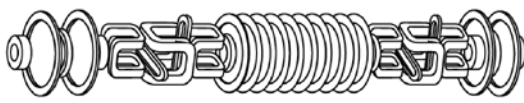


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## Operation modes of hot-cathode plasma source for linear devices

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Operation of the axisymmetric plasma source with a hot LaB<sub>6</sub> disk cathode and a cylindrical hollow anode in axial magnetic field is sensitive to the cathode-to-anode diameter ratio. When the cathode edge partially maps along magnetic field lines on to the anode surface, the discharge voltage is relatively low, less than 150 V [1], the plasma stream occupies the entire inner hole of the anode, and the plasma density profile has a characteristic bump near the anode wall. The plasma profile can be varied by magnetic coils, but the density at the axis is always smaller than at the edge. By contrast, when the cathode is mapped well within the inner diameter of the anode with a radial gap between them exceeding ~1 cm, the discharge voltage jumps to a much higher values exceeding 250 V. The plasma density profile becomes a clean Gaussian one with the width corresponding now to the size of the cathode mapped downstream in agreement with the magnetic flux conservation. Both in the low-voltage and in the high-voltage modes the plasma density reaches  $\sim 10^{13}$  cm<sup>-3</sup>, and the discharge parameters almost do not vary with magnetic field up to 2 kG. This plasma source is suitable for the use in linear devices for plasma-material interaction studies.

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## A new axisymmetric mirror experiment at UW-Madison

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The Wisconsin Axisymmetric Mirror (WAM) is a new axisymmetric experiment under construction at the University of Wisconsin-Madison. The 3 meter device has a central solenoidal field up to 0.3T with mirror coils producing up to 6T. Initial tests will use modest rf power for plasma formation (13.56MHz helicon) and heating (2.45GHz ECRH), and neutral beam injection will be utilized in a planned upgrade. Featuring all axisymmetric coils, stability will be provided by one of two methods. First it can operate in the gas dynamic regime with appropriate field expansion to conducting plasma absorbers in the end cells[1]. A second stabilizing technique will use the flow-shear induced vortex stabilization[2,3] by appropriate biasing of concentric rings in the end cell with respect to a limiter inside the central solenoid. There are several objectives of the experiment. First we plan to use the latest generation of REBCO high temperature superconducting tape for the mirror coils, possibly becoming the first fusion experiment to implement this material for plasma confinement. A second mission is using lithium-coated plasma facing materials for particle handling and pumping, as neutral particle control is imperative for successful NBI heating and fast ion confinement. Third, this device serves as a prototype for design and construction of a higher field, longer pulse device that may serve to advance the GDT fusion neutron source concept that is widely recognized as necessary for a materials and components test facility. This presentation includes data from first plasmas in the device: nearly steady state helicon discharges in the solenoidal field. Also presented is a plan of the experimental upgrades including installation of mirror coils, ECRH heating scheme, lithium evaporation system for end cells, and neutral beam injection.

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# Non-Axisymmetric Radiation from Oversized Surface Wave Oscillator Driven by Weakly Relativistic Electron Beam

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Slow-wave device is one of a promising high-power terahertz-wave source.[1] The device is based on a periodic structure that converts kinetic energy of an electron beam into that of electromagnetic (EM) wave. Surface wave oscillator (SWO) is one of the slow-wave device utilizing a cylindrical corrugated waveguide.[2] The corrugated waveguide, which has a periodic structure, forms two axisymmetric structure modes: transverse magnetic (TM) and transvers electric (TE) modes. Non-axisymmetric mode as a hybrid mode of TM and TE modes also exists. The periodic structure decreases the phase velocity of EM wave slower than the speed of light and non-axisymmetric mode is formed as a slow wave. A slow wave has an amplitude distribution concentrated on the surface of the structure when the corrugated waveguide is oversized; its radius is several times larger than wavelength of EM wave in free space. Such a wave is called surface wave. By injecting an electron beam into the waveguide, a surface wave is excited and intense radiation is generated.

In this study, we perform experiment of excitation of non-axisymmetric mode with mode number up to  $m = 20$ . The upper cutoff frequency of the non-axisymmetric mode with  $m = 20$  is 120 GHz. An electron beam is generated by applying voltage pulse less than 100 kV to a cold cathode. Generated electron beam has current on the order of 100 A. Intense radiation is observed by a detecting system which is composed by a horn antenna, a rectangular waveguide, and a crystal detector. The detector is pacific Millimeter Product GD. The rectangular waveguide has cutoff frequency 116 GHz. Hence, frequency of observed radiation is above 116 GHz. By decreasing a cathode voltage, radiation-starting condition is examined.

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## Studies of material in exposure to fusion reactor relevant loads in BINP

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The studies of material in exposure to fusion reactor relevant loads in BINP are mostly oriented on the investigations of the results of pulsed heat loads. The pulsed heat loads are dangerous to the plasma facing components due to the crack formation after them. The studies involve the development of the optical and X-ray in situ diagnostics. The pulsed heat loads are studied at BETA (Beam of Electrons for materials Test Applications) facility and at synchrotron radiation scattering station PLASMA.

The BETA test facility uses an electron beam (30–110 keV, up to 80 A), which is generated in the source with an arc plasma emitter and a multi-aperture diode electronic optical system. The pulse of the beam power has an almost rectangular shape with duration of 100–300  $\mu$ s and is used to heat a tungsten target [1]. Front view of the tungsten plate is captured by a fast CCD camera with supplied with an infrared filter for the measuring of the thermal radiation. The measured thermal radiation revealed the overheated areas along the crack on the tungsten surface [2]. The same cameras are used for the imaging of dust particles ejected from the tungsten surface. Also the scattering of the laser on dust particles was used for the characterization of the temporal distribution of the density of the particles [3]. The new diagnostic measuring the reflected by the tungsten surface laser light was developed recently [1]. The diagnostic is sensitive to the roughness of the reflecting surface. The continuous recording of light scattering from polished tungsten surface allowed measure the increase of the roughness during the pulsed heating and decreasing after it. Also the crack formation was associated with the sudden change of the measured signal. The delay between the pulsed heating and the crack formation was measured to be unexpectedly long ( $\sim$ 400 ms).

The station PLASMA uses a diffraction of synchrotron radiation for the measurements of the dynamics of the deformations and stresses of materials under pulsed heat loads [4]. The ND:YAG laser used for the simulation of pulsed heat load (energy 50 J,  $\sim$  140  $\mu$ s). Currently the measuring of the temporal evolution of the diffraction peak shape was demonstrated. The mathematical model for the interpretation of the diffractograms is under development.

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# Fuel evolution in hybrid reactor based on thorium subcritical assembly with open trap as fusion neutron source (computer simulations)

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Thorium-uranium power industry has a number of advantages over uranium-plutonium one. Taking into account of these advantages, a high-temperature gas-cooled reactor with thorium fuel looks very attractive for application in Russian Federation. Fuel assemblies filled by pellets with microencapsulated thorium-plutonium 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 create a facility that allows carrying out such experimental studies. A stand to study neutron-physical characteristics of the thorium-plutonium fuel is proposed in the paper [1]. The device consists of a fuel subcritical assembly combined with an open trap which operates as a source of fusion neutrons.

In this paper we describe results of computer simulations of the time evolution of the fuel in the pellets for long operation time of the mentioned device. The device combines a long solenoid with plasma to generate 14-MeV thermonuclear neutrons and the thorium-uranium subcritical assembly (see [1]) operating as a thermal energy source. We use the plasma parameters achieved at GDT–device experiments [2] and the magnetic field configuration allows achieving homogeneous distribution of the emission of the thermonuclear neutrons. Calculations of the characteristics of the simplified model of the stand are carried out in the 3-D formulation. The effective neutron multiplication coefficient, the neutron reproduction coefficient, the distribution of neutron fluxes and energy release are obtained in frame of using the Monte Carlo code of PRISMA [3] with continuous neutron data (ENDF / B-VII.1). Calculations of the nuclear fuel kinetics are carried out using the RISC code [4] with data on the decays from ENDF / B-VII.O and with usage the calculation results of the fuel burnup. The fuel burnup is calculated in conjunction with the calculation of neutron transport according to the PRISMA program. In addition to the results obtained in the calculation of the PRISMA program, calculations of the burn-up coefficient of various constituents of fuel are carried out using the computer code WIMSD [4].

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# Influence of plasma density gradient on emission of submillimeter waves at interaction of REB with plasma in long magnetic trap

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Research work on studying the mechanisms of submillimeter wave generation due to relaxation of a relativistic electron beam in magnetized plasma was started at the experiments on the GOL-3 facility in 2010 [1]. It has been established that spectral power density of the submillimeter wave emission from beam-plasma system is concentrated in two areas: the first one is located around of the frequency of the upper-hybrid plasma oscillations and the second occupies the band around the double value of this frequency. We interpret the EM-wave emission with the frequency in the first area as result of the direct conversion of upper hybrid plasma wave into electromagnetic one in plasma volumes with a strong plasma density gradient [2] and in the second area due to merging of two upper hybrid plasma waves into electromagnetic one [3]. In order to conduct the detail investigations of the mechanisms of the EM-wave emission from the beam-plasma system the novel facility named GOL-PET was constructed at the BINP.

The magnetic, vacuum and plasma forming systems of the GOL-PET facility has been constructed in such way that to achieve a good reproducibility of the experimental results on the EM-wave emission. The plasma with the density up to  $5 \times 10^{15} \text{ cm}^{-3}$  and its length 1.5 m is produced in the multiple-mirror or homogeneous magnetic field with  $B_{\text{mean}} \approx 4 \text{ T}$ . The plasma creation system allows forming the radial density distribution of the plasma with necessity density gradient. At these experimental conditions the upper hybrid plasma waves pumped by the relativistic electron beam can be propagating at the appropriate angle to direction of the plasma gradient and the magnetic field lines and as result can be transformed into the EM-waves with the high efficiency (see [3]).

A result of measurements of spectral characteristics of the submm radiation propagating along the axis of the GOL-PET facility is presented in the paper. The spectral properties of this plasma emission are analyzed in frequency interval  $0.1 \div 0.8 \text{ THz}$  by quasi-optical frequency-selective spectral complex with calibrated absolute sensitivity of its channels on spectral power density. In the carried out experiments, the achieving the maximal exhaust EM-waves power in the  $0.1 \div 0.3 \text{ THz}$  interval is correlates with existence of strong radial plasma gradients. The specific power of the radiation emitted from the end face of plasma column achieves  $25 \text{ kW}/(\text{sr} \cdot \text{cm}^2)$  in this frequency area.

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# Investigation of the vertical stability and conducting shell effects for a tokamak DEMO reactor

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Physics and engineering design of the equilibrium control, i.e. vertical stability, for the non-circular tokamak plasma is a critical issue. For a Japanese (JA) DEMO design, an increase in the plasma elongation at the 95% flux surface ( $\kappa_{95}$ ) larger than 1.65 is required to improve the plasma performance such as the fusion power ( $P_{\text{fusion}}$ ), plasma current ( $I_p$ ), confinement time ( $\tau_E$ ) and electron density ( $n_e$ ) [1, 2]. Installation of the conducting shell inside the vacuum vessel (VV), i.e. between the breeding blanket (BB) and backplate (BP), and improvement of the design appropriate for the remote maintenance have been investigated [3, 4]. In the practical DEMO design, the plasma shape such as  $\kappa_{95}$  and the triangularity ( $\delta_{95}$ ) is different at the upper and lower half, and the radius ratio of the plasma surface and the conducting shell ( $r_{\text{sh}}/a_p$ ) varies along the poloidal angle. Thus, it is helpful for the DEMO design to evaluate effects of the conducting shell, by using simply shaped plasma and assuming the conducting shell location.

Systematic study of the vertical stability for the DEMO plasma ( $R_p = 8.5$  m,  $a_p = 2.52$  m) was performed in some typical cases of  $\kappa_{95}$  larger than 1.65, where the shaping parameters of  $\kappa_{95}$  ( $= 1.65, 1.75$ ) and  $\delta_{95}$  ( $= 0.30, 0.35$ ) were the same at the upper and lower half, and the toroidally-symmetrical conducting shell was assumed at the same  $r_{\text{sh}}/a_p$  ( $= 1.35, 1.40$ ) along the poloidal direction as shown in Fig. 1. Here, the plasma equilibrium is basically single null divertor configuration and the conducting shell covers most of the outboard plasma surface with the poloidal angle of  $\theta = \pm 80^\circ$ . Characteristic growth rate of the vertical instability was determined by  $n^{\text{index}} + n_s(s) = 0$ , where  $n^{\text{index}}$  and  $n_s$  are the decay index of the magnetic field and the stability index characterizing the passive stabilizing effect at the angular frequency ( $s$ ), respectively.

The plasma equilibrium becomes unstable for the lower  $s$ . For the same  $r_{\text{sh}}/a_p$  ( $= 1.35$ ), the vertical instability was enhanced with increasing  $\kappa_{95}$  and decreasing the poloidal beta ( $\beta_p$ ) rather than the internal inductance ( $l_i$ ), while it was slightly reduced for higher  $\delta_{95}$ . A proposed equilibrium of the JA DEMO plasma ( $\kappa_{95} = 1.75$ ,  $l_i \sim 0.7$ ,  $\beta_p \sim 1.8$ ) was sustained by the conducting shell effect. On the other hand, lower  $\beta_p$  ( $\sim 0.1$  at the start phase) or larger  $r_{\text{sh}}/a_p$  ( $\sim 1.4$  for the thicker BB radial width), it was difficult to sustain the high  $\kappa_{95}$  plasma. In addition, effects of (i) the double null plasma configuration with the same poloidal coil arrangement, and (ii) the inboard conducting shell installing also behind the inboard BBs, are summarized.

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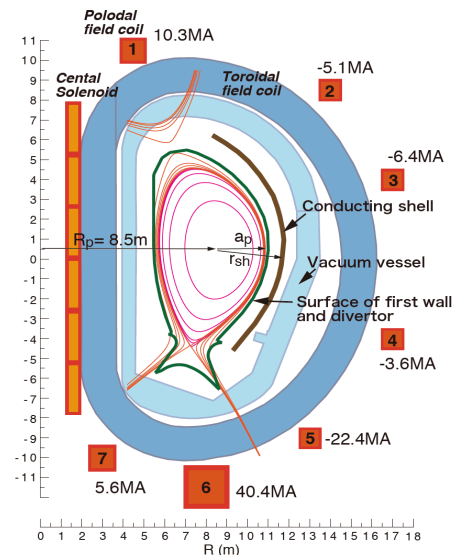


Fig.1 Single null divertor configuration of the DEMO plasma ( $I_p = 13.5$  MA) with  $\kappa_{95} = 1.65$ ,  $\delta_{95} = 0.30$ , locations of the first wall, conducting shell, vacuum vessel.

## Effect of impurity injection on particle and heat flux decay length in DiPS-2

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The heat flux decay length ( $\lambda_q$ ) in the SOL region is a decisive quantity for the divertor peak heat load of current and future devices. Despite the importance of an accurate prediction of  $\lambda_q$ , theoretical models or empirical extrapolations are generally accepted. Further, information on the change of the  $\lambda_q$  is insufficient when the impurities are injected to reduce the heat load.

Plasma parameters and transport of the magnetized plasma in linear device DiPS-2 are investigated by measuring the radial profiles of plasma parameters using fast scanning probe system (FSP). FSP is composed of triple probe, which allowed direct measurements of electron temperature, particle and heat fluxes, and Mach number [1].

It is found that the plasma extends radially far beyond the visible edge where it decays exponentially with a characteristic length of 1 cm. The measured profile can be compared to the theoretical value. Influence of particle and heat flux decay length was investigated by nitrogen injection as an impurity in He plasmas. It was observed that the heat flux decay length was slightly increased from 0.86 to 1.1 cm as increasing the impurity injection rate.

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## **Studies of plasma confinement and stability in a gas-dynamic trap: results of 2016 - 2018**

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This report provides a brief overview of the most significant results of the experimental work that were carried out on the gas-dynamic trap (GDT) device in 2016 - 2018 at the Budker Institute. The GDT device is an experimental facility for studies on the main issues of development of fusion systems based on axisymmetric mirror traps. It is an axially symmetric linear open system with a long central solenoid and high mirror ratio [1].

One of the experimental series was aimed at providing MHD stability of plasma under conditions of auxiliary ECR heating. We report plasma discharges with a very high temperature of bulk electrons and suppressed magneto-hydro-dynamic instabilities during the entire heating and magnetic confinement times. The on-axis electron temperature  $400 \pm 50$  eV at the plasma density  $10^{19} \text{ m}^{-3}$  is supported in a steady-state discharge during 1 ms. Attaining of such discharges allows deeper understanding the transport physics of high-electron-temperature regimes not possible in the previous experiments.

In another series of experiments, the study of physical processes in the expander, which determine the longitudinal energy transport, was continued. The report will present new data on the effect of gas conditions in the expander on the axial energy transport. New data about interaction of plasma with neutral gas in the expander region will be presented also.

A special series of experiments was devoted to the investigation of microinstabilities of the loss-cone type. In particular, the influence of the mass composition of plasma ions on the stability region was studied.

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# Ion beam production with LaB<sub>6</sub> hot cathode for divertor plasma simulation experiments in DT-ALPHA device

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One of important subjects in magnetically confined fusion study is controlling of heat load flowing onto the divertor plates. One method to reduce heat flux incoming to the divertor plates is to use plasma detachment by inducing volumetric recombination. However, electrons that flowing into divertor region from the scrape off layer has much higher electron temperature than that required for volumetric recombination. Therefore, gas puffing method is widely utilized to remove electron energy and maintaining low electron temperature. However, energetic plasma particles periodically exhausted by edge localized modes that associated with improved plasma confinement potentially has energy up to several keV. Therefore, there are concerns that reaction rate of the volumetric recombination in divertor region is decreased owing to energetic particles. The influence of energetic ion collision has not been well investigated because conventional divertor plasma simulator has difficulties to utilize energetic ions. Therefore, an alternative plasma source is required to conduct an experimental study of aforementioned subject. We have been proposing ion beam injection experiment using a radio-frequency (RF) plasma source DT-ALPHA and an ion beam generator to investigate the influence of energetic ions collision. From previous research using helium plasma, it is indicated that recombination rate is reduced due to energetic ion collision [2]. To understand the interaction of molecular assisted recombination (MAR) plasma with energetic hydrogen ions, we require hydrogen plasma experiment. Since hydrogen has multiple ion species (H<sup>+</sup>, H<sub>2</sub><sup>+</sup>, H<sub>3</sub><sup>+</sup>), the beam transport system requires ability to select the ion injecting to DT-ALPHA. We choose  $E \times B$  filter for hydrogen ion separation and investigated its availability in DT-ALPHA using simulation program [3]. The investigation results showed that  $E \times B$  filter is suitable for hydrogen ion separation in our device.

Reaction rate between hydrogen ion beam and target plasma would proportional to ion beam flux. Therefore, larger ion beam flux is preferable to conduct ion beam injection experiment. From our previous work, it is indicated that ion beam flux is proportional to arc current of ion source. However, hydrogen ion beam flux would decrease after ion separation approximately to 10% because H<sup>+</sup> production ratio in previous work is approximately 10 % of total hydrogen ion beam. This indicates that higher arc current operation is required to produce large flux H<sup>+</sup> beam. However, tungsten filament cathode in our current ion source may not suitable for such operation. We improved ion beam production by changing cathode to Lanthanum hexaboride (LaB<sub>6</sub>) filament which has better electron emission rate and lower evaporation rate [4]. Experiments confirmed that LaB<sub>6</sub> filament ion source can produce stable arc plasma at higher arc current than previous ion source with tungsten filament. This indicates that we can expect higher beam current from this new ion source. In the presentation, details of the ion beam production in LaB<sub>6</sub> filament ion source and comparison with previous tungsten filament ion source will be presented.

