$11^{\rm th}$ International Conference on Open Magnetic Systems for Plasma Confinement

Monday 08 August 2016 - Friday 12 August 2016

Book of Abstracts

OPEN SYSTEMS

Novosibirsk 2016

BINP SB RAS

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Status of GOL-NB Project

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Overview of the activity on the development of the new multiple-mirror trap GOL-NB to be built in Budker Institute will be presented. This device will be created in BINP in several years as a deep conversion of the existing GOL-3 facility. The device will consist of a central trap with two 0.75 MW neutral beams, two multiple-mirror solenoids, two expander tanks and a plasma gun that creates start plasma. Physical program of the device was anounced at 2014 Open Systems Conference in Daejeon. Plasma will be NBI-heated and confined in the central trap that is essentially a compact version of the GDT device with the well-known physics. The multiple-mirror sections should decrease the power and particle losses along the magnetic field. The main physical task of GOL-NB is the direct performance demonstration of the multiple-mirror sections that will change the escaping plasma flow and equilibrium plasma parameters in the central trap depending on the magnetic configuration chosen. In this paper, we will discuss new results in scenario modelling and progress in the hardware, including neutral beam injection system and start plasma source. First experiments on transport of a (1-4) $\times$ 10^{20} m^{-3} cold plasma stream through the 3-meter-long solenoids with 0.5 - 4.5 T field are already completed thus demonstrating the performance of start plasma creation system.

Overview of Recent Progress and Future in GAMMA 10/PDX Project

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In this paper an overview of the recent progress and the near future plan of GAMMA 10/PDX project is described. The GAMMA 10/PDX tandem mirror has open magnetic field configuration and improvement of plasma confinement has been demonstrated by using potential formation [1]. By making best use of the open magnetic field, divertor simulation experiments have been started at the end-cell. One of the most distinctive merits of using large tandem mirror is to be capable of achieving ion flux with high temperature ($T_i = 100 \sim 400$ eV) which is comparable to SOL plasma parameters [2]. Additional ICRF antennas have been installed in the anchor and plug/barrier cells to increase both particle and heat fluxes. A remarkable increase of the particle flux Γ_{ion} of 3.3×10^{23} particles/s·m^2 is observed when ICRF waves are applied in both east and west anchor cells together with the ECH at east plug/barrier-cell. Experiments aiming

characterization of detached plasmas in the divertor simulation experimental module (D-module) have been performed [3]. Remarkable reductions of electron temperature (T_e), heat and particle fluxes (P_{Heat}, Γ_{ion}) are observed according to the increase of the gas throughput into D-module. Comparison in applied radiator gases (Xe, Ar, Ne and N_2) showed that Xe is most effective in reduction of T_e, P_{Heat}, Γ_{ion}. Recycling studies in the end-cell is also investigated by using high-speed camera under the condition with heated tungsten target. Development of high power gyrotrons and their application to divertor simulation experiments are another important subject in the GAMMA 10/PDX project [4-5]. Gyrotrons with wide range of frequencies from 14 to 300 GHz have been developed in collaboration with JAEA, NIFS and TETD. Superimposing a short ECH pulse of $\sim$ 400 kW into ICRF-produced plasma attained the peak heat-flux value of more than 15 MW/m^2 at the west end-cell. A 28 GHz 1 MW gyrotron developed for GAMMA 10/PDX achieved an output power of 1.38 MW. The design study of a new 28/35 GHz dual-frequency gyrotron (2 MW 3 s and 0.4 MW CW) also has been completed together with the development of double-disk sapphire window. Recently development of Thomson scattering (TS) system [7] was progressed. This system enables multi-pass TS scattering signal from first to eighth passing, which improves reliability of measurement and time resolution.

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Up-grade Status of PLAMIS-II

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PLAMIS-II (PLAsma Material Interaction System) has been upgraded for plasma interaction experiments with various targets, such as Sn, Li, molten salts and ceramics. Plasma beam of 30kW source is bended 90 degrees to a horizontal target by magnetic field. Target materials are placed on a rotating hearth, which is similar with circular tray and can be heated to 800°C. We have investigated interaction of various liquid and solid target with plasma beam. The 30kW plasma gun operation mode should be changed with electric property of targets. We will present simulation results on magnetic beam guide and plasma gun. Interaction phenomenon, target evaporation properties and plasma gun operation mode will be discussed also.

Recent Progress of Plasma Confinement and Heating Studies in the Gas Dynamic Trap

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Worldwide activity of studies of plasma confinement in magnetic mirror traps decreased dramatically in the late 80's of the last century. The reason is that the mirror concept is thought to have three unattractive characteristics. The magnets are complex, the plasma is plagued with micro-instabilities and the electron temperature would never approach required keV levels. Researches on the Gas Dynamic Trap (GDT) device at the Budker Institute of Nuclear Physics demonstrated the possibility to overcome these three deficiencies. Stable high energy density plasma can be confined with simple circular magnets [1,2], micro-instabilities can be tamed [3], and electron temperatures reaching a keV have been measured [4,5]. These three accomplishments provide a basis to reconsider the mirror concept as a neutron source for materials development, nuclear fuel production, and fusion energy production. Furthermore, these three achievements allowed to go to the next level of tasks, aimed at support of the next generation of research facilities, as well as fusion reactors based on mirror traps. List of the most important next-level problems includes optimization of heating modes using neutral beam injection and auxiliary ECR heating and a detailed study of physical processes in the divertors (regions with an expanding magnetic field behind the magnetic mirrors), limiting longitudinal energy losses. The proposed report includes a brief overview of researches on the stabilization of MHD instabilities, study of micro-instabilities, and demonstration a tangible increase of the electron temperature with application of auxiliary ECR heating. According to Thomson scattering data, the electron temperature exceeds 0.9 keV thus demonstrating more than threefold increase as compared with modes, where only neutral beams were applied [4,5]. Part of the report is focused on the study a number of physical processes in the divertor, which determine the longitudinal energy transport.

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Construction of KMAX-FRC Experiment

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KMAX, KeDa Mirror with Axisysmmetricity, is undergoing a major upgrade by adding colliding Field Reserved Configurations (FRCs) in the hope to improve the plasma content in the central cell region. Very much like many current FRC experiments, KMAX-FRCs will be formed on both ends by high voltage pulsed power and simultaneously injected into the central cell for colliding and merging. However, the coils to form FRCs are placed inside the metal vacuum vessel, which allows us to realize fast control for future experiments. In addition, the 4 groups of coils with different diameters and their 4 independent pulsed power allow us to form FRCs using conical or dynamic formation technique. The status and the preliminary results of KMAX-FRC will be presented as well as some results from RF heating. While FRC has very different magnetic geometry than a simple mirror, they share many similar features especially in the FRCs open field line region. We will also show some RF heating results and some interesting discoveries on the parametric decay process.

FRC Sustainment

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Without current drive (CD) Field-Reversed-Configuration (FRC) disappears at skin time. Experiments in C-2U in Tri Alpha Energy strongly indicate that FRC survives much longer than skin time and thus suggest that some form of CD exists. In this presentation we are considering conditions under which FRC configuration can be maintained or even expanded. FRC as well as high-β open traps have a notorious property of interconnecting of all major processes: equilibrium, plasma rotation, diffusion, and CD. We are building simple self-consistent description of these processes which includes both collision and turbulent-driven effects. We are applying this description to situation close to experimental and finding conditions under which CD can exist in FRC without violating other experimental observations. We are also considering such key issues as the possibility transforming open-trap configuration into FRC in the beam-driven plasma.

JULE-PSI - a linear plasma device inside a Hot Cell

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JULE-PSI is a linear plasma device to investigate the response of neutron pre-damaged materials (including toxic materials such as beryllium) to steady - state plasma loads and transient heat loads provided by laser irradiation. JULE-PSI will be equipped with a target analysis and exchange chamber to characterize the material surface in-vacuo and will be located inside of a Hot Cell to allow for handling of activated target samples. In this contribution, we will first review the scientific case for investigations of neutron damaged materials in view of plasma - surface interactions, discussion the impact of synergistic loading conditions onto the lifetime of plasma facing components and the influence of neutron damage on fuel retention. Then, we will give a status report of the JULE-PSI project, describing the design of the plasma device and its components (plasma source, magnets, pumping system and vacuum vessel) as well as the set-up of the New Hot Cell in the High Temperature Material Laboratory of Forschungszentrum Juelich (HML), which has recently been evaluated by an external company. Currently, JULE-PSI is under construction outside of the controlled area and will be moved to HML early 2018 according to the present schedule.

Plasma confinement, heating and stability

Improved Plasma Confinement at High Beta

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A new efficient method of confinement is proposed for use in linear traps. It is based on effect of diamagnetic expulsion of the magnetic field out of the plasma volume while beta tends to one. This effect is greater in the low-field area and weaker in mirrors, thus, if the plasma pressure grows, the equilibrium in a linear trap changes in such a way that the effective mirror ratio increases. As a result, the axial particle and energy confinement becomes gas-dynamic and improves linearly with diamagnetic expansion of the plasma bubble. This effect would enable construction of a compact fusion reactor, if one could ensure suppression of pressure-driven instabilities, in particular, the ballooning instability. This paper shows how it can be done: one should use magnetic configuration with a stretch of uniform field at its minimum, and place external stabilizers near ends of that stretch. The high-beta limit of plasma equilibrium in an open trap is shown to form a roughly cylindrical bubble around the stretch of uniform field with sharp non-paraxial ends. These ends are a sole source of ballooning instability, while their positioning and geometry make them also suitable for line-tying or feedback stabilization. Given that the external stabilizers and the instability source are close, the field flexibility at high beta can be ignored. Large Larmor radii of ions in the low-field bubble could ensure stability of short-wave modes, so that external boundary stabilizers should suffice. Fast-ion confinement, startup, and the energy balance issues are also considered for a linear trap in the diamagnetic-bubble regime.
This work has been supported by Russian Science Foundation (project N 14-50-00080)

Concept Exploration Helical Mirror Device: Design and Status

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Recent results of the Gas-Dynamic Trap show the possibility of the quasistationary confinement of the plasma with high relative pressure ($\beta \approx 60\%$), mean energy of hot ions of 12 keV and the electron temperature up to 0.9 keV [1]. Highly conservative extrapolation of the Gas-Dynamic Trap physics to the optimized 10-meter-long machine with D-T fuel leads to the concept of the neutron source for material research with fusion gain factor Q = 0.05 [2]. Much higher fusion gain could be achieved by improvement of the longitudinal confinement, i.e. by increasing of the effective mirror ratio. Mirror ratio in the simple open trap is limited by the technically achievable magnetic field and is supposed to be $\sim$15-20 in neutron source concepts. Today multiple-mirror [3] and ambipolar [4] methods of the suppression of the axial heat flux are tested. Implication of the multiple-mirror suppression [5] to the neutron source project leads to the feasible fusion gain appropriate for hybrid systems.

Both of the listed above methods of the suppression are passive barriers. Recently, a new idea of active plasma counterflow pumping by the combination of helicoidal magnetic and radial electric fields was proposed [6]. Plasma rotates due to $E \times B$ drift. Periodical variations of helicoidal magnetic field move therefore along the flow in its reference frame, and induce longitudinal force acting on the trapped particles. Theory predicts exponential dependence of the flow suppression on the magnetic structure length, that is more favorable then the power dependence in passive magnetic systems.
Concept exploration device for this idea is now being constructed in BINP. In this report key issues of the design of this device are discussed: the magnetic system, the plasma gun, the biasing electrodes for the radial electric field formation, the plasma facing components and the diagnostics.
This work was supported by Russian Science Foundation (project 14-50-00080).
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Development of New Mirror Antenna for Generation of High Intermittent Heat Flux in GAMMA 10 Tandem Mirror

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Electron cyclotron heating (ECH) power modulation experiments in GAMMA 10 tandem mirror have been started in order to generate and control the high heat flux and to make the ELM (edge localized mode) like intermittent heat load pattern for divertor simulation studies. ECH for potential formation at plug region (P-ECH) produces electron flow with high energy along the magnetic filed line. Heat flux during ECH injection corresponds to the steady-state heat load of the divertor plate of ITER. Particularly, in the GAMMA 10 tandem mirror, ECH is recognized as a primary scheme to produce plasma-confining potentials. The P-ECH drives a substantial portion of the heated electrons into the loss cone and induces an intense axial flow of warm electrons, which is observed as end loss electrons. However, the maximum energy density obtained is about 0.05 MJ/m^2 [1] and is still far lower than that of ITER ELM.
To achieve the generation of higher heat flux, it is necessary to design a high efficiency mirror antenna. In the present ECH system, the e-folding radius of the power density is 62.5 mm. The development of new mirror anntena has carried out in order to concentrate the heating power on the axis. The e-folding radius of power density of new mirror antenna is 40 mm. It is expected to approach the ITER level energy density is by the upgrade the new mirror antenna with narrower e-folding radius of the power density of radiation distribution.
In this paper, preliminary experimental results in ECH power modulation by using new mirror antenna for control of high intermittent heat flux in GAMMA 10 tandem mirror for the future divertor simulation studies are presented.
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Feedback effect on flute dynamics in a mirror machine

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Active feedback can stabilize the violent flute instability and possibly make mirror traps candidates for fusion machines. A fast feedback with optical sensors and electrical actuators was implemented in a table-top mirror machine and used to study several aspects of feedback stabilization. For a cold, dense plasma the feedback reduces dramatically the flute amplitude of the first two mode. For higher temperature plasma, a significant increase of plasma density due to feedback stabilization is demonstrated. The effect of changing feedback gain and phase has some interesting feature such as asymmetry with respect to positive and negative phase shifts and non-monotonic dependence of flute amplitude on feedback gain. These effects are explained using simplified analytic model of the flute and feedback.

Transportation of plasma jet in GOL-NB multiple-mirror trap

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Further advances of a multiple-mirror plasma confinement concept [1] previously developed in the Schegol and GOL-3 experiments in the BINP will continue with a new GOL-NB facility [2]. Unlike previous generations of traps, GOL-NB will focus on the quasi-stationary multiple-mirror confinement of neutral-beam-heated plasma with moderate parameters: $T \sim 30 - 100eV$ and $n \sim 3 \times 10^{19}\ m^{-3}$ The plasma will be confined in the 2-m-long central trap of GOL-NB which ends with two multiple-mirror solenoids. The solenoids are re-used parts of the GOL-3 magnetic system with 14 corrugation periods (elementary multiple-mirror cells) of 22 cm length. The multiple-mirror confinement theory requires that the ion free path length should be comparable with the magnetic field corrugation period. Plasma heating will be provided by two 0.75 MW neutral beams that should be captured by a low-temperature start plasma created by an arc plasma gun installed in magnetic expander. In this paper, we will present new experimental results on a magnetic compression and transport of a low-temperature arc plasma along the solenoid at ∼3 m distance. The magnetic compression ratio varied from 5 to 60, the initial plasma stream diameter was about 5 cm. Theory predicts that the multiple-mirror magnetic field should not significantly decelerate and weaken the collisional low-temperature arc plasma stream. In the experiment, we compared the transport efficiency of the plasma stream in the multiple-mirror configuration of the solenoid with the same in a uniform solenoidal field [3]. As the results the plasma with $(1-4) \times 10^{20}\ m^{-3}$ density at the axis was obtained at ∼3 m distance from the arc plasma source. The experiments simulated the baseline scenario of GOL-NB filling by the start plasma. Finally, the experiments described in the paper validated the decisions made for the GOL-NB start plasma source.

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Sustainment of beam-driven FRC plasma at C-2U

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A high temperature, stable, long-lived field-reversed configuration (FRC) plasma state has been produced in the C-2U device at Tri Alpha Energy. C-2U is the next generation of C-2 device [1-3]. The tangential co-current neutral beam injection power is increased from 4 MW to 10+MW. A new edge plasma rotation control system based on biased plasma generator is used to improve plasma stability. The inner surface of the wall has Ti-coating. That reduces background neutral gas density and increases lifetime of the fast ions. C-2U experiments have demonstrated a sustainment of advanced beam-driven FRC plasma state for up to 5 ms. The overall C-2U experimental program and recent accomplishments will be reviewed.

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Kinetic instabilities in a mirror-confined plasma sustained by high-power microwave radiation

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Study of plasma instabilities in the electron cyclotron frequency range, which were carried out over the last decade at the IAP RAS (Nizhny Novgorod), has resulted in a significant progress in understanding the nature of these processes. The object of our research activities is the nonequilibrium plasma created and sustained by powerful radiation of a gyrotron (80 kW @ 37.5 GHz) under the electron cyclotron resonance (ECR) condition. ECR plasma heating allows to create plasma with at least two electron components, one of which, more dense and cold, determines the dispersion properties of the high-frequency waves, and the second, a small group of energetic electrons with a highly anisotropic velocity distribution, is responsible for the excitation (and absorption) of the unstable waves. The interaction of high-frequency waves with resonant electrons leads to the diffusion of energetic electrons in velocity space and eventually to their falling into the loss cone and precipitation from the trap. In the experiments we studied the dynamic spectrum and the intensity of stimulated electromagnetic radiation from the plasma with high temporal resolution (up to 10 ps). This technique allowed to explore the fine structure in the spectrum of excited waves.

Different conditions for instability development are implemented at three ECR discharge stages. The parameter scan is performed due to the plasma density variation in the ECR discharge. At the initial discharge stage dense plasma component is almost absent and a fast extraordinary wave can be excited. At a large density of the background plasma during the developed discharge phase cyclotron instabilities of extraordinary modes are suppressed and the whistler mode instability is observed. In a decaying plasma after the ECR heating switch-off loss-cone instabilities of the extraordinary waves are observed. Under the certain conditions the excitation of plasma waves under the double plasma resonance is observed at the very beginning of plasma decay stage. Eventually, we defined at least five different types of kinetic instabilities observed in the ECR discharge plasma.

Theoretical interpretation of the observed data is based on the balance maser equations for evolution of hot electron density and the density of electromagnetic energy. Taking into account the

plasma parameters at different discharge stages, this approach allows us to reproduce temporal features of the observed instabilities and estimate its growth rates.
This report may be of interest in the context of a laboratory modeling of nonstationary wave-particle interaction processes in nonequilibrium space plasma since the observed phenomena have much in common with similar processes occurring in the magnetosphere of the Earth, planets, and in solar coronal loops.

Mitigation of drift instabilities by a small radial flux of charged particles through the Landau-resonant layer

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Experiments and theory on magnetized electron columns have characterized a novel *algebraic* damping of drift "diocotron" modes, caused by a weak flux of electrons through the resonance (critical) layer [1]. This flux-driven damping also eliminates the unwanted ion-induced exponential instability of diocotron modes. Here we suggest that a similar flux-driven damping may mitigate the classical flute MHD instability of (*quasi*)neutral plasmas confined in non-uniform magnetic fields.
Our electron plasmas rotate at rate $\omega_{E\times B}$, and the (nominally stable) diocotron modes are characterized by amplitude A_d, $k_z = 0$, $m_\theta = 1, 2, 3, ..$, frequency $\omega_d(m_\theta)$, with a wave/fluid critical radius $r_c(m_\theta)$, where $\omega_{E\times B}(r_c) = \omega_d/m_\theta$. Application of weak external field asymmetries produces a low ($\sim 1/100$) density halo of electrons moving radially outward from the plasma core, with flux rate $F \equiv (-1/N_e)dN_e/dt$. We find that *algebraic* damping of the diocotron modes begins when the halo reaches the critical radius $r_c(m_\theta)$, proceeding as $A_d(\Delta t) = A_d(0) - \gamma * \Delta t$, with $\gamma = \beta(m_\theta) * F$.
We have also investigated the diocotron mode instability which occurs when a small number of ions are transiting the electron plasma [2]. In outline, the differential bounce-averaged azimuthal drifts of electrons and ions polarize the diocotron mode density perturbations, developing instability analogous to the classical flute MHD instability. The exponential growth rate Γ is proportional to the fractional neutralization (N_i/N_e) and to the amount of charge separation between electrons and ions in the periodic wave perturbations.
We find that the flux-induced *algebraic* damping can stabilize the exponential ion-induced instability up to the driven amplitudes limited by $A_d \leq \beta F/\Gamma$. Controlling the cross-field flux of electrons by (changing) applied to the cylindrical wall electrostatic asymmetries we have prevented the ion-induced diocotron instability from growth in a broad range of fractional neutralization. By its very nature the *algebraic* damping of exponential instabilities is most effective at low wave amplitudes A_d, so this new mitigation mechanism is extremely sensitive even for seemingly small fluxes F through the Landau-resonant layers.

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ECR discharge startup in the Gas Dynamic Trap

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A new discharge startup scenario has been developed for the Gas Dynamic Trap (GDT) magnetic mirror experiment. The primary neutral beam injection (NBI) plasma heating system requires a sufficiently dense plasma target with a degree of ionization, which is compatible with accumulation of fast ions. In the reported experiments, instead of the conventional axial plasma injection, a high-frequency radiation is used to produce such a target directly in the central cell. One of the microwave beams generated by GDT‘s electron cyclotron resonance heating (ECRH) system is used to ionize a portion of neutral gas, which is admitted to vacuum vessel. The ECR absorption of incident power supports further ionization and eventually builds up a plasma target suitable for NBI capture. With application of the NBI a steady accumulation of fast ions is observed, resulting in a discharge with aggregate fast ion energy, plasma temperature and other parameters similar to the conventional regime with the arc plasma gun. The particulars of discharge scenario and experimental data on plasma evolution during ECR heating are reported, along with the dependencies on incident microwave power, magnetic configuration and the initial pressure of neutral gas. The characteristics of high-power NBI discharge are described and differences to the conventional scenario are discussed. Experimental data is compared to theoretical models of microwave breakdown in a mirror trap.
The work is supported by the Russian Science Foundation (project No 14-12-01007).

Plasma RF stabilization in mirror machine

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A new table top mirror machine was built in order to research ways to mitigate the flute instability prevalent in these machines. One previously researched method for accomplishing this is using oscillatory fields in the ion cyclotron frequency range. Several mechanisms were suggested to stabilize the system. These include either single particle pondermotive forces, macroscopic forces or shear flow generated due to radial gradients in the plasma. The machine is one meter long with 1 Tesla mirror fields. Hydrogen plasma is heated using ion cyclotron RF fields. A description of the system and diagnostics, preliminary results and a review of these mechanism are presented.

