STABILITY AND CONFINEMENT STUDIES IN THE GAS DYNAMIC TRAP

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Abstract

Interest to magnetic mirrors went missing in the 1980's because of three key problems: magnets' complexity, micro-instabilities, and low temperature of plasma. However, researches on the Gas Dynamic Trap (GDT) device at the Budker Institute of Nuclear Physics demonstrated the possibility to overcome these difficulties. Confinement of plasma with high energy density has been performed on GDT device with simple circular coils. “Vortex confinement” has been implemented to suppress the radial losses induced by flute-like MHD instability inherent for axially symmetric devices. This technique allowed reaching local plasma beta close to 0.6. The auxiliary microwave heating on electron cyclotron resonance (ECR) frequencies raised the electron temperature up to 0.9 keV near the device axis. Alfven ion-cyclotron (AIC) instability has been observed, but not affect to the plasma power balance. The proposed report is dedicated to three following topics. The first is optimization of the “vortex confinement” in presence of ECR heating. Introducing the additional “vortex” layer inside the existing one allows extending high-temperature phase behind the atomic beams turn off time. The second is definition of critical parameters for the divertor. It was shown, that the critical wall position corresponds to expansion ratio of magnetic field K_{crit}~40. This value is in a reasonable agreement with a simple theoretical model and remains constant in the range of electron temperature up to 700 eV. The neutral gas in the divertor does not affect the discharge until its density exceeds an order of magnitude the plasma density. The third is study of unstable modes. In addition to AIC, the new type of oscillations was observed at the range of tens of ion-cyclotron frequencies. It was preliminary identified as Drift-Cyclotron Loss-Cone instability.

1. INTRODUCTION

Magnetic mirrors as a basis for fusion reactor have been investigated intermittently for more than half a century. Initial interest faded in the 1980's because of three key problems: (1) magnets are complex at the mirror regions, (2) plasma is vulnerable to micro-instabilities, (3) longitudinal losses are too high and they limit the electron temperature at a several hundred eV. Impressive progress of tokamaks at the same time leaded to halt of the mirror research program in many countries. Next decades while tokamaks were raising in parameters and technical complexity mirrors were out of focus. Researches of the last years provided the basis to reconsider mirror concept as a basis for neutron source for material development, nuclear fuel production, fusion-fission energy production, and even pure fusion reactor. Experiments on the Gas Dynamic Trap (GDT) device at the Budker Institute of Nuclear Physics demonstrated high energy density plasma confinement with simple circular coils [1] [2]. The electron temperature exceeded 0.9 keV [3] [4], while the Alfven micro-instability affected to the confinement insignificantly [5][6]. Further experiments were aimed to the following topics. The first is optimization of heating regimes and stability control. The second is detailed study of physical processes in the divertors (regions with expanding magnetic field behind the mirror, they also called expanders), limiting longitudinal losses.

The paper summarizes recent results of GDT team briefly. The content of the paper is as follows. The second section describes GDT device. The third dedicated to optimization of confinement in regimes with narrow radial profile of electron temperature. The forth section describes the experiments with expander tanks under different conditions. The fifth contains information about oscillations in the range from one to several tens of ion cyclotron frequencies.

2. GAS DYNAMIC TRAP DEVICE

The GDT device is an axially symmetric mirror [7][8] (Fig. 1). The central cell is long compared to plasma radius: mirror-to-mirror distance is 7 m, plasma radius is about 15 cm at the midplane. The mirror ratio is high (up to 40), while the magnetic field at the midplane is relatively low (0.36 T). Plasma with two ion fractions is confined in the central cell. The first fraction have high collision rate and called background or target plasma. The confinement regime of background ions is close to gas-dynamic one, that is similar to the confinement of a gas in a long bottle with two narrow throats (mirrors). Target plasma is produced by an arc discharge or by a microwave breakdown before the main phase of the experiment and sustained by a gas puffing during the main phase. The second fraction is a population of fast ions produced by inclined injection of hydrogen or deuterium atomic beams with particle energy of about 20 keV and total power of 5 MW. Fast ions are confined in the adiabatic regime which means that they are bouncing between mirror regions while energy and magnetic moment are conserved. Fast ions are slowing down primary by electron drag force and are lost due to angular scattering caused by ion collisions at energies comparable to the electron temperature. Angular distribution of fast ions is strongly anisotropic that can lead to rising of variety of micro-instabilities. “Vortex confinement” [1] is implemented to suppress the radial losses induced by flute-like MHD instability inherent to axially symmetric devices. This technique allows reaching local plasma beta close to 0.6 and electron temperature up to 250 eV [2]. Auxiliary microwave heating on electron cyclotron resonance (ECR) frequencies was applied to rise the electron temperature. Two gyrotrons were used with 0.8 MW of total power at frequency 54.4 GHz. ECR heating allowed to reach 0.9 keV of electron temperature in the regime with radially narrow power deposition profile [3],[4].