The work was partly supported by the Grant-in-Aid for Young Scientists (B) 17K14895.

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# Multiple-Mirror Traps in the Budker INP

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The overview of BINP's work on the development of multiple-mirror traps is given. The historical part of the review is devoted to the centenary of G.I. Budker who was one of the founders of open traps for plasma confinement.

The idea of a multiple-mirror plasma confinement was independently suggested in [1,2]. A recent review of results on the multiple-mirror confinement can be found in [3]. Currently, the most impressive results are from the GOL-3 device, at which  $10^{21} \text{ m}^{-3}$  plasma was heated up to 2 – 4 keV at a collective relaxation of a high-power relativistic electron beam [4]. The 50-fold improvement of the energy confinement time in a multiple-mirror configuration over a solenoidal one was demonstrated. These results and also findings from the GDT experiment have allowed developing the project of the GDMT next-generation open trap [5]. Now the program of development of multiple-mirror traps is directed to confirmation of new ideas integrated in the GDMT project. The overview of the first results from two new installations GOL-NB [6] and SMOLA [7] will be made.

[1] G. I. Budker, V. V. Mirnov, D. D. Ryutov, JETP Letters **14** (1971) 212.

[2] B. G. Logan, et al., Phys. Rev. Lett. **28** (1972) 144.

[3] A. V. Burdakov, V. V. Postupaev, Physics-Uspokhi **188** (No. 6) (2018).

[4] A. Burdakov, *et al.*, Fusion Sci. Technol. **51** (No. 2T) (2007) 106.

[5] A. Beklemishev, *et al.*, Fusion Sci. Technol. **63** (No. 1T) (2013) 46.

[6] V. V. Postupaev, *et al.*, Nuclear Fusion **57** (2017) 036012.

[7] A. V. Sudnikov, *et al.*, Fusion Eng. Des. **122** (2017) 86.



## Neutral beam injection system for the CAT experiment

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In the Budker Institute, the CAT (Compact Axisymmetric Trap) experiment is being prepared for obtaining a plasmoid with high diamagnetism in axially symmetric magnetic field. Reverse of magnetic field in the plasmoid is also possible in this experiment. The experiment is based on injection of powerful focused neutral beams with extremely large neutral power density in the plasma.

Two neutral beam injectors with the energy of hydrogen atoms of 15 keV will be used in the experiment. The neutral beam power of each injector is 2 MW, pulse duration is 5 ms. In the ion source of the injector, plasma emitter is produced by plasma jets from four arc plasma generators. Proton beam with current up to 170 A is formed by multi-slit three-electrode ion-optical system with ballistic focusing. Measured angular divergence of the formed beam along the slits is 10 mrad, divergence in the direction across the slits is 30 mrad. The injector is equipped with a neutralizer, bending magnet, residual ion dump, calorimeter, high speed pump with titanium arc evaporation. At present, similar injectors are successfully used in the experiment C2-W in TAE.

## Progress in steady-state high density TPD-type plasma source development for Demo divertor simulation experiment

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Edge and divertor plasmas of a future fusion demo reactor as the next ITER are expected longer duration, higher density and temperature plasmas in strong open magnetic field. Understanding of atomic and molecular processes including radiation transport in demo relevant high-density plasma is necessary for precious prediction of the demo divertor plasma behavior and for optimization of the divertor geometry.

In order to contribute to the issue, we have started to develop a steady-state high density plasma source for Demo diverter simulation experiment based on TPD (Test Plasma Produced by Direct current)-type discharge, which is steady-state high density plasma source had been developed at Institute of Plasma Physics, Nagoya University in 1960's [1]. The source is based on hot cathode arc discharge. The discharge region consists of a hot cathode, an anode and floating electrodes. The cathode is placed at the center of a cusp magnetic field. Arc discharge between the cathode and the anode generates high density plasma at gas pressures around 1 Torr. The produced plasma is introduced to a low gas pressure plasma test region through the anode which has a small through-hole. Typical plasma density is  $10^{19} \sim 10^{20} \text{ m}^{-3}$  with small diameter.

Results of basic research for such high density discharge as collaboration with research groups of linear plasma devices, plasma diagnostics and atomic-molecular processes will be discussed. Recent progress in development of the plasma source utilizing the TPD-II [2,3] facility in National Institute for Fusion Science will be also presented.

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[2] T. Oda, K. Sato, S. Namba *et al.*, J. Nucl. Mater. 241-243 (1997) 1238.

[3] A. Matsubara, T. Watanabe, T. Sugimoto *et al.*, J. Nucl. Mater. 337-339 (2005) 181.

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## **Development of an axisymmetric mirror-based neutron source using recent advances in technology**

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We report an overview of theoretical and experimental work at the University of Wisconsin leading to a fusion neutron source based on axisymmetric mirrors, following along the Gas Dynamic Trap line of development. The design considers the implications of several recent physics and technological advances and uses (1) off-the-shelf MRI magnets for an inexpensive central cell, (2) state-of-the-art small and planar high field REBCO magnet for plugs, (3) state-of-the-art gyrotrons to allow high density operation, (4) sloshing ions to localize neutron yield away from sensitive high field magnets at edge, (5) radio-frequency heating at the fast-ion turning points to enhance neutron yield, (6) a liquid lithium expanding diverter for heat removal, electron thermal barrier and MHD stability---lithium seems essential for pumping neutrals, minimize sputtering by ion bombardment, and minimize secondary electron emission to allow the electron thermal barrier to form.

Equilibrium, stability, plasma heating have been modeled using a Grad-Shafranov solver for the mirror including fast ion pressure coupled to the CQL3D/Genray suite of codes. We have been considering both paraxial and short-fat MHD optimizations of coil design. MHD stability is assessed using both energy principle calculations and ballooning mode eigenmode analysis.

Initial results were extremely promising. 5 MW of neutral beam injection power and 5 MW of rf heating at 15 MHz generated  $10^{15}$  neutrons/sec in DD. In addition, progress on the construction of a prototype GDT using REBCO mirror coils a lithium divertor solution will be reported.

# **Modeling of plasma production and heating by electromagnetic waves in axisymmetric mirror configuration**

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In order to analyze the physics mechanism of plasma production and heating by applying electromagnetic waves in magnetic mirror configuration and predict the time evolution and the steady state of produced plasmas, self-consistent modeling and simulation of plasma transport coupled with wave excitation, propagation and absorption is required. For axisymmetric mirror configuration, two-dimensional full wave code using the finite element method TASK/WF2D was developed [1] and recently extended to employ the integral form of dielectric tensor. This non-local property of plasma response enables us to describe kinetic effects due to wave-particle interaction, such as Landau damping, cyclotron damping, and the finite gyro radius effects for plasmas with Maxwellian distribution functions in the full wave analysis. Spatial profiles of the wave electric field and the power deposition through kinetic collisionless damping as well as conventional collisional damping are obtained. The ionization enhanced by the wave electric field and the deposited power are used as sources in the plasma transport analysis using the TASK/TF2D code. By solving the advective and diffusive transport equation coupled with Gauss's law, the time evolution of plasma density, temperature and electrostatic potential is simulated. The coupled analyses are applicable to various wave frequency ranges, electron cyclotron waves, helicon waves, lower-hybrid waves and ion cyclotron waves. Some preliminary results of plasma production using electron cyclotron waves and helicon waves will be presented.

- [1] A. Fukuyama *et al.*, Proc. of International Symposium on Plasma and Flow Simulation for Materials Processing (ISPFS, Sendai) (1997).

## Recent results of ICRF heating experiments for a divertor simulation study on GAMMA 10/PDX

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In GAMMA 10/PDX, divertor simulation experiments have been performed in the open magnetic field at the west end region. In order to control the end loss particle and heat fluxes, several heating operations were carried out using ion-cyclotron range of frequency (ICRF) heating systems in the central cell, the anchor cells, and the west plug/barrier cell.

In the central cell, high ion-temperature plasma with several keV have been produced by ion-cyclotron resonance heating, that leads to high heat flux in end region. The excited and propagated waves were observed by a multi-point measurable reflectometer [1]. For increasing the central-cell density as the source of the end loss plasma, direct heating of both the east and west anchors is important [2]. The efficiency of anchor heating was changed to using the phase control between both antennas installed in the anchor and central cells. Several phase dependencies were observed using absorption methods in anchor cell and the segmented limiter at midplane in central cell. In addition, excited ICRF waves are measured using the upgraded reflectometer system. The higher-order radial structure of ICRF waves in anchor cell was observed for the first time. Furthermore, experiments for ICRF heating near the throat in the central cell using anchor antennas, and of direct plug/barrier ICRF heating have been performed [3]. These different heating conditions denoted various properties for the end loss plasma.

This work was partly supported by the bidirectional collaborative research program of the National Institute for Fusion Science, Japan (NIFS14KUGM086 and NIFS17KUGM132).

- [1] R. Ikezoe *et al.*, *Journal of Instrumentation* **12**, C12017 (2017).
- [2] S. Sumida *et al.*, *Fusion Science and Technology* **68**, 136 (2015).
- [3] S. Jang *et al.*, *AIP Conf. Proc.* **1771**, 030011 (2016).

# **A brief review of the recent studies on liquid metal plasma-facing component concepts**

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Power and particle handling in the plasma edge region is one of the key issues, affecting the successful operation of a steady state magnetic fusion power reactor. Tungsten has widely been used for plasma-facing components in existing fusion experiments and is envisaged to be employed for the ITER divertor, perhaps with seeded impurity for radiation detachment. Unfortunately, conventionally available tungsten is known to suffer from thermal stress cracking due to its exceptionally high DBTT (for the Ductile-Brittle Transition Temperature) although most recently, efforts have been devoted to develop ductile tungsten and also W-W composite materials. It is also true that the particle reflection coefficient from tungsten is rather high, leading to high recycling operation which could deteriorate core plasma confinement.

To resolve the mechanical property issue associated with solid divertor materials, over the past decades the use of liquid metals has been proposed and implemented in a number of small-to-medium size confinement devices. Experimental data so far have been encouraging with improved confinement performance. However, there are tremendous uncertainties and yet-to-be explored nature about the behavior of free-surface liquids and vapors, interacting with the edge plasma, particularly under off-normal conditions such as disruption. Fluid dynamics simulation has begun only recently to understand the effect of liquid convection on hydrogen recycling, for example.

Presented in this paper are a brief review of the recent studies on liquid metal plasma-facing components with the emphasis on the particle recycling behavior from liquid metals such as molten lithium, with/without forced convection, under steady state plasma bombardment in a laboratory-scale plasma facility: VEHICLE-1 [1], and also a future perspective of the application of liquid metals for fusion power reactors will be presented.

[1] Y. Hirooka et al., J. Nucl. Mater. **337-339**(2005)585.

## Collisional merging formation of a field-reversed configuration for excitation of low-frequency wave in the FAT-CM device

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Collisional merging of field-reversed configuration (FRC)<sup>[1]</sup> plasmas have been conducted in the FAT-CM (FRC Amplification via Translation – Collisional Merging) device to generate a high performance FRC as a target to excite low-frequency wave; this method has been proposed as a new heating technique. In the dynamic process of the collision and merging, two FRCs are produced in the two field-reversed theta-pinch (FRTP) formation section simultaneously and translated into the central confinement section at the translation velocity up to  $\sim 200$  km/s; then the FRCs are collided and merged near the mid plane of the confinement section, and a merged FRC state is achieved. The produced FRC has higher performance, such as longer lifetime and higher trapped poloidal flux compared with single translation case. In the initial experiment of the FAT-CM device, the typical equilibrium parameters of merged FRC of  $\sim 0.2$  m in radius and  $\sim 2$  m in length are electron density  $\sim 1 \times 10^{20} \text{ m}^{-3}$ , external magnetic field  $\sim 0.08$  T and total temperature  $\sim 100$  eV, respectively. For core heating, an excited wave must propagate through the scrape-off layer with the highest magnetic field in FRC magnetic structure. For that reason, the frequency of the wave used in this experiment must be lower than the ion cyclotron frequency or higher than the electron plasma frequency because the wave out of this band is reflected or resonant outside of the separatrix of the FRC. The achieved FRC parameters is sufficient for injecting wave to be propagated into the core region of the FAT-CM FRC, and the heating effect can be expected.

[1] H. Gota *et al.*, Nucl. Fusion. **57** (2017) 116021.

# Analysis on the sensitivity of the ASDEX type fast ionization gauge in mixed radiator gases of divertor simulators

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A linear divertor simulator device with an open ended-magnetic field, like GAMMA 10/PDX, is not only useful to simulate a behavior of a divertor plasma, but also useful for a study of diagnostic tools or methods in divertor environments. The ultimate goal of this research is to establish a method to measure both total pressure and the partial pressure of neutral gases in a divertor region. The injection of neutral gases such as hydrogen, nitrogen, and noble gases for divertor region is considered in order to achieve detached plasma. When the neutral gas is introduced to the divertor, the energy of the divertor plasma can be removed as the energy of atomic radiations. The typical gas pressure at the divertor is considered to be around several Pa. The fast ionization gauge, which is also known as the ASDEX ionization gauge (AIG), is a kind of ionization gauge capable of measuring gas pressure around several Pa and therefore the use of the AIG for a divertor is proposed [1-4].

In previous work, by using a well-controlled gas pressure in the calibration chamber, calibrations of the AIG sensitivity against pure gas and mixed gases were performed and it was found that the sensitivity of the gauge is increased by more than 50 % in both the mixture He and Ar, and the mixture of H<sub>2</sub> and He [5].

This work focuses on the change of the ionization cross-sections in AIG with mixed gases. Especially the effect of metastable atoms for the ionization will be discussed. The collision energy of the electrons in the AIG is varied and the change of the ionization rate due to the collision energy will be investigated. Furthermore, the experimental results will be compared with numerical calculations of zero-dimensional models. In the presentation, detailed results and findings will be presented.

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[2] G. Haas and H.-S. Bosch, Vacuum **51**, (1998) 39.

[3] N. Hill *et al.*, Rev. Sci. Instrum. **61**, (1990) 3548.

[4] K. Ichimura *et al.*, Rev. Sci. Instrum. **87**, (2016) 11D424.

[5] K. Ichimura *et al.*, Plasma and Fusion Research. **13** (2018) 3405029.



# **Improvement of electron collection using a magnetic field suppressing mirror effect in a secondary electron direct energy converter simulator**

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D-<sup>3</sup>He nuclear fusion has been expected as an energy source for next generation because neutrons are not produced in the reaction. Most energy produced in this reaction is kinetic energy of charged particles, so direct energy conversion can be applied. An energy recovery device from protons produced in the reaction by using traveling wave (TWDEC) was proposed [1], however, some protons were not decelerated and the device efficiency was limited. In order to recover those protons passing through the TWDEC, an additional device was proposed to be settled in the downstream, which was called secondary electron (SE) direct energy converter (SEDEC) [2].

In SEDEC, a lot of metal foil electrodes are aligned in the direction of the proton beam. The incident protons penetrate the electrodes where SEs are emitted. Collectors settled on both sides of the foil electrodes catch the SEs and those energy is recovered by appropriately biased voltage. Recovering energy of SEs results in recovering energy of protons indirectly.

Although a series of experiments were performed in previous researches, the amount of collected secondary electrons was not large. The biggest problem is that most of the secondary electrons are not arriving at electron collectors, but arriving at anteroposterior foil electrodes. In order to guide the electrons to the collector, a magnetic field perpendicular to the proton beam by permanent magnets was introduced, however, it was found that magnetic mirror effect in front of the permanent magnets disturbs arrival of secondary electrons at the collectors [3]. Strength of magnetic field at the point of collectors is higher than that of foils, then electrons are reflected in front of collectors.

Suppression of the mirror effect is necessary to improve SE collection. The authors propose a new magnetic field structure, which is derived analogically from that of Helmholtz coils. The field structure between a pair of coils depends on the ratio of the coil radius to the distance between coils. The field structure becomes uniform when the ratio is equal to 1, and it becomes valley and hill when the ratio less and greater than 1, respectively. We can realize stronger magnetic field at foil electrodes than those at collectors by employing large size of permanent magnets. The experiment using a revised SEDEC simulator is in progress. The detailed results and discussion will be presented in the conference.

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[2] D. Akashi, et al., Trans. Fusion Sci. Technol. **63**(1T) (2013) 301.

[3] S. Nakamoto, et al., Fusion Sci. Technol., **68**(1) (2015) 166.

## Characteristic of upstream and downstream on detached plasma in D-module of GAMMA 10/PDX

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Reduction of the heat and particle loads at the divertor in a magnetically confined fusion device is one of the crucial issues. Production of a detached plasma by using volume recombination processes is a method of mitigation of the particle and heat loads. Cooling gases such as impurity and/or fuel gas are introduced into a divertor plasma in order to produce a detached plasma. It is expected that the detached plasma has steep gradient of temperature and density along the magnetic fields. It is important to measure the spatial distribution of the detached plasma for understanding the physical mechanisms of the detachment and impurity transport. In this study, we measured the electron temperature  $T_e$  and density  $n_e$ , the emission intensities at the upstream and downstream region.

The experiments were performed in GAMMA 10/PDX[1]. GAMMA 10/PDX is the largest tandem mirror device and consists of four sections, which are central cell, anchor cells, plug/barrier cells and end regions. In GAMMA10/PDX, divertor simulation experiments have been conducted by divertor experimental module (D-module). The D-module can be moved up and down by using an elevation system and placed on axis close to the end-mirror exit in the divertor simulation experiment. The plasma is generated and heated by ion cyclotron range of waves together with gas puffing in central cell and reaches to D-module at west end cell. D-module consists of rectangular chamber (cross-section  $50 \times 50$  cm and 100 cm in length) made of stainless steel and V-shaped target equipped with electrostatic probes and calorimeters. At inlet of D-module (upstream region), single probe is installed and can move up and down so as to measure the radial distribution of  $T_e$  and  $n_e$ . The spatial distribution of  $H_\alpha$  and  $H_\beta$  intensities in D-module are measured by a high speed camera. Cooled gas are injected from gas lines which are located at inlet of D-module and corner of V-shaped target in order to make realization of plasma detachment. Quantity of gas injection is adjusted by changing the plenum pressure of gas reservoir tank.

As a result, in upstream region, the electron temperature decreased with increasing the plenum gas pressure and its radial distribution becomes uniform. In this presentation, consideration of the energy loss process and comparison with the results of upstream and downstream region will be discussed.

[1] Y. Nakashima, *et al.*, Nucl. Fusion, **57** (2017) 116033.

## Investigation of slow wave excitation in the GAMMA 10/PDX central cell

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R. Sekine<sup>b</sup>, H. Kayano<sup>b</sup>, Y. Shima<sup>b</sup>, J. Kohagura<sup>b</sup>, M. Yoshikawa<sup>b</sup>, M. Sakamoto<sup>b</sup>,  
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Slow Alfvén wave in ion cyclotron range of frequencies (ICRF) has been used for ion heating in a mirror magnetic field configuration. It is excited in a plasma by coupling an oscillating current driven in an antenna to the wave fields. Only the wave that satisfies the dispersion relation and the boundary condition is possible to be excited. In practice, since the antenna is normally located outside of the plasma, screening of the externally applied field becomes problematic to excite the wave when the electron density increases; the coupling of the wave fields especially in the core region degrades with the increase of the electron density.

There is a demand for a DEMO fusion reactor relevant divertor plasma fluxes in a linear plasma device to study divertor physics and plasma-wall interactions. Recently, ion heating of a high density helicon plasma by a slow Alfvén wave has been tried in proto-MPEX and the increase of the ion temperature was confirmed at the plasma periphery [1]. In the GAMMA 10/PDX central cell, ion heating experiments using a slow Alfvén wave were performed under higher electron densities than the typical one of  $2 \times 10^{18} \text{ m}^{-3}$  to study the effect of electron density on the wave excitation. The radial profile of the wave intensity was measured at five axial positions around the wave excitation antenna and the resonance region by using a microwave reflectometer with antenna switching [2]. The screening effect on the wave excitation is discussed through the measured wave structures and the wave field calculations using the full-wave code TASK/WF.

