EFFECT OF THE PARAMETERS OF AN ELECTRON BEAM ON THE PROCESS OF ACCUMULATION OF HOT ELECTRONS IN A MIRROR TRAP

L. P. Zakatov and A. G. Plakhov

UDC 533.95

A study is made of the mechanism of generation and accumulation of hot electrons during the interaction of an electron beam with a cold plasma in a mirror machine. The energy density distribution of the hot component of the plasma ($nT_\perp$) along the radius of the system, the time dependence of the diamagnetism, and the escape of fast electrons from the beam region into the loss cone are measured. It is established that there is a considerable difference in the processes of accumulation of hot electrons depending on whether the beam current or beam energy is varied. It is concluded that under the conditions of these experiments the hot component of the plasma is formed from the beam electrons.

In experiments on the study of plasma heating by an electron beam in mirror traps there are no data on the effect of the beam parameters on the heating. The beam parameters selected by different authors [1-6] are connected either with the specifics of the concrete experiment or with the limited technical possibilities. The purpose of the present work is to study the effect of the current and energy of the beam on the parameters of the hot plasma generated by it. The experimental relationships of [7] indicate the manifestation of specific properties of beam heating which must be studied for an understanding of its mechanism.

The experimental apparatus is shown schematically in Fig. 1. The magnetic field of mirror configuration was produced by the system of coils 1. The magnetic field strength at the center is 1 kOe, in the mirrors 5.25 kOe, and the distance between mirrors is 80 cm. The vacuum chamber 2 with a diameter of 40 cm was evacuated to a pressure of 10^{-6} mm Hg. At the axis of the trap behind a mirror was mounted an electron beam 3 with the limiting parameters: beam current up to 20 A, energy up to 40 keV. The beam diameter in the central part was 1.2 cm. The trap was preliminary filled with a cold plasma to a concentration of $(2\text{-}5)\cdot 10^{12}$ cm^{-3} with a temperature of a few electron volts. The plasma injector 4 in the different experiments was mounted either on the axis of the system behind a mirror or perpendicular to the magnetic field in the central part of the trap.

To determine the radial distribution of plasma energy density the dependence of the energy content $Q(R) = 2\pi\int_0^R nT_\perp(R)RdR$ in different transverse profiles of the hot plasma was taken with a diamagnetic probe, where n is concentration of the hot electron component of the plasma, $T_\perp$ is the mean energy of motion of the fast electrons in the direction perpendicular to the magnetic field, and R is the radius. The plasma was confined with diaphragms 3 to 24 cm in diameter mounted in the central part of the trap. A multiturn diamagnetic probe played the role of the maximum diaphragm. With the diaphragm 3 cm in diameter control measurements were conducted simultaneously by two probes 24 and 3 cm in diameter, respectively. The readings of the two probes hardly differed and henceforth only the probe with a diameter of 24 cm was used. Graphic differentiation of the dependence Q(R) obtained made it possible to reproduce the distribution of $nT_\perp$ over the radius of the chamber.

Measurements of the fluxes and energy spectrum of the plasma electrons escaping from the trap into the loss cone were made by the identical electrostatic analyzers 7 which were mounted in the mirrors at

---

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 4, pp. 49-54, July-August, 1974. Original article submitted January 29, 1974.

the axis of the trap at opposite ends of the instrument. The analyzers (probes) had an opening in the central part for the free passage of the beam while the annular entrance slit encircled the beam. The plasma electrons from the immediate vicinity of the beam entered the probe collectors through this slit. The presence of two probes made it possible to measure the escape of electrons along the direction of the beam and opposite to it. The readings of the two probes hardly differed in all modes of operation and subsequently only one probe was used.