Computer simulation of cylindrical plasma target trap with inverse magnetic mirrors

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Computer simulation of dynamic of plasma target for highly efficient neutralization of powerful negative ion beams is considered. The plasma is confined within a magnetic trap with multipole magnetic walls. The inverse magnetic mirrors to limit plasma outflow through the inlet and outlet holes in the trap are used. Mathematical model is based on Boltzmanns equation for the distribution functions for ions and electrons and system of the Maxwells equations for the self-consistent electromagnetic fields. The combination of the modified PIC-method in the cylindrical r-z coordinates and the Monte-Carlo methods is used to solve these equations. The complex nature of the processes studied, and also the need of calculation of trajectories of billions of particles required the use scalable parallel algorithm. The use of modern supercomputers has allowed to calculate plasma dynamics, to determine plasma streams both on the walls of the trap and through end holes. According to the results of calculations, the generated plasma fills almost the entire length of the trap. The plasma outflow in end holes is sufficiently small, the loss of the plasma on the walls of the trap is inessential. Introducing of the recombination cross sections to the mathematical model will allow determining plasma lifetime and energy balance of the trap. The development of numerical algorithms was supported by the Russian scientific Fund, project no. 16-11-10028, computational experiments were supported by the Russian Foundation for Basic Research, project no. 16-01-00209, 14-01-00392, 16-31-00304.

Neutral beam injectors for the GOL-NB facility

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GOL-NB facility [1] is now developing for investigation of confinement of plasma with moderate turbulence in multi-mirror magnetic trap. Neutral injection is considered in this project as a main mean of heating plasma. The report presents status of GOL-NB team working on neutral injectors. In developing these injectors it was took into account experience of application neutral beam in GOL-3 installation [2] and data of modeling the result of applying modern injectors in this facility [3]. The main difference GOL-NB from GOL-3 is volume central cell of magnetic trap and improved evacuation, which must reduce charge exchange losses of fast particles. Two injectors with beam focus distance 1.6 m initially destined for GOL-3 were applicable for the central cell of GOL-NB without significant modernization. Design parameters of these injectors are next. Energy of atomic beam is 25 keV, power - 20.75 MW, time duration - 5 ms. Injectors structure is based on main units (arc ion source, beam forming multi-aperture structure with geometric focusing) previously tested in products placed on the number of facilities. The main attention was paid to the optimization of power and control injectors in relation to the experimental conditions on GOL3-NB facility. Technical launch of injectors held, now produced their debugging.
Injector power system includes the source of accelerating voltage, block of high-potential equipment, block of low-voltage equipment and control system. High-voltage equipment is mounted separately for each injector; low-voltage equipment is integrated. The source of accelerating

voltage (AV) is made of full-featured modular sources of 1 kV voltage with interchange at full voltage 25 kV in the power and control circuits. Amplitude and front of voltage pulse is provided by appropriate modules switching. AV Controller implements the function of system restart after the electrical breakdown. Arc discharge power unit uses chopper circuit to form pulse of stabilizes current with up to 1 kA amplitude. Discharge ignition is performed by interrupting the current in the connected in parallel to the discharge gap resistive load. Injectors are managed by using a dedicated server. One can use any connected to the information network workstation to control periodic or single injection event.

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ICRF heating in the plug/barrier region to control end-loss ions on GAMMA 10/PDX

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In the GAMMA10/PDX tandem mirror, divertor simulation experiments are carried out in the west end region. In order to control end loss ions, ion cyclotron range of frequency (ICRF) waves are used. In previous experiments, we achieved two-times increases of the particle flux ($1.7 \times 10^{23} m^{-2} s^{-1}$) while the parallel ion temperature was 100eV at the end region during ICRF heating in the central cell and the anchor cell. In order to further increase of the particle flux and the ion temperature at the end region, we tried ICRF heating with double half turn (DHT) antenna in the plug barrier cell, next to the end region. DHT antenna has been installed in the west plug/barrier cell.
Firstly, DHT antenna was driven with a frequency of 7.7MHz that is the ion cyclotron frequency near the center of the plug/barrier cell. The line density in the plug/barrier cell increased remarkably and the parallel ion temperature at the end region increased also during the ICRF heating. However, the ion flux from the central cell decreased due to the trapping in the plug/barrier cell. With additional gas injection in the plug/barrier cell, increase of the ion flux was observed. In this case, no increase of the parallel ion temperature was observed.
Secondary, we injected ICRF wave with the frequency of 7.2MHz that has no resonance layer in the plug/barrier cell. This wave can propagate to the end region and heat end loss ions. In this experiment, we observed the increase of both the ion flux and the parallel ion temperature at the end region with additional gas injection. For further increase of the particle flux at the end region we will replace the DHT antenna with Nagoya Type-III antenna that is used for the plasma production in the central cell.

Negative Ion based Neutral Injector: beam formation and transport

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The essential feature of BINP N-NBI design is the negative ion beam transporting from the source to a single-aperture 0.5-1 MeV accelerating tube via a low energy beam transport line (LEBT). This scheme purifies the beam from the co-streaming fluxes of electrons, hydrogen atoms and molecules, and cesium vapor. As a result the stresses of the accelerating tube are considerably reduced. It will enable more stable operation of the accelerator. We report the experimental results on 1 A, 90 keV H- beam production and transport through the LEBT to the calorimeter.

Emission properties of Inductively Driven Negative Ion Source for NBI

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A stable H- beam with a current ∼1A and energy 90 kV was routinely extracted and accelerated from the long-pulse surface-plasma source prototype, developed at BINP for N-NBI use. The H- ions are produced on the hot surface of a plasma grid, covered by cesium and illuminated by fast plasma particles from the inductively driven radio-frequency discharge. A multiaperture, three-electrode ion optical system is used for beam formation. The essential BINP source features are: 1) an active temperature control of the ion-optical system electrodes by circulation of hot thermal fluid through the channels, drilled in the electrode bodies, and 2) the directed cesium deposition to the plasma grid electrode using a long tube, connected to the plasma grid periphery. The long term effect of cesium was obtained just with the single cesium deposition. The high voltage strength of ion-optical system electrodes was improved with actively heated electrodes. The 90 keV H- beam is transported to the entrance of the high-voltage post-accelerator with the help of the low energy beam transport section

Status of the experiment on magnetic field reversal at BINP

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The unique result obtained in the seventies of the last century on 2SIIB (LLNL, USA) device [1] gives reason to expect for the possibility of realization of reversed magnetic field configuration in a mirror trap with powerful neutral beams. Ratio between diamagnetic field perturbation and vacuum magnetic field $\delta B/B = 0.9$ was achieved with 7 MW of full power of neutral beams and current density of neutrals 0.7 atomic A/cm^2 at the plasma axis in special series of 2XIIB

experiment. Progress in the development of neutral beam injection allows at the present time to realize the neutral current density approximately 3-4 times higher than in 2XIIB experiment at lower total power (≈ 3 MW).

Circumstances mentioned above have motivated development the project CAT (Compact Axisymmetric Toroid) directed on field-reversal experiments in axisymmetric magnetic mirror trap equipped with two geometrically focused high equivalent current density neutral beams. Estimated total current density of neutral beams on the axis of the plasma column is 3 atomic A/cm^2. Target plasma with characteristic radius a=7 cm, density of 10^{13} cm^{-3} and electron temperature about 50 eV will be generated by special plasma source, developed at the former time for AMBAL experiment.

Based on computer simulations under certain assumptions these parameters of neutral beam system and plasma source allow to obtain the field reversed configuration. Report describes physical and technical detail of the CAT project, Report describes physical and technical detail of the CAT project, which scheduled for realization at the Budker Institute.

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Composition of the high-energy neutral beam on the COMPASS tokamak

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Two identical Neutral Beam Injectors (NBI) were designed and manufactured in the Budker Institute, Novosibirsk for the COMPASS tokamak at IPP CAS, Prague. Each of them generates a neutral atom beam with energy up to 40 keV and total power up to 350 kW. The injector is composed of the ion source, the accelerating and focusing grids and the neutralizer. The ion source is filled with the working gas (deuterium or hydrogen) from a reservoir, and subsequently an RF discharge is ignited. Formed ions are accelerated and focused by the system of four grids. Finally, the ions are neutralized by charge-exchange collisions with a residual working gas in the neutralizer. Different ions are created inside the ion source, mainly D+, D2+, D3+ and D2O+ ions. All of them are accelerated to the same energy Eb. However, the molecular ions dissociate in the neutralizer and resulting neutral atoms have fractional energies, Eb/2 Eb/3 and Eb/10. These atoms have a shorter mean free path inside the plasma, therefore, they cannot penetrate as deep to the plasma as the atoms with the full energy Eb. In view of this fact, the knowledge of the beam composition is essential for understanding of NBI plasma heating. The beam composition is determined from intensities of Doppler shifted $D\alpha$ lines measured by a high resolution spectrometer. The neutral beam is observed in the beam duct located at the entrance of the tokamak vessel. A significant fraction of neutral atoms in the beam is exited and radiates. They propagate with a high forward speed causing the radiated $D\alpha$ line is shifted due to the Doppler effect. As a consequence of different discreet energies of atoms in the beam, we observe several differently shifted $D\alpha$ lines. The ratio of the intensities of the shifted $D\alpha$ lines is proportional to the ratio of the different extracted ions. The ratio of the formed ions inside the ion source depends on plasma conditions in the ion source. In the case of the NBI installed on the COMPASS tokamak, only the pressure inside the gas reservoir and RF power applied to the ion source plasma can be varied. This contribution presents the method how to determine the beam composition and its dependence on conditions in the ion source.

Coupling electromagnetic and quasi-electrostatic waves in electron cyclotron frequency range in high- devices

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Microwave heating of electrons under the electron cyclotron resonance conditions is one of the most efficient ways to increase the electron temperature of magnetically confined plasmas. Recent pprogress plasma confinement in axially symmetric magnetic traps led to the achievement of regimes, in which the ratio between plasma pressure and the magnetic field pressure (β) can be of the order of unity. Under these circumstances the Langmuir plasma frequency is much greater than the electron cyclotron frequency, $\omega_p \gg \omega_b$. Therefore, the use of common schemes of electron cyclotron heating based on direct launch of electromagnetic waves from the vacuum window meets obvious difficulties because the resonance region is screened by dense plasma for all electromagnetic modes except waves propagating strictly along the external magnetic field. However, in many cases strictly longitudinal propagation is not technically possible. One way to overcome this problem is to use the linear transformation of electromagnetic waves in quasi-electrostatic plasma oscillations in the vicinity of the plasma resonance. Once exited, the quasi-electrostatic oscillations can be effectively damped by electrons, in particular, in plasmas with $\omega_p \gg \omega_b$.
The transformation of electromagnetic waves in quasi-electrostatic waves under condition of a high-β open trap, $\omega_b \ll \omega_p \approx \omega$ shows a number of peculiar features which significantly distinguish this process both from the case a strong magnetic field $\omega_B \approx \omega_P$, which is used for heating of a dense plasma in low-β devices, and from the well-known case of Langmuir wave coupling in an isotropic medium with $\omega_b = 0$. The present work is devoted to the theoretical study of these features.
The work is supported by the Russian Science Foundation (project No 14-12-01007).

Control of energy deposition profile for electron cyclotron resonance heating in open trap

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A technique is proposed for the energy deposition profile adjustment at electron cyclotron resonance heating using relatively small perturbation of the external magnetic field in an axisymmetric magnetic trap. This method is based on high sensitivity of EC power deposition profile of quasi-longitudinal propagating right-polarized electromagnetic waves to radial inhomogenity of external magnetic field strength and direction. A possibility of an effective control of power deposition profile and heating efficiency is demonstrated both analytically and numerically for two main scenarios of electron cyclotron heating in mirror devices: the longitudinal launch of microwave radiation into a magnetic mirror region and the trapping of obliquely launched radiation by inhomogeneous plasma column.
The work is supported by the Russian Science Foundation (project No 14-12-01007).

Project of GDT-based steady-state experiment.

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Recent success in a plasma stabilization, heating and confinement in Gas Dynamic Trap (GDT) is negated by short plasma lifetime (5 ms). Transition processes such as particle buildup, ion and electron thermalization, etc. are still underway then heating sources are turned off. In this work we propose a project of a GDT-based stationary plasma experiment with pulse length long enough to finish all transition processes. Features of the project include a superconducting magnetic system with 15 T magnetic mirror field, 30 ms plasma pulse and mixed neutral particle and ECR heating. Results of numerical simulations of such experiment using DOL code are also presented.

Characteristics of SMBI Fueling with Laval Nozzle in GAMMA 10 Based on Experimental and Simulation Results

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In magnetically confined plasmas, optimization of particle fueling is a critical issue to obtain high performance plasmas. In large fusion devices, most of the particles supplied by gas puffing are ionized in the peripheral region. Pellet injection can reduce the edge recycling and help to obtain a peak density profile. However, this system is complicated and it is not easy to make a pellet small enough for density control in medium or small devices. Supersonic molecular beam injection (SMBI) system is a new fueling method 1, which can combine both advantage of the conventional gas puffer and the pellet injection. The SMBI system consists of a high-speed valve and a nozzle in order to produce a supersonic flow with low divergence. GAMMA 10 is the world largest tandem mirror and an open magnetic plasma confining device [2]. SMBI experiment in GAMMA 10 has been carried out by three conditions; without any nozzle, with straight nozzle and Laval nozzle. The first experimental results of SMBI achieved higher density plasmas at the core region than the conventional gas puffing [3]. A Laval nozzle has been newly mounted on the high-speed valve in order to improve the effectiveness of fueling by SMBI. We investigate the neutral particles behavior during SMBI by using the Laval nozzle. Comparison between the straight and the Laval nozzle is also discussed from the view of neutral transport.
Monte-Carlo simulation code (DEGAS) [4] was performed in order to analyze the behavior of neutral particle in GAMMA 10. Three-dimensional mesh-model for DEGAS has been applied to the central-cell [5]. In this mesh model, the limiters and ICRF antennae are precisely implemented in a realistic configuration. Furthermore, this mesh model was improved for modeling SMBI experiments; it was expanded around the SMBI injection port and new mesh was added to simulate the valve and the Laval nozzle. The background plasma parameters (T_e, T_i, n_e=n_i, etc) were given based on the experimental data. The neutral gas from the SMBI nozzle was modeled by introducing a σ_{div} parameter as an index of divergence angle of the initial particles. In the case that the angular profile of launched particle has a cosine distribution, σ_{div} =1. It was observed that the plenum pressure correlates with the divergence angle index. By changing

the value of σ_{div} the experimental results was fairly reproduced by the Monte-Carlo simulation code. This result will enable us to discuss the spatial structure for investigating the penetration depth. Above results contribute to the optimization of fueling. In the paper, detail results of experimental and simulation will be presented.

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Development of the 2MW, 30 ms neutral beam for plasma heating and stabilization in a magnetic trap

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A high power, relatively low energy neutral beam injector was developed to upgrade the neutral injection system for magnetic trap. The proton or deuterium beam of the ion source has the particle energy of 15 keV and current up to 170 A at a pulse duration of 30 milliseconds. The plasma emitter of the ion source is produced by superimposing highly ionized plasma jets from an array of four arc-discharge plasma generators. A multipole magnetic field produced with permanent magnets at the periphery of the plasma box is used to increase the efficiency and improve the uniformity of the plasma emitter. Multi-slit grids with 48% transparency are fabricated from bronze plates, which are spherically shaped to provide geometrical beam focusing. The focal length of the Ion Optical System is 3.5 m and the initial beam diameter is 34.8 cm. The IOS geometry and grid potentials were optimized numerically to ensure accurate beam formation. The measured angular divergences of the beam are ±0.01 rad parallel to the slits and ±0.03 rad in the transverse direction. The content of the fullenergy fraction in the beam current exceed 90%.

Transportation of Dense Electron Beam Through the Input Mirror of the Magnetic Trap GOL-3

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In the Institute of Nuclear Physics SB RAS on the open magnetic trap GOL-3 the experiments are carried out on an electron beam generation (up to 80 keV, 100 , diameter up to 8 cm) in the multiaperture diode with plasma emitter [1]. The beam is formed in moderate (0.01-0.1 T) magnetic field and is injected into the trap along increasing magnetic field up to 0.3 T. A beam duration is limited due to electrical breakdown of diode which was observed in the experiment. One of possible causes of this limitation may be electrons reflected from input magnetic mirror and an appearance of the dense plasma on the back side of the anode, which then penetrates into

the diode. The present paper considers reflection of electrons from magnetic mirror analytically and numerically, taking into account the volume charge of the beam. Generation of beam in magnetic field is accompanied by the appearance of angular divergence of its electrons. Pitch angles of electrons in the diode may occur due to imperfect of its optics, due to the presence of the azimuthal magnetic and radial electric fields of the beam, resulted in transverse velocity of electrons. They can lead to reflection of electrons in increasing magnetic field due to rise in pitch angles, reduction of longitudinal velocity of the electrons and subsequent increase of space charge. An analytical estimate of the vacuum beam current limit, taking into account the initial pitch angles of electrons and beam compression in magnetic field is made [2]. The case of the beam volume charge neutralization with pitch angles increasing in his radius is also considered. The results of numerical simulation of transport and compression beam with non-uniform distribution in radius of current and pitch angles in the magnetic field under different conditions are considered. The values of currents are obtained, for which a reflection of electrons begins. The results of simulation are compared with the results of experiments in which similar reflection and diode breakdown are observed. They are in a good agreement.
The investigation is supported by RFBR Grant No. 16-08-00785-a
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Development of 28/35 GHz dual-frequency gyrotron for ECH study

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The electron cyclotron heating (ECH) is essential for tandem mirror devices to achieve potential confinement and high electron temperature. A gyrotron is a powerful and an essential tool for ECH. Recent progress of the gyrotron has widened the use of gyrotrons for fusion research. High power and long pulse operations of the gyrotron and the efficient transmission of its output are quite important to achieve better plasma performances. Recent ECH physics experiments require 28 GHz gyrotrons for plasma experimental devices. For the ECH systems of GAMMA 10/PDX and National Spherical Torus Experiment (NSTX) at Princeton Plasma Physics Laboratory (PPPL), a gyrotron with a 1.5-2 MW output for several seconds is required. For the Q-shuUniversity Experimental with Steady-State Spherical Tokamak (QUEST) ECH system at Kyushu University, a 0.4 MW CW gyrotron is needed. Therefore, the development of the higher power and CW operational gyrotron has been started as the collaborative research. A 28 GHz 1 MW gyrotron developed for GAMMA 10/PDX achieved an output power of 1.38 MW in 2015 experiment after the power supply was improved. This gyrotron was applied to the 2013 QUEST plasma experiment campaign, and an over-dense plasma with a density at more than $1\times10^{18}m^{-3}$ was produced, which is higher than cut-off density of 8.2 GHz, and EC-driven plasma current of 66 kA was non-inductively attained with the 28 GHz injection. These successful results lead to a 28 GHz gyrotron application program of NSTX-U. The design study of a new 28/35 GHz

dual-frequency gyrotron (2 MW 3 s and 0.4 MW CW) for QUEST, NSTX-U, Heliotron J and GAMMA 10/PDX has been completed and the fabrication of the gyrotron is in progress. The first test is scheduled from June 2016. This gyrotron has a sapphire double-disk window to enable CW operation. The frequency characteristic of a double-disk window is calculated by simulation of the three-layer structure of dielectrics and can be adjusted by varying the thickness of the center dielectric (fluorocarbon coolant). A fabricated double-disk window may have the reflection that is caused by manufacturing error and the permittivity error (dependent on frequency) of the sapphire disk and the fluorocarbon coolant. Before installing a double-disk window in the dual-frequency gyrotron, we measured the dependence of reflective power on the coolant thickness including the confirmation of the small reflective power less than 2 % by both cold test using a 1 W Gunn diode and the hot test using the gyrotron output power of 600 kW. The final fine adjustment of the coolant thickness will be performed after installing the double-disk window in the new gyrotron.
This work was partially supported by the NIFS Collaborative program (NIFS11KUGM050 and COD27077) and Grants-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology of Japan (26249141 and 15H05770A).

Effect of conductive screens on the stabilization of plasma channels with currents of hundreds kAmps

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The problem of plasma structure stabilization is highly relevant for systems of low- and high-temperature plasma, in particular fusion experiment, and in order to cope with the problem different special configurations of current and magnetic systems are developed and deployed. However, the available solutions require construction of complex magnetic fields and consume considerable amounts of energy. With respect to thyratrons, which operation is characterized by the presence of normally several high current plasma channels, this issue has not been yet studied thoroughly. On the example of thyratrons TDI-type (pseudospark switches) contemplates a method of the arc discharge spatial stabilization. TDI-type thyratrons (pseudospark switches) are widely used in pulsed power applications [1]. Normally they are operated in circuits with grounded grid and, in fact, represent an arc gap, the life of which is mostly determined by erosion of its electrodes [2]. However our experience shows that TDI-thyratrons, operated on the left branch of the Paschen curve, feature certain essentials in the motion of arc channels when switching charge transfer of more than 0.1 C per shot with peak currents exceeding 10 kA. Besides, the way how the switch is connected in the circuit and the external environment, affects greatly on the service life of the tube. Based on experimental data, we analyzed the results of the influence of external conductive shield on stabilization of plasma channels in high-power pseudospark switches - thyratrons TDI-type. Both no-ferrous and ferrous shields have been tested. The preliminary calculation of the magnetic field distribution is presented. This research is a part of a work on improvement of switching capabilities of thyratrons used for transferring currents up to hundreds kA with switching energy more than 50 kJ. Further increase of the life time is associated with as the stabilization of arc channels and with the requirement to the suppression of pinching in the central part of the electrode. Similar processes take place not only in switches - thyratrons and spark gaps, but also in the high-current devices with the transportation of plasma at a sufficiently large distance (for example, in fusion colliders), so the construction of external thick screens therein may also contribute the stabilization of a plasma.
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Analysis of gas conditions influence it the GDT west expander on plasma confinement in the central cell

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A longitudinal ion and energy transport through the magnetic mirror appears to be the dominant problem in open magnetic traps physics. Cold electrons flow from field expansion area has been found to be the main mechanism that limits target plasma heating in the central cell of the Gas Dynamic Trap (GDT). One of the dominant cold electrons sources may appear a residual neutral gas in the expander. Gas and plasma interaction results in its ionization and occurring cold electrons that penetrate through the magnetic mirror into the central cell of the machine. This work is aimed to find a critical gas concentration value in the expander when it begins to effect on basic plasma parameters in the central cell of the GDT. The results obtained from these experiments are crucial for understanding the engineering requirements for the pumping system in divertors of the C-2W machine being built in Tri Alpha Energy Inc. and experimental machines of next generation being designed.