This work was partly supported by the bidirectional collaborative research program of the National Institute for Fusion Science, Japan (NIFS14KUGM086 and NIFS17KUGM132).

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[2] R. Ikezoe et al., Rev. Sci. Instrum. **88** (2017) 033504.

# Doppler spectroscopy system for the plasma velocity measurements in SMOLA helical mirror

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Suppression of the longitudinal particle and energy losses is treated as one of the main tasks for the next generation of the linear devices [1]. Main aim of the SMOLA device is to prove the concept of the helical mirror [2, 3]. This concept involves dynamic multiple mirror confinement. Variations of the helical magnetic field move in the frame of reference of the rotating plasma. Rotation is induced by the crossed radial electric and helical magnetic fields. The determination of the spatial distribution of the plasma velocity is necessary for constructing a model describing the motion of the plasma flow in a helical trap. The measurements of the plasma velocity by observation of the Doppler shift of the emission spectral lines H $\alpha$  are provided by high spatial resolution spectrometer [4].

In the spectrometric system based on the focusing spectrometer with a reciprocal linear dispersion of 0.1 nm/mm, a spatial resolution of 1.2 mm was attained. Accuracy of plasma rotation velocity determination is  $\Delta\omega \sim 10^5 \text{ s}^{-1}$ .

A set of experiments was carried out with the different configuration and amplitude of the magnetic field. The plasma emission spectra in the vicinity of the H $\alpha$  line were obtained in the regime of a forward and backward magnetic field. In this case, difference in Doppler shift in the different spatial regions is observed. This indicates the presence of plasma rotation in the expander of the device.

The radial distribution of the Doppler shift of the H $\alpha$  line is used to calculate the velocity of neutral hydrogen, which gives an estimate of the plasma rotation velocity  $\omega \approx 10^6 \text{ s}^{-1}$ . The indicated velocity corresponds to the presence of a radial electric field  $\sim 70 \text{ V / cm}$ .

Dependence of the plasma rotation velocity on the radial profile of the electrostatic potential is discussed. Potential is driven by the biases of the radially segmented end-plates.

The results of this optical diagnosis to determine the velocity when plasma receiver and limiters have arbitrary potential and the plasma dynamic motion will be presented in the report.

[1] A. D. Beklemishev, P. A. Bagryansky *et al.*, *this conference*.

[2] A. D. Beklemishev, *Fusion Sci. Technol.* No. 63(1T) (2013) 355-357.

[3] A. V. Sudnikov *et al.*, *Fusion Eng. and Design.* No. 122 (2017) 86-94.

[4] I. A. Ivanov *et al.*, *General Experimental Technique.* No.2 (2016) 100-105.

# Study of the plasma parameters in the D-module of GAMMA 10/PDX during impurity gases injection

M. S. Islam, Y. Nakashima, A. Hatayama<sup>a</sup>, H. Matsuura<sup>b</sup>, T. Iijima, K. Ichimura<sup>c</sup>, M. M. Islam, T. Yokodo, T. Yoshimoto, S. Yamashita, T. Hara, K. Nojiri, A. Terakado, M. Yoshikawa, N. Ezumi and M. Sakamoto

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In GAMMA 10/PDX, divertor simulation experiments have been performed by using a divertor simulation experimental module (D-module) [1-3]. In the D-module of GAMMA10/PDX, a V-shaped target made of tungsten has been installed. A set of Langmuir probes and calorimeters has also been installed at the upper and lower plates, respectively, of the V-shaped target for simultaneous measurement of the particle and heat fluxes. The radiator gas Kr has been considered as one of the promising radiator gas for generating the detached plasma in the divertor region of the future fusion devices. Krypton (Kr) gas has been seeded into the divertor region of many tokamak devices to investigate the radiation cooling effect of Kr. However, the detailed physical mechanism has not been investigated so far. The simple geometry of the GAMMA 10/PDX can help us to understand the detailed physical mechanism of plasma detachment during Kr injection. Therefore, Kr gas has been recently seeded into the D-module for understanding the detailed physical mechanism related to the plasma detachment in the case of Kr injection. Plasma parameters in the D-module have shown a clear dependence on the Kr gas pressure. The heat flux reduces according to the increment of Kr injection. The ion flux also reduces with the increasing Kr injection. In the initial stage of Kr injection, the electron density increases due to Kr injection. The electron density reduces with the increasing Kr injection. The electron density shows a roll-over phenomenon. The electron temperature reduces to about 2 eV by only Kr 400 mbar injection. The visible emission from the Kr-plasma interactions has also been studied by using the spectrometer. The emission from the Kr ions in the D-module reduces with the increasing gas injection, which indicates that the ionization processes suppress significantly. These results indicate the importance of Kr injection for generating the detached plasma in the divertor region.

The ionization potential and radiation cooling rate of Kr is placed between Ar and Xe. In the present D-module experiment, Kr shows the intermediate performance between Ar and Xe. The reduction order of ion flux, heat flux and electron temperature at the corner of the target plate is found to be  $Ar < Kr < Xe$ . These outcomes are consistent with the atomic database of the gases. The plasma behavior in the end-cell during Kr seeding has also been studied numerically by using the multi-fluid code "LINDA" [4-5]. The simulation results also show a promising agreement with the experimental outcomes. More detailed discussion will be presented at the conference presentation.

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## Future perspectives and status of magnetic mirror studies in Novosibirsk

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The paper reviews the present status of studies on magnetic mirrors in Novosibirsk. The lessons learned from previous generation of the mirror machines, such as AMBAL, GOL-3 and GDT are discussed. The main challenges on the way to achieve higher electron temperatures and better plasma confinement are considered. Possible approaches how to further improve the plasma parameters towards mirror-based fusion neutron source [1], fission-fusion hybrid and mirror-based fusion reactor with advanced fuel are formulated. The paper also discusses the project of the next-step mirror device, gas-dynamic multi-mirror trap (GDMT) [2], and the program of the supporting experiments in Novosibirsk.

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# Plasma particle trajectory study for a device combining hollow cathode discharge and non-adiabatic trap

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Boron Neutron Capture Therapy (BNCT) is a treatment for new cancer. BNCT is a cancer treatment method using nuclear reaction of boron and neutron. In order to obtain the neutron flux intensity required for BNCT, it is necessary to design and develop an ion source that can stably supply deuterium ions to the reaction vessel. Therefore, in this study, we study the suitable structure of the electric and magnetic fields for the ion source by calculation of plasma particle trajectory.

A rod-like anode was placed at the end of the device, and a cylindrical cathode was arranged in the center of the device. The anode has a radius of 0.0047 m and the cathode has 0.089 m. The potential difference between the anode and the cathode was set to 200 V. A Helmholtz coil was placed in the apparatus to generate a uniform magnetic field by the solenoid coil arranged outside the device and select the trapping and passing particles according to their energy. The vector potential was calculated based on the solenoid coil and the Helmholtz coil current, and this was spatially differentiated to obtain the magnetic field inside the device. The resultant magnetic field structure is an open-ended magnetic field. Five 15 coils with a radius of 0.15 m were installed between 0.3 m of the solenoid coil and the current was 1.0 kA. The Helmholtz coil had a radius of 0.12 m and the current was 5.72 kA so as to weaken the magnetic field of the solenoid coil. Deuterium ion was placed in the center and the trajectory was calculated by numerically integrating the equation of motion. For the particles colliding with the cathode and the particles reaching the end of the device, the trajectory calculation is terminated at that point.

The object of the proposed apparatus is to trap only low energy ions with a radial magnetic field and perform particle selection by a magnetic field structure that cancels the axial magnetic field by the solenoid coil with the magnetic field by the Helmholtz coil. It was confirmed that particles were selected according to the generated weak magnetic field region. Furthermore, in order to consider the effect of the sheath in the vicinity of the cathode arranged in the device, a modeled charge density is introduced and an electric field is calculated. We confirm the change of the particle trajectory by the sheath effect and report it at the conference.

# Measurement of end-loss ions originated from spontaneously excited high frequency waves by using an MCP detector on GAMMA 10

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In the central cell of GAMMA 10 tandem mirror, owing to ion cyclotron range of frequencies (ICRF) heating, ion temperature perpendicular to magnetic field line,  $T_{i\perp}$ , reaches several keV and the anisotropy which is defined as a ratio of the temperature in the perpendicular direction to the temperature in the parallel direction to the magnetic field line becomes more than 10. Under such condition, Alfvén-Ion-Cyclotron (AIC) waves are spontaneously excited in the frequency range just below the ion cyclotron frequency. The AIC waves have several discrete peaks in the frequency spectrum and the difference frequencies between each peak are around 100 kHz. It is clearly measured with a microwave reflectometer installed in the central cell that waves with the difference frequencies of the AIC waves are excited strongly in the core region [1]. In addition, it has been observed that high-energy ions are transported to the end region along the magnetic field lines with the same frequencies as difference frequencies of the AIC waves [2]. In this study, in order to understand the physics of this wave-particle interaction in more detail, we have developed east end-loss high-energy ions detector using micro-channel plate (eeMCP). The eeMCP equips ion retarding grid and secondary electron repeller. Ion retarding voltage can be varied up to 7 kV at present. Incident electrons are repelled by making use of the accelerating voltage of MCP of about -2 kV. The eeMCP can measure high-energy ions in relatively lower energy band than an existing measurement instrument using semiconductor. We measured the high-energy ions at plural radial positions with the eeMCP.

It is observed in the experiment with eeMCP that intensities of the high-energy ion fluctuations in the same frequencies as the difference frequencies near the plasma axis are significantly higher than those at the peripheral region. It is suggested that a radial dependence of the end-loss caused by the fluctuation with the difference frequencies among the AIC waves.

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# Application of He I Line Intensity Ratio Method to Lyot-Filter Based Imaging Spectrometry on MAP-II Divertor Simulator

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Spectral line intensity ratios [1] of atomic helium, "ash" of a slowed-down fusion product, has widely been applied, in combination with a collisional-radiative (CR) model [2], to the measurement of the electron temperature  $T_e$  and electron density  $n_e$ , in divertor/edge plasma of fusion reactor and linear divertor simulators. In particular, since the plasma parameters have spatial distribution, the needs of applying this method to an imaging spectrometry are becoming high.

We have developed an imaging spectrometry using a spectra camera, which consists of wavelength-tunable interference filter known as "Lyot filter (Varispec: VIS-7-20)" and CCD camera [3,4]. The Lyot filter is a type of birefringent filter based on polarization interference between multistage optical units. The wavelength tunability is achieved by varying the retardance of the nematic liquid crystals in each unit. The pass-band width had a full width at half maximum (FWHM) of 2–14 nm, and the transmittance was a maximum of about 20% in the tunable range of 400–720 nm. It means that the widely used He I line 728 nm ( $2^1P - 3^1S$ ) cannot be used.

In this paper, we propose practical combinations of spectral lines without 728 nm, intending to apply to the Lyot filter imaging spectrometry. Experiments are conducted for the low-temperature helium plasmas produced in the MAP-II (material and plasma) linear divertor simulator[5], that has been moved from the University of Tokyo to Tsukuba University in 2014.

The following group of three lines, 471( $4^3S$ ), 587( $3^3D$ ) and 706( $3^3S$ ) nm where enclosed in parentheses is the upper state of the transition, was found to be less sensitive to the radiation trapping. Such combination is robust against the assumption of the degree of radiation trapping, characterized by the equivalent trapping radius in Otsuka-Iida formula [6]. The following group of five lines, 471( $4^3S$ ), 501( $3^1P$ ), 587( $3^3D$ ), 667( $3^1D$ ) and 706( $3^3S$ ) nm, on the other hand, is sensitive to the radiation trapping so that it is possible to determine the trapping radius as well as  $T_e$  and  $n_e$ , unless the least square fitting to the evaluation function converge.

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# High-pressure limit of equilibrium in axisymmetric open traps

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Theoretical estimates show that in order to achieve fusion parameters in gas-dynamic trap an extremely long system is required. However, the recently proposed diamagnetic confinement regime at high beta allows significant reduction in reactor length due to improved confinement. Analytical equilibrium-transport model of plasma in this regime using the paraxial approximation was presented in Ref. [1]. The diamagnetic confinement regime is proposed as a possible part of the GDMT program [2]. However, one conclusion of paper [1] was that in the high-beta limit of plasma equilibrium there will appear non-paraxial areas, so that the analytic theory has limited applicability. Thus, the need of building more accurate model arose. Strong nonlinearity of the equilibrium-transfer equations in the non-paraxial case requires application of numerical methods.

In this work we used a simple theoretical model of plasma equilibrium and transport, consisting of the Grad-Shafranov equation and the particle transport equation, while the temperature is considered constant. In order to take into account the anisotropy of the plasma pressure, which always occurs in mirror traps, this model was also extended. In the presence of the anisotropy, the transverse plasma pressure was assumed to depend on the magnitude of the local magnetic field. In practice this dependence can vary since it is influenced by the presence or type of the neutral beam injection. The system of equilibrium and transport equations is modified and now includes corrections related to the pressure anisotropy.

A numerical solution algorithm for a given model dependence of the transverse plasma pressure on the amplitude of the magnetic field is developed. Numerical solutions corresponding to the diamagnetic confinement are constructed. They are in good agreement with analytical estimates based on [1]. Analysis of the solutions is carried out, in particular, the effect of the inhomogeneity of the vacuum field on the equilibrium is investigated. This allows formulation of requirements on amplitude of ripple fields in GDMT.

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## Evaluation of electron density and space potential using ion sensitive probe in D-module of GAMMA 10/PDX

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The divertor simulation experimental module (D-module) installed in the end loss region of the tandem mirror device GAMMA 10/PDX is utilized to study such as detached plasma and impurity transport [1]. Since the generated plasma in GAMMA 10/PDX has high ion and electron temperature, investigation of energy balance between ion and electron in detached process is important.

We have measured electron temperature and density, space potential as well as ion temperature by using two Ion Sensitive Probes (ISPs) placed inside and inlet of D-module. Radial position of the inlet probe is variable. The ISPs consists of two electrodes, a guard electrode and an ion collector electrode [2]. Ion temperature is measured by probe current-voltage ( $I$ - $V$ ) characteristics of the ion collector electrode. Electron temperature and density, space potential are obtained by  $I$ - $V$  characteristics of the guard electrode.

As results during detached plasma operation in GAMMA 10/PDX, electron temperature measured by the guard electrode of ISPs showed almost same to the value of LPs placed near the ISPs. However, the space potential actually measured by the guard electrode is found to be smaller than evaluated potential by LP in both the inlet and the inside. In addition, it was found that effective electron collection area for electron density measurement is smaller than the surface area of guard electrode comparing the LP measurement. These results might be caused by the influence of incident angle of magnetic field line and small Larmor radius of electrons comparing with the dimension of the guard electrode which is flush with outer ceramics tube of the ISP.

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# Time behavior of perpendicular velocity of density fluctuations with a series of electron cyclotron heatings in GAMMA 10

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Doppler reflectometry is a powerful technique to measure the perpendicular velocity of density fluctuations in magnetically confined plasma. In this technique, the frequency spectrum of backscattered wave of an order  $m \neq 0$  is observed caused by an obliquely launched microwave beam against a cutoff layer. Doppler frequency shift appeared in the spectrum is proportional to the perpendicular velocity of fluctuation/turbulence in plasma.

In GAMMA 10 a Doppler reflectometer [1] has been installed and used to measure azimuthal plasma rotation velocity in the central cell. It uses X-mode microwave (11.5-18 GHz) to probe the radial peripheral region of the plasma with typical peak density  $\sim 2 \times 10^{18} \text{ m}^{-3}$ . The reflectometer has a launching/receiving antenna system with focusing mirrors. The tilt angle of the incident microwave can be changed by rotating one of the mirrors.

In this work, a partially overlapping series of electron cyclotron heatings (ECH) called barrier ECH and plug ECH was applied to plasma produced by ion-cyclotron range of frequency (ICRF) waves. Time behavior of azimuthal velocities of density fluctuations was investigated in the peripheral region by the Doppler reflectometer in the central cell. Frequency spectra showed red shift feature indicating the electron diamagnetic direction of rotation by applying only barrier ECH. When both barrier and plug ECHs were applied smaller shift to lower frequency or unclear shift was observed comparing to barrier or plug ECH alone. On the other hand, during only plug ECH period the direction turned to blue shift, *i.e.*, the ion diamagnetic direction.

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# Stability of Drift-Cyclotron Loss-Cone and Double-Humped Modes in Multispecies Plasmas

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The concept of a neutron source based on a gas-dynamic trap (GDT) has been developed at the Budker Institute of Nuclear Physics for a number of years. Such a source can be used for materials science studies. It can also serve as a radioactive waste afterburner or subcritical nuclear reactor driver. An essential feature of the source is that it has a population of hot ions created by inclined injection of powerful atomic beams into the target warm plasma. Hot ions are confined in an adiabatic regime, which is characterized by an emptying of the loss cone.

At the GDT facility, parameters have already been reached that allow creating a neutron source for materials science applications. With some extrapolation of the GDT parameters, it is possible to create a subcritical reactor driver [1]. However, on the way to such extrapolation, there is a danger of the growth of potential oscillations of the Drift-Cyclotron Loss-Cone (DCLC) type [2]. This instability arises because of the empty loss cone in the population of hot ions in combination with the radial density gradient of the plasma. It generates potential oscillations, which are stretched along the lines of the magnetic field, run along the azimuth and have a frequency near the ion cyclotron one. The oscillations lead to anomalous scattering of ions and can provoke losses of particles and energy from the source of neutrons.

A method of stabilizing the instability of DCLC is known by filling the loss cone with warm ions. However, as the density of warm ions increases, a Double-Humped (DH) instability develops. To stabilize it, an increase in the temperature of warm ions is required, which contradicts the conditions for suppressing DCLC instability. In our recent paper [3], plasma parameters were found that are not only optimal from the point of view of neutron generation, but also exclude the excitation of DCLC and DH instabilities [3] in a plasma with one species of ions (namely, deuterium). There it was also suggested that a plasma consisting of few isotopes is more susceptible to instabilities of the DCLC and DH type.

The present paper is devoted to the search for conditions for the stabilization of a plasma with several types of ions, in particular, a mixture of deuterium and tritium. We chose neutron generator parameters and hot ion distribution functions based on the simulation results using the DOL numerical code [4]. To calculate the increments of unstable oscillations, we used the dispersion equation derived in the approximation of smallness of the wavelength in comparison with the radius of the plasma [3]. Based on the results obtained, we formulated a rule for selecting the parameters of a population of warm ions. It states that for effective stabilization of the DCLC and DH, the temperature of warm ions should exceed a certain value, and the spectrum of harmonics of cyclotron frequencies of warm ions should overlap all cyclotron harmonics of hot ions.

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# Overview of recent plasma-material interaction studies in the linear plasma device PSI-2

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Plasma-material interaction studies on the linear plasma device PSI-2 are focused 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 (RAFMs) steels.

Depending on individual tasks, material samples were exposed either to pure deuterium or noble gas or mixed species plasma. Exposure parameters were an electron density of  $\sim 10^{17}$ - $10^{19}$  m<sup>-3</sup>, an electron temperature of 3-20 eV, an ion flux to the target of  $\sim 10^{21}$ - $10^{23}$  m<sup>-2</sup>s<sup>-1</sup> 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<sup>-2</sup> by extending the duration of exposure. A Nd:YAG laser ( $\lambda = 1064$  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.

