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Abstracts of Invited and Contributed Papers

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Reactor's Perspective of Tandem Mirrors

G.I.Dimov

Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia

Possible schemes of the ambipolar thermonuclear reactors are presented.

For a scheme of axisymmetric D-T fusion reactor the energy balance is estimated and conditions of MHD-stability are discussed. Since the power for sustenance of ambipolar barriers depends from the geometry of magnetic field in the end mirrors, some possibilities of creation of compact superconductive throat coils are considered. All possible channels of energy losses of hot electrons in the thermal barriers and plugs are estimated in classical approximation. Important portions of energy of the hot electrons are lost through cyclotron emission and through heating of electrons, including the passing, from solenoid. The ECR-heating power of thermobarrier's electrons exceeds significantly.

It is shown in principle that it is possible to realize the ambipolar D-T fusion reactor with the ratio of central solenoid output power to the end mirrors plasma input power $Q_{ef} \sim 20$, in this case the length of solenoid is about 150 m.

The main unresolved plasma physics and physics-technique problems for creation of ambipolar D-T fusion reactor are pointed out.

Ambipolar fusion reactors have opportunities of realization only in case of necessity for civilization of several Gw electric power plants.

HIGH POWER 14 MeV NEUTRON SOURCES FOR TESTS OF MATERIALS

E.P.Kruglyakov

Budker Institute of Nuclear Physics,
630090 Novosibirsk, Russia

At present, there are no reliable data on the behaviour of the materials and fusion reactor components exposed to a high flux of 14 MeV neutrons up to a high fluence. This creates a great deal of uncertainty on the prognosis of the performance and endurance of candidate materials and main components of the future fusion reactor. Thus, the extensive program dedicated to qualify the materials to be used in the reactor under a high power irradiation by 14 MeV and secondary neutrons is required. Among the problems to be urgently studied there can be pointed out the following ones: end-of-life, H, He, dpa production rates, neutron activation of existing materials and test of new low activated ones, degradation of conductivity of metals, etc. To realize this program a dedicated high flux neutron source of DT-neutrons with a large enough testing zone should be constructed in a short period of time. Such a source is most important because ITER cannot fulfill the required functions of the high power neutron source. The ITER will provide a too small fluence, too late in time, for it to be able to contribute usefully to the materials selection process. On the other hand, before DEMO is built, suitable materials for the first wall and other critical elements of the fusion reactor should be selected.

At present, a lot of proposals for high flux and high power neutron sources are known. Among them there are sources based on application of accelerators of ions and on the interaction of these ions with targets, volumetric plasma neutron sources on the basis of tokamaks and mirrors, «exotic» schemes, using muon catalysis and lasers, schemes with monochromatic and broad spectrum of neutrons in the vicinities of 14 MeV. In the paper presented here the advantages and shortcomings of various approaches are discussed from the viewpoint of their feasibility taking into account economical aspects of the problem.

Longitudinal Plasma Confinement in the Gas Dynamic Trap.

A.V.Anikeev, P.A.Bagryansky, A.A.Ivanov, G.I.Kuznetsov
and N.V.Stupishin

Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia

This work is devoted to studying the plasma flow in the expander region of a gas dynamic trap. A knowledge of processes occurring in this region is essential in two aspects. The first is that the plasma flowing out the central cell eventually comes into direct contact with material wall thus depositing the energy from the central cell to the end wall. Since the longitudinal energy losses dominate in MHD-stable regimes of confinement, the data on an energy transport in the expander is important for estimations of the prospective of gas-dynamic trap as well as other open-ended systems. It might also be useful for studies of a plasma-wall interaction in other systems where plasma is inherently in contact with the wall, for example, for the divertors in tokamaks. The second aspect is that the plasma flow parameters are significant for study of the energy balance in a trap and, in the case of gas-dynamic trap, determine the contribution of the expander to the MHD-stability of the entire trap.

The Gas Dynamic Trap (GDT) [1] is an axisymmetric open trap with a large mirror ratio and a length greatly exceeding the ion mean free path of scattering into the loss cone. In these experiments the central cell plasma density was in the range of $1.\div1.5\times10^{13}$ cm^{-3}, the electron temperature was up to 25 eV (the ion temperature is believed to be the same). Under these conditions the ion mean free path exceeded the length of the mirror so as the regime of the plasma outflow through the mirrors was collisionless.

We have measured the plasma ambipolar potential in the trap, axial energy and particle's losses from the trap and their dependencies upon the plasma parameters inside the central cell. In separate experiments, we have studied an additional cooling of the central cell plasma due to contact with end walls in case of large electron emission from the plasma end dump.

The main results of the experiments are the following:

- The measured ion distribution function over energies in the expander (region behind the mirror) is in reasonable agreement with the model of the collisionless flow.
- Near the end wall the energy flux in the expander is carried mostly by the ions, while the electron heat flux is considerably smaller.
- The mean amount of energy carried outward by an ion-electron pair is 8.7±1.8 of the electron temperature inside the central cell. The mean energy of an ion striking the wall is $(6.3\pm0.1)T_e$. The measured total drop of the ambipolar potential is $(4.6\pm0.1)\ T_e$.
- It was observed that when the distance between the plasma dump and the mirror throat exceeds certain value corresponding to the magnetic field reduction of 40-50 times, the parameters of plasma end loss in trap become undepend on the electron emission from the end wall.
- The measurements of the axial temperature and potential profiles indicate that significant fraction of trapped electrons may exists in the expander between the end wall and the mirror throat. The spatial charge of trapped electrons may essentially reduce the flow of cold electrons emitted by the wall to the central cell.

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Recent Results of Experiments on the Gas Dynamic Trap

P.A.Bagryansky[1], A.V.Anikeev[1], S.Collatz[2], P.P.Deichuli[1], A.A.Ivanov[1],
A.N.Karpushov[1], S.A.Korepanov[4], A.A.Lizunov[3], V.V.Maximov[1],
S.V.Murachtin[1], K.Noack[2], G.Otto[2], K.N.Saunichev[3], I.V. Shikhovtsev[1],
N.V.Stupishin[1]

[1] *Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia*
[2] *Research Center Rossendorf Inc., Dresden, PO 510119 D-01314, Germany*
[3] *Novosibirsk State University, 630090, Novosibirsk, Russia*
[4] *Novosibirsk State Technical University, 630092 Novosibirsk,, Russia*

This report summarizes the results of experimental investigations on the Gas Dynamic Trap (GDT), which has been obtained during the last few years. The aim of these investigations is to verify physical ideas underlying GDT-based Neutron Source . During the last years GDT facility has been essentially upgraded to achieve higher plasma parameters. The most important improvements are the following:

- application of the fast titanium coating of the GDT first wall;
- Neutral Beam System upgrade;
- development of new non-invasive diagnostics to study two-component plasma with high β;
- development of new control and data acquisition systems.

These improvements enabled us to obtain plasma parameters in the GDT as follows: electron temperature- 90-110 eV, fast ion density (mean energy — 5-8 keV) — up to 10^{13} cm^{-3}, plasma β — 20-30%.

The experimental efforts were focused on the following issues:

- effect of the wall conditioning on neutral gas transport in the GDT;
- longitudinal electron heat flux in the Gas Dynamic Trap;
- confinement of the high β two-component plasma;
- detailed study of fast ion parameters in experiments with high β;
- MHD-stability limits of high β two-component plasma in the GDT;
- bulk plasma fueling by gas puffing.

