Plasma Physics Reports, Vol. 24, No. 12, 1998, pp. 995–999. Translated from Fizika Plazmy, Vol. 24, No. 12, 1998, pp. 1065–1069.

MAGNETIC CONFINEMENT SYSTEMS

Longitudinal Current in the Startup Plasma of the AMBAL-M Device

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Received September 22, 1997

Abstract—In experimental studies of the startup plasma in the end system of the AMBAL-M device, it is found that a longitudinal electron current of ~1 kA flows along the plasma stream during the plasma-source discharge. The radial profiles of the current density in several cross sections are measured by a movable magnetic probe. Near the plasma source, the current density profile is annular in shape, which is related to the geometry of the discharge channel; as the distance from the source increases, the inner part of the plasma stream is gradually filled with the current.

1. INTRODUCTION

Experimental studies of the startup plasma in the first stage of the AMBAL-M tandem mirror system are being conducted. The device is described in detail in [1, 2]. In the axisymmetric end mirror device (end cell) (Fig. 1), a hot target plasma with a radius of 10 cm, n to 6×10^{12} cm^{-3}, $T_i \approx 200$ eV, and $T_e \approx 50$ eV is produced with the help of a gas-discharge plasma source (with no additional plasma heating).

Even in the first experiments, a longitudinal electron current of about 1 kA flowing along the plasma stream was observed during the plasma-source discharge. A similar effect, i.e., the longitudinal current flowing in a plasma created by a plasma source with an annular discharge channel, was observed previously in the MAL [3] and AMBAL-Yu [4] devices. In those experiments, the current was measured by Rogowski loops with different diameters. It was found that, in the inner part of the plasma column, the electron current flows from the source toward the opposite end of the device, whereas, at the periphery, the current flows in the opposite direction. The reason for this is that a fraction of the discharge current flows out of the plasma source along the magnetic field lines and is closed across the field lines in the plasma and at the plasma collector. This current flows along the entire device, reaches the end of the device, and then closes through the plasma periphery and the vacuum chamber on the anode of the source. In the latter process, nonambipolar transverse plasma diffusion can play a significant role.

In this paper, we present the results of studies of the longitudinal current in the startup plasma of the AMBAL-M device. The magnetic flux in the given direction was measured by a movable magnetic probe. The radial profiles of the current density in several cross sections and in the entrance mirror of the device were measured by magnetic probes and a plane double-sided Langmuir probe; these measurements show that, near the plasma source, the current-density profile is annular in shape. As the distance from the plasma source increases, the inner part of the plasma stream is gradually filled by the current.

2. EXPERIMENTAL SETUP AND DIAGNOSTIC FACILITY

The schematic of the end system of the AMBAL-M device mirror device and the magnetic field lines emerging from the plasma source are shown in Fig. 1.

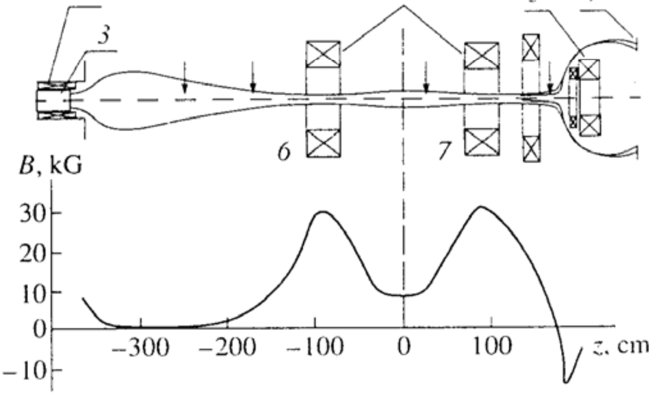

Fig. 1. Schematic of the end system of the AMBAL-M device and the magnetic field line emerging from the plasma source: (*1*) coil of the end cell, (*2*) solenoid of the plasma source, (*3*) plasma source, (*4*) plasma collector, (*5*) semi-cusp coil, (*6*) entrance mirror, and (*7*) exit mirror. Arrows mark the cross sections in which the magnetic probe measurements are performed. At the bottom, the magnetic field on the axis is shown.