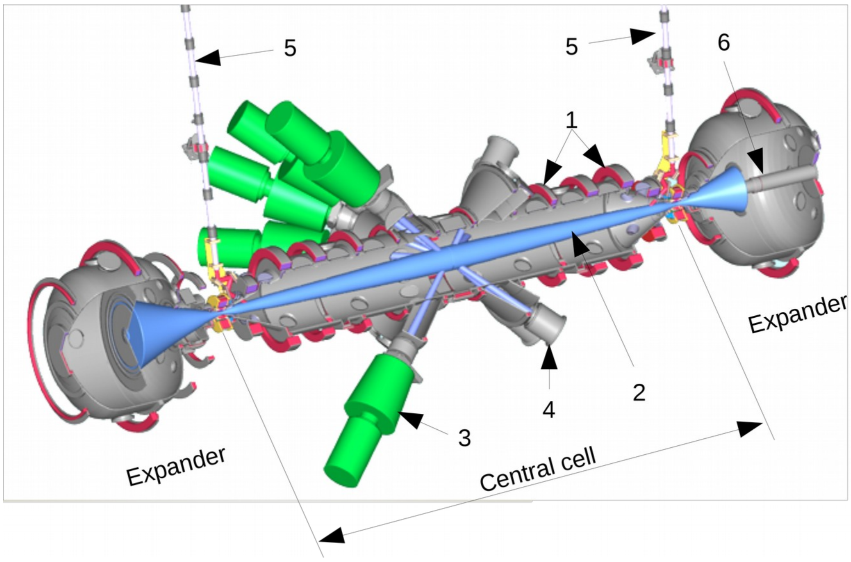

FIG. 1. GDT device: 1 – magnetic coils, 2 – plasma, 3 – neutral beam injectors, 4 – neutral beam dumps, 5 – ECR waveguides, 6 – arc plasma gun

3. OPTIMIZATION OF THE CONFINEMENT IN HIGH-TEMPERATURE REGIME

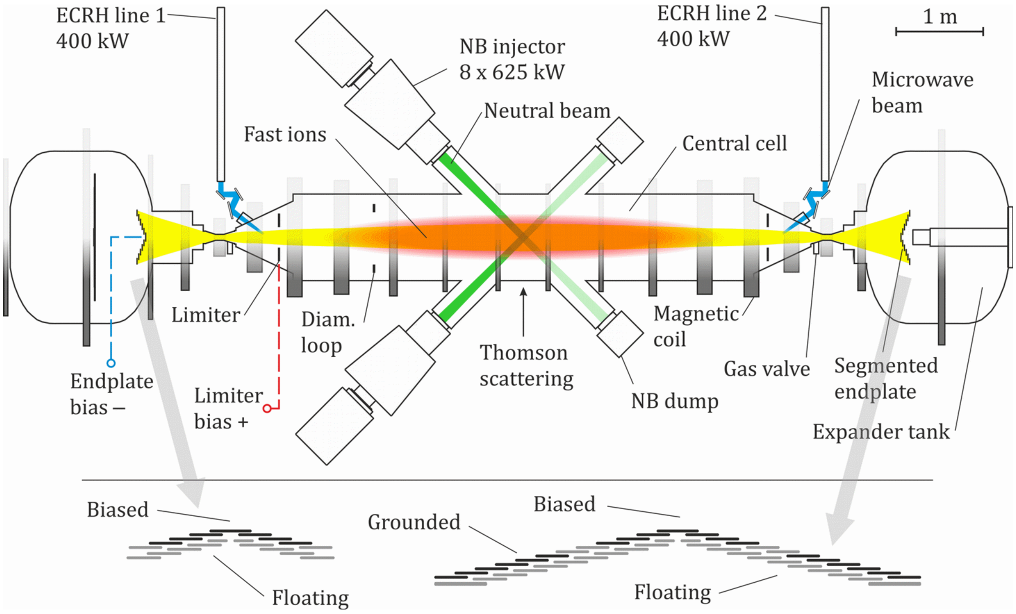

FIG. 2. GDT layout with new segmented endplates

One of the key issues of GDT program is the axial plasma confinement. Theory predicts [9][10] the electron flux suppression under reasonable conditions. This is one of the bases for fusion neutron source concept that must be checked experimentally. Low heat loss was demonstrated in previous GDT experiments with relatively cold electrons. But checking at temperatures of a keV range was still the issue.

