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7th International Conference on
Open Magnetic System for Plasma Confinement

OS2008
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July 15 ~ 18, 2008, Daejeon, Korea

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O23

Recent experiment with anisotropic hot ion plasmoid in compact mirror cell at the gas dynamic trap

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The concept of the **S**ynthesised **H**ot **I**on **P**lasmoid (SHIP) experiment in the additional compact mirror cell at the GDT facility of the Budker Institute was presented at the 29th EPS Conference in year 2002[1]. In December 2004 the experimental activity at the GDT-SHIP facility has been started. The first experiment on study of SHIP plasmas with moderate parameters of neutral beam injection was presented at 5th International Conference on Open Magnetic Systems for Plasma Confinement (July 5-9, 2004, Novosibirsk, Russia) [2]. During last years, the new power supply of the neutral beam injection system at GDT was installed and the parameters of neutral beams injected to central and compact mirror cell of GDT sufficiently increased with the prolongation of the beam pulse from 1 to 4 ms.

The SHIP experiments are performed in a small mirror section that is installed at one side of the GDT. The magnetic field on axis is in the range of 2.7 Tesla and the mirror ratio amounts ~ 2. The section is filled with warm background plasma streaming in from the central cell. This plasma component with density of ~ 1019 m-3 is maxwellised and has an electron temperature about 100 eV. The two updated neutral beam injectors perpendicularly inject a total current up to 40 atom amperes of hydrogen/deuterium atoms with the energy of 25 keV in the 4 ms pulse. Ionisation of the beams generates the high-energetic strong anisotropic ion component with the density up to 10 times more that it is of warm ion and with the mean energy about 10 keV. Build-up of anisotropic fast ion density in the compact mirror is accompanied by the rise of electrostatic potential on field lines occupied by hot ion plasmoid and ambipolar plugging was surely demonstrated in presented experiments. The high level fluctuations of the plasma potential and magnetic field were also observed in compact mirror when the ion density exceeds the critical value. Discussion about observation of micro-instability limits is also performed.

[1]. A.V. Anikeev, P.A. Bagryansky, A.A. Ivanov, K. Noack, *29th EPS Conference on Plasma Phys. and Contr. Fusion.* Contributions ECA Vol. **26B**, P-4.098 (2002).

[2]. Bagryansky PA, Anikeev AV, Ivanov AA, et al, «First results from ship experiment» *Transaction of FUSION SCIENCE AND TECHNOLOGY* **47** (1T) pp 59-62 (2005)

P02

Status and Prospects of GOL-3 Multiple Mirror Trap

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The paper reviews recent experimental results from GOL-3. During the last few years several key physical phenomena that determine plasma behavior in multimirror trap were identified in the experiments. These are:

- Suppression of electron heat conductance by three orders of magnitude during collective beam-plasma interaction. Electron temperature reaches 2–4 keV at a density of $3\cdot10^{20}$ m^{-3}.
- Fast ion heating which leads to increase of ion temperature up to ~2 keV at ~10^{21} m^{-3} density.
- Significant lowering of plasma density required for optimum, long confinement compared to classical theory due to ion scattering in turbulent plasma. The longest achieved energy confinement time (~1 ms) corresponds to theory, but for significantly lower density. This is beneficial for multimirror-trap-based fusion reactor concept.
- New class of plasma oscillations in the cells of multi mirror trap GOL-3 is observed. The oscillations are identified as bounce instability which can decrease the axial particle losses.
- Global plasma stabilization in GOL-3 is achieved by control of the magnetic shear.

Currently, efforts are focused on further development of a physical database for multimirror confinement systems and also on an upgrade of plasma heating systems of GOL-3 device.

During the upgrade of the relativistic diode assembly of the U-2 generator the beam duration was increased up to 11-12 μs with almost all the extra duration being in the high-power part of the beam pulse.

Parameters of electron distribution function during and shortly after the beam injection stops were studied with the longer beam. It was found that the electron distribution function has rather complex shape. In particular, preliminary data indicate that energetic electrons exists till the end of the heating pulse.