A reduction of sputtering of nano-structured surfaces of molybdenum and aluminium was observed in-situ by QMB, OES and the mass loss techniques. On molybdenum, fuzz structures were formed by helium at elevated target temperatures, while needle-like structures on aluminium were formed by deuterium. At an ion flux of  $\sim 1 \times 10^{22}$  m<sup>-2</sup>s<sup>-1</sup>, it typically took 30-60 min for the development of surface morphology resulting in a considerable (>25%) reduction in measured sputtering yield. For Mo, both QMB and SEM observed a continuous reduction of sputtering up to a factor of two after a fluence of He of  $4.3 \times 10^{25}$  m<sup>-2</sup>. For Al, sputtering reduced by 25% after a D fluence of  $1.5 \times 10^{25}$  m<sup>-2</sup>, but did not change significantly thereafter, indicating a saturation of the effect. By a target tilt and, therefore, a change in the incident ion angle, it was possible to efficiently remove the needle-like structure. The Al sputtering yield recovered to a value close to the initial.

The influence of plasma impurities on the deuterium retention in tungsten was studied. Following mixed plasmas were produced: pure D, D+0.03He, D+0.07Ar, D+0.1Ne, D+0.05N and D+0.03He+0.07Ar. The admixture of He reduced the D retention by one order of magnitude, while Ar increased it by about 50%. In the D+He+Ar case the effect was similar as for D+Ar. Ar probably sputtered the near-surface layer and thus overrode the effect of He. The effect of Ne appeared to be sensitive on the incident ion energy. Ne had an effect similar to Ar increasing the D retention for the ion energies above the sputtering threshold, while for lower energies its effect was less pronounced. Addition of nitrogen increased the D retention by a factor of  $\sim 10$  and  $\sim 100$  for 500 K and 770 K, respectively. Our experimental findings, i.e. the effect of Ar dominating over the effect of He and the influence of Ne depending on the incident ion energy, suggest that the competition of two processes, the creation of the porous near-surface layer and its erosion, may be the key to understanding the effect of non-reactive impurities, like Ar, Ne and He, on the D retention.

# Investigation of ICRF heating efficiency in plug/barrier cell on GAMMA 10/PDX with a full-wave code

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In the west end region on GAMMA 10/PDX, a tandem mirror plasma confinement device, divertor simulation experiments are carried out. In order to increase temperature and flux of the end-loss ions, which are utilized in the divertor simulation experiment, ion cyclotron range of frequency (ICRF) heating has been used in the west plug/barrier cell that is located next to the west end region [1]. Optimizing ICRF heating is important in order to further extend the operation regime of the divertor simulation experiment. The following two antennas are used for the ICRF heating in the west plug/barrier cell; Double Half Turn (DHT) antenna and Nagoya Type-III (Type-III) antenna. ICRF current in the DHT antenna flows in the perpendicular direction to the magnetic field line near the plasma surface. By contrast, the flowing direction of the current in the Type-III antenna contains parallel component near the surface in addition to that of DHT antenna. The preceding experiment with these antennas implies that the direction of current, parallel or perpendicular to the magnetic field line, applied on antenna affects the efficiency of the wave excitation and the ion heating. In general, the antenna location is also effective for ion heating. In order to optimize these parameters, the absorbed power at the ion cyclotron resonance region was evaluated by using a full-wave code TASK/WF[2]. In addition, these results were compared with the results of the ICRF heating experiment in the plug/barrier cell.

TASK/WF code solves the Maxwell's equations with finite elements method. In this code, cold plasma including collisional effects is assumed in order to simulate power absorption. We applied this code to the west plug/barrier cell on GAMMA 10/PDX and analyzed the propagation and damping of the ICRF wave. In this study, efficiency of the wave excitation was evaluated in terms of intensity of L-waves, of which electric fields are polarized in the same direction of ion cyclotron motion. In addition, the absorbed power at the ion cyclotron resonance region was evaluated as efficiency of ion heating.

We compared the efficiencies of the wave excitation and the ion heating between the DHT antenna and the Type-III antenna based on experiments on GAMMA 10/PDX and simulations using TASK/WF code. In addition, we analyzed frequency and location dependence of the intensity of the L-wave and the absorbed power by using TASK/WF code. Moreover, additional experiments with a Type-III antenna newly installed at different location of the previous Type-III antenna were carried out in plug/barrier cell on GAMMA 10/PDX in order to demonstrate the above simulation results. The details of these experiments and analysis are discussed.

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# **An outlook into a possible ICCD based Thomson scattering system for high temperature plasmas**

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With experience gained on developing a triple-grating ICCD Thomson scattering system that samples 63 points along a 25 mm line [1], we have written a code to estimate the number of collected scattering photons. It is shown to match well with experimental measurements, and thus give confidence on the value of multiple elements (optical transmission, detector quantum efficiency, noise, etc.) that could provide useful information in designing similar Thomson scattering systems.

Using a grating and a 2D array detector allows to directly record the dispersion curve at multiple points. The ICCD unit comes with many convenient features, which become quite useful in terms of precise timing and digitization in addition to its compactness. Usually the final data is stored in an image file (tiff.), where analysis is conducted by using various software or program languages.

We focus attention on the possibility of applying a similar system to a more challenging measurement on high temperature plasmas of  $\sim 100$  eV. Due to the broad scattering spectrum alone, photons per pixel become much less and thus have to compromise of the most efficient optical system. The Thomson scattering system composes of three major components: laser, optics, and detector. Advancements in laser and optics seems to have reached a certain level. On the other hand, increasing demand on ICCDs have brought many technical advancements, which are essential to allow high temperature measurements in the near future.

[1] K. Y. Lee *et al.*, Rev. Sci. Instrum. **89**, 013508 (2018).



# Fast Ion Physics in the Advanced FRC

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Over the last two decades, fast ion physics research has been dominated by studies of Energetic Particle Modes (EPMs) and Alfvén Eigenmodes (AEs) in toroidal devices. Clear experimental signatures of both EPMs and AEs were observed in the advanced, beam-driven field-reversed configuration (FRC) C-2U at TAE Technologies [1,2], but these observations are beginning to stress theoretical models born in the tokamak world.

From a fast ion perspective, C-2U and its successor C-2W (aka “Norman”) are more akin to beam-injected mirror machines than tokamaks. Very large neutral-beam power densities and machine-sized fast-ion orbit radii distinguish the advanced FRC and mirrors from conventional toroidal devices. However, the closed field lines and high beta of the FRC core give C-2U/W an altogether unique character. Some aspects of the fast ion modes can be described through a synthesis of existing work, but a comprehensive picture will likely require new theoretical developments.

In this presentation we will begin this work by experimentally characterizing the fast ion modes using existing frameworks.

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- [2] H. Gota *et al.*, Nucl. Fusion **57**, 116021 (2017).

## Sensitivity check of background plasma parameter during SMBI in the GAMMA 10 central-cell by 3-D Monte-Carlo simulations

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In magnetically confined plasmas, the proper control of gas fueling is very important issue. The gas fueling by supersonic molecular beam injection (SMBI) which is very simple system has been performed in the world largest tandem mirror device GAMMA 10 and higher plasma density has been achieved compared with conventional gas-puffing [1, 2]. It is important to study the neutral transport during SMBI for optimizing fueling characteristics to the plasma. Three-dimensional Monte-Carlo code DEGAS is applied to GAMMA 10 in order to investigate precisely the spatial distribution of neutral particle density during SMBI [3-5]. In order to simulate the molecular beam injected by SMBI,  $\sigma_{div}$  is introduced as an index the divergence angle of the initial particle. If the angular profile of launched particles has a cosine distribution, it is defined to be unity. The simulation results well explained the GAMMA 10 SMBI experimental results. It is found that the particles are suppressed and localized in the injection point according to the reduction of divergence angle index,  $\sigma_{div}$ . The neutral particles behavior has been shown a clear dependence on the initial particle source. When the value of initial particle source is reduced, the simulation results are mostly similar with the experimental results. In this paper the simulation is carried out in the different profiles of electron temperature in order to check the sensitivity of the background plasma parameter. The simulation results indicate that the penetration depth depended on the background plasma parameter, electron temperature. It is found that the penetration depth increases with the decrease of electron temperature. The detailed results will be presented in the conference.

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- [5] M. M. Islam *et al.*, AIP Conf. Proc. **1771** (2016) 030018.

# Stochastic behavior and Lyapunov exponent analysis in non-adiabatic traps

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The adiabatic invariant of the charged particle motion is an amount that is substantially constant in a magnetic field with small spatial non-uniformity other than the constant of motion based on the space/time symmetry, for example, a magnetic moment. Therefore, non-adiabaticity of particle motion means that a large jump occurs in adiabatic invariant by particles feeling a large magnetic field variation during one cycle of gyration motion. The non-adiabatic trap in this study is a concept of confining particles by magnetic field configuration that cancels the magnetic field created by the solenoid coil on the axis of the cylindrical confinement device by the magnetic field of the Helmholtz coil. A wide weak magnetic field region is formed at the center of the device, and the charged particle motion traveling in the axial direction becomes non-adiabatic. Momota *et al.* proposed a new confinement concept in which non-adiabatic traps are connected in the axial direction [1]. The advantage of this concept is that the net confinement time is proportional to the square of the number of traps.

Adachi *et al.* analyzed the trajectory of charged particles in a non-adiabatic trap [2]. As a result of the trajectory calculation, when completely canceling the magnetic field created by the solenoid coil, it was found that there is a relationship between the particle trapping rate of the charged particle and the Larmor radius. Adachi *et al.* also analyzed the case that the current value flowing in the Helmholtz coil was changed and the magnetic field on the axis of the device was not canceled. As a result, we found a phenomenon that the particle trapping rate becomes smaller for particles of specific energy. However, the reason why the trapping rate decreases has not yet been clarified.

Therefore, in this study, the Lyapunov exponent analysis is performed in order to link the cause of the reduced particle trapping rate with the stochastic feature of particle motion. The Lyapunov exponent is an index quantitatively indicating the degree of stochasticity. Charged particles are deuterium ion beams and radially distributed on the edge of the device using random numbers following normal distribution. We calculated the trajectory while varying the beam diameter, beam energy and current of the Helmholtz coil to examine the particle trapping rate. The Lyapunov exponent of the charged particle was obtained for each changed condition.

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## Heat flux evolution in GAMMA 10/PDX divertor experiment

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In the GAMMA 10 tandem mirror, high heat-flux generation experiments (E-divertor) with high-power plasma heating systems and detached plasma formation experiments with additional impurity gas puffing have been conducted [1]. Heat flux from the end-mirror exit is estimated with calorimetric method. Total heat load from one plasma shot is easily estimated as the product of heat content of the calorimeter head and temperature jump by plasma discharge. But this method can not give us information on time evolution of head load during detached plasma formation.

Time response of the calorimeter thermocouple embedded in the calorimeter head material has been improved [2] and large noise in thermocouple signal during ICRF heating was successfully suppressed recently with insulation amplifiers and the shielding box. This makes it possible to monitor the temperature evolution during plasma shot, and two heat flux analyzing model, that is temperature gradient method [3] and pulse decompose method [4], were applied to this calorimeter data analysis. Both method gives us reasonable heat flux data during one plasma shot and their results agree very well. According to theoretical check of pulse decompose method, delay time, where plasma heat flux reaches to steady state value after plasma shot start, is too long compared with thermocouple response time. As for delay time after plasma shot termination, electromagnetic noise due to confinement magnetic coil current still remains and makes heat flux estimation less accurate. So quantitative discussion on heat flux evolution during a plasma shot with ICRF heating and on the response of ECH additional heating is still an ongoing issue.

In this work, particle flux data obtained with langmuir probes or end loss ion energy analyzer will be compared with heat flux data. This will give us insight on end mirror region plasma buildup delay to central cell plasma production. In order to achieve farther reduction of magnetic field noise effect, moreover, reference sensor to correct calorimeter thermocouple signal unrealistic jump is designed and tried. The first results of these work will be presented on the conference. This work is partially performed with the support and under the auspices of the NIFS Collaborative Research Program ( NIFS16KLPR032/NIFS16KUGM112 ).

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# Spectroscopic measurement of electron temperature and density from He I line intensity ratio in GAMMA 10/PDX

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A spectroscopic measurement of electron temperature and density of the divertor simulation plasma has been applied to GAMMA 10/PDX. In this study, we measured time evolution of electron temperature and density when the additional electron cyclotron heating (ECH) was applied to the main plasma that was produced and heated by ion cyclotron range of frequency (ICRF) waves. The intensities of three He I lines (667.8 nm, 706.5 nm, 728.1 nm) were measured at the divertor simulation experimental module (D-module) installed in the west-end region of GAMMA 10/PDX [1]. The electron temperature and density were evaluated from intensity ratios (He I (728.1 nm)/He I (706.5 nm) and He I (667.8 nm)/He I (728.1 nm)) [1, 2] in comparison with the collisional radiative (CR) model [3].

V-shaped target in D-module is exposed to the end-loss plasma and He gas is injected into the plasma from a gas injection port of the upper side of the target [4]. An optical fiber having the diameter of 200  $\mu\text{m}$  is located on the side of D-module. The field of view is set so as to observe near the center of the target. The light from the plasma is collected by a collimator lens attached in front of the fiber and transmitted to the spectrometer. The spectroscopic measurement system for He I lines on GAMMA 10/PDX consists of the lens, the optical fiber, the interference filter and the photo-multiplier tube. The relative sensitivity of the intensities of three lines has been calibrated using a standard lamp system. Langmuir probes are installed on the upper side of V-shaped target in D-module.

When the ECH was applied to the central plasma at 50 kW for 25 ms, the electron temperature of D-module estimated from this method continued to increase from 35 eV to 60 eV, then decreased to the original level after ECH with the decay time of about 20 ms. The electron temperature measured by the spectroscopic measurement before ECH was about 40 % higher than that of the Langmuir probe. During ECH the results of electron temperature of the spectroscopic measurement and Langmuir probes were corresponded. On the other hand, the electron density was evaluated to be  $2 \times 10^{17} \text{ m}^{-3}$  with large uncertainty and it was five times larger than the density that was evaluated by a Langmuir probe. The difference is thought to be caused by low electron density of plasma that could degrade the accuracy due to the low spectral intensity.

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# Generation and Measurement 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 field line. Heat flux during ECH injection corresponds to that more than 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. The flux and the energy spectrum of end loss electrons are measured by a multi-grid energy analyzer (loss electron diagnostics, LED). End loss electrons enter the analyzer through a small hole on an electrically floating end plate that is located in front of the end wall. The collector current of the analyzer corresponds to the electron current flowing into the end plate.

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 antenna 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, experimental results are presented in ECH power modulation by using new mirror antenna to control high intermittent heat flux in GAMMA 10 tandem mirror for the future divertor simulation studies.

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## Present status and future in GAMMA 10/PDX Project

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This paper describes an overview of the recent results and the future plan of GAMMA 10/PDX project. In the Plasma Research Center, we have started a project on divertor simulation research at the end-cell of GAMMA 10/PDX by making best use of the open magnetic field [1]. GAMMA 10/PDX is a large tandem mirror device and has capability of generating high heat flux plasma flow with high ion temperature ( $T_i = 100\sim 400$  eV) using high-power plasma heating systems such as ion cyclotron range of frequency (ICRF) and electron cyclotron (EC) waves.

To control the end-loss plasma for the divertor simulation experiments, several heating operations were performed using ICRF heating system in the central cell, the anchor cells, and the west plug/barrier cell. The excited waves are measured using the upgraded reflectometer system [2] and were calculated using the full-wave code. Experiments for characterization of detached plasmas have been successfully performed in the divertor simulation experimental module (D-module) [3]. By injecting various irradiator gases (Xe, Ar, Ne and N<sub>2</sub>), remarkable reductions of electron temperature, heat and particle fluxes were observed according to the gas throughput into D-module. Comparison in applied radiator gases showed that Xe is most effective on producing detached plasmas. Investigations of molecular processes such as MAR in D-module [4] and impurity transport behavior during plasma detachment are also performed by using high-speed camera and spectrometers.

Development of high-power gyrotrons and the application to the divertor simulation experiments are also important subjects in the GAMMA 10/PDX project [5-6]. Gyrotrons with the 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 by using newly designed antenna system at both plug/barrier cells attained the peak heat-flux value of  $\sim 30$  MW/m<sup>2</sup> at the west end-cell. The design study and development of double-disk sapphire window for CW operation of new 28/35 GHz dual-frequency gyrotron also has been progressed.

Recently development of advanced Thomson scattering (TS) system [7] was progressed. A YAG Thomson scattering (TS) system has been developed for measuring radial profiles of electron temperature and density (15 radial positions) in a single laser shot in the central cell. The laser amplification system was newly installed and we successfully improved the degraded laser power after six passes in the multi-pass system to the initial laser power.

In the presentation, recent activities in Plasma Research Center are shown together with the research plan of a newly proposed device which consists of axisymmetric mirror system.

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## Development of noise-less divergence-free magnetic probe system in GAMMA 10

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To clarify the mechanism of the low frequency fluctuation at the central region plasma which was found by fast cameras, it is desirable to measure the electric/magnetic fluctuation simultaneously with the fast camera measurement. In GAMMA 10 Langmuir probes were used to measure the electric potential and ion density, and usually their signals were obtained. The magnetic probes [1] were used for measuring the magnetic fluctuation in plasma (actually the derivative of the magnetic signal by using coil was measured), however the SN ratio was very small in the central region plasma.

The density of the central region plasma in GAMMA 10 is typically an order of  $10^{18}\text{m}^{-3}$ , and, the electron and ion temperature of that are a few hundred eV and a few keV (in case of ICRF heating), respectively. Therefore, there was low  $\beta$  plasma in GAMMA 10 central region, and the signals of the magnetic fluctuation are weaker than that of tokamak/ST and Heliotron plasmas. In fact the magnetic probe, of which coil was 50 turns, was used to measure the magnetic fluctuation signal in the central region plasma since a few years ago. Those coils are usually worked in Heliotron plasma. Last year new magnetic probe of which coil was 500 turns was used in GAMMA 10, and the magnetic probe signal was measured successfully, in spite of low frequency noise ( $\sim 50\text{Hz}$ ).

This time to reduce the (low frequency) noise without sacrificing sensitivity, also to rise the frequency limit of LC resonance circuit, the divergence-free magnetic probe system is designed. This system consists of the polyhedron covered with multiple coils. For example, if it is a cube, one coil is wound on each side and is covered with six coils. Ideally, if the number of turns of each coil is the same, the sum of the signals of each coil is zero. If 500 turns are necessary to get the magnetic fluctuation signal, the winding number of the coil on the both side shall be half of that. Using the sum and difference of these coil signals makes it possible to distinguish between magnetic signals and noise.

In the presentation detailed design are introduced.

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# Thermodynamic properties of ions in the end-region of GAMMA 10/PDX

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Understanding thermodynamic behavior of ions in an open magnetic field is necessary for the fusion science and plasma propulsion engines. The aim of this study is to clarify the thermodynamic variables of ions such as the adiabatic index ( $\gamma$ ), the temperature ( $T_i$ ), and flow velocity ( $V_i$ ) in a high  $T_i$  plasma in an open magnetic field.

The GAMMA 10/PDX is a tandem mirror device in which the plasma has higher  $T_i$  than electron temperature ( $T_e$ ). It is composed of a central cell, anchor cells, barrier cells, plug cells and end regions. The end regions have an open magnetic field. A Langmuir probe (LP) and an ion energy analyzer (IEA) are installed in the west end region. The position of the IEA is downstream of the LP. The magnetic field at the position of the LP and the IEA are  $\sim 0.2$  T and  $\sim 0.01$  T, respectively. By using the LP, we evaluated  $\gamma T_{i\parallel}$  following the measurement principle in which ion flux density can be written as  $0.6n_e((\gamma kT_{i\parallel} + kT_e)/m_i)^{1/2}$  [1]. The electron density ( $n_e$ ) was derived from the electron saturation current. The ion temperature and flow velocity parallel to the magnetic field ( $T_{i\parallel}$  and  $V_{i\parallel}$ ) were evaluated by using the IEA. We compared  $\gamma T_{i\parallel}$  evaluated by the LP ( $\gamma T_{i\parallel,LP}$ ) with  $T_{i\parallel}$  evaluated by the IEA ( $T_{i\parallel,IEA}$ ).