Experiments with auxiliary ECR heating showed the possibility to reach high electron temperature [3][4]. Both gyrotrons were used to heat electrons in the near-axis region up to 0.9 keV, while outer plasma still has the temperature of about 0.1 keV. This radial gradient of electron temperature produces high radial electric field due to ambipolar effects and leads to strong azimuthal rotation of plasma. As a result, the high-temperature phase of the experiment has duration not longer than 0.6 ms and is terminated by a flute-like instability with frequency of several kHz and azimuthal wavenumber of 1. It was suggested that instability is driven by centrifugal contribution from high drift velocity itself or by an abrupt shear of drift velocity.

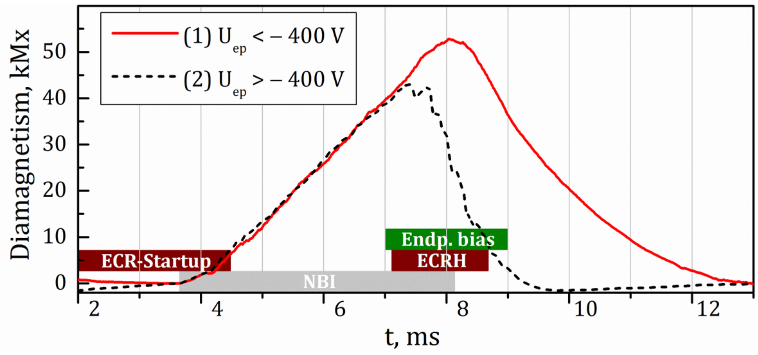

FIG. 3. Evolution of diamagnetic signal produced mostly by fast ions

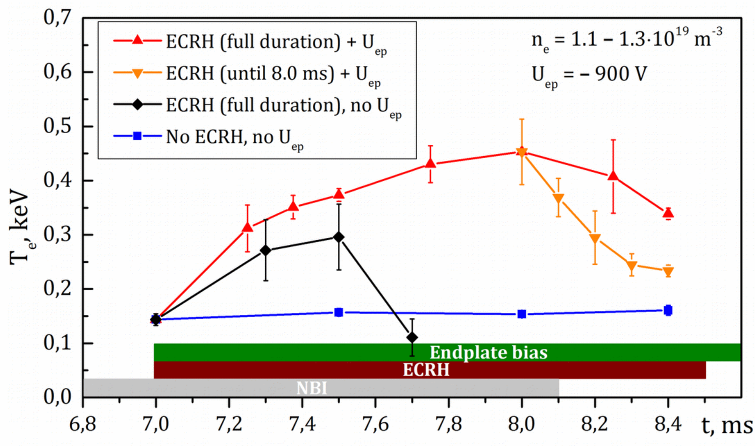

FIG. 4. Evolution of on-axis electron temperature

New plasma-facing endplates were designed to suppress the instability and extend the high-temperature phase of the experiment [11]. The stabilization technique proposed was the same as in “vortex confinement” that is applied at the plasma edge. New endplates were consisted of insulated concentric electrodes and were installed behind the mirrors on the both sides of the device (Fig. 2). They might be grounded or electrically biased separately from each other. It was technically difficult to modify potential of the arc plasma gun that was used to produce the background plasma. So, it was hidden by one of endplate and was not used in the described series of experiments. One of the gyrotrons was adopted to produce the background plasma by microwave discharge before the main phase of the experiment. The second available gyrotron was used to heat the electrons at the end of the main phase. Central parts of endplates were biased negatively to reduce the radial electric field. A typical experiment scenario is shown in Fig. 3. The fast degradation of confinement was still observed while low or no biasing voltage applied to endplates. MHD activity was observed also in case of endplates were biased without ECR heating. However, instability wass suppressed during the whole experiment if endplates were biased by $U_{ep} < -400$ V at the start of ECR heating. In this case electron temperature was still rising until the neutral beams are turned off (Fig. 4). Preliminary energy balance analysis shows that electron heat flux is still suppressed inside the near-axis region. In other words, theoretical predictions are experimentally verified up to electron temperature of 0.45 keV. The estimated energy carried away by leaving electron is 4.6±0.4 electron temperatures that is even slightly less than expected.

