Alushta-2010
International Conference-School on Plasma Physics and Controlled Fusion
and
4-th Alushta International Workshop on the Role of Electric Fields in Plasma Confinement in Stellarators and Tokamaks

Alushta (Crimea), Ukraine, September 13-18, 2010

BOOK OF ABSTRACTS

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CONTENTS

International Conference and School on Plasma Physics and Controlled Fusion ALUSHTA-2010 combined with 4-th Alushta International Workshop on the Role of Electric Fields in Plasma Confinement in Stellarators and Tokamaks follows the previous International Conferences and Workshops, which were held in Alushta in 1998, 2000, 2002, 2004, 2006, 2008 and were organized by the National Science Center "Kharkov Institute of Physics and Technology". More than 100 Ukrainian scientists and 70 foreign participants (from 16 countries) presented about 200 reports during Alushta-2008 Conference.

Alushta-2010 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 Conference Alushta-2010 the 4-th Alushta International Workshop. All the abstracts have been divided into 9 groups according to the topics of the Conference Program.

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 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 a further development of plasma physics and fusion as well as the scientific collaboration among different plasma research groups in Ukraine and abroad.

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I-01

RECENT RESULTS FROM KHARKOV STELLARATORS

V.S. Voitsenya, E.D. Volkov, V.I. Tereshin, and the U-2M and U-3M Teams

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Uragan-2M. Uragan-2M device is a medium size stellarator-type fusion device (major radius is R = 1.7 m, minor radius $\bar{a} \leq 0.24$ m) with reduced helical ripple value, moderate shear and the magnetic well (up to $\delta V'/V' \approx$-4.3%). The main parameters of the magnetic system: l = 2, m = 4 helical winding with additional toroidal magnetic field coils; maximum toroidal magnetic field strength is $B_{max} < 2.4$ T. Presence of the toroidal magnetic coils and the coils of the vertical magnetic field provides flexibility of this device in experiment.

Recently the new four-strap RF (FSA) antenna was installed and has to start operation soon, without and with controlled gas (hydrogen) puff which gives a possibility to handle with plasma of density $\geq 10^{13}$ ion/cm^3. This antenna produces plasma hardly and, therefore, for plasma production a frame antenna (FA) has to be used, and the FSA antennae pulse goes just after the FA pulse.

A series of experiments on the vacuum chamber RF wall conditioning were carried out aimed to develop a scenario for wall conditioning in a supercoducting machine. A discharge driven by the slow wave at frequencies $\omega >> \omega_{ci}$ is studied. Especially for the RF wall conditioning, a small frame antenna is designed and manufactured. It can be used both at low (~8 MHz) and high (~150 MHz) frequencies. Owing to the small size, this antenna could be inserted and removed through the vacuum gate. The experiments show the acceptable performance of the antenna in both frequency ranges.

Uragan-3M. The unique feature of the torsatron U-3M (l = 3, m = 9, R = 1 m, $\bar{a} \approx 0.12$ m, $\iota(\bar{a}) \approx 0.3$, B_{max} = 1.3 T) is that all helical and vertical magnetic field coils are placed into a large (5 m in diameter) vacuum chamber and, in such a design, a magnetic configuration with the natural helical divertor is provided. A detailed study of the characteristics of the divertor plasma flows in the regime of RF plasma production and heating at $\omega \lesssim \omega_{ci}$ is one of the key problems for investigation at this device: a vertical asymmetry of the flows due to the ∇B drift, ion and electron energy distribution in the divertor flows, fluctuations in the diverted plasma before and during transition to H-mode, etc.

The other problem being investigated in U-3M is the intensive comparative studies of the regimes before and after transition to better confinement of the low-collisional plasma ($n_e \approx 10^{12}$ ion/cm^3), namely: measurements of the plasma characteristics, calculations of the plasma turbulent fluxes, estimation of the energy confinement time. After transition the energy confinement time increases significantly and becomes close to values that can be found for U-3M experimental conditions from the conventional stallarator scaling.

The three-half-turn RF antenna was put into operation and several regimes of pulsed discharges with mean plasma density (0.5-2.0)$\cdot 10^{13}$ ion/cm^3 were investigated. At the plasma density $0.5 \cdot 10^{13}$ cm^{-3} the central electron temperature reaches ~500 eV. Ion temperature is lower, ~100 eV. The achieved energy content of plasma is higher as compared with other experiments in U-3M.

I-02

CONCEPTUAL STUDY OF A STRAIGHT FIELD LINE MIRROR HYBRID REACTOR

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The straight field line mirror (SFLM) field [1] with magnetic expanders beyond the confinement region [2] is proposed as a compact device for transmutation of nuclear waste and power production. Compared to a fusion reactor, plasma confinement demands can be relaxed if there is a strong energy multiplication by the fission reactions, i.e. $Q_r=P_{fission}/P_{fusion}>>1$. The values of Q_r is primarily restricted by fission reactor safety requirements. For the SFLM, computations suggest that values of Q_r ranging up to 150 are consistent with reactor safety. In a mirror hybrid device with $Q_r>100$ and where power loss is dominated by electron drag from the hot ions to the colder electrons, the lower bound on the electron temperature for power production can then be estimated to be around 400 eV, which may be achievable for a mirror machine, but even higher T_e values would be favorable to reduce the plasma heating power. The SFLM with its quadrupolar stabilizing fields does not rely on plasma flow into the expanders for MHD stability, and a scenario with plasma density depletion in the expanders is a possibility to increase the electron temperature. A build-up of a strong electric potential, which improves electron confinement, is associated with the plasma density depletion. Preliminary estimates suggest that an electron temperature exceeding 1 keV could be reached with a modest density depletion in the expander. Efficient power production is predicted with a fusion Q=0.15 and an electron temperature around 500 eV. A fusion power of 10 MW could then be amplified to 1.5 GW fission power in a compact 25 m long hybrid mirror machine. The magnetic field is nearly omnigenous, radiofrequency heating is aimed to produce a hot sloshing ion plasma [3] and magnetic coils are computed with sufficient space for a fission mantle in between the coils and the vacuum chamber. Neutron calculations [2,4] show that nearly all fusion neutrons penetrate into the fission mantle. All sensitive equipment can be located outside the neutron rich region and a steady state power production is possible.

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I-03

RECYCLING AND SPUTTERING STUDIES IN HYDROGEN AND HELIUM PLASMAS UNDER LITHIATED WALLS IN TJ-II

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Up to date, TJ-II is the only stellarator routinely operated on lithiated walls, thus offering the possibility to address important issues concerning the possible design of a stellarator-based reactor under very low recycling conditions [1] In this work, the important issues of fuel retention and wall erosion for H and He plasmas are addressed. Concerning erosion and implantation, the energy of the ions reaching the wall could be strongly modified under pure NBI heating due to minimization of charge exchange loses and the concomitant flattening of edge Ti profiles [2]. However, the sputtering yield of lithium was found to be significantly lower than that expected from laboratory experiments and Trim code calculations. Moreover, the dependence of that yield on edge temperature is consistent with an energy threshold much larger than that of pure lithium. In order to assess the effect of material mixing, which appears a good candidate for the observed effect [3], several degrees of mixing of the Li layer with the underlying boron were induced by the conditioning plasma.

Another topic that has been recently investigated in TJ-II is particle retention and release under H/He operation. Recycling coefficients R< 0.1 and R~0.85 for H and He, respectively, were measured, leading to good density control in ECRH and NBI heated plasmas and opening the possibility to strong He pumping by the lithium wall, as previously suggested [4]. The release of either species in the opposite plasma has also been investigated under several plasma conditions. It is concluded that thermal effects, possibly related to the diffusion of the released species across the lithium layer, can set a limit when isotope interchange is required, independently of the flux of impinging particles.

In this presentation, TJ-II as well as laboratory experiment results on Li sputtering and recycling in the presence of boron will be addressed.

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I-04

EVOLUTION OF MIRRORS IN NOVOSIBIRSK: PAST, PRESENT AND FUTURE

E.P. Kruglyakov, A.V. Burdakov, A.A. Ivanov

The history of mirror studies in the Budker Institute of Nuclear Physics is described. Appearance of modern concepts of plasma confinement in mirrors, development of heating systems acceptable for plasma heating in long traps with small diameter of plasma (such as relativistic electron beams and focused neutral beams) are presented. The modern status of Novosibirsk mirror program is described and reactor prospects are discussed.

I-05

EXPERIMENTS ON NEOCLASSICAL RIPPLE TRANSPORT AT POLOIDALLY OR/AND TEMPORALY PERTURBED SEPARATIRIX IN ELECTRON PLASMA

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Neoclassical transport due to axial asymmetries is ubiquitous in magnetic fusion plasma confinement. These plasmas typically have several locally ("*helically*")-trapped particle populations, either by design (stellarators) or due to coil discreteness (tokamaks), partitioned by separatrices from one another and from passing ("*toroidally trapped*") particles. The drift orbits for particles trapped in the two separate regions are displaced radially from one another due to the asymmetry variance, leading to the standard neoclassical transport as particles collisionally change (at rate n) from helically-trapped to toroidally-trapped and back.

This situation is dramatically modified when the separatrix is itself poloidally asymmetric (*ruffled*), or when it fluctuates due to waves in the plasma. In such a case the particles see a time-varying separatrix barrier, and without needing collisions they can chaotically transit from helically-trapped to toroidally-trapped and back. This can give enhanced transport in the low collisionality regimes associated with fusion plasmas. Our recent experiments with controlled poloidal ruffles or fluctuations on a trapping separatrix identify form of novel "*chaotic*" neoclassical transport scaling as v^0B^{-1}; and this is distinct from collisional neoclassical transport scaling as $v^{1/2}\ B^{-1/2}$. We show that this previously undiscovered regime results in enhanced transport that is independent of n and can greatly exceed standard $\sqrt{\nu}$ superbanana transport.

In the experiments we use a magnetized low-collisionality electron plasma, with a squeeze voltage $V_s\ (R_W,\theta,z,t)$ applied to a sectored central cylinder (radius R_W) to create two separate "*helically*"-trapped populations [1]. Controlled ruffle voltages $\Delta V_m(t)$ give $V_s=V_0+\Delta V_m\cos[m(\theta-\theta_m)]$; here we focus mostly on $m = 2$. Ruffles spread the separatrix energy by $\Delta\phi(r,\theta)\approx e\Delta V_m\ (r/R_W)^m$. Radial particle transport is conveniently driven by a small magnetic tilt asymmetry with controlled magnitude $\varepsilon_B\equiv B_\perp/B\leq 10^{-3}$ and chosen tilt direction $\theta_B\equiv\tan^{-1}(B_y/B_x)$. Collisions cause radial transport scaling as $\sqrt{\nu\omega_E}\varepsilon_B^2$ (where ω_E ω_E \ ν is the of $E\times B$ drift rotation frequency) due to the collisional spreading of the separatrix energy by $\Delta W_C\approx T\sqrt{\nu/\omega_E}$, as expected theoretically [2].

In contrast, chaotic transport dominates when ruffles or waves make $\Delta\phi_s(r,\theta,t)\geq\Delta W_C$; then, the effects of the ruffled separatrix on both the transport magnitude and poloidal channeling (θ -petals) become clearly distinguished in the data, and are in close quantitative agreement with recent theory. The neoclassical ripple transport shows the unambiguous and distinctive signature scaling as $\omega_\varepsilon\varepsilon_B^2\times(\Delta W_C D_{cA}+\Delta\phi_s D_{mA}\sin^2\alpha)$, where the θ-petals magnitude defined by the relative angle $\alpha\equiv\theta_B-\theta_m$ is proportional to $\Delta V_m\varepsilon_B^2B^{-1}$. This novel chaotic transport mechanism could be an important loss process at very low collisionality in many fusion systems with asymmetric separatrices such as stellarators.

The work was supported by NSF Grant PHY-0903877 and DOE Grant DE-SC0002451.

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I-06

TOKAMAK CODE TOKES MODELS AND IMPLEMENTATION

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During a few past years the code TOKES was developed [1], aiming at integrated simulation of plasma equilibriums and surface processes in tokamak devices. This paper will describes some intermediate state of the code and available numerical results obtained so far, including physical and mathematical background of incorporated models and design details. The code calculates multi-fluid plasma processes in the core and the scrape-off layer (SOL), and atomic processes at the vessel surface and in the vessel volume, by a sequence of time steps for the whole discharge. The dynamics of magnetic field and plasma currents and the currents in the poloidal field coils are also implemented. The code's models include the fuelling by spreading cold atoms in the confined plasma volume and the heating by neutral beams, the transport of radiation and neutrons in the whole vessel and the hot plasma in the core, and plasma fluxes through the separatrix or the limiter into SOL towards the wall. Also the processes of surface response to the load, such as the sputtering and the vaporization are implemented, as well as the propagation of the emitted material atoms in the vessel and their ionization in the confined plasma.

This work, supported by the European Communities under the contract EFDA/05-1305 between EURATOM and Karlsruhe Institute of Technology, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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I-07

AFFINITY AND DIFFERENCE BETWEEN ENERGETIC-ION-DRIVEN INSTABILITIES IN 2D AND 3D TOROIDAL SYSTEMS*

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Energetic (superthermal) ions are usually present in all types of toroidal fusion facilities. They are produced by neutral beam injection, radio frequency heating, and fusion reactions. The energetic ions can lead to various plasma instabilities, in particular, various Alfvén instabilities. These instabilities can considerably affect the plasma performance by expelling energetic ions from the plasma core. Moreover, there are experiments where the deterioration of the plasma energy confinement time took place during these instabilities. Meanwhile, some instabilities has no visible influence on the energetic ions and the plasma, in which case they can be used for plasma diagnostics.

Because most works dealing with energetic-ion-driven instabilities are relevant to tokamaks, it is of importance to understand when the results of these works, especially theoretical works, can be used for the description of similar phenomena in stellarators. On the other hand, the stellarator theory incorporating effects of 3D geometry can be useful for understanding instabilities in tokamaks, where the axial symmetry is broken by, e.g., magnetic islands. Therefore, comparative analysis of instabilities in various types of toroidal systems is of interest for both stellarator and tokamak communities. Such an analysis based on an overview of energetic-ion-driven instabilities in tokamaks and stellarators is carried out in this work. Instabilities in wide frequency range, from the ion/electron diamagnetic frequency to high frequencies of specific stellarator modes, are considered. Effects of the instabilities on the confinement of both the energetic ions and the bulk plasma are described. Numerical tools available for the simulation of instabilities driven by energetic ions in tokamaks and stellarators are reviewed.

Acknowledgements

The research described in this publication was made possible in part due to the Project No. 4588 of the Science and Technology Center in Ukraine.

*This report is based on an invited paper submitted to Plasma Physics and Controlled Fusion (PPCF) for publication in a PPCF cluster issue on physics at the stellarator-tokamak interface.

I-08

KINETIC MODELING OF H-MODE PEDESTAL WITH EFFECTS FROM ANOMALOUS TRANSPORT AND MHD STABILITY*

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This study addresses the development of a scaling of the H-mode pedestal in tokamak plasmas with type I ELMs. The sheared E×B flows result in a reduction of anomalous transport, which leads to the formation of an edge transport barrier and the transition to the H-mode improved confinement in tokamaks. The nonlinear interplay between anomalous and neoclassical effects motivates the development of a self consistent simulation model that includes neoclassical and anomalous effects simultaneously. For the basic kinetic neoclassical behavior, the XGC0 kinetic guiding-center code [1] is used with a realistic diverted geometry. For the anomalous transport, a radial random-walk is superposed in the Lagrangian neoclassical particle motion, using the FMCFM interface to the theory-based MMM95 and GLF23 models. These anomalous models include transport driven by drift-wave instabilities, such as the electron and ion temperature gradient driven modes and trapped electron modes. The MMM95 model includes a resistive ballooning component that is particularly important near the plasma edge. The GLF23 model is used to cross-verify the anomalous transport in the plasma core region. The effect of E×B flow shear quenching is implemented through a flow shear suppression factor [2-4]: $F_s=1/(1+(\tau_c\ \omega_{E\times B})^2)$, where τ_c is the correlation time of fluctuations for the case without flow and $\omega_{E\times B}$ is the normalized E×B flow shear rate: $\omega_{E\times B}\equiv|R\ B_\theta\ /B_\varphi\ \partial/\partial r\ (E_r\ /R\ B_\theta\ )|$. The radial electric field E_r is computed in the first-principle neoclassical kinetic XGC-0 code. Growth of the pedestal by neutral penetration and ionization is limited by an ELM instability criterion computed by the ELITE MHD stability code [5]. XGC0 and ELITE coupling is automated in the EFFIS computer science framework. H-mode pedestal profiles for two representative tokamak devices, DIII-D and Alcator C-Mod, are considered: DIII-D for low B-field, low density, high temperature plasmas; and C-Mod for a high B-field, high density plasmas. The simulations in this study use realistic diverted geometry and are self-consistent with the inclusion of kinetic neoclassical physics, theory-based anomalous transport models with the E×B flow shearing effects, as well as an MHD ELM triggering criterion. A scaling relation for the pedestal width and height is presented as a function of the scanned plasma parameters. Differences in the electron and ion temperature pedestal scalings are investigated.

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*This work supported by the U.S. Department of Energy under DE-SC0000692, DE-FC02-08ER54985, DE-FG02-06ER54845, DE-FG02-92ER54141, DE-FC02-04ER54698, DE-FG02-95ER54309, DE-FC02-99ER54512.

I-09

RELIABILITY AND PERFORMANCE OF TOKAMAK FUSION DEVICES UNDER VARIOUS PLASMA INSTABILITIES

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Plasma instability events such as disruptions, resulting runaway electrons, edge-localized modes (ELM), and vertical displacement events (VDE) are mainly the most limiting factor for successful Tokamak reactor concept. The plasma-facing components (PFC), e.g., wall, divertor, and limited surfaces of a tokamak as well as coolant structure materials are subjected to intense particle and heat loads and must maintain a clean and stable surface environment between them and the core/edge plasma. This is critical to fusion device performance.

Comprehensive research efforts are developed utilizing the HEIGHTS simulation package to study self-consistently various effects of high power transient on material operation/selection. The package consists of several models that integrate different stages of plasma-wall interactions starting from energy release at scrape-off-layer and up to the transport of the eroded debris and splashed wall materials as a result of the deposited energy. The integrated model predicts material loss, PFC lifetime from transients, and effects on core plasma performance. HEIGHTS initial simulation shows that a single event such as a major disruption, VDE, or runaway electron could severely damage the reactor wall and structural materials and disrupt operation for a significant time. HEIGHTS is used to identify safer operating window regimes and upper transient limits that PFC can withstand during various instabilities.

I-10

MATERIAL CHARACTERIZATION AND HIGH HEAT FLUX TESTING UNDER ITER SPECIFIC OPERATING CONDITIONS

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To withstand the extreme environments in a thermonuclear fusion reactor a number of technological challenges have to be met; in particular high-temperature resistant and plasma compatible materials have to be developed and qualified under ITER specific loading conditions. Special attention has to be paid to high heat flux components, i.e. to the limiters and the divertor targets with expected power densities up to about 10 MWm^{-2}. These extreme loads make high demands on the selection of qualified materials and reliable fabrication processes for actively cooled plasma facing components. The technical solutions which are considered today are mainly based on beryllium, carbon or tungsten and copper alloys or stainless steel for the heat sink.

Another important issue is the evaluation of the materials performance under short transient events which occur during Edge Localized Modes (ELMs) and during plasma disruptions. In this field significant progress has been made with the investigation of threshold values for the damaging processes such as roughening, crack formation and melting of the heat affected surfaces under ITER relevant loading scenarios. Electron beam based thermal shock experiments have been performed on a number of metallic and carbon based armour materials. In these tests the damage thresholds have been determined in single and multiple shot experiments. To perform transient heat load experiments with ELM like loading rates, i.e. millions of repetitions, the most essential machine parameter are the characteristics of the beam such as beam profile and beam diameter. Systematic analyses have been preformed which allow to quantify local energy deposition profiles as a function of beam current, acceleration voltage, the currents in the focusing coils, and the chamber pressure. Based on these parameters the experimental conditions for repetitive ELM-simulation tests have been derived.

The wall bombardment with 14 MeV neutrons in D-T-burning plasma devices and the resulting material damage are another critical issue, both, from a safety point of view, but also under the aspect of the component lifetime. Next step thermonuclear confinement devices such as ITER with an integrated neutron fluence in the order of 1 dpa do not pose any unsolvable material problems. Due to the lack of an intense 14 MeV neutron source, complex neutron irradiation experiments have been performed in material test reactors to quantify the neutron-induced material damage.

I-11

SIMULATION OF ITER ICWC SCENARIOS IN JET

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In ITER and future fusion devices, the presence of the permanent, high toroidal magnetic field resulting from operation with superconducting coils will prevent the use of conventional glow discharge conditioning technique (GDC) between ohmic plasma shots. The Ion Cyclotron Wall Conditioning (ICWC) technique based on Radio-Frequency (RF) discharges is fully compatible with high magnetic field and considered as the most promising technique available to ITER for routine wall conditioning, in particular for recovery after disruptions, isotopic ratio control and fuel removal. The ability to operate in ICWC mode has recently been confirmed as a functional requirement of the ITER main ICRF heating and current drive system.

This paper focuses on a study of ICWC discharge performance in the largest current tokamak JET using the standard ICRF heating antenna A2 in a scenario envisaged at ITER full field: on-axis location of the fundamental ICR for deuterium, $\omega=\omega_{cD+}$. To enhance the wall conditioning output, the RF discharge ignition/sustainment phases have been optimized in terms of (i) antenna-near E_z-field generation (parallel to the B_T-field) responsible for the discharge ignition, (ii) antenna coupling to low plasma density (~10^{17} m^{-3}) and (iii) plasma wave excitation/absorption over the torus in low density plasmas. The optimization procedure enabled to extend the JET A2 antenna (two modules) reliable operation in the ICWC mode over a large range: f=25 MHz, $00\pi\pi$- and monopole-phasing for the antenna current straps, coupled power $P_{RF\text{-}pl}\approx$80–250 kW (with the antenna coupling efficiency $P_{RF-pl}/P_{RF-G}\approx$0.5–0.6), gas composition (He, D_2 and their mixtures) at pressure $p_{tot}\approx2\times10^{-3}$ Pa, B_T=3.3–3.45 T, B_V=0–30 mT. The efficiency for fuel removal was assessed in the isotopic exchange scenario. The conditioning cycle with 8 identical D_2 ICWC shots (an accumulated discharge time of 72 s) in the vessel preloaded with H_2 resulted in an increase of the isotopic ratio D/(D+H) between 30% and 50% with the wall retention about 3 times higher than desorption.

The empirical direct extrapolation of the obtained experimental ICWC data to ITER size (asuming similar power density scaling) are compared with the predictions from 1-D RF full wave and 0-D/1-D RF plasma codes. The analysis indicates that the currently planned ITER ICRF H&CD system could be used for ICWC operations on ITER.

*See the Appendix of F. Romanelli et al., Proc. 22nd Int. FEC Geneva, IAEA (2008).

I-12

GENERALIZED FOKKER-PLANCK EQUATION AND UNIFIED DESCRIPTION OF BALLISTIC AND DIFFUSIVE PROCESSES

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Turbulent diffusion generated by plasma instabilities in many cases manifests anomalous properties which cannot be described on the basis of ordinary diffusion equation. In particular, mean-square particle displacement can have fractional power time behavior changing in course of the system evolution.

In the present contribution we propose the unified description of diffusion processes that crosses over from a ballistic behavior at short times to a fractional diffusion (sub- or super-diffusion) as well as ordinary diffusion at longer times using the non-Markovian generalization of the Fokker-Planck equation. The relations between the non-time-non-local kinetic coefficients and observable quantities (mean- and mean- square displacements) are established. The problem of calculations of the kinetic coefficients using the Langevin equations is discussed. Solutions of the non-Markovian equation describing diffusive processes in the real (co-ordinate) space are obtained. Such solution agrees for long times with results obtained within the continuous random walk theory but is much superior to this solution at shorter times where the effects of the ballistic region are crucial.

I-13

IMPURITY ION HEATING AND DRIFT VELOCITY IN THE AL'FA EXPERIMENT

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Al'fa was one of the first (c. 1960) large toroidal plasma experiments (major and minor radii 1.6 and 0.5 m; toroidal B~0.1 T). Extensive, early diagnostic development and results were reported for this ohmically heated device:[1] x rays, energetic electrons, and charge exchange H atoms were detected. In particular, high impurity ion energies (hundreds of eV, far above the nominal 20 eV electron temperature) and substantial toroidal drift velocities of these ions were observed spectroscopically. This impurity ion behavior has never been adequately interpreted theoretically[2,3] or related to today's experiments.

Describing loop voltage traces from the British ZETA experiment, upon which Al'fa was modelled, Artsimovich noted[2] that the "trace of V is typical of a highly nonstationary process. The amplitude of the high frequency voltage spikes is comparable to the average voltage applied to the discharge chamber. The characteristic frequency of these spikes is in the range of 10^5-10^6 Hz."

The observed impurity ion behavior in Al'fa can be explained, consistently with data from the experiment,[1-3] in terms of charged particle acceleration in its average and transient toroidal electric fields (given by the loop voltage V_L, divided by the discharge major circumference). Here the following factors are simulated by calculations of rates and time scales, etc., using data from the Al'fa experiment, cross section data, and 1-D momentum equations: (i) fluctuations in V_L caused by, e.g., changes in plasma shape, (ii) generation of transient fast electron populations during spikes in V_L, and (iii) production of highly ionized states of impurities by these electrons. Acceleration of impurity ions in the toroidal electric field leads to the spectroscopically observed effects: (iv) an apparent high temperature of the impurity ions owing to toroidal acceleration, in both directions, during spikes in V_L, along with (v) their net toroidal drift corresponding to the average (smoothed) V_L [O(800 V)].

The source of the observed impurity ion momentum in Al'fa thus appears to have been the toroidal electric field corresponding to the noisy loop voltage of these discharges. This interpretation does not require the invocation of turbulence, inward fluxes, or microfield anomalies. In general, the impurity ion population is thermally decoupled from the H (bulk) ions, as it is from the electrons, in these runaway discharges.

The model for impurity ion toroidal drift in the average (smoothed) V_L of Al'fa also applies to ohmically heated tokamaks, which are comparatively quiescent, with far lower V_L [O(2 V)] and higher confining toroidal magnetic fields. The high average V_L in Al'fa leads invariably to an (average) impurity ion drift in the direction of the toroidal current. On the other hand, toroidal impurity ion drift in tokamaks may be parallel or antiparallel to the toroidal current, depending on the plasma and device parameters, but the impurity drift will, as in Al'fa, generally be decoupled from that of the bulk hydrogenic ions.[4]

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I-14

BEAM-TARGET PLASMA INTERACTION AND THERMALIZATION

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Predominant future primary power source will be the nuclear power. It is the only way to cover increasing energy consumption, it is not the source of the greenhouse gases and the fuel will last for billions of years. By employing this energy the ecological problems arising from the CO_2 production can be trimmed down. Fusion power plants would not have problem with waste and on the other hand they will be able to produce energy with high efficiency without the need for intermediate thermal stage. The difficulties associated with mining and transportation will also disappear. If any catastrophic event should occur, the reaction would die off in a fraction of a second with no risk of radioactive contamination. There are tokamak, laser, pinch and other systems. In our work we oriented on small fraction of the questions involved in fusion program – beam target plasma interaction and thermalization.

The generalized Buneman dispersion relation for two-component plasma was derived in the case of nonzero pressure of both plasma components and longitudinally dominated magnetic field. The derived relation is also valid for other field configurations. It can be useful in a variety of plasma systems, e.g. in the analyses of plasma jet penetrating into background plasma, in beam-target physics and in tests of various MHD and hybrid numerical codes designed for the magnetized plasmas.

In parallel to the experimental research simulations are in progress. They are essential for understanding the nature of phenomena as well as experiments and theory. They assist by estimating the parameters, which cannot be measured and so they allow better comprehension the observed event. In our department was developed fully 3D PIC model of plasma fibers or beams. Code of the program is written in the FORTRAN 95 programming language. Model comprises five types of particle motion solvers (Newton, Runge-Kutta, Boris-Buneman, Leap-Frog and Canonical) and two types of field solvers (FFT and multigrid). Procedures are implemented in both relativistic and nonrelativistic variants. Model can employ periodical and non-periodical boundary conditions as well. The PIC program package numerically simulates behavior of a fiber or beam and its interaction with the background plasma or target, in particular the evolution of the magnetic field structures and turbulences. Numerical solution of a motion of the charged particles and solutions of electrical and magnetic fields form only a small part of the program package. Model includes series of functions and cooperates with other program packages for computer plasma diagnostics, graphical output and other calculations. For the visualization of fields the method LIC (Line Integral Convolution) was used. Visualization of the particles has many options, including disappearing smoke trace behind the moving particle. Useful is also the possibility to record evolution of the scene as an animation into the avi file. As other components of the package there are diagnostic functions, which allow computation of quantities which can be compared to the experiments. Whole package is in the development for several years and meanwhile several diploma and PhD students oriented in plasma physics are participating on it. PIC model developed at our department allows deep understanding of the processes present in the plasma beam, especially simulation of beam thermalization or onset and advancement of the helical modes. PIC program package could also be useful for studying shock waves in plasma, instabilities, electrical double layers, polar cusp and variety of other phenomena. In the present the model is used especially for the simulations of plasma fibers and beams, but authors are certain of the fact that it will be useful as well for the other simulations of plasma in the near future.

I-15

RECENT PROGRESS ON LASER PLASMA ACCELERATORS AND APPLICATIONS FOR COMPACT HIGH-QUALITY PARTICLE BEAM AND RADIATION SOURCES

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In this decade, worldwide experimental and theoretical researches on laser-plasma accelerators have brought about great progress in high-energy high-quality electron beams of the order of GeV-class energy and a few % energy spread. On the other hand, laser-driven production of GeV-class high-quality ion beams such as protons and carbon ions is underdeveloped, harnessing development of Petawatt-class ultra-intense lasers with high-quality and ultra-thin foil targets. These high-energy high-quality particle beams make it possible to open the door for a wide range of applications in research, and medical and industrial uses.

Here recent progress in laser-driven plasma particle accelerators including electron- and ion-acceleration is overviewed in terms of particle beam parameters such as energy, energy spread, emittance, bunch length and charge, strictly determined by acceleration mechanism or laser-plasma interaction such as the bubble mechanism in electron acceleration and radiation pressure acceleration in ion acceleration.

Although there is no practical application to date, underdeveloped are various applications of laser plasma accelerators such as a compact THz or coherent X-ray radiation source and radiation therapy driven by laser-accelerated electrons. A promising application project of laser-driven proton and ion beams to the future hadron therapy is implemented worldwide. In the future laser-plasma accelerators may come into being as a novel versatile tool for space radiation studies where a compact and cost-effective tool is required as well as inherent application to the energy-frontier particle accelerator.

I-16

LONG SEQUENCE OF RELATIVISTIC ELECTRON BUNCHES AS A DRIVER IN WAKEFIELD METHOD OF CHARGED PARTICLES ACCELERATION IN PLASMA

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Using *LCODE* 2.5D-simulation of wakefield excitation in plasma by a long sequence of relativistic electron bunches for high-gradient acceleration of charged particles was performed. Conditions for enhancement of excitation efficiency, acceleration gradient, and transformation ratio for energy transform from the exciting bunches to the accelerated bunch were investigated. Differences of 2.5D-consideration results from known 1D-consideration were revealed. Interpretations of certain results of KIPT experiments with $6x10^3$ relativistic electron bunches are given.

I-17

HIGHLIGHTS OF DENSE MAGNETIZED PLASMA RESEARCH IN POLAND

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This invited lecture presents the most important achievements of theoretical and experimental studies which have concerned dense magnetized plasmas and have been performed in Poland during recent few years. Those studies were concentrated on high-current pulse discharges performed within the large mega-joule PF-1000 facility, which was operated at the IPPLM in Warsaw and investigated by researchers from the IPJ and IPPLM. The machine was operated mainly with a pure D_2 filling, and the peak discharge current amounted to 1.5-1.8 MA.

In previous years theoretical studies concerned mainly the modeling of a current sheath dynamics on the basis of an extended 2D-MHD model. Recently attention has been paid to computer modeling of motions of accelerated primary deuterons as well as fast fusion-produced protons. An influence of so-called current filaments, which are often observed in high-current pinches, was analyzed. The obtained theoretical results have been compared with data obtained from recent experiments.

The experimental studies included detailed measurements by means of a multi-frame laser interferometer, time-integrated and time-resolved measurements of neutron yields, as well as optical emission spectroscopy of a plasma stream during its free propagation and interactions with a solid-state target. It was shown that one can determine experimental conditions when a relatively pure deuterium plasma stream arrives to the investigated target, what is of importance for studies of fusion-reactor materials.

Recent experimental efforts concerned also the corpuscular diagnostics of fast electron- and ion-beams emitted from the PF-1000 facility. To measure energy spectra of electrons the use was made of a magnetic analyzer equipped with a shielded X-ray film. It was shown that the electron beams, which are emitted from deuterium discharges supplied from a 21-27 kV, 290-480 kJ condenser bank, have energies ranging up to about 800 keV.

To investigate the ion beams there were applied small pinhole cameras equipped with shielded PM-355 track detectors. Mass- and energy-analysis of the emitted ions was performed by means of a miniature mass-spectrometer of the Thomson type. It was shown that for the experimental conditions described above the emitted ion streams consist of many deuteron micro-beams of energies ranging up to > 700 keV. It has been confirmed by the first time-resolved measurements of the deuteron beams. The appearance of such energetic deuterons is explained as an effect of non-linear phenomena occurring in a pinch column.

Recently particular attention has also been paid to measurements of an angular distribution of fast fusion-produced protons by means of pinhole cameras and shielded PM-355 detectors. It has been shown that the recorded azimuthal distribution of the fusion protons is consistent with predictions of theoretical simulations performed for the filamentary pinch column.

I-18

MEASUREMENTS OF RADIAL ELECTRIC FIELD AND GEODESIC ACOUSTIC MODE OSCILLATIONS WITH HEAVY ION BEAM PROBE IN LARGE HELICAL DEVICE

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In the toroidal magnetized plasmas, radial electric field E_r (or potential ϕ) is a very important parameter in order to understand the confinement property of plasma. In the Large Helical Device (LHD), a heavy ion beam probe (HIBP), of which maximum beam energy is 6 MeV, was installed and has been developed [1-3]. By improving components of our system, such as the electro deflector, the ion source, and the beam detector, the equilibrium potential profile and the fluctuation was measured with good signal to noise ratio.

In the case of low density high temperature plasma, the measured potential in the core region was positive and the positive radial electric field was observed. The potential at the center gradually decreased with the increase of density, and the radial electric field in the core region became negative, while the electric field in the outer region was positive. From the neoclassical theory, the positive radial electric field (electron root) in low density case and the negative radial electric field (ion root) in larger density case are predicted. And in some cases, multiple roots (both electron root and ion root) are prospected. The radial electric field predicted from neoclassical theory almost coincides with the experimental results.

The fluctuation of potential in low density plasma was observed by HIBP. When the current drive by electron cyclotron heating was applied to plasma, the fluctuation, of which frequency was a few tens kHz, was observed. This frequency and its dependence on the temperature correspond to those of geodesic acoustic mode (GAM), so we consider this mode is GAM. The mode localizes in the core region, and the fluctuation amplitude is about a few hundred volts.

In the presentation, we will show the detail of our HIBP system, improvement of system, and recent experimental results.

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I-19

LONG-RANGE CORRELATIONS IN EDGE TURBULENCE AND ROTATION EFFECTS IN BIASING AND ALFVÉN HEATING EXPERIMENTS IN TCABR

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Relevant results recently obtained in the TCABR tokamak will be reported. Long-distance correlations (LDC) of floating plasma potential fluctuations measured by the array of multi-pin Langmuir probes in the plasma edge have been investigated in the regime of the biasing H-mode. Experimental data confirm the effect of strong amplification of LDC in the potential fluctuations by biasing, recently observed in other experiments, whereas correlation of the density fluctuations is low. A new method to determine the temporal evolution of plasma rotation has been developed and the change in the plasma toroidal during electrostatic biasing has been measured. A small power Alfvén wave heating pulse was also applied to the discharges with electrode biasing (B_t =1.1T, $n_e \approx 1.1\text{-}1.6\times10^{19}/m^3$, $T_e \approx$ 350-550eV, $T_i \approx$100-150eV, and P_A = 30 kW). This produces small electron heating $\Delta T_e \approx$ 30-50eV detected by ECE emission, which is accompanied by increasing line-averaged density, CIII and CV lines and soft X-ray emission, indicating impurity accumulation in the plasma core. Strong MHD oscillations with m=2 appear with time delay about 3-4 ms after the AW application.

I-20

PHYSICS AND CONSTRUCTION STATUS OF THE WENDELSTEIN 7-X STELLARATOR

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Wendelstein 7-X is the largest stellarator device under construction. Its key element is an optimized magnetic field configuration, generated by 50 non-planar superconducting coils. It is the mission of the project to demonstrate the reactor potential of the optimized stellarator line. In particular, stellarators can operate in steady-state, which is still difficult to achieve in nowadays tokamaks. Wendelstein 7-X aims for steady-state operation of fusion-relevant plasmas for the first time.

This talk gives a comprehensive overview of the construction status of Wendelstein 7-X and outlines the key elements of the future research concept. The latter is largely based on results obtained with the predecessor device, Wendelstein 7-AS. The most relevant ones are reviewed in this talk. Operation features of Wendelstein 7-X like density and temperature profiles, ECR current drive, divertor load etc., could be predicted by numerical simulations.

CONTRIBUTED PAPERS
TOPIC 1 - Magnetic Confinement Systems:
(Stellarators, Tokamaks, Alternative Conceptions)

1-1

PLASMA DENSITY BEHAVIOR DURING RF HEATING IN THE URAGAN-3M TORSATRON (review)

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A middle-size device, the Uragan-3M torsatron/heliotron (U-3M: l = 3, m = 9, R = 100 cm, $\bar{a} \approx 12$ cm, $\iota(\bar{a}) \approx 0.3$, $B_\phi = 0.72$ T), has some characteristic properties distinct from other stellarator-type devices.

1. The toroidal magnetic field is generated by the helical windings only. The whole magnetic system, including helical coils, vertical field coils and their supports, is enclosed into a large vacuum chamber, its volume (70 m^3) being more than two orders of magnitude as large as that of the plasma volume.

2. An open natural helical divertor is realized.

3. The working gas (hydrogen) is admitted continuously into the vacuum chamber.

4. The plasma is produced and heated by RF fields in the $\omega \lesssim \omega_{ci}$ range of frequencies under conditions of the multi-mode Alfven resonance. To ignite the discharge and inject RF power into the plasma, an unshielded twisted frame-type antenna is used that is disposed under two helical coils along one helical field period.

These distinctions give rise to some characteristic features in plasma density behavior both at the active stage of discharge and after RF pulse termination and manifest themselves as follows:

- density rise after RF pulse termination;
- density decrease with heating power;
- the hydrogen pressure is necessary to be increased to retain a fixed density with RF power increase;
- divertor plasma flow (DPF) increase with RF power;
- resonance character of density and DPF versus magnetic field dependences.

The analysis of these features draws to the conclusion that all of them directly or indirectly result from the effect of plasma confinement degradation with heating power which is observed in all toroidal devices with magnetic confinement, including tokamaks and stellarators.

The objective of this presentation being of an review character is to bring together experimental results obtained in U-3M in different works and time that evidence a rising dependence of plasma loss on the heating power and to consider some important mechanisms causing such a dependence.

1-2

GYROKINETIC SIMULATION OF TOROIDAL MOMENTUM TRANSPORT IN DRIFT-WAVE PLASMA TURBULENCE

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Studies of kinetic electrons effect in the toroidal momentum transport in the ion temperature gradient (ITG) turbulence and pioneering global nonlinear gyrokinetic simulations of momentum transport in collisionless trapped electron mode (CTEM) turbulence using flagship gyrokinetic GTC code [1] are presented. The distinct off-diagonal momentum fluxes are observed. Varying the background rotation speed, the toroidal momentum pinch velocity and residual momentum flux is calculated, and used to separate the diffusive momentum flux and to calculate the intrinsic Prandtl number, defined as the ratio of true momentum to heat diffusivities, for the first time [2]. The obtained values of Prandtl number for ITG and CTEM turbulence are found to be from 0.3 to 0.9, which is consistent with experimental observations and quasilinear estimates.

The effect of kinetic electrons leads to the increase of momentum flux in the ITG turbulence, mainly due to increase of the turbulence intensity, with the ratio of momentum to the heat flux not being affected by kinetic electrons (Fig.1) [3]. The convective particle flux in this case gives relatively small contribution to the total momentum pinch. It is found that the dominant contribution to the momentum flux in CTEM case comes from the diffusive term (Fig.2), opposite to ITG case, where diagonal and off-diagonal momentum fluxes are comparable.

*In collaboration with Y. Xiao, W.L. Zhang and Z. Lin. The work was supported by SciDAC GPS, GSEP and Plasma Science Centers.

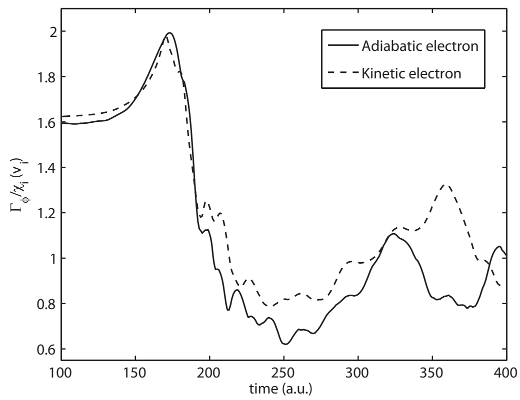

Fig.1. Time evolution of the ratio of the momentum to heat flux in the ITG turbulence with adiabatic (solid) and with kinetic electrons (dashed line).

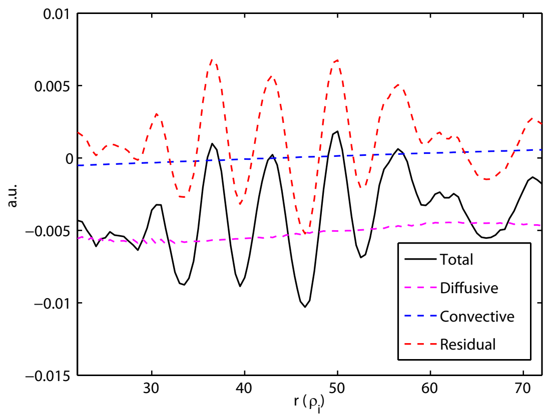

Fig.2. Structure of momentum flux in the CTEM turbulence with $\omega_\phi = (-0.1 + 0.2\, r/a) v_i / R_0$.

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1-3

LONG-DISTANCE CORRELATIONS OF FLUCTUATIONS IN TCABR TOKAMAK

Yu.K. Kuznetsov[1], I.C. Nascimento[1], R.M.O Galvão[1], C. Silva[2], H. Figueiredo[2], J.H.F. Severo[1]and participants of TCABR Joint Experiment

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One important issue related to zonal flows is the long distance correlation (LDC) of potential and density fluctuations along the equilibrium magnetic field lines. Recent results obtained in edge polarization experiments carried out in TJ-II stellarator [1,4] and ISTTOK [2] and TEXTOR [3] tokamaks indicate that the correlation length of floating potential fluctuations can be of the order of the length of the plasma column. Here we present results obtained in the TCABR tokamak during an experimental campaign organized within the framework of the IAEA Coordinated Research Project on "Joint Experiments Using Small Tokamaks"(May 2009). A graphite electrode was used to obtain biasing H-mode. The set of multi-pin Langmuir probe arrays used in the experiments includes a 20-pin rake probe, 5-pin probe, 6-pin forked probe and 8-collectors Gundestrap probe. Results obtained on TCABR confirm recent observations of LDC in potential fluctuations, whereas correlation of density fluctuations is very low. The LCD is already observable in the low confinement regime but increases strongly during L-H transition. Together with these common features, there are distinct data on dominant components in V_f. for the LCD. The LDC is caused by low frequencies f < 20-40 kHz without coherent modes in JT-II, while it is dominated by coherent mode (f ~ 1.6 kHz) in TEXTOR. Our data are more close to that of JT-II, i.e. the LCD is dominated by frequencies f<40-50 kHz in our case. We observe also strong increase in H-regime of very low frequency highly coherent fluctuations without dominant mode (f<5 kHz). The local autopower spectrum in wave number space S (k) obtained from the frequency-wave number spectrum S (k,f) shows that turbulent broadening decreases substantially and S(k) has maximum value at k = 0 in biasing H-mode.

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1-4

APPLICATION OF ELECTRODE-DRIVEN SHEAR FLOWS FOR IMPROVED PLASMA CONFINEMENT

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In open magnetic configurations (open traps, SOL) it is possible to control the plasma potential along magnetic field lines via external electrodes. Thus, there is a possibility for direct drive of shear flows and suppression of instabilities if there is a sufficient electrical contact of plasma with electrodes (such contact occurs across the Debye sheath and is not particularly good even in 100eV plasmas.) In contrast to the ITB shear flows, the governing equations in this case are strongly dissipative: the same electrical contact (line-tying) that allows control of the plasma potential negates conservation of energy and enstrophy for long-wavelength perturbations. Thus, the electrode-driven shear flows are not particularly good for simulation of ITB physics. We show that nevertheless they allow achievement of improved-confinement regimes in open traps.

The following simplified set of equations, governing the two-dimensional plasma dynamics on open field lines, is studied analytically and numerically [1]:

$$\partial_t \Delta\varphi + \{\varphi, \Delta\varphi\} = H\left(\varphi - \varphi_{fl}\right) + \nu\Delta^2\varphi + \nabla\{\nabla\varphi, P\} + \kappa\{P, r\}$$
$$\partial_t P + \{\varphi, P\} = \nu\Delta P$$

It is supposed to describe nonlinear drift-interchange modes in presence of a hot-ion species that provides the pressure, *P*. $H \geq 1$ is the line-tying coefficient, κ is the normalized curvature, while $\varphi_{fl}(r)$ is the floating potential with respect to the ground, i.e., this function of coordinates has a discontinuity at coordinates corresponding to junction of electrodes. The jump in $\varphi_{fl}(r)$ is, essentially, the source of the plasma flow, which is generated along it.

If the collisional transverse diffusion, ν, remains small, the flow layer evolves into a sort of Kelvin-Helmholtz instability, which in the nonlinear stage looks like two moving chains of quasi-stationary vortices on both sides of the central flow-layer. The transverse-to-parallel ratio of vortices is influenced by the FLR ion viscosity term, $\nabla\{\nabla\varphi, P\}$, i.e., vortices become elongated along the flow. But the most important effect is the nonlinear saturation of curvature-driven interchange modes. The flow width provides a new transverse scale that limits plasma convection across it. If the applied potential exceeds the saturated amplitude of the interchange mode the vortex chains do not overlap and the transverse transport remains small.

This theoretical picture is compared to experimental data from the gas-dynamic trap (GDT) in Novosibirsk, where the “vortex-confinement” regime with applied potentials has become standard. When the biasing potentials of order T_e are applied at the edge of the plasma column, the transverse confinement improves to values only slightly below classical diffusion. Saturated rotating m=1 or m=2 modes are seen on a variety of diagnostics, frequency and threshold parameters are in reasonable agreement with predictions of the model.

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1-5

STUDY OF COLLISIONLESS HIGH ENERGY PARTICLE LOSSES FOR URAGAN-2M TAKING INTO ACCOUNT THE INFLUENCE OF CURRENT-FEEDS AND DETACHABLE JOINTS OF THE HELICAL WINDING

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A study of collisionless charged particle losses (in particular, α-particle losses) is important for assessment of general confinement properties of stellarator devices. In the proposed report such losses are studied numerically for the magnetic configuration of U-2M (Uragan-2M [1]). For the computation of the magnetic field the influence of current-feeds and detachable joints of the helical winding has been taken into account. Because of the non-symmetric arrangement of these elements of the magnetic system, the stellarator symmetry of the resulting magnetic field of U-2M is broken. This requires a special approach for the computation of the gradient of the magnetic surface function, $\nabla\psi$, which is necessary for the numerical particle confinement study. Such an approach has been elaborated recently in [2].

To assess particle losses, target functions which have been introduced in [3,4] are used in combination with the technique of [2] for the computation of $\nabla\psi$. For the magnetic field calculations the Biot-Savart code which has been developed in [5] is used. The purpose of this code is the modeling of the magnetic field defined by the magnetic field coils and of the influence of current-feeds and detachable joints of the helical winding. For comparison, supplemental computations are performed for the magnetic field calculated using the Lagrange polynomial interpolation on a three-dimensional grid obtained with help of this Biot Savart code.

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1-6

PLASMA TURBULENCE AND LOCAL ELECTRIC FIELD INVESTIGATIONS OF THE DENSE PLASMA ON TJ-II STELLARATOR AND T-10 TOKAMAK BY HIBP DIAGNOSTIC

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Heavy Ion Beam Probe diagnostic on TJ-II stellarator has been upgraded for two point measurements to study with a good spatial (1cm) and temporal (10 μs) resolution the plasma electric potential and density, so as their fluctuations, poloidal component of electric field $E_p=(\varphi 1 - \varphi 2) / \Delta r$ [V/cm] and to extract radial turbulent particle flux $\Gamma_r = \Gamma_{EpolxBtor.} = \Gamma_{ExB.}$

Major problems of probing beam penetration into dense area of plasma and carrying out of measurements from center to edge in the existing devise consist in the following: increasing of initial intensity of the probing beams and expanding of the dynamical range of measurements. These problems were solved by comprehensive modification of the probing ion beam injector.

Recent experiments in the TJ-II stellarator with Li-coating and NBI heating have shown evidence for spontaneous L-H transition occurring at a threshold value of the plasma density. During the direct L-H transition edge and core fluctuations of local plasma potential and poloidal electric field Epol shows some reduction. The strong suppression in plasma density fluctuations and their coherence with E_{pol} at the H-mode was observed.

Heavy Ion Beam Probing becomes a new tool to study Energetic ion driven Alfvén Eigenmodes (AE) with the high spatial and frequency resolution. HIBP in the TJ-II heliac observed the locally (~1 cm) resolved AE at radii $-0.8 < r < 0.9$. The set of low m ($m<8$) branches, detected with the high frequency resolution (<5 kHz) is supposed to be Toroidally Induced Alfvén Eigenmodes (TAE). TAE are pronounced in the local density, electric potential and poloidal magnetic field oscillations, detected simultaneously by HIBP and Lengmour probes in the frequency range 50 kHz$<\omega_{AE}<$300 kHz. AE are visible in the NBI-heated plasma.

Geodesic acoustic modes (GAM) were investigated on the T-10 tokamak using Heavy Ion Beam Probe. HIBP is a powerful diagnostics to study GAMs. It is able to get simultaneously the oscillatory components for plasma electric potential and density. It was shown the GAMs are more pronounced in the plasma potential rather than density.

1-7

ON THE POSSIBILITY OF SOLVING THE PROBLEM OF CONTROLLED THERMONUCLEAR FUSION BASED ON MAGNETO INERTIAL APPROACH

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A new fusion scheme which can avoid some of the major difficulties faced in the present approaches in magnetic and inertial confinement fusion is presented. Magneto-inertial fusion represents the all-inclusive set of pulsed high-pressure (inertially confined) approaches to fusion that involve magnetic field in an essential way. Presence of a magnetic field reduces the heat conductivity and plasma should be at thermonuclear temperatures for only microseconds.

Magneto-inertial fusion (MIF) is a pulsed high energy density approach to achieving fusion in that combines features of both inertial (ICF) and magnetic fusion (MFE) techniques. When a magnetic field is embedded in a warm dense plasma ($n > 10^{27}$ m^{-3}), thermal insulation is improved, thereby allowing compression to be achieved with the use of lower power (and hence cheaper) inertial drivers (plasma liner [1] or laser driver [2]). At the instant of the maximum compression the ultrahigh magnetic field can be generated ($B > 1000$ T).

For MIF, often called MTF (magnetized-target fusion), the fusion-product alpha-particle and proton orbit and heating problem is another point of interest for this proposal. Plasma-Jet Magnetized-Target Fusion dynamics [1] 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 of MTF.

High-convergence uniform implosion and properly synchronized laser beams (laser intensity > 10^{15} W/m^2) and plasma jets (velocity > 100-200 km/s) are assumed. Possibility of adiabatic compression is discussed and different gas dynamic regimes are investigated. Analysis of schemes for laser-driven [2] and plasma jet-driven magneto-inertial fusion [1] is carried out.

The research was supported by the grant of the RFBR No. 09-08-00137.

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1-8

STUDIES OF ANOMALOUS TRANSPORT IN THE EDGE PLASMA OF THE URAGAN-3M TORSATRON

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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-frequency fluctuations were associated with trapped ion loss.

Investigations of density fluctuations with the use of probability distribution function (PDF) analysis were carried out too [2]. Basing on comparison of 3-rd (skewness, S) and 4-th (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 this work, an analysis is presented of radial turbulent flux dynamics depending on plasma heating regimes in U3-M. In [4] it is shown that the transition to the H-like mode is triggered by the short-time fast ion loss increase. This mechanism comes into operation beginning with some threshold power introduced into the plasma.

Radial turbulent flux measurements as function of plasma heating power reveals increasing of turbulent flux with introduced power increase that is in accordance with well-known effect of confinement degradation with power increase. An evident correlation of turbulent flux and average density dynamics was observed.

Spectral and statistical analysis of I_s and floating potential in SOL as a function of power introduced in plasma was carried out too.

