long pulse heat loads. This paper describes a series of applications of the codes MEMOS (in 2D and 3D versions), ENDEP and TOKES, developed at the Karlsruhe Institute of Technology, to specific ITER transient loading on both W and Be surfaces in the case of W divertor PFC melting due to disruptions (MEMOS), RE impact on Be first wall panels (MEMOS and ENDEP) and estimates of MGI driven photon radiation flash first wall heating (TOKES). An account is also given of benchmarking studies in which these codes have been compared with results obtained on the JET and TEXTOR tokamaks.

[1] R. Mitteau et al., Phys. Scr. **T145** (2011) 014081, [2] A. Loarte, et al., Phys. Scr. **T128** (2007) 222

I-02

RF DISCHARGE DYNAMICS WITH PASSING OVER L- AND H-LIKE MODE STATES IN THE URAGAN-3M TORSATRON

V. V. Chechkin, I. M. Pankratov, L. I. Grigor'eva, A. A. Beletskii, A. A. Kasilov, V. Ye. Moiseenko, V. K. Pashnev, P. Ya. Burchenko, A. V. Lozin, S. A. Tsybenko, A. S. Slavnyj, N. B. Dreval, A. P. Litvinov, A. Ye. Kulaga, R. O. Pavlichenko, N. V. Zamanov, Yu. K. Mironov, V. S. Romanov, S. M. Maznichenko, Ye. D. Volkov

Institute of Plasma Physics NSC KIPT, Kharkov, Ukraine

In the Uragan-3M (U-3M) torsatron with an open helical divertor (l = 3, m = 9, R_0 = 100 см, $\bar{a} \approx$ 12 см, $\iota(a)/2\pi \approx$ 0,3, $B_\phi \lesssim$ 1 T) a hydrogen plasma with the average density $\bar{n}_e \lesssim 2\times10^{12}$ cm^{-3} is produced and heated by RF fields in the Alfven range of frequencies ($\omega \lesssim \omega_{ci}$) with the use of an unshielded frame-like antenna with a broad spectrum of parallel wavelengths. Parallel with linear mechanisms of the Alfven wave absorption, turbulent heating and turbulent transport also strongly affect plasma parameters and its confinement..

Time variations are considered of

- average electron density and electron cyclotron emission from the plasma at different values of RF power irradiated by the antenna;
- fast ion (FI) generation and loss;
- edge radial electric field E_r and edge turbulent transport.

The results having been obtained are important for a subsequent production and heating of a denser plasma. At the heating power high enough and a certain combination of plasma parameters where optimum conditions for plasma heating arise with local Alfven resonances for wavelengths generated by the antenna being present in the plasma, the transition to the H-like confinement mode occurs.

The H-like mode transition is triggered by a short-time enhanced FI loss. Two such states separated by an L-like state are realized over the RF pulse. The H-like mode is characterized, in particular, by the reduced edge turbulent transport, this reduction correlates with a slowing-down of the mean plasma density decay and an enhanced E_r shear at the plasma boundary. Some initial, weaker E_r shear has been already formed before the H-like mode transition and is only enhanced after the transition, thus persisting after the enhanced FI loss termination. This prevents recovery of the initially high level of the edge turbulent transport.

I-03

PHYSICS AND DESIGN OF WIDE-APERTURE BIPOLAR PARTICLE SOURCES

S.V. Dudin

V.N. Karazin Kharkiv National University, 31 Kurchatov Ave., Kharkiv,61108,Ukraine

E-mail: stanislav_dudin@rambler.ru

Wide aperture positive ion sources are in common use for years in different technologies and for electric propulsion in space. In all these applications the neutralization of positive ion beam space charge or current is important task, which is usually solved with use of a neutralizer emitting electrons. The neutralizer is a dedicated device requiring additional power supply and often degrading the overall system reliability due to limited lifetime. Thus the idea of bipolar particle source that is able to emit simultaneously the directed flows of particles of both polarities looks attractive in number of applications.

In the present paper a review of known designs of bipolar particle sources is carried out for ion-electron sources classifying them by spatial or temporal separation of the oppositely charged particles. Main attention is paid to description of design, research, simulation and technology approbation of the single-grid ICP bipolar ion-electron source developed in V.N. Karazin Kharkiv National University (KhNU).

Another possible kind of bipolar particle source is ion-ion source which is capable of simultaneous emission of both positive and negative ions. Possibilities of creating bipolar ion-ion source are discussed basing on recent research results from Ecole Polytechnique (France) and from KhNU (Ukraine), particularly on comparative study of positive and negative ion flows extracted from downstream plasmas beyond magnetic and electrostatic electron filters.

I-04

PLASMODYNAMICAL DEVICES NEW GENERATION: REVIEW OF FUNDAMENTAL RESULTS AND APPLICATIONS

A.A.Goncharov

Institute of Physics NASU, 252650 Kiev

The paper is the review of current status investigations and development novel generation plasma devices based on the cylindrical plasma lens configuration. The fundamental concept of the novel plasma devices are based on application plasma optical principles of magnetic insulation electrons and equipotentialization magnetic field lines for the control of over thermal electric fields introduced into the plasma medium for manipulating non-magnetized ions. The electrostatic plasma lens is a well-explored device for focusing and manipulating high-current, large area, heavy ion beams [1]. The crossed electric and magnetic fields inherent plasma lens configuration provides the attractive method for establishing a stable plasma discharge at low pressure. Using plasma lens configuration in this way several cost-effective, low maintenance, high reliability plasma devices using permanent magnets and possessing considerable flexibility towards spatial configuration were developed. These devices can be applied both for fine ion cleaning, activation and polishing of substrates before deposition and for sputtering [2]. One particularly interesting result of this background work was observation of the essential positive potential at the floating substrate. This suggested to us the possibility of an electrostatic plasma lens for focusing and manipulating high-current beams of negatively charged particles, electrons and negative ions, that is based on the use of the cloud of positive space charge in conditions of magnetic insulation electrons. The paper describes the current status of ongoing research and development of the electrostatic plasma lens for focusing and manipulating wide aperture high current electron beams. The results carried out collaboratively between IP NASU (Kiev) and HCEI SB RAS (Tomsk) in recent years of the first experimental and theoretical investigations of intense electron beams focusing due to plasma lens with positive space charge cloud produced by the cylindrical anode layer accelerator are presented. We describe also the novel approach for effective additional elimination of micro droplets in a density flow of cathode arc plasma. This approach is based on application the cylindrical electrostatic plasma lens configuration for introducing at volume of propagating along axis's dense plasma stream convergent radially fast energetic electron beam produced by ion –electron secondary emission from electrodes of plasma optical tool. The calculations show the energy of this electron beam enough for micro droplet elimination during propagating plasma flow through plasma tool. The experimental scheme of the new plasma device was elaborated and this plasma-optical tool for effective elimination micro droplets in a passing cathode arc plasma flow has been produced. The presented experimental results and theoretical estimations clearly demonstrate an attractive possibility suggested approach for elaborated an effective micro droplets eliminators new generations.

The work was supported in part by the Russian Foundation for Basic Research and State Foundation for Basic Researches of Ukraine due to joint Russian-Ukrainian research projects (RFBR Grant No 11-08-90405, SFBR Grant No F40.2/023-2011).

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I-05

STABILITY IMPROVEMENT OF A LASER-ACCELERATED ELECTRON BEAM AND THE PULSE WIDTH MEASUREMENT OF THE ELECTRON BEAM

H. Kotaki, M. Mori, Y. Hayashi, M. Kando, I. Daito, Y. Fukuda,
A. Pirozhkov, J. K. Koga, and S. V. Bulanov

Japan Atomic Energy Agency, 8-1-7, Umemidai, Kizugawa, Kyoto 619-0215, Japan

Laser wakefield acceleration (LWFA) is regarded as a basis for the next-generation of charged particle accelerators [1]. In experiments, it has been demonstrated that LWFA is capable of generating electron bunches with high quality: quasi-monoenergetic, low in emittance, and a very short duration of the order of ten femto-seconds. Such femtosecond bunches can be used to measure ultrafast phenomena. In applications of the electron beam, it is necessary to generate a stable electron beam.

The experiments have been performed with a Ti:sapphire laser. The laser pulse with 130 mJ energy was focused onto a 3-mm-diameter gas jet. The pulse duration was 40 fs. The peak irradiance in vacuum was 7.3×10^{17} W/cm^2. The electron energy is measured with a magnetic spectrometer composed of a dipole magnet, a scintillating screen, and a CCD camera.

By using an argon gas target, we have succeeded in generating a stable electron bunch [2]. We conducted experiments for stable electron bunch generation by using nitrogen, argon, and helium gas targets. When we used a helium gas target, the stability of the electron position was unstable due to the short channel length. When the target was nitrogen, the position and the energy were stable due to the long channel length. We have succeeded in generating a stable 40 MeV electron bunch for optimum plasma density.

The electron beam oscillates in the electric field of the laser pulse. In energy space, when the electron beam is in the acceleration or deceleration phase, the electron oscillation can be observed and the electron energy spectrum can be converted to the electron pulse width. We have succeeded a measurement of the electron oscillation. The wave structure of the energy spectrum depends on the laser frequency. The pulse width (FWHM) of the electron is 1.5-cycles at a wavelength of 800 nm. The pulse width is 1.7 fs (rms).

[1] T. Tajima and J. M. Dawson, Phys. Rev. Lett. **43**, 267 (1979).
[2] M. Mori, et al., Phys. Rev. ST Accel. Beams 12, 082801 (2009); M. Mori, et al., J. Phys. Soc. Jpn. **80**, 105001 (2011).

I-06

GEODESIC ACOUSTIC MODE AND ALFVEN EIGENMODES IN TOKAMAKS WITH HIGH $q^2\beta$

Ya.I. Kolesnichenko, Yu.V. Yakovenko, O.P. Fesenyuk

Institute for Nuclear Research, Prospect Nauky 47, Kyiv, 03680, Ukraine
E-mail: yk@kinr.kiev.ua

Since 1990, after first experimental observations in TFTR and DIII-D of Toroidicity-induced Alfven Eigenmodes (TAE) destabilized by energetic ions, the TAE modes were extensively studied both experimentally and theoretically. The TAE characteristic frequency is [1]

$$\omega_{TAE} = \frac{\bar{V}_A}{2qR},$$

where V_A is the Alfven velocity, R is the major radius of the torus, and q is the tokamak safety factor. In addition, the destabilization of eigenmodes residing in the Alfven continuum gaps associated with plasma shaping was observed experimentally. On the other hand, in recent years it became clear that an important role in many phenomena is played by the geodesic acoustic mode (GAM) predicted long ago, in 1968 [2]. Its frequency is given by [2]

$$\omega_{GAM} = \sqrt{2}\frac{c_s}{R}\left(1+\frac{1}{2q^2}\right)^{1/2}$$

where c_s is the sound velocity, and $q^2 >> 1$. This equation was used in most publications dealing with phenomena involving the GAM mode.

The GAM frequency represents the upper boundary of the β-induced gap in the Alfven continuum. Because the β-induced gap is the lowest gap in Alfven continuum, $\omega_{GAM} < \omega_{TAE}$. However, it follows from (1) and (2) that $\omega_{GAM} < \omega_{TAE}$ only when $\beta_s q^2 < 1/8$, where $\beta_s \equiv c_s^2/V_A^2 \sim \beta$, β is the ratio of the plasma pressure to the magnetic field pressure. This implies that the conventional relations (1) and (2) are relevant only to low-β plasmas. For instance, when $q = 3$, they are valid at $\beta_s < 1.3\%$ (local value).

In this work, expressions relevant to plasmas with not small $q^2\overline{\beta}$, up to $q^2\overline{\beta} \sim 1$, [$\overline{\beta} = \beta_s(1+\beta_s)$] and convenient for the practical use, are obtained for the GAM frequency and the characteristic values of the frequencies of gap modes (TAE-modes, EAE - Ellipticity-induced Alfven Eigenmodes, and NAE - Noncircularity-induced Alfven Eigenmodes). It is found that at any $q^2\overline{\beta}$ the Alfven continuum in the near-axis region is described by Mathieu's equation. Due to this, simple expressions are obtained also for the limit case of $q^2\overline{\beta} >> 1$, which is of interest for conventional tokamaks with hollow current profile and high-β spherical tokamaks.

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[2] N. Winsor, J.L. Johnson, and J.M. Dawson 1968 *Phys. Fluids* **11** 2448

I-07

RECENT RESULTS OF STUDIES OF MAGNETIC FIELD DISTRIBUTION AND NEUTRON SCALING ON PF-1000 AND PF-3 FACILITIES

V. Krauz[1], K. Mitrofanov[1,2], M. Scholz[3], P. Kubes[4] V. Myalton[1], M. Paduch[3], E. Grabovski[2], L. Karpinski[3], V. Koidan[1], A. Mokeev[1], V. Vinogradov[1], Yu. Vinogradova[1], E. Zielinska[3]

[1]NRC «Kurchatov Institute», Moscow, Russia,
[2]SRC RF TRINITI, Troitsk, Moscow oblast, Russia
[3]IPPLM, Warsaw, Poland
[4]CPTU, Prague, Czech Republic

The plasma parameters achieved in plasma focus (PF) facilities, as well as the generation of various types of emission, make these facilities attractive for various practical applications. A specific feature of PFs is that the emission parameters depend strongly on the discharge current. The efficiency of current transportation to the system axis and spatial distributions of the plasma density and discharge current in the final stage of compression substantially affect plasma stability and the processes responsible for the dissipation of magnetic energy and generation of neutron and X-ray emissions. These problems become more urgent as the energy deposited in the discharge increases.

This study is devoted to the comparative analysis of the magnetic field distribution, the dynamics and structure of the plasma current sheath (PCS), and the neutron yield scaling in two largest facilities, PF-3 (Filippov-type, Kurchatov Institute, Moscow) and PF-1000 (Mather-type, IFPLM, Warsaw). The experiments were done at W=300÷500 kJ and I ~ 2 MA. Different modifications of absolutely calibrated magnetic probes were developed allowing to record azimuthal and axial components of the magnetic field, and also the optical luminescence of plasma. It has allowed to investigate fine structure of the PCS.

It is shown that the efficiency of the current transfer to the axis essentially depends on the discharge conditions. Under certain conditions the significant part of the current can remain at the insulator area and does not participate in the pinch formation. This can lead to the formation of closed current loops separated from the main discharge circuit.

The current flowing in the converging sheath at a distance up to 13 mm from the axis of the facility electrodes was measured. In the optimal operating modes, this current is equal to the total discharge current, which indicates the high efficiency of current transportation toward the axis. In such shots a compact high-quality sheath forms with shock wave in front of the magnetic piston.

It is shown that the neutron yield depends on the current compressed onto the axis. This dependence agrees well with the known scaling, $Y\text{n} \sim I^4$. The use of the total discharge current in constructing the current scaling, especially for facilities with a large stored energy, is unjustified.

The measurements of Bz-component of the magnetic field on PF-1000 facility were done. In the compression stage, the axial component of the magnetic field reaches several kG that comprises ~10% of the azimuthal component. The presence of the B_z field is a powerful argument in favor of the existence of closed magnetic configurations, which play an important role in the generating of neutrons. On the other hand, it is necessary to take into account that the presence of the B_z field in front of the PCS can hinder the pinching process and prevent the achievement of the maximum plasma and current densities.

This research has been supported in part by the Russian Foundation for Basic Research (project nos. 11-02-01212 and 11-02-90303) and by the research program no. LA08024 of the Ministry of Education, Youth and Sport of the Czech Republic.

I-08

RESPONSE OF ITER DIVERTOR MATERIALS TO TRANSIENT THERMAL LOADS

Th. Loewenhoff, J. Linke, G. Pintsuk, M. Wirtz
Forschungszentrum Jülich, EURATOM Association, 52425 Jülich, Germany

Different thermal loads are expected to act upon the divertor of the experimental fusion reactor ITER: Steady state loads in the range of 5 – 10 MWm^{-2} (with additional periods of up to 20 MWm^{-2} for less than 10 seconds) determine the base temperature of the material. Transient heat loads, induced by events such as disruptions, vertical displacement events (VDEs) and edge localised modes (ELMs), cause a sudden, very strong temperature increase in the surface of the material and are superimposed to the steady load. ELMs occur in normal operation mode, meaning they can not be avoided in certain operational regimes unless they are actively suppressed. Natural type I ELMs of high intensity (up to 10 GW/m^2 for 0.2 – 0.5 ms) are frequent (prediction for ITER: $f_{ELM} \geq 1$ Hz) and hence pose a great danger for the plasma facing materials (PFMs). Mitigation techniques can be used to decrease their power density to about 1 GWm^{-2} or below. The above mentioned surface temperature leap caused by transient heat loads induces strong temperature gradients which give rise to mechanical stresses. These stresses can be high enough to induce material deterioration even for mitigated ELMs. Hence it is of particular interest to investigate damage thresholds and mechanisms of PFMs in order to estimate the lifetime of ITER divertor PFMs and to develop more resistant materials or alloys.

Experiments, simulating transient heat loads or a simultaneous exposure to steady and transient heat loads were performed with the electron beam facilities JUDITH 1 and JUDITH 2 at Forschungszentrum Jülich, Germany. Different materials were tested, namely sintered pure and ultra high purity (W-UHP) tungsten, double forged pure tungsten (DF-W), tungsten doped with potassium (WVMW), tungsten alloys with 1 and 5wt% tantalum (WTa1, WTa5), toughness enhanced fine grain tungsten in the recrystallised state (W1.1TiC), and carbon fibre composites (CFC) of type NB41 (SNECMA). These materials were tested at different surface base temperatures up to 1200 °C with power densities up to 1.5 GWm^{-2} and pulse numbers up to 10^6. In selected cases tests with different grain orientation (parallel or perpendicular to the loaded surface) were also performed.

The results for low pulse numbers are used to compare different tungsten grades. All tungsten materials show an improved behaviour (roughening instead of cracking) when raising the base temperature above a threshold that depends on the grade. For pure tungsten and WTa5 this is below 100 °C, while it is above 200 °C for WVMW and WTa1 (all in parallel grain orientation). The tungsten grades W-UHP, WVMW, WTa1, pure W and DF-W show a similar resistance against material deterioration like cracking or roughening (damage threshold of $< 10\ MWm^{-2}s^{1/2}$), while WTa5 and W1.1TiC have a damage threshold of $> 10\ MWm^{-2}s^{1/2}$.

In the high pulse number regime DF-W was tested. It shows a damage threshold of $< 6\ MWm^{-2}s^{1/2}$ for pulse numbers of $\leq 10^6$. In contrast to the low pulse number tests an increase of the base temperature from 200 °C to 700 °C does not influence the threshold. However, the damage appears earlier and is more severe at higher surface base temperatures.

I-09

ADVANCED MODELS FOR ELECTRON CYCLOTRON CURRENT DRIVE

N.B. Marushchenko, C.D. Beidler, H. Maassberg

Max-Planck-Institut fur Plasmaphysik, EURATOM-Association, Greifswald, Germany E-mail: nikolai.marushchenko@ipp.mpg.de

The adjoint approach is a rigorous and convenient technique for calculating the current drive in plasmas. The central idea is exploiting the self-adjoint property of the linearized collision operator to express the current through the Green's function, which is proportional to the linear plasma response in the presence of an electric field that is formally identical to the solution of the Spitzer-Harm problem. At present, the adjoint approach is commonly used for calculations of the electron cyclotron current drive (ECCD) in different ray- and beam-tracing codes as well as for the parallel conductivity and bootstrap current.

The key point of the adjoint approach is the choice of model for the corresponding Spitzer function, which should preserve conservation of parallel momentum in the like-particle collisions. The classical Spitzer problem in the collisional limit can be analytically generalized to the collisionless limit where trapped particles cause an additional drag. The first limit, without trapped particle effects, i.e. $\nu_e >> \bar{\tau}_b^{-1}$ (ν_e is the collision frequency and $\bar{\tau}_b$ is the electron bounce-time), gives the upper limit for CD efficiency, while the second one (collisionless, i.e. $\nu_e << \bar{\tau}_b^{-1}$) tends to underestimate it. The intermediate collisional regime, where the contribution of barely trapped electrons can also be non-negligible, requires special attention. In general, current drive must be calculated by solving a generalized 4D Spitzer problem.

Another point which requires attention is the necessity of relativistic effects being taken into account. Contrary to the transport theory, where these effects are of minor importance, the current drive calculations require a careful consideration of the supra-thermal electrons. Since the relativistic effects behave rather differently than the collisional effects (i.e. their weight increases with the temperature), it is possible for high temperature plasmas to apply the relativistic model in the collisionless limit.

Recently, simple and fast numerical models which approximate the Spitzer problem with parallel momentum conservation have been developed and implemented in few modern ray-and beam-tracing codes. Applied to the ITER reference Scenario 2, these models have been well benchmarked against the Fokker-Planck code. Also the role of the finite collisionality effects has been checked. It was found that in regimes where the collisional detrapping time is comparable to the bounce time, ECCD efficiency has specific features which are absent in asymptotic regimes or in results drawn from interpolation between asymptotic limits. Also interesting are the marginal regimes where the Fisch-Boozer and Ohkawa effects are comparable.

I-10

PROGRESS IN HIGH-TEMPERATURE PLASMA RESEARCH AT NCBJ (FORMER IPJ) IN POLAND

M.J. Sadowski[1-2]

[1] *National Centre for Nuclear Research (NCBJ), 05-400 Otwock, Poland*
[2] *Institute of Plasma Physics and Laser Microfusion (IFPiLM), 01-497 Warsaw, Poland*
e-mail: Marek.Sadowski@ncbj.gov.pl

This invited lecture presents the most important results of theoretical and experimental studies of high-temperature plasma, which were performed at the NCBJ (former IPJ) in Otwock-Swierk, Poland, during recent two years. The research activity included: 1^0 Studies of fast electron beams and X-ray pulses emitted from plasma generated in several experimental facilities of the Z-Pinch and Tokamak type; 2^0. Investigation of solid-state nuclear track detectors (SSNTDs) used for measurements of fast ions (e.g., deuterons and protons) in Z-Pinch, Tokamak and Laser experiments; 3^0. Studies of pulsed plasma-ion streams during their free propagation and interaction with various solid targets; 4^0. Technology-oriented studies of thin metal films deposited by means of ultra-high vacuum (UHV) arc discharges.

The 1st topic included the design and construction of probes for direct measurements of fast (ripple-born and run-away) electrons in Tokamak-type facilities. Those probes were equipped with special detectors made of diamond or aluminum-nitrate (AlN) crystals, which could emit intense Cherenkov radiation. The developed Cherenkov-type probes were used for studies of the fast electrons in a small ISTTOK device in Lisbon, Portugal, and in the large TORE-SUPRA facility in Cadarache, France. Particular attention was paid to measurements performed by means of new translucent AlN radiators and to correlations of electron-induced signals with X-pulses (measured with other probes).

The 2nd topic concerned the calibration of SSNTDs of the PM-355 type and their application for measurements of fast ions in PF-type experiments, fusion-produced protons in the TEXTOR facility in Juelich, Germany, and fast ions emitted by laser-produced plasma in the PALS system in Prague, Czech Republic.

The 3rd topic concerned studies of a spatial structure of the intense plasma-ion streams emitted from PF- and RPI-type experiments, as well as mass- and energy-analysis of the ion components. Those studies embraced also measurements of fast electron-beams, as well as time-integrated and time-resolved optical emission spectroscopy of free-propagating plasma streams and plasma produced during interactions of such streams with solid targets made of materials interesting for fusion technology, e.g., graphite, tungsten and CFC.

The 4th topic was concentrated on optimization of UHV-arc devices and the deposition of thin superconducting Nb-layers as well as Pb-photocathodes needed for the development of the particle accelerator technology.

After the formation of the NCBJ (on Sept. 1, 2011) and successive reorganizations (performed on Jan. 1, 2012), the previous Department of Plasma Physics and Material Engineering became split into the Division of Plasma and Ion Technology (FM2) and the Division of Plasma Studies (TJ5). The last one concentrates all studies of high-temperature plasmas, which are carried out at NCBJ within frames of domestic (e.g., NCBiR) and international (e.g., EURATOM) research programs.

I-11

FIRST STUDIES OF ISOTOPE INTERCHANGE ON LITHIUM IN TJ-II

F. L. Tabarés and the TJ-II Team

Association Euratom/Ciemat. Av Complutense 40. 28040 Madrid, Spain

Lithium is becoming a material of high potential for Plasma Facing Components (PFC) in a Fusion Reactor [1]. The reasons for that are its low atomic number, high capability of particle and power handling, in particular in its liquid form, and its low melting point, thus opening the possibility of developing liquid PFC concepts at moderate temperatures. To date, a direct relation between the enhanced performances of Li based plasma devices and the associated low recycling of cold Li surfaces (T<400ºC) has been postulated [2]. However, hot wall operation is demanded in a fusion reactor from simple thermodynamic considerations. It is expected that D and T recycling in liquid lithium could become unity at high enough temperatures (450 ºC), so that a compromise between high recycling and low vapour pressure in the range 400-500 ºC must be achieved. At present, it is unknown whether the positive effects on plasma confinement will be lost under high recycling conditions.

In previous works [3], we have addressed the release of He and H from the lithiated walls of TJ-II in H and He plasmas respectively. Hints of diffusion limited processes and larger than expected interaction range were found. The corresponding cross sections were evaluated. In the present work, a liquid lithium limiter (LLL), based in the Capillary Porous System (CPS) has been exposed to H and D plasmas in TJ-II. Outgassing of the limter upon exposure to several plasma shots in a separated chamber has allowed for the estimation of fuel uptake and isotope exchange, while mass spectrometry in TJ-II was used for the particle balance of H/D when plasmas were produced on the solid, lithiated walls alone. The relative limiter effect in terms of particle recycling was analyzed as a function of limiter insertion into the plasma.

The results will be presented and discussed in terms of tritium inventory control under lithium PFC's in a fusion reactor.

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I-12

UNUSUAL PHYSICS OF QUANTUM PLASMAS

Yu.O. Tyshetskiy[1,2], S.V. Vladimirov[1,3], and R. Kompaneets[1]

[1]*School of Physics, University of Sydney, Australia*
[2]*Department of Physics and Technology, Kharkiv National University, Ukraine*
[3]*Joint Institute for High Temperatures, Russian Academy of Sciences, Russian Federation*

A plasma is regarded as a quantum plasma when the quantum nature of its constituent particles has an appreciable effect on its collective behaviour. Examples of quantum plasmas are the gas of charge carriers in solids (free electrons in metals, electrons and holes in semiconductors), dense matter in the "fast ignition" scenario of inertially confined fusion, the matter in the cores of some dense astrophysical objects.

In this talk, we will discuss some of the interesting features of the well-known basic plasma phenomena that appear in quantum plasmas, as compared to classical plasmas. In particular, we will consider such "elementary" phenomena as plasma shielding of charges, volume and surface wave dispersion and attenuation (including Landau damping), etc., and show how they change, often qualitatively, in quantum plasmas.

I-13

NONEQUILIBRIUM OF THE DENSE ELECTRIC ARC PLASMA CASED BY RADIATION TRANSFER

V.A. Zhovtyansky, Yu. I. Lelyukh, Ya.V. Tkachenko

The Gas Institute, National Academy of Sciences of Ukraine
39, Degtyarivs'ka St., 03113 Kyiv, Ukraine

The transport processes are the reason of deviations of the plasma state from local thermodynamic equilibrium (LTE). This effect is no exception in electric arc plasma contrary to the widespread opinion. It takes place if even plasma is so dense, that complies with Griem's LTE criterion. The reason is the radiation transfer at the condition of the radial gradient of temperature in cylindrical plasma as well as longitudinal gradient in the two-dimensional model of the arc. It was shown by one of the authors with the employees in early experimental studies. The effect mentioned was accomplished due to using of specially designed tomographic spectrometer. This spectrometer provided practically simultaneous recording of the spectral line shapes in various space elements of plasma as well as the space distribution of the spectral line emission and absorption. As was shown, the radiation from the hot arc core is able to overpopulate the resonance level of plasma forming atoms at the arc periphery, where temperature is relatively small. This non-LTE has a qualitatively another character as compared with the widely known non-equilibrium in plasma of low current discharges, where the radiation leaves freely the volume of plasma and as a result the resonance state of atoms is found to be under-populated as well as the density of electrons.

Resonance spectral transition is determining factor to plasma be in LTE. This leads to the spread of so-called two-level model of atom with two energy levels – the ground *1* and excited *2*. The basic equation for the kinetics of the population n_2 of the exited level of atom in plasma with account of the processes of radiation transfer excitation is:

$$\frac{\partial n_2(r,t)}{\partial t} = -n_2(r,t)A_{21} - n_2(r,t)\omega_{21} + n_1\omega_{12} + \int_V n_2(r',t)A_{21}K\left(|r-r'|\right)dr' , \qquad (1)$$

where A_{21} – probability of spontaneous radiating transition $2 \rightarrow 1$, n_1 – the population of ground level. Here the integral term takes into account the radiative transfer energy. The kernel $K(|r-r'|)$ is the probability that photon emitted from the arbitrary point *r'*, is absorbed in the volume of coordinate *r*. In the final version it includes integration to take into account the self-absorption along each beam:

$$K(r',r) = \frac{1}{4\pi}\int_0^\infty \iiint_V \frac{k_\nu(r')\varepsilon_\nu(r')}{|r-r'|^2} \times \exp\left[-\int_r^{r'} k_\nu(r'')dl\right] dVd\nu , \qquad (2)$$

where ε_ν is normalized per unit distribution of the frequencies of photons, emitted from upper level of spectral transition, k_ν – spectral absorption coefficient. Here, the exponent contains planimetric integral along the line connecting the points with coordinates *r* and *r′*.

The system of equations (1), (2) was extended to three-level model of the atom including the ground, metastable and resonant levels in the quasistatic approximation with the account of the splitting also of resonance and metastable levels. It was added with equations of Saha-Boltzmann, Dalton, quasineutrality and Elenbaas-Heller for the heat conductivity.

The solution of this problem illustrate clearly the above effect of growth of the resonance level population of the plasma forming atom cased by the transport of resonance radiation as well as the density of electrons on the arc periphery

I-14

DUST ION-ACOUSTIC NONLINEAR WAVE STRUCTURES UNDER CONDITIONS OF NEAR-EARTH AND LABORATORY PLASMAS

S.I. Popel

Institute for Dynamics of Geospheres RAS, Moscow, Russia

A review on dust ion-acoustic nonlinear wave structures in dusty plasmas is presented. The basic experiments on the nonlinear wave structures in dusty plasmas are described and the corresponding theoretical descriptions are given. A possibility of the existence of the dust ion-acoustic nonlinear structures under near-Earth conditions is discussed.

For the description of formation and evolution of dust ion-acoustic shocks and solitons the so-called ionization source model is forwarded. This model allows us to describe all the features of the laboratory experiments on dust ion-acoustic shocks performed at the Institute of Space and Astronautical Science (Japan) and at the University of Iowa (USA): the suppression by dust of charge separation in the front of shock; the width of the shock front; the dependence of the shock speed on dust density; the fact that shocks are excited for rather large dust densities. The most important dissipative processes, which are responsible for the generation of dust ion-acoustic shocks and influence dust ion-acoustic soliton dynamics, are investigated. Among them are the anomalous dissipation due to dust charging process; absorption and scattering of ions by dust grains; as well as the kinetic (including Landau) damping. A possibility of observation of shocks related to the dust charging process in active rocket experiments, which involve the release of some gaseous substance in near-Earth space, is shown. As an example of dust ion-acoustic shocks in nature, we consider the bow shock formed in the interaction of the solar wind with cometary dusty coma.

The dynamics of dust ion-acoustic solitons is analyzed in a wide range of dusty plasma parameters. The cases of both a positive dust grain charge arising due to the photoelectric effect caused by intense electromagnetic radiation and a negative grain charge established in the absence of electromagnetic radiation are considered. It is shown that, in dusty plasma with negatively charged dust grains, both compression and rarefaction solitons can propagate, whereas in plasma with positively charged dust grains, only compression solitons can exist. The amplitudes of soliton-like compression and rarefaction perturbations decrease in the course of their evolution and their velocities (the Mach numbers) decrease monotonically in time. We demonstrate that, after the interaction between any types of soliton-like perturbations, their velocities and shapes are restored (with a certain phase shift) to those of the corresponding perturbations propagating without interaction; i.e., they are in fact weakly dissipative solitons.

We investigate a possibility of experimental observation of the dust ion-acoustic solitons and discuss a possibility of formation of the shock wave-like structures during the soliton evolution. It is shown that the nonlinear dust ion-acoustic structures may find significant technological applications in, e.g., the so-called hypersonic aerodynamics.

This work is supported by the Presidium of the Russian Academy of Sciences (the basic research program No. 22 “Fundamental problems of research and exploration of the Solar system”), the Division of Earth Sciences of the Russian Academy of Sciences (the basic research program No. 5 “Nanoscale particles: conditions of formation, methods of analysis and recovery from mineral raw”), and the Russian Foundation for Basic Research (grant No. 12-02-00270-a).

I-15

FABRICATION OF NANOPOWDERS IN RF PLASMAS: DIAGNOSTICS AND MODELLING

Ilija Stefanović[1], Brankica Sikimić[1], Igor Denysenko[2] and Jorg Winter[1]

[1]*Experimental Physics II and Research Department "Plasmas with Complex Interactions", Ruhr Universitdt Bochum, GERMANY*

[2] *School of Physics and Technology, V. N. Karazin Kharkiv National University, Kharkiv, Ukraine*

The formation of hydrocarbon nanopowders in RF low pressure plasma and their influence on relevant plasma properties is reviewed. Despite of 20 years of research in the field, it is still important to develop an in depth understanding of the basic physical and chemical processes that lead to the formation of nanoparticles. It has been shown that by controlling the discharge parameters, such as the discharge pulsing frequency, it is possible to enhance or suppress the nucleation of protoparticles for nanoparticle formation and growth. Besides that, by modulating the RF power with low frequency signal (100 Hz - 1 kHz) and by tracing the dynamics of reactive species in the plasma afterglow, some basic properties of discharge can be understood. The experimental results have been compared with the simple hydrodynamic model of RF pulsed plasma with argon and argon/nanoparticle mixtures [1]. Between the model and experimental results there is a good quantitative agreement of electron and Ar_m^* argon metastable ($1s_5$ state) dynamics in the pure argon afterglow plasma. The model stresses the importance of the mean electron energy losses to the walls for the description of the electron density decay. However, in the presence of dust there is qualitative agreement, but the calculated Ar_m^* are three times smaller than the measured ones.

The application of electric probes in reactive plasmas is limited due to thin film formation that changes the probe characteristics. In the plasmas with immersed nanoparticles, the problem is even larger since the nanoparticle distribution in the probe vicinity changes and so does the electron and ion density. A planar RF probe has been developed for electron density measurements in plasmas with film deposition following [2]. However, the distortion of nanoparticle distribution by the presence of the probe cannot be avoided. We developed a non-intrusive diagnostics of ion densities and fluxes in reactive plasmas with nanoparticles that is based on measurements of the electrode bias voltage in the plasma afterglow.

The measurements of absolute electron and Ar_m^* metastable densities and their dynamics in the plasma afterglow will be presented and compared with the results of the model. Further, the measurements of ion densities based on the proposed diagnostics will be presented for pure argon and argon/nanoparticle mixtures. The ion densities will be compared with independently measured electron densities and the dependence on different discharge conditions will be discussed.

This work has been supported by DFG Project WI 1700/3-1, Research Department «Plasmas with Complex Interactions)) of Ruhr Universitat Bochum, Humboldt Foundation and the State Fund for Fundamental Researches of Ukraine.

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I-16

THE FORMATION OF NANOPARTICLES AND NANOCOMPOSITES IN REACTIVE PLASMAS

J. Berndt, E.Kovacevic, L.Boufendi
GREMI Université d'Orléans, France

The formation of particles in plasmas is of high interest for different areas of physics and technology. Nano – or dust particles have been observed in several different surroundings as for example in fusion devices [1], in the interstellar medium [2] or in prosessing plasmas used for the deposition of thin films [3] or the manufacturing of microelectronic devices [4].

This contribution will focus on the formation of nanoparticles in low temperature and low pressure plasmas as they are used for example for the production of polymer coatings or the fabrication of solar cells.

The formation and subsequent growth of nanoparticles in reactive plasmas is a rather complex process. It involves are large variety of chemical and physical reactions, different time scales and may have in addition a severe impact on the plasma itself. The whole process can be roughly divided into three separate phases. The basis for the formation of particles in the plasma volume are gas phase reactions which are leading to the formation of nanometer sized clusters or protoparticles. This so called nucleation phase is often followed by the coagulation phase which characterized by a strong increase of cluster- cluster collisions which results in the formation of particles with sizes up to some ten nanometers. Once the particles have reached such a size they become immediately negatively charged and the further growth of the particles occurs mainly through the sticking of neutral radicals and positive ions from the gas phase. Each of these phases (nucleation, coagulation and surface growth phase) is dominated by different charged and uncharged species (neutral radicals, positive and negative ions) and is governed by different time scales which can range from milliseconds to several minutes or even hours.

This contribution will mainly deal with the growth of nanoparticles in capacitively coupled discharges which are operated either with silane or with different hydrocarbon precursors such as CH_4, C_2H_2 or MMA. A special focus is put on pulsed discharges and on the question how the pulse frequency influences the different growth phases.

The production of nanocomposite materials with adjustable wetting characteristics will be discussed as an important example for the application of pulsed nanoparticle forming plasmas.

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I-17

ON THE USE OF DUST PARTICLES AS MICRO-PROBES IN PROCESS PLASMAS

Holger Kersten

Institute for Experimental and Applied Physics, University of Kiel, Germany

Complex (dusty) plasmas, which can form plasma or Coulomb crystals (see Fig.1) are at recent a topical research subject in plasma physics [1]. The complexity of dusty plasmas results in complicated interactions at different scales in energy, space, time and mass. Experimental and theoretical studies initiated the idea of using externally injected small particles, which are negatively charged and affected by several forces in plasma, as micro-probes. From the behavior of the particles in the surrounding plasma local electric fields can be determined ('particles as electrostatic probes') [2]. Moreover, momentum fluxes in energetic ion beams ('particles as force probes') [3] as well as energy fluxes towards the particles ('particles as thermal probes') [4] are worth studying.

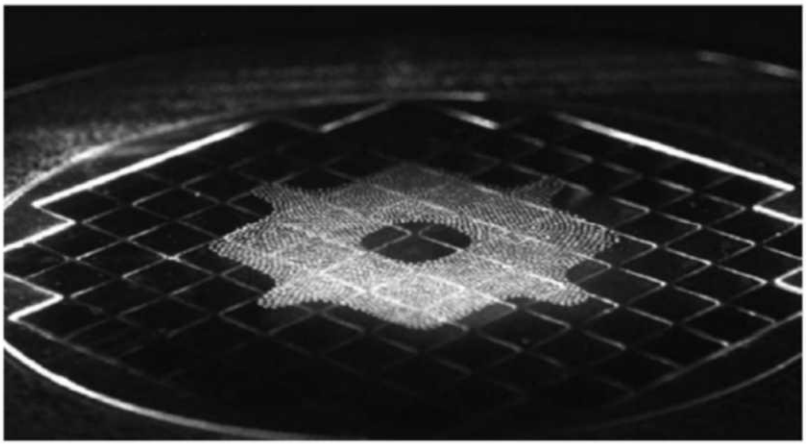

Fig.1: A two-dimensional cloud of mono-disperse dust micro-particles (10^m) is trapped in a plasma sheath in front of the adaptive electrode in an rf-plasma. The electrode is segmented, allowing for manipulation of the trapped micro-particles in real time.

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I-18

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KINETIC DESCRIPTION OF DUSTY PLASMAS AND EFFECTIVE GRAIN POTENTIALS

A.G. Zagorodny

Bogolyubov Institute for Theoretical Physics 14-b, Metrolohichna Str. 03680 Kiev, Ukraine

The basic points of the consistent kinetic theory of dusty plasmas are formulated. The equations for microscopic phase densities of plasma particles and grains are derived with regard to electron and ion absorption by grains and the relevant kinetic equations are found. Obtained equations are used for kinetic description of effective grain-grain potentials. Approximate analytical expressions for such potentials are derived and compared with the results of numerical solutions of the appropriate kinetic equations. The comparison shows satisfactory agreement between the analytical and numerical results.

The effective grain potentials in the wide range of plasma parameters (from the collisionless regime to drift-diffusive approximation) are studied numerically in detail. It is shown that charging processes strongly influences the effective interactions between the grains, in particular, due to electron and ion absorption by grains the Coulomd-like long-range behaviour of the effective potentials appears. The influence of the external magnetic on the asymptotic properties of the potential is also discussed. Obtained numerical solutions make it possible to study the dependence of stationary grain charge as well as charging currents on plasma parameters and grain size.

The screening of the moving grain is studied as well. It is shown that due to specific polarization of plasma the dynamical friction force acting on the particle under consideration can change its sign and thus to cause particle acceleration provided that the polarization force exceeds the friction force associated with neutrals. This effect was predicted using analytical estimates, but now it is confirmed on the basis of numerical solutions.

I-19

CHARACTERISTICS OF ENERGETIC-PARTICLE DRIVEN GAM IN THE LARGE HELICAL DEVICE

T. Ido, A. Shimizu, M. Osakabe, M. Nishiura, K.Toi, M.Nakamura*, R. Makino*, Y.Yoshimura, K. Itoh, S. Satake, S. Kato, and LHD experiment group

National Institute for Fusion Science, Oroshi,Toki, Gifu 509-5292, Japan Dept. of Energy Engineering and Science, Nagoya Univ., Nagoya 464-8603, Japan

Geodesic acoustic mode(GAM) is a branch of zonal flow in toroidal plasmas, and attracts much attention in the area of turbulent-transport study because the zonal flow is considered to regulate turbulence. It is driven by not only turbulence but also energetic particles which will be major players in future nuclear fusion reactors.

In recent LHD experiments, electrostatic potential fluctuation, density fluctuation and magnetic field fluctuation associated with GAMs are observed by toroidal Mirnov-coil array, reflectometry, a heavy ion beam probe (HIBP)[1][2]. The GAMs are not observed in plasmas without high-energy tangential neutral beam injection(NBI). Thus, it is concluded that the GAM is driven by the injected energetic particles.

The frequency of the energetic-particle driven GAM changes upward with the time scale of several milliseconds. The initial frequency is roughly proportional to the square-root of electron temperature. The direct measurement of the potential fluctuation and density fluctuation by HIBP revealed that spatial structures of the mode with the upward shifted frequency are consistent with the theoretical prediction of GAMs: $m = 0$ for the potential fluctuation and $m=1$ for the density fluctuation, where m is the poloidal mode number, even during the frequency change.

The potential fluctuation measured by the HIBP is roughly proportional to the magnetic field fluctuation measured by a Mirnov coil on the vacuum vessel, and the relation seems to agree with a theoretical prediction[3]. The amplitude of the potential fluctuation of the GAM reaches a few kilovolts, and the electrostatic potential energy is comparable to the electron temperature. The possibility of energy transfer from energetic particles to bulk ions via the GAM[4] with such large potential fluctuation will be also discussed in the presentation.

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I-20

MAGNETIC MIRRORS: HISTORY, RESULTS AND FUTURE PROSPECTS

A.D.Beklemishev[a,b], A.V. Burdakov[a,b,c], A.A. Ivanov[a,b], E.P.Kruglyakov[b]

[a]*Novosibirsk State University, 630090, Novosibirsk, Russia*
[b]*Budker Institute of Nuclear Physics SB RAS, 630090, Novosibirsk, Russia*
[c]*Novosibirsk Technical University, 630092, Novosibirsk, Russia*

The paper reviews milestones in development of magnetic mirrors for plasma confinement, relevance of mirrors for current plasma and materials science, and their prospects as neutron sources, drivers for fission-fusion hybrids, or even pure-fusion reactors. The evolution of open traps brought them from simple solenoids to highly sophisticated and huge tandem mirrors with quadrupole magnetic stabilizers. They tried to compete with toroidal devices for plasma temperature using ambipolar confinement and thermal barriers, but were too late and failed, and are close to extinction. A side branch of open traps went for simplicity of construction and fast-ion confinement inherent in axially symmetric mirrors. Since simplicity means lower cost of construction and servicing, and lower engineering and materials demands, such type of traps might still have an edge.

However, besides having the inherent to all open traps weak axial confinement, the axially symmetric traps have to employ special means of flute-mode stabilization, preserving axial symmetry. Several stabilization methods based on introduction of the MHD anchors (expander and cusp end cells) definitely work, while others are possible (magnetic divertors, enhanced line tying, active feedback, axial currents, etc.) The best one would have the lowest cost in terms of construction, reliability and power consumption. Recently, a method of suppression of radial plasma losses without providing MHD stability was found. It is based on generation of sheared azimuthal plasma flows at periphery using biased end plates. Whenever this biasing becomes large enough to provide closed flow-lines at the periphery even in the presence of the flute instability, the plasma resides inside this flow without considerable radial losses across the flow region. Furthermore, the radial currents, associated with the biasing and the low-level saturated modes, appear to lead to a significant pinch-effect in ions.

The emphasis is made on development of axially symmetric magnetic mirrors at the Budker Institute of Nuclear Physics in Novosibirsk that currently represents the frontline of mirror research. In particular, we discuss recent experimental results from the multiple-mirror trap GOL-3 [1] and the gas-dynamic trap GDT [2], critical technologies under development and their relevance to aims of the fusion program. The next step in this line of research is the GDMT program that will combine the GDT-style fast-ion-dominated central mirror with multiple-mirror end plugs. This superconducting device will be modular and built in stages. The first stage, GDMT-T, will consist of 5m, 7T superconducting solenoid (multiple-mirror plug of the full device). It’s 3-year scientific program is oriented primarily on PMI studies. Start of construction is planned for 2013.

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CONTRIBUTED PAPERS

TOPIC 1 - Magnetic Confinement Systems:

(***Stellarators, Tokamaks, Alternative Conceptions***)

1-01

CONTROL OF THE EDGE TURBULENT TRANSPORT BY HOT LIMITER BIASING ON THE IR-T1 TOKAMAK

M. Ghoranneviss, A. Salar Elahi, S. Mohammadi and R. Arvin
Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran

In this paper results are presented on the changes induced by hot limiter biasing in the edge transport of IR-T1 tokamak. The boundary plasma is characterized with focus on the relation between $E \times B$ sheared flows and particle transport. We proposed that the distinct behaviour of the particle confinement for positive and negative bias observed in IR-T1 is related to the low $E \times B$ shear induced by positive bias in the core periphery region associated with the appearance of large amplitude fluctuations. In addition, the effect of the electrode bias on the edge turbulent transport has been investigated identifying the changes induced in the fluctuations frequency spectrum and probability density function. We have shown that negative limiter bias reduces the propagation of large-scale events, making the fluctuations distribution more Gaussian and resulting in low amplitude fluctuations across most of the edge plasma region. For positive bias, large amplitude broad spectrum fluctuations appear in the core periphery, which increase the cross-field diffusion and contribute to the observed asymmetry in particle transport with the bias polarity.

Keywords: Tokamak, Limiter Biasing

1-02

CONFINEMENT, SPACE AND ENERGY DISTRIBUTIONS OF THE 0.5-4.5keV PLASMA IONS IN LOW DENSITY DISCHARGES OF THE U-3M TORSATRON.

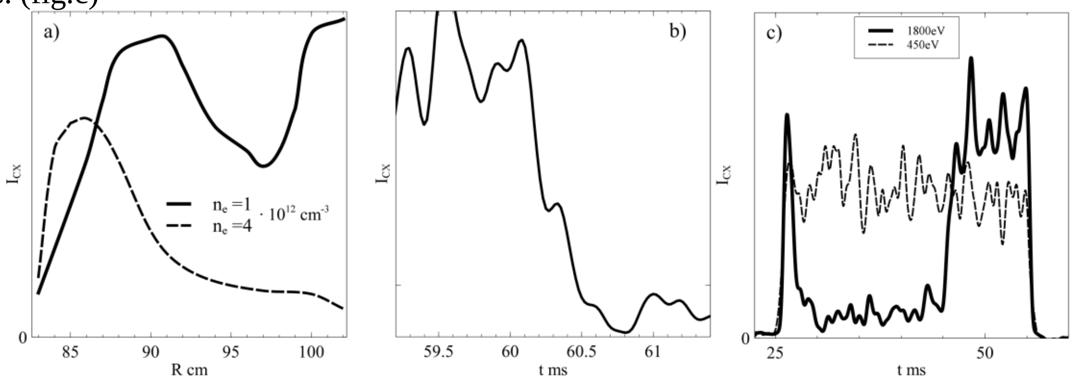
M. Dreval, A.S. Slavnyj

IPP NSC Kharkov Institute of Physics and Technology, Kharkov, Ukraine

Dependences of the charge exchange (CX) neutral fluxes are investigated using a set of U-3M discharges via neutral particle analyzers (NPA). A tangential neutral flux from major part of the U-3M cross-section is measured by one of the NPAs for parallel ion energy studies. The perpendicular ion energy distributions were measured along the vertical lines by the other NPA. The radial distribution (ρ=0.5–1) of vertical CX fluxes is studied by radial shift of vertical NAP line of sight. Fast (less than 0.5 ms) decay time of the vertical and tangential CX fluxes in the 0.5-4.5 keV range has been observed after turning off RF heating power (fig.b). This is an evidence that the confinement time of the 0.5-4.5 keV ions is less than 0.5 ms in the low density ($n_e=1\text{-}4\cdot10^{12}cm^{-1}$) U-3M discharges. The U-3M plasma volume is about 0.2 m^3 and its chamber volume is about 70 m^3. Evidently, substantial flux of the neutrals with mean free path longer than U-3M plasma size from large U-3M vacuum vessel sustains main channel of the ion energy loss via the CX collisions. Fast CX flux response to the RF power increase is also indicates that a part of the RF power directly absorbed by ions.

Radial distribution of the line integral CX fluxes shows that substantial part of the flux is collected from the central part of the plasma (from tangential to the NPA line of sight magnetic surface) [1]. In the $n_e=(1\text{-}2)\cdot10^{12}cm^{-1}$ discharges 1-2 keV fluxes of neutrals increase toward the plasma center. Clear CX flux decrease near the magnetic islands is observed in this energy range. In the $n_e=4\cdot10^{12}$ cm^{-1} discharges radial profile of the line integral of CX flux is hollow (fig.a). This is an indication that energetic ions are present in the core region in the low density case and are localized near last close magnetic surface in vicinity of the ion cyclotron zone in the $n_e=4\cdot10^{12}cm^{-1}$ case.

An increase of the high energy CX flux (>1 keV) is observed after fast addition of the frame antenna RF power. Constant flux of 0.45 keV neutrals is observed during these experiments. This is demonstration of the direct RF energy deposition into more energetic ions. (fig.c)



Anisotropy of ion temperature reconstructed owing 0.5-2.5 keV energy range [1] is observed in the $n_e=(1\text{-}2)\cdot10^{12}cm^{-1}$ discharges. Perpendicular temperature about 0.5-0.6 keV and parallel temperature about 0.2-0.3 keV is observed in such discharges with flat or slightly peaked perpendicular ion temperature profiles. Almost isotropic ion temperature about 0.2-0.3 keV is observed in the $n_e=4\cdot10^{12}$ cm^{-1} discharges. Hollow ion temperature profile with maximum near the last close magnetic surface is observed in the $n_e=4\cdot10^{12}$ cm^{-1} U-3M discharges.

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1-03

PROBLEM OF UNIFORM COMPRESSION IN MAGNETO-INERTIAL SCHEMES

A.Yu. Chirkov, S.V. Ryzhkov, V.V. Shumaev
Bauman Moscow State Technical University

Development of perspective high energy density systems such as different sources of neutrons and protons for cutting-edge materials research, non-destructive analysis, medical isotope production, chemical waste disposal, train personnel is currently under way. At present time systems with dense plasma for magneto-inertial fusion (MIF) are of great interest [1-4]. The aim of this work is to describe the processes of target compressing, heating and cooling under the conditions of a thermonuclear system with a high-temperature plasma, the development of a dense plasma device using compression of magnetized target in an externally applied magnetic field. Lawson criterion for MIF system is drawn.

MIF is an alternate (hybrid) concept to magnetic and inertial confinement fusion. Laser-driven magneto-inertial fusion [3, 4] and plasma jet driven magneto-inertial fusion [1] present the third concept of thermonuclear plasma confinement. Both may be used for magnetic flux compression and low-cost simple fusion schemes. For MIF, the fusion-product alpha-particle and proton orbit and heating problem is another point of interest. Plasma-Jet MIF dynamics has attracted a large amount of interest of scientists around the world during the last decade, partly because the plasma-jet version circumvents the difficult problem of electrode survival for the solid-liner version and the slow implosion speed of the liquid-metal version. For the MIF liner, a crucial question is whether the fusion products can heat the liner sufficiently to produce significant amounts of fusion power there, and thus the details of the orbits and the interactions of the fusion products with the liner will be very important.

An important function of the afterburner is thermal insulation of the relatively cold liner plasma from the hot fusion plasma of the target. This allows getting target temperature T several orders higher then the temperature of the liner T_L on the final stage of the compression. As a first approximation we can assume that the confinement is determined by the thermal expansion velocity of the plasma liner during the burning stage, and therefore the plasma confinement time in the considered scheme will be several orders greater than the confinement time for conventional inertial fusion. Consequently, the issue of justification of regimes with $T_L << T$ in the target with the afterburner is an important task for the prospects of such systems. The limiting factor seems to be the magnetic field.

Here we consider a limiting case of performances, which can be achieved in scheme with the afterburner in the framework of the simplest approximations. The efficiency of the scheme of the target surrounded by the liner with the afterburner can be characterized by a plasma amplification factor $Q_{pl} = W_{\text{fus}}/(W_{pl} + W_M + W_L)$, where W_{fus} is the fusion energy output during the confinement time, W_{pl} is the thermal energy of the plasma, W_M is the energy of the magnetic field, W_L is the energy of the liner.

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1-04

MODELING OF HEAT TRANSFER IN MAGNETIZED PLASMA COMPRESSED BY THE LASER BEAMS AND PLASMA JETS

V.V. Kuzenov[1,2], S.V. Ryzhkov[1]

[1]*Bauman Moscow State Technical University, 105005, Moscow, Russia*
[2]*A.Yu. Ishlinsky Institute for Problems in Mechanics RAS, 119526, Moscow, Russia*
E-mail: kuzenov@ipmnet.ru, svryzhkov@gmail.com

Magnetohydrodynamic and radiation magnetogasdynamics simulation with thermal transport, laser deposition and target implosion in external magnetic field in one and two dimensions is necessary for high energy density physics, magneto-inertial fusion and numerous applications [1-5]. Benchmarking the simulation results against experiments is important for researchers to improve the design of targets.

An improved one-dimensional radiation-hydrodynamics code which simulates plasmas in cylindrical or spherical geometries is created. It solves single-fluid, two-temperature equations of motion with contributions from diffusion, convection, heat conduction. Electromagnetic processes are described by the Maxwell-Ohm equations in plasma with final conductivity. Radiation transport is considered within the framework of multi-group diffusion approach. The transport coefficients in the given system of the equations taking into account magnetized laser plasma. External and spontaneous magnetic fields are included in the model.

Numerical simulation allows studying a number of features of nonlinear plasma dynamics. It is marked, that radial expansion of a laser plasma jet (two dimensional effects) has significant influence on the dynamics of plasma formation. First results of non-linear effects modeling for different initial parameters and edge conditions are discussed in the paper. Mathematical method developed in [6] may be applied for both impact fast ignition and uniform compression calculations.

Thermal physical properties of particles and plasma are derived using correct the Reynolds number and the Prandtle number. The calculations of thermodynamic and optical media parameters occur with the aid of computer system Asteroid, developed by S. Surzhikov [7]. The viscous forces in a flux represent the sum of works of liquid friction, heat fluxes and plasma heating by laser radiation. The electron and ion thermal conductivity coefficients in the case of magnetized plasma are calculated.

This study was supported by the Russian Ministry of Education and Science.

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1-05

ABOUT PHYSICAL PARAMETERS OF EXPERIMENTAL REACTOR-STELLARATOR IN THE CONDITIONS OF AMBIPOLARITY OF NEOCLASSICAL TRANSPORT FLUXES

V.A.Rudakov

Institute of Plasma Physics, NSC KIPT, Ukraine, 61108, Kharkiv, Akademichna st. 1
rudakov@kipt.kharkov.ua

With the use of a one-dimensional spatial–temporal numerical code the parameters of an experimental reactor-stellarator in conditions of ambipolarity of neoclassical transport fluxes were calculated. In the course of calculations the sizes of system and a magnetic field have been accepted to be the same as in experimental reactor-tokamak ITER. The system of three equations was solved: heat conductivity of electrons, heat conductivity of ions and diffusion equation which was supplemented with initial and boundary conditions. The equation for heat conductivity of electrons in the right part, besides a term with thermal conductivity, contains: power output as a result of $\alpha-$ particles energy dissipation, bremsstrahlung and cyclotron radiation losses, heating due to external energy sources, heat exchange with ions as a result of Coulomb collisions and ambipolar electric field. The equation of heat conductivity for ions takes into account heat exchange with electrons as a result Coulomb collisions and interactions with electric field, and also a term with a source of external heating of plasma was included. Density maintenance at approximately constant level was carried out by means of model of injection of fuel pellets into the plasma centre. The value of radial electric field was obtained from equality condition for ion and electron diffusion fluxes on each node of a spatial grid along a minor plasma radius. It was considered, when finding electric field, that in all cases the ion root is realized. Steady-state solutions of the system of equations for spatial distributions of ion and electron temperatures, specific fusion power, density of plasma and ambipolar electric field are obtained. The possibility of creation on a basis of stellarator systems of an experimental reactor with power of the order 500 MW as the result of D-T fuel fusion is shown. The system achieves the burning stage by means of heating power 30 - 40 MW. For maintenance of burning stage at such level of fusion power it has appeared sufficient to inject 10 MW of additional heating.

1-06

SPECTRAL ANALYSIS OF THE EDGE PLASMA TURBULENCE IN THE URAGAN-3M TORSATRON

A.A. Beletskii, L.I. Grigor'eva, V.V. Chechkin, A.A. Kasilov, I.M. Pankratov, A.Ye. Kulaga, S.A. Tsybenko, A.V. Lozin, A.S. Slavnyj, N.V. Zamanov, V.K. Pashnev, Yu.K. Mironov, V.E. Moiseenko, V.S. Romanov, R.O. Pavlichenko

Institute of Plasma Physics, National Science Center "Kharkov Institute of Physics and Technology",61108, Kharkov, Ukraine
beletskii@kipt.kharkov.ua

In the «Uragan-3M» torsatron with an open natural helical divertor (U-3M: l = 3, m = 9, R_o = 1 м, $\bar{a} \approx 0.12$ м, $\iota(\bar{a})/2\pi \approx 0.3$) and a plasma produced and heated by RF fields ($\omega \lesssim \omega_{ci}$), joint studies of low frequency (5-100 kHz) density (ion saturation current, I_s) and potential (floating potential, V_f) fluctuations near the plasma boundary and in the diverted plasma, were carried out, using Langmuir probe arrays. It was revealed that both diverted plasma flow (DPF) fluctuations and SOL fluctuations belonged to the higher- (lower-) frequency subrange depending on spatial probe position [1]. A supposition was made that the lower- (higher-) frequency fluctuations were associated with trapped ion (electron) loss.

Investigations of density fluctuations with the use of probability distribution function (PDF) analysis were carried out too [2]. Basing on comparison of the 3d (skewness, S) and 4th (kurtosis, K) moments evolution with spectral characteristics of fluctuations, on the one hand, and other U-3M diagnostics results, on the other hand, we made the next conclusions:

- Relatively large K of I_s fluctuations PDF in DPFs on the ion toroidal $\boldsymbol{B}\times\nabla B$ drift side is apparently concerned with significant amount of fast ions [3] in these DPFs;
- Anomalous radial transport direction in the SOL depends on radial location. This radial dependence changes with plasma production and heating alteration.

In [4] it is shown that the transition to the H-like mode in the U-3M is triggered by the short-time fast ion loss increase. This mechanism comes into operation beginning with some threshold power introduced into the plasma. An evident correlation of turbulent flux and average density dynamics was observed as well. As demonstrated in [5], the phenomenon of the L-H-like transition is accompanied by the transition from Lervy to Gaussian fluctuation statistics.

In this work, an analysis of a local estimate of the wavenumber-frequency spectra S(k,ω) for the V_f is presented depending on plasma creation and heating regimes in U3-M. The results are discussed.

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1-07

PLASMA FLOWS FORMATION IN THE HELICAL DIVERTOR OF THE URAGAN-3M TORSATRON AND EFFECTS ON THESE FLOWS OF THE H-LIKE MODE TRANSITION

V. V. Chechkin, L. I. Grigor'eva, I. M. Pankratov, A. A. Beletskii, A. A. Kasilov, V. Ye. Moiseenko, V. K. Pashnev, A. V. Lozin, S. A. Tsybenko, R. O. Pavlichenko, A. S. Slavnyj, N. B. Dreval, A. Ye. Kulaga, N. V. Zamanov, Yu. K. Mironov, V. S. Romanov, S. M. Maznichenko,Ye. D. Volkov

Institute of Plasma Physics, NSC KIPT, Kharkov, Ukraine

In the Uragan-3M torsatron (l = 3, m = 9, R_0 = 100 см, $\bar{a} \approx$ 12 см, $\iota(a)/2\pi \approx$ 0,3, $B_\phi \lesssim$ 1 T) the whole magnetic system is enclosed into a large vacuum chamber, its volume being ~200 times larger than the confinement volume. Thereby an open natural helical divertor is realized. The fuelling gas (hydrogen) is bled into the vacuum chamber continuously. The plasma with the average density $\bar{n}_e \lesssim 2\times10^{12}$ is produced and heated by RF fields in the Alfven range of frequencies ($\omega \lesssim \omega_{ci}$) with the use of an unshielded frame-like antenna with a broad spectrum of parallel wavelengths.

Recently [1] under similar conditions, a strong vertical asymmetry was revealed of diverted plasma flows (DPFs) outflowing into the gaps between the helical coils. The asymmetry manifested itself in the larger DPFs (presented by the ion saturation current to an electric probe) recorded on the ion $B\times\nabla B$ side ("ion side"), with ions dominating in the corresponding current to the earthed probe (positive "plasma current"). On this basis, it was suggested and confirmed by numerical modeling [1] and direct measurements [2] that the asymmetry was caused by the direct ion loss.

For the work being presented a non-steady state regime of the U-3M operation has been chosen with passing over the L- and H-like mode states, and it is examined how the diverted plasma parameters (DPF magnitude, electron density and temperature, ion energies on the ion and electron sides) change in these states. To do this, arrays of electric probes and grid analyzers arranged in the gaps between the helical coils [1, 2] are used. A recently-made conclusion [3] is confirmed that the diverted plasma parameters are strongly affected by the plasma produced by the RF antenna outside the confinement volume. It is shown that the direct electron loss also makes a substantial contribution to the DPFs vertical asymmetry. Direct measurements confirm one more conclusion independently deduced in [3] that the H-like mode transition results in the plasma loss reduction mainly through the electron channel.

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1-08

THE PROBLEM OF PLASMA DENSITY INCREASING IN THE U-3M TORSATRON AFTER THE RF-HEATING SHUTDOWN

V.K. Pashnev, I.K. Tarasov, D.A. Sitnikov, V.N. Bondarenko, A.N. Shapoval, R.O. Pavlichenko, M.I. Tarasov, E.L. Sorokovoy, A.A. Petrushenia, A.I. Skibenko, L.L. Karpuhin, V.E. Moiseenko, A.V. Lozin

Institute of Plasma Physics, National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine

The plasma density rise is observed for the low collisionality regimes of plasma confinement in the U-3M torsatron after the RF-heating pulse termination. The process of chord averaged density rise lasts for less than 3 ms and the maximal density is approximately 4 times higher than those measured during the RF-power injection phase [1].

One possible mechanism of this phenomenon is connected with the presence of a longitudinal plasma current during RF-pulse, i.e., the density rise has to correlate with current decay. It was also shown experimentally that the density rise is accompanied the H_α profile sharpening. Thus, an assumption was made that the density rise is caused by the plasma compression due to electric field which occurs during the plasma current decay.

In this work we present the experimental data which show that the current decrease correlates with the plasma column size reducing.

The maximal plasma density rises up to $6 \cdot 10^{12}$ cm^{-3} in comparison with density at the stationary stage of the RF-discharge when the maximal density does not exceed $3.2 \cdot 10^{12}$ cm^{-3}.

Basing on equations of magnetic hydrodynamics under condition of poloidal magnetic field flow conservation the expression for the plasma compression speed was obtained. The expression allowed to carry out some theoretical estimations for the real experimental conditions. The influence of the trapped particles drift on the plasma density rise was also studied and will be discussed in presentation.

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1-09

MODELING OF SOME NONSTATIONARY PROCESSES IN TOKAMAK PLASMAS

M.A. Borisov, S.V. Cherkasov, A.V. Danilov, Yu.N. Dnestrovskij, A.Yu. Dnestrovskij,
*A. Field, S.E. Lysenko, *H. Meyer, V.A. Vershkov
National Research Centre 'Kurchatov Institute', Institute of Tokamak Physics,
123182 Kurchatov Sq 1, Moscow, Russia
**Culham Science Centre, Abingdon Oxon OX14 3DB, UK*

The results of modeling of shots from two series of experiments in two tokamaks with rather different geometric parameters are presented. The first one includes two shots from the spherical tokamak MAST with current rump up, and the second one – a number of T-10 shots with periodic gas puffing. The modeling was performed with the ASTRA code in the framework of Canonical Profiles Transport Model (CPTM) [1].

The motivation for the current rump up pulses modeling was the solution of the issue, whether the neoclassical conductivity is suitable for the description of the current diffusion in the MAST. The MSE safety factor measurements carried out in this tokamak during last few years provided possibility to answer this question. The answer was "yes", and therefore this conductivity was used further for the description of the discharge evolution. This conclusion is somewhat different from the results of previous work on this topic [2], one of the possible reason might be the different representation of plasma boundary in the codes (3 moments in ASTRA and 6 moments in TRANSP).

