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MAGNETIC CONFINEMENT SYSTEMS

Formation of the Flow of Fast Electrons in the Plasma of the AMBAL-M Device

S. Yu. Taskaev

Budker Institute of Nuclear Physics, Siberian Division, Russian Academy of Sciences, pr. akademika Lavrent'eva 11, Novosibirsk, 630090 Russia

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Abstract—A hot target plasma is obtained in the end cell of the AMBAL-M device with the use of an end gas-discharge plasma source. A fairly high longitudinal electron current flowing from the plasma source to the plasma receiver is detected experimentally. The electron current is studied in the region in front of the input magnetic mirror, where the longitudinal electric field is directed outward from the mirror. Different models for plasma description are considered, and possible plasma instabilities are discussed. It is shown that a fairly high longitudinal electron current in the region where the electric field accelerates electrons results in the generation of the flow of fast electrons responsible for the current in the mirror system. *© 2000 MAIK "Nauka/Interperiodica".*

1. INTRODUCTION

A hot target plasma is obtained [2] and a fairly high longitudinal electric current [3] flowing through the plasma from the plasma source to the plasma receiver is detected in the end cell of the AMBAL-M device with the use of an end gas-discharge plasma source [1]. It is shown that the longitudinal current owes it existence to the method for the plasma production and is a fraction of the discharge current of the plasma source [4]. It is found that, as the distance from the magnetic mirror (on the plasma-source side) decreases, the plasma potential increases along the magnetic field lines (along which the current flows) [5, 2], but does not decrease, as in the case of a thermal barrier. In this paper, we study the electron current in this particular region of the electric field in front of the input magnetic mirror.

After a brief description of the experimental setup and formulation of the problem, numerical models are considered and the conclusion is drawn that a fast- electron flow is produced in the system, which is confirmed by direct measurements of the electron distribution function. In the Conclusion, we give a summary of the results obtained.

2. BRIEF DESCRIPTION OF THE EXPERIMENTAL SETUP

The schematic of the experiment is shown in Fig. 1. An annular gas-discharge plasma source[1] [1] generates a cold dense plasma flow and specifies a nonequilibrium profile of the radial electric field. The Kelvin–Helmholtz instability [6] and the longitudinal current [7] lead to an increase in the transverse ion temperature; as a result, the ion mean free path increases, a substantial fraction of the plasma flow is reflected by the magnetic field of the mirror, the plasma density decreases, and a thermal barrier is produced in the region of the input magnetic mirror. In the magnetic mirror system, the ions (whose temperature continues to grow) are confined by the magnetic field, whereas the electrons are confined by the ambipolar potential and are heated by the current and collisions with ions. The basic plasma parameters in the center of the magnetic mirror system are the following: the plasma diam-

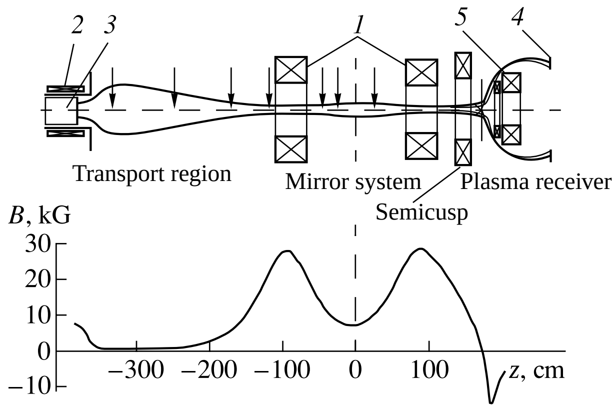

Fig. 1. Schematic of the end cell of the AMBAL-M device and the magnetic field line emerging from the plasma source: (*1*) coils of the mirror system, (*2*) plasma-source solenoid, (*3*) gas-discharge plasma source, (*4*) plasma receiver, and (*5*) semicusp coils. Arrows mark the cross sections in which the Langmuir probe measurements were carried out. At the bottom, the profile of the magnetic field on the axis is shown.

[1] The gas-discharge plasma source is shaped as a ring 11 cm in the inner diameter and 13 cm in the outer diameter.

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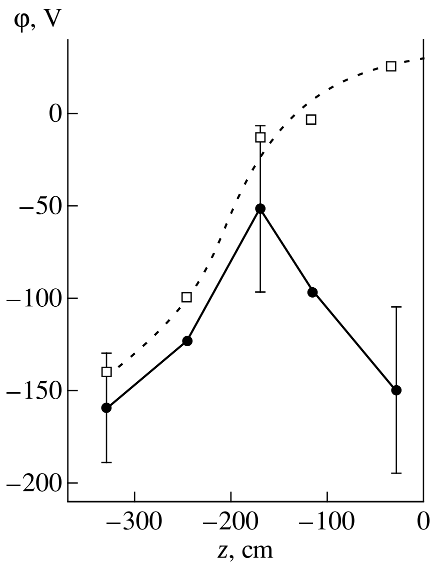

Fig. 2. Longitudinal profile of the floating potential of the Langmuir probe (solid line) and space potential (dashed line) along the magnetic field (at a 3.4-cm radius in the central plane of the mirror system) at the instant 1.4 ms.