The results of the experiments can be summarize as follows:

- The MHD-stable confinement of high β plasma was achieved by using a stabilizing cusp end cell. Measurements have shown that the stabilizing capacity of the cusp end cell appeared to be high enough to keep the entire plasma within stability margins in the presence of fast ions whose energy content exceeded 3-5 times that of the bulk plasma.
- Longitudinal confinement times of energy and particles in a bulk plasma are in a reasonable agreement with theoretical predictions. Longitudinal energy losses through the mirrors essentially exceed transverse losses.
- The measured parameters of fast ions were compared with those obtained by Monte Carlo numerical simulations in order to reveal possible enhanced angular scattering caused by presence of instabilities. Within the measurement accuracy (±10%), no anomalies in the relaxation of fast ions have been observed.

AMBAL–M Status

T.D. Akhmetov, V.S. Belkin, E.D. Bender, V.I. Davydenko, G.I. Dimov,
A.S. Donin, A.N. Dranichnikov, V.G. Igoshin, A.A. Kabantsev,
Yu.V. Kovalenko, A.S. Krivenko, I.I. Morozov, V.B. Reva, V.Ya. Savkin,
G.I. Shulzhenko, V.G. Sokolov, M.Yu. Stepanov, and S.Yu. Taskaev

Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia

Investigation of the hot initial plasma created in an axisymmetric end system of the ambipolar trap AMBAL–M has been completed. In the end mirror we obtained the MHD stable plasma with the electron temperature of 50 eV, ion temperature 200 eV, and density about 10^{13} cm^{-3}. In an MHD anchor — the semicusp, a transverse profile of the plasma pressure favorable for the MHD stability was obtained. Pulsed injection of fast atoms with the current of 100 A demonstrated sufficient accumulation rate of the fast ion population trapped into the initial plasma.

Two quasistationary atomic injectors of the end mirror were prepared for work. In these injectors proton beams were obtained with the energy of 25 keV, current up to 50 A per beam and up to 80 msec duration. After their charge-exchange, the atomic beams were passed through an MHD stabilizing shell and the target plasma.

Principal vacuum units of the 2-nd stage of the installation were tested and prepaired for assembly. One-half of the magnet-vacuum system of the AMBAL-M central solenoid was assembled and tested for vacuum.

Gas-dynamic trap experiment: status and perspectives.

A.A.Ivanov, K.V.Lotov, A.N.Karpushov

Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia

The paper reports on the present status of the gas-dynamic trap (GDT) experiment and plasma parameters recently achieved with increased neutral beam power. Also discussed in the paper are possible future experiments in the GDT which would enable to advance further in establishing the required plasma physics data base for the GDT-based neutron source and its Hydrogen Prototype as well. In particular, the following issues are considered:

1. Stability margins of ballooning modes in GDT high beta plasma.
2. Prospective of expander end cell as MHD anchor for GDT.
3. Operational limits of the GDT with further increase of injected neutral beam power and pulse duration.
4. Generation of D-D neutrons.
5. Production of synthesized hot ion plasma blobs in local mirror cell in GDT.
6. Diagnostic potential of ballistic bunching of injected fast ions in GDT.

Experimental Verification of the MHD Dynamo in the Axisymmetric Linear Machine

A.A.Kabantsev, V.B.Reva, V.G.Sokolov

Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia

Generation of stationary large-scale magnetic fields by turbulent motion of an electrically conducting fluid plays an important role not only for astrophysical applications, but also for magnetic fusion confinement phenomena. The dynamo phenomenon, in wich the magnetic-field-aligned electric current is self-generated by plasma dynamics, has been a mystery in magnetically confined laboratory plasmas and astrophysical plasmas for many decades. The well-studied MHD dynamo α-effect comes from hydrodynamical helical properties of turbulent motions [1]. The effect is characterized by the alignment between mean magnetic fields and mean currents. The coefficient connecting these two quantities is linearly dependent on the turbulent part of the residual helicity, $\left\langle -\vec{u}\cdot\vec{\omega} + \vec{b}\cdot\vec{j}\right\rangle$, where $\vec{u}$, $\vec{\omega}$, $\vec{b}$ and $\vec{j}$ are fluctuations of the velocity $\vec{U}$, the vorticity $\vec{\Omega}\left(= rot\,\vec{U}\right)$, the magnetic field $\vec{B}$ and the electric current $\vec{J}\left(= rot\,\vec{B}\right)$, respectively, and $\langle\ \rangle$ denotes the ensemble mean. Under this dynamo the mean electric current is produced in the direction parallel or antiparallel to the mean magnetic field $\vec{B}_0$. In particular, the α-effect leads to the generation of high plasma current along the magnetic field in reversed field pinches [2]. We found that the α-effect takes place also in axisymmetric linear machines.

In axisymmetric mirror traps AMBAL-M and MAL the electrostatic turbulence, having mean helicity $\langle\vec{u}\cdot\vec{\omega}\rangle \approx 6\cdot 10^6\ m/s^2$, caused as a result of unstable differential rotation of plasma column in crossed $\vec{E}\times\vec{B}$ fields. By manipulating the trap's magnetic and plasma conditions, we can obtain both the parallel and the antiparallel $\vec{B}_0$ electric current to the order of 100 A/cm^2 (total current up to 6 kA) in the plasma. The measured mean electromotive force $F_{em} = \left\langle\vec{u}\times\vec{b}\right\rangle$ has linear growth with turbulent diffusion coefficient $D_T\left(\vec{r}, t\right)$ and reaches up to 50 V/m. By measuring each term, the parallel MHD mean-field Ohm's law is observed to hold within experimental error bars during plasma flow pulse.. A comprehensive physical picture of the dynamo phenomena has been obtained.

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Energy Confinement of the High β Two-component Plasma in the Gas-Dynamic Trap

A.N.Karpushov, A.V.Anikeev, P.A.Bagryansky, A.A.Ivanov, S.A.Korepanov[1],
A.A.Lizunov[2], V.V.Maximov, S.V.Murachtin, K.Noack[3], K.N.Saunichev[2]

Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia
[1] *Novosibirsk State Technical University, K.Marx Prospekt, 20, 630092 Novosibirsk,, Russia.*
[2] *Novosibirsk State University, 630090, Novosibirsk, Russia*
[3] *Research Center Rossendorf Inc., Dresden, PO 510119 D-01314, Germany*

The present report describes the experimental data on the energy balance of the GDT plasma in high-β discharges. Parameters of the GDT experiment are listed in Table 1. Six neutral beams were injected into dense target plasma at the midplane of the device. About 60% of the injected atoms were trapped providing fast ions build up. Significant progress in the plasma parameters was achieved with higher neutral beam power [1]. Total power of six neutral beams with energies 13.0-17.5 keV and pulse duration of 1.1ms was increased from 2.5 to 4.2MW. Thomson scattering system was used to measure the electron temperature, which was about 100 eV during the last stage of the NB-heating.