A next step in the development of multimirror systems should provide significantly longer plasma lifetime. This requires development of new techniques of plasma heating in addition to existing high-power relativistic electron beam. Neutral beam injection is considered to be effective for auxiliary plasma heating in GOL-3. High density, short lifetime, small plasma radius and high gas pressure near the wall are the challenges which complicate use of neutral beam injection in GOL-3. First results of the experiments with injection of sub-MW NBI are presented in the paper.

In general, current GOL-3 parameters demonstrate good prospects of a multimirror trap as a fusion reactor.

P20

EXACT GROWTH RATE OF THE RELATIVISYIC ELECTRON BEAM INSTABILITY IN A MAGNETIZED PLASMA

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The linear phase of the instability of a relativistic electron beam propagating in a magnetized plasma is analyzed in the general kinetic framework. Physical situations involving beam-plasma instabilities are quite numerous: from fast ignition scenarios in inertial confinement fusion to plasma heating in open magnetic systems. To find the growth rate of the instability at an arbitrary value of the longitudinal magnetic field and arbitrary wavevector k, a numerical algorithm is developed that solves the fully electromagnetic kinetic dispersion equation.

The algorithm is applied to the conditions typical of plasma heating by powerful relativistic electron beams. Here the beam can be considered as a monoenergetic one with a rather wide angular spread so that the growth rates obtained with analytically tractable kinetic or fluid approximations are not correct. Particular attention is given to the transition from a weak magnetic field, when oblique modes play an important role, to the strong magnetic field, when the instability becomes one-dimensional.

P21

COMPUTER SIMULATION OF RELATIVISTIC ELECTRON BEAM RELAXATION IN PLASMA

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Relaxation of a relativistic electron beam injected into a plasma-filled half-space is studied numerically with 1D and 2D models. This study is motivated by the significant progress in plasma heating achieved in experiments at mirror traps. An important step in understanding of the physical processes responsible for saturation of the beam instability was made by the theoretical model [1], in which the main stabilizing role was assigned to trapping of beam particles. Another important effect that can limit the wave growth and provide the spectral transfer of resonant wave energy to the nonresonant part of the wave spectrum is caused by deformation of the plasma density profile due to the ponderomotive force of growing wave packets. In order to explore if these effects can saturate the instability without any plasma nonlinearity, we developed a hybrid 1D code in which the electron beam is represented by macro-particles and the plasma is treated as a linear continuous medium. The results of 1D simulations are benchmarked with 2D particle-in-cell simulations in which both plasma nonlinearities and excitation of oblique electromagnetic modes are included.

P22

Relativistic effects on the equilibrium of electron plasmas

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Relativistic effects on the cold fluid radial equilibrium of electron plasmas confined in Malmberg-Penning traps, with or without a coaxial inner charged conductor [1,2], are analyzed for rigid and sheared modes of plasma rotation.

The changes with respect to the non-relativistic results turn out to be especially pronounced for the fast rotational equilibrium solutions. In this case, the density profile for a solid plasma column becomes nearly parabolic rather than stepwise as predicted by the non-relativistic theory.

Relativistic effects can also limit the outer radius of an annular plasma column. Analytical estimates of this maximum radius are found both for rigid plasma rotation and in the case of a uniform plasma density.

Finally, a class of sheared equilibria is found where the Brillouin density limit valid for the case of rigid rotation can be overcome.

[1] I. Kotelnikov, M. Romé and R. Pozzoli, Phys. Lett. A 372, 1445 (2008).
[2] I. Kotelnikov, M. Romé and R. Pozzoli, Phys. Lett. A 372, 2450 (2008).

P23

Dynamics of electron distribution function in multiple mirror trap GOL-3

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Essential progress in experiments on dense plasma heating by a high-power electron beam was achieved at the GOL-3 facility. The electron beam with ~0.8 MeV energy, ~30 kA current, ~8 μs pulse duration, and ~150 kJ total energy content heated deuterium plasma of 10^{21} m^{-3} density up to 2-3 keV temperature. The confinement time in these experiments was ~1 ms. The high electron temperature in the linear trap was obtained due to 1000-fold turbulent suppression of longitudinal electron thermal conductivity during the beam pulse that is provided by Langmuir microturbulence, excited in the process of the beam relaxation in the plasma.