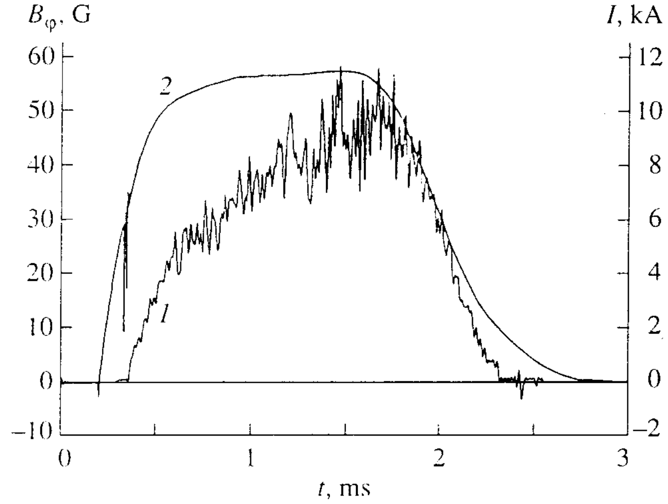

Fig. 2. Time dependences of (*1*) the azimuthal magnetic field at $z = -168$ cm and $r = 6$ cm and (*2*) the plasma-source discharge current.

Plasma with a characteristic temperature of 10 eV and density $n \approx 2 \times 10^{14}$ cm^{-3} flows out of the source with a velocity on the order of the thermal velocity and then flows along the magnetic field lines. The filling of the device with a plasma is accompanied by an increase in the transverse ion temperature (from 10 eV at the source outlet to 200 eV in the end cell) due to the onset of the Kelvin–Helmholtz instability (KHI) and by a transverse plasma diffusion. The results of the experimental studies of a hot startup plasma in the AMBAL-M device are presented in detail in [5]. Simultaneously, the longitudinal electron current begins to flow along the plasma column. This current can reach thirty percent of the discharge current in the plasma source. The radial profiles of the current were reconstructed from measured profiles of the azimuthal magnetic field created by this current.

The magnetic probe was a multiturn coil with NS = 330 turn cm^2, which was placed inside the insulating case made from boron nitride. The probe was mounted on a movable rod, which was also covered with an insulator and inserted into the plasma with the help of a coordinate unit. We measured the current profiles in four cross sections of the plasma column (see Fig. 1): in the transport region between the plasma source and the entrance mirror ($z = -243$ cm and $z = -168$ cm), in the mirror device (z = +25), and at the entrance into semi cusp ($z = +157$ cm).

The contact methods of plasma diagnostics, such as Langmuir and magnetic probes, can substantially affect the plasma, e.g., limiting the electron temperature due to heat removal through metal elements inserted in the plasma. In the experiments, much attention was paid to this point. In particular, in [5], in which the possible influence of probes on the plasma density and temperature was studied, it was shown that the probes only slightly perturb the plasma parameters. In our case, the conditions were appropriate for the use of probes, because, due to KHI, a high power (100 kW) was introduced into the plasma during the 2-ms operation of the plasma source, which resulted in ion heating [7]. Therefore, during the source operation, the probes slightly affected the plasma parameters. This was confirmed by the fact that, when a magnetic probe was inserted into the plasma, the time dependences of the plasma temperature and probe potential remained almost unchanged and the electron temperature decreased negligibly. The experiments showed that mechanical destruction of probes under the action of plasma is absent. Thus, the use of contact plasma diagnostics is well justified under our conditions.

3. MEASUREMENT OF THE MAGNETIC FIELD AND RECONSTRUCTION OF THE CURRENT PROFILE

The signal of the magnetic probe oriented in the r–z plane is the e.m.f. induced by the magnetic field of the longitudinal current

$$\mathcal{E} = -\frac{1}{c}\frac{d\Phi_m}{dt},$$

where $\Phi_m = \langle B_\varphi NS \rangle$ is the magnetic flux through the probe coil. This signal was integrated with a time constant much greater than the duration of the plasma-source pulse. Therefore, the signal applied to the analog-to-digital converter was $U(t) \propto B_\varphi \langle NS \rangle$. The quantity $\langle NS \rangle$ was determined by the calibration in the given magnetic field. Figure 2 shows the typical time dependence of the azimuthal magnetic field in the $z = -168$ cm cross section (transport region). In the same figure, we present the time dependence of the discharge current of the plasma source.

