DYNAMICS OF POTENTIALS OF A PLASMA JET HEATED BY NEUTRAL BEAMS

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Experiments in AMBAL-Yu mirror system [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 mirror with minimum-B. Beams of 16 keV hydrogen atoms were injected perpendicularly to the axis. 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 near its end system. 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. Due to 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 significantly (by a factor of 2.5).

Here is one of the first explanations of the phenomenon. A cold ion is replaced by a hot one with the larger Larmor radius due to charge-exchange of a high energy atom on a cold ion. Therefore, the total density of ions increases on the periphery and decreases in the center. As the end is a conductor the electrons in the center flow out of the mirror along the magnetic field lines, and on the periphery they flow inside. The development of two-flow instability and the transport of plasma across the magnetic field lines are possible. But the measurements carried out with a cesium low-energy atom analyzer [3] did not show any significant transverse plasma flow. Another variation of the explanation is the following. As hot ions in the occupied area heat electrons directly due to collisions, then a subsonic electron flow is accelerated. The electrons leave the hot ion region more quickly, and the flow from the gun is not changed. A longitudinal electric field appears at the boundary that accelerates the ions (note that the longitudinal electric field here has another sign according to the right model described below). The plasma flow is accelerated, the plasma density decreases. But this model does not explain many experimental results.

1 Numerical model

An understanding came when the plasma stream was considered within the framework of magnetic hydrodynamics [4, 5]. The set of equations includes the continuity, motion, and heat flux equations for both electrons and protons. Time-dependent problem of plasma flow by the two-fluid magnetohydrodynamics approach with allowance for the population of hot ions in a mirror was considered [6]. Numerical calculations were made. The time-dependent solution for the plasma jet parameters on axis was determined. Good agreement was found between the results of simulations and all experimental data [6].

The main experimental results are the following: electron temperature in the mirror increased to 25 eV; the jet dimensions do not change; between the injection region and the input throat, a shock wave propagating upstream is observed; the analyzers and bolometer that are located at the plasma receiver detect a substantial increase in the ion energy and heat flux. At the same time, the jet-plasma parameters measured with the probe in the upstream region from the input throat do not change noticeably. Plasma source operation do not change. Plasma ion-cyclotron radiation does not grow. Since the injected beams are symmetrical with respect to the axis, the momentum transfer from the neutral beams to the target plasma does not play an important role.

The numerical calculation results of the time evolution of the potentials are given in [7]. The phenomenon appeared to be explained more clearly in terms of potentials. Now let us turn to the discussion of the time evolution of the potentials.

2 Discussion of the time evolution of the potentials

The injection of atomic beams leads to a rapid accumulation 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 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 from 10 eV to 25 eV within 10 μs.

The heated electrons are trying to escape from the mirror cell, and plasma potential in the mirror increases significantly and confines these heated electrons in the mirror. As a result, a longitudinal electric fields arises, which decelerates the 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 decreases. Consequently, since the plasma velocity does not change, the plasma density begins to decrease. 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 ions. Recall that the plasma potential in the mirror increases significantly so that 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 is high, the electron temperature increases in front of the mirror cell. The ion temperature also increases due to electron-ion collisions. The plasma potential profile becomes smooth: in the zone between the plasma source and the injection region, both the plasma density and electron temperature increase, and within the mirror cell, electrons can be confined in a relatively shallow potential well. However, in the steady state, the value of the plasma potential in the mirror 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 effect of the electrons that escape from the region in which the temperature is higher on the plasma ions is weaker 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 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. However, at the center of the mirror, the sum of plasma potential and thermal force potential in the initial stage is equal to that in the steady state. Consequently, the flow velocity and, thus, the plasma density remain unchanged.

The only effect is the work produced by the ion-pressure forces. In the steady state, the ion-pressure potential ($\varphi_p = \int \frac{1}{n} \frac{\partial p_i}{\partial z} dz$) 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 pressure forces, we consider the behavior of the ions that escape from the mirror cell. An increase in the plasma potential, which ensures electron confinement in the mirror cell, causes an increase in the gradient of the ambipolar potential at the exit side of the mirror cell. The electric field (but not only this field) accelerates ions more strongly and takes them away from the mirror. The ions leave the mirror more quickly. At the same time, the plasma flow through the mirror 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 stage, the drop in the total potential (the sum of potentials of the electric field, thermal force, ion pressure and viscous force) between the plasma source and the mirror cell increases, which is associated with a low plasma density within the mirror 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.

3 Conclusion

Observations and calculations concerning this phenomenon can be concluded in the following way. 1). Injected hot ions heat efficiently plasma jet ions not directly but through electrons. 2). Heating leads to the increase of the flow velocity of a plasma jet and accordingly to the decrease of plasma density. Work produced by ion-pressure forces exerts primary influence on decrease of the plasma density. The effect resembles the well-known effect of one-fluid hydrodynamics — the heating of a subsonic jet leads to its acceleration. 3). In order to confine the heated 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 ions that escape from a mirror cell. The ion escape occurs mainly under the action of the electric field. At the initial moment of hot ion accumulation the increase of the ambipolar potential leads to the repulsion of input ions, a reduction of plasma flow, and a decrease in plasma density. 4). To study the processes under consideration, it is important to take into account the longitudinal thermal force.

It was cleared out that this effect of plasma density decrease while heating was realized in the case of a sufficient dense subsonic jet being the target plasma. The way of heating may differ from neutral beams. The power should not necessarily been put directly into ions.

The experiments showed that in the case of a collisionless target plasma at heating by neutral beams an opposite effect was observed — an increase of plasma density up to 10 %. The confinement of collisionless ions was improved while heating. This situation of collisionless target plasma had place in the famous experiments in the 2XIIB machine [8] and so the effect of decrease of plasma density which we detected could not show itself.

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