The results of modeling for two MAST discharges: Ohmic (#24433) and NBI-heated (#24434) are presented. For both pulses the plasma current rumped up during 170 ms until the value of 0.85 MA, while the chord averaged plasma density until 3.5×10^{19} m^{-3} during 200 ms, the magnetic field was 0.5 T, the NBI power deposition for the pulse #24434 was at the level of 1.5 MW. The modeling was performed in two stages. In the first stage only the plasma current distribution was modeled with prescribed electron and ion temperatures and plasma density. Then the full transport model was used. Two expressions for neoclassical conductivity were under study: Hirshman conductivity [3] and Sauter-Angioni conductivity [4]. In both cases the simulated safety factor profiles met the MSE measurements and the agreement was even better for more simple Hirshman expression.

The experiments with periodic gas puffing have proved to be a powerful tool for plasma diffusion investigation [5]. The new series of T-10 experiments was carried out in 2011 in ohmic discharges with the toroidal magnetic field B_T=2.4 T, current I_p=200 kA and densities 1.7, 2.5 and 3.5×10^{19} m^{-3}, and for density 2.5×10^{19} m^{-3} with currents 130, 200 and 300 kA. The attempt to explain the experimental spatial distribution of modulation amplitudes and phases by means of simple diffusion model with constant in time diffusion coefficient and pinch velocity failed in the case of higher densities, so a complex model with periodic variation of parameters has to be constructed. However, the usual version of the CPTM model with constant in time coefficients demonstrates the capability to meet the experimental profiles of modulation amplitude and phase shift.

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1-10

EFFECT OF NOBLE GAS INJECTION ON DISCHARGE DISRUPTION IN T-10 TOKAMAK

M.M.Dremin, A.M.Kakurin, V.G.Kapralov*, A.Ya.Kislov, D.A.Kislov, V.A.Krupin, S.V.Krylov, S.G.Maltsev, V.G.Merezhkin, G.E.Notkin, Yu.D.Pavlov, D.V.Sarychev, A.M.Stefanovskij

National Research Center «Kurchatov Institute», Moscow, Russian Federation
** State Polytechnic University, St. Petersburg, Russian Federation*

Results of investigation of noble gas injection effects on discharge disruption in T-10 tokamak in a discharges with plasma current 250 ÷ 300 кA and q = 3 ÷ 2,4 are presented. Disruptions were initiated by different methods – density rump-up to the limit level and/or injection of deuterium or impurity pellet. Injection of noble gases (He, Ar, Xe) was produced both during steady state and during current quench phase of discharge disruption. The main plasma parameters during current quench phase were estimated by means of spectroscopic diagnostic. It was found that current quench during discharge disruption develops in two phases (slow – up to $I_p \sim 30$ MA/s and fast – up to 80 MA/s) which characterizes by a different time scales and different time duration. It was shown that injection of deuterium pellets don't change the current quench behavior (at least – at their parameters provided by available injector) seemingly due to low plasma temperature during this phase of disruption. While noble gas puffing with high pressure jets (up to 60 atm with particle flow up to 10^{24} s^{-1}) from newly developed fast electromagnetic valve near the plasma boundary (massive gas injection – MGI) it could be possible to transfer current quench from slow to fast phase, and initiate a secondary MHD-perturbation (identified by negative loop voltage spikes) during not too fast current rump-down $\tau = I/\dot{I} \geq 10$ ms. Range of τ values with negative spike generation don't depend practically on gas species and pressure. In special discharge scenarios favouring runaway beams formation during current quench phase their development could be suppressed by well-timed injection of gas jet.

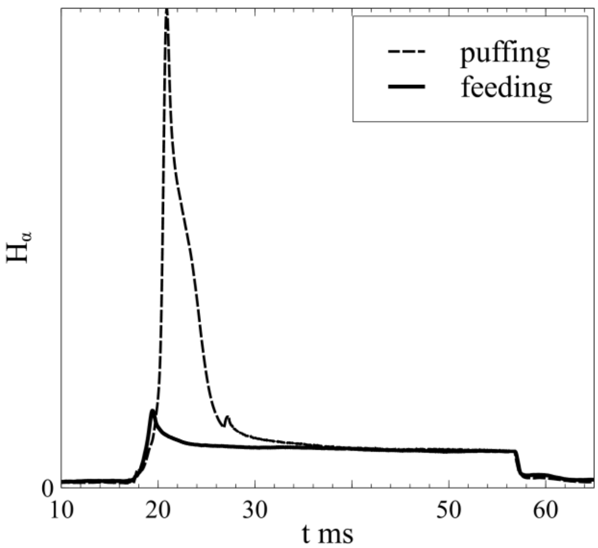
1-11

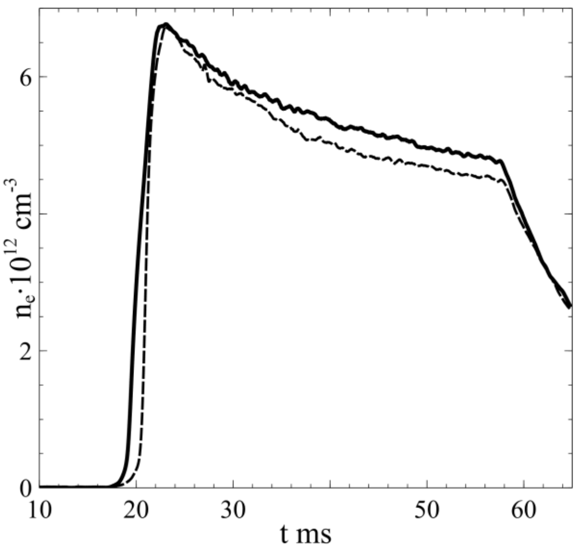
U-3M PLASMA START-UP SCENARIO SUSTAINED BY GAS PUFFING AS A DIFFERENT PLASMA CONFINEMENT SCENARIO; FIRST RESULTS.

M. Dreval, E L Sorokovoy, Yu.K. Mironov, R.O. Pavlichenko, A.V. Lozin, V.S. Romanov and V. K. Pashnev

IPP NSC Kharkov Institute of Physics and Technology, Kharkov, Ukraine

The U-3M plasma volume is about 0.2 m^3 and its chamber volume is about 70 m^3. Evidently, substantial flux of the neutrals with mean free path longer than U-3M plasma size from large U-3M vacuum vessel sustains main channel of the ion energy loss via the CX collisions. In order to reduce flux of the neutrals different discharge start-up scenario has been proposed. Absence of constant working gas feeding in this scenario open a possibility to reduce working gas pressure in the U-3M vessel. Time of the U-3M vessel filling by the hydrogen gas after sharp gas puffing (GP) pulse is about 10-20 ms according to the test experiments. In discharges with 5-6 kV in the RF generators and proposed GP start-up scenario a delay between GP pulse and plasma creation was smaller when the GP filling time. This is an indication that GP stream injected into the plasma volume is ionized faster than gas outflow from the injection region to the U-3M vacuum vessel. The GP injection into the frame antenna plasma region was controlled by computer-based system and piezoelectric valve. A remaining between pulses pressure of the hydrogen was about 10^{-6} Torr in the GP discharges and about $2 \cdot 10^{-5}$ Torr in conventional gas feeding discharges. Same level of the electron density has been achieved in the discharge under consideration and conventional 5-6 kV discharge maintained by the constant gas feeding only. An emission of the hydrogen line H_α was monitored in the GP injection region. Different behavior of the hydrogen emission line H_α has been observed in proposed and conventional discharges. The H_α emission waveform in the considered discharges is similar to its waveforms in the conventional devises where chamber and plasma sizes are close each other. This is an indication that considered scenario is promising for achievement of similar to conventional toroidal devises discharge in the chamber-less torsatron U-3M.





1-12

AUXILIARY ECR HEATING SYSTEM FOR THE GAS DYNAMIC TRAP

A. G. Shalashov[1], E. D. Gospodchikov[1], O. B. Smolyakova[1],
P.A. Bagryansky[2], V. I. Malygin[1], M. Thumm[3]
[1]*Institute of Applied Physics of the Russian Academy of Sciences,*
Ulyanova str. 46, 603950, Nizhny Novgorod, Russia

[2]*Budker Institute of Nuclear Physics of the Siberian Branch of the Russian Academy of Sciences, akademika Lavrentieva prospect 11, 630090, Novosibirsk, Russia*

[3]*Institut für Hochfrequenztechnik und Elektronik, Karlsruhe Institut für Technologie, Engesserstraße 5, 76131, Karlsruhe, Germany*

Physics aspects of a new system for electron cyclotron resonance heating (ECRH) at the magnetic mirror device Gas Dynamic Trap (GDT, Budker Institute, Novosibirsk) are discussed. This system based on two 400 kW / 54.5 GHz gyrotrons is aimed at increasing the electron temperature up to the range 250–350 eV for improved energy confinement of hot ions. The key physical issue of the GDT magnetic field topology is that conventional ECRH geometries are not accessible. The proposed solution is based on a peculiar effect of radiation trapping in inhomogeneous magnetized plasma. Under specific conditions oblique launch of gyrotron radiation results in generation of right-hand-polarized (R) electromagnetic waves propagating with high $N_{\|}$ in the vicinity of the cyclotron resonance layer, which leads to effective single-pass absorption of the injected microwave power. In the present paper we investigate numerically an optimized ECRH scenario based on the proposed mechanism of wave propagation and discuss the design of the ECRH system which is currently under construction at the Budker Institute [1].

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1-13

MEASUREMENTS OF PLASMA DENSITY IN URAGAN-3M TORSATRON USING DUAL-POLARIZATION INTERFEROMETRY

V.L. Berezhnyj, V.V. Filippov, D.L. Grekov, K.K. Tretyak

Institute of Plasma Physics, National Science Center "Kharkov Institute of Physics and Technology", Akademicheskaya str. 1, 61108 Kharkov, Ukraine

Ordinary (O-) mode interferometry is well known and commonly used plasma diagnostic. The O-mode wave number depends only on plasma density in the case of perpendicular to the confining magnetic field probing:

$$k_O = \frac{\omega}{c}\sqrt{\varepsilon_3},\ \varepsilon_3 = 1 - \frac{\omega_p^2}{\omega^2}.$$

So, O-mode phase shift

$$\varphi_O = 2\int_{-a}^{a} k_O dl$$

is proportional to an average plasma density $\bar{n}$ along the chord of probing for the wave frequency ω greater than plasma frequency ω_p.

For extraordinary (X-) mode perpendicular probing

$$k_X = \frac{\omega}{c}\sqrt{\frac{\varepsilon_1^2 - \varepsilon_2^2}{\varepsilon_1}},\ \varepsilon_1 = 1 - \frac{\omega_p^2}{\omega^2 - \omega_e^2},\ \varepsilon_2 = \frac{\omega_e}{\omega}\frac{\omega_p^2}{\omega^2 - \omega_e^2},$$

and X-mode phase shift depends on plasma density and confining magnetic field distributions. As magnetic field is known for torsatron-type devices, additional information on plasma density profile can be inferred from the X-mode phase shift measurements. For example, this may be plasma density profile peakedness $\bar{n}/n_0$, where n_0 is the plasma density in the centre of minor cross-section (it is supposed that plasma profile is monotonic).

The dual polarization interferometer was placed very close to E-E minor cross-section of U-3M torsatron. For details of experimental setup see [1]. First measurements of phase shifts were made. The interpretation of obtained results will be presented.

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1-14

RADIO-FREQUENCY EQUIPMENT FOR URAGAN STELLARATORS

Kramskoy E.D., Korovin V.B., Moiseenko V.E.
Institute of Plasma Physics NSC "KIPT', Kharkov, Ukraine

The description of technical devices that constitute a high-frequency complex for plasma production and heating in the Uragan-2M stellarator [1] is given. Design of the high-voltage high-frequency pulse generator "Kaskad" ("Kaskad-1", "Kaskad-2") is described, the analysis of its schematic diagram is provided. The high-frequency vibrations' generators are single-staged; they are assembled according to the push-pull autogenerator's circuit with the "GI-26A" valves. 2 valves are powered up by parallel connection in each autogenerator's shoulder for high-frequency current increase under the given anode voltage [5]. The distinct feature of high-frequency generators which are used for plasma production is a very wide range of loading resistance values: during the impulse the resistance changes from very high values (when the generator is working on no-load mode before the beginning of the neutral gas break-down in a stellarator) to several Ohms - when plasma is created. The thyristor multistage anode modulator provides gradual increase of the voltage to avoid high voltage peaks on feed-throughs.

Various matching devices that provide generator output resistance matching with the load (adjusted to antenna loading resistance) have been designed aiming to transmit maximum generator power to antenna [2]. The matching circuit with an additional parallel oscillatory circuit is used in the design of the matching devices. High-frequency wave power which is transmitted to the antenna - $P_н$ - is chosen as a criterion for the matching degree. The power was defined by measuring the incident and reflected wave levels ratio in the high-frequency cable.

When carrying out experiments on Uragan-2M antennas of various design and inductance values (0.3 μH - 1.32 μH) were used. A small frame antenna with water cooling is used for cleaning stellarator vacuum chamber by high-frequency discharge of 132 MHz in continuous mode. A frame-type antenna with inductance of 1.32 μH is used for creating pulse high-frequency discharge in plasma [4]. Resistance $r_н$ which is brought into such antenna's circuit by plasma is 0.5 - 6 Ohm [6]. The "crankshaft"-type antenna with inductance La=0.49 μH or the 4 strap-type antenna (inductance value altogether with feed-through is 0.2 μH) is used for further plasma heating [7]. For this antenna a special matching device was developed that realizes the schema of a compound capacitive connection with generator's circuit [3].

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1-15

MEASUREMENTS OF WALL CONDITIONING RATE AT URAGAN-2M

V.B. Korovin, E.D. Kramskoy, V.E. Moiseenko, D.I. Baron, S.M. Maznichenko, S.I., Solodovchenko, V.Ya. Chernishenko, A.F. Shtan.
Institute of Plasma Physics NSC "KIPT', Kharkov, Ukraine

Uragan 2M is a medium size stellarator with the chamber made of stainless steel. The volume of the vacuum chamber is 3.88 м3, the volume occupied by the plasma is 1.48 $м^3$. According to the calculations, the volume of the chamber altogether with the drainage branch pipes is 4.2 $м^3$. Uragan-2M chamber is pumped out by 3 turbo-molecular pumps. There is a cryogenic trap in the input branch pipe of one of the pumps.

Under RF cleaning CO, H_2, H_2O, CH_4 volatile species are found in the pumped out gases [1]. When cooling the trap with liquid nitrogen some of these gases will condense at its surface [2].

During the process of radio-frequency (RF) chamber cleaning the cryogenic trap is pumping. Afterwards the trap was cut-off from the vacuum chamber heated up. The cutted – off brunch pipe segment with the cryogenic trap inside it has a volume around 35 l, the active surface area is 0.105 m^2. As the trap surface temperature increases and condensate evaporates, the pressure inside the segment increases. The pressure was measured by the ionization vacuum meter, and the amount of pumped out of the chamber gas was than estimated.

For radio frequency wall conditioning the ultrahigh frequency generator is constructed with GI-4A tube according to the single-cascade generator design that operates in continuous mode at frequencies 132-136 MHz. The anode voltage varies from 1 to 5.5 kV. The generator feeds for the frame-type antenna with water cooling.

At the first stage functionality was checked and method sensitivity was defined. The maximum pressure of $5 \cdot 10^{-1}$ Torr is the limiting factor for the experiment. Therefore, to fit this requirement, the "exposition" period (i.e. the cleaning period) is varying experimentally. The verification has shown that the "exposition" period should be around 1 hour of the RF cleaning. Respectively, 1 hour time period was chosen for the experiments.

After Uragan-2M chamber RF cleaning for 12 hours a day during 2 weeks with the following vacuum pumping out the effectiveness of RF cleaning was estimated.

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1-16

MAGNETIC SURFACES OF A COMBINED MAGNETIC SYSTEM

V.G. Kotenko [1], V.E. Moiseenko [1], Yu.F. Sergeev [1], E.L. Sorokovoy [1], O. Ågren [2]

[1]*Institute of Plasma Physics, National Science Center "Kharkiv Institute of Physics and Technology" Akademichna 1, 61108 Kharkiv, Ukraine*
[3] *Ångström Laboratory, Uppsala University,SE-75121 Uppsala, Sweden*

The existence of closed magnetic surfaces of a combined magnetic system is shown by numerical simulations. The numeric model contains a magnetic system of the *l=2* torsatron with the coils of an additional toroidal magnetic field and the mirror-type magnetic system. The mirror-type magnetic system is realized by switching off one of the coils of an additional toroidal magnetic field. Numerical studies were undertaken to study finite width and other peculiarities of the U-2M torsatron helical coils and the coils of the additional toroidal magnetic field.

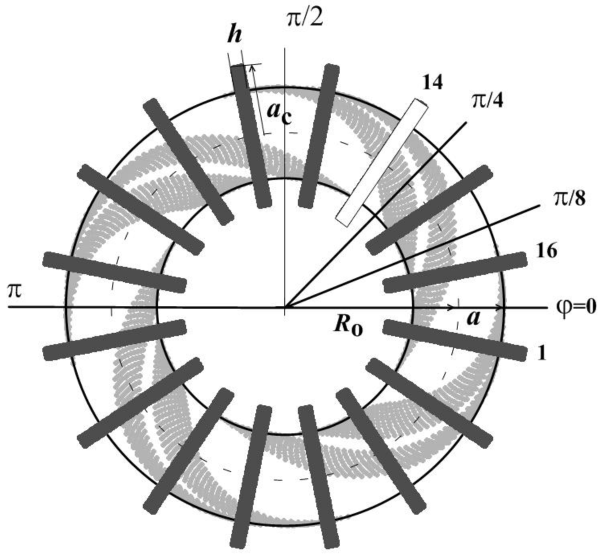

Fig.1. Top view of the magnetic system of the *l*=2 torsatron numeric model. The position of dead coil 14 of the additional toroidal magnetic field is indicated.

As a result, the cross-section of the magnetic surface configuration is brought to agreement with the extension of the U-2M torsatron vacuum chamber, and there appear a magnetic field ripple with an acceptable magnitude within the context of the proposal [1].

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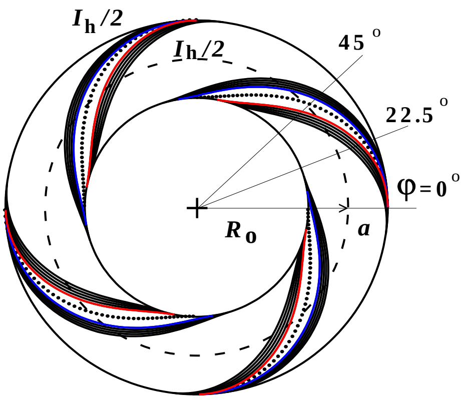
1-17

SPECIAL CORRECTING WINDING FOR *l*=2 TORSATRON WITH INTERNAL SPLITTING OF HELICAL COILS

V. G. Kotenko

Institute of Plasma Physics, National Science Center "Kharkiv Institute of Physics and Technology" Kharkiv 61108, Ukraine

The standard (external) splitting of helical coils of the *l*=2 torsatron toroidal magnetic system into two equal parts is promising for fusion reactor magnetic system [1, 2]. In this paper the *l*=2 torsatron toroidal magnetic system with non-standard (internal, [3]) splitting of helical coils into two equal parts is discussed to complete the information. In this system unlike the system with standard (external) splitting of the helical coils, maximum helical coil splitting is observed on the minor torus equator, and the split-type coils have the points of contact on the major torus equator (see Fig.1 a). The numerical calculations were carried out to show that the non-standard (internal) split-type special correcting winding (i-split-type SCW, see Fig.1 b) gives the possibility of controlling the position of the magnetic surface configuration in the direction perpendicular to the torus equatorial plane. The i-split-type SCW magnetic field influence on the magnetic surface parameters has been studied. It turns to be analogous the influence of the split-type SCW [4] for the *l*=2 torsatron magnetic system with standard (external) splitting of helical coils. An idea on the i-split-type SCW magnetic field structure is obtained by numerical simulations on the effect of this field as a minority magnetic field imposed on the magnetic field of a well-known configuration.



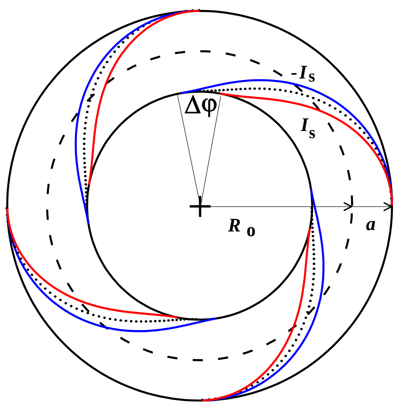


Fig.1. Top view of internal split-type main helical coils of the calculation model (*a*) and, separately, the internal split-type SCW (*b*), Δφ is the toroidal angle of splitting. The helical base lines are shown as dotted lines. The toroidal azimuths of poloidal cross-sections are indicated. The additional magnetic field coils are not shown.

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1-18

FEASIBILITY OF CREATING ISLAND DIVERTOR IN THE URAGAN-2M TORSATRON

G.G. Lesnyakov, A.N. Shapoval, O.S. Pavlichenko

Institute of Plasma Physics, National Science Center "Kharkiv Institute of Physics and Technology", 61108 Kharkiv, Ukraine

Magnetic configuration of the Uragan-2M torsatron with additional toroidal magnetic field looks like to be a quite complicated in the view of a feasibility of the scheme with divertor:

- practically, in all magnetic configuration regimes, which are suitable for operation with plasma, the separatrix of the natural magnetic divertor cannot be inscribed into the size of the vacuum chamber;
- in many possible operational regimes the plasma diffusing out of the confinement volume streams along magnetic field lines of a broad ergodic region to the wall near apexes of elliptical-shape magnetic surfaces;
- besides, practically in most cases, the separatrix of magnetic islands and its vicinity are usually disrupted at the edge of the confinement volume and formed the distributed region of the plasma that is predominantly outflowing to the vacuum chamber wall.

Therefore, it seems that the only proper conception still to make the helical divertor is an island divertor conception. This conception must be based on such configuration regimes when large in size magnetic islands, or their remains, exist at an edge of the region with closed magnetic surfaces.

The experimental investigations of magnetic field structure carried out with the use of the method of scanning luminescence rod, together with numerical investigations, allow to find a few configuration regimes with islands realizing at the $i/2\pi=1/3$ and 2/5 rotational transforms and located outside the last closed magnetic surface, as well as to track magnetic field lines in vicinity of islands and in an ergodic region. The indicated island structures could be cut off by the vacuum chamber wall however this process could be controlled by changing the vertical magnetic field. In another version of the feasibility of the island divertor conception, when the islands are located inside but close to the last outermost magnetic surfaces, a moving local limiter can be used.

1-19

USAGE OF THREE-HALFTURN ANTENNA AT THE URAGAN-3M DEVICE

A.V. Lozin, V.E. Moiseenko, L.I. Grygor‘eva, M.M. Kozulya, A. Yu. Krasyuk, A.E. Kulaga, E.D. Kramskoy, S.M. Maznichenko, Yu.K. Mironov, R.O. Pavlichenko, N.V. Zamanov, V.S. Romanov, V.Ya. Chernyshenko, V.V. Chechkin, and team of torsatron “Uragan-3M”

National Science Center ‘‘Kharkiv Institute of Physics and Technology”, Akademichna St. 1, Kharkiv, Ukraine

Three-halfturn (THT) antenna is regularly used at “Uragan-3M” device for Alvén plasma heating, while initial plasma is created with loop antenna which pulse precedes THT antenna impulse. The characteristic feature of this THT antenna regime is a possibility of operation at low initial neutral gas pressure ~3-5·10^{-6} Torr. Plasma density increases gradually during impulse and can approach 10^{13} cm^{-3}. Mainly plasma electrons are heated up to the temperature about 100 eV.

RF power was supplied to antenna in a programmable way (by three-step increase) to the Uragan-3M plasma with the aim of keeping minimal start-up time of discharge and minimizing the antenna voltage. However, the programmable steps don’t guarantee reproducible plasma generation (no gas breakdown occurs with probability of 3%). Moreover, the discharge start-up time (Δt) randomly deviates within the margins of 3-7 ms, that doesn’t allow maintaining stationary regime in reproducible way. THT antenna doesn’t create dense plasma in standard regime of “Uragam-3M” (toroidal magnetic field ≈0.72 T, RF heating frequency 8.6MHz), but low dense plasma ≈10^{10} cm^{-3} is created sufficiently stably. This effect can be explained by slow wave generation that is excited by THT antenna via electrostatic mechanism. Experiments show that such plasma is quite suitable as initial for further stable production of dense plasma with the help of loop antenna.

Decrease of magnetic field decreases a critical density value, starting from which Alvén resonances appear in plasma column. As soon as this value gets less than the plasma density created with the slow wave, plasma production becomes possible in the relay-race mode regime [1]. It’s experimentally shown that THT antenna impulse creates high temperature dense plasma at magnetic field less than 0.7 T without pre-ionization, and plasma creation delay time decreases with magnetic field.

Simultaneous work of loop and THT antennas provided high temperature dense plasma during whole impulse at magnetic field 6.8 T. The role of THT antenna was to create target plasma and to maintain plasma parameters both simultaneously with loop antenna and after loop antenna switch-off.

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1-20

ELECTRIC FIELDS STUDY WITH HIBP IN OH AND ECRH PLASMAS ON T-10

A.V. Melnikov[1], K.S. Dyabilin[1], L.G. Eliseev[1], M.Yu. Isaev[1], I.A. Krasilnikov[1], L.I. Krupnik[2], S.E. Lysenko[1], V.A. Mavrin[1], S.V. Perfilov[1], V.I. Zenin[1], and HIBP team[1, 2]

[1] *Institute of Tokamak Physics, NRC "Kurchatov Institute", Moscow, Russia*
[2] *Institute of Plasma Physics, NSC KIPT, 310108 Kharkov, Ukraine*

The direct measurements of the electric potential φ in the core plasma are very important for understanding of the role of the radial electric field E_r as the confinement regulating mechanism. The new observations of the potential evolution were performed in the T-10 tokamak (B_0=1.5-2.5 T, R=1.5 m, a=0.3 m) with Heavy Ion Beam Probing (HIBP) in a wide range of densities $\bar{n}_e$=(0.6-4.7)×10^{19} m^{-3}. Ohmic (OH) and ECRH D_2 plasmas (T_e<1 keV, T_i<0.7 keV) are characterized by a negative potential up to φ(0)=-1400 V at the centre and monotonically increasing towards the edge. The density rise due to gas puffing is accompanied by an increasing the absolute value of the negative potential. Correspondingly, the average E_r increases from -18 V/cm to -60 V/cm. This is valid both for the steady-state plasmas and for the initial stage with ramped plasma current and density. When the density approaches a certain value $\bar{n}_e$=2.5-3.5×10^{19} m^{-3}, the growth of potential saturates, while the plasma stored energy is still growing with density. Note, that in the NBI heated regimes in the TJ-II stellarator, φ also saturates, when the density is about $\bar{n}_e$= 3.5×10^{19} m^{-3} [1]. Powerful electron cyclotron heating (ECRH, P_{EC}< 3 MW) leads to the increase of T_e up to 3 keV, diminishing of the central line-averaged density ("pump-out") up to $\Delta n_e/n_e$ <30% and the decrease of the absolute potential value, Δφ=200-400 V. Δφ is constant, ~400 V, independently on the density up to $\bar{n}_e$=2.5×10^{19} m^{-3} and then decreases up to 200 V, when the density raises up to 5×10^{19} m^{-3}. At the very low density, $\bar{n}_e$=(0.6-0.8)×10^{19} m^{-3}, the edge E_r decays up to zero. The ECR heating leads to the formation of the positive edge E_r.

Neoclassical modeling (both analytical and numerical VENUS+δf code [2], taking into account the toroidal field ripple) agrees with measured φ profiles. When the ion and electron temperatures are comparable, T_e/T_i ~1, the ion flux dominates and E_r<0. When T_e/T_i >>1, E_r may be positive because the ion and electron fluxes become comparable.

In summary, these results present the important features of φ profiles and non-linear links between the potential and the energy confinement.

Acknowledgments

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1-21

TOPOLOGICAL GROUNDS FOR THE FAST KINEMATIC DINAMO ORIGIN IN A KNOTTED THERMONUCLEAR REACTOR

Maksyuta M.V., Golovach G.P., Martysh Ye.V.

Taras Shevchenko Kyiv National University, Radiophysical Department

The paper [1] deals with the construction of so-called knotted thermonuclear reactor where according to the preliminary estimations the origin of poloidal-toroidal magnetic surfaces capable to quite an effective high-temperature plasma confinement is possible. Naturally, to prove it convincingly it is necessary to trace the evolution of very strong mutual-each other stipulated distributions of hydrodynamic $\vec{v}\ \ t$ velocities and $\vec{B}\ \ t$ magnetic field in such a "knotted plasma". For this, at least, we must solve the following equation system of the ideal magnetic hydrodynamics (see, for example, [2]):

$$\frac{\partial \vec{v}}{\partial t} = -\ \ \vec{v},\nabla\ \ \vec{v} + \ \ \mathrm{rot}\,\vec{B}\ \ \times \vec{B} - \nabla p, \quad \frac{\partial \vec{B}}{\partial t} = \mathrm{rot}\left[\vec{v},\vec{B}\right], \quad \mathrm{div}\,\vec{v} = \mathrm{div}\,\vec{B} = 0\,,$$

since in the first approach plasma can be treated non-compressible and carrying a "frozen" divergenceless magnetic field $\vec{B}$ (the coefficients in these equations are normalized by a proper choice of measurement units). However this problem can be treated in another way: without solving these non-linear equations in quite a complicated knotted region M , trying to substantiate the origination of exponentially increasing magnetic field in the conditions of a fast kinematic dinamo (so the velocity field $\vec{v}\ \ t$ is called) by means a number of topologic characteristics. For example as it follows from [3], one of the most important topologic characteristics for the divergenceless vector field which is the magnetic field $\vec{B}$ inside a knotted thermonuclear reactor is a spirality κ, which is proportional to a linkage coefficient lk of any two $\vec{B}$ vector field lines: $\kappa\ \ \vec{B}\ \ = lk \cdot Q^2$, where Q – a field $\vec{B}$ stream through any section of a knotted volume. It helps to determine a lower border of a magnetic field $\vec{B}$ energy: $E \geq C\left|\kappa\ \ \vec{B}\ \ \right|$, where C – a positive constant depending on a form and a dimension of a compact region M [3].

Thus, to the grounds shown in [1], the given paper deals with the additional arguments in favour of plasma confinement in multiple knotted volumes since their complicated topology by itself leads to the self-confined strong magnetic fields origin which may contribute to thermonuclear synthesis reaction rise.

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1-22

ENERGY AND PITCH-ANGLE DISTRIBUTION OF THE PROMPT LOSSES IN TOKAMAK WITH NON-CIRCULAR CROSS-SECTION

A.O. Moskvitin[1], V.O. Yavorskij[2,3], V.Ya. Goloborod'ko[2,3],
Yu.K. Moskvitina[4], O.A. Shyshkin[1]
[1] *V.N. Karazin Kharkiv National University, Ukraine, Kharkiv*
[2] *Institute for Nuclear Research, Ukrainian Academy of Sciences, Ukraine, Kyiv,*
[3] *Association EURATOM-OEAW, Institute for Theoretical Physics, Austria, Innsbruck*
[4] *National Science Centre "Kharkov Physics and Technology Institute", Ukraine, Kharkiv*
E-mail: Anton.Moskvitin@gmail.com

Charged fusion product (CFP) losses together with neutron fluxes are expected to cause main damage of a fusion reactor first wall. Accurate simulation of fast ion (FI) dynamics in tokamaks is important for predicting the heat load in future fusion reactors [1]. The identification and interpretation of the loss mechanisms of FI in present day tokamak plasmas [2-4] needs precise modeling of the lost FI spatial and velocity distributions. Typically, relevant simulations are based on Monte Carlo approaches [5,6]. A detailed predictive modeling of FI loss distributions requires the development of new approaches [1,4] or at least a substantial improvement of the existing methods [7, 8].

Technique of calculation the pitch-angle, energy and poloidal distributions of the flux of CFPs, lost to the first wall of axisymmetric tokamak due to first orbit (FO) loss mechanism is developed. This technique extends the approach for evaluation the poloidal distributions of FO loss of CFPs in tokamaks proposed in [7]. The upgraded technique enables to calculate distributions of lost FIs in wide class of tokamak magnetic configurations. Analytical model of the magnetic field used in this study [9] takes into account Shafranov shift, elongation, triangularity and up-down asymmetry. Using this model, it is also possible to carry out test particle simulations using the same numerical model of the magnetic configuration [4]. Smooth axially symmetric 2D wall is assumed here. The spatial and velocity dependence of the CFP source is taken into account in the developed approach. Treatment in terms of constants of motion (COM) space allows substantial reducing the computational efforts for simulation the lost particles flux at a given point of the first wall. The effect of finite Larmor radius is taken into account in the developed approach by appropriate modification of the boundary values of motion invariants.

The theoretical basis of the developed code is presented along with results of the test runs of this code. All test runs were provided for tritons with energy about 1 MeV. Cross-check of the newly upgraded approach against full orbit calculations is presented and it shows reasonable agreement. Statistical uncertainties are estimated.

The developed approach is useful for simulation the pitch and energy distributions of FIs lost to the scintillator detector [10] in present-day tokamaks [2,3] as well as for calculation of the CFP fluxes to the plasma-facing wall in future tokamak-reactors [5,6].

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1-23

INFLUENCE OF BACKGROUND PLASMA ON DENSITY OF RF FIELD ENERGY AND OHMIC LOSSES IN WALLS OF COAXIAL GYROTRON CAVITY

Yu.K. Moskvitina[1,2], G.I. Zaginaylov[1,2], V.I Tkachenko[1,2]

[1] *National Science Centre "Kharkov Physics and Technology Institute", Ukraine, Kharkiv*
[2] V.*N. Karazin Kharkiv National University, Ukraine, Kharkiv*

E-mail: Yu.Moskvitina@gmail.com

Gyrotrons are seen as the most promising configurations for high-power Electron Cyclotron Resonance Heating (ECRH) and current drive in tokamaks and stellarators [1, 2]. New generation of nowadays millimeter-wave gyrotrons developed for plasma heating utilize coaxial cavities operating in high-order modes. The choice of modes is dictated by the mode selection requirements and the admissible level of the heat load on the cavity walls. These devices can deliver microwave power more than 2 MW and have potentials for further increasing power-handling capabilities. For example, 170 GHz coaxial cavity gyrotrons with 2 MW output power are regarded as potential ECRH sources in ITER [3, 4]. Low density background plasma appears in the coaxial gyrotron cavity in the long pulse regimes and can influence gyrotron operation.

In present work the effect of low density background plasma on the electromagnetic field energy density in the ITER relevant coaxial gyrotron cavity is studied. The model of cold collisionless magnitoactive plasma is used. It is assumed that plasma uniformly fills the cavity. The dispersion equation for TE modes for the case of a coaxial waveguide is derived analytically in the low density background plasma approximation. The effect of inner rod corrugation is taken into account using the impedance model. The numerical code was developed for numerical analysis of the dispersion equation. Our present study predominantly is focused on high order $TE_{34,19}$ mode, which is operational for the last version of the 170 GHz coaxial cavity gyrotron, and neighborhood modes. The dispersion relation and expression for the density of RF energy in plasma-filled coaxial gyrotron cavity are derived in the analytical form and analyzed numerically. It is shown that presence of low density plasma in coaxial gyrotron cavity effects positively on coaxial gyrotron operation leading to the increasing the volume density of RF energy inside the coaxial gyrotron cavity and decreasing Ohmic losses in walls of outer and inner conductors due to modification of the transverse field distribution.

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1-24

ENERGY AND PARTICLE FLUXES IN PRESENCE OF RMP IN AXISSYMETRIC 2D TOKAMAK PLASMAS

Yu.K. Moskvitina[1], A.O. Moskvitin[2], O.A. Shyshkin[2]
V.O. Yavorskij[3,4] V.Ya. Goloborod'ko[3,4]
[1] *National Science Centre "Kharkov Physics and Technology Institute", Ukraine, Kharkiv*
[2] *V.N. Karazin Kharkiv National University, Ukraine, Kharkiv*
[3] *Institute for Nuclear Research, Ukrainian Academy of Sciences, Ukraine, Kyiv,*
[4] *Association EURATOM-OEAW, Institute for Theoretical Physics, Austria, Innsbruck*
E-mail: Yu.Moskvitina@gmail.com

The confinement of energetic ions such as charged fusion product (CFP) is essential to maintain burning plasma conditions. The fusion energy carried by CFP should be transferred to the background plasma in order to maintain ignition and, on the other hand, these fusion product ions should be removed partly thermalized for decreasing radiation energy loss.

While in many studies the tokamak has been associated with an axisymmetric configuration, the real toroidal magnetic field lines will always exhibit undulations. We focus our present study on fusion $\alpha-$particle losses driven by RMPs which are used for mitigation of edge localized modes (ELMs) [1]. Besides that, simulations for $D-{}^{3}He$ fusion protons were carried out as well.

A natural consequence of RMP excitation is the formation of magnetic islands together with stochastic magnetic layers at the plasma edge. The formation of these resonant magnetic field structures are associated with irregularities of the energetic α-particle orbits, which can substantially increase the loss of fast ions from the plasma periphery. [2-3].The modification of edge transport properties of fusion products can be regarded as the crucial point for approving the application of RMPs on future fusion reactors, e.g. ITER [4].

For this purpose a specific numerical code IFOSIT (Ion Full Orbit Simulation in Torus) was developed [5], which simulates the dynamics of the particle ensemble. The simulation is based on the test-particle approach. To calculate each particle trajectory the numerical solution of the full orbit equation is performed by the Runge-Kutta method. Coulomb collisions are taken into account by a 3-dimensional Monte Carlo operator employing a continuous spectrum of random velocity changes [6]. The magnetic field model of the original IFOSIT code was improved by the analytical model of the magnetic field, which takes into account Shafranov shift, elongation, triangularity and up-down asymmetry [7]. Besides that, the spatial and velocity dependence of the CFP source can be taken into account in the renewed code now as well. Smooth axially symmetric 2D wall is assumed here. Optimized calculation procedures gives an opportunity to increase number of particles in simulated ensemble and to estimate statistic uncertainties. New options are employed in renewed IFOSIT: calculation of energy and particle fluxes, calculation of the spatial and velocity distributions of lost and confined particles and time evolution of these distributions.

Test runs of the renewed code are presented. The effect of non-circular flux cross section on RMP driven losses of CFP is demonstrated. The estimation of the statistic uncertainties is presented as well.

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1-25

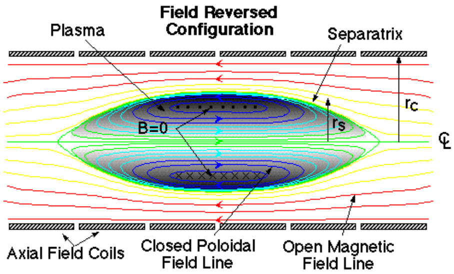
FIRST RESULTS OF FORMING AN FRC - FIELD REVERSED CONFIGURATION

A.Mozgovoy, V.Nikulin and E.Peregudova

P.N. Lebedev Physical Institute, Moscow, Russia,

mozgovoy@sci.lebedev.ru, vnik@sci.lebedev.ru, peregudova@sci.lebedev.ru

The compression of plasma and its subsequent heating is the key process in internal thermonuclear fusion. Most effective compression is achieved in a Field Reversed Configuration scheme (FRC)



The proposed earlier scheme for obtaining an FRC (1) requires regulated switching-on of several condenser batteries with microseconds delays.

The dielectric chamber has 850-mm long and a diameter of 500 mm. The ends of flanges are made of Plexiglas. Two windings are wound on the chamber:- storage solenoid (multi-start winding -7 of 6 turns each) and a compression winding (multi-start winding, 24 of 2 turns each). Ten electrodes are placed on the flanges in which voltage is produced by means of cables to excite a longitudinal current and also to create a toroidal field in the chamber.

The cables of return current are placed longitudinally along the chamber.

Three independent condenser blocks with the total capacitance 300 μF, and voltage up to 40 kV were used.

The first block fed the storage solenoid through the current breaker (an exploding wire).

The second block is switched on before current break in the solenoid to create a toroidal magnetic in the chamber. The third block is fired (after the current break off in the storage solenoid) for the compression current turn in plasma to the center of the chamber.

Using magnetic probes it is easy to measure magnetic field in the chamber after solenoid's current is breaking off.

In experiments with about 60 kJ the efficiency of energy transfer was more than 70%. It means that the energy of magnetic field supports only by current in plasma and can be used for plasma heating. Lifetime of plasma was less 100 μsec. Gas pressure – 0.01-5 torr.

1. A Method of Forming FRC - Field Reversed Configuration International Conference and School on Plasma Physics and Controlled Fusion .., Alushta-2008

1-26

FORMATION OF A HIGH ENERGY DENSITY FIELD REVERSED CONFIGURATION

I.V. Romadanov, S.V. Ryzhkov

Bauman Moscow State Technical University

Formation of a compact toroid (CT) or field reversed configuration (FRC) [1-3] with a maximum input of energy and the capture of the magnetic field into plasma is an important scientific and technical challenge. The proposed method of formation is similar to the formation of FRC based on θ-pinch [1], but has some differences, which will be described below. One of the main CT formation problems is the low level of the captured magnetic flux.

In the modern experiments, level of trapped magnetic flux does not exceed 20-30% in the best experiments. In our experiments a level of longitudinal magnetic field is captured by the plasma reached at least 60% (in experiments with a quartz chamber up to 90%). These results show that this formation method is perspective.

A study of compact torus formation with a longitudinal current was done [4]. This method of formation has not been used before, and was tested for the first time. Experiments showed that this method can significantly increase the energy input into plasma.

A theoretical study of possibility to use that configuration as a plasma rocket engine was done [5-7].

During experiments using two cameras were used. Both were made of dielectric materials but with different diameters. Larger diameter chamber gave the expected increase in the lifetime of the configuration. Experiments with a small camera gave an increase in the value of the captured magnetic flux. Reason is the better material quality (quartz). Diagnostic system was developed using the B-probe to determine the magnetic flux.

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1-27

ELECTRON TEMPERATURE EFFECTS IN LINEAR COUPLING OF ELECTRON-CYCLOTRON WAVES NEAR THE CUT-OFF LAYERS IN FUSION PLASMAS

E.D. Gospodchikov, T.A. Khusainov, A.G. Shalashov

Institute of Applied Physics of Russian Academy of Sciences,
Ulyanova str. 46, 603950, Nizhny Novgorod, Russia

Ordinary and extraordinary wave coupling in the electron-cyclotron frequency range in non-one-dimensionally inhomogeneous magnetized plasmas in a vicinity of the plasma cut-off surface is studied with taking into account electron thermal motion and tokamak magnetic field topology. Previously developed theory of the ultra-high-frequency O-X mode coupling in a toroidal plasma [1-5] has been generalised. Reduced wave equations that describe the normal wave interaction in the considered case are found and solved analytically. Thermal effects essential for the microwave heating of overdense plasma in large scale experiment (ITER like) are analyzed.

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1-28

MODIFICATION OF ^{3}He MINORITY DISTRIBUTION FUNCTION IN D PLASMA DUE TO ICRF MINORITY SELECTIVE HEATING IN ITER LIKE TOROIDAL CONFIGURATION: NUMERICAL SIMULATIONS

O.A. Shyshkin, A.O. Moskvitin, Yu.K. Moskvitina

V.N.Karazin Kharkiv National University, Svobody sq. 4, 61022, Kharkiv, UKRAINE.

Oleg.Shyshkin@gmail.com

In order to decrease the neutron load on plasma facing components and superconducting coils in fusion reactor one can use the fuel cycle based on D–^{3}He as alternative to D–T [1]. The crucial point is the fact that the thermal reactivity of D–^{3}He is much lower than that of D–T. In this case the approach such as ICRF catalyzed fusion should be developed. The main idea of this technique is to modify reagent distribution function in order to achieve favorable reaction rate for nuclear fusion energy production [2]. Recent experimental results show high efficiency of ICRH acceleration of ^{3}He minority in D plasma in order to increase fusion reaction rates. The effect of transition to non-Maxwellian plasma is essential for reactor aspects studies both in tokamaks and stellarators.

The objective of present work is to study numerically the modification of ^{3}He minority distribution function from Maxwellian to non-Maxwellian due to ICRF selective heating of ^{3}He ions in ITER like magnetic configuration. This study is done by means of numerical code, based on test-particle approach [3, 4]. This code solves the guiding center equation of a general vector form. To simulate the Coulomb collisions of test-particle with the other species the discretized collision operator based on binomial distribution is used [5]. The magnetic field model corresponds to ITER device including the characteristic size and the shape of magnetic surfaces. A simplified model for ICRF heating is included in code as well [6].

The simulation of ^{3}He minority heating on the main harmonic under frequency F_{RF}=50 MHz demonstrates the effective acceleration of particles (^{3}He ions) to high energies and formation of non-Maxwellian distribution function with the elongated tail. Moreover the energy from RF heating is deposited in the perpendicular velocity of the test-particle and hence the distribution function is turned to anisotropic shape.

The important consequence of distribution function modification and formation of energetic tail for one of reacting species (^{3}He) is the possibility to increase the averaged reactivity of D^{3}He reaction. The values of reactivity are calculated for different distribution function shapes of ^{3}He that appear in different time slices during RF heating. The comparative analysis of the enhanced reactivity with that of thermal distributions is presented as well.

The increase of reactivity is an important issue for the performance of fusion reactors, which needs further detailed studies.

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1-29

PLASMA OSCILLATIONS PROPAGATING ALONG THE MAGNETIC FIELD IN THE URAGAN-2M TORSATRON

A.I. Skibenko, I.B. Pinos, A.V. Prokopenko

Institute of Plasma Physics NSC KIPT, Kharkiv, Ukraine

The paper presents the results of plasma oscillations analysis for the 2008 Uragan-2M (U-2M) experimental campaign. Microwave probing of U-2M plasma was carried out in two toroidally spaced transverse cross sections. All obtained data were intensively studied using correlation and spectral analyses [1]. Ordinary mode microwave interferometer operated at frequencies greater than the maximum plasma frequency. Thus, this diagnostics effectively responds to the long-wavelength plasma oscillations and allows to measure the average density along a chord intersecting the magnetic axis (f_1 = 36.6 GHz), where the density is maximum and along the chord shifted by 8.2 cm, (f_2 = 31.2 GHz). All data were digitized at 1 MHz sampling rate.

Rigorous spectral and correlation analysis (phase shift, cross-correlation function (CCF, coherency, power and cross-spectra) were applied to analyze plasma fluctuations using the interferometry data. From the period or shift of the CCF maximum one could obtain the velocity of the plasma wave and the phase shift gives the value of fluctuations wave number. From cross-spectra analysis rather cross-spectra distinct oscillations in the range 200 ÷ 300 kHz were observed. Their frequency increases for higher magnetic field and decreases with rising plasma density, what could be attributed to existence of Alfven eigenmodes.

The estimated Alfven eigenmodes frequency was calculated from the measured values of electron density and magnetic field [2] under the assumption that the discharge takes place in hydrogen. Calculated frequency values appeared to be higher than that from the interferometry spectral analysis. This may be due to the presence of impurities in the plasma.

In this case, the ratio of the effective mass of the ion to proton mass could be deducted as square of the calculated and measured frequency ratio and its radial profile could be approximated. These measurements allow us to describe the density profile with the modeled function of central density and the degree of the polynomial radial approximation. In the case of monotonic profiles for which the maximum density is at the magnetic axis, the ratio of edge and plasma density could be obtained. For the analysis of plasma oscillations all fluctuation time intervals have to be at the quasistationary phase of the discharge. The depth of modulation of wave by plasma oscillations increases when the maximal plasma density is approaching to the cut-off density. With that the values of density fluctuations have to be less than difference between maximum and critical density as well as modulation period has to be much above the time of wave propagation in plasmas [3].

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1-30

MODERNIZATION OF THE T-15 TOKAMAK – CURRENT STATUS AND PLANS.

A.V. Sushkov[1)], E.A. Azizov [1)], V.A. Belyakov [2)], E.N.Bondarchuk[2)], P.P. Khvostenko [1)], S.V. Krasnov[2)], V.A. Krylov [2)], O.Yu. Smirnov [2)].

[1)] *Institute of Tokamak Physics, NRC "Kurchatov Institute", Kurchatov Square, 1, 123182, Moscow, RF.*

[2)] *Scientific Research Institute of Electrophysical Apparatus, Metallostroy, 196641, St. Petersburg, RF.*

Status of the project of the T-15 tokamak modernization is outlined. The main goal of the modernization is to replace iron cored, circular cross section limiter tokamak (aspect ratio ~ 3.5) on the air cored machine (aspect ratio ~ 2.2) with the ITER-like divertor configuration of the magnetic field. The new installation should use existing in Kurchatov Institute infrastructure of T-10 and T-15 tokamaks: buildings, power supplies and plasma heating systems.

Base technical data of the new tokamak:

Major plasma radius	1.48 m
Minor plasma radius	0.67 m
Aspect ratio	2.2
Elongation	1.7-1.9
Triangularity	0.3-0.4
Magnetic field at plasma axis	2 T
Plasma current	2 MA
Pulse length	10 s
Plasma heating power	15 MW

Physical tasks of the new device are: investigation of the particle and energy transport in plasma core; magnetohydrodynamic instabilities and disruption control in the ITER-like plasma configuration; plasma turbulence investigations; long pulse, non-inductive current drive operation; testing of the ITER diagnostics systems; plasma edge physic; divertor studies; technological problems of the long pulse operation under reactor-like power load on the divertor plates.

The project is now starting implement in Kurchatov Institute. The design is completed and manufacture of the vacuum chamber and electromagnetic system parts will start in this year.
The paper presents design of the vacuum chamber and electromagnetic system. The descriptions of the auxiliary plasma heating facilities and main plasma diagnostics systems will be also presented.

1-31

ELECTROMAGNETIC OSCILLATIONS AT THE EDGE OF THE "URAGAN-3M" CONFINEMENT VOLUME

V.K. Pashnev, I.K. Tarasov, M.I. Tarasov, D.A. Sitnikov, S.A. Tsybenko, I.B. Pinos, K.N. Stepanov, V.V. Olshansky, O.M. Shvets, E.L. Sorokovoy, A.A. Petrushenja, A.V. Lozin, V.E. Moiseenko, A.P. Pugovkin, Yu.K. Mironov, A.N. Shapoval

Institute of Plasma Physics, National Science Center
"Kharkov Institute of Physics and Technology", Kharkov, Ukraine

In this work we present the results of experimental study of the dynamics and spectrum of electromagnetic oscillations, which was carried out by the use of a set of high-frequency magnetic probes [1]. The main attention was paid to the oscillation excitation processes during the RF-power introduction into the "Uragan-3M" torsatron confinement volume for plasma production and heating. The dynamics of electromagnetic oscillations was considered in a broad spectrum of the ion-cyclotron RF-heating frequency harmonics. The measurements were carried out for different regimes of plasma creation and heating. The correlation analysis of the signals obtained from a set of radially separated 3-component magnetic probes was provided. The obtained experimental data were compared with the results of experimental study of the electrostatic fluctuations at the "Uragan-3M" edge plasma [2]. On our point, the additional data on the magnetic component of the edge fluctuations may provide a deeper insight into the nature of observed fluctuations. Thus, the recent experimental results can help to understand a number of processes observed when plasma in the "Uragan-3M" torsatron is produced and maintained by RF power.

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1-32

THE DYNAMICS OF INDUCTIVELY ACCELERATED ELECTRONS IN THE U-3M TORSATRON

I.K. Tarasov, M.I. Tarasov, D.A. Sitnikov, V.K. Pashnev, I.G. Goncharov, V.M. Listopad, N.V. Lymar

Institute of Plasma Physics, National Science Center “Kharkov Institute of Physics and Technology”, Kharkov, Ukraine

Recent studies have shown that the flows of runaway electrons may be formed in both tokamaks and stellarators. In particular, such flows may be formed during the confining magnetic field intensity variation, which is usually observed in the devices where the magnetic field is formed by a pulse of current in the magnetic field coils. Non-zero dH/dt creates an electric field which could accelerate the charged particles and, eventually create the flow.

We have already carried out some sort of measurements which allowed to detect the high energy electrons presence in the U-3M torsatron vacuum chamber. For example, the X-Ray measurements have shown that some of accelerated electrons have the energies of 0.8 MeV and more.

In this work we continue our previous studies of the flow parameters. Also we investigate the conditions of its formation and propagation. In particular the results of measurements the flow current of high energy electrons current are presented together with the flow radiation which was studied at different frequency ranges.

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1-33

EFFICIENCY OF PPLASMA BIASING BY MOVEABLE LOCALIZED EMISSIVE LIMITER IN IR-T1 TOKAMAK

Reza Arvin, M. Ghoranneviss, A. Salar Elahi, M. Ghasemloo, S. Mohammadi and N. Mohammadi

Plasma physics research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran

The correlation between the efficiency of plasma biasing and the position of a localized emissive limiter has been investigated. It has been found that two distinct zones of limiter position can be distinguished in IR-T1 plasma: Far-zone at $r_{lim} > 11$ cm, and Close-zone at $r_{lim} < 11$ cm. The strongest modifications of edge plasma potential take place for both positive and negative emissive limiter biasing when it is positioned inside Close-zone. The transition between zones is correlated with effective screening of the wall by the limiter, being more efficient as it is immersed deeper into the plasma. The indicative difference between zones can be a difference of non-ambipolar fluxes flowed onto short-circuited limiter: mostly positive (ion) inside Far-zone, and mostly negative (electron) inside Close-zone.

PACS: 52.40.Hf, 52.55.Ez Key words: biasing, edge plasma, particle confinement

1-34

DIAMAGNETIC EFFECT IN MULTIPOLE PLASMA TRAPS-GALATEAS

A.M. Bishaev[1], A.I. Bugrova[1], M.B. Gavrikov[2], M.V. Kozintseva[1], A.S. Lipatov[1], V.V.Savelyev[2], A.S. Sigov[1], P.G. Smirnov[1], I.A. Tarelkin[1], P.P. Khramtsov[3], M.I. Shaposhnikov[1]

[1] *Moscow State Technical University of Radio Engineering, Electronics and Automation, 119454, Moscow, Russia*
E-mail: bishaev@mirea.ru
[2] *Keldysh Institute of Applied Mathematics of RAS, 125047, Moscow, Russia,*
E-mail: ssvvvv@rambler.ru
[3]*Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus, 220072, Minsk, Republic of Belarus*

The experiments on the measurement of the diamagnetic current in the multipole plasma trap-Galatea "Trimyx-3M (microwave)" are described in the report. The measurements have been carried out using Rogowski loop [1]. The loop has encircled the cross-section of the toroidal plasma volume and measured the total azimuthal current in plasma. These experiments have shown, as in [1], the diamagnetic current running in the azimuth direction is generated in the trap after the injection of plasmoid into the trap. The interaction of this current with the magnetic field formed by the trap coils leads to the plasma confinement. Calculations of the plasma equilibrium for this trap by Grad-Shafranov equation show plasma volume in the trap consists of four fields. In the first field (the field of the external magnetic crust) the current runs in the same direction as currents in the trap magnetic coils immersed into the plasma volume ("myxini"). In the fields around three myxini currents run in the opposite direction. The pointed out fields have the common boundary along the separatrix of the magnetic field. Therefore the measured diamagnetic current is the sum of currents of the opposite direction. Based on the pressure under the equilibrium remains constant on the magnetic surface [2], the relationships between currents running in the different fields of the plasma volume have been obtained. This made possible to establish the fact of proportionality of the measured diamagnetic current to the maximal plasma pressure and also to determine the dependence of the proportionality coefficient from the value of the trap magnetic field. Calculations of the maximal plasma pressure in the trap for the different values of the magnetic field have shown, with the magnetic field increase the plasma pressure in the trap increases. This is in accordance with the dependence of the pressure from the value of the magnetic field obtained by the parameters of captured into the trap plasmoids determined with the help of calorimeter and magnetic probes.

The determined proportionality of the measured diamagnetic current to the pressure in the trap shows the value of the measured diamagnetic current is proportional to the energy in the plasma volume. Determined by the measured dependence of the diamagnetic current value from time, the energy confinement time in the trap increases with the increase of the magnetic field and is approximately two times less than particles life time in the trap.

The work has been carried out in the frames of realization of FPP "Research and research-educational personnel of innovational Russia" for 2009-2013y.y. and under the partial financial support of RFBR.

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1-35

STATIONARY TWO-FLUID MHD CONFIGURATIONS IN A TOKAMAK

Gavrikov M.B., Savelyev V.V.

Keldysh Institute of Applied Mathematics RAS, Moscow, RF, nadya_p@cosnitive.ru, ssvvvv@rambler.ru

This report presents the first results on the equilibrium configurations of the tokamak plasma. Equilibrium is determined by the condition $V_i = 0$, but taking into full account the inertia of electrons, whose influence on the equilibrium leads to an additional equation for the function of the total current J, absent in MHD plasmastatic. The result [1] is the system of two equations for the magnetic flux function W and the function J

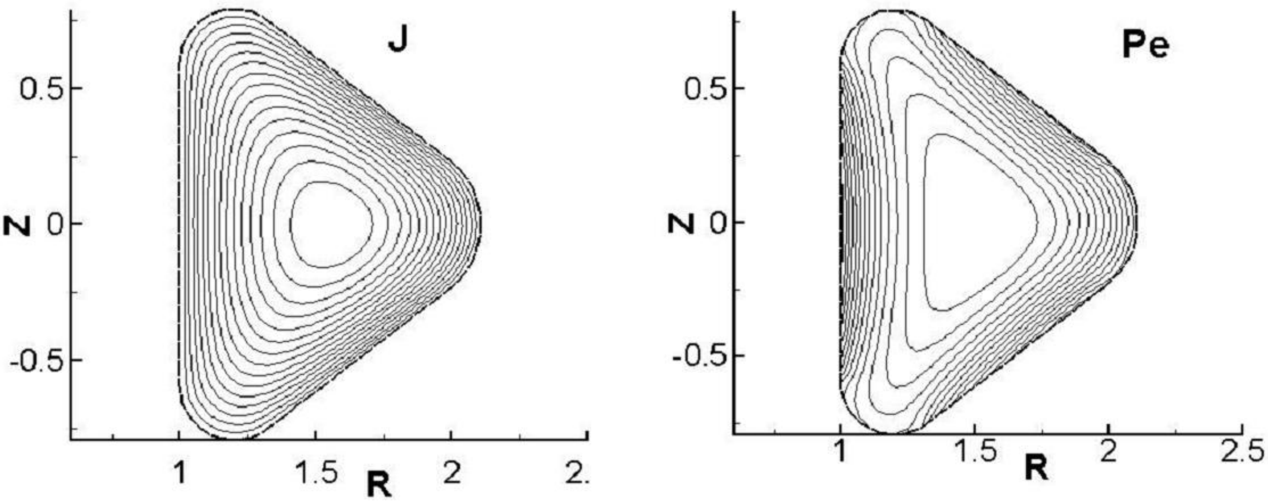
$$\Delta^* \Psi - \frac{8\pi^2 e}{cm_e} n(\frac{1}{2\pi}\frac{e}{c}\Psi + K(J)) = 0, \qquad \Delta^*\Psi = \frac{\partial^2 \Psi}{\partial r^2} - \frac{1}{r}\frac{\partial \Psi}{\partial r} + \frac{\partial^2 \Psi}{\partial z^2}$$

$$\frac{m_e}{4\pi^2 e^2}[\frac{\partial}{\partial z}(\frac{1}{rn}\frac{\partial J}{\partial z}) + \frac{\partial}{\partial r}(\frac{1}{rn}\frac{\partial J}{\partial r})] - rn(\frac{dF}{dJ} - m_e T_e \frac{ds_e}{dJ}) - \frac{j_\varphi}{e}\frac{dK}{dJ} - \frac{1}{\pi c^2}\frac{J}{r} = 0 \qquad (1)$$

The system (1) is closed by the Bernoulli (energy) and angular momentum integrals, which allow to determine the value of the azimuthal current j_v and particle density n

$$\frac{m_e}{2}\mathbf{V}_e^2 - e\Phi + m_e W_e = F(J) \quad , \quad rm_e V_{e,\varphi} - \frac{1}{2\pi}\frac{e}{c}(\Psi + \pi r^2 H_z) = K(J) \qquad (2)$$

Here - $F\ (J\ )$and K (J) are arbitrary functions. The function s_e (J) determines the entropy of the electrons and is also considered as given. The figure gives an example of the level curves of $J(r, z)$ and the electron pressure $P_e(r, z)$for a tokamak of a "triangular" cross section with the adiabatic index $y = 3$.



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1-36

ABOUT LEVITATION OF SUPERCONDUCTING RINGS FOR MAGNETIC SYSTEM OF MULTIPOLE PLASMA TRAP

A.M. Bishaev[1], A.A. Bush[1], M.B. Gavrikov[2], I.S. Gordeev[1], A.I. Denis'uk[1], K.Y. Kamentsev[1], M.V. Kozintseva[1], V.V.Savelyev[2], A.S. Sigov[1]

[1] *Moscow State Technical University of Radio Engineering, Electronics and Automation, 119454, Moscow, Russia E-mail: kozintseva@mirea.ru*
[2] *Keldysh Institute of Applied Mathematics RAS, 125047, Moscow, Russia, E-mail: ssvvvv@rambler.ru*

The possibility of the creation of the magnetic system of the multipole plasma trap with levitating magnetic coils [1] is investigated. With this purpose the analytical dependence of the potential energy of the system consisting of two or three superconducting rings (one of them is fixed), which trapped the given fluxes, from the coordinates of the free rings has been obtained for the homogeneous field of the gravity force in the thin rings approximation. Calculations in Mathcad system have shown the local minimum of the potential energy of such system exists under the determined values of parameters.

Using experimental data on the magnetic flux trapping for HTSC rings on the base of the faze Y123, selected for the experiments carrying out, their concrete dimensions and masses, with the help of calculations in Mathcad system of the pointed out dependence for the potential energy, the search of the equilibrium states for the system of two or three HTSC rings has been carried out.

The existence of the equilibrium states of any pair from the given HTSC rings for the trapped flows of the same, or- of the opposite in sign, found by calculations, has been confirmed experimentally. Under the trapping by rings of fluxes of the same sign, the levitating state of HTSC ring in the field of the fixed and placed above HTSC ring was stable relative to vertical displacements, to horizontal displacements and to the rotation about a horizontal axis. Under the trapping by rings of fluxes of the opposite in sign, the found equilibrium states of HTSC ring in the field of the fixed and placed lower HTSC ring were stable relative to vertical displacements, however their stability relative to the rotation about a horizontal axis has been observed only for some values of trapped fluxes.

The analogous dependences have been obtained for the potential energy of the system in which a usual ring with the invariable in value current is fixed instead of superconducting ring, and one or two superconducting rings are levitating. Calculations in Mathcad system have shown the local minimum of the potential energy of such system exists under the determined values of parameters.

On the base of carried out experiments and calculations the laboratory model of levitating quadrupole has been developed [2].

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1-37

ELECTRIC FIELD DYNAMICS STUDIES IN TUMAN-3M TOKAMAK

A.A. Belokurov[1], L.G. Askinazi[1], A.D. Komarov[2], V.A. Kornev[1], S.V. Krikunov[1], L.I. Krupnik[2], S.V. Lebedev[1], A.S. Tukachinsky[1], M.I. Vildjunas[1], N.A. Zhubr[1]

[1] *Ioffe Phys.-Tech. Institute, St. Petersburg, Russia*
[2] *IPP NSC KIPT, Kharkov, Ukraine*

Electric field and its fluctuations play major role in generation and suppression of anomalous transport in tokamak plasma. Inhomogeneous radial electric field suppresses anomalous flows and leads to transition to improved confinement regime. Zonal flows and geodesic acoustic modes (GAM), driven by turbulence, are another mechanism of inhomogeneous radial electric field.

Direct measurements of electric field are possible by obtaining the values of plasma potential in two closely spaced points of plasma. Such experiments were carried out on tokamak TUMAN-3M by means of double-point heavy ion beam probe (HIBP) diagnostic and Lagmuire probes. During the experiments tokamak operated with toroidal magnetic field up to 1.05 T; plasma current 140-160 kA; average electron density $0.8\text{-}1.5 \cdot 10^{13}$ cm^{-3} in L-mode and $2\text{-}3 \cdot 10^{13}$ cm^{-3} in H-mode; ohmic heating (mainly) and co-NBI were used.

As a result of the measurements, electric field (both mean and oscillating) and electron density evolution was investigated in regimes with and without LH-transition. Studies of potential, electric field and density fluctuations were made, resulting in detection of oscillations, which can be interpreted as GAM. Sample volumes of the HIBP diagnostic were situated near the peripheral transport barrier during the LH-transition (r ~ 19-20 cm); Langmuire probes measurement region was in the range of 1-1.5 cm inside LCFS (r ~ 19.5-20 cm).

Immediately before LH-transition radial electric field value E_r was about 0…-10 kV/m; more negative values were obtained in discharges with higher plasma density, which generally correlated with higher values of toroidal magnetic field and plasma current.

In discharges with relatively weak toroidal magnetic field ($B_T < 0.95$ T) LH-transitions were accompanied firstly by rather fast (during the time, comparable with the time of LH-transition - 1.5-2 ms) drop of radial electric field (it became negative, with higher absolute value), then electric field slowly evolved to even more negative values. If there was a backwards (HL) transition during the H-mode, absolute value of electric field simultaneously decreased (became less negative).

In discharges with stronger toroidal magnetic field (up to 1.05 T) with LH-transition, the evolution of electric field during the transition was less pronounced than in discharges with lower magnetic field. In case sequential LH- and HL-transitions, a correlation between electric field value and confinement mode was observed.

Plasma potential and local density oscillations with GAM frequency (~ 30-40 kHz) were observed in the L-mode phase using HIBP and Langmuire probes. Measurements showed that GAM did not develop in discharges with higher plasma density or with strong MHD activity; GAM decayed after LH-transition. HIBP measurements indicate GAM oscillations only on potential signal with no oscillations of electric field observed. This can be interpreted as that GAM are localized closer to periphery than HIBP measurement point, and have a spatial structure of few oscillation periods.