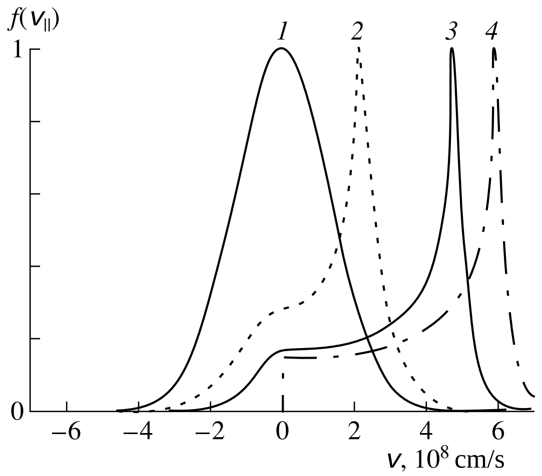

Fig. 3. Electron distribution functions over longitudinal velocities at z = (*1*) –243 cm, (*2*) –168 cm, (*3*) –115 cm, and (*4*) in the magnetic mirror region. The potential difference between the input magnetic mirror and the z = –243-cm cross section is 100 V.

eter is 20 cm, the plasma density is 6×10^{12} cm^{-3}, the electron temperature is 50 eV, and the ion temperature is 200 eV. A detailed description of the device and the experimental results are presented in [2–5].

3. FORMULATION OF THE PROBLEM

One of the most important and interesting results obtained in the AMBAL-M experiments is the presence of the longitudinal electric field accelerating the electrons toward the mirror system. This field was observed in the transport region in front of the input magnetic mirror at a radius approximately equal to the half-radius of the plasma stream flowing from the gas-discharge plasma source. The electric field at other radii decelerates electrons, which is typical of the formation of the thermal barrier [2, 5]. The measured longitudinal profiles of the floating potential of the Langmuir probe and the space potential are presented in Fig. 2. The space potential is determined by the point of inflection of the electron part of the **I**–**V** characteristic of an asymmetric double probe [8]. The value of the excess of the space potential above the floating potential of the probe for the Maxwellian particle distribution is well known. In the case in question, the excess is approximately (2–3)T_e because of a higher ion temperature. Such an excess potential is observed near the plasma source ($z < -240$ cm), where the plasma is dense and cold ($T_e \approx 8$ eV). The difference between the space potential and floating potential increases with distance from the plasma source (see [5], Figs. 9, 11) because of the increase in the electron temperature (see [2], Fig. 6). The presence of the electric field (up to 0.7 eV/cm) accelerating the electrons and extending over two meters in front of the input magnetic mirror is seen in Fig. 2. In [5], it was assumed that a fairly high electron current flows just in this region rather than along the magnetic lines coming out of the gas-discharge plasma source. Later, this assumption was confirmed experimentally in [3].

The problem of the electron current flowing in the region of the accelerating electric field is of great interest. Let us consider several models for this phenomenon.

4. SIMULATION

4.1. Two-Fluid Magnetohydrodynamics

Because of the small plasma density in the magnetic-mirror region, the electron mean free path determined by the Coulomb collisions reaches several meters and is 3– 10 times the magnetic-field-variation scale length $L = B/(\partial B/\partial z)$. Therefore, the hydrodynamic approximation is invalid. However, if the electrons are scattered on the turbulent oscillations arising due to instabilities, the hydrodynamic approach is applicable. The electron distribution function can be represented as the Maxwellian distribution shifted by the flow velocity. However, the existence of such a collisional flow generates the problems of how to fit the calculated potential distribution to the measured one and how to explain the high electron temperature [5]. To achieve an agreement with the measured electron temperature, a very high heating power is required, because the energy carried away due to convection and heat conduction increases substantially. With such high energy losses, it is hardly possible to heat this turbulent plasma flow by injecting available neutral beams.

Although it seems that scattering by waves does not lead to the turbulent collisional flow of the plasma jet, only experiments can confirm this assumption- – whether it will be the injection of neutral beams or the measurements of the electron distribution function in the mirror system.

4.2. Kinetic Model

Another method for studying the current flowing in the plasma is the kinetic approach [9]. Let us consider a collisionless plasma described by the Vlasov equation [10]. We assume that the electrons move from the initial point denoted by the index 0, where their distribution is Maxwellian, toward the higher magnetic field. In addition, the electrons are in the accelerating electric field. The electron distribution function f is found from the laws of conservation of energy and the magnetic moment. In the absence of collisions, the total time derivative is $df/dt = 0$. In phase space, the particles move along the lines at which f is constant. The electron distribution function is Maxwellian but has a sharp boundary, beyond which the distribution function vanishes. In the plane ($v_\parallel$, $v_\perp$), the contours of the distribution function are circles and the boundary beyond which the distribution function vanishes is an ellipse

$$\frac{mv_\perp^2}{2}\left(1-\frac{B_0}{B}\right)+\frac{mv_\parallel^2}{2}=e\varphi-e\varphi_0$$

for $v_\parallel > 0$ and a hyperbola

$$\frac{mv_\perp^2}{2}\left(1-\frac{B_m}{B}\right)+\frac{mv_\parallel^2}{2}=e\varphi-e\varphi_m$$

for $v_\parallel < 0$. Here, the index m refers to the quantity in the magnetic mirror region. In order for these boundaries to be joined at the point $v_\parallel = 0$, the dependence of the potential on the magnetic field must be linear.

