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MAGNETIC CONFINEMENT SYSTEMS

Dynamics of the Potential of a Plasma Jet Heated by Atomic Beams in a Mirror System

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Abstract—In experiments on plasma heating in the AMBAL-Yu mirror system, the density of a target plasma jet was found to decrease substantially during the injection of high-energy atomic beams. In previous work, a model was developed that can adequately describe this phenomenon, and the experimental and simulation results were compared. Here, the dynamics of the potential of a plasma jet heated by atomic beams in a mirror system is considered in order to better understand the observed decrease in the target-plasma density.

Experiments in the AMBAL-Yu device [1] revealed an unexpected and interesting phenomenon: a substantial decrease in the density of the target plasma jet during the injection of high-energy hydrogen atoms.

The AMBAL-Yu is a classical single-stage tandem mirror system with a mirror ratio of two and mirror distance of 1 m. A beam of 16 keV hydrogen atoms with a flow current (expressed in electric current units) up to 160 A was injected into the plasma transverse to the axis of the system; the injection time was 200 μs. Before the injection, the device was filled with a plasma with a density of 2.4×10^{14} cm^{-3} and with characteristic electron and ion temperatures of about 10 eV. The plasma jet was produced by an arc source with a slot discharge channel [2], which was located outside the mirror system near its end side. The plasma jet generated by this source entered the mirror cell along the magnetic field lines. The jet was subsonic upstream and supersonic downstream from the exit side of the mirror cell. After the injection of atomic beams, a population of hot ions with an average energy of 6 keV and density up to 1.1×10^{13} cm^{-3} was generated in a plasma volume of 3 l. At the same time, the density of the target plasma jet decreased markedly (by a factor of 2.5).

In previous work [3], the results of these experiments were presented, and a time-dependent problem of plasma flow was considered by the two-fluid magnetohydrodynamic approach with allowance for the population of hot ions in a mirror system. Also, a scheme for numerical calculations was described, and good agreement was found between the results of simulations and all experimental data. The processes under consideration were explained in terms of plasma pressure distributions [3, 4].

Here, we study the dynamics of the potential of a plasma jet heated by atomic beams in a mirror system in order to provide a better understanding of the observed decrease in the target-plasma density. We use the results of computer calculations carried out in [3]. Since they are in good agreement with all experimental data, it is convenient to use only the computation diagrams to interpret the phenomenon under investigation. In [3], one can find experimental data on the behavior of the plasma potential, electron temperature, plasma density, etc.

DISCUSSION OF THE TIME EVOLUTION OF THE POTENTIALS

Figure 1 shows profiles of the magnetic field and the density of hot ions along the axis of the system (the point $z = 0$ corresponds to the center of the mirror system, and the plasma source is located at the point $z = -170$ cm). We assume that the density of the hot ions increases linearly during the first 10 μs, and then remains at a constant 2×10^{12} cm^{-3}. The energy of the hot ions is 5 keV.

The injection of atomic beams leads to a rapid increase in the number of hot ions. Hot ions rapidly lose their energy in Coulomb collisions with electrons and ions of the target plasma. For example, the time during which hot ions are decelerated by the plasma, which is still dense and cold in the initial stage of injection, is equal to 3 μs. Most of the energy of the hot ions is converted into the energy of the plasma electrons, and only a small fraction of this energy is transferred to the ions of a target plasma. As a result, the electron temperature increases rapidly. Figure 2a displays longitudinal profiles of the electron temperature at different characteristic times. We can see that at the center of the mirror system, this temperature increases rapidly from 10 to 18 eV within 10 μs.

The heated electrons are trying to escape from the plasma, and its potential increases markedly and confines these heated electrons in the system. As a result, a longitudinal electric field arises, which decelerates the

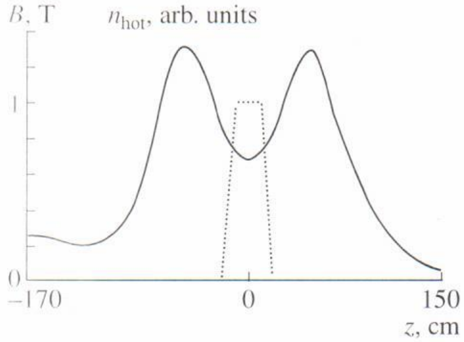

Fig. 1. Longitudinal profiles of the magnetic field (solid curve) and the density of the hot ions (dotted curve).