2-01

EFFECT OF THE MINORITY IONS ON THE ICRF HEATING OF FUSION PLASMAS

I.V. Pavlenko, I.O. Girka, B.I. Leviga

V.N. Karazin Kharkiv National University, Svobody Sq. 4, Kharkiv 61022, Ukraine.

The tritium minority heating scenarios at ITER could provide an effective triton heating by the fast wave but the designed frequency range (40- 55 MHz) is out of the required relation between the frequency and the magnetic field values. That is why a main attention is paid to the ICRF heating scenarios at tritium second harmonic and the minority heating of hydrogen, deuterium or He^3 [1]. On the one hand the tritium second harmonic heating provides mainly the heating of the tritium tails when the particles transfer partially the power to the electrons through the collisions and can leave the confinement volume due to the large Larmor radius orbits. On the other hand even the pure D-T experiments contain at least about 0.1% of He^3 as a result of the tritium radioactive decay. This provides additionally the He^3 minority heating (co-located with the tritium second harmonic heating) even without the external He^3 injection. But the He^3 injection could be useful at initial stage of the D-T experiments to reach the core ion temperature enough high for an effective ion heating at tritium second harmonic at second stage [2, 3]. At the same time the further increase in the He^3 concentration shifts the experiments from the minority heating regimes to the mode conversion ones. That is why the sensitivity of the D-T experiments to the presence of He^3 ions should be studied in details.

The experimental conditions of the ICRF heating D-T scenarios at JET are tested on the sensitivity to the He^3 fraction. Usually the relation between the ICRF frequency and magnetic field values is chosen to locate the tritium resonance at second harmonic in the plasma centre. For small concentrations of T and He^3 it provides almost a central T/He^3 heating and a deuterium minority heating at high field side. The radial distribution of the power absorbed by the different ions is calculated using the nonlinear bounce- averaged Fokker- Planck code. The calculations were oriented on the experimental conditions of the JET D-T fusion discharges #41734 and #41735 without He^3 and with 4% He^3 concentration, respectively. The frequency was 34 MHz, the confinement magnetic field value was 3.4 T. The central electron density was about $3\cdot10^{13}$ cm^{-3} with the central electron temperature about 9 keV. The ion temperature changed along the radius almost linearly from 7 keV in the centre. The ICRF antenna worked with the dipole phasing which meant the maximum of the antenna spectrum somewhere at $k_{\|}=6.75$ m^{-1}.

The optimal concentration of He^3 has been calculated to reach a highest core wave damping. The partitioning of the absorbed wave power between T, D and He^3 has been obtained for the different values of the He^3 concentration. The distribution functions of the He^3 ions and especially of the tritium ions have been calculated to estimate the tail energy. The radial profiles of the absorbed ICRF power have been obtained. The results will allow predicting the role of the He^3 fraction in the future tritium plasma experiments at tokamak ITER.

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2-02

THE INVESTIGATION OF ADIABAT SHAPING IN INERTIAL CONFINEMENT FUSION

Hadighe, Ashouri; Abbas, Ghasemizad [*]; Masume, Ahmadi

Department of Physics, University of Guilan, Rasht, Iran

Achieving nuclear energy through inertial confinement fusion (ICF) has been under studying for more than half a century. But, up to now, the challenges facing ICF have prevented this goal. Arising hydrodynamic instability particularly the one known as Rayleigh-Taylor instability in the plasma fuel of deuterium and tritium is one of these barriers that should be removed as much as possible. R-T instability can finally leads to a mixture of hot and cold material and prevent high compressibility and reduce energy gain of reaction. So, controlling the growth of R-T instability can help success of ICF. It has been shown that mass ablation from the outer surface of target during the irradiation of laser beam can reduce the growth rate of R-T instability. The higher the ablation velocity, the lower the growth rate. So, some methods by which ablation velocity can be increased have been looked for. It has been shown that bigger adiabat amounts at the outer surface of target increase ablation velocity. On the other hand, it can be understood that high energy gain needs smaller adiabat at the inner part. Therefore, we need to shape adiabat so that we have a maximum at the outer surface and a minimum in the inner parts. Adiabat shaping can be achieved in two ways; decaying shock (DS) and Relaxation (RX). In DS method, first we apply a high intensity laser beam to the target that cause a shock wave propagating into the target leaving a high adiabat at the outer surface. Then we reduce laser intensity dramatically, without turning it off, launching a rarefaction wave propagating in sound speed toward the shock wave. After being overtaken by the rarefaction wave, the shock wave starts decaying, so the inner adiabat becomes smaller and smaller. In this paper, the condition of having different value of maximum adiabat at outer surface has been considered. According to some simulation done before, it is shown that we can't have some special values of adiabat at the outer surface because of energy limitations, so we should introduce an optimum condition in which we have an accepted adiabat in the inner and outer pats of the capsule regarding the required energy. Finally, we show that how using prepulses around 100ps is more favorable and can lead to higher outer adiabat without losing lots of mass during ablation.

2-03

SELF-CONSISTENT MODELLING OF PLASMA DENSITY INCREASE WITH RADIO-FREQUENCY HEATING

V.E. Moiseenko[1], Yu.S. Stadnik[1], A.I. Lyssoivan[2]

[1] *Institute of Plasma Physics, National Science Center "Kharkiv Institute of Physics and Technology", 61108 Kharkiv, Ukraine*

[2] *Laboratory for Plasma Physics - ERM/KMS, Association EURATOM - BELGIAN STATE, 1000 Brussels, Belgium*

In stellarator type machines, besides the electron-cyclotron method, the plasma production in the ion-cyclotron range of frequencies is practiced (see e.g. [1]). The self-consistent model of the radio-frequency (RF) plasma production in stellarators is described in this work. With this model of plasma production, one can perform calculations for different antenna systems. The self-consistent model includes the system of the particle and energy balance equations and the boundary problem for the Maxwell's equations. The balance of the electron energy includes the RF heating, the energy losses for the excitation and the ionization of atoms by the electron impact, energy exchange with ions vie Coulomb collisions and the losses caused by the heat transport. The balance of the charged particles includes the particle supply owing to ionization and the diffusion particle losses. In the model, it is assumed that the neutral gas is uniformly distributed throughout the vacuum chamber volume, including the plasma column. Besides plasma build-up inside the confinement volume, the RF field produces plasma outside it. The losses of the charged particles in this zone have a direct character because the particles of plasma escape to the wall along lines of force of the magnetic field. This process is accounted in the model in tau-approximation. The RF power density is calculated from the solution of the boundary problem for the Maxwell's equations. The collisional and Landau wave damping are accounted as mechanisms of the RF field dumping. The Maxwell's equations are solved each time moment for the current plasma density and temperature distributions. The calculated value of the local RF power, deposited to the electron component of plasma, is used in the energy balance equation. This value influences on the electron temperature and, in this way, on the ionization rate which determines the evolution of plasma density. The model for the stellarator plasma column is the plasma cylinder with identical ends. The plasma is assumed to be azimuthally symmetrical and uniformly distributed along plasma column. The Crank-Nicholson method is used for solving the system of the balance equations. The Maxwell's equations are solved in 1D using the Fourier series in the azimuthal and the longitudinal coordinates. Using this self-consistent model, the plasma density ramp-up with four-strap π-phased antenna is modelled. Antenna is fed with the frequency below ion-cyclotron and, plasma production in the Alfvén resonance heating regime is realized.

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2-04

MODELLING OF ICRF HEATING AND CURRENT DRIVE IN TOKAMAK PLASMA WITH TWO ION SPECIES

D.L. Grekov, S.V. Kasilov, K.K. Tretyak

*Institute of Plasma Physics, National Science Center "Kharkov Institute of Physics and Technology", Akademicheskaya str. 1, 61108 Kharkov, Ukrain*e

Ion cyclotron mode conversion regime (ICMC) is a popular regime for heating tokamak plasma with two ion species. In most cases these species are hydrogen and deuterium. To understand the underlying physics of the heating, the model with one dimensional inhomogeneity of plasma parameters was exploited very often. At the same time, two dimensional effects play an essential role in propagation and absorption of both, launched fast magnetosonic wave (FMSW) and converted small scale wave. Depending on device and plasma parameters, the converted wave may be the ion Bernstein wave (IBW) or Alfven wave (Stix mode).

For computation of electromagnetic field of the fast magnetosonic wave in a tokamak, a numerical code FAW2 has been developed. FAW2 allows treatment of general tokamak magnetic field configurations including the poloidal divertor and real wall geometry directly using the equilibrium parameters obtained by EFIT code. FAW2 has been applied for calculation of FMSW propagation in tokamak plasma with light (H) minority ions and D majority ions. An artificial collisional damping was introduced in the components of plasma dielectric tensor in the vicinity of the conversion layer to simulate the transformation of FMSW into small scale waves. This allows one to estimate the spatial distribution of the converted power in the minor cross-section of the torus.

Propagation and damping of small scale waves has been studied with the help of ray tracing code which uses the same equilibrium parameters. Effects of finite ion Larmour radius are taken into account in this code. Electron and minority ion current densities have been calculated in linear aproximation using current drive efficiencies calculated by kinetic equation solver SYNCH [1]. Dependencies of current drive efficiency on antenna position, plasma density, light minority concentration and temperature have been studied.

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2-05

STUDY OF HYBRID X PINCHES IN DIFFERENT CONDITIONS.

A. R. Mingaleev, T.A. Shelkovenko, S. A. Pikuz I. N. Tilikin,
S. N. Mishin, V. M. Romanova

P.N. Lebedev Institute, Moscow, 119991 Russia

C. L. Hoyt, A. D. Cahill and D. A. Hammer
Cornell University, Ithaca ,NY 14853USA

A hybrid X pinch configuration consisting of solid conical electrodes connected by a wire has been tested first on a 45 ns rise time, 500 kA peak current pulsed power XP generator[1]. In present work the hybrid X pinch was studied on pulsers with current from 250 kA to 1.2 MA and current rise time from 45 ns to 170 ns. In all experiments the hybrid pinches have the same 60° electrodes made of tungsten with 5% copper. The wires were loaded trough 1 mm holes in the cones. The wire diameter and the gap between electrodes were varied according to the pulser current amplitude and rise time. Mg, Al, Ti, Ni, NiCr, Cu, Mo, Pd, Ag, W and Au wires having lengths ranging from 0.6 to 2.5 mm were tested in the experiments. The wire diameters were varied from 12 to 200 μm for different experimental conditions. The experiments have shown that for each generator, it is possible to find the wire material, diameter and length for which the X pinches generate an intense single burst of soft x-rays and develop a single hot spot with micron size. Also they generated less hard x-ray intensity than that measured in comparable standard X pinches. Absence of x-rays with photon energies > 20 keV associated with long-lived electron beams[2] in explained by fast closure of the diode by expanding dense plasma from the electrodes. At the same time short-lived electron beam produces bright small-size x-ray source in 8-15 keV spectral band usable for point-projection radiography. The hybrid X pinch have been successfully used as a source of pure continuum radiation with flat spectrum for imaging absorption x-ray spectroscopy of relatively cold plasma of exploded Al wires and wire arrays[3]. Hollow and filled tubes from Al, Ni and polyethylene were tested as a load on COBRA pulser (1.2 MA, 100 ns rise time), that expands possibilities of hybrid X pinch applications, for example in studying of the matter under extreme conditions.

To study the physical processes and dynamics of H-X pinch mini-diode and micropinch development experiments with changeable level of the current and risetime have been performed. The experiments have been shown that early stage of the micropinch development looks like single wire explosion with shock waves [4]and stratification formation.

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2-06

A NONRESONANCE PHOTON NEUTRALIZER FOR NEGATIVE ION BEAMS

S.S.Popov, A.V. Burdakov, A.A. Ivanov, I.A. Kotelnikov

Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia

A traditional approach to produce a neutral beam from the negative ion H^-,D^- beam for further application for plasma heating or neutral beam assisted diagnostics, is its neutralization in a gas or plasma target for detachment of the excess electrons. However, these approach has a significant limitation on efficiency. At present, for example, for the designed heating injectors with the 1 MeV beam [1] neutralization efficiency in the gas and plasma targets will be 60% and 85% correspondingly [2], which considerably affects the overall efficiency of the injectors. In addition, application of these neutralizers is associated with complications, which might be significant in some applications, including the deterioration of the vacuum conditions due to gas puffing, the positive ions appearance in atomic beam.

Photodetachment of an electron from a high-energy negative ions is an attractive method of the beam neutralization. Such method does not require a gas- or plasma-puffing into the neutralizer vessel; it does not produce positive ions and it assists to beam cleaning from fractions of impurity negative ions. The photodetachment of an electron corresponds to the following process: $H^- + h\nu \Rightarrow H^0 + e$. Similarly to most of the negative ions, the H^- ion has a single stable state. Nevertheless the photodetachment is possible from an excited state. Photodetachment cross section is well known (see, for example, [3]). This cross-section is large enough in a broad photon energy range which practically overlaps all the visible and near IR spectrum. Such photons cannot knock out electron from H^0 or all electrons from H^- and produce the positive ions. This approach has been proposed in 1975 by J.H. Fink and A.M. Frank [4]. Since that time a number of projects of photon neutralizer have been proposed. As a rule they are based on an optic resonator similar to Fabri-Perot cells. This needs the very high reflectance mirrors, powerful light source with thin line and very precise tune of all the optic elements. For example, in a scheme considered in [5], the reflectance of mirrors should be not less than 99.96%, the total laser output power is to be 800 kW with output intensity about 300W/cm^2 and the laser bandwidth should be less than 100 Hz. It is hardly possible that these parameters together could be realized. In this paper we present an approach based on application of a non-resonance photo-neutralizer. Conceivable characteristics of such a neutralizer are assessed.

The proposed approach has a number of advantages in comparison with the other porposed schemes of the photo-neutralizer.

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2-07

STRATIFICATION UPON ELECTIRCAL EXPLOSION OF THIN WIRES

V.M. Romanova, A.R. Mingaleev, A.E. Ter-Oganesyan, T.A. Shelkovenko, S.A. Pikuz

P.N. Lebedev Physical Institute (FIAN), 119991 Leninsky pr. 53, Moscow, Russia

Transverse stratification of matter which is often observed upon electrical explosion of thin wires (EEW), has still not been convincingly explained. The extensive experimental data accumulated in over a half-century in observing this phenomenon remains the fragmentary with regards to the parameters and conditions of EEW, poorly systematized and not critically comprehended. This applies even to the concept itself: what are “strata”? In shadow images of x-ray and laser probing they look like a sequence of dark and light transverse bands. That is traditionally interpreted as an alternation of layers of high and low density matter (thus, we often find in the literature the terms "discs" or "pancakes"). However, is this really so?

Presented experimental study of stratification of matter upon the nanosecond electric explosion of thin wires was carried out on various installations: from not very large low-inductance pulse generator (I_{max} 10 kA, current rise in 10^{10} A/s) to a high-current vacuum diode (300 kA and more than 10^{12} A/s); also there were used data of our experiments on wire-array explosions on mega-ampere machines MAGPIE and COBRA. Conditions of strata formation in air and vacuum were studied, including EEW regimes with current pauses.

An analysis of the experimental data permits to suggest that the mechanism of strata formation is primarily a “surface” mechanism developing in the tubular core. In this case, strata are not layers with more or less uniform density of matter but rather hollow rings (or possibly toroids). That the core is tubular is clearly seen, for example, on images obtained by means of x-ray probing. This also follows from molecular-dynamic calculation [1].

Another important conclusion following from the results of many experiments is the absence of current in the core when observing transversal stratification. At first glance, this assertion may seem quite unexpected since it is considered that it is precisely current flowing in the discharge channel that is the main cause for inducing all the instabilities in the EEW process. However, this occurs, evidently, at a very early stage (possibly still linear) of the explosion and does not have as yet direct experimental confirmation: scientists today do not have at their disposal instruments with sufficient temporal and spatial resolution for investigating processes in the dense core of the unexpanded wire. All observations of stratificated matter should be attributed to a much later stage of the process, when due to shunting of the discharge channel or, in conditions of current pause setting in, already developed-structure of the strata continues to exist as if "by inertia". Moreover, from EEW experiments with internal character of secondary breakdown [2], it follows that current flowing through products of explosion (i.e., in already greatly expanded core), on the contrary, hinder the maintenance of any regularity in their structure, even if at an earlier stage it could have been the cause of its arising.

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2-08

QUASILINEAR KINETIC MODELLING OF RMP PENETRATION INTO A TOKAMAK PLASMA

M. F. Heyn[1], I. B. Ivanov[1,2], S. V. Kasilov[1,3], W. Kernbiehler[1], and P. Leitner[1]

[1] *Institut für Theoretische Physik - Computational Physics,Technische Universität Graz, Association EURATOM-ÖAW, Petersgasse 16, A-8010, Graz, Austria*
[2]*Petersburg Nuclear Physics Institute, 188300, Gatchina, Leningrad Region, Russia*
[3] *Institute of Plasma Physics, National Science Center Kharkov Institute of Physics and Technology, Ul. Akademicheskaya 1, 61108 Kharkov, Ukraine*

Resonant magnetic field perturbations (RMPs) are presently used for mitigation of edge localised modes (ELMs) in tokamak H-regimes. This method is foreseen to be used in ITER. At the same time the basic question how well do RMPs penetrate into the plasma has not obtained a final answer yet. Linear theory [1,2] predicts that RMPs are strongly, by a few orders of magnitude, shielded at the respective resonant magnetic surfaces. As is known from MHD theory, there is a RMP generated torque acting on the plasma. This torque tends to slow down the electron fluid motion across the magnetic field lines and, for a certain threshold value of the RMP amplitude, causes RMPs to penetrate. In this report, the problem of RMP penetration is addressed within quasilinear theory in kinetic approximation. The linear problem for the RMP electromagnetic fields is solved by the code KiLCA (Kinetic Linear Cylindrical Approximation) [2,3] and this solution is selfconsistently used for the computation of the evolution of the background plasma parameters using a 1-D balance code. It has been found that thresholds of RMP bifurcation obtained in the modelling are in the range of RMP amplitudes used in current experiments. In contrast to earlier MHD theories [3], the main quantity changed by RMPs is the electron temperature but not so much the toroidal rotation velocity. The change is such that the perpendicular electron fluid velocity becomes zero around the resonant surface and RMP shielding is modified but not removed completely. This fact that the electron diamagnetic velocity is the most affected quantity agrees with a feature observed in recent quasilinear modelling based on Drift-MHD theory [4].

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3-01

PLASMA-SURFACE INTERACTION AND MECHANISMS OF DUST PRODUCTION IN ITER ELM SIMULATION EXPERIMENTS WITH QSPA Kh-50

V.A. Makhlaj[1], I.E. Garkusha[1], N.N. Aksenov[1], O.V. Byrka[1], A.A. Chuvilo[1], I. Landman[2], S.I. Lebedev[1], P.B. Shevchuk[1]

[1] *Institute of Plasma Physics of the NSC KIPT, 61108 Kharkov, Ukraine*
[2]*Karlsruhe Institute of Technology (KIT), IHM, 76344 Karlsruhe, Germany.*

Experimental simulations of ITER transient events with relevant surface heat load parameters (energy density and the pulse duration) as well as particle loads were carried out with a quasi-stationary plasma accelerator QSPA Kh-50 that is largest and most powerful device of this kind. The main parameters of the streams are as follows: ion impact energy about 0.4 keV, maximum plasma pressure 3.2 bar, and the stream diameter 18 cm. The surface energy load measured with a calorimeter achieved 1.1 MJ/m^2. The plasma pulse shape is approximately triangular, pulse duration 0.25 ms.

Performed studies of plasma-surface interaction include measurements of plasma parameters in front of the exposed surfaces for normal and inclined plasma stream incidence, impurities dynamics in near-surface plasma and energy deposited to the material surface. Particular attention is paid to the material erosion due to particles ejection from the tungsten surfaces both in the form of droplets and solid dust. Estimation of tungsten surface damage carried out also. Surface analysis was performed with an optical microscope MMR-4 equipped with a CCD camera and Scanning Electron Microscopy (SEM) JEOL JSM-6390. Measurements of weight losses and microhardness of the surface were analyzed also.

After the first plasma pulses the major cracks network appeared on the exposed tungsten surface for the heat load above 0.3 MJ/m^2 and the initial target temperatures below DBTT. Further evolution of the major cracks was observed by a width increase only. The major cracks development and it bifurcation led to generation dust particles with sizes up to tens μm. This mechanism would be dominating for first transient impacts when major crack mesh is formed

The evident decrease in the energy threshold for the cracking development was found for grooving number of repetitive plasma pulses. Even if there were no cracks at all for the applied low heat loads and small irradiation dose, nevertheless there appeared cracks on tungsten surface after more than 20 and 100 plasma pulses with the heat load of 0.2 MJ/m^2 and 0.15 MJ/m^2, correspondingly. It should be noted that these experimental data agree with analytical estimations with cod PEGASUS.

Melting of surface and development of fine meshes of cracks along the grain boundaries are accompanied by resolidified bridges formation through the fine cracks in the course of melt motion and capillary effects. With next impacts (even without melting) such bridges produce nm-size dust.

A stressed formation of sub-micron and nanometer-size cellular structures in the modified melting surface layer of the exposed W targets has been observed. SEM investigations showed such structures also for repetitive pulses without melting. This surface modification could be a factor inducing the intensification of the W dust formation from the nano-particles and the destruction of the submicron cells even at conditions with the avoided W cracking.

3-02

EXPERIMENTAL STUDY OF TUNGSTEN IMPURITY FORMATION AND ITS DYNAMICS AT PLASMA GUN FACILITY MK-200 UNDER CONDITION RELEVANT TO TRANSIENT EVENTS IN ITER.

N.I. Arkhipov, S.V. Karelov, I.M. Poznyak, V.M. Safronov, D.A. Toporkov

State Research Center of Russian Federation Troitsk Institute for Innovation and Fusion Research, 142190 Troitsk, Moscow reg., Russia

Tungsten is foreseen presently as the main candidate armour material for the divertor targets in ITER. During tokamak transient processes, such as Edge Localized Modes (ELMs) and mitigated disruptions, the armour material is exposed to intense streams of hot plasma that can cause a severe erosion of the exposed material. Erosion restricts lifetime of the divertor components and leads to production of impurities, which can penetrate into the hot fusion plasma causing its radiative cooling.

The plasma heat loads, which are expected in ITER, are not achieved in the existing tokamak machines. Erosion of candidate armour materials is studied in the laboratory experiments by use of other devices such as plasma guns and electron beams, which are capable to simulate, at least in part, the loading condition of interest. In the present work, the tungsten targets have been tested by intense plasma streams at the pulsed plasma gun MK-200UG. The targets were exposed to the plasma heat fluxes relevant to ITER ELMs and mitigated disruptions.

The targets were irradiated by hot magnetized hydrogen plasma streams with impact ion energy E_i = 2 - 3 keV, pulse duration t = 0.05 ms and energy density varying in the range q = 0.1 – 1 MJ/m^2. The plasma stream diameter is d = 6 – 8 cm and the magnetic field is B = 0.5 – 2 T. Primary attention has been focused on investigation of impurity formation due to tungsten evaporation and on investigation of impurity transport along the magnetic field lines from the irradiated target. Optical and EUV spectroscopy was applied as diagnostics. A pinhole camera equipped absolutely calibrated AXUV photodiodes is used to investigate dynamics of the tungsten plasma.

The following questions were studied:

- evaluation of the energy threshold for tungsten evaporation;
- measurement of the velocity of the tungsten impurities;
- determination of the tungsten plasma radiation intensity as a function of the distance to the target surface.

The spectral data obtained were compared with the numerical calculations.

3-03

RESEARCH ON STELLARATOR-MIRROR FISSION-FUSION HYBRID

V.E. Moiseenko[1], V.G. Kotenko[1], S.V. Chernitskiy[1], O. Ågren[2], K. Noack[2], Yu.S. Stadnik[1], A.P. Kovtun[1], V.S. Voitsenya[1], I.E. Garkusha[1], S.I. Dovgalyuk[3]

[1] *National Science Center ''Kharkiv Institute of Physics and Technology", Akademichna St. 1, Kharkiv, Ukraine*

[2] *Uppsala University, Box 534, SE-7512 Uppsala, Sweden*

[3] *Concord Group, Kirova ave. 82-G, 49061 Dnipropetrovsk, Ukraine*

In the fission-fusion hybrid described in Ref. [1] neutrons are generated in deuterium-tritium plasma confined magnetically in a stellarator-type system. The stellarator provides steady-state operation (for a year or more) of the device and offers relatively good confinement for warm Maxwellian plasma. The hot minority tritium ions are sustained in the plasma by radio-frequency heating or neutral beam injection (NBI). Since high energy ions are poorly confined in stellarators, it is proposed in Ref. [1] to embed into the stellarator a mirror trap with lower magnetic field. A scheme with NBI at the mirror ends is considered. The NBI is normal to the magnetic field and targets plasma just near the fission mantle border (Fig. 1). The generated hot ions have predominately perpendicular kinetic energy. Because of the mirror trapping effect, the hot ion motion is restricted to the mirror part of the device. Energy balance calculations for such a system are performed. In a power plant scale the plasma part of the considered hybrid machine is rather compact with a size comparable to existing fusion devices. An experimental device could be built in small scale for a proof-of-principle purpose, and even under these conditions it may have a positive power output.

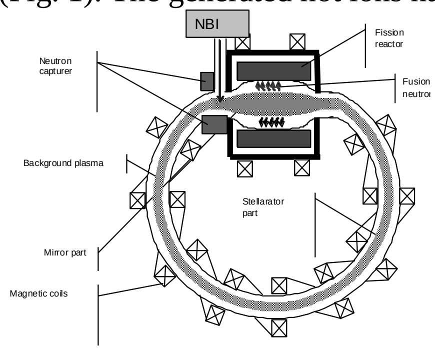

Fig. 1. Sketch of the fission-fusion hybrid.

NBI is studied numerically for the above-mentioned hybrid scheme. The model takes into account Coulomb collisions between the hot ions and the background plasma. The geometry of the confining magnetic field is accounted for via a numerical bounce averaging procedure. Along with the kinetic calculations the neutron generation intensity and its spatial distribution are computed.

Neutron calculations have been performed with the MCNPX code, and the principal design of the reactor part is made using the developments from Ref. [2]. Neutron outflux at different outer parts of the reactor is calculated.

Numerical simulations have also been performed [3] on the structure of a magnetic field created by the magnetic system of a combined plasma trap. For the stellarator type magnetic system the numerical model contains a magnetic system of an $l=2$ torsatron with the coils of an additional toroidal magnetic field. The mirror-type magnetic system element could be produced by a single current-carrying turn (which locally decreases the magnetic field) enveloping a region of closed magnetic surfaces of the torsatron. The calculations indicate existence of closed magnetic surfaces for a broad range of values of the additional magnetic field magnitude and the magnetic field of the single turn. An implementation of a closed magnetic surface configuration for the stellarator-mirror system seems therefore feasible.

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3-04

EFFECT OF RELATIVISTIC NONLINEARITY ON THE DYNAMICS OF GAUSSIAN SPIKES ON GAUSSIAN LASER BEAM IN MAGNETOPLASMA

Munish Aggarwal, Arvinder Singh

Department of Physics, National Institute of Technology, Jalandhar-144011, India
Email: sonuphy333@gmail.com *Email:*arvinder6@lycos.com

In the present paper, we have investigated the effect of relativistic nonlinearity on the growth dynamics of a Gaussian perturbation superimposed on a Gaussian laser beam in a magnetoplasma. Nonlinear differential equations for beam width parameter of the main beam, growth and width of the laser spike are set up by using WKB and Paraxial ray approximation. These coupled ordinary differential equations are solved numerically by using Runge Kutta method. Effect of self-focusing/defocusing of the main beam and spike is analyzed on the growth dynamics of the spike along with the plasma density.

Keywords: Self-focusing . Growth . Gaussian . Ripple . Ponderomotive . Magnetoplasma

3-05

SELF FOCUSING OF LASER BEAM UNDER PLASMA DENSITY RAMP IN COLLISIONLESS MAGNETOPLASMA

Munish Aggarwal, Harish Kumar

Department of Physics, College of Engineering and Managament, Kapurthala, India
Email: sonuphy333@gmail.com

In this paper self-focusing of a short laser pulse in collisionless magnetoplasma under a plasma density ramp is analyzed. The pulse may acquire a minimum spot size due to the self-focusing. Beyond the focus, the nonlinear refraction starts weakening, and the spot size of the laser pulse increases, resulting in an oscillatory self-focusing and defocusing behavior of the beam with the propagation distance. In order to dominate self focusing, we introduce a localized upward plasma density ramp. Due to the upward plasma density ramp, the laser beam retains a minimum spot size. The effect of the magnetic field is also observed on the self-focusing/defocusing of the laser beam. The plasma density ramp of the considered type may be observed in gas jet plasma experiments.

Keywords: Self-focusing . Gaussian . plasma density ramp. collisionless . Magnetoplasma

3-06

SIMULATION OF NEUTRON-IRRADIATED TUNGSTEN MIRRORS

A.Kh. Alimov[1], A.F. Bardamid[2], A.I. Belyaeva[3], A.A. Galuza[3], A.A. Kasilov[4], I.V. Kolenov[3], V.G. Konovalov[4], I.V. Ryzhkov[4], A.A. Savchenko[3], A.F. Shtan[4], O.O. Skoryk[4], S.I. Solodovchenko[4], B. Tyburska-Püschel[5], V.S. Voitsenya[4]

[1]Hydrogen Isotope Research Center, University of Toyama, Toyama 930-8555, Japan;
[2]Taras Shevchenko National University, 01033 Kiev, Ukraine;
[3]National Technical University "KPI", Kharkov, Ukraine;
[4]IPP NSC KIPT, 61108 Kharkov, Ukraine;
[5]Max-Planck-Institut für Plasmaphysik, EURATOM Association, D-85748 Garching, Germany

Due to its favorable physical properties, such as low erosion yield and high melting temperature, tungsten (W) is a candidate material for plasma-facing high heat-flux structures in future fusion reactors. In ITER, the total area of W tiles in divertor area will be ≈50 m^2, and it is likely that Be tiles of the first wall will be replaced by tungsten ones. Moreover, W is considered as a candidate for in-vessel mirror materials for optical diagnostic systems. In the course of deuterium-tritium plasma discharges, due to appearance of defects and change of surface relief caused by irradiation with fusion neutrons and charge exchange atoms, some characteristics of the W surface can be changed, such as sorption capacity of deuterium and tritium, ability to reflect electromagnetic radiation emanating by plasma, and the rate of sputtering by charge exchange atoms.

The effects of neutron-induced displacement damage on the retention of hydrogen isotopes have been simulated by irradiation of tungsten targets with 20 MeV W ions [1-2].

In the present study, a development of the surface topography of W mirrors pre-damaged with 20 MeV W ions under long-term sputtering was examined. Two types of tungsten with a purity of 99.99 wt.% produced by A.L.M.T. Corp., Japan, were used in this work: (i) a polycrystalline ITER-grade tungsten and (ii) the polycrystalline W fully recrystallized at 2073 K for 1 hour after cutting and polishing. The specimens were prepared as high optical quality mirrors (10×10×2 mm^3 in size) to investigate a change of optical properties under surface sputtering. The front side of the specimens was irradiated with 20 MeV W ions to damage levels of 0.3 dpa and 3.0 dpa at the damage peak situated at a depth of 1.35 μm. The other side of the specimen served as a reference surface. The damaged surface was sputtered with 600 eV Ar ions up to a depth of 3.9 μm that significantly exceeds the depth of the damaged zone (~2.1 μm).

As follows from the obtained data, self-damaging of tungsten mirror specimens with 20 MeV W ions does not influence on optical properties, surface topography, and sputtering yield. This observation gives a good reason to make an optimistic conclusion that the neutron irradiation, at least at the damage level would be achieved in ITER, has not to make an additional contribution in the processes developing under impact of charge exchange atoms only.

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3-07

MAGNETIC SURFACES STELLARATOR-MIRROR HYBRID AT URAGAN-2M DEVICE

G.G. Lesnyakov, S.P. Gubarev, V.G. Kotenko, M.N. Makhov, V.E. Moiseenko, G.P. Opaleva, A.N. Shapoval, V.S. Voitsenya, M.I. Zolototrubova

Institute of Plasma Physics, National Science Center "Kharkiv Institute of Physics and Technology", 61108 Kharkiv, Ukraine

This research is performed for grounding of a possibility of creation of the fusion neutron source on the base of plasma trap with combined magnetic system [1] for driving a sub-critical fast nuclear reactor. The experiments on measuring magnetic surfaces at Uragan-2M, a torsatron with additional toroidal field, have been performed when the stellarator-mirror magnetic system is created by switching off one toroidal coil. The experiments confirm existence of closed magnetic surfaces in such a combined system in regime with k_{φ}= 0.24 (k_{φ} is the ratio of the toroidal magnetic field of the helical winding to the total toroidal field). The parameters of the magnetic configuration are in reasonable agreement with the numerical calculations [2].

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3-08

COMPARING OF IRRADIATION NON-UNIFORMITY AND STOPPING POWER OF BISMUTH AND CESIUM ION BEAMS IN A HEAVY ION FUSION TARGET

[1]Gholamzadeh, Leila; [2]Ahmadi, Masoume

[1]Department of Physics, University of Yazd, Iran
[2]Department of Physics, University of Guilan, Iran

Due to a favorable energy deposition behavior of heavy ions in matter, high accelerator efficiency and their high repetition rate, it is expected that the heavy ion beam (HIB) would be one of energy driver candidates to operate a future inertial confinement fusion power plant. Hence, in recent years OK-1code is used to calculate the energy deposition of heavy ion beams and their irradiation non-uniformity onto a spherical target that this code is based on the stopping power of ions in matter. We used from OK-1 code and we evaluated energy deposition and their irradiation non-uniformity for the bismuth and cesium ion beams in a pellet by 12,20,32,60 &120 beam irradiation schemes. The simulation results show that bismuth ion beams have higher deposited energy and lower range and non-uniformity value than cesium ion beams.

3-09

NEUTRONIC MODEL OF A FUSION NEUTRON SOURCE

S.V. Chernitskiy [1], V. E. Moiseenko [2], O.Ågren[3]

[1] *"Nuclear Fuel Cycle" Science and Technology Establishment, National Science Center "Kharkiv Institute of Physics and Technology", Akademichna St. 1, 61108 Kharkiv, Ukraine*
[2] *Institute of Plasma Physics, National Science Center "Kharkiv Institute of Physics and Technology", Akademichna St. 1, 61108 Kharkiv, Ukraine*
[3] *Uppsala University, Ångström Laboratory, SE-75121 Uppsala, Sweden*

The applications of neutrons are unique because of the distinctive properties of the interaction of neutrons with matter. Neutrons interact with nuclei but not with the electron shells. Scattering length vary greatly for different isotopes of one element. The neutron diagnostics can provide a high isotopic contrast giving the possibility to differentiate light nuclei from heavier ones. The capabilities of neutron diffraction are manifested most clearly in hydrogen-containing systems, such as polymers, biological systems, organic and water solutions. Besides, a neutron has a magnetic moment. Therefore, neutron diffraction is a direct method to diagnose magnetic structures, both in the interior and on the surface. Beams of polarized neutrons are especially effective tools for magnetic diagnostics. Neutrons interact only weakly with matter, so they do not destroy even the delicate biological systems and can penetrate deeply into the interior, which is important for studying their volumetric properties.

Powerful sources of fusion neutrons with energies ~ 14 MeV are of particular interest. A stand-alone application of fusion neutrons is testing of materials for fusion reactor. The purpose of this study is to find a principal design of a steady-state fusion neutron source. The MCNPX numerical code has been used to model the neutron kinetics and to calculate the neutron flux in the contemplated location of sample exposure.

In the calculation model the main part of the source has a cylindrical shape with an inner radius of 88 cm and a length of 4 m. A vacuum chamber with a radius of 0.5 m contains a 4 m long hot D-T plasma which produces fusion neutrons. For the first wall a thickness of 3 cm was chosen. Behind the first wall is a liquid-metal coolant for heat removal. Two versions of the coolant have been considered: lead and bismuth eutectic (LBE), and sodium. A shield surrounding the model was used to absorb the outcoming neutrons.

The paper presents calculation results for the neutron flux and spectrum at the sample area and inside the first wall for the two coolants. The radial leakage of neutrons through the shield has also been calculated.

3-10
NEUTRONIC MODEL OF A STELLARATOR-MIRROR FUSION-FISSION HYBRID

S.V. Chernitskiy [1], K. Noack [2], V. E. Moiseenko [3], O. Ågren [2]

[1] *"Nuclear Fuel Cycle" Science and Technology Establishment, National Science Center ''Kharkiv Institute of Physics and Technology", Akademichna St. 1, 61108 Kharkiv, Ukraine*
[2] *Uppsala University, Ångström Laboratory, SE-75121 Uppsala, Sweden*
[3] *Institute of Plasma Physics, National Science Center ''Kharkiv Institute of Physics and Technology", Akademichna St. 1, 61108 Kharkiv, Ukraine*

The MCNPX numerical code has been used to model the neutron transport of a mirror based fusion-fission reactor. The purpose of this paper is to find a principal design of the fission mantle which fits to the neutron source and to calculate the leakage of neutrons through the mantle surface of the fission reactor.

In the calculation model, the fission reactor part has a cylindrical shape with an inner radius 1.658 m and a 4 m length. The fuel is the "standard" spent nuclear fuel with isotopic composition of the spent nuclear fuel from PWR after uranium-238 removal. Inside the fission reactor core is a vacuum chamber with a radius 0.5 m containing a 4 m long hot plasma producing fusion neutrons. Such a scheme of the subcritical system, but in a bigger scale, is proposed and studied in the article [K. Noack, V.E. Moiseenko, O. Ågren, A. Hagnestål Annals of Nucl. Energy **38**, Issues 2-3, (2010) p. 578.]. To sustain the hot ion plasma which is responsible for the fusion neutron production, neutral beam injection is considered. In such a scheme, some fusion neutrons are generated outside the reactor core near the injection point. This part of the plasma column is surrounded by a vessel filled with borated water to absorb the fusion neutrons.

Calculation results for the radial leakage of neutrons through the mantle surface of the fission reactor are presented. These calculations predict that the power released with neutrons from the reactor to outer space would be small and will not exceed the value of 5.7 kW when the reactor thermal power is 1 GW_{th}.

3-11

OPTICAL DESIGN OF H-ALPHA AND VISIBLE SPECTROSCOPY FOR ITER

A.V. Gorshkov, A.G. Alekseyev, D.Yu. Vukolov

NRC "Kurchatov Institue", Moscow, Russia

The paper presents the design of optical channels for H-alpha and Visible Spectroscopy, located in the upper and equatorial ports of ITER. The main optimization criteria are minimizing the number of optical components and reduction of the channel aperture inside the vacuum port. The only parabolic mirror, which is located in the front-end first mirror assembly (FMA), images the entrance aperture of the channel at the vacuum window. The relay lens is located just behind the vacuum window. The image produced by the relay lens is located on the field lens located near the bioshield. The field lens matches an aperture of the relay and camera lenses. Rotary double-wedge compensator scheme is proposed for the compensation of slow variations of the optical axes due to the ITER vacuum vessel size variations with respect to a bioshield owing to thermal and evacuation drifts. A number of cameras equipped with narrow-band filters are used for imaging of inner an outer ITER walls at H-alpha and Be spectral lines. Image numerical aperture of the camera lens is adjusted to a standard optical fiber numerical aperture (NA = 0.22). Optical resolution of channels on the H-alpha line is ~12 mm at the inner wall and ~22 mm in the outer wall, which are reasonably sufficient for the measurements with the use of 60 mm diameter optical dumps to be installed into the ITER wall for the divertor stray light suppression.

Statistical assessment of measurement accuracy of the hydrogen lines and impurities in ITER are presented as well for the background radiation level of 10^{17} Photon/s/m^2/ster/nm. It is shown that intensity of hydrogen lines could be measured with 10% accuracy at maximum optical resolution. The spatial resolution of beryllium lines worsens up to 150 mm mostly due to the pixel binning required for 10% measurement accuracy for the emission intensity over 10^{15} Photon/s/m^2/ster.

3-12

STUDY OF CONTAMINATION AND CLEANING OF THE IN-VESSEL MIRRORS FOR ITER OPTICAL DIAGNOSTICS ON T-10 TOKAMAK AND QSPA-T FACILITY

S.Grashin[1], I.Arkhipov[1], N.Klimov[2], K.Vukolov[1], V.Budaev[1], N.Svechnikov[1], A.Karpov[1], V.Stankevich[1], A.Zhitlukhin[2], D.Kovalenko[2], V.Podkovyrov[2]

[1]*NRC 'Kurchatov Institute', Kurchatov square 1, Moscow 123182, Russian Federation.*

[2]*SRC TRINITI, Pushkovykh street 12, Troitsk, Moscow Region, 142190, Russian Federation.*

Deposition of contamination films on the surface of the first mirrors for ITER optical diagnostics has changed significantly their reflectivity. Therefore, it is extremely needed that experimental data on deposition rate, structure and content of the films as well as identification of the mechanisms responsible for the films formation were obtained under ITER-relevant conditions. In this work, deposition processes of carbon and carbon-tungsten mixed films on metallic (SS, Mo) and silicon mirrors have been studied on tokamak T-10 and plasma gun QSPA-T facility under controlled conditions.

Tokamak T-10 has the scrape-off-layer parameters similar to those of ITER and large fluxes of impurities onto the first wall. This justify using the T-10 tokamak equipped with graphite limiters for experimental study of contamination processes of ITER in-vessel optics despite the difference in pulse duration (1 s and 400 s correspondingly). In our experiments, the mirrors were exposed near the tokamak first wall in the different points of the SOL with specially designed diagnostic inserts. Plasma gun QSPA-T provides pulse plasma heat loads on the target of 1 ms in the range of 0.2–5 MJ/m^2 expected during ITER ELMs and disruptions. In the QSPA-T experiments both graphite and tungsten targets were used.

Surface morphology and optical properties of a-C:H films were investigated by SEM, AFM, spectrophotometry and ellipsometry. As a result, deposition rates of the films were estimated. Analysis of electron structure and composition of the films has been performed by XPS and AXS methods. Analysis of hard diamond like a-C:H films deposited in two diagnostic sections (close to and far from graphite elements) of T-10 tokamak during working discharge has shown that deposition rate falls down significantly with distance from graphite limiters. It means that the carbon sputtered from the limiters mainly in the form of neutrals. Deposition rate for disruptive discharges was 2.5-3 times higher than for the stable one. Films surface is complicated and include micro particles and globular nanostructures.

Cleaning processes of the mirrors were investigated during wall conditioning regime. It was found that the deposition of soft a-C:H films occurred at the sample temperature of 100-200 C instead of erosion. The deposition rate was more than order lower than for working discharge. But it not depends on the distance from graphite limiters. It seems that the mechanisms of sputtering and transport of the carbon for working and conditioning discharge are quite different.

For QSPA-T deposition rate was much higher than for working discharge of T-10. In contrast with tokamak, QSPA-T films contain the metal impurities of W, Fe, Cr, Zn and Cu mainly in oxide chemical state. The successful experiments were fulfilled on cleaning of the mirrors deposited on tokamak T-10 and QSPA-T by the laser ablation method and by the inductive plasma discharge.

3-13

RELATIVISTIC NEOCLASSICAL FLUXES IN HOT PLASMAS

I. Marushchenko[1], N.A. Azarenkov[1], N.B. Marushchenko[2]

[1] V. N. Karazin Kharkiv National University, Kharkov, Ukraine
[2] Max-Planck-Institut fur Plasmaphysik, IPP EUROATOM, Greifswald, Germany

In recent years it was well recognized that plasmas in astrophysics need to be described with relativistic effects taken into account and the necessary Lorentz-covariant formalism in kinetics and statistical physics was developed. Following this line, self-consistent relativistic magnetohydrodynamics was recently developed and a specific features of the kinetics and equilibrium in relativistic non-neutral plasmas were studied. Since the fusion reactor scenarios require a high temperatures, the role of relativistic effects for electrons in toroidal devices also becomes an actual question. In principle, the relativistic effects do not create any significant contribution in the transport processes for existing tokamaks and stellarators, but those need to be examined for ITER and DEMO, where the expected electron temperatures are sufficiently high (20-35 keV). Apart from this, the reactions possible in future aneutronic fusion reactors with D-^{3}He, D-D and p-^{11}B require an actually relativistic temperatures up to 100 keV. The common opinion about a negligible role of the relativistic effects in transport physics is based on the assumption that those are important only for suprathermal electrons (for example, the running-away electrons in tokamaks), while the bulk electrons are rather non-relativistic even for high temperatures. At the same time, the relativistic effects can appear also due to a macroscopic features of the relativistic thermodynamic equilibrium given by the Jüttner distribution function, called also the relativistic Maxwellian. In particular, contrary to the non-relativistic Maxwellian, the shape of the Jüttner distribution function, which is Gaussian only in the non-relativistic limit, depends from the temperature and, as consequence, the relative "weight" of the bulk electrons is decreasing with a growth of temperature.

In the present work the examination of the relativistic effects in the neoclassical transport theory is presented. Contrary to the astrophysics, where the relativistic transport and MHD theories are usually represented in covariant formulation which guaranties the Lorentz invariance of the equations in any moving system, we reformulate the standard neoclassical theory by only introducing the relativistic drift-motion equations and assuming that the thermodynamic equilibrium for the relativistic electrons is given by the relativistic Maxwellian. In order to simplify any numerics and to adapt the new description for existing transport codes, the formulation proposed here is actually very similar to the standard one that significantly simplifies a possible update and benchmarking of the relativistic and non-relativistic approaches side-by-side. According to our calculations of the radial fluxes in 1/nu regime, performed in the relativistic approach and compared with those in non-relativistic limit, the relativistic effect on both particle and conductive heat fluxes is quite strong, reducing the latter for about 8% already at the temperatures around 20 keV, and for high temperatures around 100 keV, that can be reached in future reactors, the decrease of a fluxes caused by the relativism is expected to be 7 to 15%.

3-14

EFFECT OF PLASMA ROTATION ON THE RESONANCE MAGNETIC PERTURBATIONS AT THE EDGE OF TOKAMAK PLASMAS

I.M. Pankratov[1,2], I.V. Pavlenko[2], O. A. Pomazan[2] and A.Ya. Omelchenko[1]

[1]*Institute of Plasma Physics, NSC "Kharkiv Institute of Physics and Technology", Academicheskaya Str.1, 61108 Kharkiv, Ukraine*
[2]*V.N. Karazin Kharkiv National University, Svobody Sq. 4, Kharkiv 61022, Ukraine.*

Control of Edge Localized Modes (ELMs) is a critical issue of the present day large tokamaks and future ITER operation. ELMs are short bursts of particles and energy at tokamak plasma edge observed in H-mode operation [1]. Melting, erosion and evaporation of divertor target plates may occur as results of these bursts. Many experiments at DIII-D have shown that ELMs can be suppressed by small external low frequency helical magnetic perturbations [2, 3]. Until now understanding of the underlying physics of ELMs and their suppressions is far to be complete.

Possibility of the pressure perturbation resonant excitation (due to the plasma rotation) by external helical magnetic perturbations at the plasma edge has been shown early in the frame of one-fluid MHD [4]. In this case the plasma response has to be taken into account (a perfect shielding is not assumed).

The influence of these pressure perturbations on external helical magnetic field at the plasma edge is investigated in the present paper. Considered plasma parameters are closed to the ones from DIII-D experiments [2, 3]. Poloidal and toroidal plasma rotations are taken into account.

In [5] the influence of the external helical field on the equilibrium of ideal plasma was investigated in the frame of MHD theory, when a perfect shielding of the external resonant field was assumed.

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3-15

ACTIVE AND PASSIVE DEPOSITION MITIGATION TECHNIQUES FOR ITER DIVERTOR THOMSON SCATTERING DIAGNOSTICS

A.G. Razdobarin[1], E.E. Mukhin[1], V.V. Semenov[1], S. Yu. Tolstyakov[1], M.M. Kochergin[1], G.S. Kurskiev[1], K.A. Podushnikova[1], S.V. Masyukevich[1], P.V. Chernakov[1], A.E. Gorodetsky[2], V.L. Bukhovets[2], R. Kh. Zalavutdinov[2], A.P. Zakharov[2], I.I. Arkhipov[2], A.S. Smirnov[3], T.V. Chernoizumskaja[3], E.M. Khilkevitch[1,3], S.V. Bulovich[3]

[1] *Ioffe Physical-Technical Institute, St Petersburg, 26 Polytechnicheskaya, Russian Federation*
[2] *Frumkin Institute of Physical Chemistry and Electrochemistry, Moscow, 31 Leninsky, Russian Federation*
[3] *Saint-Petersburg State Polytechnic University, St Petersburg, 29 Polytechnicheskaya, Russian Federation*

According to recent experiments in plasma fusion machines, the contamination of optical elements under deposition-dominated conditions in ITER will result in fast degradation of their optical characteristics [1]. The development of deposition-mitigation techniques is an important part of R&D plan for the ITER divertor Thomson scattering (TS) diagnostics to be placed in the area featuring extremely high contaminant concentration and rather low (less than 1 eV) energy of charge-exchange neutrals. In suggested design active and passive protection techniques are combined in one system to mitigate both dust and radicals deposition. The first collecting mirror of TS diagnostics is intended to be subjected to continuous plasma treatment in the course of ITER shots. The main argument for this approach is that it can prevent the formation of solid, persistent depositions which may be resistant to cleaning treatment. The discharge is to operate under strong permanent magnetic field and ITER vacuum conditions that impose certain restrictions on the design of a plasma reactor. The capacitively coupled RF discharge with the first collecting mirror as a ground electrode has been developed and is being tested.

In addition to plasma cleaning technique the gas puffing system is designed to protect laser window and the first collecting mirror. The deuterium counter-flow in the laser launcher channel was shown to suppress micron-sized dust particles transportation towards the laser window. It is also expected to be effective to reduce the impurities concentration in the vicinity of optical surfaces. The implementation of plasma cleaning and blowing out techniques, are discussed along with the results of recent experiments on the suppression of α-CH films deposition in the channel with the ridged profile.

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3-16

INFLUENCE OF BACKGROUND PLASMA ON ELECTROMAGNETIC PROPERTIES OF COAXIAL GYROTRON CAVITY

[1]V.I. Shcherbinin, [1,2]G.I. Zaginaylov, [3]K. Schuenemann
[1]National Science Center "Kharkov Institute of Physics and Technology"
61108, Kharkov, Academicheskaya str., 1, tel. 8-057-335-08-47
[2]V.N. Karazin Kharkov National University
[3]Technical University Hamburg-Harburg
E-mail: vshch@ukr.net

Nowadays gyrotrons based on coaxial cavities with a corrugated inner conductor offer a serious alternative to conventional gyrotrons in the perspective of increasing the unit power to several megawatts, in a frequency range compatible with the ITER requirements. A collaborative effort between European institutions and a commercial partner has been launched by the European Fusion Development Agreement in 2003, aiming at the development of an industrial 2-MW 170-GHz continuous-wave (CW) coaxial cavity gyrotron for ITER. Recently, 2.2 MW record power with 30 % efficiency has been generated with the short-pulse (one millisecond) pre-prototype tube of this gyrotron at Karlsruhe Institute of Technology [1]. A potential to further increase the output power of coaxial cavity gyrotrons up to 4-MW level is now under design study [2].

The unique opportunity to reach the multi-megawatt level of gyrotron output power is to utilize high-current electron beams of about hundred of amperes. The utilization of such beams inevitably leads to impact ionization of background gas inside gyrotron cavities.

Plasma, once created in the cavity, initially concentrates inside beam volume and its influence on gyrotron operation is minimal. But electrostatic forces between plasma charges force them to diffuse. According to [3] the time needed for the plasma particles to fill completely the gyrotron cavity amounts to several milliseconds. When gyrotron has much longer operating time, plasma in gyrotron cavity becomes evident and neutralizes the beam space charge. Beam compensation with the time scale of about hundred of milliseconds is observed in experiments with conventional megawatt-class CW gyrotrons. These gyrotrons have substantially lower beam currents than 2-MW 170-GHz coaxial cavity gyrotron. Therefore, one can expect noticeable plasma effect on operation of this gyrotron in forthcoming experiments with increased pulse length.

The problem of low-density plasma influence on electromagnetic properties of coaxial gyrotron cavities is considered. It is shown that plasma leads to downshift of cavity eigenfrequencies. The effect is stronger for the modes whose frequencies are closer to the cyclotron frequency of the plasma electrons. It is found that plasma influence on quality factors of cavity modes is noticeable only when the impedance of corrugation insert is rather small. In this case modes with caustic radiuses that are close to the radius of corrugation insert experience the strongest effect. The opposite dependences of Q values on plasma density have been observed for modes differing in sign of azimuth index. We have estimated the most probable plasma densities inside cavities of 170-GHz coaxial gyrotrons [1] and [2]. These values belong to domain of applicability of our theoretical approach.

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3-17

CLASSIFICATION OF HYDROCARBON FILMS DEPOSITED UNDER ITER-RELEVANT CONDITIONS

I. Arkhipov[1], N. Klimov[2], V. Stankevich[1], N. Svechnikov[1], V. Budaev[1], and K. Vukolov[1]

[1]NRC 'Kurchatov Institute', Kurchatov square 1, Moscow 123182, Russian Federation.
SRC TRINITI, Pushkovykh street 12, Troitsk, Moscow Region 142190, Russian Federation.

Elements of construction of modern tokamaks manufactured from carbon materials undergoing to intensive erosion during working and cleaning plasma discharges. Codeposition of erosion products (carbon, hydrocarbon radicals) and hydrogen leads to growth of amorphous hydrocarbon films which can influence on many important aspects of tokamak working. In this work, comparative analysis of surface morphology, electronic structure and composition of such films have been carried out.

Hydrocarbon films were deposited under ITER-relevant conditions in plasma gun QSPA-T and tokamak T-10. Pulse duration of QSPA-T is equal to about 0.5 ms which relevant to transient events of tokamaks such as ELMs and disruptions. In tokamak T-10 the films were obtained both in regime of stable working pulses with 1 s duration and regime of disruptions. Deuterium inductive Taylor-type discharge in tokamak T-10 was used to obtain "steady-state" type of hydrocarbon films.

Electronic structure of ITER-relevant hydrocarbon films obtained in T-10 tokamak and QSPS-T plasma gun under controlled conditions have been investigated by XPS and AXES techniques. A new method of film characterization by analysis of XPS valence band spectra together with estimation of a band gap (Eg) value was developed. The band gap value may be used for simple evaluation of hydrogen content in the hydrocarbon films. To our opinion, this is a very sensitive instrument to observe spectral differences as well as in-gap states, which may refer to defects (dangling bonds) and impurities acting as adsorption centers for hydrogen isotopes and hydrocarbons. It is important that application of this approach allows to determine the band gap values not only in the hydrocarbon films but in mixed and metallic (Be, Mo, W) films also.

Surface morphology and optical properties (thickness and refractive index) of hydrocarbon films deposited on stainless steel and Mo mirrors as well as on Si probes were investigated by SEM and ellipsometry. As a result, deposition rates for different type films were estimated. Analysis of hard hydrocarbon films deposited in two diagnostic sections of T-10 close to and far from graphite limiters during working pulses has shown that the deposition rate falls significantly with distance from carbon source. Cleaning of the mirrors by inductive deuterium discharge was studied during wall conditioning regime. It was found that instead of erosion, the deposition of soft a-C:H films on the mirrors occurred at temperatures below 120 C in both sections at about the same rate.

Hydrocarbon films were analyzed by a ternary (H, C sp^2 , C sp^3) phase diagram. On this diagram, the T-10 and QSPA-T films were positioned in quite compact region between diamond- and polymer-like a-CH films. Difference between XPS and ellipsometric data may be due to non-uniformity of the films in thickness.

4-01

MAGNETIZED PLASMA IN STRONG ELECTRIC FIELD: FROM PARAMETRIC TURBULENCE TO ENHANCED CONFINEMENT

V.S.Mikhailenko[1], V.V Mikhailenko[2], K.N.Stepanov[3]

[1]*V.N.Karazin Kharkov National University, 61108 Kharkov, Ukraine*
[2]*Pusan National University, Pusan, South Korea*
[3]*National Science Center "Kharkov Institute of Physics and Technology", 61108 Kharkov, Ukraine*

The processes of the interaction of plasma with strong pumping electric field (as in RF plasma heating) or with stationary or slowly varying electric field (as in the regimes of the enhanced confinement) are the most abundant sources of new physical effects and their theoretical descriptions. This report is devoted to the unified kinetic approach to the theory of parametric turbulence and to the theory of plasma turbulence in strong shear flow across the confined magnetic field. The key point in that theory is the usage of the spatial and velocity variables which are co-moving with plasma particles in magnetic and strong electric field. This methodology appears effective for the development the theory of the parametric instabilities and for the investigation of the temporal evolution of instabilities in shear flows. The application of the transformation to the turbulent electric field gives the renormalized theories of the parametric turbulence and the theory of strong turbulence of plasma shear flows. That theory accounted for the process of the turbulent scattering of plasma particles as a mechanism of the saturation or suppression of the plasma turbulence and reduction of the anomalous transport.

4-02

HIGH-FREQUENCY GENERATION DURING THE ELECTRON FLOW DECELERATION AND REFLECTION BY THE ELECTROSTATIC POTENTIAL

I.K.Tarasov, A.V.Pashchenko, M.I. Tarasov, D.A. Sitnikov, S.S. Romanov, I.M. Shapoval

Institute of Plasma Physics, National Science Center
“Kharkov Institute of Physics and Technology”, Kharkov, Ukraine

Today the generation of RF electromagnetic waves during the electron flow deceleration in an external electrostatic field is a well-known effect. Moreover, a number of RF-generating schemes were developed according to this mechanism. In the most of such schemes the electron flow is reflected by the external electric field. As it was estimated later this mechanism is not the only possible. In particular it was shown that the RF-generation may also be observed in the absence of the reflected beam particles.

In this work we present the results of experimental study of the RF-oscillations generation at the classic flat triode configuration for both presence and absence of the reflected particles flow. The amplitude and frequency dynamics is studied. The main characteristic parameters behavior for both cases was analyzed and compared.

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4-03

ANALYSIS OF PROJECTS OF HYBRID REACTOR BASED ON MAGNETIC FUSION FOR WASTE MANAGEMENT

E. A. Azizov, G. G. Gladush

FSUE SRC RF Troitsk Institute for Innovation and Fusion Research, Russia, Troitsk, Moscow region,
email: gladush@triniti.ru

. In the last decade in the fusion community the impression that the fastest way to implement of thermonuclear fusion is using it to solve the problems of nuclear power. One of the most important problems is the efficient disposal of spent nuclear fuel. The use of hybrid reactors transmutator for recycling spent nuclear fuel is not only economic but social and political nature associated recently with the wariness of society to the development of nuclear energy. In view of this development and creation of fusion neutron source (FNS) for the disposal of long-lived nuclides in the first place, actinides, are perhaps the most relevant.

Fusion neutrons can be generated in an appropriately designed tokamaks and open magnetic traps. To date, this is the most technologically advanced areas, although the stellarator, accelerator and laser projects also are actively developing. Attention to the fusion-fission hybrid reactor was originally (1977) due to fuel supply issue of the growing park of thermal reactors. This is a problem in our time as the development of need fast reactors not substantially progressed to date. The idea and design of the some modern tokamak hybrids in general, similar to modern designs, including ITER(FDS-EM,China;SABR,USA). Because of the sizes of such tokamak are close to the ITER tokamak, its cost will exceed the cost of ITER, which makes this pro-draft acceptable only within the framework of broad international cooperation.

The project of FNS-based gas-dynamic trap with superconducting coils in details are developing in Institute of Nuclear Physics SB RAS. It involves the power to bring the neutron flux up to 4MW (at P_{NBI} = 114 MW) and subcritical reactor to 1 GW.

The most developed project transmutator reactor on the basis of a compact toroid is a project of JUST-T tokamak with A = 2(TRINITI). The choice of a moderate size aspect ratio A is due to the ability to use the first stage of warm EMS. Numerical calculations showed that the use of a such tokamak reactor can transmute minor actinides from 10 - 15 VVER-1000 reactors. In spherical tokamaks with A ~ 1.5 high parameters are achieved with moderate resources and of financial costs. Therefore, starting from the end of the last century, many countries have begun this development (in China, the USA and England). In small spherical tokamak FNS-ST (R = 0.48 m, r = 0,28 m, Kurchatov Institute) with a magnetic field of 2 T is quite high fluxes of fast neutrons> 7 10^{13} n/cm^2 can be achieved even with copper coils, cooled by water. Molten salt blanket for this FNS consists of four independent modules, the surrounding vacuum chamber. A comparison of the efficiency of generation of neutrons in various projects is carried out.

4-04

RAYLEIGH-TAYLOR INSTABILITY IN PLASMAS WITH SELF-GENERATED MAGNETIC FIELD AND HEAT CONDUCTION

Frank Modica[1], Tomasz Plewa[1], Andrey V. Zhiglo[2]

[1] *Department of Scientific Computing, Florida State University, Tallahassee, FL, USA*
[2] *Institute for Theoretical Physics, NSC Kharkov Institute of Physics and Technology, Kharkov, Ukraine*

Rayleigh-Taylor instability (RTI) is a generic hydrodynamic phenomenon occurring when a denser fluid is supported by a lighter one in gravitational field, or when it is accelerated by the lighter fluid. Developed RTI often governs the global dynamics of the system, like in core-collapse supernovae (CCSN: blast wave accelerating stratified stellar material), young supernovae remnants (supernova ejecta decelerated by the shocked interstellar medium), targets in inertial confinement fusion experiments (material compressed and accelerated by impulse heating by laser or particle beams).
In the simplest canonical setting (ideal hydrodynamics) RTI growth rate in linear regime is higher for shorter perturbation wavelengths, hence the morphology of developed RTI shows complex fractal-like structure. After RTI enters nonlinear regime mushroom-like caps start developing on the rising bubbles of lighter fluid, which later go on producing smaller-scale structures on the interface between the two fluids. This is pronouncedly different from what is observed experimentally in laser-evaporated target experiments [1] designed to mimic conditions at the blast wave in CCSN. In those experiments columns of lighter plasma penetrate deeper into the denser one than classical RTI simulations predict, with the growth of secondary features suppressed.
We study numerically the effects of magnetic fields self-generated via Biermann Battery effect on RTI dynamics. In setups close to studied in [1] we get magnetic fields of order 1-10 MG, at which magnetic pressure gets comparable to the thermodynamic pressure of the plasma. Comparable magnetic fields generated were observed experimentally. A lot of effects start playing significant role in magnetic field evolution and the plasma dynamics at fields this strong, such as Hall effect, ambipolar diffusion, transport phenomena becoming anisotropic, dependent on the magnetic field. Heat conduction becomes very effective at high temperatures (~a few 10^7 K) reached, influencing RTI dynamics. We incorporated these effects into FLASH code [2], performed numerical tests in 2D and 3D problems, studied the effects of the mentioned phenomena on RTI. In setups modeling experiments [1] proper inclusion of magnetic effects leads to nonlinear RTI evolution resembling experimental results, with smaller scale features suppressed and less mixing taking place.

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4-05

KINETIC SIMULATION OF LOW PRESSURE RF DISCHARGE IN NONUNIFORM AXISYMMETRIC MAGNETIC FIELD

V.V.Olshansky

National Science Center "Kharkov Institute of Physics and Technology", 1, Akademichna Street, 61108, Kharkiv, Ukraine

An implicit 2D3V PIC/MCC code has been developed for the kinetic simulation of low pressure RF discharges. The code uses coupled particle-in-cell method (PIC) for calculation collisionless dynamic of the plasma particles and Monte-Carlo method (MCC) for taking in account the particle collisions. This method allows to compute self-consistent distributions of the fields, plasma density and energy of the particles from first principles. The disadvantage of PlC/MCC is that it consumes more computational resources compared to other numerical methods. For the computation time reduction a number of physical and numerical methods of speeding up the code were introduced, such as the implicit schemes of the particles motion and fields computation, the electron sub-cycling, different weights of electrons and ions, using of the initial diffusion density profile, preliminary simulation stage with the reduced ion mass and null-collisional Monte-Carlo method. An addition the parallel scheme of the particle motion and the fields calculation is used. These speeding up techniques allow to reduce the numerical simulation time on the order of value.

As an application the developed code is applied to the plasma dynamic investigation in capacitively coupled plasma RF discharge enhanced by the external magnetic field which is used in the neutral loop discharges (NLD). For the pressure of the order of a few millitorr and the various magnetic field configurations the spatial distribution of the averaged over RF period electron energy and electron density are found. Likewise it is obtained the electron distribution function near the X-point, at the separatrix and far from the neutral loop. In dependance on the pressure and the magnetic field geometry the electron temperature can increase several times in the neutral loop region.

The results of the carried out investigations are compared with the published experimental data and with the data obtained earlier by the numerical modeling of the inductive discharge with the neutral loop (ICP-NLD).

4-06

THE DYNAMICS OF 3D DIOCOTRONIC WAVE DURING THE "HOT" ELECTRON FLOW PROPAGATION IN THE DRIFT SPACE

I.K. Tarasov, M.I. Tarasov, D.A. Sitnikov

Institute of Plasma Physics, National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine

In the second half of XX century special attention was paid to the problem of plasma trapping and confinement in the different magnetic and electrical field configurations. In particular a huge amount of publications were dedicated to the charged particles confinement in the cylindrical Penning trap. Such systems allowed to observe and to study some interesting effects in the plasma column dynamics.

Unfortunately Penning traps weren't so useful in studying the effects developed during the charged particles flow propagation along the magnetic field axis. For these investigations we have used a cylindrical setup without the axial confining field. The width of the flow particles distribution by longitudinal velocities is close by its magnitude to the average longitudinal velocity.

The experimental results have shown the diocotronic instability development. The diocotronic waves had pronounced azimuthal and longitudinal components. It was also detected that the instability development is localized in the potential dip which is created by the flow particles spatial charge.