The axisymmetric geometry of the magnetic field allows reconstruction of the profile of the longitudinal current $I_z(r)$ by the formula

$$B_\varphi(r) = \frac{2I_z(r)}{cr}.$$

It should be noted that, in order to determine the current by this formula, the plasma column must be axisymmetric, the plasma axis must coincide with the device axis, the probe must move exactly in the radial direction, and the size of the probe must be negligibly small. The measurement showed that the average value of the azimuthal magnetic field to a good accuracy turned to zero on the axis, i.e., the center of the plasma column coincided with the axis of the device within ±0.5 cm. Figure 3 presents the radial profile of the total current at 1600 μs after the beginning of the plasma-source discharge. The polarity of the magnetic-probe signal was determined beforehand, and, for convenience, we assume that the direction of the electron current from the plasma source to the opposite end of the device is positive (further, we will refer to the direction of the electron current as the direction of the longitudinal current).

The current density is obtained by the differentiation of $I_z(r)$

$$j_z(r) = \frac{1}{2\pi r}\frac{dI_z(r)}{dr}.$$

The dependence $j_z(r)$ is presented in Fig. 4. We note that the current was directed toward the plasma collector only for $r \leq 7$ cm, and, at the plasma periphery, its direction was opposite; i.e., it flowed toward the plasma source. It is seen in Fig. 3 that a 1.4-kA current flows from the plasma source, and a current of 0.3–0.4 kA flows in the opposite direction at the plasma periphery. The maximum current flowing toward the plasma collector took the following values: ≈1.6 kA at $z = -243$ cm, ≈1.4 kA at $z = -168$ cm, ≈1.2 kA at $z = +25$ cm, and ≈1.0 kA at $z = +157$ cm.

The presence of the electron current was also confirmed by the measurements carried out with a double-sided plane Langmuir probe located near the entrance mirror ($z = -116$ cm). The probe was oriented across the magnetic field lines, so that one collecting surface was facing the plasma source, whereas the other surface was turned to the opposite direction. From the floating potentials of both surfaces it is seen that the electron flux to the surface facing the source exceeds the flux facing the other direction. This means that the flow velocity of electrons is not equal to zero. We reconstruct the flow velocity under the assumption that the electron velocity distribution function is a Maxwellian distribution function shifted by the value of this velocity. The measurements showed that, in this cross section, the electron flow velocity was comparable with the thermal one: $u_e \sim 0.6\, v_{Te}$.

In order to trace more clearly how the current density profile varied with distance from the plasma source, the radial profiles were matched along the magnetic field lines to the outlet cross section of the plasma source. The current density was normalized to the magnetic flux; i.e., $j_z(r)rdr = j_{0z}(r_0)r_0dr_0$, where r_0 and j_0 corresponded to the outlet cross section of the plasma source, while r and j corresponded to those plasma cross sections in which the measurements were performed. It is seen from Fig. 5 that, as the distance from the plasma source increases, the cavity in the distribution $j_{0z}(r)$ decreases and then disappears. In the transport region ($z = -243$ cm), the profile still keeps the annular structure. In the next cross section ($z = -168$ cm), the cavity is substantially decreased, and the maximum of the current density shifts inward even more with respect to the discharge channel of the plasma source. In the mirror and behind it, the current density is maximum on the axis. The measurements carried out in the semicusp show that the electron current flows mainly along the field lines toward the narrow annular slit, whereas at most 10–15% of the total current flows along the axis of the device.

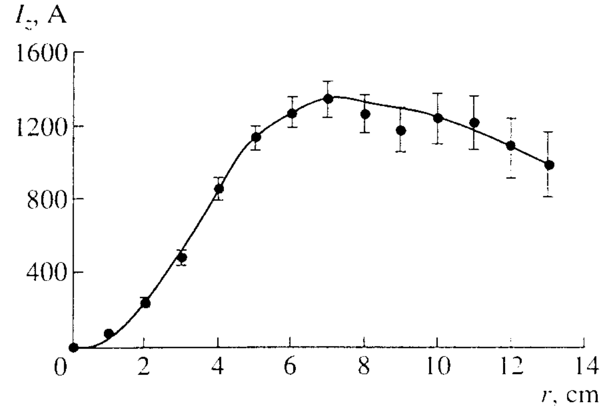

Fig. 3. Distribution of the longitudinal current flowing inside a cylinder of radius r at $z = -168$ cm and $t = 1600$ μs.

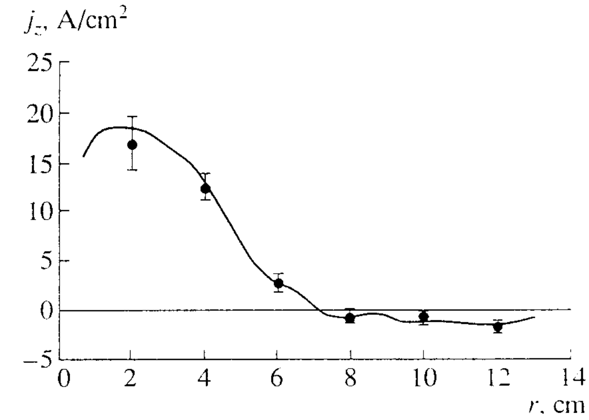

Fig. 4. Radial profile of the longitudinal current density at $z = -168$ and $t = 1600$ μs.