Magnetic field at the midplane		0.22 T
Mirror ratio		15-45
Base pressure		$2.5\text{-}5.0\times10^{-5}$ Pa
Neutral beams:	power	3.9-4.2 MW
	duration	1.1 msec
	energy	13.0-17.5 keV
Trapped power		2.2-2.6MW
Energy contents:	of fast ions	600-800 J
	of target plasma	170-230 J
Electron temperature		90-110 eV
Bulk plasma density		$3\text{-}13\times10^{13}$ cm^{-3}
Fast ions mean energy		5-8 keV
Max. Density of fast ions		$\sim10^{13}$ cm^{-3}
Electron drag power		1.2-1.5 MW
Energy confinement time:		
	of fast ions	0.3-0.8 msec
	of target plasma	0.16-0.5 msec
Max. plasma β		20-30 %

Table 1. The GDT parameters

The parameters of fast ions and target plasma were measured by a set of diagnostics. The numerical codes [2] were used to compare the experimental data with the theoretical models [3], that enable us to draw the following conclusions:

- fast ions energy balance is dominated by electron drag and charge-exchange losses, their energy confinement time is close to the prediction based on the Coulomb interaction with the bulk plasma particles;
- the main channel of the target plasma losses is a collisional outflux through the mirrors.

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Wall Conditioning and Neutral Gas Transport at the GDT Facility

S. V. Murachtin[1] ,P. A. Bagryansky[1], E. D. Bender[1], A. A. Ivanov[1],
A. N. Karpushov[1], K. Noack[2], St. Krahl[2], S. Collatz[2].

[1]*Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia*
[2]*Research Center Rossendorf, Inc., P.O. Box 510119, D-01314 Dresden, Germany*

The GDT is an axisimmetric open trap with a high mirror ratio [1] for confinement of a collisional plasma. The study of the fast ions population is one of the main objectives of the GDT experimental research program. In order to decrease the charge-exchange losses of the ions the reduction of the neutral recycling at the chamber wall is an essential demand. For that purpose an array of Ti-evaporators of electric-arc type has been installed inside the central cell of the device. This system and its application procedure have been optimized to allow the fast and homogeneous coating of the wall surface. To improve the adhesion of the film on the wall the inner surface of the chamber has been covered by stainless steel panels which were undergone several special treatments. After five years of operation it may be established that the evaporation system works with high reliability and that seeding of the plasma by titanium has not been observed.

The evolution of the neutral gas density in the presence of neutral beam injection has been studied by special measurements and by means of the Monte Carlo code TUBE [2]. The good agreement between experimental and numerical results allows to conclude that:

- in contrast to the case without the Ti-coating, the recycling coefficient of the fast neutrals, the energy of which covers the range of (0.1-17) keV, is close to unity; this fact also implies that the evaporated titanium film has the neutral recycling coefficient close to that of pure metallic titanium.
- there are no other considerable sources of neutrals than those proposed by the TUBE code being relevant for the present experiments.

The installed Ti-evaporation system enables to perform experiments with neutral beam injection producing fast ions with a mean charge-exchange lifetime of about 10 ms that exceeds the present experiment duration. This favourable situation has been mainly achieved by the drastically reduction of the fast neutral recycling at the chamber wall.

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Submegajoule Microsecond E-Beams for Plasma Heating in Solenoids and Microwave Generation.

A.V. Arzhannikov, V.B. Bobylev, V.S. Koidan, V.S. Nikolaev, S.L. Sinitsky, M.A. Shcheglov

Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia

One of the most promising ways to create a plasma with fusion parameters in a multimirror solenoid, is to heat a plasma column by high-current relativistic E-beam. The problem of obtaining the E-beam with a current density, an angular spread and an energy content suitable for plasma heating can be divided on three tasks which have to be solved. Firstly, one have to construct a high voltage pulse generator with adequate energy content. Secondly, a diode for generation of the electron beam have to be done. And finally, a system transforming the generated beam to the beam with the pointed parameters adequate for the plasma heating, have to be constructed.

In this paper approaches for solving the indicated tasks at the BINP are described. It is discussed the choice of the pulse generator and it has been shown that the Fitch-schema is suitable for reaching 1 MJ energy level at ten microsecond duration. Three types of the accelerator diodes: plane axial symmetric diode, plasma filed one, and magnetically insulated ribbon diode, are analyzed in order to generate the beam with megajoule energy content. Limits of energy content established as a result of analyses of our experimental studies for these diodes at the accelerators U-1, U-2, and U-3, are pointed in the paper. To obtain required current density at a small angular spread, various systems of transforming and compression of the beam cross section are examined.

In 1994 at the U-2 accelerator the beam generated with a ribbon cross section, has achieved the energy content about 0.4 MJ. After its transforming and compression with the efficiency 70% it has the parameters suitable for plasma heating at the GOL-3-II facility. In the paper we discuss the way for reaching two time higher level in the beam energy content.

The electron beam with a ribbon cross section have good prospects in generation of a microwave power at a few millimeter wavelength. Using of these beams to obtain tens kilojoules pulses of the microwave radiation is also analyzed in the paper.

Trapping and Confinement of Fast Electrons in a Magnetic Pit for a Scheme of Two-Stage Heating of Plasma by Electron Beam in a Solenoid*

V.T.Astrelin, E.V.Bobukh[1]

Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia
[1] Novosibirsk State University, 630090, Novosibirsk, Russia

A problem of decelerating, scattering and trapping of an electron flow by a plasma in a magnetic trap is considered. Energy of electrons significantly exceeds a thermal energy of plasma particles. The problem is provoked by current experiments on plasma heating with a relativistic electron beam in a long solenoid trap using the scheme of two-stage heating [1]. For improvement of fast electrons capture and confinement of a dense plasma cloud it is placed in a local minimum of a magnetic field (in a "magnetic pit ").

Electrons in the pit are described by distribution function $f\ (t,\ \varepsilon,\ \theta,\ z)$ in terms of time, energy, pitch angle and longitudinal coordinate of a particle, accordingly. A density of initial electrons flow is supposed small in comparison with density of plasma in the pit. The magnetic configuration and plasma density shape are arbitrary but constant in time.

A kinetic equation for distribution function in approximation of large electron mean free path in comparison with length of a pit was obtained and numerically solved. A dependence of capture efficiency on plasma density, mirror ratio and ions charge number was investigated.

A results of calculations show that for parameters close to real experiment a trapping of electrons may be sufficient and brings to increasing concentration of captured particles at 2-5 times in comparison with concentration of transiting electron flow. The lifetime of electrons in a pit makes possible a transfer of their energy to a temperature of a basic plasma. This effect can be used in current experiments on plasma heating in a magnetic trap, and for generation of powerful ultra-violet radiation on GOL-3-II facility.

The authors are thankful to A.Burdakov for suggested problem and useful discussions.

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Experiments on ICRH at the End System of AMBAL-M

T.D.Akhmetov[1], E.D.Bender[1], V.S.Belkin[1], V.I.Davydenko[1], V.G.Igoshin[2], Yu.S.Khramov[2], Yu.V.Kovalenko[1], A.S.Krivenko[2], V.G.Sokolov[1], V.B.Reva[1]

[1]*Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia*
[2]*Novosibirsk State University, 630090, Novosibirsk, Russia*

Experiments on ICR-heating of plasma are carrying out at the end system of AMBAL-M. The heating at a frequency of 11,7 MHz is performed by an antenna of "Nagoya–III" type installed in the transition region between the mirror and the semicusp with the voltage at the antenna up to 8 kV, 200–300 kW power introduced into the plasma and up to 40 ms pulse duration. In the experiments a 1,5 times increase in the energy content of the initial plasma was observed. The observed increase of the plasma pressure in the MHD-anchor — semicusp, enhances the MHD-stability safety factor of the whole plasma in the end system. Measurements of the RF fields spectrum in the plasma demonstrated the emergence of the second frequency harmonic having the power up to 20 % relative to the first harmonic. The experiments with a small radius of the initial plasma demonstrated that ICR-heating leads to a radius increase as a result of diffusion enhancement. Varying the magnetic field strength in the mirror we found that the plasma heating in the mirror occurred both at the first and at the second frequency harmonics. The heating does not result in any detectable distortion of the azimuthal symmetry of the initial plasma.