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4-07

NUMERICAL SIMULATION OF COMPRESSION PLASMA FLOWS, GENERATED BY MAGNETOPLASMA COMPRESSOR

V.M. Astashynski, S.I. Ananin
B.I. Stepanov Institute of Physics of the National Academy of Sciences of Belarus, 68 Nezalezhnastsi Ave., 220072, Minsk, Belarus
I.E. Garkusha[1], D.G. Solyakov[1]
[1]Institute of Plasma Physics of the NSC KIPT, 61108, Kharkov, Ukraine

The compression plasma flows generated by quasi-stationary high-current plasma accelerators provide a great potential in applications connected with modification of surfaces of solids for the purpose of obtaining of required properties.

The present paper is devoted to numerical simulation of different gases plasma flow parameters, generated by magnetoplasma compressors (MPC) such as developed at the B.I. Stepanov Institute of Physics of the National Academy of Sciences of Belarus and at the Institute of Plasma Physics of the NSC KIPT, Kharkov, Ukraine. The calculations were carried out for the geometry of discharge device described in [1, Fig. 1]. To numerically simulate the compression plasma flow parameters in such gas-discharge MPC, an approach developed at the B.I. Stepanov Institute of Physics was used. It is based on the method of large (“coarse") particles with the magnetic field taken into account and radiative energy transfer introduced in terms of a two-stream multi-group approximation for a 2-D region [2, 3]. This approach makes it possible to describe the structure and dynamics of partially ionized compression plasma flows in high-current plasma accelerators and to carry out the optimization of plasma acceleration in such installations.

The simulation was carried out for two different modes of the accelerator work: for the residual gas mode, in which the discharge was taking place in discharge chamber prefilled with the working gas, and for the mode, in which the working gas is injected in MPC during the discharge. In these calculations, the total current time dependencies recorded in experiments were used for border conditions.

As a result of numerical simulation, the spatial distributions of plasma parameters (pressure, electron concentration, temperature and velocity of the plasma flow) and current distributions for various conditions of gas supply and for the various dependencies of the total current versus time were received. It was shown that in some regimes the plasma flow acceleration come along in non-optimal way. For example, if the initial total current rise is too big, the current vortex is formed on the entrance of the plasma accelerator. This current vortex prevents plasma axial acceleration. As a result, most of the energy stored in capacitor banks may be spared in some cases not on the acceleration of the plasma flow along the system axis but on ohmic heating of plasma which is leaving the system between anode bars.

In summary, our model can be used for optimization of plasma flows acceleration in described conditions.

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4-08

ELECTRIC DISCHARGE IN THE TRANSVERSE GAS FLOW AT ATMOSPHERIC PRESSURE

Iryna Prysiazhnevych[1], Valeriy Chernyak[1], Evgen Martysh[1], Tamara Lisitchenko[1], N.V. Belenok[2]

[1]*Taras Shevchenko Kyiv National University, chernyak_v@ukr.net*
[2]*National Technical University of Ukraine "Kyiv Polytechnical Institute", Prosp. Peremogy 37, Kiev 03056, Ukraine*

Physical features of the transverse arc discharge (TA) and its atmospheric pressure plasma were investigated for the wide range of gas flow rates (0 ÷ 3/4 of the sound speed) and for the different gas content (atomic – Ar, molecular – air) and different character of gas flows (from laminar to turbulent). Component composition of the plasmaforming gas; electronic excitation temperatures T_e^* of atoms, vibration T_v^* and rotation T_r^* temperatures of molecules in the generated plasma were determined by optical emission spectroscopy. The electron distribution function and its average energy were calculated by using Bolsigplus code. The comparative analysis was made of the TA plasma parameters and other "transversal" gas-dynamic plasma sources known from the literature.

The difference between T_e^* of electrode material atoms (cooper) and atoms of blowing gas (oxygen, hydrogen, argon) was found. It can be explained by the additional mechanism of the population of electronic states of cooper atoms due to the ion-ion recombination.

It was shown that when the gas flow rate achieves values larger than the drift velocity of ions in an electric field of the discharge further increasing of the voltage drop on the discharge starts with the gas flow rate growth, which is accompanied by appearance of numerous filament structures oriented along the gas flow.

4-09

STUDIES ON X-RAY AND NEUTRON EMISSION FROM 2.2 KJ PLASMA FOCUS DEVICE

N. Talukdar, T. K. Borthakur, , N. K. Neog

Centre of Plasma Physics-Institute for Plasma Research, Nazirakhat, Sonapur, Assam, Pin-782402
E-mail: tkborthakur@yahoo.co.uk

Plasma focus (PF) is a rich source of pulse X-ray and neutron emission. The measurement and analysis of X-ray and neutron emission from a 2.2 kJ PF device has been carried out using photo multiplier tube (PMT), PIN diode, pin-hole camera, vacuum photodiode (VPD) and neutron bubble dosimeter. The soft X-rays are more or less emitted in multiple pulses. Hot spots are found to be present in the X-ray emitting zones of pinched plasma column. The neutron emissions are more in numbers as well as more energetic in axial direction as compared to the radial one. The neutron's anisotropic emission may be influenced by beam-target mechanism

Key word: plasma focus, X-ray, neutron

4-10

DRIFT MOTION OF CHARGED PARTICLEIN WAVE FIELD OF MAGNETIC PUMPINGUNDER CHERENKOV AND CYCLOTRON RESONANCE CONDITIONS

K.N. Stepanov, Yu. N. Yeliseyev

Institute of Plasma Physics, National Science Center
"Kharkov Institute of Physics and Technology" Kharkov, Ukraine

Interaction of particles with a wave is a basis for calculation of effect of a selective heating of ions in a developed ICR-method of isotope separation [1]. In the report the solution of a problem on the charged particle motion in the homogeneous magnetic field and in the vortex electromagnetic field of a wave of magnetic pumping of small amplitude under cherenkov and cyclotron resonance conditions is presented in the drift approximation.

The wave is produced by the azimuthal surface current $j_\varphi = j_0\delta(r-a)\cos(k_z z-\omega t)$ modelling the current of the solenoidal antenna. Its usage is considered within the method of ICR-separation [1]. The wave field has components E_φ, H_r, H_z [2]. Particle motion is described by cylindrical coordinates of the Larmor center R, θ coordinates of a particle on the Larmor circle ρ, $\vartheta = \vartheta_0 - \omega_c t$ and longitudinal variables $z = z_0 + \int_0^t v_z dt$, v_z. In the absence of wave the coordinates $R, \theta, \rho, \vartheta_0, z_0, v_z$ are the integrals of motion. In the presence of wave of small amplitude they vary slowly. Using the summation theorem for Bessel functions, the equations of drift motion of a particle are derived by the method of averaging [3] and three first integrals of the drift motion are found:

$$\rho^2 - R^2 = C_1 \ , \quad v_z - \ \omega_c k_z / 2n \ R^2 = C_2 \ , \quad H \equiv H_0 + H_1 = C_3 .$$

H is a Hamiltonian of a particle in the magnetic field and in the field of a pumping wave, $H_0 = \ m\omega_c^2\rho^2 + mv_z^2 \ / 2$, $H_1 = -e \ \omega_c / \omega \ \rho A I_n \ \Lambda R \ I_n' \ \Lambda\rho \ \cos\Psi_n$, Ψ_n is a phase slowly changing in resonance conditions, $\Psi_n \equiv n(\vartheta_0 - \theta) + (\omega - n\omega_{ci})t - k_z z$, $A = E_0 / I_1(\Lambda a)$, $E_0 = \ 4\pi\omega / c^2 \ \ j_0 a K_1(\Lambda a) I_1(\Lambda a)$, $\Lambda^2 = k_z^2 - \omega^2 / c^2 > 0$. The two first integrals coincide with integrals of the drift motion of a particle in the field of a potential wave with azimuthal number $m = 0$ [3]. The found integrals make it possible to integrate on time the equations of drift motion, to build particle trajectories in a phase space R, ρ, Ψ and thus to solve completely in the drift approximation a problem about the motion of charged particle in the field of a wave of a magnetic pumping under Cherenkov and cyclotron resonance conditions. The solution is obtained at arbitrary value of particle Larmor radius.

As results from the first integral, the increasing of radius of the Larmor centre R follows the increasing of a particle Larmor radius ρ and vice-versa. This peculiarity explains the observed radial drift of particles interacting with a pumping wave in numerical calculations [4, 5].

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4-11

FIELD PENETRATION AND STOCHASTIC PLASMA HEATING IN CYLINDRICAL SURFACE WAVE PLASMA

N.A. Azarenkov, A.V. Gapon

Kharkiv National V.N. Karasin University, 31 Kurchatov ave., Kharkiv,61108,Ukraine;
E-mail: gapon@pht.univer.kharkov.ua

The problem of electromagnetic field penetration in the plasma has a long history. The anomalous skin-effect [1] is a typical example demonstrated the physics of question, key point of which is the interaction between electric field and thermally moving particles. In this work we consider cylindrical plasma with density profile formed in the free-fall regime and homogeneous in longitudinal direction. Dielectric tube filled with the plasma also serves as circular waveguide with specific electromagnetic modes [2]. Interaction between electrons and electromagnetic field of the E_{01} mode and circular polarized H_{11} mode was studied. The quasilinear theory [3,4] was used in the investigation. For each of these modes there are groups of electrons resonantly exchanging with the electromagnetic field. As the E_{01} mode is axially symmetrical one, we have resonance due to radial movement in the ambipolar potential well. In the case of circular polarized H_{11} mode there are two groups of circularly moved particles phased with the electric field. In the other hand, mode field distribution interrelates with particle kinetics. We obtain energy transfer rates due to resonant interaction for E_{01} and H_{11} modes, radial field distributions and electron energy distribution functions.

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4-12

CYCLOTRON WAVE ABSORPTION IN LARGE ASPECT RATIO ELONGATED TOKAMAKS

N.I. Grishanov[1,2], N.A. Azarenkov[1]

[1]*V.N.Karazin Kharkov National University, Kharkov, Ukraine*
[2]*Ukrainian State Academy of Railway Transport, Kharkov, Ukraine*

Tokamaks represent a promising route to controlled thermonuclear fusion. In order to achieve the fusion conditions in these devices an additional plasma heating must be employed. Effective schemes of heating and current drive in tokamak plasmas can be realised by the wave dissipation in the range of ion-cyclotron resonance (ICR) and electron cyclotron resonance (ECR) frequencies. As is well known, the kinetic wave theory of high-temperature toroidal plasmas should be based on the solution of Vlasov-Maxwell's equations. However, this problem is not simple even in the scope of linear theory since to solve the wave equations it is necessary to use the suitable kinetic dielectric (or conductivity or susceptibility) tensor valid in the given frequency range for a realistic two- or three-dimensional plasma model. In this paper the transverse dielectric susceptibility elements are derived for radio frequency waves in a two-dimensional (2D) axisymmetric large aspect ratio tokamak with elliptic magnetic surfaces. A collisionless plasma model is considered. The linearized Vlasov equation is solved separately for untrapped, *t*-trapped and *d*-trapped particles as a boundary-value problem using an approach developed in Refs. [1,2]. Periodicity of the perturbed distribution function over the poloidal angle is used for untrapped (passing or circulating) particles. Whereas, the continuity of the perturbed distribution function at the reflection points (where the parallel velocity is equal to zero) is used for *t*-trapped and *d*-trapped particles. The fundamental (first order) cyclotron and bounce resonances are taken into account. A coordinate system with the "straight" magnetic field lines is used. To evaluate the wave susceptibility tensor, the perturbed values are Fourier decomposed in the poloidal angle. Due to the 2D magnetic field nonuniformity, the whole spectrum of the perturbed electric field is present in a given harmonic of the perturbed current density. The separate contributions of untrapped, *t*-trapped and *d*-trapped particles to the transverse susceptibility elements are written by summation of bounce-resonant terms, which include the double integration in velocity space, the phase coefficients, the standard elementary and plasma dispersion functions, elliptic and the quasi-elliptic integrals. It must be pointed out that the dielectric characteristics are derived neglecting drift effects and the finite particle-orbit widths. These effects (as well as the finite pressure and Larmor radius corrections) can be accounted in the next order of perturbations over the magnetization parameter. The susceptibility elements, evaluated in this paper, are suitable for estimating the wave dissipation by the fundamental cyclotron resonance damping (e.g. during the plasma heating and current drive generation) in the frequency range of ICR and/or ECR. The dissipated wave power is expressed by the summation of terms including the imaginary parts of both the diagonal and non-diagonal elements of the transverse susceptibility.

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4-13

ON DISPERSION RELATION OF SLOW CIRCULAR POLARIZED ELECTROMAGNETIC WAVES IN PLASMAS

E.D.Gospodchikov, E.V. Suvorov

Institute of Applied Physics RAS, 603950, Nizhny Novgorod, Russia

Within a linear theory, the dispersion relation for electromagnetic waves in cold isotropic plasma forbids propagation of slow waves with phase velocities lower than the speed of light. However, this limitation may be overcome by taking into account the electron trapping by a finite amplitude electromagnetic wave which is possible in a hot plasma with a fast electron tale. In the present communication, Hamilton equations for electrons interacting with slow circular polarized electromagnetic wave are solved in a self-consistent way. Based on these solutions the interaction between the fast electrons and propagating circular wave is described kinetically, and the non-linear dispersion relation is obtained. As a result, specific conditions for the slow wave propagation in a two component plasma are analyzed.

4-14

TRANSMISSION OF A P-POLARIZED ELECTROMAGNETIC WAVE THROUGH A TWO-LAYER PLASMA STRUCTURE

S. Ivko[1], I. Denysenko[1], A. Smolyakov[2], N.A. Azarenkov[1], R. Trofymenko[1]

[1]Department of Physics and Technology, V. N. Karazin Kharkiv National University, Svobody sq. 4, 61022 Kharkiv, Ukraine
[2]Department of Physics and Engineering Physics, University of Saskatchewan, Saskatoon, Saskatchewan, Canada S7N 5E2

Transmission of a *p*-polarized electromagnetic wave through a two-layer plasma structure is studied. The case when the plasma layers are spatially nonuniform is considered. The reflection coefficient is calculated numerically for different slab parameters. Analytical solutions are obtained for thin slab case and when the plasma nonuniformity is weak (using the WKB approach). The conditions, when the reflection coefficient equals to zero, are found. For the uniform plasma case, energy fluxes and energy density of the wave in the plasma slabs are studied. It is also studied how the two-layer plasma structure affects the wave phase.

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4-15

PLASMA INSTABILITY IN THE AFTERGLOW OF ECR DISCHARGE SUSTAINED IN A MIRROR TRAP

I. Izotov[1], D. Mansfeld[1], V.Skalyga[1], V. Zorin[1], T. Grahn[2], T. Kalvas[2], H. Koivisto[2], J. Komppula[2], P. Peura[2], O. Tarvainen[2] and V. Toivanen[2]

[1]*Institute of Applied Physics, RAS, 46 Ul`yanova st., 603950 Nizhny Novgorod, Russian Federation*

[2]*University of Jyväskylä, Department of Physics, P.O. Box 35 (YFL), 40500 Jyväskylä, Finland*

A number of studies have been devoted to the investigations of plasma decay in ECR heated discharges confined in a mirror magnetic trap. The motivation of this work is to study plasma instabilities causing perturbations of ion current during the plasma decay.

Present work is devoted to time-resolved diagnostics of non-linear effects observed during the afterglow plasma decay of an 14 GHz Electron Cyclotron Resonance Ion Source (ECRIS) at JYFL operated in pulsed mode. Plasma instabilities causing perturbations of extracted ion current during the decay were observed and studied. It is shown that these perturbations are associated with precipitation of high energy electrons along the magnetic field lines and strong bursts of bremsstrahlung emission. The effect of ion source settings on the onset of the observed instabilities was investigated. Based on the experimental data and estimated plasma properties it is assumed that the instabilities are of cyclotron type. The conclusion is supported by a comparison to another type of plasma devices (SMIS 37, IAP RAS) exhibiting similar characteristics but operating in a different plasma confinement regime.

4-16

A THEORETICAL STUDY OF SURFACE LOCALIZED MODES IN FREE SPACE

A.P. Kovtun*, V.E. Moiseenko

Institute of Plasma Physics, National Science Center "Kharkov Institute of Physics and Technology", 61108 Kharkiv, Ukraine;
* *E-mail: akovtun@kipt.kharkov.ua*

Recently, a formalism is developed to describe localized waves in plasma [1]. The reason for localization of the wave is the existence of two close cutoff surfaces and the wave travels between them. For the case of a radially inhomogeneous plasma cylinder, one of the cutoff surfaces located farther from the axis appears for the reason of the plasma density decrease at the edge of the plasma column. The other one is a consequence of cylindrical curvature.

Localized waves exist in free space [2]. For such waves both cutoff surfaces are the result of curvature of the guiding surface. However, if the wave does not propagate in azimuthal direction (m=0) the localization of the wave is not pronounced. In the report, the case when the localized wave propagates also in azimuthal direction is considered. A transformation of the Maxwell's equations to the geometry aligned to the ray trajectory is made, and a combination of WKB theory with the exponential-polynomial expansion is used to find approximate solutions. It is found that the surface of wave-field localization is a hyperboloid.

Using such localized wave a cavity could be formed with two reflecting surfaces. A shape of the reflecting surface for double-mode resonator is calculated. It is a section of eccentric paraboloid placed perpendicularly to the guiding surface of the wave.

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4-17

PHASE AND GROUP VELOCITIES OF ECTROMAGNETIC EIGEN WAVES OF LEFT-HAND MATERIAL SLAB

N.A. Azarenkov, V.K. Galaydych, V.P. Olefir, A.E. Sporov

Kharkiv National University, Institute of High Technologies,
Department of Physics and Technology Kurchatov av. 31, 61108 Kharkiv, Ukraine
e-mail: vpolefir@gmail.com

At present times the intensive theoretical and experimental studies of new artificial materials are carried out in numerous scientific laboratories all over the world. These studies are stipulated by the perspective usage in different technological applications, such as image processing, optical cloaking and superlensing [1]. The basic feature of these materials is the fact that the directions of the group and phase velocities of electromagnetic eigenwaves in such materials are opposite directed. So, usually such materials are called left-handed materials [2].

This work is devoted to the study of phase and group velocities of the electromagnetic eigenwaves that propagate along the left-handed planar slab that bounded by the ordinary right-handed dielectrics with different permittivity values at the both sides of considered slab. Also, we present the results of the study of the dispersion relations and transverse wave field structure of the considered electromagnetic wave. The electromagnetic properties of left-handed material slab were described with the help of experimentally obtained expressions for effective permittivity and effective permeability, which are usually used in the majority of theoretical studies [3]. As it was shown in our previous studies [4] the considered waveguide structure possesses the number of eigenwaves of TM- and TE-polarization. Some of these waves exist in the range of frequency and wavenumber, where the slab demonstrates left-handed properties.

In this work it was obtained the analytical expressions for the group velocities of the considered eigenwaves. On the basis of such expressions it was studied the dependence of group velocity of the waves upon the thickness of left-hand material slab. The results obtained with the help of analytical formulas were compared with the results obtained by the numerical studies.

One of the important directions of the investigation is the determination of the effective methods of wave phase and energy characteristics control. It was obtained that the changing of the thickness of left-handed material slab can be effectively used for such control.

The results obtained in this work can be useful for the future image processing applications.

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4-18

ION VISCOSITY INFLUENCE ON THE CURRENT SHEET FORMING AND HEATING

A. A. Kurov, K. N. Stepanov
National Science Center "Kharkov Institute of Physics and Technology"

The research of ion viscosity influence on the forming and heating of current sheet in a X-line magnetic configuration in terms of equations of multicomponent magnetic hydrodynamics was carried out. An analysis of the magnetic fields data which is received on CS-2D device (Prokhorov General Physics Institute, Russian Academy of Sciences), allows to reveal that besides Ampere force, which takes part in the current sheet forming and plasma acceleration, essential role can take force of plasma pressure and viscid stress force. These two forces become equal to Ampere force by order of magnitude after a lapse of time. Such estimations show that viscid friction force responsible for the heating of plasma ion component (Ar^+ ions) and heating time of these ions has order of magnitude of heating time to be measured. The received time of ion-to-ion collisions coincides by order of magnitude with typical time within the sheet macroscopic parameters are changed, free path and Larmor radius of the ions have the same order like typical distance does, when such macroscopic sheet parameters like density, temperature, magnetic field component and current density across the magnetic field are changed. In this case the magnetohydrodynamic description of current sheet dynamics can not be used and carried out estimations is valid only by order of magnitude and point on considerable role of the dissipative processes of the viscosity upon the formation of a current sheet.

4-19

THE LOWER HYBRID TURBULENCE DRIVEN BY INHOMOGENEOUS ION-RING DISTRIBUTION

V.S. Mikhailenko, D.V. Chibisov,

V.N. Karazin Kharkiv National University, Institute of High Technologies, Department of Physics and Technology Kurchatov av. 31, 61108 Kharkiv, Ukraine;

Lower hybrid waves (LHWs) are commonly found in laboratory and space plasmas [1,2]. One of the possible mechanisms of LHWs excitation is the ion-ring distribution in velocity space. The theoretical model, used for the analysis of the stability of LHWs in plasmas with ion-ring distribution, usually assumed plasma components as a spatially homogeneous or weakly inhomogeneous and infinite, so that the local approximation in slab model is valid [3]. This approximation is unjustified, however, in the laboratory experiments, as well as for small-scale ion beams in the Earth's ionosphere, where radial spread of ions orbits are of the order of or even much less than the ion Larmor radius and strong spatial inhomogeneity of ion-ring distribution and cylindrical geometry of plasma should be taken into account. The same conclusion is applicable for the ions in the localized structures in the Earth's ionosphere, such as lower hybrid solitary structures [4], where ions can have a ring-like distribution with axis encircling orbits.

The aim of this work is to study the LHWs in homogeneous plasma driven by ion-ring beam perpendicular to the magnetic field, which has a spread of velocities and radial positions of the guiding centers of ions. It is assumed that ion beam has a cylindrical symmetry, and all the ions rotate around the axis of symmetry. Also assume that Larmor radius of the ion-ring distribution exceeds the scale of radial inhomogeneity of beam density. It is shown that unstable LHWs are essentially small-scale cylindrical waves with the azimuthal wavenumbers which satisfied inequality $|\mathrm{m}| > \omega_{lh} / \ \omega_{ci} - \omega_{i*}$ under condition $m < 0$. The source of free energy for excitation of LHWs is the ion-ring current across the magnetic field, although the effect of inhomogeneity of the ion-ring distribution on the conditions of instability also takes place. Despite the fact that the oscillation frequency is much greater than the ion cyclotron frequency, the excitation of instability occurs only due to cyclotron motion of the ion-ring beam which is manifested in the Doppler shift of the frequency of oscillations.

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4-20

SCALING LAWS FOR THE HELICON EIGENMODES IN A NONUNIFORM PLASMA CYLINDER

N.A. Beloshenko and K.P. Shamrai

Institute for Nuclear Research, NAS of Ukraine, Kiev, Ukraine

The problem of helicon wave eigenmodes in a radially nonuniform plasma cylinder was examined in numerous papers in application to helicon discharges, fusion plasmas etc. (e.g., [1,2]). However, recently this problem was addressed again [3], for the following reason. As is known, the helicon wave dispersion relation is $\omega = \omega_{ce} k_z k c^2 / \omega_{pe}^2$, where ω, k_z and $k = (k_z^2 + k_\perp^2)^{1/2}$ are the frequency and the longitudinal and total wave numbers ($k_\perp$: the transverse wave number). For infinite uniform plasma, if the frequency is fixed (normally, by an rf generator), the dispersion relation yields the scaling for the plane waves propagating along the magnetic fields in the form $n_0 / B_0 \propto k_z^2$ where n_0 is a plasma density and B_0 an ambient magnetic field. For radially bounded nonuniform plasma, the dispersion is normally evaluated by assuming $k_\perp \sim a^{-1}$ where $a = \min\{R, L_n\}$ with R and L_n being the cylinder radius and the characteristic density nonuniformity scale. For long waves, $k_z a << 1$, the total wave number $k \sim a^{-1}$, and the scaling evaluated from the dispersion relation is $n / B_0 \propto k_z$ where n is a radially averaged density. At the same time, some experiments (e.g., [4,5]) with the excitation of non-axisymmetric waves (the aximuthal number $m \neq 0$; normally $m = +1$) show the long wave scaling as $n / B_0 \propto k_z^2$, which is similar to the plane wave case. As possible explanation of this fact, it was assumed that the radially localized helicon modes are excited which have off-axis localization in the region of the strongest radial density gradient [6].

We have examined the helicon eigenmodes in a radially nonuniform plasma cylinder using the helicon approximation (i.e., under assumption that the axial wave field $E_z = 0$). This approximation is valid if the plasma density at the boundary with a confining vessel is considerably less than the center density, and if the axial wavenumbers lie in the range $2(\omega/c)(\omega_{p\max}/\omega_{ce}) < k_z < (\omega/c)(\omega_{p\max}/\sqrt{\omega\omega_{ce}})$ where $\omega_{p\max}$ is the center plasma frequency. These inequalities imply that the surface of helicon wave coalescence with the quasi-electrostatic (Trivelpiece-Gould) wave is absent in the plasma bulk whereas the surface of helicon wave cut-off is present there. We found, both analytically and numerically, that there exist a set of helicon modes which have on-axis localization and the long-wave scaling that depends on the azimuthal number m. For the axisymmetric ($m = 0$) modes, the scaling is as expected from the above evaluation, $n / B_0 \propto k_z$, whereas for the non-axisymmetric modes ($m \neq 0$) the scaling is $n / B_0 \propto k_z^2$. This is argued physically and is supposed to give one more possible explanation for the experimental data.

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4-21

Effective evaluation of the exact relativistic plasma dispersion functions

S.S. Pavlov,[1] F. Castejón,[2,3] M. Tereshchenko[3]

[1] *Institute of Plasma Physics, NSC KhIPT, Kharkov, Ukraine*
[2] *Laboratorio Nacional de Fusión, EURATOM / CIEMAT, Madrid, Spain*
[3] *BIFI: Instituto de Biocomputación y Física de Sistemas Complejos, Zaragoza, Spain*

The computation of the exact relativistic plasma dispersion functions (PDFs) [1,2] is a necessary basis for both electron cyclotron wave analysis in the laboratory thermonuclear plasmas and ion cyclotron wave analysis in extreme astrophysical plasmas like in the cases of strong magnetic fields of white dwarfs and neutron stars or strong gravitational fields around black holes. Taking into account relativistic effects are rather essential, especially in the quasiperpendicular wave propagation and/or high temperature and/or high harmonic regimes. Routinely, PDFs must be evaluated repeatedly in many applications, therefore the efficiency of the numerical algorithm involved in their calculation is of primary importance.

The theory of continued fractions of Jacobi has been proved to provide such a fast calculation method for large-$|z|$ values, being z the argument of the PDFs, in the complex region in combination with the Taylor expansion of special kind for the remaining values of $|z|$ for both nonrelativistic PDF, given by $w(z) = \exp(-z^2)\,\mathrm{erfc}(-iz)$ [3] and the weakly relativistic PDFs [4,5]. Here it is worth to note, that the technique [4] lacks stability when $|z|$ becomes large.

The main purpose of the present work is to extend the computational technique [5], developed for the computation of the weakly relativistic PDFs in whole complex region, to the more complicated case of the exact relativistic PDFs.

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4-22

EIGEN DIPOLAR ELECTROMAGNETIC WAVES OF COAXIAL PLASMA-METALL WAVEGUIDE STRUCTURE WITH AZIMUTH MAGNETIC FIELD

N.A. Azarenkov, V.P. Olefir, A.E. Sporov

Kharkiv National University, Institute of High Technologies,
Department of Physics and Technology Kurchatov av. 31, 61108 Kharkiv, Ukraine
e-mail: vpolefir@gmail.com

Till now, the coaxial plasma-metal waveguide structures are the object of intensive both theoretical and experimental studies. This is stipulated by the fact that such waveguide structures are widely used in the devices of plasma electronics [1] and also as the discharge chambers for plasma-technological processes [2, 3]. The basic attention in previous researches was paid to the eigen electromagnetic waves with azimuth wavenumber $m = 0$ [4] due to its wide usage in different applications. But it is necessary to mention, that dipolar wave with $m = \pm 1$ also often used for various technological applications [5]. Electrodynamic properties of such dipolar waves essentially differ from the symmetric waves with $m = 0$ [4].

In the paper presented, it was considered the cylindrical coaxial waveguide structure that consists of inner metal cylinder of radius R_1 that is placed on the axis of the structure. Cylindrical plasma layer with outer radius R_2 surrounds inner metal cylinder. The vacuum gap ($R_2 < r < R_3$) separates this plasma layer from waveguide metal wall of radius R_3. The main advantage of these structures upon others is the possibility of effective control of eigen wave properties by the varying of the direct current J_z that flows along the central metal cylinder and creates radial non-uniform azimuth magnetic field $H_0(r)$.

Cylindrical plasma layer ($R_1 < r < R_2$) was studied in hydrodynamic approach. It was considered the cases when electron collisions is not taken and is taken into account. It was also investigated radially uniform and radially non-uniform plasma with given plasma density radial profile.

It was obtained the existence of several eigen modes with different radial wave field structure, that can propagate in such waveguide under the given parameters. It was considered the dispersion properties and spatial attenuation of these waves. The radial structure, phase and group velocities were studies as well. It was obtained that it is possible to control effectively the dispersion properties, group velocity and spatial attenuation of these waves due to external magnetic field variation, that creates by direct current J_z.

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5-01

ALFVEN WAVE INSTABILITY BASED ON TEMPERATURE ANISOTROPY WITH NON-MAXWELLIAN DISTRIBUTION FUNCTION

M. N. S. Qureshi and Sundas Saeed

Department of Physics, GC University, Lahore 54000, Pakistan

Space observations by numerous satellites reveal that the distributions often posses non-Maxwellian characteristics such as high energy tails or flat top (broad shoulders) in the profile of distribution functions. Distributions with high energy tails are well modelled by family of kappa type distribution. However, when distributions contain flat tops with or without high energy particles, generalized (r , q) distribution function is the best choice. In general the spectral index r corresponds to the flat part of the distribution and q to the high energy tail in the profile of the distribution function. Generalized (r , q) distribution function is a generalized form of kappa or Maxwellian distribution functions and reduces to the kappa distribution function when $r \rightarrow 0$ and $q = (\kappa + 1)$ and reduces to the Maxwellian distribution in the limit when $r \rightarrow 0$ and $q \rightarrow \infty$. By following the kinetic theory, we employ this distribution function to study the Alfven waves in anisotropic plasma with two ion components and found that Alfven wave can grow when there is temperature anisotropy in plasma. Instability conditions are the studied for different density and temperature ratios. We also study the condition for which Alfven wave experiences Landau damping. Our theoretical results confirms the observation of growth rates observed by CLUSTER around the bow shock.

5-02

SATELLITE OBSERVATIONS OF PLASMA-WAVE DISTURBANCES, INDUCED BY HIGH-POWER RADIO EMISSION FROM THE NWC TRANSMITTER

A.S.Belov[1], G.A.Markov[1], M. Parrot[2]

[1]N.I. Lobachevsky State University of Nizhny Novgorod, Nizhny Novgorod, Russia
[2]Environment Physics and Chemistry Laboratory, Orleans, France

It is known, that operating VLF transmitters turbulize the illuminated region of the ionosphere by its radio emission [1, 2]. Plasma-wave structures, generated in the ionosphere by VLF emission from a ground-based transmitter, determine characteristics of the radio communication in this frequency range and allow changing the local ionosphere-magnetosphere coupling.

In this work we present the results of measuring the characteristics of such induced plasma-wave structures, obtained by using the onboard equipment of the French microsatellite DEMETER during its passage above the 1-MW VLF transmitter NWC (21°49′ S, 114°10′ E) over a period of 2004-2010 years. A unique set of high-sensitivity DEMETER instruments allowed registering the main plasma parameters and electromagnetic field intensities.

Significant disturbances of the plasma density, coincident with the localization zone of high intensity of NWC signal, were observed at altitudes of the Earth's outer ionosphere, in the region of a disturbed magnetic flux tube. Induced density disturbances elongated along the geomagnetic field that allow one to identify them as artificial plasma-wave channel (density duct) with nonuniform (stratified) distribution of plasma density. The typical transverse scale of the density duct was approximately ~ 1000 km. In this artificial density duct, channeled propagation of whistlers at the transmitter frequency and stimulation of intensive quasi-electrostatic oscillations were observed. Since the plasma density distribution is nonuniform and fast changeable in duct, the spectrum width of quasi-electrostatic emissions excited via conversion whistler waves on these irregularities is noticeably wider than spectrum of the VLF transmitter signal.

In the region of the disturbed magnetic flux tube, the velocity of the ion flow direction changes its sign and upward (in direction from the Earth) flows were observed. As a result, the density of the main plasma ions is redistributed.

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5-03

NONSTATIONARY GENERATION OF ELECTROMAGNETIC RADIATION IN NONEQUILIBRIUM MIRROR-CONFINED PLASMA

M.E. Viktorov, D.A. Mansfeld, S.V. Golubev, A.G. Shalashov

The Institute of Applied Physics RAS, Nizhny Novgorod, Russia

Non-equilibrium plasma produced by electron cyclotron resonance (ECR) discharge allows investigating in laboratory setup a number of processes of resonant interaction between waves and particles. One of such processes is plasma cyclotron maser which operates in magnetosphere of the Earth and other planets and results in the generation of broadband bursts of radiation and charged particles precipitation from the geomagnetic trap. In this paper we discuss results of experimental study of cyclotron instability development during plasma decay after pulsed ECR discharge in a mirror magnetic trap. We observed the excitation of electromagnetic waves which propagate nearly perpendicular to the magnetic field and cause precipitation of energetic electrons to the trap ends. Observed instability has much in common with the phenomena observed in space magnetic traps, such as the generation of auroral kilometer radio emission (AKR) of the Earth, where the effective resonant interaction of waves and particles occurs in areas with low density of plasma. We performed analytical and numerical estimates of growth rates of unstable modes for different distribution functions of energetic particle velocity on the kinetic equation basis in the weakly relativistic limit. The results of these estimates agree with experimental data and describe the observed spectrum of electromagnetic radiation. Our experimental results and their comparison to the theory allow us to expect that future experiments will provide a more detailed study of such phenomena that play an important role in the dynamics of laboratory, geospace, planetary, and solar plasmas.

5-04

GENERATION OF WIDEBAND ELECTROMAGNETIC RADIATION ON A DECAY STAGE OF A MIRROR CONFINED PLASMA PRODUCED BY ECR DISCHARGE

A.G. Shalashov, S. V. Golubev, E.D. Gospodchikov,
D. A. Mansfeld, M. E. Viktorov, A. V. Vodopyanov

Institute of Applied Physics of Russian Academy of Sciences,
Ulyanova str. 46, 603950, Nizhny Novgorod, Russia

We demonstrate the use of a laboratory setup (SMIS37, IAP RAS, Nizhny Novgorod) based on a magnetic mirror trap with plasma sustained by a gyrotron radiation under the electron cyclotron resonance (ECR) conditions aimed at identifying the role of the background plasma as a trigger of a cyclotron maser instability. New regime of instability in the decaying plasma after the gyrotron switch-off has been revealed under conditions in which the electron plasma frequency is much less than the electron gyrofrequency [1]. At this stage, we observe the excitation of electromagnetic waves which propagate nearly perpendicular to the magnetic field and cause precipitation of energetic electrons to the trap ends. The instability is detected as series of quasi-periodic broadband pulses of electromagnetic radiation (25-27 GHz frequency, typical pulse duration of 1-10 microseconds) and related precipitation of energetic (7-10 keV) electrons. It was interpreted as a special regime of relaxation oscillations, in which a decrease in the wave energy losses provides repeated recovery of the instability conditions and thus serves as an effective source of free energy [2]. A new nonlinear regime of electron cyclotron instability is discussed aimed at explanation of complex temporal patterns of stimulated electromagnetic radiation from a mirror trap with non-equilibrium plasma typical of ECR discharge [3]. This regime is characterized by self-modulation of a plasma cyclotron maser due to coherent interference of two counter-propagating unstable waves resulting in spatial modulation of amplification. The resulted maser dynamics show rather complex behavior: single spikes may join in bursts, the interval between spikes may become irregular, generation may be switched to a stochastic regime etc. The proposed theoretical model allows reproducing multi-scale time behavior of quasi-periodic pulses of electromagnetic radiation and related precipitation of energetic electrons detected experimentally.

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6-01

MHD CHARACTERISTICS OF COMPRESSION ZONE IN PLASMA STREAM GENERATED BY MPC

V.V. Chebotarev, T.N. Cherednychenko, D.V. Eliseev, I.E. Garkusha, A.N. Kozlov[1], N.V. Kulik, M.S. Ladygina, A.K. Marchenko, Ya.I. Morgal, Yu.V. Petrov, D.G. Solyakov, V.V. Staltsov.
Institute of Plasma Physics of the NSC KIPT, 61108, Kharkov, Ukraine
[1]Keldysh Institute of Applied Mathematics, RAS, Moscow, Russia

Investigation of local plasma parameters in MHG flow and characterization of plasma streams, generated by different types of plasma accelerators and magneto-plasma compressors, is one of actual and important from point of view basic plasma dynamics research and plasma applications in different technologists.

The present paper devoted to analysis of magneto-hydrodynamic characteristics of the plasma stream generated by the MPC compact geometry [1]. Such important parameters as spatial electric current distributions in plasma stream, plasma density in compression zone have been investigated.

Experiments were carrying out in MPC devices [2]. MPC accelerating channel forms by cooper electrodes, outer multi roads anode with diameter in outer part 8 cm and inner solid cathode with diameter 2 cm. Total length of MPC channel was 10 cm. MPC was installed in vacuum chamber with diameter 40 cm and length 200 cm. Maximum voltage in capacitor bank was 20 kV, maximum discharge current was 500 kA. All experiments were performed in mode of MPC operation in residual Helium with pressure from 0.5 Tor to 10 Tor.

Experimentally it was shown that maximum value of electrical current which flow outside MPC channel not more than (15-20) % of total discharge current. Toroidal electric current vortex with current value up to 50% of discharge current has been observed in plasma stream. Magnetic field displacement from compression zone is discovered.

Spatial distributions of electromagnetic force in plasma stream were calculated. It was shown that plasma stream is decelerate in compression zone. Kinetic energy of plasma stream converted to thermal energy in compression zone and plasma temperature, estimated from pressure balance equation, reach value (60-100) eV. Compression zone forms in time moment of 5-6 μs from the discharge start in MPC channel for both residual gas pressures. Compression zone parameters and its spatial position depend on residual gas pressure. Maximum compression is observed in distance 1-6 cm from cathode output at pressure 2 tor. Compression zone moved to cathode output and its dimension in longitudinal direction decreased up to 2-3 cm with increasing residual gas pressure up to 10 tor. Maximum value of plasma density in compression zone reaches $(3\text{-}4).10^{18}$ cm^{-3}.

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6-02

MASS-SEPARATION OF IMPURITIES IN THE ION BEAM SYSTEMS WITH REVERSED MAGNETIC BEAM FOCUSING

O.I. Girka, I.A. Bizyukov, A.A. Bizyukov, K.N. Sereda, S.S. Gerashchenko, M.O. Azarenkov

V.N. Karazin Kharkiv National University
alexxxgir@gmail.com

The FALCON ion source [1] is designed for material research for ITER and future DEMO reactor. It is capable of generating steady-state (up to 200 h) high-current (≈5-300 mA) ion beam focused into a spot of ≈3 mm in diameter. This corresponds to a particle flux of $4\times10^{21} – 3\times10^{23}$ $m^{-2}s^{-1}$ and heat flux of 0.3 – 21 $MW\cdot m^{-2}$.

Present work describes experimental and theoretical investigation of FALCON ion source intrinsic capability for impurities mass-separation. Calculations have confirmed principal opportunity for mass-separation of the impurities in the focused ion beam. The ion trajectories were analyzed for the whole energy range. The spatial distribution of ions with energy of 0.65-5 keV in the plane of the crossover of H+ ions was calculated using measured distribution function. At the same time, O+ ion impurities are separated out of the main beam spot and form the circle with a diameter of 6 mm. As a result, the central part of the spot is free of impurities due to magnetic separation.

Experiments on magnetic mass-separation in FALCON ion source were performed. The impurities were modeled by adding 5% of Ar and O in working gas. Obtained experimental data are in good agreement with numerical calculations and confirmed the intrinsic capability of impurities mass-separation.

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6-03

RECENT ADVANCES OF LITHIUM PROGRAM T-11M

[1]V.B. Lazarev, [1]Mirnov S.V., [1]N.T. Djigailo, [1]A.N. Kostina, [1]V.M. Nesterenko,
[2]Vertkov A.V., [2]Lyublinski I.E.

[1]TRINITI, Troitsk, Moscow region, Russian Federation
[2]State Enterprise «Red Star» Moscow, Russian Federation

Previous experiments with lithium limiters on the basis of thin capillary-porous structures (CPS) in T-11M tokamak [1] and FTU tokamak [2] have shown promising results: decreasing $Z_{eff}(0)$ and heat load on the PFC of the limiter due to lithization and reradiation by lithium of the part of power flux from center. At present, Li T-11M program is focused mainly on the tasks of a steady-state tokamak: namely, the creation and investigation of an emitter-collector limiter system in the tokamak SOL to minimize the amount of lithium in the tokamak vessel.

The recent lithium activity in T-11M had three directions: investigation of different Li-limiters, investigation of long-term effects of lithium behavior in hydrogen plasma and development of a new kind of CPS limiters.

The new so-called R-limiter was used as Li collector for investigation of lithium fluxes close to the plasma boundary and the chamber wall. It was shown, that Li circulation near the limiter multiplied up to 4 times the primary lithium flux from limiter. Only 10% of this flux is lost on the tokamak vessel wall.

The deuterium glow discharge was used to test the long-term lithium degradation under the deuterium bombardment. It was shown that such degradation is small. That means that the Li-limiter can be used as Li-emitter in steady-state tokamak operation.

A new vertical lithium limiter was successfully tested in T-11M. In all previous experiments rail limiters were installed horizontally at the bottom of the tokamak vessel. However, the vertical arrangement of the lithium limiter on the outer or inner surface of the toroidal vessel is also possible and is of interest in the development of the concept of steady-state tokamak fusion reactor or a tokamak neutron source. The position on the external contour of tor is the most unfavorable in terms of interaction with the runaway electrons. At the same time the size of the horizontal port allows to install a longer rail limiter that can provide some advantages, for example, to increase the proportion of Li circulation through the limiter and thus reduce losses of lithium on the walls of the tokamak vessel. We present the first results obtained in this year's experiments with vertical lithium limiter upright in the small tokamak T-11M (R=0.7m, a=18÷20cm). Experiments were carried out at 1Tl toroidal field and plasma current of 60÷100kA. We obtained stable discharges with plasma density $(1.5 \div 6)\cdot 10^{19} m^{-3}$ and longer than 200ms. We detected the phenomenon which looks like L-H transition and H-mode. ELM-like phenomena were found at high density near Greenwald limit at the moment of H-L transition. Radial profiles of the ion flows of deuterium and lithium in the SOL were investigated for various plasma densities. It is shown that the distributions have the exponential form with a e-fold lenght λ = 3.5cm for lithium ions and λ = 5.2cm for deuterium ions. Estimations of the part of lithium, returning to the surface of the vertical lithium limiter, according to the radial profile give the value of about 75%. The appearance of lithium limiter surface after prolonged operation (after 1000 discharges) in T-11M tokamak will also be presented.

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6-04

EFFECT OF INCREASING SURFACE ROUGHNESS ON SPUTTERING AND REFLECTION

I. Bizyukov[1], A. Mutzke[2], R. Schneider[3]

[1] V.N. Karazin Kharkiv National University, 31 Kurchatov Ave., Kharkiv 61108, Ukraine
[2] Max-Planck-Institut für Plasmaphysik, Wendelsteinstr. 1, 17491 Greifswald, Germany
[3] Ernst-Moritz-Arndt University, Felix-Hausdorff-Str. 6, 17489 Greifswald, Germany

The sputtering of surface atoms by ion bombardment is now well understood and can be reproduced by numerical simulations with a reasonable accuracy. The drawback of the existing models is inability to handle non-plane surface, i.e. surface with morphology. The influence of surface morphology on sputtering is not understood well, because there was no suitable model, which was able to provide a comprehensive description. To overcome this drawback,

SDTrimSP-2D code has been developed to simulate interaction of ions with the 2-D non-planar surfaces. It is basically a 2-D extension of SDTrimSP code, which is, in turn a generalized version of the TRIDYN program. The code belongs to the TRIM family and it incorporates the same physical model. The code has been validated by experiment. It is capable to predict fluence dependent evolution of the surface morphology and macroscopic parameters of the ion-surface interactions, like sputter yields, reflection coefficient, elemental areal densities, etc.

In present work, the SDTrimSP-2D code was used for numerical simulation of the interaction of ions with a 2D periodical structure as idealized test system to investigate the influence of surface roughness on sputtering. A Si pitch grating was exposed to flux of 6 keV Ar^+ ions. Sputtering yield and reflection coefficient have been studied as a function of the size of the pitch grating structure as equivalent of a surface roughness. Simulations show that the most important changes in ion-surface interactions occur, when the structure size gets approximately equal to the size of the collisional cascade. The increase of the characteristic roughness size leads to strong rise in sputtering and reflection. Sputtering and reflection decrease with increasing angle of incidence of the impinging ions, if the structure size is much larger than the collisional cascade.

6-05

BEHAVIOR OF MIRROR SPECIMENS FABRICATED OF AMORPHOUS ALLOYS UNDER IMPACT OF IONS OF DEUTERIUM AND ARGON PLASMAS

V.S. Voitsenya[a*], A.F. Bardamid[b], A.I. Belyaeva[c], V.N. Bondarenko[a], J.W. Davis[d], A.A. Galuza[c], V.G. Konovalov[a], K.V. Kovtun[a], I.V. Ryzhkov[a], A.N. Shapoval[a], A.F. Shtan'[a], S.I. Solodovchenko[a], O.V. Trembach[a], A.A. Vasil'ev[a]

[a]National Science Center "KIPT", 61108 Kharkov, Ukraine;
[b]Taras Shevchenko National University, 01033 Kiev, Ukraine;
[c]National Technical University "KhPI", 61002 Kharkov, Ukraine;
[d]University of Toronto Institute for Aerospace Studies, 4925 Dufferin St., Toronto, ON, Canada M3H5T6

For diagnosing plasma in the experimental fusion reactor ITER many methods of optical diagnostics will be used for measuring different plasma characteristics, and every method has to be based on reflective optics. Among several in-vessel mirrors of every scheme, the plasma facing mirror (First Mirror, FM) will be subjected to all kind radiations emanated by thermonuclear plasma, and erosion of mirror surface caused by charge exchange atoms (CXA) can directly result in development of surface roughness and degradation of optical properties. Besides, some mirrors will be a subject of deposition of material eroded due to plasma impact on the main inner components (beryllium, tungsten, CFC). As was shown in many experiments on existing fusion devices, predominance of sputtering or deposition of contaminant depends strongly on mirror location, i.e., is it in an erosion dominated or deposition dominated position. To diminish the role of sputtering it was suggested to fabricate the FMs from single crystal materials. However, at that there exists an anxiety about gradual worsening of initial perfect single crystal structure under neutron irradiation what can lead to appearance of roughness due to CXA bombardment. It seems that the use of FM material which structure has no any order on the scale over a few nanometers (much less the wavelength of light) could be better solution of the FM problem in the case when erosion due to CXA sputtering dominates.

Such nano-scale structure is peculiar to amorphous alloys, and about two decades ago the technology was developed for fabrication of amorphous molds with the size (> 1 cm) sufficient for mirror specimens to be prepared.

The first laboratory experiments provided by the authors of this presentation demonstrated that the amorphous mirror specimens have much higher resistance to long-term sputtering (with Ar^+ ions) than the specimens of the same material after crystallization. Principal difference was found out between behavior of these specimens when they were exposed to low energy (<100 eV) ions of deuterium: amorphous specimens absorbed deuterium with efficiency 15-20 % whereas crystallized specimens became to destroy at much less ion fluence.

The short review of results obtained during detail studies [1-4] of behavior of mirror specimens made of ZrTiNiCuBe amorphous alloys under impact of argon ions and ions of deuterium plasma will be given in the presentation.

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6-06

TEMPERATURE EFFECTS ON BEHAVIOR OF Mo FILM MIRRORS UNDER IMPACT OF DEUTERIUM PLASMA IONS

V.G. Konovalov, B. Eren[1], L. Marot[1], I.V. Ryzhkov, A.N. Shapoval, A.F. Shtan', O.O. Skoryk, S.I. Solodovchenko, V.S. Voitsenya

IPP National Science Center KIPT, Kharkov 61108, Ukraine
[1]Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland

In spite of long-term investigations directed to solution of the problem of in-vessel mirrors for plasma diagnostics in ITER, still some unanswered questions exist as for the mirror materials and for the methods of cleaning of mirrors from redeposited material of erosion of walls and divertor plates. Among the possible candidates the prospect ones are mirrors in the form of film mirrors with Rh or Mo film on substrate of polycrystalline metal: stainless steel or molybdenum. The principal possibility of fabrication of film coatings resistant to long time plasma impact was demonstrated in [1]. Thus, in the case of success in developing the technology, film mirrors could substitute expensive single crystal Mo mirrors.

Development of technology of Mo and Rh films deposition on different substrates, investigation of their properties and the resistance to plasma impact in laboratory stands and in operating fusion devices are being provided for years in the Department of Physics, University of Basel [2-3]. In the present communication the results of laboratory studies of one set of Mo film mirrors (film thickness ~2 μm) on stainless steel substrate are presented.

The mirror specimens were subjected to ions of ECR plasma in deuterium. The ions were accelerated by the negative voltage -200 V applied to the mirror holder. The temperature of specimens during exposures was the room temperature for some specimens and up to ~220°C for others, and one specimen was exposed at ~100°C. The reflectance at normal incidence was measured in the wavelength range 220-650 nm, and the surface state (like appearance of blisters) was controlled by means of optical microscope. The thickness of layer sputtered due to plasma impact was measured by measuring the mass loss.

It was found that all specimens exposed at room temperature (5 items) and the one exposed at ~100°C became blistered whereas the surface of those specimens exposed at temperature near 200°C remained clean from blisters up to sputtering about half of the initial Mo film thickness.

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6-07

SPECULAR AND DIFFUSIVE REFLECTANCE OF STAINLESS STEEL MIRRORS SPUTTERED WITH Ar^+ IONS

V.G. Konovalov, I.V. Ryzhkov, A.N. Shapoval, A.F. Shtan', O.O. Skoryk, S.I. Solodovchenko, V.S. Voitsenya

IPP National Science Center KIPT, Kharkov 61108, Ukraine

When sputtering a polycrystalline mirror, its initial smooth surface turns into the surface with a step structure. This transformation is because sputtering coefficient of every metal grain depends on the orientation of its main crystallographic axes relatively to the mirror surface, and the orientation of adjoining grains is, as a rule, different. Due to development of a step structure relief during long term sputtering, the degradation of mirror optical properties occurs. Previously such effect was observed for reflectance at normal incidence when stainless steel mirrors were sputtered with deuterium plasma ions of different energy [1].

The present work is devoted to investigation of the dynamics of reflective properties of stainless steel (the Soviet analog of SS316 steel) mirrors subjected to bombardment with argon plasma ions of fixed energies: 300, 600 and 1000 eV. Measurements of reflectance were provided by: (i) traditional method using the Tolansky scheme [2] (normal incidence of light) in the wavelength range λ=220-650 nm [1], and (ii) the new, suggested in our group, method, with registration of an image of a sharp delineated light source (λ=500 nm) after reflection (at an angle 45°) from the mirror under the test. The second method (so called image quality method, IQ) gives possibility to make a clear separation among specular (SR) and diffusive (DR) components of reflectance. The state of the mirror surface was controlled by the use of optical and interferometer microscopes, as well as by profilometry.

It was discovered that the rate of SR degradation in the course of sputtering greatly grows with increasing the energy of bombarding Ar^+ ions. As a result, with the same thickness of layer sputtered with ions of different energy the SR values do differ significantly. The effect was found to be much greater than it was observed in the case of normal light incidence when similar mirrors were exposed to deuterium plasma ions with different energy [1].

Analyzing the obtained results we made the conclusion that the rise of the rate of SR degradation with ion energy is due to the rise of the rate of surface roughness. This can be possible only if the difference in the sputtering rate of metal grains with different orientation of crystallographic planes relatively to the mirror surface is increasing with ion energy increasing. On our knowledge, previously similar statement did not appear in the literature.

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6-08

BEHAVIOR OF OPTICAL PROPERTIES OF MIRRORS WITH DIELECTRIC PROTECTING COATINGS UNDER IMPACT OF DEUTERIUM PLASMA IONS

V.N. Bondarenko[1], V.G. Konovalov[1], E.E. Mukhin[2], A.G. Razdobarin[2], I.V. Ryzhkov[1], A.N. Shapoval[1], A.F. Shtan[1], O.O. Skoryk[1], S.I. Solodovchenko[1], V.S. Voitsenya[1]

[1]IPP National Science Center KIPT, Kharkov 61108, Ukraine;
[2]A.F. Ioffe Physico-Technical Institute, Polytechnicheskaya 26, St Petersburg, 194021, Russia

Those mirrors preceded for plasma diagnosing in ITER divertor will be located in areas with preferred deposition and thus will suffer from contamination with erosion products of divertor plates (carbon-carbon composite) and in much less degree of the first wall (beryllium). In such conditions preservation of mirror optical properties has to depend not on the composition of depositing material only but on the mirror material also. It was found out [1] that deterioration of mirror reflectance caused by contamination with a hydrocarbon deposit can be minimized if mirrors fabricated of highly reflecting metals (Al, Ag) are coated with an antireflective dielectric layer. Important property of highly reflecting mirrors protected by an oxide layer is a weak dependence of their optical characteristics in the visible range of spectrum to appearance of a hydrocarbon film. In this property such mirrors do strongly differ from the mirrors with similar protective coating fabricated from metals with mach smaller sputtering yield but with a rather low reflectance (W, Mo) [1].

In the present work we describe the results of experiments with Al and Ag film mirrors deposited on a Si substrate and protected with an oxyde layer (Al_2O_3 or ZrO_2). The mirrors were exposed to ions of deuterium plasma with energy 40-150 eV. The oxide film thickness was evaluated by fitting the locations of maxima and minima of interference pattern in measured and calculated spectra of reflected light in the range 220-650 nm. The values of spectral reflectance $R(\lambda)$ were measured for different mirror specimens depending on ion energy and ion fluence; the surface morphology was also studied.

It was found that after exposing in deuterium plasma, the optical properties of both Al and Ag mirrors degrade strongly in the case of Al_2O_3 coating. The reason of mirror deterioration is the degradation of protecting layer which became partly coated with blisters and the degradation of the reflective metal films also. At the same time, on the surface of mirrors with ZrO_2 coating only little change of optical properties was observed. The dependence of erosion rate of ZrO_2 film withing ion energy interval 60-150 eV was obtained.

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6-09

THE INFLUENCE OF WALL CONDITIONING PROCEDURES ON OUTGASSING RATE OF STAINLESS-STEEL IN THE URAGAN-2M TORSATRON

G.P. Glazunov, D.I. Baron, M.N. Bondarenko, V.Ya. Chernyshenko, A.L. Konotopskiy, V.M. Listopad, S.M. Maznichenko, V.E. Moiseenko, V.K. Pashnev

Institute of Plasma Physics, National Science Center
"Kharkov Institute of Physics and Technology", 61108 Kharkov, Ukraine
E mail: glazunov@ipp.kharkov.ua

The thermal desorption method has been developed for operative diagnosing impurity level of Uragan-2M (U-2M) vacuum chamber surfaces in situ [1]. To perform the experiments the device was designed, manufactured and installed in the U-2M vacuum chamber, which gives possibility to register low flows of gases desorbed from the 12KH18N10T stainless steel (SS) strip-like probe during its pulsed heating up to temperature 250-300ºC.

The investigations were carried out of SS probe outgassing rate and estimation of the number of monolayers on its surface after preliminary pumping and RF discharge cleaning in one of conditioning regimes. The decrease of surface impurity by more than one order of magnitude was measured (Fig. 1) at the vacuum improvement from $1.6\cdot10^{-6}$ Torr up to $6.5\cdot10^{-7}$ Torr after pumping and RF discharge cleaning. The black color points in Fig. 1 shows the SS outgasing data after long time pumping. The grey color point is the data of the SS outgasing rate after RF discharge cleaning.

Mass-spectrometric measurements has shown H_2O(18 a.m.u.), Co_2(44 a.m.u.) and 28 a.m.u., as the main gases desorbed from probe surface during its heating. Heavy hydrocarbon masses were also registered. Some practical conclusions were made for the U-2M wall conditioning procedure but to provide the estimation of efficiency of various scenarios of wall conditioning process in the U-2M torsatron the additional experiments will be provided.

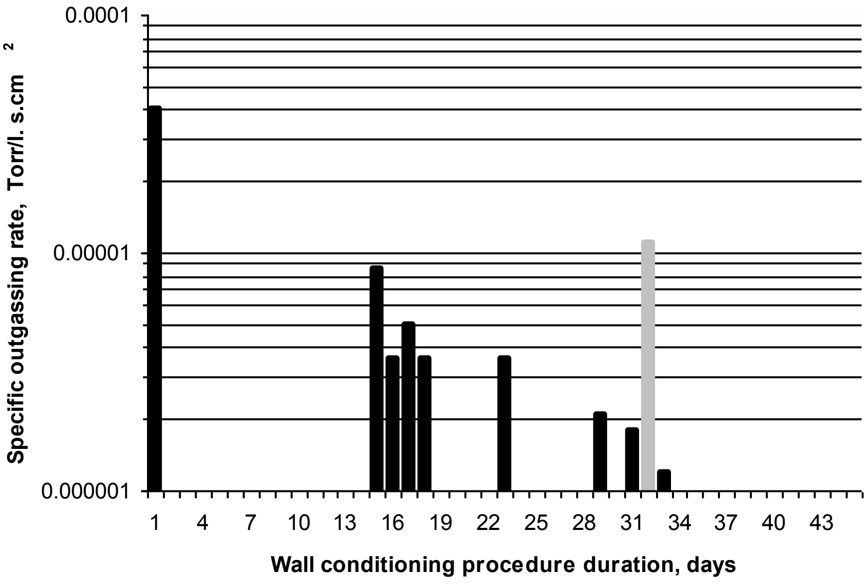

Fig.1. Stainless steel probe outgasing rate (250ºC) on the time of U-2M wall conditioning process.

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6-10

PRESENT STATUS OF THE DEVELOPMENT THE POSITIVE SPACE CHARGE PLASMA LENSES FOR FOCUSING INTENSE NEGATIVE CHARGED PARTICLE BEAMS

A.A. Goncharov[1], A.M. Dobrovolskiy[1], S.M. Dunets[1], I.V. Litovko[2], V.I. Gushenets[3], E.M. Oks[3], A.S. Bugaev[3]

[1]Institute of Physics NAS of Ukraine, Kiev 03028, pr. Nauki, 46, Ukraine
[2]Institute for Nuclear Research NAS of Ukraine, Kiev 03650, pr. Nauki, 47, Ukraine
[3]High-Current Electronics Institute SB of RAS, Tomsk, pr. Akademicheski, 4, Russia

We describe the new experimental and simulation results of wide-aperture (6 cm) non-relativistic (up to 18 keV) intense (up to 400 mA) electron beam focusing by the positive-space-charge plasma lens. The plasma electron source based on electron extraction from vacuum arc discharge with hollow anode was used for generation of this beam. Recently [1, 2] we proposed and explored a new original plasma-optical tool for negative charged particle beams focusing and manipulating with a dynamic cloud of non-magnetized free positive ions and magnetically isolated electrons produced by a toroidal plasma source like an anode layer thruster. In such kind systems the electrons are separated from ions by relatively strong magnetic field in the discharge channel. The accelerated ions are weakly affected by the magnetic field owing to their mass. We used two modifications of lenses in the experiments. In the first modification of the lens we optimized the magnetic field and simultaneously increased the positive ions energy by use of the new pulsed power supply. Focusing of the electron beam by electrostatic plasma lens was separeted from magnetic focusing experimentally and the compression factor was up to about 5. The first modification had restrictions due to momentum aberrations leading to double-humped space charge potential distribution. The second lens modification is a result of the further efforts to eliminate these drawbacks. The results of the computer simulation are shown good agreement with experimental data. Obtained experimental results demonstrate the possibility to create a low-cost high-effective tool for negatively-charged particle beam focusing without influence of momentum aberrations.

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6-11

INCREASING THE DENSITY OF ENERGY IN A PLASMA PINCH IN THREE-DIMENSIONAL COMPRESSION OF TUNGSTEN QUASISPHERICAL WIRE ARRAY (QSWA).

A. N. Gritzuk, V. V. Aleksandrov, E. V. Grabovskiy, K. N. Mitrofanov, G. M. Oleinik, A.P.Shevel'ko *

Troitsk Institute for Innovation and Fusion Research, Troitsk, 142190 Russia

**P.N. Lebedev Physical Institute of the RAS, Moscow, Russia*

griar@triniti.ru

We studied the conditions for increasing the energy density and the concentration of ions in a plasma pinch during compression in the center of the QSWA. A new method was developed for recording the X-ray image of the plasma formation in hard quanta with energies above 20 keV in the implosion of the QSWA, containing the substance with a high atomic number (tungsten, bismuth). Presented are the results of studying the spatial distribution of hard X-ray sources (HXR) in the images of the pinch on the basis of the QSWA made of tungsten wires. It was found that under these conditions, the sources of HXR form a spatially homogeneous plasma formation in the central region of the QSWA, which is located symmetrically relative to the axis of the QSWA. Taking into account the mechanisms HXR generation in the plasma pinch we discuss the possibility of investigating the distribution of ion density of the plasma formation in the center of the QSWA. Presented are the results of experiments on the implosion of the QSWA of tungsten wires forming the mass per unit length on the latitudinal angle.

The data is presented for the study of the radial and axial spatial distribution of the emission of XUV radiation in a pinch at the implosion of the QSWA of tungsten wires using a spectrograph with reflective grating. The recording of the spectra of tungsten in the range of photon energy 20 - 2500 eV with a spatial resolution along the radius and along the axis of the liner was carried out using a grazing incidence spectrograph with a concave diffraction grating (Rowland radius of 1 m) and a spatial gap, installed at the entrance of the spectrograph. For the imaging of XUV spectra we used film type UF-4.

Shown are the spectra of X-ray emission of the plasma generated in various areas of the QSWA. It was found that the spectral energy density (SED) in the region of maximum intensity of the XUV spectrum emitted from the axial region of the liner in the case of the QSWA significantly exceeds the value of SED obtained for the near-electrode regions of the QSWA. From the XUV spectra with radial resolution we obtained the dependence of the diameter of the emitting region on the wavelength. For the first time we achieved the increase in the energy density in the plasma implosion profiled by weight of QSWA up to 35.4 $TВт/см^3$ compared with 6.9 $TВт/см^3$ for cylindrical wire arrays (CWA) with the same parameters for the same current of 2.5 MA.

This study was supported in part by the Russian Ministry of Education under the Federal Target Program "Research and development on priority directions of scientific-technological complex of Russia for 2007-2012" by the state contract no. 16.518.11.7001 and the Russian Foundation for Basic Research (project nos. № 11-02-01027-a).

6-12

IONOLUMINESCENCE of SILICA BOMBARDED by 420 keV MOLECULAR HYDROGEN IONS

O. V. Kalantaryan, S. I. Kononenko, V. P. Zhurenko

Kharkiv National University named by Vasiliy Karazin,
Kurchatov Av., 31, Kharkiv, 61108, Ukraine. kononenko@htuni.kharkov.ua

Construction of thermonuclear devices requires transparent materials such as glass and crystals. They can be mostly used as materials for optical elements. In a thermonuclear reactor such elements are windows designed for optical diagnostics. Silica glass is widely used in modern devices and facilities both as insulators and optical elements for diagnostics and optical radiation input-outputs. It is considered to be convenient as window for UV and visible spectroscopy in thermonuclear facilities. One of the possible ways of silica monitoring under ion irradiation is our ionoluminescence technique [1-2].

Earlier we have proposed new technique to monitor proton and molecular hydrogen absorbed dose up to $4.35 \cdot 10^{10}$ Gr in silica (see, for example, [1]). The technique is based on change of SiO_2 ionoluminescence spectra in process of ion bombardment and relation between the light intensity at some defined wavelengths and absorbed dose. We found absorption dose calibrating curve for H_2^+ irradiation of silica [3]. This curve is used by the technique proposed by us for H_2^+ absorption dose monitoring (up to 4.35×10^{10} Gr) in silica.

But the absorption dose calibrating curve has ambiguity at the beginning of absorption dose growth. We performed some additional experiments in order to remove the ambiguity and develop our monitoring technique. This paper deals with study of angular spectral characteristics of silica luminescence induced by fast molecular hydrogen ions at observation angles varying from 0° to 70° in order.

We found the most evident changes in the spectrum shape in the red band region with apparent angular dependence for absorption doses upto 2×10^{10} Gr. The data extends possibility of our remote monitoring technique for silica irradiated by H_2^+.

The facts cleared-up can be explained by complicated dynamic processes of defect formation and blocking (E'-centres and non-bridging oxygen centers) with growth of ion absorption dose.

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6-13

IMPLOSION OF THE FOAMY-WIRE CONSTRUCTIONS ON ANGARA-5-1 FACILITY

K. Mitrofanov, V. Alexandrov, E. Grabovsky, A. Grizuk, Yan Laukhin, G. Oleinik, I. Frolov

SRC RF TRINITI, 142191, Troitsk, Moscow reg., Russia
mitrofan@triniti.ru

This report presents results of a nested liners implosion study under the influence of a strong current pulse. Experiments were carried out on the plasma compression of nested liners on Angara-5-1 facility (I≤4 MA, Δt~100 ns). The purpose of these experiments was to study the compactness of plasma compression. We used the dynamics of the spatial magnetic field distribution and temporal profile of the generated soft x-rays pulse (SXR) as the indicators of compact pinch compression. This paper presents the experimental results of the magnetic field spatial distribution and pulse power profile of SXR measurements by the nested liners implosion - foam-wire (F-W) constructions. These kinds of liners were composed of two nested cascades, one of which was a multiwire array, and the second was a hollow/solid cylindrical liner made from low density foam (foam liner). Foam liner was made of agar-agar foam in the form of a hollow or solid cylinder with the wall thickness of 100-200 microns. In some experiments, one of the F-W construction cascades was made of foam of organic acid - $C_{20}H_{17}O_6$ in the solid phase. The wire array was made from 40 thin tungsten wires (diameter 6 microns) located at radii 12 mm or 20 mm.