Code Development for the Calculations of the Time-dependent Multimode Oscillations in the Cavity of the Future High-Power Gyrotrons

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High-power millimeter-wave gyrotrons for fusion plasma applications are designed for continuous-wave or long-pulse operation. It becomes an indispensable tool for controlled fusion ECH and ECCD experiments. Recently, many studies[1,2,3] have devoted to high-power and long-pulse gyrotrons and multi-frequency gyrotrons are required for experimental flexibility and research collaborations. In the development of these gyrotrons, two of the important issues are the increase of the radiated power and to provide a stable operation in the single desired mode. To handle thermal losses, the resonators of these gyrotrons have a diameter much larger than a wavelength. It means that the gyrotrons operate in very high-order modes. The interaction of the electron beam with many modes and the mode competition during gyrotron startup are important. For the gyrotron development in the future plan, the computing code for the time-dependent and multimodes of the wave-guide-cavity gyrotron oscillators has been developed.
Several studies [1] have shown that the excitation of one or two parasitic modes is practically unavoidable. The mode competition during gyrotron startup is the important problem because

the cyclotron resonance condition can be fulfilled for a large number of modes during the voltage rise from zero to its nominal value. The optimum design of the resonant cavity for gyrotron oscillators requires the analysis of the startup scenario. The present code calculates the cavity RF profile function by solving the set of the relativistic single-particle equations of motion and generalized telegraphers equations simultaneously to reach a self-consistent solution in the dynamic system that takes into account the effects of the electron beam in the field produced by a superposition of modes. The pitch factor and velocity spreads of the electron beams are calculated by the use of the electron trajectory code EGUN[4].
The computing code includes a time-dependent description of the electromagnetic field and a self-consistent analysis of the electron beams. The basic procedure is to solve the coupled equations in the cavity geometry by applying radiation boundary conditions. These coupled equations are integrated using the iterative predictor-corrector scheme and the Runge-Kutta integration scheme. The parallel algorithms are used for the required accuracy in calculation and the reduction of the computer time. We present the calculation results of the gyrotron for an application to the ECH system in GAMMA 10/PDX.
This work was partially supported by Grants-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology of Japan (26249141).
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The Research of photoneutralization of negative hydrogen and deuterium (ions) beam in nonresonance photon open trap.

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Atomic powerful sources will be used as a source of heating of the plasma in future fusion reactors. To achieve high power efficiency of neutral injection the target with high neutralization coefficient is necessary in such systems. Currently, the main approach to neutralize the ion beams is to use a gas target, the effectiveness of which at high energies (1 MeV) does not exceed 60%. In addition these approaches significantly affect the vacuum conditions and the appearance of impurities in the beam. A possible solution to the transformation of the negative ion beam to atomic one with high efficiency without flaws is a "photon trap", as the basic process of this method is based on the photodetachment of an electron from a negative ion. The use of the mechanism allows neutral atoms yield to reach 100%. Photon storage trap is designed as a system of parallel placed mirrors 25 cm long, consisting of individual cylindrical and spherical mirrors with a characteristic transverse dimension of 50 mm and a radius of curvature of 250 mm. The effectiveness of this approach is mainly determined by the quality of the reflecting surface. It is practically independent from the quality of the injected radiation and does not require high precision alignment of optical elements. In such a system the photons undergo multiple reflections. This paper presents the results of research photoneutralization beams of negative ions of hydrogen and deuterium at the experimental stand. Experiments were carried out using an injector with a beam energy 6-12 keV and a current of 1 A, the laser power up to 2 kW. Neutralization coefficient obtained for negative hydrogen ions is ~90% and ~95% for deuterium. Experiments to determine the dependence of the beam neutralization factor on the laser power to the target have been carried out. These results demonstrate the high efficiency of this method and opportunities of the photon detachment target for powerful beams of negative ions neutralization.

Recent progress in development of neutral beams for fusion studies

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Series of neutral beams with ballistic focusing were developed in several recent years for fusion studies in Budker Insitute. Diagnostic neutral beam injectors for large stellarator W-7X and tokamak T-15 were produced and tested. A high power, relatively low energy neutral beam injector was developed to upgrade of the neutral beam system of the gas dynamic trap device and C2-U experiment. The ion source of the injector forms a proton beam with the particle energy of 15 keV, current of up to 175 A, and pulse duration up to 30 ms. In a first stage of the TCV upgrade program, a 1 MW tangentially launched neutral beam of Deuterium or Hydrogen was installed. Development of powerful steady state ion sources is discussed in the report.

High-speed pumping system characteristics of 2 MW neutral beam injector based on Ti gettering

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The 15 kV, 2 MW neutral beam injector (NBI) was developed for C-2U magnetic trap experiments. Important part of the NBI is efficient pumping system which provided a good vacuum condition during beam pulse. The pressure rise during the NBI operation and accompanying gas flow to the fusion device is a negative factor both for the beam transportation and for fusion experiment. The high-speed pumping system based on four Ti-bar arc-discharge evaporators placed inside LN2-cooled volume was developed and succesfully used in vacuum chamber of the 2 MW NBI. The results of calculations and tests are presented both at the room and at the LN2 temperatures of the gettered surface. Achieved pumping speeds are about 10^5 and $4 \cdot 10^5$ l/s correspondingly. Also gas capacitance of the gettered surface and conditions of uniform gettering were established.

Experimental study of coupling of low-frequency electromagnetic waves with plasma in strong magnetic field

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Helicons (circularly-polarized electromagnetic waves) propagate in a plasma with density exceeded cut-off for its frequency, and provide effective energy delivery to plasma. Accordingly, helicon discharge is one of the most suitable way for production of high-density low-temperature plasma. Helicon plasma sources, operating in the MHz frequency range and respectively low magnetic fields (0.01-0.1 T), capable to create plasma with density up to 10^{14} cm^{-3}. At the same time, next generation of linear plasma facilities for both for PMI studies and fusion applications requires production of plasma with density above this limit. Theoretical studies predict that such increasing of density can be achieved by application of powerful microwave sources of GHz range frequency. The aim of the presented experiments is experimental verification of theoretical predictions and search of conditions for effective delivery of electromagnetic power to plasma towards development of stationary source of dense plasma for linear facilities. Interaction of 2.45 GHz electromagnetic radiation with low-temperature plasma column, confined in a strong magnetic field, was studied on the GOL-3 facility. Plasma was created by external source (arc plasma gun) placed on the edge of the facility. Microwave power is transferred from moderate power (1.4 kW) magnetron source to o-ring antenna, separated from plasma column by quartz tube. Coupling of antenna with plasma (reflected-to-direct wave ratio) and spatial structure of the wave are measured for various plasma densities and magnetic fields in the facility. The results of experiments supports theoretical prediction of effective coupling of GHz-range electromagnetic waves with plasma.

Extracting grid enhancement in triode ion optical system of power neutral beam injector

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Thriode ion optical system is used typically in high power neutral beam injectors. The geometry of elementary cell is result of many factors such as beam parameters, aplying plasma source type and availabel fabrication technologies. The first (extracting grid) is most important for high-quality beam formation. A new design of the extracting grid in accelerating elementary cell of multy-slit ion optical system was suggested to improve beam characteristics and to simplify fabrication. The design was analyzed with numerical simulation and tested in experiments. These results were successfully used in modern high power neutral injectors of Budker Institute.

Oscillating Mirror Instability in Plasma with Sloshing Ions

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In recent experiment on the GDT the longitudinal oscillations of plasma were observed [1]. The mode is discrete with frequency close to the bounce frequency of hot ions. It has typically zero angular wave-number and seems to be radially correlated. While the oscillation looks like sound-like standing wave it is well known that in plasma with hot ions the ion sound wave should be dumped strongly. However in case of GDT experiment the plasma has high beta and the distribution function of ions is far from equilibrium in contradistinction to usual assumptions of ion sound theory. In present work kinetic approach is utilized to study the influence of the high beta on the dispersion of slow magnetic sound. It is shown that in plasma with sloshing ions the oscillating mode could exist even in limit of cold electrons if beta is high enough. The mode has sound-like frequency and is be unstable because the resonant interaction with ions. The threshold of the instability depends strongly on the distribution of ions.

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Potential Profile in Expander of Mirror Trap

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Axially symmetric magnetic mirrors could be attractive as neutron source and alternative fusion reactor [1,2]. Plasma losses from mirrors are dominated by longitudinal outflow. Ions are confined between mirrors in central region of trap. Commonly plasma in a trap has positive electrostatic potential that holds the electron loss equal to the ion loss. The secondary emission of electrons from end plate along with ionization of neutral gas in expander region can strongly affect the confinement. The potential barrier height will be reduced if secondary electrons can penetrate the inner region of trap. Those electrons could overcome the mirror due to acceleration by electric field. It depends strongly on distribution of electrostatic potential along the lines of magnetic field. Scattering of electrons results in trapping of a part of them between the magnetic mirror and Debye sheath at the wall. Presence of the trapped population moves a part of potential drop from the sheath to expander area. Thus, expansion of the magnetic field behind a mirror can reduce electrons recycling from the wall [3,4]. In present work numerical kinetic model is developed to study the influence of electron scattering on the distribution of electric potential in expander. The model solves collisional kinetic equation for electrons. It is supposed that ions flow through the expander is collisionless. The electric potential is determined from the quasi-neutrality condition.

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Transport phenomena

Preferential confinement and field-aligned acceleration of energetic ions in a Reversed Field Pinch

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Reconnection-driven heating of ions is a powerful process in many astrophysical and laboratory plasmas, including CT merging and reversed-field pinch (RFP) discharges. The RFP is often characterized by rapid ion heating during impulsive reconnection, generating an ion distribution with an enhanced bulk temperature, mainly perpendicular to magnetic field. In the Madison Symmetric Torus RFP, a subset of discharges with the strongest reconnection events develop a very anisotropic, high energy tail parallel to magnetic field in addition to bulk perpendicular heating, which produces a fusion neutron flux orders of magnitude higher than that expected from a Maxwellian distribution. Here we demonstrate that two factors in addition to a perpendicular bulk heating mechanism must be considered to explain this distribution. First, ion runaway can occur in the strong parallel-to-B electric field induced by a rapid equilibrium change triggered by reconnection-based relaxation; this effect is particularly strong on sufficiently energetic ions whose guiding centers drift substantially from magnetic field lines. Second, the confinement of ions varies dramatically as a function of velocity. While thermal ions are governed by stochastic diffusion along tearing-altered field lines (and radial diffusion increases with parallel speed), the energetic ions are well confined, only weakly affected by a stochastic magnetic field. High energy ions traveling mainly in the direction of plasma current are nearly classically confined, while counter-propagating ions experience an intermediate confinement, greater than that of thermal ions but significantly less than classical expectations. The details of ion confinement tend to reinforce the asymmetric drive of the parallel electric field, resulting in a very asymmetric, anisotropic distribution.
Experiments with neutral beam injection elegantly confirm the ion runaway process and fast ion confinement characteristics in MST. Neutral particle analyzers measure an unrestricted parallel acceleration of the fast test particle distribution during the reconnection event. The energy gain is larger for higher initial ion energy (reduced drag), and deceleration is observed with reversed electric field (counter-current injection) according to runaway dynamics and confirmed with Fokker-Planck modeling. Work supported by USDOE. Portions of the work were accomplished with the use of infrastructure of Complex DOL (BINP, Russia).

3D Ion Distribution Resulting from Neutral Beam and ICRF Heating in an Axisymmetric Mirror

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The CQL3D bounce-averaged Fokker-Planck (FP) code[1]has been widely applied within the tokamak modeling community. For the reported work, it has been augmented to include axisymmetric open-field-line geometry, suitable for calculation of energetic ion and electron distributions in the low collisionality, tau_bounce « tau_collision, regime of energetic particles in mirrors. Our

target application is calculation of energetic ion and electron distributions in GDT-like devices [2]. A time-dependent, particle-conserving, finite difference solution of the bounce-averaged collisional FP equation is obtained for particle distribution f(u,theta,rho,t), where u is momentum per mass, theta is pitch angle with respect to the magnetic field vector, and rho is a normalized function of magnetic flux function. A neutral beam source is provided by the NFREYA Monte Carlo beam deposition code, which has been benchmarked against the NUBEAM deposition code. The effects of radiofrequency wave heating are obtained based on the general Stix quasilinear wave-particle diffusion coefficients [3], using ray tracing data. GENRAY-C, a new general magnetic geometry variant of the all-frequency plasma-wave ray tracing code GENRAY[4] adapted to mirror machines, provides ray data ; iteration between CQL3D and ray quasilinear absorption is used to obtain self-consistency with the nonthermal distributions. Applications are made for fast and ion cyclotron wave heating of ions, and electron cyclotron heating of electrons.
The bounce-averaged code calculates the nonthermal distributions of trapped particles; the untrapped particles are lost in a particle transit time. Except that for near- and sub-thermal approximately Maxwellian particles , we do not apply the loss operator. A set of synthetic diagnostics based on the nonthermal distributions is available, for example for xray spectra, electron cyclotron emission, neutral particle spectra, and neutron rates. CQL3D is well-benchmarked against experiments such as lower hybrid current drive in C-Mod [5], and neutral beam/high harmonic fast wave in NSTX[6].
Preliminary results with 4 MW of 25 keV D neutral beam at 45 deg pitch angle injection into a 3e13 /cm^3, T=1 keV GDT-like D-plasma[7] give a neutron rate of 6.6e11 n/sec. Shine through of the neutral beam is 22%. An additional 0.27MW of absorbed fast wave RF power increases the neutron rate to 2.2e12 n/sec.

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Electron dynamics in SOL plasma with expander divertor

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Reducing electron heat losses in the open field region of FRC is important for sustaining higher temperature in the core and favorable beam energy deposition. Here, at Tri Alpha Energy, magnetic expander divertor will be used to attain these objectives in C-2W - next generation FRC device. A 3-D (2 velocity and 1 spatial) Vlasov Fokker Planck code Ksol has been developed to study the electron dynamics in the open magnetic field region connected to expander divertor. A confinement vessel (CV) has been added to simulation area recently to make simulation setup more realistic. With this code improvement electron distribution function is calculated self-consistently by balancing source in CV and losses in the expander. Overall effect of non-Maxwellian distribution at mirror location is decreasing electron temperature in the divertor and increasing pre-sheath electrostatic potential compared to previously reported case without CV. As a result of these rearrangements, Debye sheath becomes substantially lower what is favorable for plasma interaction with divertor plates.

Direct measurement of the plasma leak-width in an optimized, high ionization fraction multi-dipole ring cusp

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The leak width of plasma in the WiPAL multi-dipole ring cusp[1] has been directly measured using a novel array of probes embedded in the insulating plasma limiters. The large plasma volume ($\approx$10 m^3), small loss area associated with strong rare earth permanent magnets, and large heating power ($\leq$ 200 kW) allowed for a broad range of electron temperatures, ion temperatures, plasma densities, ionization fractions, and ion masses, all of which were accurately measured. Plasma parameters measured at the surface of ceramic limiter tiles covering the magnets and along radial chords in the cusp field indicate density and temperature are nearly constant on magnetic field lines and that the mirror forces play little role in confining the plasma other than to constrict the loss area. Particle balance modeling is used to determine the cross field diffusion from the measured parallel losses at the limiters. The experimentally determined cross field diffusion (which determines the leak width) is consistent with ambipolar diffusion across five orders of magnitude. This ambipolar diffusion for a given field line is set primarily by the electron-neutral collisions in the region where the magnetic field is the weakest, even though these plasmas can have ionization fractions near 1.

The implications of the plasma losses on charge, particle, and energy balance will be then discussed. The primary heating source is currently a set of 8, LaB_6 cathodes injecting 100s of amps of fast electron current at $\sim$400 volts. Plasma potential is set by ambipolarity, but is strongly dependent upon the size of the electron collecting anodes within the plasma. Electron and ion energy confinement is strongly coupled to the plasma potential.

In addition to describing these confinement results, a brief overview of the physics goals for the WiPAL facility will be described. Its mission involves creating a weakly monetized, but hot and conducting plasma suitable for studying dynamos, magnetic reconnection, shocks, and other astrophysical plasma processes.

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Study of plasma electron thermal conductivity in the magnetic mirror

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Most part of open magnetic systems has the device for the expansion of the plasma stream flowing out of the trap. Using of such a magnetic nozzle (expander) allows solving a series of physical and technical challenges: to reduce the thermal load on the end wall, to carry out direct recuperation of plasma energy into electricity, and so on. In addition, expanding magnetic field can also suppress the electron heat flow between the central part of the trap and plasma absorber. Unfortunately, the current models of plasma in the expander seem to be oversimplified and cannot be applied to a modes corresponding to large devices such as the neutron source or fusion reactor. In particular, it requires further development of the electron kinetic theory, as well as the account of balance and the dynamics of neutral gas. GDT expander physics studied experimentally earlier, but at much lower plasma parameters than todays. Thus, more precise investigations of electron longitudinal confinement physics in an open trap is important in terms of future applications. In recent experiments on the GDT well-studied method of vortex confinement had been used to suppress the transverse plasma losses arising by the MHD instabilities development. This method allowed to reach the relative pressure of plasma $\beta = 0.6$ which is record value for axisymmetric mirrors as well as an electron temperature exceeding of 0.6 keV. Such temperature has been achieved in recent experiments with additional plasma heating by microwave radiation on the electron cyclotron resonance (ECR). These advances bring the neutron sources projects based on axisymmetric mirrors to the competitive level. Thus, there is a possibility of direct experimental verification of such projects in order to extrapolate the results for future fusion reactors. For realization of mentioned tasks a series of experiments were carried out on the GDT device. Measurements of potential, the average energy of the electrons and its density in the expander as a function of position along the magnetic field line at high electron temperature in the center of the trap were carried out. The minimum degree of expansion which is necessary for the electron heat conductivity suppression from the open trap was defined. The expansion ratio was varied using a movable central section of the end wall. It should be noted that the physics of the expander for the different types of open traps is quite similar, so the studies carried out on GDT can be useful for a wide range of other projects.

Particle-in-cell simulation of field reversal in an mirror trap with neutral beam injection

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Azimuthal current generation in a mirror trap via powerful off-axis neutral beam injection [1] is method of field-reversal configuration (FRC) formation. Theoretical consideration [2] shows that method faces with numerous difficulties, for example, MHD instabilities of high pressure plasma and fast ions current cancellation by electron current at field null. Experimental investigation of field reversal in 2XIIB machine has shown that increasing of fast ions pressure is limited by anomalous ions scattering caused by excitation of kinetic instability (probably the drift-cyclotron loss-cone instability).

Facility for experimental studying of field reversal in mirror machine is being designed in the Budker INP SB RAS now [3]. 3D hybrid Particle-in-Cell code was developed for studying processes which can prevent field reversal. The injection geometry (including ballistic beams focusing) and fast atoms trapping because of charge exchanging and ionization are taken into account. 3D PiC method taking into account the ion-ion collisions, charge-exchanging and electron drag is used for calculation of the charges and currents generated by fast ions. Electrons evolution, electron charges and currents are calculated from the two-fluid MHD equations taking into account finite electron viscosity and conductivity. Evolution of target ions can be calculated by the PiC method or by solving of the two-fluid MHD equations. Thus various processes can be studied, such as MHD and kinetic instabilities, electron current self-generation, target plasma penetration through closed field lines.

The preliminary results of simulations of field reversal under the parameters of planned experiment are presented. In axisymmetric case (dependence of fields on the azimuthal coordinate is neglected) the field reversal is achieved if electron temperature is high enough (of the order 100 eV). Fast ions losses caused by the electron drag are unacceptably high when temperature is too lower. The small-scale convection which prevents the electron current self-generation is observed. Probably the convection is driven by Kelvin-Helmholtz instability caused by potential drop between areas with closed and opened field lines [4]. Anomalous fast ions scattering caused by kinetic instabilities is observed in fully 3D simulations. Ways of the MHD and kinetic instabilities stabilizing are discussed.

This work was supported by Russian Science Foundation (Project No. 14-50-00080).

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Coulomb collisions in a "single" ionized plasma

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In plasmas, the physics of transport phenomena notably depends on Coulomb collisions. Real plasmas are substituted, either explicitly or in indirect form, by probabilistic plasma ensembles in the usual theoretical considerations of the effect of the collisions on the plasma evolution. We have repeatedly shown earlier that such a substitution substantially lessens the reliability of plasma macrophysical scenarios. (See [1, 2].) This motivates the development and study of kinetic models of plasma evolution due to the collisions without using the plasma ensemble substitution. For this purpose, we have previously developed a special two-time formalism that we call *the high-informative correlation analysis of plasma kinetics* (see the above references). It is aimed at reducing the full plasma description to simpler plasma kinetic models oriented to specific physical contexts. We have used it to model the plasma evolution in the situation typical of the first traditional theoretical studies of the plasma collisional relaxation. That is, we assume that a thermodynamically non-equilibrium fully ionized plasma is macroscopically stable, homogeneous, and isotropic, and that the external magnetic field is absent. We report respective rates of change of the distribution functions of plasma particles and compare them with their analogs stemming from the well-known Lenard-Balescu equation.
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Radial and Axial Transport in Trap Sections with Helical Corrugation

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Sections with helical corrugation of the magnetic field are currently considered for supplemental improvement of axial confinement in gas-dynamic mirror traps [1,2]. The $E \times B$ plasma rotation in such a field leads to the effective axial motion of magnetic mirrors. If it is coupled to enhanced plasma scattering (to facilitate ion exchanges between trapped and passing populations) such motion is capable of transferring axial momentum from the magnetic field coils to the plasma flow. Theory also predicts radial pinch effect coupled to this momentum transfer that is capable of contracting or expanding the discharge in radius. The fact is that different components of plasma transport in helically corrugated sections are inherently coupled and should be considered together.
This paper will attempt theoretical description and numerical modeling of the radial and axial transport components in a low-corrugation-helical-mirror section that is attached to a plasma reservoir (main trap cell). Different models of ion scattering (classical and turbulent) are considered. A new method of plasma refueling by means of the radial pinch of cold ions from the plasma periphery is suggested. Design of the ionization zone in the low-field phase of the corrugation as in the helical plasma thruster [3] allows to inject almost all cold ions into the reservoir

without significant cold-ion outflow into the expander. This lowers the energy cost of refueling and eliminates the risk of charge-exchange losses associated with schemes of the main-cell refueling. Besides, the effective momentum transfer from the magnetic field to the cold inflow provides a new way of transferring axial momentum to weakly collisional plasmas. Additional plasma scattering caused by such a flow is accounted for.