At the limiting ICR-heating power we found that after the 3 ms pulse of the initial plasma created by the gas-discharge source, the quasistationary plasma with duration of 40 ms was sustained in the mirror during RF-power input. Measurements of the hydrogen pressure by fast vacuum magnetron gauges showed that in the quasistationary regime the pressure near the plasma increased up to $3\text{–}5\cdot10^{-5}$ Torr in several milliseconds because of considerable recycling, and further remained practically constant.

The quasistationary plasma has the density $\sim10^{12}$ cm^{-3}, electron temperature ~40 eV, ion energy 300–400 eV, and may be an appropriate target plasma for creation of a hot electron population by the planned ECR-heating at the second harmonic.

Recent Results on the GOL-3-II Facility

A.V.Arzhannikov, V.T.Astrelin, A.V.Burdakov, V.G.Ivanenko, V.S.Koidan,
V.V.Konyukhov, A.G.Makarov, K.I.Mekler, P.I.Melnikov, V.S.Nikolaev,
S.S.Perin, S.V.Polosatkin, V.V.Postupaev, A.F.Rovenskikh, S.L.Sinitsky

Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia

GOL-3-II facility [1] is an open trap with *12 m* long plasma column in the longitudinal magnetic field of up to *5 T* in the homogeneous part and up to *10 T* in end mirrors. There is possibility to change the magnetic field configuration. Plasma density can be varied in 10^{14}-10^{17} cm^{-3} range. Microsecond electron beam with total energy of *0.2 MJ* generated by U-2 accelerator[2], is injected into plasma through the input mirror.

Collective interaction of electron beam with a plasma, its fast heating and confinement are investigated at this facility.

In the paper recent results performed at this facility are presented.

The efficiency of collective electron beam deceleration up to *40%* is achieved in 10^{15} cm^{-3} plasma. The characteristic electron temperature of ~ *2 keV* at plasma density *(1-2)*10^{15} cm^{-3} is obtained. At the two-stage heating of a dense (~10^{16} cm^{-3}) plasma the electron temperature of *300-500 eV* and the ion temperature of *100-200 eV* are reached.

Feasibility of experiments on "wall" and multimirror plasma confinement at GOL-3-II facility are discussed.

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Influence of End Potential Plates on Plasma Heating and Confinement

S. Yu. Taskaev

Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia

Hot target plasma was obtained without additional heating in an open trap AMBAL-M from arc source located behind the mirror [1]. Previously longitudinal electron current in plasma was found and investigated. In this paper transverse ion current in the plasma periphery has been considered. The model of longitudinal electron current generation and the model of effective electron heating are presented and discussed. Radial and longitudinal profiles of plasma density, potential and electron temperature have been measured. The main classical (collision) processes leading to transverse current are considered in detail. The Vlasov equation and simplified Fokker-Planck equation in nonuniform fields have been solved. Development of instability, particle and energy balances in the mirror have been considered.

The significant longitudinal electron current experimentally detected was found to be a part of plasma gun discharge current. Electron current of the inner ring cathode flows along the magnetic field lines to plasma receiver, then it is taken up by end of device, then it returns along conducting vacuum chamber and finally it is closed upon the outer ring anode in transporting area on plasma periphery. The current shorting was determined to be provided by the following processes at plasma periphery: 1) nonambipolar transverse diffusion from ion-ion collisions; 2) transverse current suppressed essentially by magnetic field in positive radial electric field from electron-ion collisions, which is increased due to conductivity fluctuations; 3) longitudinal current from the extending outward grounded frame of a solenoid to the anode of the gun. The big value of the current is explained by the non-equilibrium radial electric field in plasma, given by the arc source electrode potentials.

The longitudinal electron current flows out into the mirror to provide quasineutrality. As plasma density in the throat is low, the current needs the electric field accelerating the electrons to be formed in front of the throat. The found longitudinal electric field forms the population of fast electrons that transport the current. The electron flow heats the trapped electrons effectively (due to the ambipolar potential and the high velocity of the flow electrons) as a result of the Coulomb collisions. This «non-joule» non-turbulent effective heating of electrons by the current in an open trap has been first identified and investigated.

The model described shows the possibility of obtaining of hot plasma in a mirror and the possibility of change in plasma confinement by control of the radial profile of the electric field using end potential electrodes. The plasma state obtained is close to the one which can be described basing on the classical (collisional) phenomena. This control of the radial profile of the potential and the «classical» character of the plasma obtained are pointed out as characteristic favourable features of open traps.

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Features of transport phenomena in turbulent beam-heated plasma

A.V.Arzhannikov, V.T.Astrelin, A.V.Burdakov, V.S.Koidan, K.I.Mekler, P.I.Melnikov, V.V.Postupaev, A.F.Rovenskikh, M.A.Shcheglov, S.L.Sinitsky

Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia

Experiments on fast plasma heating by relativistic electron beam on the GOL-3 facility succeed in creation of a 10^{15} cm^{-3} plasma with electron temperature of up to few keV. The heating is produced due to two-stream instability of the beam that causes high level of plasma microturbulence. The experiments show some specific features of plasma behaviour during the beam injection. The beam-induced turbulence is the reason of non-classical transport processes in the plasma. Anomalies in longitudinal thermal conductivity, resistivity of the plasma and in lifetime of hot electrons are observed. Transition to classical transport coefficients occurs when the plasma turbulence disappears after the beam injection stops.

Investigation of Electrostatic and Magnetic Oscillation of Turbulent Plasma Flow in Mirror Traps

S.A.Beher [+], A.A.Kabantsev, V.B.Reva, V.G.Sokolov

Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia
[+] Novosibirsk State University, 630090, Novosibirsk, Russia

In axisymmetric mirror trap AMBAL-M [1] the initial plasma was formed by arc source with circular gas-discharge channel. The first experiments with such sources have shown that the electrostatic low frequency Kelvin-Helmholtz instability (KHI) of flute type is excited in plasma stream with differential rotation in crossed $\boldsymbol{E} \times \boldsymbol{B}$ fields. This instability results in the strong electrostatic turbulence, which leads to the generation of electric current with value of several kA in plasma column along the magnetic field [2]. This work is devoted to the investigation of electrostatic and magnetic oscillations in plasma of MAL mirror trap and study of local mode structure of exited electric current.

The total electric current generated along the plasma stream and measured with Rogowski coil is 3-4 kA. The current oscillations are about 5 %. In the spectra of observed fluctuations the 1, 3 and 5 modes of main frequency KHI prevail.

The measurement of local magnetic and electrostatic fields was made by special probe. In the spectra of oscillations high mutual coherency between $\boldsymbol{E}_\varphi$ and $\boldsymbol{B}_\varphi$ in 3 harmonic of main frequency KHI are observed. The obtained transport coefficients agree with coefficient of turbulent diffusion [2].