ions that enter the mirror cell and accelerates the ions that escape from this cell. Because of the ion deceleration, the plasma flow through the mirror system decreases. Consequently, since the plasma velocity does not change, the plasma density begins to decrease. Figure 2b represents longitudinal profiles of the plasma jet. Because the ions are decelerated in the region in front of the injection region, the deceleration of the plasma flow results in an increase in the plasma density. On the other hand, the flux of the ions that are accelerated behind this region overtakes the flux of the ions that were accelerated earlier and whose acceleration rate was lower; consequently, the plasma flow behind this region increases. After 100 μs, the plasma flow becomes the same as it was at the initial instant. This state of the flow will be referred to as the steady state. Our aim here is to study the corresponding density evolution.

First, we analyze the processes that occur in the zone between the plasma source and the injection region. The plasma flow is governed by the motion of the plasma ions. We use the equation of motion in the form $Mn\frac{du}{dt} = -\frac{\partial p_i}{\partial z} - \frac{\partial \pi_{izz}}{\partial z} + enE_z + 0.71n\frac{\partial T_e}{\partial z}$. It is convenient to describe the plasma flow in terms of the plasma jet potential, because, in the steady state, there is a simple relationship between the change in the flow velocity and the potential: $\Delta\frac{Mu^2}{2} = -\Delta\varphi$. We assume that the potential at the plasma source is equal to zero.

Figure 3a depicts the potential of the electric field, $\varphi_E(z) = -e\int_{-170}^{z} E_z\,dz$. Recall that the potential in the mirror system increases markedly so that plasma electrons whose heating rate is high are confined by the corresponding longitudinal electric field, which decelerates the ions that enter the mirror cell. Consequently, the plasma density starts to increase. Since the electron thermal conductivity in front of the cell is high, the electron temperature increases. The ion temperature also increases due to electron–ion collisions. The potential profile becomes smooth: in the zone between the plasma source and the injection region, both the plasma density and plasma temperature increase, and, within the mirror cell, plasma electrons can be confined in a relatively shallow potential well. However, in the steady state, the value of the electric field potential in the mirror system exceeds the corresponding value before the injection; i.e., the ions that enter the mirror cell are, as before, decelerated by the electric field. In the steady state, the plasma flow again becomes the same as it was at the initial instant. This raises the question as to why the plasma density decreases. At first glance, the plasma density should increase, because the plasma flow is decelerated by the electric field.

We take into account a thermal force that is driven by the longitudinal gradient of the electron temperature. The potential of the thermal force can be written

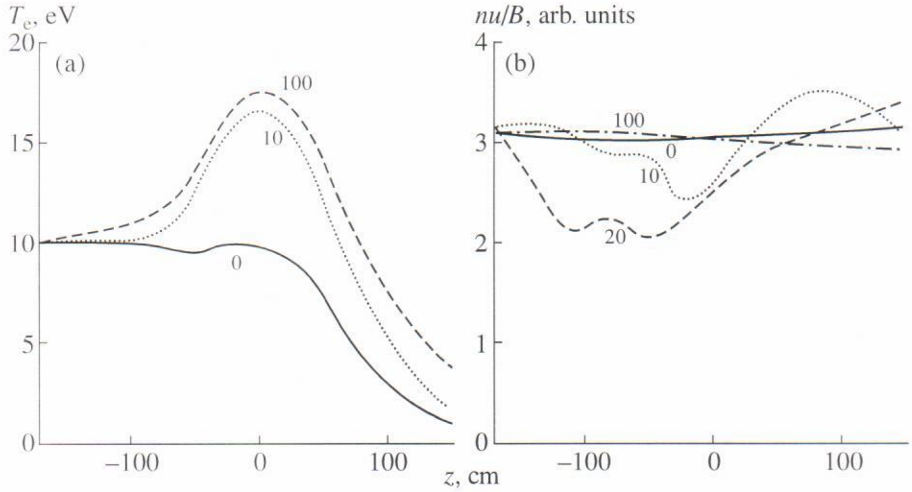

Fig. 2. Longitudinal profiles of (a) the electron temperature and (b) the plasma flow at different times. (Here and below, the numbers correspond to different times (in microseconds), starting from the time at which the population of hot ions appears in a mirror system.)