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1-9

LOCALIZATION OF ROTATING MHD MODES BY POLOIDAL SOFT X-RAY DETECTOR ARRAYS IN THE STOR-M TOKAMAK*

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A technique is presented for determining the radial location of the rotating magnetohydrodynamic (MHD) modes by use of soft x-ray (SXR) detector arrays. The location is determined by examining the difference in the SXR emission intensity integrated through two adjacent lines of sight. This technique significantly improves the signal-to-noise ratio by suppressing the influence of non-rotating background MHD fluctuations. The radial dependence of the line integrated SXR emission intensity on mode numbers and the magnetic island geometry is modelled numerically. The technique has been applied to the STOR-M SXR data to locate the radial position of the MHD modes.

*Supported by NSERC and CRC, Canada.

1-10

INVESTIGATION OF ENERGY AND MASS BALANCE IN "TRIMYX-3M" GALATEA MULTIPOLE MAGNETIC TRAP

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The investigations of the energy and mass balance and, accordingly, measurements of particles life time τ_p and energy confinement time τ_E in plasma in most cases are interdependent and mutually complementary. Simultaneous measurements of τ_p and τ_E allow to obtain the most full information about transfer processes and other plasma properties.

In the work using Rogowski loop, measurements of the diamagnetic current, generating in the trap plasma volume under its filling by plasmoids have been carried out. These measurements are confirmed by signals from diamagnetic probes. The mean value of the energy in plasma volume and its change in the process of the trap filling by plasma and its decay have been determined by the magnitude of diamagnetic current. These measurements are carried out simultaneously with the measurement of the time dependence of mean plasma density by microwave interferometer. Measurements have been carried out at "Trimyx-3M" Galatea multipole magnetic trap [1, 2].

The problem of measurement of diamagnetic current which value is about (0,1÷1)% of the current in trap coils has been solved by manufacturing Rogowski loop of the length ~2,5m and locating it so that the loop has not covered trap coils. Besides in experiments with the using of diamagnetic probes (wire coils of diameter 200mm and 340mm), installed at the axis of the trap magnetic system out of plasma volume, it succeeded in obtaining signals concerned with plasma current. The current in trap coils achieves maximum at the moment of plasmoid injection into the trap and the derivative of magnetic flux of this current, which is measured by both Rogowski loop and diamagnetic probes, is close to zero at this moment. The measurement of derivative of magnetic flux, generating by diamagnetic currents, with respect to time is possible due to the fact the rate of change of magnetic flux generating by diamagnetic currents is by an order of magnitude and more higher, than the rate of change of magnetic flux generating by currents in trap coils. Signals from Rogowski loop and diamagnetic probes have been numerically integrated and in such a way the values of diamagnetic current and magnetic flux have been determined. Calculations of equilibrium configurations in the trap "Trimyx-3M" [3] have shown the existence of diamagnetic currents in two opposite directions, and the value of one current is about a few percentages from the other. Therefore one may consider Rogowski loop allows to measure the magnitude of the total diamagnetic current in plasma.

Carried out experiments have shown the process of diamagnetic current attainment lasts ~70mcs after the plasmoid injection into the trap. Signals from diamagnetic probes decrease down to zero to 220-th microsecond, whereas the duration of signal from interferometer is more than 1ms. The estimation of value of the average plasma temperature by the diamagnetic current value agrees with the estimation from calorimetric measurements.

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. on the state contract #P957.

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1-11

KINETIC ANALYSIS OF THE AXIALLY-SYMMETRIC MIRROR BASED SYSTEMS FOR FUSION APPLICATIONS

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Axially symmetric magnetic mirror trap is very attractive system from the engineering view point due to its simplicity and possibility of high-β confinement (β = plasma pressure / magnetic pressure). Low cost fusion reactors and neutron generators for power engineering, materials technology, and fusion-fission reactor can be developed on the base of such system. One of them is Open machine with strong plasma collisionality known as Gas Dynamic Trap (GDT); its promising application is neutron generator [1]. Note that ambipolar electrostatic end plugging by the compact end cell shows the essential improvement of plasma confinement in GDT experiments [2].

The work includes results of studies of fusion systems operating in collisionless regimes with electrostatic end plugging. The transition from gas dynamic (strongly collisional) to kinetic collisionless confinement allows realizing high fusion efficiency at relatively small length of open system. The feature of the system under consideration is the plasma heating by the strong injection of neutral particles. The efficiency criterion is the fusion plasma amplification factor $Q_{pl} = P_{fus}/P_{\mathrm{inj}}$, where P_{fus} is the fusion power, P_{inj} is the injection power absorbed by the plasma. Injection of high-energy (or fast) particles into warm thermal plasma affects essentially on the fusion plasma properties. To calculate the heat transfer between fast particle and warm plasma kinetic models and numerical codes are developed. Very important effect of the fast particles is the increase of the fusion reactivity in comparison with thermal Maxwellian plasma. Previous analysis shows the modeling of fast ion kinetics is key element of physical justification of high efficiency of open-ended magnetic traps [3]. We consider magnetic systems with the following parameters: the magnetic induction of the central solenoid B_0 = 1.5…2 T, magnetic field in the mirror coil B_m up to 20 T, a volume averaged beta value $\beta \approx 0.5$.

We have proposed and investigated a very compact pulsed neutron source with appropriate high efficiency regimes with $Q_{pl} \approx 1$. We also analyze regimes with $Q_{pl} \approx 10$ for mirror based reactors using conventional D–T and advanced D–^{3}He fuels. Application of the axially symmetric open trap for classical stationary magnetic fusion device is compared with its prospects for high-density magneto-inertial fusion regimes.

Work was partially supported by Russian Foundation for Basic Research (projects 08-08-00459-a and 10-02-90734-mob_st) and the Ministry of Education and Science of Russian Federation in framework of Presidential Program (grant MK-1811.2010.8).

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1-12

ON POSSIBILITY OF PRESSURE PERTURBATION RESONANT EXCITATION BY AN EXTERNAL LOW FREQUENCY HELICAL FIELD NEAR EDGE PLASMA

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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 edge plasma observed in H-mode operation [1]. Melting, erosion and evaporation of divertor target plates may occur as results of these bursts. Many experiments in DIII-D have shown that ELMs can be suppressed by small external low frequency helical magnetic perturbations [2]. Until now, understanding of the underlying physics of ELMs and their suppressions has been far from complete.

In Ref. [3] the influence of an external helical field on the equilibrium of ideal plasma was investigated in the frame of MHD theory. A perfect shielding of the external resonant field was assumed.

In the present paper, a possibility of pressure perturbation resonant excitation near the plasma edge is shown. The equations that describe the influence of external low frequency helical magnetic perturbations on the ballooning and peeling modes excitation are derived on the basis of MHD equations for a case when all poloidal harmonic amplitudes of external perturbations have finite values. Plasma rotation and plasma response are taken into account.

Early influence of external low frequency helical magnetic perturbations on the ballooning and peeling modes was studied for one dominant poloidal external mode and neighboring poloidal modes were considered as small [4].

On the basis of the presented equations, interpretation of the ELM’s control experiments in the tokamaks JET, DIII-D and future ITER operation may be made.

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1-13

ON A POSSIBLE MECHANISM OF HARMONICS' GENERATION OF RF FIELD IN A NEAR-ANTENNA REGION OF PLASMA IN URAGAN-3M

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In the l=3 torsatron Uragan-3M plasma is produced and heated by RF field excited in the ion resonance frequency range $\omega = (0.8\div1)\omega_{\beta i}$. However, in the spectra of some diagnostics other harmonics are frequently observed, $f_n = n\cdot f_0$ (n=2,3,4…11), with amplitudes of second and third harmonics comparable to the fundamental harmonic amplitude. The excitation of harmonics was related either to nonlinear processes [1] or to entire RF generator itself [2].

Appearance of harmonics of RF field can result in decrease of the power at the reference frequency, to represent a noise disturbance for some diagnostics, and to complicate understanding of the heating process of plasma. Thus, shedding light on mechanism of their generation is of interest in RF plasma heating experiments.

The important feature of RF discharges is formation of a space charge (SC) of positive ions near the negative electrode [3]. This SC possesses nonlinear characteristics [4]. At the early beginning of the RF pulse the antenna in U-3M can be considered as a cold cathode. The RF field can penetrate into a discharge volume only through the SC layer. Taking into account the nonlinear character of interaction of the RF field with this layer, the process of interaction can be presented as the sum $X_{out}(t) = k[X_{in}(t) + \varepsilon\cdot X^2_{in}(t)]$. Then, the pump mode $A_1\cos(\omega t)$ at the output of SC will be depicted by the relation: $x_{out}(t)=A_1\cos(\omega t)+\varepsilon/2\cdot A_1^2\cos(2\omega t)+ \varepsilon/2\cdot A_1^2$. We see that at the output not only the main component $\cos(\omega t)$ but also its second harmonic $\cos(2\omega t)$ and the fixed term $\varepsilon/2\cdot A_1^2$, indicating the rectification effect do appear.

If first and second harmonics are then interacting with SC, four more harmonics of RF field occurs. Supposing that this process is of an avalanche character, the interaction of lowest modes with SC leads to appearance of increasing numbers of modes.

Such a mechanism of high harmonics' generation is supported by the fact that they are registered in many experiments on RF plasma heating; it is also explains the reason why sometimes the second harmonic has higher amplitude than the fundamental one, what is the mechanism of appearance of combination frequencies ($\omega_1 \pm \omega_2$) in the case of two pump modes, and supports the well known fact as for rectification of the RF field in the constant component.

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1-14

EFFECTS OF RECTIFICATION AND RUN-AWAY ELECTRONS GENERATION IN TORSATRON U-3M DURING RF POWER PLASMA PRODUCTION

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A large body of measurements show existence of a high positive spatial potential in the near-electrode space of RF discharges [1,2]. This potential U_0 appears due to rectification of RF voltage as the result of interaction of RF voltage and a space charge (SC) of positive ions in a near-electrode layer, the latter has a non-linear current-voltage characteristics. The absolute value of U_0 is of the order of an alternating voltage: $U_0 = V_{\sim}/\pi$ [1].

In conditions of experiments on the U-3M torsatron, under interaction of RF field $A_1\cos(\omega t)$ with the SC the processes of harmonic generation and rectification are realized:

$$X_{out}(t) = A_1\cos(\omega t) + \varepsilon/2\cdot A_1^2\cos(2\omega t) + \varepsilon/2\cdot A_1^2.$$

A fixed term $\Delta = \varepsilon/2\cdot A_1^2$ corresponds to the shift of the mean value what means the existence of the rectification. If several harmonics are interacting with SC simultaneously, the shift of the mean value is significantly higher:

$$\sum_{n=1}^{10}\Delta = \frac{\varepsilon}{2}A_1^2(A_2^2 + A_3^2 + ... + A_{10}^2),$$

as it is defined by a nonlinearity factor ε of the space charge and the amplitudes of RF harmonics that are taking part in the interaction.

Appearance of positive potential results in acceleration of ions from a near-antenna plasma. Under bombardment of the antenna surface by these ions the flux of heavy impurities can come into plasma. Such process occurred in experiments on Uragan-3M [3]. Due to field electron emission and ion-electron emission a beam of electrons is created from the antenna surface. These electrons are accelerated by the same Coulomb SC field. In the acceleration process some part of plasma electrons produced due to gas ionization can also be involved [4]. The indirect indication on the existence of run-away electrons is a sharp increase of H_β line emission 9 ms later the RF power was switched off, i.e. after drop of H_β intensity practically to zero [5].

Summarizing, the processes of RF field harmonic generation, rectification and acceleration of electrons are the results of interaction of RF field with a non-linear element – the spatial charge of positive ions near antennae.

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1-15

CREATION OF MULTIPOLE MAGNETIC TRAP "TRIMYX-3M (MICROWAVE)"

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Based upon results of experimental researches on plasma confinement in "Trimyx-3M" multipole magnetic trap [1, 2] the requirements have been developed to new trap "Trimyx-3M (microwave)" and the main of them are the next: a) decrease of the length of the field with the strong magnetic field along the line of plasmoids injection into the trap; b) providing of possibility of microwave power input into plasma volume. In accordance with them the optimal configuration of magnetic field of new trap "Trimyx-3M (microwave)" has been developed and calculated. As in the trap "Trimyx-3M" the magnetic system of new trap consists of three main magnetic coils-myxini. There are used four coils-repulsers in the trap "Trimyx-3M (microwave)" instead of one coil-repulser and solenoid in the trap "Trimyx-3M". The value of barrier magnetic field in the trap "Trimyx-3M (microwave)" insignificantly differs from the one in the trap "Trimyx-3M". Only one myxine is located in the symmetry plane in new trap. This has allowed to satisfy all requirements stated above. For the developed magnetic system the coils immersed into plasma (myxini) are unload from magnetic force interaction and the extent of the strong magnetic field along the line of plasmoid injection is three times less than in the trap "Trimyx-3M". The last circumstance has allowed to make the coils of the sluice (system for the local decrease of the trap magnetic field in the moment of plasmoid penetration through the magnetic crust of the trap) more compact and effective. All magnetic coils of "Trimyx-3M (microwave)" have been manufactured from the wire of type PETV-2 of diameter 2,5mm. Coils have been winded in two wires and impregnated with the epoxy resin. Before the trap assembly, the coil insulation has been checked on the breakdown by the voltage 3kV. Microwave system at the frequency 2,45GHz with the power up to 1kW has been developed in order to heat an electron component of plasma in the trap. This system consists of magnetron, coaxially-waveguide line, vacuum flange, microwave hermo-lead-in, waveguide- horn line of the power input.

Carried out measurements of magnetic field distribution along the injection line under the stationary electric power supply of trap coils have completely confirmed the calculation results, and measurements of current in trap coils under a pulsed power supply have indicated, that under the charging voltage 2kV on the power supply the value of barrier magnetic field is ~ 0,112T, that exceeds by 10% the field in the old trap. Measurements on the microwave system have shown that it is possible to input 0,5kW into the chamber. Measurements of plasma density and diamagnetic currents in the trap have been also carried out under injection into it of plasmoids with the energy of ions directed motion (20÷40)eV and (100÷200)eV, accordingly. It has been shown, that as in the trap "Trimyx-3M" the value of mean density reaches $(3\div5)\cdot10^{18}$ м$^{-3}$, and the value of diamagnetic currents reaches 100A.

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. on the state contract #P957.

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1-16

STUDIES OF ELECTRON LOSS CONTRIBUTION TO THE ASYMMETRY OF PLASMA FLOWS IN THE HELICAL DIVERTOR OF THE URAGAN-3M TORSATRON

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In the Uragan-3M (U-3M) torsatron/heliotron with an open natural helical divertor (l = 3, m = 9, R = 100 cm, $\bar{a} \approx 12$ cm, $\iota(\bar{a}) \approx 0.3$, $B_\phi = 0.7$ T) under conditions of RF plasma production and heating ($\omega \lesssim \omega_{ci}$, $\bar{n}_e \sim 10^{12}$ cm^{-3}, $T_e(0) \sim 1$ keV) with a two-temperature ion energy distribution ($T_{i1} \sim 50$-80 eV, $T_{i2} \sim 250$-400 eV) + suprathermal tail up to several keV, a strong up-down asymmetry of the plasma divertor flows (PDF) has been observed recently. In particular, the asymmetry displays in the larger ambipolar PDF outflowing on the ion toroidal drift $\mathbf{B}\times\nabla B$ side ("ion side") and in an excess of ions in the corresponding non-ambipolar flow. On this basis a conclusion has been drawn that the asymmetry is caused by the direct (collisionless, non-diffusional) ion loss. This has been validated by a numerical modeling of charged particle loss and direct measurements of energies of ions outflowing to the divertor on the ion side and opposite ("electron") side.

The objective of this work is an experimental elucidation of electron contribution to the PDF asymmetry. To do this, arrays of plane Langmuir probes arranged poloidally in the divertor region in the gaps between the helical coils in two symmetric poloidal gross-sections of the U-3M torus. As a result of IV characteristic processing, it is shown that the hotter electrons outflowing to the PDF on the electron side make a more significant contribution to the flow up-down asymmetry than fast ions escaping to the PDF mainly on the ion side.
Changes in the density and temperature of electrons that escape to PDF on the electron side have been studied in the process of the H-like confinement mode transition. These changes occur more substantial than those on the ion side with a lower electron temperature. Possible reasons for these changes are discussed.

1-17

TOROIDAL ANGULAR MOMENTUM TRANSPORT MODELLING IN TOKAMAKS

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The neutral beam injection causes strong toroidal rotation of tokamak plasma. As this rotation can affect the heat transport, it is intensively investigated both experimentally and theoretically. In presented report we describe the extended canonical profiles transport model, which now includes the transport of electron and ion temperatures, plasma density and the toroidal momentum driven by the external torque. At first we derive the simplest equilibrium equation for rotating plasma. Then we solve the variation problem to find the minimal total plasma energy with condition that the toroidal current is conserved. The Euler equations for this problem define the canonical profiles of pressure $p_c(\rho)$ and angular frequency $\omega_c(\rho)$, linked as $\omega_c \sim p_c^{1/3}$. The set of transport equations is amended by the equation for the angular momentum $n\ m_i\ R^2\ \omega$, which includes the radial flux

$$q_\omega = -n\ m_i\ R^2\ \chi_\omega^{PC}\ \omega\ (\omega'/\omega - \omega_c'/\omega_c).$$

The term in brackets presents the deviation of the relative gradient of rotation frequency from the canonical one, R is a major radius, n is the plasma density (in 10^{19} m^{-3}), m_i is the ionic mass. The stiffness (diffusivity) of the rotation profile χ_ω^{PC} is assumed to be proportional to the stiffness of the electron temperature profile χ_e^{PC}: $\chi_\omega^{PC} = C_\omega\ \chi_e^{PC}$. The value of χ_e^{PC} was defined in our previous papers, and the constant C_ω was derived from the comparison of rotation modelling with experimental results for 10 JET shots, extracted from the ITER database: $C_\omega = 0.5 / n^{1/3}$.

The model has proved to describe the angular momentum transport adequately. In particular, for JET pulse #52014 with very high density ($10.5 \cdot 10^{19}$ m^{-3}) the experimental profile of angular frequency was a maximum at the plasma centre. From the other hand, such a high density leads to peripheral deposition of beam particles and hollow torque profile. Apparently, such a plasma behaviour can be the evidence of anomalous momentum pinch, directed to the plasma center, which is intrinsic to the model. The RMS deviation of simulated angular momentum profiles from the experimental ones usually does not exceed 15%.

For further verification of the model the simulation of a number of MAST pulses was performed. The results seem to be promising also.

The work is supported by Grants: RFBR 08-07-00182, FASI 02.740.11.5062 and UKAEA 3000132057.

1-18

THE TRANSITION TO THE REGIME OF IMPROVED CONFINEMENT IN TORSATRON U-3M IN RANGE OF RARE COLLISION FREQUENCIES

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In the l=3 torsatron U-3M, plasma is created and heated by RF waves. In experiments, where the plasma particles are in a low-collisional regime, the measurements of basic plasma parameters and energy confinement time were performed being based on data of magnetic diagnostics. The toroidal current in plasma reached 1700 A; this value can be fully explained by neoclassical processes occurring in the confinement volume. It was found that majority plasma energy is stored in the electronic component, indicating on the preferential heating of electrons in the chosen heating conditions.

In the studied discharges, at the moment when average density approached $\overline{n}_e \approx 1.2\text{x}10^{18}$ m^{-3}, a spontaneous transition to better confinement mode was observed that was accompanied by the increase of plasma energy content in ~1.7 times. The energy confinement time before the energy content rise was τ_E = 2.6 ms, and after the transition, before shutting down the RF power, $\tau_E \approx 4.5$ ms, what is close to values found from existing stellarator scaling.

It was also determined the time of transition to the regime with better plasma confinement, which is about 130 microseconds. The magnitude of the power per every plasma particle before the transition to improved confinement mode, is W = 0.22x10^{-19} MW/particle, in a quite good correspondence with values obtained in some other stellarator experiments (CHS, L2).

In the investigated discharges, the process of "self-cleansing" of the plasma from impurities in the confinement region was observed, what provides the value of $Z_{eff} \approx 1 \div 1.5$ from the middle to the end of the discharge instead of $Z_{eff} \approx 3.5$ at the initial stage of the discharge.

1-19

DESIGN OF MULTICHORD SOFT X-RAY DETECTION ARRAYS FOR THE URAGAN-2M STELLARATOR

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Two miniature pinhole camera arrays for spatially and temporally resolved measurements of soft X-ray emission have been designed for the URAGAN-2M stellarator. The power of soft X-ray filtered by different filters has been calculated numerically in order to optimize applicability of two-foil temperature measurement technique. In the initial operation, a Be foil with the thickness of 10 μm and Al filter of 3 μm have been chosen to test signal strength and to test two-foil temperature measurement technique. SXR photodiode photocurrent amplifiers with bandwidth up to 5 MHz have been designed for signal amplification. Digitizers with 12 bit resolution and sampling rate up to 8 MS/ s have been tested for SXR data acquisition.

1-20

URAGAN-3M ION ENERGY DISTRIBUTION MEASUREMENTS DURING FRAME ANTENNA HEATING VIA ION CYCLOTRON FREQUENCIES RANGE

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An energy sweeping technique has been developed and applied for charge exchange (CX) neutral particle diagnostics in the URAGAN-3M torsatron. It allows measure the ion energy distribution from 100eV up to 4keV every 1-2 ms and its spatial distribution in a half of plasma column area (ρ=0.5-1) in the inner plasma part (R=90-100cm). Measurements have been done during low density (n_e=0.5-1·10^{-12}) frame antenna radio frequency (RF) plasma discharges in the RF frequency range close to the ion cyclotron frequency. Presence of the ions with energies up to 4keV has been confirmed experimentally. It has been observed that the distribution is close to the Maxwellian one in the energy range 400eV-2.5keV. The ion temperature T_i=300-600eV has been determined from this range of the distribution function. This is an indication of direct RF energy deposition into the ions due to negligible ion-electron energy exchange. Radial dependences of CX flux and ion temperature have been studied using set of similar discharges. A structure of URAGAN-3M magnetic surfaces allows estimate local ion temperature in magnetic surface tangential to CX line of sight. This magnetic surface adds major contribution to the CX signal. The ion temperature distribution is flat in the range ρ=0.5-1. This is an indication of the ion energy deposition location close to the plasma edge. The CX neutral particles flux from outer plasma part disappear immediately after the end of RF heating pulse, in contrast to central flux (from ρ=0.6-0.5). The CX flux from plasma edge is defined by the direct ion heating because of negligible plasma diffusion. This is additional confirmation of the outer location of direct ions heating in the URAGAN-3M torsatron.

1-21

FIRST TESTS OF THE BIASED MOVABLE B_4C-LIMITER IN THE URAGAN-2M TORSATRON UNDER RF AND UHF WALL CONDITIONING

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The multifunctional limiter for the Uragan-2M (U-2M) torsatron was designed and fabricated. It consists of the limiter head made of boron carbide plate by hot pressing in vacuum [1], the mechanism of its displacement, and the Longmuir probe. The limiter head is placed on an isolator and grounded through resistance. This allowed to measure signals from the limiter plate (current, potential). After check on hermiticity, the limiter was installed in the U-2M to test under edge plasma conditions (Fig.1). At the beginning the limiter will be used for studying the possibility of the mechanical preventing of plasma-wall interactions, however, in future the construction allows to provide other experiments, like electrode biasing experiments, plasma-materials interaction, solid target boronization process, etc.

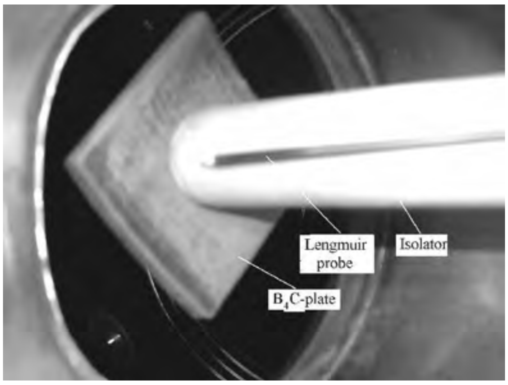

Fig.1. The movable limiter in situ in the branch pipe #1 of the Uragan-2M torsatron

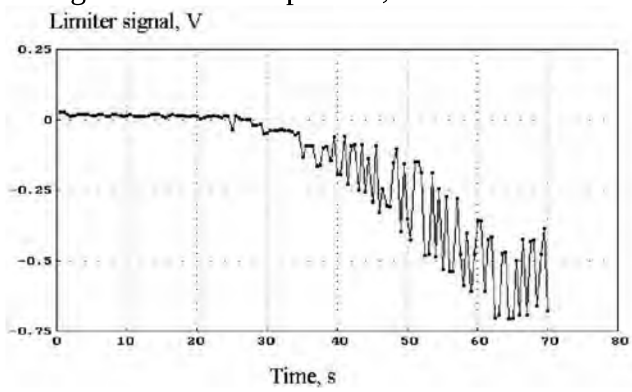

Fig.2. Time dependence of the limiter signal intensity during its moving to plasma axis

The tests were carried out in the stationary discharge cleaning regime with typical for U-2M plasma parameters: hydrogen pressure $1\cdot10^{-2}$ Pa, electron density ~ $2\cdot10^{12}$ cm^{-3}, electron temperature ~ 10-15 eV, magnetic field ~ 0.075T, the RF generator power ~1 kW at the frequency 8.3 MHz, the UHF generator power ~2 kW at the frequency 2.45 GHz (electron-cyclotron resonance conditions). During the tests the limiter plate was moved from the chamber wall to the axis along the distance up to 7 cm. With that the signals from the Longmuir probes and the intensity of H_α line were measured. The signal from the limiter was also registered on the PC with the help of the WAD-AIK-BUS module (Fig. 2).

Preliminary Longmuir probe experiments show that plasma characteristics are practically independent of the limiter plate position for both RF and UHF discharges. Spectroscopic measurements also do not demonstrate any essential influence of the limiter plate being moved in the plasma on H_α line intensity. At the same time the limiter signal changes its polarity (from positive to negative) at the distance of 4.5-5 cm from chamber wall, and its intensity increases essentially. The analysis was carried out to optimize the limiter head configuration and to understand the nature of the limiter signals observed. The estimations were made to use this limiter for partial solid target boronization of the U-2M vacuum chamber wall, too.

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1-22

ICFR MODE CONVERSION EFFICIENCY IN A TWO-ION COMPONENT PLASMA IN TEXTOR

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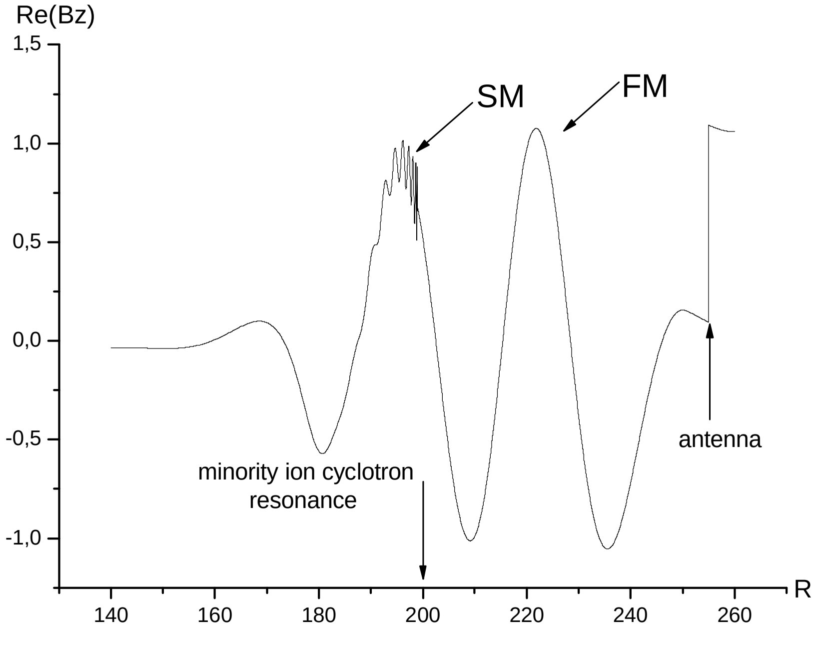
Mode conversion of the fast magnetosonic wave into a short-wavelength wave is studied in the presence of ion cyclotron absorption and direct electron damping in a tokamak plasma. In plasmas with two (a majority and a light minority) ion species, fast magnetosonic waves launched from the low-field side ICRF antennas can convert to a slow mode traveling towards the high-field side, away from the ion-cyclotron resonance point. However, in scenarii with insignificant finite Larmor radius effects, slow mode runs towards the low field side, i.e. towards the cyclotron resonance point, if the component of confining filed along the big radius of torus is taken into account (Fig. 1). The efficiency of conversion has been studied with the help of one-dimensional code which computes "full-wave" solution of Maxwell equations with cold conductivity. The dependencies of conversion efficiency on plasma density, minority concentration, frequency, confining magnetic field value and position of minority cyclotron resonance have been established.



1-23

ON SINGLE-MODE EQUILIBRIUM AND SELF-ORGANIZATION OF REVERSAL FIELD PINCH

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At present, it is established that toroidal discharges to be qualified as a reversal field pinches (RFP) with improved confinement are defined by the "quasi-single mode" (QSM) nearly laminar oscillations picture, being the low-amplitude pattern at that [1]. This gives a basis to think that the single dominant mode in the MGD spectrum is inherent in the RFP nature and may be used to found the dynamic quasi-linear equilibrium model of RFP discharges. In this paper, the magnetic configuration of cylindrical z-pinch is considered on the basis of general magneto-static equation $rot\mathrm{B}=\alpha\mathrm{B}+\beta\mathrm{B}\times\mathrm{e}_r$ where the value $\alpha(r)$ is determined by the B-projection of the Ohm's law for high conducting plasma and $\beta(r)$ – by the radial plasma equilibrium as a consequence of the single mode perturbations averaging. The helical mode m=1, n≈10 is taken into consideration which belongs to the Alfven spectrum of unstable kinks of force-free paramagnetic configuration without perturbations but with parameters $\alpha a>1$, $\beta a<<1$ (a is plasma radius) to be close to ones observed experimentally for high current pinches. The frequency and increment of the kink as well as radial amplitude distributions are determined by solution of the Hain-Lust linear diffusive pinch boundary problem in formulating [2]. It is shown the squared amplitude contribution of velocity and magnetic field oscillations into α (magnetic dynamo "α-effect") и β (abnormal diamagnetic "β-effect") stabilize the kink. At that, the additional azimuth current is generated, and the B_z reversal realize in the outer plasma region. The dominant mode is chosen by the condition of marginal stability under maximal amplitude. It is characteristic that not high amplitudes need for this: the velocity perturbations are measured in the "milli-Alfven" scale whereas magnetic perturbations are found of percents in comparison with B_z at the pinch axis. The presented quasi-linear model of RFP equilibrium conforms to basic features of the observed QSM self-organization also if to take account of radial transport aspects.

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1-24

A MODIFIED *lm*=1 STELLARATOR MAGNETIC SYSTEM

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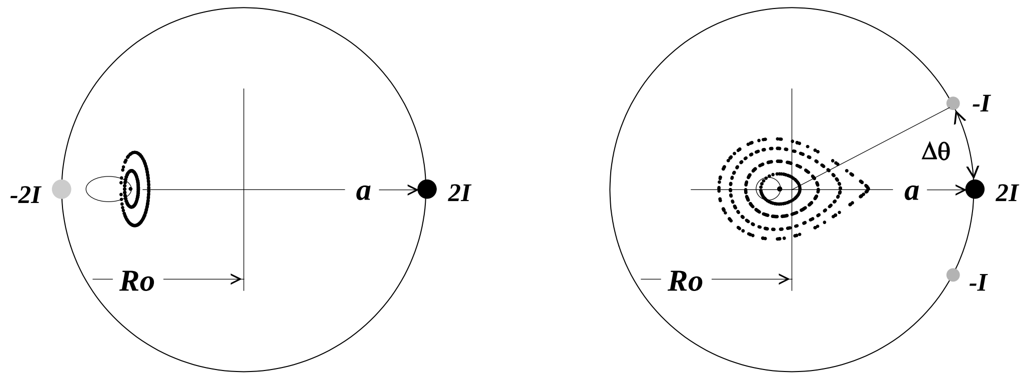
The work deals with magnetic surface properties in a new modification of the *l*=1 polarity stellarator with a single (*m*=1) helical coil pitch along the whole length of the torus. Thus, the stellarator contains only one magnetic field period, *lm*=1. The essence of the modification consists in that one of the two helical coils of *lm*=1 stellarator is fully split into two equal parts. The parts have equivalent currents (-*I*) and are displaced symmetrically relative to the unsplit helical coil (current 2*I*) by a certain angle $|\Delta\theta|<\pi$ in the poloidal direction (see fig.1).

Numerical calculations have shown that as distinct from an ordinary *l*=1 polarity stellarator [1, 2], the region of magnetic surface existence in the modified *lm*=1 stellarator can be localized in the neighborhood of the circular axis of the torus. The helical coil system of the modified *lm*=1 stellarator under consideration ($\Delta\theta=30^o$) allows one to realize helical divertor configurations similar to those in a tokamak [3].



a) *b*)

Poloidal cross-sections of closed magnetic surface configurations and helical coil tracks in a) ordinary lm=1 stellarator and b) modified lm=1 stellarator, $a/R_o=0.3$

Thin solid circles represent the toroidal projection of magnetic axis tracks. The toroidal field coils are not shown.

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1-25

INVESTIGATION OF POSSIBILITY OF CREATION OF LEVITATING QUADRUPOLE

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In the investigated up to now traps-Galateas [1-4] coils immersed into plasma (so named “myxini”) are structurally fixed by holders. Myxini have to levitate in thermonuclear reactor. There are now created big plants with levitating superconducting dipoles LDX [5] and RT-1[6] in USA and Japan accordingly.

There are presented results of the development of the model of the levitating quadrupole in the report. It is shown that such system must be consist of two levitating coils-myxini; unlevitating coils which compensate myxini magnetic attraction – “repulsers” and unlevitating coils which compensate myxini gravity – “antigravity” coils. Currents in repulsers may be comparable with the currents in myxini by the order of magnitude, and one chooses such location of repulsers under which the trap barrier field becomes higher. Currents in antigravity coils are by the order of magnitude smaller than in myxini. It means the fields produced by antigravity coils will not practically disturb the main magnetic configuration. However calculated in the field of the direct currents equilibrium magnetic configurations are unstable. Therefore in order to ensure stable equilibrium position it is necessary to use superconducting materials under manufacturing of myxini, repulsers and antigravity coils.

In order to confirm experimentally the possibility of levitation of two rings with current, the rings from high-temperature superconductor of the type $YB_2Cu_3O_x$ of the faze Y 123 with diameters from 20mm up to 50mm have been manufactured. The manufacturing technique has allowed to obtain the rings by agglomeration and also quasi-monocrystal rings. The density of the critical current is equal to $5{\cdot}10^4$ A/cm^2 in the last. It has been shown two such rings levitate in the field of the system of four permanent magnets with the alternating poles and the equilibrium position of every ring has been stable one. Thus the possibility of creation of the model of levitating quadrupole is experimentally demonstrated.

On the base of carried out experiments and calculations there have been developed several variants of the model of levitating quadrupole with myxini located in parallel horizontal planes at the given distance from each other, which are differed in the number and location of auxiliary coils. 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. on the state contract #P957.

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1-26

EXPERIMENTAL RESEARCH OF THE MULTISLIT ELECTROMAGNETIC TRAP "JUPITER F"

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The basic idea of electromagnetic traps is surface character of plasma confinement. The holding plasma magnetic field, which is formed by conductors or coils with alternating polarity of current inclusion, is characterized by a deep magnetic hole.

Such design of magnetic system allows applying ferromagnetic materials to strengthening a magnetic induction in electromagnetic traps. Also the application of ferromagnetic materials can considerably simplify the electrostatic "locking" system in circular magnetic slits and to increase energy of electron injection. For validate of these assumptions the installation "Jupiter F" is engender.

The first experimental researches of plasma accumulation and confinement in a multislit electromagnetic trap "Jupiter F" [1] are presented in this paper. In these experiments, we measured the injection current of electrons through the axial apertures, currents loss of electrons from traps to limit the accumulation of the plasma region of the diaphragm and the currents of loss of ions in the annular magnetic slits.

The plasma in the electromagnetic trap is created by the ionization of the neutral gas electrons, which are injected through axial aperture. For realization of Brillouin injection electronic guns are placed in the field of a weak magnetic field in axial concentrators. In this case the electronic beam is injected in the central region of the trap where the magnetic field is absent.

Power of the magnetic system in these experiments was carried out by constant current source, which allows changing the current in the magnetic coils from 0 to 200 A. Constant current source power supply included three seconds. Electron injection was carried out at the end of the third second. The duration of the pulse injection was 12 ms.

To measure the plasma density used microwave interferometer.

The first experiments to study the accumulation and retention of plasma in multislit electromagnetic trap "Jupiter F" permit the following conclusions:

- Application of the ferromagnetic screen led to an increase in the magnetic field more than doubled. This means that the costs of establishing the confining magnetic field are reduced by more than four times.
- Obtain a plasma density of $0.8 * 10^{12}$ cm^{-3} in the central region of the trap at a current in a magnetic system 200 A. In such a configuration, installation," Jupiter 2M3" [2], but without the ferromagnetic core has been obtained, the plasma density $2 * 10^{12}$ cm^{-3} at current in the magnetic system 2000 A.
- The possibility of the Brillouin electron injection through the annular magnetic gap due to secondary electron emission from the central electrodes of an electromagnetic trap with ferromagnetic cores.

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1-27

THE INFLUENCE OF FOCUSING STREAMS OF CHARGED PARTICLES ON THE PLASMA PARAMETERS OF AN ELECTROMAGNETIC TRAP "JUPITER 2M" WITH ELECTRONIC INJECTION

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One of the unique properties of electromagnetic traps is the existence of radial electric fields, which are forming and accelerating ion flows in the center of the system. Focusing of charged particles in the center of the system leads to a marked increase in plasma density and, consequently, to increase the fusion power for the same loss of charged particles and energy. Depending on the geometry of the magnetic field can be spherical or cylindrical focusing streams of charged particles.

At the spherical focusing, the plasma density increases to the center proportionally $1/r^2$ up to some radius r_0, which determines the accuracy of focusing. The thermonuclear reactions power is proportional to the product of plasma volume on the square of the density and grows as $1/r_0$ with the improvement of focusing terms. Even at a moderate focusing $r_0 = 0.1R$ released by thermonuclear reactions power increases 37 times, which greatly reduces the plasma density near the magnetic surfaces and reduce the magnetic field in magnetic slits.

Ions, formed as a result of ionization of neutral atoms at the boundary of the potential well, experiencing acceleration in the radial electric field. Their speed of longitudinal motion many times the transverse component. Collisional processes do not take the particle from the area where the clash took place, changing only the radius, which will move the particle after the collision. The intensity of the thermonuclear reactions increases with increasing plasma density, it is maximal in focus. Out of focus products of thermonuclear reactions will make the maximum positive charge, creating the maximum negative potential and the potential well for retaining ions. According to theoretical estimates, the maximum plasma density in the focus, limited by collisional processes, $ne \approx 5 * 10^{19}$ cm^{-3}. This is twice the density neutral gas at atmospheric pressure, but with a thermonuclear temperature.

When the cylindrical focusing the plasma density increases towards the center of the field is proportional to the radius and thermonuclear power has a logarithmic dependence on the radius of the focusing r_0. In this case, fusion power increases to $1 + 2\ln(R/r_0)$ times.

The influence of focusing streams of charged particles on the plasma parameters were performed on the "Jupiter 2M" [1]. The plasma density in the central region of the trap was measured with a corpuscular diagnostics, plasma density in the section under the coils - 8-mm interferometer. The plasma density in the central region of the trap exceeds the average cross-sectional density at the central coils in nf/nsr = 2.97 times, which is a consequence of focusing streams of charged particles in the radial electric field of space charge. Radius, to which you are focusing streams of charged particles, $r_0 = 4$ cm.

Existence of such a focusing will increase the fusion power of $1 + 2\ln(R/r_0) = 3.02$ times in thermonuclear reactor.

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1-28

MODELLING OF DEGRADATION OF THE EFFICIENCY OF NBI HEATING IN NSTX DISCHARGES WITH HIGH FREQUENCY ALFVÉNIC ACTIVITY

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Recently a surprising result was reported: increasing the power of the Neutral Beam Injection (NBI) by a factor of three in experiments on the spherical torus NSTX did not increase the plasma temperature in the central region and even resulted in its drop when high frequency Global Alfvén Eigenmodes (in the range of 0.5 - 1.1MHz) were destabilized [1].

In this report we present a simple model which demonstrates that the mentioned NSTX observations can have a natural explanation due to a new phenomenon – the energy channelling produced by NBI driven Alfvén instabilities, see Fig. 1 [2]. The energy channelling was predicted in Ref. [2] (see also [3]). According to our model, in the considered experiments with the highest NBI power (6 MW) the energy channelling significantly decreased the efficiency of the plasma heating, leading to the deposition of the energy of injected ions at the plasma periphery.

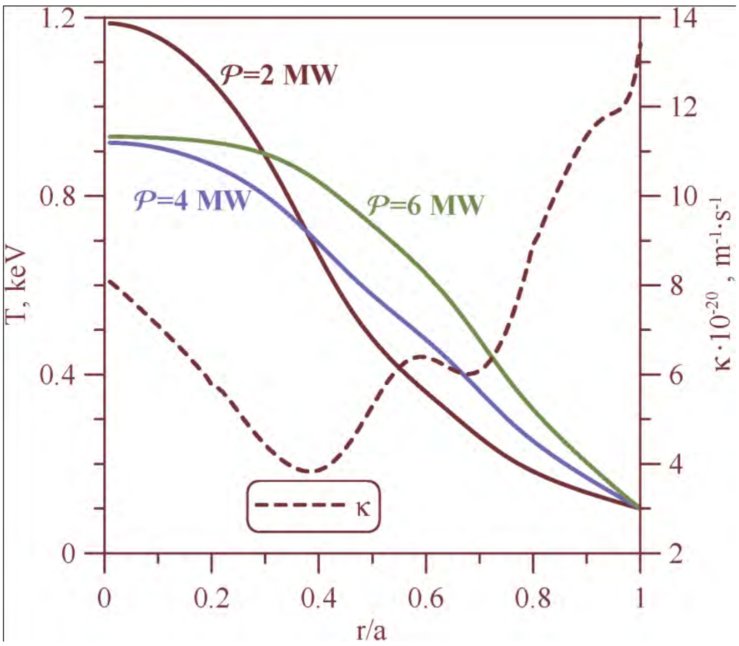

Fig. 1. The calculated plasma temperature (solid lines) for various magnitudes of the injected power ($\mathcal{P}$) in NSTX well agrees with the measured temperature shown in [1]. It was assumed that the efficiency of the energy channelling is maximum at the maximum injected energy ($\mathcal{P}$ = 6 MW) and $\kappa(r)$ does not depend on $\mathcal{P}$, where $\kappa(r) \equiv n_e(\chi_e + \chi_i)$, χ_e and χ_i are the heat conductivity coefficients, n_e is the electron density. The coefficient χ_e was taken equal to that in discharges with $\mathcal{P}$ = 2 MW, and χ_i was the neoclassical coefficient.

Acknowledgements. The work is carried out within the STCU Project #4588.

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PLASMA RESTRICTION BY MEANS OF POLOIDAL-TOROIDAL MAGNETIC SURFACES

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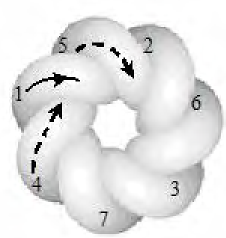
As it is stated, for example, in [1] a pinch with a longitudinal magnetic field is more stable due to the depression of both short wave (tongue-types) and long wave (cylinder-symmetric) excitations by means of quasi-elastic forces. Such longitudinal fields appear, for example, in stellarators and various spiral traps [2]. The authors show a preference for the latter constructions and specifically for multiply knotted volumes (in the given figure a similar volume is shown as 7-foil) [3]. This knotted construction must lead to so-called poloidal-toroidal magnetic surfaces. For example, a magnetic field (solid directed line represented in leaf 1) is generated by plasma current flowing from a leaf 4 to a leaf 5 (dotted directed line) and simultaneously takes part in the maintenance of this current.



Schematic representation of poloidal-toroidal magnetic surface origination in 7-foil volume

Magnetic field evaluation in the paper is made in the coordinate system related to *n*-foil which vector equation is written down as follows

$$\vec{\rho} = \{[R + r\cos((n+1/2)\varphi)]\cos\varphi, [R + r\cos((n+1/2)\varphi)]\sin\varphi, \pm r\sin((n+1/2)\varphi)\},$$

where $-2\pi \le \varphi \le 2\pi$, R, r are tore parameters on the surface of which one can place this space curve (here the signs "$\pm$" correspond to a left- and right-hand *n*-foils). Choosing this curve to be axes of an orthogonal curved line of Mercier coordinate system (see, for example, [4]), one may consistently find Lame parameters, write down necessary differential operators and calculate self-coordinately a topologic structure of poloidal-toroidal magnetic surface.

Besides, as it is seen from the figure, in such magnetic trap constructions distant regions inside become neighboring in an outside region. Maybe, just such constructions are going to be the most optimal for plasma magnetic restriction (namely a self-restriction) of plasma and at last, the solution of the main task of a controlled thermonuclear synthesis.

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1-30

A NEW FACILITY FOR FORMING AN *FRC* - FIELD REVERSED CONFIGURATION

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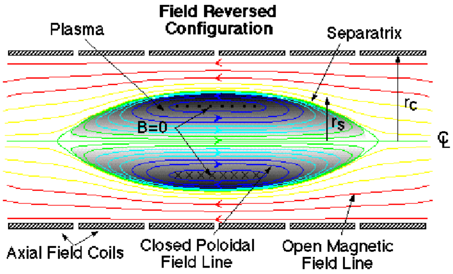
The compression of plasma and its subsequent heating is the key process in internal thermonuclear fusion. Most effective compression is achieved in a Field Reversed Configuration scheme (FRC)



The scheme proposed earlier for obtaining an FRC [1] requires regulated switching-on of several condenser batteries with microsecond delays and the possibility of obtaining a crow-bar regime (dragging out the drop in current in an inductive load) as well as cutting-off current from the load after its first half-period.

For these purposes, an installation was constructed having double vacuum spark-gaps to realize the aforementioned functions. The spark-gaps are of a coaxial form with sectionalized insulators. The spark-gaps have little jitter, a broad range of voltage regulation and are not limited for passing current as a result of a plasma method of firing.

The construction allows for disassembling a spark-gap to clean the electrodes without disconnecting the cables transmitting current.

This installation can also be effectively used as a power source in other experiments, in particular for a plasma focus. The results presented are for experiments in forming an FRC with a total energy supply of up to 50 kJ.

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1-31

BALANCE OF HYDROGEN IN THE VACUUM CHAMBER OF TORSATRON U-3M DURING THE RF-DISCHARGE

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The measurements of the hydrogen pressure in the vacuum chamber with a volume of 70 m^3 during the RF-discharge in U-3M torsatron were conducted. A 30% reduction of pressure in the vacuum chamber at the end of the RF-pulse was observed. The amount of particles, which can be ionized in the confinement volume and in the peripheral plasma during the RF-pulse, was estimated. This number is about one order of magnitude less than that corresponding to the observed pressure decrease. The estimations of amount of low density plasma on the far periphery of the confinement volume and/or in the vicinity of the RF antenna that is required for explanation of the observed discrepancies were carried out.

The measurements of the distribution of the hydrogen emission line H_α were fulfilled. The lifetime of particles in the confinement volume in the regime of rare collisions was calculated. The portion of fast (Frank-Condon) hydrogen atoms in the whole volume of the vacuum chamber was estimated.

1-32

DYNAMICS BEHAVIOR OF MAIN PLASMA PARAMETERS DURING A SPONTANEOUS TRANSITION TO IMPROVED CONFINEMENT REGIME IN TORSATRON U-3M

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On the basis of magnetic and X-ray measurements, and taking into account the ion temperature determined from the spectrum of charge exchange atoms (Z_{eff}) the temporal behavior of electron temperature and the mean charge of ions were obtained. It is shown that the most part of the energy stored in the electron component of plasma, denoting the preferential heating of electrons. It is shown that after the transition to better confinement the average electron temperature doubles, which indicates an improvement of energy confinement in the electron channel. Also, one can observe the rise of ion temperature in 1.4-times, which is apparently due to the heat exchange between electrons and ions.

In investigated discharge regime the decrease with time of Z_{eff} of the confined plasma was observed indicating realization of some "self-cleaning" process. The value of Z_{eff} decreased from $Z_{eff} \geq 3$ at the early discharge state by $Z_{eff} \approx 1 \div 1.5$ from the middle to the end of the discharge. The rather high initial Z_{eff} is, probably, observed due influx of metal atoms from RF-powered antenna at the initial stage of the discharge.

1-33

THE POWER BALANCE OF AN ANEUTRONIC FIELD-REVERSED CONFIGURATION PLASMA

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In this paper we consider a compact toroid [1] as a fusion reactor [2], namely field-reversed configuration where the plasma magnetized by a purely poloidal field. This magnetic configuration has attractive features, notably a linear geometry and high-β (beta is the ratio of plasma pressure to external magnetic field pressure). Fusion system based on a compact configuration where the plasma confined inside closed magnetic field lines and separated from a conducting wall by the area of the open magnetic flux allows to achieve high specific impulse and thrust.

The power losses due to charged particle transport, neutrons, and radiation are taken into account. The global plasma power balance is given by:

$$P_{fus} + P_{inj} = P_{brem} + P_{tran} + P_{syn},$$

where P_{fus} is the fusion power, P_{inj} is the injection power, P_{tran} is the charged particle transport power, P_{brem} is the bremsstrahlung power, and P_{syn} is the synchrotron radiation power.

Main plasma parameters and fusion energy gain factor are obtained. The comparison of D-T reactor with D-^{3}He source is made. Prospects of D-^{3}He fueled fusion jet are presented.

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1-34

NUMERICAL SIMULATION OF TRANSPORT PROCESSES IN STELLARATOR URAGAN 2M IN THE CONDITIONS OF AMBIPOLAR DIFFUSION FLUXES

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Based on supposition about the neoclassical transport of plasma a one-dimensional numerical code, intended for the design of space-temporal behavior of plasma in a reactor-stellarator, was adapted for modeling of the experimental regimes of plasma in a stellarator Uragan-2M. The feature of the code is an account of equality ion and electron diffusive fluxes of plasma due to the ambipolar electric field. In the accepted model the fluxes of electrons correspond the modes of - $1/\nu$, and ions -$\nu^{1/2}$ of neoclassical theory of transport for the stellarator systems. The system of equations, including two equations for thermal conductivity and equation of diffusion for plasma density, was solved. The solution of task is begun with finding of the radial electric field from the condition of equality of diffusive fluxes of Se = Si on every step of spatial net. There are three roots of the equation in general case. The problem of finding of the realized root decides by set up of initial conditions. The steady distributing of parameters of plasma is got, including distributing of temperatures, density and radial electric field. The found decisions allow to compare calculating and experimental parameters of plasma, that does more reliable prognostication of parameters of the experimental devices of next generation and thermonuclear reactor.

1-35

SELF-CONSISTENT MODEL OF RF PLASMA PRODUCTION IN STELLARATOR

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The purpose of this work is modelling RF plasma production in stellarators in the ion-cyclotron range of frequencies (ICRF). A recently developed self-consistent model simulates plasma production with arbitrary ICRF antennas and includes the system of the particle and energy balance equations for the electrons, ions and neutrals and the boundary problem for the Maxwell's equations. The balance of the electron energy includes the RF heating source, the energy losses for the electron impact excitation and ionization of atoms and the losses caused by the heat transport. The balance of the charged particles includes accounts for the ionization and diffusion losses. In the model, it is assumed that the neutral gas is uniformly distributed in 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: the particles of plasma escape to the wall along lines of force of the magnetic field. This effect is accounted in the model. To make the system of the balance equations closed it is necessary to determine the single external quantity in it, RF power density. This quantity can be found from the solution of the boundary problem for the Maxwell's equations. The Maxwell's equations are solved at each time moment for the current plasma density and temperature distributions. The Maxwell's equations solution allows determining a local value of the electron RF heating power, which influences on the ionization rate and, in this way, on the evolution of plasma density. The electrons are heated by the RF field owing to collisional and Landau wave damping. The problem is solved in cylindrical geometry. The plasma is assumed to be azimuthally symmetrical and uniformly distributed along plasma column. The Crank-Nicholson method is used for solving a system of the balance equations. The Maxwell's equations are solved in 1D using the Fourier series in the azimuthal and the longitudinal coordinates. The results of calculations of RF plasma production in the Uragan-2M stellarator with the frame-type antenna are presented.

This work is supported in part by STCU project № 4216.

1-36

HYPERTHERMAL ELECTRONS FLOW PARAMETERS FLUCTUATIONS IN THE EDGE PLASMA DURING ICR HEATING ON THE U-3M TORSATRON

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A number of interesting effects was observed in the framework of the experimental investigation of the hyperthermal electrons flow which was formed in the U-3M torsatron during the magnetic field pulse. The oscillatory activity was registered in the flow of charged particles observed at the area of last closed magnetic surface during the plasma creation and ICR-heating represented a special interest. It was noticed that the flow was modulated with a number of harmonics of near-ion-cyclotron frequencies. At the vicinity of each spectral line a number of satellites was observed. Thus the suggestion about a parametric excitation of the ion Bernstein waves was made [1,2]. It is useful to note that considered oscillatory activity was registered not only during the RF – heating pulse but also at the edge of the magnetic field pulse (during the time interval in which the magnetic field intensity is falling) when plasma is not created and heated by introducing RF-power into the confinement area.

This report contains the results of experimental investigation of the oscillations observed during the ICR – heating pulse and on the magnetic field pulse edge. The spectrums observed in the both cases were compared to find out the oscillations physics.