The system of 6 azimuthal magnetic probes disposed equdistant on two different radii are used for measurement of local $\boldsymbol{B}_\varphi$. The mutual coherency of this signals makes it possible to represent oscillating longitudinal electric current by space modes and filaments. For each selected mode the value of filament current, filament radius and total cross mode displacement are determined by the data obtained from azimuthal magnetic probes.

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Dynamics of Plasma Jet Heated by Neutral Beams in a Mirror

A. A. Kabantsev, V. G. Sokolov and S. Yu. Taskaev

Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia

In experiments on plasma heating by neutral beams at a mirror system, an interesting and unexpected phenomenon was observed: the trapping of high-energy hydrogen atoms by the jet-plasma target accompanied by the production of a hot-ion population results in a substantial decrease in the plasma density [1]. The dynamics of the potentials of an electric field, thermal force, ion pressure, and viscous force are considered in detail [2]. In this paper experimental results are given. Time-dependent problem of plasma flow is considered by the two-fluid magnetohydrodynamic approach with allowance for the population of hot ions in a mirror system, a numerical modeling is carried out, an adequacy between the model and the phenomenon is shown, and an explanation of the phenomenon is given. The conditions of the effect realization are determined. The results of the confirming experiments are given.

Observations and calculations concerning this phenomenon can be concluded in the following way. 1). Injected hot ions heat effectively plasma jet ions not directly but through electrons. 2). Heating leads to the increase of flow velocity of a plasma jet and accordingly the decrease of plasma density. Work produced by ion-pressure forces exerts primary influence on decrease of the plasma density. The effect reminds the well-know effect of one-fluid hydrodynamics — the heating of a subsonic jet leads to its acceleration. 3). In order to confine the heated electrons in a mirror system, the ambipolar potential increases. An increase in the gradient of this potential causes an increase in the acceleration rate of ions that escape from a mirror cell. The ion escape occurs mainly under the action of the electric field. At the initial moment of hot ion accumulation the increase of the ambipolar potential leads to the brake of input ions, a reduction of plasma flow, and a decrease in plasma density. 4). To study the processes under consideration, it is important to take into account the longitudinal thermal force.

It was cleared out that this effect of plasma density decrease while heating was realized in the case of dense enough subsonic jet being target plasma. The way of heating may differ from neutral beams. The power should not necessarily been put directly into ions.

The experiments showed that in the case of collisionless target plasma at heating by neutral beams an opposite effect was observed — plasma density increase up to 10 %. The confinement of collisionless ions was improved while heating. This situation of collisionless target plasma had place in the famous experiments in the 2XIIB machine [3] and so the effect of decrease of plasma density which we detected could not show itself.

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MHD stability of the plasma in the end system of AMBAL–M

T.D. Akhmetov and V.I. Davydenko

Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia

We discuss MHD stability of the plasma in the completely axisymmetric end system of AMBAL–M and suggest a physical model to interpret the experimental results. To explain the observed MHD stability of the end mirror plasma when an MHD stabilizer — the semicusp is switched off and the average field line curvature is unfavorable, a model is proposed which assumes that the plasma at the periphery has an electric contact with a limiter. As a result, the potential of flute perturbations vanishes at the plasma periphery. In this case finite larmor radius effects may stabilize the most dangerous first (global) mode because of nonlinear dependence of plasma perturbations on radius.

The radial plasma pressure profile in the semicusp was measured by a local magnetic probe. This profile has a characteristic dip near the axis corresponding to the region where the ion motion becomes nonadiabatic and the ions cannot be confined. Based on this profile and other plasma parameters measured in the mirror, contributions of the mirror and semicusp to the stability integral with respect to the global mode excitation were compared. The estimated stabilizing contibution of the semicusp is 3÷4 times greater than the destabilizing contribution of the mirror, thus the hot initial plasma in the end system has sufficient safety factor.

AXIAL SHEAR INSTABILITY IN "TACHYON" REGION

Yu. A. Tsidulko
Budker Institute of Nuclear Physics, Novosibirsk, Russia

S. Bilikmen, E. Marji, V. V. Mirnov, G. Öke
Middle East Technical University, Ankara, Turkey

ABSTRACT

The plasma axial-shear flow instability was firstly recognized by Kadomtsev [?] in flute like limit. The instability arises due to variation of an equilibrium $\mathbf{E} \times \mathbf{B}$ rotation along the axial direction in which the magnetic field is aligned. The two fluid MHD equations for incompressible perturbation (taking into account FLR effects) being treated in WKB approximation in transversal direction yield one scalar Klein-Gordon type equation with one dimensional effective potential $U(s)$ and effective mass $m(s)$ [?]. Only axisymmetric, paraxial geometry is analyzed in order to separate the desired effects from effects related to variation of cross-sectional shape of the magnetic flux tube. In this work the effective potential is considered for a semi-infinite bounded plasma to be first in the form of square well for analytical study and then linear nature to do study in so called "tachyon" region [?]. Growth rates as a function of the potential well depth and other parameters are calculated. The main attention is paid to the case when effective mass is imaginary ("tachyon" regime). Corresponding increase of the growth rates is observed in this regime. The results obtained are interesting for the stability problem of such open devices as GDT, GAMMA-10, AMBAL-M and scrape-off layer in tokamak divertors.

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The Gas Dynamic Trap as Neutron Source for Material Test Irradiations

U. Fischer[1], A. Möslang[1] and A. A. Ivanov[2]

[1] *Forschungszentrum Karlsruhe, P. O. Box 3640, D-76021 Karlsruhe, Germany*
[2] *Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia*

The gas dynamic trap (GDT) mirror machine has been proposed as volumetric neutron source for fusion material test irradiations by the Budker Institute of Nuclear Physics, Novosibirsk, [1, 2]. On the basis of the GDT plasma confinement concept, 14 MeV neutrons are generated at high production rates in the two end sections of the axially symmetrical central mirror cell localised closed to the magnetic mirrors. Thus a high neutron wall loading at a low overall fusion power can be provided in the two end sections of the central cell serving as suitable material irradiation test regions.

In this paper, we present an evaluation of the GDT as intense neutron source for fusion material test irradiations. This includes comparisons to irradiation conditions in fusion reactor systems (ITER, Demo) and the International Fusion Material Irradiation Facility (IFMIF) as well as a conceptual design for a helium-cooled tubular test assembly elaborated for the largest of the two test zones taking proper account of neutronics, thermal-hydraulic and mechanical aspects.

The tubular test assembly incorporates 10 rigs of about 200 cm length used for inserting instrumented test capsules with miniaturized specimens taking advantage of the „small specimen test technology". The proposed design allows individual temperatures in each of the rigs, and active heating systems inside the capsules ensures specimen temperature stability even during beam-off periods.

It is shown that the GDT neutron source can provide favourable conditions for fusion material irradiation testing. It provides the correct fusion neutron spectrum at a reasonable neutron wall loading and a large irradiation volume. Major concern is about the maximum achievable dpa accumulation of less than 15 dpa per full power year on the basis of the present design parameters of the GDT neutron source. A design upgrading is recommended to allow for higher neutron wall loadings in the material test regions.

