J. Plasma Fusion Res. SERIES, Vol. 4 (2001) 199–202

Increase of Hot Initial Plasma Energy Content in the End System of AMBAL-M During Hydrogen Puffing

AKHMETOV Timour*, BEKHER Sergei, DAVYDENKO Vladimir, KRIVENKO Aleksandr, MURAVIEV Maksim, REVA Vladimir and SOKOLOV Vladimir
Budker Institute of Nuclear Physics, Prospect Lavrentieva 11, Novosibirsk, 630090, Russia

(Received: 5 December 2000 / Accepted: 27 August 2001)

Abstract

At the end system of the completely axisymmetric mirror trap AMBAL-M the experiments on creation and study of a hot initial plasma have been performed. In the experiments a gas-box was used for hydrogen supply into the hot startup plasma in the mirror trap to increase the plasma density. The hot initial plasma in the trap was produced by the trapping of a plasma stream with developed electrostatic turbulence generated by a gas-discharge source located outside the entrance throat. It was found that in addition to the increase in the plasma density by a factor of 2–3, hydrogen puffing resulted in an unexpected nearly twofold diamagnetism increase. The gas puffing did not reduce the electron temperature in the trap. Essential for explanation of the observed effect is the fact that with the gas puffing the measured plasma potential in the trap increased. The increase in the plasma potential enhanced the trapping of the ion flow entering the trap and increased the average energy of the electron flow entering the trap. It was found that with the increasing hydrogen puffing rate plasma parameters in the trap were saturated.

Keywords:

magnetic mirror trap, plasma confinement, heating, gas puffing

1. Introduction

The ambipolar magnetic mirror trap AMBAL-M [1-3] is a completely axisymmetric machine, and experimental investigations performed at it are of fundamental importance for a future thermonuclear reactor. Investigations at AMBAL-M are divided into two stages. Since 1993 the experiments at the end system (Fig. 1) consisting of a simple mirror trap and semicusp have been carried out. In this system, a hot initial plasma was obtained using a gas-discharge plasma source located outside a magnetic throat. Thermal insulation in the entrance throat and electron heating in the mirror trap by the axial current flowing along the plasma were studied. Consistent accumulation of fast ions in the mirror trap plasma during pulse

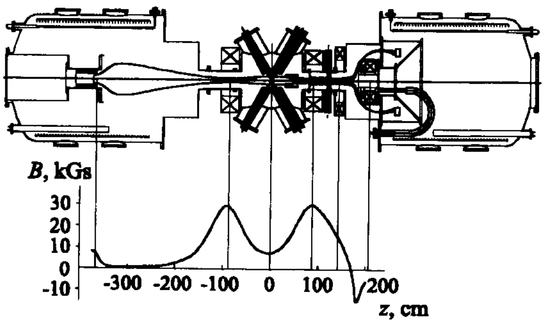

Fig. 1 Top view of the magnetic system and vacuum chamber of the end system of AMBAL-M. Magnetic field line starting from the plasma source (z = –375, r = 6 cm) is shown. Below is given the magnetic field profile at the axis.

*Corresponding author's e-mail: akhmetov@inp.nsk.su

injection of powerful neutral beams was demonstrated and experiments on ICR heating of the initial plasma were performed.

However, the plasma density in the mirror trap was limited by the value of the plasma flow produced by the source. Therefore, in order to increase the plasma density, additional fueling mechanisms were required. One of the commonly used and predictable ways to increase the plasma density is the use of gas puffing during the pulse of the hot plasma, when ionization of this gas by the hot plasma leads to controllable production of the additional plasma. In the present paper recent experiments at the end system on enhancement of the initial plasma parameters in the mirror trap during hydrogen puffing through a gas-box are described.

2. Creation of the Initial Plasma in the Trap and Its Parameters

The initial plasma in the end system of AMBAL-M is created by a gas-discharge plasma source which generates a plasma stream with a density $\sim 10^{14}$ cm^{-3}, electron and ion temperatures ~10 eV. This stream from an annular discharge channel flows along magnetic field lines and enters the mirror trap. Since there is a strong radial electric field $E_r \sim 200 \div 300$ V/cm between the cylindrical electrodes of the plasma source, the plasma rotates in the azimuthal direction in the crossed radial electric and axial magnetic fields. This rotation velocity in our conditions has a strong radial shear, which leads to the Kelvin-Helmholtz instability, and as a result, the electrostatic turbulence develops in the plasma stream. This turbulence leads to strong ion heating up to 250 eV in the trap and to the radial diffusion of the plasma. Thus, the radial profile of the plasma density, which has a shape of a narrow annulus near the plasma source, is smoothed by the diffusion and becomes flat in the mirror trap with a typical value of $\sim 6 \cdot 10^{12}$ cm^{-3} in the midplane.