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1-37

THE DYNAMICS OF HYPERTHERMAL ELECTRONS IN THE U-3M TORSATRON

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The phenomena of hyperthermal electrons flow formation was investigated in the framework of study of the factors that cause X-ray radiation output observed on the magnetic field pulse edges. The flow formation takes place during the time intervals in which the magnetic field intensity varies significantly. Together with the X-ray radiation a number of diagnostics such as microwave radiometry and reflectometry, H_{α}, magnetic and Langmuir probes have shown a noticeable variation of the signal level during these intervals. Such reaction was interpreted as an evidence of plasma creation. The level and the character of observed signals depended critically on the residual gas pressure. In particular, the residual gas pressure reducing results in the signal amplitude growing in each of the diagnostic channels. Besides, the microwave radiometry signal has shown a noticeable level during the whole magnetic field pulse.

The interest to the hyperthermal or run-away electrons is caused by necessity of taking into account its contribution into the energy balance especially when the plasma density is low [1,2]. The investigation of the flow structure and dynamics allows to obtain the information about the magnetic field topology.

In this work the results of experimental study of the hyperthermal electrons flow structure for different experimental conditions are presented. In particular, the influence of ICR – heating parameters is studied. The level of signal variations in the diagnostic channels was also monitored.

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2-1

EFFECT OF THE RADIAL ELECTRICAL FIELD IN LOWER HYBRID HEATING EXPERIMENT ON FT-2 TOKAMAK

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The Lower Hybrid Heating (LHH) scheme [1] has been routinely used at FT-2 tokamak to provide ion and electron heating and a transition to improved confinement regimes with Internal Transport Barrier (ITB) at RF power level 90 - 100 kW [2]. Recently the possibility of LHH at enhanced power level ($P_{\mathrm{LHH}} \approx 2P_{\mathrm{OH}} = 180$ kW) resulting in a transition to improved energy confinement regime during RF pulse and in the post heating stage has been demonstrated [3]. The LH heating efficiency of the ion component at the high RF power level remains the same high as at the lower powers.

Experiment demonstrates, that on-axis LHH at enhanced HF power results in higher $T_i(\rho=0cm)$ rise (100 → 300)eV with ITB formation at ρ = (4÷5) cm). The central electron temperature increases also (300 → 500) and remains at the high level for about 5 ms after the RF pulse switch off. Improved energy confinement transition is observed.

Rise of the E_r (measured spectroscopically using the CIII (464.7nm) line emissivity) and its shear ω_s in the region 4÷5cm could result in the ITB formation observed at $T_i(\rho)$ profiles during LHH. Measurements demonstrate that E_r data differ from the standard neoclassical E_r^{Stand} values. They are larger at the middle radii and smaller in the LCFS vicinity.

The spectroscopically measured radial profiles of $V_{Er}\times B(\rho)$ velocity at periphery are close to the profiles of the poloidal velocity of fluctuations derived from the Doppler Reflectometry (DR) measurements.

The drastic fluctuation suppression, measured by DR practically at all frequencies (fluctuation frequency band f<1MHz and k~(1÷6)cm^{-1}), is detected slightly before the velocity inversion in the region 7cm. The observed suppression of the density fluctuations is in a good agreement with the Langmuir probe measurements.

The scan of the plasma region by the UHR Doppler BS diagnostics from r = 5 cm to 7.5 cm has shown that two small-scale drift modes (TEM and ETG) are suppressed during LH-heating on the plasma periphery. The first small-scale drift mode (lower frequency, LF) associated with the small-scale component of TEM usually decreases (or grows), in accordance with the peripheral decrease (or rise) of the electron thermal conductivity.

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2-2

RF HEATING BELOW ION-CYCLOTRON FREQUENCIES IN URAGAN TORSATRONS

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Two torsatron (stellarator) machines are in operation in IPP-Kharkiv. Uragan-3M is a small size torsatron with l=3, m= 9, R_0 = 1m major radius, $\bar{a} \approx 0.12$m average plasma radius and toroidal magnetic field $B_0 \leq 1$ T. The whole magnetic system is enclosed into a large 5m diameter vacuum chamber. Uragan-2M is a medium-size torsatron with reduced helical ripples. This machine has the major plasma radius R = 1.7 m, the average minor plasma radius $a \leq 0.24$ m and the toroidal magnetic field $B_0 \leq 1$ T. The Alfvén resonance heating in a high $k_{\|}$ regime is used on both machines. This method of heating is advantageous for small size devices since the heating can be accomplished at lower plasma densities than the minority and second harmonic heating. Both machines equipped with two antennas. One is a frame-type antenna for low density plasma production. Another antenna in Uragan-3M is an unshielded THT (three-half-turn) antenna [1] that consists of 3 straps oriented in poloidal direction. In regular discharges the frame antenna creates plasma with the density $\langle n_e \rangle \approx 0.5 \ldots 2\times10^{12}$ cm^{-3} and temperature $\langle T_e \rangle \approx 1$keV [2]. The THT antenna is usually not used to produce plasma and, therefore, its pulse follows the pulse of the frame antenna. A series of experiments is performed aimed to study the features of the discharge with the THT antenna. Electron temperatures in the range $\langle T_e \rangle \approx 0.2 \ldots 0.4$ keV are achieved at the plasma densities an order of magnitude higher than produced by the frame antenna $\langle n_e \rangle \approx 0.5 \ldots 1.5\times10^{13}$ cm^{-3}. Plasma pressure is increased up to 5 times. A new 4-strap shielded antenna is manufactured and installed in Uragan-2M. First experimental data for radio-frequency heating with this antenna are presented.

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2-3

ICRF HEATING OF HYDROGEN PLASMAS WITH TWO MODE CONVERSION LAYERS

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ICRF mode conversion heating is widely used in present-day tokamaks [1]. This heating regime is used for transport studies, for non-inductive current drive, for impurity pump-out, to drive plasma rotation, etc. Fuchs *et al* showed that an enhancement of the conversion efficiency is possible due to the additional reflection of the fast wave from the high-field side cutoff [2]. Optimal conversion enhancement is achieved when the reflected waves have nearly equal amplitudes and opposite phases. The first experimental evidence of this effect was shown in JET for (^{3}He)-D plasmas [3]. It was recently also tested in JET (^{3}He)-H plasma [4]. The latter is an inverted scenario, for which a much lower ^{3}He concentration is needed to reach the mode conversion heating regime. As H majority scenarios will extensively be used in the initial non-activated phase of the ITER operation [5], studying the heating potential in such plasmas is important.

Due to the presence of the intrinsic D-like species in JET (e.g., C^{6+}, ^{4}He), a supplementary conversion layer is produced in the plasma. This results in a complicated picture of the mode conversion physics. The theory of mode conversion in plasmas with two ion-ion hybrid resonances [6] is used to analyze the role of D-like species in the (^{3}He)-H heating scenario. Particularly, it is shown that in such plasmas the Fuchs effect of constructive/destructive interference occurs, which leads to the possible mode conversion enhancement. The location and transparency properties of each of the conversion layers strongly depend on the concentrations of both minority species. Thus, by carefully choosing the minority concentrations the mode conversion efficiency can be maximized. The mutual effect of the minority species on the opposite conversion layer is discussed. The experimentally observed reduction in the ^{3}He critical concentration needed for the transition from minority heating to mode conversion in the presence of carbon ions is explained within the developed theory. The dependence of the heating efficiency on various parameters (plasma composition, density profile, antenna spectrum, etc.) will be presented.

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2-4

INVESTIGATION OF DISTRIBUTION OF CONDUCTING AND NONCONDUCTING MATTER IN THE DISCHARGE CHANNEL

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Distribution of matter in the discharge channel formed upon a nanosecond electrical explosion of Al wire in vacuum was studied experimentally and theoretically. Simultaneous use of optical and UV diagnostics and numerical results made it possible to distinguish qualitatively different regions of the discharge channel, such as the current-carrying plasma layers and the region occupied by a weakly conducting cold matter. Several series of experiments with 25 μm diameter 12 mm long wires were performed; the charging voltage and the current amplitude were U_0 = 20 kV and I_{max} ~ 10 kA, respectively (see for example S.I. Tkachenko, et. al., Plasma Physics Reports, 2009, Vol. 35, No. 9, p. 734). Shadow and schlieren images of the discharge channel were obtained using optical probing at the second harmonic of a YAG:Nd^{+3} laser (λ = 0.532 μm, τ ~ 10 ns).

The simulations of electrical wire explosion were performed by means of Lagrangian–Eulerian code RAZRYAD based on Braginskii two–temperature model; in this code the homogeneous conservative implicit finite-difference MHD schemes was realized. The radiation energy transport was simulated in multigroup spectral approximation with the use of diffusion model. Heat– and electro– conductivity anisotropy in magnetic field is taken into account. The code allows utilization of data tables for thermal and optical matter properties. The tables of thermophysical and optical properties for metals constructed according to model published in A.F. Nikiforov, V.G. Novikov, V.B. Uvarov, Quantum-Statistical Models of Hot Dense Matter and Methods for Computation Opacity and Equation of State (Fismatlit, Moscow, 2000) were used in our computations. We have investigated the influence of initial data (in particularly “cold start” simulation) and the radiation energy transfer upon the evolution of matter parameters and current density distribution in the discharge channel. Several variants with differing amounts of spectral groups were evaluated. The numerical results are compared with experimental data.

Work supported by the RFBR 08-08-00688, 09-01-12109-ofi_m, programs 02.740.11.0447 and 2.1.1/5470.

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MODELLING OF MODE CONVERSION HEATING AND CURRENT DRIVE IN ION CYCLOTRON FREQUENCY RANGE

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Mode conversion in a plasma with two sorts of ions can be used for generation of a steady state current. Typically, in the case of light minority, FMSW converts into a slow wave (SW) which propagates from the high field side towards the minority ion cyclotron resonance zone. While approaching this zone, component of SW wave vector in the direction of major radius strongly increases and becomes dominant in the parallel wave vector. As the result, absorption of SW drives the currents of oposite signs at the upper and lower parts of torus. Since these currents almost cancel each other, in order to to drive the current, the up-down asymetric excitation of fast magnetosonic wave (FMSW) has been proposed.

In this report such a current drive scenario is modelled numerically. Distribution of electromagnetic field in the plasma is computed with the help of the resonant layer method [1] taking into account non local wave-plasma coupling and heat current of minority ions. Electron and minority ion current densities are calculated in linear aproximation using current drive efficiencies calculated using kinetic equation solver SYNCH [2].

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2-6

MODE CONVERSION IN HYDROGEN PLASMAS WITH IMPURITIES

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Effective Ion Cyclotron Resonance Frequency (ICRF) heating of hydrogen plasmas requires a presence of the minority ions. The value of the minority ion fraction defines the channel of the launched power absorption. For small minority concentration the Fast Wave (FW) power is absorbed by the minority ions through the cyclotron mechanism. With minority concentration increasing the efficiency of the minority heating decreases but FW power is converted partially to the short wavelength modes which are absorbed effectively by electrons. These two regimes of ICRF heating are known as minority and mode conversion heating [1].

Recent experiments on ICRF heating of hydrogen plasmas in tokamak JET [2] have reported an important role of the carbon impurity (the carbon fraction can exceed 2%). Carbon impurity in (He3)H plasmas decreases the critical value of the minority concentration when the transition from the minority heating to the mode conversion regime is observed. Also it excludes the minority heating regime in (D)H plasmas. Though these conclusions are enough general they don’t take into consideration the importance of the antenna phasing and radial positions of the ion- ion hybrid layers for effective mode conversion.

The theory of the mode conversion in the hydrogen plasmas with the carbon impurity [3] is applied to describe the experiments in tokamak JET. The numerical simulations confirm the analytical results. The efficiency of the mode conversion is defined by the conditions of the interference between two reflected FW. One FW is reflected from the minority evanescence layer but another one is reflected dominantly either from the impurity evanescence layer or from the R- cutoff layer at high field side of the magnetic field. Dominant type of second reflection is defined by the impurity concentration, the FW parallel wave number and the radial positions of the resonances. The developed theory predicts a difference in the mode conversion efficiency for both cases. Therefore the mode conversion experiments in tokamak JET [2] are analyzed in details for dipole and ±90° phasing. The explanation of the obtained data is proposed. Sensitivity of the mode conversion efficiency to the radial positions of the resonances and cutoffs is estimated for the considered experimental conditions. The critical minority concentration is clearly seen experimentally and it does not depend on the reflected FW interference. But for larger minority concentrations, the interference conditions define the mode conversion efficiency and, as a result, a relation between the ion and electron channels of power absorption (especially for high temperature plasmas). In such a way the impurity ions not only reduce the concentration threshold between the minority heating and mode conversion regimes but also affect essentially on the location and the efficiency of the mode conversion.

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2-7

STUDY OF PLASMA POTENTIAL, ITS FLUCTUATIONS AND TURBULENCE ROTATION IN THE T-10 TOKAMAK

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The direct experimental study of plasma radial electric field E_r is the key issue to clarify $E\times B$ shear stabilization mechanisms. The plasma turbulence rotation measurements, compared with $E_r\times B_t$ drift rotation may explain whether turbulence moves together with the plasma or independently. The absolute value of the core plasma potential φ was measured in the T-10 tokamak by Heavy Ion Beam Probing (HIBP) with Tl^+ beam energy $E_b \leq 300$ keV and the beam current up to 200 μA. This allows us to observe the core potential (and E_r) at high densities and in a wide radial area. At the limiter, the plasma potential and density were measured by Langmuir probes. The core plasma turbulence was studied by correlation reflectometry (CR). The regimes with Ohmic (OH), on- and off-axis ECR heating (B_t = 1.55–2.4 T, I_p = 140-250 kA, $\bar{n}_e = (1.3 – 4.1)\times10^{19}$ m^{-3}, $P_{EC} < 1.5$ MW) were studied. It was shown that the plasma potential has negative sign in the whole observation area. The potential well becomes deeper and the mean E_r becomes more negative with the rise of density and energy confinement time. During ECRH phase, the absolute potential well becomes significantly shallower, E_r decreases and confinement degrades. The potential has a weak dependence on I_p. In all observed regimes, $E_r(r)$ ~ const in the whole radial range of HIBP measurements.

The plasma column rotates not as a rigid body due to the $B_t(R)$ dependence. The typical values for $E\times B$ drift angular velocities are $\Omega_{E\times B} \sim 1.5\times10^4$ radian/s for the OH, and $\Omega_{E\times B} \sim 1.25\times10^4$ radian/s for ECRH stages. That is the broadband drift-wave turbulence tends to rotate together with the $E\times B$ driven bulk plasma.

The plasma fluctuations in the frequency range of Geodesic Acoustic Modes (GAMs) may be possible mechanism of the turbulence self-regulation. The theory proposes the unified dispersion relation for GAMs and Beta induced Alfven Eigenmodes (BAE). These modes are studied by HIBP, CR and Langmuir probes. In the low B_t regime, the mode frequency is close to a constant over the investigated radial interval (0.2<ρ<0.9), showing inconsistency with theoretical predictions in the absolute value and radial dependence. These modes are seen on the plasma potential as a main peak, also in some cases a higher frequency satellite appears. The modes are more pronounced during ECRH, when the typical frequencies are seen in the band from 22-27 kHz over the whole plasma cross-section. At the outer edge, ρ = 0.95, the frequency value is consistent with theoretical prediction, which may be indicative these mode are the edge driven eigenmodes. The frequency weakly depends on the magnetic field and plasma density. With the density rise, the satellite and main peaks consequently disappear. The amplitude of the induced potential perturbations with ECRH is quite pronounced, about a few tens of Volts, increasing towards the plasma centre. The modes demonstrate the features of the spatially global eigenmodes.

This work is supported by Grants: FASI 02.740.11.5062, RFBR 10-02-01385, 08-02-01326.

2-8

INFLUENCE OF MAGNETIC FIELD DIRECTIONS INHOMOGENEITY ON LONGITUDINAL PROPAGATION OF WAVE BEAMS IN AXISYMMETRICAL MAGNETIC TRAP

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In axisymmetrical magnetic traps inhomogenity of magnetic field intensity is that of the magnetic field direction are closely related to each other. These two types of inhomogeneities essentially change the structure of electromagnetic wave beams with frequencies of the order of electron cyclotron frequency. For example it was shown [1] that inhomogeneity of magnetic field direction was responsible for strong refraction of electromagnetic waves in overcritical plasma confined in axisymmetrical magnetic trap which for longitudinal launch of rf power resulted in essential decrease of the heating efficiency in a system.

We present a number of examples which demonstrate a large variety of wave beam behavior depending on plasma and magnetic field inhomogeneity such as exponential widening of wave beam for overcritical plasmas, channeling of right polarized wave in undercritical plasmas, changing of critical point type for ray trajectories near electron cyclotron surface (“saddle” or “junction” [2]), new critical point appearance etc. Some results of analytical and numerical investigations of inhomogeneity influence are presented.

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2-9

SURFACE MODES EXCITATION UNDER FAST WAVE EXCITATION IN MAGNETOACTIVE PLASMAS IN THE $\omega > \omega_{ci}$ FREQUENCY REGION

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An excitation of fast mode (FW) of fast magnetosonic waves in magnetoactive plasmas in the $\omega > \omega_{ci}$ frequency range can as well lead to surface modes excitation, connected with gyrotropic properties of plasma and its inhomogeneity [1]. In plasma hating scenarios, using minority heating method, this effect can amplify the peripheral RF energy absorption due to the ion minority cyclotron resonance and, consequently, lead to flattening of the energy absorption profile and finally to efficiency decreasing of that RF plasma heating method.

To investigate the excitation, propagation and absorption of electromagnetic waves in plasmas, taking into account the two-dimensional inhomogeneity of both plasma and metallic surface, surrounding a plasma column, it was developed a numerical model on the ground of fictitious regions method [2]. The model given allows one to investigate the wave physics in approximation of the two-dimensional plasma inhomogeneity for different plasma column configurations, typical for magnetic traps of both tokamak and stellarator type, in the presence of the metallic elements, located in the vicinity of plasma column.

Investigations on the base this numerical model of FW excitation, propagation and absorption scenarios, using minority heating with different plasma parameters, have demonstrated a possibility of the intensive surface modes generation in the presence of metallic surfaces, with different configuration and placed near a plasma column. The negative consequences of this effect may be proved more essential, than in the case of the surface modes excitation due only to plasma inhomogeneity.

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3-1

EROSION MECHANISMS AND EROSION PRODUCTS IN TUNGSTEN TARGETS EXPOSED TO PLASMA HEAT LOADS RELEVANT TO ELMS AND MITIGATED DISRUPTIONS IN ITER

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Tungsten is foreseen presently as candidate armour material for the divertor targets in ITER. During tokamak transient processes, such as Edge Localized Modes (ELMs) and mitigated disruptions, the targets will be exposed to the plasma heat loads up to $q = 10$ MJ/m^2 on the time scale of the order of $t = 1$ ms that can cause a severe erosion of the exposed material. Plasma-induced erosion of the armour material is one of the major concern for safe, successful and reliable tokamak-reactor operation. Erosion restricts lifetime of the divertor components and produces the material dust, which being tritiated, radioactive and chemically reactive presents a serious problem for a safety. In addition the material erosion leads to production of impurities, which can penetrate into the hot fusion plasma causing its radiative cooling. The exact amount and properties of the eroded materials are critically important to lifetime and safety analysis of tokamak-reactor.

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 and quasi-stationary plasma gun QSPA-T. The targets were exposed to the plasma heat fluxes relevant to ITER ELMs and mitigated disruptions.

At MK-200UG facility, 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. Optical and VUV spectroscopy was applied as diagnostics.

At QSPA-T facility, the tungsten targets were tested without magnetic field by hydrogen plasma steams with pulse duration $t = 0.5$ ms and heat load $q = 0.2 – 2$ MJ/m^2. The plasma stream diameter is $d = 5$ cm, impact ion energy $E_i = 0.1 - 0.2$ keV. The experiment was aimed mainly at the study of tungsten erosion caused by melt motion and its displacement along the target surface as well as by melt splashing and ejection of droplets. Onset conditions of these erosion mechanisms and their contributions to the resultant erosion are analyzed. The measured melt displacement is compared with the results of numerical modeling based on the hydrodynamic melt motion induced by the plasma stream pressure.

3-2

TUNGSTEN COATINGS UNDER FUSION RELEVANT HEAT LOADS

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Components for first wall applications in future nuclear fusion devices need to fulfill special requirements, e.g. good thermal conductivity, a reasonable strength value as well as a good compatibility with a deuterium – tritium plasma. Furthermore neutron irradiation has not to lead to an unacceptable activation and a significantly degradation of material properties.
Especially transient and/or cyclic thermal loads in magnetic confinement experiments like ITER or DEMO have a severe impact on the material damage of the plasma facing components. They usually occur with quasi static pulses of about 400 s or longer. In addition, short pulses appear during operation resulting from Edge Localized Modes (ELMs). These thermal shock loads have pulse durations of approximately 500 µs and energy densities of about 1 MJ/m^2 and above, which lead to significant material changes, e.g. crack formation and melting on the surface of the plasma facing components.
Tungsten coatings are discussed to be used as armour materials for the first wall of fusion devices instead of bulk tungsten components. In order to quantify the material degradation under transient loads, 25 µm thick tungsten coatings on a fiber-reinforced graphite substrate were exposed to repeated short fusion relevant thermal pulses. An example of material degradation during electron beam loading is shown in Figure. Thus the application limits of the coatings are characterised and compared with bulk tungsten materials. In parallel Finite Element simulations were performed in ANSYS.

Fig. Brittle destruction of tungsten coatings on CFC substrate during thermal shock in the electron beam facility JUDITH 1 at FZJ (absorbed power density: 237 MW/m^2 for 1 ms)

3-3

HIGH HEAT FLUX PLASMA TESTING OF ITER DIVERTOR MATERIALS UNDER ELM RELEVANT CONDITIONS IN QSPA Kh-50

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Divertor armor response to the repetitive plasma impacts during the transient events in ITER and DEMO remains one of the most important issues that determine the tokamak performance. Erosion of plasma-facing components (PFCs) restricts the divertor lifetime, leads to contamination of the hot plasma by heavy impurities and can produce a substantial amount of the material dust.

In this paper, experimental simulations of ITER ELMs impacts with relevant load parameters (energy density and the pulse duration as well as particle loads) were performed with quasi-steady-state plasma accelerator QSPA Kh-50 that is largest and most powerful device of this kind. The main parameters of QSPA Kh-50 hydrogen plasma streams were as follows: ion impact energy about 0.4 keV, maximum plasma pressure 3.2 bar, and the plasma stream diameter 18 cm. The plasma pulse shape is approximately triangular, pulse duration 0.25 ms and the heat loads varied in the range 0.2–2.5 MJ/m^2.

Performed studies of plasma-surface interaction include measurements of plasma energy deposited to the material surface as a function of the impacting energy and angles of plasma streams incidence for W, C and adjoined W-C surfaces under repetitive ELM relevant plasma exposures[*]. Droplet splashing at the tungsten surface as a source of enhanced evaporation is discussed also.

The paper also describes the cracks analysis and the results of residual stress measurements for deformed W targets with elongated grains, which is ITER reference material manufactured by Plansee AG. The elongated grain orientation was perpendicular to the surface. The targets were preheated to different bulk temperatures T_0 in a range of 200-600°C, aiming at estimating effects of Ductile-to-Brittle Transition Temperature (DBTT) on material cracking. The influence of material modification by initial plasma exposures on cracking thresholds was estimated.

The energy threshold for cracking development is found to be ~0,3 MJ/m^2 for QSPA Kh-50 pulse of 0.25 ms duration and triangular pulse shape. The DBTT is experimentally estimated. The DB-transition occurs in the temperature range of 200 ºC $\leq T_{DBTT} <$ 300 ºC. For initial temperature $T_0 >$ 300 C no major cracks are formed on the exposed surface. Major cracks network forms only in cases of initial target temperatures below DBTT. Mesh of cells of major crack network (0.8-1.3 mm) near the center of the spot of applied load is larger (up to 2 times) than in the peripheral region. Typical cell sizes of intergranular micro-cracks network are 10 to 80 µm. Most of cells are within 10 – 40 µm, which corresponds to the grain size of this W grade. The micro-cracks propagate along the grain boundaries completely surrounding the grains.

Performed measurements demonstrate that the residual stress does not practically depend on initial target temperature and significantly grows with increasing thermal loads.

** This work was supported in part by STCU within the project 4155*

3-4

MATERIALS SCIENCE PROBLEMS IN MANUFACTURE OF WELDED COMPONENTS OF DEMO THERMONUCLEAR REACTOR

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The new generation of heat-resistant high-chromium steels, strengthened by nanoparticles of oxides, is planned to be used in structural elements of welded components of the DEMO thermonuclear reactor.

Steels of EUROFER ODS type should provide a low susceptibility to degradation in the process of service. In thermonuclear reactors the use of combinations of the following materials is also envisaged:

- stainless steel of 316LN type with 310LN;
- dissimilar joints of 316LN with tungsten;
- bimetal of copper with tungsten;
- bimetal of EUROFER ODS with tungsten.

The large dimensions of load-carrying and protective elements of the body, complicated design solutions of large-size components demand for the new technologies of welding. The high sensitivity to embrittlement of joints, possibility of formation of intermetallic interlayers in the process of manufacture and long-term service requires the comprehensive investigations of effect of loading conditions on their serviceability.

The updated approaches to the solution of problems both in the field of welding and also in the development of special technologies of joining the structural materials of the thermonuclear reactor of the DEMO type are considered.

3-5

REDEPOSITION OF THE CARBON IN THE SOL OF THE T-10 TOKAMAK AND ITS INFLUENS ON REFLECTIVITY OF THE IN-VESSEL MIRRORS

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Erosion and redeposition of plasma-facing materials in modern tokamaks result in the formation of the carbon films and dust depositions. The accumulation of the tritium in such deposits is a problem for a fusion reactor. Another aspect of the problem is the degradation of the in-vessel optical elements of plasma diagnostics in the reactor. In particular, for ITER the degradation of first mirrors is most critical issue. Experiments at ITER-relevant conditions are necessary for measurements of erosion and deposition rates, investigation of composition and morphology of deposits, and identification of redeposition mechanisms. This information is very important for the development of methods for the protection and cleaning of optical elements.

The redeposition of the carbon, sputtered from the graphite limiters was investigated on the T-10 tokamak, by exposure of the mirrors and samples in the different points of the SOL. Redeposition was investigated in working as well as in cleaning discharges of T-10. Composition of the films was measured with using of Auger-spectroscopy and EPMA. Surface structure and morphology were investigated by optical and electron microscopes and by profilometer. Thickness and optical parameters (refractive index and extinction coefficient) of the films were estimated by ellipsometry. Reflectivity of the mirrors before and after deposition was measured by spectrophotometer.

For the working discharges of T-10 the deposition rate was 0.1 nm/sec (1 shot=1 s) at the position far (about 1 m.) from the graphite limiters. But it was increased more than order of magnitude in a close vicinity to the limiter. It means that the toroidal transport of the sputtered carbon not very pronounced in the SOL. Deposition rate also sharply reduces when the radial distance from both plasma border and limiters increases. The deposited films are amorphous and consist from carbon and hydrogen without any metallic species (Fe, Cr, Ni). The reflectivity of the mirrors decreased strongly with the films deposition, especially in the wavelength range (190-400 nm).

For the cleaning discharge deposition rate was more than order lower than for the working one. But due to the long duration of the cleaning procedure on T-10 (hundreds ours per experimental campaign) it contributes strongly to the total redeposition of the sputtered carbon and to contamination of the in-vessel mirrors.

The experiments in the SOL of tokamak T-10 are convenient instrument for the ITER-relevant investigations of the erosion and redeposition of plasma-facing components as well as degradation of the in-vessel elements of optical diagnostics in a real tokamak conditions.

3-6

ITER FUSION POWER MEASUREMENT USING DIVERTOR NEUTRON FLUX MONITOR

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ITER, currently under construction in Cadarashe Centre in the South of France, aims to demonstrate fusion plasma ignition and produce a net gain of energy. The machine has been designed to produce 500MW of fusion power for 50 MW of auxiliary heating and reach Q≥10. ITER plasma volume will be approximately 840 cubic metres. Since a considerable part of fusion power is realized in the neutron radiation and because neutrons leave fusion plasma without any absorption, neutron flux detection is a practicable method of fusion power measurement. That is a complicated technical problem due to strong diagnostic requirements – wide dynamic range (10^4), fast temporal response (> 1 ms) and high accuracy (>10%). ITER neutron diagnostic system consists of several subsystems such as vertical and horizontal multichannel neutron collimators, activation system and neutron flux monitors. The last subsystem includes several fission chambers which will be installed inside tokamak vacuum vessel around the plasma. The conceptual design of neutron flux monitor system has been discussed in several publications [1,2,3]. In the present paper we consider in detail an improved conceptual design of neutron flux monitor proposed for installation in lower part of tokamak vacuum vessel in Divertor Cassette [2]. MCNP simulation with model included vacuum vessel, blanket shielding module, divertor cassette and other machine construction was carried out. Neutron energy spectrum as well nuclear heating of divertor neutron flux monitor has been calculated. Based on results of MCNP simulation we propose an optimization of fission chambers sensitivity to provide the possibility of operation in count rate mode over full dynamic range. Hydraulic, thermal and mechanical analysis of neutron flux monitor housing was carried out using ANSYS code. It was show that current design of the divertor neutron flux under normal ITER operation will be overheated thus further construction improvement is necessary. The most attractive advantage of divertor neutron flux monitor is a close position to the plasma and as result it could be in-situ calibrated with good statistics and required precision. The calibration procedure has been proposed and analyzed.

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3-7

LASER DAMAGE INVESTIGATIONS OF QUARTZ *KU*-1 AND SAPPHIRE OPTICAL ELEMENTS FOR DIVERTOR THOMSON SCATTERING DIAGNOSTIC OF ITER

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This paper is devoted to the study of laser damage thresholds of optical elements, which is supposed to be used in laser input channel of divertor Thomson scattering diagnostic of ITER as protective elements of first mirror. In these investigations laser damage thresholds of quartz and two kinds of sapphire “ultraviolet” and “infrared” were measured. A number of sapphire samples was irradiated by neutrons up to 10^{19} n/cm^2 and annealed. Chemical analysis of the two types of sapphire showed that only the content of chromium in “infrared” sapphire was on the order more than in ”ultraviolet“ one.

For the experiments Nd:YAG laser working with 10 Hz repetition rate was used. Laser pulse parameters are: duration - 16 ns, the energy – 250…300 mJ. The experiments have not identified a dependency of laser damage thresholds on a number of laser pulses affecting on optical elements. A break could occur after sample irradiation by a number of several hundreds pulses, but this has been observed near damage threshold and is probably connected with laser energy fluctuations. A damage is absent after influence of 2.2×10^5 laser pulses if laser energy density decreases by 40% from threshold level on a sample.

Laser damage thresholds of different unirradiated sapphire elements are practically identical. “Ultraviolet” sapphire showed better laser resistance after neutron irradiation and subsequent annealing: threshold fell only on 10%. The “infrared” sapphire thresholds have decreased by 30%.

3-8

EFFECT OF NITROGEN, OXYGEN, NEON AND ARGON ON PINCH CURRENT AND SOFT X-RAY EMISSION IN SAHAND PLASMA FOCUS

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The effect of Nitrogen, oxygen, neon and argon as a working gas in Sahand as a Filippov type plasma focus facility (90kJ, 25kV) on pinch current has been researched. In the first section of paper, at 0.25 Torr pressure and 14kV working voltage, the effect of gas type on comparative study of soft X-ray is investigated. With experimental data we find that in argon and neon the Sahand emitted more X-ray rather than nitrogen and oxygen. Furthermore the result shows that in Sahand with nitrogen and oxygen as a working gas, the pinch occur in 14kV at 0.25 Torr pressure but in neon and argon at 0.25 Torr at different voltages the pinch occur. Decrease in time difference between maximum current and pinch current with increase in atomic number is another result in our research. The results of this work can help us in choosing gas type to use for X-ray source as an application of plasma focus devices.

3-9

CLEANING TECHNIQUES FOR FIRST MIRRORS IN ITER

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In-vessel optics in ITER will undergo to fast degradation owing to intensive contamination by products of plasma-induced erosion of first-wall elements, divertor tiles and some other factors. For example, first mirror of divertor Thomson Scattering (TS) diagnostics will be placed in conditions of amorphous hydrocarbon (a-C:H) film deposition and plasma irradiation (gamma, x-rays and UV). In this case, effective in situ cleaning techniques should be developed to retain high optical reflective characteristics of the optics.

In this work a three-electrode (cathode, anode and additional electrode) H_2 flowing glow discharge has been applied for cleaning of mirror surfaces from a-C:H films. Stainless steel and Mo mirrors have been used. The mirrors were placed on the additional electrode located in the vicinity of a positive column boundary. Carbon films obtained in tokamak T-10 during working pulses and deposited by magnetron discharge coupled with x-ray irradiation were removed using the same glow discharge.

Chemical composition and morphology of the a-C:H films deposited on mirror surface have been analyzed by electron probe microanalysis and scanning electron microscope. Thicknesses and optical parameters (refractive index and extinction coefficient) of the layers have been estimated by ellipsometry. The reflectivity of the mirrors before and after removal of the a-C:H film has been measured by a spectrophotometer in a wavelength range of 190-1100 nm.

It has been shown that utilization of H_2 glow discharge allows to remove the a-C:H films with rate up to several nm/min that is quite convenient for divertor TS diagnostics. Moreover, additive of a small amount of methane (up to 6%) in H_2 flow do not lead to deposition of hydrocarbon films or surface erosion of the mirrors. Thus glow discharge in H_2 flow may be used as in situ cleaning techniques not only between but also during the course of working pulses of fusion reactor.

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NEUTRON-TEMPERATURE OSCILATIONS IN NEUTRON MULTIPLYING SYSTEMS AND IN BLANKETS OF THERMONUCLEAR REACTORS

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An excitation and propagation of neutron fields oscillations methods got development in aims of noise diagnostics of the systems, multiplying neutrons [1]. Oscillations in a multiplying medium with a coolant are described the connected system of equations, including ***o***f thermal-neutron diffusion equation, taking into account neutron multiplication and their capture by nuclei, and hydrodynamic equations of compressible liquid [2]. Evolution of the neutron field in the blanket of hybrid thermonuclear reactor with neutron multiplication is determined by external source of neutrons, their inertia, diffusion, a nuclear capture and multiplying because of nuclear fission, by the convective transport of neutrons and heat. Acoustic oscillations, because of their large wavelength as compared to lengths of waves of neutron-temperature oscillations with the same frequency, are uncoupled from them. In the multiplying neutrons systems and blanket a task is taken to the solution of dispersion equation for oscillation, both neutron field and of coolant oscillations related to them. One of modes is a neutron wave in approximation of weak *connection* with the second wave (by a convective temperature mode), which propagates with a weak decrease in the same direction as the coolant motion. The analysis of neutron-temperature and neutron oscillations is executed. These oscillations are excited by the periodic in time external sources of heat and fluxes of neutrons in the condensed media of blanket and in the core of reactor. The numerical analysis of dispersion equation is executed in the conditions of both in weak and strong connection between the branches of oscillations. Numerical calculations confirm conclusions of analytical researches in approaching of weak connection. As a result of analysis of graphics of dependences of complex wave numbers from the frequency the important conclusions are got about propagation features and spatial decrease (growth) of the strongly coupled neutron-temperature oscillations, in particular, in the conditions of dependence of capture time of thermal neutron by the fission nuclei from the "effective" temperature of thermal neutrons. Oscillations of the neutron field in the blanket and neutron-temperature oscillations in the multiplying neutrons media propagate as neutron or coupled neutron-temperature waves with the decrease (growth) of their amplitudes. The analysis of their amplitude-frequency characteristics allows both to measure the kinetic coefficients of behavior of neutron fields and to get information about the thermo-mechanical state of blanket and of the neutron multiplying systems [3].

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TOPIC 4 – BASIC PLASMA PHYSICS

4-1

IMPURITY ION DRIFT AND TOROIDAL ROTATION IN TOKAMAKS

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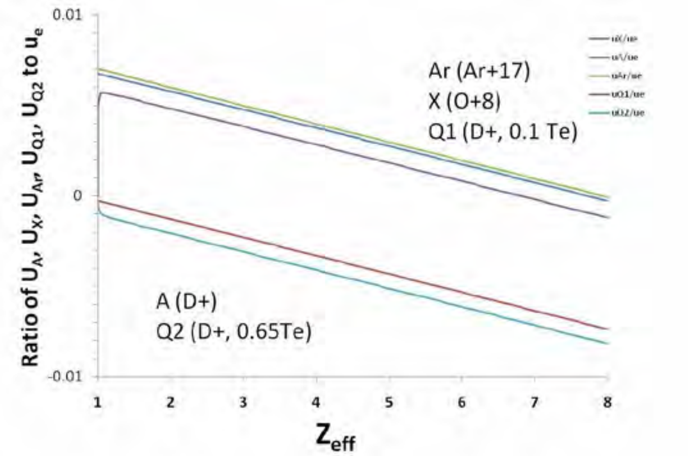
Toroidal rotation of tokamak plasmas is widely regarded as important for plasma diagnostics and control[1] and has been discussed in many theoretical and experimental studies. The underlying hypothesis of impurity ion drift coupled to that of the bulk ions, so the plasma rotates as a unit (single fluid, MHD model), is rarely examined.[2,3]

This is an analysis of the toroidal drifts of bulk (hydrogenic) and impurity ions, and electrons in ohmically heated tokamaks. Observed ion drift is consistently explained by a 1-D model with plasma parameters conserved on flux surfaces. These calculations show that the drifts are usually decoupled, so the notion of "toroidal rotation" does not hold.

The assumptions of the model are: (i) drift motion is along the toroidal magnetic field, (ii) plasma quansineutrality, (iii) current density obeys Ohm's law, (iv) zero net plasma toroidal momentum (no external sources or radial transport), (v) 1-D momentum equation for each species (electrons "e," and hydrogenic "A" and impurity "X" ions). Two classes of problems are examined: relative drift velocities of the plasma species (easily understood in terms of symmetry between A and X ions) and their absolute drift velocities.

The first result is that the impurity and bulk ion drift velocities are generally unequal in ohmically heated tokamak plasmas. The figure shows the calculated drift velocities, relative to the electron drift, for deuterium (u_A/u_e), fully ionized oxygen impurity (u_X/u_e), and trace (0 density) Ar^{+17} ions (u_{Ar}/u_e, close to u_X/u_e), and trace groups of nonthermal deuterium ions (Q1 and Q2), as functions of the effective charge Z_{eff} of the plasma. The temperatures of the D^+, O^{+8} and Ar^{+17} ions are $0.6T_e$, and of Q1 and Q2, $0.1T_e$ and $0.65T_e$. (The results depend only on the ratios to T_e). The upper curves correspond to drift opposite the plasma current; the lower, to drift along it.



In most cases the impurity drift is the result of the forces owing to the toroidal electric field and to drag on the plasma electrons, superimposed on the bulk (hydrogenic) ion drift velocity. The direction of the impurity drift changes (from opposite the toroidal current) when (i) the toroidal electric field approaches (roughly) the Dreicer field, i.e., the electrons begin to run away and Ohm's law fails,[4] or (ii) the conductivity mechanism changes, as during RF current drive (e.g., elevated hydrogenic ion drift in ICH).[5] Neutral beam injection easily dominates these force terms, and once a collision term for the fast beam ions is included, the major observed features can be calculated readily with this type of model.[6]

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4-2

RENORMALIZED NON-MODAL THEORY OF TURBULENCE OF PLASMA SHEAR FLOWS

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In our report, we present the results of the non-linear investigations of the temporal evolution and saturation of drift turbulence in shear flows, which has the non-modal approach as its foundation. The performed analysis reveals that the course of events in temporal evolution of the instabilities in plasma shear flows depends on the magnitude of the velocity shear. The evolution proceeds differently in the case of strong velocity shear (order of the drift frequency) and in the case of moderate velocity shear (order of the growth rate, but much less than the drift wave frequency).

In our report we present

– non-modal non-linear renormalized hydrodynamic theory of drift turbulence of plasma shear flows;

– linear non-modal approach to kinetic theory of plasma shear flows;

– renormalized nonlinear non-modal kinetic theory of the turbulence of plasma shear flows.

The consistent investigation of the temporal evolution of the turbulence in plasma shear flows requires all these theories, which are developed here for the first time. We develop the non-modal renormalized hydrodynamic theory of drift modes in plasma shear flows on the base of the Hasegawa-Wakatani model. This theory accounted for the effect of the turbulent motion of the plasma in the ensemble of shearing modes with random phases on the saturation of the drift resistive instability. Using the developed two-time scale procedure (quasi–markovian approximation) of the calculation of the dispersion tensor for turbulent displacements of the plasma, we obtained the nonlinear integral balance equation, which determines the level of the non-modal drift turbulence, which established due to the random turbulent motion of plasma. Level of drift turbulence is determined. It appears to be comparable to the mixing length estimate level. In contrast to the case of plasma without shear flows, for which the steady state establishes at this level, it is transient for plasma shear flows and it holds only for limited time. The time evolution of the potential is characterized by the non-modal effect of the enhanced dispersion, due to which the electrostatic potential decreases with time as $\left(V_0{}'t\right)^{-2}$. It is important to note, that the Markovian approximation for the analysis of the turbulent scattering of plasma parcels at this stage is not valid.

Because of the secular growth of the component $k_x\left(t\right)$ of the wave number along the velocity shear, the results obtained above on the ground of fluid equations have a limited validity in the investigations of long time evolution of the turbulence in plasma shear flows. For this reason we develop here a new linear non-modal approach to kinetic theory on the ground of the Vlasov-Poisson system, which properly treats the long-time evolution of the perturbations with arbitrary values of the $k_{\perp}\left(t\right)\rho_i$. We obtain that in the linear non-modal kinetic theory of plasma shear flows, the velocity shear appears in the integral equation for the electrostatic potential as the non-modal time-dependent effect of the finite Larmor radius. We derive the non-modal evolutionary solution of that integral equation for the electrostatic potential for hydrodynamic and kinetic drift-type instabilities of plasmas in shear flow.

We develop for the first time the renormalized non-linear non-modal kinetic theory, which accounts for a new combined effect of the turbulent scattering of ions across shear flow due to their interactions with sheared modes and their convection by shear flow.

4-3

QUANTIFYING EDGE PLASMA TURBULENCE BY ANOMALOUS DYNAMICS

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In experimental investigations of edge plasma turbulence much attention is paid to the statistical data analysis which is of importance for creating adequate theoretical models. From the experiment we obtain the time series, and subsequent statistical analysis provides information about the main probabilistic quantities such as distribution, scale (non)invariance and measures of interdependence. On the other hand, new ideas developed in the statistical theory of *anomalous dynamics in complex systems* may appear to be fruitful for the description of plasma turbulence [1]. Indeed, many of the current challenges in the physics of plasmas arise from fundamentally multiscale, nonlinear, and non-Gaussian nature of plasma fluctuation processes which can be explained within the concept of *"strange kinetics"* [2]. From the theoretical point of view, strange kinetics is intimately connected to a description based on the *Lévy stable probability laws and strongly correlated random processes*. It has been realized that these theoretical tools are mathematically related to the expanding area of *fractional differential equations*, i.e., to derivatives and integrals of non-integer order [3]. Recently, *fractional kinetic equations* of the diffusion, diffusion-advection, and Fokker-Planck type were recognized as a useful approach to the description of transport dynamics in complex systems which are governed by anomalous diffusion and/or slow relaxation patterns. Here we propose and discuss semi-phenomenological models of the edge plasma turbulence based on kinetic equations with fractional derivatives. We demonstrate that the diffusion equations with distributed order derivatives can serve as a useful tool for the description of turbulent phenomena lacking a unique scale invariance [4]. The use of correlated continuous time random walk approach is required to account for the observed long-time correlations in plasma data [5]. Moreover, we present the results based on the advanced tools of statistical data analysis [6] and demonstrate that the density and potential fluctuations measured by Langmuir probes in the edge plasma of the URAGAN-3M torsatron [7] behave like the Lévy flight processes whose characteristics depend on the probe position. We quantify the Lévy processes before and after the LH transition. As a measure of interdependence we propose the *codifference* for characterizing the behavior of the observed Lévy flight process [8].

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4-4

EFFECT OF DUST CHARGE FLUCTUATION AND FINITE DUST TEMPERATURE ON RADIATIVE INSTABILITY OF GRAVITATING MAGNETIZED DUSTY PLASMA

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The combined effect of dust charge fluctuation and finite dust temperature is investigated on radiative condensation instability of self-gravitating magnetized dusty plasma. The basic equations of the problem are formulized and linearized. The homogeneous magnetized plasma medium is considered which consists of extremely massive and charged hot dust grains. We assume that the electrons are inertia less with finite thermal conductivity but the ions are inertia less having infinite thermal conductivity. A general dispersion relation is obtained using the normal mode analysis technique. This dispersion relation is further reduced for both radiative and gravitating configurations. The modified Jeans criterion of instability is determined including effects of dust charge fluctuation, dust temperature and magnetic field. The condition of radiative instability is also discussed considering the effects of various parameters. The expressions for critical Jeans wavenumber and Jeans wavelength are also obtained in the present analysis. The growth rate of Jeans instability and radiative instability is plotted taking numerical parameters of magnetic field, dust charge fluctuation, dust temperature and radiative heat-loss functions. It is observed that the growth rate of Jeans instability and radiative instability significantly modified due to the presence of these parameters. We find that the radiative cooling function, dust charge fluctuation, magnetic field and dust temperature increase the acoustic stabilization of the Jeans instability. The present results are applicable to understand the formation of molecular dusty clouds through the radiative cooling and gravitational collapse process.

4-5

SYMMETRIES OF THE 3D HIGH FREQUENCY PLASMA OSCILLATIONS

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Coherent nonlinear wave structures like the Bernstein-Greene-Kruskal equilibria were studied and successfully applied to understand high frequency processes in plasmas. Recently, attempts are made (see, e.g. [1]) to generalize these results to the spatially three dimensional case. As usual, symmetry properties are important which help us to find exact solutions and conservation laws. Finding of the symmetry groups for the 3D plasma theory models is essentially simplified by the use of the recent Maple 12 package standard programs.

Different 3D modifications of the model were considered. More complicated models with the constant homogeneous external and the perturbations of the internal magnetic field taken into account were considered, too. Symmetry transformations were found both for the electron and electron – positron plasmas in cold plasma approximation, water – bag kinetic and isothermal hydrodynamic models.

As a rule, the cold plasma symmetries are the most extensive ones for a given model equations. So we can expect that such transformations exhaust the full symmetry group of the considered kinetic integro-differential Vlasov-Maxwell equations for the 3D high frequency plasma oscillations.

The symmetries found previously in the one dimensional case [2] are the conditional symmetries of the 3D model.

In the presence of an external constant homogeneous magnetic field only the rotation around the magnetic field direction remains among the rotational symmetries. Moreover, the similarity properties are reduced in this case.

So, 1D symmetries previously obtained in [2] are now generalized to the 3D case. One can expect that extended [3] symmetries are possible even in the 3D case.

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4-6

MODE-IMPEDANCE TECHNIQUE FOR MODELING OF ELECTROMAGNETIC WAVE PROPAGATION IN PLASMAS

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In the present communication we propose a relatively simple general technique for modeling the propagation of electromagnetic waves in the anisotropic and gyrotropic media with spatial dispersion such as hot magnetized plasmas. That provides a new way for analytical and numerical studies of "full wave" problems in plasma physics that require exact solutions of Maxwell equations. Several examples of such a treatment are considered to demonstrate the flexibility and computational robustness of the proposed technique.

The mode-impedance is technique is based on the idea of the invariant embedding originally developed by Ambartsumyan and Chandrasekhar for isotropic media [1, 2]. Our technique is suited to solution of wave propagation problems in complex media possessing a reach mode structure due to the dielectric anisotropy, gyrotropy and spatial dispersion [3]. The mode-impedance reformulation of the invariant embedding approach results in new equations that are more transparent, highlight fundamental relationships between reflection and transmission properties of the medium, and are rather flexible for further analytical and numerical studies. Using the proposed technique one can develop a numerical model free of the mathematical "stiffness" typical of straightforward integration of wave equations in a vicinity of linear mode-conversion regions and plasma resonances. The "stiffness" appears due to the presence of large evanescence or damping regions and due to the essential spread in wavelengths of propagating waves. In this aspect, the mode-impedance technique may compete with the finite-element methods widely used for treatment of the stiff wave problems (e.g. Maxwell equations).

The proposed formalism has been proved to be very effective in the modeling of wave propagation both in the one- and multi- dimensionally inhomogeneous magnetized plasmas, as was demonstrated in this paper for the ordinary, extraordinary and electrostatic (Bernstein) waves in the electron cyclotron range.

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4-7

CROSSTALK BETWEEN TWO PLASMONIC WAVEGUIDES

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The existence of electromagnetic surface waves propagating at the interface of a plasma-like medium has been known for several decades. They are widely used in various modern applications spanning from gas discharges and plasma technologies to semiconductor and plasma electronics. Recently, electromagnetic surface waves coupled to collective oscillations of conduction electrons in metals have got “the second birth” due to their ability to overcome the diffraction limit for ordinary electromagnetic waves in dielectrics [1]. Owing to their evanescent fields, these surface waves (also called as surface plasmon polaritons) can concentrate energy into subwavelength regions as small as a few nanometers. This and other extraordinary features of surface plasmon polaritons have given rise to the new and rapidly emerging field – plasmonics.

The rapid development of plasmonics during the last years has revealed the great potential of surface plasmon polaritons maintained by metallic nanostructures [2]. They were successfully employed in a diverse range of applications, such as super-lensing, subwavelength lithography, extraordinary optical transmission, highly-sensitive biosensing etc. Additionally, the recent advances in development of plasmonic waveguides have shown that surface plasmon polaritons can bridge photonics and nanoelectronics [2] to fully exploit the advantages of both the technologies.

In this report, we present a study on surface plasmon polaritons propagating in a nano-strip waveguide, being a fundamental component of any plasmonic device and guiding the light below the diffraction limit. We aim to investigate dispersion characteristics of the surface plasmon polaritons, mode confinement, as well as to study crosstalk between two closely set plasmonic waveguides in order to determine optimal distance between the neighbor waveguides for fast data transmission.

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4-8

OSCILLATION SPECTRUM OF ELECTRON PLASMA CONTAINING SMALL FRACTION OF IONS OF BACKGROUND GAS (AZIMUTH WAVE NUMBER *m = 2*)

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The spectrum of oscillations of the cylindrical plasma waveguide completely filled with the homogeneous neutral "cold" plasma is known for a long time. It consists of the family of electron Trivelpiece–Gould (TG) modes. Their frequencies coincide with the upper and low hybrid frequencies in neglect of the ion influence. In charged plasma the frequencies of TG modes are equal to the hybrid frequencies Doppler shifted by the electron rotation [1]. This shift gives to spectrum of TG modes unexpected features which in neutral plasma are not present: due to the Doppler shift the frequencies of TG modes in the charged plasma fall into the low–frequency region [2, 3]. In the presence of ions it will lead to interaction of electron and ion modes and their instability. It is shown [3], that at $m = 1$ only the low hybrid ("oblique " Langmuir) mode falls into the low–frequency region, and at $m > 1$ – the upper hybrid mode too. In [3] the spectrum of modes of the charged plasma, containing a small density fraction of ions born by ionization of atoms (molecules) of background gas by electron impact, is computed. The ions are described by an equilibrium distribution function [2], adequately taking into account the peculiarity of ion birth. It is anisotropic and possesses the features of the degenerate Fermi-Dirac distribution and of the «rigid rotator» one. The nonlocal dispersion equation is obtained analytically. It is valid over the entire range of allowable electric and magnetic field strengths. The oscillation spectrum with the azimuth wave number $m = 1$ is evaluated from it.

In present report the calculation results of oscillation spectrum with the azimuth number $m = 2$ are presented. The overall picture of modes behavior in the low hybrid frequency area remains identical with a case $m = 1$. The spectrum consists of the family of TG modes and of the families of "modified" of ion cyclotron (MIC) modes. TG modes are unstable in a vicinity of crossing the non–negative harmonics of MIC frequency. MIC modes are unstable over a wide range of electric and magnetic field strengths. TG modes have the fastest growth rates. The oscillations of small amplitude are observed on the frequency dependences of MIC modes just as it occurs on dispersion dependences of metal plasma. They are caused by the similarity of ion distribution function to Fermi-Dirac degenerate distribution. There is also a peculiarity of a behavior of frequency dependences of MIC modes in a neighborhood of a pole of a component of electron dielectric permeability tensor $\varepsilon_{\perp}$.

Interaction of upper hybrid modes with the ion modes which takes place in the area of stronger electric fields possesses the following features. Various radial TG modes are located very closely to each other. They cross the ion frequency region almost vertically. The growth rates of upper hybrid modes are faster than the growth rates of low hybrid modes.

The modes having azimuth wave number m = 1, 2 exhaust the all variety of types of behavior of TG and MIC modes of the non-neutral plasma. I.e. the modes with $m > 2$ behave (topologically) in the same manner as the modes with azimuth wave number m = 2 .

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4-9

ELECTROMAGNETIC WAVES IN LEFT-HAND MATERIAL SLAB THAT BOUNDED BY MEDIA WITH DIFFERENT PERMITTIVITY

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In recent years the new artificial materials have been created with both negative effective permittivity and effective permeability over some frequency ranges [1]. The materials of such type are often called left-handed materials, because Poynting vector in such media is opposite to the wave vector.

The existence of left-handed materials opens up the new research fields in modern science and technology. Devices, based on the waves that propagate in the left handed materials are the matters of intensive theoretical and experimental studies [2].