The radial distribution of the magnetic field in a space between cascades, and within inner cascade of F-W construction was investigated by the technique of miniature magnetic probes. The measured radial distribution of the magnetic field was compared with calculations of the magnetic field structure by the 1-D MHD program, which simulates stationary plasma flow within double nested liners. It is shown that the development of supersonic and subsonic regimes of the plasma flow determines the spatial structure of the current and the magnetic field distribution inside such liners. The paper discusses some features of the plasma pinch formation and compensation of a plasma zippering effect near the axis of nested F-W construction. We were interested in the effect of reducing the zippering plasma from outer wire array by introducing an internal foam liner. The structure of the emitting region of Z-pinch plasma formed by the compression foam-wire constructions was recorded by means of integral pinhole cameras, by a frame registration system of x-ray images based on MCP with registration on the CCD and by a glanced incident spectrograph (GIS). It was recorded that in the spectral range from 300 eV to 600 eV the spectral density of radiation from Z-pinch "hot" areas was more than 10 times value of spectral radiation density from the neighboring regions of the pinch plasma. Thus the visible size of hot areas decreases with growth of photon energy. It is shown that by changing the parameters of both the outer and inner cascades of F-W construction it is possible to optimize the x-ray power pulse amplitude and its duration. X-ray power pulses with amplitude about 3 TW and duration less than 10 ns in the optimal mode of plasma compression were received. The effective compression of the plasma on the final implosion phase occurs at high velocity of up to 220 km/s. In this case the plasma was compressed to a radius about 0.5 mm by the moment of X-ray power maximum. The experiments with F-W constructions show the possibility of forming a power pulse - to single-peaked or two-peak structure of the x-ray power pulse.

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6-14

RADIATION OF THE LYMAN ALPHA LINE AT IONIZATION FRONT IN QSPA

A.N. Kozlov[1], I.E. Garkusha[2], V.S. Konovalov[1], V.G. Novikov[1]

[1]Keldysh Institute of Applied Mathematics, RAS, Moscow, Russia

[2]Institute of Plasma Physics of the NSC KIPT, 61108, Kharkov, Ukraine

The elementary coaxial plasma accelerator [1] schematically consists of the two coaxial electrodes connected to an electric circuit. A neutral gas being introduced between the electrodes is ionized, and ionization front is formed. Behind the front the ionized plasma is accelerated along the channel axis due to the Ampere force. Some small plasma accelerators can be used as the first step of the greater system of the quasi-steady plasma accelerator (QSPA). In the first step the ionization and preliminary acceleration of plasma is carried out. In the experimental researches of QSPA (see, for example, [1-5]) the high degree of stability and azimuthal symmetry of the low-temperature plasma streams were observed.

The theoretical researches and numerical modeling play the significant role in studying of QSPA (see, for example, [6-8]). The ionization front in the accelerator channel essentially differs from the usual ionizing shock waves of compression. The temperature and speed sharply increase at the ionization front. At the same time the density and a magnetic field sharply decrease. The narrow ionization front according to the experiments has been obtained within the framework of the numerical model [6] where the system of the MHD-equations is combined with the ionization and recombination kinetic equations in the hydrogen plasma.

Solution of the radiation transport equation is based on calculation of the plasma emissivity and photon absorption coefficients for the known distributions of temperature and density. Absorption and radiation in lines is defined by the line profile of the corresponding bound-bound processes. The effective technique of calculation of the line profile which takes into account the different broadening mechanisms is stated in [9].

Despite of small line widths the essential part of all radiation energy is transferred in the Lyman alpha line. It is shown that the Ly-alpha brings the greatest contribution to values of density of the radiation energy and the radiation energy flux in the accelerator channel. Distribution of the radiation intensity at the Ly-alpha center in the radial direction of the plasma accelerator channel is obtained. The peak of distribution is located at the ionization front. The calculated results stimulate the corresponding experimental researches.

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6-15

CALCULATIONS OF THE COMPRESSIBLE PLASMA STREAMS GENERATED IN QSPA FROM THE VARIOUS GASES

A.N. Kozlov[1], D.G. Solyakov[2], N.A. Ageychik[3], M.A. Velichkin[3], E.I. Seytkhalilova[3]

[1]*Keldysh Institute of Applied Mathematics, RAS, Moscow, Russia*
[2]*Institute of Plasma Physics of the NSC KIPT, 61108, Kharkov, Ukraine*
[3]*Moscow State University, Faculty of Mechanics and Mathematics, Moscow, Russia*

Studying of the multicomponent plasma dynamics is one of the actual directions of researches in the modern plasma physics and the computing plasmadynamics. Presence of impurity renders the essential influence on the dynamic characteristics of the plasma streams. The first stage of these complex researches is directed on revealing of properties and the comparative analysis of plasma streams of various structures. The modern level of researches on of the quasi-steady plasma accelerators (QSPA) (see, for example, [1-3]) including their modifications at the presence of an additional longitudinal magnetic field [4-5], and the magneto plasma compressors (MPC) (see, for example, [6-7]) allows to use for generation of plasma the various gases including hydrogen, helium, nitrogen, xenon. The given researches provide the possible realization of some technological applications.

The numerical research of dynamics of streams in the channel and the compressible flows on an output from QSPA is carried out for the plasma generated from hydrogen, argon and xenon. The MHD equations in the one-liquid approach taking into account the final conductivity of medium, the heat conductivity and the effective losses of energy on radiation underlie the numerical model of the two-dimensional axisymmetric plasma flows generally non-stationary (see, for example, [8-9]). As a result of calculations of the quasi-steady axisymmetric plasma flows the tow-dimensional distributions of such dynamic variables as speed, density and temperature are received. It is established that the structure of plasma influences the dynamic characteristics of streams and the distribution of temperature first of all. It is supposed that the computational results will be compared to the experimental data.

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6-16

CHARGE EXCHANGE NEUTRALS RESEARCH IN EDGE PLASMA OF T-10 TOKAMAK

V. Nikolaeva[1)], V. Kurnaev[1)], V. Budaev[2)], S. Grashin[2)], A. Litnovsky[3)], U. Breuer[3)]

[1)] *National Research Nuclear University "MEPhI", Moscow, Russia*
[2)] *National Research Centre "Kurchatov Institute", Moscow, Russia*
[3)] *Institute of Plasma Physics, Forschungszentrum Juelich, Germany*

E-mail: valentina_nikolaeva@mail.ru

Neutrals, formed in plasma as result of the charge-exchange (CX) processes, play an important role in modern fusion devices with magnetic confinement. Neutral atoms irradiating the surface of plasma facing components (PFC) can cause an erosion and destruction of the surface. Angular distribution of incident particles is not fully explored, but is crucial issue for understanding processes occurring under the ions and neutrals influence on the surface of PFC. Since it is well known that the processes of penetration, reflection and sputtering depend on the incident angle at which the particles come to the surface [1].

The passive collecting probe has been developed by Plasma Physics Department of NRNU MEPhI to study the energy and angular distributions of neutral particles in the peripheral region of a tokamak.

The probe was placed in T-10 tokamak , at the radius of 34 cm, during 82 pulses that approximately equal to 82 seconds.

After exposure. the silicon sample was analyzed by secondary ion mass spectrometry (SIMS) at Forschungszentrum Juelich. The deuterium depth profile in the silicon sample was considered to detect the preferential charge-exchange neutrals direction. The difference was noticed in the calculation of deuterium in various parts of the sample.

Then, experimental results were compared with calculations of angular distributions of the charge-exchange neutrals, which were obtained by using the modified model Neutral II [2] that considers angular distribution of fast charge-exchange neutrals that leave plasma.

The anisotropy of the charge-exchange neutrals distribution is observed. The preferential charge-exchange neutrals direction corresponds to the output of charge-exchange neutrals from the core plasma region and the wall. The experimental dependence of the deuterium intensity on sputtering time was compared with the previously modeling calculations of the angular and energy distributions of the charge-exchange neutrals. The experimental results do not contradict the modeling calculations, agreement is observed. It confirms that more extensive experiments with the collecting probe are justified and can provide information about angular and energy distributions details of the charge-exchange neutrals bombarding the walls of the tokamak.

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6-17

A SUCCESSFUL SEARCH FOR THE CONFIGURATION OF THE DISCHARGE CHAMBER ON PHILIPPOV TYPE PLASMA FOCUS.

Kryukov L.H., Mozgovoy A.G., Nikulin V.Ya., Polukhin* S.N., Volobuev I.V.

Lebedev Physical Institute.

Preliminary experiments done in the plasma focus (PF) installation of Filippov type (E = 70kJ and the current of about 1MA) indicated on the existence near insulator a significant parasitic currents [1]. To suppress them, as well as to optimize discharge circuit the key elements of the discharge chamber (an insulator, an anode and a cathode liner) were changed. As a result, the absolute neutron yield were increased by 30 times and reached the value Yn = $5 \cdot 10^{10}$ neutrons per pulse while the maximum discharge current decreased from 1.1MA in 0.85MA

Research is being conducted as part of an overall strategy which assumes that the saturation of the neutron yield of PF of Mather type in the MJ range caused by a decrease rate of rise of discharge current with increasing energy of PF installation. Such limitation of increasing of the current is determined by high inductance of the discharge chamber of plasma focus of this type [2]. The authors believe that the Filippov type PF, which has much lower inductance, due to the planar geometry of the electrodes is a promising device and allow to overcome the above problems.

In the report will be discussed ways of increasing the discharge current is not due to a costly increase in energy of installations, but primarily by reducing the inductance of each element of the discharge circuit.

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* snpol@mail.ru

6-18

ENERGY CHARACTERISTICS OF PLASMA STREAM, GENERATED BY MPC

I.E. Garkusha, V.V. Chebotarev, N.V. Kulik, M.S. Ladygina, A.K. Marchenko, Yu.V. Petrov, D.G. Solyakov, D.V. Eliseev, V.V. Staltsov, T.N. Cherednychenko, Ya.I. Morgal, V.M. Astashynski[1], S.I. Ananin[1]

Institute of Plasma Physics of the NSC KIPT, 61108, Kharkov, Ukraine

[1]B. I. Stepanov Institute of Physics,National Academy of Sciences of Belarus

68 Nezalezhnastsi ave.,220072 Minsk, Belarus

Plasma streams of different gases, generated by magnetoplasma compressor (MPC) of compact geometry, can be applied in different technological applications, namely in plasma treatment of targets with complex geometry. Plasma discharge efficiency, plasma stream energy density and plasma stream velocity are important parameters for optimization of MPC operation modes for improvement of target treatment.

The present paper is devoted to analysis of integral characteristics of plasma discharge and energy distributions in plasma streams of different gases, generated by MPC.

Experiments were carried out in compact MPC device [1, 2]. MPC accelerating channel forms by cooper coaxial electrodes, outer multi roads anode with diameter in outer part 8 cm and inner solid cathode with diameter of 2 cm. Total length of MPC channel was 10 cm. MPC was installed in vacuum chamber with diameter of 40 cm and length of 200 cm. Maximum voltage in capacitor bank was 20 kV, maximum discharge current was 500 kA. All experiments were performed in MPC operation mode in residual helium or argon with pressure varied from 0.5 Torr to 10 Torr. Rogowski coil and voltage divider were used for discharge current and discharge voltage measurements respectively. Local movable cooper calorimeter with diameter of 5 mm was applied for energy density radial distributions measurements at the distance of 11 cm from MPC output (end of compression zone that is formed at the axis).

It was shown experimentally that energy characteristics strongly depend on residual gas pressure. Discharge voltage and energy density in near axis region decreased with increasing gas pressure for both used working gases. Dependencies of energy density on the discharge current and radial distributions of energy density for different residual gas pressure for both gases, in other words for different mass flow rates, were investigated.

Energy conversion efficiency from electric discharge in accelerating channel to plasma stream was about 0.4-0.5 for argon and it increased up to 0.85-0.9 for operation with helium for all investigated MPC regimes.

Plasma streams with energy density up to 50-60 J/cm^2 at the distance 11 cm from MPC output and with total energy content up to 4-5 kJ was obtained.

This investigation has been supported by the State Fund for Fundamental Researches under Grant F41.2/030.

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6-19

COMBINED EXPOSURE OF TUNGSTEN BY STATIONARY AND TRANSIENT HYDROGEN PLASMAS HEAT LOADS: PRELIMINARY RESULTS

N.N. Aksenov[1], A.A. Chuvilo[1], V.A. Makhlaj[1], I.E. Garkusha[1],
I.A. Bizyukov[2], O.I. Girka[2],
S.V. Bazdyreva[3], S.V. Malykhin[3], A.T. Pugachov[3]

[1] *Institute of Plasma Physics of the NSC KIPT, 61108 Kharkov, Ukraine*
[2] *V.N. Karazin Kharkiv National University, Svobody sq., 4, 61022, Kharkov, Ukraine*
[3] *Kharkov Polytechnic Institute, NTU, 61002, Kharkov, Ukraine*

Estimation of respond the ITER relevant materials to ITER-like powerful stationary and/or transient plasma loads remain one of important issues' for realisation of fusion reactor project. This information can be received in the simulation experiments with such heat loads.

Experimental simulations of ITER transient events with relevant surface heat load parameters (energy density and the pulse duration) as well as particle loads are carried out with most powerful device of its kind – a quasi-stationary plasma accelerator QSPA Kh-50. The main parameters of the streams are as follows: ion impact energy about 0.4 keV, maximum plasma pressure 3.2 bar, and the stream diameter 18 cm. The surface energy load measured with a calorimeter achieved 0.75 MJm^{-2}. The plasma pulse shape is approximately triangular, pulse duration of 0.25 ms.

Steady-state irradiation of the sample was produced by using FALCON ion source, which design is based on Hall thrusters with anode layer. The FALCON ion source generates a hydrogen ion beam with a particle flux of up to 10^{22} $m^{-2}s^{-1}$ and heat flux is in the range of (0.2÷0.7) MWm^{-2}. Typical ion energy is in the kilo electron volt range.

Surface analysis was carried out with an optical microscope MMR-4 equipped with a CCD camera and Scanning Electron Microscopy (SEM) JEOL JSM-6390. Measurements of weight losses, microhardness and roughness of the surface were performed also. To study micro-structural evolution of exposed W targets, X-ray diffraction technique (XRD) has been used. The so called 'ϑ-2ϑ scans' were performed using a monochromatic K_α line of Cu anode radiation. Diffraction peaks intensity, their profiles, and their angular positions were analyzed in order to evaluate the texture, the size of coherent scattering zone, the macrostrain and the lattice parameters.

Transient heat load to tungsten surfaces led to symmetrical tensile stresses creation on W surface layer as a result of plasma irradiation. The residual stress grows with the increase in energy load. Some relaxation of stresses was observed for a large number of pulses. The stress relaxation was also found for small number of combined exposure by stationary and transient heat loads. The dynamics of tungsten lattice spacing in the stress-free section was discussed for transient heat loads as well as for combined plasma exposure.

6-20

CHARACTERIZATION OF QSPA PLASMA STREAMS IN PLASMA -SURFACE INTERACTION EXPERIMENTS

V.A. Makhlaj

Institute of Plasma Physics of the NSC KIPT, 61108 Kharkov, Ukraine

Experimental studies of plasma-surface interaction (PSI) during simulating the disruptions, Edge Localized Modes (ELM) and other transient events in the International Thermonuclear Experimental Reactor (ITER) are important for determination of erosion mechanisms of plasma facing materials. The dynamics of erosion products, the impurities transport in the plasma, and the influence of vapor shield on the plasma energy transfer to material surface are also momentous issues for fusion reactor. Heat loads to ITER divertor surfaces associated with the Type I ELMs are supposed to be up to Q = 3 MJ/m^2 during τ = (0.1…0.5) ms for each event. In present-day tokamaks, experimental simulations of high-energy fluxes expected to fusion reactor are quite problematic. For this reason, the simulation experiments are carried out by using a number of powerful test facilities, namely the electron beam facility, the Quasi-Stationary Plasma Accelerators (QSPA), plasma guns and others. QSPAs well reproduce the energy densities (Q) and pulse durations (τ) of ITER ELMs. QSPA Kh-50 is the largest and most powerful device of this class, which generate by magnetized plasma streams of high energy density.

Plasma heat loads were varied by both changing the dynamics and quantity of gas filled the accelerator channel and changing the working voltage of accelerator QSPA Kh-50. Plasma streams duration of 0.25 ms and the energy density varied in the range 0.5…30 MJ/m^2 were received. Such energy density relevant to transient heat loads in divertor ITER . During the injection and motion of quasi-study-state plasma streams in longitudinal magnetic field the magnetized plasma streams are obtained with full energy content up to 120 kJ.

Influence of target inclination and neighborhood W and C as divertor components on the material response to the repetitive plasma heat loads was analyzed. The experiments included also study of tungsten thresholds of cracking, melting, evaporation, the cracks analysis in target exposed by QSPA plasma streams. Calorimetric measurements demonstrate that even for plasma exposures, which not result in the tungsten melting, the absorbed heat load is not more 60% of the impact plasma energy. The shielding layer created near surface target is responsible for decreasing part of incident plasma energy which is delivered to the surface. The additional shielding of tungsten by C cloud was found for adjoined W-C sample due to enhanced evaporation of carbon.

7-01

INVESTIGATION OF PLASMA LENSES IN NSC KIPT

I.N.Onishchenko

NSC Kharkov Institute of Physics and Technology, Kharkov, Ukraine

The results of conducted at NSC KIPT theoretical and experimental studies of focusing electron and ion beams with using plasma lens are presented. Several mechanisms of beam focusing in plasma are investigated that caused by: a - plasma compensation of defocusing own fields of the beam [1], b - electric and magnetic fields presented in charged current-carrying plasma, ejected from the plasma gun [2], c - high-frequency wakefield excited in plasma by a sequence of relativistic electron bunches [3]. The possibility to obtain at plasma density 10^{14}cm^{-3} high gradient of focusing field $3\cdot10^{5}$G/cm, an order exceeding the maximum gradient of the doublet of quadruple lenses, that allows increasing essentially the density of microbunches at the beam crossover. Focusing ion beam (energy 5MeV, current 30mA) of the accelerator "Ural" by an azimuthal magnetic field is investigated in plasma of density 10^{11}-10^{15}cm^{-3}, produced by a coaxial plasma gun, that provides a decrease in the diameter of the ion beam 10 times. Focusing of the sequence of bunches of relativistic electrons (energy 14MeV, current 12A) of the accelerator "Lik" by plasma wakefield excited in plasma of density 10^{11}cm^{-3} is demonstrated. Numerical simulation and experimental study of radial-phase dynamics of driver bunches, exciting wakefield in plasma, and the bunches accelerated in these fields on the base of the linear resonant electron accelerator “Almaz-2”, producing a long sequence of relativistic electron bunches of energy 4.5MeV, charge 0.16nC, length 1.7cm, diameter 1.0cm each is being carried out.

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7-02

STABILIZATION OF CLASSIC AND QUANTUM SYSTEMS

V.A. Buts

N SC "Kharkov Institute of Physics and Technology" 61108, Kharkov, Ukraine. E-mail: vbuts@kipt.kharkov.ua

The quantum Zeno effect (QZE) has been predicted in theoretical work [1]. The effect allows stabilizing states of a quantum system by frequent observations of the system's state. The QZE has been confirmed by several experimental investigations (see for example [2-3]). QZM explanation is based on the processes of observation and the wave function collapse, which are usually out of scope of the conventional quantum theory.

Work [4] suggests another explanation for mechanism of quantum states stabilization. It lies inside the frame of conventional quantum mechanics and is easy explainable using the classical quantum mechanics approaches. Namely, let's consider a quantum system in an initial state which we want to conserve. We have shown that, to achieve the stabilization one should know the life time of the initial state and should start changing the characteristics of the initial state or the characteristics of the state to which the system tends to transit. The faster change of the parameters leads to lover probability of the transition. The characteristic parameter of the suppression is the ratio of the initial state life time to the period of the changes imposed on the system. The higher ratio causes higher stability of the initial state. Such feature of the stabilization resembles the stability of a whirligig. That is why we name this mechanism as the mechanism of quantum whirligig. It is possible that such mechanism has been observed in number of experiments [4-5].

We show that similar stabilization can be successfully achieved not only in quantum, but in classical mechanics systems too. We also report how the suggested mechanism can be used for stabilization of various plasma and beam instabilities. Particularly, the conditions for stabilization of plasma-beam instability and decay instability in plasma have been investigated alongside with the more elaborate theory of the photoeffect suppression.

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7-03

LOW PRESSURE DISCHARGE INITIATED BY MICROWAVE RADIATION WITH STOCHASTICALLY JUMPING PHASE

A.M. Artamoshkin[1], A.F. Alisov[1], O.V. Bolotov[1], V.I. Golota[1], V.I. Karas`[1,*], I.V. Karas`[1], A.M. Yegorov[1], I.A. Zagrebelny[1], I.F. Potapenko[2]

[1] *National Science Center Kharkov Institute of Physics & Technology of NASU, 1 Akademicheskaya street, Kharkov, 61108, Ukraine, e-mail: karas@kipt.kharkov.ua*

[2] *Keldysh Institute of Applied Mathematics of RAS, Miusskaya sq. 4, Moscow, 125047, Russia*

In this report we describe results of the theoretical and experimental investigations of the plasma discharge, initiated by microwave radiation with stochastically jumping phase (MWJP) in a coaxial waveguide in the optimal mode of the beam-plasma generator (BPG). Present results continue the line of the previous research. We experimentally examine the characteristics of the discharge plasma in a wide range of air pressure. The conditions of a microwave discharge ignition, its stable maintenance in air by MWJP, and the pressure range at which required power is minimal are found.

RF heating is very important field in connection with fundamental questions of plasma physics and applications. The issues widely discussed in literature are connected with additional plasma heating in tokamaks, the nature of accelerated particles in space plasmas, gas discharge physics. It is worth mentioning that one of the difficulties associated with additional plasma heating in tokamaks is a well-known dependence of the Rutherford cross-section on velocity. As a consequence, the probability of collisions decreases with plasma temperature rising, thus creating obstacles for further plasma heating. Another important challenge in interaction of RF radiation with plasma is a barrier of penetration of the radiation into the overdense plasma.

At the stage of discharge in the coaxial waveguide, the discharge becomes nonuniform along its length due to the strong absorption of MWJP. The electric field amplitude decreases by more than one order when approaching to the waveguide exit.

If the discharge has a place in the spectrum of the output signal from the coaxial waveguide is not spectral components corresponding to the maximum values in the spectrum of input into the coaxial waveguide. During the maintenance of MWJP discharge in the waveguide, gas ionization leads to almost complete damping of the main spectral components of the input microwave signal. With air pressure decreasing, the optical radiation from the discharge becomes more reach with shorter wavelength. Thus, if at the pressure of 20 Pa, the radiation has red colour, then at pressure of 2Pa the radiation becomes blue. Microwave oscillations and glow discharge exist in time almost throughout the pulse duration of electron beam current in BPG.

When the frequency of MWJP signal and the frequency of phase jumps are those as observed in the conducted investigations, there is enough to have the magnitude of electric field equals to 50 V/cm, for the creation and maintainence of the discharge in air.

Thus, based on the quantitative indicators, such as the electric field intensity, frequencies of MWJP and phase jumps it can be expected the following. The prospective creation of an efficient light radiation source of low power (100 W) in a wide range of air pressure, in which the discharge is ignited and maintained stably, becomes a reality.

The results might also be of some use in connection with additional plasma heating in nuclear fusion devices due the fact that, the electron heating by microwave radiation with jumping phase is collisionless. Thus the heating efficiency by MWJP does not decreas when the temperature increases, whereas the usual heating by the regular radiation is to be collisional and becomes less and less efficient.

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7-04

PLASMA WAKEFIELD EXCITATION, POSSESSING OF HOMOGENEOUS FOCUSING OF ELECTRON BUNCHES

V.I.Maslov, I.N.Onishchenko, I.P.Yarovaya[1]

NSC Kharkov Institute of Physics & Technology, 61108 Kharkov, Ukraine
[1] Karazin Kharkov National University, Kharkov, 61108, Ukraine

The focusing of bunches by wakefield, excited in plasma by resonant sequence of relativistic electron bunches (repetition frequency of the bunches ω_m coincides with the plasma frequency $\omega_m=\omega_p$), is inhomogeneous. In [1] the mechanism of focusing by plasma wakefield, in which all bunches of sequence are focused identically and uniformly, has been proposed and numerically investigated. In this paper we analytically and numerically investigate by 2.5D code LCODE [2] this wakefield plasma lens for relativistic electron bunches. We have shown that all bunches of sequence are focused identically and uniformly. For this it is necessary that bunches have lengths, equal $\Delta\xi_b=q(\lambda/2)$, q=1, 2, … the charge of 1-st bunch equals half of the charges of the other bunches, the porosity between bunches equals $\delta\xi=p\lambda$, p=1, 2, … Analytically and by numerical simulation it is shown that only 1-st bunch is in finite $E_z\neq0$. Other bunches are in zero longitudinal electrical wakefield $E_z=0$. Hence the 1-st bunch interchange by energy with wakefield. The subsequent bunches do not interchange by energy with wakefield and the amplitude of wakefield does not change along sequence. Radial wake force F_r in regions, occupied by bunches, is approximately constant along bunches. In the case of inhomogeneous longitudinal distribution of electron bunch density the middle of bunches are focused more slower than fronts.

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7-05

SPECTRUM CONTROL IN THE COURSE OF MICROWAVE NANOSECOND PULSE IN SUBGIGAWATT POWER LEVEL PLASMA RELATIVISTIC MICROWAVE OSCILLATOR

D.K.Ulyanov, O.T.Loza*, R.V.Baranov*

A.M.Prokhorov General physics institute RAS, Moscow, Russia

** Peoples' Friendship University of Russia, Moscow, Russia*

Plasma relativistic microwave oscillator (PRMO) is a device capable to vary its emission spectrum in a very broad range. PRMO is a relativistic traveling wave tube with plasma as a slow-wave structure. Earlier we presented first repetitively-rated PRMO with the pulse power 10^8 W and the radiation frequency tunable electronically within two octaves from a pulse to a pulse according to any preset algorithm [1]. The spectrum width of a PRMO is also tunable from a single spectral line to 100% of the mean frequency [2].

In this work we demonstrate means of control over PRMO emission frequency within a single HPM pulse. Experiments [3] with G-band PRMO revealed a possibility of significant changes in frequency during 70 ns of microwave pulse. One of those results was repeated later and registered by a high bandwidth oscilloscope, it is shown in Fig.1a. The time domain spectrum shows that during 60 ns emission frequency changes from 3.5 GHz to 3.8 GHz. The power level of 50 MW was measured using a microwave calorimeter overlapping the outlet horn of the PRMO.

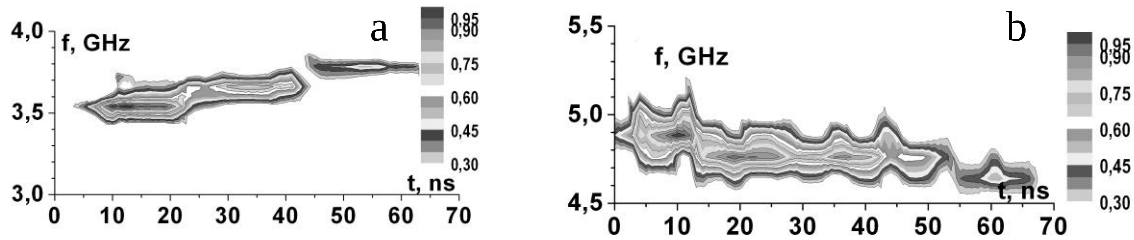

Fig. 1 Frequency tuning in G-band, 50-MW pulse: a – rise, b - reduction

Emission frequency depends on the density of plasma prepared in PRMO using a special electron beam for gas ionization; the frequency rises with a rise of plasma density. In the course of HPM pulse either way is possible for the preformed plasma density changes. The density rise is due to further gas ionization in microwave fields ~ 100 kV/cm. Adjusting gas pressure from $5 \cdot 10^{-5}$ to $3 \cdot 10^{-3}$ Torr allows plasma to increase its density with a certain rate. The decrease of plasma density is determined by the effect found in [4], namely, the displacement of plasma electrons by electrostatic field of high-current relativistic electron beam. A balance between the two mechanisms of plasma density variation permits to raise emission frequency in the course of HPM pulse, to maintain it constant or even to decrease it a little as shown in Fig.1b. The last mentioned result refers to the PRMO operating in the range from 4.9 GHz to 4.6 GHz.

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7-06

EXCITITION OF THE QUASISTATIONARY WAKEVAWE FIELD BY ELECTRON BUNCH IN PLASMA

Yu.M. Tolochkevich, T.E. Litoshenko, I.O. Anisimov
Taras Shevchenko National University of Kyiv, Radio Physics Faculty
yura.tolochkevich@gmail.com, taras.litoshenko@gmail.com, ioa@univ.kiev.ua

Dynamics of electron beams and bunches in plasma take one of the leading places in plasma electronics. Charged particles' acceleration by a powerful wake wave fields excited in plasma by relativistic electron bunches [1], inhomogeneous plasma diagnostics using transition radiation of electron bunches and beams [2] are actual problems in this field. Bunch-plasma simulation results obtained by 2.5 D electromagnetic code [3] are presented at this paper.

Beam-plasma system was simulated in 2.5D cylindrical geometry. The system with the shape of cylindrical resonator is filled with homogeneous nonisothermal plasma. Plasma consists of electrons with temperature 1eV and hydrogen ions with temperature 0.1eV. Electron bunch of cylindrical shape with sharp forefront is injected into plasma. Initial bunch velocity is $3{\cdot}10^7$m/s. Initial duration of electron bunch is equal to 4 periods of Langmuir plasma oscillation.

Sharp forefront of the bunch excites wake field. All other electrons of the bunch are moving in the field of the excited wave which leads to the formation of microbunches. When microbunches are formed wakewave is resonantly excited by every microbunch and its amplitude increases significantly.

The intensity of the excited electric field in the left part of the simulation volume remains high even after the bunch leaves this region and slowly decreases (Fig. 1). This field exists as a sequence of minima and maxima which propagate rightwards with phase velocity of Langmuir wave. The envelope of the wave is quasistationary located in the volume. This could be explained that Langmuir soliton is excited

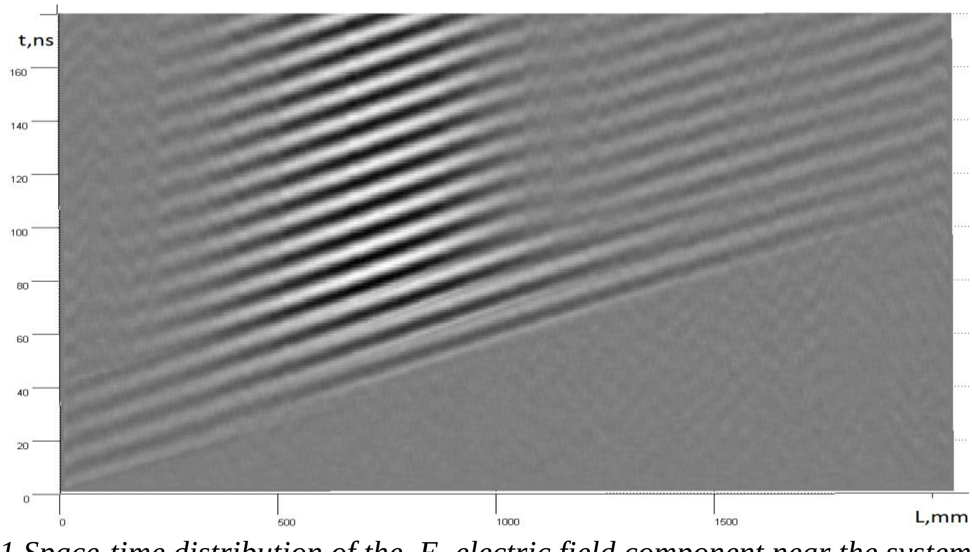

Fig.1 Space-time distribution of the E_z electric field component near the system axis

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7-07

STOCHASTIC HEATING AND STOCHASTIC ACCELERATION OF CHARGED PARTICLES

V.A.Buts, V.V.Kuzmin, A.P.Tolstoluzhsky

National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine

Two schemes of interaction of charged particles are compared: with the wave field of chaotic phase change and with the field of a transverse electromagnetic wave in the presence of external static magnetic field. For studying the dynamics of charged particles in the field of wave with chaotic phase change, there was simulated the wave which phase jump occurs during an arbitrary moment of time. For such a case the dependence of dynamics of charged particles on the value of jump and frequency of jump occurrences is analysed. It is shown that motion of charged particles in the field of such wave is chaotic. On average, the energy of charged particles increases with time in accordance with the diffusion law. The optimum values of jump at which the increment of energy rise is maximal are found. The analysis of charged particles dynamics in the field of transverse electromagnetic wave in the presence of external static magnetic field was carried out for different wave-field intensity and different strength of external magnetic field. It was shown that in conditions of overlapping cyclotron resonances the dynamics of charged particles has a stochastic character. On average, the particle energy rise also obeys the diffusion law. The comparative analysis of two mentioned schemes demonstrates that with the same value of energy in the wave, the scheme of acceleration in the wave field in condition when nonlinear resonances are overlapping is more preferable in most cases. Especially this concerns the case of the optical wavelength range.

7-08

ESTIMATES OF LIMITING CURRENT OF CHARGED-PARTICLE BEAM IN COAXIAL DRIFT TUBE

T. Yatsenko[1], G. V. Sotnikov[2], K. Ilyenko[1]

[1]*Institute for Radiophysics and Electronics of NAS of Ukraine*
vul. Akad. Proskury, 12, Kharkiv, 61085, Ukraine
Ph.: +380 57 7203331, e-mail: t.dream@gmx.net

[2]*National Science Centre "Kharkov Institute of Physics and Technology" of NAS of Ukraine*
1 Akademicheskaya Street, Kharkov, 61108, Ukraine
Ph.: +380 57 3356623, e-mail: sotnikov@kipt.kharkov.ua

Some authors last decade paid attention to studying of space-charge limiting (SCL) current of relativistic charged-particle beams propagated in infinitely long coaxial drift tubes with a dielectric insert lining an outer (or inner) conductor and the bias applied to the inner conductor in approximation of strong magnetic field [1–3] .

Previously we received the analytical and numerical estimates of SCL current of relativistic charged particle beams propagated in infinitely long grounded coaxial drift tubes [4]. Based on the method developed in the paper [4] we received analytical estimate of the first and the second of the SCL current of a charged-particle beam propagating in an infinitely long drift tube with the dielectric insert lining the outer conductor depended on the bias V_0 applied to the inner conductor of this drift tube in the approximation of strong magnetic field. We prove that our estimates of SCL current has the regular limits to all known cases. Also we receive the estimates of radius on which the potential generated by charged-particle beam reaches its extreme value and the estimates of potential extreme value. One should note that for grounded coaxial drift tubes the potential extremal value is attained inside the beam. Obtained analytical estimates are compared with the numerical modelling of the SCL current.

Numerically, we find the SCL current of axisymmetric charge-particle beam of finite thickness propagating in the strong axial magnetic field in a coaxial drift tube of finite length, for simplicity, we assume that there is no bias voltage on the inner drift tube conductor and the dielectric insert lining the outer drift tube conductor is absent. The obtained results confirm the correctness of using for drift tubes which length is more than 3-4 their radii of analytical expressions obtained for infinitely long coaxial drift tubes as reasonable estimates of limiting current in drift tubes of finite length [5].

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7-09

WAVES IN PLASMA-FILLED WAVEGUIDE SATISFYING THE DISPERSION RELATION FOR R AND L CIRCULAR WAVES IN UNBOUNDED MAGNETOACTIVE PLASMA

[1]V.I. Shcherbinin, [1,2]V.I. Tkachenko, [3]K. Schuenemann

[1]National Science Center "Kharkov Institute of Physics and Technology"
61108, Kharkov, Academicheskaya str., 1, tel. 8-057-335-08-47
[2]V.N. Karazin Kharkov National University
[3]Technical University Hamburg-Harburg
E-mail: vshch@ukr.net

Plasma-filled waveguides have potential to be used as electrodynamic structures in high-power microwave devices and high-gradient accelerators. Cylindrical waveguide completely filled with uniform magnetoactive plasma is a sample of such structure.

Nowadays its dispersion properties are well-studied practically for arbitrary ω and β (ω - frequency, β - longitudinal wave number). An exception is the case of ω and β satisfying the dispersion relation for R and L circular waves in unbounded magnetoactive plasma. In this case the denominators of general expressions for transverse field components [1] become zero. This fact has been attributed either to inability of such waves to propagate in plasma-filled waveguide [2] or to inability of expressions [1] to evaluate their fields [3, 4].

We found that in the case when the denominators of these expressions vanish, their numerators vanish as well. This makes the field representation indeterminate. We have evaluated this indeterminate form. The field components turned out to be finite for those points of the dispersion curves of R and L circular waves that simultaneously satisfy the dispersion relations of plasma-filled waveguide. This proves their belonging to domain of applicability of general field expressions [1]. We have shown that these points are different for waveguide modes having different signs of azimuth index m. This fact was not taken into account in [4]. For waves with $m > 0$ and $m < 0$ satisfying the dispersion relation for R and L circular waves, respectively, we have also determined the relationship between field amplitudes of general [1] and particular [4] field representations.

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7-10

FORMATION OF CHARGED PARTICLES' FLOWS IN THE BACKGROUND PLASMA AT THE INITIAL STAGE OF THE BEAM-PLASMA INSTABILITY

D. M. Tanygina, I. O. Anisimov, S. M. Levitskiy

Taras Shevchenko National University of Kyiv, Kiev, Ukraine

Interaction of electron beams with plasma is one of the most important problems of plasma physics. Most analytical studies of the beam-plasma instability paid the primary attention to instability mechanisms at the linear stage of the beam-plasma interaction [1]. Non-linear effects play an essential role in the beam-plasma interaction. These effects demonstrate themselves both in the electron beam and in plasma, and were observed in numerous experiments [2]. However, kinetic effects in the background plasma, which take place during the development of beam-plasma instability, are not entirely studied.

The aim of the present work is to study the formation of background plasma charged particles' (both electrons and ions) flows at the initial stage of the beam-plasma instability via computer simulation. We consider the initial stage as the time period during which the significant deformation of ions' density profile is not observed; in other words, redistribution of plasma density doesn't lead to reverse influence on the HF-field distribution in plasma.

To study the formation of plasma particles' flows, one-dimensional computer simulation using modified package PDP1 [3] was carried out. Simulation was carried out for several beams' current densities for the given beams' velocity, and for three different beams' velocities for given current density.

At the initial stages of the beam-plasma instability the flow of plasma electrons appears in the area of the intensive HF electric field. This flow is directed to the beams' injector (oppositely to the direction of the beam motion). In the same region the flows of plasma ions appear with both directions. Moreover, the ions' flow, directed along the electron beams' propagation direction, is more intensive.

To explain the reason of plasma electrons' flow formation, we considered an instantaneous space distribution of electric field, exited by the electron beam. Localization of flows' formation area coincides with the area of the most intensive quasi-stationary electric field. Under the influence of negative field, plasma electrons are accelerated to the collector. Consequently they appear in the area of larger positive field, and finally they start to move to the beams' injector. Otherwise, negative field accelerates ions to the injector, and positive field – to the collector. Thus, electrons of the background plasma are accelerated to the injector, while ions are accelerated both to injector, and (primarily) to the collector. Thereby, the electron beam, which is decelerated by the exited HF-electric field, indirectly transfers its impulse exactly to plasma ions.

Calculation shows that the cause of quasi-stationary electric field formation is plasma electrons' extrusion from the region of intensive HF electric field. Peculiarities of the quasi-stationary field space distribution are defined by the distribution of HF field intensity.

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7-11

SIMULATION OF INITIAL STAGE OF THE BEAM-PLASMA DISCHARGE IN HELIUM VIA PIC METHOD

I.O. Anisimov, B.P. Kosarevych, M.J. Soloviova

Taras Shevchenko National University of Kyiv, Radio Physics Faculty,
64 Volodymyrs'ka St., 01033, Kyiv, Ukraine
ioa@univ.kiev.ua, kosarevich@i.ua, mariia.soloviova@gmail.com

The recent interest to the beam-plasma discharge (BPD) is caused by its possible practical application. BPD as well as other types of discharges can be a source of non-equilibrium plasma. Its electron temperature can reach ~10^1 eV. So BPD can be used for carrying out plasma-chemical reactions with the energy threshold. Electron beam can transmit to plasma up to 50 per cent of its kinetic energy. Deposition technologies, including chemical vapor deposition (CVD) and plasma enhanced CVD (PECVD) can be based on BPD.

One-dimensional package PDP1 [1] is used for simulation of the BPD initial stage. Electron beam is injected into the interelectrode space filled by the partially ionized plasma. Neutral gas is taken into account as background, and its pressure is given. As the beam electron density is much smaller than plasma density, the specific kind of particles corresponds to the beam electrons. The package deals with the following elementary processes: elastic electrons-neutrals collisions, neutrals excitation and ionization by electron impact. Simulation parameters are taken close to experimental values [2].

Simulation of the initial stage of BPD in helium was carried out for beam current densities 100, 200, 500, 1000, 2000 A/m^2, and neutral gas pressures 10^{-3},10^{-2}, 0.1 Torr.

Spatial and temporal dependencies of electron and ion plasma densities, beam electron density and electric field for the simulation time corresponding to 100 periods of electron plasma oscillations were analyzed. Distribution of plasma ions is similar to the intensity of ionization processes in space. The distribution of plasma electrons almost repeats the distribution of ions, but electrons feel electric field better. The frequency of the plasma electrons distribution corresponds to the frequency of the electric field.

According to the results of the simulation there are 3 typical regimes of the beam interaction with weakly ionized plasma.

At low pressures BPI is developed, beam is modulated by excited BPI HF field. However, additional gas ionization is not observed as the mean free path of electrons in a neutral gas are comparable to the system length.

At higher pressures mean free path decreases. As a result, BPD ignites. However, the increase of the degree of the gas ionization does not exceed its initial value.

At high current densities and higher pressures gas ionization is significant. Plasma density can exceed an order of the initial background value. In this mode ionization of the background plasma first starts closer to the left electrode. But variation of the background plasma density leads to moving of BPI from this area. Consequently, the area of intense electric field and intense gas ionization moves away from the injector. Therefore, the final distribution of plasma density can be non-monotonous.

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7-12

EXPLOSIVE INSTABILITY IN THE PLASMA-BEAM SYSTEM

V.A. Buts, I.K. Kovalchuk

National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine
E-mail: vbuts@kipt.kharkov.ua

In this repot some results on investigation of the dynamics of explosive instability arising in the plasma-beam system are presented; when not only the slow-beam wave with negative energy is taken into account but the fast-beam wave also. To solve the task of interest, the set of equations in dimensionless variables for slowly varying amplitudes of waves that take part in the nonlinear interaction is used. Besides two beam modes with positive and negative energies, any two eigenmodes of investigated electrodynamics system are participating in the process of interaction. Thus a four-wave interaction is under consideration. The beam wave frequencies amount $\omega_{11,12} = k_{1z}V \pm \delta\omega$ (k_{1z} – wave vector of beam modes, V – beam velocity, $\delta\omega$ – value that is proportional to the plasma beam frequency). Frequencies and wave vectors of other two waves satisfy the conditions $k_{1z}= k_{2z+} k_{3z}$, $\omega_2+\omega_3\approx k_{1z}V$. Indexes 2 and 3 correspond to these waves. Two cases were investigated numerically. First one corresponds to synchronism of second and third waves with the slow-beam wave ($\omega_2+\omega_3=k_{1z}V-\delta\omega$). In the second case these waves are in synchronism with fast-beam wave ($\omega_2+\omega_3=k_{1z}V+\delta\omega$).

Main results

1. Explosive instability does not arise when $\delta\omega=0$. However, due to existing of the wave with negative energy, the amplitudes of all interacting waves do exponentially increase. The expression for increment of this instability was obtained.

2. For small $\delta\omega \neq 0$, after some time interval the exponential growth is replaced by an explosive one. With increasing δω, the time for explosive instability to start is decreasing and reaches a minimum at $\delta\omega/k_{1z}V\approx 0.01$. Then this time interval increases again to the value that corresponds to the beginning of explosive instability in the system, which consists of slow-beam wave and other two modes of the system.

3. When second and third waves are in synchronism with a slow-beam wave, the dynamics of the system does not change qualitatively and is similar to the dynamics of the ordinary explosive instability in the range of $\delta\omega/k_{1z}V$ from 0.1 to 0.2.

4. The dynamics of system does essentially change at $\delta\omega/k_{1z}V=0.2$ in the case of synchronism between second and third waves with the fast-beam mode. The time interval for the start of explosive instability increases on the order of values. The process of nonlinear wave interaction with quasi-regular energy exchange between interacting modes is observed. But after this long time, the amplitudes of waves begin to grow explosively.

Thus, with addition of wave with positive energy in a three wave explosive interaction the dynamics of this interaction do essentially change. Similar significant change of dynamics takes place for three-wave interaction of waves with positive energy when a wave with negative energy is included into this interaction.

7-13

NONLINEAR ANALYSIS OF MM WAVES EXCITATION BY HIGH–CURRENT REB IN DIELECTRIC RESONATOR

K.V. Galaydych[1], Yu.F. Lonin[1], A.G. Ponomarev[1], Yu.V. Prokopenko[2], G.V. Sotnikov[1]

[1]NSC "Kharkov institute physics and technology", NAS of Ukraine, Kharkov, Ukraine
[2]Usikov Institute of Radiophysics and Electronics, NAS of Ukraine, Kharkov, Ukraine

A nonlinear self-consistent theory of excitation of millimeter wave lengths electromagnetic fields by high current relativistic electron beam in cylindrical resonator with a dielectric rod is constructed. For generation of high frequency waves is used an azimuthally-modulated electron beam. Excited fields are presented in the form of a superposition of a solenoidal field and a potential one. Solenoidal electromagnetic field is presented by an expansion of the required fields into solenoidal field of the empty dielectric resonator. A potential field is presented by the eigenfunction expansion method. For an excited field the analytical expressions, that take into account both longitudinal and transverse dynamics of beam particles are derived. Along with the equations of motion they provide a self-consistent description of the dynamics of generated fields and electron beam. The formulated nonlinear theory has allowed investigating numerically the nonlinear analysis of mm waves excitation by relativistic electron beam in dielectric resonator. Numerical simulations were carried out for the parameters of the experiment [1]. The results of numerical studies show that the main contribution in stored energy of the resonator brings the high frequency mode which azimuthal index coincides with modulation number (number of microbeams) of the electron beam. The symmetric azimuthal mode is significantly less than this high frequency mode.

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7-14

ACCELERATION AND STABILITY OF HIGH-CURRENT ION BEAM IN INDUCTION FIELDS

V.I.Karas', O.V.Manuilenko, V.P. Tarakanov, O.V.Fedorovskaya

National Science Center Kharkov Institute of Physics & Technology, NASU, Akademicheskaya street,1, Kharkov, 61108, Ukraine E-mail: ***karas@kipt.kharkov.ua***

[1]*Joint Institute for High Temperatures, RAS, Moscow, 125412,Russia*

In report 1D nonlinear analytic theory of high-current ion beam filamentation is formulated. The 2D3V particle-in-cell simulation results of hollow compensated ion beam (CIB) acceleration and stability dynamics in linear induction linac are presented. It is shown, that additional transverse injection of the electron beams in magnetoisolated gaps (cusps) improves the ion beam quality and provides his uniform acceleration all along the accelerator length. CIB filamentation instability in the absence and in the presence of external magnetic field is considered.

One of the most promising methods of obtaining high-current ion beams for heavy ion fusion (HIF) is the application of linear induction accelerators (LIA). The proposed method in NSC KIPT collective focusing of high-current ion beam [1] allows a more compact accelerator, which is, to be not only an effective driver for HIF, but also many technological applications. Using the cusp magnetic field leads to the isolation of accelerating gaps, without requiring additional central conductor, which greatly simplifies the design. The mechanism of bulk charge neutralization of the ion beam with an electron in an axially symmetric accelerating gap imposes on the parameters of the latter the following conditions: electron beam energy of the particles ε0 must be greater than the energy expended to overcome the potential barrier of the accelerating gap and significantly less than the energy required for electrons to overcome the magnetic isolation. For ion beam compensation were additionally injected electron beams in the second, fourth and sixth cusps [2]. These beams are optimized so that their density in the place of meeting with the CIB was almost equal to its density. It was also used to optimize injection time and place so that the fronts of additional beams met with the front of the CIB in the same time points in each cusp, where there is the additional injection of electron beams. In such conditions, the ion beam, while maintaining a high current (beam current ~ 50 kA), gaining energy uniformly along the length of the accelerator, while maintaining high brightness.

For non-relativistic infinite plane charged particles beam in the long-order approximation, and neglecting the effect of inhibiting the induction field, excited at the development of filamentation in the absence of an external longitudinal magnetic field and collisions in the system, filamentation is described a system of two nonlinear equations. Hodograph transform of this equations system is reduced to a system of two linear equations, analytical solution is obtained. It is shown that the compression of the filaments is more rapid exponential, and for a finite time could be attained, the spatial period of perturbations at the development of beam filamentation in a dense plasma is maintained at all times. For the numerical study of filamentation instability used 3-dimensional code KARAT. KARAT is fully relativistic electromagnetic code based on the PiC-method (Particle-in-Cell). The code KARAT Maxwell's equations are solved using finite-difference, and for material equations PiC method. It is shown that in the absence of an external magnetic field, the CIB has significant own fields, leading to instability. It was established that the external longitudinal magnetic field exerts a stabilizing effect on the electron and ion beams.

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7-15

MEASUREMENTS OF PLASMA DENSITY PRODUCED AT PASSAGE OF A SEQUENCE OF RELATIVISTIC ELECTRON BUNCHES THROUGH THE NEUTRAL GAS

V.A. Kiselev, A.F. Linnik, I.N. Onishchenko, V.I. Pristupa, B.I. Ivanov, V.P. Prishchepov.

NSC Kharkov Institute of Physics and Technology, Kharkov, Ukraine

For investigations of wakefield excitation by a sequence of relativistic electron bunches in plasma produced by their passage through the neutral gas the measurements of the density of obtained weakly ionized plasma is an important problem. To obtain so-called "resonant" plasma (plasma frequency is equal to bunch repetition frequency) for relativistic energy of bunches we should use neutral gas at high pressure because of small cross-section of collision ionization, that results in high collision frequency of plasma electrons with neutrals. Among the known non-contact methods of high-frequency plasma diagnostics for measuring plasma density under such conditions the most suitable method is using an open cylindrical or barrel-shaped resonator [1]. Open symmetrical barrel-shaped resonator with a distributed coupling system operating in the 8-mm wavelength range is presented for plasma density determination. It was shown that for ejection of a sequence of bunches of relativistic electrons with energy of 4.5 MeV in open atmosphere the density of produced plasma was $3 \cdot 10^{10}$ cm^{-3}. When the plasma was produced in a cylindrical resonator filled with air at atmospheric pressure the plasma density was increased to 10^{11} cm^{-3}. Plasma density increase is conditioned by additional ionization in the wakefield, which amplitude measured by high-frequency probe was higher by order in the resonator case.

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7-16

ACCELERATION AND FOCUSING OF ELECTRON BUNCHES BY WAKEFIELDS IN PLASMA PRODUCED IN NEUTRAL GAS BY A NONRESONANT SEQUENCE OF BUNCHES

V.A. Kiselev, A.F. Linnik, V.I.Maslov, I.N. Onishchenko, V.I. Pristupa, I.P.Yarovaya

NSC Kharkov Institute of Physics and Technology, Kharkov, Ukraine

Experimental results on wakefield excitation by a sequence of relativistic electron bunches in plasma produced at their passage through neutral gas are presented for the "nonresonant" case, when the bunch repetition frequency does not coincide with the plasma frequency. The processes of acceleration and focusing of a certain part of bunches the same sequence, which are shifted in the corresponding phases due to the frequencies difference. Such difference appears when the pressure of neutral gas is changed, that leads to the change of produced plasma density. Magnetic analyzer with registration of energy spectrum by means of bunches imprints on glass plates mounted on the sidewall of the chamber shows the presence of both bunches which lose energy on wakefield excitation and ones which are accelerated in this wakefield. Their ratio and the characteritics of energy spectrum is depended on the frequency difference arisen at gas pressure changing. Focusing/defocusing of bunches was determined by their transverse dimensions observed on bunches imprints on glass plates. It was shown that there are two groups of bunches – a) focused bunches that give strong darkening of the central part of the imprint and b) defocused ones that form a halo on the imprint of much larger diameter than the diameter of the initial bunches. The ratio between these groups depends on the frequency difference. Due to the finite size of Faraday cup diameter we observed the gaps of measured beam current, that indicates the defocusing of bunches and their incomplete hit into the Faraday cup. By the depth of the beam current gaps we can estimate bunch electrons scattering by the transversal component of wakefield, which allows estimating wakefield amplitude.

7-17

ACCELERATION OF THE SHORT HIGH-CURRENT COMPENSATED ION BUNCHES IN THE PEAKED FENCE MAGNETIC FIELD WITH ADDITIONAL SPACE CHARGE COMPENSATION BY THERMAL ELECTRONS: 2D3V PIC SIMULATION

O.V.Manuilenko

NSC «Kharkov Institute of Physics and Technology»
e-mail: ovm@kipt.kharkov.ua

The transport and acceleration of the hollow high-current ion beam which is compensated by electron beam in 1-6 magnetoinsulated accelerating gaps have been studied in [1-5]. It was shown that the injection of additional high-current electron beams in cusps leads to increase of accelerated ion beam monochromaticity and to reduction it divergency. In the present work the particle in cell simulation results, within the limits of the complete set of the Maxwell-Vlasov equations, of the short high-current compensated tubular ion bunches transportation and acceleration in the peaked fence magnetic field are presented. The ion bunch current, at injection in the cusp, is compensated by electrons. It is shown that additional compensation of the accelerated ion bunch space charge by thermal electrons leads to reduction of its energy dispersion and divergence on an exit from the cusp. It is shown also that overcompensation of the ion bunch space charge by thermal electrons leads not only to increase of energy spread and divergence of an ion bunch on an exit from the cusp, but also to deceleration of an ion bunch.

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7-18

WAKEFIELD EXCITATION IN PLASMA BY SEQUENCE OF SHAPED ELECTRON BUNCHES

V.I.Maslov, I.N.Onishchenko, I.P.Yarovaya[1]

NSC Kharkov Institute of Physics & Technology, 61108 Kharkov, Ukraine
[1] Karazin Kharkov National University, Kharkov, 61108, Ukraine

The transformation ratio, defined as ratio $T_E=E_2/E_1$ of the wakefield E_2, which is excited in plasma by sequence of the electron bunches, to the field E_1, in which an electron bunch is decelerated, is considered with charge shaping along each bunch according to linear law. In [1] the transformation ratio increase is investigated in linear and nonlinear cases at charge shaping according to linear law along sequence as well as along each bunch. The bunch length equals to nonlinear wave-length $\Delta\xi_b=\lambda$. The porosity between bunches also equals $\delta\xi=\lambda$. Then $T_E>2\pi N$ can be derived, N is the number of bunches. In this paper it is shown that this large transformation ratio can be eachived also for other length of bunches $\Delta\xi_b=\lambda$, 2λ, .. and for other porosity between them $\delta\xi=\lambda$, 2λ, ...

Also the optimized infinite sequence of the electron bunches – drivers, the charge in which is distributed according to truncated (without spout) triangles, and bunches – witnesses at $T_E\approx 2\pi N$ has veen derived using 2.5D code LCODE [2].

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7-19

NUMERICAL SIMULATION OF PLASMA WAKEFIELD EXCITATION BY A SEQUENCE OF LASER PULSES

V.I.Maslov, I.N.Onishchenko, O.M.Svistun

NSC Kharkov Institute of Physics & Technology, 61108 Kharkov, Ukraine

vmaslov@kipt.kharkov.ua

The intense plasma wakefield excitation by a single intense laser pulse has allowed to other authors to achieve large accelerating field. At excitation of the wakefield by one intensive laser pulse two bubbles are formed at certain conditions after it and an electron bunch is accelerated in each of them. I.e. an intensive laser pulse can form a sequence of twoaccelerated electron bunches. Also after these two bubbles wake is excited. Hence it would be useful to enhance this wake and to use it for the electron bunch acceleration for current increase of accelerated electron beam. I.e. the question arises about possibility of wakefield excitation by sequence of laser pulses. To address this question the authors of this material study by numerical simulation, using fully relativistic electromagnetic PIC code-UMKA2D3V, self - consistent effect of three short laser pulses on the uniform plasma. It is shown that, if laser pulses are located through one bubble, pulses stabilize positions of the field steepening and bunch of the accelerated electrons is formed only by the last pulse. If laser impulses are located through two bubbles, after every pulse the electron bunch is accelerated. Thus, as every second field steepening is stabilized by a laser pulse, the second electron bunches after every pulse are not formed unlike the case of one pulse or they are nonmonoenergetical beams. Thus, although bubble after the last pulse is excited with a time delay relatively to first bubble, the accelerated bunches in the first and last bubbles can be formed approximately simultaneously, as amplitudes of bubbles grow along the sequence.

For this number of bunches the coherent addition of excited wakefields has been shown.

7-20

ELECTRON ENERGY INCREASE IN STOCHASTICALLY GIVEN FIELD AND GAS DISCHARGE

V. Ostroushko

NSC "Kharkov Institute of Physics and Technology" NASU, Kharkov, Ukraine

Recently the versatile investigations of low-pressure microwave gas discharge in non-sinusoidal field are carried out [1]. To explain the found phenomena it is paid attention to jumps of phase. As the theoretical base it is used the paper [2], in which the action of stochastic field on plasma is considered and some relationships for time evolution of plasma characteristic are obtained. The aim of the present report is to clarify the possibilities of application of the paper [2] results to gas discharge.

In [2], it is obtained electrons energy increase in stochastically given field. In linear approximation, it is found the perturbation of distribution function in the field of waves, and the slow evolution of relevant characteristics is obtained with use of averaging over realizations of stochastic process. With taking into account the connection between correlation function and power spectral density, the obtained relationships show that the rate of system slow evolution is determined by power spectral density at resonant frequencies. It is characteristic for systems without dissipation, in which at external force frequency corresponding to resonant one the amplitude of oscillation increases. And if the Fourier transform of correlation coefficient has the frequency dependence used in the paper [2], then at any frequency (in particular, at resonant ones) there is nonzero power, and just it is the cause of electron energy increase. Such frequency dependence is characteristic for different stochastic processes, not only for one consisting of piecewise sinusoid with jumps of phase, and the obtained in [2] electron energy increase takes place in each stochastic process having nonzero value of Fourier transform of correlation coefficient of the electric field strength at resonant frequency. It may be presented the examples of such processes and the examples of similar processes modified so, that their dependence gives zero value at resonant frequency and the phenomenon of electron energy increase disappears. So, heating of plasma by random field may be explained by transition of some power to resonant frequencies.

Simple consideration of one-dimensional motion of single electron in the varying field shows, that electron displacement before achievement of required energy is minimal in the case when electric field strength is unidirectional and maximum possible. Fortuitousness gives intervals of prolonged one-way electron acceleration with formal absence of constant field, but accelerating electron to achieve required energy, it is inexpedient to reverse field direction ahead of goal attainment. On the other hand, a quick change of field is a possible mean to redistribute some power to resonant frequencies and to ensure electron energy increase, as it is described in the paper [2].

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7-21

INCREASING THE EFFICIENCY OF HF AZIMUTHAL SURFACE WAVE EXCITATION BY ANNULAR ELECTRON BEAM IN PLASMA WAVEGUIDE WITH NONCIRCULAR INTERFACE OF PLASMA COLUMN

I.O. Girka, V.O. Girka, I.V. Pavlenko
V.N. Karazin Kharkiv National University, Svobody Sq.4, 61022, Kharkiv, Ukraine

Extraordinary polarized electromagnetic perturbations of surface type (with E_r, E_φ, B_z components of electromagnetic field) are known to propagate across the axis of circular-cross-section cylindrical metal waveguides filled partially by cold collisionless plasma [1].

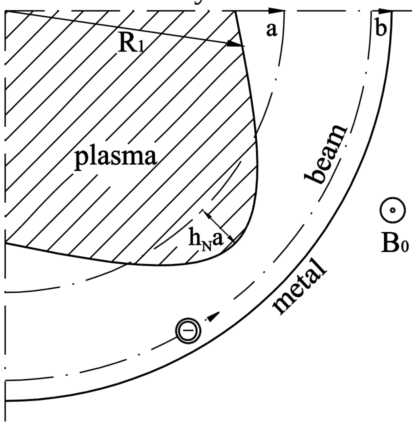

Fig. 1. Schematic of the plasma-beam system

These waves were entitled to as Azimuthal Surface Waves (ASW). In the case of high density plasma column, $\Omega_e>|\omega_e|$ (here Ω_e and ω_e are Langmuir and electron cyclotron frequencies respectively), the ASW can propagate in two frequency ranges: nearby the electron cyclotron frequency and over the upper hybrid frequency. In the second frequency range that is called as High Frequency (HF) range the ASW propagate only with negative azimuthal wave numbers $m<0$. The HF ASW are shown to be efficiently excited by annular flow of electrons rotating along Larmor orbits in the gap that separates plasma column from the metal wall [2]. The beam is described by the model of oscillators' flow [3].

Multicomponent hybrid plasma waveguides are well-known to be used in the devices of plasma electronics. Dispersion properties of ASW can be modified by making the cross-section of the plasma column different from a circular shape [4], e.g. $R_1=a(1+h_N\cos(N\varphi))$, see Fig. 1.

Possibility of increasing the HF ASW growth rates due to resonant beam-plasma interaction by applying an appropriate shape of the plasma cross-section is shown in this paper. The results of numerical studying the initial stage of beam-wave interaction are demonstrated in Fig. 2. Parameters of the plasma-beam system are as follows: m=–2, $\Omega_e/|\omega_e|$=3.5, $b–a$=0.2a, n_{beam}=0.01n_{plasma}, h_N=0.1, N=1,2,16. Dashed line shows the ASW growth rates in the case h_N =0 multiplied by 10^3.

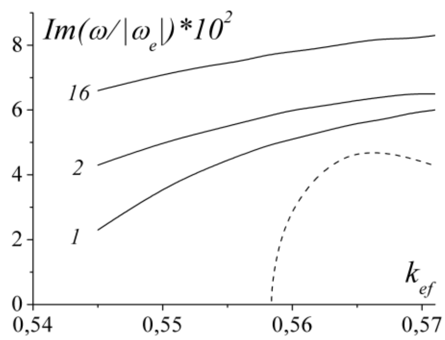

Fig. 2. HF ASW growth rates vs $k_{ef}=|m|c/(\Omega_e a)$

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7-22

BEAM RESONANT INSTABILITY OF LOW FREQUENCY AZIMUTHAL SURFACE WAVES IN CYLINDRICAL WAVEGUIDES WITH NONCIRCULAR PLASMA INTERFACE

I.O. Girka, Ia.I. Morgal

V.N. Karazin Kharkiv National University, Svobody Sq.4, 61022, Kharkiv, Ukraine

Electromagnetic perturbations of extraordinary polarization (with E_r, E_φ, B_z components of the field) can propagate across the axis of circular-cross-section cylindrical metal waveguides filled partially by cold collisionless plasma in the form of surface type waves [1]. These waves are called as Azimuthal Surface Waves (ASW). In the case of dense plasma, $\Omega_e>|\omega_e|$ (here Ω_e and ω_e are Langmuir and electron cyclotron frequencies respectively), the ASW can propagate in two frequency ranges, in particular, nearby the electron cyclotron frequency. This frequency range is referred as Low Frequency (LF) one. The LF ASW are shown to be efficiently excited by annular flow of electrons rotating along Larmor orbits in the gap that separates plasma column from the metal wall [2]. The beam is described by the model of oscillators' flow [3]. Note that application of annular beam gives a possibility to develop more compact electronic devices with higher efficiency than in the case of longitudinal beams.

Multicomponent hybrid plasma waveguides are well-known to be used in the devices of plasma electronics. Dispersion properties of LF ASW can be controlled by making the cross-section of the plasma column different from a circular shape [4], e.g. $R_1=a(1+h_N\cos(N\varphi))$. In this case we do not deal with the case $N=2|m|$, in which deviation of plasma interface from circular shape causes greater influence on LF ASW dispersion properties.

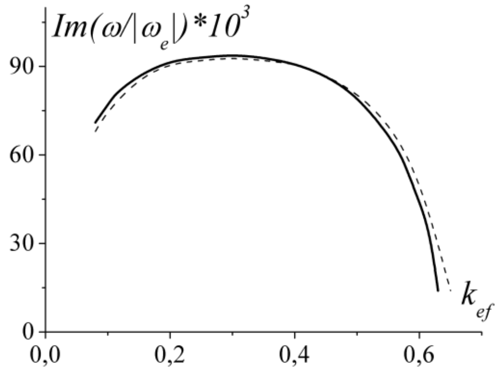

Fig. LF ASW growth rates vs $k_{ef}=|m|c/(\Omega_e a)$

Possibility of the LF ASW excitation by annular electron beam in plasma waveguides with noncircular plasma interface is shown in this paper. The results of numerical studying the initial stage of beam-wave interaction are demonstrated in Fig. Parameters of the plasma-beam system are as follows: $m=-2$, $\Omega_e/|\omega_e|=8$, $b-a=0.1a$, $n_{beam}=10^{-3}n_{plasma}$, $h_N=0.05$, $N=1$. Dashed line shows the LF ASW growth rates in the case $h_N=0$. Application of noncircular plasma interface does not affect drastically the absolute value of growth rate but shifts the range of effective wave numbers k_{ef} for which efficient excitation of LF ASW is observed to smaller values of k_{ef} (to greater values of b and n_{plasma}).