As the plasma stream moves from the plasma source to the entrance magnetic throat of the mirror trap, ions become collisionless and owing to conservation of the magnetic moment $\mu = v_\perp^2/B$ (where $v_\perp$ is the transverse ion velocity and B is the magnetic field strength) a substantial part of the plasma stream reflects from the region of strong magnetic field, leading to a considerable density decrease towards the trap. Electrons remain Maxwellian and their density is governed by the Boltzmann distribution in the electrostatic potential along the magnetic field lines $n \propto \exp(e\varphi/T_e)$, where T_e is the electron temperature, φ is

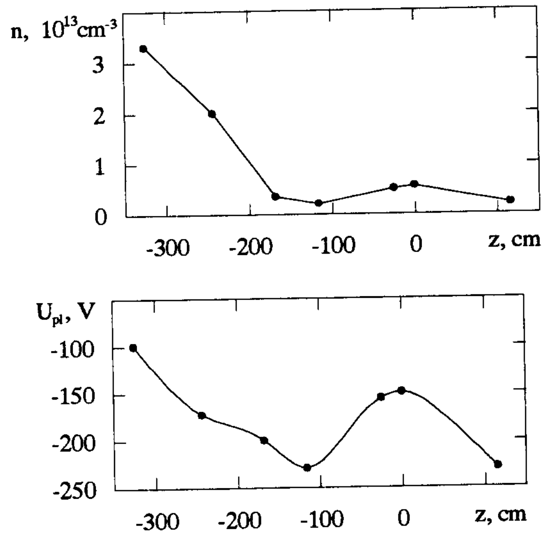

Fig. 2 Axial distributions of the plasma density and plasma potential.

the plasma potential and e is the absolute value of the electron charge. Thus $e(\varphi(z) - \varphi_0) = T_e \cdot \ln(n(z)/n_0)$, the axial potential profile qualitatively reflects the density profile, and there is a potential minimum in the entrance throat, which prevents the electrons captured in the trap from flowing back to the plasma source. Plasma potential in the center of the trap (Fig. 2) is $\sim 50 \div 100$ V higher than in the entrance throat, thus leading to thermal insulation of the electrons in the trap which have a typical temperature ~50 eV, from cold electrons near the plasma source. Another mechanism leading to plasma heating is the presence of the axial electric current of ~1.5 kA flowing through the plasma, which results in the Joule heating of the electrons. Thus, the hot initial plasma in the trap with the ion temperature ~250 eV and electron temperature ~50 eV is created during the pulse of the plasma source. The ions are heated by the electrostatic turbulence developed in the plasma and sustained by the power of the plasma source. The electrons obtain energy in electron-ion collisions, and due to the Joule heating by the axial electron current in the plasma. The electron temperature remains relatively high thanks to the thermal insulation of the trapped plasma by the electrostatic potential well, which substantially reduces electron thermal conductivity between the trap and the plasma source.

3. Experiments with Hydrogen Puffing into the Initial Plasma in the Trap

After detailed investigations of the initial plasma in the trap attempts were made to increase the plasma density and temperature by different means. One of the simplest methods to increase the plasma density is to add some amount of molecular hydrogen into the hot plasma. The gas is ionized by the electron impact and charge-exchange processes and the total amount of plasma should increase. In order to make this gas supply more efficient and spatially uniform we installed a special gas-box inside the mirror trap. The gas-box is a circular metal tube surrounding the plasma, and it has narrow diaphragms on its ends. After entering the gas-box the hydrogen molecules reflect from its walls and penetrate into the plasma volume. The gas-box in our machine was installed in the mirror trap between the midplane and the exit throat and the hydrogen puffing was performed at various rates from 2 to 10 Torr·L/s.

From the very beginning of the experiments with this gas-box we obtained the unexpected result. The plasma diamagnetism in the mirror trap increased during the gas puffing. From the oscillogram presented in Fig. 3 one can see the increase in the plasma diamagnetism and also the increase in its growth rate. The diamagnetism increase points to additional heating or better confinement of the trapped plasma, or both of these factors. Therefore, experimental study of this effect was made. It was found out that at moderate hydrogen puffing ~2 Torr·L/s the electron temperature grows from 40–45 eV to 55–60 eV together with the density increase. With increased hydrogen puffing rate ~10 Torr·L/s the electron temperature in the central region remained almost the same and fell down to 30–35 eV at the periphery. The plasma density and energy content increased nonlinearly with the value of the hydrogen puffing rate. With small hydrogen supply, the plasma density and diamagnetism increased sharply and then the rate of growth decreased. The ion saturation current profiles for three gas puffing rates are presented in Fig. 4, and one can easily observe that puffing at 2 Torr·L/s led almost to the same increase in the ion saturation current as the increase of the puffing rate from 2 to 10 Torr·L/s. It is essential that during the hydrogen puffing the ambipolar potential of the plasma considerably increased, which was confirmed by the profiles of the probe floating potential presented in Fig. 5. An average ion energy measured by an end-loss energy analyzer, did not change within the experimental

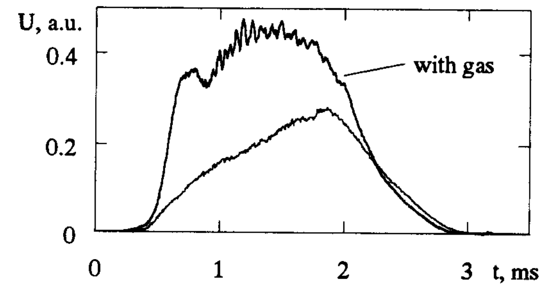

Fig. 3 Plasma diamagnetism without gas and with hydrogen puffing at 2.5 Torr·L/s.