The aim of this work is to investigate the specific features of the electromagnetic waves that propagate along the interfaces of a left-handed planar slab that bounded by the ordinary right-handed media with different permittivity. We present the results of the study of the dispersion relations, wave field structure of the electromagnetic waves investigated. To describe the electrodynamics properties of the left-handed material slab it was used the experimentally obtained expressions for effective permittivity and effective permeability, which are usually used in the majority of theoretical studies [3].

At the both sides of this left-handed planar slab there are placed the semi-bounded regions of ordinary dielectric with different constant permittivity and permeability. It was obtained that these differences strongly effects on the electrodynamics characteristics of the waves considered. It was investigated the dispersion properties and the wave field spatial structure for rather thick and rather thin left-handed material slabs. It was determined the dispersion characteristics as of the pure surface waves, as also the volume ones. It was obtained that in the case when external magnetic field is absent the waveguide structure considered possesses the eigenwaves of TM- or p-polarization and TE- or s-polarization. The difference of permittivity of right-hand materials essentially influence on the dispersion and spatial wave field structure of TM-waves. The influence of these parameters on the TE-waves is much weakly.

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

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<u>4-10</u>

PARAMETRIC EFFECT OF AN ALTERNATING ELECTRIC FIELD ON SURFACE ELECTRON CYCLOTRON X- AND O-MODES

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Theory of parametric excitation of the surface electron cyclotron X- and O-modes in plasma filled waveguide is developed. Theoretical research is carried out using kinetic description for the plasma particles affected both by constant magnetic field and alternating electric field. The external magnetic field is assumed to be parallel to Z axis, plasma occupies semi-plane $x \geq 0$, alternating electric field is perpendicular to Z axis, its frequency is close to the electron cyclotron frequency. Electromagnetic field of these cyclotron modes is described by set of Maxwell equations. It is solved using the Fourier expansion method. Doing that just two components of the X- and O-modes' wave vectors, which are perpendicular to the external magnetic field, have been taken into the consideration. Nonlinear boundary conditions have been formulated to derive the sets of equations for harmonics of the tangential electric field, which describe the parametrical excitation of the waves. It has been done using the residues theory. Analytical expressions for growth rates of the X- and O-modes' parametrical instability have been obtained taking into account three harmonics, namely main harmonic and two nearest satellites. Values of their growth rates are examined analytically and numerically.

4-11

NONLOCAL APPROACH AND PLASMA DENSITY PROFILES IN POSITIVE COLUMN

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The glow discharge positive column is under consideration. In the report we consider joint forming of the ambipolar potential profile and the electron energy distribution function (EEDF). The last is calculated in accordance with the nonlocal approach [1], and is based on the ambipolar potential profile, which in its turn depends on electron production, determined by the EEDF. The plasma density profiles, obtained this way, are compared with the plasma profiles obtained from the classical free-fall and diffusion transport models, based on assumption of maxwellian EEDF with constant temperature over the plasma column.

It is intuitively clear, that plasma density profiles obtained in assumption of constant electron temperature should differ from ones obtained in the nonlocal approach. The reason consists in the fact that the nonlocal approach results in ionization frequency not uniform along the discharge radius. In it turn, this gives plasma profiles “sharpened” in the discharge axis in comparison with, for example, Langmuir problem solution [2].

Our calculation reveals the above consideration. Calculations performed for the electron density of order 1e8-1e11 cm-3, and the ground gas (argon) pressure 1e-4 – 1 Tor.

We investigate profiles of plasma density, ambipolar potential, ionization degree, as well as absolute values of plasma density, sheath layer potential drop, electric current strength. Longitudinal electric field strength and plasma column radius are considered as independent parameters.

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4-12

SOLITONS IN TWO-FLUID MHD

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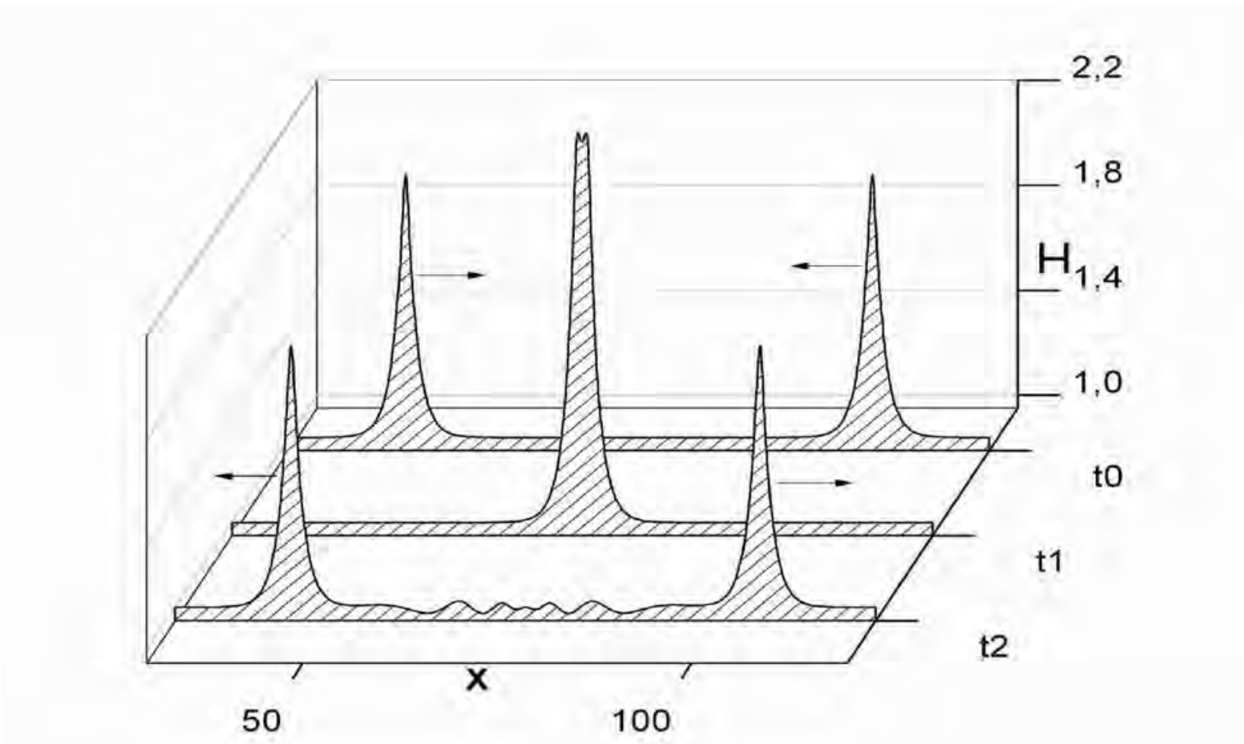
The results of analytical and numerical investigation of solitary waves on the basis of two-fluid MHD with non-zero electron inertia for cold plasma are presented in the report. Nonlinear waves with linear polarization of a magnetic and electric fields are considered.

$$\frac{\partial\rho}{\partial t}+\frac{\partial\rho U_x}{\partial x}=0\ ,\quad \frac{\partial\rho U_x}{\partial t}+\frac{\partial}{\partial x}\left(\rho U_x^2+\frac{H_z^2}{8\pi}\right)=0$$

$$\frac{1}{c}\frac{\partial H_z}{\partial t}+\frac{\partial E_y}{\partial x}=0,\quad E_y-\frac{c^2 m_i m_e}{4\pi\rho e^2}\frac{\partial^2 E_y}{\partial x^2}=\frac{U_x H_z}{c}-\frac{c m_i m_e}{4\pi\rho e^2}\frac{\partial}{\partial x}\left(U_x\frac{\partial H_z}{\partial x}\right) \qquad (1)$$

Non-zero mass of electron and respectively nonlocal Ohm's law are the reason for wave dispersion. This effect is especially important for short waves then $\left(ck/\omega_{pe}\right)^2>>1$. A main difference of the present work is the using of the "exact" equations (1), instead of the modeling equations. The phase velocity of solitary wave a has to satisfy with condition $V_A<|a|<2V_A$ ($V_A=H_0/\sqrt{4\pi\rho_0}$) and its amplitude is proportional to phase velocity - $H_S=2(|a|/V_A-1)H_0$. It is numerically shown, that solitary waves are solitons really, i.e. their interaction is similar to interaction of colliding particles. On figure it is shown as an example the process of «collision» of two solitons with equal amplitudes and opposite signs of phase velocity.



4-13

SELFCONSISTENT NUMERICAL SIMULATION OF POWER ABSOPTION IN HELICON PLASMAS

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The self consistent computer simulation results of RF power absorption in helicon plasmas are presented for stationary state. The steady-state fluid equations and Maxwell's equations are solved self-consistently in nonuniform external magnetic field. The power absorption efficiency for the uniform and nonuniform external magnetic fields is compared.

The comparative analysis has shown that in the uniform magnetic field directed along plasma boundary main power absorption occurs in the near antenna region. In this case narrow strips of power absorption appear. They diverge with the small angles with respect to the direction of the magnetic field lines. Appearance of the resonant strips of power absorption is the evidence of the Trivelpiece-Gould mode excitation. These strips correspond to resonant cones of the group velocity of the Trivelpiece-Gould waves [1]. The part of the power absorption is distributed along the resonant cones of the group velocity of the Trivelpiece-Gould waves and decrease away from antenna due to strong dissipation. It is shown that in the case of nonuniform magnetic field power absorption in the helicon source plasma can be more effective than for the uniform magnetic filed. Moreover the average power absorption is found to be high over whole plasma radius, although in the axial direction it varies considerably. The spatial absorption pattern in this case differs essentially from the case of uniform magnetic field, when the main power absorption occurs at the near antenna region and the part of the power is distributed along the resonant cones of the group velocity of the Trivelpiece-Gould waves and rapidly decreases moving away from antenna.

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4-14

SURFACE WAVES FOR PLASMONIC INTERCONNECTS

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The performance and speed of on-chip interconnects based on electronic signals greatly suffer from the continuous miniaturization and scaling according to Moore's law. Now, they are approaching their fundamental limits determined by increased circuit delay and power dissipation that accompany the miniaturization. This makes further improvement for electronic interconnects very hard. One of the most promising solutions to resolve the "interconnect bottleneck" issue is believed to be in substitution of the information carriers. In particular, attention has been paid to optical technologies, which can achieve higher data transmission, bandwidth, as well as reduced power dissipation [1]. However, performance of traditional optical interconnects is limited by the diffraction law. This makes such optical devices bulky compared to nanoscale electronic components and creates additional problems for their integration with other on-chip devices.

Recent research in the rapidly emerging field of plasmonics has shown that the size-mismatch issue inherent in traditional optical interconnects can be resolved by using plasmonic components, which manipulate light at subwavelegth scale (below the diffraction limit) and can bridge the gap between nanoscale electronics and microscale photonics [1]. In particular, plasmonic waveguides that maintain propagating surface waves are the most feasible way to improve the existing electronic on-chip interconnects [2]. They offer a unique opportunity to replace slow electrons (as the information carriers) by fast plasmonic surface waves and to get substantially higher bandwidth and lower latency compared to electronic components.

In this report, we aim to study plasmonic surface waves propagating in a rectangular strip waveguide made of gold. We investigate and analyze the effect of the waveguide geometrical parameters on the propagation characteristics, such as dispersion relation, propagation distance, and mode confinement, of electromagnetic surface waves.

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4-15

DISPERSION RELATIONS FOR FIELD-ALIGNED CYCLOTRON WAVES IN AN AXISYMMETRIC TOKAMAK PLASMA WITH ANISOTROPIC TEMPERATURE

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As s well known, the temperature anisotropy generated by cyclotron resonance heating of magnetized plasmas can be a reason of cyclotron wave instabilities in considered plasma devises. Recently [1], an anisotropic ion temperature was measured during high power High Harmonic Fast Wave heating in helium plasmas on the National Spherical Torus Experiment, with the transverse ion temperature roughly twice the parallel ion temperature. Moreover, the measured spectral distribution suggests that two populations of cold and hot ions are present in the plasma. In the paper [2], using the full wave TORIC code to analyze the eigenmode structure, there was shown that wave plasma interactions play an important role in tokamak dynamics in a wide range of frequencies. In particular, the fast ions from neutral beam injection can excite compressional and/or global Alfven eigenmodes with frequencies near the fundamental ion cyclotron frequency, and “slow waves” appear to propagate along the equilibrium magnetic field. However, the two-dimensional (2D) kinetic wave theory in axisymmetric toroidal plasmas should be based on the solution of Maxwell's equations using the correct ‘kinetic’ dielectric tensor. In this paper we evaluate the dispersion characteristics of the field-aligned electromagnetic cyclotron waves in a large aspect ratio tokamak with circular magnetic surfaces, having the high-energy particles with anisotropic temperature. The specific feature of tokamaks is the fact that the parallel velocity of charged particles moving along the stationary magnetic field lines is not constant (in contrast to a straight magnetic field case). Since magnetic field is axisymmetric and has one minimum in an equatorial plane, all plasma particles should be separated on two groups of the so-called trapped and untrapped particles. The main contributions of these particles to the transverse dielectric tensor elements are derived by solving the linearized Vlasov equations for their perturbed distribution functions as a boundary-value problem accounting for the cyclotron and bounce resonances in the zero-order over the magnetization parameters. The bi-Maxwellian distribution function is used to model the energetic particles (ions or electrons). The dispersion relations are derived for waves in the frequency range of the fundamental ion-cyclotron and electron-cyclotron resonances. Our dispersion relations are suitable to analyze the excitation/dissipation of both the left-hand and right-hand polarized waves. As in the uniform magnetic field case, the growth/damping rate of the ion-cyclotron waves in the 2D tokamaks is defined by the contribution of the energetic trapped and untrapped ions to the imaginary part of the transverse susceptibility elements.

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4-16

A THEORETICAL STUDY OF SURFACE LOCALIZED MODES IN FREE SPACE

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Recently, a formalism is developed to describe localized waves in plasma [1]. Such localized waves could exist in free space. In the report, azimuthally symmetrical surface localized modes in free space are analyzed. A transformation of the Helmholtz equation 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. Also for this problem, a shape of the reflecting surface for single-mode resonator is calculated. It is a section of eccentric paraboloid.

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4-17

NONLINEAR ELECTROSTATIC WAVES IN UNMAGNETIZED PAIR-ION PLASMAS

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Nonlinear electrostatic structures are studied in unmagnetized pair-ion plasmas. The low amplitude solitons and double layer structures are obtained using reductive perturbation method in non-dissipative and ideal plasmas. It is found that both electrostatic potential hump (compressive) and dip (rarefactive) solitons and double layers structures are obtained depending on the temperature ratio between and positive and negative ion species. The Kortewge-de Vries-Burger (KdVB) equation is also derived by taking into dissipation through kinematic viscosity of both positive and negative ions plasmas. Both rarefactive and compressive solitons and monotonic shocks solutions are obtained using Tan hyperbolic method. The structure dependence on temperature ratios between pair ion species is also shown numerically. The oscillatory shock solutions in pair-ion plasmas are also discussed. The present study may have some relevance for understanding the formation of electrostatic structures in laboratory produced pair-ion plasmas.

4-18

WEAKLY RELATIVISTIC PLASMA DISPERSION FUNCTIONS COMPUTATION ON THE BASE SUPERASYMPTOTIC AND HYPERASUMPTOTIC SERIES

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Evaluation of the weakly relativistic plasma dispersion functions (PDFs) is a ground of EC wave analysis in the laboratory thermonuclear plasmas. As a rule, in numerical applications these functions are calculated massively, therefore the efficiency of involved computational algorithm is of primary importance.

One can apply the method of fast calculation of nonrelativistic PDF $w(z) = \exp(-z^2)\,\mathrm{erfc}(-iz)$ on the base superasymtotic and hyperasymptotic series [1] for fast computation of the weakly relativistic PDFs, as follows. The two lowest-order PDFs can be expressed in terms of $w(z)$ [2] and computed using the above method, and then those of higher orders are sequentially evaluated by employing the 2nd-order recursion relation between them. However, this technique lacks stability when the argument of $w(z)$ becomes large [3].

The superasymptotic part of another, direct (without use of the recurrent calculations) algorithm for the weakly relativistic PDFs computation in the large-$|z|$ region was developed in [4]. The main purpose of the present work is to develop the reminder hyperasymptotic part of the algorithm [1] for evaluation of those functions in the region of small and moderate $|z|$ values and thus providing the fast computation in whole complex region.

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4-19

INHOMOGENEOUS RELATIVISTIC PLASMA DIELECTRIC TENSOR

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Deriving of fully relativistic plasma dielectric tensor, taking into account the inhomogeneity and spatial dispersion of plasma, is a basic for development of numerical wave models describing excitation, propagation and absorption of electromagnetic waves in thermonuclear toroidal plasma devices in the electron cyclotron frequency range. An importance of taking exactly into account relativistic effects in this frequency range follows from the fact that those effects can arise even in laboratory plasmas with moderate temperatures and become dominant in quasi-perpendicular, in respect to magnetic field, propagation regime.

The main purpose of present work is giving the way to derive components of 1D-inhomogeneous plasma dielectric tensor, taking into account the spatial dispersion, in terms of the exact plasma dispersion functions [1,2], which are a generalization of the weakly relativistic plasma dispersion functions to the case of arbitrary temperatures and wave parameters. Tensor components there analytically obtained on the base of the inhomogeneous kinetic equation of Vlasov in the fully relativistic form of Trubnikov [3] and perturbation in finite electron Larmor radius technique.

Results of present work may be used for a development of the fully relativistic numerical wave models in electron cyclotron frequency range and ion cyclotron frequency range as well in relativistic regimes.

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4-20

SYMMETRIC AND DIPOLAR ELECTROMAGNETIC WAVES IN COAXIAL STRUCTURE FILLED BY NON-UNIFORM DISSIPATIVE PLASMA WITH AZIMUTH MAGNETIC FIELD

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At present time it has been carried out the intensive study of electrodynamics properties of coaxial plasma-metal waveguide structures that are widely used in the devices of plasma electronics [1] and also as discharge chambers for gas discharge sustaining [2,3]. The properties of waves that propagate in such waveguide are determined by the azimuth wave field structure [4]. The aim of this report is the investigation of dispersion properties, spatial attenuation coefficient and radial wave field structure of high-frequency symmetric and dipolar electromagnetic waves that propagate in coaxial waveguide structure with non-uniform azimuth external magnetic field, partially filled by non-uniform dissipative plasma.

The wave considered propagates along the coaxial waveguide system that consists of metal rod of radius R_1, which is placed at the axis of plasma column. This rod is enclosed by the cylindrical plasma layer of radius R_2. The vacuum gap ($R_2 < r < R_3$) separates the plasma layer from waveguide metal wall with radius R_3. The direct current J_z flows along the inner metal rod and creates radial non-uniform azimuth magnetic field $H_0(r)$. Plasma was considered in the hydrodynamic approach as cold dissipative medium with constant effective collisional frequency ν. It was supposed that plasma density is radial non-uniform and vary slightly along the plasma column. Plasma density radial profile $n(r)$ was chosen in the bell-shaped form given by $n(r) = n(r_{\max})\exp\left(-\mu(r - r_{\max})^2 / r_\delta^2\right)$. The non–uniformity parameter of μ describes the gradient of plasma density profile and varies from $\mu = 0$ (radial uniform profile) to $\mu = 1$. The parameter $r_{\max}$ is radial coordinate, where plasma density culminates its maximum, and parameter r_δ characterizes the width of bell-shaped profile.

Phase characteristics and spatial attenuation coefficient of symmetric and dipolar waves of considered coaxial structure essentially depend upon the value and the direction of direct current J_z. It has been also studied the influence of vacuum gap thickness and effective collisional frequency on phase characteristics, spatial attenuation coefficient and radial wave field structure of the waves considered.

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4-21

CONSERVATION OF MAGNETIC MOMENT OF CHARGED PARTICLES IN STATIC ELECTROMAGNETIC FIELDS

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In the report, the adiabatic motion of charged particles in static electromagnetic fields is analyzed. The standard formula of the magnetic moment of a charged particle is $\mu = \frac{m\mathrm{v}_\perp^2}{2B}$, where $\mathrm{v}_\perp$ is the velocity component perpendicular to the magnetic field $\mathbf{B}$. The magnetic moment is one of the approximate invariants of motion if the motion is adiabatic. Following Jean's theorem, magnetic moment could be used for construction of solutions to the Vlasov equation. However, usage of the above given formula for the magnetic moment may lead to inaccuracies in calculating the moments of the distribution function. The aim of the work is to derive a corrected expression for the magnetic moment that allows one to use this invariant in kinetic calculations and to obtain the equation describing its temporal evolution. The approach used to solve this problem is based on theoretical analysis of Newton's equations with account of the small adiabaticity parameter, i.e. the ratio of the particle Larmor radius to the characteristic scale of the non-uniformity. The equation for the corrected magnetic moment is obtained in coordinate-independent form. The derived local corrections to the magnetic moment invariant are oscillating and are associated with the particle drift. They have no influence on conservation of the magnetic moment in average, but they give a contribution to the diamagnetic current when a guiding center drift is present. The right-hand side of the equation determines the slow variation of the magnetic moment in time, and are associated with the guiding center drift. The corrections to the magnetic moment invariant are consistent with the standard expressions for the first order drift and parallel motion of the guiding center.

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THE STABILITY OF MAGNETIZED NON-NEUTRAL PLASMA FLOW WITH THE RADIAL SHEAR OF DRIFT VELOCITY

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The results of experimental study of the magnetized non-neutral plasma flow stability are presented here. Considered flow has cylindrical symmetry and radially sheared own electric field. In the framework of the experiments carried out the flow is injected into the drift tube and spreads along its axis. The flow particles are limited radially by longitudinal magnetic field. Together with the radial shear of electric field this factor results in formation of the particles drift velocity radial shear.

The stability of such systems was previously investigated theoretically in [1,2] in the framework of 2D model.

The experiments have shown the instability development which appeared in generation of the electrostatic waves with pronounced azimuthal component. The waves exhibited a pronounced nonlinearity which caused a strong amplitude modulation and frequency spectrum widening. The measurement of the amplitude modulation depth, averaged frequency and frequency band width were carried out under different experimental conditions. During these measurements the variation of such parameters as the intensity of longitudinal magnetic field and the acceleration voltage was performed. Also the systems reaction on the electric field perturbation created by introduction of the conductive rod into the plasma flow was studied.

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PERMITTIVITY OF PLASMA UNDERGOING RANDOM WAVE FIELD

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Electrodynamic properties of plasma can be described in terms of its permittivity. In the derivation of linear permittivity it is implied that particle motion is regular, and wave field is small enough, thus bounce time of resonant particle in a wave is much larger than time of wave decay. Such assumptions are not valid for turbulent plasma where a lot of waves is excited. Resonance interaction of particles with a set of waves is qualitatively different from interaction with a single wave. Even for low field intensity the motion of resonant particles is stochastic, it can no longer be considered as a superposition of regular motion in the field of individual waves. Under the influence of multiple waves particles diffuse in velocity and coordinate space.

Modification of permittivity for turbulent plasma proposed by Dupree [1] was performed as a correction to a propagator of free particle with account for diffusion of particle orbits. In this and similar following approaches were assumed that orbits diffuse on time scale of the order of field correlation time in the same way as on time scale of wave damping.

Direct simulation has shown however that for fields of moderate intensity (Kubo number is of the order of the unit) the behavior of particles on early stage is different from asymptotic regime [2]. For such fields an effect of trapping of resonant particles by waves is essential [3]. To calculate a permittivity of plasma in the presence of random fields of moderate intensity it is necessary to find a propagator (transition probability of particle between two points of phase space) which matches the behavior of particles on different time scales, and takes into account particle trapping.

Such propagator was found as a solution of the Fokker-Planck equation with diffusion coefficient determined by the wave spectrum and dependent on time and velocity. This solution was tested against a direct simulation. Permittivity of plasma in electric field of random waves of moderate intensity is given in terms of particle transition probability with account for particle diffusion in both coordinate and velocity space.

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5-1

DUST ION ACOUSTIC SHOCK WAVES IN DUSTY PLASMAS ARTICLE I. WITH RESONANT ELECTRONS

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A Theoretical investigation of the one-dimensional dynamics of nonlinear electrostatic dust ion-acoustic waves in an un-magnetized dusty plasma consisting of warm ions, charge fluctuating stationary dust grains and trapped as well as free electrons has been made by the reductive perturbation technique. The basic features of dust ion-acoustic shock waves are studied by deriving a new modified Burgers-like equation. It is shown that the special patterns of nonlinear electrostatic waves are significantly modified by the presence of trapped electron component and dust charge fluctuations. In particular, the dust charge fluctuation is a source of dissipation, and is also responsible for the formation of the dust ion-acoustic shock waves. Furthermore, a stronger nonlinearity in comparison to the isothermal electron is found which is due to the effect of non-isothermal electrons which follows the vortex-like electron distribution. The results of the present work should help us in understanding the localized electrostatic disturbances in space and laboratory dusty plasmas.

5-2

SHEAR-FLOW-DRIVEN ION CYCLOTRON INSTABILITY OF MULTICOMPONENT MAGNETIC FIELD-ALIGNED PLASMA FLOW

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The investigations of the auroral region of the Earth ionosphere have discovered the inhomogeneous structures of electrostatic potentials which correlated with regions of the formation and acceleration of the magnetic field-aligned upward ion beams. One of the main signatures of these beams is the gradient of the flow velocity across the magnetic field (flow velocity shear) V_0' which can reaches specifically for $O+$ ions values $6\omega_{ci}$ [1]. The upflowing ion beams are mainly composed of $H+$ and $O+$ ions whose composition varies significantly from beam to beam. These auroral ion beams are often correlated with electrostatic ion cyclotron (EIC) oscillations having the cyclotron frequencies of hydrogen and oxygen ions. It was shown that the flow velocity shear along with other mechanisms may be responsible for the excitation of EIC instability in the auroral ionosphere [2, 3].

The shear-flow-driven EIC instability was researched in plasma with single ion species. However, the application of these results in ionosphere investigations requires taking into account the presence of several ion components, the relative concentrations of which are changed significantly with the altitude in ionospheric plasma. We carry out the study of the shear-flow-driven EIC instability in sheared magnetic field-aligned plasma flow with two, $H+$ and $O+$, ion species assuming that the oxygen ions are main species, while hydrogen ions are background one, so that the frequency of oscillation approximately equals the $O+$ cyclotron frequency.

We have been obtained and solved analytically the dispersion equation for ion-hydrodynamic mode when the waves propagate nearly perpendicularly to the magnetic field but under the assumption that electrons are adiabatic. It is shown that the instability threshold respect to the velocity shear value and wave numbers across to the magnetic field do not depends on the relative concentration of oxygen ions and remains for low $O+$ relative concentration the same as for pure oxygen plasma. We have analyzed the instability growth rate depends on the wavelength along the magnetic field for different values of oxygen ions relative concentrations α_O. This analysis showed that the maximal value of the growth rate, which is achieved at a certain wavelength, is reduces with decreasing α_O. However, the long wavelengths threshold on the parallel to magnetic field shifts towards longer wavelengths, and longer wavelengths become unstable. The dispersion equation has been solved also numerically and showed good agreement with the analytical results.

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5-3

SPECTRUM OF PLASMA DENSITY FLUCTUATIONS IN THE QUIET SOLAR PHOTOSPHERE

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The solar surface is divided into active and quiet regions through differences in the morphology of magnetic fields at the photosphere. Magnetic fields in quiet regions (QR) tend to be spatially disorganized, with both polarities occurring in roughly equal proportions, and have relatively short lifetimes. The strength of magnetic fields B in QR does not usually exceed 100-200 G. Data of observations show that motions of gas in the photosphere have turbulent nature. It was established that spectra associated with the chaotic velocity field of photospheric flows obey power laws, which are consistent with spectrum of Kolmogorov turbulence. Due to improvement in spatial resolution of observations of the photosphere, good grounds appear for study of small-scale processes there.

The aim of the present report is to consider formation of small-scale plasma density fluctuations by turbulent motions of gas in quiet regions of the solar photosphere.

The photosphere is weakly ionized plasma and can be described by a three-fluid model. We assume that ion-electron plasma is submerged in the turbulent flow of incompressible gas and the gas motions are not affected by electrically charged particles. Taking into account a vertical gradient in mean plasma density and a uniform magnetic field, an expression for the spatial spectrum $S(k)$ of the fluctuations with length-scales corresponding to the inertial range of turbulence is derived. Using the expression, two wave-number ranges are revealed in the spectrum. The fluctuations with smaller wave-numbers ($k<k_B$) result from destruction of mean plasma density gradient by turbulent mixing of the gas, for them $S(k)\propto k^{-3}$. The fluctuations with larger wave-numbers ($k>k_B$) are formed by interaction of plasma embedded in the turbulent flow with the magnetic field and $S(k)\propto k^{-1}$. The wave-number $k_B=1/(\Omega_i\tau_i L_N)$ defines these wave-number ranges (Ω_i is the ion gyrofrequency, τ_i the mean time between collisions of ions with neutrals, L_N the length-scale of background plasma density gradient).

The obtained expression allowed us to estimate changes in $S(k)$ for QR with the field strength B from 5 to 200 G at the altitude of 200 km. It is shown that if the whole spectrum is approximated by a power-law k^{-p} then the index p has to decrease from 2.09 (B=5 G) to 1.34 (B=200 G), whereas the rms amplitude of the fluctuations (length-scales <100 km) around the mean plasma density has to slightly increase from 5.33 to 5.34 % with B. The change in the spectrum are explained by change in k_B with the strength of magnetic field. Relatively weak influence of magnetic field on the fluctuation amplitude results from a more important role of the mean plasma-density gradient for generation of the fluctuations.

6-1

SOME KEY ISSUES AND RESEARCH NEEDS FOR PLASMA/SURFACE INTERACTION ANALYSIS IN TOKAMAKS[1]

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Recent plasma/surface interaction modeling and code/data comparisons of tokamaks shows several key plasma physics issues, materials issues, and research needs. These include:

Sheath at divertor: Erosion/redeposition analysis of the planned National Spherical Torus Experiment (NSTX) liquid lithium divertor (LLD) shows the importance of the sheath structure on emitted lithium transport. Sheath width at the LLD surface may be small (~50 µm Debye sheath only), compared to e.g., ITER (~1 mm magnetic sheath + Debye sheath), due to the weaker magnetic field and higher incidence angle (~0.5 T @ 5-10° NSTX; vs. 5 T @ 1-2° ITER). Thus, e.g., ionization of evaporated Li atoms occurs mostly *outside* of the sheath. Transport of sputtered molybdenum (possible replacement coating for carbon at the NSTX inner divertor) is also affected (e.g., redeposited ion energy/angles) by the sheath type.

Kinetic effects: Transport of sputtered and evaporated lithium atoms/ions in the NSTX/LLD low D-recycle (high D/Li trapping), low-collisionality (high T_e, low N_e) scrape-off layer (sol) plasma is dominated by kinetic effects, including large Li ion gyroradius and Li atom/ion collision mean free paths.

Net sputtering erosion: Alcator C-MOD Mo divertor analysis shows a major code/data discrepancy, with data showing order-of-magnitude higher net erosion, over a 1300 second campaign, than predicted. This could be due to an unknown anomalous transport process, incorrect plasma characterization, and/or diagnostic Mo tiles thin film issue.

Tungsten performance: Erosion/redeposition analysis of the ITER tungsten divertor shows acceptable pure-tungsten sputtering/transport, and probably acceptable effects of helium and beryllium impingement on the tungsten surface nanostructure evolution and sputter response, but more work is needed.

Diagnostics: There is a major need for improved in-situ near-surface plasma parameter, and real-time gross and net erosion diagnostics.

Supercomputing: There is a major need for full-process plasma/surface interaction supercomputing, with e.g., real-time coupling of plasma core, plasma edge/sol, mixed-material surface response, and impurity transport codes.

[1] Work supported by the United States Department of Energy, Office of Fusion Energy.

6-2

PONDEROMOTIVE FORCE AND STEADY CURRENT INDUCED IN A PLASMA BY A ROTATING RF FIELD GENERATED WITH PHASED ANTENNAS

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The rotating magnetic field (RMF) is an efficient mean to initiate and sustain a field reversed configuration (FRC) which is of interest for nuclear fusion [1,2] and space propulsion [3]. The RMFs were also employed to generate helicon (whistler) waves, to produce a helicon discharge [4] and to model space-relevant phenomena [5].

The generation of a steady current in the RMF scheme is normally analyzed with two simplifying assumptions: (1) axial uniformity of the rf fields and (2) inertialess electrons. Then the RMF penetration depth into plasma is evaluated in terms of a classical (collisional) skin depth. Meanwhile, axial field nonuniformity (i.e., finiteness of the effective axial wavenumber k_z), which is always imposed by a finite antenna length and/or by a finite plasma length, results in increase of the penetration depth of electromagnetic oscillations as compared with the skin depth. On the other hand, taking of electron inertia into account engages quasi-electrostatic oscillations which can efficiently take the power off the electromagnetic oscillations and, thus, contribute substantially to the current generation. Moreover, with the electron inertia included, one more source of the steady current generation, in addition to the Ampere force, arises from the convective term in the fluid electron motion equation.

We report on modeling of the rotating rf field excitation in a plasma by various phased antennas (double-saddle and helical ones). Computations were made on basis of the linear full electromagnetic model and the modified computer code described in Ref. 6. Using these data, we evaluated a time-averaged specific ponderomotive force, which acts on electrons and arises from a combination of the Ampere force and the convective term, as well as an integral ponderomotive force.

Computations have shown that inclusion of finite k_z and of electrostatic wave excitation has a crucial effect on the ponderomotive force and the steady current. Under condition $k_z \approx \delta^{-1}(\omega/\omega_{ce})^{1/2}$ (δ : collisionless skin depth), the helicon-type waves excited are very weakly damped due to collisions but experience an efficient mode conversion into electrostatic oscillations. The latter effect occurs mainly near the radial plasma edge where, for this reason, both the steady current and the ponderomotive force are strongly enhanced. Possible applications of the results obtained to electric propulsion are discussed.

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6-3

LONGITUDINAL DIAMAGNETIC EFFECTS IN BEAM-PLASMA SYSTEM EMDEDDED IN AN EXTERNAL MAGNETIC FIELD

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High-current electron beams are generated in an external magnetic field in vacuum behave as a diamagnetic and force the magnetic field out of its volumes in radial direction. Under the condition of conservation of magnetic flux the magnetic field inside of the beam decreases and increases outside. In a beam-plasma systems embedded in a magnetic field (plasma filled diodes or a beam in a plasma channel) another state of the beam can be realized with increased to the axis of the system total magnetic field. Radial focusing of the beam is ensured by electrostatic field of an ion pivot and self azimuthal magnetic field of the beam. Plasma electrons are forced out from this region by beam electrons. For the case of homogeneous external magnetic field it results in many times increasing of magnetic field as compared with external one inside small near axis region. If the external magnetic field changes in longitudinal direction then the value of magnetic field from the region of beam injection is transferred along near axis region of the system. It looks like as a “magnetic needle” and resembles “frozen field” effect but the physics is different. The sign of magnetic field gradient does not influence on this effect. Different beam-plasma systems were considered by means of computer simulation. Computer simulation was performed using electromagnetic PIC code KARAT.

This work is supported by the RFBR under grant 09-02-00715.

6-4

KEY PROPERTIES OF MIXED W-C-D SURFACE RELATED TO TUNGSTEN EROSION

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The current ITER design envisages beryllium at the first wall, tungsten coatings in the baffle region of the divertor and graphite-based components for the target plates exposed to the high- heat flux. The proximity of the tungsten and carbon surfaces will unavoidably lead to formation of the mixed surface, which will be exposed to mixed particle flux. Erosion of tungsten surface due to sputtering should occur under rather complicated conditions. The incident ion flux will include fuel ions and neutrals, as well as energetic carbon ions, providing the formation of the mixed surface. The erosion of the mixed W-C surface may be further complicated by the elevated temperature of the surface.

The simulations and experiments show that the formation of the mixed W-C surface decreases the sputtering yield. The number of tungsten atoms is lower in the mixed surface, because they are partly replaced by implanted carbon atoms. Correspondingly, number of tungsten atoms, available for sputtering, is also lower. The system reaches steady-state, when number of implanted carbon ions equals the number of reflected and sputtered ones. However, this balance may be shifted by surface temperature, which may induce extra removal of carbon due to chemical erosion or radiation-enhanced sublimation.

The effect of surface temperature has been studied experimentally and it has been found that the contribution of chemical erosion peaks at room temperature and decreases with increasing surface temperature. The radiation-enhanced sublimation is negligible at 900 K and at higher surface temperature the mixed W-C surface appears to be less prone to sublimation than pure carbon. Therefore, the surface temperature has a dual influence on the mixed surface. It has no influence, when the mixed surface is exposed to the particle flux. At the same time, it prevents the formation of carbon over-layer on top of tungsten. One can conclude that the role of temperature effects is the uncovering the tungsten surface and exposing it to the particle flux.

6-5

INVESTIGATION OF COLLISION AREA OF TWO GAS-DISCHARGE COMPRESSION PLASMA FLOWS DIRECTED TOWARDS EACH OTHER

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New opportunities for generating highly concentrated energy fluxes are opened up through the use of a plasmadynamic interaction of accelerated plasma flows directed towards each other, which results in plasma formations with the extremely high-energy content. Such formations are of great interest from a viewpoint of some pressing problems in photochemistry and high-temperature related to studying extreme states of various substances and modifying their properties.

The results of investigations into interaction processes of opposed compression plasma flows generated by magnetoplasma compressors (MPC) of compact geometry are presented. The compression plasma flows were obtained using a gas-discharge MPC powered with a capacitive storage (C_0 = 1200 mF) operating at initial voltages, U_0, from 3 up to 5 kV. The MPC employing hydrogen, nitrogen, and argon as plasma-forming substances was operated in a "residual gas" mode. The collision of two oppositely directed compression plasma flows results in the emergence of a quasi-stationary spherical plasma formation whose life time can reach values exceeding 100 μs. By varying plasma parameters of each of interacting flows and a delay of the MPC run, it is possible to control the length, location, and parameters of the plasma formation. Interferometric studies show that the quasistationary plasma formation resulting from the collision of the two opposed compression plasma flows is confined from both sides by collisional shock waves, which raises the efficiency of the kinetic energy thermalization of the colliding plasma flows.

The collision area of two compression plasma flows represents a powerful emitting source. Under the experimental conditions at U_0 = 3,5 kV and 5 kV, the plasma velocity in the compression flow amounts to $4 \cdot 10^6$ cm/s and $7 \cdot 10^6$ cm/s, respectively. An increase in the velocities of the interacting flows causes the plasma brightness temperature in the collision zone to be raised from ~ $40 \cdot 10^3$ K to ~ $60 \cdot 10^3$ K in a spectral region of 465-555 nm. At the same time, the brightness temperature at U_0 = 3,5 kV in the 465-555 nm region is by 1.4 times higher than that in the 745-1120 nm region and at U_0 = 5 kV the temperature ratio reaches ~1.6.

To simulate numerically the processes accompanying the interaction of oppositely directed compression plasma flows, a model was developed describing the plasma structure and dynamics in a discharge camera.

6-6

COMPRESSION ZONE FORMATION IN MAGNETOPLASMA COMPRESSOR OPERATING WITH HEAVY GASES

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Investigations of dense magnetized plasmas of different gases are of importance for various scientific and technological applications such as generators of hot plasma and efficient fuelling techniques (plasmoids), testing of fusion reactor materials with high energy loads etc. Dense plasma is especially attractive object of investigations aimed at development of efficient source of multicharged ions and intense radiation in a wide wavelength range (from XR and EUV to infrared radiation).

Present work is devoted to experimental investigations of the plasma compression zone dynamics and its influence on radiation characteristics. The construction of MPC of compact geometry with conical copper electrodes is described. Experimental device is able to generate dense plasma streams of different working gases and their mixtures, particularly, He, N, Xe, He+Xe. Modernization of MPC gas supply system allowed us to operate in two different modes. In first one the discharge occurs under the pulsed injection of pure Xe to the interelectrode gap with different time delays. In second mode the discharge occurs in helium under different residual pressures with additional local injection of xenon directly into the compression zone. Maximum value of discharge current achieved 500 kA for U_c=20 kV and discharge half-period was ~ 10 μs.

Comprehensive information about dynamics of compression zone formation, it position, plasma parameters and geometric dimensions was obtained using spectral diagnostics. Appearance of impurities in plasma stream resulted from erosion of electrodes was also detected and analyzed. Plasma stream density ~10^{18} cm^{-3} was measured at MPC outlet by Stark broadening of Xe spectral lines. Electron temperature was estimated using the ratio of Xe lines intensities in visible wavelength range. Its value is about 5-7 eV, but taking into account observed Xe V spectral lines emission, averaged T_e in compression zone with typical diameter of 1 cm evidently achieved 20 eV.

Rather high values of plasma temperature in compression region follow also from EUV radiation measurements. EUV radiation intensity was detected by registration system consisting on absolutely calibrated AXUV diodes with integrated thin-films filter for different wavelength ranges (17-80 nm, 5 – 13 nm) and multi-layered MoSi mirrors. Modernization of MPC gas supply scheme allowed prevention of self-absorption for Xe radiation emission and, thus, increase of EUV radiation energy in 12.2 -15.8 nm wave range from 33 mJ up to 60 mJ.

Spatial distributions measurements of frozen magnetic field in MPC plasma stream were carried out with set of local movable magnetic probes. Reconstruction of electrical current distributions has been performed using Maxwell equations. Results of these measurements show that total value of electric currents flowing outside accelerating channel is about 25-30% of discharge current I_d. Development of electric current vortexes in plasma was found. Current loops promote the formation of compact plasma toroid. The current vortexes appearance is attributed to the inclined shock wave formation in compression zone which affects on plasma dynamics outside the source. In some regimes the current displacement from the compression region was observed. Pressure balance at the boundary achieved at the B-field energy of (10-15) J/cm^3.

6-7

EROSION PLASMA COUNTER-FLOWS INTERACTION DYNAMICS IN A CONFINED AREA

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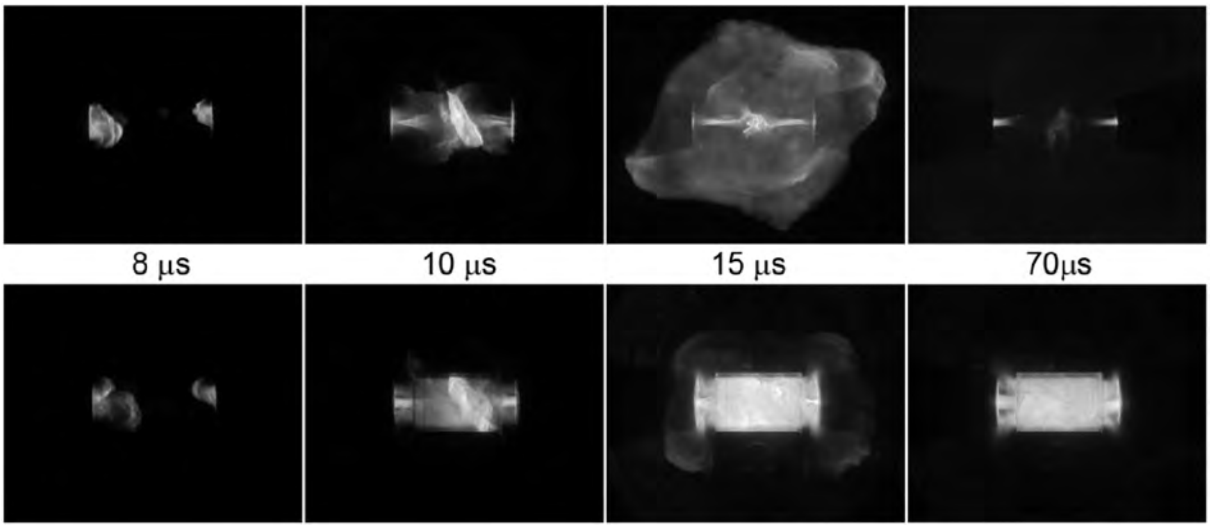
Study of physical processes of interaction of plasma erosion flows is of undoubted fundamental and practical interest to solve actual scientific and applied problems of quantum electronics, photochemistry, radiation plasma dynamics, etc. The below interaction process is based on high-current discharges of magnetoplasma compressor of erosion type in vacuum and, as a rule, in the conditions when a cumulative zone is confined in the radial direction by transparent cylindrical walls.

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 having an outlet cross section 20 mm in dia. The accelerator was mounted in a vacuum chamber by means of copper co-axial current supply. Visualization, photography and spectral investigation were made through special vacuum chamber optical windows. Each accelerator was put into operation by discharging a condenser battery.

Our experiments (Figure) show that the collision of plasma flows in the confined area is characterized by large time of existence of the cumulative zone in comparison with the collision in the unconfined area. The spectrum analysis of free erosion plasma flow luminescence let to measure the main characteristics such as temperature and electrons' concentration. Basic parameters are determined in experiments: plasma temperature is $3.8 \cdot 10^4$ K and plasma electron concentration is $2 \cdot 10^{16}$ cm^{-3}.



Collision dynamics of erosion plasma counter-flows in the unconfined area (top) and in the area confined by a quartz tube (bottom)

6-8

EXCITATION OF AN ANNULAR HELICON PLASMA BY VARIOUS ANTENNAS

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Annular helicon plasma sources are being developed for use as a pre-ionization stage in a Hall-effect thrusters (HETs). The idea is to supply high-density plasma produced by a helicon discharge into the acceleration region of the HET. A new device, the Helicon Hall Thruster (HHT) was suggested to combine the efficient ionization mechanism of a helicon source with the favorable plasma acceleration properties of a HET [1,2], in order to enhance thrust-to-power ratio. The physics and applications of conventional helicon sources have been studied for a long time, and the methods for increasing the efficiency of plasma production in these devices, such as the antenna design, were understood in sufficient details. Meanwhile, the annular sources were examined in a few papers only, and their physics and operating characteristics are not clear yet. For example, theoretical analysis of wave fields was restricted to eigenmodes only [3], and no antenna coupling and rf power absorption were considered.

We present computation results on the rf fields and power absorption in the annular helicon plasma. The model and the appropriate computer code, which are based on the method of normal modes, were developed as modifications of those reported in Ref. 4. The plasma loading resistance and the rf power absorption profiles were computed in a broad range of physical parameters. Various antennas, both internal, and external, and combined were examined in order to find out conditions for efficient antenna coupling and rf power deposition.

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6-9

WALL CONDITIONING RF DISCHARGES IN URAGAN-2M TORSATRON

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The studies of the RF discharges for wall conditioning have been performed at Uragan-2M torsatron (stellarator). The purpose of the RF discharge wall conditioning is the removal of adsorbed by the wall species, so that they may then be pumped out of the vacuum chamber. This can be done by ion or atom impact owing to the momentum transfer or chemical interaction. In the magnetically confined plasma, the outflow of ions is not intensive and their flux to the wall of the vacuum vessel is not uniformly distributed. In such conditions, the wall conditioning with chemically active neutral atoms and molecules is advantageous. Such neutrals are produced intensively in partially ionized plasma when the degree of ionization is low. A scenario for wall conditioning is studied for the discharges in hydrogen. In this scenario the cleaning agents are hydrogen atoms resulting from the dissociation of the hydrogen molecules. If the electron temperature in the discharge is less than the ionization threshold, i.e. 4…10 eV, the dissociation rate is higher than the ionization one, and one electron produces a number of neutral atoms during its lifetime.

Continuous RF discharges in Uragan-2M torsatron are sustained by the 1 kW RF oscillator in the frequency range 4.5…8.8 MHz and 2.5 kW oscillator with frequency 150 MHz. For wall conditioning a special small size antenna is designed. It could be fed by both generators. The discharge parameters are measured in wide range of confining magnetic field and pressures. The dependence on launched power is also investigated. Evolution of the impurities in the discharge signified by the optical measurements, the residual gas composition and partial pressures measured with the mass-spectrometer indicate the wall conditioning. Their development is analyzed during days of operation.

6-10

THE DEVELOPMENT OF THE POSITIVE SPACE CHARGE PLASMA LENS FOR MANIPULATING HIGH CURRENT BEAMS OF NEGATIVELY CHARGED PARTICLES

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The configuration of a plasma lens with crossed electric and magnetic fields provides an attractive way to maintain a stable plasma discharge at low pressure and create numerous cost effective, robust construction plasma devices for ion treatment and deposition of exotic coatings. One of them is a device initially elaborated and designed as a cylindrical plasma source for ion treatment of cylindrical symmetry parts complicated in shape. In our previous works it was first proposed as a positive space charge plasma lens based on the principle of magnetic isolation of electrons for manipulating high current beams of negatively charged particles [1]. To restrict the influence of the finite magnetic field in the lens volume the modified magnetic configuration was elaborated and applied. Here we describe new experimental and theoretical results of the lens development.

Floating potential distributions in the lens with a modified magnetic field under different anode potentials are investigated. It is shown that reducing the magnetic field at the area of the lens axis doesn’t change essentially shapes of floating potential distributions in comparison with our previous measurement of the space charge distribution in the volume of plasma lens without additional magnetic poles. It is demonstrated experimentally that there is no noticeable difference between positions of floating potential peaks in the range of anode potential values as wide as 700-1500 V. It is established that with anode potential growing, the performance of space charge creation decreases. Radial electric field profiles in the center of the lens at different anode potentials are complicated shapes. It is noticed that the electric field magnitude depends weakly upon anode potential at a given pressure in the lens.

Numerical simulations of the lens according to the new improved theoretical model have been carried out. Angular and energy distributions of ions converging to the axis of the lens were considered. The transverse magnetic field leading to a momentum aberration of converging ion beam was taken into account. The qualitative agreement of numerical results with experimental data is shown.

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6-11

PHENOMENON OF THE CURRENT CRISIS IN PLASMA ACCELERATORS WITH DIFFERENT GEOMETRY OF THE IMPENETRABLE ELECTRODES

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On the basis of the developed two-dimensional two-fluid MHD model it is carried out the research of the processes near to the continuous impenetrable electrodes in the channels of the quasi-steady plasma accelerators (QSPA). Now the various modifications of the QSPA (see, for example, [1-5]) which allow to solve partially the problem of the interaction of the plasma streams with electrodes are offered and tested. The last experimental development [5] based on the theoretical analysis [6-7] answers a mode of the ion current transport regime with the penetrated electrodes at presence of an additional longitudinal magnetic field.

The continuous impenetrable electrodes use in a lot of cases. The theoretical analysis of dynamics of the plasma streams across a magnetic field in a vicinity of the equipotential impenetrable electrode on the basis of the generalized Ohm's law is presented in [1]. The account of the Hall effect ($\mathbf{V}_e \neq \mathbf{V}_i$) and parameter $\omega_e \tau_e$ can lead to a reorganization of the flow structure. In experiments this phenomenon is shown on the volt-ampere characteristics and accompanied by erosion of electrodes. Thus the current in system cannot exceed the some critical value defined by the approximate experimental relation for the given mass flux.

The developed two-fluid MHD model takes into account the Hal effect, the conductivity tensor of the medium and the dependence of the transport coefficients from $\omega_e \tau_e$. The various modifications of the two-fluid MHD model answer the statement of the various boundary conditions and have been used earlier for the comparison of the numerical and analytical models [6], and also for the analysis of the ion current transport regime in QSPA with an additional longitudinal magnetic field [7]. In the present work it is a question of the numerical researches of the processes near to the continuous electrodes in the plasma accelerators with the unique azimuthal component of the magnetic field.

The corresponding boundary conditions define the character of the interaction of plasma with a surface of electrodes. The researches have confirmed the theory of the phenomenon of the current crisis. The formation of a layer near to the anode and the occurrence under the certain conditions of the current crisis are revealed. The available experimental data defining the border of occurrence of the critical modes [1] are compared to the results of the numerical experiments. The analysis of the influence of geometry of the impenetrable electrodes on the process of formation of the current crisis is carried out.

The work has been executed at the financial support of RFBR (grant 09-01-12056) and RAS (program No. 14 of the basic researches of Presidium RAS, the project - 301).

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6-12

RADIATION GAS DYNAMICS OF NEAR-SURFACE LASER PLUMES IN AR

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Interaction of laser radiation with a metal barrier is numerically studied. The following general parameters of laser radiation are considered: wavelength is varied in the region 0.3-10.6 microns, duration of the laser pulses 10^{-8}-10^{-7} s, density of the laser radiation is $q < 10^{10}$ W/cm^2. Material of the metallic barrier - Al. An environment was argon. In this case an interaction of the laser radiation with metallic barrier is accompanied by occurrence of plasma in pairs a material of the barrier and surrounding gas.

For this reason, numerical simulation model, which is presented in the paper and intended for interpretation of available experimental data, and also for prediction various characteristics of the interaction, is constructed on the basis of the equations of multi-species one-temperature radiative gasdynamics in view of electromagnetic fields and turbulence of plasma.

Feature of the given model is the account of movement of boundary region dividing a metallic barrier, laser plasma and surrounding gas. Electromagnetic processes are described by system of the Maxwell-Ohm equations in plasma with final conductivity. Radiation transfer is considered within the framework of multi-group approach.

System of equation of the one-temperature radiating magneto-gasdynamics is supplemented with the equations describing processes of heating and evaporation of metallic barrier under action of laser radiation and thermal radiation of laser plasma. It consists from quasi two dimensional equation of heat conductivity in moving system of coordinates (the wave of evaporation connected to front) in perpendicular direction to surface of the metallic barrier. The system of the equations also contains kinetic equation for superficial evaporations of condensed substance within the framework of the Knudsen model.

The numeric solution of this equation system is based on splitting by physical processes and spatial directions. The solution of splitted equations occurs by the variant of compact finite-difference scheme of 7-th order, which has been developed. At radiation transfer equations solution the modified alternative-triangular method has been used. The equations for magnetic induction are solved by semi-implicit splitting method.

Values of threshold of laser intensity, resulting to "flash" of absorption and formation near surface laser plasmas are found. It is discovered, that time of a delay of occurrence of plasma formation near to metallic barrier depends on size of laser radiation focusing, density of a surrounding gas, and energy of laser radiation.