Let the electron acceleration by the electric field start near the point where the probe is located ($z = –243$ cm) and terminate in the mirror system, the potential difference being 100 eV. The corresponding evolution of the electron distribution function $f(v_\parallel)$ over longitudinal velocities with decreasing distance from the magnetic mirror is shown in Fig. 3.

4.3. Runaway Electrons

It is difficult to model the real experimental situation because the plasma flow is collisional near the plasma source and collisionless in the mirror region. It is well known that, in the presence of an accelerating electric field, runaway electrons can be generated in the collisional plasma. Runaway electrons are fast electrons that on average accelerate rather than decelerate, because the friction force (~$1/v$) decreases with increasing the electron velocity. In the electric field E, the electrons with velocity v_z become runaways if $v_z > \sqrt{4\pi e^3\lambda n/mE}$ [11]. As the distance from the magnetic mirror decreases, the plasma density decreases and the boundary of the runaway region shifts to lower velocities; as a result, more and more electrons become runaways. Near the mirror region, the runaway boundary corresponds to the velocity $v_z \approx 2 \times 10^8$ cm/s, which is close to the thermal electron velocity; therefore, a substantial fraction of electrons become runaways.

4.4. Summary

When the accelerating potential is much greater than the initial temperature (as in our case), the collisionless acceleration in the constant magnetic field leads to the formation of a beam of electrons with close longitudinal velocities. In the increasing magnetic field, there is energy transfer between the degrees of freedom because of the conservation of the adiabatic invariant. As a result, for a given potential difference, electrons with different transverse momentums gain different longitudinal velocities, as is seen in Fig. 3. An even greater dispersion of the fast-electron beam in longitudinal velocities results from the absence of a sharp acceleration boundary in velocity space because of a smooth decrease in the plasma density with decreasing distance from the magnetic mirror.

The onset of the Buneman instability [12] and the build-up of Langmuir oscillations can also contribute to the broadening of the electron beam in energy space. According to the estimate from [13], the formation of a plateau in the electron distribution function due to Langmuir turbulence must proceed rather rapidly (on a space scale of ~1 cm). Therefore, there can exist a situation similar to the propagation of a monoenergetic electron beam in a plasma, which was considered in [14]. In that paper, it was shown that an electron distribution with a plateau is established at each point, the maximum velocity in the plateau being constant.

5. EXPERIMENTAL RESULTS

The presence of the fast-electron flow in the mirror system is seen from the **I–V** characteristic of the Langmuir probe placed in the region where the current flows. The **I–V** characteristic shows the presence of both regions with the positive derivative $\partial f(\mathcal{E})/\partial\mathcal{E}$ and the plateau (linear dependence of the current on the voltage) in the electron energy distribution function. However, an accurate interpretation of these results leaves unclear the problems associated with the secondary electron emission, a possible change in the potential jump near the surface [15], and the possible existence of the linear transient region in the **I–V** characteristic [16]. Therefore, we designed a special small-size movable electron-energy analyzer and used it to measure the electron distribution function over longitudinal energies in the mirror system. A detailed description of the analyzer and obtained experimental results are presented in [17]. The analyzer measurements show that, in the current channel, the electron distribution function of the arriving electrons over longitudinal velocities differs from the Maxwellian distribution function and, in the energy range from 150 to 350 eV, is shaped like a plateau. Fast electrons with the density $\sim 10^{11}$ cm^{-3} are responsible for the transport of the main part of the detected longitudinal current [3]. Thus, the experimental results show that the longitudinal electron current in the mirror system is carried by fast electrons that are produced in the region of the accelerating electric field, in front of the magnetic mirror.

6. CONCLUSION

In the previous experiments with a target plasma in the AMBAL-M device, it was found that, in front of the input magnetic mirror, there is a longitudinal electric field directed outward from the magnetic mirror. It was shown that a high electron current flowing into the mirror system exists in this region.

In this paper, we have considered various models for a plasma description and have shown that the presence of an electron current in the region of the accelerating electric field leads to the generation of a flow of fast electrons that carry the current in the mirror system. The fast-electron flow is recorded experimentally.

The production of a fast-electron flow is not characteristic of open magnetic confinement systems. Further investigations of the processes related to this phenomenon (in particular, the formation of an accelerating electric field and the influence of the fast-electron flow on the confinement and heating of the plasma in the mirror system) are of considerable interest.

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