This work has been supported by Russian Science Foundation (project N 14-50-00080)

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Longitudinal electron energy distribution measurements in PR-2 mirror machine

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Beam-plasma discharge is used in PR-2 (fig.1) [1]. Plasma parameters can be varied in a wide range. It is important to know the longitudinal electron energy distribution. Precise definition of electron energy distribution function allows interpreting Langmuir probe characteristics in a more accurate way. In addition, it allows understanding processes in auto-oscillating regime at plasma-surface interaction. [1, 2]

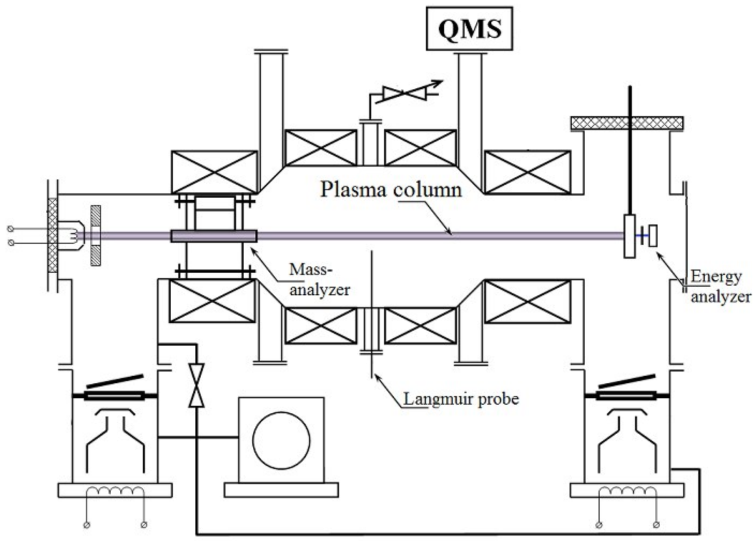

Figure 1: Scheme of linear plasma device PR-2

The linear plasma device PR-2 has mirror ratio 1,55. Beam-plasma discharge is provided by electron beam 1 - 10 kV, power up to 10 kW. Measurements were carried out behind the magnet mirror with small-size integral electrostatic energy analyzer. The analyzer has long circular diaphragm with small radius to cut ions off. [3] The long (2 mm) diaphragm (d = 0,5 mm) is mounted on water-cooled collector with an aperture. The ions with larmor radius more than 0,5d are cut off. Integral electrostatic energy analyzer [4] is mounted behind the diaphragm. Retarding electrode is made of wide metal plate with a small aperture. Thus distortion of an electric field is negligible. Retarding potential is up to 10 kV. Second electrode and current detector is a Faraday cup under small positive potential (∼ 30 V). The analyzer can measure electron energy distribution up to 10 kV.

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Study of the impurity transport by injecting the gas to D-module in GAMMA 10/PDX

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Divertor magnetic field configuration has been utilized to protect the nuclear fusion reactor from high heat flow from fusion plasmas. The reduction of the heat load to the divertor plate by promoting the radiation cooling is an important subject to form the detached plasma [1-3]. GAMMA 10/PDX consists of central-cell, anchor-cell, plug/barrier-cell and end-cell. Plasma heating devices, such as neutral beam injection (NBI), electron cyclotron resonance heating (ECRH) and ion cyclotron range of frequency (ICRF) have been installed. In GAMMA 10/PDX, ICRF wave heating is used to make high-temperature hydrogen plasma and high heat flux plasma flow is generated at the end-cell by making use of the open magnetic field. The divertor simulation experimental module (D-module) has been installed in the west end-cell. A V-shaped target plate made of tungsten is mounted in this module. The angle of V-shaped target plate can be varied from 15 to 80 degree. Several gas injection ports have been installed in D-module in order to investigate radiation cooling by injecting impurity gases. There are several spectrometers installed at end-cell and plug/barrier-cell. The purpose of this study is to analyze the mechanism of radiation cooling, formation of detached plasma and the impurity transport. In the experiment, various types of gases (Argon, Xenon, Neon, Nitrogen and Hydrogen) have been injected into D-module. In this experiment, the emission spectra of impurity particles were measured by using spectrometers under several conditions, such as changing the gas throughput and gas injection timing. It is found that increasing the quantity of neon and nitrogen gas injection, the emission spectra of neon continued to rise. However, in the case of nitrogen, the emission intensity was saturated at the plug/barrier-cell. The effect of barrier-ECH injection on impurity transport also investigated from the comparison of the spectral measurements in the end-cell and plug/barrier-cell. Time evolution of specific emission spectra shows the reduction of the impurity transport. In this paper, detailed results of spectral measurements in gas injection experiments are presented. Discussion on the behavior of the impurity transport and on the change of the electron temperature and density will be also described.

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Peculiarities of Thomas-Fermi and Hartree models for high magnetic field open systems.

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The comparative analysis of various thermodynamic models for calculation of a plasma state which are based on statistical model of Thomas-Fermi (without quantum and exchange corrections) and quantum-mechanical model of Hartree-Fock-Slater (the Hartree model - without taking into account the exchange correction) is done. It is observed that numerical calculations of a charge and potential in a nuclear cell by Hartree method for a case of multielectronic atom are complex and in this case can be replaced with calculations using simple model of Thomas-Fermi with different corrections. At the same time it is noted that Thomas-Fermi model, as a rule, doesn't consider energy of electron correlation. Influence of a strong magnetic field on properties of plasma in magnetic systems with open field lines is discussed.

Impurities effects on operation of the GDMT facility

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A project of a new linear device for confinement of fusion plasmas is under development in the Budker Institute of Nuclear Physics, Novosibirsk. The new facility named GDMT utilizes several physical effects discovered and studied in the last decade on the GOL-3 and GDT devices. In the GDMT device, plasmas with fast sloshing ions will be confined in an axially-symmetric solenoid with multi-mirror sections attached at both ends. The multi-mirror end sections are 5 m long and composed of superconducting coils with magnetic field up to 7.5 T. Quasi-stationary operation of the facility with increased confinement time of plasma may lead to impurities accumulation that can cause increase of radiation cooling, scattering and forced losses of fast ions. Expected sources of impurities and its influence to plasma confinement are discussed in the paper. For several elements such as oxygen, tungsten and molybdenum we estimate expected influx to a plasma, dynamics of ionization and confinement in the trap, and related radiation losses and increase of effective charge. Main expected source of light impurities in plasma is contamination of neutral beams. Ordinary, ion beams, generated by ion sources of beam injection system, contain fraction of accelerated water ion H_2O^+, that dissociates in charge-exchange target and results in contamination of neutral beam by fast oxygen atoms. Decrease of oxygen content in a neutral beam below 1% is a challenge. Therefore, it is possible to estimate oxygen ion flux $5 \times 10^{19}\ s^{-1}$ and concentration of oxygen ions in plasma ($n_O = 3 \times 10^{11}\ cm^{-3}$ with radiation loss power about 15 kW and increase of Zeff to about 1,5. Physical sputtering of a limiter and unipolar arcing are considered as sources of heavy impurities. Physical sputtering by plasma ion bombardment is a fundamental process, which determines minimal erosion rate and impurities production from plasma-facing components. Lower-bound estimate of heavy impurities flux to plasma from the limiter is $5 \times 10^{17}\ s^{-1}$ that cause radiation loss power 40 kW. Unipolar arcs accompanies with release of 10^{17} atoms of limiter material to a plasma. Every such events will cause to increase of effective charge to a value about 4 with dramatic loss of population of fast ions in plasma.

Calculating diffusion and heat fluxes due to compression of magnetized target

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There are several areas that require the use of fusion technology, knowledge and technical solutions already at present, before the commissioning of stationary thermonuclear systems, e.g. fusion-fission hybrid reactor to burn transuranic and minor actinide fuels. The study of heat and burning in compression (due to fast liners and powerful drivers) of plasma in extreme heat conditions is one of these problems. Simulation of the operating modes and dense plasma at compression stage is necessary to ensure and control thermal process. The mathematical model for determining the heat fluxes and plasma flows to the first chamber wall is based on the modeling of transport (diffusion, thermal, radiative) processes of atoms, ions, electrons, molecules, photons in a strong magnetic field. Note that there are many papers, devoted to the description of thermomechanical effects of X-rays on a fused barrier [1-2]. We numerically simulated the impact of the X-ray, which is formed by the ignition of deuterium-tritium target, on the first wall within the concept of magneto-inertial fusion (MIF) [3-10].
This study was supported by the Ministry of Education and Science of the Russian Federation (Project # GosZadanie 13.79.2014/K).

Effect of Alfvén ion-cyclotron instability on ion dynamic in an axisymmetric mirror trap

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Alfvén ion-cyclotron (AIC) instability is an electromagnetic instability which leads to excitation of elliptically-polarized waves rotating in the direction of ion gyro-rotation and propagating along external magnetic field. The instability causes anomalous ions scattering and can influences on particles and energy losses. For example, confinement in the central cell of TMX device was limited by AIC instability which was excited in end cells and heats up central cell ions [1]. The hot ions anisotropy in the central cell of GAMMA-10 device is limited by AIC instability which causes hot ion angle scattering [2]. Insignificant increasing of fast ions axial losses caused by AIC instability is observed in the central cell of GDT device [3].
The ion motion in an axisymmetric mirror trap with electric and magnetic field perturbations is investigated analytically and numerically in present work. The most intense interaction between wave and ions occurs near minimum of mirror field where cyclotron resonant condition $v_{\|} = v_r \equiv (\omega - \Omega_{ci})/k_{\|}$ can be satisfied, here Ω_{ci} is the ion cyclotron frequency and ω and $k_{\|}$ are wave frequency and wave vector. Particle energy can changes over many bounce-periods essentially if changing of phase difference between ion gyro-rotation and wave field rotation during bounce-period equals integer number [4]. In other words, ion energy changes essentially when the following resonant condition takes place: $\omega - \langle\Omega_{ci}\rangle = n\Omega_b$, here $\langle\Omega_{ci}\rangle$ is the ion-cyclotron frequency averaged over bounce period and Ω_b is the bounce frequency. As well as in the case of electron cyclotron resonance heating [4, 5], the interaction between bounce-oscillations and AIC wave leads to chaotic dynamic of ions having relatively low transversal energy and $v_{\|} \sim v_r$. Thus the diffusion on magnet momentum arises which results in anomalous axial losses of ions.
The distribution of fields perturbations are calculates from linear WKB analysis of instability threshold [6], fields distributions found from the Pearlstein-Berk approximation are used for

analytical calculations. The margin of chaos area and diffusion coefficient is estimated analytically and ions losses caused by AIC instability are calculated. Also transversal ion diffusion is considered. The analytical calculations are compared with numerical simulation of ion dynamic.
This work has been supported by Russian Science Foundation (Project No. 14-50-00080).
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Plasma diagnostics

Jet Outflow Measurements on the C-2U Advanced Beam-Driven Field-Reversed Configuration Plasma Experiment

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Experiments demonstrating sustainment of field-reversed configuration (FRC) plasma via neutral beam injection have been carried out on C-2U. Knowledge and control of the axial outflow of plasma particles and energy along open-magnetic-field lines are of crucial importance to successful confinement of FRC plasma, and in particular to FRC core temperature ramp-up. A diverse suite of diagnostics was utilized to perform measurements of plasma in the open field lines, including passive Doppler impurity spectroscopy, microwave interferometry, triple Langmuir probe measurements and radial impurity emission profile scanning. Results of these measurements will be presented. In addition, correlation between velocity profiles of the open-field-line plasma outflow to FRC particle and energy decay rates will be discussed.

First results of ECE measurements at the GDT mirror trap

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This paper summarizes the results of experiments on electron cyclotron emission (ECE) measurements at the axially symmetric magnetic mirror device gas dynamic trap GDT (Budker Institute, Novosibirsk). The new ECE diagnostics has been installed to facilitate the successful ECRH experiment and operates in the vicinity of the ECRH frequency (54.5 GHz). The particulars of plasma EC emission were studied experimentally in a broad range of discharge scenarios in GDT. Measured thermal spectra have validated the existing physical conceptions about the EC resonance heating of plasma in the machine, in particular the significance of the auxiliary ECR surface in the launching port that affects the wave propagation in core plasma. Efficiency of the dedicated non-planar magnetic coil for the suppression of the auxiliary resonance have been validated with the thermal ECE measurements. Measured non-thermal ECE spectra have unambiguously confirmed the existence of suprathermal electrons in GDT for the first time. As it turned out, these electrons are generated by the intense microwave field both during the ECR start-up (breakdown) stage and during the ECR heating of the main plasma. Time dependence of ECE level corresponding to variation of confining magnetic field allowed to reconstruct distribution function of suprathermal electron and estimate their population.
The work is supported by the Russian Science Foundation (project No 14-12-01007).

Development of internal ICRF wave detection using microwave reflectometry on GAMMA 10

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Control of waves in ion cyclotron range of frequencies (ICRF) is crucial for better performance of the GAMMA 10 plasma, which utilizes ICRF heating as the main heating scheme and is susceptible to an unstable ICRF wave named as Alfvén-ion-cyclotron (AIC) wave. Traditional beach heating using a slow wave has been used in GAMMA 10, and is very effective for realizing high ion-temperature plasma of the order of kilo-electron volts near the midplane of the central mirror field. However, there remains much to be cleared in association with ICRF heating in a mirror configuration; e.g. saturation of confined energy against ICRF heating power, transient-like variation of heating efficiency observed in the ramp-up phase of the GAMMA 10 plasma, significant sensitivity of heating efficiency to the magnetic field strength, and so on. In order to clarify these fundamental things, experimental assessment of internal wave-field structure has been desired.
We have been developing one of such measurement systems by using microwave reflectometry. Recent development of our reflectometer system enabled clear separation of phase modulation component from amplitude modulation component included in the reflected microwave and gave good coherent signals associated with the global structure of the ICRF waves. Interestingly, the amplitude modulations at the wave frequencies suddenly lost coherency with increasing distance between measurement points, contrary to what observed for the phase modulations. The long correlation beyond the half plasma radius, which is confirmed for the phase modulation signals, indicate that they nicely reflect radially expanded eigenmode structures, which are theoretically predicted characteristic of ICRF waves for a low-density small-sized plasma column like the GAMMA 10 plasma.
We successfully obtained precise radial profiles of the density fluctuations associated with the externally applied ICRF waves and spontaneously excited AIC waves by using the developed reflectometer system, which could give us insights into ICRF wave physics related to above mentioned unclear issues. Damping picture of slow wave near its ion-cyclotron resonance layer was already observed, which will be a first step towards the clarification and improved control of the GAMMA 10 plasma.

Visible light tomography diagnostic for imaging of spatial profiles of plasma emission in the gas dynamic trap divertor

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One of the most important research directions on the Gas Dynamic Trap (GDT) magnetic mirror [1] is a complex study of the divertor physics. The foundation stone of this research program is a study of physical processes in a volume of divertor with expanding magnetic field lines. The exploration of the region near the plasma absorber is also considered. Because of neutralization of the plasma flux on the absorber surface, the adjacent plasma layer is characterized by a high density of atomic and molecular particles. Such a compound considerably affects the whole system particle balance, thus having an effect on the electrostatic potential spatial distribution. Measurement of intensity distributions of light emitted by atoms of plasma offer a direct instrument to observe the dynamics of this plasma component. In this paper, a new visible light tomography diagnostic system is proposed. The two-dimensional tomographic system is designed, constructed and installed on GDT. An avalanche photodiode (APD) based detector for visible light wavelength is used. The optical system, consisting of interference optical filters and gathering lenses, integrates light along 42 lines of sight (LOS). Lines of sight form a pattern laying in the plane that is perpendicular to the plasma flow direction. The entire optical registration system consists of two diagnostic bundles with 21 LOS in each: the first one provides a spatial coverage from the center of the plasma flux to the edge, the second one covers a region from one edge to the opposite one. The light detecting part of the diagnostic is composed of 14 measuring modules. Each detection module has three APDs bound by one pair of lens and narrowband interference filter. The main features of the system are following: (i) a high sensitivity in 650-660 nm wavelength region; (ii) a time resolution better than 1 mks; (iii) a fan-beam geometry of LOS. All measurement modules were absolutely calibrated on a test stand and the optical system throughput was measured to get absolute intensity values. The optimal signal-to-noise ratio of an APD with a fast two-stage transimpedance amplifier reached approximately eighty in the signal bandwidth of 3.2 MHz. This provides a respectable dynamic range, which meets requirements of a physical experiment in GDT divertor plasmas. First measurement results are also discussed in the paper.

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Developing a high resolution Thomson scattering system

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Having very fine spatial resolution of 63 measurable points along a 25-mm line, the high-resolution Thomson scattering system has been tested with several trial runs. The system uses a frequency doubled (532 nm) Nd:YAG laser with 0.25 J/pulse at 20 Hz. The scattered light is collected and sent to a triple-grating spectrometer (1800 grooves/mm) via optical fibers. The main purpose of using three gratings is to eliminate unwanted stray-light, where the central portion of the spectrum is mostly eliminated by a mask (thin block). Further reduction of stray-light is accomplished by rejection of n=2 components through multiple gratings. The final image is amplified and recorded by an ICCD camera (QE∼50%). Due to relatively low optical transmission, accumulation of many images is necessary to produce interpretive data. Maximum likelihood estimation is used to find best fitting parameters T_e and n_e with experimental data. In addition, a feature of acquiring plasma background light with scattered shots during a single sequence of image collection is incorporate into the controls. The ICCD camera capture images at 40 Hz while the laser is operated at 20 Hz. In such a way, obtained images intervene between background and scattered shots. After a few trial runs, we have located several problems with the system. Upon tackling each problem, the signal-to-noise ratio still turns out to be rather low than expected. This led us to believe, there is a major transmission lose within the spectrometer. Turns out that the intermediate slit opening was not wide enough. Presently, the triple-grating spectrometer is undergoing a full optical re-alignment. After re-calibration of the Thomson scattering system, we anticipate improved data for the next set of plasma shots.

Status of GAMMA 10/PDX-Thomson scattering system

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In the tandem mirror GAMMA 10/PDX, the yttrium-aluminium-garnet (YAG)- Thomson scattering (TS) system have been constructed for electron temperature and density radial profile measurements. GAMMA 10/PDX is an effectively axisymmetrized minimum-B anchored tandem mirror with thermal barrier at both end-mirrors and a divertor simulation module is installed in the west end cell for divertor simulation experiments. Typical electron density, electron and ion temperatures are about 2×10^{18} m^{-3}, 40 eV, and 5 keV, respectively. We can successfully measure the radial profiles of electron temperature and density in the central cell of GAMMA 10/PDX by using the YAG-TS system in a single laser shot. By using the high speed oscilloscopes and their data collection program, we can measure the time dependent electron temperatures and densities every 100 ms in a single plasma shot. Moreover, in order to increase the TS signal intensities, we have constructed a multi-pass TS system of the polarization based system with image relaying optics. The clear multi-pass TS scattering signals from first to eighth passing lasers through the plasma were successfully obtained. The five times larger TS signal intensity were indicated. The multi-pass TS system improves the measurement resolution and time resolution.

Development of motional Stark effect diagnostic with laser-induced fluorescence for measurement of magnetic field in high-beta plasmas

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The method of measurement of magnetic fields in plasmas based on the motional Stark effect (MSE) was first developed in 1989 [1]. Since the first implementation, diagnostics based on this approach became a premier instrument for measurements of magnetic and electric fields in magnetically confined plasmas. In the gas dynamic trap mirror device (GDT) [2], a spectral MSE diagnostics deliver information on spatial distributions of magnetic field and pressure in the plasma with fusion deuteron population. Calculation of transverse pressure deduced from the MSE data, yielded approaching 0.6 in recent experiments [3]. After precise tuning of the diagnostic deuterium beam, the spectral MSE system on GDT is capable of measuring of magnetic fields as low as 0.29 T [4]. Further study of high-beta plasma equilibrium in GDT and the projected experiment for creation of a plasmoid with a reversed magnetic field, require a challenging extension of detectable fields down to few millitesla. This task can be solved combining a laser-induced fluorescence (LIF) approach with analysis of atomic beam light emission. The proof-of-principle for the combined MSE-LIF method was successfully demonstrated [5]. Our paper describes the project of development of the MSE-LIF diagnostic for simultaneous measurements of spatial profiles of the magnetic field magnitude and direction in a plasma. An upgraded ion source produces the 50 keV focused deuterium beam with the 1-ampere atomic current and the ultra-small energy spread. For excitation of upper energy levels for the Balmer-alpha optical transition, the specially designed dye laser is used. Fast scanning of the laser wavelength over spectrum emitted by beam atoms, resolves individual lines enabling the calculation of the magnetic field magnitude. At the same time, a photoelastic modulator sweeps the laser ray polarization to detect the magnetic field direction. The optical registration system does not include a spectrometer or polarimetry instrument, which makes it relatively simple and inexpensive. Each line of sight uses a single large area avalanche photodiode to detect the optical signal.

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End Loss Analyzer System for Measurements of Plasma Flux at the C-2U Divertor Electrode

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The C-2U experiment at Tri Alpha Energy can sustain advanced beam-driven field- reversed configuration (FRC) plasmas for 5+ ms. An end loss analyzer system was developed to study thermal transport on the open field lines that surround the FRC core and connect it to the divertors through magnetic end plugs. The system is mounted directly to the divertor electrode and consists of gridded retarding-potential analyzers that measure ion current and ion energy as well as pyroelectric crystal bolometers that measure the total power flux. This combination enables calculation of the energy lost per escaping electron/ion pair. Special care was taken in the physical and electronic construction of the analyzer elements so that they could be mounted to the divertor electrode. A laser-drilled stainless steel attenuation plate at the entrance to the gridded retarding-potential analyzer reduces neutral gas load and plasma density by a factor of 60 to prevent collisions and space charge limitations inside the device. In addition, all of the electronics for the measurement are isolated from ground so that they can float to the bias potential of the electrode (up to 1kV below ground). Measurements from the analyzer system will be presented.