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DESIGN OF THE MAGNET SYSTEM FOR NEUTRON YIELD ZONE OF PLASMA NEUTRON GENERATOR BASED ON THE GAS-DYNAMIC TRAP

V.V.Korshakov, V.G.Krasnoperov
D.V.Efremov Research Institute of Electrophysical Apparatus 189631, St.Petersburg, Russia
A.A.Ivanov, Yu.A.Tsidulko
G.I. Budker Institute of Nuclear Physics 630090, Novosibirsk, Russia

There no weekly activate materials nowadays that has ability to outstay hard radiation of reactor neutrons during 10 years without considerable degradation. Without such materials it is impossible to build safety and ecology acceptable fusion reactor. Neutron generator for experiencing of materials must to has flow density of neutrons about 1-5 ÌÂò/ì2. The spectrum of this neutron flow must be like spectrum of fusion reactor /1-3/. Neutron source based on mirror gap. The neutron source based on mirror gap has some advantages in comparison other neutron source /4/. Electromagnet system of neutron source based on mirror gap consists two mirror gaps /6/ and coils between them that produce intended distribution of field strength. Last achievement in superconductor technology allow to build experimental coil that produce 17-21T on axis /7/.

In report there are submitted results of design and computation electromagnet system of zone of neutron emission for three cases: 17, 21 and 25 T field strength in mirror magnet. For every case dimensions and parameters of system of zone of neutron emission. In case 25T field strength in mirror magnet the of zone of neutron emission has maximum dimensions and parameters but consumption power of resistive coils is 3 MW. Electromagnet system of case 17T can be done wholly from superconductor nowadays but in this case there are minimum dimensions and parameters of zone of neutron emission. . Electromagnet system of case 21T can be done wholly from superconductor after improvement of parameters of superconductor and in this case there are acceptable dimensions and parameters of zone of neutron emission

In conclusion of report are given parameters of superconductors that they are needed to achieve intended distribution of field strength on mirror magnet axis.

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NOVOSIBIRSK GDT-NS FUSION MATERIAL IRRADIATION FACILITY

A RADIATION SHIELD NEUTRON POTENTIALITIES STUDY

B.V.Robouch[1], V.I.Volosov[2], A.A.Ivanov[2], Yu.A.Tsidulko[2], L.Ingrosso[3] and J.S.Brzosko[4].

[1]*Associazione EURATOM-ENEA sulla Fusione CP.65, 00044 Frascati(RM) Italy.*
[2]*Budker Institute of Nuclear Physics, Siberian Division of the Academy of Science of Russia, Novosibirsk-630090, Russia.*
[3]*Via Gregorio XIII 7, 00040-Monte Porzio Catone, Italy.*
[4]*Neutronics/Photonics R&D, Jersey City, NJ-07304-1906, Avogadro Energy Systems Inc., Staten Island, NY-10301, USA..*

The paper presents the results of a numerical study of the feasibility of a protective-shielding of the vital parts of the Fusion Material Irradiation Facility (FMIF) Neutron Source (NS) based on the Novosibirsk Gas Dynamic Trap (GDT) and the facility neutron potentialities. The mirror type machine is planed to produce 10^{18} DT-neutrons/s over 10-years (3×10^{26} neutrons).

Simulations use the 3DAMC-VINIA Monte Carlo code with its Drizzle-shower splitting technique and two-step cascade (bilinear functional) treatment, ENDF/B6 files, and a model as per the engineering-design, with precise computer representations of critical parts of the facility.

The proposed shielding ensures survival of the facility, as per project tolerances, with further shield reduction and optimization possible. Present partial shield reductions around the plasma column consent $2.5m^3$ for irradiation space with $0.06m^3$ at 0.3×10^{14} thermonuclear uncollided n_{DT}-neutrons/s (0.5 MW/m^2) and 0.7×10^{14} collided ones, axial damage gradients below 2%/cm, and ~30 dpa in Fe-type materials at end-of-life.

Diagnostic neutral beam injectors for large plasma physics experiments.

A.A.Ivanov, G.F.Abdrashitov, V.S.Belkin, A.I.Gorbovsky, V.I.Davydenko,
P.P.Deichuli, A.N.Dranichnikov, V.A.Kapitonov, V.Ya.Kremyansky,
V.V.Mishagin, A.A.Podminogin, V.Ya.Savkin, I.V.Shikhovtsev, A.V.Sitnikov,
A.S.Medvedko, Yu.A.Evtushenko, V.V.Kolmogorov, I.I.Averbuch, R.Uhlemann[1]

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Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia
[1]IPP, KFA Juelich, Germany

Low-divergent, quasi-stationary neutral beams are often applied in modern magnetic fusion devices as a diagnostic tool providing unique information about plasma parameters. The most important requirements to these beams are sufficiently large current and energy of the particles, so that the beam could penetrate to plasma core. At the same time, duration of the beams should be long enough, close to that of a plasma shot, amounting to, at least, a few seconds for large machines. We developed neutral beam injector which is capable to meet above mentioned requirements. Plasma emitter in the injector is provided alternatively radio frequency or arc discharge in hydrogen (deuterium).

The injector was designed to be rated at energy 50 keV, equivalent beam current (for hydrogen) of up to 1A and pulse duration of up to 10s. Generally, in the measurements a modulation of the diagnostic beam enables one to improve signal to noise ratio. Therefore, the developed power supplies for the injector were designed to provide the modulated beam. One version of high voltage power supply based on use of a pulse transformer. In this version modulation frequency is fixed to 500Hz. Output voltage is stabilized by a stack of varistors. Alternatively, we also developed high voltage modulator based on low frequency invertors working at 8kHz frequency in which the modulation of output voltage frequency is variable with upper limit of about 500 Hz. In order to minimize the voltage ripples the different invertors, with total number of six, are connected in series to the load each having certain phase shifts.

With grids shaped to focus the beam 4m downstream from the source, we obtained angular divergence, characterized by half-width to the 1/e current points (measured by secondary emission detectors), of ± 0.7 degree (for 50keV energy). Distinctive feature of the ion source is that in order to simplify fabrication of the injector, a thermal inertia-type ion optical system with «thick» electrodes is used. In such a design the grids are cooled between pulses by water flowing not directly in the channels in the grid bodies but in the tubes soldered to the supporting flanges. This approach is applicable in the case if injector operates with sufficiently long intervals between the pulses so that averaged power released on the grids appears to be small enough.

Experimental tests indicate that the grids are capable to handle a pulse thermal load when operated at 50 kV and extracted ion current of, at least, 1.7A for 4s, with a duty cycle of about 1.5% for cooling. In the paper we discuss the experimental results obtained during the injector testing in comparison with the results of numerical simulation of the beam formation in the elementary cell.

The measurements of plasma density profile in GDT using diagnostic injector DINA-5

S.A.Korepanov[1], P.A.Bagryansky, P.P.Deichuli, A.A.Ivanov

Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia
1 Novosibirsk State Technical University, K.Marx Prospekt, 20, 630092, Novosibirsk, Russia

The diagnostic based on neutral beam injector DINA-5 is developed for the plasma density measurement in midplane of Gas Dynamic Trap (GDT) experiment. Characteristic value of the plasma density in GDT is 10^{14} cm^{-3}, the temperature is ~100 eV. The deuterium neutral beam with energy of 25 keV and equivalent current of up to 2 A is injected perpendicularly to plasma column at the midplane of the device. Beam attenuates 2-3 times passing through the plasma. The generated ions are deflected by the magnetic field and are registered by a detector array located between the plasma and first. The deuterium ions produced in various points along the initial beam trajectory detected. The level of the signal in each detector depends on the local plasma density in corresponding point, enabling to reconstruct the plasma density profile along the beam.