4. EXPANDER PHYSICS

Axial confinement is also affected by conditions in expander cells. In the idealized device particles leaved the central cell and reached the endplates in expanders are disappearing. In this case axial loss power is $Q_e \sim T_e^{3/2}$, where T_e is electron temperature in the central cell, and mean energy of lost electron is several T_e. In the real device interactions with endplates and gas behind the mirrors produces cold plasma inside expander cells. Ions of this plasma cannot overcome the electrostatic barrier of the central cell. But cold electrons can appear inside the electrostatic well and could pass through the mirror to the central cell. Every entered cold electron will expel a hot one for quasineutrality which will lead to a drastic rise of axial losses.

Theoretical works [9][10] predict the suppression of axial losses close to an ideal values if the endplates are placed in the low enough magnetic field: $K < K_{crit}$, where $K = B_{mirror} / B_{ep}$ – is the ratio between magnetic fields in the mirror and at the endplate (called “expansion ratio”), $K_{crit} \approx (m_i/m_e)^{1/2} \approx 40$ – is the square root of ion to electron mass ratio. Previously this prediction was experimentally confirmed in GDT device with electron temperature of several tens of eV [12].

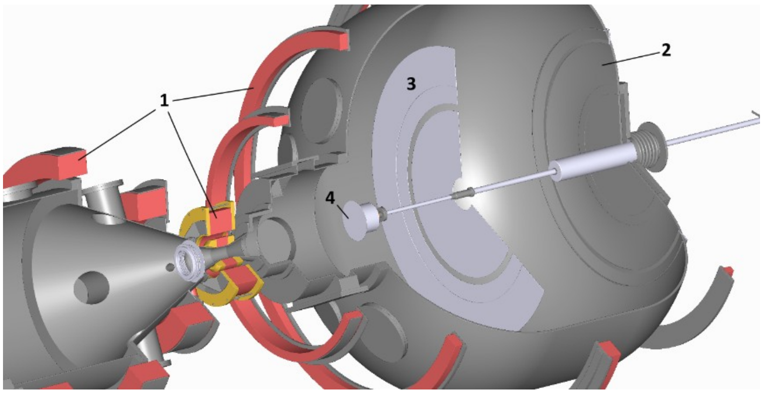

FIG. 5. Experiment with movable plasma collector: 1 – magnetic coils, 2 – expander tank, 3 – endplate, 4 – movable collector

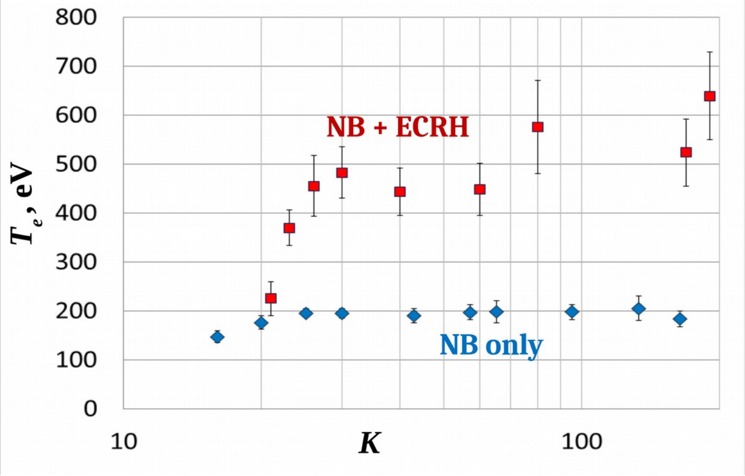

FIG. 6. On-axis electron temperature in the central cell vs. expansion ratio of the movable collector. Plasma is heated by by neutral beams only (diamonds) and by neutral beams together with ECR (squares)

Recent work was intended to check theoretical predictions at keV range of temperature [13]. Both gyrotrons were used for ECR and heated electrons up to 600-700 eV, while the target plasma was produced by arc-discharge gun. The small part of endplate called “movable collector” ccould be placed in a different axial positions and vary the expansion ratio in the range $1 \le K \le 200$ (Fig. 5). Only at $K < 30\text{-}40$ movable collector disturbs the central cell plasma parameters (Fig. 6). Potential drop in the Debye layer of the movable collector was several tens of eV in the range of expansion ratio $K \geq 40$ and slowly decreased with the increase of K. Mean electron energy was measured only for $K \geq 100$ and had a value of 15-20 eV. Both values were much lower than electron temperature in the central cell. That agrees with theoretical predictions stated confinement of cold plasma in the expander and negligible inward fluxes at high expansion ratios.