In order to study the transverse displacement of the longitudinal current, we used a set of three magnetic probes measuring the azimuthal magnetic field. These probes were located equidistantly along the azimuth in the cross section $z = +47$ cm at a radius of 10 cm. Since the radius at which the probes were positioned was greater than the width of the radial profile of the longitudinal current, the magnetic field measured by the probe depended only on the value of the total current and the position of the center of the current flow. Therefore, the simultaneous measurements carried out with three probes allowed us to determine the total current and the position of the center of the current flow. As a result of processing a series of pulses, it was found that the center of the current flow shifted in the radial direction by at most 1 cm. When the maximum current was reached, the circulation of the current-flow center around the device axis was observed.

We also measured the current to the grounded Langmuir probe, which was located near the plasma source

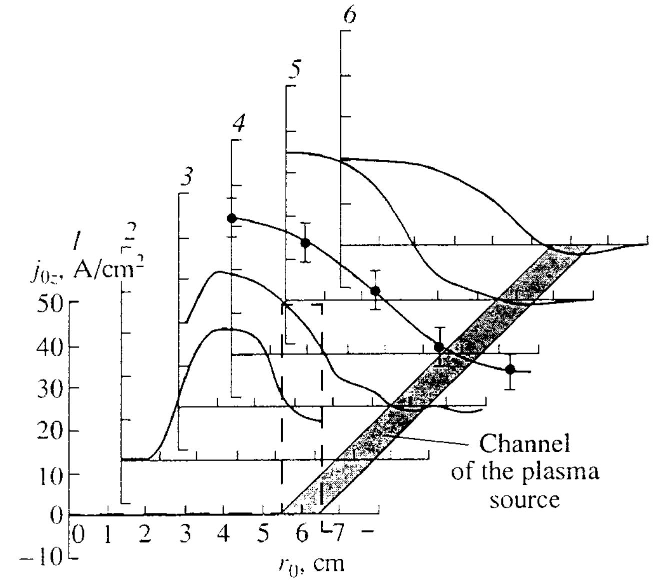

Fig. 5. Profiles of $j_z(r)$ at t = 1600 μs in successive transverse cross sections (the profiles are matched along the magnetic field lines to the outlet cross section of the plasma source located at z = −370 cm): (*1*) z = −370 cm (assumed profile shown by a dashed line), (*2*) z = −243 cm, (*3*) z = −168 cm, (*4*) z = − 116 cm (measurements with the use of a plane Langmuir probe), (*5*) z = +25, and (*6*) z = +157.

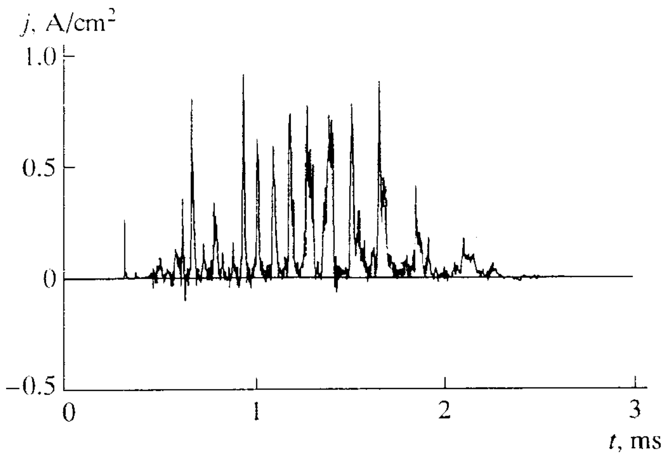

Fig. 6. Time dependence of the current density at the peripheral grounded Langmuir probe at z = −325 and r = 40 cm.

outside the main plasma flow. In this region, the current to the probe appeared to be positive (Fig. 6).