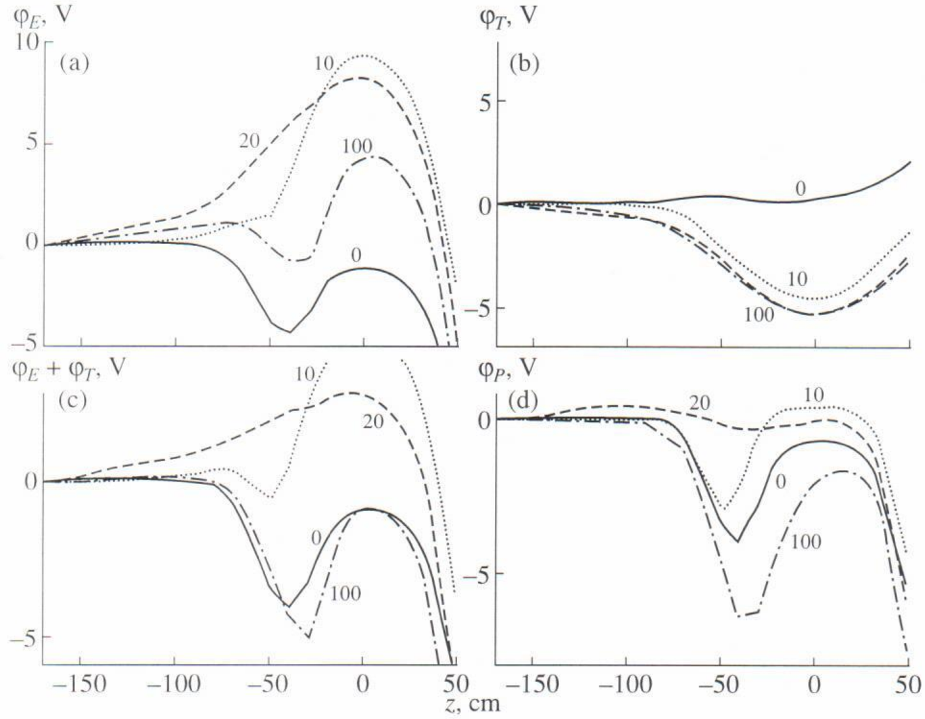

Fig. 3. Longitudinal profiles of (a) the electric field, (b) the thermal force, (c) the sum of the potentials of the electric field and the thermal force, and (d) the ion pressure at different times.

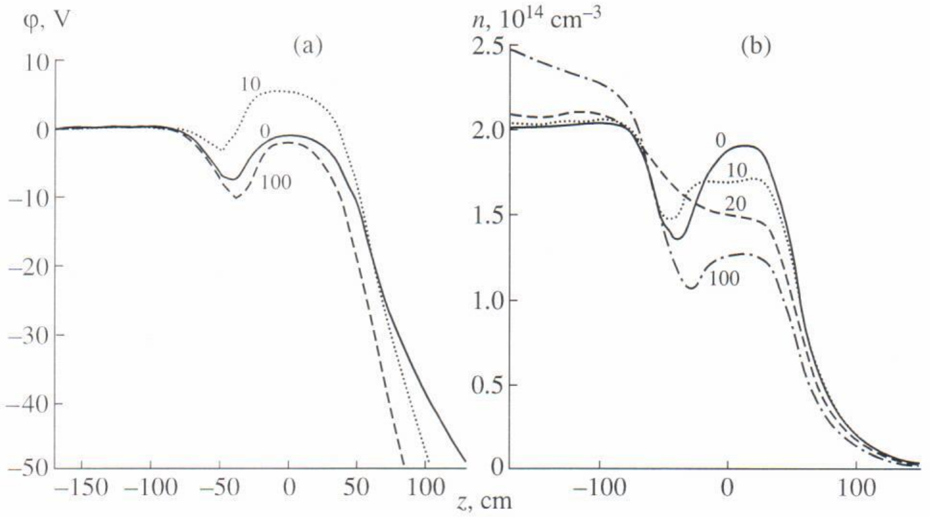

Fig. 4. Longitudinal profiles of (a) the summarized potential and (b) the plasma density at different times.