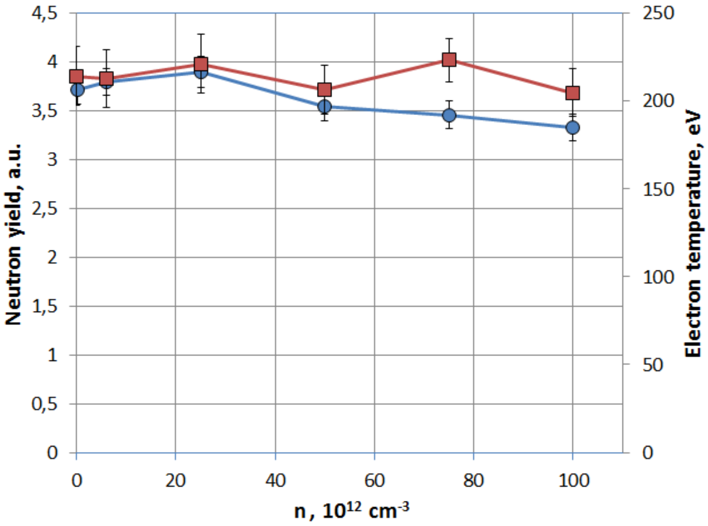

FIG. 7. Total neutron yield (circles) and on-axis electron temperature in the central cell (squares) vs. density of gas in the expander cell

The next question is an acceptable vacuum conditions in expander cells. Theory implies cold plasma is produced by rare collisions of particles outcomes from the central cell. This balance seems to be highly perturbed in the presence of high density residual gas. In this case molecules come into the plasma streaming out from the mirror and are ionized producing extra cold ions and electrons. Cold ions moves to endplates and modifies the ion current. Cold electrons may feed up the population of confined particles in the expander. Simple estimations show that gas density of $n_g = 10^{12}$ cm^{-3} is enough to significantly modify an ion flux coming to endplates in GDT device.

Experiments were carried out in a regime with neutral beams heating only. It was observed that parameters of the central plasma do not perturbed up to $n_g = 10^{14}$ cm^{-3} that exceeds the estimation 100 times (Fig. 7). This effect might be explained as follows: plasma heats the gas locally and rising gas pressure pushes it out of the plasma column. Experiments with $n_g > 10^{14}$ cm^{-3} are not presented because gas of so high density in expander breaks the central cell vacuum conditions during the preliminary phase of the experiment.

5. HIGH-FREQUENCY OSCILLATIONS

The critical issue of the mirror program is the kinetic stability. Two types of instabilities were identified as the most dangerous for GDT device: Alfven Ion Cyclotron (AIC) and Drift-Cyclotron Loss Cone (DCLC). Development of AIC instability was observed in previous work [5]. Detailed theoretical analysis [14] shows that mirrors with skew injection of neutral beams might have a little degradation of the confinement due to AIC. Current theoretical work is focused on the DCLC [15][16].

Experimental work is still in progress. Oscillations of the magnetic field are detected by single-turn wire probes placed close to the plasma edge. Typical spectrum got by the probe in the pure deuterium regime is presented on the Fig. 8. A set of equidistant lines is observed at frequency range 20-70 MHz that preliminary identified as DCLC mode. The distance between adjacent lines is about 5.3-5.5 MHz that is close to the ion-cyclotron frequency at turning points of fast ions. Two facts are agreed with DCLC theory. Firstly, the frequency is close to ion-cyclotron harmonic. And secondly, the density of fast ions has maximum and density of warm ions have minimum at turning points, so these regions are the mostly unstable. The effect of this mode on confinement needs to be clarified in future experiments. Till now significant degradation of the confinement had not been found, but small oscillations of diamagnetic signal were observed.

Additional experimental series was carried out with different isotopes. Neutral beams were still deuterium, but the arc discharge gun and gas puffing systems were fed by hydrogen. This case should be less stable according to theory [16]. But no oscillations were observed experimentally in the range of tens MHz. It can be caused by two reasons. On the one hand, the overall confinement degrades with hydrogen. Thermal velocity of hydrogen is higher than deuterium one, that leads to rise of background plasma axial losses. On the other hand, small amount of deuterium could come to the target plasma from the wall and from slowed down fast ions. And this amount might be enough to reach the stability. Nevertheless, this study should be performed more accurately in future.