Stationary diagnostics of magnetized plasmas

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Stationary plasma diagnostics of local parameters and ion mass-spectrum are necessary to control discharge regimes and plasma composition during the experiments. Corpuscular diagnostics of plasma ion flux can provide information about plasma-chemical kinetic of the discharge. Usually optical spectroscopy is used for determination of the plasma composition [1, 2], but often it cannot deliver the reliable information. The residual gas analysis, for example by quadrupole mass-spectrometer, can provide information of the neutral species in vacuum chamber, but not of the ion composition of plasma. In-situ mass-spectrometry systems based on the mass separation and detection of plasma ions are usually complicate, for example the omegatron mass-spectrometer [3] requires an additional RF source of the electrical field and ultra-high-vacuum differential pumping, the plasma ions mass-spectrometer (PIMS) [4] is based on the cycloidal focusing in the perpendicular electrical and strong magnetic field, which is not always used on linear plasma devices. A simpler ion separation method of magnetized plasmas is using own-magnetic field of the plasma device as a separating factor. The idea of stationary mass-spectrometer using own-magnetic field is widely used [5, 6], but usually it is not possible to measure both positive

and negative ions in one experiment. Combined diagnostics module (CDM) for in-situ analysis of both the local parameters and ion mass spectrum of magnetized plasmas developed for the linear plasma device PR-2 is presented.

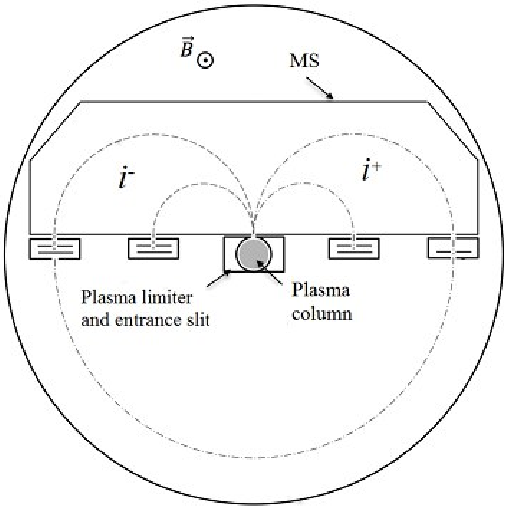

Figure 2: Scheme of CDM on PR-2.

Scheme of CDM is shown on Fig. 1. It consists of the static mass-spectrometer (MS) and the probe system containing twelve single Langmuir probes. MS is based on classical scheme of static magnetic ion separator with 180° magnetic deflection of the accelerated ions. Symmetrical MS allows to measure relative fluxes of both positive and negative ions from plasma column. Ions reaching the entrance slit are accelerated by the electrical field applied in the accelerating gap. Then they are deflected by the magnetic field of plasma device and as a result separated by M/Z ratio. Mass-spectrum of plasma ions is obtained by changing the accelerating voltage, and registered by four ion collectors placed at different radii of ion trajectories. The collector at the lower radius is used for a rough mass-analysis of typical light working gases. The second collector has a better mass resolution and is used for more accurate measurements in a heavier mass range.

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Diagnostic system to study sub-THz emission from open trap at strong beam-plasma interaction

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The motivation of the research activity at the GOL-3T device [1] is to study sub-THz wave generation in a plasma column due to intense relativistic electron beam-plasma interaction [2]. To solve this task, a special complex of diagnostics was developed. This complex is intended to measure main plasma and beam parameters and also the characteristics of the electromagnetic waves.

The plasma density is measured in two cross-sections of the plasma column by two laser diagnostics. One of them is Michelson interferometer [3] based on CO2 laser (10.6 m). The other one is Thomson scattering system [4] based on Nd:YAG-laser. The scattering system gives the density in 9 local areas over the diameter of the plasma column with temporal resolution. The increase in the plasma pressure during the beam passing through the plasma column is measured by diamagnetic probes located in various cross sections along the axis of the device. The electron beam currents in various parts of the device are measured by a set of Rogowski coils. The energy of the injected electrons beam is calculated from the measurements of an accelerator diode voltage. The angular spread of the beam electrons and their energy distribution are measured in some additional experiments.

The EM-radiation at 100 - 500 GHz frequency bandis registered by detectors based on Schottky barrier diodes [5]. The spectral power density of the radiation in this interval is analyzed by an 8-channel polychromator. Additionally, a set of single detectors arranged along the length of the plasma column are used to obtain the axial distribution of the radiation power. The radiation power of frequencies upper than 500 GHz is registered by a calorimeter (Thomas Keating Limited) and a special superconducting detector. The electromagnetic wave emission along the column axis is measured by means of mirrors reflecting the radiation in the direction perpendicular the axis at the end of the trap.

This research was financially supported by RSCF under Project No. #14-12-00610 for the investigation of sub-terahertz emission from plasmas. The upgrade of the radiometric system was funded by RFBR Grant 14-02-31225-a and the Ministry of Education and Science of RF under the State Assignment Contract No. #3002.

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Diagnostic molecular beam on the MCP basis

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The main problem in open magnetic traps is a longitudinal energy transport through a magnetic mirror. Heating target plasma in the central cell Gas Dynamic Trap (GDT) is limited reversed flow of cold electrons from the region expander. The interaction of cold electrons space charge and ambipolar potential can lead to deformation of the electrostatic potential and emerging of "trapped" electrons. In the GDT device, we study the influence of the neutral gas in the expander on the basic parameters of plasma in the central cell. An artificial local target of the neutral gas will be formed on the axis in the expander. A grid energy analyzer for detecting ions accelerated in the ambipolar potential will be set on the target plate. Moving the artificial target along the axis one can measure an ambipolar potential profile. We have created an intense molecular source based on microchannel plates (MCP). It forms a helium beam with divergence angle 0.1 rad., current density on the axis 100 mA/cm^2 and an average particle beam energy 0.03 eV. The poster shows experimental measurements of the current density profile molecular beam. This result was compared with the theoretical model.

Spatial distribution measurement of molecular activated recombination using hydrogen Balmer line intensities of divertor simulation plasma in GAMMA 10/PDX

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Understanding of divertor plasma phenomena is one of the most important issues for the stable plasma sustainment. A divertor plate was exposed to high heat and particle fluxes. To reduce the heat load on the divertor plate, divertor detachment is effective. In GAMMA 10/PDX, a divertor simulation experimental module (D-module) has been installed in the west-end region to study divertor detachment and plasma-wall interaction. The plasma was sustained by ion cyclotron heating, and the V-shaped target which is installed in the D-module was exposed to the end-loss plasma. Moreover, additional hydrogen gas was injected in the D-module. The electron density near the target plate increased with increase in the hydrogen neutral pressure due to the additional hydrogen gas supply and then it decreased. This density roll-over indicates the plasma was detached.

In this study, we have measured spatial distribution of the intensities of Balmer lines in front of the V-shaped target indicating that the plasma detachment was occurred due to molecular activated recombination (MAR). We observed the ratio of Balmer and line intensities to study the spatial distribution of MAR. The strong region of intensity ratio of Balmer and line intensities moved to upstream from the corner of V-shaped target with increase in gas pressure. This means that the region of MAR moved to the upstream. We will discuss the relation between the spatial distribution of MAR and plasma parameters such as electron temperature and hydrogen molecular density.

Evaluation of heat flux from the plasma flow by using calorimeter in the GAMMA 10/PDX end-cell

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In the tandem mirror device GAMMA 10/PDX in University of Tsukuba, divertor simulation experiments were conducted for analyzing physical mechanism of detachment plasma [1-3]. The divertor simulation experimental module (D-module), in which a V-shaped target is mounted, was installed in the west end-cell of GAMMA 10/PDX. In the GAMMA 10/PDX, heat flux measurements have been carried out by using calorimeters. Each calorimeter consists of a substrate which is connected to thermocouple. The heat flux is evaluated from temperature difference (T) between before and after plasma discharge and the plasma duration time [4]. The heat flux was measured at two different locations in GAMMA 10/PDX end-cell. The first one, calorimeters are installed at the lower V-shaped target and its corner. There are 13 calorimeters which installed on the lower V-shaped target. The calorimeters on V-shaped target consist of stainless steel substrate (ϕ10mm, 0.2mm in thickness) which is connected to thermocouple (K type). The second one, other type of calorimeter is installed near the west end mirror. The calorimeter in this point consist of copper substrate. This calorimeter is measured the heat flux in the case that additional heating experiments. Short and high heat-flux is generated by additional heating with electron cyclotron resonance heating (ECRH). The heat flux of additional heating is evaluated from temperature increment during plasma discharge with ECRH and without ECRH. In the heat flux measurements by using calorimeters on lower V-shaped target, reduction of the heat-flux was observed according to throughput of the noble gas. In the additional heating experiments, the dependence of the heat flux on the ECRH power was observed. The heat flux reaches about 15 MW/m^2 in the case with ECRH power 380kW. In this paper, detailed results of heat flux measurements are presented and the improvement of heat flux evaluation will be also discussed.
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Multi-second neutral beam injector (60kV, 6A) for plasma diagnostics in the upgraded T-15 device.

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Diagnostic neutral beam injector on the based arc-discharge plasma generator with cold cathode has been produced and successfully tested at BINP for upgraded T-15 tokamak (Kurchatov Institute, Moscow).
One of the main advantages of cold cathode type of arc plasma source is a high proton fraction 80%-90%. However, the lifetime of the plasma source is limited due to intensive electrodes erosion, especially at the cathode region. An optimized design of the cathode and the nearest electrodes is found which reduces the erosion and allows us to increase the pulse length. Compared with the

prototype designed for TCV machine [1] significantly improved characteristics of the generator. The plasma source produces the extracted ion current up to 7 A at a low angular divergence. Arc plasma generator has been tested with a pulse duration up to 4 second.

The beam is extracted and accelerated by a four-grids ion-optics system. The diameter of plasma emitter at first grid is about 160 mm. Ion-optical systems, vacuum tank and beam duct are similar to those used in the diagnostic injector for Alcator C-mod devise (Boston). [2].

The main parameters of the NBI:

— particle energy up to 60 keV
— beam current (in ions) - 6.1 A
— intensive arc discharge current up to 600 A
— focal length - 4 m
— beam divergence - less than10 mrad
— duty ratio - from 1:1 to 1:10
— active pulse duration - 1 second
— full pulse duration - up to 11 seconds
— working species of ion - hydrogen (deuterium and another species also are possible).

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Measurements of the beam angular divergence at U2 accelerator

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For effective generation of THz-radiation in experiments on beam - plasma interaction the relativistic electron beam with small angular divergence of the electrons and high current density is required. To produce such beams at electron energy ∼1MeV and current of about few tens of kA the creation of reliable diagnostics for measuring the angular divergence of the beam electrons in the guiding magnetic field is very important. To solve this task we have elaborated and constructed a new angular detector based on the regularities of the transmission of magnetized electrons through cylindrical channels in absorbing material. The detector consists of few coaxial collectors with inner holes of different diameter, placed consequently. Simulations of the electron motion, reflection and absorption in the detector performed with code Geant4, showed good angular resolution of the detector ∼0.05 rad and the possibility to obtain the distribution function of the beam electrons on their initial pitch-angle. The results of measuring the angular divergence and angular distribution of the electrons in the magnetic field 0.6 T for the E-beam generated by the accelerator U-2 are discussed in the paper.

Fusion yield registration in the gas dynamic trap

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Gas dynamic trap facility (GDT) is axisymmetric magnetic mirror trap for fusion plasma confinement [1]. There are fusion reactions in GDT during deuterium injection:
D + D -> He3 (0.82 MeV) + n (2.45 MeV)
D + D -> T (1.01 MeV) + p (3.02 MeV)
Thus registration of fusion reaction products is important contactless plasma diagnostics. This diagnostics contains information about fast particle distribution function, influence microinstabilities and collective effects to fast particles in GDT facility. Moreover it is direct simulation of neutron flux distribution for support theoretical and numerical research of GDT based neutron source. As well as proton and neutron registration is used in GDT research [2]. Registration of neutrons in magnetic confinement facilities contains such advantages as: no influence of magnetic and electric fields, you may mount your detector out of vacuum vessel, but it is difficult to collimate thus it is difficult to obtain high spatial resolution. Neutron detectors based on PMT and plastic scintillator are used for timing measurements of DD reaction yield. On the other hand 3.02 MeV protons may be collimate easily, and you can obtain enough spatial resolution of your diagnostics. Detectors based on photodiode are used for 3.02 MeV proton registration. It works in counting mode, it is insensitive to magnetic field and neutron background of GDT experiment condition. Thus additional flux calibration do not require. Fusion proton diagnostics are used for absolute measurements with spatial resolution few cm. Multichannel system of fusion proton registration in the GDT with high spatial (tenth of cm) and timing (~100 mks) resolution is developed by authors of the report. System for radial distribution of 3.02 MeV proton emissions is based on set of photodiode. Sensors are placed near the mirror point. System for longitude distribution is based on set of photodiode placed along the GDT device (detectors work in counting mode). Results will be presented in the report. Gas dynamic trap facility generates 2×10^9 neutrons per 5 ms. The DD product yield was measured 2 $10^9 \text{cm}^{-1}\text{s}^{-1}$ near the mirror point. Neutron flux was $3 \times 10^{11}\ s^{-1}$ (in the same place). There is linear growth of neutron flux during experimental shot according to data of timing distribution of neutron flux detector so there is no steady-state plasma confinement regime in the GDT device.
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Calorimeter for the high power neutral beams with reduced cooling water flow

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The power neutral beam injector has the power density few tens of kW/cm^2 at a normal surface to the beam axis. The problem of the reliable beam absorber and calorimeter is complicate enougth at a such power density. Typically the turbulized water flow at high speed required which encrease both the water discharge and the hydraulic drop. A simple design of the MW power beam target based on narrow coaxial slit channels with spiral turbulizer was developed and successfully used in neutral injection systems the for a steady-state heat removal.

Heavy ion beam probe for measurements of plasma potential profile in GDT device

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Spatial profile of electric potential is one of the principal plasma characteristics. However, potential have never been measured directly in high-temperature regimes of plasma in Gas-Dynamic Trap (GDT) device. Presented report is dedicated to the project of heavy ion beam probe (HIBP) for measurements of electric potential along plasma diameter at the midplane of GDT device. Beam of primary ions Xe^{+1} is produced by 4-electrode accelerating system and has the following parameters: current up to 7 mA, ion energy of 60-70 keV, size of 4 mm and angular spread at the level of 1/e about 4 mrad. Secondary ions Xe^{+2} are produced by primary beam ionization in plasma and enter the small aperture detector based on 30-degrees electrostatic energy analyzer. Each of the 8 detector channels provides electric potential measurement with accuracy of 10-50 V and spatial resolution of 2 cm at sampling rate of about 0.1 MHz.

Plasma-wall interaction

Hydrogen recycling study utilizing end region in the GAMMA 10/PDX tandem mirror

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In GAMMA 10/PDX, studies on the boundary plasma and plasma surface interaction have been done using the end region making best use of the tandem mirror device. The features of GAMMA 10/PDX for the boundary plasma and PSI studies are the following: (1) high ion temperature of the plasma exposed to the D-module (i.e. a few hundreds eV), (2) high magnetic field (0.15 $\sim$ 1.5 T), (3) large plasma size (0.1 $\sim$ 0.3 m), (4) low background pressure in the vacuum vessel and (5) high controllability of the plasma exposure since plasma heating systems of ECH, ICH and NBI are equipped. Noted that ion energy of the plasma is distributed, meaning that condition of PSI is equivalent to that of the torus plasma from a viewpoint of hydrogen recycling.
The divertor simulation experimental module (D-module) has been installed in the west end region. The D-module consists of a rectangular box (0.5 m square and 0.7 m in length) with an inlet aperture at the front panel and a V-shaped target inside the box. Tungsten target plates with the thickness of 0.2 mm are attached on the V-shaped base made of Cu. The target size is 0.3 m in width and 0.35 m in length. The open-angle of the V-shaped base can remotely be changed from 15 degrees to 80 degrees. The sheath electric heaters are attached on the backside of the Cu base to control the target temperature ($T_{\rm target}$) up to 573 K. Besides, additional hydrogen gas can be supplied into the D-module.
The V-shaped tungsten target in the D-module is exposed to the end loss plasma. The effect of additional hydrogen gas supply into the D-module on the recycling is investigated. The density roll-over due to the additional gas supply has clearly been observed, indicating that the plasma near the target is detached. The dependence of the Hα and Hβ line intensities on the neutral pressure suggests that molecular activated recombination (MAR) occurred near the corner of the V-shaped target. When the $T_{\rm target}$ was increased upto 573 K shot by shot in another experiment, it is found that the intensities of balmer lines inside the V-shaped target and the electron density increased with increase in $T_{\rm target}$, indicating that the recycling was enhanced due to increase in the target temperature.

Ion sensitive probe measurement of the GAMMA 10/PDX divertor simulation plasma

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Ion sensitive probe (ISP) is an electrical probe used for measuring ion temperature (Ti) in magnetized plasmas [1]. Simultaneously, electron temperature (Te) and plasma space potential (Vs) are also available. Recently, the ISP was installed in the divertor simulation module (D-module) of the largest tandem mirror plasma device GAMMA 10/PDX in order to evaluate the property of the high temperature end loss plasmas which are equivalent of the edge and divertor plasmas in tokamak and helical devices. These measurements are expected to contribute to realizing the important physics in handling extremely high heat and/or particle load to the plasma facing components of magnetic fusion devices.
The installed ISP consists of two electrodes that an ion collector and electron guard electrode. The ion collector only collects ions at positive potential higher than Vs. This behavior is based on the difference of the gyro radius between the ion and the electron in a magnetic field. A recess distance of the ion collector (h) is one of the important parameters for the probe design. Then the h-parameter was optimized by using the typical experimental conditions of the probe position in the D-module.
So far, we have tested the ISP measurement for several discharge and neutral gas pressure conditions. For example, in the case of hydrogen gas pressure range < 2 Pa, Ti evaluated by using the ion collector of the ISP shows about 6 eV which corresponds to the perpendicular component of Ti in principle. On the other hand, parallel Ti estimated by using ion saturation current on the electron guard electrode of the ISP shows almost ten times higher than the perpendicular one. This result is qualitatively consistent with the existence of strong temperature anisotropy in the open magnetic field, because the ions of the end loss plasma in the GAMMA 10/PDX usually have a few hundred eV as parallel Ti. In this paper, we show the detail of the newly designed ISP for open magnetic field plasma in GAMMA 10/PDX and discuss the validity of the measurement. Furthermore, the influence of high ion temperature on probe current will be discussed.
This work is performed with the support of JSPS KAKENHI Grant Number 25420888 and NIFS Collaborative Research Program (NIFS13KLPP027).
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Recent Results of Characterization of Detached Plasma in Divertor Simulation Experiments Using the GAMMA 10/PDX Tandem Mirror

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The divertor simulation research has been started by making use of high heat-flux plasma flow from the large tandem mirror device GAMMA 10/PDX in Plasma Research Center [1-2]. A crucial advantage of using large tandem mirror is a capability of generating ion flux with high

temperature (100∼ 400 eV) comparable to SOL plasma parameters and its controllability.
In GAMMA 10/PDX, high-power plasma heating systems are installed such as ion cyclotron range of frequency (ICRF) heating, electron cyclotron heating (ECH) and neutral beam injection (NBI). By using above systems, high heat/particle-flux generation and divertor simulation experiments under similar circumstances of actual fusion devices have been performed [3]. So far the heat flux P_{Heat} of ≥ 1 MW/m^2 and the particle flux Γ_{ion} of 3.3× 10^{23} particles/sm^2 were achieved. Recently divertor simulation experiments toward the realization and characterization of detached plasma were extensively started using a divertor simulation experimental module (D-module) in the west end-cell [4-5]. In D-module V-shaped two tungsten plates are mounted together with gas injection and diagnostic systems. On the V-shaped target and behind the gap at the V-shaped corner, array of Langmuir probe and calorimeter are installed for evaluation of radiation cooling and plasma detachment. In order to investigate the behavior of impurities and to capture the 2-D visible image of light emission in front of the V-shaped target, visible spectrometers and high-speed camera are installed. In detached plasma formation experiments from high temperature plasma ($n_e \sim 2 \times 10^{18}$ m^{-3}, $T_{i//}$ ∼150 eV and $T_e \sim 30$ eV), the dependences of gas injection on the reduction of T_e, Γ_{ion} and P_{Heat} near the target plate were investigated using H_2 and noble gases injection into D-module. In cases of noble gases, the above plasma parameters decreased with the increase of the gas throughput. It was found that Xe gas was most effective on electron cooling and reduction of particle and heat fluxes down to less than 10 %. The above results are almost consistent with the observation from an absolutely calibrated visible spectrometer viewing the inside of D-module. Furthermore, in the case with a simultaneous injection of H_2 and Xe, the ion flux was almost fully suppressed, which indicates the existence of Molecular Activated Recombination in D-module.
In this paper, detailed results of characterizing the plasma detachment are described and the physical mechanism of the plasma detachment will be discussed.