The space resolution of the diagnostic is determined by the transverse size of the beam in the direction across the magnetic field. To achieve better space resolution the initial cylindrical beam was transformed in to the ribbon-line beam by diaphragm with the slot-hole the size 0.8 m in the direction perpendicular to the magnetic field. In order to increase the useable signal the size of the beam along the plasma axis was not specially limited and amounts to about 6 cm.

In the experiments with the powerful neutral beam injection the plasma diamagnetism achieves considerable value ($\beta \sim 30\%$) therefor it has to be taken into account for the accurate calculation of the D^+ trajectories.

The space resolution of the method was estimated to be about 2 cm. The duration of the beam (up to 5 ms) is large enough to overlap the duration of the GDT shots.

Optimum Interferometry on Plasma Devices

V. V. Kubarev

Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia

Optimum interfermeters having maximum accuracy of measurement of plasma density profile was examined in the report. The possibility of creation of the interferometers with laser and detector noises more smaller than vibrational noises and parasitic signal connected with refraction of the radiation was shown. Two latter factors are practicaly unremoved and have inverse dependence on wavelength of the radiation. So for each device there is definite optimum wavelength for what accuracy of measurement of plasma density profile is maximum. Different optimum interferometers on base of universal ultralow-noise poweful infrared and submillimeter laser [1–4] was considered. Parameters of the interferometers was discribed for some plasma profiles and variouse levels of the vibrations.

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Ballistic Bunching of Fast Ions in a Mirror Trap

K. V. Lotov and A. A. Ivanov

Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia

The fast ions produced inside a mirror trap by neutral beam injection could form periodic short-lived density peaks near a turning point if the injection energy is properly modulated in time. Parameters of these density peaks depend on the energy modulation law, energy and angular spreads of the injector, scattering of bunched ions on the background plasma, and some other factors.

The most fundamental limitation on the peak bunch density is imposed by the own energy spread of the bunched ions. For the neutron source based on the gas-dynamic trap (GDT) [1], this constraint allows to increase the peak ion density 1.2-1.5 times. The shorter is the modulation period, the greater is the density peaking.

Another serious restriction on the bunch density can appear because of the angular spread (initial or acquired) of the bunched particles. However, this restriction can be avoided by the special choice of magnetic field profile, for which particle bounce-periods are independent on pitch-angles.

For practical applications of the ballistic bunching, the bunch should appear at all field lines simultaneously and at the same cross-section of the trap. The criterion of identical behaviour of particles on different field lines is derived. This criterion is easy to meet if the plasma pressure inside the trap is much less than the magnetic field pressure.

With the ballistic bunching, it is possible to produce controllable short bursts of the neutron flux in the GDT-based neutron source. However, the bunching has no effect on the average neutron yield because of the short duration of neutron bursts. The modulation of the neutron flux could significantly extend the field of application for the neutron source. Also, the bunching could serve as a precise plasma diagnostics in mirror traps.

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Study of Electron Temperature Profiles in GDT during Neutral Beam Heating by Thomson Scattering System

V.V.Maximov

Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia

Thomson scattering system based on a ruby laser was applied in GDT to measure the electron temperature during intense neutral beam injection. The system is capable to measure radial profile of electron temperature in the midplane over plasma radii varing from 0 to 12 cm. For this purpose the focusing lens is moved from shot to shot along the laser beam. The scattered light condenser with the polychromator is correspondingly rotated. Angle of scattering is in the range of 86 - 97 degrees. Polychromator has 9 wavelength channels coupled to 9 photomultiplier tubes by means of fiber optics. Combined shield protects tubes and signal cables from the stray magnetic fields of the device and electromagnetic noise.

Adjustment of the optical system is carried out without opening to air. In order to reduce background light the set of diaphragms and light traps was installed. It enables to measure the electron temperature at minimal plasma density of ~10^{13} cm^{-3}. Plasma light introduces additional problems in signals registration for the most sensitive channels. The time between shots (about 3 minutes) is long enough to collect, archivate the all data and subsequently calculate the electron temperature. In the paper, the data on radial profiles and temporal behavour of electron temperature during neutral beam heating at GDT are presented in comparison with the data from other diagnostics (triple probes and diamagnetic loops). In the experiments, electron temperature of the target exceeding 100 eV was observed. The measured dependence of the maximal electron temperature from the injected neutral beam power is also discussed in the paper.

H_α spectroscopy for hot plasma parameters measurement

P.I.Melnikov, I.A.Ivanov

Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia

The use of H_α profile for measurement of plasma density founded on H.R.Griem calculations [1] of H_α line broadening in a low temperature plasma (1–4 eV). The later works (see, for example, [2,3,4]) only refines these calculations. So, application of H_α spectroscopy was limited by temperature of investigated plasma. But H_α line is very strong in the hot plasma too! This is can be caused by both background hydrogen penetration in the plasma volume or artificial implantation of the hydrogen. The H_α profile of a hot plasma have a strong dependence of the plasma density and the ion temperature. For the definition of these parameters with H_α line contour we made the accurate calculation of H_α profile in a wide range of main variables ($n_e=10^{15}–10^{17}$ cm^{-3}, T_e=1–500 eV).

In the calculation process we avoid any simplification and get the precision profile for any plasma density and electron temperature with H-ALPHA programme codes. Estimated accuracy was less than 1%. Ion temperature should take into account by pure convolution of the calculated and Doppler contours. Calculated H_α profile for low temperature was in a good agreement with H.R.Griem calculations [1].

In the experiments with hot plasma the calculated profile had being bring into coincidence with measured contour by changing n_e, T_e, T_i parameters. Measurements of the plasma density ($5{\cdot}10^{15}–5{\cdot}10^{16}$ cm^{-3}) and ion temperature (10 –200 eV) by H_α spectroscopy system shows the full agreement with Thomson scattering system and diamagnetic loop system dates.

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IR Thomson Scattering Systems for Measurement of n_e, T_e Profiles in Open Traps

V.F. Gurko, O.I.Meshkov, L.N.Vyacheslavov, , and V.F.Zharov

Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia

Two laser scattering systems based on Nd-glass laser and avalanche photodiodes are proposed. First system is designed for observation of radial profiles of the electron plasma density and temperature. Each of its 2-4 spectral modules consists of 25 spatial channels and includes a bandpass interference filter, F/0.9 camera lens , and 25-channel linear array of the avalanche photodiodes followed by amplifiers and ADCs. Every of 25 spatial channel can view the plasma volume with an adjustable length of 1.5-15 mm along the radius of a trap. In the IR spectral region the plasma background radiation is small and the main source of noise is the amplifier noise, which permits in this case observation of a plasma of a density of 10^{12} cm^{-3} with the S/N >10. The temporal resolution of the detectors easily allows a further increase in the signal amplitude by 2-3 times with 2-3 additional passes of the probe beam through the plasma.

The second system is intended for measuring the longitudinal n_e and T_e profiles and uses the LIDAR technique, which is more suitable for open traps than for large tokomaks because of considerable larger scattering length. A relative simple pulse compressed probe laser (0.5-1 ns , 10J), commercially available high speed APD/ preamplifier modules, and ADC, as well as interference filters and high rejection holographic notch filter can provide longitudinal measurements with the spatial resolution $l \leq$ 20 cm and S/N >10 for $n_e \geq 10^{12}$ cm^{-3}.