as $\varphi_T(z) = 0.71(T_e(-170) - T_e(z))$. Figure 3b shows a longitudinal profile of this potential. The effect of the electrons that escape from the region in which the plasma temperature is higher on the plasma ions is weaker than that of the electrons that escape from the region where the temperature is lower. The reason is that the collision time depends strongly on the flow velocity, $\tau \sim v^3$. Although the momentum acquired by the plasma ions due to their collisions with hotter electrons is higher than that acquired due to collisions with colder electrons, in the latter case, the collisions are more frequent. Consequently, the thermal force accelerates the ions that enter the mirror cell.

Figure 3c displays the sum of the longitudinal potentials of the electric field and thermal force. One can see that, in the intermediate stage, both the thermal force and the electric field also affect the deceleration process. However, at the center of the mirror system, the sum of these potentials in the initial state is equal to that in the steady state. Consequently, the flow velocity and, thus, the plasma density remain unchanged.

Figure 3d clearly show that the only effect is the work produced by the ion-pressure forces. The potential of the ion pressure is defined by the relationship $\varphi_p(z) = \int_{-170}^{z} \frac{1}{n} \frac{\partial p_i}{\partial z} dz$. We can see that, in the steady state, this potential is lower than that in the initial stage. Consequently, in the steady state, the flow velocity is higher and the plasma density is lower than in the initial stage.

In order to better understand the work produced by the pressure forces, we consider the behavior of the ions that escape from the mirror cell. Let us analyze the summarized profile shown in Fig. 4a. This profile corresponds to the sum of the longitudinal potentials of the following quantities: electric field, thermal force, ion pressure, and (for completeness) viscous force. An increase in the plasma potential, which ensures electron confinement in the mirror system, causes an increase in the gradient of the ambipolar potential at the exit side of the mirror cell. The rate of acceleration of plasma ions by the electric field (but not solely by this field) is higher than that for the plasma electrons. Consequently, the rate at which the plasma ions escape from the mirror cell is also higher than that for the plasma electrons. At the same time, the plasma flow through the system decreases, which results in a substantial decrease in the ion density within the mirror cell. When the plasma flow becomes the same as it was in the initial sage, the drop in the potential between the plasma source and the mirror cell increases, which is associated with a low plasma density within the cell. Since the acceleration rate of the ions that enter the mirror cell is higher, the flow velocity of these ions increases, and, consequently, the density of these ions decreases. Figure 4b shows longitudinal profiles of the plasma density.

Finally, we should mention the famous experiments carried out in the 2XIIB machine [5]. In those experiments, in accordance with the diagrams presented in that paper, the density of the target plasma decreased during the injection of atomic beams. However, this point has escaped the attention of researchers, probably because they suggested that this decrease was associated with an obvious mechanism for the replacement (due to charge exchange) of a target-plasma ion by a hot ion. Note that, since the ion temperature of the plasma jet in those experiments was high, the plasma flow in the mirror system was collisionless (see, e.g., Fig. 9 in [6]) and the effect under consideration (which is typical of collision-dominated plasmas) did not manifest itself.

CONCLUSION

We have studied the dynamics of the potentials of a plasma jet heated by atomic beams in mirror systems. Based on the results obtained, we have proposed an interpretation of the 3 observed decrease in the density of a target plasma jet during the injection of atomic beams. The results of experiments and calculations can be summarized as follows (the first and second conclusions are taken from [3]).

(1) Ions of a target plasma jet are heated effectively by the injected hot ions through their collisions with plasma electrons.

(2) The ion heating increases the flow velocity of the plasma jet and, accordingly, decreases the plasma density.

(3) In order to confine the heated plasma electrons in a mirror system, the ambipolar potential increases. An increase in the gradient of this potential causes an increase in the acceleration rate of the ions that escape from the mirror cell. The ion escape occurs under the action of the electric field. In the initial stage (when the plasma density increases), an increase in the ambipolar potential leads to deceleration of the injected ions, a reduction of the plasma flow, and a decrease in the plasma density.

(4) To study the processes under consideration, it is important to take into account the longitudinal thermal force.

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