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Applications of synchrotron radiation scattering for studies of plasma facing components in Siberian Synchrotron and Terahertz Radiation Centre

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The residual mechanical deformation and stress were measured in the preliminary experiments carried out at synchrotron radiation (SR) scattering stations on VEPP-3 in the Siberian Center of Synchrotron and Terahertz Radiation. The deformation and stress were calculated on the base of the dependence of the scattering angle on the inclination of the tungsten sample. Significant changes in the SR diffraction are found as the result of material recrystallization or irradiation of the material by plasma. It implies that the SR scattering diagnostics may be an informative instrument for in-situ observations of the state of the plasma facing components. The next stage of the SR scattering diagnostics development at the novel scattering station Plasma is the dynamic measurements during pulsed heat loads. Currently a 1J YAG laser is used for the 0.2ms heat load simulation and a 100J laser is under development. The parameters of the heating are sufficient for simulation of the expected pulsed heat load in ITER. The destructive effect of pulsed heat loads is caused by mechanical stresses that occur in highly non-uniformly heated materials. The main aim of the current development of diagnostics based on SR scattering is the dynamic measurements of the mechanical deformation and stress dependences on the depth below the surface. It looks like the rotation of crystallographic planes due to mechanical deformations is the dominant effect in the SR scattering. So the deformation and stress distributions may be calculated using measurements of the diffraction peak parameters of SR passed through the sample. The set of requirements (the pass through material, dynamical measurements of pulsed processes) determines restrictions on SR brightness and energy. The SR from VEPP-4 with energy 69keV will be used for experiments with tungsten. Also a single crystal samples are necessary for increasing of the diffraction peak brightness. Currently the one-dimensional gas X-ray detector DIMEX is used for measurements. The development of the silicon detector for increasing of the sensitivity and to decrease of the instrumental diffraction peak width is in progress. The diffraction peak parameters for SR reflected by germanium single crystal were observed in the first dynamic experiments. The changes of intensity and position of the diffraction peak were measured during the pulsed laser irradiation of material. The result demonstrated possibility of the dynamic experiments. The recent experiments were aimed at measurements of the diffraction peaks passed through the single crystal tungsten sample. The X-ray patterns were observed at phosphor plate for sample thickness of $200\mu m$ and $500\mu m$ with crystallographic orientation [111]. One of the diffraction peaks was measured by one-dimensional X-ray detector with exposure $10\mu s$. The measurements of the diffraction peak dynamic during the pulsed laser irradiation of material and during the cooling stage will be the next step. It will give data on the dynamics of the spatial distributions of the mechanical deformation and stress.

Recent results of plasma-material interaction studies in the linear plasma device PSI-2

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The fuel retention and the lifetime of plasma-facing components are critical plasma-material interaction factors potentially limiting the availability of a magnetic fusion reactor. Linear plasma devices are excellent test beds for investigating specific questions of plasma-material interaction. The materials can be tested under well-defined exposure conditions relevant to both divertor and main chamber boundary plasmas. This contribution summarizes the recent plasma-material interaction studies on the linear plasma device PSI-2 focusing on the topics of fuel retention, erosion and evolution of surface morphology of metallic materials. The aim of these studies is the qualification of plasma-facing materials proposed for future fusion reactors: tungsten and reduced activation ferritic martensitic (RAFM) steels. Depending on individual tasks, material samples were exposed either to pure deuterium or noble gas or mixed species plasma. The fraction of impurities such as helium, argon or nitrogen added to deuterium plasma was controlled by optical emission spectroscopy and in-situ mass analyzer. Exposure parameters were an electron density of $\sim 10^{17}$ - 10^{19} m^{-3}, an electron temperature of 3-20 eV, an ion flux to the target of $\sim 10^{21}$ - 10^{23} $m^{-2}s^{-1}$ and an incident ion energy of 20-300 eV, controlled by the target biasing. The sample temperature can be controlled in a range between 400-1400 K, covering the values for different first wall regions in a reactor. The incident ion fluence can be varied in a range between $\sim 10^{23}$ - 10^{27} m^{-2} by extending the duration of exposure. A Nd:YAG laser (=1064 nm) with a maximal energy per pulse of 32 J and a duration of 1 ms was used to apply repetitive heat loads for the ELM simulation on material samples. Optical emission spectroscopy (OES), target mass-loss technique and recently installed in-situ quartz microbalance (QMB) were employed to quantify the amount of eroded material. The deuterium retention was investigated by thermal desorption spectrometry (TDS) and nuclear reaction analysis (NRA). Scanning electron microscopy (SEM) including focused ion beam (FIB) cross-sectioning and transmission electron microscopy (TEM) was used to observe the evolution of the surface morphology. The results and conclusions from the recent plasma-material interaction studies on PSI-2 will be presented.

Novel electron beam based test facility for observation of dynamics of tungsten errosion under intense elm-like heat loads

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Tungsten erosion is greatly increased under impact of intense transient heat loads corresponding to unmitigated ELM type I events and major disruptions in ITER. The enhanced erosion is associated with melt layer creation, its splashing and ejection of dust particles. In addition to the increase of erosion, tungsten dust particles can penetrate to the plasma core and greatly raise plasma radiation cooling, which harms plasma confinement. Dust accumulation in the ITER vessel leads to increase of tritium retention so the total dust amount stored in the vessel is strictly limited by radiation hazard requirements. Present tokamaks or specially worked out test facilities are still unable to completely reproduce conditions in the ITER divertor associated with transient heat loads. The novel test facility developed at the Budker Institute of Nuclear Physics in Novosibirsk is intended to simulate ELM-like heat loads without too high plasma pressure on the tungsten melt layer typical for QSPA plasma guns. It is especially designed for studies of dynamics of tungsten erosion. The facility is based on electron beam (70-90 keV, 40-80A) with nearly rectangular pulse of 0.1-0.3 ms duration for heating of the tungsten target. Good angular characteristics permit compressing the beam in converging magnetic field and delivering a heat load near 10 GW/m^2 on the target with an area of $\sim$1 cm^2. The ablation plume created by the heat load of tungsten target emits only spectral lines of neutral and single ionized tungsten according to spectral measurements. Relatively weak WI and WII spectral lines in the near infrared (NIR) region above 865 nm permits imaging of the tungsten target in the NIR spectral range during process of it heating and cooling. Fast CCD cameras with minimal exposure time of 7 μs are used for visualization of dynamics of target erosion by recording of 1.4 megapixel frames during a single heating pulse. These cameras are applied for observation of dynamics of tungsten target in the NIR as well as in in the light of 532 nm continuous laser during the heating process and after it. Additionally, tungsten microparticles ejected from the target are analyzed experimentally. Images of these particles are recorded by fast CCD cameras. Besides, we use scattering of light of continuous laser (532 nm, 0.8 W) for the observation of dust particles in the size range of 2-30 microns, emitted from the surface of tungsten under the influence of transient heat load.

Study of tungsten impurity formation and its dynamics at plasma gun facility MK-200 under condition relevant to transient events in ITER

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

radiative cooling [1]. The properties of the eroded materials are critically important to 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 [2]. The targets were exposed to the plasma heat fluxes relevant to ITER ELMs and mitigated disruptions.
The targets were irradiated by hot magnetized hydrogen plasma streams with impact ion energy Ei = 2 - 3 keV, pulse duration t = 0.05 ms and energy density varying in the range q = 0.1 - 1 MJ/m^2. The plasma stream diameter is d = 6 - 8 cm and the magnetic field is B = 0.5 - 2 T. Primary attention has been focused on investigation of impurity formation due to tungsten evaporation and on investigation of impurity transport along the magnetic field lines from the irradiated target. Optical and EUV spectroscopy was applied to determine the chemical composition and ionization state of near-surface plasma. A pinhole camera equipped with absolutely calibrated AXUV photodiodes was used to study the dynamics of tungsten plasma. A foil bolometer was used to measure the absolute radiation loss of tungsten impurity in hydrogen plasma. The following points were studied:

- energy threshold for tungsten evaporation;
- velocity of tungsten impurities;
- effective thickness of the near-surface plasma layer;
- tungsten plasma radiation as a function of distance to the target surface.

The obtained spectral data were compared with the numerical calculations [3].
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Periodical plasma structures controlled by oblique magnetic field

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A series of stationary two-dimensional (both parallel and transverse to the magnetic field) weak double layers with three, four, or more potential steps has been observed in a laboratory experiment in magnetized plasma in Ref. [1].
In this work, we present the results of kinetic and experimental study of the effect of magnetic field configuration on the nonthermal plasma (T_i=0.1 eV, T_e=1-10 eV) at low gas pressure (P=0.1 mTorr) bounded by cylindrical chamber. The periodical plasma structures with peaked plasma density were found both in 2D Particle in cell Monte Carlo collision (PIC MCC) simulations and in the experiment for the condition when the electron Larmor radius is comparable to the Debye length. We calculated the electron and ion densities, charge distributions, electrical potential distribution and etc for different angles between magnetic field and wall. We solved the system of equations which includes Boltzmann equations for electron and ion distribution functions (with elastic and inelastic collisions) and Poisson equation for the electric potential distribution. The calculations were performed with PlasmaNov code developed by Schweigert V. A. and Schweigert I. V. (see, for example [2]) with PIC MCC method.

The intense electrical current was found to flow along the magnetic field lines in narrow periodical channels. The multiple weak double layers (electrical potential steps) were associated with the peaked plasma (charge) distribution. The transverse spatial size scales of the periodical plasma structure depend on the oblique magnetic field magnitude ($B < 200G$), magnetic field angle relative to the axis of symmetry of the chamber and mean electron energy.

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Analysis of H line emission process on detachment formation in the divertor simulator TPD-SheetIV

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In the design of fusion reactors for high power and long pulse operation, vast heat flux will be expected and perfectly detached plasma must be produced and sustained much more reliably. In a linear divertor plasma simulator TPD-SheetIV[1], so-called long leg divertor configuration is constructed by connecting the rectangular duct to the entrance of the V-shaped divertor and studied its effect on the formation of detachment of divertor plasma experimentally. In order to study the neutral behavior in detail and understand the basic mechanism of detached plasma, simulation study with DEGAS 2 Monte Carlo code [2] is conducted[3]. In our experiment, the hydrogen atomic and molecular ion currents (H+, H2+, H3+) are measured by omegatron mass analyzer located behind the target plate in TPD-SheetIV. It was found that by fine adjustment of gas puffing into divertor, the production amount of the molecular ion changes dramatically[4]. With the increasing of contact gas flow, density ratio of molecular ions (H2+, H3+) becomes dominant than that of atomic ion. This experiment result indicates that molecular ions make important rolls in the detachment plasma formation. The Generating mechanisms of molecular ions are complicated, and they are dependent on the plasma conditions. Excited atoms are generated by molecular ions, and H alpha is released from excited atoms. Therefore, H alpha is indicator of the amount of molecular ions. In [5], contribution of H excitation and H2 dissociation for H alpha is compared with Collisional Radiative model (CR model). In this work, the CR model is also applied to TDP-SheetIV detached divertor experiment and studied the atomic and molecular process. In the conference, the calculation result by using the model will be discussed.
This work is partially performed with the support and under the auspices of the NIFS Collaborative Research Program
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Electron temperature and density distributions of detached plasma in divertor simulation experiments in GAMMA 10/PDX

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In GAMMA 10/PDX tandem mirror, divertor simulation experiments have been carried out by using a divertor simulation experimental module (D-module) installed in the west end region. To understand characteristics of plasma detachment in the module, electron temperature and density distributions of the divertor simulation plasma have been measured by Langmuir probes. The D-module consists of a cuboid box made of stainless steel and a V-shaped target. The size of the D-module is 500 mm x 700 mm x 480 mm. The width of the target is 300 mm and its depth is 350 mm. The surface of the V-shaped target is covered with tungsten plates with the thickness of 0.2 mm. In this study, the open angle of the V-shaped target was 45 degrees. Thirteen Langmuir probes are installed on the upper target and two probes are installed near the inlet of the D-module.

The electron temperature near the corner of the target decreased to about 2 eV with increase in the neutral pressure in the D-module by the additional hydrogen gas injection. The electron density first increased from an order of 10^{16} m^{-3} to 10^{17} m^{-3} with increase in the neutral gas pressure and then decreased, indicating that the plasma was detached. The detachment seems to be caused by molecular activated recombination (MAR) from the spectroscopic measurement of the Balmer lines of hydrogen. When the plasma was detached, the electron density in the D-module measured along an axial direction decreased toward the corner of the target plate. And the position of the peak density moved to upstream of the plasma. This result indicates that the recombination region expanded to upstream with increase in the neutral gas pressure. On the other hand, increasing the gas pressure changed the horizontal distribution of the plasma density near the target plate from the peaked profile to the flat one, although the electron temperature distribution was almost flat.

Theoretical modeling of shielding for electron beam and plasma flow

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According to modern concepts in a fusion reactor with magnetic confinement first wall will be exposed to continuous and pulsed plasma flows, neutrons, and so on, leading to damage of the materials. So the continuous heat load to divertor plates in the experimental fusion reactor ITER is supposed to be about 10 MW/m^2 and a pulsed heat loads up to 10 GW/m^2 during few milliseconds [1]. Such pulsed heat loads on a material can be experimentally simulated by electron beams, lasers and plasma fluxes [2,3]. This work is focused on the numerical modeling of the heating and shielding effect in the interaction of the electron beam and the plasma flow with materials. The shielding of electron beam is supposed to be reduced in comparison with the plasma flow due to larger stopping range for electrons. The simulation was performed for the tungsten as a promising material for divertor plates. The parameters close to GOL-3 electron beam (duration 100 μs, surface power 2 GW/m^2, electron energy 55 keV, exposed area 4 cm^2)

were taken for numerical modelling. The same values of the power flux and the duration were used for plasma flow modeling. The heat release was supposed to be surface at the case.
The one-dimensional thermal conductivity equation was solved for calculation of temperature propagation into material. Special conductivity and capacity of tungsten were taken as function of temperature because of its significant dependence, especially near melting point. One-dimensional approximation is acceptable, because depth of heating at least an order of magnitude less than the typical radius of the exposed area. The shielding effect also was assumed to be one-dimensional. The approach is valid if the evaporated material does not move along the material surface to the typical size of exposed area. So the energy flow reached surface depends only on the amount of the vaporized material. Rate of vaporization into vacuum is supposed to depends on surface temperature. For shielding of plasma were used model of energy scattering on nuclei [4]. Shielding of free electrons is based on its stopping range. The discussed model was used to calculate the power fluxes and the durations at which the shielding effect become significant for heating of the material. Roughly it happens if the thickness of the evaporated layer becomes close to heating particle penetration depth. Calculations show that electron beam heats surface more effective than plasma flow with similar initial power flux and duration. At the certain power flux and heating duration, the calculated surface temperature of the tungsten heated by the electron beam was a 2000 K higher than by plasma flow.

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Modeling of crack formation after pulse heat load in ITER-grade tungsten

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Transient events in large plasma devices lead to significant heat loads to plasma-facing components. The experimental simulations of pulsed heat loads on tungsten demonstrate crack formation [1]. The failure is caused by mechanical stresses in a material with non-uniform temperature distribution. In the case of a thin heated surface layer the stress is oriented parallel to the surface and is proportional to the local temperature rise [2]. The heating leads to compressive stress only. The tensile stress causing the crack formation appears during the cooling stage due to plastic deformation [3]. The yield strength and ultimate tensile strength for tungsten manufactured according to ITER specification are both of the same order at any temperature [4]. Therefore the correct theoretical simulation of crack formation requires taking into account both the plastic and the elastic deformation.
The data on tungsten from the ITER Materials Properties Handbook [4] were used for the numerical calculations. First, the temperature dependence of the thermal conductivity and the thermal capacity were used to calculate the one-dimensional temperature distribution. Then the temporal behaviour of mechanical stress and deformation were calculated with respect to the temperature dependence of mechanical properties. The plastic deformation and strain hardening were described by the Hollomons equation [5]. The same parameters were used for both the compressive and the tensile deformations. The simultaneous changes of elastic and plastic deformations allows numerical modeling of smooth growth of stress up to the ultimate tensile stress during the ductile-to-brittle transition. The calculations for stress-relieved tungsten demonstrate the threshold of crack formation near 0.4 GW/m^2 for 1 ms irradiation and the crack formation even at temperatures above 1000°C.

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Study of beam-material interaction by using hydrogen ion beam

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In order to realize nuclear fusion reactors, it is one of the most important issues that the development of plasma facing materials. For example, the materials used in the divertor are exposed to high heat plasma-flow and are significantly damaged. Heat-load characteristics of the materials have been researched in all over the world by using various heat sources such as particle beams and laser light [1,2]. GAMMA 10/PDX is the largest tandem mirror device in the world and is structured by a central-cell, anchor-cells, plug/barrier-cells and end-cells. The divertor simulation experimental module (D-module) is installed in the west end-cell of GAMMA 10/PDX and investigation on plasma-wall interaction have been performed [3]. Recently, in order to study beam-material interaction, an ion beam injector was built up and installed at the west end-cell. Hydrogen ion beam is injected by using a bucket-type ion source in which a cusp magnetic field is applied. Maximum operation parameters of the ion source are 20 kV, 10 A, 3 ms. The ion beam system is placed on the end-cell axis and is injected the west end mirror coil. A magnetic field having 0 to 3 Tesla magnetic field intensity can be applied at the coil. The distance of the ion source and the coil is about 6 m and the mirror ratio is ~1,300. Due to this magnetic field gradient, the ion beam is converged toward the mirror throat.
Our goal is to study beam-material interaction to reveal the physical mechanism of beam facing materials under the circumstances with converging magnetic field configuration. We choose the materials which are going to be used in ITER such as tungsten and molybdenum.
In order to investigate the beam characteristics, calorimeters, high-speed video cameras and tungsten targets are prepared. Calorimeters are mainly used for measuring beam intensity. Spatial distribution of light emission from beam-material interaction can be captured by high-speed video camera. In the present experiment, tungsten is used for target material.
First experiments have been carried out in order to evaluate the beam characteristics. By scanning the calorimeter installed at 0.8 m downstream of the ion source, the beam divergence angle is determined to be about 2.6 degrees. The beam spatial distribution and the light emission of beam-material interaction are converged as increasing the magnetic field strength. In the presentation, we describe the detail of the ion source characteristics, the examination method and results. We will also have discussion about the beam converging effect in magnetic field.

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Comparison of tungsten modification after irradiation at different facilities for PSI studies

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Results from different facilities for PSI studies are compared and their relevance to each other and conditions of ITER transient events are discussed. For PSI studies at the GOL-3 we can use different e-beam sources and can vary energy loads to the targets form 0.3 to 30 MJ/m^2. For PSI studies also used tokamaks, linear plasma machines including QSPA (quasi-stationary plasma accelerators), e-beams and lasers.
At QSPA the vapor shield effect limits the power that is delivered to the surface at the level of 4.5 GW/m^2. This effect is determined by relative low energy of ions, which is about one order of magnitude lower than ion energy expected in ITER ($1 \div 2.5$ keV during ELM). This plasma pressure in QSPA experiments is at least one order of magnitude stronger than that expected in ITER and can result in different mechanism of droplet ejection in simulations.
At energy loads corresponding to ITER transient events (ELMs, disruptions, etc.) only macroscopic erosion mechanisms are important. It is cracking, droplet formation and macroscopic mass losses of the target. Cracking occurs after irradiations during cooling stage or by plastic deformation at the peak temperature. So details of plasma stream parameters are not important, only target temperature play role. Macroscopic mass losses strongly correspond with melting of the thin surface layer and key role for melting play heat loads.
Heat flux plays key role to the targets surface erosion.

Expansion of dense plasma formed on solid target exposed to focused electron beam

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Performance of flash radiography units implies a high spatial resolution. Thus, focused electron beams are utilized to produce bremsstrahlung x-ray at the solid target. It results in the strong heating of the target up to 1-10 eV temperature and formation of dense plasma. The plasma expands into vacuum after the pulse of electron beam. In case of multi-pulse operation mode of radiography unit the plasma produced by the first pulse can strongly affect subsequent pulses. The interaction of electron beam with plasma cloud strongly depends on its electron density. Although the plasma is highly ionized at first moment it cools down adiabatically during expansion. Thus the plasma should recombine rapidly according to Saha equation. However the recombination rate decreases because of plasma expansion and the degree of ionization could be frozen. In present work we utilize the model of Zeldovich and Raizer to estimate the electron density in the target plasma. The typical parameters of radiography units based on linear induction accelerators is considered. It is shown that electron density in plasma expanding after first pulse is high enough to affect subsequent electron beams.

Observation of dust particles ejected from tungsten surface under impact of intense transient heat load

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Erosion is highly increased under impact of intense transient heat loads corresponding to ELM type I events in ITER. The heightened erosion is associated with melt layer creation and ejection of dust particles. High power electron beam (up to 10 MW, up to 0.3 ms) is employed for experimental simulation of the impact of intense transient heat loads at the level expected for ELMs type I in ITER on metal surfaces. The impact produced by the electron beam on metal target is characterized by small direct pressure and low vapor shield effect, which differentiate it from that attained with plasma guns and lasers. Small angle continuous wave laser light scattering and fast imaging of droplets are employed for observation of dynamics of dust particles emitted from the target during and after heating pulse. Imaging of hot particles without laser illumination with 7μs exposition enables measurement of particle velocities after heating pulse. Gradual decrease in particle velocity with the delay from heating termination is clearly observed.

Observation of the tungsten surface damage under ITER-relevant transient heat loads during and after electron beam pulse

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Plasma-facing components undergo severe transient heat loads (up to 10 MJ/m^2) in the reactor-size tokamaks caused by the various plasma instabilities (type I ELMs, VDEs, etc.) and disruptions. Such conditions lead to erosion of the divertor material (cracks, melting, dust formation, droplet ejection, etc.) and can induce mechanical destruction of the tungsten plates and plasma cooling due to the radiation losses. Specialized test facility with a novel long-pulse electron beam injector with the plasma emitter was developed in BINP SB RAS for simulating ITER-relevant ELM-like heat loads. The beam generator applies acceleration voltage up to 100 kV to electrons with a total current 40 - 80 A and a pulse duration 0.1 - 0.3 ms. After compression in the converging magnetic field it delivers heat load up to 10 GW/m^2 on the target with an area of $\sim$1 cm^2. Heating by the electron beam creates a relatively low plasma radiation intensity (comparing with QSPAs), that allows a direct target imaging during the heat load.
A set of in-situ optical target surface diagnostics is used for research of the target surface modification. The high-speed cameras gather target surface thermal radiation in near infrared range. Surface temperature field is recovered by an absolute calibration by a ribbon tungsten lamp. One dimensional thermal radiation distribution during the beam impact is obtained by the fiber optics. Lightening with a continuous wave laser light (Nd:YAG, 2ω) is used for an observation of melted layer dynamics. The target surface was pictured in the scattered cw laser light by camera with a narrowband interference filter.