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7-23

ABOUT FEATURES OF ELECTROMAGNETIC FIELD AT DISCRETE CHANGE OF THE VELOCITY FOR THE POINT CHARGE PARTICLE

S. D. Prijmenko

Institute for Plasma Electronics and New Methods of Acceleration, National Science Center. "Kharkov Institute of Physics and Technology", 1 Akademicheskya Sr., Kharkov, 61108, Ukraine, sprijmenko@kipt.kharkov.ua

The electromagnetic field formation at discrete change of the velocity for the point charge particle with the use of the Lienard-Wiechert potentials is considered. Scattering angles are arbitrary, and the velocity varies in the arbitrary range as on magnitude and a direction. Expressions for scalar and vector potentials, electric and magnetic field strengths, and also the energy flux of an electromagnetic field in the Fresnel and Fraunhofer zones are derived. Formulas in the unitary form describe an electromagnetic field before the dispersion, at the instant of the dispersion and after the dispersion.

The front is created through a discrete change of a velocity at the instant of the dispersion. On the front scalar and vector potentials have a discontinuity of the first kind. The electromagnetic field strength represents the wave packet consisting of waves with step, delta-shaped and truncated delta-shaped wave fronts. Wave with step front to one side of and waves with delta-shaped and truncated delta-shaped fronts on the other hand have space dependence inversely proportional to the square and to the first degree of distance from a source point to an observation point.

Components of an electric field strength with step and delta-shaped fronts are dictated by scalar and vector potentials, i.e. include potential and rotational components, and the component with truncated delta-shaped wave front is dictated by only vector potential. Presence of the potential electric field strength comparable to the value of the rotational electric field strength in the Fraunhofer zone or a wave zone is seted.

It is shown that in the presence of the potential electric field strength the conservation law of the energy has the form

$$div(\varphi\varepsilon_0(\partial\vec{E}/\partial t)) + div[\vec{H}\times(\partial\vec{A}/\partial t)] + \varepsilon_0\vec{E}\cdot(\partial\vec{E}/\partial t) + \mu_0\vec{H}\cdot(\partial\vec{H}/\partial t) = -\vec{E}\cdot\vec{j}\,,$$

where ε_0 also μ_0 are dielectric and magnetic permeabilitis of the vacuum, φ and $\vec{A}$ are scalar and vector potentials, $\vec{E}$ and $\vec{H}$ are electric and magnetic field strengths, $\vec{j}$ and t are a current density and a time accordingly. The energy flux of an electromagnetic field includes of two components. To the first component $div(\varphi\varepsilon_0(\partial\vec{E}/\partial t))$ the potential energy flux conform to mainly. This flux is proportional to the product of a scalar potential on a current density of the displacement and is directed on a displacement current. The asymmetrical delta-shaped wave front corresponds to this flux. The second component $div[\vec{H}\times(\partial\vec{A}/\partial t)]$ is dictated by a vector product of a magnetic field strength on the electric field strength, related to a vector potential. This component is formed by a transversal electromagnetic wave.

Calculation results of the electromagnetic field strength in the space-time and space-frequency areas are presented. Components of the electric and magnetic field strengths with the step front have significantly distinct low frequency spectral density. Components of the strengths with the delta-shaped front have constant spectral density. Directivity diagrams of the energy flux for the electromagnetic field, corresponding potential and rotational components of the electric field are calculated.

8-01

THE RESEARCH OF DOUBLE-PULSE DISCHARGE IN A PLASMA-LIQUID SYSTEM WITH CYLINDRICAL GEOMETRY

Valeriy Chernyak[1], Sergij Sidoruk[1], Vitalij Yukhymenko[1], Marchuk V.Ef.[2], Evgen Martysh[1], Oleg Fedorovich[3]

[1] Taras Shevchenko Kyiv National University, chernyak_v@ukr.net

[2]PAS "KVAZAR", Kiev, Ukraine

[3]Institute of Nuclear Research, National Academy of Sciences of Ukraine, Kiev, Ukraine

The results of acoustic signals generation by two consistent dischargers of microsecond duration in a cylindrical liquid system are presented. The radius/height ratio of the cylinder, made of stainless steel, is ~ 13.5. Both discharges occur between two electrodes located on the cylinder axis. Height / interelectrode distance ratio of the cylinder is ~ 3. The delay time between the discharges has been regulated and changed in a broad spectrum: from the moment of the first diverging acoustic wave arrival, generated in the water by the first discharge on the metal side wall before the axial collapse completion time of the cylindrical converging wave reflected from the wall. The energy in the storage capacitors varied in the range of 1 - 100 J. The switches were: the air discharger for the first discharge and hydrogen thyratron for the second one.

8-02

PARTICULARITIES OF THE NEGATIVE STREAMER PROPAGATION IN HOMOGENEOUS AND INHOMOGENEOUS ELECTRIC FIELDS. COMPUTER SIMULATION

O.V. Manuilenko[1], V.I.Golota

NSC «Kharkov Institute of Physics and Technology»
e-mail: ovm@kipt.kharkov.ua

The paper presents the results of numerical simulations the propagation of a negative streamer in nitrogen in the plane - plane and the needle - plane geometries. Computer simulations has been performed by finite element method, which allows to accurately describe the boundaries of complicated shape. It is shown that the propagation velocity of the negative streamer in a nonuniform electric field (the needle - plane geometry) is always greater than its velocity in a uniform field (the plane - plane geometry) at the same potentials on the electrodes. It is shown that the behavior of the streamer velocity versus time has four specific areas: (1) a sharp drop at the beginning of the movement, (2) propagation with a constant velocity, (3) the area of the first (weak) acceleration, and (4) the area of the second (strong) acceleration at the approach of the streamer head to the anode. It is shown that with decreasing curvature radius of the needle the streamer propagation velocity increases. The growth of the streamer speed, with decreasing of the needle curvature radius, is stopped when the needle curvature radius reaches a certain critical size. It is shown that in the region of the strong nonlinearity, when the dynamics of the streamer propagation is determined by the space charge, its velocity as a function of the longitudinal coordinate is independent of the needle curvature radius.

8-03

TREATMENT OF POLYIMIDE FILMS IN PLASMA OF CAPACITIVE RF DISCHARGE AT ATMOSPPHERIC PRESSURE FOR LIQUID CRYSTAL ALIGNMENT

[1]Bazhenov V.Yu., [1]Kravchuk R.M, [2]Kuzmichev A.I., [1]Tsiolko V.V., [1]Piun V.M., [2]Chaplinskiy R.Yu., [1]Yaroschuk O.V.

[1]Institute of Physics NAS of Ukraine, [2]National Technical University of Ukraine "KPI"

Increase of dimension and resolution of liquid crystal (LC) displays imposes strict requirements to their manufacturing technology. Essential stage in LC display manufacturing consists in formation of surface force anisotropy at alignment surfaces of glass plates contained in sandwich-like display structure. Most often, alignment layers are formed by mechanical rubbing of polyimide film deposited on the glass plate surface. However, stochastic distribution of velvet threads in the rubbing device leads to formation of defects in uniform distribution of surface forces and to decrease of the display quality. Promising methods of LC alignment are: aligning layer deposition from gas phase, photo-alignment, and treatment of aligning surfaces by ion and plasma beams in vacuum [1]. In spite of obvious advantages of the last method [2], it is more complicated and expensive for commercial application, as compared to rubbing method. More promising is the application of plasma flows at atmospheric pressure for creation of the alignment layers [3].

Goal of the present paper is experimental study of the process of aligning layer formation at polyimide film surface under action of non-thermal argon plasma flow from capacitive RF discharge at atmospheric pressure.

For realization of the goal, the reactor for creation of extended flat plasma flow was constructed on a basis of flat capacitive RF discharge geometry. Copper electrodes were separated from the discharge gap by Polycor (Al_2O_3) substrates having 60 x 54 mm dimensions and 1 mm thickness. Discharge gap thickness was 1 mm. Working gas (argon) was supplied to the reactor through 22 holes, each having 0,8 mm diameter. The system for powering the reactor consisted from 13,56 MHz RF generator, two matching circuits, low-frequency (3 kHz) high-voltage module for the discharge ignition, and module for decoupling the circuits with different frequencies.

In result of performed experiments, optimum geometrical and electrical parameters of the setup were determined, as well as the conditions of sample treatment by RF discharge plasma flow for obtaining LC alignment on polyimide layers. It was found that, depending on duration of the plasma treatment, LC alignment is possible in two modes – either along, or perpendicularly to the treatment direction.

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8-04

PROPERTIES OF THE PULSED PLASMA-LIQUID SYSTEMS WITH ACOUSTIC WAVES FOCUSING

Sidoruk S.M.[1], Yukhymenko V.V.[1], Chernyak V.Ya.[1], Marchuk V.E.[2], Gavrylyuk E.Yu.[1], Martysh E.V.[1], O.A. Fedorovich[3]

[1]Taras Shevchenko Kyiv National University, Radio Physics department, prosp.Glushkova, 4G, 03122, Kyiv, Ukraine, e-mail: mstquevshoke@ukr.net
[2]PAS "KVAZAR", Kyiv, Ukraine
[3]Institute of Nuclear Research, National Academy of Sciences of Ukraine, Kyiv, Ukraine

The pulsed plasma-liquid system that allows to generate non-isothermal plasma at high values of discharge voltage and current, and focused acoustic waves, creating by the axial electric discharge, after reflection from the inner cylindrical surface of the metal was observed in this paper.

The convergent acoustic waves generation efficiency in such systems was shown. The influence of the discharge current and acoustic signal amplitude from the capacitor energy rise by increasing capacity and by increasing the charging voltage value was investigated. The transition of the discharge current in the saturation mode with increasing charging voltage to 50 kV at constant capacity was observed. The effect of plasma pulse generation with frequencies 15 and 100 Hz at amplitude of the acoustic signal in pulsed plasma-liquid system was investigated.

The influence of water plasma-chemical treatment in the pulse plasma-liquid system at pH value was investigated and it was found H^+ ions increasing by almost two orders of magnitude. In addition, the efficiency of phenol aqueous solution different molar concentrations destruction in pulsed plasma-liquid system was investigated and it was show the advance of destruction efficiency in this system compared with similar DC systems.

8-05

THE OBTAINING AND PROPERTIES INVESTIGATION OF PLASMA FORMATION AT PULSE DISCHARGE IN WATER AEROSOL

V.V. Iukhymenko[1], I.I. Fedirchyk[1], V.Ya. Chernyak[1], E.V. Martysh[1],
O.A. Fedorovich[2], T.E. Lisitchenko[1], N.V. Belenok[3]

[1]Taras Shevchenko Kyiv National University, Faculty of Radio Physics, Prospect Acad. Glushkova 4G, Kyiv 03022, Ukraine, e-mail: yvitaliy@ukr.net;
[2]Institute for Nuclear Research, Ukrainian Academy of Sciences, Prosp. Nauki 47, Kyiv 03680, Ukraine
[3]National Technical University of Ukraine "Kyiv Polytechnical Institute", Prosp. Peremogy 37, Kyiv 03056, Ukraine

Study of the pulse discharge in various environments is the one of the priorities research in modern plasmachemistry. One of these systems is pulsed discharge in water aerosols. Impulse discharge in water aerosol is often observed in experiments with electric discharge on air-liquid border due to dispersion of liquid drops. Other applications of aerosol discharge are fuel efficiency improvement and natural long-life plasmoid research. The observation of this phenomenon suggests the existence of a mechanism of energy storage in aerosol drops during discharge. This type of discharge is promising for use in the process of fuel reforming to improve combustion efficiency

Aerosol source consists of fluoroplastic cylindrical vessel filled with water, a piezoceramic emitter connected to ultrasonic generator and an air compressor. The vessel is covered by plastic lid with a cone-shaped air nozzle in the centre. The vibrations of the emitter are causing creation of a water fountain under the nozzle from which the small water drops are scattered into the air and form aerosol. The air flow is blowing out aerosol through the nozzle to the discharge area.

The discharge is caused by reservoir capacitor charged with a high-voltage generator. Between a capacitor and narrow copper electrodes was an air gap. Two different capacitors were used: one with capacity 15 nF charged to 19,5 kV and one with 2 μF charged to 14 kV, which resulted in ~ 3 and ~ 200 J of stored energy respectfully.

The discharge current was measured by a Rogowski loop. The current and voltage were measured by digital oscilloscope (Metrix MTX1054). The discharge area was filmed with a digital camera with frame rate of 30 frames-per-second.

The common values of discharge current and voltage were 5,5 kA and 13 kV. Analysis of obtained results showed an existence of moving glowing particles on times considerably bigger (~100 ms) than duration of the discharge (~100 μs).

Integral emission spectrum of the discharge was captured by photo-electric multiplier. The duration of glowing in discharge area was in a few times longer then the duration of discharge current impulse.

Research are showed that the impulse electric discharge in aerosol with energy close to 200 J leads to volumetric process with changed spectrum and generation of plasmoids which have lifetimes of >100 ms without support of discharge.

8-06

REFORMING OF BIOETHANOL IN THE SYSTEM WITH REVERSE VORTEX AIR/CO_2 FLOW OF "TORNADO" TYPE WITH LIQUID ELECTRODE

O.A. Nedybaliuk[1], Ol.V. Solomenko[1], V.Ya. Chernyak[1], E.V. Martysh[1], T.E. Lisitchenko[1], L.V. Simonchik[2], A.I. Liptuga[3], N.V. Belenok[4]

[1]*Taras Shevchenko National University, Faculty of Radio Physics, Prospect Acad. Glushkova 4G, Kyiv, 03022, Ukraine*
[2] *B.I. Stepanov Institute of Physics, National Academy of Sciences, Minsk, Belorusssia*
[3] *V.E. Lashkaryov Institute of Semiconductor Physics, National Academy of Science of Ukraine, Prospect Nauki 41, Kyiv, 03028, Ukraine*
[4]*National Technical University of Ukraine "Kyiv Polytechnic Institute", Prospect Peremogy 37, Kiev 03056, Ukraine*

In this paper we studied the reforming of bioethanol using the combined system that includes a plasma processing and handling in the pyrolysis chamber. As the plasma source was used plasma-liquid system with back-vortex flow of gas (a mixture of air and CO_2) and liquid electrode. Carbon dioxide was added in reforming the system to influence the plasma-chemical processes in the conversion of hydrocarbons. As the working fluid were used distilled water and ethanol solution in distilled water (ratio C_2H_5OH/H_2O = 1/9,5). The working gas used was a mixture of air with CO_2 in a wide range of relations. The system was investigated by emission spectroscopy, current-voltage characteristics, gas chromatography, mass spectroscopy and absorption of infrared radiation. In the emission spectra revealed that the plasma of the interelectrode gap contains components such as atoms H, O, C, and the molecules OH, NH, CN. It was found that increasing the amount of CO_2 in the working gas leads to an increase in the concentration of oxygen and hydrogen in the plasma, the concentration of molecules does not change within the error limits. The temperatures of the excited electron population of T_e^*, T_v^* of the vibrational and rotational levels of T_r^* components of the plasma as well as the relative concentration of these components in the plasma were definited. The plasma is close to isothermal, temperature, component, within the error limits, are close in value. We also show that the addition of CO_2 into the working gas in the reforming of bioethanol increases the amount of hydrogen (H_2) in the exit gas.

8-07

PARTICLE CHARGING IN BEAM-PLASMA SYSTEMS

A.A. Bizyukov[1], E.V. Romashchenko[2], K.N. Sereda[1], S.N. Abolmasov[3]

[1]*V.N. Karazin Kharkiv National University, Svobody sq., 4, 61077, Kharkiv, Ukraine*
[2]*V.Dahl East Ukrainian National University, 20A, Bl. Molodyozhnyi, Lugansk 91034 , Ukraine*
[3]*LPICM, CNRS UMR 7647, Ecole Polytechnique, 91128 Palaiseau, France*

The generation of particles ranging in the size from several microns to a few hundred microns has been observed in many technological vacuum-plasma processes such as vacuum arc methods for depositing decorative and hardening coatings. The presence of particles in the plasma flow worsens the coating parameters. This is a serious detriment which must be avoided. In recent years it has become obvious that the presence of dust in plasmas does not always result in undesirable consequences. Current interest derives from the use of positively charged particles. Positive charge has useful implications for plasma processing, since particles are confined in a discharge only if they have a negative charge. For both these aspects, the avoidance of “bad” particles as well as the innovative use of “good” particles, a thorough understanding of the charge mechanism of particles in plasmas is required.

We propose a Fokker-Planck description of the charging of particle in a beam-plasma discharge. This model deals with the discrete nature of charging process. It is established that the sign and value of the grain charge play dominant role. It has been shown that injection of an electron beam into a dusty plasmas can significantly increase the negative potential of a dust grain at small values of secondary electron emission coefficients. This allows to raise the efficiency of plasma purification methods, namely evaporation and Rayleigh decay of macroparticles. In the range of beam electron energies at which the secondary electron emission coefficient is $\delta>1$, the grain charge can become positive. In this case particles will be expelled from plasma and will either strike the electrode.

8-08

MULTIFUNCTIONAL TiN COATINGS AND THEIR APPLICATIONS

V.M. Shulayev, V.S. Taran

NSC Kharkov Institute of Physics and Technology,
Akademicheskaya St., 1, 61108,Kharkov, Ukraine.
shulayev@kipt.kharkov.ua, vtaran@ipp.kharkov.ua

Nowadays the multi-functional films and coatings of titanium nitride are being prior ones among practically used strengthening, erosion- and corrosion-proof, decorative and other types coatings. These ones are the most commercialized films and coatings. These ones are manufactured by hundreds of companies and firms using decades of trade marks all over developed countries of the world. Technologies and equipment for their synthesis are widely industrially developed. The processes of titanium nitride coatings synthesis are ecologically clean. The coatings are chemically inert to environmental factors. For example, their usage as strengthening and decorative ones is economically based. The complete industrial branches on the basement of titanium nitride coatings have been formed; and new scientific directions of physics and technology as well.

8-09

CHARACTERISTICS OF DISCHARGE IN CROSSED EH FIELDS NEAR BREAKDOWN CURVE IN ACCELERATION AND PLASMA REGIME

A. Jamirzoev, S.Yakovin, A. Zykov

V.N. Karazin Kharkiv National University, 31 Kurchatov Ave., Kharkiv 61108, Ukraine

E-mail: zykova.anya@gmail.com

In the present study the characteristics of discharge in crossed EH fields in acceleration and plasma regimes have been researched at low voltages near the breakdown curve. The new experimental data for current-voltage characteristic and their dependence on Argon pressure and magnetic fields strength are presented. It is shown that initial stage of the current-voltage characteristic in acceleration and plasma regime are quite similar and correspond to regime with “oscillating” electrons. The theoretic model based on the energy balance of electrons is presented as well as the comparison of the theory with the experiment.

The obtained results may be useful for further development of magnetron sputtering systems and plasma accelerators with closed electrons drift.

8-10

EFFECT OF THE PARAMETERS OF A GAS-DISCHARGE PLASMA ON THE EQUILIBRIUM TEMPERATURE AND FLOATING POTENTIAL OF MACROPARTICLE

A.A. Bizyukov[1], A.D. Chibisov[1], E.V. Romashchenko[2]

[1]*V.N. Karazin Kharkiv National University, Svobody sq., 4, 61077, Kharkiv, Ukraine*
[2]*V.Dahl East Ukrainian National University, 20A, Bl. Molodyozhnyi, Lugansk 91034 , Ukraine*

Macroparticles in gas-discharge plasma with high energy beams are charging due to different processes and as a result has some charge and corresponding floating potential. The main charge processes of macroparticle are flows of ions and electrons from plasma and beams as well as various types of emission at the surface of macroparticle [1-3]. Due to collisions with plasma and beam particles the energy transfer to a macroparticle and resulting heating also occurs. However, due to thermal radiation which cools macroparticle the temperature reaches a certain equilibrium value [1,4]. The value of floating potential as well as the equilibrium temperature is largely determined by the plasma parameters such as plasma density, electron and ion temperatures as well as beam energy.

The aim of this work is to study the effect of the plasma density as well as the energy of the electron and ion beams on the floating potential and the equilibrium temperature. It is shown that without energetic beams with increasing of plasma density to $5 \cdot 10^{12} cm^{-3}$ an intensive heating of macroparticlies up to temperatures of 2000-3000°K occurs due to increasing of the flows of ions and electrons. At such temperatures, the effect of thermionic emission becomes significant which leads to a sharp drop in the modulus of floating potential of macroparticly. In turn, this change of potential is the cause of a change in the flows of ions and electrons of plasma, and transferred their energy. Thus the self-consistent problem of determining the equilibrium temperature and the corresponding equilibrium potential is solved. Effect of energy of the electron and ion beams on a floating potential of macroparticlies and its equilibrium temperature is also investigated. The presence of high-energy electron beam is the cause of an increase in the equilibrium temperature of macroparticle already at plasma densities of the order $10^{9} cm^{-3}$ so that the effect of thermionic emission is a significant. This in turn leads to a modification of the floating potential of macroparticle. The presence of high-energy ion beam causes a decrease in the modulus of floating potential and change in the flows of ions and electrons of plasma as well as in equilibrium temperature of macroparticle.

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8-11

EXPERIMENTAL INVESTIGATION OF DISCHARGE FROM FLOATING CONDUCTIVE PARTICLES IN AIR

N. A. Bogatov

Institute of applied physics RAS, 46 Ul'yanov str., 603950 Nizhnii Novgorod, Russia

Gas discharge initiated by conductive particles in external electric field takes place in many natural and technological processes. Extensive known data on threshold and volt-ampere characteristics of discharges from electrodes can not be directly applied to isolated particles because of different electric field structure. This report is devoted to the experimental investigation of discharge (it may be corona or streamer breakdown) initiated by metal particles situated in a homogeneous electric field of flat gas gap. Threshold value of homogeneous electric field strength needed for discharge from particles igniting and the dependence of corona discharge current on electric field strength were measured for a wide set of particles of different forms and sizes. Some theoretical estimation is also presented.

8-12

SPECTROSCOPIC ANALYSIS OF THE ROTATIONAL STRUCTURE IN THE EMISSION SPECTRA OF THE CORONA DISCHARGE

O.V. Bolotov, V.I. Golota

NSC "Kharkov Institute of Physics and Technology",
Institute of plasma electronics and new methods of acceleration

Abstract

The emission spectra of the second positive nitrogen system for the corona discharge in ambient air at different burning regimes were obtained. The discharge emission spectra for positive streamer corona regime and negative corona diffuse regime were investigated. All spectra were registered from the active zone of the discharge at different applied voltages.

Rotational structure of spectral lines was analyzed and the spectra were identified. Distribution of emission intensity in electronic-vibration –rotational bands, corresponding to transition $C^3\Pi_u$ - $B^3\Pi_g$ of molecular nitrogen, was analyzed. The comparison between experimental data and theoretical calculations using the model of non-rigid rotor $E_j = B\cdot J\cdot\ J+1\ - D\cdot\left[J\cdot\ J+1\ \right]^2$ was carried out. On the basis of the analysis of rotational structure of spectral lines the rotational temperature of nitrogen molecules was specified. The dependence of the rotational temperature on the applied voltage as well as on the discharge burning regime was shown. It was shown, that the rotational temperature increases together with the applied voltage and the value of the rotational temperature at the negative corona diffuse regime is higher than at the positive streamer corona regime.

8-13

EXPERIMENTAL INVESTIGATION AND COMPUTER SIMULATION OF THE SPUTTERING MAGNETRON DEVICE WITH TWO EROSION ZONES

R.V. Bogdanov*, O.M. Kostiukevych**
Taras Shevchenko National University of Kyiv, Faculty of Radio Physics,
Prosp. Acad. Glushkova 2/5, Kyiv 03022, Ukraine
**e-mail: RSemsterFX@gmail.com*
*** e-mail: mirror@ukr.net*

The aim of this work is to build the computer model of the magnetron sputtering device for the needs of nanotechnology. The computer model of magnetron sputtering device with two erosion zones of cathode-target (which is the additional module for the industrial vacuum system ВУП-5), which based on the Monte Carlo algorithm was built. The main modeling results were confirmed in similar conditions on the real magnetron sputtering device.

Using the computer simulation, the data were obtained, which are difficult to get directly from experimental conditions. The practical applicability of the program lies on the prediction of energy parameters of ions that bombard the cathode-target, and their distribution on the surface of the cathode. This allows the prediction of the effectiveness of material sputtering in the appropriate surface zones of the cathode-target, which is important to analyze the process of deposition of coatings.

In the real experiments there was observed, that variation of discharge voltage within the limits that characteristic for this magnetron sputtering device, the effect of individual initiation of internal and external zone of discharge have taken place. This is typically for discharge currents up to I_d = 5-15 mA and for the corresponding voltages (the pressure of working gas Ar was near p = 1,33 Pa). At the higher pressures (p = 6,65 Pa) both discharge zones are usually ignited. The computer calculation by using of the developed simulation program has showed the similar regimes. From experimental measurements it was found, that the magnetic field with surface decreases in “*e”* times at increasing distance from the cathode at of about 3 mm in internal and 5 mm in external zone. If at low pressures the cathode plasma sheath is larger than 3 mm (for example), then the electron confinement by magnetic field in internal zone is less effective that in external zone, because the electrons in internal zone provides less number of ionizations if they can do before it left the cathode sheath.

The simulation shows, that with the relatively large width of the cathode sheath (d_E = 16 mm), corresponding to pressures of argon working gas p = 1,33 Pa, the most number of ionizations committed by electrons occurs in it. At a pressure p = 1,33 Pa, the energy, which the ions can to achieve, less than in case where they have been created outside the thin cathode sheath (d_E = 3,2 mm), that is typically for pressure p = 6,65 Pa. In regions where the tangential to the cathode magnetic field component is maximal, the elevation of electrons up the cathode is minimal, and energy that the ions can to reach in the accelerating electric field, is also minimal. However, in these areas should place the most effective magnetic confinement of electrons, which provides maximum number of ionization acts and, consequently, greatest intensity of the cathode-target erosion.

To check of the modeling results, there were made the test targets for this magnetron sputtering system, which were produced in it by the way of deposition of a copper coating on a thin non-magnetic stainless steel. If the zone of the discharge were ignited, the layer of copper on the test target under this zone was completely demolished after the time span 10-30 min.

At the second stage, the stainless steel target with the thin concentric isolated rings was made, which allowed the measuring of the parts of the distributed discharge current along of the target. These measurements also corresponded to simulation results.

8-14

THE EFFECT OF PLASMA TREATMENT OF DIFFERENT CATHODE MATERIALS ON CURRENT-VOLTAGE CHARACTERISTICS OF MIRROR PENNING DISCHARGE IN AIR

G.P. Glazunov, M.N. Bondarenko, F.L. Konotopskiy
Institute of Plasma Physics, National Science Center
“Kharkov Institute of Physics and Technology”, 61108 Kharkov, Ukraine
E mail: glazunov@ipp.kharkov.ua

The behavior of current-voltage characteristics (CVC) of mirror Penning discharges in air has been studied in dependence on cathode material. Such materials as stainless steel 12KH18N10T, copper, titanium, aluminium, tungsten were used as cathodes. The experiments were carried out in the DSM-1 device [1]. The pressure of work gas was $2{\cdot}10^{-3}$ Torr for all experiments. Discharge duration was 10-15 min., discharge voltage was in the range of 300-2000 V, discharge current changed from 5 to 100 mA. It was shown that the CVC behavior for such materials as Ti, Cu, W is typical for mirror Penning discharges. But if to use stainless steel or Al as cathodes it was observed the non-typical CVC behavior, namely, the drastic increase of discharge current after threshold value of discharge voltage. (Fig. 1). To ascertain the physical-chemical mechanisms of such effect the investigations has been carried out of the influence of plasma treatment in inert gases (helium, argon) on CVC of discharges with cathodes made of stainless steel. The analysis of the obtained data has shown that discharge current abrupt increasing could be caused with plasma-chemical reaction behavior on the cathode surface[2], which leads to cathode emission current and, consequently, discharge current increasing.

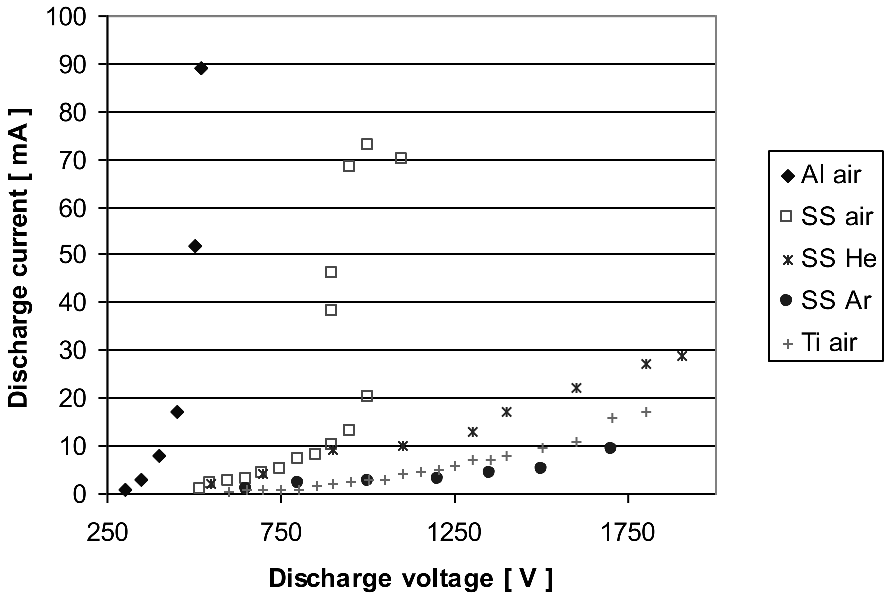

Fig. 1. Current-voltage characteristics of mirror Penning discharges.

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8-15

NON-EQUILIBRIUM PLASMA PROPERTIES OF ELECTRIC ARC DISCHARGE IN AIR BETWEEN COPPER ELECTRODES

V. Boretskij[2], A. Veklich[2], Y. Cressault[1], A. Gleizes[1], Ph. Teulet[1]

[1] *Université de Toulouse; UPS, INPT; LAPLACE (Laboratoire Plasma et Conversion d'Energie); 118 route de Narbonne, F-31062 Toulouse cedex 9, France*
[2] *Taras Shevchenko Kiev National University, Radio Physics Faculty, 64, Volodymirs'ka Str., Kiev, 0133, Ukraine*

In our previous investigation [1] the deviation from local thermodynamic equilibrium (LTE) of electric discharge plasma between copper electrodes in CO_2 flow at arc currents $\geq$ 30 A was shown. It was shown that the non-equilibrium thermal dissociation take place in such plasma. This paper is devoted to examine if any deviation from LTE take place for other plasma mixtures with molecular gases, namely, air – Cu.

The investigations of plasma parameters of free burning discharge as well as discharge in air flow of 4.79, 9.97 and 6.45 slpm between copper electrodes at arc currents 3.5, 30, 50 and 100 A were carried out by optical emission spectroscopy. Electrode assembly, optical scheme and experimental arrangement, which were used in experiments, are described in detail in [1]. Plasma temperatures were calculated by Boltzmann plot method using spectroscopic data from [2]. Electron densities were obtained from the absolute intensity of CuI 465.1 nm spectral line and width of CuI 448.0 nm spectral line using spectroscopic data from [3].

Experimentally obtained radial distributions of plasma temperature and electron density were used in calculation of plasma composition by special technique of calculation described in detail in [4]. By the results of calculation it was shown that plasma state is not in LTE in the central part of the discharge channel at arc current 100 A. As was early suggested [4] the main reason of plasma state deviation from LTE is nonequilibrium dissociation. The two-temperature technique to estimate composition of such nonequilibrium plasma was proposed in [1]. The results of such kind two-temperature calculation were used to obtain effective temperatures of N_2 molecule dissociation and plasma components concentrations in the case of non-LTE plasma. Experimental plasma compositions were used to calculate transport properties of such plasma. The method of this calculation is described in detail in [5].

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8-16

INFLUENCE OF EXTERNAL MAGNETIC FIELD ON INTENSITY AND DIRECTIVITY DIAGRAM OF EUV RADIATION FROM HIGH-CURRENT PULSE PLASMA DIODE

Ie.V. Borgun[1], N.A.Azarenkov[1], A. Hassanein[2], A.F. Tseluyko[1], V.I.Maslov[1], D.L.Ryabchikov[1], Y.Grechko[1]

[1] *Karazin Kharkiv National University, pl. Svobody 4, Kharkov 61077, Ukraine*

[2] *School of Nuclear Engineering, Purdue University, 400 Central Drive, West Lafayette, IN 47907-2017, USA*

E-mail: ievgeniia.borgun@mail.ru

The work is devoted to the reseach of additional methods of the control of the intensity and orientation of the extreme ultraviolet radiation from high-current pulse plasma diode. In this material the control by changing the current density at the anode as well as the influence of the additional external longitudinal magnetic field on the intensity and directivity diagram of the EUV radiation are investigated. The experiments are carried out with the longitudinal plasma diode in which the work cathode surface essentially more than the work anode surface. It leads to formation of the dense emitting plasma in the near anode region. The discharge is excited after filling of discharge gap by the primary plasma being ejected from the cathode side. The current density is 0.1-1.0 MA/cm^2. The discharge occurres in the tin vapor due to an evaporation of the electrode surface covered by tin. The magnetic field source is the permanent ring magnet. The maximum value of magnetic field is~840 O. It is set coaxially with the axis of the discharge. In the experiments the permanent magnet is shifted along axis to 3 positions, which correspond to the minimum, maximum values and an inversion point of magnetic field at the anode face. In the investigation in addition to the discharge characteristics the intensity of the radiation in 12.2-15.8 nm wavelength range is measured with help of two semiconductor detectors AXUV-20 being set longitudinal and transverse to the discharge axis. It is noted that with the additional external magnetic field the work stability of the high-current pulse diode increases and the energy expenditure for the primary plasma generation decreases.

The narrow spike pulses of radiation are observed in three half-periods of the discharge current oscillation. The radiation pulses have the different intensity and orientation coefficient for each oscillation half-period. The orientation coefficient is ratio of the longitudinal radiation intensity to transverse radiation intensity ($I_{long}/I_{tran} <1$ – transverse, $I_{long}/I_{tran} >1$ – longitudinal).

The experimental results show that in the case of the magnetic field maximum at the anode in the all half-periods of current oscillation the radiation is observed to be isotropic. The radiation intensity is remained almost unchanged compared with case of the magnetic field absence. In the case of the magnetic field minimum at the anode the intensity is increased. At the lower discharge voltages the radiation is longitudinal and at the high – transverse. The radiation intensity is achieved the greatest value when the inversion point of the magnetic field is set at the anode. Herewith at the all discharge voltages the radiation has been transverse.

Thus the relatively small (compared to the intrinsic magnetic field value 50-100 кO) external magnetic field promotes the improvement the stability work of the pulse high-current plasma diode and effects on the EUV radiation orientation and intensity.

8-17

A BENT NEEDLE-TO-PLANE CORONA DISCHARGE FUNGICIDAL TREATMENT OF SURFACES: ZONES OF *CANDIDA ALBICANS* GROWTH INHIBITION CHANGES

Karol Bujaček[1], Vladyslava Fantova[1], Vítězslav Kříha[1]

1) Czech Technical University in Prague, Faculty of Electrical Engineering, Department of Physics. Technická 2, 166 27Prague

Nowadays well known decontaminations effects of low temperature plasma leads to study properties of many different decontamination techniques and devices. The pin-to-plane corona discharge is simple and easy to use source of the low temperature plasma. The principal drawback of this plasma source consists in relatively small treated area and the modifications of classical configuration are intensively studied. A *Candida albicans* yeast is widely used as a model organism for surface decontamination effect testing. The main goal of this study is to discover dependency of the inhibition zone size on the needle geometry and angle between needle and plane in plane to needle electrode configuration.

In our experiments both negative and positive corona discharges for decontamination of the surface with *Candida albicans* yeasts inoculated were used. As the plane electrode the Petri dish with agar surface electrically connected to the circuit was used. The needle electrode made of medical needle was placed perpendicularly over the plane. Needles of different shapes were used: they were bent at angles from 0° (straight one) to 80°. The distance between the plane electrode and the tip of the needle was kept in all experiments. Suspension with *Candida albicans* yeasts was spilt on the Petri dish (inoculation), exposed to the discharge and put for overnight cultivation into cultivation chamber (37 °C). Afterwards the inhibition zones sizes and their shapes were evaluated. As the result we observe that the inhibition zones are prolonged in the direction of the tip of needle axis and their sizes grows for bigger angles. This effect was more visible in the case of the positive corona discharge treatment. In case of the negative corona discharge the inhibition zone was observed not only under the tip, but also under the slant part of the needle whereas in the case of the positive corona discharge the inhibition zone was observed mostly in front of the tip of the needle. In this study we confirm the hypothesis that shape and size of the inhibition zone can be modified by the configuration of the electrodes and it can be said that lean of the tip of the needle can be one of the important parameters of this kind of device and it should be studied in the future. Adjusting of the shape of the needle together with other parameters of the discharge and/or geometry of the sharp electrode could cause broadening of the inhibition zone size.

8-18

HIGH-CURRENT PULSED OPERATION MODES OF THE PLANAR MSS WITH MAGNETICALLY INSULATED ANODE WITHOUT TRANSITION TO THE ARC DISCHARGE

A.A. Bizyukov[1], K.N. Sereda[1], V.V. Sleptsov[2], I.K. Tarasov[1], A.G. Chunadra[1]

[1]*V.N. Karazin Kharkiv National University, Svobody sq., 4, 61077, Kharkiv, Ukraine.*
[2]*K.E. Tsiolkovsky Russian State Technological University (MATI), Orshanskaya 3, 121552, Moscow, Russia.*

Magnetron sputtering systems (MSS) find wide application in techniques of deposition of coatings on substrates of various materials. Recently interest is shown in the pulsed operating regimes of MSS, which allow to reduce energetic influence on surface of processed sample. Due to high density of the pulsed plasma the synthesis of coatings of complex composition is provided, the range of technological parameters increases, uniformity of deposition of coatings on the complex relief and stability relatively arc formation on target improve. Pulsed magnetron discharge can exist in a wide range of parameters, has many forms depending on the sort of material and design of electrodes, magnetic field magnitude and configuration, features of power supply. One of the main factors that determines operating characteristics of MSS, is configuration of the magnetic field over the cathode of magnetron, which determines temperature influence on operational surface and uniformity of deposited coating.

In this work the features of high-current operating regimes of planar magnetron sputtering system with magneto-insulated anode without transition to arc discharge regime was studied. It was experimentally shown that the usage of this configuration of magnetic field provides effective interruption of arc current without forced external switch off the magnetron discharge. At the same time oscillograms of discharge current and voltage show, that the frequency of arc discharge disruptions corresponds to spatial modulation of near-anode magnetic field, and their duration doesn't exceed characteristic time of formation of cathode spots of the second kind. Pulsed discharges with average magnetron discharge current up to 60A were obtained, that substantially exceeds the currents of stationary operating regimes of MSS, and with durations up to 10msec. Taking into account, that characteristic time of formation of the cathode spot of the second kind is 10-7 sec, obtained regimes may be considered as quasistationary. Photometric studies of surface sputtered target of MSS at the moment of discharge pulse allows to classify arc disruptions as cathode spots of the first kind (sparking), that significantly increases transfer of target material in comparison with the regime of ion-atom sputtering, without generation of droplet phase. Microscopic studies of deposited coatings showed the absence of droplets and hard fragments of the target material.

8-19

SPECTROSCOPIC AND CORPUSCULAR ANALYSIS OF LASER-PRODUCED CARBON PLASMA

A. Czarnecka[1], M. Kubkowska[1], E. Skladnik-Sadowska[2], E. Kowalska-Strzęciwilk[1], P. Parys[1], M.J. Sadowski[1-2], , K. Malinowski[2], R. Kwiatkowski[2], and M. Ladygina[3]

[1] *Institute of Plasma Physics and Laser Microfusion (IPPLM), 01-497 Warsaw, Poland;*
[2] *National Centre for Nuclear Research (NCBJ) 05-400 Otwock, Poland;*
[3] *Institute of Plasma Physics, NSC KIPT, 61-108 Kharkov, Ukraine*
e-mail: agata.czarnecka@ifpilm.pl

This paper refers to material studies needed for fusion technology, e.g., in the ITER facility it is planned to use some Tungsten (W) and Carbon (C) based materials for the divertor plates. A Carbon Fiber Composite (CFC) is one of the most promising materials due to its resistance to extreme high heat loads. Therefore, our team has performed some research on behavior of CFC samples under high thermal loads induced by intense laser pulses.

The paper describes spectroscopic and corpuscular measurements of laser-produced carbon plasma, which was created at surfaces of three targets made of CFC of the Snecma-N11 type with different crystallographic orientations. In order to irradiate the investigated samples the use was made of a Nd:YAG laser (EKSPLA) which at the wavelength of 1064 nm could deliver 3.5 ns pulses of energy ranging up to 430 mJ. Experiments were performed in a vacuum chamber under the initial pressure equal to 5×10^{-5} mbar. A Mechelle®900 optical spectrometer equipped with a CCD detector was used to record spectra emitted from the produced carbon-plasma. The acquisition time was 5 μs, and a delay between the laser pulse and the exposition start was 200 ns. The recorded optical spectra showed carbon lines ranging from CI to CIV. Basing on the Stark broadening of the CII 426.7 nm line it was possible to estimate the electron density of plasma from each investigated sample.

Corpuscular measurements of the emitted ions were carried out by means of an electrostatic ion-energy analyzer and ion collector. The ion signals obtained from the analyzer showed that the plasma produced at surfaces of the three investigated CFC samples emitted carbon ions with positive electrical charges ranging up to 4. A signal from the ion collector, which was located at a distance of 50 cm from the target centre, allowed to estimate an average energy value of the carbon ions for each irradiated sample. Profilometric measurements and investigations with an optical microscope showed that applied laser irradiation caused considerable structural changes on the surface of the irradiated CFC targets.

8-20

DEPENDENCE OF RF BREAKDOWN CURVE ON ELECTRODE GEOMETRY IN CCP REACTOR

A.N. Dahov, S.V. Dudin, V.A. Lisovskiy, V.M. Pletniov

V.N. Karazin Kharkiv National University, 31 Kurchatov Ave., Kharkiv 61108, Ukraine
E-mail: stanislav_dudin@rambler.ru

Results of experimental and theoretical study of RF capacitively coupled discharge breakdown in reactor for reactive ion etching of semiconductors are presented. Taking into account complex geometry of the reactor with asymmetric electrodes the main attention has been paid to influence of geometric factor on the breakdown curve. Experiments have shown that the geometry of the electrodes has impact on the breakdown curve only at lowest gas pressure (<100 mTorr). In cylindrical configuration the curve has region of ambiguity, while for asymmetric configuration similar to GEC reference cell the low pressure part of the breakdown curve is almost vertical. The experimental data are compared to the numerical simulation results obtained using the particle-in-cell/Monte Carlo (PIC/MCC) code. The comparison shows qualitative consistence of the results with general tendency of theoretical curves to be slightly shifted to higher pressures that can be explained by simultaneous action of different kinds of electron emission from the electrodes, while we accounted only for secondary electron emission. Both theory and experiment show influence of secondary electron yield from different electrode materials (aluminum, steel, graphite) on the low-pressure part of the breakdown curve.

8-21

THE SURFACE PROPERTIES OF Ta_2O_5 CERAMIC COATINGS AND NEXT CORRELATIONS WITH CELL RESPONSE IN VIVO AND IN VITRO TESTS

N. Donkov, E. Mateev, A. Zykova [1], V. Safonov[2], V. Luk'yanchenko[3]

Institute of Electronics, Bulgarian Academy of Sciences, Sofia, Bulgaria

[1]Institute of Surface Engineering, Kharkov, Ukraine

[2]National Science Centre „Kharkov Institute of Physics and Technology", Kharkov

[3]INMASTERS Ltd, Kharkov, Ukraine

The implants applied now for operative treatment with a dielectric coatings in an electret state, create normal biopotential in the osteosynthesis area that prevents the atrophy and necrosis formation, the bone tissue deformation and surface strains of large joints, reducing the terms of treatment and minimizing the postoperative complications. Charged or polar, electrostatic fields can influence on the cell/material interactions and next response of biological molecules to the surfaces. The surface charge parameters of the solid surface could play an important role in the mechanisms of the initial and long-term cell adhesion on the biomaterial surface at different surface charge densities.

For electret coating deposition it is necessary to provide a high purity and a given stoichiometric composition of dielectric coatings in the electret state. Thus the major factors are the optimum regime of their manufacturing and the precision control of the technological process of electret coating deposition.

The study of e-beam evaporated Ta_2O_5 film structure and properties effect on cell/material response and behavior in vitro and in vivo tests was performed. The samples were formed on titanium substrates. The evaporation process was carried out at initial vacuum of 7×10^{-6}Torr, operational-mode vacuum of 3×10^{-5}Torr, anode current of 50mA and calculated evaporation power of 350W [1]. The deposition rate under these conditions was 28nm/min. The layer thickness and the deposition rate were controlled by a digital thin-film deposition monitor MSV-1843/H MIKI-EEV operating at 6MHz [1].

The electron beam evaporator consists of a heated tungsten filament apertured by screen, surrounding the filament. Both the apertured anode and the crucible are at a ground potential. Accelerating voltage U_a is applied to the filament and to the screen. The magnetic field is created by an electromagnet. The evaporation power P_{ev} needed to heat the crucible containing the evaporated metal is the product of the anode current I_a and U_a (7kV).

The surface properties and structure of e-beam evaporated Ta_2O_5 films were investigated by means of SEM, XPS and XRD methods. The research of near-surface electric fields distributions and surface charge densities was measured by means of dynamic capacitor method and correlations of surface characteristics, field distributions and their effect on the interactions with biological objects was presented. The cyto toxicity and cyto compatibility were estimated by in vitro tests and tissue ingrowth was analysed in vivo tests.

The results show that the surface properties and charge states are strongly influenced by the preliminary treatment and the deposition conditions. The deposition process controlling allows one to control the surface parameters of the e-beam evaporated Ta_2O_5 films and the next positive biological response of live organisms. The possibility of controlled cell adhesion and tissue ingrowth on the biomaterial surfaces may propose novel methods of surface functionalization for next biomedical and tissue-engineering applications.

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8-22

METAL MICRO-DETECTORS: DEVELOPMENT OF "TRANSPARENT" POSITION SENSITIVE DETECTOR FOR BEAM DIAGNOSTICS

O. Kovalchuk[1], V. Pugatch[1], O. Fedorovich[1], O. Okhrimenko[1], D. Storozhyk[1], V. Kyva[1], M. Campbell[2], X. Llopart[2], S. Pospisil[3], Y. Prezado[4], M. Renier[4]

[1]*Institute for Nuclear Research, National Academy of Sciences of Ukraine, Kiev*
[2]*CERN, Geneva, Switzerland*
[3]*Institute of Experimental and Applied Physics, Prague, Czech Republic*
[4]*ESRF, Grenoble, France*

Metal Microstrip Detector (MMD) represents a novel position sensitive detector for wide range of applications. It has been developed at the Institute for Nuclear Research NASU for the beam profile monitoring of the synchrotron radiation as well as for the charged particles beam profile monitoring. MMD is a 0.5 – 1.0 micro-meter thick semi-transparent radiation hard micro-strip detector able for non-destructive online measurements of radiation beam parameters. The many advantages of MMD allow using them for:

- Beam profile monitoring (Beam profile, Beam position, Intensity distribution in the beam)
- Detectors at the focal plane of mass-spectrometers and electron microscopes
- Imaging sensors for X-ray and charged particle applications
- Precise dose distribution measurements for micro-biology, medicine etc.

MMD technology includes some stages: micro-strip layout made by photo-lithography on silicon wafer, plasma-chemistry etching of the silicon wafer in the operating window, micro-cabling connection to the readout electronics and DAQ.

Currently we have succeeded to produce MMD up to 30 micron pitch of strips (2 microns between strips) and up to 1024 strips. Commercially available read-out systems (VA_SCM3 microchip preamplifier, Time Pix readout chip, Gotthard, X-DAS) have been studied for use with MMD. Characterization studies of the MMD measuring synchrotron radiation (ESRF, France), proton beam (Tandem-generator at KINR), X-Rays (KINR) are presented in details.

This type of sensors can be used for visualization and detection hot plasma emission.

8-23

ON THE "ENLIGHTENMENT" NONIDEAL HYDROGEN-OXYGEN PLASMA AT A CONCENTRATION OF $N_E \leq 3\cdot10^{19}$ CM^{-3}

O.A.Fedorovich

Institute for Nuclear Research of NASU, Kiev, oafedorovich@kinr.kiev.ua

For the experimental determination of the plasma emissivity ξ measurements of the intensity distribution of the emission spectrum, the channel radius, optical depth τ, the channel inhomogeneity it is necessary. For calculation the average along the beam of observation ξ it is necessary to know N_e and temperature T. All these data have been obtained experimentally in this work, and the inhomogeneity parameter (M = 0,84 - 0,93) is calculated as [1]. With τ decrease the emission spectrum of the channel PDW still continuous, but on his background it is possible to choose the hydrogen lines: first H_α, later H_β, and still later H_γ. From H_α lines intensity distribution in the reabsorbed and broadened in the plasma microfield wings, distribution τ can obtain in the far wings. If the change in absolute value τ not happens when you change the wavelength, it is accepted as τ continuum, taking into account that the transition line wing in the continuum is smooth [2]. The intensity of radiation from τ also took into account. N_e was determined from the broadening of the H_α lines and T is determined by the intensity at the maximum of the emission reabsorbed H_α lines. I the calculation of spectral distributions ξ carried out on the four formulas.

The first calculation is performed for hydrogen plasma by the Kramers-Unsold formula for the total free-free and free-bound radiation. The value ξ was also calculated by the formula Biberman-Norman [3]. The third calculation is carried out according to the formula of Norman [4] for the NP. From the results of the calculation is clear that at $N_e = 3{,}5\cdot10^{17}$ cm^{-3}, the calculated values of ξ for the total continuous spectrum is somewhat less experimental. This is agreeing with the data of other authors. With increasing N_e values up to $3\cdot10^{18}$ cm^{-3} is observed the opposite effect – the ξ, values calculated for all three formulas, greater than the experimental values. The theoretical values for a series boundary practically agree with experimental ones. In the "gap" region and in the longer-wavelength region the experimental values of ξ is several times smaller than calculated. Closest to the experiment values is ξ calculated by the Norman formula [4]. With further increase of N_e (for $N_e = 7\cdot10^{18}$ cm $^{-3}$) calculated ξ values of the order of magnitude higher than the experimental. When $N_e = 3\cdot10^{19}$ cm^{-3}, the calculated values more than experimental two orders of magnitude. The best agreement with the experimental ξ values given by the Norman formula [4] at longer wavelengths, than defines by Ingliss-Teller shift. Smallest discrepancies between theory and experiment is observed at the boundary of the Balmer series, where difference in ξ is 10 - 50 times. If we consider non-infringement of the principle of spectroscopic stability, the difference between theory and experiment in the "gap" region reaches three orders of magnitude, especially in the area of 600 nm. It can be concluded that the experimentally determined ξ values of the spectral distributions at $N_e > 3\cdot10^{18}$ cm^{-3} much smaller than the given by formulas for an ideal plasma. And in the hydrogen - oxygen NP observed the effect of "enlightenment."

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8-24

ON THE INFLUENCE OF THE DEGREE OF HYDROGEN-OXYGEN NONIDEAL PLASMA FACTORS IN DECAY

O.A. Fedorovich, L.M. Voitenko

Institute for Nuclear Research of NASU, Kiev, oafedorovich@kinr.kiev.ua

The recombination processes of non-ideal plasma (NP) are poorly studied. It is experimentally possible to get only the plasma decay coefficients. In the plasma channel of the pulsed discharges in water (PDW) we have the pressures about 10^2 - 10^4 bar and the temperatures about 5 - 45 • 10^3 K. Under such conditions occurs intensive ionization. It's necessary to take into account at calculation of the recombination coefficients. Plasma decay coefficient is defined on formula: $K_d = \frac{dN_e}{dt \cdot N_e^2} = \frac{N_a}{N_e} b - \alpha \cdot N_i$. Experimentally decay coefficients can be defined on formula $K_d = \frac{dN_e}{dt \cdot N_e^2}$, where N_e - electron concentration, b - coefficient of ionization, N_i - ion concentration, α - the coefficient of recombination. If no additional input of energy in the plasma channel, and the electron concentration decreases with time, then calculating of the electrons concentration from time, receive К.

We are received the experimental dependency of К from degree of plasmas non-ideality at Γ = 0,2-4,5. First, the values of K decrease sharply with increasing Γ from 0.1 to 0.3 on three orders, and then start to increase nearly on order of magnitude, pass the maximum and, at increase Γ from 2 to 4.5, exists slow reduction of the decay coefficient on order. Qualitatively, the experimental results agree with those, calculated theoretically on the work Lankin-Norman [1]. But there are quantitative differences. For Γ < 1 the K experimental values two orders of magnitude lower than theoretical, and at T = 4 are the same. At Γ > 4 theoretical values of the recombination rate becomes smaller than experimental values.

Calculated values of the recombination coefficients on formulas given in Romanovsky [2], several orders of magnitude higher than the experimental values. But the calculated values are parallel to the experimental one. In this paper we considered only the effect of electric microfield in NP.

Comparison with the calculated values on the work [3] shows that the experimental results on the decay of NP well described at Γ ≥ 0, 5. It should be noted that in [3] calculation was performed for ultracold plasma. For small values of Γ there is a greater discrepancy than estimated by Lankin-Norman theory.

It should be noted that the parameter "degree of non-ideality" is ambiguous. It depends not only on N_e, but also on the plasma temperature. Experimentally, the unambiguous dependence of K on the electron concentration was obtained only in the NP [4]. The known theoretical work does not describe the experimental dependence of the degree of plasmas non-ideality. Apparently, G is not unambiguous parameter to describe its influence on the rate of plasma decay.

Some theoretical calculations do not take into account the effects of "non-realization" of atoms levels in strong microfields in NP. Accordingly, there is no level to which it would be possible recombination of electrons. Experimentally there are observed sharp increase of the decay rate of the hydrogen-oxygen plasma with the advent of the hydrogen emission lines.

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8-25

SELF-COMPENSATION OF THE FOCUSED ION BEAM SPASE CHARGE

A.A. Bizyukov[1], O.I. Girka[1], E.V. Romashchenko[2], K.N. Sereda[1], N.N.Yunakov[1]
[1]V.N. Karazin Kharkiv National University, Svobody sq., 4, 61077, Kharkiv, Ukraine
[2]V.Dahl East Ukrainian National University, 20A, Bl. Molodyozhnyi, Lugansk 91034 , Ukraine

Magnitude and spatial distribution of the electric potential of the focused ion beam in the drift region are studied both theoretically and experimentally. The gap of electric potential for the compensating electrons is shown to be formed nearby the plane of the beam crossover. This allowed explaining the anomalous brightness and spatial distribution of light emission of gas in this region, as well as the deviation of ion trajectories from the ballistic ones.

8-26

NITRIDING, OXIDATION AND CARBURIZATION OF TITANIUM AND STEELS IN NON-SELF MAINTAINED GASEOUS DISCHARGE.

Timoshenko A.I., Taran V.S., Misiruck I.A.

Institute of Plasma Physics, NSC Kharkov Institute of Physics and Technology, Akademicheskaya St.1, 61108 Kharkov, Ukraine

The samples of stainless steel (SS), high speed steel (HSS) and of titanium (Ti) were exposed to fluxes of ions N^+, O^+, and $C_mH_n^+$ with a current density of 20÷30 mA/cm^2. The ion fluxes having an energy of 20÷30 eV have been ejected from hollow anode into hollow cathode (vacuum chamber), where the samples have been placed. The processing time was 20 minutes for all samples. The temperature of samples could be changed by applying a negative potential to its fixture and has been maintained for SS at 700 ^{0}C, for HSS at 550 ^{0}C and for Ti at 550, 700 and 1000 ^{0}C. It has been found that the oxidation of Ti is going faster than the nitriding does. The surface microhardness of samples treated by fluxes of ions in non-self maintained gaseous discharge grows from 1.5 for HSS (except the carburization) to 6 times for Ti and SS.

8-27

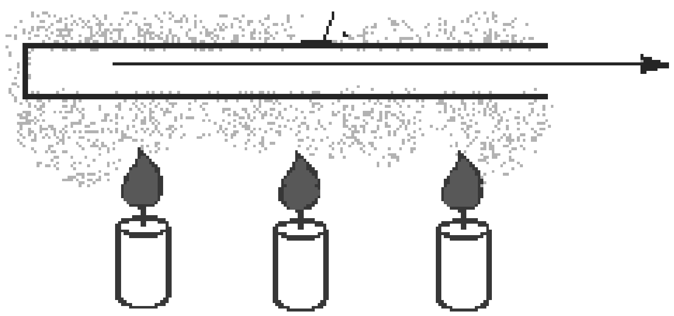
PURE HYDROGEN GENERATOR FOR PLASMA DEVICES

G.P. Glazunov
Institute of Plasma Physics, National Science Center
"Kharkov Institute of Physics and Technology", 61108 Kharkov, Ukraine
E mail: glazunov@ipp.kharkov.ua

High purity hydrogen is required for scientific investigations in many plasma devices. Also it is used in chemical, electronic and others industries. Most of present technologies for making of high pure hydrogen consists, per se, from two main technological processes: making of technical hydrogen with low purity and its cleaning up to high level of purity [1]. The essential power inputs are required for both processes. Then produced pure hydrogen is compressed in balloons and it is not excluded that hydrogen from balloon has the same purity as produced hydrogen. Besides in some cases the use of hydrogen balloons may not be preferred, e.g., for safety reasons. The scheme combining the processes of hydrogen generation and admission was suggested in the work [2] where pure hydrogen was generated by means of thermal decomposition of alcohol vapor on the palladium membrane surface.

Recently the new technology was developed for pure hydrogen production (purity is 99,999 vol.% and higher), when pure hydrogen is generated in only one technological process - making (generation) of hydrogen as coproduct during hydrocarbons utilization, e.g. during combustion of flammable hydrogen-containing materials (such as natural gas, benzene, gasoline, alcohol, etc.) [3]. The principle of this technology is clear from Fig.1.

Diffusion-catalytic membrane



Flame source

Fig. 1.

Laboratory model hydrogen generator was created and tested (hydrogen capacity about 1 Ncm^3/s; 3,6 l/hour). Note, that such capacity is enough to provide with pure hydrogen such large plasma device as torsatron Uragan-2M in both work and discharge cleaning regimes. High level of generated hydrogen purity was confirmed with help of mass-spectrometric investigations on the special stand. The physical-chemical mechanisms are discussed to explain pure hydrogen generation from the flame of combustion and its inlet to high-vacuum systems

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8-28

THE THEORY OF NON-LOCAL IONIZATION IN GLOW DISCHARGE AND HOLLOW CATHODE

Vladimir V. Gorin

Kyiv National Taras Shevchenko University, 60 Volodymyrs'ka St., 01601 Kyiv, Ukraine

vgorin@univ.kiev.ua

This is the mathematical theory. It has been developed during last 10 years. Primary customer of this work was Pohang Accelerator Laboratory (PAL), Pohang, Republic Korea.

Hollow cathode device was invented by F. Paschen almost hundred years ago (1916). During the time passed it became very usable time-independent instrument for plasma investigations and numerous technology applications.

But all this time the theory of the device was absent. It was caused mainly with two reasons. First was: an appearance in 30th years of XX century the Engel and Shteenbeck cathode sheath theory for glow discharge in plane capacitor, which was described with two simple ordinary differential equations (the Poisson and the Townsend equation) and rather simple formulae. The customers of the theory were the professionals in gas discharge experimental technique, they were not much of mathematicians. So, it seemed, the theory of glow discharge was mainly developed, - to describe a hollow cathode it need only to find special multiplication factors for the hollow cathode effect, which could be considered as special hollow cathode correction of formulae obtained.

Second reason was a successful use of differential equations in all branches of physics and technology, so technicians could not imagine anything more for theory.

Differential equations give local description of mechanical systems, fields and distributions. Hollow cathode turned out to be special device, which needs non-local description for its source of ionisation. The Engel and Shteenbeck cathode sheath did not suit to it. Also to describe negative glow.

New theory is non-local. Starting from special form of the boltzmann equation it derives the integral equation for a source of ionisation in glow discharge (V. V. Gorin, 2008, 2010). The equation has great generality in geometry, and it enables to describe the ionisation source in hollow cathode. It does not conflict with classical cathode sheath theory, but rather extends it so significantly, that it cannot be regarded as a “correction”.

New equation needs investigation of existence and uniqueness for its solution. It is formulated and proved the theorem about it. In a proof of the theorem many of useful structures and formulae have arisen. All of them have clear physical sense and, taking together, enable to describe physical structure of non-local electron avalanche, which creates a non-local source of ionisation. Also they enable to describe general properties of electron energy spectrum in hollow cathode configuration.

Of course, these mathematical structures do not look very simply (like the Ohm’s law). But it seems, the way from general to particular is much more easy, than quite the contrary. And application of these structures and formulae to develop the analytical models of glow devices with concrete geometry is waiting for work of researchers.

The theoretical model for simplest configuration of one-dimensional plane hollow cathode is developed and calculated. The calculations of theoretical model demonstrate good agreement with experimental results for devices most closely identical to this geometry. The non-local theory enables to simulate the hollow cathode effect, that was impossible in classical theory. Old theory can be derived from new one, but not conversely.

New theory is waiting to be applied!

8-29

ELECTRON KINETICS IN MICROPLASMA DISCHARGE INSIDE DIELECTRIC CELL WITH EQUIPOTENTIAL COPLANAR ELECTRODES

O.I.Kelnyk, O.V.Samchuk

Taras Shevchenko National University of Kyiv, Radio Physics Faculty
60 Volodymyrs'ka St.,01033, Kyiv, Ukraine
oles@univ.kiev.ua

Microplasma discharges are applied widely as UV photons sources for phosphor excitation inside dielectric cells of plasma display panels (PDP, [1]). This type of displays have rather small energetic efficacy, mostly due to the small size and large pressure in the discharge cell. So more investigations are necessary in order to find a way to increase microplasma discharge UV luminosity and, consequently, PDP energetic efficiency. This luminosity can be increased if electron energy distribution in the discharge will be non-equilibrium with more high energy electrons capable for excitation and ionization. This work is devoted to the comparison of electron energy distributions of microplasma discharges inside typical coplanar PDP cell for the cases of equipotential and non-equipotential coplanar electrodes.

Simulation were carried out for microplasma discharge inside the dielectric cell with 600*200 μm dimensions with 500 Torr total pressure of Ne (95%) - Xe (5%) gas mixture typical for PDPs [1]. Electrodes' geometry was also typical for PDP cell: two coplanar electrodes at the front of the cell and one address electrode at the rear. Our original 2D electrostatic PiC code for weakly ionized plasma was applied. Elementary processes of about 100 kinds were taken into account via the Monte Carlo method. Simulations were carried out for equipotential coplanar electrodes in the comparison with the case when the discharge voltage is applied between them. Discharge voltage was considered about 250V.

For equipotential coplanar electrodes, typical volume discharge was observed in the simulation. For this case, total discharge current waveform as well as waveforms of its electron/ion components have similarity with volume regime for non-equipotential coplanar electrodes but begins to grow slightly earlier, have larger magnitude and decays more quickly for the same discharge voltage. Contrary, there is important difference for electron energy distribution functions. For non-equipotential coplanar electrodes, this function is close to the Maxwellian shape, with additional electrons in the high-energy bands capable for excitation and ionization [2]. But, in the case of equipotential coplanar electrodes, electron energy distribution function becomes very different from Maxwellian shape, becoming close to the Dryuvesteyn function. For such distribution function, electron lack exists in the energy band above 4eV. This is typical for gas discharges in two-electrode configuration. In contrast, for nonequipotential coplanar electrodes have electrons in that energy band in the numbers exceeding even the Maxwellian distribution function. Such effect is related to the electrons' additional acceleration due to the strong electrostatic field in the region between two non-equipotential coplanar electrodes. So the voltage applied between the coplanar electrodes can produce the non-equilibrium electrons and increase the PDP cell energetic efficacy.

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8-30

NORMAL AND ABNORMAL REGIMES OF DC DISCHARGE BURNING IN N_2O

V.A. Lisovskiy [1),2)], E.P. Artushenko [1)], V.A. Derevyanko [1)], V.D. Yegorenkov [1)]

[1)] *Kharkov National University, 61022, Kharkov, Svobody Sq. 4, Ukraine*
[2)] *Scientific Center of Physical Technologies, Kharkov, 61022, Svobody Sq., 6, Ukraine*
E-mail: lisovskiy@yahoo.com

Dc discharge in N_2O is widely applied in gas discharge infrared lasers (where N_2O is used instead of CO_2). However, available references practically do not contain information concerning even regimes of burning and current-voltage characteristics (CVCs) of dc discharge in N_2O, therefore studies of this discharge are of a large interest.

The present report is devoted to studying the normal and abnormal regimes of dc discharge in N_2O with the inter-electrode distance values $L = 0.5$, 1 and 2 cm within the pressure range of $p = 0.05–10$ Torr. The inner diameter of the cylindrical discharge glass tube was 56 mm. We registered CVCs of the dc discharge in which one observed a characteristic dogleg feature when the transition from the normal regime to abnormal one occurred. The normal current density values were determined from the location of the dogleg feature in CVC and a known electrode area.

At large N_2O pressure the ratio of the normal current density to gas pressure squared was shown to remain constant and to equal $J_n/p^2 = 0.44 \pm 0.03$ mA/(cm·Torr)^2 for any inter-electrode distance value (within the L range we studied). On decreasing N_2O pressure the J_n/p^2 ratio grows and for narrow inter-electrode distance it may approach some or even some tens of mA/(cm·Torr)^2. For $L = 2$ cm the normal regime is observed only at the N_2O pressure values above the inflection point on the dc breakdown curve for this inter-electrode distance ($pL \geq 0.6$ Torr·cm). But for narrow distance values $L = 0.5$ and 1 cm the normal regime may exist in a much broader N_2O pressure range to the right as well as to the left of the dc breakdown curve minimum. Its existence region is limited from the low pressure side only by the appearance of the obstructed regime at the left-hand branch of the breakdown curve when a complete cathode sheath cannot fit the inter-electrode distance.