The achieved plasma parameters support our vision of a multiple mirror trap as the alternative path to a fusion reactor. The key physical problem for a multimirror-based reactor is a possibility to keep turbulent suppression of axial heat flow during the full plasma burning pulse by injection of a steady electron beam. Significant improvement in the presented experiments is increase in the beam injection time up to ~12 μs, with the full power part of the pulse being doubled in duration at the same total energy content. This allows us to study dynamics of heating and the electron distribution function during a gradual decrease of energy of injected electrons.

Thomson scattering system with 90° and 8° scattering angles enables measurements within the energy range up to 20 keV. The experiments clearly show the non-equilibrium electron distribution function. Features will be discussed in the paper. Preliminary results indicate that turbulent suppression keeps for a longer period, than with the electron beam of shorter duration.

P24

EXPERIMENT WITH LARGE-MIRROR-RATIO CORRUGATION AT MULTIPLE MIRROR TRAP GOL-3

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Multimirror approach to plasma confinement for fusion is studied at the GOL-3 facility in Novosibirsk [1]. The plasma of $10^{20}\div10^{22}$ m^{-3} density is confined in a 12-meter-long solenoid, which produces axially periodical (corrugated) magnetic field. In the basic operation regime the solenoid consists of 55 magnetic cells with B_{max}/B_{min}=4.8/3.2 T (mirror ratio R=1.5). The plasma is heated up to 1-2 keV ion temperature (at ~10^{21} m^{-3} density) by a high power relativistic electron beam (~0.8 MeV, ~30 kA, ~8 μs, ~120 kJ). Energy confinement time is ~1 ms that is in agreement with current theory.

Magnetic configuration of GOL-3 is quite flexible. This paper presents first physical results from special experiments with a section of stronger corrugation. Five corrugation cells with B_{max}/B_{min}=6.0/2.2 T (R~2.7) with the combined length of 220 cm were created in the beginning of the plasma column. Classical theory of the multimirror confinement (see, e.g., review [2]) predicts that the confinement time should scale as R^2. However, the measured confinement time is much higher than predicted by this theory. The discrepancy is currently attributed to collective scattering of ions in parallel velocity that is associated with periodic pulses of neutron flux. If this is the case, there should be a not too high optimum in R.

First data on the plasma heating and confinement in the above conditions are presented. As predicted, period of pulsations of neutron flux increased. This fact supports the existing interpretation of improved longitudinal confinement as due to excitation of bounce oscillations by axial plasma flow.

[1] A. Burdakov, et al., Fusion Science and Technology, 51 (No. 2T), 106 (2007).
[2] V. V. Mirnov and A. J. Lichtenberg, Reviews of Plasma Physics, 19, 53 (1996).

P25

FIRST EXPERIMENTS ON NEUTRAL INJECTION IN MULTIMIRROR TRAP GOL-3

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Multimirror plasma confinement is investigated in Budker Institute of Nuclear Physics as one of alternative concepts of magnetic nuclear fusion. Significant progress in physics of multimirror confinement, which was achieved in GOL-3 experiments, improves prospects for an axisymmetric linear fusion reactor with $\beta \sim 1$ and moderate (10^{21}-10^{22} m^{-3}) plasma density. Such approach requires development of new techniques of plasma heating in addition to existing high-power relativistic electron beam. High density, short lifetime, small plasma radius and high gas pressure near the wall are the challenges which complicate use of neutral beam injection in GOL-3. A supposed NBI system for GOL-3 should have ~10 MW at ~1 ms pulse in order to keep plasma parameters at a reasonable level during the confinement phase. First results of sub-MW NBI are presented in the paper.