The probe laser (30J, 10ns, 1.06 Om, 0.2 mrad) and the prototype of a single spectral module for radial measurements have been developed an used in an experiment.

Asymmetric centrifugal magnetic trap and some problems of magnetic fusion reactor

Volosov V.I.

Budker Institute of Nuclear Physics, Novosibirsk, Russia

There are assume commonly for continuously operating magnetic thermonuclear reactor , that the reactions products (in DT reaction - alfa particles) are magneticaly confined in the volume of reactor and leave their energy in the plasma. The plasma heating by the reactions products compensate the plasma energy losses. Due to the presence of alfa particles some problems are arising in this scheme of reactor.

Part of them were discussed in the project of ITER: MHD activity connected with the alfa particles, problem of "ashremouving", overheat of electrons and so on [1-3]. The other - the beta-alfa parameter in this regime can be the order or higher then beta for plasma ; it's the problem as for DT reaction (ITER) so for DD and D3He reactions [3]. The problem of energy direct conversion for the reactions products is significant for systems with Q >> 1.

In the case, then the reactions products go out from the reactor for the transit time and all their energy is transformed into the electrical energy in the direct converter, all these problems are absent. The example of similar device is a reactor on the base of asymmetric centrifugal magnetic trap. The magnetic system of the device is asymmetric; the role of two magnetic plugs is different. In one plug there is an electrode system through which electric fields are introduced into the plasma. Plasma heating and stabilization also realize by this system. The reactions products are removed through another plug, behind which there is a direct converter of energy of these particles [4]. The problems connected with realization of this reactor are discussed.

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Interaction of hot electron plasma with solids at the GOL-3 facility

A.V.Arzhannikov, V.T.Astrelin, A.V.Burdakov, P. Z. Chebotaev, V.S.Koidan,
K.I.Mekler, P.I.Melnikov, V.V.Postupaev, A.F.Rovenskikh, S.L.Sinitsky,
M.A.Shcheglov, H.Wuerz[1]

Budker Institute of Nuclear Physics , 630090 Novosibirsk, Russia
[1] Forshungzentrum Karlsruhe, Postfach 3640, 76021 Karlsruhe, Germany

Experiments on the interaction of powerful hot electrons stream from open trap with solids were performed at the GOL-3 facility. The aim of the experiments was to study of behavior of the plasma facing components under ITER disruption conditions. Material erosion and properties of the vapor layer were studied.

Irradiation of the graphite target by hot electron plasma stream leads to explosive (brittle) erosion of the graphite and formation of vapor cloud mixed with dust. The erosion depth of the graphite depends on energy density and reaches 0.5-1 mm for energy density of the fast electrons stream of 20-60 MJ/m^2. The specific energy value for graphite volumetric destruction was obtained to be 10 kJ/g.

Vapor layer consists of graphite dust, vapor cloud and plasma corona. Dust fraction has velocities about 10^5 cm/s and the distribution of the dust particles over size gives characteristic value 1-2 μm. But mass losses of the target is caused mainly by large (≥10μm) particles. Dust fraction redeposits to facing walls and has structure like carbon black.

The conditions for long-lifetime operation of the plasma and e-beam graphite receiver at GOL-3 facility were found.

On the basis of analysis of experimental data the conclusion is drown that under conditions typical for ITER disruption the explosive destruction of material can occur.

Applications of rotating plasma.

I.N.Churkin, V.I.Volosov, A.G.Steshov

Budker Institute of Nuclear Physics, Novosibirsk, Russia

Rotating plasma can be formed by an axis symmetric trap with radial electrical and axis magnetic fields. Plasma ions rotate around the trap axis as well as plasma electrons.

Physical features and possible applications of trap with rotating plasma are considered. Investigations of hot hydrogen rotating plasma were carried out at the PSP-2 device [1]. Obtained MHD-stability plasma with ion energy of up to 80-100 kev was close to some parameters of thermonuclear plasma. Rotating plasma with heavy ions can be created at some conditions by means of cathode sputtering by ion bombardment and further ionization of sputtered atoms by plasma [2]. Created ions have been magnetized inside interelectrode area, what allows to use rotating plasma with heavy ions for technological applications.

The possibilities of generation of multicomponent atomic fluxes and plasma flow was investigated at the source in crossed fields (SCF) device. Acceleration of magnetized ions inside plasma by radial electrical field is used at the source of multicomponent fluxes. The fan fluxes of accelerated atoms leave the source. There are not space charge limitations on a flux intensity in the source. Main parameters of generated atomic fluxes are following: flux intensity of up to 50 mA/cm^2, energy of accelerated atoms of up to 10 kev [3]. Experiments on surface treatment by fluxes of various atoms were carried out at the SCF-device [3,4].

The different application of rotating plasma with heavy ions is the source of plasma flow [5]. The dense plasma cloud is formed near cathode area and leaves out the source along magnetic field. Main parameters of plasma flow generated by the pulse (duration of several msec) SCF-device were experimental obtained. Sources of such type can be used for space engines and isotope separation systems.

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Source of VUV emission based on beam-heated plasma of GOL-3-II facility

V.T.Astrelin, A.V.Arzhannikov, E.V.Bobukh, A.V.Burdakov, I.A.Ivanov, N.G.Karlykhanov*, V.S.Koidan, V.A.Lykov*, K.I.Mekler, P.I.Melnikov, V.G.Nikolaev*, S.V.Polosatkin, V.V.Postupaev, A.F.Rovenskikh, S.L.Sinitsky, A.Yu.Zabolotsky

Budker Institute of Nuclear Physics, Novosibirsk, Russia
**All-Russian Scientific Research Institute of Technical Physics, Snezhinsk, Russia*

New approach to a VUV source based on mirror-confined plasma is presented. A plasma cloud with $n_e=10^{16}$-10^{17} cm^{-3} and $T_e=10$-50 eV serves as an active medium. Such plasma can be obtained in GOL-3 facility by means of two-stage heating by relativistic electron beam. Current experiments on GOL-3-II facility are described. Results of recent study of VUV flush from hydrogen and nitrogen plasma with calculations of ionization balance and radiation power are presented. Transitions in Li-like ions for recombination scheme and in Ne-like ions for collision excitation scheme are considered as a candidates for coherent VUV generation. Prospects of population inversion and gain achievement are discussed.

Trap with crossed ExH fields as source of atomic fluxes for surface treatment.

A.G.Steshov, I.N.Churkin, V.I.Volosov

Budker Institute of Nuclear Physics, Novosibirsk, Russia

Different types of discharges both with magnetized ions and electrons and with only magnetized electrons can been generated at different macroscopic parameters of the trap with axial magnetic and radial electrical fields.

These discharges can form atomic fluxes of gas and conducting materials with wide energetic spectra which can be used for surface treatment. The use of magnetron discharge [1] and heavy ion discharge [2] for surface treatment is known.

The investigations of the various discharges and generated atomic fluxes were carried out at the pulse SCF-device.

The main parameters of generated atomic fluxes and operating features of the device at various discharges are considered. Experimental results of surface treatment by atomic fluxes at different operating regimes of the device are presented.

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