Research on crack formation and melted layer motion with the heat loads near and above melting threshold was carried out on this facility. Surface of the tungsten target was imaged during and after (more than 5ms) electron beam exposure. Detached parts of the target and crack edges were pictured through their higher thermal radiation in comparison with surrounding surface. In addition, local hot spots (few mm^2) were found after more than 5 ms heating ending. Specific crack net formation was observed after the first pulse and developed with subsequent exposures. Post-mortem analysis of damaged surface included scanning electron microscopy and standard cross-section cutting procedure. Matching of the NIR surface pictures and SEM and cross-section revealed connection of the horizontal crack propagation and the local hot areas, that can be explained with suppressed thermal conductivity. Motion of the melted layer was found through comparison of serial pictures of the target surface under the heat load far above melting threshold.

Study of Plasma Behavior During Impurity Injection in the End-cell of GAMMA10/PDX by Fluid Code

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GAMMA 10/PDX is the world's largest linear device which is 27 m long. In GAMMA 10/PDX, divertor simulation experiments have been started by using a divertor simulation experimental module (D-module) in which a V-shaped target made of tungsten has been installed [1]. In order to understand the effect of impurity injection into the D-module, we injected impurity Ar gas into the D-module and measured the electron density, electron temperature, heat flux and ion flux. It has been found that the plasma parameters in the D-module depend on the gas throughput. Reduction of electron temperature, heat and ion fluxes has been observed according to the increase of impurity injection [1]. These outcomes indicate that detached plasma is generated. A numerical simulation study by using a Multi-fluid code [2-3] has been started in order to understand the energy loss processes and the plasma behaviors under the same conditions of the divertor simulation experiments in the GAMMA 10/PDX. This fluid code consists of five equations based on the same model as B2 code. The B2 code, which is the core of SOLPS4.0 code package, was originally developed by B.J. Braams [4]. The numerical meshes have been created on the basis of the GAMMA 10/PDX magnetic field configuration approximately same manner as B2 code. The convergence of the equations has been checked by analyzing the residual error of each equation. The tungsten target has been designed at the end of the mesh. The effect of neutral hydrogen and Ar impurity injection on the plasma parameters has been investigated numerically. Recycling hydrogen atoms and molecules by the target plate have been also included in this model. In the present study, the neutral model has been improved. Simulation results based on the new neutral model will be presented in this paper. Reduction of electron and ion temperature, heat flux has been observed with the increasing injected neutral Ar and hydrogen density. At lower injected Ar density, it has been observed that electron density increases almost linearly. However, at higher Ar injection, electron density goes to be saturated. The tendency of saturation in electron density is observed at higher injected Ar density region, which indicates that the plasma in the end region approaches to the plasma detachment state. In order to investigate energy loss processes, atomic processes of Ar and hydrogen have been included in this model. It has been found that the charge-exchange (CX) loss between hydrogen neutral and hydrogen ion is the dominant process. More detailed results will be presented at the conference.
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Heating of tungsten target by intense pulse electron beam

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In Budker Institute of Nuclear Physics are studied the dynamics of tungsten erosion by pulsed electron beam with parameters of heat loads close to the ELM-type events in ITER. For these studies used a number of sophisticated optical measurements such as laser scattering, high-speed photography and so on, but one must also to clearly understand which part of the energy of the beam is absorbed in the target for each shot of the electron gun. Surprisingly, the issue of absorption of electron beam with such intense power density of 10 GW/m^2 and energy of 50-100 keV is not enough studied, in contrast to the "classical" measurement of absorption of electron beams in the matter, to determine their albedo and stopping power. It is connected both to the complexity of the formation of beams with such "exotic" parameters as well as difficult to take into account variety of processes on the target like: phase transitions of tungsten in the heating area, electrons interaction with plasma plume form target, the formation of droplets, etc. This report presents an experimental and numerical study of the absorption of the electron beam with a heat power of 10 GW/m^2 on the tungsten target with linear dimensions of 30 mm for 70 mm and a thickness of 3 mm. Beam parameters were obtained by various diagnostics such as: the voltage in the diode, currents in the accelerator gap, on the Faraday cylinder and on the target. Also, X-ray power from the target was measured by a sensor based on BGO scintillator and photomultiplier. Calorimetric measurements of the tungsten sample were made by temperature sensor LM35, and temporal dynamics of surface temperature was fixed by infrared detector. Experimentally obtained heating of tungsten samples, were compared with a three dimensional calculations. Initial conditions of last one were taken from one-dimensional model taking into account all phase transitions in the area of beam absorption.

Applications of mirror plasmas

Formation of UV-radiating strongly non-equilibrium plasma with multiply charged ions in the expanding high-pressure gas jet

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In the present paper we target the physics of transition from subsonic to supersonic regimes in the expanding plasma flow. Originated form ECR ion sources, this problem is generalized to describe of the stationary highly-localized plasma discharge formed under resonant microwave heating in a gas jet freely expanding after a high-pressure nozzle. The peculiar feature of such a discharge is formation of a strongly non-equilibrium plasma flow with multiply charged ions and the electron temperature being much greater than the temperature of ions. We study possibilities for conjugating the slow movement of initially neutral dense gas and the supersonic flow of accelerated plasma, or, equivalently, a smooth transition from ion-acoustic barrier in the expanding flow with a varying charge state distribution. In such regimes, being of particular interest for applications, an average ion charge is consistently increased along the plasma flow, simultaneously the fraction of power losses due to line emission of highly charged ions is growing, and the emission spectrum is shifted to the shorter UV wave range. The proposed model is used to understand and optimize the recent experiments performed at IAP, Nizhny Novgorod, and aimed at demonstration of a new possibility of development of a point source of extreme ultraviolet radiation for the projective lithography. In these experiments, a line emission of multiply charged ions of noble gases has been investigated in the non-equilibrium discharge supported by high-power sub-millimeter waves in the expanding gas flow. The work is supported by the Russian Science Foundation (project No 14-12-00609).

Mechanisms of enhanced electromagnetic emission in laboratory beam-plasma systems

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It has been found that the laboratory experiments on the injection of a high-current electron beam into a magnetized plasma at the GOL-3 mirror trap is always accompanied by generation of sub-terahertz radiation lying near the plasma frequency and its second harmonic. It has been also observed that this radiation becomes more efficient if the plasma radius is decreased down to the radiation wavelength and if the guiding magnetic field is corrugated along the plasma column. In our view, the observed enhancement in radiation efficiency may be explained, in the first case, by the antenna mechanism [1] in which the vacuum EM waves can be directly generated by a thin plasma and, in the second case, by the linear mode conversion of the beam-driven plasma waves on the density gradients which are usually produced in the corrugated regime.

In this work, using both analytical theory and PIC simulations, we investigate what part of the total beam power injected with the beam into a thin plasma can be converted into the power of electromagnetic emission. It is shown that, if a thin plasma has a longitudinal density modulation with the period comparable to the wavelength of the dominant beam-driven mode,

it radiates EM waves near the plasma frequency like a plasma antenna and the efficiency of this radiation reaches 5-10%. Simulations of the steady-state beam injection into the initially uniform plasma demonstrate that such a quasi-1D density modulation can appear self-consistently due to the development of the modulational instability driven by the large-amplitude beam mode. In this case, the antenna mechanism provides the radiation efficiency of 1%, which has been also observed in the laboratory experiments with 100 keV electron beam [2].
Another way to enhance electromagnetic emission in the laboratory experiments with high-current electron beams is to create the specially oriented large-scale density gradients allowing for the complete linear conversion of the most unstable beam-driven waves into electromagnetic O modes. We find the fastest growing modes in the beam-plasma system for typical beam and plasma parameters in our experiments and calculate the corresponding range of possible orientations of the density gradient in a plane plasma slab.
Since the total power of electron beams reaches tens of gigawatts, the proposed mechanisms can be important for designing a terahertz radiation source with the gigawatt power level.
This work is supported by RFBR (grant 15-32-20432) and the Russian Scientific Foundation (grant 14-12-00610).

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Studies of plasma production in a linear device with plane LaB_6 cathode and hollow anode

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A plane circular LaB_6 cathode and a hollow anode are used for the arc discharge plasma production in a newly developed linear plasma device with the axially symmetric magnetic field. The cathode is heated by radiation from a graphite foil flat spiral. A separately powered magnetic coil located around the plasma source is used to vary the radial distance between the outermost magnetic field line from the cathode and the inner anode surface. The discharge geometry defines distinct operational modes: partially direct discharge and magnetic insulation. The magnetic field in the source can be varied from 0 to 2.2 kG while preserving the chosen field geometry, with the discharge voltage and current depending on the particular mode. A hydrogen plasma stream with an almost uniform density of up to $2{\cdot}10^{13}$ cm^{-3} for a diameter of about 5 cm is produced. The measured dependence of the discharge characteristics on the magnetic field is discussed.

Beam-Plasma System as a Source of Powerful Submillimeter and Terahertz Radiation (Experimental and Theoretical studies)

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Beam-plasma systems widely exist in the outer space. Electromagnetic radiation from such sources has been measured and interpreted by astrophysics researchers since the middle of the last century. Verification of astrophysical models of different mechanisms of space plasma electromagnetic radiation requires supporting laboratory experiments. Since 2010 we carry out such experiments and theoretical research by the collaboration of BINP and NSU [1]. Experiments described in the paper [1] were realized on the GOL-3 facility that was constructed and applied to study the beam-plasma interaction for achieving fusion plasma parameters. To carry out the experiments on investigation of the transformation processes of the plasma waves-electromagnetic radiation, we reconstructed the GOL-3 facility. At the first step of the reconstruction, the GOL-3T device was created and then this device was additionally modified for research on the application of the beam-plasma system as a source of terahertz radiation. This modified device GOL-PET [2] is currently used for the beam-plasma experiments.

The presented paper will describe results of GOL-PET experiments on the emission from the beam-plasma system in the frequency interval 0.1-0.7 THz. We will present results of the measurements of the spectral composition and direction of the emission from a magnetized plasma column during passing of a high current relativistic electron beam (~0.6 MeV, ~10 kA, 8 s). The experimental results will be composed with theoretical study of the radiation generation by this system. Prospects of the application of such system as a powerful source will be discussed as well.

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Development of high-power gas discharge and electronic vacuum devices for pulsed electrophysic. Current status and prospects

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In the paper the most recent results of research and development efforts made by Pulsed Technologies ltd are presented. Design and essential characteristics of more than 36 types of high-power high-voltage switches TDI- and TPI-thyratrons (pseudospark switches) [1], TGI- thyratrons at 250 MW pulse and 0.5 MW average power, spark gaps, as well as X-ray tubes of the new generation are described. High power pulse thyratrons contribute the major part of production volume of our company. Thyratrons used to be the most important switches for Pulsed Power applications, as indicator of which serves the fact that from volume 1 (1950) to volume 10 the titles of IEEE International Power Modulator Conferences involved a phrase Hydrogen Thyratron". Currently, solid state switches keep replacing plasma switches in the most of pulsed power applications. However, there are some important niches in which thyratrons and pseudospark switches are still out of competition. The report contains a list of publications and examples of emerging applications of these switches in the innovative equipment of leading world institutions, including high-power Pulsed Electrophysics, colliders [2] and accelerators of various types [3], in medical equipment, industry and etc..

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Studies of the helicon plasma source with inhomogeneous magnetic field

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Helicon plasma source was developed as a prototype for application in linear plasma devises for plasma material interaction. Using Nagoya-type-III antenna hydrogen plasma is produced at 13.56 MHz frequency and with rf power up to 5 kW inside a quartz discharge chamber of 108 mm outer diameter and 400 mm axial length. Five coils installed outside the discharge chamber produce the magnetic field with two maxima at the ends of the chamber. Efficiency of plasma production and density distribution are very sensitive to geometry and magnetic field strength. In this paper, radial distribution of the plasma density and electron temperature as a function of the rf power, magnetic field geometry and strength, and gas pressure are presented and discussed.

Design Optimization of a Helical Plasma Thruster

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Design of the Helical Plasma Thruster [1] is based on axial acceleration of rotating magnetized plasmas in magnetic field with helical corrugation, similar to principles incorporated into SMOLA open trap [2]. The idea is that the propellant ionization zone can be placed into the local magnetic well, so that initial ions are trapped. The $E \times B$ plasma rotation is provided by an applied radial

electric field. Then, from the rotating plasma viewpoint,the magnetic wells of the helically corrugated field look like axially moving mirror traps. Specific shaping of the corrugation can allow continuous acceleration of trapped plasma ions along the magnetic field by diamagnetic forces. The accelerated propellant is expelled through the expanding field of magnetic nozzle. By features of the acceleration principle the Helical Plasma Thruster may operate at high energy densities but requires a rather high axial magnetic field, which places it in the same class as the VASIMR rocket engine. It also allows in-flight variability of specific impulse, power and thrust. This presentation will discuss possible restrictions of the thruster geometry and design and routes to design optimization for specific propellants and operational requirements.
This work has been supported by Russian Science Foundation (project N 14-50-00080)
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Theory of electromagnetic wave generation via a beam-plasma antenna

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The problem of electromagnetic radiation from plasma near the plasma frequency and its second harmonic has been actively studied for decades. At this moment, there are many different approaches to this problem. However, most of them assume that the plasma size significantly exceeds the wavelength of generated radiation. Our interest to this problem is motivated by the experiments on the electron beam interaction with a thin magnetized plasma at the GOL-3 mirror trap. It has been found that the radiation efficiency in these experiments can reach 1% [1].
In this work, we formulate the theory of electromagnetic emission near the plasma frequency for the case of the finite-size beam-plasma system typical to laboratory experiments. If the density of a thin plasma column is modulated along the magnetic field, such a system can radiate like an ordinary antenna. It has been recently shown that, in the simplified case of a plane plasma slab in which the period of density modulation equals to the wavelength of the most unstable beam-driven mode, theoretical predictions are confirmed by particle-in-cell simulations [2-3]. To describe the turbulent regime with the wide spectrum of density perturbations, we generalize our theoretical approach to the arbitrary lengths of longitudinal density modulation and calculate the power of electromagnetic radiation in the more realistic cylindrical geometry. It is shown that the most efficient radiation can be generated for those modulation lengths at which the plasma becomes transparent for the radiated electromagnetic waves.
This work is supported by RFBR (grant 15-32-20432) and the Russian Scientific Foundation (grant 14-12-00610).

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Properties of sub-THz Waves Generated by the Plasma during Interaction with Relativistic Electron Beam

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In the paper, last experiments results on sub-THz wave emission from the area of relativistic electron beam-plasma interaction in the GOL-PET device are described 1. A plasma column with the diameter of 6 cm, length of 2.5 m and its density $(0.2-2)\times 10^{15}$ cm^{-3} is confined by multiple-mirror magnetic field with mean value of 4 T. The electron beam (REB) injected into the column, has the following parameters: energy $E_b \sim 0.8MeV$, current $I_b \sim 30kA$, current density $J_b \sim 2kA/cm^2$ in the mean magnetic field. Previous studies [2] have shown that the beam is pumping the plasma electron oscillations in a vicinity of the upper hybrid wave branch. These plasma oscillations can be converted in electromagnetic waves on regular or artificial plasma density gradients (the plasma radiation with the upper hybrid frequency). The electromagnetic waves with the double upper hybrid frequency are also generated in the beam-plasma system due to coalescence of the plasma oscillations in case of high level of the oscillation energy density. The described experiments are devoted to measure the spectral properties of the generated radiation and the directions of the sub-THz plasma emission in depending on plasma and beam parameters. As results of these experiments, the wave emission with the specific power concentrated in the direction along the axis of the plasma column, in the frequency interval 0.25-0.5 THz has been obtained at the plasma density about of 10^{15} cm^{-3}. This research was financially supported by RSCF under Project No. #14-12-00610 for the investigation of sub-terahertz emission from plasmas. The upgrade of the radiometric system was funded by the Ministry of Education and Science of RF under the State Assignment Contract No. #3002.

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H+ and D+ high current ion beams formation from ECR discharge sustained by 75 GHz gyrotron radiation

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Operation of modern high power accelerators often requires production of intense beams of hydrogen ions. H+ and D+ beams are utilized or envisioned for use in linear accelerators. Requirements for the brightness of such beams grow together with the demand of accelerator development and arising experimental needs. New facilities aiming at outperforming the previous generation accelerators are usually designed for higher beam currents. Enhancing the hydrogen beam intensity and maintaining low transverse emittance at the same time is, however, becoming increasingly difficult. The most modern accelerators require hydrogen ion beams with currents up to hundreds of mA (pulsed or CW), and normalized emittance less than 0.2-0-3 $\pi \cdot mm \cdot mrad$ to keep the beam losses at high energy sections of the linac below commonly imposed 1 W/m limit. The latest results of high current H+ and D+ beams formation from plasma of ECR discharge sustained by 75 GHz / 200 kW gyrotron radiation in open magnetic trap of simple mirror configuration at the Institute of Applied Physics (IAP RAS) are presented. High microwave power and frequency allow sustaining higher density hydrogen plasma (ne up to $7 \cdot 10^{13}$ cm^{-3}) in comparison to conventional ECRISs or microwave sources. The low ion temperature, on the order of a few eV, is beneficial to produce light ion beams with low emittance. Results on ion beam extraction and emittance measurements are presented. Work was performed in frame of realization of federal targeted program R&D in Priority Fields of the S&T Complex of Russia (2014-2020) contract #14.604.21.0065 (unique identification number RFMEFI60414X0065).

Excitation of electromagnetic waves in dense plasma during the injection of supersonic plasma flows into magnetic arch

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In this work a new experimental approach is suggested to study interaction of supersonic (ion Mach number up to 2.7) dense (up to 10^{15} cm^{-3}) plasma flows with inhomogeneous magnetic field (an arched magnetic trap with a field strength up to 3.3 T) which opens wide opportunities to model space plasma processes in laboratory conditions. Fully ionized plasma flows with density from 10^{13} cm^{-3} to 10^{15} cm^{-3} are created by plasma generator on the basis of pulsed vacuum arc discharge. Then plasma is injected in an arched open magnetic trap along or across magnetic field lines. The filling of the arched magnetic trap with dense plasma and further magnetic field lines break by dense plasma flow were experimentally demonstrated.
The process of plasma deceleration during the injection of plasma flow across the magnetic field lines was experimentally demonstrated. Pulsed plasma microwave emission at the electron cyclotron frequency range was observed. It was shown that frequency spectrum of plasma emission is determined by position of deceleration region in the magnetic field of the magnetic arc, and is affected by plasma density. Frequency spectrum shifts to higher frequencies with increasing of arc current (plasma density) because the deceleration region of plasma flow moves into higher magnetic field. The observed emission can be related to the cyclotron mechanism of generation by non-equilibrium energetic electrons in dense plasma.

Particle-in-cell simulations of 100 keV electron beam interaction with a thin magnetized plasma

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Beam-plasma interaction plays an important role in different physical systems relevant to gamma-ray bursts, generation of high-energy cosmic rays, type III solar radio bursts as well as in laboratory beam-plasma experiments. It has been observed that the beam-plasma interaction at the GOL-3 mirror trap results in the intensive sub-THz radiation near ω_p and $2\omega_p$. The most efficient regime of electromagnetic emission has been found for the experiments with the reduced plasma diameter and the long-pulse 100 keV electron beam. The radiation power has been estimated as 1% of the total beam power in this case [1].
Recent simulations with relativistic electron beams have shown that a similar level of efficiency can be achieved in a thin plasma with the diameter comparable to the radiation wavelength. It has been explained by the mechanism of the beam-driven plasma antenna [2].
The feature of the GOL-3 facility is the long-time injection of an electron beam. To simulate such a situation, one cannot use simplified numerical models with periodic boundary conditions. To study the realistic problem of beam injection, we have developed the unique 2D3V particle-in-cell (PIC) code allowing for the continuous beam inflow through the plasma boundary and the detection of radiation escaping from the finite-size plasma. This code has been recently used to verify the theory of beam-plasma antenna [3].
Modeling the real spatial and temporal scales of laboratory experiments requires enormous computational resources. We solve this problem by using several graphics processing units (GPU). According to this approach, for the first time, we are succeeded in simulation of 100 keV electron beam injection into the real-size plasma column in the GOL-3 facility. In such a formulation not only qualitative, but also quantitative comparison with the real experiment is possible.
This work is supported by RFBR (grant 15-32-20432) and the Russian Scientific Foundation (grant 14-12-00610).

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Plasma Source Based on Helicon Discharge for a Plasma Accelerator

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Since the introduction of the term "helicon" scientific community's interest in this phenomenon grew. Currently, several international groups conducted a number of large-scale experiments in this field of plasma physics [1-9]. These studies have shown that the installations based on helicon discharge are very attractive as a source of high density plasma due to the large resource exploitation. The use of helicon sources in the technologies deposition will significantly reduce the cost of equipment maintenance, in the absence of its erosion. However, it is necessary to determine the qualitative component of the considered technology of ions deposited substances. This paper presents the results of a study of the empirical dependence of plasma parameters (degree of ionization, plasma density, temperature) from the input parameters (power, frequency, current, magnetic induction) using a number of azimuthally asymmetric antennas for the helicon plasma source used ionization of Tungsten (W), Molybdenum (Mo) and Titanium (Ti). Different antenna configurations for helicon source are considered and compared. Use of a helicon discharge as the plasma source for a plasma-based space thruster is discussed.
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Design of permanent magnet trap for high current gasdynamic ECR ion sources with plasma heating by gyrotron radiation with frequency up to 45 GHz

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During recent research in the IAP RAS a new type of ECR ion sources with plasma heating by powerful gyrotron millimeter wave radiation was developed. Due to the high frequency and power of heating microwaves plasma with unique parameters (density of about 10^{13} cm^{-3}, the electron temperature of 100 eV and a temperature of the order of 1 eV ions) could be created in a magnetic trap of the ion source. Under such conditions a so-called quasi-gasdynamic plasma confinement regime, characterized by a short lifetime (about 10 microseconds), is realized in the source trap. Such short lifetime in combination with high plasma density allows to create ion beams of light or heavy multiply charged ions with current density up to 800 mA/cm^2. The possibility of such hydrogen and deuterium ion beams formation has been demonstrated at pulsed experimental facility SMIS 37 in case of plasma heating with gyrotron microwave radiation at frequency of 37.5 GHz and a power of 100 kW and using of a simple mirror magnetic trap created by a pair of pulsed solenoids. Further research on the development of high current ECR ion sources demands higher pulse repetition rate or transition to a CW regime of the ion beam generation. In this case, the use of pulsed magnetic systems becomes impossible. In this paper we propose a design of a magnetic trap with mirror field configuration produced with permanent magnets for plasma confinement in the ion source of the type described. The magnetic field of the trap at its mirrors is 1.5 T, i.e. it allows to realize ECR plasma heating by radiation with frequencies up to 45 GHz. The use of a permanent magnet trap has a number of significant advantages over a "warm" or superconducting coils: it allows to operate both in pulsed and continuous mode; it eliminates the need for high-voltage insulation of solenoids from the discharge chamber placed under high potential; it does not require constant cooling; it doesnt require power supply and consequently it has a compact size and provides higher reliability of the entire device. Another extremely important advantage of the permanent magnet trap is configuration of magnetic field lines more resistant to the MHD perturbations compared to a simple mirror trap.