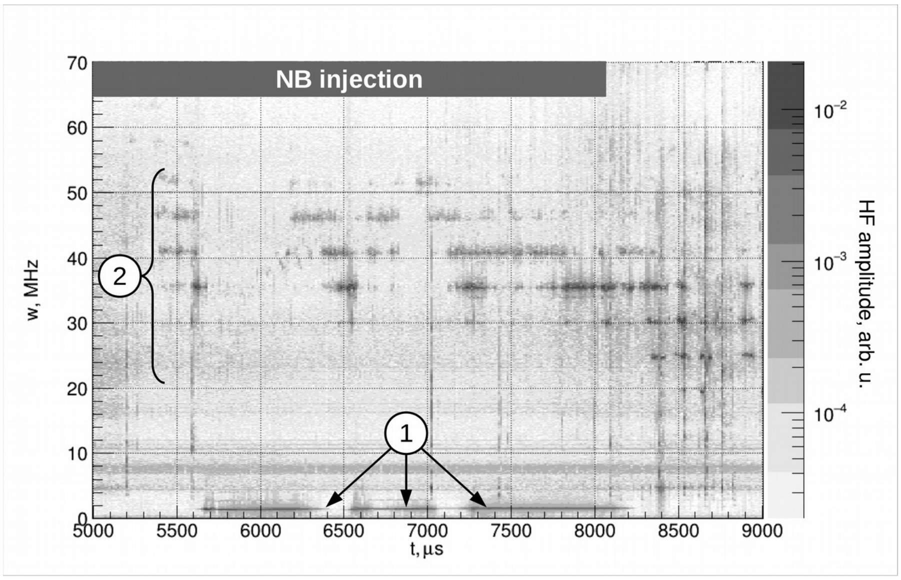

FIG. 8. Evolution of magnetic field oscillations spectrum: 1 – AIC near the frequency of 1 MHz, 2 – equidistant lines with step of about 5.3-5.5 MHz

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REFERENCES

[1] Beklemishev, A.D., Bagryansky, P.A., Chaschin, M.S., et al., Fusion Sci. Technol 57, 351 (2010).
[2] Simonen, T.C., Anikeev, A.V., Bagryansky, P.A., et al., J. Fusion Energ. 29, 558 (2010).
[3] Bagryansky, P.A., Shalashov, A.G., Gospodchikov, E.D., et al., Phys. Rev. Lett. 114, 205001 (2015).
[4] Bagryansky, P.A., Anikeev, A.V., Denisov, G.G., et al., Nucl. Fusion 55, 053009 (2015).
[5] Zaytsev, K.V., Anikeev, A.V., Bagryansky, P.A., et al., Physica Scripta 2014 (161), 014004 (2014).
[6] Anikeev, A.V., Bagryansky, P.A., Zaitsev, K.V., et. al., Plasma Phys. Rep. 41 (10), 773 (2015).
[7] Mirnov V.V., and Ryutov, D.D., Sov. Tech. Phys. Lett. 5, 279 (1979).
[8] Ivanov, A.A., and Prikhodko, V.V., Plasma Phys. Control. Fusion 55, 063001 (2013).
[9] Konkashbaev, I.K., Landman, I.S., and Ulinich, F.R., J. Exp. Theor. Phys. 47, 501 (1978).
[10] Ryutov, D.D., Fusion Sci. Technol. 47, 148 (2005).
[11] Yakovlev, D.V., Shalashov, A.G., Gospodchikov, E.D., et. al., Nucl. Fusion 58, 094001 (2018).
[12] Anikeev, A., Bagryansky, P., Kuznetsov, G., et. al., Plasma Phys. Rep. 25 (10), 775 (1999).
[13] Soldatkina, E., Anikeev, M., Bagryansky, P., et al., Phys. Plasmas 24, 022505 (2017).
[14] Tsidulko, Y.A., Chernoshtanov, I.S., Plasma Phys. Rep. 40 (12), 955 (2014).
[15] Kotelnikov, I.A., Chernoshtanov, I.S., Prikhodko, V.V., Phys. Plasmas 24, 122512 (2017).
[16] Kotelnikov, I.A., Chernoshtanov, Phys. Plasmas 25, 082501 (2018).