Complication of radiative gas dynamic processes are observed at density of laser radiation $\sim 10^6 - 10^{10}$ W/cm^2 . Waves of absorption of the laser radiation, moving from a place of breakdown towards to radiation of the laser are observed. Thus, there is shielding of illuminated surfaces of a metallic barrier, a reduction of temperature of a material, that in some cases is accompanied by the termination of evaporation. As a whole, the mode of evaporation in this case has pulsing character. The detailed analysis of laws of formation and scattering of plasma formation will be submitted in the paper.

Acknowledgements

Work is executed within the framework of the basic researches program of Russian Academy of Science and RFBR (Russia) – Consortium EINSTEIN (Italy) Grant 09-08-92422-KE-a

6-13

EFFECT OF AN EXPLOSIVE ELECTRON EMISSION ON MAGNETIZED SHEATH BETWEEN PLASMA AND ISOLATED WALL

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Plasma is separated from plasma reactors walls by a space charge sheath (Langmuir–Debye sheath) because of the mobility difference between ions and electrons. The phenomena in sheath play a considerable role in the various plasma technologies of solid surfaces processing and controlled thermonuclear power production. Due to essentially nonlinear character of the sheath it seems actually to study its properties by means of computer modeling.

One of the most interesting phenomena bound with sheath is formation of an unipolar arc. According to modern representations unipolar arcs lead to corrupting of walls. Particularly, an unipolar arc is the emission source of heavy ions which are sources of the enhanced Bremsstrahlung radiation losses of energy.

Essential for this kind of discharges is that one electrode serves both as cathode and anode. The cathode is the region of explosive electron emission, the anode is ringlike area surrounding the cathode. Explosive electron emission can appear on some cathode surface defects caused by enhanced electric fields near them, then complement by thermal and secondary electron emission. In some conditions, that should be determined, the return flow of electrons appears around emitting spot. This return flow closes the current loop of the unipolar arc.

A two-dimensional model of magnetized sheath is considered. One edge of modeling area is a wall with the floating potential. The ion flow with directed Bohm velocity is defined from opposite edge. The area between edges is filled with argon. The secondary electron emission with its coefficient γ is taken into account.

High-density electron flow injection is defined from central small area of wall to take into consideration the explosive electron emission.

Simulations were made by means of Particle-in-Cell method and Monte-Carlo method to take into account following reactions caused by electron and ion impact in our code:

- elastic electron-neutral collisions $Ar + e^- \rightarrow Ar + e^-$;
- elastic ion-neutral collisions $Ar + Ar^+ \rightarrow Ar + Ar^+$;
- ionization $Ar + e^- \rightarrow Ar^+ + 2e^-$;
- neutral excitation by electron heat $Ar + e^- \rightarrow Ar^* + e^-$;
- charge exchange between ions and atoms $Ar + Ar^+ \rightarrow Ar^+ + Ar$.

Following parameters were used: electron and ion densities $n_{e,i} = 10^{15}\ m^{-3}$, electron temperature $T_e = 2,5$ eV, ion temperature $T_i = 0,04$ eV, explosive emission current density j_{em} = 10^3-10^5 A/m^2, magnetic induction is chosen within $0.01 \div 0.2$ tesla, the angle of the magnetic field to the wall was $\theta = 8^\circ$. According to suggested approach, the sheath modification caused by explosive emission has been obtained. There are an potential minimum formation near the wall. It seems like the potential profile in vacuum diode with thermo- or auto-electron emission. This means electric field diversion in the region of emission. It leads to return flow of electrons around emitting spot.

When current density of explosive emission reaches j = 10^5 A/м^2, the return current to wall has the same order as the direct current. On the basis of this result we can determine the ignition of the unipolar arc. It is shown that the magnetic field increasing reduces the reverse flow of electrons on the wall, thereby preventing the development of unipolar arc.

6-14

CHARACTERISTICS OF PLASMA STREAMS AND OPTIMIZATION OF OPERATIONAL REGIMES FOR MAGNETOPLASMA COMPRESSOR

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Spatial and time distributions of plasma stream density as well as plasma pressure distributions are able to provide detailed information about dynamics of plasma stream and, therefore, there are important characteristics of magnetoplasma compressor (MPC) from the point of view optimization of MPC operation regimes.

In these studies, several local movable piezoelectric detectors were designed and manufactured for plasma pressure measurements with necessary spatial and temporal resolution. All detectors were calibrated for absolute measurements of plasma pressure at different distances from the MPC output [1]. It was obtained that plasma pressure in the compression region is achieved 22-25 bar that indicates efficiency of MPC as dense plasma source. On the base of plasma pressure measurements several important plasma parameters, e.g. plasma stream velocity and plasma temperature were estimated. It was found that average plasma temperature in dense plasma stream, generated by MPC is in the range of 20-40 eV.

Results of energy density measurements in MPC plasma streams are presented also. Radial distributions of energy density were obtained using set of small movable calorimeters. In near axis region the energy density value achieves 40 J/cm^2. Effective diameter of high-energy plasma stream was estimated. Also, performed analysis of current and voltage waveforms and energy measurements in plasma in different distances from MPC output have shown that about 30% of discharge energy in MPC converts to the energy of generated plasma stream.

Spectroscopy measurements of electron density in plasma stream generated by MPC are discussed. In particular, effects that can influence on accuracy of plasma density measurements by broadening spectral lines are analyzed. It was demonstrated that most important one is self-absorption of spectral lines. In the case of known optical thickness, the real value of electron density can be calculated with accounting self-absorption using the method described in [2]. In present paper, estimations of plasma thickness were made and resulting electron density was calculated. Radial distribution plasma density was reconstructed for particular MPC operation mode using Abel inversion procedure, i.e. azimuthal symmetry of plasma stream was presupposed. As was found the maximum value of plasma density in compression region achieved 10^{18} cm^{-3}.

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6-15

INFLUENCE OF HYDROGEN AND HELIUM PLASMA STREAMS EXPOSURES ON MODIFICATION OF TUNGSTEN STRUCTURE UNDER POWERFUL TRANSIENT LOADS

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One of important issues that need to be studied experimentally in the ITER simulation conditions is behavior of divertor materials under the helium ions bombardment during multi-pulsed repetitive ELM-like plasma loads, which are below/close to the melting threshold. The effects of helium ions impact (blistering, flaking), helium dynamics in surface layers, its influence on cracking development in tungsten (helium retention in microcracks volume) are still actual topics. This paper presents the results of comparative studies of W targets response to the plasma exposures at QSPA Kh-50 facility and pulsed plasma gun PPA, which were performed with various number of hydrogen and helium plasma pulses. Plasma loads were chosen either below the melting threshold or providing conditions of pronounced melting.

The pulsed plasma accelerator PPA generates plasma streams with ion energy up to 2 keV, plasma density (2-20) × 10^{15} cm^{-3}, a maximum specific power of about 10 MW/cm^2 and plasma energy density varied in the range of (5-40) J/cm^2. The plasma stream duration was 3-6 μs. Both, helium and hydrogen were used as working gases.

The main plasma parameters of QSPA hydrogen plasma streams are as follows: the ion energy is about 0.4 keV, the maximum plasma pressure is 3.2 bar (time averaged pressure during the pulse is 1.6-1.7 bar) and the plasma stream diameter is 0.18 m. The plasma pulse shape is triangular with pulse duration of 0.25 ms. The surface energy load measured with a calorimeter was chosen either 0.45 MJ/m^2, which is below the melting threshold, or 0.75 MJ/m^2, which resulted in pronounced melting.

X-ray diffraction (XRD) has been used to study the micro-structural evolution of exposed W targets of several grades: sintered, rolled etc. XRD ϑ-2ϑ scans were performed using a monochromatic K_{α} line of Cu anode radiation. Analysis of diffraction peaks intensity, profiles, and their angular positions was applied to evaluate the texture, the coherent scattering zone size, the macro-strain and the lattice parameters. Surface observations with optical microscopy and SEM were performed also.

It is shown that uniform tensile stresses are created in thin surface layer of tungsten target in result of plasma exposure. Main residual stresses are caused by first plasma pulses. For regimes with melting, residual stresses are mainly attributed to re-solidification of melt layer. Non uniform changes of both stress-free lattice spacing and half-width of diffraction maximum are observed under heat loads above the tungsten melting threshold. This result can be explained by introducing light impurities into the melt layer structure. Differences in evolution of tungsten substructure after exposures with helium and hydrogen plasma streams are discussed.

6-16

TWO-DIMENSIONAL SIMULATION OF DYNAMIC DUST CLOUDS IN THE PLASMA BOUNDARY NEAR THE WALL

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Studies of levitation and dynamics of charged dust grains are of significant interest in space and low-temperature laboratory plasma discharges [1]. Charged dust particularly also appear at tokamak edges as natural contaminants arising from the plasma interaction with divertor plates, plasma limiters and blankets [2]. Due to their heavy masses and tendency to form self-organized structures the dust particles affect waves, instabilities and transport processes. Recent laboratory experiments [3] have conclusively demonstrated the motions of charged dust clouds near negatively biased electrodes in low temperature dusty plasma discharges. In a dusty plasma sheath the dust grains execute bouncing motions, which are repeatedly away and towards the electrode.

In this article, we investigate the behavior of a dust cloud in the field of the plasma sheath. Specifically, we determine the place of a dust cloud localization, viz. the distance from the wall, and also discuss the form of the cloud. We assume that the dynamics of a dust cloud is significantly influenced by the sheath electric force and gravity, and that the wall has a negative potential and is absolutely absorbing.

We consider the wall region of two-dimensional dusty plasma model, wherein the plasma is contaminated by dust charged grains. Plasma consist of electrons, ions and dust particles with densities n_e, n_i, n_d. At initial time electron and ions are distributed uniformly in space. Dust grains acquire a charge and influence the potential of the electric field φ, which is described by Poisson equation. The movement of dust particles and ions is governed by hydrodynamics equations, electrons are assumed to be in thermal equilibrium. It is assumed that the forces on the dust consist of electrostatic, gravity and ion drag forces.

The spatial distributions of parameters were obtained at various initial densities and radii of dust grains at different times.

Results show that peaks of the dust density are formed in space of the dust cloud and dust particles perform the oscillations along radial axis. Moreover, dust cloud is compressed along axial axis and it is formed thin layer under the wall. It is shown that ion density is increased in the dust cloud and has peaks on the boundaries of dust cloud. Dust clouds modify potential spatial profiles thus that minimum of electric potential is appeared near the dust cloud boundary from the direction of plasma. This potential drop is accelerate ions toward the dust cloud and it is potential barrier for negative dust particles.

This work was supported by joint NASU-RFFR grant.

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6-17

ANALYSIS OF THE NON-THERMAL X-RAY OSCILLATIONS IN THE T-10 TOKAMAK

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Spatial and time evolution of the non-thermal (20-200keV) electrons is studied in the T-10 tokamak plasma during density limit disruption, powerful ECRH heating, and during initial stage of the discharge. The T-10 diagnostic system consists of two CdTe tomographic arrays (10+6 detectors), miniature in-vessel CdTe detector with movable 2D Soller collimators, and multi-wire gas detectors (64 channels in two arrays). Identification of the spatial localization of the non-thermal x-ray perturbations is provided by 2D tomographic reconstruction technique based on Cormack inversion. Detailed description of the diagnostic technique, data acquisition system, and analysis algorithms is presented.

Experiments in the T-10 tokamak have indicated that current decay during disruption instability is represented by series of minor disruptions accompanied by intensive bursts of the non-thermal x-ray and bolometric radiation and periodic "humps" of the soft x-ray intensity. Analysis indicated that non-thermal x-ray bursts can be connected with generation of the electrons beams around magnetic surfaces with rational q values during series of minor disruptions. The beams are accelerated continuously at the later stage of the disruption and can lead to a powerful runaway beam avalanches.

Application of the CdTe and multi-wire detectors can provide valuable information not only on the non-thermal electrons but allows also identification of the plasma shape and position, studies of MHD modes, and testing of the feedback systems. However, high fluxes of fusion neutrons and gamma radiation in ITER-like tokamak complicates installation of the traditional X-ray arrays (with semiconductor detectors) due to their high sensitivity to noise and damage induced by neutrons. Solution of the problem could be connected with using radiation hardening detectors or by use of additional x-ray optics. Present paper discusses possible effects of the high radiation fields on CdTe and wire detectors. Possible application of the X-ray imaging techniques based on radiation-hardening multi-wire detectors is considered for ITER-like experiments.

The work is supported by RFBR 08-02-01345 and и NWO-RFBR 047.018.002.

6-18

STUDY OF THE DEPOSITED LAYERS OF PFC-MATERIALS PRODUCED BY BOMBARDMENT WITH HYDROGEN ISOTOPES IONS

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Application of basic materials, primarily of CFC and tungsten, as materials of the magnetron sputtering system cathode offers modeling of plasma facing component (PFC) operation in conditions similar to those expected in the International Thermonuclear Experimental Reactor (ITER). An analysis shows that the working conditions for the ITER-reactor for PFC are close to those in magnetron and modeling of ITER plasma facing component operation is possible. Above all, this opportunity applies to a particle energy spectrum that has a maximum of material sputtering coefficient in the range of several hundreds electron volts and to the density of particle flux incident onto a surface. Moreover, a return of sputtering products onto the wall surface will take place in a reactor. The deposition and re-deposition of particles of different materials onto the surface will result in essential modification of material properties. Since this problem requires additional studies, we draw our main attention under implementation of this work to experiments of mutual deposition and re-deposition of different materials.

For modeling of plasma – wall interaction we used the facility of magnetron-type – “MOWGLI”, that is similar the ”MAGRAS“-facility (it was used in Bauman University for beryllium sample testing). The tungsten- or graphite-cathode of the magnetron was bombarded by the compensated hydrogen-isotopes ion beams with the energy of 200 - 500 eV. The ion flux intensities were equal 1 10^{17} cm^2s^{-1} - 5 10^{17} cm^2s^{-1} that allowed one to produce the sprayed and deposited layers for the time of one hour or a few hours long. The thickness of the deposited layers was in range 100 - 300 Angstrom. The cathode temperature was varied in the range of 600 - 800 K. The gas pressure in vacuum vessel was varied from 0.1 to 5 Pa. We could model modes of sputtering, deposition and re-deposition of sputtered particles to the surface of sprayed target.

A monocrystalline silicon was used as a collector of the sputtered particles in a mode of sputtering – deposition. The sprayed target served in a mode of re-deposition as a collector of particles. The scanning electron microscopy was used for studying the cathode surface and the deposited layers microstructures. The chemical composition of a surface layer was determined by the Rutherford back-scattering technique in the Van-de-Graaf accelerator. The hydrogen isotope accumulation and their distribution within the sputtered and re-deposited layers in depth were determined using the elastic recoil nuclei detection technique.

There were atoms of isotopes of hydrogen together with the sputtered atoms in deposited layers at the collector surface. The ratio of hydrogen isotopes atoms of and the sputtered atoms of a target (W, CFC) depended on energy of bombarding ions and target temperature. Besides, the properties of analyzed layers strongly depended on quantity of impurity basic gas. Therefore in experiments we used pure deuterium with the maintenance of impurity no more than 0.2 %.

At the next stage of experiments we used the azimuthally nonuniform C-W cathode of magnetron. In this case, the targets were differently combined in terms of C:W area ratios and used for studies of mutual re-deposition of the erosion products. Due to azimuth drift of electrons in magnetron, the discharge was homogeneous even when the cathodes were made of materials with significantly different properties. Due to high pressure the cathode erosion products scatter on the ambient gas and predominantly return back to the target surface. In cases of mixed-material targets, we examined the re-deposition patterns.

This work was supported by the federal program "Scientific and pedagogical personal of innovative Russia 2009-2013" (project P294).

7-1

ABOUT THREE MECHANISMS OF TRANSFORMATION OF LOW-FREQUENCY ENERGY OF OSCILATIONS TO THE ENERGY OF HIGH-FREQUENCY OSCILATIONS

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The brief review of the most important results which have been gotten at study of the mechanism of the high numbers harmonics excitation by nonrelativistic oscillators, the mechanism of quantum whirligig effect (QWE) and the mechanism of secondary resonances is given.

There was early shown by us, that nonrelativistic oscillators which are moving in media with weak non-uniform periodic heterogeneity or in such potential, can effectively radiate the high numbers harmonics. At this, the spectrum of radiation excited by the nonrelativistic oscillators is similar to the spectrum of the relativistic oscillators. It means that the maximum of the spectrum is in a vicinity of high numbers harmonics. The mechanism of such radiation was found out. The similar radiation takes place and at movement of the charged particles in periodic potential. . In this case adequate theory should be the quantum theory. It was shown that the most effective radiation of the charged particles in periodic potential arises when in the interaction with an electromagnetic field participates of a fast component of complex structure of wave function, which describes dynamics of particles in periodic potential.

The analysis of the QWE mechanism is carried out. It is shown, that this mechanism is similar to the quantum Zeno effect (QZE). Moreover, at the certain assumptions (the quantum transitions with radiation and absorption of quantum are similar to collapse of wave functions) these two effects coincide. The results of some experiments on detection of QZE are considered. It is shown, that for an explanation most of them it is enough to involve in consideration the QWE. This conclusion is important, because the QWE does not leave for frameworks of the traditional quantum mechanics. It is known, that the QZE requires attraction of the quantum theory of measurements.

Simple example, in which the effect of a secondary resonance is shown, is two identical linear oscillators, which are weakly connected. It is known, that there appear a new large characteristic time - the period of transferring of energy between these oscillators. The size of this period is back proportional to value of connection between oscillators. The presence of low-frequency oscillations of such dynamic system (two identical linear weak connected oscillators) allows by external low-frequency resonant perturbations to transform the energy from this low-frequency perturbation in energy of fast moving of these oscillators. The real examples of such oscillators can be two identical connected resonators. The conditions are found, at which the energy of external low-frequency perturbation can be passed to energy of high-frequency moving of the connected systems. In particular, it was shown, that for this purpose the periodic low-frequency perturbation of the connection factor between oscillators can be used. At this, it has been found, that only in case of not mutual connection the parametrical amplification of amplitudes of high-frequency oscillation can be occur. At symmetric (mutual connection) such opportunity vanishes.

The various variants of use of three considered mechanisms for transformation of energy of low-frequency perturbations to energy high-frequency are discussed. At this, under high-frequency we understand the oscillations which frequencies, for example, lay in a x-ray range. As low-frequency fluctuations in this case it is possible to consider the optical radiation.

7-2

COMPUTER SIMULATION RESULTS IN THE STUDY OF THE PLASMA RELATIVISTIC MICROWAVE AMPLIFIER

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The dependence of the parameters of the 3.2-GHz emission from a plasma relativistic microwave amplifier (PRMA) on the external conditions is studied both experimentally and numerically by varying the plasma density, magnetic field strength, input signal amplitude, and plasma waveguide length. This work is a continuation of paper [1], in which experimental studies of a plasma relativistic microwave amplifier were begun. The experimental data are compared with the results of numerical simulations carried out with the KARAT computer code [2]. The annular REB was simulated by the particle-in-cell (PIC) method with a fixed particle charge. The time dependence of the beam current was calculated according to the Fedosov formula, taking into account the known time dependence of the beam electron energy. Therefore, effects related to the finite value of the magnetic field, such as the excitation and suppression of waves in plasma under the resonance conditions of the anomalous and normal Doppler effects, were taken into account too. The plasma was modeled as a continuous annular medium with a fixed radial distribution. The normal Doppler effect is employed to suppress the generation mode; moreover, microwave absorbers are also placed inside the plasma waveguide for the same purpose. The microwave absorber was modeled using the perfect matched layer (PML) method, in which the tangent component of the phase velocity inside the PML layer is assumed to be the same as in vacuum for all frequencies and all angles of incidence. Numerical simulations have confirmed the effect of suppression of noise in a beam--plasma system in the presence of a sufficiently intense monochromatic input signal, as was previously observed in [1]. Thus, we have demonstrated that, in both the experiment and simulations, the parameters of the output radiation depend in a similar manner on the external factors. This indicates that the actual parameters of the electromagnetic field and electron beam inside the plasma waveguide (which cannot be measured directly) should agree qualitatively with those given by simulations. When analyzing the fields inside the plasma waveguide, we used the values of the plasma density and magnetic field at which the calculated radiation parameters agreed well with the measured ones. The effect of suppression of noise at sufficiently high input powers can also be seen in the phase portrait of the electron beam. In the absence of an input signal, strong interaction between the electron beam and electromagnetic fields in the plasma waveguide is observed. This results in the deceleration of the electron beam and the appearance of a large amount of electrons moving toward the REB. Since the spectrum of excited waves is broad, the modulation of the momentum of the beam electrons is chaotic.

This work was supported by the Government contract according the competition NK_592P.

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7-3

EVOLUTION OF THE MODULATED ELECTRON BEAM IN THE DENSE PLASMA BARRIER

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Problem of the evolution of the modulated electron beams in plasma is interesting due to its possible applications such as dense plasma barrier transillumination for electromagnetic waves using electron beams [1], planning of the experiments on electron beams' injection into space and ionosphere plasma and interpretation of their results, diagnostics of inhomogeneous plasma via transition radiation of electron beams [2] etc.

This report presents results of simulation of the modulated electron beams' evolution in the dense homogeneous and inhomogeneous plasma. Simulation was carried out for 1D and 2D geometry using PIC method.

Effects of the concurrence between the resonant mode of a beam-plasma system and space charge wave of the beam at the modulation frequency are discussed [3-4]. Influence of the beam-plasma turbulence mode on the evolution of the modulated beam was studied [5]. Evolution of the velocity distribution function of the modulated beam during its motion in the dense plasma was treated [6-7]. Influence of the background plasma inhomogeneity on the modulated beam evolution was studied [8-9]. For 2D simulation the influence of the beam transversal restriction is discussed.

Simulation results are compared with previous laboratory experiments.

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7-4

THE LOW PRESSURE DISCHARGE INDUCED BY MICROWAVE RADIATION WITH STOCHASTICALLY JUMPING PHASE

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In report the results are presented from experimental studies on the unique beam-plasma generator of microwave radiation with a stochastically jumping phase (MWRSJP). To interpreted the experimental results, a computer code is developed that allows one to simulate the process of gas ionization by electrons heated in the MWRSJP field and the behavior of plasma particles in such a field.

In [1-2], it was shown both theoretically and experimentally that the phenomenon of anomalous penetration of microwave radiation into plasma, conditions for gas breakdown and maintenance of a microwave gas discharge, and collisionless electron heating in a microwave field are related to stochastic jumps of the phase of microwave radiation. In the present work, the effect of high-power pulsed decimeter MWRSJP on the plasma produced in a rarefied gas filling a coaxial waveguide was studied using the beam-plasma generator (BPG) created at the NSC KIPT [3] and upgraded for the given experimental conditions.

The conditions for ignition and maintenance of a microwave discharge in air by MWRSJP are found both experimentally and theoretically, and the pressure range in which the power required for discharge ignition and maintenance is minimum are determined. The results of one- and two-dimensional numerical simulations can be formulated as follows.

(i) The intensity of collisionless electron heating increases with increasing rate of phase jumps in MWRSJP.

(ii) There is an optimal phase jump rate at which the rate of gas ionization and, accordingly, the growth rate of the electron and ion densities growth are maximum. The optimal phase jump rate is equal to the ionization frequency at electron energies close to the ionization energy of the working gas.

(iii) The results of numerical simulations agree are qualitatively with the experimental data.

The original SPECRAY code has been used to calculate the spectral radiation intensity along a ray for the known profile of the absorption coefficient under the assumption that the medium is in thermodynamic equilibrium and does not scatter radiation.

It should be noted that the spectral components corresponding to the maximum of the MWRSJP spectrum at the input to the waveguide are practically absent at the waveguide output. As the air pressure decreases, the optical radiation spectrum of the discharge shifts toward shorter wavelength range. The results of this work can be used to develop of a new type of efficient sources of optical radiation with a quasi-solar spectrum. This may result in a breakthrough in the field of lighting engineering.

This work was supported in part by the Russian Foundation for Basic Research (project no. 09 - 02-90442) and the Fundamental Researches State Fund of Ukraine (project no. F 28.02/055).

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7-5

THE REGULAR AND CHAOTIC DYNAMICS AT WEAK-NONLINEAR INTERACTION OF WAVES

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In the present paper some new aspects of dynamics of weak-nonlinear interactions of waves are discussed. First of all it is shown that essential growth of the degree of the coherence of the decaying wave can be observed at three-wave interactions. The most important result is that that the part of energy of the decaying wave goes to the field of the low-frequency wave. This part of energy can be very insignificant while together with this insignificant energy all entropy practically remove from the decaying wave. The degree of the coherence of the decaying wave essentially grows in this case. The dynamics of the regimes of the decaying waves is investigated. The existence of the regime at which the degree of the coherence of the decaying packet of waves essentially grows and also regimes with chaotic dynamics are shown. The dynamics of weak-nonlinear interactions of waves in the schemes that represents practical interest is investigated. The models which appear at the description of processes in plasma when intensive laser radiation impacts on plasma and in particular the case of two laser streams (beat wave scheme) are investigated. The most interesting result of this section is that at the unlimited number of degrees of freedom (the unlimited number of interacting waves) the viewed model has the rigorous analytical solution and no complex chaotic regimes in it appear. In actual conditions the number of waves is restricted. It is shown that depending on dispersion features of medium and depending on starting conditions regimes with both regular, and with chaotic dynamics can be realized in such models.

Regimes with chaotic dynamics at weak-nonlinear interaction of waves can find significant practical application. In particular they can be used for control of the spectrum characteristics of practically any generator. However, as show numerical estimations, large intensity of fields of interacting waves are in most cases necessary for practical implementation of these conditions. The magnitude of interacting waves at which the regime of the regular dynamics transfers to the chaotic regime, appears the greater the more distance between natural waves of investigated electrodynamic structure. Therefore such electrodynamic structures in which the distance between natural waves was small enough are necessary for successful implementation of chaotic regimes at the moderate values of fields. With this purpose the well known plasma model - a waveguide filled with rare plasma investigated. It is shown, that in such structure there can be fast natural waves with close values of frequencies and wave vectors.

7-6

DIFFUSION IN VELOCITY OF CHARGED PARTICLES SCATTERING THE ELECTROMAGNETIC WAVE

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Results of theoretical study into scattering of an external plane monochromatic electromagnetic wave by identical charged particles in view of the scattered radiation influence on particles motion are presented. The velocity diffusion of particles caused by collisions of particles and fields of the scattered radiation is considered. The principal analytical tool used in this study was the analytic descriptive model of motion of the point identical charged particles in their scattered radiation field.

To calculate velocity diffusion we have calculated the mean-square spread in the velocity of test particles as functions of time. The diffusion of particles on longitudinal velocity (along the direction of external electromagnetic wave propagation) has been investigated. Analytical expressions for mean-square value of the velocity caused by radiating effects, have been found for small times over which the displacement of particles due to thermal motion is less than the wavelength of radiation and for greater times as well when this displacement is much more than the wavelength of radiation. The change of dependence on time of increase spread rate in the velocity in these two cases is revealed. The obtained analytical formulas determine the mean-square spread in the velocity of particles at scattering of an external electromagnetic wave as a function of parameters of this wave and the system of the charged particles.

7-7

WAKEFIELDS EXCITATION IN PLASMA, FORMED BY A SEQUENCE OF ELECTRON BUNCHES IN NEUTRAL GAS, ACCELERATING AND FOCUSING ELECTRONS BY THEM

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Experiments on wakefield excitation by a sequence of $6x10^3$ relativistic electron bunches in plasma, formed by head bunches of the same sequence in neutral gas of various pressure are presented. The ranges of pressure are found, in which beam-plasma discharge is developed, that leads to intensification of plasma generation. Acceleration and focusing of bunches electrons that is determined by bunch geometry (ratio of the bunch length to its diameter) and detuning of the bunches repetition frequency and wakefield frequency, are investigated. Phenomenon of periodic excitation of wakefield and corresponding periodic modulation of the current of the beam passed through plasma is discovered and physical mechanism of this phenomenon is clarified.

7-8

MECHANISM OF PLASMA WAKEFIELD EXCITATION BY A NONRESONANT SEQUENCE OF RELATIVISTIC ELECTRON BUNCHES WITH REPETITION FREQUENCY LESS THAN PLASMA FREQUENCY

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Resonant wakefield excitation by long sequence of relativistic electron bunches is difficult because realization of homogeneous and stationary plasma in experiments is difficult [1]. Results of 2.5D numerical simulation by the 2d3v code LCODE [2] of plasma wakefield excitation by a nonresonant sequence of relativistic electron bunches with repetition frequency smaller than plasma frequency are presented. Parameters are close to experimentally researched in NSC KIPT [1]. A periodical sequence of short relativistic electron bunches of energy 2MeV, charge 0.32nC, rms length $2\sigma_z$=1.7cm, rms radius σ_r=0.5cm, rms angular spread σ_θ=0.05mrad, repetition period 360ps excites a wakefield in plasma. The plasma of density larger than the resonant one $10^{11}cm^{-3}$ is simulated, so the frequency of the excited wave is different from the frequency of bunches repetition. The temporal dynamics of spatial distribution of bunch electron density, of exited longitudinal electric field and radial focusing/defocusing force have been researched. Because of bunch repetition and plasma frequencies detuning the wakefield beatings are occurred. The bunches in the maximum of beating experience focusing radial force. The mechanism of excitation by long nonresonant sequence of relativistic electron bunches, when the frequency of the excited wave is larger the frequency of bunches repetition, is the asymmetry appearance between energy exchange of bunches with wakefield at first and second fronts of beating due to radial dynamics of bunches. The time of asymmetry appearance has been estimated.

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ABOUT CONDITIONS OF EFFECTIVE INTERACTION OF WAVES IN NON-UNIFORM, NON-STATIONARY AND NONLINEAR MEDIUM

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At distribution of waves in periodically non-uniform or nonlinear medium the waves can effectively interact at performance of the certain conditions. These conditions are known. They are known as a synchronism condition. Most simple these conditions look at propagation of waves in medium, which dielectric permeability is possible to present as: $\varepsilon = \varepsilon_0 + \tilde{\varepsilon}$, $\tilde{\varepsilon} = q\cos(\kappa r - \Omega t)$, $q << 1$ (for example in plasma). Namely they look like: $\Delta k \equiv k_1 - k_0 \pm \breve{\kappa} = 0, \Delta\omega \equiv \omega_1 - \omega_0 \pm \Omega = 0$. At fulfillment of these conditions it is possible to say, that there is a three-wave interaction. And, one of these waves represents a wave of dielectric permeability which is given and don't changed. Then between two other waves, which the wave vectors and frequencies satisfy to this condition, there will be occur a periodic exchange of energy. Examples of such interactions are the interaction of waves in plasma, and also interaction of waves in crystals (pendulum solution). At presence detuning ($\Delta k \neq 0$, $\Delta\omega \neq 0$), the efficiency of interaction essentially decreases. The waves exchange only part of their energy.

The real interaction of waves occurs in the distributed systems, i.e. the process of interaction take place along the certain lines (characteristic lines) in four-dimensional space (t, r). At this, it is possible to expect, that detuning along one of spatial axes can be compensated by detuning along other spatial axes. In the report the results of researches of such opportunity are stated. It is shown, that really the effective interaction between waves in the distributed systems can occur at large detuning. The conditions of effective interaction of waves at this get such kind: $\Delta k \cdot k_0 - \Delta\omega \cdot \omega_0 \cdot \varepsilon_0 / c^2 = 0$ and $\Delta k \cdot k_1 - \Delta\omega \cdot \omega_1 \cdot \varepsilon_0 / c^2 = 0$. It is visible, that these new conditions of interaction, as a special case, contain old conditions ($\Delta k = 0$, $\Delta\omega = 0$).However they point out on existence of some new opportunities for effective interaction of waves in the distributed systems. In this work the most important consequences of these new conditions of effective interaction of waves are analyzed. In particular, it is shown, that the except of the well-known Bragg reflection, at which wavelength of the reflected wave must be about the period of heterogeneity, can exist the complete reflection and such radiation, the wavelength of which is much more than the period of the heterogeneity.

7-10

TRANSITION RADIATION OF THE CHARGED PARTICLE IN THE INHOMOGENEOUS PLASMA WITH THE LONGITUDINAL MAGNETIC FIELD

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Transition radiation in plasma attracts interest because of its possible applications (usage of modulated electron beams as radiation emitters in ionosphere [1], transillumination of plasma barriers via electron beams [2], diagnostics of inhomogeneous plasma using transition radiation of electron bunches [3] etc). But this fundamental problem was not yet solved even for the simplest model of cold planarly-stratified plasma with magnetic field parallel to its density gradient [4]. In this work linear transformation of the given current waves into electromagnetic waves for such model was studied.

Charged particle moving in inhomogeneous cold collisionless plasma along the density gradient parallel to external homogeneous magnetic field is treated. Plasma density depends only on z-coordinate and increases monotonically from the certain small value with increase of z. Magnetic and electric fields are expressed in terms of vector potential. Fourier transformation is applied to the equation, and obtained vector equation is transformed to set of three scalar equations. From this set equation for x-component of vector potential is obtained. This equation is the fourth-order differential equation, and it can be solved using method proposed in [5] for analysis of distributed reflection. General solution of homogeneous equation is superposition of four plasma eigenwaves (ordinary and extraordinary), and for each type of the eigenwave there are two waves moving forward and backward to the particle velocity. Right part of differential equation containing the current's derivative should be considered to solve inhomogeneous equation. Method of constants' variation is used, and it results to the set of four linear equations (relatively to the wave amplitudes and their derivatives). From this set derivatives of wave amplitudes are obtained. Expression for these derivatives contain summands with $\exp[i(\pm k_1 \pm k_2)]$ ($k_{1,2}$ are z-components of eigenwaves' vectors) describing the mutual transformation of eigenwaves, and summands with $\exp[i(\pm k_{1,2} - \kappa_z z)]$ (κ_z is z-component of the current wave vector) describing transformation of current wave into eigenwaves. This transformation is transition radiation so such summands are integrated using residue method for poles' vicinities and stationary phase method for the vicinities of Cherenkov resonance points. Magnitudes of transition radiation of ordinary and extraordinary waves are obtained.

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7-11

CONTROLLED ANOMALOUS TRANSMISSION THROUGH PLASMA LAYERS

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The materials with negative dielectric permittivity $\varepsilon < 0$ and magnetic permeability $\mu < 0$ (metamaterials) have attracted much attention in recent years. The increased interest in properties of such media has been driven by their potential applications in various branches of science and technology. Such materials give a possibility of creating so-called superlens: a subwavelength optical imaging system without the diffraction limit [1] based on the amplification of evanescent waves due to surface mode resonances. Manipulation of light at the subwavelength scale opens the possibilities for all optical computer components which would combine advantages of wide band photonics and nanoscale electronics [2].

We study optical properties of a two-layer plasma configuration surrounded by vacuum. The dielectric constant of the first layer is positive $0 < \varepsilon < 1$, while the second layer is a negative dielectric media $\varepsilon < 0$. It was found earlier [3] that a *p*-polarized electromagnetic wave with frequency below the cut-off obliquely incident at the first layer can be totally transmitted through the plasma structure. The transparency of dense plasma occurs as a result of surface mode excitation. The surface wave at the plasma-plasma interface amplifies the transmitted wave, which is evanescent in plasma. A configuration of layers with dielectric constants of opposite signs can be created artificially in composite structures with alternating layers of metal films and semiconductors in which the electron density can be controlled externally by an electric field. In addition, an external magnetic field can be used to control the plasma dielectric permittivity. We investigate the influence of the magnetic field on dispersion of the surface waves at plasma-plasma interface and on resonance transparency of the two-layer plasma structure. The conditions of the resonant transmission is obtained.

This work was supported by the NATO Collaborative Linkage Grant CBP.NUKR.CLG.983378.

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7-12

ON STUDIES OF THE NEGATIVE POINT-TO-PLANE CORONA AT HIGH PRESSURE

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This review concentrates on results of the experimental and theoretical study and the numerical simulation of low power, non-equilibrium plasma at atmospheric pressure. While studying the negative point-to-plane corona in air, Trichel revealed the presence of regular relaxation pulses. An improved understanding of fundamental discharge phenomena and optimization of plasma processes are key prerequisites for future applications and success. This is where numerical modelling can offer great benefits. Morrow R. et al works carried out to date with their main focus being the hydrodynamic drift–diffusion model. They have described a new powerful tool for the accurate and efficient characterization of gas discharges, namely the FE-FCT algorithm, which has been developed and validated in order to make gas discharge modelling in complex geometries in their full three-dimensional form possible. Napartovich A.P. et al experience in modelling Trichel pulses showed that the interplay between processes controlling the pulse dynamics is more or less understandable. The results from the numerical simulations of a negative corona in air demonstrated that the experimentally observed regime of self-oscillations, known as Trichel pulses, is well described by a three-dimensional axisymmetric model that is based on the standard transport equations and in which the electrons are assumed to be produced only through the ion-induced secondary emission at the cathode. The simulations of Napartovich A.P. et al work, which were carried out without any reference to the adjustable parameters, show that the region of steep gradients near the needle is, in fact, far shorter (tens rather than hundreds of microns) and that the cross-sectional area of the current channel changes significantly with time. Gupta D.K. et al have numerically studied the negative corona current pulse in air at atmospheric pressure by solving the continuity equation for electrons, positive ions and negative ions in conjunction with the electric field. In this simulation, they have retained only the secondary emission of the electrons from the cathode by ion impact as a feedback source. There can be two cases for which no step on the leading edge can be observed. First, if the feedback source also starts decreasing during the plasma formation phase, the current does not get enough secondary electrons for enhancement, as happens in their work at low voltages. Second, if the ionization rate is very high then the plasma formation time (step width) becomes too short to be noticed during the fast rise time of the current pulse, and therefore the phases of the current rise before and after the step appear as continuous. Chernak M. et al presented the results of experiments designed to test existing theories for the negative corona (Trichel) pulse formation. The experiments represent the first systematic study of the role of cathode electron photoemission in the negative corona (Trichel) current pulse formation and include the first report of a step observed on the pulse leading edge in pure oxygen at atmospheric pressure. In contrast to the generally accepted theories by Loeb and Morrow , present indications are that the ionization mechanism controlling the pulse formation is a feed-forward-to-gas streamer mechanism. Rees T., et al numerical simulation of a Trichel pulse in air at atmospheric pressure explains the fast rise time of the current pulse in terms of field-effect emission. Moreover, this simulation allows one to take the cathode material and its surface state into account. The implemented by Soria-Hoyo et al PIC method has proved to be very efficient in simulating long sequences of Trichel pulses. In the regime of stable Trichel pulses, the numerical results are in good agreement with the characteristics of real Trichel pulses.

The result demonstrates that the information obtained from the waveforms of current pulses is not sufficient to decide the dominating mechanism of electron emission. From the foregoing famous authors concluded that detailed quantitative theories capable of explaining the complexity of the mechanism for stepped negative corona pulses are not available at present.

7-13

DESIGN OF RADIATION OF DIPOL ELECTRON-BEAMS ANTENNA

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The urgency of the problem of generation and radiation of ultra-wideband (UWB) signals makes experimenting with new methods of excitation of the radiating systems. Search options combinations of existing emitters stationary signals, and new methods of excitation of nonstationary signals leads to interesting results that need to carry out multiparameter optimization in each case as the emitting and generating systems. The complexity of such an analysis relates primarily to the complexity of the mathematical modeling of a simple model, which reliably describe the field in the far zone, which occurs when the impact of the real signal to the real radiating structure. For such tasks as a method of analysis with sufficient accuracy can be used finite difference method in time domain.

To generate radiation of high intensity in recent times often used high-current electron accelerators (HCEA). Studies of the generation process and the formation of the pulsed electromagnetic radiation using the technique of HCEA led to the development of electron-beam antenna (EBA), in which the radiating structure connected to the collector of the accelerator, is excited directly by an electron beam [1,2]. Theoretical and experimental studies indicate the possibility of generating pulses with a relatively wide range, which is determined by the spread of the electron energy at the front of the beam. Experimentally investigated the TEM antenna and the opportunity for UWB radiation with high field intensity in the far field. In this paper we present the simulation results of the dipole EBA excitation pulses of different shapes.

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7-14

NEW MECHANISM OF INSTABILITY DEVELOPMENT OF RELATIVISTIC ELECTRON BEAM IN PLASMA, DETERMINED BY ITS ELECTRON FOCUSING/DEFOCUSING

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Preparation of sequence of electron bunches is the very important problem (see [1, 2]). At large relativistic factor of the beam γ_b>>1 the transversal mass of beam particles is essentially less than their longitudinal mass, m_{er}<<m_{ez}. It leads to that at instability development of relativistic electron beam in plasma transversal motion of beam electrons is realized first of all. We simulate the instability development of relativistic electron beam of finite radius in plasma and we show that focusing and defocusing of electron beam are developed first of all due to m_{er}<<m_{ez}. In this paper the results of numerical simulation (by code LCODE) of formation of sequence of relativistic electron bunches due to development of instability of radial focusing and defocusing of continues beam of finite radius are presented. The formation of sequence from continues beam of small density, from dense beam and formation of sequence of bunches, densities of which grow along sequence, from long shaped bunch has been simulated.

Now the wakefield electron bubble is investigated widely [3-5]. In this paper the results of numerical simulation (by code LCODE) of excitation of the wakefield electron bubbles are presented. It is shown, that the wakefield bubble can be excited by non dense bunch but by chain of smaller density electron bunches.

If the energy is spent for bubble excitation, it is useful to strengthen its wake and to use for acceleration of chain of electron bunches, thus increasing the current of accelerated beam. Optimal difference of frequencies of following of bunches and following of wakefield bubbles exists, so N-1 drive-bunches strengthen chain of wakefield bubbles and part of N-th bunch gets in maximal accelerating wakefield.

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7-15

PLASMA ELECTRONS' FLOW FORMATION DUE TO THE MECHANISM OF LANDAU DAMPING IN THE HOMOGENEOUS BEAM-PLASMA SYSTEM

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Interaction of electron beams with plasma is one of the most interesting problems of plasma physics. Interest to this problem is caused by the possibility to use electron beams as a probes for diagnostics of magnetic and electric fields in plasmas, including HF fields, and by various instabilities excited in the beam-plasma systems, that sometimes can result in the beam-plasma discharge ignition [1]. However, these processes don't represent all the variety of effects that take place during the beam-plasma interaction. In particular, some kinetic effects that take place in beam-plasma systems, are usually left out of the scope of the investigations.

In our previous work [2] longitudinal acceleration of plasma electrons due to the impulse, transmitted by the electron beam, was studied both theoretically and by means of the computer simulation. However, for the case of collisionless plasma without magnetic field interaction between electron beam and plasma electrons can be realized only through the electric fields of the charged particles. Strong electric HF field exited by the electron beam during its motion in plasma demonstrates the most essential influence on plasma electrons. Electron beams' energy and impulse transmission to plasma electrons can take place only by the intermediation of this field.

The aim of this work is to study numerically the time evolution of the plasma electrons' velocity distribution function in homogeneous beam-plasma system to find out the flows of plasma electrons, and their correlation with evolution of spatial distribution of the electric field and plasma density profile.For this purpose one-dimensional computer simulation using modified PDP1 code [3] was carried out.

During some time interval one can observe the extension of distribution function in the direction of beams' propagation. Formation of such a "tail" on the distribution function is caused by the resonant plasma electrons trapped by the beam excited Langmuir wave, and for 1D model this effect can be associated with the presence of plasma electrons' directed flows. Due to the mechanism of Landau damping the magnitude of the electric field, exited in plasma by the electron beam, gradually decreases during the time interval when plasma electron flows are observed. At the late stages of interaction one can observe the formation of caverns on the ions' density profile, so the energy of the electric field is spending on deformation of the plasma density profile.

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7-16

PROCESS INVESTIGATION OF CHAOTIC DECAY IN THE RESONATOR FILLED WITH PLASMA

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Nonlinear interaction of waves in the plasma filled electrodynamics system has both scientific and practical meaning. Large number of natural oscillations with different structures in such systems provide wide possibilities for using them in technical applications, in particular for designing HF generators of different purposes.

The results of our investigations may be used for designing generators of chaotic signals. The processes of nonlinear wave decay in the electrodynamics system filled by magnetoactive plasma may be used for this purpose. It was shown before that HF wave in such system may decay into new HF and LF ones. The results of experimental investigations of such process qualitatively agree with the results of theoretical investigations. The oscillations branch that may be used for decay were defined theoretically.

The experimental set up contains multi mode resonator placed into external longitudinal magnetic field. The resonator length is 65 cm, its radius is 7.5 cm. The value of applied magnetic field is 950 Gs. The plasma in resonator is created by means of electron beam with energy 600 eV and current 80 mA. The plasma density is $n_p \sim 10^9$ cm^{-3}, and plasma radius is 2 cm. To excite the pump wave in the resonator at frequency 2.77GGz the magnetron generator is used. In the experiment it was discovered that the duration of exciting oscillation is essentially larger than the magnetron pulse duration. The exciting duration of the resonator oscillation is 2 mcs. The appearance of LF oscillations in the resonator was defined experimentally. It points out that in resonator there is nonlinear decay of HF oscillations (excited by external source - magnetron) into a new HF wave and a LF one. The spectrum of LF oscillations was investigated. It was shown that when the HF power that inputs into the resonator increases then the spectrum width of these oscillations increases too. It qualitatively agrees with the results of theoretical investigations.

In the experiment the new burst of HF oscillations appears in resonator some microseconds after the finishing of the main pulse. The duration, the delay time of the bursts from the main pulse and their number depend on experiment conditions. Their repetition is quasi periodical. The amplitude of every next burst decreases as a result of damping

Two possible mechanisms of appearance of these bursts are analyzed. One of them is conditioned by electron cyclotron instability. The other is connected with Fermi-Pasta-Ulam problem.

7-17

DISPERSION PROPERTIES OF ELECTROMAGNETIC WAVES IN CYLINDRICAL WAVEGUIDES FILLED WITH MAGNETOACTIVE PLASMA

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Investigation of the dispersion properties of electromagnetic waves of cylindrical waveguides filled with plasma under constant external magnetic field has attracted and continues to attract the attention of scientists. It is shown in the lists of publications made during the second half of last century [1, 2] and recently published papers [3, 4]. This subject is of scientific and practical interest for solving a number of modern technological problems such as: development of new powerful generators of electromagnetic waves, development of promising devices for transport of high-current beams of charged particles, search for effective methods of plasma acceleration of charged particles, etc. Cylindrical waveguides with perfectly conducting walls filled with plasma under longitudinal external magnetic field are the most suitable plasma-filled structures for solving the above-mentioned problems because they can be easily described analytically, are simple for experimental realization and are already widely used.

In the articles cited above, which number, if desired, can be significantly extended, the numerical methods are used to investigate the dispersion properties of electromagnetic waves. Unfortunately, the results obtained in this way do not provide a sufficiently general description of electromagnetic waves, which can be obtained only analytically.

This paper presents the methods of analytical solutions of the dispersion equation. The topology of electromagnetic fields is also built. It is shown that the dispersion properties of cylindrical waveguides filled with plasma under constant external magnetic field of finite value are determined by an infinite set of points on the dispersion plane (ω, k_z), where - ω - frequency of electromagnetic wave and k_z - longitudinal wave number. The general form of this set is defined.

Infinity of the set i correlates with an infinity set of the roots of Bessel function of l-th order: $J_l(x_i)=0$, where $x_i^2>0$. The forbidden bands for the electromagnetic waves are also investigated. It is shown that in this region of parameters of electromagnetic waves all the components of electric E and magnetic H fields are identically zero.

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7-18

DYNAMICS OF THE ELECTRON BUNCHES IN HOMOGENEOUS PLASMA: 2.5D ELECTROMAGNETIC SIMULATION

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Dynamics of electron beams and bunches in plasma take one of the leading places in plasma electronics. Charged particles' acceleration by power wake wave fields excited in plasma by relativistic electron bunches [1], inhomogeneous plasma diagnostics using transition radiation of electron bunches and beams [2], transillumination of the plasma barriers for electromagnetic waves using electron beams [3] are actual problems in this field. Theoretical description of processes that can occur in beam-plasma system is generally very complicated or infeasible, therefore computer simulation is often used. PIC method is widespread method of such simulation. Electrostatic nonrelativistic 1D [4] and 2D [5] PIC codes were used in our previous simulations. But there were numerous restrictions in those codes: only nonrelativistic beams could be used, external and self-generated magnetic fields weren't taken into account. Also any effects connected with electromagnetic waves propagation or radioemission in plasmas couldn't be observed.

Therefore new fully electromagnetic relativistic plasma simulation code was created [6]. Beam-plasma system was simulated in 2.5D cylindrical geometry. In this model the space grid has two dimensions, a particle has the form of ring, which can move along a z axis and which radius can increase or decrease, but, they can turn around axis of system, i.e. have an azimuthal component of velocity. Also three components of electric and magnetic field are present at the system. It is possible to simulate the propagation of electromagnetic waves E and H type.

The code was used for study of dynamics of the electron bunch with initially rectangular density profile injected into homogeneous plasma. Both relativistic and non-relativistic bunches were treated. Evolution of the density profile of electron bunches in radial and longitudinal direction was studied. An impact of relativistic factor on the bunch-plasma interaction was analysed. Excitation of electromagnetic wake field was investigated and compared to the results of previous simulations.

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7-19

DIAGNOSTICS OF PARAMETERS OF LOW-VACUUM GAS-DISCHARGE ELECTRON GUNS IN CONDITIONS OF PLASMA BACKGROUND

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The low-vacuum gas-discharge electron guns (LDEG) based on a high-voltage glow discharge are used for solution of various scientific and application problems in conditions of intermediate and low vacuum [1]. However, within the residual gas pressure range 0.1...1000 Pa, transportation of electron beams (EB) is realizing in the presence of plasma background. This circumstance restricts the application of those diagnostic devices for measuring the EB parameters which are exploiting in a high vacuum. In this connection, the problem arises on fabrication of diagnostic devices for measuring parameters of LDEG. Its solution was carried out by complex methods on the basis of the developed diagnostic devices. The plasma density n_e and electron temperature T_e were measured by double probes; the average concentration $\overline{n_e}$ and effective frequency of collisions ν_{EF} – by UHF-interferometer; the radial density profile of current $j(r)$, energy and velocity $\upsilon(r)$ of electrons in the EB cross section – by a "hole camera"; the energy characteristics of LDEG (energy *W*, power *N*, power losses N_X, coefficient of efficiency) were measured by the calorimeter device.

The measurements of parameters of plasma created by EB were provided simultaneously by double probes and the UHF-interferometer. The average electron concentration $\overline{n_e}$ found by probe measurements was in a satisfactory agreement with interferometer data: at pressure of helium 133 Pa, $n_e \approx 0.7 \cdot 10^{10}\, cm^{-3}$ and $n_e \approx 1.1 \cdot 10^{10}\ cm^{-3}$, correspondingly. The effective collision frequency amounts $\nu_{EF} = 2 \cdot 10^8 c^{-1}$.

The Faraday cup could not be used for measuring EB parameters due to ionic neutralization of charge. Thus, for this purpose a special device was developed on the basis of a "hole chamber" method [2]. High efficiency of the device was proven experimentally.

The developed calorimeter measurer of EB power allows to measure energy characteristics of LDEG in low vacuum [3]. For example, the coefficient of efficiency of LDEG of the EDG-9 type was 84...71 % in the pressure range of helium from 10 Pa to 140 Pa at U=20 kV.

The use of developed complex methods and the devices for measuring EB parameters in conditions of plasma background gave chance to select the most rational operating mode of LDEG when working off the technological process.

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7-20

MATHEMATICAL MODEL OF AN EXCITATION BY ELECTRON BEAM OF "WHISPERING GALLERY" MODES IN CYLINDRICAL DIELECTRIC RESONATOR

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Elaboration of electromagnetic radiation sources of millimeter and sub-millimeter range of wave lengths and, especially, range above one terahertz is a perspective and actively investigated direction. At present a generation of oscillations of millimetric wave lengths is provided with classical sources: magnetrons, klystrons and back wave oscillators. However level of radiation power of these sources decreases sharply when passing to sub-millimeter wave lengths.

In spite of these limitations possibility of obtaining of power THz radiation due to classical mechanism of transition and Cherenkov radiations actively develops. It became possible due to considerable progress in obtaining of short (some tens microns and less) high current (with charge of some tens nC) relativistic electron bunches. Recently [1] it was demonstrated experimentally that high levels of electromagnetic fields of the THz frequency range it is possible to reach in dielectric waveguide, due to Cherenkov radiation of power electron bunches. In order to obtain such radiation dielectric structures with the cross-section sizes of order of hundreds microns are necessary.

As the alternative way of an obtaining of high frequency radiation in the paper [2] it is proposed to use a cylindrical dielectric resonator excited by the azimuthally modulated relativistic electron beams. The electron beam excites great numbers of "whispering gallery" modes with frequencies of several tens GHz. Thus structures with millimeter and sub-millimeter dimensions aren't required.

In this work the mathematical model for the description of excitation of "whispering gallery" modes by the azimutalno-modulated electron beam is constructed. The investigated structure is the metal resonator on axis of which it is placed dielectric rod. In vacuum gap. along dielectric rod surface, the azimutally-modulated beam propagates. The beam is represented as a set of some number (generally any) electron beams of cylindrical cross-sections, azimuthal spacing between beams are the same. Construction of mathematical model is based on the general theory of resonator excitation. The dispersion equation for determination of eigen frequencies of "whispering gallery" modes is obtained, eigen waves and their norms are found. Using them, the integro-differential equations for eigen wave amplitudes are derived. Total field is series of eigen waves with determined amplitudes. It is shown that at use of thin electron beams in decomposition of total field there are only modes with azimuthal index equal to quantity of electron beams.