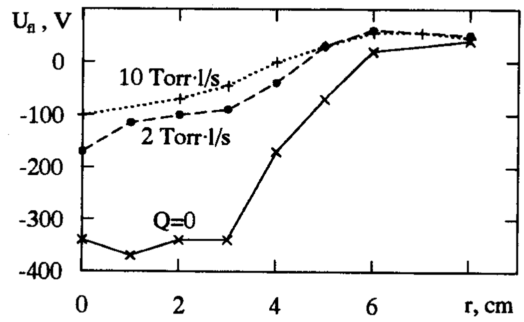

Fig. 5 Probe floating potential with different gas-puffing rates.

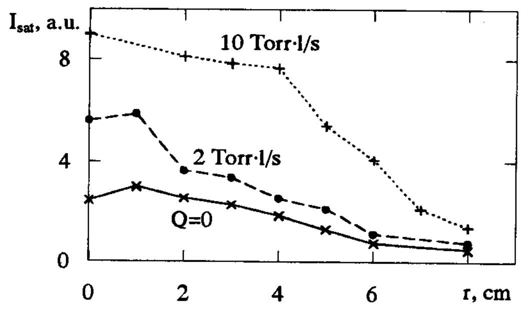

Fig. 4 Ion saturation current in the trap with different gas-puffing rates.

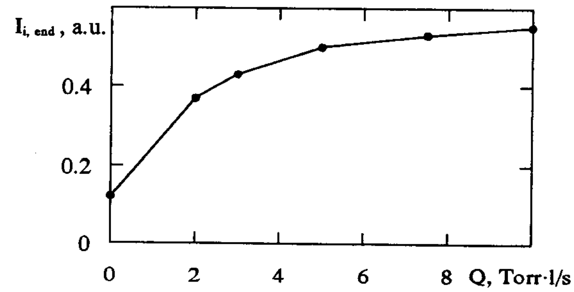

Fig. 6 End-loss ion current as a function of the hydrogen flow into the gas-box.

accuracy and was 400 ± 60 eV. The nonlinear dependence of plasma density on the hydrogen puffing rate was also substantiated by the end-loss ion current measurement using a gridded ion-energy analyzer at the axis (Fig. 6).

The observed improvement of the plasma energy content can be explained by enhancement of relaxation of the axial electron current flowing in the plasma in the axial direction, and by the increase in the plasma potential in the trap which improved the electron confinement. The axial current of ~1–1.6 kA with an average electron energy of ~250–300 eV flowed through the plasma and the fraction of electrons captured into the mirror trap plasma due to classical collisions was estimated as ~0.3 [2]. When the plasma density increased as a result of ionization of the puffed hydrogen, the electron capturing from the flow improved. Since with the density increase the ambipolar potential grew in the mirror trap and practically did not change outside the entrance throat, an average energy of the captured electrons also increased.

In order to achieve better understanding of the plasma confinement and influence of gas puffing, we have developed a numerical model of the plasma creation in the trap by the plasma source and gas puffing into this plasma. For simplicity we use a zero-order model, i.e. it does not account for spatial variation of the plasma and gas parameters and the plasma is characterized by its typical length and radius. Interaction between the plasma and gas is described by simple balance equations for the ion and gas densities, ion and electron energies. We consider two ion populations: relatively hot ions with a typical energy of 200 eV, which are generated by the plasma source and captured into the trap, and relatively cold ions with a typical energy of several tens of electronvolts, which are produced from cold 2 eV Frank-Condon atoms in the charge-exchange and electron-impact ionization processes. First numerical results obtained from this model provide promising qualitative and quantitative agreement with the experimental data. The model requires further improvement in order to account more accurately for the influence of the increase in the electrostatic potential in the trap on electron and ion capturing from the plasma stream. This numerical model will be useful for planning experiments with a gas-box, which will be installed in a long solenoid of a new modification of the AMBAL-M machine [3]. Similar gas puffing is successfully used in a long central cell of the ambipolar trap GAMMA 10 [4].

4. Conclusions

In the experiments with the hydrogen puffing into the initial plasma created in the end system of AMBAL-M, the plasma density was increased about 3 times. At the same time, the gas puffing did not cause degradation of the ion and electron temperatures in the mirror trap. This result is explained both by the enhanced electron and ion capturing from the hot plasma stream generated by the plasma source, and by continuous ion and electron heating during the pulse of the plasma source. The gas-box proved its efficiency as a simple tool for increasing the plasma density, and a similar gas-box will be used in experiments at the new modification of AMBAL-M with a long solenoid.

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