Axial Plasma Confinement in Gas Dynamic Trap*)

Elena I. SOLDATKINA, Peter A. BAGRYANSKY, Alexey D. BEKLEMISHEV, Eduard A. FEDORENKOV, Zakhar E. KONSHIN, Olga A. KOROBEYNIKOVA, Andrey A. LIZUNOV, Vladimir V. MAKSIMOV, Sergey V. MURAKHTIN, Egor I. PINZHENIN, Vadim V. PRIKHODKO, Valery Ya. SAVKIN, Alexander L. SOLOMAKHIN and Dmitry V. YAKOVLEV

Budker Institute of Nuclear Physics, 11 Lavrentieva prospect, Novosibirsk 630090, Russia
Novosibirsk State University, 2 Pirogova street, Novosibirsk 630090, Russia

(Received 25 September 2018 / Accepted 22 November 2018)

Presented paper is the next step in the research of axial transport in Gas Dynamic Trap. Experiments dedicated to the neutral gas role in the expander of mirror device were carried out. Ion current density distribution measured at the end plate does not depend on neutral gas density in the expander. Experimental indications of neutral gas extrusion from the axis of the expander to its periphery were observed. Numerical model describing such extrusion by elastic collisions of neutrals with plasma ions is in agreement with experimental data.

Keywords: controlled fusion, magnetic plasma confinement, mirror trap, axial transport

DOI: 10.1585/pfr.14.2402006

1. Introduction

An important feature of open magnetic traps is an existence of direct contact of hot plasma along magnetic field lines with cold surface of plasma absorbers, which inevitably must be placed in area with expanding magnetic field beyond magnetic mirrors. This is the reason why we should investigate physical mechanisms defining energy transport along magnetic field lines and build theoretical and numerical models which can get reliable extrapolations of longitudinal energy and particle fluxes in reactor-like machines.

The major attention should be payed on phenomena, taking place in magnetic expander of the trap (region between magnetic mirror and the surface of plasma absorber).

Even in case of no magnetic expansion electron heat flow in collisionless plasma is limited by ambipolar potential barrier that appears near the surface of plasma absorber and reflects the majority of electrons. There is a danger, that in real thermonuclear plasma potential drop in Debye sheath near the wall will be higher than the threshold of appearing unipolar arc, and when arcs emerge, potential drop possibly disappears. Secondary electrons in expanding magnetic field will be partly reflected by magnetic mirror back to the wall, and it is possible to decrease electron flow much more by increasing mirror ratio. The theoretic limit for longitudinal losses is close to $8T_e$ for every electron-ion couple, leaving the trap.

This simple model can be improved while considering electron scattering in the volume of the expander. Indeed, secondary electrons that cannot penetrate to the mirror is confined as in an adiabatic trap. Population of trapped electrons can be formed in the expander in the presence of weak scattering. In this case an ambipolar field does not concentrate in Debye sheath but distributes in the volume of the expander [1]. This field gives a possibility to avoid unipolar arcs on absorbers in plasma with fusion temperatures. According to the theory, if mirror ratio for magnetic field in the expander exceeds 40 (for hydrogen plasma), the majority of secondary electrons cannot penetrate to the mirror throat and electron heat flow saturates on the level of theoretic limit $8T_e$ per electron-ion couple.

All these regimes were predicted theoretically [1, 2] and realized in the experiments with conditions close to collisionless regime at Gas Dynamic Trap (GDT) in Budker Institute of Nuclear Physics [3, 4]. Those experimental researches showed that there is a population of cold electrons confined in the expander by the effective Yushmanov's potential. In case of magnetic field expansion (magnetic field in the mirror related to magnetic field on the end plate) $K > 40$, potential drop in the Debye layer at the plasma collector and energy of confined electrons are much lower than T_e in the center of the magnetic trap. Also, at $K \approx 40$ it's possible to achieve stable plasma confinement with high electron temperature (about 0.7 keV).

The theory implies the plasma flow into the expander is close to collisionless. This imposes stringent restrictions on the vacuum conditions in the expander. It is not clear what level of residual gas we can afford and what happens when there are significant number of neutrals. It seems quite possible that residual gas will be ionized thereby the

author's e-mail: e.i.soldatkina@inp.nsk.su

*) This article is based on the presentation at the 12th International Conference on Open Magnetic Systems for Plasma Confinement (OS2018).

population of trapped electrons will increase and begin to affect significantly on the plasma in the trap. It is also obvious that it will be very difficult to satisfy the requirements of high vacuum conditions in the expander of the operating fusion reactor.

Influence of neutral gas on processes in GDT expander is the key issue of this paper.