Plasma parameters such as  $T_{i\parallel,IEA}$  were varied by changing ICRF heating applied at upstream cells. The ion temperature  $T_{i\parallel,IEA}$  increased from  $\sim 140$  eV to  $\sim 280$  eV. At the position of LP,  $T_e$  increased from  $\sim 20$  eV to  $\sim 30$  eV,  $n_e$  decreased from  $\sim 3 \times 10^{16} \text{ m}^{-3}$  to  $\sim 1 \times 10^{16} \text{ m}^{-3}$ , and  $\gamma T_{i\parallel,LP}$  increased from  $\sim 150$  eV to  $\sim 650$  eV. Evaluated  $\gamma T_{i\parallel,LP}$  increased with  $T_{i\parallel,IEA}$  but they were not in a proportional relationship. It seems that downstream  $T_{i\parallel}$  increases with upstream  $T_{i\parallel}$ . In the presentation, the difference in value between  $\gamma T_{i\parallel,LP}$  and  $T_{i\parallel,IEA}$  and the value of  $\gamma$  are discussed from the point of view of conservation of magnetic moment by comparison among experimental results and simulation results using a plasma fluid model incorporating the anisotropic ion pressure [2] and a particle model [3].

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## Code development for the calculations of the electron beams 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. They have been known as attractive sources of high power millimeter and submillimeter waves for electron cyclotron heating (ECH) and current control of magnetically confined plasmas in controlled fusion research. For this purpose, gyrotrons operating in the quasi-continuous regime with a pulse duration in the frequency range 10–300 GHz and with an output power of  $\sim 1$  MW and higher are required. Recently, many studies[1,2,3] have devoted to high-power and long-pulse gyrotrons. Multi-frequency gyrotrons are desired for experimental flexibility and research collaborations in the present devices and are indispensable in the Demo reactor.

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. The efficiency and limiting attainable parameters of gyrotrons are determined by the quality of the electron beam formed in them. For high-power gyrotrons, electron beams are required in which high values of current and electron oscillatory energy are combined with a small velocity spread and the required transverse structure of the beam. The efficiency and output power of gyrotrons are significantly restricted by spreads in the transverse velocity and structure of the beam. For the gyrotron development in the future plan, the computing code for the interaction of the electron beam with many modes in the waveguide-cavity gyrotron oscillators has been developed. Several studies have shown that several types of the fluctuation of the electron beam in nonuniform magnetic fields and in crossed fields can play a role and their study is important for understanding a number of phenomena which can affect beam quality. The optimum design of the resonant cavity for gyrotron oscillators requires the analysis of the fluctuation.

The present code calculates the cavity RF profile function by solving the set of the relativistic single-particle equations of motion and generalized telegrapher's equations simultaneously to reach a self-consistent solution in the dynamic system that takes into account the effects of the fluctuation of the electron beam. 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.

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# Study of Spoof Plasmon Formed on Periodically Corrugated Metal Surface Based on Cavity Resonance Method

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Metamaterials like grating or the corrugated wall have a surface with sub-wavelength structures, which form plasmon polariton-like surface modes [1]. This kind of surface wave is called spoof plasmon and considered the microwave and THz equivalent of optical surface plasmon polaritons for metals. For surface plasmon polaritons, the dispersion characteristics are fixed by the physical property of metal surface. On the other hand, spoof plasmons due to the periodic structures can be controlled by parameters of structure [2], and may be very useful for electromagnetic generations and waveguiding up to terahertz wave. Spoof plasmons are now attracting attention in widespread applications, especially in the terahertz application areas, such as plasma heating, plasma diagnostics, telecommunication systems, radar systems, and material research. And the highly confined guiding of spoof plasmon has been verified using a planar plasmonic metamaterial [3]. For a cylindrical geometry, the boundary condition on the side ends of planar corrugation is replaced by an azimuthally periodic condition in the cylindrical coordinate system, resulting in cylindrical spoof plasmons [4].

In this work, we study properties of spoof plasmon due to corrugated structures on cylindrical metal surface. Since this surface wave is propagating along the metal surface and are reflected at the structure ends, a resonator is formed in the same way as the conventional waveguide cavity. And hence, the surface-wave resonator can be used to examine properties of surface wave by employing a cavity resonance method, in which the microwave reflection and/or transmission are measured as a function of frequency by a network analyzer [5]. Discrete resonant modes are measured by exciting the surface-wave resonator with antennas utilizing coupling between the surface plasmon polariton and spoof plasmon. The dispersion characteristics and the reflections of spoof plasmon on the corrugation are examined by comparing numerical and experimental results.

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# Performance Test of 28/35 GHz Dual-Frequency Gyrotron for CW Operation

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Gyrotron is a high-power millimeter source mainly used for electron cyclotron heating (ECH). At the Plasma Research Center (PRC) of the University of Tsukuba, a 28/35GHz dual-frequency gyrotron has been developed for the collaborative research on the plasma heating and current drive [1]. For the GAMMA 10/PDX and the National Spherical Torus Experiment (NSTX-U) of the Princeton Plasma Physics Laboratory (PPPL), a 28 GHz gyrotron with an output power of 1.5–2 MW for several seconds is required. For the Helical-Axis Heliotron (Heliotron J) of the Kyoto University, a 35 GHz gyrotron with an output power of 1 MW for several seconds is needed. The Q-shu University Experimental with Steady-State Spherical Tokamak (QUEST) of the Kyushu University requires a 28 GHz 0.4 MW Continuous Wave (CW) gyrotron. This high power and CW operational dual-frequency gyrotron satisfies the above requirements.

In order to enable CW operation, the output window of the gyrotron is a sapphire double-disk window flowing a fluorocarbon coolant between two sapphire disks. The sapphire disks of the output window are heated by dielectric loss. The temperature of sapphire disk must be kept below a boiling point of the coolant. Two-dimensional non-steady-state heat conduction analysis shows that CW operation is possible with a heat transfer coefficient of more than 1500 W/m<sup>2</sup>K. The cooled surface temperature of sapphire disk is saturated under 80 °C which is lower than the boiling point of the coolant.

To investigate the characteristics of the window experimentally, we measured the temperature evolutions at the center of output window surface with infrared (IR) camera. The temperature rise during oscillation of 0.45 MW 2 s and the temperature decay after oscillation were measured at each coolant flow rate of 10, 20, 30, 40, and 50 L/min. By comparing the calculation results with the measurement ones, surface heat transfer coefficient  $h$  was evaluated for each flow rate. As a result, when the flow rate is 30 L/min or more, it is indicated the 0.4 MW CW operation at 28 GHz is possible.

This work was partially supported by the NIFS collaborative program (NIFS16KUGM106 and COD29746) and the grant-in-aid for scientific research from the Ministry of Education, Science, Sports and Culture of Japan (26249141 and 15H05770B).

[1] T. Kariya, T. Imai, R. Minami *et. al.*, Nucl. Fusion **55** (2015) 093009

# Development of a high-density plasma in converging field following a magnetic beach plasma source

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Plasmas in open field lines, which are connected to that in production and heating regions via converging magnetic field configuration in linear devices, are applied to studies on divertor plasma physics, plasma material interaction, energetic ion and wave interaction. In terms of electron energy controllability, the electron cyclotron resonance (ECR) with magnetic beach configuration has advantage for the plasma source. We have developed such an linear device with an ECR plasma source[1]. While the first plasma was successfully produced, a transition phenomenon was observed in the ion saturation current. In order to establish a high-density operation required for divertor plasma and energetic ion studies, utilizing the transition phenomenon is significant. In this presentation, investigation of the phenomenon and characterization of the plasma in converging field region are described.

The experiments were performed using a linear plasma device, Nagoya University Magnetoplasma Basic Experiment (NUMBER), which consists of an ECR plasma production region with 2.45 GHz microwave power supply and a test region supplying target plasmas for study on divertor plasma and energetic ion. The former requires about 0.1 T of magnetic beach configuration, while the latter supplies up to 0.3 T of uniform field. Those two regions are longitudinally connected to each other. Since the magnetic beach configuration matches with the ECR condition, a local minimum magnetic field of about  $\sim 0.05$  T exists in between these two regions making a magnetic mirror before entering the test region. The magnetic coil current for the test region is supplied by a pulse operated power supply, flat top duration of which is about 4 ms. Langmuir probe measurements are applied both in the production region and the test region.

Helium plasma was produced. The electron density  $n_e \sim 1 \times 10^{18} \text{ m}^{-3}$  and temperature  $T_e \sim 5$  eV were obtained in the test region for the flat top time. Measurement of the ion saturation current showed that rapid increase / decrease of ion saturation current as the magnetic field strength in the test region changes. The transition occurred simultaneously both in the production region and the test region. The ion saturation current stayed higher value when the magnetic field strength in the test region was higher than that in the production region. The electron density was higher for the higher ion saturation current phase, while the temperature kept almost constant. Steep density gradient was found in radial profile of plasma column, which was appeared when the outermost field line connected the production region and the test region. Formation mechanism of the higher ion saturation current phase is considered in terms of plasma production and transport along the converging field line.

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## Neutron spectrometer based on stilbene scintillator.

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Neutron diagnostics are an important tool for determining fusion power, power density, plasma ion temperature in DD fusion experiments. Furthermore the neutron spectrometer is an important tool for determining the relative power released in each of the reactions (DD reaction and DT reaction) in the forthcoming experiments with DT plasma. The concentration of deuterium and tritium in the plasma can be estimated using this technique. Thus, it is important to create a neutron spectrometer at an energy range from 1 MeV to 15 MeV.

An additional complication in the neutron spectroscopy experiments is that the contribution to the signal is provided by the x-ray emission from the plasma and gamma ray formed, for example, as a result of (n, $\gamma$ ) reactions. One of the methods of reducing the contribution to the measurements is to use organic scintillators, in which the shape of the light flash depends on the type of registered particle: neutrons, alpha particles and gamma rays have different decay times in stilbene, p-terphenyl, liquid scintillators NE213, BC501. The analysis of the pulse shape makes it possible to register the spectra separately for particles of each sort.

A neutron spectrometer based on a single-crystal stilbene scintillator (size: d=30 mm, L=30 mm), PMT 9266B and FPGA was developed in the laboratory. Such a spectrometer operates in real time with the separation neutron and gamma events. The frequency gradient analysis [1] is implemented for the separation of events, and the error in the separation method is less than methods based on the analysis of the shape of the pulse. It is shown that events can be confidently discriminated: the fraction of events identified incorrectly does not exceed 0.1% for gamma-ray energy corresponding to <sup>137</sup>Cs energy (which corresponds to a neutron energy of  $\sim 1.5$  MeV). The FOM = 1.2 (separation criteria) was obtained for mixed neutron gamma AmBe source. Neutrons from 1.5 MeV to 10 MeV were registered. Gamma rays from 0.4 MeV to 4.2 MeV were registered.

Energy calibration of the detector was carried out: radionuclide sources of gamma rays (<sup>133</sup>Ba, <sup>137</sup>Cs, <sup>22</sup>Na, <sup>60</sup>Co), and mixed neutron and gamma ray (<sup>232</sup>Cf and AmBe) was used. A calibration by the DD and DT neutron sources was carried out in addition. The report will show the spectra of 2.45 MeV and 14 MeV neutrons, measured simultaneously. The energy resolution of the detector will be presented. The registered count rate is  $2 \cdot 10^5 \text{ sec}^{-1}$  (in real time operation regime). In addition, the report will provide data on the measurement of 2.45 MeV neutrons in the Gas dynamic trap device.

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# Observation of plasma MHD activity on GDT by charge exchange atoms

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An important task of the Gas Dynamic Trap (GDT) experiments remains physics of fast particles. Population of fast particles is formed in the plasma as a result of neutral beam injection heating. The distribution function of fast particles is strongly anisotropic in velocity space and it is determined by the angular spread of the NBIs ( $\sim 5^\circ$ ), the deceleration of fast particles by electrons ( $\tau_{ei}$ ), and the scattering by ions ( $\tau_{ii}$ ). The characteristic times of these processes exceed the duration of the NBI heating (5 ms), and the ratio of the times  $\tau_{ei} / \tau_{ii}$  less than 1, thus the particles retain a narrow angular distribution throughout the plasma experiment.

Thereby, the GDL plasma possesses parameters of the thermonuclear range, and contains a population of highly anisotropic fast ions. The density of fast particles can exceed the density of the target plasma in some experimental conditions [1]. Anisotropy of the distribution function leads to the appearance of micro-instabilities, for example, Alfvén ion cyclotron, which, however, does not lead to a significant loss of fast particles [2]. The possibility of plasma confinement with plasma  $\beta$  up to 0.6 [3] is demonstrated, the formation of a relatively narrow radial profile of fast particles is shown [4]. Stabilization of MHD activity in conditions with maximum plasma parameters is realized by creating a layer of shear flow rotation at the periphery of the plasma [5].

The complex of fast particle diagnostics was supplemented by multichannel monitors of charge-exchange atoms. Diagnosis is realized according to the scheme of pinhole camera. AXUV photodiodes and experimental avalanche diodes [6] are used as sensitive elements in the diagnostics. Such diodes have a thin dead layer and allow us to detect particles with energies above 1 keV.

First detector located near the center of GDT and observing the plasma at the pitch angle of the fast particles makes it possible to obtain the ratio of the signal from radiation to the signal from particles  $10^{-4}$ . It is provided by strongly anisotropic distribution function of fast ions and using artificial target (Heating beams are used as artificial target with stable parameters in this case). The second detector is located near the mirror point, where the density of fast particles can exceed the density of the target plasma.

It will be shown evolution of fast particle emission as a result of MHD oscillations and plasma disruptions. It is shown that the flux of fast particles is modulated with a frequency of plasma shear flows [5]. The experimental data will be compared with the results of modeling. The model takes into account active target produced heating beams in the central plane of the GDL, residual gas concentration, the shear flows of the plasma and fast particle loss as a result of these processes.

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# First Plasma in Start Configuration of GOL-NB Multiple-Mirror Trap

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The conceptual design of the GDMT reactor-grade next-generation open trap is under development in the Budker Institute of Nuclear Physics [1]. The GOL-NB program was introduced at the Open Systems - 2014 [2] as the support experiment that should improve physical knowledge base on the multiple-mirror confinement. Physics and hardware of GOL-NB was discussed in more details in [3]. The assembly schedule of the device supposes the first plasma and the first experimental session to be achieved in a reduced start configuration that was assembled in the spring of 2018.

The final configuration of GOL-NB will include a 2.5-m-long central gasdynamic trap with the magnetic field of  $B_{\min} = 0.3 - 0.6$  T in the midplane, two attached multiple-mirror sections of 3 m each with  $B_{\max} = 4.5$  T (this gives the mirror ratio  $R = 15$  for  $B_{\min} = 0.3$  T and  $R = 7.5$  for  $B_{\min} = 0.6$  T), and two end magnetic flux expanders that house a start plasma creation system, plasma receiver endplates and a system of biased electrodes for plasma stabilization. Plasma will be heated by two 0.75 MW, 25 keV neutral beams. The device replaces the previous GOL-3 multiple-mirror solenoid and reuses some of its hardware and infrastructure.

The start configuration of GOL-NB includes both expander tanks, a start arc plasma source, a multiple-mirror solenoid with 34 coils (instead of  $2 \times 28$  coils in the final system), and a short temporary section for the on-site commissioning of NBIs. The main central trap will be added later when its production will be completed. In the start configuration of GOL-NB, commissioning of different subsystems and the first plasma are scheduled.

The main scientific task of this step will be demonstration of a lossless cold plasma transport along the multiple-mirror magnetic field as the simulation of a supposed technique of filling the central trap with the start plasma. This technique utilizes the following feature of the multiple-mirror confinement. A multiple-mirror field effectively decreases axial plasma flow if the ion free path length is comparable with the field corrugation period,  $\lambda \approx l$ . This will be the main regime for the hot plasma confinement in GOL-NB. For the cold start plasma,  $\lambda \ll l$  and theory predicts almost free plasma flow. Preliminary experiments with a prototype plasma source in the old GOL-3 section of the magnetic system revealed no significant differences of cold plasma transport in regimes with the multiple-mirror field from ones in a uniform magnetic field.

The assembly status and the latest experimental results from GOL-NB will be presented in the paper.

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# Advanced Beam-Driven Field-Reversed Configuration Research at TAE Technologies

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Alternatives to DT fusion fuels, such as  $pB^{11}$ , could provide for a truly clean and abundant energy source. Our privately funded US company, TAE Technologies, Inc., is developing fusion energy generators based on a high-beta, advanced beam-driven Field-Reversed Configuration (FRC) for magnetic plasma confinement. Demonstration of the sustained operation of such a device in 2015 [1] provided the confidence to move forward with the construction of our 5<sup>th</sup> generation experimental platform, C-2W (also called “Norman”). It has been designed, built and commissioned in 2017 with the aim to achieve higher temperatures, magnetic fields, and thus plasma confinement times. During the course of its early operation C-2W has already surpassed the plasma performance of its predecessor, C-2U. The initial results of C-2W experiments and follow-on steps in TAE’s program towards harnessing fusion, based on alternative fuel cycles, will be discussed.

[1] H. Gota *et al.*, Nucl. Fusion **57**, 116021 (2017).

# Coherent and Incoherent Magnetic Fluctuations in Core and Jet Regions of the C-2W Field-Reversed Configuration Device

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C-2W is the world's premier beam-driven field-reversed configuration (FRC) experimental device. It is a new machine built on the principles of operation learned from its predecessors C-2/2U [1, 2]. An extensive Mirnov array of magnetic field probes are installed throughout the confinement vessel (CV) and inner divertors on C-2W; a total of 10 azimuthal rings of 8 probes each. Each probe is capable of detecting fluctuations in the magnetic field at frequencies up to 10 MHz.

MHD modes and other fluctuations are detected within the axial envelope of the FRC. The coherent modes are also seen in the jet region of the CV and in the inner divertor. This indicates the entire plasma column from end to end of the device is influenced by the motion of the FRC core. Correlations between these fluctuations throughout the CV will be presented and implications of the same will be discussed.

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[2] H. Gota *et al.*, Nucl. Fusion **57**, 116021 (2017).

# Monte Carlo simulation of dissipation processes in ion beam plasma

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A beam plasma confined in linear devices often brings about beneficial applications because of its simple structure. When the deuteron beams are axially injected from both sides of linear device, it behaves as a neutron generator by D-D nuclear fusion reactions. As an effective cancer treatment method which takes advantage of the reaction between neutron and boron, BNCT (Boron neutron capture therapy) is usable. It is possible to apply the device to BNCT apparatus. In this study, we numerically analyzed beam plasma dissipation processes in the linear reaction chamber to design a neutron source that can satisfy the neutron generation rate required by BNCT.

The deuterons are accelerated by electrostatic potential gaps at both ends of the reaction chamber. This deuteron ion beams diffuse and lose its energy as interacting with other background ions and electrons in the chamber. In order to evaluate this influence of dissipation processes, we simulated the ion-ion and ion-electron collisions by using the particles trajectory method including Monte Carlo binary collision models proposed by T. Takizuka & H. Abe [1]. In their method, binary collisions take place in the pairs of particles chosen randomly. The resulting scattering angle is sampled through a Gaussian distribution to calculate the change in velocities.

Using this model, we calculated for injection of deuterium ion beam particles for plasma into the chamber and analyzed its dissipation. We have evaluated some ion beam parameters such as diffusion coefficient and slowing-down of the axial velocity component from calculation results. By adequately adjusting the electron temperature inside the reaction chamber and the external axial magnetic field, it is suggested to keep sufficient deuterium ion beam confinement time.