Diode for high-brightness REB generation intended for beam-plasma experiments

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Sub-terahertz emission from a plasma column at exciting strong Langmuir oscillation by a high current relativistic electron beam (REB) was experimentally studied at the GOL-3 facility (BINP)1. The typical parameters of the beam used in the experiments, were the following: $0.5 \div 0.7$ MeV/20 kA/10 mcs. In recent experiments the beam current density was about $1 \div 2$ kA/cm^2 in a plasma column with the density $\sim 2 \div 4 \cdot 10^{14}$ cm^{-3} that allowed us to get sub THz-emission in the frequency range 100œ400 GHz.
To extend our experiments to the range of 1 THz we have to inject the beam into the plasma column of higher density $1 \div 2 \cdot 10^{15}$ cm^{-3}. For achieving the effective excitation of the plasma waves at this density, the substantial increase of the beam brightness is required. To solve this problem we have performed 2-D self-consistent simulations of the beam formation at various geometries of a magnetically insulated ribbon diode by the usage of numerical code POISSON-2.

In addition, in the computer simulations we also considered the transformation of the generated ribbon beam to a circular one and its compression to the radius ~2 cm in the magnetic field ~4 T in which the plasma column is placed. The quality of 2-D self-consistent simulations was tested by the data comparison with the results of measurements of the beam current density and the angular spread of the beam electrons at the previous experiments. Good agreement of the theoretical data with the experimental results allowed us to use the computer simulations for designing a novel diode configuration for the high brightness beam generation. The new diode configuration is described and discussed in the paper.

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A plasma target for neutralization of the negative ion beam

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The results of the experimental study of build-up and confinement of low-temperature plasma target for neutralization of high energy negative ion beam are presented in the paper.
The plasma target cylindrical vacuum chamber is 1.2 m long and 0.2 m in diameter. The axisymmetric multicusp magnetic field is formed at the periphery of the target chamber by using an array of the permanent NdFeB magnets which are placed closely on the thin chamber walls. The magnetic field at the surface of the chamber reaches 7 kGs. The target chamber are ended by the two diaphragms with the two 0.1m diameter apertures for the negative ion beam passing through. For reduction of the plasma losses through the ends, the inverse magnetic field are formed in the apertures 1.
The plasma is produced in the target by ionization of the working gas by electrons, which emitted by six plane LaB6 cathode, which are placed uniformly over azimuth at the center of the plasma target near the wall.
The discharge duration is set to 1 s. In short pulses at 300 kW power, the hydrogen plasma with density n_i $2.5\cdot10^{13}$ cm^{-3} is produced. Spatial profiles of the plasma parameters in the target were measured.

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Mirror-based 14 MeV neutron sources

Mirror based fusion neutron source: current status and prospective

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Budker Institute of Nuclear Physics in worldwide collaboration develops a project of a 14 MeV neutron source for fusion material studies and other applications [1,2]. The projected neutron source of plasma type is based on the gas dynamic trap (GDT), which is a special magnetic mirror system for plasma confinement [3]. Essential progress in plasma parameters was performed in recent experiments at the GDT facility in the Budker Institute, which is a hydrogen (deuterium) prototype of the source. Stable confinement of hot-ion plasmas with the relative pressure exceeding 0.5 was demonstrated. In these experiments, the density of fast deuterons with the mean energy of 10 keV, accumulated due to injection of powerful atomic beams, reached 5.0E19 per cubic metre. The electron temperature was increased up to 1 keV in the regime with additional electron cyclotron resonance heating (ECRH) of a moderate power [4]. These achievements shift the projects of a GDT-based neutron source on a higher level of competitive ability and make possible today to construct a source with reasonable parameters, suitable for materials testing. The report presents a recent progress in experimental studies and status of numerical simulations of the mirror based fusion neutron source and its possible applications including a fusion material test facility and a fusion-fission hybrid system.
Current research activity in the Budker Intitute is supported by the Russian Scientific Foundation Grant 14-50-00080.

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Improvement of Fusion Energy Gain of GDT Based Fusion Neutron Source by Change of Neutral Beam Injection Position

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Gas Dynamic Trap (GDT) is very attractive as a kind of fusion neutron source for material test and driving transmutation reactor due to its linear and compact structure, easiness of construction and maintenance, relatively low cost and tritium consumption. These years, two type of conceptual designs of GDT-based neuron source, named FDS-GDT, have been designed by extrapolating from GDT experiment results as next generation of fusion neutron source by Institute of Nuclear Energy Safety Technology (CAS)·FDS Team in China, which focus on fusion safety and fusion nuclear science and technology research. The lower fusion power design of FDS-GDT is for fusion material irradiation test with a few megawatts of fusion power produced by using tens neutral beam injection and 25T mirror magnetic field. About $2MW/m^2$ of maximum neutron wall loading can be achieved in testing zone. The higher fusion power design of FDS-GDT is design to produce about tens megawatts of fusion power, by using more than 100MW neutral beam injection and 30T mirror magnetic field, which will be used as a hybrid reactor driver for nuclear waste transmutation.
In order to improve fusion energy gain and reduce magnet requirement for the GDT, a method that the neutral beam is obliquely injected at higher magnetic field position rather than midplane of GDT was proposed so that turning point of fast ions could concentrate in the zone with higher magnetic field and be more close to the mirror throat. This method could reduce the mirror field and utilize the mirror environment more effectively without reduce the mirror ratio, and finally, provide more possibility to improve the fusion energy gain of GDT. With this method, one conceptual design of GDT based neutron source was proposed based on the latest experiment results with 0.6 of pressure ratio, and 10T of mirror magnetic field that is more practical under current magnet technology. The mirror ratio is 200 so that the end loss of plasma could be reduce greatly and the electron temperature could be higher than 1keV. The length of mirror to mirror is 20m, power of NBI is 10 MW and 6 MW is absorbed. Injection angle is 30° and magnetic field of injection position is 1.25 T, so that the fast ions could concentrated in the zone of turning point with 5T of magnetic field. With 0.6 of maximum plasma beta, this could produce 1.27×10^{21} m^{-3} of fast ions density and 3MW of fusion power. In this situation, the confinement time of fast ions is 4.9ms, calculated by considering scattering loss due to collision among fast ions, which is different from the previous design philosophy ignoring the scattering loss of fast ions. Because new characteristic of fast and plasma transport were also emerged, more detailed analysis for the confinement of fast ions and transverse loss was given.

Neutron yield from high-pressure NBI-sustained deuterium plasma

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The possibility on neutron generation is considered for the D-D plasma. The advantage of D-D reaction is that no needs for external tritium source. 14 MeV neutrons can be produced due to burn of tritium produced in D-D reaction. Powerful neutral beam injection can be used to increase the reaction rate. Plasma power gain Q $\sim$ 1 can be achieved at electron temperature of about 100 keV and deuteron injection energy of about 2 MeV. To realize such a scheme plasma pressure should be approximately equal to the magnetic pressure for this type of fusion fuel. So, it can be potentially realized in the mirror-based system.

Work was supported by the Ministry of Education and Science of the Russian Federation, the contract No.13.2573.2014/K.

Assessment of neutron production in neutral beam injector of TCV tokamak

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Neutral beam (NB) injector for the TCV tokamak has been designed to produce a deuterium beam with energy 30 keV, equivalent current up to 50 A, and pulse duration 2 s. The injector operation is accompanied by generation of fast neutrons produced in deuterium-deuterium collisions via a nuclear fusion reaction D(D,n)3He. Main sources of the neutrons are a a beam neutralizer and a deuterium-saturated surface of beam dump. Measurements of the neutron yields from the both sources were produced on the prototype of TCV injector in the Budker Institute of Nuclear Physics. Neutron yields from neutralizer and beam dump are equal to 9.5x10^8 s^{-1} and 2.3x10^9 s^{-1} for the nominal parameters of the injector (30 kV, 50 A). The results of the measurements are compared with a model of deuterium accumulation in the beam dump.

Optimization of GDT- and GDMT-based neutron sources with Hooke-Jeeves and differential evolution algorithms

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Suggested report is dedicated to the assessment of capabilities of fusion neutron sources (FNSs) predominantly designed for using within subcritical hybrids for nuclear technology applications and based either on gas-dynamic trap (GDT) [1] or on the concept of gas-dynamic multiple-mirror trap (GDMT) [2]. The former of the mentioned mirror machines is an experimental facility under operation in Budker Institute of Nuclear Physics, while the latter is a project developed in the same organization and expected to provide a better axial confinement time in comparison with GDT due to the effect of ion collective scattering in tailing mirror sections with small mirror ratio (the effect was previously observed in experiments on GOL-3 device [3, 4]).
In mathematical terms the problem of the study has been formulated as searching the global maximum of fusion performance (Q_{eng}), the latter considered as a function of engineering parameters of the mirror machine. To carry out the optimization the differential evolution method [5] and a simplified modification of the Hooke-Jeeves algorithm [6] were used. It is important to mention, that the numerical investigation has also taken into account a number of constraints on plasma characteristics so as to provide physical credibility of the considered mirror configurations. The DOL code previously described in [7] was applied to calculate neutron source characteristics at each step of the optimization process.
Concerning GDT-based FNSs, quite numerous investigations of similar kind have been published in recent years. Nevertheless, optimization attempts were not based on any systematic approach (the only exception is the work [8] dedicated to numerical investigation of a GDT-based FNS for material testing). On the opposite, current research is focused on regular optimization of mirror trap parameters, while the numerical model used is adequate to the contemporary understanding

of GDT physics. As for the GDMT concept, though a confinement approach being less reliable in terms of experimental validation is considered, estimating the capabilities of GDMT-based FNSs is instructive from the viewpoint of the assessment of the concept prospects.

This work has been supported by Russian Science Foundation (project no. 14-50-00080).

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Subcritical assembly with fusion neutron source as a device for studies of neutron-physical characteristics of thorium fuel

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Thorium-uranium power industry has a number of advantages over uranium-plutonium one and a high-temperature gas-cooled reactor with thorium fuel is very attractive for application in Russian Federation. Fuel assemblies filled by pellets with microencapsulated thorium-uranium kernels should be used in such reactors. In open fuel cycle the operation time of such reactor will be up to 10 years. Since the novel fuel assemblies with the microencapsulated kernels were not studied in neutron-physical experiments for regimes of this reactor it is necessary to have a device that allows carrying out such experimental studies. These experimental studies should be devoted to several topics. The multiplying properties of nuclear fuel compositions based on thorium and the spatial distribution of neutron fluxes in the fuel assemblies and fuel blocks are among of them. Studies on this device will give scientific information for supplement of the evaluated nuclear database. The overall structure of the mentioned above device is described in the paper. The device would operate with a thorium subcritical assembly driven a fast neutron source. A long magnetic trap with injection of high energy neutral beams into a plasma column will serve as a source of 14-MeV thermonuclear neutrons [1]. The source of fast neutrons is placed in to the graphite subcritical assembly as the central column. The subcritical assembly design consists of Fuel Block of the Unified Design [2]. Calculation model of subcritical assembly was created using MCU-5 program [3]. Geometrical module of MCU-5 allows simulating 3D systems with different complexity geometry using combinatorial approach based on description of complicated systems by combinations of elementary bodies and surfaces. Preliminary analysis of the experimental and theoretical results on the GDT shows a prospect of the project [4]. The detailed analysis of the requirements for the plasma as the neutron source is presented in the paper. Key peculiarities of the engineering solution on plasma heating and confinement in the device are discussed as well.

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Development of deuterium-loaded targets for D-D neutron generator based on high-current gasdynamic ECR ion source

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Development of a new generation of D-D neutron generators based on high-current gasdynamic ECR sources of deuterium ions requires engineering and creation of a neutron-generating target containing deuterium. Existing D-D neutron generators consist of deuterium ion (deuteron) source with extracted beam energy of 100-200 keV and deuterium saturated neutron production target. The deuteron beam is directed towards the target, provoking the nuclear reaction and neutron emission. However state-of-the-art D-D generators based on conventional ion sources deliver only 1-10 mA/cm^2 deuteron current density to the target and do not provide necessary neutron flux density for modern applications. Increasing the current density of deuterium ion beams bombarding the target is one of the obvious ways to amplify the neutron yield in D-D generators. A so-called high current quasi-gasdynamic ECR ion source with plasma heating by millimeter wave gyrotron radiation was suggested to be used in a scheme of D-D neutron generator. Ion source of that type was developed in the Institute of Applied Physics of Russian Academy of Sciences. It can produce deuteron ion beams with current density up to 700-800 mA/cm^2. The use of this source allows a significant increase in neutron yield, though increasing the target stress. In order to fulfill requirements of modern applications for neutron flux the target must be able to withstand a constant load of up to 1 eA of deuterium ion current with energy of 100 keV, providing efficiency of neutron generation on the level of $10^1$1 neutrons per second. A lot of investigations on the proper target and wafer materials selection to be done along with target saturation technique working off for successful creation of the target. An experimental setup built for target saturation with deuterium is described in the present work. The setup consists of water-cooled vacuum chamber, set of vacuum pumps, oxygen, deuterium and air gases feeding system, PC-based target and wafer heater, and load-unload system. In the frame of conducted experimental studies optimal parameters of target material annealing for its proper degassing and pumping the impurities. Optimal saturation process stages parameters such as time, temperature, temperature gradient and deuterium pressure have been determined for creating high quality deuterium-saturated titanium targets. Experimental investigations of target quality were performed with secondary ion mass-spectrometry method (SIMS). SIMS results showed that the quality of obtained samples and deuterium content at surface layer are high enough for its successful use in the D-D neutron generator.

Prospects of mirror-based reactors

pB11 fusion: trends and physics issues

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Alternative to DT fusion fuels such as pB11 could provide truly clean and abundant energy source. Projection to pB11 reactor based on advanced, neutral beam driven FRC plasma configuration developed in TAE will be discussed in the presentation. New data for pB11 cross section [1] predict higher fusion rates than it was assumed before and opens possibility to achieve higher Q than it was expected earlier [2]. Although fusion reactivity of pB11 is higher than or comparable with other alternative fuels it requires higher plasma temperature. FRC plasma configuration provides a unique opportunity to reach plasma temperature needed for pB11 burn. Low magnetic field allows avoid excessive synchrotron radiation from plasma and favorable scaling of plasma confinement with temperature makes it possible to reach the required $n\tau$. Potential candidates for design points for the future pB11 device are presented. Physics and engineering issues of creating a viable plasma energy generator based on pB11 reaction are discussed.
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The BINP Road Map for Developement of Fusion Reactor Based on a Linear Machine

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In the paper, we present and discuss the Budker Institute long term plans for laying the plasma physics database for an advanced fuel fusion reactor based on the axisymmetric linear magnetic trap. General approach to development of the reactor utilizes the idea of confinement of a plasma with utmost pressure value confined in the linear device with the multi-mirror end sections attached at both ends to suppress the axial plasma losses. To develop the required database a stepwise approach is applied, which suggests construction of the several experimental devices with successively increased plasma parameters, which incorporate the different constituents of the approach. Ultimately, after successful proves of the ideas in the experiments, a prototype of the reactor will be constructed in the Budker Institute.

Multiple Mirror Trap: Milestones and Future

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A fusion reactor concept on the basis of a linear trap is developing in BINP. These studies incorporate multiple-mirror sections which should reduce significantly longitudinal plasma losses from a confinement zone as an important element of a central trap. The most efficient operation regime of multiple-mirror sections is at the mean free path of ions approximately equal to the

length of an individual mirror cell. Transition to such mode of the improved confinement, in particular in the conditions of appearance of plasma turbulence, is the task that requires more research. In the paper the main physical findings on the multiple-mirror confinement useful for forecast of the plasma behavior at reactor conditions will be discussed. Basic results were received on the GOL-3 multiple-mirror trap in which plasma of 10^{21} m^{-3} density was heated by a high-power electron beam up to 2 - 4 keV temperature. The key milestones were: the demonstration of effective plasma heating by the electron beam due to collective effects, the achievement of theoretically predicted level of energy confinement time under optimal conditions, and finally, the discovery of a bounce instability that improves longitudinal confinement. Modern projects of high-performance open traps with a central confinement zone and multiple-mirror end sections (like the GDMT project) require more experimental information for performance prediction of the multiple-mirrors for plasmas with low level of turbulence. Direct demonstration of a confinement improvement by multi-mirror sections in the magnetic configuration relevant to the reactor one is required. For this purpose, the GOL-NB facility will be created in BIMP. The main tasks of GOL-NB and the progress in its construction will be discussed. In addition, a new plasma device SMOLA with a helical multiple-mirror magnetic field which should check an idea of an active confinement control is announced.

Prospects for an Advanced Fusion Fuel Tandem Mirror Reactor

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Recent advances in high-field superconducting technology together with the development of MeV neutral beams and multi-megawatt high-frequency gyrotrons provide motivation to consider Generation II tandem mirror fusion concepts which could burn a range of fuels from DT to DD to possibly p11B. Advanced fuels require high electron temperatures in the end plugs but lower electron temperatures in the center cell to avoid excess Bremstrahlung losses. A new result in this paper shows that strong heating of electrons in the end plugs decouples these temperatures as needed to burn advanced fuels, without the need for externally imposed thermal barriers.

Our considerations incorporate unexploited physics results from past US experiments and recent advances from the GDT facility in Novosibirsk Russia. We envision ignited plasma confined in a simple solenoid with small high-field axisymmetric mirror cells at both ends. Axisymmetric MHD stability can be provided by several methods. Here we consider kinetic stabilization by plasma pressure in the good curvature region just beyond the outermost mirrors. Since magnetic mirror system performance favors high temperature plasmas, (e.g. 100 keV) so it is natural to consider advanced fuel options. High field circular magnets enables high mirror ratios to improve axial confinement and also enables compact end cells to reduce the auxiliary power required to electrostatically confine the central cell plasma. MeV level neutral beams and high power ECH provides the end cell electrostatic plasma potential that axially confines central cell plasma. Direct energy conversion is considered for untrapped and unneutralized neutral beam energy recovery and to recover plasma end loss energy. We have evaluated the fusion power gain (Q) as the product of three factors. Q=Lc x C x F. Here Lc is the fusion power producing central cell length, C is a physical size and plasma characterization parameter and F defines the fusion fuel characteristics. For Q = 15 to 20 we find central cell lengths $10 < Lc < 200$ m (depending on the magnetic field strength, the design dimensions and the fusion fuel). Example design parameters will be presented together with suggestions for more detailed study such as startup, control of synchrotron radiation and emergence of trapped particle and drift cyclotron modes. The calculation to be presented indicates the existence of an encouraging design space warranting more comprehensive modeling and for experimental investigations. This work was inspired by our late colleague, Richard F. Post (1918 - 2015).

High Magnetic Field Symmetric Mirror D-D Reactors for Applied Nuclear Science

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The successful high mirror ratio Rm=Bmax/Bmin=35 Gas Dynamic Trap [1] mirror machine may provide an economical path for a high neutron fluence fusion device. Neutron flux of order 2 MW/m^2 1yr is required to determine the life-time of various wall designs for future toroidal fusion power reactors. These neutron fluences are well beyond the reach of the current ITER, Large Helical Device and the Wendelstein 7X toroidal fusion plasma machines under development. In addition, there is simplicity of the design and operation of the linear mirror confinement vessels and with their large, symmetric end exhaust chambers that add an economical and practical external control mechanism for nuclear plasma. We investigate the parameters for the angles, positions and power requirements for both the neutral beam injectors [NBIs] and the parameters of the X-mode electron cyclotron heating [ECH] antennas to optimize the stability and fusion power production within the GDT architecture. The anisotropy of the RF driven fast electron distribution function is important both for the stability of the plasma to drift-loss cone instability and the reduction of the collisional electron scattering into the loss cone. We parameterize and optimize both the NBI and the ECH system specifications for optimal neutron flux production. Neutron fluxes of order 10^{12} n/s to 10^{14} n/s are estimated from one second driven deuterium plasmas.

The mirror neutron source would enable an aggressive fusion materials program as well as a component development program that would test modules of Li-blankets, tritium processing systems, and plasma heating technologies. Preliminary estimates of the duty cycle of the system show that the neutron flux is sufficient to produce an attractive alternative source of the expensive radiopharmaceutical of Technetium - 99 for daily use in hospitals throughout the United States. The Center for Electromechanics [CEM] at the Pickle Research Park at the University of Texas has the experience and electric power to build a new GDT facility. In September 2015 a FES-DoE solicited White Paper from the mirror community describing the Symmetric Mirror Project was received by OFES [3].

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Reactor neutron shielding based on expirience of ITER designing

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One of the important engineering issue of mirror-based reactors is a neutron shielding of reactor construction and diagnostics, and providing the human access to the maintenance area. Unfortunately, in modern plasma society have not examples of big open plasma installation that can be using for investigating this question. That is why to very important to use experience of the ITER project which under construction now. Report consist describing the organization of neutron shielding for ITERs equatorial port #11. Described the possibility installation a diagnostics inside the neutron shielding and organization of shielding for vacuum extension. In paper are present the calculations of neutron flux and estimation of shutdown dose rate.

Influence of lithium on the fusion gain in deuterium plasma

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The effect of a small amount of lithium is considered that it improves the energy balance of D-D fusion. From the Lawson criterion viewpoint, optimal lithium to deuterium density ratio is 0.3-0.4. Yield in neutrons with energy of 14 MeV is about 50% by the addition of lithium-6 and about 35% by the addition of lithium-7. Temperature of 100 keV is required. Possibility of the use of such a fuel mixture is studied for the conditions of the mirror-based fusion neutron source.
Work was supported by the Ministry of Education and Science of the Russian Federation, the contract No.13.2573.2014/K.