2. Neutral Gas in the Expander

Experiments described in the paper were carried out at GDT, which is an axially symmetric magnetic mirror machine [5]. The main part of the GDT device is a 7 m long solenoid, with a magnetic field at the midplane up to 0.35 T and a mirror ratio $R = 35$. The GDT facility is intended for the confinement of plasmas with two ion components. One component is deuterium plasma with an isotropic Maxwell velocity distribution. This plasma has electron and ion temperatures of up to 250 eV and a density of $\sim$1 - 3$\cdot 10^{19}$ m^{-3} and is confined in a gas dynamic mode. Confinement of such plasma in the GDT is similar to that of a gas in a vessel with a small hole. The particle lifetime in the GDT is about $\tau_{\|} = L{\cdot}R/V_{\mathrm{i}}$, where L is the trap length, R is the mirror ratio, and V_{i} is the ion thermal velocity. Another component consists of fast deuterons with an average energy of $\sim$10 keV and density up to $5{\cdot}10^{19}$ m^{-3} and is produced by intense deuterium neutral beam injection (NBI) of 5 ms duration, 22 - 25 keV particles energy and 5 MW power. This component is confined in adiabatic mode.

The theory mentioned above implies the plasma flow into the expander is close to collisionless. This imposes stringent restrictions on the vacuum conditions in the expander. It is not clear what level of residual gas we can afford and what happens when there are significant number of neutrals. It seems quite possible that residual gas will be ionized, thereby the population of trapped electrons will be increased and it will begin to affect significantly on the plasma in the trap. It is also obvious that it will be very difficult to satisfy the requirements of high vacuum conditions in the expander of the operating fusion reactor.

Simple estimations based on analysis of elementary processes taking place in plasma show that in the region of GDT near the mirror ($K = 10$, plasma diameter 15 cm, $n = 10^{12}$ cm^{-3}) neutrals should be ionized with probability close to the unity. Therefore, ion current to the end plate should increase essentially and we can register it directly.

It's possible to make an upper-bound estimate: if every gas molecule gives an electron to the plasma, and current of these "cold" electrons becomes equal to the ion current from the trap, the situation should be very unfavorable for plasma confinement. Using such estimation the critical gas density appears to be $n_{\mathrm{crit}} = 10^{12}$ cm^{-3}.

However, main plasma parameters such as electron temperature and neutron yield remain constant in much wider range – up to $n = 10^{14}$ cm^{-3} (Fig. 1). Fast ions energy content is constant as well in this range.

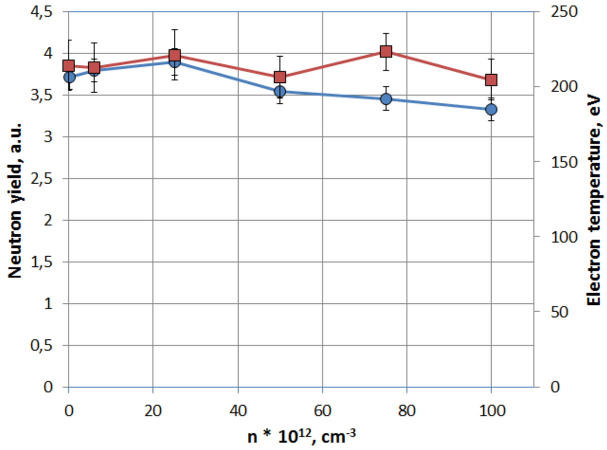

Fig. 1 Neutron yield (circles) and electron temperature in the central cell (squares) on neutral gas density in the expander.

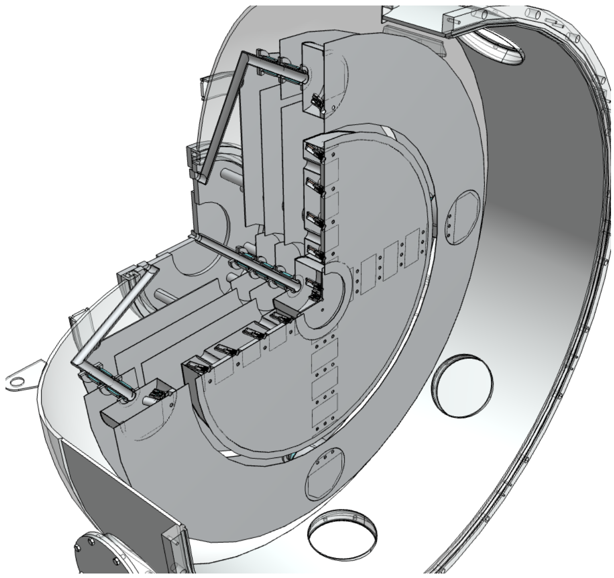

Fig. 2 Scheme of end plate in western expander of GDT.