Finally, we have considered about relationship between deuteron ion beam energy and D-D reaction rate for beam particles, and found out the appropriate conditions for neutron generation rate required.

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# Global instability structure in a linear beam confinement system

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Boron neutron capture therapy (BNCT) has drawn attention in recent years as a new cancer treatment method that does not damage healthy cells. BNCT utilizes the nuclear reaction of boron and neutron, and its key issue is the development of a compact neutron source that enables the generation of neutrons necessary for treatment.

Momota *et al.* propose a neutron source utilizing neutrons generated by DD reaction, confining a beam deuteron (D) of about 30 keV in a device combining an open-end solenoid magnetic field and an electrostatic field [1]. Neutron can decelerate with heavy water of about 1 m in the traveling direction. In order for the proposed neutron source to be realized, it is necessary for the beam plasma to maintain stable configuration. In order to investigate the stability of the beam plasma, Matsui *et al.* carried out a full-particle simulation for linear electron beam plasma [2]. As a result, it was confirmed that sausage instability and kink instability occurred over time in the density distribution of electrons, and it also transited to a twisted structure. In addition, by investigating the time evolution of the radial force acting on the beam plasma, the growth process of sausage instability and kink instability was clarified. However, a detailed analysis of the macroscopic structural change has been regarded as a future task.

In this study, a 3-dimensional full-particle simulation is performed on a linear beam plasma, and its temporal and spatial changes are clarified by Fourier analysis. In particular, since spatial variation of high wavenumbers was observed in the axial direction, the relationship between wave number and angular frequency is clarified.

[1] H. Momota *et al.*, J. Fusion Energ. **28** (2009) 191.

[2] T. Matsui *et al.*, Plasma Fusion Res. (in press).

## MHD stabilization of high-electron-temperature discharge in the GDT experiment

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MHD stabilization of a strongly heated plasma with large temperature gradients is a quite universal problem faced in most magnetic fusion experiments. In this report, we make a step towards solving this critical problem for open trap. We describe a technique to deal with the increased transport brought about by the electron cyclotron heating in axisymmetric magnetic mirror device. The technique is based on shaping of the plasma potential by means of a set of specifically biased electrodes facing plasma at both open ends of a trap. In the experiments with combined microwave and neutral beam plasma heating performed in the GDT (gas-dynamic trap) facility at the Budker Institute, we show that a value of on-axis electron temperature up to 450 eV at plasma density  $1.2 \cdot 10^{19} \text{ m}^{-3}$  can be supported steadily for 1.5 ms limited by the available heating and magnetic confinement systems. With regards to the absolute values of electron temperature, we note that these results are completely in line with previously reported record values [1], considering the increased plasma density and halved microwave power of the current experiment. Therefore there is virtually no overhead cost to applying the developed stabilization technique. The minimum value of the external potential sufficient for stabilizing the plasma is quite modest, so likely our technique may be extrapolated to even higher temperatures and to larger devices without overwhelming engineering difficulties.

Stable high-temperature discharge, no longer degraded by low-frequency instabilities, offered a unique opportunity to check quantitatively the basic plasma confinement physics in a new range of parameters. In particular, by performing a dedicated experiment with a stable high-temperature plasma, we show that the longitudinal gas-dynamic energy loss rate is in good agreement with available experimental data and theoretical expectations.

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## Burst microwave emissions and micro-instabilities driven by strong ECRH in the GDT experiment

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In this paper, we discuss the burst activity observed during and after the electron cyclotron resonance heating (ECRH) in the gas-dynamic trap (GDT) facility at the Budker Institute. Such activity is detected in the following, usually correlated, channels:

- Electron cyclotron emission (ECE) at 55-59 GHz near ECRH frequency 54.5 GHz
- Wideband microwave radiation at 2-24 GHz, 27-36 GHz, 38-47 GHz measured with the digital oscilloscope
- Hard X-ray obtained from photoelectric multiplier of the neutron detector
- Escaping fast electrons measured with the pin diode and plasma probe.

Studied phenomena are related to fast electrons and plasma micro-instabilities generated by strong ECRH. The fraction of fast electrons in GDT is moderate compared to other devices. Indeed, an efficient power deposition into the thermal plasma component is considered as one of the major achievements of this experiment [1]. Nevertheless, suprathreshold electrons play an essential role in ECR plasma start-up recently implemented at GDT: electrons with energies about 10 keV are entirely responsible for the gas ionization and plasma pressure at initial stages of gas breakdown and seed plasma build-up [2]. Measured non-thermal ECE have unambiguously confirmed the existence of suprathreshold electrons generated during the ECR heating of the main plasma [3]. Explanation of time dependence of ECE level observed in the varying magnetic field and decaying plasma is a rather challenging task. Our hypothesis is based on the concept of stimulated micro-instabilities that cause fast losses of suprathreshold electrons. Such instabilities are observed at GDT as broadband electromagnetic pulses in 5 – 50 GHz band and synchronized precipitations of fast electrons. Despite some similarities to kinetic EC instabilities in small traps [4], detailed explanation of such events is still a matter of our efforts.

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# Control of electron-cyclotron instability driven by strong ECRH in a minimum- $B$ magnetic trap

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We discuss the first experimental evidence of a controlled transition from the generation of periodic bursts of electromagnetic radiation into continuous-wave regime of a cyclotron maser formed in magnetically confined non-equilibrium plasma [1]. The kinetic cyclotron instability of the extraordinary wave of weakly inhomogeneous magnetized plasma is driven by the anisotropic electron population resulting from electron cyclotron plasma heating in MHD-stable minimum- $B$  open magnetic trap. The experiment is performed with the ECR ion source (A-ECR-U type) at JYFL accelerator laboratory [2].

In the present communication we focus on the theoretical model that motivates and explains the experiment. We show that the observed non-trivial dynamics may be caused by the temporal modulation of the electron distribution function due to excitation of unstable kinetic modes. Similar systems have been previously studied theoretically in the context of space cyclotron masers in planet magnetospheres and other astrophysical objects [3], and also have much in common with laser excitation mechanisms. Except being of fundamental interest, our results are important for applications such as the development of ECR ion sources. Particle ejections, which are inherent to the burst regime of the cyclotron instability, cause oscillations of the plasma potential and the beam current accompanied with a significant decrease of the average ion charge [4]. The low-power CW regime would allow to avoid these non-desirable effects and improve the ion source performance.

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# Analytical experiment of time evolution of deceleration effect in traveling wave direct energy converter using dual-frequency modulation

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Traveling wave direct energy converter (TWDEC) was proposed as an efficient energy recovery device for D-<sup>3</sup>He fusion power generation [1]. It is designed to convert the kinetic energy of 14.7 MeV protons produced by fusion reaction and is based on the inverse process of a linear accelerator. TWDEC consists of a modulator and a decelerator. Incident protons are introduced into the modulator and bunched up in the downstream by velocity modulation. The bunched protons are introduced into the decelerator, in which the protons are trapped and decelerated by traveling wave field in the decelerator. The reduced kinetic energy of the protons is converted into electric energy.

In the research on modulation process, single sinusoidal wave was used conventionally. This scheme does not necessarily provide complete bunching. The use of dual-frequency for modulation process was proposed to improve bunching. The bunching effect was examined experimentally, and the research of the optimization of dual-frequency modulation has been continuing [2].

We simultaneously performed an experimental research for deceleration effect with dual-frequency modulation. In an ion beam pulsed for 500  $\mu$ s, the conditions of the conventional single sinusoidal modulation and the dual-frequency one were applied in series. As a result, the deceleration effect was observed, and we also found the effect increased with time. In the previous research on modulation process, time variation of modulation effect was observed which had not been clarified yet [3]. The modulation effect increased with time, and it took a certain period to become steady state. The deceleration effect depends on the modulation effect, so the temporal change of the deceleration effect might be due to the temporal change of the modulation effect. The effect of dual-frequency modulation method was not distinguished from the other effects concerned with the modulation in the former deceleration experiment [4].

This paper treats the deceleration effect to dual-frequency modulated particle beam with excluding time variation. The time variation of the beam itself and that of modulation effect continue for 300  $\mu$ s and 540  $\mu$ s, respectively. In the present experiment, we extended the beam duration to 1000  $\mu$ s from 500  $\mu$ s of the former experiment. As a result, the deceleration effect increased with time and arrived at the steady state, when the result only included the deceleration effect with dual-frequency modulation. According to the result, deceleration efficiency for the dual-frequency modulation was higher compared with that for the single sinusoidal modulation. We will explain the details in the conference.

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# Examination of bunching effect of dual-frequency modulation in a traveling wave direct energy converter simulator

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Traveling wave direct energy converter was proposed as an efficient energy recovery device for fast protons created in D-<sup>3</sup>He fusion [1]. It works based on an inverse process of a linear accelerator: a continuous proton flow from a reactor is velocity modulated, which results in bunching of the beam in the downstream. A deceleration field of traveling wave is applied to the bunched beam for recovering kinetic energy of the protons, so better bunching possibly improves conversion efficiency.

A sinusoidal wave is usually used for the modulation field, however, some part of the particles do not bunch with the wave. The authors studied more efficient modulation field for bunching, and proposed a dual-frequency modulation method, in which an approximated ideal wave for modulation was realized by combination of the fundamental frequency ( $\omega$ ) and the second harmonic frequency ( $2\omega$ ) waves [2]. The first examination experiment of the method was performed, however, an expected result could not be obtained. The cause of the failure might be the treatment of ion running time between two electrodes and the approximation of the waveform. This report shows the second experiment in which revised treatments are introduced.

In the actual usage of the  $2\omega$  wave, a supplementary electrode is necessary. The revised scheme was designed by taking ion running time between these electrodes into account, which meant the  $2\omega$  wave should be applied with an appropriate time lag, and resulted in modification of the phase. As for amplitude of the  $2\omega$  wave, an orbit calculation revealed that the value of the Fourier component of the ideal wave was not necessarily the optimum amplitude. The time variation of the synthesized field strength is important to design the amplitude of the  $2\omega$  wave.

The revised modulation system was arranged and a simulation experiment was performed. The beam current was measured by a Faraday cup, and the bunching effect was evaluated by Fourier analysis of the current. The third harmonic component of the measured current was referred to avoid influence of radiation noise, and a good agreement between numerical and experimental results was obtained. The details of experimental arrangement, numerical orbit calculation, and their results will be presented in the conference.

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## Electrode biasing stabilization in C-2W field-reversed configuration experiments

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The C-2W is new generation of successful experimental projects C-2 and C-2U [1,2] and represents a mirror machine with field-reversed configuration (FRC) as a plasma core. Coaxial electrodes and limiters in divertors can be electrically biased to introduce a radial electric field in plasma. It is shown experimentally that plasma rotation magnifies the effect of conductive wall stabilization in large scale modes, while a differential rotation (shearing) stabilizes small scale modes.

The new electrodes and limiters were designed with high voltage requirements, installed in divertors, tested up to 15 kV in vacuum, and successfully used in C-2W experiments. We have started C-2W operations with electrodes in the outer divertors and obtained stable plasma by optimizations of magnetic-field axial profile and biasing voltage/current. Biasing voltage of 2 kV appears to be sufficient to stabilize FRC, while its current seems to be  $>5$  kA. Plasma duration is up to  $\sim 9$  ms using outer-divertor electrodes, which is long enough to transfer biasing regions/areas from outer to inner divertors on C-2W. The details of electrode-biasing systems as well as experimental results will be presented.

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## Axial Plasma Confinement in Gas Dynamic Trap

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A key parameter of future thermonuclear systems is their energy efficiency, which rapidly increases with the increase in the electron temperature of the confined plasma. One of the factors limiting the electron temperature can be high thermal conductivity of the plasma along the magnetic field lines, which is determined by a number of complex kinetic processes in the expanders - areas of the expanding magnetic flux behind the magnetic mirrors. Therefore, it is necessary to study this loss channel in detail and determine the conditions under which it can be suppressed to levels acceptable for thermonuclear applications of open magnetic traps. Theoretical studies on this problem have been carried out earlier; however, the methods of physical processes analysis in the expanders have been oversimplified. Experimental studies aimed at solving the problem were performed only for low values of the electron temperature of the scale of 20 eV [1]. Due to the recent works on GDT facility in BINP SB RAS there is an opportunity to study in detail the longitudinal transport of plasma particles and energy with parameters closely approaching the parameters of projected neutron sources based on open magnetic traps. Stable confinement of plasma with a high relative pressure ( $\beta = 0.6$ ) was demonstrated; by means of additional ECR heating system, a record value of the electron temperature (about 1 keV) for quasi-stationary open magnetic traps was obtained; the associated increase in the retention time of high-energy ions and the thermonuclear neutrons yield is demonstrated. These achievements motivate the following research steps towards the development of a nuclear fusion reactor, and one of such steps should be the investigation of the longitudinal transport of particles and energy in the mirror cell.

In the first experimental series, the plasma parameters in the expander of the gas-dynamic trap were measured, namely the electric potential in the Debye layer near the surface of plasma absorber and the average electron energy as a function of the longitudinal coordinate [2]. The presence of a population of cold electrons trapped in the expander region was shown. The minimum value of the magnetic field expansion degree at still insignificant increase in longitudinal losses is determined.

To construct a complete model of longitudinal thermal conductivity in the open trap expander, a direct measurement of the density of longitudinal particle and energy fluxes dependences on number of parameters is required, namely, on the plasma temperature and density in the central part of the GDT, on the degree of magnetic flux expansion in the region of end absorbers location and on the density of the neutral gas in the expander. The results of these experiments will be presented in the report.

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# First Experimental Campaign on SMOLA Helical Mirror

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The existing technique of multiple-mirror suppression of the axial heat flux combined with gas-dynamic central cell [1] can provide effective mirror ratios  $>100$ , which gives feasible fusion gain appropriate for hybrid systems. At the same time, better plasma flow suppression may give higher fusion parameters suitable for non-tritium or aneutronic reactors. Budker INP proposal for next generation linear plasma device [2] involves 50-meter-long trap with static or dynamic multiple mirror sections and  $Q_{DT} \sim 0.1$  (conservative gas-dynamic estimation at high  $\beta$ ) to  $Q_{DT} \sim 1$  (estimation based on the new methods of improved confinement).

This report presents the first experimental results on the new method of active plasma flow suppression in a helical magnetic field [3]. This method renews the idea of a plasma flow control with moving mirrors. Plasma rotation in  $\mathbf{E} \times \mathbf{B}$  fields can be utilized to create periodical variations of helicoidal magnetic field moving upstream in plasma's frame of reference. These variations transfer momentum to trapped particles and lead to plasma pumping towards the central trap. Theory predicts exponential dependence of the flow suppression on the magnetic structure length, that is more favorable than the power dependence in passive mirrors [4]. Plasma biasing or natural ambipolar potential can drive the rotation. The first case also leads to plasma pinching that counteracts the collisional radial diffusion.

Concept exploration device SMOLA with a helical mirror system [5] started operation in a start configuration in BINP in the end of 2017. Major aims of the first experiments were preliminary observations of plasma behavior at changes of the magnetic configuration, regardless of the confinement efficiency. Influence of the classical multiple mirror confinement were avoided by use of two regimes with the same configuration of the magnetic field lines but opposite direction of the magnetic field. These regimes correspond to the different direction of the rotation and switching from plasma confinement to the accelerated pumping out. Plasma stream modification by the helical plugging compared both to the regime of straight magnetic field and the regime of accelerated pumping out was clearly shown. In this report, the main results of the first experimental campaign are discussed.

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# **The path of KMAX experiment to improve the confinement of central cell plasmas**

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The KMAX is an axisymmetric mirror consisting of a central cell, two end cells and two expanders with total axial length  $\sim 12$  meters. One of the purposes of KMAX is to test a new idea to minimize the axial particle loss from the central cell. Currently the plasma is injected to the central cell from two washer guns on both sides, and then radio frequency wave heating is applied based on the well-known magnetic beach approach. With total power of 150 kW, the diamagnetism is found to increase more than 15-folds. Different plasma source has also been tested in KMAX, namely, colliding and merging FRC. The field reversal is confirmed by internal probe measurements. The next step is to combine the merging FRCs with RF heating, which can at least improve the open field line plasmas. In parallel with these efforts, we are applying rotating magnetic fields (RMF) in the end cells in the hope to form rf-sustained field reversed configurations. The idea is to test if the RMF-FRC in the end cell can capture the axially lost particles, or increase the plasma potential locally, which then lead to a better confinement of central cell plasma. Preliminary results of these experiments will be reported.

# Diagnosics for Surface of Tungsten Exposed to Deuterium Plasma by Spectroscopic Ellipsometry

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In-situ measurement of the surface condition is important to understand plasma-wall interaction (PWI), since the surface condition continues to change during the plasma exposure and it also changes due to exposure to the atmosphere in the case of postmortem analysis. A spectroscopic ellipsometer has been installed in the PWI simulator APSEDAS to measure the surface condition in real time and in-situ. A spectroscopic ellipsometry is an effective method to diagnose surface condition non-destructively with high accuracy and is commonly used in the field of semiconductors [1].

The spectroscopic ellipsometry system consists of a xenon lamp, rod lens, polarizer, sample, rotation analyzer, zoom lens, and spectrometer. Two slits were added in front of and behind the polarizer so that the xenon lamp light was irradiated only on the sample. The incident angle was  $\sim 75^\circ$ , which was in the vicinity of the pseudo-Brewster angle of tungsten. Phase difference ( $\Delta$ ) and amplitude ratio ( $\Psi$ ) of the tungsten surface exposed to the plasma are measured.

With APSEDAS, the cylindrical plasma is produced by radio frequency wave of 13.56 MHz. A target sample was fixed on the water-cooled stage and exposed [2]. The tungsten sample was exposed to D plasma 3 times. The electron density ( $n_e$ ) and temperature ( $T_e$ ) of the D plasma were  $\sim 3.1 \times 10^{17} \text{ m}^{-3}$  and  $\sim 10 \text{ eV}$ , respectively. The ion flux estimated from  $n_e$  and  $T_e$  was  $\sim 4.1 \times 10^{21} \text{ D}^+ \text{ m}^{-2} \text{ s}^{-1}$ . The space potential ( $V_s$ ) was 28 V. The fluence of D to sample was  $\sim 2.0 \times 10^{25} \text{ m}^{-2}$  for each plasma exposure and surface temperature was  $\sim 490 \text{ K}$ . At every exposure the sample was taken out from the chamber and annealed at  $900 \text{ }^\circ\text{C}$  for 1h by the infrared ray lamp.

After the D plasma exposure,  $\Delta$  increased by  $5^\circ$  at most and  $\Psi$  decreased by  $1.5^\circ$  at most in the wavelength range of 400-800 nm. After annealing at  $900 \text{ }^\circ\text{C}$ ,  $\Delta$  and  $\Psi$  changed by the exposure returned to the previous values. D plasma exposure and annealing are considered to cause the changes of refractive index,  $n$ , and extinction coefficient,  $k$ .

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## Ion temperature measurement of divertor-simulating plasma aiming for detached divertor formation study

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Compatibility between sustainment of a well-confined plasma and mitigation of heat load flowing onto the divertor plates is one of the most important subjects in fusion-related studies. Detached divertor formation is a promising candidate for handling large heat load and it is recognized that the volumetric recombination plays an important role for forming the detached divertor. Although volumetric recombination has a large reaction rate in low electron temperature region typically below 1 eV, electrons flowing into the divertor region have much higher temperature than 1 eV. Therefore, electron energy removal is indispensable to enhance volumetric recombination in the divertor region. In relatively higher electron temperature region, typically  $T_e > 5$  eV, electrons lose their energy through the electron impact ionization and excitation. On the other hand, in lower electron temperature region ( $T_e < 5$  eV), electrons strongly couple with ions, and the temperature relaxation between electrons and ions becomes an important process for electron energy dissipation. Therefore, evaluation of energy flow among electrons, ions, and neutrals is important to obtain comprehensive understanding of the detached divertor formation. Some studies using detached/recombining plasma support this energy diagram [1, 2]. To evaluate amount of the energy transferred through the e-i temperature relaxation, measurement of the ion temperature is required as well as the electron temperature. However, experimental study of the energy transfer with ion temperature measurement has not been performed yet. Recently, we have developed an ion sensitive probe (ISP) [3], and introduced it to a radio-frequency (RF) plasma device. Development of the ISP enables us to investigate ion temperature in divertor-simulating plasma.