It is seen from comparison of the current density profiles in successive cross sections that the process of filling the inner part of the plasma column by the current is not purely diffusive, because the diffusion should result in a decrease in the current density normalized on the magnetic flux as compared to the initial current density. Therefore, we can conclude that, in addition to the radial diffusion which causes the spread of the annular current distribution and filling the inner hollow region with the current, there is another process that manifests itself in an increase in the current density on the axis as the distance from the plasma source increases. Nevertheless, we can estimate the transverse-diffusion coefficient in order of magnitude. Taking into account that $j_e = neu_e$ and determining the current density from the probe measurements, we find the electron flow velocity. Thus, for example, the maximum current density in the cross section z = −243 cm is 4 A/cm^2 and the density is about 2×10^{13} cm^{-3}. Therefore, the electron flow velocity in this cross section is estimated as $u_e \sim 10^6$ cm/s. Determining the change in the longitudinal current near the device axis in two successive cross sections, we can estimate the coefficient of transverse current diffusion as $D_{\perp j} \sim 10^5$ cm^2/s. The same estimate was previously obtained for the transverse plasma diffusion coefficient, when the spread of a similar plasma stream propagating through a long transport region was measured. In [8, 9], this spread was attributed to diffusion arising due to the onset of KHI.

The filling of the cavity in the radial distribution of the longitudinal current in the transport region cannot be explained by the classical transverse current diffusion caused by Coulomb collisions and, seemingly, is associated with the plasma stream turbulence. The filling of the inner part of the stream by the current is affected by the flattening of the radial profile of the plasma potential with an increase in distance from the plasma source [5]. The flattening of the potential profile results in a decrease in the longitudinal electric field on the field lines going out of the gas-discharge channel of the plasma source and in an increase in the longitudinal electric field on the inner lines. This change in the longitudinal electric field can result in the inward radial shift of the longitudinal current as the stream flows along the transport region. However, the quantitative explanation of the filling of the inner cavity in the radial distribution of the longitudinal current is still lacking.

4. CONCLUSION

We have experimentally studied a 1-kA longitudinal electron current flowing through the plasma during the discharge in the plasma source of the AMBAL-M device. The radial profiles of the current density in several cross sections have been measured with a movable magnetic probe. It has been found that, near the plasma source, the current density profile is annular in shape; as the distance from the plasma source increases, the inner part of the plasma stream is gradually filled with a current. Throughout the discharge, the amplitude of the transverse displacement of the center of the radial current distribution with respect to the axis of the mirror system is at most 1 cm.

ACKNOWLEDGMENTS

We thank G.I. Dimov for his continuing interest to this work and valuable remarks and A.D. Beklemishev for useful discussions. This work was supported in part by the Russian Foundation for Basic Research, project nos. 95-02-05316 and 96-02-19296.

REFERENCES

1. Dimov, G.I., *Vopr. Atom. Nauki Tekh., Ser.: Termoyad. Sintez*, 1990, no. 1, p. 19.
2. Belkin, V.S., Bender, E.D., *et al.*, *Proc. Int. Conf. on Open Plasma Systems for Fusion*, Novosibirsk, 1993, p. 37.
3. Kabantsev, A.A. and Taskaev, S.Yu., *Fiz. Plazmy*, 1989, vol. 15, p. 724 [*Sov. J. Plasma Phys.* (Engl. transl.), vol. 15, p. 418].
4. Bender, E.D., Chupriyanov, V.E., Dimov, G.I., *et al.*, *Proc. 8th Piero Caldirola Int. School of Plasma Physics: Physics of Alternative Confinement Schemes*, Varenna, 1990, p. 157.
5. Akhmetov, T.D., Belkin, V.S., Bender, E.D., *et al.*, *Fiz. Plazmy*, 1997, vol. 23, p. 988 [*Plasma Phys. Rep.* (Engl. transl.), vol. 23, p. 911].
6. Zweben, S.J., Menyuk, C.R., and Taylor, R.J., *Phys. Rev. Lett.*, 1979, vol. 42, p. 1270.
7. Kabantsev, A.A. and Taskaev, S.Yu., *Fiz. Plazmy*, 1992, vol. 18, p. 635 [*Sov. J. Plasma Phys.* (Engl. transl.), vol. 18, p. 331].
8. Kabantsev, A.A. and Taskaev, S.Yu., *Fiz. Plazmy*, 1990, vol. 16, p. 700 [*Sov. J. Plasma Phys.* (Engl. transl.), vol. 16, p. 406].
9. Kabantsev, A.A, *Preprint of Budker Inst. of Nuclear Physics, Siberian Division, Russ. Acad. Sci.*, Novosibirsk, 1995, no. 95-80.

Translated by A. D. Smirnova