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8-1

PLASMA ASSISTED COMBUSTION OF PARAFIN

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Gasoline, diesel, and turbine engines could soon burn cleaner or be more fuel efficient through the application of Plasma Assisted Combustion. The using of plasma for rocket engineering can to help resolve a series of additional problems. It is the fuel regression rate or steerability of rocket engine wholly. The general advantages of paraffin as a green rocket fuel are high caloricity, ecological compatibility, safety of keeping and high chemical inertness to external factors, etc. The results of assembly investigations of combustion, plasma assisted combustion and paraffin fusion kinetics are represented in this work.

It is know that gasoline, diesel, and turbine engines could soon burn cleaner or be more fuel efficient through the application of Plasma Assisted Combustion. The technology consists of an electronic device that can be attached to an existing fuel injector that applies electrical voltage to the atomized fuel stream prior to combustion - generating a plasma in the fuel. This effect essentially breaks down the long chains of hydrocarbons in the fuel into smaller parts - allowing the fuel to be burned more completely, resulting in more miles per gallon, or reducing harmful emissions.

The using of plasma for rocket engineering can to help resolve a series of additional problems. It is the fuel regression rate or steerability of rocket engine wholly. The results of assembly investigations of combustion, plasma assisted combustion and paraffin fusion kinetics are represented in this work. The general advantages of paraffin as a green fuel are high caloricity, ecological compatibility, safety of keeping and high chemical inertness to external factors, etc.

The commercial stearin was used as a investigated paraffin. The paraffin weight in reactor to combustion was 3 g. The time of full fuel combustion was ~ 1 min for value of air flow into reactor 200 cm^3s^{-1}. The ratio of fuel to oxygen was ≈ 1/1 for experiment conditions.

The steady torch was existed for ratio of fuel energy to energy that was inputted to electrical discharge ~ 20 (= 136.8 / 6).

It is known, that the problem of low regression rate of ecological paraffin fuel impede to full paraffin using in the engines to wide class of flying vehicles.

Spraying of paraffin fuels with carbon atom quantity C<22 at plasma reforming takes place because of origin of capillary waves. However, the spraying is the effect of stable lost for fusion layer for case C≥ 22. This lost of stable can to have explosive character.

The time profile of squared diameter changing for paraffin particles was measured during burning process at burning kinetics investigation

The combustion of paraffin particles was made with using stationary torch. The obtaining experimental results was enabled to define burning constant rate. It was 0,402 mm^2/s.

8-2

EFFECTIVE DISSOCIATION TEMPERATURE FOR ESTIMATION OF ELECTRIC ARC PLASMA COMPOSITION

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A large amount of arc plasma investigation has been carried out. This is caused by wide application of electric arc discharges in different shielding gases or their mixtures in numerous industrial processes. Therefore it is important to perform investigations to have full understanding of physical processes in discharge plasma, at the electrode surface and their interaction as well as influence of environment.

In our previous investigations [1] we found that in some experimental modes the plasma state is not in local thermal equilibrium (LTE). It was shown that hydrodynamic cooling does not effect on the deviation from LTE in monoatomic. It was supposed that this effect has no influence on state of molecule gas plasma too. Therefore, it was assumed that only the thermal dissociation plays the key role in deviation from LTE. Naturally, partial LTE model must be used to describe plasma properties in such case.

The main aim of this study is an estimation of plasma composition under assumption of two temperature behavior based on experimentally obtained plasma temperature, electron density and metal content.

The electric arc was ignited between copper non-cooled electrodes. The arc discharge gap was of 8 mm. The arc currents were of 3.5, 30, 50 and 100 A. Monochromator coupled with CCD linear image sensor (B/W) Sony ILX526A [2] were used in investigations of spatial distribution of spectral line emission. The control of the CCD linear image sensor was realized by the IBM personal computer. Additionally Fabri-Perrot interferometer was used to study shapes of several CuI lines in different points of plasma. Plasma temperature was obtained by Boltzmann plot method. Electron density was measured from the width of spectral lines, broadened mainly by quadratic Stark effect. Copper atom content was obtained by laser absorption spectroscopy technique [3].

Experimental profiles of temperature, electron density and copper atom concentration were used as initial data in calculation of plasma composition. Constant for dissociation was assumed to be an unknown value. The result of calculation allowed estimating the plasma composition and effective dissociation temperature.

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8-3

PROPERTIES OF PLASMA AFTERGLOW WITH LARGE DUST DENSITY

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A spatially-averaged theoretical model for an argon plasma afterglow with nano- and micro-sized particles (dust particles) is developed. The model consists of the balance equations for electrons, ions and metastable (4s) and resonance (4s and 4p) state atoms, the equation for the dust particle charge and the power balance equation. The electron and ion losses and the electron energy loss on chamber walls as well as on dust particles are accounted for. We consider the case when the dust charge density is larger than the electron density.

The model is used to calculate the time-dependencies of the electron and metastable densities, the electron temperature, the dust charge, the electron and ion losses and the electron energy loss. The calculations are related to experimental conditions [1, 2]. The calculated electron and metastable densities in the afterglow are compared with those measured in the experiments [1, 2] and found to be in a good qualitative agreement.

In the dusty plasma experiment [1], the electron density first decreases with increasing of time *t*, then increases and reaches a maximum at $t \sim 0.5$ ms, and then again decreases. Using the model, it is shown that the electron density increase may be due to metastable pooling, secondary electron emission due to ion – dust particle collisions and secondary electron emission due to metastable-dust particle collisions.

The metastable density in the dusty plasma is essentially larger than the density in the dust-free plasma [2]. The metastable density enlargement is due to enhancement of the electron temperature in the steady-state dusty plasma comparing with that in the dust-free plasma. In the dust-free as well as dusty plasma afterglows, the argon metastable atoms are lost from the discharge mainly due to their diffusion to the electrodes. In the dusty case, the diffusion loss dominates over the loss in metastable-dust collisions [2].

The electron temperature decreases faster in the dusty plasma afterglow than that in the dust-free plasma. This the temperature relaxation time is shorter due to the electron energy loss on dust particles.

This work was supported by the Humboldt Foundation, DFG WI 1700/3-1 and Research Department “Plasma with Complex Interactions”, Ruhr-University Bochum.

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8-4

COMPUTER SIMULATION OF DUST TRANSPORT PHENOMENA IN A RF DISCHARGE

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Particle contamination during plasma processing of semiconductors is known to be a significant contributor to reductions in product yield. Particles can charge negatively in a plasma and trap in minima of combined gravitational and electric potential fields, forming dust clouds [1]. There have been many experiments on fine particles, which have clarified various interesting features of fine particles in plasmas. Strong interactions of dust particles and the openness of the system lead to self-organization and 'structurization' of initially homogeneous dust clouds into a complex aggregate of dissipative dust structures and dust voids, with sharp boundaries between them [2]. These structures become quasi-stationary within short time scales and they are determined by a limited number of parameters controlling the structure. Here, we are interested in shape and structure of fine-particle clouds, namely the effect of particulate size on the spatial distribution of dust in a plasma environment is investigated through the simulation of a dust transport model coupled with plasma model.

This article focuses on simulation of dust transport in capacitively coupled, parallel pate, rf plasma reactors. A two dimensional PIC/MCC simulation is employed to predict plasma properties which have major effects on dust behaviour in the reactor. Individual particulate trajectories are tracked, taking into account the various forces acting on the particulate. Gravitational, electrostatic, ion drag, neutral drag forces are considered to describe the particulate motion in the plasma environment. The electrostatic force consists of two components. The first one is determined by effect of electrons and ions on dust particles, the second one is determined by a dust particles interaction. In this study, the presence of dust particles influences on plasma parameters and plasma influences on dust particles.

In this paper we present results for argon discharges with dust particles. Calculations were carried under the microgravity and in a laboratory conditions with different dust radius, number of dust particles and the neutral gas pressure. The frequency and amplitude of the radio-frequency voltagy were $w = 13{,}56MH, U = 500V$.

Results of calculations under laboratory conditions show that dust particles form two arched dust layers at edges sheaths near electrods. Forming of dust structures is defined by a superposition of forces, acting on the dust particles. Dust particles of radius $r_d = 1\,\mu m$ in the bottom layer form small clouds. The reason of this effect is the rise of oscillations in the dust layer.

The particles under microgravity conditions ocupy their equilibrium position in the sentral part of the discharge chamber. Besides, the void formation is observed in the center of the dust cloud. It is generally results from the balance of the electrostatic and the ion drag forces acting on a dust particles. It is can be seen that negative dust charge influences on the potential in a discharge and spatial distribution of electrons significantly.

This work was supported by joint NASU-RFFR grant.

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8-5

ENERGY CHARACTERISTICS OF GLOW DISCHARGE IN A SPHERICAL GEOMETRY

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An abnormal glow discharges (GD) are widely using in technological processes of the constructional details' surface modification providing maximal localization of the technological action on a treated surface. Unfortunately, the rich material of publications available for today in this area is limited, mainly, to empirically obtained dependences regarding application of plasma as technological atmospheres. It does not allow making the strict analysis of efficiency parameters.

A basis of analytical methods for optimization of processes should make, naturally, the careful analysis of physical processes in the plasmas as technological atmospheres. These processes are studied both experimentally and theoretically. The discharge plasma is generated in nitrogen or N_2-Ar mixture at the pressure 50 ÷ 250 Pa and discharge current up to 120 mA. The cathode is metal plate 5 cm in diameter or sphere up to 3 cm in diameter in the central part of the discharge volume of 0.1 m^3. The constructional details to be modified were placed on this plate. The temperature of cathode was controlled by a thermocouple. The density of charged particles and the electrical potential distribution were measured by Langmuir probes, which could move along the radius of the chamber. GD was powered by rectified voltage up to 1500 V.

This system was approximated as spherical diode in numerical simulation. The balance equations for the density of charged particles and Poisson equation added with equation for heat conductivity are taken into account in the theoretical part of investigation. As is shown, the correct account of the anode fall of potential plays a key role to represent adequately the volt-ampere characteristic (VAC) of the spherical.

As it is well known, despite the influence of nonlocal effects, the estimated VAC of GD in fluid model is well correspond to the real. This is due to the fact that only a small part of fast electrons from their total number is responsible for these effects.

Previously we simulated spherical GD, paying special attention to the problem of adequate description of the diffusion processes. The role of the latter can be very significant at low pressures. The system of fluid equations was solved in this case. The results obtained were in a good agreement with the basic tendencies of experiment. At the same time, there were some problems concerning quantitative consistency between numerically obtained results and experimental one.

The influence of cathode temperature on the processes in discharge volume might be taken into account to further approach of experimentally obtained and numerically calculated VAC. In this case the set of equation in fluid model was added with equation for heat conductivity. The last equation describes the influence of the hot cathode on the processes in discharge volume. With account of this equation the temperature of gas in discharge volume is changed from 800 K at the cathode to 400 K at the distance 5 cm from it.

8-6

PLASMA REFORMING OF ETHANOL IN DGCLW DISCHARGE

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Combustion efficiency plays a critical role in performance of chemical energy conversion and chemical jet propulsion systems. For this reason, searching of innovative ideas and approaches to efficient combustion is very important for progress toward the development of more advanced combustion technologies.

From physics and chemistry of fuel combustion it is known that addition of light inflammable gases (H_2, CO) essentially improves ignition/combustion of heavy oil and bio-fuels. Therefore hydrogen is considered as one of the most prospective energy sources for the future that can be renewable, ecologically clean and environmentally safe. Among possible technologies for free hydrogen production, including steam reforming and partial oxidation of bio-fuels, a low-temperature plasma-assisted fuel reforming is believed to be a good alternative approach.

For plasma fuel reforming, various methods using thermal and non-thermal plasma are known. Thermal plasma, which is thermodynamically equilibrium, has characteristics of high ionization by higher energetic density. This has merits of good rate of fuel decomposition but demerits of poor chemical selectivity and high specific energy consumption. Non-thermal (low-temperature) plasma, which is kinetically non-equilibrium, has characteristics of low ionization but benefits of high reactivity and selectivity of chemical transformations providing high enough productivity at relatively low energy consumption; this can be obtained by high voltage discharging in a flow at low or high atmospheric pressures.

One of the potential sources of non-thermal plasma that can provide simultaneously a high level of non-equilibrium and high density of reacting species in the plasma-liquid system is the electric discharge in a flowing gas channel with liquid wall (DGCLW). Also DGCLW discharge can work in the bubbling microporous liquid which has a very large ratio of the plasma-liquid contact surface to the plasma volume. As is known the ultrasonic (US) cavitation is a very effective method for creating micropores in liquid. Therefore, the DGCLW with additional US pumping is also very interesting for research and development.

This paper presents the results of experimental and theoretical investigations of the process of non-thermal plasma-assisted reforming of aqueous ethanol solutions in the dynamic plasma liquid systems using the DC electric discharges in a gas channel with liquid wall and the additional excitation of ultrasonic field in liquid. The experiments show possibilities and efficiency of low-temperature plasma-chemical conversion of liquid ethanol into hydrogen-rich synthesis gas in different regimes. The numerical modelling clarifies the nature and explains the kinetic mechanisms of non-equilibrium plasma-chemical transformations in the plasma-liquid systems in different modes.

8-7

PLASMA OF ELECTRIC ARC BETWEEN COMPOSITE ELECTRODES ON SILVER BASE

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The plasma parameters of electric arc discharge were investigated by optical emission spectroscopy and linear laser absorption spectroscopy as well. The composites on silver base, in particular Ag-CuO, were used as electrodes materials. Effects of these elements in the composition of materials on secondary structure of electrodes surface were studied. The condition of the electrodes surface has been investigated by optical and electron microscopy (Neophot, Superprobe).

The arc was ignited in air between the end surfaces of the non-cooled electrodes. We used the next parameters of electric arc: the diameter of the rod electrodes was 6 mm, the arc discharge gap was 8 mm and arc current was 3.5 and 30 A.

The determination of copper vapour spatial distribution in electric arc discharge plasma was carried out by linear laser absorption spectroscopy. Copper vapour laser “Criostat 1” was used in such techniques. The CCD array coupled with a personal computer was used in registrations.

The spatial distribution of the temperature and the electron density in plasma of electric arc discharge between Ag-CuO electrodes are determined by optical emission spectroscopy techniques. Selection of AgI spectral lines as well as their spectroscopic data was provided by comparisons of such kind data of preliminary chosen CuI spectral lines. The copper vapour distribution in the discharge gap was determined by optical emission spectroscopy in assumption of local thermodynamic equilibrium and linear laser absorption spectroscopy techniques as well.

It was found by the metallographic analysis of working layers of Ag-CuO composition that under influence of a heat flow from the arc discharge in air in a working layer the secondary structure is formed.

So, the complex spectroscopy techniques in the investigations of plasma parameters of electric arc discharge between composite Ag-CuO electrodes were performed. The type of secondary structure is depended from composition of electrode material and discharge-current magnitude as well.

8-8

MATERIAL SURFACE MODIFICATION UNDER THE ACTION OF COMPRESSION PLASMA FLOW LOADED WITH DOPING ELEMENTS

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The action of high-power compression plasma flows loaded with doping elements on various materials makes it possible to implement principles of a new scientific discipline under development – surface plasma metallurgy. Such an energy- and resource-saving approach enables one to obtain materials whose surface can be of practically any specified structural-phase composition which is unapproachable to other techniques.

Presented in the report are the results of the substantial improvement in surface properties of various materials (construction and tool steels, hard alloys, semiconductors, etc.) exposed to compression plasma flows loaded with doping elements which causes the efficient structural-phase transformations and deep doping of the modified layer with gas-phase and metallic hardening elements. Compression plasma flows were generated by a gas-discharge quasistationary plasma accelerator of the type of a magnetoplasma compressor (MPC) with capacitor bank energy up to 15 kJ. Under experimental conditions with nitrogen as a working gas in a vacuum chamber of MPC, the electron temperature and concentration of plasma comprising the compression flow reached 2-5 eV and 10^{16} – 10^{18} cm^{-3} respectively at the discharge duration of ~ 150 μs. A finely dispersed powder of the doping elements was introduced in the compression plasma flow by means of a devised electromechanical injector.
Exposure of BT 1.0 titanium samples to the compression plasma flow loaded with Cr particles results in the appearance of hardening nitrides and β-Ti(Cr) solid solution that substantially improve tribologic properties of a target surface (hardness increases by 1.5 – 2.5 times and a friction coefficient reduces by 4.5 times). When processing aluminium and its alloys by compression plasma flows with introduced Ti additives, produced in the modified layer are strengthening phases (nitrides and intermetallic compounds) due to which the microhardness of the surface layer increases by 4-7 times. The action of the same plasma flow on a silicon wafer results in the formation of a deep (up to 7 microns) doped layer containing titanium silicides among them a most low-resistance titanium disilicide, $TiSi_2$, which are in great demand in micro-, opto- and nanoelectronics.

This work has been supported by the Belarusian Fund for Fundamental Research (Grant F10R–212).

8-9

PLASMA LIQUID SYSTEM WITH REVERSE VORTEX FLOW OF TORNADO TYPE (TORNADO-LE)

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Today, hydrogen is considered as one of the most perspective energy sources for the future that can be renewable, ecologically clean and environmentally safe. Among possible technologies for hydrogen (H_2) production, including steam reforming and partial oxidation of hydrocarbons, a low-temperature plasma-assisted reforming of biomass-derived ethanol (ethyl alcohol C_2H_5OH) is believed to be a good alternative approach. There are various electric-discharge techniques of plasma conversion of ethanol into H_2 using thermal (equilibrium) and nonthermal (nonequilibrium) plasmas: arc, corona, spark, MW, RF, DBD, etc. Among them, one of the most efficient is the plasma processing in the dynamic plasma-liquid systems (PLS) using the DC discharge in a reverse vortex gas flow of tornado type with a "liquid" electrode (TORNADO-LE).

PLS reactor was prepared with the DC discharge in a reverse vortex gas flow of tornado type with a "liquid" electrode (TORNADO-LE). It consists of a cylindrical quartz vessel by diameter of 9 cm and height of 5 cm, sealed by the flanges at the top and at the bottom. The vessel was filled by the work liquid through the inlet pipe and the level of liquid was controlled by the spray pump. Minimal static pressure above the liquid surface during the vortex gas flow is located near the central axis, it creates the column of liquid at the gas-liquid interface in the form of the cone with the height of ~1 cm above the liquid surface (without electric discharge).

The voltage was supplied between the upper electrode and the lower electrode in the liquid with the help of the DC power source powered up to 10 kV. Two modes of the discharge operation were studied: the mode with “liquid” cathode (LC) and the mode with “solid” cathode (SC): “+” is on the flange in the LC mode, and “-” is on the flange in the SC mode. The voltage was supplied between the upper electrode and the lower electrode in the liquid with the help of the DC power source powered up to 10 kV. Two modes of the discharge operation were studied: the mode with “liquid” cathode (LC) and the mode with “solid” cathode (SC): “+” is on the flange in the LC mode, and “-” is on the flange in the SC mode. The conditions of breakdown in the discharge chamber were regulated by three parameters: by the level of the work liquid; by the gas flow rate G; and by the value of voltage U. The ignition of discharge usually began from the appearance of the axial streamer; the time of establishment of the self-sustained mode of operation was ~1-2 s. The range of discharge currents varied within 100-400 mA. The pressure in the discharge chamber during the discharge operation was ~1.2 atm, the static pressure outside the reactor was ~1 atm. The elongated ~5 cm plasma torch (10) was formed during the discharge burning in the camera.

Current-voltage characteristics of the TORNADO-LE with the “liquid” and “solid” cathode working in water at different airflow rates was measured.

Mass-spectroscopic measurements of the hydrogen concentrations in output gas products after the ethanol processing in the TORNADO-LE were made. Also output gas composition was measured by gas-chromatography (H_2 - 28%, CO - 17,5%, N_2 - 55%, CO_2 - 4,5%). The data are given for the case of mixture $C_2H_5OH : H_2O$ = 1:7 and airflow rate G=55 cm^3/s.

The dependence of the coefficient of energy transformation for the ethanol reforming in the PLS with the TORNADO-LE as a function of the ethanol concentration in the ethanol-water solution was measured. Speed generation of synthesis gas is 0,2 m^3 per hour.

8-10

EXPERIMENTAL INVESTIGATION OF GAS-VAPOR DISCHARGE BETWEEN JET ELECTROLYTE CATHODE AND SOLID ANODE AT LOW PRESSURES

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One of the novel methods of obtaining non-equilibrium low temperature plasma is to use a gas-vapor discharge between an electrolyte jet and a solid anode at low pressures. The non-equilibrium plasma of a gas-vapor discharge has a variety of properties useful for a number of practical applications.

In this work studied are the forms of electric discharges between a jet electrolyte cathode and a solid anode (metal or dielectric) in wide ranges of pressures (1 ÷ 760 Torr), jet lengths (2 ÷ 100 mm), jet diameters (2 ÷ 5 mm). Solutions of NaCl, $CuSO_4$, NH_4SO_4 in tap water were used as electrolyte.

It is established that in the range of pressures 760 ÷ 364 Torr a multichannel discharge is burning along the electrolyte jet. The discharge transforms to a glow discharge with the decrease of pressure from 304 to 1 Torr. The transition of a multichannel discharge to a glow discharge is observed for the first time. The negative glow of blue color engulfs the electrolyte jet. The plasma column of the glow discharge is observed when the jet comes off the surface of the solid anode.

8-11

PHOTOEMISSION DISCHARGE

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The paper presents the results of theoretical analysis of self-sustained unipolar electron discharge where volume ionization is absent and electrons appear due to photoemission from cathode under the influence of ultraviolet radiation generated in the discharge. Then the electrons drift and diffuse to the gas discharge volume. This type of gas discharges we called photoemission discharge (PD). The main advantage of PD as a mean for gas excitation in discharge applications is the absence of ions which usually play a negative role in gas discharge devices.

Threshold and volt-ampere characteristics of direct current PD are determined. The parameters of gas gap needed for realizing of PD are found.

8-12

CHARGING PROCESSES OF METAL MACROPARTICLES IN THE LOW-TEMPERATURE PLASMA AT PRESENCE OF HIGHT-ENEGRY ELECTRON BEAM

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The implementation of various vacuum-plasma technological processes of processing of a surface of a solid body important influence on quality of processing is rendered by cleanliness of gas medium and a composition of streams of the charged and neutral particles on a handled surface. In particular, essential meaning has presence of macroparticles in a plasma flow, such as cluster ions, dust originating from the environment, melted drops coming from material of electrodes, etc.

One of major factors influencing dynamics of single macroparticles in plasma and, consequently, the behaviour of “dust plasma” as a whole, is an electrostatic charge of macroparticles, which they gain due to interaction with the charged and neutral particles of environmental plasma. The basic mechanisms of a charge of macroparticles in plasma concern: uptake of streams of electrons and ions from plasma, secondary ion-electronic and electron-electron emission, a thermionic emission. The steady-state value of electrostatic potential of a macroparticle can be derived from the balance of currents flowing through its surface.

Typically, laboratory plasma transports the charge and consequently represents the conducting plasma environment and currents of charged particles. Therefore, the macroparticle-plasma system is of particular interest, where presence electronic component with the velocity vector exceeding the ion velocity vector provides essential contribution.

The temperature of macroparticles increases due to energy exchange with with electrons and plasma ions through the collisions. However, the heat process may be intensified by introducing beam coupling system, which changes character of processes governing the energy exchange.

Present work studies the influence of parameters of beam-plasma system and macroparticle temperature on its potential. Theoretically, within the limits of orbital model, it is shown, that in a gamut of low meanings of temperature of a macroparticle, its potential is spotted by a relation of densities of a beam coupling and plasma, and also quantity of energy of electrons of a bundle. It is shown, that increase of macroparticle temperature leads to decrease of its potential due to growth of the thermo-electron current at the expense of a thermionic emission.

8-13

CONTROL OF PLANAR MAGNETRON SPUTTERING SYSTEM OPERATING MODES BY ADDITIONAL ANODE MAGNETIC FIELD

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Rapid development of the solid surface treatment technologies forces the improvement of the vacuum-plasma processing equipment. Magnetron sputtering method is one of wide spread occurrence methods among the variety of film deposition methods. Magnetic field configuration under the sputtering target is the major factor causing magnetron-sputtering system working parameters.

Magnetic field configuration defines potential distribution in the main particle generation discharge region where current-carrying electrons are magnetized and also it defines sputtering target erosion zone. Besides, the magnetic field configuration defines the neutral and charged particles fluxes to the operating surface direction as well as temperature load to the operating surface and coating homogeneity. It is necessary to consider a lot of parameters and carefully choose the operating conditions to realize specific film deposition problem by magnetron-sputtering system. It turns out that there is no way to modify the magnetic field configuration in modern magnetron-sputtering systems because the magnetic field is created by the permanent magnets system or coils.

In current paper the control of planar magnetron sputtering system operating modes by additional anode magnetic field was investigated. The additional anode magnetic field was created by the permanent magnets and magnetic circuits system out of conventional magnetron-sputtering system. The influence of magnetic field configuration alteration on discharge characteristics was investigated both theoretically and experimentally. It was shown that additional anode magnetic field substantially affects to planar magnetron-sputtering system balancing and allows adjusting the electron fluxes intensity to the operating surface.

It was experimentally shown that the magnetic field intensity increasing stabilizes the low-current discharge. The magnetic field intensity increasing prevents the discharge extinction by the ignition of semi-self-maintained magnetron-type discharge in magnetic arc upon the sputtering target. The transverse anode magnetic field provides the electrons drift in the same direction as in cathode arc magnetic field. The additional anode magnetic field creation by the outer magnets and magnetic circuits application allows providing any required magnetron sputtering system operating conditions without additional power supplies and basic construction conventional equipment engineering change.

8-14

PHASE STATES OF MACROPARTICLES UNDER INTERACTION OF keV ION BEAM WITH DUSTY PLASMA

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Dusty plasma is one of the most intensive developing branches of the modern plasma physics. Dusty plasma research is of huge practical importance because of macroparticles presence in a lot of vacuum-plasma processes.

Peculiarities of the keV-energy charge-compensated ion beam interaction with dusty plasma macroparticles is studied theoretically in this report.

Electric potential of dusty plasma macroparticle in such ion-plasma systems is shown to be negative. It is determined by the average energy of electrons which compensate ion beam. These electrons' energy is much less than that of beam ions. Cross-section of interaction between beam ions and the macroparticle is equal with high accuracy to that of macroparticle. Ion beam core uses to be under the positive potential. Negative potential of the dusty plasma macroaprticles makes conditions for their capture into the core of ion beam and their efficient interaction with ion beam.

Heat and mass balances of the macroparticles in ion-beam system are considered. It is shown that it takes several dozens of seconds for the temperature of macroparticles to reach the melting temperature. Decreasing of the macroparticles mass is associated with both sputtering by the ion beam and evaporating after reaching the melting temperature.

Numerical simulations demonstrate that the ion beam – dusty plasma system can compete in the respect of energy efficiency of substance evaporating with existing industrial evaporating systems which are designed for thin films depositing and utilize containers in the form of crucibles for the substance to be evaporated.

8-15

ION-BEAM SYSTEM FOR NANOTRIMMING OF FUNCTIONAL MICROELECTRONICS LAYERS

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The report describes the system, which uses a corrective ion-beam etching to adjust the thickness of the microelectronics functional layers with high precision on substrates with a diameter of 100 to 200 mm. The system consists of the medium-energy anode layer ion source [1], which generates a focused ion beam with a diameter of 3 mm on the wafer, and the coordinate scanning-positioning system with the programmed control for the ion beam. Ion source provides non-filament self-neutralization of ion beam charge. This feature is based on the hollow cathode effect with a transverse magnetic field. The source is capable to produce ion beams of chemically active gases. The etching rate of local functional layers is controlled by the variation of the beam power. The precision positioning and measurement of layer thickness provides comprehensive control over the intensity of the etching and its location on the wafer.

The ion-beam trimming process involves two stages. At first, three-rayed interferometer obtains the topography of the functional layer surface. This topography map is used calculating local parameters of the etching process. Then the functional layer on the wafer is etched by scanning ion beam using the polar coordinates. The ion beam power and position is controlled according to the topography. The trimming allows to decrease the thickness inhomogeneous below a nanometer.

As a result, the thickness uniformity improves 7x per single pass; 20x ultimate thickness uniformity improvement; up to 8 wafers per hour of throughput depending on application; minimum thickness loss can be approached to zero if needed (patent pending); film thickness distribution can be adjusted to +/- 4A.

Ion-beam system can be used in many technological processes and for a number of applications, where improvement of the surface roughness is required. Examples of such applications are gradient films and structures generation; correction of high-quality optics errors polishing; storage device production (smoothing the surface after chemical-mechanical processing, adjusting the thickness of the thin-film magnetic heads), and devices on bulk and surface acoustic waves (adjusting the thickness of the functional layers - the operating frequency); adjustment of the optical films thickness; optimization of the electric resistivity of resistive and infrared films.

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8-16

ANODE CURVATURE INFLUENCE ON CHARACTERISTICS OF NEGATIVE CORONA DISCHARGE UNDER TRICHEL PULSED MODE

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Experimental study of electrodynamics characteristics of negative corona discharge in air under Trichel pulsed mode are presented.

Corona discharge dynamics is rather difficult and non-stationary process which is depend on conditions at the cathode area and drift zone of discharge gap. The processes occurring at the cathode area were studied a lot, but the processes that occurring at the drift zone were not investigated good. The influence of anode dimensions and curvature on discharge current parameters in strongly non-uniform electric field was studied. Point to plane and point to sphere electrode systems were used. The dependence of anode dimensions and curvature on current pulses frequency was established. It was shown that at the same conditions the decreasing of anode curvature causes the increasing of current pulses frequency. At the same time the parameters of Trichel pulses remain constant for different anode curvatures. It is necessary to note that the variation of anode dimensions has a proportional action on current pulses frequency; however the increasing of the applied voltage disturbs the effect. The increasing of average discharge current value under decreasing of anode curvature also observed.

It was experimentally shown that only under defined range of applied voltages we can observe the influence of anode dimensions and curvature on characteristics of discharge current. Research results indicate that current pulses frequency probably depend on rate of negative bulk charge relaxation, and anode curvature determines the intensity of physical processes which are responsible for relaxation effect.

Also the anode glowing spatial characteristics for different anode curvatures were investigated.

8-17

EROSION OF VACUUM-ARC TiN-COATINGS IN PLASMA OF STATIONARY MAGNETRON TYPE DISCHARGES

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The process was studied of an erosion of titanium nitride coatings deposited on stainless steel (SS) substrates with help of vacuum-arc method using two different technological ways: with high voltage negative pulses on substrate and without of the ones. The erosion rates were measured with weight loss method by sample weighting before and after exposure in the stationary plasma of magnetron type discharges. The typical discharge parameters were: ion current values were 40-180 mA, cathode potential values were 400-1000V, magnetic field was 0.05T, work gas pressure (hydrogen, helium, nitrogen, argon) was about 0.2 Pa. The edge plasma characteristics were measured using Longmuir probe, such as electron temperature, electron density and plasma potential. As distinct from the most TiN sputtering literature data obtained at the room temperature of the samples, in our case the sample temperatures were in the range of 500-1000ºC. The necessity of such researches was caused by the fact that some elements with TiN-coatings are supposed to be used in the Uragan-2M torsatron (limiters, RF antennas components etc.). In conditions of impact of power plasma flows the work temperature of plasma facing components can be essentially higher than room temperature. For comparison SS erosion characteristics were measured, too.

It was shown that the absolute values of TiN erosion rates for both kinds of the samples were in about 2 times lower than that for SS samples and weakly depends on the temperature. At the low values of discharge current the erosion rate of TiN films, deposited with the use of high voltage negative pulses on substrate, is essentially lower than that for the samples made with the usual technology (without high voltage negative pulses on substrate). But when discharge current increases (sample temperature increases) the erosion rate values becomes similar for both types of the samples. The possible physical mechanism is suggested and discussed to explain such character of the erosion behavior.

8-18

INFLUENCE OF PLASMA STREAM PARAMETERS IN PULSED PLASMA GUN ON MODIFICATION PROCESSES IN EXPOSED STRUCTURAL MATERIALS

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This paper is focused on investigation of helium, nitrogen and krypton plasma streams generated by pulsed plasma gun PPA. The main objection of this study is adjustment of plasma treatment regimes for different materials that allows achieving optimal thickness of modified layer with simultaneously minimal value of surface roughness. Features of materials alloying from gas and metallic plasma as a result of the plasma ions mixing with the steel substrate in liquid phase are discussed also.

The PPA device consists of coaxial set of electrodes with anode diameter of 14cm and cathode diameter of 5cm and vacuum chamber of 120cm in length and 100cm in diameter. The power supply system is capacitor battery with stored energy of 60kJ for U=35kV. The amplitude of a discharge current is ~400 kA, plasma stream duration is 3-6µs. The pulsed plasma accelerator generates plasma streams with ion energy up to 2keV, plasma density (2-20)x10^{14} cm^{-3}, average specific power of about 10 MW/cm^2 and plasma energy density varied in the range of (5-40) J/cm^2. The regime of plasma treatment was chosen with variation either accelerator discharge voltage or the distance of the exposed samples from the PPA output.

Diagnostics of pulsed helium, nitrogen and krypton plasma streams and their interaction with materials included optical techniques, calorimeters, different probes and piezodetectors.

Modification of thin (0.5-2 µm) PVD coatings of MoN, C+W, TiN, TiC, Cr, Cr+CrN and others with the pulsed plasma processing are analyzed. Mechanisms of surface modification of a different alloys and coating irradiated with pulsed plasma streams of different ions are discussed. It is shown that pulsed plasma treatment may result in essential improvement of physical and mechanical properties of exposed materials. For example, microhardness of samples with Cr coating, after plasma treatment, increased in 2,5 time.

Experiments with different steels and cast iron reveal possibility for essential increase of their wear resistance in result of applied combination of coatings deposition with pulsed plasma processing. Alloying of surface layer in result of the coating-substrate mixing in liquid stage allows achievement of desirable chemical composition in surface layers being most loaded in all machine components. In particular, combined plasma processing is found to be prospective for modification of piston rings and other machine parts operating in conditions of bearing or dry friction.

8-19

SPATIAL DISTRIBUTIONS OF PLASMA PARAMETERS IN ICP REACTOR

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The results of systematic experimental researches of ICP reactor [1] are presented in this paper. Experimental results on spatial distribution of local plasma parameters (plasma density, temperature and electron energy distribution function) and radial profiles of ion current to processed surface are presented for atomic (Ar) and molecular (N_2,CF_4) gases. The plasma parameters were measured by movable Langmuir probe with automated computer-based processing of the probe traces [2]. The radial profiles of the ion current to the processed surface were measured by means of an array of plane probes placed on the surface of the substrate holder. It is discovered that for argon pressure $p < 350$ mTorr the radial current density profile is convex with the maximum at the discharge axis. For the pressures $p > 350$ mTorr the profile becomes concave with the minimum current density at the axis. It should be noted that the profile shape transformation with the pressure change isn't monotonic. At the pressure < 1 mTorr the profile is convex and shows pure uniformity. The best uniformity of the ion flow appears at the pressure 2 mTorr, then the uniformity becomes worth with the pressure growth to 60 mTorr. The further increase of the pressure leads to the uniformity improvement, but at the pressure >1 Torr the uniformity becomes pure again due to the local minimum appearing in the center. The plasma density radial distribution shows analogous shape transformation with the pressure change. For the pressure 20 mTorr the distribution has the maximum in the center while at 60 mTorr the local minimum appears at the discharge axis. At the further pressure growth the maximum moves to the center again and for the pressures greater than 140 mTorr the profile becomes concave with the maximum near the inductive coil. Relation between the plasma density profile and the ion current density radial distribution is discussed. Comparison of the obtained results with the calculations executed using 2D-fluid model [3] has allowed to reveal the main rules of the ion flux profile formation.

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8-20

OPTIMIZATION OF OZONE CONCENTRATION DURING OZONE-DYNAMICAL TYRE DISINTEGRATION

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The ozone disintegration kinetics in the chemical reactor intended for tyres disintegration was experimentally and theoretically investigated. Ozone was synthesized in barrierless ozonators on the streamer discharge. As power inputs on ozone synthesis are great enough and ozone disintegrates fast, the optimization of the chemical reactor is necessary.

The chemical reactor for tyres decomposition in the ozone-air environment represents the fed by cylindrical chamber, which feeds from the ozonator by ozone-air mixture with specified volume speed and with known ozone concentration. The output of the used mixture is carried out in surrounding space, which volume speed is also known. As a result of ozone disintegration in the volume and on the reactor walls, and output of the used mixture from the reactor, the time-dependent ozone concentration is established in it. In paper the analytical expression for dependence of ozone concentration in the reactor from time and from the parameters of a problem, such as volume speed, the feeding of the ozone-air mixture on the reactor input, ozone concentration on the input in the reactor, volume speed of the used mixture output, the volume of the reactor and the area of its internal surface is received. It is shown that experimental results coincide with good accuracy with analytical, received in the assumption that the ozone disintegration kinetics is the kinetics of first order, and also with simulation.

8-21

ABOUT INFLUENCE OF ENERGY OF ELECTRONS AND IONS ON SPEED OF ELECTRON- AND ION-STIMULATED PLASMACHEMICAL ETCHING OF SILICON

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In spite of wide application plasmachemical etching (PCE) in the technological processes of microelectronic, computer and microwave engineering, components of radio electronics and etc., physics of PCE process researched not enough. Influence of electrons and ions energy on speed of different materials etching in PCE is not researched. In this work the influence of electrons and ions energy on silicon etching speed was investigated.

Researches were realized in plasmachemical reactor (PCR) with the reserved drift of electrons [1]. It was possible to change the energy of ions in PCR by few methods. One of them is a change of value and configuration of the magnetic field. It is thus possible to change self-bias voltage in PCR from -40V to -200 V. Average ion energy [2] approximately corresponds to energy of particle in the electric field of self-bias voltage. Change of the magnetic field intensity lead to accordingly changes of parameters chemically active plasma (at other parameters of discharge invariable), and speed of etching changes. Second method of change of active electrode bias voltage consist in supply constant potential through the filter on discharge gap of HFD. Under such conditions succeeded to receive both positive and negative potential on an active electrode with transition through «0», that allows to select or ion- and electron-stimulated etching or only chemical etching without electronic- and ionic stimulation.

Research of influence self-bias voltage values (U_{sb}) on etching speed of monosilicon realized at the same current discharge, magnetic intensity, magnetic field structure, pressures of working gas, area of monosilicon plate (which are exposed to the etching) and constant HF-power in a reactor. The range of U_{sb} without the discharge breakdown was -220-0-+200 V. Positive potential, input on an active electrode, causes electronic and negative ions of fluorine surface processes stimulation. Thus there is an increase of etching speed with the increase of positive bias potential, but polymeric films appear at surface silicon. At the increase of negative bias potential the etching speed is increased at first, but at voltage above –(160-230) V occur decrease of monosilicon etching speed independently of bias voltage modify method. To explain it by influence of the increase of energy contribution to discharge power due to direct current power contribution is not possible, since it makes a few percents from a HF power contribution. Other possible mechanisms of influence of ions energy on monosilicon etching speed are examined.

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8-22

THE EMPIRICAL FORMULA OF DEPENDENCE OF FACTOR OF DISINTEGRATION OF NONIDEAL PLASMA FROM ELECTRONS CONCENTRATION

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Recombination processes in nonideal plasma (NP) are investigated insufficiently as theoretically so experimentally. This is a consequence of complexity of the theoretical description of processes proceeding in nonideal plasma [1-4]. Experimental results are too difficult for receiving, since nonideal plasma exists in laboratory conditions very short times - nano-micro and millisecond. There are no equipment and techniques allowing to measure parameters NP. Only last years some theoretical works devoted to this subject [3-4] have appeared. Experimental examine of theoretical works is necessary.

Given work is devoted to finding of the empirical formula for dependence of plasma decay rate on concentration. In work [5-6] experimental results of dependences of decay factors from electron concentration in double logarithmic scale are resulted. By results of these works the decay factor of plasma practically linearly decreasing with increasing in electron concentration in plasma and the empirical formula is picked up:

$$K=4.9\cdot 10^{8}\,(N_e)^{-1,2}=4,9\cdot 10^{8}\cdot (N_e)^{-6/5}$$

where $\dfrac{dN_e}{dt} \Big/ n_e^2$ = K - (cm^3 / s) factor of decay, N_e - (cm^{-3}) concentration electrons. This formula describes dependence K from N_e in a range of concentration electrons 10^{17} cm^{-3} $\leq N_e \leq 10^{22}$ cm^{-3} and the range of temperatures (7-35) 10^3 K. The data for hydrogen -oxygen plasma in the range 10^{17} - 10^{20}, and for 10^{20} - 10^{22} cm^{-3} tungsten plasma are received. Magnitude ions charge and temperature were not taken into account. Experimental data on the decay factors for three discharge modes are received. The temperature changed within the limits of (7 - 35) $\cdot 10^3$ K. In tungsten plasma the second ionization is possible. Comparison of the received results with theoretical calculations on works [2-4] is made. At comparison of experimental results with the theoretical work [2] the big distinction which, decreases with reduction N_e, is received. The mechanism triple recombination – electron – electron – ion is supposed. The theoretical work [3] predicts reduction of decay factor with increase in electron concentration that qualitatively coincides with the results received experimentally. In this work it is supposed binary recombination, instead of triple. In work [4] presence of a maximum at a degree of nonideality $\Gamma \sim 1$ is supposed, but influence of an ion charge on a recombination factor is taken into account.

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8-23

VOLT-AMPERE CHARACTERISTIC OF MAGNETOSTIMULATED DIELECTRIC BARRIER DISCHARGE

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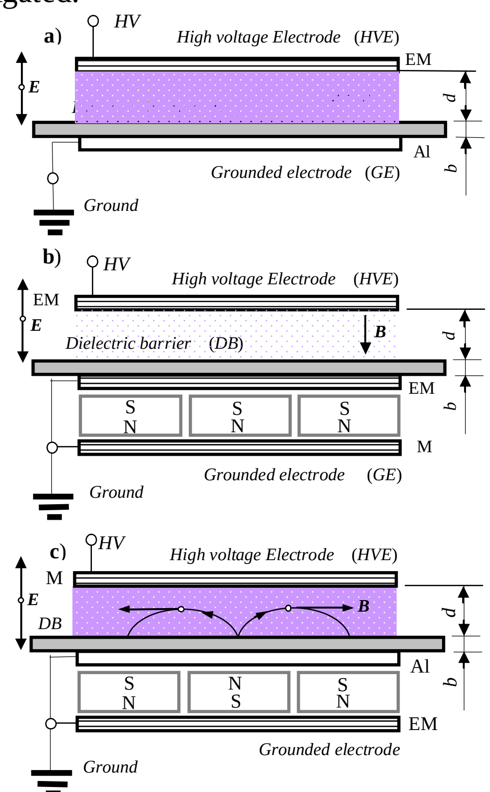
Plasma technologies applications and especially non uniform plasma applications have to look for in industry. These applications can increase their development and area of use in the near future.

Rare-earth constant magnets are use to decrease construction and devices dimensions. Electrical and magnetic polarizations of dielectric barrier influenced on barrier electrical discharge burning. The magnetic and electric polarizations define typical modification and technological characteristics of barrier discharge.

In the paper there was investigated diode and triode plasma systems in magnetic simulation conditions at wide air gap variation.

An important factor in the utility of magnetron plasma sources for sputtering at low pressures and other vacuum applications is their drift-induced uniformity over large distances. The usual configuration in planar magnetron sputtering plasma sources is a long, oval racetrack in which the plasma undergoes E/B drift around the racetrack. This drift ensures uniformity of the negative glowplasma in the direction perpendicular to the electric and magnetic fields. In the high-pressure (atmospheric) dielectric barrier and hybrid corona-dielectric barrier non-equilibrium plasma sources this technology is not usable yet. New innovative method of magnetic stimulation is demonstrated. The first of them is characterized by crossed or co-linear electric and magnetic fields, and the second – by a parallel-plate or co-planar dielectric barrier plasma source with at least one silicone electrical steel powered electrode. Surface density of real power increasing and discharge state changing with the voltage variation are investigated.



8-24

COMPARISON COLLISIONLESS MECHANISMS OF ABSORPTION OF ENERGY IN DISCHARGES SUSTAINED BY SURFACE WAVES AT LOW PRESSURES

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In low-pressure surface-wave plasma (SWP), when the electron mean free path is larger or comparable with the discharge length, collisionless absorption mechanism, such as stochastic heating or resonance absorption will play an important role. In the first case electrons are heated collisionlessly by repeated interactions with field that are localized within a sheath, skin depth layer [1]. In the second case, usually consider two channels of absorption. It is a quasilinear transfer of energy from the transverse (radial) field component to a hot electron "tail" of the energy distribution function [2,3] or is mode conversion from a long-wavelength electromagnetic wave to a short-wavelength plasma wave [4].

It is necessary to note, that authors [2-4], have not paid attention to result of numerical calculations [5] according to which, fast particles are thrown out aside decrease of density. And for sources of plasma this fact means simply loss of particles on walls. Hence additional research of a role of this mechanism in SWP is necessary.

In this contribution we present a kinetic model of low pressure SWP in cylindrical geometry at conditions for which the electron diffuses in real space much faster then in energy space, so that the non-local approximation [6] can be applied. The full self-consistent system of equation for the kinetic description of nonlocal, nonuniform SWP of low-pressure is derived.

Having added in the quasilinear diffusion calculated by analogy with [3], we have received the system generalizing all known for SWP. With the help of these equations it is possible to calculate the power deposition into a unit volume of plasma. It allows comparing stochastic and resonant mechanism of absorption of energy, and to establish a prevailing role of the first mechanism in overwhelming number of cases.

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8-25

ATMOSPHERIC PRESSURE DBD FOR TiO_2-like THIN FILM DEPOSITION ON POLYMERIC SUBSTRATES

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Titanium dioxide due to its attractive properties has been broadly used in residual water treatment, building, textiles, paints, windows, and other various photocatalytic applications. Among wide variety of methods, plasma processing has a definite advantage over other chemical deposition methods from ecological point of view. Atmospheric DBD plasma owing to its low temperature makes possible to use this technology for surface modification as well as for thin film deposition on different polymeric substrates. Additional advantage of atmospheric plasma sources is their attractive price.

In our study we investigated the process of atmospheric dielectric barrier discharge (ADBD) application for deposition of thin films of titanium oxide. Thin films were deposited from metal-organic precursor on polystyrene substrates and polyamide fibres. Smooth and hydrophilic TiO_x thin films on polystyrene substrates were obtained after optimization of deposition conditions. Exploration focused on the influence of Ar/TTIP and oxygen gas flow rates on the plasma deposition process and surface properties of thin titanium oxide films on polystyrene substrates. Surface morphology was studied with AFM. Chemical compound changes of films were studied by X-ray photoelectron spectroscopy (XPS). Contact angle (CA) measurements were used for studies of thin films aging. TiO_x film (about 100 nm thick) hydrophilicity was time stable, CA increased gradually from 5° to 15° during month after deposition as opposed to clean polystyrene (about 75°). High concentration of carbon-oxygen contamination was found in all samples due to open air deposition process.

Titanium oxide deposition on polyamide fibres with ADBD was explored, too. Samples covered by titanium oxide proved by abrasion resistance tests to be more stable as opposed to unmodified samples. Scan electron microscopy was used for surface analysis of thin titanium oxide films deposited on polyamide ropes. Evidently the thin film deposited in ADBD was relatively homogeneous, but caused slight sticking of individual fibres and also some small dust-like particles on the modified surface were observed.

This research has been supported by the MPO of the Czech Republic, project No. FI-IM5/065 and Czech Technical University of Prague grant No. SGS10/266/OHK3/3T/13.

8-26

DETERMINING THE ROTATIONAL VELOCITY OF GAS-METAL MULTICOMPONENT PLASMA IN A REFLEX DISCHARGE

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One of the properties of a plasma, formed and being in the crossed E×H fields, is its drift rotation. Under certain conditions in the rotating plasma the development of different instabilities can take place that results, for example, in the plasma ion component heating [1, 2]. In the case of multicomponent plasma the plasma column rotation leads to the spatial separation of the ion component [3]. There several cases are possible. The first case: plasma contains ions of an equal mass but being in the different charge states, in this case the high-Z ions are drifting into the plasma column center. The second case: plasma contains ions of a different mass and, due to the centrifugal forces there is a possibility of radial separation between these ions. And the third case is, in point of fact, the combination of the first and the second. The efficiency of radial ion separation directly depends on the rotational velocity.

In connection with the above the determination of the rotational velocity of multicomponent plasma is of undoubted interest.

In the present work performed were measurements on the parametric dependences of the rotational velocity of multicomponent gas-metal plasma formed in the pulsed reflex discharge. Gas-metal plasma was formed as a result of the discharge in the working medium of a substance composed of H_2, Ar or a gas mixture 88.9%Kr-7%Xe-4%N_2-0.1%O_2 and a sputtered cathode material. Cathodes were made of a monometallic Ti or a composite material, namely, Cu with Ti deposited by the CIB method. A maximum plasma density was $n_p \geq 6.5\ 10^{13}$ cm^{-3}, discharge voltage $U_{dis.} \leq 4$ kV, duration and maximum value of the discharge current intensity were ~ 1 μs and I_{dis} ~ 1.8 kA, respectively. A pulsed mirror configuration magnetic field of 18 μs duration was formed by a solenoid composed of six coils having a maximum field strength $H_0 \leq 6.5$ kOe. To determine the rotational velocity of the plasma layer with $n_p = n_{crit.}$, we used a microwave fluctuation reflectometry at a frequency of f = 37.13 and 72.88 GHz based on the determination of the cross-correlation function of two poloidally spaced microwave signals reflected from the uniform-density plasma layer. Plasma location was performed by the O-wave across the plasma column in the same cross-section for both frequencies. The experimental data were used to evaluate the radial electric field strength in the plasma and the separation factor of relatively heavy and light particles (ions) of the plasma medium.

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8-27

DECOMPOSITION VAPORS DICHLOROETHANE IN BARRIERLESS DISCHARGE

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- In the low-temperature plasma of the gas discharge there is the activation of oxidative processes, thus providing additional oxidation of toxic compounds to less hazardous oxides. The model pollutant in this paper was chosen dichloroethane. Investigation of the effectiveness of the decomposition of dichloroethane in the low-temperature plasma of the gas discharge will determine the prospects of development of technologies of air purification from halocarbon plasma chemical methods.
- Preparation of a gas mixture model was carried out by bubbling air flow through the vessel with liquid dichloroethane for steamy. The initial concentration of dichloroethane (ClCH2CH2Cl) was 1000 mg/m^3, air flow, the saturated vapor of dichloroethane, was 0,5 l/min. Analysis of samples was carried out on a gas chromatograph HP 5890 Series II equipped with a capillary chromatographic column Rtex-5 30m * 0,53 mmID * 1,5 um df, with the chemical composition of the stationary layer of 5% diphenyl and 95% dimethyl polysiloxane and a flame ionization detector. High-voltage power supply allows to create high-voltage pulses of microsecond duration (1-2,2 ms) with a pulse repetition rate 1-15 kHz and amplitude up to 15 kV.
- For the plasma reactor with electrode gap of 5 mm, the amplitude of the high-voltage pulse, at which the ignition of the discharge was 5.9 kV, with pulse repetition rate of 15 kHz. When the voltage was 8.1 kV high-voltage pulse turned into spark breakdown.
- Under the influence of high-energy electrons the reaction of ionization and dissociation of dichloroethane takes place. Under experimental conditions there are no other chromatographic peaks on the chromatograms, only the dichloroethane peak was recorded.
- With the growth of the embedded power the degree of dichloroethane decomposition increases. When the embedded power is 100 W in the conditions of prebreakdown discharge with the amplitude of the voltage pulse 7.9 kV dichloride decomposes at 100%.
- In the experiments, the exposure time of ethylene dichloride in plasma chemical reactor was 12 seconds. Since the bit field in the gas discharge of this type represents the plasma channels of small radius, reaching from the tip of star-shaped electrodes to the surface of the tube, then by optimizing the geometry and selection of dichloroethane exposure time in the discharge region the effectiveness of this type of system can be greatly enhanced.

8-28

ANALYSIS OF THE LTE VALIDITY IN THE PULSED HIGH PRESSURE RADIATIVE CESIUM DISCHARGE

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The research of the pulsed high-pressure cesium discharge is of the interest in connection with the problem of a creation of environmentally safe effective light sources with a high luminous efficacy and high colour rendering index. The theory of such discharge was developed in [1] in the assumption which cofirms that plasma occurs in the state of LTE. In this work, influence of various processes on LTE existence is considered. For this purpose the special parameters δ_k are calculated. These parameters take into account the influence of the following factors on the LTE:

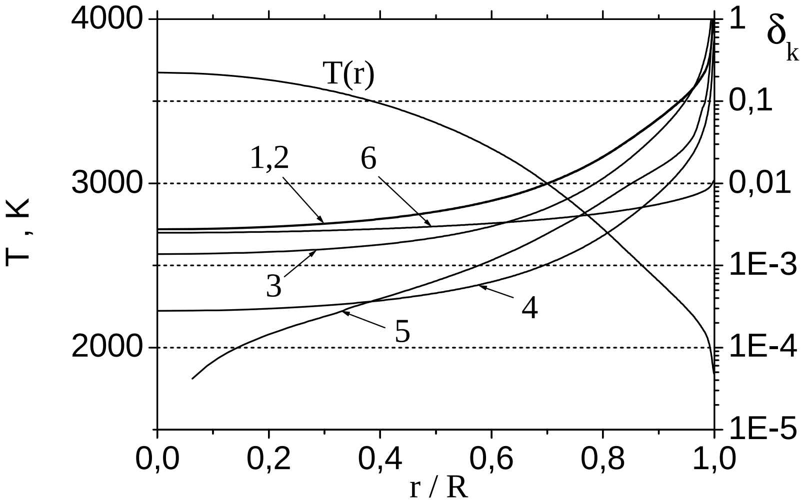
$\delta_k = n_e n_i < v_e \sigma^{ph}_{rec,\gamma} > / \alpha_\gamma n_e^2 n_i$, k = 1,2 – escape of 6P and 5D recombination continua from plasma; α_γ is a coefficient of collisional recombination; $\sigma^{ph}_{rec,\gamma}$ is a cross section of electron-ion photorecombination to γ state of cesium atom (γ = 6P and 5D accordingly);

$\delta_k = A_{\gamma\gamma'} \theta_{\gamma\gamma'} / n_e < v_e \sigma_{\gamma\gamma'} >$, k = 3,4 – escape of radiation in the discrete spectrum (6P-6S and 4F-5D transitions accordingly); $\theta_{\gamma\gamma'}$ is a probability of the photon escape;

$\delta_5 = \sqrt{D_{ia} \tau_{rec}} / \left(n_i / (\partial\, n_i / \partial\, r) \right)$ – ion recombination length divided by the characteristic length of inhomogeneity of plasma; τ_{rec} is a time of the electron-ion recombination; D_{ia} is a coefficient of the ambipolar diffusion;

$\delta_6 = n_a < v_e \sigma^{6P}_{ea} > / n_e < v_e \sigma_{ee} >$ – deviation from maxwellian electron distribution owing to unelastic collisions; σ^{6P}_{ea} is a cross section of 6P level excitation by plasma electrons.