Experiments are conducted in the RF plasma device DT-ALPHA. DT-ALPHA consists of a stainless steel vacuum chamber and a quartz pipe. Plasma production method is 13.56 MHz RF discharge. Maximum RF heating power is 3 kW. At the upstream edge, helium working gas was supplied into the device. In the present study, ion temperature is measured approximately 0.5 m away from the quartz pipe. Typical value of the magnetic field strength where the ISP is installed is approximately  $B = 0.15$  T. At helium neutral pressure  $p \sim 0.3$  Pa and RF heating power  $P_{RF} \sim 140$  W, ion temperature near central region of a cylindrical plasma is approximately  $T_i = 8$  eV. In the presentation, details of the spatial profile of ion temperature and energy balance between electrons and ions will be reported and discussed. In addition,  $T_i$  obtained by the ISP will be compared to that obtained by spectroscopic measurement.

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# Theoretical framework of relation between anomalous resistivity and toroidal spin-up of field-reversed configurations

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A field-reversed configuration (FRC) [1] has a magnetic structure closed inside the separatrix and an open field structure to the outside. An FRC is in an extremely high beta state, and synchrotron radiation loss is relatively small even at high temperatures, so it is expected as a core plasma of advanced fuel fusion like D-<sup>3</sup>He[2]. Furthermore, because it has no structural material inside, it can be translated in the axial direction. In recent years, by combining the translation of two FRCs and the configuration maintenance technology by NBI and plasma gun, performance far exceeding the conventional flux lifetime has been realized [3]. Therefore, physical research on FRC plasma is entering an important phase toward further improvement of FRC performance.

When evaluated from the magnetic flux decay in the FRC experiment, the resistance of the plasma is anomalous, and the anomaly factor is estimated to be about 3-10. The plasma current of FRC is mainly maintained by electrons, and since the electron toroidal current is reduced by this anomalous resistance, so relatively fast magnetic flux decay occurs. Although the reason for this is not clarified at present, it is expected that magnetic fluctuation affecting the electron motion exists. Also, in the FRC experiment generated by the field reversed theta pinch method, spontaneous toroidal spin-up is observed, and accompanying rotational instability is an important problem to be suppressed. One of the authors have proposed a model in which flux damping directly converts to FRC angular momentum with respect to the origin of FRC toroidal spin-up[4].

In this research, we construct a theoretical framework for the relationship between toroidal spin-up and anomalous transport and report it at the conference.

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# Development of the Thomson Scattering Measurement System for Diagnosing Upstream Plasmas in NAGDIS-II

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One of the problems which have to be solved is how to reduce the high heat flux flowing into the divertor plates in future fusion reactors.<sup>[1,2]</sup> Plasma detachment is thought to be a promising method for solving this problem.<sup>[3,4]</sup> In the linear divertor plasma simulator, NAGDIS-II, detached plasma has been actively studied by using Langmuir probes and the passive spectroscopy, and it was shown that there are issues for applying to detached plasmas.<sup>[3,4]</sup> Recently, laser Thomson scattering (LTS) system was successfully introduced in the downstream of NAGDIS-II for the accurate measurement of radial distributions of the electron temperature ( $T_e$ ) and the electron density ( $n_e$ ) with the high spatial resolution<sup>[4]</sup>. Although downstream plasma parameters became to be acquired with high accuracy, measurement system in the upstream region has been still inadequate for discussing the scale length along the magnetic field and so on without the disturbance.

In this study, we established a new LTS measurement system in the upstream region of NAGDIS-II. We employed a Nd:YAG laser with a second harmonic, the wavelength of which was 532 nm, passing through the upstream plasma via the Brewster windows. The scattered ray, which gives  $T_e$  and  $n_e$ , was led to the spectroscope through the mirror and the optic fiber bundle. The LTS signal was measured with a spectrometer; two camera lens and a volume phase holographic transmission grating (2600 l/mm) comprised the spectrometer, and CCD (charge coupled device) with GEN III image intensifier was used for detector. The mirror was installed inside the vacuum vessel to collect the LTS signal at the scattering angle of 60 degrees, because there is no viewing port on the top of NAGDIS-II. The optic fiber bundle, which consists of 23 aligned optic fibers, can be shifted slightly to be positioned and give radial distributions of plasma parameter over a range of about 35 mm. By using this system, radial distributions of  $T_e$  and  $n_e$  in the upstream region were obtained, which was mountain shape. For example,  $T_e$  was 4.5 eV and  $n_e$  was  $2.7 \times 10^{19} \text{ m}^{-3}$  at the center of the plasma,  $R = 0$  mm ( $R$  is radial position of plasma), and  $T_e$  was 1.4 eV and  $n_e$  was  $3.6 \times 10^{18} \text{ m}^{-3}$  at  $R = 20.9$  mm. Additionally, we compared plasma parameters obtained from the upstream LTS and the single Langmuir probe. They show the parameters measured by new LTS is reasonable in upstream region of NAGDIS-II.

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# Analysis of Ar Impurity Transport in the Large Tandem Mirror Device GAMMA 10/PDX Plasmas

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Argon (Ar) impurity seeding to enhance the radiation energy loss in SOL/Divertor plasmas is one of the candidates to reduce the heat load on the divertor plates in fusion reactors. The purpose of this study is to understand the Ar impurity transport in the GAMMA 10/PDX[1] plasma by means of the numerical simulation codes, the LINDA [2] and IMPGYRO [3] code.

The LINDA code is a two-dimensional (2-D) plasma fluid code for linear divertor simulation devices. The code outputs the plasma density  $n_e$ , flow velocity  $u_{||}$  parallel to the magnetic field lines, electron temperature  $T_e$  and ion temperature  $T_i$ . The IMPGYRO code is impurity transport code which directly follows the gyro-motion of the Monte-Carlo test particles. The thermal force and frictional force due to coulomb collision are simulated by the Monte-Carlo Binary Collision Method [4,5]. The IMPGYRO code has been originally designed for the high-Z metal impurity ions like tungsten. In this study, the code has been improved so as to apply to the simulation of Ar.

In the present simulation, the IMPGYRO code is applied to the plug/barrier-cell and the end-cell region of the GAMMA 10/PDX with the fixed background plasma profiles calculated by the LINDA code with 50×320 numerical grids. The Ar test particles have been injected from the location  $(r, z)=(0.012 \text{ m}, 10.68 \text{ m})$  with a monotonic energy ( $E=0.026 \text{ eV}$ ) with a cosine angular distribution.

Figure 1 shows the 2-D total density profile of the Ar impurity summed up over all the charge states, including Ar neutrals. The density is normalized by the maximum density in the calculation domain. The result has been checked by comparison with analytic expressions for the thermal force and frictional force. The Ar density profile shown in Fig.1 is reasonably explained by the force balance between thermal force and frictional force along the magnetic field line.

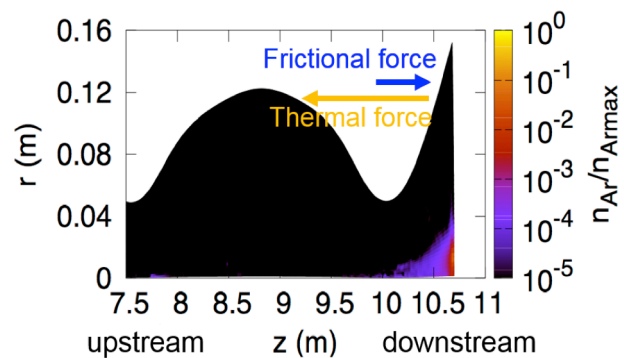


Fig.1 2-D density profile of the Ar impurity (Z=0-18).

On the basis of the initial calculations above, the investigation on effects of the background density and the divertor geometry (V-shaped divertor plate) on the Ar transport are now underway in order to make a comparison between the numerical results with those experiments and will be reported in the conference.

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## Recent advancement of research on plasma direct energy conversion

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Since proposal of ARTEMIS [1], direct energy conversion for fusion system has been studied. The energy conversion system of ARTEMIS consists of a pair of cusp-type and traveling wave direct energy converters (CuspDEC and TWDEC, respectively) placed both ends of a D-<sup>3</sup>He FRC reactor. The authors have examined the proposed system experimentally and numerically, and also have extended the research field to an additional conversion device using secondary electron emission (SEDEC) and an application to the diverter problem of toroidal devices. This paper gives overview of the recent advancement of the research.

The main function of CuspDEC is separation of charged particles. The authors proposed an application of CuspDEC to divertor plasma to reduce thermal load of the divertor plate [2]. The reduction of thermal load was demonstrated by using ion beam [3], and a project of total demonstration with charge separation on GAMMA PDX is in progress. The most important subject of CuspDEC is to improve capability of separation of high density plasma. An additional scheme assisting separation based on a nonlinear effect of radio frequency field was proposed for this subject. The experimental study was developed and was continuing [4].

As for TWDEC, a great improvement of energy recovery was achieved by an introduction of constant deceleration scheme [5]. The energy conversion efficiency exceeded 30 %, and over 50 % could be estimated if a problem in the modulation was solved. The modulation problem is a phenomenon that the modulation effect varies with time. A certain time is necessary to obtain an enough modulation effect, and a physical mechanism of the phenomenon is not clear. On one hand, an analytical study of beam scattering due to bunching was started [6]. The scattering phenomenon was observed, showing the phenomenon varied with time. Its time constant was similar to that of the time-varying modulation effect. The research of scattering is expected to clarify the problem of modulation effect.

An SEDEC is placed in the downstream of TWDEC. It was proposed as an additional device to recover some protons which were not decelerated in the TWDEC [7]. The protons are incident into a lot of metal foils aligned in the direction of the proton beam. Secondary electrons are emitted on the penetration of the protons, and are recovered by appropriately biased collectors. Following to studies of emission characteristics, various ideas for collection and recovery of electrons were proposed. The present research is focused on a modification of magnetic field introduced.

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# **Studies on plasma generation in a thruster using a single helical antenna with variable axial length**

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Recent space exploration has a wide variety from short distance/time mission to long one, so propulsion system suitable for the mission is indispensable. The VASIMR engine developed by NASA and AD ASTRA makes it possible to control thrust and specific impulse individually by separating functional parts of plasma generation and ion heating [1]. However, separation of functional parts requires multiple antennas and power sources, and thus, the apparatus becomes large and complicated.

The authors proposed a simpler structure with independent control of plasma generation and ion heating by using one helical antenna, which could miniaturize a thruster [2]. A helical antenna can excite different polarized waves bi-directionally. For a right helical antenna, left- and right-hand polarized waves can be launched in the co- and anti-directions of the external magnetic field, respectively. As the former and the latter waves, L and R waves can be expected, respectively. The independent control of thrust and specific impulse can be expected by the control of those waves similar to the VASIMR.

The external magnetic field is an important parameter to control L and R waves. The frequency of the RF power source is usually fixed, so wavelength of the excited wave will be changed as the magnetic field is varied. In such a situation, wave excitation efficiency will be deteriorated. To overcome this problem, the authors proposed a new structure of the antenna. A variable pitch helical antenna (VPHA) has axial antenna straps composed of rickrack metal plates winded a glass tube. The straps are fixed to axially movable supports, so the axial size of the antenna, and thus the axial radiation spectrum can be varied by adjusting the position of the supports. We can control the radiation spectrum by changing the antenna axial length and improve the excitation efficiency of the wave by matching the radiation spectrum with the dispersion of the target wave.

A prototype VPHA was manufactured and an initial experiment of plasma production was performed [3]. Produced plasma density had a different dependency on RF power and external magnetic field according to the antenna axial length. The experiment is continuing and in the second stage where RF power increases and a wave measurement equipment is installed. The detailed results and discussion will be presented in the conference.

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# Working characteristics of a combined plasma source for ion-ion separation experiments in direct energy conversion

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D-<sup>3</sup>He fusion is an excellent power generation method in the viewpoint of environmental conservation since neutrons are hardly generated. As most of the generated energy is kinetic energy of charged particles, direct energy conversion is possible. The charged particles have different energy and electric polarity, so separation of the particles is necessary for efficient energy conversion. An energy recovery system consisting of a cusp type direct energy converter (CuspDEC) and a traveling wave direct energy converter was proposed [1], where the former one separated and recovered electrons and thermal ions and the latter one recovered protons of 14.7 MeV. As for the CuspDEC, separation between electrons and ions has been well studied, but few experimental studies about separation between thermal ions and protons (ion-ion separation) are found.

In an experimental study of ion-ion separation, ions with different energies are necessary. The authors were proposed a new structure of combined plasma source: a high energy ion source and a low energy plasma source are connected in series [2]. The high energy ion and the low energy plasma simulate a fusion proton and a fuel plasma including alpha particles, respectively. Following to the preliminary report of the partial operation of the device [2], this report treats the completed construction and whole operation of the device.

The combined plasma source consists of two sets of rf plasma generators. Each generator has a glass discharge tube, an rf antenna, and two magnetic coils. An rf power source and a coil current source for each generator are independent. A gas feeder is also independent, so different ion species can be created. High voltage can be applied to the generator in the upstream, and a high energy ion beam can be supplied. Another generator in the downstream provides a thermal plasma consisting of ions and electrons with low energies. The glass tube of the downstream generator has a hollow around the axis, where high energy ions created in the upstream generator pass through. As a result, a thermal plasma including high energy ions can be supplied at the end of the device.

The working characteristics of the device were examined by a Faraday cup (FCP) settled at the end of the device. Currents measured by the FCP were evaluated to the variation of gas pressure, rf power, and magnetic field strength for both generators. For the high energy ion beam, characteristics to the acceleration voltage and the beam convergence voltage were also evaluated. The details of the results including plans of ion-ion separation experiments will be presented in the conference.

This work is supported by a Grant-in-Aid for Scientific Research (16H04317) from Japan Society for the Promotion of Science.

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# Effects of curved divergent magnetic field on H<sub>2</sub> / He mixture plasma in the linear divertor simulator TPD-Sheet IV

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Steady-state fusion reactors and DEMO reactors will have much higher heat flux from the core than that from ITER, which itself exhibits heat flux that is several times larger than that available in the current fusion reactors. Therefore, for the development of such advanced reactors, it is necessary to enable additional heat removal. Recently, advanced divertor aiming at additional heat removal by improving the magnetic field structure has been studied. The use of the advanced divertor such as a Super-X divertor (SXD) and Snowflake divertor (SFD) is one possible solution for the issue of heat load. A number of studies have simulated the advanced divertor, and experiments had been conducted on several large devices. However, the experiment is still not enough and it has not reached the practical stage. Also, fundamental experiments to clarify characteristics of advanced divertor have not yet been performed. Therefore, we conducted fundamental experiments to investigate the variation of characteristics about the backflow, detached plasma and heat load by the magnetic field. We had reported the characteristics of the neutral-particles backflow under the curved divergent magnetic field [1]. In this work, we experimentally examined the generation of detached plasma and the behavior of charged particles and neutrals in the mixed plasma (H<sub>2</sub> + He) under the curved magnetic field. The experiments had been performed by a linear divertor simulator, known as the Test plasma Produced by Directed current discharge for the Sheet plasma IV (TPD-Sheet IV) [1-3]. The plasma parameters such as the space potential, the electron temperature and electron density were measured by Langmuir probes. In addition, a visible spectroscopy was performed for the same position of the probe measurement. The heat load on the target was evaluated by an IR camera. As a result, it has been suggested the detached plasma in the mixed plasma under curved magnetic field is affected by the proportion of He to H<sub>2</sub> in the plasma source.

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# Observation of potential increase in the central cell due to ICRF heating in the non-axisymmetric anchor cell on GAMMA 10/PDX

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GAMMA 10/PDX is composed of multi magnetic mirror cells. A central cell is the main plasma confinement region and anchor cells keep the MHD stability of whole plasma with the minimum-B configuration. Plasmas are mainly produced and heated by using Ion Cyclotron Range of Frequency (ICRF) waves. Recently, the divertor simulation experiments are performed at the end region by using end-loss plasmas from the central cell. To extend the operation regime of the divertor simulation experiments, additional ICRF heating experiments has been carried out in the anchor cell [1]. When the additional ICRF heating with antennas installed in the anchor cell, remarkable increment of potential is observed in the central cell. The potential distribution along the magnetic field line has large influence on the end-loss plasmas. It is an important issue to understand the physical mechanisms of these potential increase.

The metal limiter installed near the midplane of the central cell is a limiter segmented into eight elements in the azimuthal direction [2]. As each element is electrically floated from ground, the azimuthal distribution of the floating potentials at the peripheral region can be measured. To measure the floating potential at the peripheral region in non-axisymmetric region of the anchor cell, electrically floated metal tips are newly installed outside of the plasma in the anchor cell.

Experiments of additional ICRF heating with the antenna in the anchor cell have been performed in the following two cases. One is a case when applied ICRF waves have ion cyclotron resonance layers in the central and anchor cells. Another is a case when the frequency of applied ICRF waves is lower enough than ion cyclotron frequencies in both central and anchor cells, that is, the waves have no resonance layer there. As the results, significant increment of the potential in the central cell is observed in both cases. The result implies that the increase of the floating potential does not depend on the ion cyclotron resonance heating in the central and anchor cells. On the other hand, the significant decrease of the floating potential in the anchor cell is observed with some of the metal tips. It is suggested that electrons are transported in the radial direction in the non-axisymmetric magnetic configuration of the anchor cell due to interaction with the applied ICRF waves.

In this paper, the mechanisms for the increase of the floating potential in the central cell is discussed, focusing on the interaction between ICRF waves and electrons.

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# Analysis of multipoint fluctuations in the transient discharge from attached to detached states in GAMMA 10/PDX

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We have carried out the multipoint-fluctuation measurement in the transient discharge from attached to detached states in the tandem mirror device GAMMA 10/PDX. As the result, blob- and hole-like structures outstanding during the rollover of the ion particle flux were firstly confirmed at the radially outer side edge in the divertor simulation experimental module (D-module). In addition, analysis of the two-dimensional H $\alpha$  emission indicates existences of odd and even mode fluctuations along the magnetic field.

Plasma detachment is a key issue for the success of the fusion reactor DEMO, because huge heat flux should inflict great damage on the divertor material without the detachment. Although an accurate prediction of the divertor flux under the detached condition is quite essential, experimentally-observed reduction of the particle flux is not easily reproduced in the numerical simulations. SOLPS modeling of ASDEX-U suggested that an introduction of the enhanced cross-field transport coefficient in the divertor region could reproduce the divertor footprint profile in the detached state [1]. Such the enhanced transport, which contributes to the reduction of the peak flux, was reported in experiments with several magnetic confinement devices, including tokamak [2], helical [3], and linear configurations [4]. In the scrape-off layer, on the other hand, an enhancement of the well-known radial transport of filaments, so-called “blobby plasma transport”, was recently reported under the detached divertor case [5]. In order to obtain the sufficient accuracy in the detached plasma simulation, it should be important to promote further understanding of the enhanced cross-field transport in relation to the plasma detachment.