8-31

AXIAL STRUCTURE OF DC GLOW DISCHARGE NEGATIVE GLOW IN NITROGEN

V.A. Lisovskiy [1),2)], V.A. Derevyanko [1)], E.A. Kravchenko [1)], V.D. Yegorenkov [1)]

[1)] *Kharkov National University, 61022, Kharkov, Svobody Sq. 4, Ukraine*

[2)] *Scientific Center of Physical Technologies, Kharkov, 61022, Svobody Sq., 6, Ukraine*

E-mail: lisovskiy@yahoo.com

Glow dc discharge is widely applied in pumping gas lasers, for nitriding surfaces of various materials, tools, plasma sterilization etc. Therefore studies of glow discharge (as a whole and of some particular parts of it) are of great interest. This report employs a single Langmuir probe to register axial profiles of plasma parameters in a negative glow of dc glow discharge in nitrogen.

We performed our studies in nitrogen within the pressure range of p = 0.05–0.5 Torr. The flat cathode and anode were spaced L = 245 mm apart. The inner diameter of the cylindrical discharge glass tube was 56 mm. We registered plasma parameter profiles with a single nichrome Langmuir probe 1.5 mm long and 0.18 mm in diameter. Plasma concentration n_i was calculated from the ion branch of the probe current and the measured electron temperature.

Consider the axial profiles of plasma parameters for the nitrogen pressure of 0.05 Torr. Under these conditions the glow discharge consists of a cathode sheath and a negative glow approaching the anode surface (the maximum possible negative glow length might be larger but only a part of it found its place inside this inter-electrode gap). The electron temperature T_e was 0.3–0.5 eV almost within the total discharge gap but near the negative glow-cathode sheath interface we observed a sharp T_e increase. Electric field is usually small in the negative glow what is supported by the axial potential profile we registered. The voltage drop across the total negative glow amount to about 3 V. The average field intensity was approximately 0.15 V/cm. The axial profile of the positive ion concentration possesses a maximum in the negative glow not far from the cathode sheath boundary. Moving away from the cathode the ion concentration falls uniformly almost to the anode according to the power law $1/z^{0.8}$, if the z coordinate is counted from the cathode surface. And only near the anode surface the ion concentrations falls fast to zero.

Now consider a case with higher nitrogen pressure of 0.3 Torr, here the discharge current was 5 mA. Electron temperature in the negative glow decreases from the cathode sheath boundary and it approaches the smallest value $T_e \approx 1.2$ eV at the anode end of the negative glow. Along the negative glow the plasma potential lowers by about 5 V. Axial profile of plasma concentration possesses a maximum in the negative glow near the cathode sheath boundary similar to the case of low pressure. Along the negative glow the plasma concentration decreases by about 16 times and it approaches its minimum in the transition region to the dark Faraday space. Note that the plasma concentration decrease by 15-16 times was observed at all nitrogen pressure and discharge current values when the negative glow completely found its place within the inter-electrode gap.

Thus this paper reports the studies with a Langmuir probe technique of axial plasma parameters such as electron temperature, potential and plasma concentration of dc glow discharge in nitrogen at different gas pressure values. It demonstrates that in the negative glow the electric field strength is small and axial profiles of plasma concentration and electron temperature possess maxima. These parameters approach their minima at the negative glow-dark Faraday space interface. Along the negative glow the plasma concentration is found to decrease 15-16 times at all gas pressure and discharge current values we studied.

8-32

INVESTIGATIONS OF THERMAL PLASMA WITH METAL IMPURITIES. PART I: THE INFLUENCE OF ELECTRODES COMPOSITION ON PLASMA PROPERTIES

Veklich A.N, Lebid A.V., Soroka P.V., Boretskij V.F., Babich I.L.

Taras Shevchenko Kyiv National University, 64, Volodymyrs`ka Str., Kyiv, Ukraine
e-mail: van@univ.kiev.ua, tgctg@yandex.ru

Composite materials on copper base are widely used for contacts and electrodes in switching devices for the electrical engineering industry. Exploitation efficiency of switching devices is determined by mass transfer of electrode’s materials inside discharge gap. Amount of metal vapours in discharge gap affected by mutual interaction between electrode’s material and electric arc plasma, which appeared during switching. Therefore, investigations of such plasma can be useful for optimization of new composite materials, their composition and fabricating technologies.

Traditionally, composite electrodes on copper base fabricate by methods of powder metallurgy, particularly by the copper infiltration of the high-melting component. Alternative technology is electron beam evaporation with condensation in vacuum. Investigations of electric arc plasma between composite electrodes usually are performed by optical emission and absorption spectroscopy.

Because of the discharge spatial and temporal instability the method of the single tomographic recording of the spectral line emission was used. A spectral device with 3000-pixel CCD linear image sensor (B/W) Sony ILX526A accomplished fast scanning of spatial distribution of radial intensity.

The arc was ignited between non-cooled electrodes in argon with flow rate 6.4 slpm. The discharge gap was 8 mm, arc current - 3.5 and 30 A. To avoid the metal droplet appearing a pulsing high current mode was used: the current pulse 30 A was put on the "duty" low-current (3.5A) discharge. The pulse duration ranged up to 30 ms.

This paper deals with results of experimental spectroscopic investigations of plasma of electric arc discharge between composite Cu-Mo electrodes, fabricated by different technology. It was found that plasma properties strongly depend on structure and composition of electrodes.

8-33

INVESTIGATIONS OF THERMAL PLASMA WITH METAL IMPURITIES. PART II: PECULIARITIES OF SPECTROSCOPY BY WI, MoI AND CuI SPECTRAL LINES

Veklich A.N, Lebid A.V., Soroka P.V., Boretskij V.F., Babich I.L.

Taras Shevchenko Kyiv National University, 64, Volodymyrs`ka Str., Kyiv, Ukraine
e-mail: van@univ.kiev.ua, tgctg@yandex.ru

Diagnostic of plasma is important part of numerous scientific investigations and industrial applications. The optical emission spectroscopy (OES) is the most widely used method for arc plasma diagnostic. It allows obtaining such important characteristics of arc as temperature and electron density without disturbing of plasma object. Existence of local thermodynamic equilibrium and axisymmetric configuration of the arc are assumed in such kind of measurements.

Time dependent changing of spectral line intensities occurs in arcs between multicomponent electrodes due to irregular injection of electrode material into discharge gap. So, non-simultaneous registration of spectral lines can lead to inaccuracy results, especially in methods which are based on intensities comparison. Therefore, diagnostic technique for simultaneous registration of spectral and spatial distribution of emission intensity was developed.

As applications of composite materials in switching devices for the electrical engineering industry stimulate the interest in studying of the arc discharge plasma between electrodes produced from such materials, in this paper spectroscopic investigations of electric arc discharge between Cu-Mo and Cu-W composite electrodes are carried out.

Additionally, spectroscopic investigation of electric arc plasma between Cu-Mo and Cu-W can clarify some diagnostic problems of plasma with impurities of high-melting metals, respectively molybdenum and tungsten. In particular, analysis of Mo and W atomic spectral lines in visible spectral range for the purpose of OES applications are performed

8-34

STOCHASTIC HEATING OF ELECTRONS IN CAPACITIVE RF DISCHARGES BY PLASMA OSCILLATIONS

O.V. Manuilenko

NSC «Kharkov Institute of Physics and Technology»
e-mail:ovm@kipt.kharkov.ua

Experiments [1] and particle-in-cell Monte Carlo (PIC-MCC) simulations [2-5] show that electron energy distribution function (EEDF) in an argon RF capacitively coupled discharge (CCD) has a large number of low-energy electrons. The EEDF in CCD can be represented as a sum of two Maxwellian distributions [1-5] with two electron temperatures T_{low}=0.3 eV and T_{high}=3.1 eV, and plasma densities $N_{low}=1.3*10^{10}$ cm^{-3} and N_{high}= $1.3*10^{9}$ cm^{-3}. The low-energy elecrton group, with its temperature close to the energy of the Ramsauer minimum, has an extremely low electron-neutral (e-n) collision cross section corresponding to a low e-n collision frequency. These electrons oscillates collisionlessly in the weak bulk RF field, and unable to gain energy either from the RF field due to Ohmic heating or from the oscillating RF sheath due to stochastic heating. High-energy electrons effectively interact with argon atoms in elastic, excitation and ionization collisions and serve as the source of the low-energy electrons for the most part due to ionization. These electrons compensate energy losses mainly through stochastic heating on the oscillating plasma-sheath boundaries. In order to increase plasma density in CCDs one needs to increase the high-energy electrons population. This can be done by heating of low-energy electrons in the plasma bulk by (i) the collisionless electron bounce resonance heating [6-9], and by (ii) the stochastic electron heating due to plasma oscillations. It is necessary to emphasize, that the stochastic heating in the bulk plasma is usually more effective than the stochastic heating due to interaction with oscillating boundaries [10,11]. Stochastic heating of electrons by plasma oscillations excited in the CCD plasma is investigated theoretically and numerically. We have obtained the criterion, when the stochastic heating of low-energy electrons by plasma oscillations take place. PIC-MCC simulation shows that this heating mechanism can be sufficiently effective in order to increase plasma density and to control EEDF in CCDs.

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8-35

KINETICS OF ARGON PLASMA NEGATIVE GLOW IN PRESENCE OF METASTABLE ATOMS

V. Yu. Bazhenov, S.V. Matsevich, V.M. Piun, A.V. Ryabtsev, V.V. Tsiolko

Institute of Physics NAS of Ukraine, Gas Electronics Department
Nauky av. 46, Kyiv, 03028, Ukraine
e-mail: tsiolko@iop.kiev.ua

Argon and its mixtures with reactive gases in a form of low pressure discharge plasma are widely used for etching and surface modifying processes in industry. In the most cases, understanding of plasma kinetics for these processes is very important for achieving the best treatment results. This information can be obtained from the study of electron energy distribution function (EEDF).

In this work EEDF low temperature argon plasma in the hollow cathode is investigated for 2 – 12 Pa gas pressure range. It is shown experimentally and theoretically that the EEDF is essentially bi-maxwellian. One can see a knee on the EEDF near 4 eV value, and two effective electron temperatures (0.4-0.5 eV and 3.5-4 eV for low-energy and high-energy part, respectively). It is supposed that this shape of the EEDF can be due to excitation of $2p_1$ - $2p_{10}$ levels of argon ($3p^5 4p$ configuration) from metastable $1s_5$ and $1s_3$ levels ($3p^5 4s$ configuration).

Concentration of metastable argon atoms is measured by means of detecting the emission of lines sharing the same upper level, and subsequent calculation of the concentration taking into account light re-absorption in the plasma. Measured concentration of argon atoms in metastable $1s_5$ state is about 10^{11} cm^{-3}.

Simulation of kinetic processes in the discharge on a basis of one-dimensional model confirms two-temperature shape of the EEDF for concentrations of metastable atoms of about those measured experimentally. The simulation also shows that the EEDF is strongly affected by electric field strength, as well as metastable atoms concentration.

8-36

PLASMA ASSISTED COMBUSTION OF PARAFFIN MIXTURE

O.A. Nedybaliuk[1], V.Ya. Chernyak[1], E.V. Martysh[1], T.E. Lisitchenko[1], O.Yu. Aktan[2], S.G. Orlovska[3], N.V. Belenok[4]

[1] *Faculty of Radio-Physics, Kyiv National Taras Shevchenko University, Prospect Acad. Glushkova 4G, Kyiv 03022, Ukraine*
[2] *Faculty of Physics, Kyiv National Taras Shevchenko University, Prospect Acad. Glushkova 4, Kyiv 03022, Ukraine*
[3] *Dept. of Thermal Physics, Odessa National Universiy, Dvorjans'ka str. 2, Odessa 65026, Ukraine*
[4]*National Technical University of Ukraine "Kyiv Polytechnic Institute", Prospect Peremogy 37, Kiev 03056, Ukraine*
oanedybaliuk@gmail.com

The idea of using a nonequilibrium low temperature plasma for ignition or combustion stabilization seems to be promising today. A number of papers devoted to results review on different gas discharges, used for plasma-assisted ignition and combustion, namely: streamers, dielectric barrier discharges, radiofrequency discharges, pulsed nanosecond discharges (sparks, dielectric barrier discharges, volume nanosecond discharges) and different mechanisms for them, such as ion chemistry and chemistry of excited species, are proposed and investigated. However, the focus was only gas-phase fuel mixtures, and studies to stabilize the solid fuels combustion are practically absent.
In recent years the idea of using paraffin to create new fuel was realized. It is well-known that paraffin is saturated carbons which contain only carbon and hydrogen and have the general formula C_nH_{2n+2}. The paraffin can be found in the liquid and solid state depending on the number of $-CH_2-$ groups. In spite of the presence of merit significant paraffin based fuel, the question about its advantage in the comparison with the traditional petrol fuels is debatable. One of this discussion reasons connected with chemical sluggishness of paraffin. The need for an additional activation of the combustion appears in connection with this fact. Plasma stimulation is the most effective means for this purpose. Depending on the field of application, the paraffin based fuels can exist in a liquid and solid state. Such experiments for solid paraffin and its mixtures were not carried out in contrast to liquid paraffin. In this work the results of solid paraffin combustion with the aid of the plasma of transverse and rotational glidding arc studies are represented.
The question of the additional activation of paraffin based solid fuels is examined. The use of plasma stimulation for this purpose is proposed. The mixture of n-paraffin and stearin in the solid state as the model of the solid paraffin based fuel is used. The plasma assisted combustion of this model is experimentally investigated. The voltage-current characteristics of discharge at the different regimes are measured. The emission spectrums of a flame and the plasma torch emission spectrum are obtained. The population temperatures of excited rotational levels are determined. The flame temperature during the combustion of solid paraffin containing mixture is calculated.

8-37

RADIATED EMISSION FROM HALL ACCELERATOR (THRUSTER)

S.A. Oghienko
National Airspace University "Kharkov Aviation Institute",
Chkalov st. 17, Kharkov 61070, Ukraine, e-mail: oghienko@yahoo.com

The frequency band of a radio signal used for communication through an Earth ionosphere is interfered with a band of electromagnetic (EM) waves generated in plasma of the Hall accelerator (thruster). The general power of EM emission is estimated base on experimental data - emission power density in the f≈2…5 GHz band as ~10^{-3} W, and also ~10^{-7} W according to date obtained by other researchers in close operation modes of accelerator. Till now it is not revealed publications where there would be an analysis of how this emission can be generated and which would be prove by qualitative calculation.

The power of not coherent EM emission that can be generated in various ways in GHz band in plasma with characteristic parameters plotted in fig. 1 were estimated as the next.

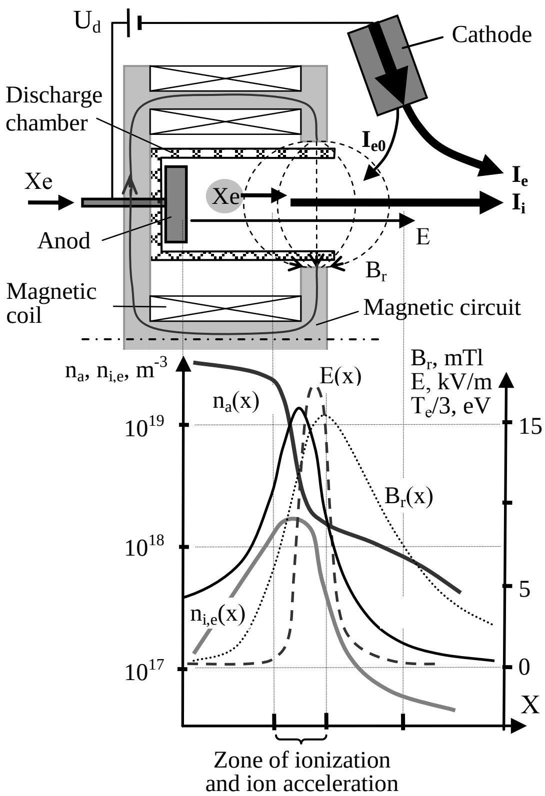

Fig. 1. Plasma parameters distribution in the discharge interval.

The band of w≈10…40 GHz and power N_{emAH}≈10^{-10} W of EM emission generated by electrons, accelerated in potential drop $\Delta\varphi_w$≈1 V in the space region of extension ≤1 mm in an azimuthal direction of an ion stream, were calculated. Power of EM emission N_{emW}≈$2\cdot10^{-10}$ W (in a band of probable frequencies w≈10…40 GHz) generated by electrons, accelerated in potential drop $\Delta\varphi_w$≈2.5·T_e in close to the wall layer of ≈1 mm thickness, was calculated. It is suppose that in both cases owing to antenna preliminary phasing of movement of electrons it can be generated coherent EM emission of power up to N_{em}~$10^{-3…-4}$ W.

Electron cyclotron frequency band in plasma in the zone of gas ionization and ion acceleration is w_b=2…3 GHz that only at the 4^{th}…5^{th} harmonic reaches experimental value w=2·π·f≈12 GHz. Power N_{emC5s} of EM emission at the 5^{th} harmonic from plasma in this zone of volume V_{DC}≈$5\cdot10^{-5}$ m^3 is only N_{emC5s}≈$2\cdot10^{-25}$ W.

It was calculated power of plasma waves N_{plV-C}≈1…3 W generated at frequency w≈12 GHz in a band of 2 GHz owing to Vavilov-Cherenkov effect in the region out the accelerator but close it, where the stream of electrons (emitted by the cathode) with temperature T_{eS}≈0.5 eV and velocity V_s=(2…3)·10^6 m/s moves in plasma with temperature T_{ePL}≈1…0.5 eV. Increment μ of plasma waves generation in this region of instability of a system stream-plasma is only μ≈-1.5 m^{-1} and a share of coherent waves is very small. By transmission of plasma waves power to power of EM emission (due to plasma density heterogeneities) in the same frequency band with factor Q~10^{-7} it was calculated power of EM emission N_{emV-C}=N_{plV-C}·Q≈(1…3)·10^{-7} Вт within the corner ≈15^0 to direction V_s.

8-38

INFLUENCE OF ELECTRON EMISSION EFFECTIVENESS ON CHARACTERISTICS OF NEGATIVE CORONA DISCHARGE

O. Bolotov, V. Golota, V. Ostroushko

NSC "Kharkov Institute of Physics and Technology" NASU, Kharkov, Ukraine

Investigations of negative corona glow in atmospheric air in Trichel pulse mode show considerable expansion of glow region in direction transverse to field direction when the mode approaches to stationary one.

It was carried out axially symmetric numerical simulation with account of ionization, attachment, ion-ion and ion-electron recombination in discharge gap and ion-electron emission and photoemission from cathode. If ion-electron emission coefficient value is taken $10^{-3} – 10^{-4}$, as it is usual for simulations, then calculations give the mode with interval between pulses a some hundreds nanoseconds, which is less than experimental value, approximately, by factor 10. Such result is coordinated with the simple estimations for self-consistent discharge operation based on impact ionization and ion-electron emission in the structure used in experiment, in connection with small contribution of negative ions to the field in the region of intensive electron multiplication, in the considered conditions. The pulse interval may be greater in the case when self-consistent pulse development needs the region with dimension some greater than curvature radius of cathode tip and negative ion contribution to field in part of the mentioned region far from cathode is essential, and so, negative ion influence on renewing of self-consistent pulse development is essential. The dimension of the region necessary for self-consistent pulse development may be greater, in particular, if the taken ion-electron emission coefficient value is smaller. The small effectiveness of ion-electron emission, in comparison with photoemission, in atmospheric air, is in accordance with available data.

When the value of ion-electron emission coefficient taken in simulations was considerably diminished the interval between pulses become much greater, and also, it was expanded in the direction transverse to symmetry axis the region, in which maximal in time value of electron density is not small and electric field strength is sufficient to excite molecules to states, transitions from which are accompanied with radiation in the visible range. When effectiveness of ion-electron emission diminishes, in the considered axially symmetrical structure, the parts of the surfaces of constant field strength and particles densities far from the symmetry axis draw to cathode nearer to a greater degree than the parts of the surfaces near the symmetry axis. It results from the need to enhance the applied field to ensure self-consistent pulse development, in the case of decrease of emission effectiveness, and relevant applied voltage enlarging is accompanied with field enhancing far from axis, where field is comparatively weak. Relative effectiveness of influence of field enhancing on impact ionization, which may be characterized by logarithmic derivative of ionization coefficient with respect to field strength, grows with field weakening. So, with voltage increase, the part of the region with relatively intense glow far from the symmetry axis draw to cathode nearer to a greater degree than the part of the region near the symmetry axis. As a result, in the case of small ion-electron emission coefficient it is observed the expansion of glow in the transverse direction.

The interval between pulses depends, in particular, on the electric field strength in the region of negative ion drift close to cathode. If anode is replaced with one having smaller curvature radius then electric field in discharge gap is redistributed: it becomes stronger near anode and weaker near cathode, which slows down the negative ion drift in the region closer to cathode and results in slowing down of renewal of electric field near cathode after previous pulse. As a result, with decrease of radius of anode curvature the interval between pulses increases.

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ON THE INFLUENCE OF METAL IMPURITIES ON THE TRANSPORT PROPERTIES OF MULTICOMPONENT ARC PLASMA

P. V. Porytskyy

Institute for Nuclear Research, pr. Nauky 47, Kyiv 03680 , Ukraine
e-mail: poryts@kinr.kiev.ua

The influence of metal impurities (copper, alkali and alkali-earth metals) on the transport properties of thermal plasma is considered in the ambient atmosphere of argon and carbon dioxide. The calculations are carried out, and it is shown that a small amount of metal causes the essential changes in the values of transport coefficients in comparison with the case of pure gaseous mixture of argon and carbon dioxide. It is revealed that the influence of the Ramsauer effect on transport properties can be neutralized by additions of metal into ambient argon.

The Grad method of moments [1,2] is used to calculate the transport coefficients (electrical and thermal conductivities, viscosity, diffusion coefficients). The approach based on Lorentzian plasma model [3,4] is used for control of calculation procedure. The obtained results are compared with the data calculated with the Chapman-Enskog method [5-7]. It is deduced that for the case of the Grad method the suitable precision of calculations of transport coefficients can reached for more simple and faster calculation procedure than in the case of the Chapman-Enskog method.

The applicability of the calculation procedure based on the Grad method is presented for the case of thermal plasma. It is shown that the approximation of 13-moments is suitable to calculate the coefficients due to heavy particle transfer. For electronic transport coefficients it is needed to use the higher approximations of the Grad method.

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8-40

INFLUENCE OF ADDITIONAL ELECTRON SOURCE UPON THE MICROPLASMA DISCHARGE INSIDE DIELECTRIC CELL

O.I.Kelnyk, O.V.Samchuk

Taras Shevchenko National University of Kyiv, Radio Physics Faculty
60 Volodymyrs'ka St.,01033, Kyiv, Ukraine
oles@univ.kiev.ua

Small energetic efficacy (about 1%) is a main problem for plasma display panels' (PDP, [1]) applications. Such displays usually apply microplasma discharge as a source of UV radiation and most energy losses in PDP cell are related directly to this discharge. So searching for the ways to increase this efficiency is important for PDP technology improvement. For that purpose, one can use the additional electron current source at the stages of discharge ignition and firing. In this report, we investigate the influence of such additional electron source on discharge current waveforms via the computer simulations.

Computer simulations were performed for the standard dielectric PDP cell [1] with 500*200μm sizes and coplanar electrodes' configuration. One coplanar electrode was considered under the -250V potential, two another were grounded. Discharge were fired in gas mixture containing 90% neon and 10% xenon with 500 Torr total pressure. Simulation was carried out with our original 2D code [2] that applies the particles-in-cells (PiC) method with Monte Carlo method for collisions (about 100 elementary processes were taken into account). Two kinds of additional electron source were considered - one pulse of electrons at the beginning of discharge ignition and permanent modulated electron current. That source was positioned near the non-grounded coplanar electrode.

Without the additional electron current source, features of discharge current waveforms were discussed in our previous work [3]. In this work we studied such waveforms for additional modulated electron stream with average value of 5 μA (10% of discharge current pulse magnitude) and modulation amplitude 2.5 μA. Comparison of discharge current waveforms with and without the additional current source was carried out for all three electrodes. For non-grounded coplanar electrode, additional current with 10% of total discharge current magnitude make this magnitude 50% larger due to the better discharge ignition conditions in the additional electrons' source presence. Also, there are some oscillations of modulated additional current at discharge damping stage because the beam-plasma instability. For grounded coplanar electrode, additional electron current practically don't make any changes because this current do not flow to this electrode. For address electrode one can see pulsations with relatively large period in the presence of additional source. In the case of additional starting electron pulse, discharge current waveforms changes similarly except the beam-plasma instability that cannot develop without permanent additional current. Nevertheless, magnitude of discharge current pulse is also increased. discharge

Both pulse and permanent additional electron current sources improve the energetic efficiency of microplasma discharge inside the dielectric PDP cell to about 10%.

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8-41

FEATURES OF MICROPLASMA DISCHARGE IN DIELECTRIC PDP CELL WITH AUXILIARY COPLANAR ELECTRODE

O.I.Kelnyk, O.V.Samchuk
Taras Shevchenko National University of Kyiv, Radio Physics Faculty
60 Volodymyrs'ka St.,01033, Kyiv, Ukraine
oles@univ.kiev.ua

Multi-electrode discharge configurations are proposed in the large amount of research works where auxiliary electrode in the cell of plasma display panel (PDP, [1]) is applied for control voltage pulses at reset and address periods. According to recent works [2], for the similar discharge cell parameters and voltages, auxiliary electrode make it possible to lower the discharge firing voltage as well as minimum address voltage. Furthermore, the address discharge time lag is reduced considerable more in comparison with the conventional waveforms in standard coplanar configuration. This work is devoted to computer simulation of the processes in microplasma discharge inside typical dielectric PDP cell in order to investigate the electron energy distribution in the case of relatively high voltage applied to the auxiliary coplanar electrode.

Simulation was carried out with our original 2D electrostatic PIC-MC code for weakly ionized discharge plasma in the Ne(95%)-Xe(5%) gas mixture inside the dielectrically insulated cell with 600*200 μm dimensions. Total pressure inside the cell was considered 500 Torr. There were two main coplanar electrodes covering almost all front side of the cell except the 60 μm gap (conventional PDP cell [1]). Thin (about 10 μm) auxiliary electrode positioned in the middle of this gap. Simulations were carried out with standard discharge voltages of 230V, 250V and 270V (see [3]) applied between grounded address electrode and one of coplanar electrodes. Another coplanar electrode was also grounded. In order to obtain strong electric field inside the cell, relatively high voltage of 500V was applied to auxiliary electrode for first 100ns time period. After that, potential of auxiliary electrode was set average between the coplanar ones. Results were compared to the previous ones for coplanar microplasma discharge without auxiliary electrode [3].

Regardless the fact that electric potential disturbance from auxiliary electrode inside dielectric cell is rather small due to the screening, discharge current waveform in this case has a shape of sharper pulse that begins earlier, have larger magnitude and drops quicker at discharge decay stage. Also two discharge regimes, the volume and the coplanar, were observed. Number of striation structures [4] is lowered and they become to form at both sides from main discharge region due to its smaller size.

Electron energy distribution function differs both from Maxwell function and from the similar function for the case without auxiliary electrode. There are additional electrons in the high energy band capable to neutrals' excitation and ionization. These additional electrons are produced by strong electric field in small area near the auxiliary electrode that accelerates charge particles. So the auxiliary electrode can be used for control of non-equilibrium electron energy distribution function.

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8-42

PULSED MAGNETRON SPUTTERING SYSTEM POWER SUPPLY WITHOUT LIMITATION AND FORCED INTERRUPTION OF THE DISCHARGE CURRENT

A.A. Bizyukov[1], K.N. Sereda[1], V.V. Sleptsov[2], I.K. Tarasov[1], A.G. Chunadra[1]

[1]*V.N. Karazin Kharkiv National University, Svobody sq., 4, 61077, Kharkiv, Ukraine*
[2]*K.E. Tsiolkovsky Russian State Technological University (MATI), Orshanskaya 3, 121552, Moscow, Russia*

Recently the film deposition technique by means of the magnetron sputtering (MSS) is widely used in fabrication of microelectronic devices, displays, and manufacturing of functional and decorative coatings. The size of operational surface may vary from several millimeters to several meters, for example glass panels and roll materials. The efficiency of magnetron sputtering deposition is proportional to the power applied to the discharge, and considering that magnetron discharge operates as voltage stabilizer, it is proportional to magnitude of the discharge current. Technological objective of the roll material coating is increasing the deposition rate, and thus increasing the discharge current. In a MSS exceeding the certain current threshold leads to a change of a glowing regime from glow discharge to arc discharge. The transition to the arc discharge regime leads to formation of the cathode spots of the second kind and generation of droplets of the target material, that substantially deteriorate the quality of the coatings.

The application of pulsed operation modes of MSS would greatly reduce the impact of negative factors on the quality of obtained films. In particular, pulsed plasma-assisted processing of the surfaces provides lower temperature loads on products, increases thickness uniformity of the coating that is deposited on the surface with complex relief, suppresses the formation of stressed states in films. Launching of standard planar MSS in pulsed operating regimes requires development of the special pulse power supplies, which provide feeding electrodes of the system with voltage pulses of the magnitude, sufficient for breakdown and glowing of the magnetron discharge, with various frequencies and duration, and magnitude of discharge current, sufficient for film deposition with required mass transfer rate.

In this paper the power supply design of the planar magnetron sputtering system using the pulse power unit is presented. The proposed design of the pulse power unit (without forced limiting and interrupting of discharge current) well operates in technological range of glowing of magnetron discharge. Pulsed discharges with duration up to 10 *ms* and discharge current up to $60\,A$ with pressure in operational chamber $(1 \div 5)\cdot 10^{-3}\,Torr$ were obtained. Photorecording of the surface of sputtered target of MSS at the moments of discharge pulses gives evidence of absence of cathode spots of the second kind.

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EXPERIMENTAL SIMULATION OF METAL-HYDRIDE CATHODE WORKING IN PENNING DISCHARGE

I.V. Borgun, D.L. Ryabchikov, I.N. Sereda, A.F. Tseluyko
Kharkiv national university by V.N. Karazin

For effective operating of plasma particle sources it is necessary to feed the working substance immediate in the working part of a source. It often causes a number of technical inconveniences and leads to increasing of size and final cost of the device as well. For sources working on hydrogen there is an alternative way of this problem solution. It is perspective to apply the solid-state reversible hydrogen generator based on metal-hydride of Zr–V system as a cathode material of the discharge. The hydrogen yield (desorbtion) is caused by thermal heating of the sample. The operating factor influenced on the value of desorbed hydrogen flux is discharge current. But the first experiments on penning type ion source with metal-hydride cathode showed a number of differences in discharge conditions and its emissive ability. Particularly at heightened anode voltage the transition of the source at electron emission mode in longitudinal direction is observed. This effect is apparently connected with HF instability developed in the discharge and demands the further investigations.

In the paper the experimental simulation of metal-hydride cathode working in the penning type source of charged particles have been carried out with aim to reveal the factors responsible for electron emission. With that end in view balloon hydrogen feeding was realized through the one of the discharge cathode. The general discharge characteristics, HF oscillation spectra of space potential and emissive ability of the device have been carried out. The comparative analysis of data for metal-hydride cathode [1] and results of this experiment have been taken.

It was set, that in case of the discharge with metal-hydride cathode the ratio between radial and axial electric fields distribution is that the maximum ionization occurs in anode layer. Thus in conditions of high radial and low axial electric fields the electrons ejected from instable anode layer could leave the discharge in longitudinal direction. In simulation experiment the area of intense ionization expands on the central part of the discharge as well. Axial electric field is high and electrons can not overcome potential barriers close to cathodes. The discharge works as ion source. It was shown as well, that addition hydrogen flux from a cathode influences only on axial electric field distribution.

Thus, the results of the experiment showed the determinative role of metal-hydride cathode in the processes of axial electrons flux forming from the reflective discharges. Metal-hydride is a source of atomic hydrogen in unbalanced state that, apparently, the determining factor in HF instability and axial electron flux emission development.

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8-44

PROPAGATION OF MULTICOMPONENT PLASMA OSCILLATIONS ALONG THE MAGNETIC FIELD IN THE PULSED REFLEX DISCHARGE

Yu.V.Kovtun, A.I.Skibenko, E.I.Skibenko, I.B.Pinos, Yu.V.Larin, V.B.Yuferov

National Science Center "Kharkov Institute of Physics and Technology", NAS of Ukraine
1, Akademicheskaya, Kharkov, 61108
E-mail: Ykovtun@kipt.kharkov.ua

Plasma in the crossed $\boldsymbol{E}\times\boldsymbol{B}$ fields is interesting for solving a wide range of scientific and applied problems of plasma physics in the field of investigations into the laboratory, fission and extraterrestrial plasmas [1]. A particular feature of the plasma being in the crossed $\boldsymbol{E}\times\boldsymbol{B}$ fields is its drift rotation which, in the case of multicomponent plasma, leads to the spatial ion component separation. Investigations were carried out to estimate an opportunity of using the rotation-plasma device for material separation and to develop facilities and complexes designed for material separation into the mass groups and elements [2]. One of a special case in the large class of rotation-plasma devices [1] is a reflex discharge. Investigations on the reflex discharge have the many years' history, however, at present some problems are not studied or poorly understood. For example, it is the question about the plasma excitation in the reflex discharge and oscillation propagation along the magnetic field.

In the paper presented are preliminary results of investigations into the multicomponent gas-metal plasma arising in the high-current reflex discharge, in particular on the plasma oscillation propagation along the magnetic field. The previous investigations on this subject are described in [3.4]. The gas-metal plasma was formed due to the discharge in the medium of firing Ar gas and sputtered cathode material (Ti). Maximum plasma density was $N_p \geq 1\times10^{14}$ cm^{-3}. Discharge voltage and current were $U_{dis.} \leq 4$ kV and $I_{dis.} \sim 1.8$ kA respectively. The pulsed magnetic field of 18 ms duration had a mirror configuration with a maximum induction in the device center, $B_0 \leq 0.34$ T. The plasma oscillation propagation was investigated using the microwave fluctuation reflectometry. In the case under consideration, unlike [3,4], the homs of microwave transmit-receiving antennas were spaced along the magnetic field. The use of joint correlation functions of reflected microwave signals made it possible to determine characteristic times of plasma oscillation propagation along the magnetic field. Plasma location was carried out by the O-wave having the wave length $\lambda = 8$ mm. Comparison between the autocorrelation functions of reflected microwave signals spaced along the magnetic field has shown that periods of autocorrelation functions are close to each other, i.e. the angular rotation velocities are similar and such a dependence corresponds to the isorotation law.

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8-45

ON THE INFLUENCE OF ELECTRODE EROSION ON THE PROPERTIES OF NONIDEAL PLASMA OF UNDERWATER DISCHARGES

P.D. Starchyk, and P. V. Porytskyy

Institute for Nuclear Research, pr. Nauky 47, Kyiv 03680 , Ukraine
e-mails: starchik@kinr.kiev.ua, poryts@kinr.kiev.ua

The underwater discharges are studied intensively in connection with its various technological applications. In arcs and electrical pulse discharges in liquids a high-density non-ideal plasma column contacts with limiting it condensed medium. The processes on the contact interface are essentially for the properties of the discharge as a whole. The most important influence on plasma of electrical pulse discharges in liquid (EPD) have the processes in a zone of its contact with condensed medium [1,2].

At the initial phase of EPD small-scale irregularities of heat flow distribution were detected on a surface of channels. Development of such perturbations was accompanied by space modulation of an irradiation intensity, strain of a surface of channels, drop of conductance of plasma. One from reasons it is established further by comparison of a strain of a surface of plasma channels of EPD with outcomes of simulation on the basis of a solution of the task to development of Rayleigh-Taylor instability (RT-instability).

The irregularities have caused the turbulent mixing of ionized gas-vapor-liquid mixture in the channel of discharge. Because of that the plasma consists of a number of various components at high pressure. In the paper the transport properties (electrical and thermal conductivities, viscosity, diffusion coefficients) of multicomponent plasma are studied for the conditions of underwater discharges.

The most important factors determined the properties are the following: gaseous and plasma non-idealities, multicomponent contents. To include the factors into consideration the combined calculation procedure is used on the base of the Grad's method [3,4] and Lee-More theory [5]. The non-ideality corrections to equation of state are made according to [6-8]. The obtained results are compared with the previous calculations based on the Lorentzian theory [9].

The erosion of electrodes leads to the appearance of metal impurities in the plasma channel of discharge. The calculations are carried out, and it is shown that a small amount of metal causes the essential changes in the values of transport coefficients in comparison with the case of pure water mixture. The problem of differentiation of so-called 'thin' and 'thick' discharges is discussed.

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DEVICE FOR OZONE CONCETRATION MONITORING OCM-3

V.S. Taran, S.P. Gubarev, G.P. Opaleva, M.I. Zolototrubova.

Institute of Plasma Physics, NSC Kharkov Institute of Physics and Technology, Akademicheskaya St., 1, 61108, Kharkov, Ukraine.

The Kharkov Institute of Physics and Technology has been actively working to develop the microprocessor devices for ozone measuring instruments such as:

- device based on ozone optical (UV) absorption (measurement of O_3 to 80 mg/ l);
- ozone meter based on corona discharge (measurement of O_3 to 40 mg/ l);
- meter- indicator of ozone MACs.

This paper describes a developed microprocessor device for measuring health-hazardous concentrations of ozone in the room and alarming in the case of exceeding the maximum allowable concentration (MAC) or other level of concentration specified by software.

Due to increased production of ozone sterilizers and the expansion of the scope of the ozone technologies the question of it's safety use is actual. A lot of widely used ozone measuring concentration instruments, such as Ozone-MAC, produced OKBA Angarsk (Russia) [1], the analyzer 3-02.P-R (Smolenskpribor, Russia) [2], Ozone Monitor Model 205 (2B Technologies, USA) [3], etc. are quite expensive (up to $ 4,000) and the lack of their production in Ukraine the task of developing low-cost domestic analogs is put.

Device provides automatic measuring of ozone concentration, indicating the current value of concentration, setting threshold and turning on of audio alarm, transferring data to a central computer. Device OCM-3includes a microcontroller, a communicator with a computer display, indicator, alarm function and controlling unit. The microcontroller is implemented on the base of an integrated circuit PIC18F2550 produced by Microchip Technology Inc.[4]. In this device was used solid-state sensor of MQ-131 series produced by HENAN HANWEI ELECTRONICS CO., LTD.[5].OCM-3 is low-cost, simple device which allows to use it in a wide sphere of ozone technologies to ensure the safety of personnel. *The prototype of the device is made.*

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8-47

THE SIMULTANEOUS SYNTHESIS OF HYDROGEN-RICH GAS AND OXIDATION OF FINE METAL PARTICLES IN WATER VAPOUR PLASMA

V. Valincius, V. Grigaitiene, P. Valatkevicius, A. Tamosiunas

Lithuanian Energy Institute, Breslaujos 3, LT-44403 Kaunas, Lithuania

The demand for knowledge on the fuel conversion and production of hydrogen as an alternative energy source has significantly increased in the recent decades. It is well known that thermal water vapour plasma is an unique ambient and may affect the production of syngas and formation of fine particles or granules. This process may also occur during plasma spraying and deposition of coatings for wide range of applications.

The present study offers a possibility for production of hydrogen-rich gas and additional deposition of small metal oxide dispersed particles by the employment of nonequilibrium water vapour arc plasma at atmospheric pressure. A newly developed linear, sectional, atmospheric pressure arc plasma source with a button-type hot cathode and water-cooling step-formed copper or stainless steel anode has been employed for a realization of fuel conversion process (Fig. 1.). Over-heated water vapour has been used as a plasma forming gas at the arc current intensity of 180 A.

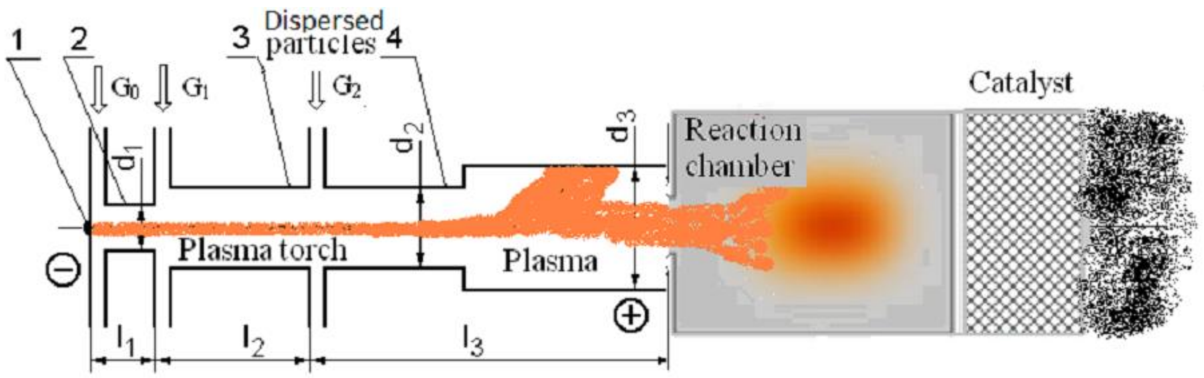

Fig. 1. Water vapour plasma device for fuel conversion and production of hydrogen-rich gas. 1 - cathode junction, 2 - ignition section, 3 - neutrode, 4 - anode. *Go* is injection of initial ignition gas (argon), G_1 - injection of over-heated water vapour, G_3 - injection of additional gas mixed with *C* or *Cu* dispersed particles

By using a properly designed plasma jet reactor connected to the plasma generator (PG), heating gas by energy of electric discharge and keeping the fluid flowtemperature at 3600 K, it is possible to produce dissociated water vapour plasma, avoid the reverse fusion and extract hydrogen or hydrogen-rich gas simultaneously with an oxidation of copper or carbon dispersed particles.

The emission spectra of exhaust Ar/water vapour plasma jet at the exit nozzle of the PG was measured for the determination of elemental composition by means of AOS4-1 spectrometer. It was found that copper and carbon particles effectively remove the oxygen and improve the output of hydrogen in the gasification products.

As a conclusion, it can be stated that the employment of results of the present study enables constructing a specific device which allows a highly efficient production of the synthetic gas containing an increased amount of hydrogen and its use in the production of second generation fuels. The injection of carbon or copper dispersed particles is considered for a better removal of dissociated oxygen and simultaneous synthesis of fine particles for wide range of applications.

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INVESTIGATION OF PULSE BARRIER DISCHARGE IN WATER–AIR MEDIUM

V.S. Taran, V.V. Krasnyj, A.S. Lozina, O.G. Chechelnitskij, O.M Shvets

Institute of Plasma Physics of the National Science Center "Kharkov Institute of Physics and Technology", 61108, Kharkov, Ukraine

Today, barrier discharges are effectively used to introduce discharge products into liquid medium [1-3]. The paper presents the results of utilization of pulse barrier discharge in water-air medium used for water cleaning and disinfection due to ozone generation and formation of various radicals. In order to obtain the optimal ozone concentration dependent on water flow rate and applied voltage the electrical characteristics of the discharge have been investigated. Spectroscopic investigations have been carried out using 2SL40-2-3648USB type spectrometer within the range of 200-800 nm in water-air gap of the discharge. The change of OH and N_2 intensity peaks in discharge as a function of applied voltage was obtained. Oxidation dynamics of indigo liquid solution was determined by microscope-spectrophotometer. It was found that at ozone concentration of 0.7 mg/l, radicals played the main role during inactivation of E.coli test cultures.

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8-49

PLASMA CATALYSIS OF CARBON NANOPARTICLES SYNTHESIS IN THE PYROLYTIC CHAMBER

Iu.P. Veremii, K.V. Iukhymenko, V.Ya. Chernyak, [*]A.I. Leptuga, T.E. Lisitchenko, [**]V.P. Demchina, [**]V.S. Kudryavzev

Taras Shevchenko Kyiv National University, Dept. of Physical Electronics, Volodymyrska str. 64, 01033 Kyiv, Ukraine
[*] *V.Ye. Lashkaryov Institute of Semiconductor Physics of NASU, Nauki pr. 41, 03028 Kyiv, Ukraine*
[**]*Institute of Gas of NASU, Degtjarivska St. 39, Kyiv 03113, Ukraine*

e-mail: veremii@i.ua, chernyak_v@ukr.net

An alternative approach to synthesis carbon nanoparticles from liquid hydrocarbons using non-equilibrium heterophase plasma was consider. Plasma-liquid system reactor was prepared with the DC discharge in a reverse vortex gas flow of tornado type with a "liquid" electrode (TORNADO-LE). The range of discharge currents varied within 50-250 mA. The pressure in the discharge chamber during the discharge operation was ~ 1.2 bar; the static pressure outside the reactor was ~ 1 bar.

We divided in the system the area of the atomization of raw materials and the pyrolytic reaction chamber in which the inject particles serve to create growth centers.

Removed by the flow of gas dust particles with the gathered nanomaterials were collected from sample bottle filled of distilled water, and separate out by decantation and evaporation. Dust particles from the mixture eliminated by processing samples by acid with repeated washing distilled water, and followed by evaporation.

Emission spectra were measured with system that was made up of optical fiber, spectrum device with CCD-line and PC. The spectrometer worked in range 200 – 1200 nm with resolution 0.6 nm. PC was used as a control device for measuring and data processing.

The high-speed photo camera Nikon L100 was used in supervision for the process of discharge ignition and existence.

Analysis of gas samples was carried out on gas chromatograph 6890N Agilen.

Purified carbon samples were studied by IR spectroscopy. The tables of characteristic frequencies, the bands of the IR spectrum can be associated with certain functional groups that make up molecules, such as: CH, CH2, CH3, CO, C-C bond in aromatic rings. These functional groups have been traced by us in the spectral range from 3600 to 1000 cm^{-1}.

The comparison of the results of Raman spectroscopy and infrared spectroscopy carbon samples.

For the first time discharge with reverse gas flow of "TORNADO" type with liquid electrode was realized and the possibility of carbon nanomaterials removal from plasma by chemically passive dust particles was shown.

8-50

SOURCE OF REACTIVE NITROGEN BASED ON ECR PLASMA

Vodopyanov A., Mansfeld D., Golubev S.

Institute of Applied Physics of Russia Academy of Sciences

Currently, nitrides of metals of Group III of the periodic system of elements (AlN, GaN, InN) are among the most promising materials for the development of new types of optoelectronic devices operating in a wide range of wavelengths, as well as powerful electronic devices of the microwave range. One of the key problems in the synthesis of group III nitrides is the development of an effective source of reactive nitrogen, which is necessary for incorporation into the crystal lattice.

The paper describes the source of reactive (atomic) nitrogen based on ECR discharge plasma, sustained by technological gyrotron radiation. The radiation frequency is 24 GHz, the radiation power is up to 2 kW. Heating at a high frequency radiation (as compared to traditionally used radiation sources - magnetrons with operating frequency of 2.45 GHz) allows maintaining the plasma in a wide pressure range from 10^{-4} mbar to 10 mbar and the plasma density to reach more than 10^{12} cm^{-3} . This paper presents the results of nitrogen plasma parameters measurements using Langmuir probe. High density of the plasma in the source provides a large flow of reactive (atomic) nitrogen. The flow of atomic nitrogen is estimated by the growth rate of indium nitride films. The flux is at least more than $2 \cdot 10^{17}$ min^{-1}. We also discuss other ways to measure the nitrogen flow.

8-51

TECHNOLOGICAL APPROBATION OF INTEGRAL CLUSTER SET-UP FOR COMPLEX COMPOUND COMPOSITES SYNTHESIS

S. Yakovin[1], S. Dudin[1], A. Zykov[1], A. Shyshkov[1], V. Farenik[2]

[1] *V.N. Karazin Kharkov National University, Kurchatov Ave. 31, Kharkov, Ukraine*

[2] *Scientific Center of Physical Technologies, 6 Svobody Sq., Kharkiv, 61022, Ukraine*

In previous study the results of elaboration and investigations of cluster technological setup for synthesis of complex compound composites were demonstrated. The presented set-up consists of complimentary DC-magnetron system, RF-inductive plasma source and ion source. The set-up system allows to independently form the fluxes of metal atoms, chemically active particles, ions and also to synthesize the thin films of complex compound composites, including nano composites.

In the present paper the results of technological approbation of the integral cluster set-up for synthesis of various types of high-quality coatings such as Al_2O_3, TiO_2, ZrO_2 and others with coating thickness up to 10 mkm are presented. Volt-ampere characteristics of magnetron discharge in argon and mixtures with oxygen, nitrogen for various gas pressures and for various target materials have been measured. Dependences of discharge parameters on target material, pressure and composition of working gas are analyzed.

The research was financially supported by government research program of Ministry of Education and Science of Ukraine.

8-52

THE STUDY OF THE NEAR-WALL LAYER IN THE DENSE PLASMA

V.A. Zhovtyansky[1], E.P.Kolesnikova[2]

[1]The Gas Institute of NASU, 39 Degtyarivs'ka St., 03113 Kyiv, Ukraine
[2]National Technical University of Ukraine "KPI", 37 Pobedy Av., 03056 Kyiv, Ukraine

Generally it is possible to enter concept of a near-wall layer, where deviations from the local thermal equilibrium (LTE) are localized. Deviations of three types are most important:

– a distinction between the temperatures of electrons T_e and heavy particles T_h, defined as a length L_e where electron thermal conductivity and heating of the electrons by the ambipolar electric field are comparable to electron energy exchange in collisions with heavy particles

$$L_e = \lambda_{ei}(\delta)^{-1/2}, \quad (1)$$

where λ_{ei} is mean free path of charged particles and δ – accommodation coefficient;

– a violation of ionization equilibrium, defined as the recombination length L_r, where the rate of variation of the charged particle density due to ambipolar diffusion is comparable to the ionization or recombination rates (the latter rates are of the same order of magnitude if the considered conditions are not too distant from ionization equilibrium)

$$L_r = (D_{ia}/\alpha N_e^2)^{1/2}, \quad (2)$$

where D_{ia} is coefficient of diffusion of ions in atoms and α – recombination coefficient;

– a violation of quasineutrality, defined by the Debye radius L_d, as a scale

$$L_0 = L_d(eU_p/kT_e)^{3/4}, \quad (3)$$

where U_p is the voltage across the layer.

The ordinary hierarchy of characteristic lengths for near-wall layer is

$$L_0 << \lambda_{ia} << L_e << L_r. \quad (4)$$

In this case the layer properties may be studied analytically.

In this work were studied the role of near-surface processes in the decay of the pulse electric arc plasma in argon and helium. The electron density consisted of $2\cdot10^{16}$–10^{15} cm^{-3} and the hierarchy of characteristic lengths for near-wall layer becomes

$$L_0 << \lambda_{ia} << L_e \sim L_r. \quad (5)$$

As is shown the electric probes are a very useful diagnostic instrument in this case. Certainly, the probes cannot be applied to local measurements of plasma parameters in the near-wall sheath, as it thickness does not exceed, as a rule, 0.1 mm. However a similar sheath surrounds a probe itself; that is why the conclusions on its properties can be reached on the base of a probe characteristic determination. In this case a probe is already the instrument for integral measurements of the plasma parameters averaged over a mentioned sheath thickness.

In the near-wall plasma, the parameter $\eta = L_r/\lambda_{ia}$ is determining factor in attenuation of diffusion flow of charge particles from plasma on a wall. In this case the density of ion saturation current for a cylindrical probe j_i of radius R_p may be presented as

$$j_i = (1/4)eN_e v_i \lambda_{ia}/R_p, \quad (5)$$

e. g. it differs by a multiplier λ_{ia}/R_p from a case of Langmuir probe.

It follows one of the remarkable properties of the probe in analyzing regime: the value $I_i \sim 2\pi R_p j_i$ of ion saturation current for a cylindrical probe is independent on its radius R_p. It allows identifying directly a probe operating regime, using double probes of different diameters and comparing their ion saturation currents. It was determined that the diffusion flow of the charge particles to the wall is lowered by a factor of 50 due to near-surface layer. It was also shown that the standard assumption of equality of temperatures of the heavy particles T_h, in the near-surface plasma and wall T_w, is not fulfilling in the near-probe region.

9-01

BEHAVIOUR OF ELECTRON CYCLOTRON EMISSION FOR OPTICALLY THIN PLASMAS DURING VARIOUS RF PLASMA PRODUCTION SCENARIOS AT URAGAN-3M TORSATRON

R.O. Pavlichenko, A.E. Kulaga, N.V. Zamanov, V. Ye. Moiseenko, A.V. Lozin, Yu.K. Mironov, V.S. Romanov, V.V. Chechkin, L.I. Grigor'eva

Institute of Plasma Physics NSC KIPT, Kharkiv, Ukraine

Radial profile of second harmonic X-mode (X2) electron cyclotron emission (ECE) was observed for optically thin plasma produced by Alfven resonance heating in Uragan-3M (U-3M) torsatron. The radiation was detected from the low field side. For the ECE frequency range 31-37 GHz the reconstruction of electron temperature profile was done for several consecutive shots with the assumption that plasma parameters do not vary from shot to shot. Radial electron temperature profile was derived from "radiation temperature" profile using approximation formula for the plasma optical thickness. The applied conversion procedure ignores multiple reflections from the walls (due to "open magnetic system" of the U-3M device) of the vacuum chamber: according to estimation it gives sufficiently small errors. For special plasma production conditions (additional gas-puffing) an ECE "cut-off" phenomenon (rapid signal drop) due to the overdense plasma is clearly observed.

Thus, it is possible to estimate the value of the local "threshold" electron density. In the absence of Thomson scattering system, the temperature data were cross-checked with other electron temperature related diagnostics (dual foils SXR, optics, etc.). For low density plasma ne$\sim$(0.9$-$2.3)$\times 10^{18}$ m^{-3} and for the magnetic field which was set to 0.72 T strong "afterglow radiation" has been observed after switching off the RF heating pulse.

A new six channel superheterodyne radiometer operating within frequency range 57-74 GHz which is optimized for the X2 radiation (central magnetic field 0.95-1.15 T) is under installation for the plasma experiments. As an initial phase, the experiments for observing optically thin X3 radiation from low field side (central field of 0.68-0.72 T) were performed at the 60 GHz frequency.

For the case where the main magnetic field was downshifted to 0.7-0.68T the rather significant narrowing of the hot plasma radius was observed. This could be attributed to the enhanced heating scenario where RF heating power profile is more shifted to the plasma center.

9-02

DEVELOPMENT AND USE OF CHERENKOV-TYPE DETECTORS FOR MEASUREMENTS OF FAST ELECTRONS IN TOKAMAKS

J. Zebrowski[1], L. Jakubowski[1], M.J. Sadowski[1-2], M. Rabinski[1], K. Malinowski[1], R.Mirowski[1], M. Jakubowski[1], V.V. Plyusnin[3], Ph. Lotte[4] and J-Y. Pascal[4]

[1] *National Centre for Nuclear Research (NCBJ), 05-400 Otwock, Poland*
[2] *Institute of Plasma Physics and Laser Microfusion (IFPiLM), 01-497 Warsaw, Poland*
[3] *Association Euratom/IST, Instituto de Plasmas e Fusão Nuclear, 1049-001 Lisboa, Portugal*
[4] *Association Euratom/CEA, IRFM, F-13108 St Paul-lez-Durance, France*
e-mail: Jaroslaw.Zebrowski@ncbj.gov.pl

The paper reports on progress in design and use of novel detectors for experimental studies of fast (run-away and ripple-born) electrons in various experiments of the tokamak type. The idea of the use of a Cherenkov effect for direct on-line measurements of the fast electrons within tokamaks was presented by scientists from the NCBJ (former IPJ) several years ago. Successive efforts led to the development of prototype detector heads equipped with diamond or aluminum nitrate (AlN) crystals, which were shielded with very thin metal filters in order to eliminate the visible light from plasma and to enable a rough energy analysis of electrons. Those Cherenkov radiators were coupled through optical-fiber cables with fast photomultipliers. Those prototypes were applied for test measurements within the CASTOR experiment in Prague, and later in the ISSTOK device in Lisbon. The preliminary results were presented in several papers, but the main aim remained to develop the Cherenkov detectors for the TORE-SUPRA experiment in Cadarache.

On the basis of feasibility studies and test experiment a Cherenkov probe was also manufactured and applied in the TORE-SUPRA facility. The results obtained by means of that Cherenkov probe were published and it was decided to continue the development of such probes in order to make possible multi-channel measurements and more accurate estimates of electron energies.

During recent two years a new Cherenkov probe equipped with four separate AlN-crystal radiators coated with thin molybdenum filters of different thicknesses has been constructed. Improvements concerned the filter deposition technique, which was based on ultra-high vacuum arc discharges, and the use of new translucent AlN-crystals, those had higher transmission of light signals. New test measurement in the ISSTOK have showed that that majority of fast electrons has energy < 90 keV. Correlations of such electrons with hard X-ray signals (measured simultaneously with X-ray probes) have also been investigated.

Another new Cherenkov probe has been designed and manufactured for TORE-SUPRA experiments. Some preliminary measurements have shown that in the scrape-off-layer region there appear many electron beams of energy < 150 keV. In order to calibrate this probe a small electron accelerator has been constructed and used. The electron-induced signals from calibration measurements enable now more accurate estimation of electron energy in tokamak experiments to be carried out. The main issues of the Cherenkov measurements performed so far have been summarized and discussed.

9-03

STATUS OF MJ PLASMA-FOCUS EXPERIMENT

M. Scholz[1], L. Karpinski[1], V. Krauz[2], P. Kubes[3], M. Paduch[1] and M.J. Sadowski[1&4]

[1] *Institute of Plasma Physics and Laser Microfusion (IPPLM), 01-497 Warsaw, Poland*
[2] *National Research Centre "Kurchatov Institute", Moscow, Russia*
[3] *Czech Technical University (CVUT), 166-27 Prague, Czech Republic*
[4] *National Centre for Nuclear Research (NCBJ), 05-400 Otwock, Poland*
e-mail: Marek.Scholz@ifpilm.pl

The paper presents the most interesting results of the recent research on nuclear fusion reactions and properties of pulse plasma streams, which were generated within the large PF-1000 facility operated at the Institute of Plasma Physics and Laser Microfusion (IPPLM) in Warsaw, Poland.

In general Plasma-Focus (PF) devices belong to the family of the dynamic non-cylindrical Z-pinches, and they are based on pulsed high-current discharges realized between two coaxial electrodes, which are placed in a vacuum chamber filled up with a working gas under appropriate pressure. In general, the PF devices can be considered as power transformers, in which the energy stored in the magnetic field is quickly converted into energy of the pinch plasma. The period from the breakdown to the pinch formation lasts usually a few microseconds. The final stages of a PF discharge are much shorter and they usually last from several tens to a few hundreds of nanoseconds (depending on PF device characteristics).

During the last years the interest in PF devices has considerably grown, because such facilities are ones of the most efficient sources of pulsed fusion neutron emission. The experimental neutron scaling law, which was determined on the basis of measurements performed within devices equipped with condenser banks of energy ranging from a few to hundreds kJ, was described by a simple formula $Y_n \sim I^{3..3-5}$. However, later experimental investigations carried out within MJ-scale devices have showed that there is a certain condenser bank energy limit, above which the scaling law becomes not valid and the neutron yield does not rise up.

Hence, the essential problem to be solved in contemporary PF studies appears to be the determination of the proper bank energy limit. In order to achieve this aim one must understand physics which dominates the dense magnetized plasma formation. This problem is closely related with neutron production mechanisms, as well as plasma dynamics and physics of the conversion of magnetic field energy into the pinch plasma energy. During recent years the experimental studies of high-current PF discharges have been continued at IPPLM within the large PF-1000 facility, which has been operated up to 1 MJ. The recent experimental results are summarized and analyzed.

9-04

OPTICAL EMISSION SPECTROSCOPY OF PULSED PLASMA STREAMS EMITTED FROM A MODIFIED PF-1000 FACILITY

E. Skladnik-Sadowska[1], R. Kwiatkowski[1], K. Malinowski[1], M.J. Sadowski[1-2], M. Kubkowska[2], M. Paduch[2], M. Scholz[2] and E. Zielinska[2]

[1] *National Centre for Nuclear Research (NCBJ), 05-400 Otwock, Poland*
[2] *Institute of Plasma Physics and Laser Microfusion (IFPiLM), 01-497 Warsaw, Poland*
e-mail: Elzbieta.Skladnik-Sadowska@ncbj.gov.pl

The paper presents results of the recent spectroscopic studies of pulsed plasma streams generated within the PF-1000 facility at the IFPiLM in Warsaw. This facility has recently been equipped with a modified inner electrode, which consisted of a thick-wall 230-mmm-dia. Cu-tube and the front Cu-plate with a central tungsten (W) insert of 50 mm in diameter. Interactions of a collapsing current sheath and fast electron beams with this W-insert have changed characteristics of the X-ray emission considerably. Since modifications of the electrode configuration and experimental conditions within the PF-1000 facility could also change characteristics of the emitted plasma-ion streams, it appeared necessary to perform new spectroscopic measurements. The main aim was to record optical emission spectra at different distances from the electrode outlets during various periods of the main discharge, and in particular - to determine changes in the emitted spectral lines for different temporal instants after the current peculiarity (current dip).

The described studies were performed within the PF-1000 facility operated at a pure D_2 filling (under the initial pressure of 1.3 hPa) and powered by a condenser bank charged initially to 24 kV, 380 kJ. The maximum discharge current amounted to 1.8 MA. The optical measurements were started by taking time-integrated pictures of the visible radiation emitted from plasma-ion streams, which was observed behind the optical window and various optical filters, and recorded by means of a CCD camera.

Spectroscopic measurements were performed side-on behind an optical window and an optical collimator coupled with an optical-fiber cable. The use was made of a Mechelle®900 spectrometer. The first series of the spectroscopic measurements was carried out at an angle of 67^0 to the z-axis in order to record emission from plasma produced at the centre of the W-insert. The second series of measurements was performed side-on, in different z-planes (i.e., at various z-distances varied in several steps from 0 to 14 cm from the electrode ends) and with the exposition equal to 5 μs - in order to record time-integrated optical spectra of discharges. The last series of measurements was carried out at distances of 3.5, 6.5 and 8.5 cm from the electrode outlets, with the exposition equal to 100 ns - in order to determine dynamics of the emission of various spectral lines, and in particular of the deuterium and tungsten (WI and WII) lines. This paper presents the most important experimental results and their analysis.

9-05

IONS TEMPERATURE PROFILE MEASUREMENTS WITH AID OF CXRS DIAGNOSTIC AT T-10 TOKAMAK.

A.Barsukov, K Vukolov, E.Gorbunov, Yu.Gott, A.Dnestrovskij, L.Klyuchnikov, V.Korolev, K.Korobov, S.Krasnyanskij, V.Krupin, T.Myalton, N.Naumenko**, A.Nemec, V.Nosachev, Yu.Skosyrev, A Sushkov, G.Tilinin, S.Tugarinov*

RSC Kurchatov Institute, Moscow, RF
**SRC TRINITI, Troitsk, Moscow reg., RF*
***IPh NASB, Minsk, BR*

CXRS diagnostics for ion temperature profiles measurements was created at T-10 on the base of the DINA-6 diagnostic beam with atoms energy 30 keV. Diagnostics was created for modelling of the CXRS diagnostics for ITER. Spectroscopic equipments and methodic of the CXRS diagnostics of ITER are being tested in the diagnostic scheme at T-10.

High performance of spectral equipment allows to provide reliable measurements of ion temperature using the CXRS lines of plasma impurities (CVI 5291 A, HeII 4686 A, etc) and the line of the bulk gas (D_α 6561 A). The possibility of providing of CXRS measurements using the D_α line is very important because of the low concentration of impurities, and so, low intensity of CXRS signal of plasma impurity lines in plasma of T-10.

Ion temperature profiles of T-10 plasma were measured via CXRS diagnostic in shots with various current and density values, with different bulk gases and using of different CXRS lines.

Systematic discrepancy was found by detailed comparison of ion temperature profiles, measured by D_α 6561 A and CVI 5291 A lines. Ion temperature profile measured by D_α line is lower in the plasma centre and broader than profile, measured by carbon line. This discrepancy can be explained by the "halo" effect, which leads to worsening of spatial resolution of CXRS measurements and to deformation of measured ion temperature profile.

Direct measurements of intensities of the CXRS lines of deuterium and carbon inside and outside of the diagnostic beam area have confirmed the existence of the "halo" effect for the D_α line and showed the absence of the "halo" effect for the CVI line.

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9-06

FAST XUV PLASMA IMAGING IN T-11M TOKAMAK

A. Alekseyev, A. Belov, A. Panov

SRC RF TRINITI, Troitsk, Russia

Silicon extreme ultraviolet (XUV) photodiodes are very popular in plasma researches owing to fast response (< 1 μs), and high sensitivity (≥ 0.1 A/W) in wide spectral range 1…5000 eV [1-5]. They provide an opportunity to develop multi-channel diagnostics with good spatial and temporal resolution, and high S/N ratio in a broadband frequency range [2]. However, a direct 2D plasma imaging still is not possible due to limited variety of commercially available detectors manufactured mostly in single-element and linear array packages with wide-edge design preventing their assembling into a matrix array. Special mathematical codes are to be developed for the recovery of plasma XUV emission profile [3], which have quite limited applicability to MHD-active plasmas with reduced poloidal and toroidal symmetries of the emission profile.

For this reason, an experimental 16×16 hybrid matrix array detector unit had been developed recently for the fast XUV plasma imaging with up to 10^6 fps frame rate [4-6]. The detectors were manufactured by the original technology of Ioffe Institute (SPb) providing the spectral response curves very similar to those of well-known AXUV detectors from IRD Inc. Corporation (USA).

The details of diagnostics design and the resent results are present, obtained from this detector array installed into tangential vacuum port of the T-11M tokamak for imaging of fast impurity transport events during the development of plasma MHD instabilities, e.g. major and minor disruptions.

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9-07

MICROWAVE INTERFEROMETER WITH TWO POLARIZATIONS DESIGNED FOR DENSITY RADIAL DISTRIBUTION MEASUREMENT IN THE U-3M AND U-2M TORSATRONS

V.L. Berezhnyj, V.V. Filippov

IPP NSC Kharkov Institute of Physics and Technology, Kharkov, Ukraine

Microwave plasma diagnostics design for modern plasma devices should be optimized for maximum information obtaining from single diagnostics and its minimal size (due to limited number of the diagnostic ports). It is also important to use available standard waveguide equipment.