The results of calculations are shown in the figure for the characteristic profile of temperature T(r) at the pressure P = 180 torr. It is evident, that LTE approach is valid practically in the total volume of plasma. Deviations from LTE take place only in narrow near wall layer. It is convinient to replace a consideration of this layer by the statement of the corresponding boundary conditions.



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8-29

OBSTRUCTED DC GLOW DISCHARGE IN LOW-PRESSURE NITROGEN

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We studied in experiment the obstructed and abnormal modes of dc glow discharge in nitrogen as well as the transition between them. The measurements were made in a tube of 55 mm in radius with the inter-electrode gap of 10 mm. The nitrogen pressure range under study was $p = 0.08 - 10$ Torr. It is shown that the obstructed discharge may exist only in the gas pressure range $p < 0.2$ Torr under conditions corresponding to the left-hand branch of Paschen curve (the breakdown curve minimum was at the pressure of $p = 0.55$ Torr). The dc glow discharge in the nitrogen pressure range $p < 0.2$ Torr was shown to possess an S–shaped current-voltage characteristic (obstructed and abnormal burning modes possess growing CVCs but the transition between them was accompanied by the negative CVC). The transition from the obstructed mode to the abnormal is shown to be accompanied by LF relaxation oscillations of the discharge current in a kilohertz range. These oscillations are probably due to the negative glow forming and decaying near the anode. They are observed in a limited gas pressure and current ranges. The oscillation amplitude amounted to 5% of the total current.

At gas pressure of 0.1 and 0.11 Torr only the obstructed discharge was observed. At higher pressure, when discharge current approaches some critical value, a negative glow starts to form near the anode, and the transition from the obstructed to the abnormal mode of burning is observed. This transition is accompanied by lowering the voltage across the electrodes with current growing, the CVC assumes an S – like shape, and the oscillogram demonstrates the current oscillations of several kilohertz in frequency. These LF oscillations exist in the limited ranges of pressure and current. After the negative glow is formed completely, the discharge is burning in the abnormal mode in which the current grows with the voltage increase across the electrodes. At low pressure the oscillation frequency approaches 8 kHz. This low frequency is associated with a large departure time of positive ions out of the discharge gap. Increasing pressure causes the increase in the collision rate between ions and molecules and increases the time required for ions for travelling from the anode to the cathode thus leading to the decrease in the oscillation frequency. With the growth of the current the concentration of charged particles within the gap increases, the field strength near the cathode grows but near the anode it falls. The plasma concentration near the anode increases abruptly and the current grows. Then, according to Ohm's law for the total circuit, the voltage across the electrodes decreases. This involves the ionization lowering within the cathode sheath. The region of dense plasma formed near the anode expands, a portion of electrons go to the anode, and positive ions move to the cathode. With the ionization decreased the charged particle loss involves the discharge current lowering observable in the oscillogram. After a portion of positive ions leave the discharge gap and the current decreases, the voltage across the electrodes increases, and intense electron avalanches develop in the cathode sheath again. In its turn this leads to a fast growth of the discharge current, and the processes is repeated.

8-30

ANODE DIAMETER EFFECT ON IGNITION AND BURNING OF DC DISCHARGE

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This paper studies how an anode diameter value affects ignition and CVC of the dc glow discharge. The measurements were performed in the discharge tube of 55 mm in diameter with the inter-electrode distance of L = 20 mm, the anode radii were R = 0.18 mm, 3 mm, 5 mm, 55 mm. The nitrogen pressure range under study was p = 0.08 – 10 Torr. The decrease in anode diameter is shown to cause a shift of breakdown curves to higher gas pressure and breakdown voltage values. Probably this behavior of breakdown curves is associated with the increase of the dielectric wall area and charged particle loss due to diffusion with moderate anode diameter values. Decreasing the anode diameter is shown to increase the discharge extinction voltage. The discharge current is found to grow slower with the voltage across the electrodes increasing for small anode diameter values. In the normal mode of burning for moderate anodes the decrease in the discharge current is accompanied with a considerable increase of the voltage across the electrodes. Probably it is associated with an enhanced escape of charged particles due to ambipolar diffusion caused by discharge column narrowing when electrons are moving to the anode of small diameter. A bright anode glow is found to be present around the small anode in the total range of gas pressure under study, thus indicating the availability of a large positive voltage drop across the anode sheath.

8-31

INFLUENCE OF ARGON ADMIXTURE ON CHARACTERISTICS OF NITROGEN STRONGLY NON-UNIFORM NON-EQUILIBRIUM MICROWAVE DISCHARGE

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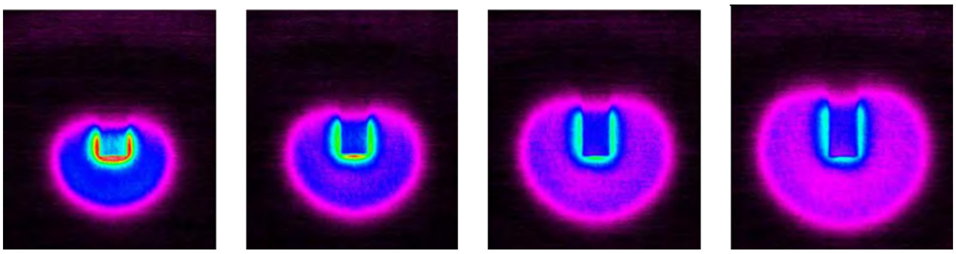
Gas additions to the basic plasma gas enable to change the plasma parameters and can be used for plasma diagnostics. The strongly non-uniform non-equilibrium electrode microwave discharge (EMD) [1] was earlier studied in hydrogen with admixture of Ar and in the mixture of nitrogen with hydrogen [2, 3]. Some results of investigation of influence of argon additions on the plasma emission of nitrogen EMD are presented in this paper. Experimental set-up was described in detail in [1, 2]. The discharge chamber was stainless steel cylinder with diameter of 150 mm, the powered electrode/antenna with outer diameter of 5 mm was introduced through the vacuum joint in the upper cover of the chamber. Experiments were carried out at pressure 1 Torr and the incident power 50 – 120 W(frequency 2,45 GHz). Plasma gases were N_2 with flow rate 10 - 20 sccm and Ar with flow rates 0-20 sccm. Discharge emission through the lateral quartz window was focused by the quartz lens, collected by the movable optical fiber (diameter 100 microns), and recorded with spectrographs AvaSpec-2048, AvaSpec-3648 and AvaSpec-2048-4-RM. Discharge spectra were measured in three points along the discharge axis: in the bright near electrode region, and in the middle point of the radius of the discharge sphere along the axis and in the perpendicular direction. Changes of the discharge structure with addition of Ar to N_2 were recorded with video camera K-008.



0 0,16 0,4 0,8

argon flow rate, sccm

Influence of the Ar content on the N_2 EMD image (N_2 flow rate 10 sccm).

It was shown that EMD in the mixture have an increased diameter even at 2 % Ar admixture as compared with pure nitrogen (Figure). It was shown that addition of Ar to N_2 results in decreasing of the plasma absorbed power at constant incident power. This effect is noticeable at small admixtures and increases with increasing concentration of Ar. To study the processes in the strongly non-uniform EMD and possibilities to use the Ar-admixture for plasma diagnostics the self-consistent modeling of the EMD was fulfilled on the base of one dimensional model which was earlier developed for the discharge with the electrodes with spherical symmetry in quasi-static approximation [4]. Modeling showed that known kinetic processes of argon-nitrogen collisions can not lead to the observed experimental results at small Ar-admixtures.

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8-32

SEMI-EMPIRICAL MODELING OF MICROWAVE EFFECT ON THE ELECTRON ENERGY DISTRIBUTION FUNCTION IN POSITIVE COLUMN OF A MEDIUM PRESSURE Cs-Xe DC DISCHARGE

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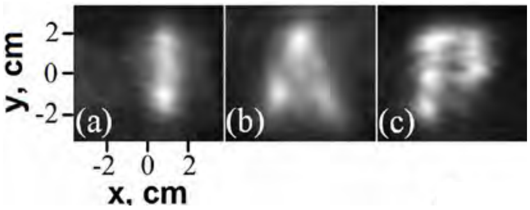
High-sensitive technique for real-time imaging of millimeter wave (MMW) spatial distribution using the visible continuum from the flat positive column (PC) of a medium-pressure Cs-Xe DC discharge was proposed and developed in the Institute of Applied Physics RAS [1]. The imaging technique is based on the fact that the intensity of the e-Xe bremsstrahlung continuum from the PC increases in the visible region when the plasma electrons are heated by millimeter waves. As an example, the near-field MMW images of the slits in the foils that have shapes of the letters I, A, and P from acronyms for Institute of Applied Physics obtained using the technique are shown in Figure [2].



This paper presents the results of numerical modeling of plasma electrons heating in PC of Cs-Xe discharge under microwave effect. Semi-empirical model for calculation of the electron energy distribution function (EEDF) in the PC of Cs-Xe discharge at medium gas pressures is developed. The Boltzmann equation for isotropic part of the EEDF in the two term approximation taking into account elastic, inelastic and electron-electron collisions was used for calculation [3]. Calculations of EEDF, effective electron temperature, and elastic and inelastic collision losses of the electron energy depending on the DC electric field strength and intensity of the incident microwaves were carried out in the range of partial pressures of gas components which are typical for spatial homogeneous PC of Cs-Xe discharge.

It is shown that the EEDF in PC is close to the Maxwell distribution at the electron energies less than 3 eV while it deviates from the Maxwell one for higher electron energies. At the electron energies less than 6 eV the EEDF can be represented approximately by the two-temperature distribution with different temperatures in the range of slow (< 3 eV) and fast (3-6 eV) electrons. In the absence of microwaves the effective electron temperature in PC increases from 0.4 to 0.5 eV when the DC field in PC increases from 1 to 1.5 V/cm. This result is in good agreement with results of measurements. Effect of millimeter waves with intensities less than 3 W/cm^2 on spatially homogeneous PC increases the electron temperature proportional to the intensity of microwaves. The electron temperature increases by 0.15 eV for microwave intensity 1 W/cm^2. Microwave effect decreases the deviation of the EEDF from the Maxwell function. The elastic collisions of electrons with Xe atoms are the main channel of electron energy losses. Inelastic losses of the electron energy in their collisions with Cs atoms are of several tents percents of the total energy consumption.

This work was partially supported by RFBR (Project No 09-08-00728-a).

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8-33

PLASMA FOCUS INSTALLATIONS FOR TECHNOLOGIES

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In the report the results of researches on application of super-power high-speed jets of dense plasma with the energy flux density of 10^8-10^{10} Вт/см^2 in technologies are submitted. As the generator of such plasma jets plasma focus installations (PF) are used. Result of such influence is the occurrence of shock waves, excess point defects, implantation of high-energy ion components in a material, at intensities, on many orders exceeding intensity at usually used implantation, acceleration of diffusion processes and phase transformations. In the report possibilities of application of PF installations for test of materials intended for use of materials in extreme conditions, in particular in thermonuclear devices are considered. In report are also described results of researches on:

- the creation of nano–dispersed materials and nano-structured coverings;
- the alloying of metals by chemically inactive elements with them;
- the development of methods of putting high adhesive coverings, including nanocoverings from inactive chemically or neutral elements;
- the influence of powerful shock waves on high temperature superconducting materials.

This research has been supported by the grant of President of RF: NSH-3370.2010.2

8-34

STRUCTURE OF Fe-Cu COATINGS PREPARED BY THE MAGNETRON SPUTTERING METHOD

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This paper reports the results of our investigations concerning a study of the morphology and the structures of the Fe-Cu coatings deposited by magnetron sputtering method. Fe, Cu and layered Fe/Cu coatings were fabricated by the non-reactive magnetron sputtering in the Ar atmosphere. The coatings were deposited on silicon and sapphire (001) substrates by DC sputtering using a dual-gun system. In our experiments the two WMK 50 magnetron gun supplied from DORA Power Supply (DPS) unit were used. The magnetron targets of 50 mm in diameter were made of iron and copper. The coating were deposited as a the function of deposition time and number of the elemental layers. The deposition time of the Fe and Cu layers were: 30 seconds or 3 minutes. We analyzed layered Fe-Cu coatings with 1, 2 and 4 repetitions of Fe and Cu elemental layers, namely Fe/Cu, (Fe/Cu)x2 and (Fe/Cu)x4.The experiments were conducted at different DC sputtering power (0.7 to 2 kW) and different gas pressure in the vacuum chamber (0.5 to 1.2 Pa).

The morphology and microstructure of the deposited coatings were characterized by using scanning (SEM) and transmission (TEM) electron microscopes. The crystalline phases of the Fe , Cu and the layered Fe/Cu coatings were identified by an X-ray diffraction measurements.

The results of our investigation show that the Fe-Cu coatings are characterized by nanocrystalline structure. X-ray diffraction measurements revealed polycrystalline structure of the layer's materials. The preferential structure orientation (111) was observed for polycrystalline Cu layers which were synthesized on the sapphire (001) substrate.
Currently the optical emission spectroscopy (OES) of magnetron plasmas with a wavelength range of 350–900 nm for DC planar magnetron sputtering of copper and iron in argon atmosphere are carried out. Results of these investigations will deliver information on properties of plasma generated in our processes.

8-35

ELECTRON TRANSPORTATION ACROSS MAGNETIC FIELD IN HALL ACCELERATOR

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Development of space and ground plasma technologies are curried out based on the understanding of the processes in the Hall type plasma accelerator. Hypotheses about regularities of electron transportation in an interelectrode interval are offered.

It is supposed, that electron transportation across a magnetic field occurs because of dispersion of electrons on quasi-stationary plasma heterogeneities, extended in an axial direction (Fig. 1). These heterogeneities of plasma arise because of heterogeneity of gas ionization in a discharge chamber (DC). Because of axial acceleration of ions in DC the heterogeneity in a stream of plasma are kept in the form of extended along an axis tubes. Owing to electron drift (v_{dr}) in an azimuthal direction there is a polarization of charges and there is a local azimuthal heterogeneity of electric field potential $\Delta\varphi_{het}$. Under influence of this local azimuthal electric field close drift of electrons can be braked. "Slow" electrons can be displaced in an axial electric field in DC growing discharge current.

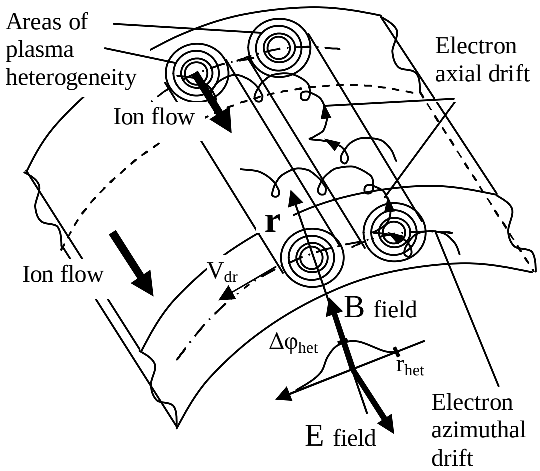

Fig. 1. Electron dispersion on plasma heterogeneities in a stream of ions

It is supposed, that in the area of local heterogeneity of plasma concentration Δn_i (Fig. 2) fluctuations of a local electric field potential along a direction the center-border are excited casually, and then are supported (owing to periodic collective movement of electrons born in this area). These fluctuations break down the closed drift of electrons, and also form electron distribution function on velocities close to the Maxwell distribution.

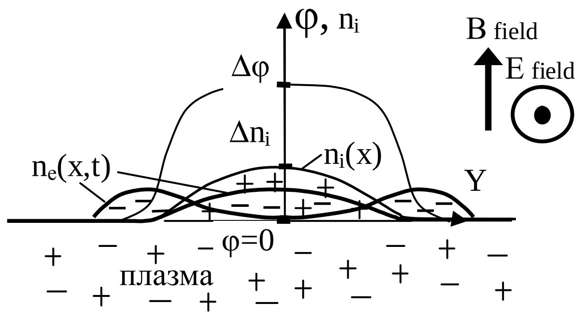

Fig. 2. Distribution of concentration of "motionless" ions $n_i(x)$ and electrons $n_e(x,t)$ changing in phase in the field of plasma heterogeneities

Conclusion

Electron "maxwellisation" and electron transportation along an axial electric field and perpendicular to a magnetic field (the order of 10 mTl) in plasma (concentration of $10^{17 \ldots 18}$ m^{-3}) of Hall accelerator can occur because of electron scattering in an electric field of local plasma heterogeneities of quasi-stationary and pulsating type.

8-36

CURRENT CATHODE SPOTS IN GLOW DISCHARGE NORMAL REGIME AS STATIONARY DISSIPATIVE STRUCTURE: MACROSCOPIC PARAMETERS

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It is well known that cathode layer of normal glow discharge is a source of various bright examples of stationary structures [1]. In normal regime of glow discharge in wide range of discharge current values (i) current spots occupy only part of cathode surface; (ii) voltage drop is independent on the current and less then self-sustainment value of Townsend discharge voltage drop; (iii) current density in the cathode current spot is independent on the current spot area [2].

In our work we treated the main phenomena observed in the cathode layer such as normal current density effect, cathode current spot propagation and transition between normal and subnormal regimes from the point of view of the theory of active media [3-5]. It is demonstrated that constancy of voltage drop, current density and zero-value traveling wave velocity is caused by existence of external resistance.

Dependence of the structure main parameters on pressure and voltage drop on the discharge was calculated. Obtained results are in good correspondence with numerical simulation.

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8-37

ON THE INFLUENCE OF TUNGSTEN IMPURITIES ON THE TRANSPORT PROPERTIES OF THERMAL PLASMA

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The influence of tungsten impurities on the transport properties of thermal plasma is considered in the ambient atmosphere of argon. The calculations are carried out, and it is shown that a small amount of tungsten causes the essential changes in the values of transport coefficients in comparison with the case of pure argon. 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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8-38

TANTALUM PENTOXIDE CERAMIC COATINGS DEPOSITION ON Ti4Al6V SUBSTRATES FOR BIOMEDICAL APPLICATIONS

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The interest to dielectric materials and coatings applications has considerably increased in various areas of science and technique in recent years. 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. 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. Tantalum and tantalum based compounds have a high potential in the biomedical field. At the present study tantalum pentoxide ceramic coatings are presented as perspective biomaterials for various biomedical applications.

The study of e-beam evaporated Ta_2O_5 film structure and properties effect on cell/material response was performed. The samples were formed on Ti alloy substrates (Ti4Al6V). 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. 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.

The surface properties and structure of as-deposited and annealed at 500°C e-beam evaporated Ta_2O_5 films were investigated by means of XPS and XRD methods. X-ray photoelectron spectroscopy was carried out using ESCALAB MkII (VG Scientific) electron spectrometer at a base pressure in the analysis chamber of 5x10-10 mbar (during the measurement 1x10-8 mbar), using AlKalpha X-ray source (excitation energy hν=1486.6 eV).

The values of surface free energy and its polar and dispersion components calculated by Wu method for two liquids and Owens-Wendt-Rabel-Kaeble' method for the liquid system (α-bromonaphthalene- formamide-ethylene glycol-diidomethane- glycerol-water) were determined from contact angle measurements at 20°C. Cyto toxicity and cyto compatibility was estimated at in vitro tests. The analysis of cell adhesion on substrates was made by means optical microscope, SEM and AFM methods.

The results demonstrated the good cyto compatibility of e-beam evaporated Ta_2O_5 coatings especially in the case of annealed films with strong stoichiometric Ta_2O_5 composition. The best biological response parameters (cell number, proliferation function, morphology) were obtained in the case of materials with the most parameters of polar part component of SFE and fractional polarity. The results show that the surface properties are strongly influenced by the preliminary treatment. The deposition and treatment conditions changing allows one to control the surface parameters of the e-beam evaporated Ta_2O_5 films and the next positive cell response.

The research project was supported by the Bulgarian-Ukrainian Academies of Science international scientific cooperation program.

8-39

CURRENT WAVEFORMS FOR PULSE MICRODISCHARGE INSIDE DIELECTRIC CELL

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Microscopic gas discharges are being applied in various plasma technological processes as well as in plasma displays (PDP, [1]). One of the most important problems for such discharges' applications is increasing of their efficacy. Optimization of the applied voltage (and, consequently, discharge current) waveform is one of ways to make a microdischarge more energetically efficient. In this work, discharge current waveforms are being investigated for the case of the gas microdischarge inside dielectric cell with three isolated electrodes. Investigation is carried out via the computer simulation with particles in cells (PiC) method. For such an investigation, original 2D electrostatic PiC code [2] with Monte Carlo collision simulation was applied. About 100 elementary processes were taken into account [3]. Dielectric cell dimensions were considered 0.5*0.2 mm (typical PDP cell size). Gas mixture was 90% Ne and 10% Xe with 450 and 50 torr partial pressures respectively. Discharge driven voltage was applied to one of two coplanar bus electrodes (based on the front glass plate of cell). Another bus electrode and address electrode (on the cell backplate) was considered grounded. Driven voltage had a trapezoid waveform with 100 ns front length, and it's magnitude was varied in 200-300V region (near the optimal discharge ignition conditions).

Discharge current waveforms obtained from simulation have different shapes for lower and higher voltage from the region described above. For the lower voltages (about 200V), current pulse had sufficiently non-monotonous shape. That can be explained with the fact that the potential relief inside the cell is rebuilding faster for smaller driven voltage so secondary electron avalanches can occur before the current saturation. For higher voltages like 250V, current pulse becomes monotonous because the slow potential relief rebuilding. For non-monotonous current waveform with lower driven voltage, microdischarge was slightly more energetically efficient.

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8-40

MICROPLASMA DISCHARGE STRIATION IN THE PDP CELL

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Microdischarges (microplasma discharges) are an energy source for the plasma display panel (PDP, [1]) luminescence. So the problem of such a discharge energetic efficiency is very important for practical application. Discharge is more energetically efficient for luminescence purpose if the energy distribution function for charged particles becomes non-maxwellian with more particles on higher energies capable for excitation and ionization. One of the way to obtain such a non-maxwellian distribution is using a plasma with striation structures when the charged particles can accelerate between plasma strates. Striation of glow-like gas discharge is a well-known experimental fact so this work is devoted to investigation of microdischarge striation for the dielectric PDP cell. Investigation was carried out via the PiC computer simulation with original 2D electrostatic PiC where more then 100 different elementary processes were taken into account via Monte Carlo simulation. Dielectric cell with typical for PDP dimensions (0.5*0.2 mm) were considered filled with gas mixture of 450 torr Ne and 50 torr Xe. Coplanar electrodes structure [1] was considered.

For the 200V microdischarge driven voltage amplitude, discharge was efficiently striated at the early evolution stage (discharge current forefront). First strate outside the main discharge region appears when the atomic and excimer ions of neon (Ne^+ and Ne_2^+) appear in that separated region. On later stages, atomic and excimer ions' density in this strate increases and new strates appear. Such a result is corresponding to the experiments [2-3]. Potential relief between the discharge strates have a regions with relatively strong electric field and charged particles accelerate in that field. As a result, one can see a non-maxwellian distribution for electrons and ions. That can be used for PDP energy efficacy increasing.

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8-41

OPTIMIZATION OF A VACUUM SPARK DISCHARGE AS A X-RAY SOURCE

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High-current vacuum spark discharges are intense sources of X-ray radiation. Specific character of formation and development of such type of discharges cause their dependence on the initial plasma parameters used for the main discharge triggering. As a rule the initial plasma is produced by auxiliary discharge of a trigger type.

This paper presents the experimental studies of the effect of the trigger energy and the trigger location in relation to discharge gap on the spatial and temporal stability and emission parameters of the X-ray sources, formed in low-inductance vacuum spark discharge.

The measurements were carried out on the micropinch setup Zona-2. The cathode was a 20 mm diameter plane iron cylinder with a 3 mm hole in its centre. The anode had a form of a 3 mm peaked iron rod and it was separated by 5 mm gap from the cathode. The capacitance of the main capacitor was 20 μF , and the discharge period was 8,5 μs. The discharge current ran up to 100 kA under the 10 kV charging voltage. The trigger electrode was placed radially either on the edge of the cathode surface or was moved 25 mm distance away from the discharge axis.

The change of trigger discharge energy was realized by changing the trigger capacitor value with constant charging voltage and by using the pulse tansformer in saturation mode. The trigger pulse amplitude was variated from 20 A to 1.8 kA, and the pulse duration was variated from 500 ns to 1.6 μs with rise time from 100 ns to 600 ns. The measurements were carried out for both trigger pulse polarities.

The investigation showed a notable dependence of X-ray emission moment, pulse amplitude and spatial location of X-ray sources on trigger discharge parameters. The optimal results with respect to stability of hot spots formation (with temporal jitter within of 300 ns and spatial localization within the range 500μm) and to X-ray intensity are obtained when a trigger electrode is placed on the edge of a cathode surface and a positive pulse with about 30 A current peak, 100 ns rise time and 900 ns pulse duration is applied to it. The change of pulse polarity with the same parameters results in observable reduction of hot spot formation probability. In this case the most intensive X-ray radiation is observed from diffuse cloud by anode end. Double decrease of the trigger pulse duration leads in preference to diffuse X-ray glow of several areas in the discharge gap and close to the anode. Double increase of the trigger pulse duration result in the increase of anode glow intensity and decrease of hot spots glow intensity in X-ray range. Increase in the trigger pulse current up to 1kA increases a number of X-ray pulses up to four. In this case the overall region of X-ray emission is increased and X ray intensity from separate hot spot is decreased. When placing the trigger electrode alongside of the discharge gap stable X-ray emission is observed only at the trigger current over 1kA and sufficiently large spatial and temporal jitters occur.

The analysis of multichannel pinhole images through different filters indicates the main contribution of the recorded X-ray corresponds to energy range from 3 keV to 10 keV, the contribution of the bremsstrahlung and recombination radiations from separate discharge regions reaches 50%.

The investigation corroborates the initial discharge conditions effect on low-inducance vacuum spark evolution. The conditions for primary forming of the hot spots of small spatial and temporal jitter are determined.

8-42

ETHANOL REFORMING IN PLASMA-LIQUID SYSTEM WITH POSTDISCHARGE HIGHTEMPERATURE PYROLITIC CHAMBER

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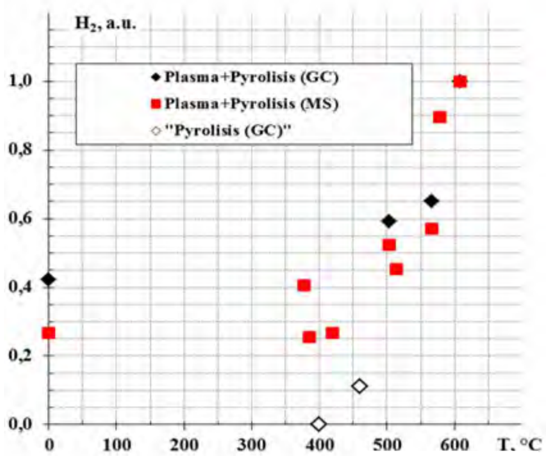

Fig. 1. H_2 intensity (MS) and partial H_2 content in syngas products (GC) after the ethanol reforming vs. Postdischarge pyrolitic chamber temperature

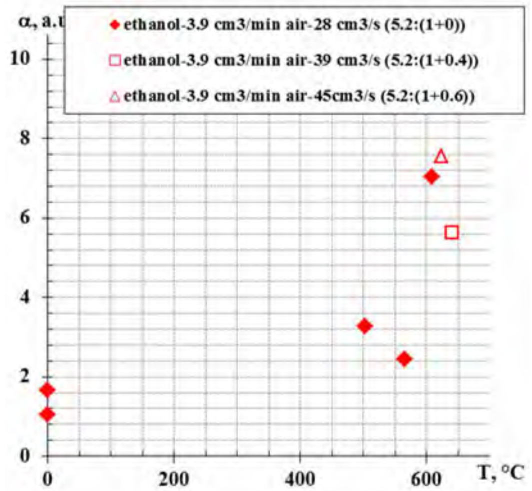

Fig. 2. Energy efficiency of ethanol reforming vs. temperature in the postdischarge pyrolytic chamber

For plasma fuel reforming, various methods using thermal and non-thermal plasma are known. Non-thermal (low-temperature) plasma, which is kinetically non-equilibrium, has characteristics of low ionization but benefits of high reactivity and selectivity of chemical transformations providing high enough productivity at relatively low energy consumption; this can be obtained by high voltage discharging in a flow at low or high atmospheric pressures. For reforming with plasma support (pyrolysis, steam reforming , partial oxidization) it is preferable to utilize the high plasma flow rate generators: the pulsed systems and systems on the base of TORNADO discharge type etc. Thus, in work ethanol reformation at high temperature partial oxidation pyrolisis with pulsed plasma assist was investigated. The ethanol postdischarge pyrolysis studies results after initial plasma-assisted ethanol reforming are presented in Figs. 1, 2: The parameters in the system were following: pulsed discharge frequency of 420 Hz, air flow rate of 17-28 cm^3/s, time of treatment (measurements) up to 10 min (600 s); the temperature in the pyrolytic chamber varied from 0 to 870 K. Fig. 1 shows the H_2 intensity obtained by mass-spectrometry and the partial H_2 content in syngas products measured by gas-chromatography after the treatment. One can see a good correlation between gas chromatography and mass-spectrometry data.

Fig. 2 shows the values of energy efficiency α in the system depending on temperature in the postdischarge pyrolytic chamber. It is seen an energy efficiency increase with increasing temperature. Some modes with the change of air flow modes (correspond to additional air supply into the pyrolytic chamber compared with an air supply in the discharge) have lower energy efficiency than the mode with a constant air flow because of varying partial output of isobutene $_iC_4H_{10}$.

8-43

RADIATION OF MULTICOMPONENT GAS-METAL PLASMA OF A PULSED REFLEX DISCHARGE

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A reflex discharge, known as a Penning discharge, is a discharge of an axisymmetric geometry taking place in the crossed electric and magnetic fields [1]. At present, the Penning discharge, realized in many applied and engineering problems, continues to be extensively investigated despite its long history [2, 3]. However, there is a deficiency of experimental data in the investigation of the pulsed reflex discharge, in particular, in the determination of an elemental composition and intensity of plasma radiation, as well as, in the investigation of properties of both gas- and gas-metal multicomponent plasmas, that it very important for determining the energy balance of systems under study.

In the present work we have measured parametric dependences of the optic radiation intensity, determined an elemental and discharge composition of the formed multicomponent plasma, performed a comparative analysis of the radiation from different gas-metal plasmas having uniform average density in the investigated range of wavelengths belonging to waves formed by the discharge in the medium of a working substance composed of H_2, Ar or gas mixture 88.9%Kr-7%Xe-4%N_2-0.1%O_2 and a sputtered cathode material. Cathodes were made of a monometallic Ti or a composite material, namely, Cu with Ti deposited by the CIB method. The following diagnostic tools were used: the time dependence of the average plasma density was determined by means of a microwave interferometer at the operating wave length λ = 8 mm; the time dependence of the plasma radiation intensity in the range of wavelengths λ=180-1100 nm was measured by a photodiode FDUK-13U operating in the photodiode mode, the time constant of the signal rise front was $\tau_н \sim 300$ ns; the elemental composition of the formed plasma was determined by the spectroscopic method. The radiation was recorded via the diagnostic window, made of quartz glass KU 1, being at a distance of 220 mm from the plasma boundary. The area of a photo-receiving surface was Ø 2.5 mm, the threshold response at λ_{max} $P_{thres.}$= 0.4 10^{-14} W/Hz$^{1/2}$. The radiation measurements in the ultraviolet and near infrared spectrum ranges were carried out using the filters: optical glasses UFS-2 in the ultraviolet region and IKS-1 in the infrared region.

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8-44

ON THE TRANSPORT PROPERTIES OF A NONIDEAL PLASMA OF UNDERWATER DISCHARGES

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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].

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8-45

OZONIZER WITH SUPERIMPOSED DISCHARGE FOR INACTIVATION OF MICROORGANISMS

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The ozonizer, where the double barrier discharge in combination with the surface discharge is used for ozone generation, is proposed for inactivation of microorganisms. Two high-voltage pulsed 10W and 20W power supplies have been used for the discharge ignition in ozone generator that has three parallel electrodes (central, surface, and outer one). The phase between applied voltages may be varied from 0° to 180°, the breakdown voltage for the discharge gap of 2.5 mm is smaller than in DBD (6 and 8 kV, respectively), and output ozone concentration is higher and reaches up to 30 mg/l at the output of ozone generator. The ozone-air mix runs to the sterilization camera filled with water, where the ultrasonic cavitation is generated by the ultrasonic 50W source. The water temperature is maintained at 15°C by the Peltier cooler. Under this condition, the ozone concentration in water medium is 10 mg/l.

The following test results show the effectiveness of the sterilizer. Time intervals required for inactivation of typical bacteria groups in the sterilizer are as follows: E. coli 055 K 59 № 3912/41 – 2 minutes, Staphylococcus aureus ATCC № 25923 – 2 minutes, Pseudomonas Aeruginoza 27/99 – 2 minutes, Cl. oedematiens 198 – 5 minutes, B. cereus № 8035 – 10 minutes. Selection of the water temperature, the ozone concentrations and ultrasonic power allowed to determine the time necessary for destroying the row of micro organisms.

8-46

INVESTIGATION OF OZONE FORMATION IN THE PLASMA FORMED AS A RESULT OF THE BARRIER DISCHARGE

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Ozonizers on the basis of the barrier discharge are now the basic industrial sources of ozone. The further perfection of ozone generators basically is directed both on increase of ozone synthesis efficiency, and on increase of a work resource. Obviously, successful realisation of such tendencies is impossible without deep studying of the spatial and the time structure of the barrier discharge. Forms and the sizes of the microdischarge channel are its essential parametres as define finally density of the power contribution to ozonized gas. Definition of the channel geometry represents difficult and not up to the end solved problem owing to a statistical property of microdischarges occurrence.

The expanded part of the microdischarge channel, applying on a dielectric barrier, is the most productive on ozone [1]. It is connected by that in the barrier discharge during the reaction

$$O_2 + O \rightarrow O_3^*$$

a raised ozone molecule is appears. If quickly not to remove the given excitation there is a decomposition of a molecule of ozone. Molecule excitation disappears as a result of its collision with other particle:

$$O_3^* + M \rightarrow O_3 + M\ .$$

If ozone is synthesized in the barrier discharge near to an electrode surface the probability of an ozone molecule collision with an electrode surface considerably increases. Thus, at removal from an electrode surface the efficiency of ozone synthesis essentially decreases.

In the given paper they are obtained analytical correlations, allowing research the influence of different geometric and physical parameters on evolution of barrier discharge near the electrodes with different cross-sections. Obtained correlations allow estimate the barrier discharge existence time. They are confirmed and shown new essential particularities of barrier discharge evolutions.

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8-47

APPLICATION OF HF DISCHARGE FOR NITRIDING OF INNER SURFACES OF CYLYNDRICAL SPECIMENS MADE FROM TITANIUM AND STAINLESS STEEL

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In this article investigated effectiveness of nitriding inner surfaces cylindrical specimens made from Ti and SS. For nitriding of internal surfaces of cylindrical specimens from Ti and SS used HF discharge with a hollow cathode, because of more high power efficiency from oscillation of electrons in it.[1] It allows to lower working pressure, temperature and duration of process, as compared to other method.[2,3,4]. Before nitriding cleaning of internal surface was conducted by ions Ar in HF plasma (1 kV) at pressure $P=8\times10^{-3}$ Torr. Cleaning time ≈ 5÷10 min. Nitriding was conducted by the ions of N in HF plasma (1,5 kV) at pressure $P=1\times10^{-2}$ Torr. Time of nitriding was 60 min. The temperature of nitriding did not exceed 100 ^{o}C. External magnetic field ~ 30 Oe. The diametr of specimens did not exceed 20 mm.

For determination of microhardness of the nitrided layer was used microhardness meter PMT-2 with different loads on indentor. The microhardness of the treated speciemen compared with initial was increased in 2 times. The estimation of thickness of the nitride layer was conducted ~ 4÷5 μm.

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8-48

INFLUENCE OF PLASMA NUCLEI ON RADIATION DIRECTIVITY IN HIGH-CURRENT PULSE PLASMA DIODE

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At paper [1] in high-current pulse plasma diode in tin vapor against the background recombination radiation the powerful directed peak radiation in the wave range 12.2–15.8 nm in inductive phase of discharge evolution was detected. For clearing-up the reason of radiation directivity the investigations were continued using a system of rapid photorecording with the exposition time of ~10 ns. As a rapid shutter the electro-optical converter worked in pulse mode was applied. The image of different phases was carried out by the different pulse delay supplying from controlling unit with following fixing by digital camera. Simultaneously with the image producing the measurement of radiation intensity in longitudinal and trasverse direction were performed by the instrumentality of registration system based on semiconductor photodiodes AXUV-20 [2]. For radiation zone determination the space scanning of discharge gap was carried out.

In result of experiments the images of discharge gap were obtained in the moment of peak radiation appearing and of its absent. It was set, that the generation of peak radiation occurs in separate section of anode region of the discharge but the peak radiation is corresponded the dense low-sized plasma formations appearing. It was pointed out the association between the form of plasma forming and the radiation directivity for each peak.

In the first half-period of the discharge current oscillation the powerful peak radiation of ~200 ns duration of strong longitudinal directivity ($I_{\parallel}/I_{\perp} \sim 50$) is forming by dense plasma formation in the form of elongated needle (d~ 0.5 mm, l~ 7 mm). In the second one close to discharge current maximum the peak radiation of transverse directivity is forming ($I_{\parallel}/I_{\perp} \sim 0.2$). The generation zone is oblate in longitudinal direction spheroid (d~ 1 mm, l~ 0.8 mm). After this peak in 200 ns follows the peak-satellite of longitudinal direction ($I_{\parallel}/I_{\perp} \sim 10$). The generation zone of peak-satellite is the area of dense plasma in the form of cylinder (d~ 0.7 mm, l~ 4 mm). Forming the plasma cylinder is the evolution of oblate spheroid. It should be pointed out, that appearing of the peak-satellite and changing the form of plasma forming is observed in narrow band of discharge voltages.

The connection between the form of radiated volume and radiation directivity could give occasion to confirmation of conclusion about presence of radiation-induced radiation in plasma of multiply ionized atoms made in [1].

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8-49

DYNAMIC OF WALL CURRENTS IN PULSE PLASMA DIODE IN TIN VAPOR

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One way of creating intensive light sources with wave length of 13.4 nm for nanolithography is using high-current pulse discharges in tin vapor. The tin feature is presence of powerful emission line of the same wave length in radiation spectrum, which ensures by transitions in 7 – 12-fold ionized atoms. This allows obtaining high conversion ratio of input energy in radiation in wide band of external parameters [1]. However using powerful discharges causes the problem of first mirror of Bragg optic of nanolithographer placed close to discharge and influenced not only by intensive radiation from plasma but flow of high-energy charged particles. It leads to reflection degradation and could result in fully destruction. In this paper the dynamic of charged particle flow from the discharge is experimentally investigated in order to determinate the most safe place of the first mirror of nanolithographer. In the experiments the system described in [2] was applied.

The investigations of dynamic of current distribution were carried out using 16 collectors set in different points around the discharge gap. The particles energy was estimated by the method of retarding field. The range of measurement is 8–20 cm from the discharge axis and 0–7.5 cm from anode plane.

Basing on obtained current space distribution for discharge voltage from 6 kV up to 12 kV it was established that the most intensive current had been observed in circle area of 2.5 cm length in the anode plane with strong falling toward the cathode. In the radial direction the current intensity fell on 2 orders of magnitude at distance increasing from 8 to 12 cm. At that in the first half-cycle of discharge current the positive current on collectors was observed, but in the second one – negative. The particles energy was ~ 50 eV in both cases. The maximum densities of positive current were at the rate of 100–250 A/cm^2 but the negative one – up to 100 A/cm^2. Averaged through the discharge pulse the maximum power got into the wall reached the value up to 20 kW/cm^2 but the energy – 30 mJ/cm^2.

Thus, it has been established that at using high-current discharges in metal vapor as radiation source even at ultra low pressure there is fairly significant range of increased energy loads on a collecting mirror. But the positive moment is its sharp spatial confining. Therefore at lithography system with plasma emission source creating it should be taken into account the spatial distribution of high energy loads zone in the every specific case to choose the set of the mirror out of this region.

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8-50

PLASMA CLEANING OF THE SURFACES FROM OXIDES: THE STATE OF THE ART

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Last two decades much progress was achieved in development and perfection of the conditioning procedure for preparation of vacuum vessel of a fusion device to plasma experiments. As a result of this, the amount of impurities in the plasma of working discharges in majority of fusion devices under operation decreased significantly. However, the time being spent usually for conditioning of any fusion device much exceeds the time of operation in working regimes. As examples, in the Tore Supra tokamak during experimental campaign 2003-2004 the total time for conditioning was 976 hrs and the operating time of all working discharges 7 hrs 10 min; in Large Helical Device (LHD) during campaign 2003 these time intervals were 1004 hrs and 4 hrs 43 min; in the T-10 tokamak, correspondingly, 393 hrs and 27 min. Therefore, any increase of conditioning efficiency would allow to increase the experimental time and to shorten the running costs of any given fusion device.

As a rule, the main impurities that are necessary to decrease by providing the conditioning procedure are carbon and oxygen. In this paper the methods (with application of plasma) are reviewed, which are usually used to suppress the amount of oxygen on the surfaces that have to be cleaned for different reasons.

It was found by analyzing numerous published data, that at present there are four kinds of sources of information relatively plasma cleaning of the metal surfaces from oxygen. First – the quite old investigations provided in seventies on several stands and in fusion devices with an aim to find optimal conditions for cleaning; second – investigations connected with the development of microelectronics, where there is the need to clean micro-contacts; third – investigations directed to solution of the problem of a foolproof long time conservation of archeological metallic artifacts; fourth – recent experiments on several fusion devices with application of discharges in oxygen as the part of the whole wall conditioning procedure.

In the presentation we will follow this gradation of the sources of data relating the application of plasma for cleaning metal surfaces and will give the examples of results obtained in every of indicated field of science and technology.

Additionally will be presented some recent results on efficiency of cleaning oxidized films from the mirrors of some metals; these results were obtained in experiments modeling behavior of in-vessel mirrors of optical diagnostics in ITER.

8-51

SIMULATING STUDY OF PLASMACHEMICAL EROSION OF A-C:H FILMS IN A ECR DISCHARGE PLASMA

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For decreasing the influx of impurities into the plasma confinement volume, the wall conditioning procedures are in practice at every fusion device, with the use of different kind stationary or pulse discharges in hydrogen: glow, Ohmic, radio frequency (RF), discharge in conditions of electron cyclotron resonance (ECR). The control for the state of wall surfaces is realized by means of special collectors, the surface of which is time to time analyzed with some standard methods. For providing surface analyses, the collectors are taken out from the vacuum vessel. Recently it was suggested to control the quality of cleaning the walls of vacuum chamber of the stellarator type fusion device Uragan-2M by means of mirrors installed into the vacuum chamber. The idea of this suggestion is as follows. Before mirror installation, the carbon-containing film is deposited (e.g., a-C:H film) on its surface, and the *in situ* measurements of reflectance (e.g., at the He-Ne laser wavelength) during the conditioning procedure can give possibility to make conclusion about the cleaning efficiency.

To estimate the prospect of such method, preliminary simulating experiments on the special stand DSM-2 were carried out, where ECR plasma was produced by UHF power (≈400 W at frequency 2.37 GHz). The electron temperature did not exceed 5 eV, and the plasma density in the place of mirror location was $\sim 5\cdot 10^9$ cm^{-3}. No any voltage was applied to the mirror holder thus the ion energy was ≤15 eV. Thus, the mechanism of film etching was chemical erosion.

In experiments the SS and Cu mirror were coated with a-C:H film in a non-self-maintained discharge in a propane-butane mixture. The amorphous film was transparent in visible light. The samples were weighted before and after film deposition. The initial film thickness was found by means of interferometer microscope. The spectral reflectance (R) was measured in the range 220-650 nm after every short-term exposure in the ECR plasma discharge. By analyzing the dynamics of the interferometer picture the thickness of the rest film can be estimated. The sputtering by plasma ions was continued up to disappearance of the interferometer character of spectral reflectance and afterwards the control weighing was made. From the whole set of data the value of refraction index of the a-C:H film was found, $n=1.45\div1.55$, which does not contradict to published values.

It should be mentioned that at that stage the reflectance of both mirror samples was significantly below than before the film deposition, and initial reflectance value was reached only after exposing samples to higher ion energy (300 eV). It is supposed that the carbide interface appeared during the deposition process of the a-C:H film; carbides are known to be strongly resistant to chemical erosion with low energy hydrogen projectiles.

8-52

ABOUT CHANGE OF PLASMA PARAMETERS OF GAS SOURCE WITH INCANDESCENT CATHODE AT ADDITIONAL APPLICATION OF HF DISCHARGE

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Experimental research of gas source with incandescent cathode and parameters of created plasma at application of additional HF power into discharge were carried out. Parameters of arc discharge are such as described in [1, 2]. HF field was created by generator with frequency 3-8 MHz, power 1,5 kW. Parameters of created plasma measured by means of Langmuir probes and multielectrode electrical probes are submitted. Magnetic field – 0-1,5 kOe, discharge voltage – 0-300 V, vacuum – 10^{-3}-10^{-4} Torr. Magnitudes of magnetic fields and neutral gas density considerably differ from mentioned in work [2, 3].

Researches showed possibility of increase of ionization degree and plasma density distribution uniformity at application high-frequency power into plasma created by gas source with incandescent cathode.

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8-53

ABOUT MAGNETIC FIELDS INFLUENCE ON AUTONOMOUS PLASMOIDS OVER A WATER SURFACE

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At researching of autonomous plasmoids over a water surface, the features of discharge initial stage were considered. The hypothesis about the cause of a large air and water gaps (more than 25 cm and 10 cm accordingly) flashover at small disruption voltage, (up to 4 kV) was suggested [1].

In addition a magnetic fields influence on the formed plasmoid, was explored. It was found, that a plasmoid proper, does not possess diamagnetic effect, not pushed out by a magnetic field, which means it's paramagnetic. The autonomous plasmoid may consist of complex molecules gangs, such as H^+, H_2O, OH^-, or Na^+, H_2O, Cl^-, with their own magnetic moments and thus represent the ion-ion plasma.

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8-54

ABOUT SPATIAL DISTRIBUTION OF CHARGED PARTICLES FLOWS AT THE PLASMA ROTATION IN CROSSED ELECTRIC AND MAGNETIC FIELDS

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In cylindrical vacuum chamber with diameter 40 sm, length 160 sm, with profiled longitudinal magnetic field, by means of arc source with incandescent cathode steady multicomponent gas plasma (Xe, Kr, Ar, CO_2) with density n~10^{10} sm^{-3}, T_i ~1 eV, T_e ~5 eV was created [1]. Density of the neutral gas is at a rate of 1-3 10^{12} sm^{-3}. The measurements of ions plasma flows on two systems of probes, which are located on butt and lateral surfaces of the vacuum chamber, were carried out. The application of the radial electric field E_r with magnitude ≤10-20 V/sm on plasma, moving in longitudinal magnetic field B with intensity under 2 кOe, brought the plasma to rotation. Correlation change of the values of the plasma rotation frequency ω_E and cyclotron frequency of the separate ions plasma rotation ω_{ci} was assigned by change of the values B and E_r. Received current signals on butt and lateral collectors correlate as minimum on butt collectors coincides with maximum on some lateral electrodes. At the same time position of the minimum coincides with equality of the values ω_E and ω_{ci} that can point to achieving of the mode of ion-cyclotron instability predicted in work of Mihaylovskiy A.B., Cypin V.S. [1] and realized in work of Rogkov A.M., Stepanov K.N., Suprunenko V.A., Farenik V.I. [2].

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8-55

THE EFFECT OF UNINTENTIONAL OXYGEN INCORPORATION INTO Cr-CrN-DLC COATINGS DEPOSITED BY MePIIID METHOD USING FILTERED CATHODIC VACUUM ARC CARBON AND METAL PLASMA

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Diamond-like carbon (DLC) coatings are widely used in various fields of industry, due to its excellent tribological and mechanical properties. In this paper, we studied the multilayer Cr/CrN/DLC coatings deposited by a hybrid MePIIID (Metal Plasma Immersion Ion Implantation and Deposition) method on substrates made of high speed steel HS 6-5-2. In the carried out hybrid processes of multilayer coatings creation the streams of filtered carbon and metal plasma generated in low pressure arc discharge were used in both ion implantation and deposition phases. Investigation of the chemical composition of multi-layer Cr/CrN/DLC coatings using GDOES and XPS methods allowed to find small amount of oxygen in deposited DLC film and identify the cause of this. Additional alloying with chromium during the synthesis of DLC films reduced the concentration of oxygen in the films, but complete removal of the oxygen failed. The presence of oxygen in the film affects the properties of DLC coatings, which was confirmed by the investigation of the hardness and adhesion. Investigation of the surface morphology of Cr-CrN and DLC films by the atomic force microscopy allowed to see the structure of the surface of the films deposited from filtered plasma and determine the quality of plasma flow filtering by separators of different designs used in our experiments.

8-56

OPTIMIZATION OF THE PLASMA ELECTROSTATIC FILTER USING Taguchi METHOD

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To date, there is not much work about the study and use of electrostatic filters to reduce the droplet phase in the flow of vacuum-arc plasma. We investigated the flow of carbon and metal vacuum arc plasma, produced in DC discharge with superimposed high-current arc pulses, through the electrostatic filter. The effectiveness of the plasma flow was studied for different distance between the filter blinds and their different tilt angle in relation to the filter axis. The dependence of the ion current of the plasma flow on the current of electrostatic separator, the pressure of inert gas and the distance between the blinds was determined using the Langmuir probe. The plan of the experiment was developed using Taguchi’s method of design of experiments. The obtained results of the measurements were processed according to the Taguchi’s procedure and the optimal experimental conditions, which guarantee maximal cleaning efficiency at maximal transmission of carbon and metal plasma through the filter were determined. In the future work, these findings will be very important when designing the final construction of the filter.

8-57

LOW TEMPERATURE PLASMA AT LOW PRESSURES IN THE PROCESS OF SURFACE TREATMENT OF MATERIALS

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The plasma technologies for processing of metal and alloy surfaces find wide applications in recent years due to their high productivity and quality of processing.

The object of this work is to investigate electric discharges between a steel anode (the diameter of cylindrical anode was 3 mm) and electrolyte (1% solution of $(NH_4)_2SO_4$ in tap water) at atmospheric and lower pressures. The discharge was filmed by the video-recorder Sony HDR–SR12E.

The pictures taken during the fast rate video recording revealed that a multi-channel discharge is burning at atmospheric pressure. The multi-channel discharge is characterized by the presence of a large number of micro-discharges appearing in the region between the electrolyte and the immersed anode. In the initial moment of time there occurs electrolysis near the anode, then a gas-vapor shell is formed, and the multi-channel discharge goes to burning in an electrohydrodynamical regimen. Because of the turbulization process the electrolyte is intensely evaporated and all the components of the electrolyte-anode-plasma system are actively mixed. The electrolyte temperature reaches 80ºC.

When the pressure is lowered to 10^3 Pa the transition of the multi-channel discharge in 1% solution of $(NH_4)_2SO_4$ to a glow discharge is observed. At the voltage of 200 V the discharge is flashed during about 1 s time. The glow discharge burns continuously at voltages above 300 V, the electrolyte at this time is violently boiling forming spatters. The violet glowing which is characteristic to a glow discharge is observed both in the near-anode region and in the electrolyte volume. Ta this time there occurs non-stationary turbulent mixing in the electrolyte-plasma system. In comparison with the multi-channel discharge at atmospheric pressure the electrolyte temperature rises slower at low pressures.

The voltage-current characteristics show that at low pressures (above 10^3 Pa) the discharge voltage is decreased with the increase of current from 2 A to 11 A.

The experiments showed that the discharge in 1% solution of $(NH_4)_2SO_4$ at atmospheric pressure has a decontaminating and polishing effect on the surface of a steel sample, while the discharge at lower pressures has not such an effect.