In this study, we aimed to investigate the blobby plasma transport and its response against the plasma detachment in GAMMA 10/PDX. Massive gas puffing was performed during a 400 ms long discharge to compare attached, detached, and transient states. In the D-module, which was located at the west end cell, there were a number of Langmuir probes. By keeping the negative bias, we measured multipoint ion saturation current fluctuations. Analysis results with several statistical techniques indicated that there were blob- and hole-like structures at the outer side edge in the D-module, and they were outstanding in the transient state. We simultaneously measured H $\alpha$  emission from the side of the D-module. Detected mode behaviors with odd and even mode numbers will be discussed with the motion of blob-like structures.

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# Dynamic response of plasma detachment caused by MAR to transient heat flux in GAMMA 10/PDX

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Understanding of divertor plasma phenomena is one of the most important issues for the stable plasma operation. Plasma detachment is indispensable for reducing heat and particle fluxes to divertor, and plasma recombination plays an important role in plasma detachment. It is feared that the edge localized mode (ELM) disrupts plasma detachment and damages divertor plates. In this study, we measured dynamic response of detached plasma to transient heat flux in GAMMA 10/PDX.

In GAMMA 10/PDX, divertor detachment and plasma-wall interaction have been studied by using a divertor simulation experimental module (D-module) which is installed in the west-end region. The main plasma is produced and maintained by ion cyclotron range of frequency (ICRF) heating at central cell, and the V-shaped target in the D-module is exposed to the end loss plasma. Langmuir probes are installed on the upper target and near the inlet of the D-module to measure the electron density, the electron temperature and ion saturation current. The spatial distributions of the  $H_\alpha$  and  $H_\beta$  line intensities ( $I_{H\alpha}$ ,  $I_{H\beta}$ ) of the divertor simulation plasma are measured by a high-speed camera. An interference filter ( $656 \text{ nm} \pm 10 \text{ nm}$ ,  $486 \text{ nm} \pm 10 \text{ nm}$ ) is installed in front of the camera. When hydrogen gas is additionally supplied to the D-module, the electron temperature decreases from several tens of eV to several eV, and rollover of electron density is observed, showing plasma detachment. In addition, the increase in  $I_{H\alpha}$  is observed even after electron density rollover, which shows molecular activated recombination (MAR) leads to plasma detachment [1].

Electron cyclotron resonance heating (ECH) was applied to the main plasma of GAMMA 10/PDX for 12 ms after the density rolled over. The electron density increased from  $\sim 1 \times 10^{17} / \text{m}^3$  to  $\sim 2 \times 10^{17} / \text{m}^3$  and the ion saturation current increased from  $\sim 2 \text{ mA}$  to  $\sim 3 \text{ mA}$  by applying ECH. On the other hand, electron temperature was not measured at just after ECH, and at least that did not change at about 5 eV during ECH other than just after. A significantly increase in  $I_{H\alpha}$  and  $I_{H\beta}$  by about 3 times near the corner of the V-shaped target was observed. It is considered that the divertor simulation plasma transition from detached plasma to attached plasma by additional ECH. The value of  $I_{H\alpha}/I_{H\beta}$ , which is considered a good monitor for occurrence of MAR [1], decreased just after the ECH and then recovered to that before the ECH. It suggests that the occurrence of MAR decreased just after ECH and then recovered to that before the ECH, and the reaction processes of MAR have a curious transition just after ECH.

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# Spontaneous Ion Temperature Gradient in Inhomogeneous Magnetic Fields and Its Effect on the Parallel Heat Transport

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In Scrape-off layer (SOL)-divertor plasma code packages such as SOLPS, SONIC and UEDGE used in designing divertors in future experimental devices or fusion reactors, a plasma is described by a fluid model from the view point of the computational time. In order to guarantee validity of application of a fluid model to a wide range of collisionality, kinetic corrections to the closure models are indispensable. The parallel conductive heat flux  $q_{\parallel}$  is modeled by the Fick's law,  $q_{\parallel} = -\kappa_{\parallel}\nabla_{\parallel}T$ , in which the parallel heat conductivity  $\kappa_{\parallel}$  is usually corrected by a harmonic average of the Spitzer-Härm  $q_{\parallel}^{\text{SH}}$  and the free-streaming  $q_{\parallel}^{\text{FS}}$  heat fluxes like  $q_{\parallel} = \left(1/q_{\parallel}^{\text{SH}} + 1/(\alpha q_{\parallel}^{\text{FS}})\right)^{-1}$  with a heat-flux limiting factor  $\alpha$  provided by kinetic simulations [1, 2]. In inhomogeneous magnetic fields, however, a spontaneous parallel gradient of temperature  $\nabla_{\parallel}T$  arises without  $q_{\parallel}$  in collisionless conditions due to the mirror force. The ratio of the maximum to the minimum magnetic field strength in the SOL region can be  $B_{\text{max}}/B_{\text{min}} \sim 2$  even for a typical aspect ratio of  $R/a \sim 3$ . It is, thus, necessary that an appropriate model for  $q_{\parallel}$  in inhomogeneous magnetic fields be provided.

We have been studying SOL-divertor plasmas by using a plasma fluid model incorporating the anisotropic ion temperature ( $T_{\parallel}$  and  $T_{\perp}$ ) in inhomogeneous magnetic fields without a parallel conductive heat flux of ion  $q_{\parallel,i}$  [3] or with a Fick's-law type  $q_{\parallel,i}$  [4]. In the present study, we introduce generalized models for  $q_{\parallel,i}$  appropriate in inhomogeneous magnetic fields. By introducing  $q_{\parallel,i\perp} = -(2/3)\kappa_{\parallel,i\perp}B\nabla_{\parallel}(T_{\perp}/B)$  instead of a Fick's-law type  $q_{\parallel,i\perp} = -(2/3)\kappa_{\parallel,i\perp}\nabla_{\parallel}T_{\perp}$  into the parallel transport equation of the perpendicular ion energy and solving it numerically, we have been successfully obtaining solutions of  $T_{\perp}/B = \text{const.}$  in collisionless conditions which directly reflects the conservation of the magnetic moment  $\mu \equiv m_i v_{\perp}^2/2B$ . A generalized model for  $q_{\parallel,i\parallel}$  is also being introduced.

In the presentation, we show some results of an investigation on the characteristic times of the mirror confinement obtained by using the generalized models for  $q_{\parallel,i}$  and compare it with theories. We also show some results of a comparison between our simulation model and the divertor simulation experiments conducted in the end region of the tandem mirror device GAMMA 10/PDX. Its plasma is characterized by a highly anisotropic ion temperature caused by active ICRF heating and low collisionality [5], and hence is suitable for benchmarking the generalized models for  $q_{\parallel,i}$ .

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# Analysis of Molecular Activated Recombination in Detached Divertor Plasmas

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It is important to understand the dynamic behavior of detachment state, especially the response to the heat pulse by Edge Localized Mode (ELM). Although several researches have been done so far with such purpose, numerical modeling has not fully developed to clarify how the detachment state is affected to the ELM. To analyze it, there are two points we are focusing on; 1) In a situation with ELM, energy distribution deviates from thermodynamic equilibrium with Maxwell distribution. 2) Not only basic atomic-molecular processes but also molecular activated recombination (MAR) has received attention as an important process to realize detachment state, especially in a linear plasma device, GAMMA10/PDX[1]. Therefore in this study, we develop a zero-dimensional (0D) model of atomic-molecular processes which takes into account those two points, i.e., non-Maxwellian distribution and the effect of MAR.

As a first step, we analyze the static behavior of detachment state. In the 0D model, the time evolution of plasma and neutral particle density is calculated from the rate equation for each principal quantum number and vibrational excitation level, which enables us to include MAR in the model. From the calculation, we compare the rate of ion-electron recombination (IER: three body and radiative recombination), with that of the MAR and H ionization. Following two cases are calculated using typical density  $n_e$  of each machine: (a)  $n_e = 1 \times 10^{17} \text{ m}^{-3}$  for GAMMA10/PDX[1], (b)  $n_e = 1 \times 10^{19} \text{ m}^{-3}$ . Plasma temperature is set as 1 eV in the both cases.

Figure 1 shows reaction rate of MAR, IER and H ionization for the case (a) and (b). In the case (a), the rate of MAR is dominant. On the other hand, the rate of IER and H ionization are dominant in the case (b), and MAR does not contribute to detachment state at all. From the results, we can conclude that MAR becomes dominant when plasma density is low. This density dependence of MAR is one of the reasons that MAR has been observed especially in the linear fusion devices, such as GAMMA10/PDX.

So far, we have focused on the static behavior of MAR and suggested that MAR has more dominant effect in the case with lower density. As a next step, we will focus more on the dynamic behavior, e.g., how the detachment state reacts to the heat pulse by ELM.

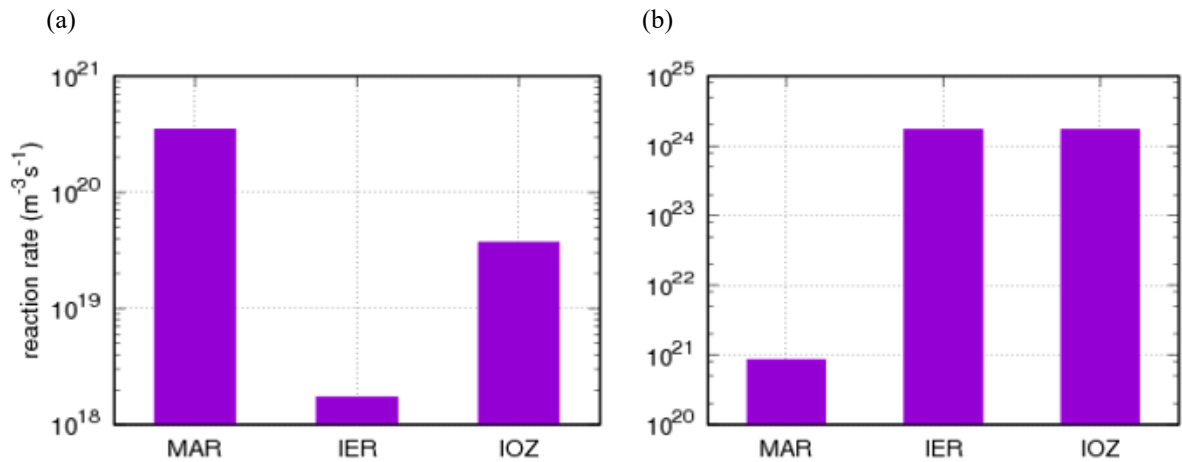


Fig.1 Reaction rate of recombination and ionization for the case of (a) and (b)

[1] M. Sakamoto, *et al.*, Nuclear Materials and Energy, **12**, 1004(2017).

# Confinement of D-<sup>3</sup>He fusion product particles in a non-adiabatic trap

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A non-adiabatic trap is an open confinement concept in which a wide external weak magnetic field region is formed in the center of the device. By canceling the axial magnetic field generated by the solenoid coil by the Helmholtz coil, a magnetic field structure of the non-adiabatic trap is formed. Adiabaticity in the particle motion typified by the preservation of the magnetic moment breaks in the center weak magnetic field region and the particle motion becomes stochastic. Using this non-adiabatic feature in particle motion, the confinement concept of a nuclear fusion reactor in which multiple non-adiabatic traps are connected in the axial direction was proposed by Momota[1]. Assuming that the confinement time of a single non-adiabatic trap is  $\tau$  and the number of connected traps is  $M$ , it is advantageous to concatenate that the net confinement time of the connected system is proportional to  $\tau M^2$ . Also, the plasma confined in the non-adiabatic trap is macroscopically stable because the magnetic field at the center of the device has a good curvature. Moreover, since it is a high beta plasma, synchrotron radiation loss is small, and it can be expected as a core plasma of advanced nuclear fusion like D-<sup>3</sup>He. In addition, it becomes natural divertor configuration with open-ended magnetic field, and introduction of high energy nuclear fusion product particles to the direct energy converter enables reactor design with high plant efficiency. Therefore, in this study, we investigated whether D-<sup>3</sup>He nuclear fusion particles can be confined by non-adiabatic trap. By calculating the accessible region of the 14.7-MeV protons by the Störmer potential, it became clear that the orbit loss never occurs, as it is open at the end of the device but can not reach the device wall. We calculate the particle trajectories of 14.7-MeV protons and will report the results of statistical investigations of changes in magnetic moment and the influence on the confinement of Coulomb collisions.

[1] H. Momota *et al.*, J. Fusion Energ. **27** (2008) 77.

# Hybrid simulation of high-beta linear plasma column applied with low frequency waves

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A field-reversed configuration (FRC) [1] is an extremely high-beta plasma and in singly-connected structure, and the nature of FRC plasma results in simpler reactor design. Since the lifetime of FRC formed by conventional field-reversed theta pinch method [2] is, however, as short as several tens or hundreds of micro-seconds. Recent FRC research has succeeded in extending the lifetime by neutral beam injection at TAE Technology, USA [3]. While the lifetime has been greatly extended, ion heating technology has not yet been established. The FRC has a field null point inside the plasma, and the resonance surface is narrow because of the high non-uniformity of the magnetic field, and it is said that it is not suitable for wave heating such as ECH. However, the effect of wave application to FRC is not clearly understood.

In order to clarify the characteristics of low frequency wave applied to FRC, we performed a hybrid simulation in which ions in plasma are regarded as particles and electrons are regarded as fluid. FRC has a spatial variation in the axial direction, however in our study this time we assumed the midplane of the FRC to be uniform in the axial direction in order to simply analyze the wave applied to the high beta plasma. Here, this configuration is called high-beta linear plasma column. In addition, a simulation model applying periodic boundary conditions was adopted at the device end. The antenna for wave application is a loop antenna, and the installation position is the center of the device outside the separatrix. The antenna current is 3 [kA] and 30 [kA], and the frequency is 80 [kHz].

As a result, we observed waves transmitted by shear Alfvén waves outside the separatrix due to the applied wave. Also, in this simulation model, since the frequency of 80 [kHz] has a resonance point near the separatrix, the wave is absorbed there, and the amplitude of the wave inside the separatrix is small. We analyze the heating effect near the resonance point and the dispersion relation of the excited waves in detail.

[1] M. Tuszewski, Nucl. Fusion. **28** (1988) 2033.

[2] A. L. Hoffman *et al.*, Fusion Technol. **9** (1986) 48.

[3] H. Guo *et al.*, Nat. Commun. **6** (2015) 6897.

## **Two dimensional H $\alpha$ emission measurements using the multi-channel H $\alpha$ array system in GAMMA 10 / PDX.**

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We developed the multi-channel H $\alpha$  array system for measuring two dimensional (2D) radial profiles of H $\alpha$  emissivity in the central cell of the tandem mirrors GAMMA 10/PDX. GAMMA 10/PDX is an effectively axisymmetric minimum-B anchored tandem mirror with thermal barrier at both end-mirrors. The plasma is created by plasma guns, and heated and sustained using ion cyclotron heating (ICH) systems. In addition to ICH, the electron cyclotron heating is applied to produce the electron and ion confinement potential in the plug and barrier cells. In end region, we installed the divertor simulation experimental module to perform the divertor simulation experiments.

The multi-channel H $\alpha$  array system is constructed by two dimensional optical collection system consist of twelve lenses, H $\alpha$  filters, and bundled optical fibers in vertical and horizontal direction. The bundled optical fibers lead the H $\alpha$  light to photomultiplier tubes with preamplifiers. The output of the preamplifier is connected to the CAMAC system. The measurable radiation positions are normally 3 cm intervals in vertical and horizontal directions and time resolution is 20  $\mu$ sec. We installed the multi-channel H $\alpha$  array system to the GAMMA10/PDX central cell.

In order to study H $\alpha$  emission behavior and its fluctuation in the hot ion mode plasma experiments with applying additional ICH, we used the new tomography method of Phillips-Tikhonov (PT)-method. Moreover, we used collisional-radiative (CR) model for neutral hydrogen density calculation after considering the electron density and temperature measured by the Thomson scattering system. After applying the Fast Fourier Transform (FFT) analysis to the 2D H $\alpha$  emissivity profiles, we can obtain the 2D fluctuation images for the first time. It is useful for detailed fluctuation study in the magnetically confinement plasmas.

# **Ion Cyclotron Resonant Heating in the Central Cell of the Keda Mirror with AXisymmetricity (KMAX)**

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We report the recent results of ion cyclotron resonance heating (ICRH) in the central cell of the KMAX mirror, as well as some preliminary results of RF launching experiment in the region of mirror throat. For central cell heating, we found the plasma diamagnetism increases by 15-fold, with a corresponding peak  $\beta_{\perp} \sim 2\%$ , density  $\sim 1.5 \times 10^{18} m^{-3}$ , and total temperature  $\sim 60$  eV for a total RF power of 100 kW. The effects of the magnetic configuration on resonance heating and wave emission are studied by varying the magnetic fields at the midplane. The axial phase speed measurements suggest that the excited wave is a slow wave in the plasma core and a fast wave at the edge. For wave launching experiment, we will show the design of RF system and discuss the waves which it may excite.

# Progress of Thomson scattering system in the tandem mirror GAMMA 10/PDX

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We developed the YAG Thomson scattering (TS) system for measuring radial profiles of electron temperature and density in a single laser shot and plasma shot in the central cell of the tandem mirror GAMMA 10/PDX. The optical collection system for TS light is constructed by three spherical mirrors and nine bundled optical fibers. The measurable radial positions are normally 5 cm intervals in the region of  $\pm 20$  cm. By using the lab jack system, we can change the bundled optical fibers position movable and we can measure radial profiles of electron temperature and density in more detail. We can successfully measure the radial electron temperatures and densities at fifteen radial positions in three plasma shots. For the in-situ calibration for the electron density measurement of TS system, we compare it to the electron line density measured by using the multi-channel microwave interferometer system.

In order to increase the TS signal intensities and improving the TS diagnostic time resolution, the multi-pass Thomson scattering (MPTS) system is the most useful method. In GAMMA 10/PDX, the MPTS system has been developed. It is a polarization-based configuration with an image relaying system. The MPTS system has been constructed for enhancing the Thomson scattered signals for the improvement of measurement accuracy and the MHz sampling time resolution. In these days, we have been developing the new MPTS system with the laser amplification system to increase the pass number of the MPTS signals. The laser amplification system can improve the degraded laser power after six passed in the multi-pass system to the initial laser power. We successfully obtained the continued multi-pass signals after the laser amplification system in the gas scattering experiments.

Moreover, we installed the end region TS system in GAMMA 10/PDX. In the end region, the divertor simulation experimental module (D-module) was installed to study divertor plasma. In D-module plasma, the plasma density is very low, then the end region TS system needs to have a large solid angle collection optics. We installed the collection optics in the vacuum chamber of the GAMMA 10/PDX end tank. In the previous end region TS system had large stray light. Then we installed the beam apertures along the laser beam. We intend to measure the end region electron temperature and density using the end region TS system.



# Numerical studies of plasma flow and electrostatic potential formation in expander divertor

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## **Abstract.**

Expander divertors are an important element of devices with open field lines (FRCs or open traps). Magnetic field expansion decreases the heat load on the target plates and reduces negative effects of plasma surface interaction (secondary emission, arcing, etc.). In this report we present the results of numerical studies of expander divertor physics recently done in TAE Technologies, Inc. New results include studies of the *effect of neutrals on the plasma flow in the expanded magnetic field* performed with the 2D MHD code Q2D and *self-consistent description of electron kinetics in the geometry including both divertor and confinement vessel* simulated by the 3D kinetic code KSOL. Neutrals affect the plasma flow in many ways. They slow-down the flow by ionization and charge-exchange (CX) processes. There is also the opposite effect caused by the acceleration of cold ions created by ionization and CX in the self-consistent electric field. The dominance of one of the effects depends on the location of the neutral source and can be determined only numerically. Optimization studies show that gas puff near the last confining mirror coil may create a positive effect on plasma confinement. Studies of self-consistent electron kinetics showed that the overall electric potential at the divertor plates may be much lower than potential estimated from simplified theories, which may explain the very weak electrostatic potential observed in the GDT divertor.