A practical interest rises to simultaneous exploits of two polarizations of the microwave field in a single diagnostics. If the wave vector $\boldsymbol{k}$ is perpendicular to the magnetic field ***B*****,** the plasma dielectric permittivity $\boldsymbol{\varepsilon}$ can be substantially different for the cases when the wave electric field ***E*** is parallel or perpendicular to magnetic field**.** In the case of the microwave frequency is higher than electron cyclotron $\boldsymbol{\omega_{ce}}$ and electron plasma $\boldsymbol{\omega_{pe}}$ frequencies the permittivity is expressed as follows:

$$\boldsymbol{E} \parallel \boldsymbol{B} \rightarrow \boldsymbol{\varepsilon} = \mathbf{1} - \frac{\omega_{pe}^2}{\omega^2}$$

$$\boldsymbol{E} \perp \boldsymbol{B} \rightarrow \boldsymbol{\varepsilon} = \mathbf{1} - \frac{\omega_{pe}^2}{\omega^2}\frac{1-\frac{\omega_{pe}^2}{\omega^2}}{1-\frac{\omega_{pe}^2}{\omega^2}-\frac{\omega_{ce}^2}{\omega^2}}$$

Recently a new microwave diagnostic technique was designed and tested on the U-3M and U-2M torsatrons. A transmitting horn-type antenna radiates simultaneously microwaves of two polarizations. A receiving horn-type antenna is also received two polarizations of the microwave. Its size is slowly decreased to the standard waveguide size 11x5.5 mm^2. This waveguide is oversized for frequency range 33-38 GHz, and therefore allows both polarizations to propagate. Decupling of these two polarizations and their independent comparison with the input wave is necessary for such an analysis. A standard polarization selector has been designed and manufactured for available standard waveguide cross-sections 7.2x3.4 mm^2 operating in a single mode.

The developed interferometer schemes allow to determine radial distributions of the electron density according to the method described in ref. [1].

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9-08

SPARK DISCHARGE AT HIGH PRESSURE IN ARGON AS A PULSED LIGHT SOURCE FOR SHADOWGRAPH MEASUREMENTS

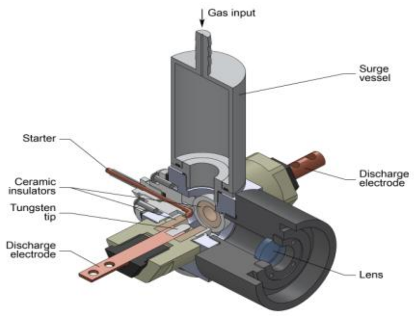
P.P. Khramtsov, O.G. Penyazkov, V.M. Grishchenko, M.Yu. Chernik, I.A. Shikh

A.V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus, Minsk, 220072, Belarus

Shadow method diagnostics of bright plasmas is complicated by need of use more bright blinker than investigated plasma. That is why for obtaining shadow patterns of compressed plasma in plasma flows collision area, suitable not only for qualitative analysis but also for quantitative interpretation of experimental data, a blinker, based on spark impulse discharge in argon was developed (Fig. 1).

Argon pressure in a discharge chamber was 2 atm. The source of light based on a pulsed spark discharge in argon allowed obtaining a light pulse with duration of 3 μs (at the level 0.7 of maximum light intensity). A lamp operating voltage was 20 kV. Usage of this light source in a shadow device allowed registering time-resolved shadow patterns of plasma flows collision.

Registration of optical emission spectrum from discharge was made by spectrometer S150A-IV. The dotted line indicates the spectral region used for the diagnosis of compressed plasma by shadow method (Fig. 2).



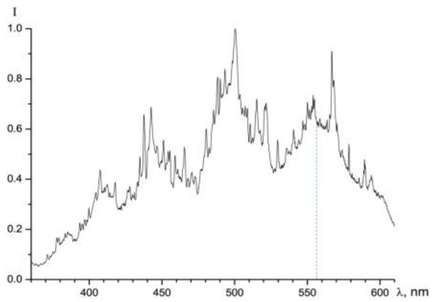


Fig. 1. The design of a pulsed light source

Fig. 2. Optical emission spectrum from discharge in argon at high pressMethod of the electron temperature in argon plasma determination under the assumption of local thermodynamic equilibrium is based on the fact that the densities of various excited states are proportional to the products of statistical weights to the Boltzmann factors of these states. According to this temperature is inversely proportional to the logarithm of the ratio of the total intensities of lines appear at transitions from different upper levels, on conditions that none of these lines are not subject to self-absorption [1].

For the analysis two emission lines of doubly ionized argon atom (500.94 nm and 437.49 nm.) were used. The calculated temperature is 4 eV. The calculation of the electron density in plasma was carried out in accordance with the theory of spectral line broadening due to the quadratic Stark effect [2]. The half-width of argon line $\lambda = 486.0$ nm is $\Delta\lambda_{S,\,4} = 1.04$ nm. So, the electron density was amounted $4.9 \cdot 10^{18}$ $см^{-3}$.

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9-09

PROGRESS IN MASS- AND ENERGY-ANALYSIS OF ION BEAMS EMITTED FROM RPI- AND PF-TYPE DISCHARGES

K. Czaus[1], E. Skladnik-Sadowska[1], M.J. Sadowski[1-2], R. Kwiatkowski[1], K. Malinowski[1], and J. Zebrowski[1]

[1] *National Centre for Nuclear Research (NCBJ), 05-400 Otwock, Poland*
[2] *Institute of Plasma Physics and Laser Microfusion (IFPiLM), 01-497 Warsaw, Poland*
e-mail: Krzysztof.Czaus @ncbj.gov.pl

The paper describes progress in experimental studies of ion beams, which are generated and accelerated within RPI (Rod Plasma Injector) and PF (Plasma-Focus) devices. In order to perform mass- and energy-analysis of such ion beams the use was made of different mass-spectrometers of the Thomson type. Detailed ion measurements in the RPI-IBIS facility were first performed with a large Thomson analyzer placed at the plasma discharge axis, but outside the vacuum chamber. To make possible ion measurements near an outlet of the plasma injector (located inside a large vacuum chamber) two dedicated Thomson analyzers were designed and constructed.

A smaller Thomson analyzer, which was designed and manufactured at the IPJ (now NCBJ), was first applied for studies of ion beams in the large PF-1000 facility operated at IFPiLM. Time-integrated ion parabolas were recorded on PM-355 nuclear track detectors placed in the analyzer image plane, and the obtained results showed that the mass- and energy-spectra of the ions can easily be measured at a chosen distance from the electrode outlets. Some preliminary results were reported at an international conference PLASMA-2010.

The next step was to perform adaptation of that Thomson analyzer also for time-resolved measurements of ions. For this purpose the analyzer was equipped with miniature scintillation detectors located in chosen places along the deuteron parabola. This modified Thomson analyzer was used for time-resolved measurements within the RPI-IBIS facility. The obtained results, which were partially reported at the international conference PLASMA-2011, proved that the described modifications opened new possibilities for diagnostics of pulsed plasma-ion streams, but it was also found that further improvements of the analyzer construction would be reasonable.

During the recent few months the construction of the Thomson analyzer has been changed in order to make possible a differential pumping of the inlet-diaphragm system through an axial tube, which could also serve as a support for the analyzer positioning at different distances. This version of the analyzer has been used for measurements within the PF-360 and RPI-IBIS facilities. Particular attention has been paid to time-resolved measurements of ions emitted from the RPI-IBIS experiment. This paper presents the newest experimental results and their quantitative analysis.

9-10

THE DEVELOPMENT OF LIGHT ION INJECTOR FOR THE PLASMA DIAGNOSTIC SYSTEM BASED ON BEAM EMISSION SPECTROSCOPY

I.Bondarenko, A. Chmyga, G. Deshko, A. Komarov, A. Kozachek, L. Krupnik, S. Khrebtov, A. Zhezhera.

Institute of Plasma Physics, NSC KIPT, Kharkov, Ukraine.

The development of light ion injector and neutralizer for the BES plasma diagnostic system of Uragan-2M stellarator and its first testing results are presented in this work. This injector will be used for neutral beam plasma diagnostic systems. Diagnostic systems based on neutral beams of Li or Na atoms permits to investigate space profiles of plasma density, ions of impurities and magnetic field distribution in the edge area of fusion plasmas. This method bases on registration of visual light radiation from neutral probing beam exited by plasma electrons [1-3]. These diagnostic systems consist on two main parts – neutral beam injector and secondary light signal registration system. These systems have now rather low level of optics signal depending on neutral beam current value, in particular ASDEX U diagnostic injector have primary ion beam current 1.5-3 mA for beam energy 35 keV. The light ion beam accelerator based on 5-electrode ion optics system instead of classical 3-electrode system allows obtaining 4-5 mA Li or Na ion current with ion beam energy of 20-30 keV.

The neutralizer is necessary for light ion lithium or sodium beams converting into fast atomic beams. The light ions neutralization coefficient has strong dependence on beam energy. In the energy range of 20-70 keV the neutralization coefficient is 95-68% [1]. For plasma edge diagnostic the optimal operational energy is 20-30 keV.

The neutralizer design with sodium stream directed along the ion beam trajectory is operated, in particular, in ASDEX-U BES diagnostic system. [1]. The main disadvantage of this design is that sodium vapor is spreading in bough directions along the beam trajectory – towards accelerator and plasma volume. The metal sodium appearance in accelerator leads to decreasing the electric insulation features, the sodium appearance in the fusion plasma leads to its cooling. The using of sodium stream across to beam trajectory will dismiss this disadvantage.

The neutralizer design was developed, manufactured and tested. Supersonic sodium stream is formed with the help of Laval jet. The possibility of alkali ion beam neutralization by transverse supersonic sodium vapor stream was proved. The ion optics system and neutralizer optimization is in progress.

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9-11

DEVELOPMENT OF THE BEAM PROBE DIAGNOSTIC (HIBP) ON STELLARATOR "URAGAN-2M"

A. Chmyga, G. Deshko, A. Komarov, A. Kozachek, L. Krupnik, S. Khrebtov, A. Zhezhera.
*Institute of Plasma Physics, NSC KIPT, Kharkov, Ukraine***.**

This report presents novel elaborations in Heavy Ion Beam Probe (HIBP) diagnostics fulfilled in the IPP NSC KIPT for Ukrainian stellarator Uragan 2M to make investigation of the plasma parameters, electric and magnetic fields of this device.

The direct measurements of the plasma electric potential and its oscillatory component in the core plasma are of primary importance for understanding the role of the radial electric field $\mathbf{E_r}$ in confinement improvement mechanisms [1, 2]. Heavy Ion Beam Probe (HIBP) is a unique diagnostic to study directly plasma electric potential and turbulence characteristics in toroidal plasmas from the core to the edge [3, 4]. HIBP is used in the some existing devices with magnetic plasma confinement to study the plasma potential with high spatial (< 1 cm) and temporal (1 μs) resolution

The calculations for U2-M HIBP application were done by computer code and found of the optimized geometry and probing beam parameters.. Trajectories of the probing heavy Tl^+ and Cs^+ beams were obtained for existing entrance and exit diagnostic ports and two values of the confinement magnetic field: $B_0 = 0.5\div0.8$ T (first stage device operation) and 2.0÷2.4 T(second one). The HIBP measurable radial range is $0.1<r/a<1$. Necessary energies of Cs^+ ion beam for existing magnetic field (0.5 T) is 90 keV and Tl^+ probing ion beam of 150 and 800 keV respectively for the two next steps of stellarator operation (0.8÷2.0 T).

At present this HIBP diagnostic system is manufactured, tested and installed on Uragan-2M. It consists of two parts. They are: injector of the primary ions with energy up to 200 keV and probing beam intensity up to 200 μA, and energy electrostatic analyzer of the secondary ions with energy resolution $\Delta E/E \sim 10^{-4}$ and operation voltage up to 40 kV. Ion beam injector was tested at the test device to ion beam energy of 90 keV, beam current – 160 μA, beam diameter of 6 mm at the 4.5 m focusing distance.

It is proposed a program of the electric potential profiles measurements in different regimes of stellarator operation, as well as plasma turbulence investigations.

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9-12

MEASUREMENTS OF THE PLASMA ISOTOPIC COMPOSITION IN ITER BY MEANS OF THE VISIBLE SPECTROSCOPY

A.A.Medvedev, A.V.Sushkov

National Research Center "Kurchatov Institute"

Akademika Kurchatova pl.1, Moscow, 123182, Russia

Contact e-mail: medvedev@nfi.kiae.ru

One of the main objectives of the H-alpha Spectroscopy (+visible spectroscopy) ITER diagnostic system is the measurement of the plasma isotopic composition at the main plasma periphery. To get information on the $n_H/n_D/n_T$ ratio it is necessary to analyze the spectrum shape of a Balmer line. As showed the simulations performed [1], the analysis is rather complicated. Due to Zeeman Effect each isotopic component turns into a triplet. Besides, in common, the Doppler and Stark effects must be taken into account. A deconvolution in principle can be done for the observations performed at a limited plasma region where parameters, which influence the spectral shape, can be considered as homogeneous ones. However, such the measurements are impossible due to very strong diffusive scattering of light on the metallic wall surface. For beryllium which supposed to be used the reflection factor can achieve 30 to 40 percent. Thus and so, wherever the visible cone is directed, the stray light both from the divertor region and from the extended area of the main plasma periphery will be recorded. That is why overlapping of spectra from different locations is inevitable. It makes solving of the reversed problem practically impossible.

To enable the measurements we propose the following strategy. A small measurement enclosure (ME), connected to the main chamber with a wide short pipeline, is arranged inside a diagnostic port. Measures to suppress the hitting of the plasma stray light into the ME are taken. During the working shot of the reactor the glow discharge is ignited inside the ME. The light of the discharge is transmitted by means of mirror/lens optical elements beyond the biological shied and then, by fibers, to a high resolution spectrometer.

The temporal resolution of the measurements, performed in such a way, is limited by the ratio of the pipeline vacuum conductivity to the volume of the ME. The estimated operation speed will not exceed several tens milliseconds, that is close to the measurement requirements.

The proposed technique has several valuable merits:

- the background light can be suppressed completely, that enables to minimize the statistical error of the measurements;
- low density and mean energy of the particles inside the ME makes Stark and Doppler broadenings very small, therefore the decomposition of the spectrum is transparent;
- the magnetic field in the glow discharge bulk is both practically uniform and known in value that allows one to identify exactly the positions of Zeeman components of the spectrum.

And, at last, the proposed design of the light transmitting system gives a possibility to avoid any degradation of used optical elements.

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9-13

SIMULATION AND EXPERIMENTAL RESEARCH OF LANGMUIR PROBE OPERATION IN ELECTRO-NEGATIVE PLASMA

S.V. Dudin[1], D.V.Rafalskyi[2], D.A.Naymark[1]

[1] V.N. Karasin Kharkiv National University, 31 Kurchatov Ave., Kharkiv,61108,Ukraine
[2] Scientific Center of Physical Technologies, 6 Svobody Sq., Kharkiv, 61022, Ukraine
E-mail: stanislav_dudin@rambler.ru

The mathematical model of cylindrical Langmuir probe describing dependence of positive ion current collected by the probe on the basic parameters of electronegative plasma such as probe potential, densities of electrons, positive and negative ions, relation between ion and electron temperatures is built. The model is based on the theory of radial motion of charged particles. It covers wide parameters domain of the electronegative plasma, particularly the whole range typical for technological systems. The model is built for the collisionless case corresponding to low gas pressures.

The experimental measurements of probe characteristics in electronegative plasma in a wide range of parameters confirming the high reliability of the model has been made. For the experiments we used a probe with diameter of 70 microns and a length of 5 mm. The measurements were carried in secondary electronegative plasma separated from primary inductively coupled plasma by novel electrostatic grid-type electron filter with the following filling gases: Ar, O_2, SF_6, and their mixtures at pressures in the range 10^{-3} – 10^{-2} Torr.

The model can be used for probe data analysis in laboratory and technological electronegative plasma as well as for further progress in simulation of space charge layers in plasma containing negative ions.

9-14

NUMERICAL SIMULATION AND EXPERIMENTAL INVESTIGATION OF BIPOLAR SINGLE-GRID ENERGY ANALYZERS

D.V. Rafalskyi [1], S.V. Dudin [2], P.A. Srebniuk[2], V.I. Farenik[1]

[1] Scientific Center of Physical Technologies. Svobody sq. 6, 61022, Kharkiv, Ukraine
[2] Department of Physics and Technology, V. N. Karazin Kharkiv National University, Kurchatova ave. 31, 61108, Kharkiv, Ukraine

In present work the results of numerical simulation and experimental investigation of bipolar single-grid energy analyzers capable of simultaneous analysis of both positively and negatively charged particles are presented. The numerical simulation was conducted using the PIC (Particle in Cell) numerical code. The main result obtained in the simulation is the collector current-voltage traces measured at the different grid biasing. Also, the spatial distributions of ion and electron density and the distribution of plasma potential are calculated.

The simulation results has shown the possibility of hysteresis at bidirectional measurement of the collector current-voltage traces due to formation of secondary plasma between the analyzer grid and collector. “Plasma mode” of operation, which occurs at “left-to-right” trace measurement allows to increase the resolution of the analyzer by the factor of 2 for low ion energy range due to partial compensation of the ion beam space charge inside the energy analyzer. The simulation results show that the observed effect appears at the low ion beam energy only (0-100eV), that was associated with the following condition for the “plasma mode” formation: space charge sheath thickness should be less then the distance between the analyzer grid and collector (according to the Child’s Law for the flat geometry). Analysis of the obtained results shows that secondary electron emission plays a key role in the plasma formation inside the energy analyzer.

Additionally, the series of the experimental measurements of the current-voltage traces of the planar single-grid energy analyzer is conducted. The experiments were performed on the original high-vacuum setup equipped with the single-grid broad beam bipolar source of the charged particles based on the ICP discharge. Current voltage traces are measured with the precision measuring device “PlasmaMeter”. The existence of hysteresis at the low ion energy (<50eV) is confirmed by the experimental bidirectional measurement of the collector current-voltage traces.

9-15

MICROPROCESSOR BASED HARDWARE-SOFTWARE COMPLEX FOR INVESTIGATING THE MAGNETIC SURFACES OF TORSATRON "URAGAN-2M"

S.P. Gubarev,G.G.Lesnyakov, G.P. Opaleva, A.N.Shapoval,V.S.Taran, M.I. Zolototrubova

Institute of Plasma Physics, NSC Kharkov Institute of Physics and Technology, Akademicheskaya St., 1, 61108 Kharkov, Ukraine.

This paper describes the microprocessor hardware and software complex designed to control the fluorescent rod scanning in the poloidal cross section of vacuum toroidal chamber in order to study the structure of magnetic surfaces in the torsatron "URAGAN-2M."

The method of scanning fluorescent rod is used to study the magnetic surfaces in URAGAN-2M torsatron [1, 2]. The microprocessor hardware and software complex is a portable microprocessor device, completely replacing hardware and software complex based on personal computer [3]. The hardware is implemented on the basis of the complex integral PIC18F2620 microcontroller manufactured by Microchip Technology Inc., which is the market leader in the class of 8-bit microcontrollers with RISK architecture [4]. PIC18F2620 is a single integrated circuit that combines of high performance 8-bit microprocessor, the various memory modules, timer modules, internal and external clocking, analog and digital input-output ports, communication ports, interrupting and comparing modules, PWM modules, diagnostics and power management, energy consumption, etc.

Device includes microcontroller, a communication device with the object, the control device, LCD display and developed software, which is loaded into the electronic memory of the microcontroller.

The controller provides the choice of scanning chamber modes, receiving and converting analog signals from the sensors of the fluorescent rod, controlling motor signals of the rod according to the programmed algorithm for each of the selected scanning modes.

The results of measurements, the state of nodes, mode indication are shown on the LCD display.

All software modules are created in the environment of development MPLAB IDE in a specialized language C18, designed for the program of the microcontrollers of the 18-th series.

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9-16

THE BROADENING OF SPECTRUM OF OSCILLATIONS EXCITED BY ACTIVE ANTENNA ARRAY

I.K. Tarasov, M.I. Tarasov, D.A. Sitnikov, V.M. Listopad, N.V. Lymar

Institute of Plasma Physics, National Science Center
"Kharkov Institute of Physics and Technology", Kharkov, Ukraine

The plasma was heated by two active antenna arrays. The noise generator based on the nonlinear feedback scheme was used as a master oscillator. The noise generators output was applied to the antenna arrays amplifiers, which were working in both linear and 'key' regimes. After that the oscillations frequency in plasma was increased from 20 MHz to 110 MHz

Similar measurements were made with the pulse generators used as master oscillators. The pulses repeating frequency was up to 30 MHz. The variation of delay between the generated pulses allowed to keep the plasma oscillation frequency level in the range of 150 – 200 MHz.

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9-17

NEW APPLICATIONS OF DOPPLER REFLECTOMETRY

V.V. Bulanin[1], L G Askinazi[2], A.D. Gurchenko[2], E.Z. Gusakov[2], V.K. Gusev[2], L.A. Esipov[2], S.V. Lebedev[2], A.V. Petrov[1], Yu.V. Petrov[2], D.V. Prisyazhnyuk[1], K. Standaert[3], A.S. Tukachinsky[2], A.Yu. Yashin[1]

[1]St. Petersburg State Polytechnical University, St. Petersburg, Russia
[2]Ioffe Institute of the Russian Academy of Sciences, St. Petersburg, Russia
[3] Ghent University, Ghent, Belgium

Doppler reflectometry is based on microwave backscattering under the oblique incidence of probing microwave beam. The diagnostic allows one to derive perpendicular plasma rotational velocity from the Doppler frequency shift of scattered radiation induced by moving plasma density fluctuation. That is why the method was widely applied to research of evolution of the rotation in tokamaks and stellarators. Two new applications of the Doppler reflectometry concerning turbulent intermittent events of meso and micro scales in toroidal devices are presented in the report.

At present, zonal flows and associated geodesic acoustic modes (GAMs) are widely discussed and investigated since they are believed to moderate drift-wave turbulence and hence edge transport. Being localized radial electric field perturbations the zonal flows and GAMs can be detected as plasma ExB rotation using the Doppler reflectometry technique [1]. We report results of GAM study in limiter discharges of the FT-2 and TUMAN-3M tokamaks of Ioffe Institute. The GAMs are detected as oscillations of the poloidal velocity and have been observed in a periphery region of the both tokamaks in Ohmic regime or/and in a phase before the L-H transitions. The GAM frequencies are found to be close to the theoretically predicted frequencies. The observed GAMs were found to exhibit intermittency character in line with a predator-pray model of the GAM developing. The Doppler reflectometry data were compared with the HIPB diagnostic results in the TUMAN-3M tokamak and with the data obtained by the enhanced microwave backscattering technique in the FT-2 tokamak.

Another novel application of the Doppler reflectometry has been recently proposed for study of filament like structures in tokamak plasma [2]. The filaments appeared as a result of non-linear developing of peeling-ballooning or/and kinetic-ballooning instabilities are assumed to control the H-mode pedestal parameters and to play an important role to the thermal load on both first wall and diverter plates [3]. Filament structures were intensively studied using fast camera images and reciprocating probes. A new approach for filament structures registration is based on microwave backscattering from the structures in the Doppler reflectometry experiment. Filaments manifest themselves as intensive quasi-coherent bursts of the reflectometer detector signal. Analysis of these quasi-coherent bursts makes it possible to determine such properties of filaments as its perpendicular velocity, size and distance between filaments. The possibility to detect filaments via Doppler reflectometry has been shown in the Globus-M spherical tokamak during NBI H-mode with strong type-I ELMs. The filaments associated with ELMs and filaments arising between ELMs were detected by Doppler reflectometry in a vicinity of edge transport barrier. The specific features of filaments and conditions of their appearance have been investigated.

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9-18

TURBULENCE MICROSCALES AND ELECTRODE EROSION CONTROL BY DIGITAL SPECKLE TECHNOLOGY WITH NANOMETRIC RESOLUTION

N.B. Bazylev, N.A. Fomin

Luikov Heat and Mass Transfer Institute NASB, Minsk, 220072, Belarus

Modern optical techniques based on computer-aided image pattern analysis extends the methods of rough surface/plasma flow visualization and control and allows the quantitative derivation of a two dimensional map of defection angle experienced by probing coherent light passing through a flow under study or by coherent speckled light scattered by rough surface under study. Such line-in-sight diagnostics with the use of digital images analyses becomes especially attractive when turning to the statistical analysis of the microscale turbulent plasma fluctuations as well as micro- and nanostructures of a rough surface destruction with nanometric resolution [1, 2].

Since the seventies of the last century, speckle photography is used intensively for measuring temperature and density fields in fluid and plasma flows. In comparison to the classical optical visualisation methods, the SP provides a much higher local resolution of the experimental values in the plane of measurement. The quantity that can be measured is the angle of deflection of the light transmitted through the refractive index field, similar to the case of a schlieren system, where the distribution of this angle is visualised in a qualitative form. It has been shown, that quantitative measurements by means of speckle photography can be performed in turbulent plasma flows an as well. Similar techniques can be used for electrodes erosion control with nanometric resolution.

Principles for measuring the light deflection angles by means of SP is illustrated in Fig. 1.

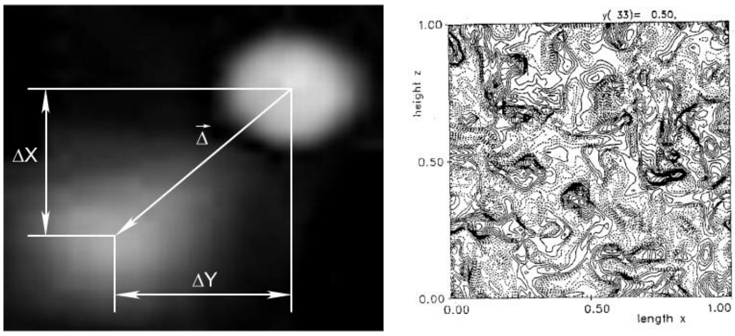

Fig. 1. Illustration of speckles distortion and displacement measurement by statistical analysis of speckled image and isolines of speckle displacements due to surface degradation

Thus, with "high density" speckle photography data the precision of the turbulence microscale determination using integral transform for the isotropic turbulence and erosion control of electrodes are rather higher.

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9-19

TOEPHLER PHOTOMETRIC MEASUREMENTS OF ELECTRON DENSITY IN COLLIDING COUNTER-FLOWS OF EROSION PLASMA

P.P. Khramtsov, O.G. Penyazkov, V.M. Grishchenko, M.Yu. Chernik, I.A. Shikh

A.V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus, Minsk, 220072, Belarus

The aim of this work is research of qausi-stationary high energy plasma formations for practical applications in high thermal physics and diagnostic of materials under extreme conditions. Visual examination, high speed photography and shadow investigation are to be discussed in the paper (Fig. 1).

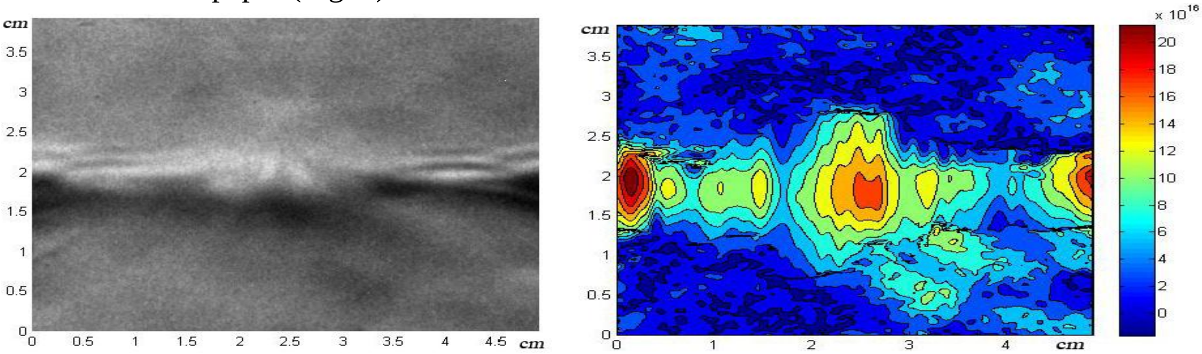

Fig. 1. Results of shadow method diagnostics (15 μs from accelerators operation start): on the right – the shadow pattern, on the left – the calculated distribution of electron density, cm^{-3})

Investigated interaction process is based on high-current discharges of plasma erosion accelerators in vacuum. An end erosion plasma accelerator is a system of two coaxial copper electrodes separated by a caprolone insulator. An outer copper electrode is shaped as a convergent nozzle. The accelerator was mounted in a vacuum chamber equipped with special vacuum chamber optical windows. Shadowgraphs of colliding plasma counter-flows were made using knife and slit method [1]. The source of light based on a pulsed spark discharge in argon at high pressure with light pulse duration is 3 μs was used. Averaged free electron density in the interaction area was calculated from intensity distribution of shadow photographs.

For the shadow photograph of luminous plasma we must be sure that the plasma emission is not detected by the camera, while the radiation from the light source has been registered. To reach this effect a light filter system with transmission peak at 547 nm was mounted before the CCD-camera. At this wavelength the relative intensity in plasma spectrum is low while in argon lamp spectrum it is near-maximum.

A shadow patterns data processing revealed that the localized stable spherical plasma structure forms in a collision zone by 15 μs from accelerators operation start. An electron density inside this structure reaches a maximum value $8{,}4\cdot10^{16}$ cm^{-3} between 15 and 20 μs from accelerators operation start, at this moment a discharge current tops. After 20 μs electron density decreases and plasma structure downsizing occurs. The results of electron density measurements are in good agreement with data obtained by spectral method [2].

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9-20

Recent Results of the Electric Potential Profiles and Plasma Turbulence Study and Diagnostic Development of HIBP in TJ-II

L. Krupnik and HIBP teams

Institute of Plasma Physics, NSC "KIPT", Kharkov, Ukraine
e-mail address: krupnik@ipp.kharkov.ua

Plasma electric potential and its fluctuations in a core plasma are of an importance for the understanding the confinement improvement mechanisms and the role of electric field E_r in toroidal plasma confinement. Heavy Ion Beam Probe (HIBP) diagnostic is a unique tool to study directly the plasma potential, density and its fluctuations with high spatial (<1cm) and temporal (1μs) resolution in the core and edge plasmas. HIBP diagnostic on the TJ-II stellarator (four-period flexible heliac, B_0=1T, R=1.5m, a=0.22m) has been upgraded for two point measurements with a poloidal separation Δx = 1cm to study directly poloidal component of electric field $E_{pol}=(\varphi_1 - \varphi_2) / \Delta x$ [V/cm] and to extract radial turbulent particle flux $\Gamma_r = \Gamma_{EpolxBtor.} = \Gamma_{ExB}$.

To penetrate into the dense area of plasma and carry out the measurements from the center to the edge of the plasma column makes a problem for HIBP measurements. This problem was solved by comprehensive investigation of the thermoionic emission of solid state ion sources, resulting in the increase of initial intensity of the probing beam and expanding of the dynamical range of measurements.

Potential profile evolution was measured in ECRH and NBI heated plasmas ($P_{ECRH} \leq 600$kW, $P_{NBI} \leq 900$kW (port through), E_{NBI}=30kV). Low density ECRH plasmas ($n=0.3\text{-}1.1\times10^{19}m^{-3}$) are characterized by positive potential up to $\varphi(0)$ = +1200V at the centre. The minor area of the negative potential may appear at the edge depending on the plasma density. The density rise is accompanied by the decrease of potential, which evolves to the less absolute values becoming fully negative if $n>1.5\times10^{19}m^{-3}$. Contrary, the rise of T_e due to P_{ECRH} increase leads to the linear potential rise. NBI plasma is characterized by fully negative potential. The density rise is accompanied by increase of absolute potential. When density approaches $n=2.0\text{-}2.5\times10^{19}$ m^{-3}, the potential saturates at $\varphi(0)$ = - 600V. L-H transition spontaneously happening in NBI plasma is characterized by further potential drop ~ -100V, formation of the edge layer of the negative E_r~ -100V/cm, strong suppression of the density oscillations and turbulent particle flux at the edge and bulk plasma. Broadband turbulence is suppressed in both spontaneous and biased transitions to improved confinement regimes. Thus, potential behavior in TJ-II shows clear link between the negative electric field formation, turbulence suppression and rise of the plasma density and plasma confinement. Similar trend has been observed in tokamaks. Modelling shows that neoclassical mechanisms give significant contribution in the core electric potential formation. Various types of quasi-coherent potential oscillations were observed, among them Alfvén Eigenmodes and a new type of instability modes in TJ-II.

Conventional HIBP diagnostic is being used on TJ-II from 2000-th. It has shown significant results on plasma profiles and oscillations. The second HIBP system have been recently developed and installed on TJ-II, so the duo-HIBP system is created. The HIBPs are shifted by 90^o in toroidal direction, which allow us to study systematically long-range correlations in plasma potential and density, toroidal and poloidal structure of plasma turbulence and instability modes in the core and edge plasmas.

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BRAKING RADIO EMISSION PARTICLE CONDENSED DISPERSED PHASE IN THE PLASMA OF COMBUSTION PRODUCTS

V.I. Marenkov
Odessa National I. I. Mechnikov University, 2 Dvoryanskay Str.,65026 Odessa, Ukraine
E-mail:maren0@ukr.net

High-temperature plasma formations that contain condensed macroparticles (MP) of nano- and microscopic sizes are formed in the atmosphere and space under the action of energy concentrated fluxes on the matter. Self-consistent interaction of the plasma micro field and charges determines at any time the acceleration of charged particles in electromagnetic field of heterogeneous plasma (HP), which, in its turn, leads to generation of the plasma radiation field. The amplitude-frequency characteristic (AFC) of bremsstrahlung HP charges carry the information about the electron-ion processes in the micro-scale plasma system.

In this paper we propose a new statistical model for determining the integrated intensity of the bremsstrahlung HP in radio range. The mechanism of formation of radio-frequency component in the plasma of combustion products, metalized fuels is defined. The main point of the model theory - a statistical averaging of the temporal sequence of quasi-harmonic oscillations of a charged particle in the LaGrange coordinates a single cell screening committed in the local, time-evolving system of an electrostatic field. In this case, the deformation of the cell through the redistribution of the local charge density is taken into account by introducing effective "electrostatic images» of a removable particle. In the statistical approach "quasi-neutral plasma cells" [1-3] developed a method of analyzing the amplitude-frequency response of the heterogeneous plasma radio emission, providing opportunities for tele-diagnosis parameters of the component composition and microstructure of plasma formation. Based on the model theory of integral relations was carried out a computer experiments to determine the plasma bremsstrahlung intensity of combustion products of aluminized propellants in the radio frequency range. It is shown that the intensity of the radio emission of thermal plasma with condensed dust grains at temperatures [2000-3500] lies in the gigahertz range. The AFC of the radio emission from the plasma of combustion products (PCP) of aluminum powder in the air is found. A comparative analysis of the calculated parameters of the amplitude-frequency characteristics of the radio emission of PCP with the data of full-scale experiment to measure the relative intensities of the spectral components of the signal [4] is carried out. A good qualitative and quantitative agreement between theory and experiment data is registered. As a part of the approach proposed a new method of contactless diagnostics of PCP, based on the comparative analysis of the intensity its electromagnetic radiation in the radio range.

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Contributed Papers of Adjoint Workshop "Nano- and micro-sized structures in plasmas"

The aim of the Workshop is to bring together scientists working on new and exciting areas of fabrication and characterisation of nano- and microstructures in plasmas and on their effects on plasma properties. .

Topics:

1. Formation of nano- and micro-sized structures in plasmas
2. Processing of nano- and micro-sized structures in gas discharge chambers
3. Properties of plasmas with nano- and micro- objects
4. Characteristics of nano- and micro-sized structures formed in plasma environment

Invited talks:

1. Dust ion-acoustic nonlinear wave structures under conditions of near-Earth and laboratory plasmas Dr. Sergey I. Popel, Moscow, Russia (See **I-14**, p. 16)
2. Fabrication of nanopowders in RF plasmas: diagnostics and modelling Dr. Ilija Stefanovic, Bochum, Germany (See **I-15**, p. 17)
3. The formation of nanoparticles and nanocomposites in reactive plasmas Dr. Johannes Berndt, Orleans, France (See **I-16**, p.18).
4. On the use of dust particles as micro-probes in process plasmas Dr. H. Kersten, Kiel, Germany (See **I-17**, p.19)
5. Kinetic description of dusty plasmas and effective grain potentials. Dr. A.G. Zagorodny Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine (See **I-18**, p.20)

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W-01

PLASMA BASED FUNCTIONALIZATION OF ADVANCED CARBON MATERIALS: NANOPARTICLES, NANOTUBES AND GRAPHENES

E. Kovacevic[1], J. Berndt[1], Th. Strunskus[2], N. Camara[3], L. Boufendi[1], M. Gaillard[1], Ch. Leborgne[1]

[1]*GREMI, Universite d'Orleans, France*
[2]*Christian-Albrechts-University of Kiel, Institute of Material Science, Kiel, Germany*
[3]*GREMAN, Université de Tours/CNRS Tours, France*

Advanced carbon materials as for example carbon based nanoparticles, carbon naonotubes or graphene are important building blocks for novel applications in science and technology. They can be used for example as gas sensors, electron emitters, catalysts or for new design concepts for mirofluidic elements or lab on chip applications. One important requirement for future applications concerns the surface modification or doping of these materials, which can result in controllable changes of their electronic [1] or chemical [2] properties. Specific functional groups of interest are here in particular nitrogen [3] or oxygen [4] containing groups or even complex organic molecules [2].
This contribution will focus on the use of low temperature plasmas which are not only versatile tools for the synthesis of advanced carbon materials [5,6] but also very suitable for the controlled surface modification of these materials. We will report here about first experiments dealing with the controlled functionalization of carbon nanoparticles, carbon nanotubes and graphenes by means of low temperature nitrogen containing plasmas.
The effect of the plasma treatment on the different carbon materials is analyzed by means of Near edge x-ray absorption fine spectroscopy (NEXAFS) and XPS. Additional information about the effect of the plasma treatment on the surface properties of the materials are obtained by means of contact angle measurements.

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W-02

TITAN'S AEROSOLS ANALOGUES PRODUCED BY RF PLASMA

Thomas Gautier[1,2], Nathalie Carrasco[1], Ahmed Mahjoub[1], Cyril Szopa[1], Guy Cernogora[1], Edith Hadamcik[1]

[1]*LATMOS, Université de Versailles St Quentin, 11bvd d'Alembert 78280 Guyancourt, France*
[2]*ExperimentalPhysik II, Ruhr Universität Bochum, 44780 Bochum, Germany*

Titan’s atmosphere is the place of a complex organic chemistry initiated from its main constituents, *i.e.* N_2 and CH_4. This very active chemistry generates aerosols which play a significant role in the atmospheric and surface chemical and physical properties of the satellite. Moreover, the nature of these complex organics makes them of great interest for astrobiology, considering that such a complex organic material is produced from natural processes.

In order to study the chemistry at the origin of these aerosols, and their chemical nature, we use a dusty plasma experiment, named PAMPRE [1], that simulates the atmospheric reactivity on Titan. This experiment uses a Capacitively Coupled Plasma discharge [2], produced in a continuous gas flow, to induce chemistry between N_2 and CH_4. More complex molecules are then formed in the reactive medium and the propagation of the chemical chain leads to the production of solid particles, so called *tholins*, considered as analogues of Titan’s aerosols.

In this work we will focus on the absorption properties of tholins in the mid- and far- infrared [3]. Tholins material was deposited as thin film on different substrates. Analyses were performed at the SMIS beamline of SOLEIL synchrotron facility (France). We used a NicPlan microscope coupled to a Nicolet Magna System 560 Fourier Transformed InfraRed spectrometer. The detector used for far-IR was silicon doped bolometer cooled down to 4.2K with liquid helium.

Tholins spectrum obtained can then be compared to Titan's aerosols spectra obtained by the Cassini space probe orbiting Saturn (NASA/ESA). Comparison shows a good agreement between laboratory data and observational data on all the waverange. This comparison also allows attributing to aerosols some features that were still unexplained in Cassini spectra.

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W-03

BEHAVIOR OF FINE-CRYSTALLINE MIRROR SPECIMENS UNDER LONG-TERM SPUTTERING

A.F. Bardamid[1], A.I. Belyaeva[2], V.N. Bondarenko[3], A.A. Galuza[2], V.G. Konovalov[3], I.V. Ryzhkov[3], A.A. Savchenko[2], A.N. Shapoval[3], A.A. Kasilov[3], S.I. Solodovchenko[3], V.S. Voitsenya[3], Zhou Zhang-jian[4]

[1]*Taras Shevchenko National University, 01033 Kiev, Ukraine;*
[2]*National technical university "KPI", Kharkov, Ukraine;*
[3]*IPP NSC KIPT, 61108 Kharkov, Ukraine*
[4]*University of Science and Technology Beijing, Beijing 100 083, China*

One reason of degradation of plasma facing mirrors (First Mirrors, FM) of optical methods for plasma diagnostics in ITER will be sputtering by charge exchange atoms (CXA) resulting in increase of the surface roughness. To avoid degradation of mirror optical properties, it was suggested [1,2] to fabricate FMs from single crystals. Another promising possibility way [1] is the use of materials which have so fine structure that characteristic size of the surface roughness growing would be much less than the wavelength of the light of mirror working range. Such materials – amorphous and nano-structural alloys – are now produced with the size that gives possibility to provide model studies with mirror specimens.

Such investigations were provided in the Institute of Plasma Physics of the National Science Center KIPT, with an aim to study the behavior of optical properties and the character of relief developing on the surface of fine-structure materials due to long-term sputtering. The mirror specimens from amorphous $Zr_{41.2}Ti_{13.5}Cu_{12.5}Ni_{10}Be_{22.5}$ alloy crystallized at 773°K for one hour possessed the lowest crystalline particle size (30-70 nm); the grains of a fine-dispersed alloy Cu-Cr-Zr were of noticeably larger size (200-300 nm), and the grains of a fine-grain molybdenum and tungsten were even larger (200-400 nm).

All mirror specimens were sputtered by ions of deuterium (Cu-Cr-Zr alloy) or Ar plasmas up to the ion fluence when the developed relief can be measured by means of profilometry, interferometry, or scanning electron microscopy (i.e., after sputtering the layer 2.5-4 μm in thickness). It was found that along with inhomogeneities with the longitudinal scale of a single grain there appear the inhomogeneities of much larger scale, what can lead to degradation of optical properties in a much longer wavelengths region.

To clear up the reason of this fact, computer modeling was provided assuming that all grains are of equal size and the grain of every orientation (12 in total) of crystallographic axis has some fixed sputtering rate in the angle interval ±15º. The results demonstrate that the developing microrelief has not only one-grain-size scale component along the surface but also the much longer scale inhomogeneities, many times (10-25) exceeding the size of an individual grain.

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W-04

DESTRUCTION OF MICROPARTICLES RELATED TO DUSTY PLASMA PROCESSES AND POSSIBLE TECHNOLOGICAL APPLICATIONS

T.I. Morozova, S.I. Kopnin, S.I. Popel

Institute for Dynamics of Geospheres RAS, Moscow, Russia

A method of destruction of microparticles related to dusty plasma processes is discussed. The method includes the creation of dust particle charges exceeding their limiting values when the destruction process of the particles starts. The destruction is connected with the fact that the surface charge of the dust particle creates the electrostatic pressure. When the electrostatic pressure becomes higher than the strength of the particle, the particle destroys. It is shown that the destruction of dust particles is possible when the particles are charged positively. Technological applications of dust particle destruction can be associated with the separation of nano- and microscale monomineral fractions from polymineral microparticles. For this purpose one can use modern sources of synchrotron radiation to achieve the limiting positive values of dust particle charges. This method can be utilized, e.g., for processing of gold ore from particular deposits.

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W-05

GROWTH RATES OF FOREST OF SINGLE-WALLED CARBON NANOTUBES IN PLASMA-ENHANCED CHEMICAL VAPOR DEPOSITION

G. Burmaka, I. Denysenko, N. A. Azarenkov

Department of Physics and Technology, V. N. Karazin Kharkiv National University, Svobody sq. 4, 61022 Kharkiv, Ukraine

The surface diffusion model is developed, which describes the growth of forest of single-walled carbon nanotubes in plasma-enhanced chemical vapor deposition. Using the model, the growth rate of nanotubes, diffusion length and residence time of carbon atoms on nanotube surfaces are determined, as functions of different external parameters. The model accounts for nonuniformity in deposition of neutral particles on surface of nanotubes from discharge chamber, interactions of hydrocarbon molecules and carbon atoms with etching gas, thermal and ion-induced dissociation of hydrocarbon molecules adsorbed on surface of nanotubes, decomposition of hydrocarbon ions on nanotube surface, as well as diffusion of carbon atoms on surface of nanotubes. The growth rates as functions of the carbon nanotube length are obtained numerically and analytically for different ion and neutral fluxes and different substrate temperatures.

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W-06

THE INTERACTION OF DUST PARTICLES IN MAGNETIZED PLASMAS

G.O.Gavrysh, O. Yu. Kravchenko, T.E.Lisitchenko, I. Koval
Taras Shevchenko Kyiv University, Volodymirs'ka Str. 64, 01601 Kyiv, Ukraine
kay@univ.kiev.ua

The problem of the charging of dust particles in plasmas is one of the main tasks to be studied. Dust particles immersed in plasma acquire charges whose sign and magnitude strongly affect on the properties of the plasma as well as the properties of the ensemble of dust particles itself. The charge of the dust grains is of great interest to understand the behaviour of particles in processing plasmas used for thin-film production, in processes of growing particles in the gas phase by nucleation and aggregation [1] as well as for the study of space plasmas [2]. Recently interest to research of dust structures in a magnetic field has increased [3]. In this regard, the determination of the charge of dust particles and forces acting on them in plasmas with magnetic field is important.

The traditional method used to determine the interaction of dust particles with plasmas is by means of the Orbital Motion Limited (OML) theory. In some articles it was shown that this theory is not accurate in case high gas pressure, at a strong interaction between particles and when a relative drift is added [1,2]. Various numerical methods can be employed to solve this problem. Among them, direct integration of the equation of motion of plasma particles represents a numerical experiment with significance approaching experiments in laboratory.

In the present paper the process of charging and shielding of dust particles is studied using computer simulation. The three-dimensional P^3M method is applied as the most complete description of plasma particles motion and interaction with macroscopic dust grains. The interaction between plasma particles and neutral gas was simulated using Monte-Carlo method for describing of elementary processes, such as elastic, excitation, ionization, charge exchange processes.

Spherical conductive dust particles were located in nondisturbed low pressure low temperature plasma in the presence of ion flow at various values of the neutral gas density and magnetic field. The spatial distributions of plasma particles around dust grains were obtained at different magnetic fields and ion flow velocities. The formation of the ion clouds behind dust particles owing to focusing of ion flows was observed. We have demonstrated that the density of the ion clouds considerably decreases with increasing magnetic field. The dependence of the ion drag force on neutral gas pressure and magnetic field was investigated. It was shown that higher ion concentration due to ionization and charge exchange processes results in growing of the ion drag force. With increasing magnetic field the charge of dust particles is reduced, which leads to a decrease of the ion drag force.

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W-07

THE ESTIMATION OF TUNGSTEN AND ODS TUNGSTEN DAMAGES AFTER DENSE PLASMA EXPOSURE ON PF-12 AND PF-1000

V. Shirokova[1)], T. Laas[1)], J. Priimets[1)], E.V. Demina[2)], M.D. Prusakova[2)], M. Scholtz[3)]

[1)] *Institute of Mathematics and Natural Sciences, Tallinn University, Estonia*
[2)] *A. A. Baikov Institute of Metallurgy and Materials Sciences, Moscow, Russia*
[3)] *Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland*
E-mail: veroonika.pelohh@gmail.com

Experiments using the plasma focus device PF-12 (Tallinn University) and PF-1000 (Warsaw Plasma Physics and Laser Microfusion Institute) have been carried out to investigate the behavior and damage in pure tungsten and ODS tungsten (ODS – oxide dispersed strengthened). These materials may be suitable candidates for the divertor in a thermonuclear reactors.

The pure and ODS tungsten were manufactured by PLANSEE using powder metallurgy technology. Tungsten was doped with 1% of lanthanum oxide, and was then isostatically pressed, sintered and rolled. The pure tungsten was made by a similar process. The 20x20 mm samples were 4 mm thick. Materials were exposed to deuterium plasma for 2 and 8 shots on PF-12 at distances of 3.5, 6.5, and 10.5 cm, and by 2 shots on PF-1000 at 7-7.5 cm.

Both the original and the irradiated samples were investigated by optical and scanning electron microscopy, by local X-ray spectroscopic analysis and by X-ray phase-shift analysis. Also the microstructure, microroughness and microhardness of the samples were investigated.

The analysis by electron microscopy shows that the plasma exposure produced wave-like structures, a melt-layer and a mesh of microcracks. The wavelength and amplitude of these structures is practically the same in both materials. The mesh of cracks that appears on the surface is caused by crystallization of the melt-layer by fast cooling. The density of microcracks in the ODS tungsten surface increases more gradually with the number of shots than in the pure tungsten case.

The X-ray phase-shift analysis shows about 5-10% all second phases availability. The lattice parameter of the ODS tungsten after irradiation was decrease. The second phases are localized and in good accordance with each other, which have their own physical, chemical and mechanical properties and influence on the material behavior.

The microhardness has a reduced value near the surface, and at depth oscillations about some mean value of hardness is observed. In some samples a hardness gradient appears with depth. The hardness increases in at greater depths, out of the thermal influence zone. The hardness gradient could either be due to the impact wave caused by the plasma exposure or alternatively the mechanical processing of the samples.

Taking into consideration that alloys W-%1La_2O_3 can be more readily machine processed and that the brittleness of ODS tungsten is lower than W, W-%1La_2O_3 may be a useful alternative to pure tungsten in fusion reactor construction.

W-08

THE INFLUENCE OF IRRADIATION BY HYDROGEN PLASMA ON THE STRUCTURE AND PHASE COMPOZITION Ti-Zr-Ni ALLOYS CONTAINING QUASICRYSTALLINE PHASE

S.V. Bazdyreva[1], I.E. Garkusha[2], V.A. Makhlaj[2], S.V. Malykhin[1], A.T. Pugachov[1]
[1] *Kharkov Polytechnic Institute, NTU, 61002 Kharkov, Ukraine*
e-mail: malykhin@kpi.kharkov.ua, тел.: +38 (057) 7076194
[2] *Institute of Plasma Physics of the NSC KIPT, Kharkov, 61108, Ukraine*
e-mail: makhlay@kipt.kharkov.ua, тел.: +38 (057) 3356726

Choice of facing materials and estimation of it response to high heat and particles fluxes remain one of important issues for realization of fusion reactor project. It all stimulated research and developed new materials. New radiation-resistant materials are quasi-crystal on the base Ti-Zr-Ni. They have naturally and noncyclical structure of nanoclusters of fifths order. Response of quasicrystal to ITER ELM-like heat load did not studied until now. The results of investigation Ti-Zr-Ni alloy with quasi-crystal phase exposed by ITER ELM like heat load are presented in this paper.

The samples have been exposed to hydrogen plasma streams produced by the quasi-steady-state plasma accelerator QSPA Kh-50. The massive sample of Ti41, 5Zr41,5Ni17 obtained after solidification from the melt was used for the plasma load tests. The main parameters of QSPA plasma streams were as follows: ion impact energy about 0.4 keV, the maximum plasma pressure 3.2 bars, and the stream diameter about 18 cm. The surface energy loads measured with a calorimeter were achieved 0.6 MJ/m^2 (near the tungsten melting threshold). The plasma pulse shape was approximately triangular, and the pulse duration was 0.25 ms. A surface analysis was carried out with an MMR-4 optical microscope equipped with a CCD camera and Scanning Electron Microscopy (SEM) of the JEOL JSM-6390 type. To study a micro-structural evolution of the exposed targets, the X-ray diffraction technique (XRD) has been used.

It is determined that the initial state is characterized by the presence of crystal-approximant phase (W-phase) with lattice constant a_W = 1.428 nm, (main phase) and the icosahedral quasicrystalline *i*-phase with quasicrystalline parameter a_q = 0,518 nm. The irradiation causes the formation of smooth cracks on the surface the plates that are typical for amorphous materials, and asperities, having the shape of dodecahedrons and triacontahedron. The content of the icosahedral phase is significantly increased, and the quasicrystalline parameter decreases to a_q = 0,517 nm due to reduced of the content of the most easily melting element in the alloy - nickel Increasing the number of pulses does not change the phase composition and structure parameters.

W-09

THE ION FLUX AND SHEATH PROPERTIES IN THE AFTERGLOW OF PURE ARGON AND OF ARGON WITH NEGATIVELY CHARGED DUST PARTICLES

Brankica Sikimić[1], Igor Denysenko [2], Ilija Stefanović [1], Jörg Winter [1]

[1] *Institute for Experimental Physics II, Ruhr Universität Bochum, 44801 Bochum, Germany*
[2] *School of Physics and Technology, V. N. Karazin Kharkiv National University Kharkiv, Ukraine*

It has been experimentally observed that the thin film deposition as well as dust particles in plasma volume influence the discharge properties in radio frequency reactive plasmas, like electron density, electrode self-bias voltage or Ar* metastable density [1,2]. To improve the understanding of the processes in the plasma afterglow, the theoretical study of the dynamics of the ion flux and the sheath width was carried out by using experimental results of time dependent electron density, electrode self-bias, electron temperature T_e, and plasma potential V_p as input parameters. The experimental data were obtained for a 13.56 MHz low-pressure capacitively-coupled argon discharge, as explained in [2]. The signal from the RF generator was modulated by a square-wave signal at frequency of 100 Hz and duty cycle of 50%. The RF input power was 20 W and the total gas pressure was kept constant at 0.1 mbar. A hydrocarbon film on the electrodes was deposited by adding ~ 5% of acetylene in chamber for different time intervals. The growth rate of the deposited film was estimated to be about 1.5 nm/min in the separately performed optical ellipsometry measurements. The ion flux was deduced from the change of electrode self-bias voltage and its decay time in the plasma afterglow, similar to the RF biased planar electrostatic probe [3]. It was found theoretically that the sheath size increases more slowly and the average ion flux to an electrode becomes larger with growing film thickness. The dependence of the calculated ion flux on the film deposition time is in a good qualitative agreement with the dependence obtained in experiment. The effect of dust particles on the ion density at the sheath-plasma boundary was also analyzed.

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W-10

SIMULATION OF THE EXPIRATION OF THE PLASMA JET WITH A DISPERSED PHASE IN AN AXISYMMETRIC CHAMBER

O. Yu. Kravchenko, E. V. Kurhanovich, I.S. Marushchak
Taras Shevchenko Kiev University Volodymirs'ka Str. 64, 01033 Kiev, Ukraine

Plasma flows with disperse phase widespread in plasma and plasma-chemical technologies. Investigation of the characteristics of these flows is necessary in the processing of ultrafine powders of metals, in the plasma-chemical receipt of various substances, and other. Low-temperature plasma is also used in the processes of surface modification coatings.

The aim of this article was to modeling, computation and numerical analysis of the expiry of plasma jets with dust particles into the vessel, taking into account the interference of the jet with solid walls of the vessel. The problem was solved in the time-dependent formulation. The quasi neutral low ionized plasma jet enters with the axis velocity v_f into the cylindrical vessel with radius $R = 100mm$ and length $L = 200\,mm$ through the round nozzle. At the entrance of the nozzle (diameter of the outlet section of 10 mm) were given plasma parameters (the total pressure P_0, total temperature T_0, total plasma density ρ_0) and parameters of the disperse phase flow (density, drift velocity and temperature of dust particles). All plasma parameters are constant in this cross-section during a simulation time. Plasma stream moves in this vessel interacting with contained there neutral gas (which has some initial parameters) and departs through the side hole.

Plasma jet is described by set of hydrodynamic equations which consist of momentum equations, continuity equation and energy conservation law for quasineutral plasmas and disperse phase (dust particles). The model takes into account the interfacial force, thermal interaction between plasma and dust particles and recombination of the plasma on the surface of dust particles. The system of equations is solved numerically by the method of large particles [1]. The calculations were carried out at different parameters of plasma flow entering in the vessel and continued until a steady flow of plasma. As results, spatial distributions of the plasma parameters and disperse phase parameters (densities, drift velocities, temperatures and the plasma pressure) were obtained in various times. The influence of a disperse phase on parameters of a plasma stream is investigated.

Distribution of dust particles in the chamber is also studied at various parameters of plasma streams.

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W-11

GRAIN CHARGING IN WEAKLY IONIZED PLASMA IN THE PRESENCE OF EXTERNAL MAGNETIC FIELD

A.I. Momot, A.G. Zagorodny*

Taras Shevchenko National University of Kyiv, Faculty of Physics, 64, Volodymyrs'ka St., 01601 Kyiv, Ukraine

**Bogolyubov Institute for Theoretical Physics 14-b, Metrolohichna str. Kyiv, 03680, Ukraine*

The selfconsistent numerical calculations of spherical grain charging in weakly-ionized magnetoactive plasma are performed. Grain absorbs encountered plasma particles, so the charging currents exist. The plasma dynamics is described by the drift-diffusion approximation, i.e. the plasma particle number flux densities toward the grain are given by

$$\mathbf{\Gamma}_\alpha = n_\alpha \mathbf{x}_\alpha = -\hat{D}_\alpha \left(\frac{e_\alpha}{T_\alpha} n_\alpha \nabla \varphi + \nabla n_\alpha \right),$$

and satisfy the continuity equation $\nabla \mathbf{\Gamma}_\alpha = 0$. Here, $\alpha = e, i$, n_α is number density, $\hat{D}_\alpha$ is diffusion tensor, $e_i = e$, $e_e = -e$. Electric potential φ is determined by the Poisson's equation. The following boundary conditions were used in the calculations: $n_\alpha \big|_{z^2 + r_\perp^2 = a^2} = 0$ (grain absorbs all encountered electrons and ions), $\mathbf{n}\nabla\varphi \big|_{z^2 + r_\perp^2 = a^2} = -q/a^2$ (Gauss law), $n_\alpha \big|_{z^2 + r_\perp^2 = R^2} = n_{\alpha 0}$, $\varphi \big|_{z^2 + r_\perp^2 = R^2} = 0$ and on the other boundaries $\mathbf{n}\nabla\varphi \big|_{z=0, r_{\perp=0}} = 0$, $\mathbf{n}\nabla n_\alpha \big|_{z=0, r_{\perp=0}} = 0$.

Stationary grain charge q, as well as plasma particle currents, are calculated using the equality of the electron and ion fluxes. The potential and plasma particle distributions for wide range of plasma parameters and strength of the magnetic induction field are studied in details. Numerical calculations confirm the existence of the long-range Coulomb like part of the potential. The potential distribution is not isotropic and depends on the angle between radius vector and magnetic field direction. The typical distribution of normalized potential ($-e\varphi/T$) lines is shown on Fig. 1. The following parameters were used in this computation: grain radius $a = 0.5 r_D$ (r_D is Debye length), $D_{e\Box}/D_{i\Box} = 1000$, $T_e = T_i$, $\Omega_i/\nu_i = 0.02$, where $\Omega_\alpha = e_\alpha B / m_\alpha c$ is the cyclotron frequency, ν_α is the collision frequency.

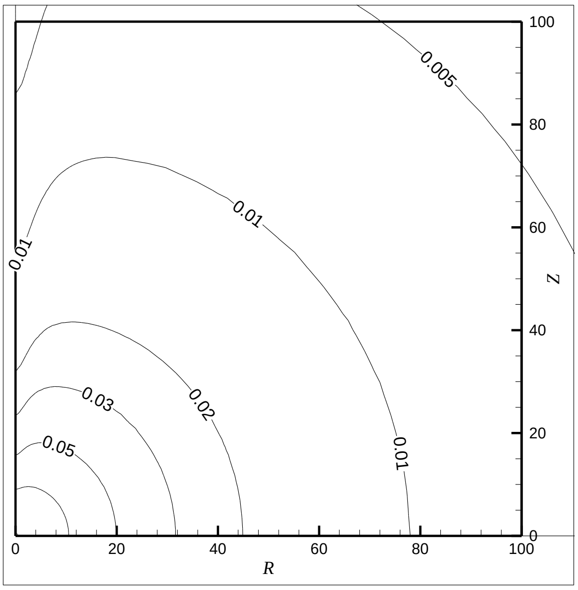

Fig.1. Potential ($-e\varphi/T$) lines in weakly-ionized magnetoactive plasma with spherical grain. $R=r/r_D$, $Z=z/r_D$

Thus, constant external magnetic field can considerably change the grains interaction in dusty plasma.

W-12

EFFECT OF GRAIN SIZE OF SELF-GRAVITATIONAL INSTABILITY OF STRONGLY COUPLED COMPLEX PLASMA

R P Prajapati[1] and R K Chhajlani[2]

[1]*Dept. of Pure & Applied Physics, G. G. Central University, Bilaspur (C.G.), India*
[2]*S. S. in Physics, Vikram University, Ujjain (M. P.), India*
E-mail: prajapati_iter@yahoo.com

It is well known that many astrophysical object consist micro and nano size dust grains which play strong role in the collective phenomena of plasma. In this paper effect of charged grain size on self-gravitational instability of strongly coupled dusty plasma is studied. The basic equations of the problem are formulated using the generalized hydrodynamic model and a general dispersion relation is obtained using the normal mode analysis. We discuss this dispersion relation for transverse and longitudinal mode of propagations. The condition of Jeans instability is obtained for such a system and effect of grain size is discussed. It is found that strong coupling of plasma particles modify the fundamental criterion of Jeans instability. In transverse mode it is found that Jeans instability criterion gets modified due to the presence of magnetic field, shear viscosity and fluid viscosity but in longitudinal mode it is unaffected due to the presence of magnetic field. From the curves we found that all these parameters have stabilizing influence on the growth rate of Jeans instability.

PD-1

COMPARISON OF DBD DISCHARGE MODES FUNGICIDAL EFFECT ON *CANDIDA ALBICANS* GROWTH

Jan Sláma[1], Vítězslav Kříha[1], Jaroslav Julák[2], Vladyslava Fantova[1]

[1]*Department of Physics, Faculty of Electrical Engineering,*
Czech Technical University in Prague,
Technická 2, 166 27 Prague, Czech Republic

[2]*Institute of Immunology and Microbiology, First Faculty of Medicine,*
Charles University in Prague
Studničkova 7, 128 00 Prague 2, Czech Republic

slamajan@fel.cvut.cz

The dielectric barrier discharge (DBD) has been intensively studied as a promising tool for microbial inactivation and decontamination in many medical and biological applications due to its easy feasibility and modesty on power supply.

In our investigation, we attempted to compare the influence of various DBD modes on artificially biologically contaminated surface. We used barrier discharge, which can generally occur in two modes – filamentary (spark discharge) and diffuse (glow discharge) mode. The discharge in both cases was powered by AC source 12 kV/50 Hz and operated in air at atmospheric pressure and room temperature. Sabouraud agar, cut into circular sections of 2 cm in diameter, was used as a model surface. The sections were uniformly inoculated with 0.1 ml of freshly grown *Candida albicans* yeast suspension at concetration of 10^6 cfu·cm^{-2}.
The inoculated surface was treated by two DBD modes: filamentary and quasi-homogeneous DBD. In case of filamentary DBD the contaminated agar surface is treated by plasma generated between the agar surface and the pinpoint high voltage electrode. On the other hand in case of quasi-homogeneous DBD the contaminated surface is treated by plasma between agar surface and dielectric barrier. The exposition time for both discharge configurations (i.e. discharge regimes) varied from 15 seconds up to 30 minutes.

After cultivation at 36 °C for 48 hours, the area of treated surface without any *Candida* colonies was evaluated and compared for various DBD modes and exposure times. The quasi-homogeneous DBD appeared to be more efficient in comparison with the filamentary DBD. In the case of quasi-homogeneous DBD, as shorter exposure times were necessary to produce exposed agar sections free of yeast growth, i.e., displaying the total yeast inhibition. Furthermore, no surface changes have been observed on agars exposed by diffuse DBD, whereas after exposure to filamentary DBD or DC corona discharges one can find small gaps caused by the filaments in the agar surface.

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PD-2

ACTIVE CONTROL OF ATMOSPHERIC PRESSURE DISCHARGES

Jan Sláma[1], Jan Bauer[2], Stanislav Flígl[2], Vítězslav Kříha[1]

[1]*Department of Physics, Faculty of Electrical Engineering,*
Czech Technical University in Prague,
Technická 2, 166 27 Prague, Czech Republic

[2]*Department of Electric Drives and Traction, Faculty of Electrical Engineering,*
Czech Technical University in Prague,
Technická 2, 166 27 Prague, Czech Republic

slamajan@fel.cvut.cz

The properties of plasma are given by the discharge type, physical properties of electrode system, working gas composition and its flow, evolution of inner instabilities, outer impedance and external fields. The control of non-thermal atmospheric pressure electrical discharges parameters can be arranged by passive electrical elements (resistors, capacitors, inductive loads and autotransformers) or by active electrical components based on semi-conductors. The active approach give us the chance to affect the behavior by fast control of electrical properties of the power supply.

The voltage for the discharge is usually obtained from the HV transformer included within the source chain structure. Usage of the transformer simplifies the control of the output voltage and herby the discharge, because on low voltage side the power electronics technology is always simpler. One possible solution of control is to add autotransformer in front of the HV transformer. This enables control of the output voltage however the frequency remains the same as the frequency of mains cannot be changed. Second possible solution is usage of power electronics, namely voltage inverter. This solution offers possibility to control both output voltage and frequency. However it also increases the vulnerability of the system and it rises the requirements on the speed and accuracy of the control.

From the point of control, the solution with converter offers also the possibility to control the shape of the voltage. Inverter can be easily controlled to produce rectangular shape of the output voltage (square wave modulation) or a sinusoidal one can be reached too (sophisticated pulse-width modulation with a sinusoidal reference signal). Faster control of the output also offers possibility to control the filaments, because the current control loop with fast response can be easily added.

This contribution strives to study and compare behavior of the discharge supplied form the source of variable voltage and fixed frequency – autotransformer and from the source with the semiconductor converter on its input. Since discharges can be regarded as highly nonlinear load, any kind of predictive load would be of advantage. However this will require more investigation in the field of discharge mathematical description in order to balance the requirements to the used components.

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