Injector was mounted in a special section which forms a local mirror trap with B_{max}/B_{min}=4.8/2.5 T in the central part of the 12-meter-long multiple mirror (corrugated) solenoid. Deuterium beam with 15-18 keV energy, 0.45-0.55 MW power, and pulse duration 0.8 ms was injected into the trap normally to the axis. In the discussed experiments the injector had a planar ion source, so the beam diameter was larger than the plasma one. Beam attenuation profile was measured by a set of detectors in a beam dump.

A special axial profile of initial gas-puff and plasma density with $2 \cdot 10^{20}$ m^{-3} minimum in the injection point allows reducing losses of the neutral beam outside the plasma column below 20%. The capture of beam atoms in the trap reached 87%. Next planned step of the experiments is development of a 1 MW injector module with geometrical focusing into ~4 cm diameter.

P26

Kinetic Calculation of Axial Losses in a Multiple-Mirror Trap

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Recent results from the GOL-3 multiple-mirror trap show that the good axial confinement of plasma occurs at much lower densities than predicted by the classic quasi-hydrodynamic model of Mirnov and Lichtenberg. This stresses importance of further development of the theory that would describe the parallel plasma losses under low collisionality conditions, when the plasma flow cannot be described via diffusion. The natural way of plasma description under such conditions is by the direct solution of the kinetic equation. Once the distribution function is found, all its moments can be calculated directly, in particular, the particle and heat fluxes along the field. Another natural advantage of the kinetic treatment is its ability to describe situations, when different collisionality regimes occur in different regions of the phase space or in different places of the same trap.

The present work is the first step of the long way to the full kinetic modeling of the GOL-3 device. At this stage we solve the stationary kinetic equation with the linearized Landau collision integral, under the small-scale corrugation approximation, i.e., under assumption, that the mean free path is much longer than the cell length of the trap. This is in accordance with the current plasma parameters in the GOL-3.

The results show that there is a smooth transition from the obvious collisionless kinetic flow (when the mean free path is greater than the length of the whole trap) to the multiple-mirror plasma confinement regime (when the trap is much longer). An important feature is the absence of large gradients of the distribution function at the boundaries between the locally trapped and passing populations, except in the collisionless regime. We also found that though the Mirnov-Lichtenberg model applies in the strongly collisional regime, it overestimates the diffusion coefficient by a factor of square root of pi (probably due to misprint in original papers).

P28

Suppression of Flute Modes by Biasing Plasma in Axially Symmetric Open Traps

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In the axially symmetric gas-dynamic trap (the GDT, Novosibirsk, Russia) the external potentials are applied to limiters and concentric sections of the end walls. As a result, the trap now routinely operates in regimes with an average magnetic hill (which should be strongly MHD-unstable to interchange modes) with negligible transverse losses even at $\beta \sim 60\%$. It means that the sheared flows can suppress not just the transport by drift-modes, but the much stronger MHD-interchange convection as well. The fact greatly improves prospects for axially symmetric confinement in mirror traps.

This talk will present the detailed analytic theory and numerical simulation of formation of the vortex transport barrier, which occurs in the GDT and can be used under similar conditions in other open magnetic traps. The idea of the interpretation of the improved plasma confinement in the GDT can be explained as follows: let the hot part of the plasma reside inside of a 2D vortex. It will not be carried to the wall by convection if the vortex flow lines even under perturbations remain closed and more-or-less concentric, and if the vortex itself is somehow tied to its place. Both conditions can be satisfied if the vortex flow is supported by the stationary wall potentials and the saturated amplitude of the interchange is smaller than that of the vortex. The theory includes explanation of the nonlinear resistive saturation of the flute (interchange) modes due to combined effects of the shear flow, currents to the end wall, and the ion viscosity.

P44

On interpreting the diamagnetism of a compact plasmoid

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Diamagnetic loops are widespread diagnostics for measuring the pressure of magnetized plasma. A simplest diamagnetic loop represents a conductive contour or a coil surrounding the plasma column. The loop measures the temporal change of the magnetic flux induced by the plasma diamagnetic currents. Handling this diagnostic for measuring the diamagnetism of a sufficiently long plasma column is well known. However in some experimental environments such as Synthesized Hot Ion Plasmoid (SHIP) [1] the plasma has a compact shape resembling a thin disk. The conductive walls of the vacuum chamber can also affect the results of the diamagnetic measurements in pulsed experiments.