8-58

EFFICIENCY OF THE NITRIDING PROCESS IN GLOW DISCHARGE PLASMA

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In recent years it became known that the atomic nitrogen is main agent responsible for the efficiency of nitriding the surface of metal products. N_2-Ar mixture is the better of technological atmospheres in this connection, where active dissociation of N_2 takes place. That is why the problem of determination of the content of atomic nitrogen in glow discharge (GD) plasma in a nitrogen-argon mixture is considered in this paper. Influence of mixture composition on the rate constant of dissociation of molecular nitrogen, accountable for producing of atomic nitrogen is determined by simulation way, and parameters of plasma - from an experiment, on the basis of measuring with double probes. A function of distribution of electrons on energies is founded by numeral integration of Boltzmann equation. The last one was written in the binomial approaching for mixture of molecular nitrogen and argon.

The role of atomic nitrogen was analyzed by determining its density N_a, on the basis of calculating the electron distribution function in view of its dependence on the component composition of the technological atmosphere and plasma parameters. The latter include the rate of flow ν and temperature T of the working gas, as given parameters, and two determined experimentally: the density N_e and the field E. In principle, we were simulated $N_e(r)$ and $E(r)$ using fluid model. Nevertheless, this model cannot explain the fact, that experimentally observed extension of ionization region (~ 3 cm), substantially exceeds the thickness of the calculated near-cathode layer (0,4 cm). Therefore, we proceed analogously to the paper [1] where the averaged parameters of the plasma in this region are introduced. Namely, we used the average values of N_e and E measured by double probes. It is also assumed that the temperature of the gas near the cathode is 800º K. Since the positive column of the investigated GD is not limited to the transverse direction, the illumination in this region is absent (it is believed that this region corresponds to the dark part of corona discharge.

As is shown the maximum value of theoretically determined atomic nitrogen in discharge corresponds with maximal microhardness of a modified layer depending on the compound of nitrogen-argon mixture.

We were studied by spectroscopy method the mentioned above ionization region. The spectra of luminous from GD plasma were recorded with spectrometer S100-2048. In this case molybdenum and cooper were used as material of cathode, and nitrogen and argon - as plasma forming technological atmospheres. The specific result is that in the spectra of gases and metals mentioned only spectral lines from high exited states of atoms were observed. This feature may be used in further quantitative study GD plasma by spectral method.

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8-59

CURRENT-VOLTAGE CHARACTERISTICS OF COMBINED MAGNETRON – RF INDUCTIVE DISCHARGE

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The results of experimental measurements and theoretical modelling of combined magnetron and RF inductive discharges at cluster technological set-up for synthesis of complex compound composites were presented at study. DC-magnetron system was used for sputtering of the target material, RF-inductive discharge for surface cleaning and activation before coating deposition and also for next reactive gas activation and ion bombardment during process of complex compound composites synthesis.

The current-voltage characteristics at off-line and synchronous working regimes were measured and next comparative analysis was made. On the basis of power balance equation the theoretical model of combine discharge were presented and obtained the good agreement between the proposed theoretical model and experimental results.

The research was financially supported by government research program of Ministry of Education and Science of Ukraine.

8-60

INTEGRAL CLUSTER SET-UP FOR COMPLEX COMPOUND COMPOSITES SYNTHESIS

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At present study the results of elaboration and investigations of cluster technological set-up 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. The various types of high-quality coatings, such as Al_2O_3, AlN, TiO_2, TiN, TiAlN, TiAlNO and others with coating thickness up to 10 μm and work area up to 1500 sm^2 were obtained at presented set-up.

The research was financially supported by government research program of Ministry Of Education and Science of Ukraine.

8-61

DIPOLE ELECTRON RADIATION OF HETEROGENEOUS LOW - TEMPERATURE PLASMA IN THE RADIO-FREQUENCY RANGE

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The electromagnetic radiation of the charged particles of the heterogeneous plasma (HP) contains information about the electron-ionic processes in its bulk, and it is the reliable tool of plasma diagnostics. Collisions of the free charges of plasma and their interaction with its self-consistent electromagnetic field is combined with the acceleration of the motion of charges, and as consequence with appearance of the dipole electromagnetic radiation (DER) [1]. The connection of the characteristics (DER) of HP electrons and its local electrophysical parameters of plasma - the urgent and important for the applications, but unresolved problem, being at present the subject of intensive experimental and theoretical studies. The work is dedicated to its separate, insufficiently investigated aspect - the mechanism of generation by HP electrons the electromagnetic waves of radio-frequency range. Basic original results are the obtained within the framework works: The new statistical approach to the description of the appearance of collective oscillating processes in the free electrons subsystem of heterogeneous plasma (HP) is proposed. It is established that the drive gear of shaping of integral electromagnetic signal in the volume HP is the aharmonic fluctuating motion of free charges in the self-consistent electrostatic field of the instantaneous cells of the electroneutrality of plasma system. With the use of ideas of statistical cell model for the electron-ion plasma processes [2], is determined the power of dipole radiation of DER electronic component of the plasma of the products of the combustion of the metalized fuels. It is shown, that the maximum of the intensity of DER is determined by the electrons, which are localized in the HP electroneutrality cells near the macroparticle surfaces. The dependence of the averaged power of DER on the temperature is investigated, and is revealed the connection of the parameters of the aharmonic oscillating modes of electronic component with the ionizing parameters HP. In Fig. 1A) and 1B) the characteristic dependences of frequency and power of the dipole electron radiation of the combustion products plasma as the functions of radial fluctuation displacement and determining thermodynamic parameters (temperature - T, concentration - n_p and size - r_p macroparticles) are given.

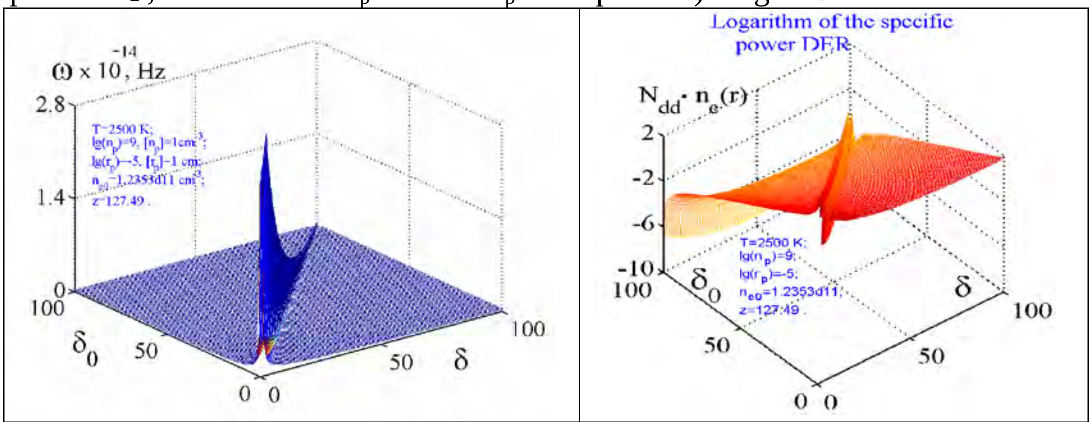

Fig.1. Frequency -1A) and specific power – 1B) of the combustion plasma DER.

The qualitative and quantitative comparative analysis of the obtained dependences with the data of the full-scale measurements of the power of the electromagnetic radiation of the plasma of combustion products in the radio-frequency range is carried out. Possible applications of the obtained results for control and diagnostics by processes in the modern plasma technologies are discussed in details.

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8-62

POLYESTER FABRIC WETTABILITY IMPROVEMENT UPON APPLICATION OF ATMOSPHERIC DIELECTRIC BARRIER PLASMA

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Polymers are produced in large volumes all over the world. They exhibit excellent mechanical properties, good chemical resistance and they are also easy workable. Unfortunately, the structure of polymer molecules causes problems when applied in praxis, e.g. by dyeing, printing or bonding and polymer surface has to be modified before these processes. The most common modification is the application of chemical methods, unfortunately these are not too environment friendly.

Final characteristics of polymers are the compromise between wanted surface and bulk properties. Important change of the polymer use-value can be caused by modification of characteristics of its upper structural units (i.e. in region under the surface deep some tens of nanometers). These changes – and modification – can be performed among others by treatment with the “cold” plasma and moreover with low costs and minimum environmental impact.

Modification of polymer surface characteristics may proceed during functionalization, when plasma particles react with polymer surface molecules and new chemical functional groups are formed on polymer surface. These chemical reactions can be influenced by the composition of atmosphere in the plasma reactor, e.g. application of oxygen plasma leads to polymer surface energy and wettability increase.

Earlier we successfully tested possibility of application of atmospheric dielectric barrier discharge (ADBD) sustaining in air at atmospheric pressure for Polyester (i.e. polyethylene terephtalate, PES) fibres hydrophilicity improvement.

ADBD was operated in the filamentary regime.

To influence the efficiency of this process, we studied correlation of the ADBD supply voltage frequency and modification efficiency presented by hydrophilicity changes expressed by means of the area of feathering time evolution (drop test). Experiments proved that growing supply voltage frequency shortens necessary modification time.

This research has been supported by the Czech Technical University of Prague grant No. SGS10/266/OHK3/3T/13and project MSM 4644788501.

8-63

GLIDING DISCHARGE: EFFECT OF ELECTRODES' DESIGN AND POSITION ON PLASMA FLOW PROFILE

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In high voltage electrical industry there are known many types of discharges – corona, dielectric barrier discharge, gliding discharge etc. Most of them, in classical electrotechnics unwanted, cause damages and power looses. However in last decades many researchers have focused on technological utilization of above enumerated types of discharges for technical purposes, e.g. sterilization, surface modification, thin film deposition and so on. Discharges can be operated at low, atmospheric and high pressures.

Plasmachemical reactor applying gliding discharge – a discharge created in gas flowing between electrodes in presence of intensive electric field – usually contains some gas inlet into the interelectrode region. Discharge activates gas particles pumped in this region. Activated gas/plasma outlet flow profile is mostly determined by the form and mutual position of electrodes, nature and the flow rate of the working gas and power supply voltage. Knowledge of plasma flow profile is valuable in decision making in case of technical applications.

Contribution deals with the effect of electrodes' design and position on plasma flow profile at the reactor outlet. Flow profiles were studied for three basic two-electrodes configurations – low-divergent, circular and highly-divergent configurations – in air plasma at atmospheric pressure by dominant oxygen and nitrogen lines spectral intensity measurement.

Results are discussed with reference to homogeneity of the plasma flow.

This research has been supported by the Czech Technical University in Prague grant No. SGS10/266/OHK3/3T/13 and project MPO FI-IM5/065.

9-1

PROGRESS IN DEVELOPMENT AND APPLICATIONS OF CHERENKOV-TYPE DETECTORS FOR FAST ELECTRON STUDIES IN TOKAMAKS

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The paper presents advance in a new method developed in the Institute for Nuclear Studies for direct detection of high-energy (super-thermal, runaway) electrons generated in tokamaks. The technique in question is based on registration of the Cherenkov radiation, emitted by energetic electrons, moving through a transparent medium (radiator body) with a velocity higher than the velocity of light in this material. The main aim of the presented studies was to develop a diagnostic technique applicable for investigation of fast electron beams within magnetic confinement fusion (MCF) facilities.

On the basis of the feasibility studies [1], i.e. heat transfer simulations, comparative analysis of applicable materials – some prototypes of the one- and four-channel measuring head have been designed, constructed and tested within several small, medium and large devices. In particular, the measurements have been performed within CASTOR [2-3], ISTTOK [4-5] and TORE-SUPRA [5] tokamaks.

The developed method enables the identification of electron beams, the determination of their spatial distribution, as well as the measurements of their temporal characteristics. Research on the time-correlations of the obtained data with the other phenomena within tokamaks, e.g. with the generation of X-ray pulses, the emission of neutrons and energetic ion beams, etc., are of primary importance for the verification of different theoretical models and for solving the plasma engineering problems.

Applications of the presented diagnostics have proved the usefulness of the one- and four-channel versions of the detecting head for fast electron studies in tokamaks.

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9-2

RECENT STUDIES OF THE ION EMISSION FROM HIGH-CURRENT PF-1000 EXPERIMENTS

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The paper presents results of the recent experimental studies of ion streams emitted from a large PF-1000 plasma-focus facility [1] operated with the D_2 filling and powered from a condenser bank charged to 21-27 kV, 290-480 kJ. The peak discharge current amounted to about 1.5-1.8 MA. To investigate a spatial structure of the ion streams the use was made of small pinhole cameras with nuclear track detectors of the PM-355 type, which were placed at different distances from the electrode outlet and at different angles to the electrode axis. To select ions of energy higher than a chosen threshold value the PM-355 detectors were shielded by thin absorption filters made of pure Al-foils of different thickness. The irradiated detectors were etched under standard conditions and the developed tracks were analyzed with an optical microscope. The ion images obtained at 0^0, as well as those recorded at 60^0 and 90^0 to the z-axis, showed that the investigated ion streams consist of many micro-beams of primary deuterons of energies ranging up to > 700 keV and some primary protons (originating from hydrogen remnants) of energies ranging to > 525 keV. The ion pinhole measurements were for the first time performed at 180^0 (behind an axial opening in the central electrode) and they proved that some primary deuterons are accelerated and emitted also in the upstream direction.

In order to investigate an energy spectrum of the ions emitted along the z-axis the use was made of a miniature Thomson-type spectrometer [2] which could be placed inside the large PF-1000 chamber. The ion parabolas, which were recorded upon PM-355 track detectors irradiated during several 480 kJ discharges, proved that the emitted deuterons had energies in the range from about 25 keV to about 1000 keV, while the population of protons (from hydrogen remnants) was about two orders smaller and their energies were within the range of 35-300 keV. The emission of so energetic ions constituted experimental evidence that non-linear phenomena in a PF pinch column induce strong electrical fields which can effectively accelerate primary ions.

To study dynamics of the ion emission preliminary time-resolved measurements were performed by means of miniature scintillation detectors, which were placed with the pinhole camera and coupled through separate optical cables with fast photomultipliers. The measurements performed along the z-axis, at a distance of 162 cm from the electrode outlet, showed distinct signals which might correspond to deuterons of energy < 2 MeV and protons of energy < 200 keV. The time-resolved ion measurements will be continued in order to investigate acceleration processes occurring mainly within the PF pinch column.

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9-3

SPECTROSCOPIC INVESTIGATION OF PF-1000 DISCHARGES UNDER DIFFERENT EXPERIMENTAL CONDITIONS

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The emission from a free-propagation plasma streams was studied in experiments with a 1 MJ plasma-focus (PF-1000) facility operated at the IPPLM in Warsaw, Poland. The machine was filled up with a pure deuterium gas (D_2) at the pressure of (0.75 - 2.4) hPa or a mixture of deuterium and argon at the pressure of (0.9-1.3 hPa of D_2 and 7-10 % of Ar). Discharges were supplied from a 1.32 mF condenser bank charged up to the initial voltage ranging from 21 kV to 27 kV, what corresponded to energy varied from 290 to 480 kJ. The maximum discharge current depended strongly on the initial charging voltage and it amounted to 1.5 - 1.8 MA, respectively.

Optical spectra emitted by a plasma stream at a distance of 30 cm from the electrodes ends were collected by means of a quartz collimator and transferred through a quartz fiber cable to a Mechelle900 spectrometer. Spectroscopic measurements were performed at different experimental conditions, i.e. different initial pressures of the working gases, different charging voltages and various acquisition times. In the observed wavelength range from 350 nm to 1000 nm, the most intense lines originated from the applied working gases. In some cases there were recorded distinct copper (Cu) and iron (Fe) lines which resulted from materials released from the electrodes and the insulator. Their intensity depended on the pinch intensity. As a reference point for the measured spectra, the use was made of a signal corresponding to the discharge current peculiarity (so-called a „dip"). From an analysis of the shape and intensity of the recorded and identified spectral lines it was possible to estimate the dependence of the electron density on the time delay after the „dip". In most of the cases an approach assuming the Stark broadening of deuterium Balmer lines - D_β and D_γ was applied. The D_α line was not taken into account because of its strong re-absorption, what made the quantitative analysis difficult.

The recorded temporal evolution of the optical spectrum was very helpful in the determination of a time period when the spectra did not include a lot of impurity lines, like Cu- or Fe-ones. The application of this finding made it possible to perform some experiments concerning spectroscopic research on the interaction of free-propagating plasma streams with pure tungsten targets. In the recorded spectra WI and WII lines were identified, however, the resolution of the spectrometer was not good enough for their quantitative analysis.

9-4

THERMIONIC LITHIUM ION EMITTERS IN LI BEAM PROBE

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The Lithium Beam Probe (LBP) has been widely used for the measurements of various parameters of the edge plasma in thermonuclear plasma devices. At the heart of the LBP is a source of lithium ions. The intensity of the ion beam determines the signal-to-noise ratio, and is responsible for the confidence of the LBP data. Good reliability of the solid-state β-eucriptite thermionic ion sources initially favored them as the preferred and standard in LBP applications.

The emission current of the commercial β-eucriptite thermionic Li^+ emitters used in early LBP experiments was not high, being ~0.04 mA/cm^2. Observation of up to 1 mA/cm^2 of β-eucryptite emission current in some experiments caused people to purchase uncoated emitters and to coat them themselves in house. Currently, practically all LBPs use Li^+ emitters that are domestically prepared. A wide dispersion of emission currents of these emitters, (0.04-1.7) mA/cm^2, prepared with the same materials, suggests that even a small difference in emitter preparation procedures influences the emissive properties of the emitter. If this is correct, it is reasonable to expect that the preparation technology can be optimized to increase the emission capabilities of the emitters.

In the early work of Blewett and Jones [1], it was hypothesized that the crystal structure of solid-state emitters can be the clue to the mechanism of the ion emission. From that point of view, it is interesting to compare the domestic emitter preparation procedures with a well-elaborated fabrication technology of glass-ceramics.

This contribution attempts to consider the influence of the microstructure of the emitter on its emission characteristics, on the basis of the available literature data. The aim is to identify possible modifications in the fabrication procedures and/or treatment of high performance Li^+ emitters.

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9-5

DIAGNOSTICS OF AVERAGE TEMPERATURE FIELDS AND ELECTRON CONCENTRATIONS IN A SURFACE BARRIER DISCHARGE PLASMA OVER JOUKOWSKI AIRFOIL

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In computational modeling of the process of ionized gas flow past an airfoil, an important role is played by the information on the distribution of electrons in the modeled flow. The aim of the present work is to measure by the optical method the distribution of averaged temperature and concentration values of electrons in the near-surface barrier discharge formed over the Joukowski airfoil (Fig.1).

Experiments on the investigation of the ionized flow, induced by a high-frequency barrier discharge, past the Joukowski airfoil were performed on an IZK-463 mirror-meniscus interferometer adjusted in the regime of a shadow instrument (Fig.2).

Fig.1 Image of the discharge glow

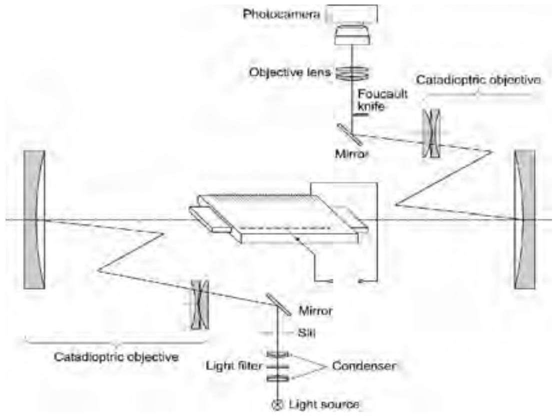

Fig.2 Experimental setup for optical measurements

The focal length of the lens of the receiving part was F = 3213.5 mm at a diameter of the observed field of 800 mm. The width of the slit $\Delta x = 0.1$ mm. To average turbulent pulsations in the flow, photography of the shadow patterns was carried out with exposure $\Delta t = 2$ sec. Blue and red color filters with maximum transmittance at $\lambda_b = 420$ nm and $\lambda_r = 650$ nm, respectively, were mounted alternately into the illuminating part of the device. The refractive index of the plasma depends on both the molecular composition of the gas and the density of free electrons and can be written in the form of the following relation:

$$n-1=k\rho\left(1+\beta T\right)-K\lambda^2 N_e \qquad (1)$$

Solving the set of equations (1) for $\lambda_r = 650$ nm and $\lambda_b = 420$ nm and using dispersion formula for refraction index of air (2) we obtain temperature and concentration of electrons.

$$n-1=\frac{1}{10^6}\left[64,328+\frac{29498,1}{146-10^6/\lambda^2}+\frac{255,4}{41-10^6/\lambda^2}\right] \qquad (2)$$

Here k is Gladstone–Dale constant, n is refractive index of the medium, T is averaged temperature of the electron N_e is electron density, β is thermal coefficient of volumetric expansion, ρ is medium density, λ is probe radiation wavelength.

An accuracy of this method of barrier discharge plasma diagnostics is discussed. Electron concentration measurements of the order of 10^{15} m^{-3} have a measurement error ~ 1% calculated using this method of error estimation.

9-6

DIAGNOSTICS OF MULTICOMPONENT ELECTRIC ARC PLASMA

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We study the thermal electric arc plasma in complex gas-metal vapour mixtures. Characteristic of such arcs is determining influence of electrode vapour on properties of arc plasma. The insignificant impurity (about 1%) of electrode metal vapour appreciably changes plasma parameters of the discharge in a rather wide temperature range.

Plasma composition was calculated in an assumption of the LTE. The obtained electron density and the temperature in plasma were used as initial parameters in these calculations. The influence of the copper vapour on plasma parameters were analysed.

The transport coefficients of a plasma of copper-nitrogen, copper-argon and copper-carbon dioxide mixtures at atmospheric pressure were calculated. Gas thermal conductivity was calculated as a sum of three contributions (gas, electronic, reactional). Gas thermal conductivity and viscosity were obtained using the method of Chapman and Enskog [1]. Electronic thermal conductivity and electrical conductivity have been calculated using the method of Grad [2]. In addition, for argon plasma the method of Frost was used [3].

The obtained results show that at low temperatures (5000K < T < 7000K) the electrical conductivity and electronic thermal conductivity are clearly increased by the presence of copper.

The results are compared with recent data [4]. We conclude that the Grad’s method can be preferable in the studies of the multicomponent plasma of electric arc discharges in comparison with other methods. We conclude that the Frost’s expression is more preferable than Grad’s method in calculations of the electrical conductivity of Ar-Cu mixtures.

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9-7

X-RAY LINE SPECTROMETRY IN EXPERIMENTS WITH THE ALUMINIUM Z-PINCH

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X-ray line spectrometry with temporal resolution was developed for registration of [He]- and [H]-like aluminium ions spectrum. It was chosen a scheme with scintillator converting X-ray spectrum into the visible image, which was transferred through the flexible optical fiber to the entrance slit of the streak camera. This scheme is not as sensitive and fast as a scheme with direct X-ray registration by the open image convertor tube. But, it is very convenient to set a spectral range, varying the angle of incidence and the distance between the crystal and scintillator.

In Z-pinch experiment on the high current S-300 generator aluminium line spectrum was registered with nanosecond time resolution. The simultaneous beginning of [He]- and [H]-like aluminium ions radiation was observed, that is the evidence of high electron temperature existence in the plasma for a long time before the main part of the load comes to the axis.

The great changing of radiating plasma parameters was found after the computer treatment of line spectra: the electron concentration is varied in five times ($(3\div14)\cdot10^{19}$ cm^{-3}), electron temperature in two times ($0.3\div1$ keV), ion temperature in five times ($20\div100$ keV) – during 50 nanoseconds. The great difference between the electron and ion temperature holds during all radiation time and demonstrates the ineffective energy transfer from the kinetic energy of ions to electron. The hot plasma mass contains usually a small part of the initial part of the load.

This work was supported by grants of RFBR 08-02-01102 and НШ-6536.2010.2.

9-8

STUDIES OF RUN-AWAY ELECTRON BEAMS AND HARD X-RAY EMISSION IN ISTTOK TOKAMAK

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The paper describes experimental studies of electron beams emitted from a plasma torus within the ISTTOK tokamak, which were performed by means of a new four-channel detector. The technique based on the use of the Cherenkov-type detectors has enabled the detection of energetic electrons (energies higher than 60 keV) and determination of their spatial and temporal parameters in the ISTTOK discharges [1]. The Cherenkov-type detector measuring head was equipped with four radiators made of machinable alumina-nitrate (AlN) polycrystals of 10 mm in diameter and 1 mm in thickness each. The whole detector was fixed to a movable support, which enabled the radiators to be placed in chosen positions at the minor radius of ISTTOK tokamak. The radiators were coated with molybdenum (Mo) layers of different thickness. Since one of the most important characteristics is the electron energy distribution, the main aim of this study was to perform some estimations of an energy spectrum of the recorded electrons. Special attention was paid to measurements of hard X-rays emitted from ISTTOK discharges and to investigation of their correlation with run-away electron beams. The experimentally investigated correlation of the fast electrons and the HXR peaks from ISSTOK discharges shows that the both emissions are strongly coupled.

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9-9

PECULIARITIES OF THE RADIOMETRIC MEASUREMENTS ON URAGAN-3M TORSATRON FOR RF HEATED PLASMA

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Frequency spectrum (radial profile) of X-mode second harmonic electron cyclotron emission was observed for optically thin plasma produced by Alfvén resonance heating in Uragan-3M torsatron. It is a medium size torsatron device with $l=3$, $m=9$, R_0=1m major radius, $\bar{a} \approx 0.12m$ average plasma radius and toroidal magnetic field $B_0 \le 1T$. In the case when $0.68 \le B_0(T) \le 0.72$ Radial electron temperature profile $T_e(R)$ within frequency range $31.5 \le f_{ECE}^{2X}(GHz) \le 37.5$ is covered a significant portion of the plasma column radius $1.00 \le R(m) \le 1.16$. $T_e(R)$ derived from "radiation temperature" profile $T_{rad}(R)$. This procedure neglects multiple reflections of ECE radiation from the torsatron inner structure (mainly from helical coils). At the present, one channel receiver measures $T_{rad}(f_{ECE}^{2X})$ at a single frequency per plasma shot. Profile reconstruction was done for several consecutive shots in assumption of the constant plasma parameters. In the absence of Thomson scattering system the temperature data were cross-checked with other electron temperature related diagnostics (SXR, optics, etc.).

We relate the mismatch effect of the ECE radiation data ($T_{rad}(R)$) by the strong modification of emission level by plasma opacity (small plasma optical depth) and by the scrambling effect. This effect results from both O-X mode conversion and change in the trajectory due to the multiple reflection of emitting ray at the vessel inner metallic components.

Electron temperature is calculated from radiation temperature using tokamak approximation formula for the optical thickness $\tau \sim 3.7\times10^{-14} n_e(R)\, T_e(R)\, R / B_0$ (here the plasma density is in cm^{-3}, electron temperature is in keV, tore major radius R is in cm, and the magnetic field is in kG). The difference in ECE and other data is explained using some modification of electron density profile. For special plasma production conditions (additional gas-puffing) an ECE "cut-off" phenomena (rapid signal losses) due to the overdense plasma is clearly observed.

The importance of the of the O-X mode conversion and other problems of measuring transmitted from the plasma radiation using an oversized transmission system are discussed and the chosen measurement and calibration technique are revealed and described. A future extension of the ECE system, a multichannel ECE radiometer is underway now. It will primarily aimed for the high field ($0.95 \le B_0(T) \le 1.15$) operation at second X-mode $57 \le f_{ECE}^{2X}(GHz) \le 74$ but will be tested at first for low-field discharges under the third X-mode operation. Plasma transport relevant electron temperature fluctuations could be measured by this multichannel system.

9-10

NEWLY COMMISSIONED MICROWAVE DIAGNOSTICS FOR URAGAN'S PLASMA EXPERIMENTS: FEASIBILITY STUDY

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We present the implementation of two new microwave diagnostic systems. One of them was designed to measure electron cyclotron emission (ECE) at the second harmonic X-mode in Uragan-2M, Uragan-3M stellarators bulk plasmas. The plasma devices are briefly described, and the ECE measurements technique relevant to this type of diagnostic is reviewed. The six channel superheterodyne radiometer operated within frequency range $57 \le f_{ECE}^{2X}(GHz) \le 74$ that optimized for the central magnetic field of $0.95 \le B_0(T) \le 1.15$. The problems of measuring transmitted from the plasma radiation using an oversized transmission system are discussed and the chosen measurement and calibration technique are revealed and described. Some data demonstrating both instruments characteristics are presented. Results of preliminary tests and experiments as well as comments on future implementations are used to illustrate the discussion.

A new $f_0 = 140GHz(\lambda_0 \approx 2mm)$, one-frequency microwave interferometer system has been developed to diagnose bulk plasmas on Uragan-2M, Uragan-3M torsatrons. This interferometer prepared to replace the old system that was under operation for more than 25 years. This diagnostic will measure the line-averaged density across central chord leg. For O-mode polarization with a "cut-off" density of over $n_c = 2.4\times 10^{14} cm^{-3}$, additional temporal measurements of moderate electron density fluctuation are expected. Output power of the radiation source is $P_0 = 40\, mW$ and to minimize signal loses a new optimized waveguide transmission line have been installed. System is equipped with I-Q detection system with phase deviation accuracy of 0.1^0 that corresponds to minimal detectable density or density fluctuations level $n_{min} = 4.2\times 10^8 cm^{-3}$. Preliminary data which shows some system instrumental characteristics and measurement capabilities are presented and comparison with old system are discussed.

9-11

HIBP DIAGNOSTIC INJECTORS FOR URAGAN - 2M AND TJ-II STELLARATORS

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The design and testing of the Heavy Ion Beam Probe (HIBP) plasma diagnostic injectors for stellarator Uragan-2M and TJ-II is presented in this work. The increasing of plasma density in modern fusion devices up to $3\text{-}7{*}10^{19}m^{-3}$ (TJ-II and T-10) leads to huge probing ion beam absorption in central plasma area. One way to obtain the HIBP information from plasma centre is the increasing of primary ion beam current. In IPP NSC KIPT a new modification of HIBP injectors for TJ-II and Uragan 2M stellarators was developed and tested. This modification based on three-electrode pre-focusing lens with flat extracting electrode was tested in Kharkov for Cs^+ ion beam with energy up to 100 keV and ion current up to 300 µA. These accelerators have the system for remote control of ion beam focusing distance. This system also permits to switch on the primary ion beam only for fusion device operation time (up to several seconds) that leads to substantial saving of thermo-ion emitter resource.

9-12

INVESTIGATIONS OF THERMO-IONIC EMITTERS OF HEAVY ALKALI METALS FOR DIAGNOSTIC INJECTOR OF “URAGAN-2M” STELLARATOR

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The results of solid-state thermo-ionic emitters of Cs^+ and Tl^+ ions investigations are presented. These emitters are planned to use in heavy ion beam diagnostic system for “Uragan-2M” stellarator. According to estimations for HIBP diagnostic system operations it is necessary to have primary deam current up to 0,5 mA. The aim of these investigations was determination of emission rate, mass-spectrum of ion beam during the beam extraction time and heavy ion beam current stability in area of 0,5 mA.

9-13

EXPERIMENTAL STUDIES OF ION EMISSION FROM RPI-IBIS FACILITY AND MODELING OF ION MOTIONS

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The paper presents results of the recent measurements of ion beams emitted from an RPI-IBIS plasma injector system and some preliminary results of the corresponding theoretical modeling. The RPI-IBIS facility was equipped with coaxial transparent electrodes made of thin molybdenum rods and a fast acting electromagnetic valve for the injection of pure hydrogen or deuterium. Plasma discharges were initiated with a variable time delay (τ) after the gas injection and they were powered from a condenser bank charged to 33 kV, 44 kJ.

The first part describes measurements of spatial distributions and energy values of intense ion beams, which were performed by means of ion-pinhole cameras equipped with nuclear track detectors of the PM-355 type. Those detectors were shielded by thin absorption filters made of pure Al-foils of different thickness, which made possible to record ion beams of energy higher than the chosen threshold value. Detailed analysis of ion mass- and energy-spectra was performed by means a Thomson-type analyzer. Ion emission characteristics were determined for different operational modes which depended on the chosen τ values. Those studies were accompanied by some optical observations.

The second part of the paper presents the most important results of numerical simulations of ion motions within the RPI-IBIS facility, which were performed on the basis of a single-particle model. In particular there are presented trajectories of ions of different energies as well as corresponding ion spatial distributions and ion energy spectra. The conclusions from the described modeling are compared with the previous experimental studies. The reported results are of importance for the realization of research in a frame of the Polish-Ukrainian scientific collaboration agreement.

9-14

THE INFLUENCE OF THE THERMAL RADIATION BACKGROUND ON PERFORMANCE OF ITER DIAGNOSTICS BASED UPON VISIBLE SPECTROSCOPY

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The main objectives of the ITER diagnostic system called *H-alpha Spectroscopy (+visible spectroscopy)* are measurements on visible Balmer lines. The system is intended to solve a number of important problems including monitoring of hydrogen lines' time behavior (necessary for determination of L-H transition point and ELM's type), space resolved measurements (information on hydrogen recycling and ionization particle source), and spectral shape analysis (evaluation of the isotopic ratio at the plasma periphery).

Apart from the tasks mentioned above it would be very useful to utilize the diagnostic for monitoring of impurity lines. The parameters of the input optics, of spectrometric and detection hardware used in the system enable to perform measurements at any spectral region in the range from 430 to 700 nm. The sensitivity of the system is enough for detection of the most luminous lines of the main impurities.

However, when such the measurements are planned one has to take into account some significant differences of the experimental conditions in ITER as compared to those in small machines. One of the most essential distinctions is very high level of the plasma background radiation. This case can make substantially worse attainable parameters of the measurements (accuracy, temporal and space resolution). That is why the main goal of the performed work was to estimate the value of plasma background in ITER and compare it to the intensity of the lines to be measured.

The visible background radiation in ITER has two basic components: bremsstrahlung and thermal radiation reflected from wall surface. Calculation of the bremsstrahlung at the known plasma parameters offers no difficulty and this component was taken into account at the feasibility study performed previously for the *H-alpha Spectroscopy*. It was shown that for ratio of main Balmer lines (H_α, H_β) and continuum enables to reach assigned measurement specifications. This report is dedicated basically to the analysis of the less apparent component of the background, namely: reflected thermal radiation.

The mechanism of the phenomenon is the following. Some elements of the reactor disposed inside the vacuum camera will be heated. It concerns first of all the divertor components. The area of the hot elements is large and temperature can substantially exceed 1300 K. Some part of emitted thermal radiation comes on the wall surface and then reflects diffusely into large solid angle. For beryllium that is considered as material for blanket the reflection coefficient at the visible region can reach 30-40%. Thereby wherever the visible cone of a diagnostic is directed the thermal radiation background will be detected together with the useful signal.

The rated dependences of the scattered thermal radiation on the temperature of the hot elements and wavelength of the detected light are given in the report. The data allow one to estimate the feasibility of different spectroscopic measurements in the ITER relevant conditions.

9-15

MAGNETIC DIAGNOSTIC IN U-2M TORSATRON

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By applying magnetic diagnostics in a stellarator, one can determine some very important characteristics of plasma, such as the longitudinal plasma current, plasma energy content, shift of magnetic surfaces; it is possible also to obtain the information about plasma pressure profile, magnetic islands' structure, structure of MHD instabilities, etc.

This paper describes the scheme for application of magnetic sensors in the U-2M torsatron, and describes the methods of taking into account the influence of the metal environment on data to be obtained with these magnetic sensors.

Because of presence of thick stainless steel vacuum chamber (wall thickness is up to 8 mm) and due to moderate duration of plasma heating pulse (up to 100 ms), the magnetic sensors have to be placed within the vacuum chamber for obtaining the real information about the magnetic fields and plasma currents.

The developed magnetic diagnostics for torsatron U-2M will consist of two main components:

1) a system of diamagnetic loops to register the changes of the toroidal magnetic flux;

2) 5 sets of 16 coils, installed in different cross-sections along the torus to measure the variations along the toroidal angle of zero, first and second harmonics of the poloidal magnetic field, the longitudinal current in the plasma, and the amplitude of poloidal magnetic field components along the small and large azimuthal angles of the plasma column in the frequency range of 10Hz ÷ 200 kHz.

9-16

REAL-TIME MONITORING OF THE ION AND ELECTRON TEMPERATURE WITH RETARDING FIELD ANALYZER

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The retarding field analyzer (RFA) is known as the more appropriate diagnostic tool for the ion temperature measurements in the scrape-off-layer (SOL) plasma of the thermonuclear plasma devices [1]. The temporal resolution in standard RFA application is, as a rule, restricted by few milliseconds, being determined by the bandwidth characteristics of the RFA powering circuit. In this contribution an effectively DC operation of RFA is considered, allowing, however, for the real time monitoring of the plasma ion and electron temperatures. The method is based on two point measurements on the RFA *I-V* characteristic with two differently DC biased RFA electrodes. The preliminary results obtained with the proposed method in SOL plasma of the tokamak ISTTOK will be presented also.

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9-17

DIAGNOSTIC SYSTEM FOR EUV RADIATION MEASUREMENTS FROM DENSE XENON PLASMA GENERATED BY MPC

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MPC of compact geometry has been designed and tested as a source of EUV radiation. For these studies Xenon and also combination of different gases were used for generation of gas discharge and for direct injection into compression zone. EUV radiation is generated in plasma compression zone where plasma temperature achieves at least several tens eV. In present paper diagnostic system for registration of EUV radiation is described and tested. It was applied for radiation measurements in different MPC modes of operations.

The registration system for measurements of EUV radiation was designed on the base of combination of different types of AXUVs photodiodes (IRD). AXUV detectors are precisely calibrated semiconductor devices with integrated think film filters for measurement of EUV in different selected wave length ranges.

The influence of electrons and ions flow from generated plasma stream on AXUV registration system and results of the measurements has been investigated. Several diaphragms and NdFeB permanent magnets with strong deflecting magnetic field were applied to prevent electrons and ions flow to the detector surface. It is shown that the total current on AXUV was less than 10^{-6} A.

EUV radiation measurements in different MPC modes of operation are discussed, namely for pure Xe discharge with pulsed Xe injection into MPC discharge gap and for operation regime with discharge in He under various residual pressures and consecutive local Xe injection directly into compression zone.

The dependencies of EUV radiation energy and power in various operation modes and for different magnitudes of discharge current and time delays between pulsed Xe injection and discharge ignition were measured. As was find that EUV radiation is generated in plasma compression zone and radiation energy strongly depends on MPC discharge scenario. Maximum radiation energy in wave-length range 12.5-15.2 nm was observed in MPC mode of operation with local Xe injection directly into compression zone. It allows essential decrease of EUV absorption by peripheral plasma in MPC.

9-18

TWO-PULSE THOMSON SCATTERING SYSTEM FOR MEASUREMENTS OF SPATIAL DYNAMICS OF ELECTRON DISTRIBUTION FUNCTION IN MULTI-MIRROR TRAP GOL-3

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In recent years, considerable progress has been achieved in studying of the beam-plasma system in the GOL-3 multimirror trap [1]. New interesting effects, such as fast ion heating, suppression of longitudinal electron heat transport, excitation of large-scale plasma density fluctuations, and the generation of neutron flux oscillations at μs-time scale were found [1, 2]. To describe these effects, various models have been proposed that require additional experimental verification. In papers [3, 4] the main attention was focused on measurements of plasma electron distribution function details with Thomson scattering (TS). In these experiments a single pulse laser was employed that makes possible observation of fast dynamics of the distribution function only on shot-by-shot basis. Typically in magnetic confinement plasma systems the temporal resolution in TS measurements is achieved by using either several repetition rate lasers combined into a single beamline [5] or with lasers operating in a burst mode [6]. A burst mode operating ensemble of separate Nd:YAG lasers can provide a μs-range time resolution. The standard energy in a single laser pulse for such laser systems is 1-2J that is not sufficient for experiments on GOL-3. Here TS is required to measure non-Maxwellian plasma electron distribution function with electron tails extended up to heating electron beam energy ~1MeV and under condition of intense and fast varied plasma background light. The previous Nd-glass laser produced 20J single laser pulse in a system of master oscillator and two amplifiers [3] and enabled detection of plasma electrons with energy up to 20 keV [3]. New laser should extend this ability to several spatial locations in radial and/or axial directions and for at least two laser pulses during a single plasma shot. Generally, information on axial variation of plasma parameters is essential for mirror plasmas. TS can fit this requirement with the use of the LIDAR layout [7], or simply by forcing a probe laser beam to pass trough plasma several times each time at different axial location. In this work, setup of the new Thomson scattering diagnostics is described. First results from measurements of the electron distribution function in the GOL-3 multimirror trap are presented.

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9-19

THE ACQUISITION SYSTEM OF EXPERIMENTAL DATA FOR “URAGAN-2M“

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The given work is focused on the data acquisition system created by NSC KIPT for automated collection of high – temperature plasma diagnostic information in real time on stellarator “Uragan-2M”. This system provides synchronous multi-channel high-speed measurement of electrical signals from sensors installed and diagnostic equipment, collecting and displaying information, archive it on the server and electronic data repository that allows users to access files with a registered diagnostic information. Implementation of this system in the practice of physical experiments on the “Uragan-2M” has provided the technical feasibility of remote access to equipment located at a certain safe distance of investigator and working in conditions of high electric, magnetic and high-frequency fields. The hardware part consists of a lot of multifunction boards L-783 and E20-10 produced by L-CARD company, and the PIC18F2550 microcontroller company Microchip.

9-20

PLASMA POLOIDAL ROTATION DYNAMICS ON U-3M TORSATRON

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Plasma poloidal rotation due to ExB in tokamaks and stellarators is accompanied by transport barriers influencing energy and particle transport. Therefore measurements of plasma rotation velocity are important.

Doppler reflectometry is based on measurement of frequency shift reflected wave at oblique wave reflection [1]. Reflecting plasma layer perturbed by fluctuations acts like a diffraction grating and tilted antenna can receive a Bragg backscattered signal (-1 order) at perturbation wave number

$$k_\theta = 2k_0 \sin(\varphi),$$

where k_0 – probing wave number and φ - wave tilt angle. Taking into account, the Doppler shift

$$\Delta\Omega = k_\theta \cdot V_\theta,$$

one can define rotation velocity V_θ. Position of reflecting layer, k – number and velocity ranges are scanned by changing of microwave frequency and antenna tilt angle [2].

In this report the results of experimental study of the plasma rotation dynamics in the U-3M torsatron during the discharge transition to the mode of improved plasma confinement are presented. The rotation velocity is measured using the methods of Doppler reflectometry.

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9-21

ION TEMPERATURE PROFILE MEASUREMENTS VIA CHARGE EXCHANGE RECOMBINATION SPECTROSCOPY (CXRS) AT T-10 TOKAMAK

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Active Charge Exchange Recombination Spectroscopy (CXRS) is used in most of the present fusion experiments as a proven tool for local measurements of the main ions in the plasma. A comprehensive diagnostic coverage of intrinsic and injected impurities is essential for any self consistent plasma simulation and prediction of plasma performance. This technique is utilized for a wide variety of measurements in the plasma edge and core, including ion temperature (via Doppler broadening of intrinsic impurity lines, which are efficiently populated by charge exchange from beam atoms), plasma rotation (via Doppler shift of the same impurity lines), and impurity density profile measurements (via quantitative spectroscopy of the impurity line intensities). A CXRS diagnostic for T-10 based on a diagnostic beam of a 30 keV hydrogen atoms. At the presence of neutral beam injection, intense charge exchange recombination reaction appears at plasma volume intersecting by the beam. The equation that describe this process is: $H^0 + A^{z+} \Rightarrow H^+ + A^{*(z-1)+}$,where is A^{z+} is a fully stripped ion, $A^{*(z-1)+}$ is a hydrogen-like ions in an excited state, that subsequently decays by prompt emission. The visible radiation produce by the most intense decay transitions with Δn=1 between high n-levels.

High Etendue Spectrometer (HES), which is appear as the prototype of spectrometer for ITER CXRS system, was used for active spectroscopy at T-10 Tokamak. Spectral lines has used for active CXRS measurements is next: HeII (n=4–3) 468.6 nm; CVI (n=8–7) 529.1 nm; DI (n=3–2) 656.1 nm.

Ion temperature profile was measured by using active spectroscopy at T-10 Tokamak, with the different spectral lines application. Ion temperature value and radial profile does not depend from which spectral lines was used for measurements. On the other hand, measured ion temperature value and profile is a function of plasma shot parameters.

9-22

COMPARISON OF BEHAVIOR UNDER ION BOMBARDMENT OF AMORPHOUS AND CRYSTALLIZED MIRRORS FABRICATED FROM AMORPHOUS ALLOY Zr(41.2%)Ti(13.8%)Cu(12.5%)Ni(10%)Be(22.5%)

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Amorphous metallic alloys (AMA) are a typical example of the materials with extremely small order units: "…with a characteristic scale of the short-range order equal to 1.5–3 nm…" [1]. Therefore AMA of an appropriate composition can be an ideal material for those in-vessel mirror of optical methods of plasma diagnostics in ITER which have to be located in so called "erosion-dominated zones". This is because the scale of the roughness on the surface of AMA developing under sputtering with plasma ions and charge exchange atoms has to be of the order of the inhomogeneity scales, thus to be much less than the typical characteristic wavelength of the electromagnetic radiation used for plasma diagnostics (≥100 nm). Similar supposition was for the first time appeared more than ten years ago [2], and since that time a quite wide program simulating behavior of AMA mirrors in ITER was provided with some results published in [3,4].

The AMA moldings composed of five metals with indicated atomic composition Zr(41.2%)Ti(13.8%)Cu(12.5%)Ni(10%)Be(22.5%) were cast in National Science Centre "Kharkov Institute of Physics and Technology". The thickness of moldings was 8 mm, thus two identical billets for fabrication of mirror samples with diameter 22 mm and thickness 3 mm were prepared. After one half of every pair was transformed into a crystalline structure by annealing at 773 K during one hour, all samples were polished to a mirror quality and subjected to impact of ions of deuterium or argon plasma with ion energy either in the keV energy range or with ion energy ≤60 eV. Initial reflectance values of both halves were close to each other but mirrors behaved very differently being exposed to plasma ions: (i) the crystallized mirror surface became roughen after Ar ion bombardment but surface of amorphous one continued to be smooth, (ii) having been exposed to ions of deuterium plasma, one crystallized mirror fully disintegrated and another became cracked after absorption of small amount of deuterium but for amorphous ones there was no saturation observed for deuterium absorption and no change of the surface roughness after much higher D^+ ion fluence. Reflectance of both structure mirror samples dropped after exposure to keV-energy ions of deuterium plasma and restored after much longer exposures to low energy ions. With that the thickness of an oxidized layer, correspondingly, increases or decreases, as results of SIMS demonstrate. This effect does qualitatively resemble the behavior of Be mirrors [5] and is probably due to existence of beryllium in the alloy composition.

The details of difference in behavior of amorphous and crystallized AMA mirrors will be discussed in the presentation.

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9-23

MODIFICATION OF TUNGSTEN OPTICAL PROPERTIES DUE TO EXPOSURETO LOW-ENERGY, HIGH FLUX DEUTERIUM PLASMA IONS

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This paper is devoted to investigation of temperature effects on modification of surface morphology and optical properties of tungsten mirror samples exposed to low energy deuterium ions (38 eV) up to ion fluence 10^{26} D/m^2. It was found that the surface state weakly depends on the exposure temperature in the range 320-695 K with the exception of the narrow region around 535 K, where drastic change of all optical characteristics occurs; this region is characterized by active blistering [1]. It is worthy to note that the reflectance found in direct measurements at normal incidence (solid line in Fig.1) drops in the wavelength interval 220-650 nm, whereas the estimations of reflectance using the ellipsometry data demonstrate some increase (dotted line in Fig.1).

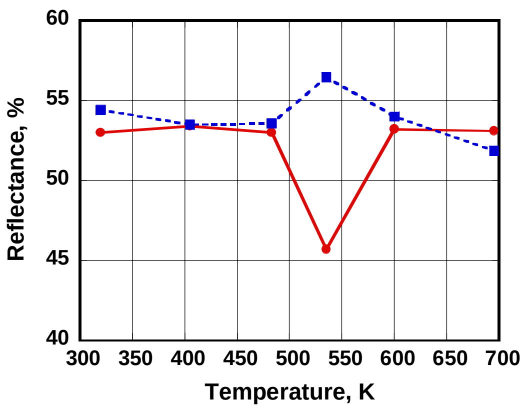

Fig. 1. Reflectance of specimens (λ=632.8 nm) exposed at different temperatures

The reason of this difference is that both methods, reflectometry and ellipsometry, are based on different physical effects. In reflectometry of specular reflection, the full energy specularly reflected from the sample is measured, thus the surface defects result in increase of diffusive component and, correspondingly, to decrease of the specular reflectance.

The ellipsometry methods are based on investigation of changing the polarization state of the specular component only and therefore they give the information on the specular reflecting parts of the surface, without taking into account the parts which scatter the light.

In the case of strongly blistered surface of the specimen exposed at 535 K, the ellipsometry brings information about the parts of surface that is still free from blisters. Thus the strong modification of ellipsometric characteristics means, probably, significant modification of the electronic structure for this particular specimen as distinct from those exposed at other temperatures.

Summarizing, on the surface of the specimen exposed to D^+ ions at 535 K two processes are realized: appearance of blisters and modification of the electronic structure in a near-surface layer.

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9-24

CHANGES TO THE REFLECTANCE OF BE MIRRORS UNDER IMPACT OF OXYGEN-CONTAMINATED DEUTERIUM PLASMAS

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A quite big portion of diagnostic complex in ITER will consist of optical methods of measuring plasma parameters with the use of plasma facing in-vessel mirrors (PFM). Because of Be first wall, the deposit growing on those PFMs located in the deposition-dominated zone of vacuum vessel will consist mainly of beryllium, what transforms the mirror of any metal to the one with Be optical properties. However, it is no concern of Be PFMs, the optical properties of which can not be changed after Be deposit appears (Be film on Be surface!). Thus, the investigation of behavior of Be mirrors in conditions approximate to the typical PFM conditions in ITER is important, i.e., when mirrors are subjected to fluxes of hydrogen isotopes with some amount of oxygen. Such investigations were provided during several years and main results will be presented in this report.

When providing the experiments with Be mirrors, similar behavior of mirrors fabricated of its diagonal analog, aluminum, was also investigated what gave chance to widen the list of surface analysis techniques.

Exposures of mirrors to deuterium plasma ions were carried out in the DSM-2 stand, where some amount of water vapors were registered during electron cyclotron resonance discharge (magnetron frequency 2.37 GHz) with deuterium as a working gas. Energy of ions bombarding the mirror samples was either in keV-energy range (up to 1.35 keV) or with energy $\leq$ 60 eV. In some experiments the reflectance in the range 220-650 nm at normal incidence was measured *in situ* or *ex situ* after every exposure.

A significant drop of reflectance was observed after short exposures to keV-energy range ions and practically full reflectance restoration – after much longer exposures to low energy ions. The ellipsometry and XPS methods for Be mirror samples, the ellipsometry, Auger and SIMS methods for Al mirror samples showed that the drop of reflectance is due to (i) partial or full transformation of oxide film into a hydroxide film ($BeO \rightarrow Be(OD)_2$, $Al_2O_3 \rightarrow Al(OD)_3$ and/or $Al_2O_3 \rightarrow AlOOD$) and (ii) rise of the transformed film thickness. The restoration of reflectance by low energy ions of deuterium plasma is mainly due to chemical erosion of transformed film, as it was observed with ion energy 20 eV, i.e., less than the threshold for physical sputtering of oxides.

The ATM data demonstrated the modification of the spatial structure (in the range 2-5nm) of the initial and transformed uppermost film without significant effect on the reflectance, when mirrors were subjected in series to keV and low energy deuterium plasma ions.

Acknowledgements

This work was partially supported by the STCU project №3668.

9-25

TOKAMAK ISTTOK: CURRENT STATUS IN DEVELOPMENT OF METHODS FOR CHARACTERIZATION OF SUPER-THERMAL AND RUNAWAY ELECTRONS

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A combination of low plasma density ($<n_e> \cong (1\div5)\cdot10^{18}$ m^{-3}) with high current densities (0.2-0.4 MA/m^2) in the ISTTOK tokamak is typical for regimes of tokamak discharges with significant populations of super-thermal or runaway electrons. In large tokamaks runaway (or super-thermal) electrons sometimes constitute serious problem in a view of their detrimental interaction with plasma facing components. Therefore, development of methods for runaway electron characterization including numerical models and their verification by experimental measurements is essential. Several approaches to characterize energetic electrons in ISTTOK plasmas have been applied. Numerical simulations of runaway generation process and direct observations of runaway electrons using Cherenkov-type detectors (single and with four channels) have been performed [1]. These detectors were designed recently for measurements of energetic electrons in tokamaks [2]. Experiments on the ISTTOK tokamak allowed to: (i) - determine the presence of runaway electrons and access their energies; (ii) - to verify the results of numerical modeling; and (iii) - to confirm the validity of used model at low energy thresholds for runaway process in ISTTOK. 4-channel detector has demonstrated the capability to obtain experimental data simultaneously in different energy ranges of fast electrons. Temporal evolution of the measured signals revealed close correlation between all channels at very similar measured emission values confirming the model of mono-energetic fast electron population generated due to Dreicer mechanism. Energy threshold of detectors used for measurements allowed distinguishing the population of electrons with energies higher than 80 keV, in some cases higher than 100 keV. The presence of fast electron populations with such energies inevitably should cause the appearance of X-rays emission. Measurements of X-rays emission have been used for verification of the measuring capabilities of 4-channel Cherenkov-type detector. Comparison of the data on X-ray radiation to the data obtained from different channels of the Cherenkov-type detector has demonstrated close correlation between Cherenkov radiation and X-ray emission signals.

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Alushta-2010
International Conference-School on Plasma Physics and Controlled Fusion
and
4-th Alushta International Workshop
on the Role of Electric Fields in Plasma Confinement
in Stellarators and Tokamaks
Alushta (Crimea), Ukraine, September 13-18, 2010

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