Measured by gauge head PMM46 gas density (hydrogen was puffed) in the expander is hundred times higher than upper-bound estimate, but there is no degradation of plasma confinement. To find out the mechanism of such behavior we used six ion current probes (three electrodes, collector biased by −1600 V) mounted radially on the end plate (Fig. 2).

Figure 3 demonstrates profiles of ion current density measured by the probes for three different values of neutral gas density. In the gas density range of $(10^{10} \div 10^{14})$ cm^{-3} ion current density varies no more than about 20% of value. The total ion current on the end plate remain constant in this range of gas densities.

To investigate neutral gas behavior in the expander the optic tomography is now being developed at GDT (Fig. 4).

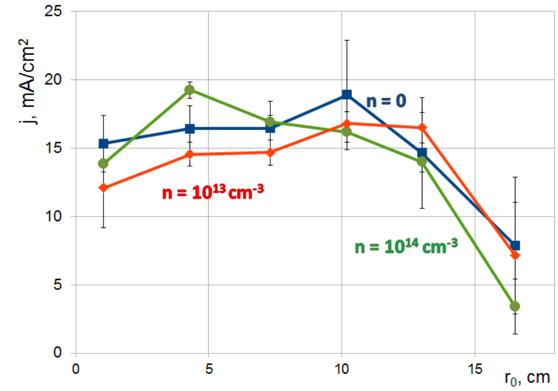

Fig. 3 Ion current density on radius for three different values of neutral gas density in the expander: no gas (squares), $n = 10^{13}\ \mathrm{cm}^{-3}$ (diamonds) and $n = 10^{14}\ \mathrm{cm}^{-3}$ (circles).

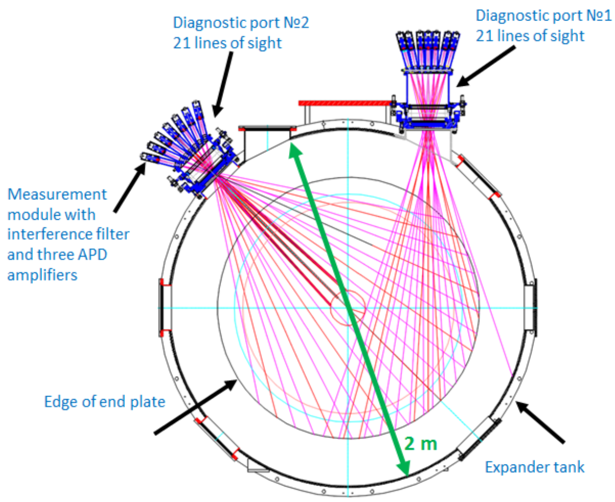

Fig. 4 Layout of optic tomography system in GDT expander.

This is a system consisting of 42 channels, which can register radiation of Hα and Dα lines in the expander using narrow-banded interference filters. Avalanche photodiodes with broadband amplifiers are being used as detectors of radiation. This system allows investigating plasma dynamics in range of frequencies up to 1 MHz. We can estimate radial profile of radiation in the expander by one-dimensional code constructed for the moment.

Typical results on radiation profiles are shown at Fig. 5. NBI pulse starts at 4 ms from GDT impulse beginning and finishes at 9 ms. As far as radiation intensity indicates gas density profile, therefore from the Fig. 5 (a) it's obvious that gas moves from the axis to the periphery during the impulse. Herewith the radiation at the periphery is rising at higher values of puffed gas density (Fig. 5 (b)).

3. Numerical Model

Results obtained can be interpreted as absence of gas ionization in the expander region and extruding of neutral