In the report, set of formulas for interpreting the diamagnetic measurements of compact plasmoid in a conducting chamber is derived. The formulas are written in the form of an integral transformation relating the magnetic flux to the radial pressure profile of the plasmoid. An inverse transformation is also found. Particular examples of applying the newly derived formulas to the SHIP experiment are given. They show that the conductive chamber has essential effect on the result of the measurements. The optimisation of the loop geometry that allows maximizing the measured signal is also described.

[1] *Anikeev A.V., Bagryansy P.A., Ivanov A.A., et al.* J. Fus. Energy **26**, 103 (2007)

P45

Equilibrium of nonneutral plasmas in a Malmberg-Penning trap with a tilted magnetic field

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A constraint is derived, which allows to select admissible plasma equilibria in a Malmberg-Penning trap in the presence of a non-uniform and a non-axisymmetric magnetic field. The approach is based on previous works on the equilibrium of nonneutral plasmas on a set of nested toroidal magnetic surfaces [1] and on the equilibrium of quasineutral plasmas in tandem mirrors [2], and makes use of curvilinear flux coordinates for the magnetic field [3]. The constraint is used to analyze the effect of a weak tilted magnetic field perturbation on the equilibrium of a nonneutral plasma confined in a Malmberg-Penning trap. Examples of analytically solvable equilibria are given.

[1] T. S. Pedersen and A. H. Boozer, Phys. Rev. Lett. **88**, 205002 (2002).
[2] D. D. Ryutov and G. V. Stupakov, in *Reviews of Plasma Physics*, edited by B. B. Kadomtsev (Consultants Bureau, New York, 1987), vol. 13, pp. 93-202.
[3] I. Kotelnikov, M. Romé, and A. Kabantsev, Phys. Plasmas **13**, 092108 (2006).

P46

DEVELOPMENT OF A MULTI-CHANNEL DISPERSION INTERFEROMETER AT TEXTOR

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The design and main characteristics of fourteen-channel dispersion interferometer for plasma profile measurement and control in TEXTOR tokamak are presented. The diagnostic is engineered on the basis of modular concept, 10.6 μm CO2 laser source and all optical and mechanical elements of each module arranged in a compact housing. A set of mirrors and retro-reflectors inside the TEXTOR vacuum vessel serve to provide full coverage of the torus cross-section with twelve vertical and two diagonal lines of sight, no rigid frame for vibration isolation is required. Results of testing of the single-channel prototype diagnostic and the pilot module of the multi-channel dispersion interferometer are presented.

P47

STEADY-STATE CONFINEMENT OF HOT ION PLASMA IN THE GAS DYNAMIC TRAP

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The paper summarizes recent experimental results in the gas dynamic trap device in the Budker Institute, Novosibirsk. The gas dynamic trap (or GDT) is the mirror device where Maxwellian plasma component and fast anisotropic ions are confined in the axially symmetric magnetic field. The GDT heating system is capable of injection of six focused 20-25 keV hydrogen or deuterium beams. The total beam power delivered to the central cell plasma reached 4 MW in the 5 ms pulse. Two additional focused 25 keV beams provide up to 1.2 MW in the compact mirror section attached to the GDT central cell.

Analysis of the global energy and particle balance together with the Monte-Carlo equilibrium modeling allowed to conclude that two-component plasma confined in a steady-state regime. The characteristic plasma lifetimes are 4 to 5 times less then the experiment duration. A peripheral gas-puff near the mirror region enabled to maintain the radial profile of background plasma during the NBI pulse. The peak density of anisotropic ions with the mean energy of 10 keV exceeded 4x1019 m-3, that is comparable to background plasma density in reported experiments. Accordingly, the maximal beta value was about 0.6. Background plasma electron temperature was also significantly increased from ~100eV up to 200 eV. The stability against MHD interchange modes limited the plasma lifetime in previous studies, was established using the set of biased radial limiters and sectioned end wall.