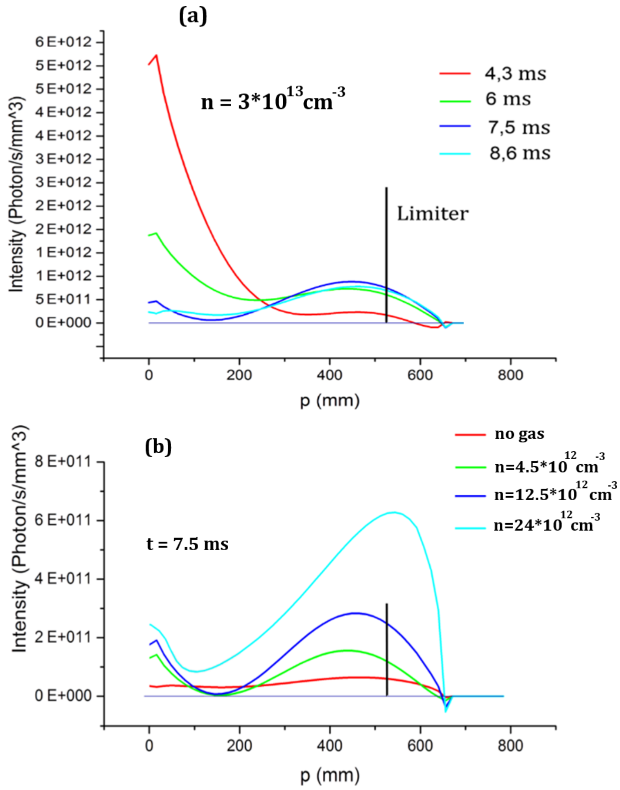

Fig. 5 Radial profiles of Hα line intensity in GDT expander: (a) for different moments of the GDT impulse at neutral gas density of $n = 3{\cdot}10^{13}\ \mathrm{cm}^{-3}$, (b) for different densities of neutral gas at the moment of 7.5 ms.

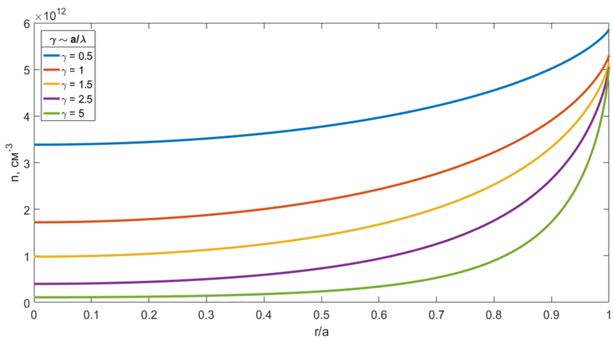

Fig. 6 Radial distribution of gas density for various collision frequencies calculated by kinetic numerical code.

gas from the axis of the expander to its periphery. To describe gas behavior computational model had been created. This model is based on the numerical solution of kinetic equation for neutral gas, which has initially Maxwellian distribution function and interacts with plasma ions by elastic collisions $H_2 + D^+ \rightarrow D^+ + H_2$ (0.5 eV), cross section $\sigma = 3{\cdot}10^{-15}\ \mathrm{cm}^{-2}$ [6]. Kinetic equation for gas particles had been solved in the region inside the cylindrical plasma column with fixed parameters; the collisions with large transmitted momentum had been taken into account.

Figure 6 represents radial distribution of gas density calculated by means of described model for various collision frequencies ($\gamma = a/\lambda$ – collision parameter, a – plasma radius, λ – electron mean free path, initial gas density $n_0 = 10^{13}\,\mathrm{cm}^{-3}$).

Numerical results on gas density profile inside plasma column also show gas extrusion from the plasma which is in a principal agreement with experimental data. This model is now under development. It's planned to include in it a gas dynamic part to calculate gas behavior in region between plasma and chamber and also to consider some inelastic processes.

4. Conclusions

Experiments to study the influence of neutral gas in the expander on plasma confinement in the central part of the GDT were carried out. It is shown that the key parameters of the plasma remain constant over a wide range of gas densities in the expander: from 10^{10} to $10^{14}\,\mathrm{cm}^{-3}$.

The ion current density on the end probes varies by no more than 20% in this range of gas densities. The assumption that the gas is extruded from plasma due to elastic collisions has experimental basis and is confirmed by preliminary numerical calculations; a corresponding computational model is being developed.

In the first approximation, it can be argued that in a fusion reactor based on an open trap, the requirements for vacuum systems for expanders can be significantly softened compared to those originally planned.

Acknowledgments

This research is supported by Russian Science Foundation, project No. 18-72-10084 from 31.07.2018.

[1] I.K. Konkashbaev *et al.*, J. Exp. Theor. Phys. **74**, 956 (1978).
[2] D. Ryutov, Fusion Sci. Technol. **47**, 148 (2005).
[3] A.V. Anikeev *et al.*, Plasma Phys. Rep. **25**, No. 10, 775 (1999).
[4] E. Soldatkina *et al.*, Phys. Plasmas **24**, 022505 (2017).
[5] A.A. Ivanov and V.V. Prikhodko, Plasma Phys. Control. Fusion **55**, 063001 (2013).
[6] P.S. Krstic and D.R. Schultz, *Atomic and Plasma-Material Interaction Data for Fusion*, Volume 8 (IAEA, Vienna, 1998).