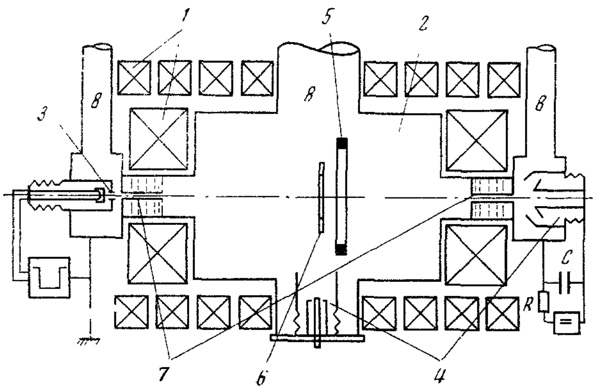

Fig. 1

A negative sawtooth voltage pulse with a duration of 150 μsec and an amplitude of 4 kV was applied to the analyzer grid of the probe. The current from the collector was recorded by an oscillograph. It was established with a special test that the current signals from the collector had a rectangular form when constant retarding potentials were supplied to the analyzer grid, i.e., the shape of the pulse at the cathode of the electron gun was reproduced. This fact made it possible to obtain distribution functions of the plasma electrons with respect to longitudinal energies through graphic differentiation of the oscillograms of collector current when a voltage pulse decreasing linearly in amplitude was supplied to the analyzer grid of the probe [8].

The variation in the plasma concentration was monitored by microwave interferometers at wavelengths of 0.8 and 3 cm. The system was evacuated through the pipe 8.

A series of curves of the radial distributions of energy of density $nT_\perp(R)$ of the hot component of the plasma for different beam energies at the same current of 10 A is shown in Fig. 2. Curves 1-4 correspond to voltages of 18, 24, 30, and 36 kV. In the immediate vicinity of the beam the readings of the diamagnetic probe correspond to the mean density of the transverse energy of the beam particles which they acquire in scattering on oscillations. It is proportional to the beam energy. Then there is a sharp drop in all the curves and at a radius of 2 cm they differ very little. At larger radii the value $nT_\perp$ depends essentially on the beam energy. At the maximum energy the plasma occupies the entire space and the value $nT_\perp$ increases linearly with radius. On the curves corresponding to lower beam energies the linear increase changes into a rapid decrease and the plasma does not reach the largest diaphragm. At the minimum beam energy $nT_\perp$ is almost constant up to a radius of 5 cm and then decreases rapidly. The most significant differences in the distributions occur at large distances in comparison with the beam radius. The increase in the energy content of the hot plasma with an increase in the beam energy occurs because of its accumulation in the peripheral regions of the trap.

Oscillograms of the diamagnetic signals, showing the time dependence of the energy content for different beam energies at the same current of 5 A with a confining diaphragm 12 cm in radius, are shown in Fig. 3. At a beam energy of 30 keV (Fig. 3a), the diamagnetic signal increases for a long time while the hot plasma does not touch the diaphragm. At a beam energy of 15 keV (Fig. 2b) the diamagnetic signal is considerably decreased in amplitude and is more rapidly established at a consatnt level. In this case the hot plasma did not reach the diaphragm (Fig. 2) and its temperature, measured from the X-ray spectrum, decreased from 200 to 140 keV. The decrease in temperature is also indicated by the faster decrease in the diamagnetic signal of the oscillogram ofFig. 3b after the beam is turned off.

The radial distributions of plasma energy density and the time dependences of the energy content obtained showed that relatively small changes in the beam energy can control processes of diffusion and accumulation of the hot plasma in the trap. It can be expected that the escape of fast electrons into the loss cone is also sensitive to changes in the beam energy.

Distribution functions of the plasma electrons escaping through the mirror from the beam region at a current of 5 A are shown in Fig. 4. It is seen that the distribution functions differ considerably for beam energies of 30 keV (curve 1) and 15 keV (curve 2). At the higher beam energy more than half the escaping particles are concentrated in the energy range of (0-0.5) keV. For an energy twice as low the picture changes considerably; the spectrum of escaping particles is shifted toward high energies and the flux of energetic electrons (more than 0.5 keV) becomes dominant. Thus, an increase in the initial beam energy leads to a decrease in the loss of fast electrons along the magnetic field and to their more efficient accumulation in the trap.

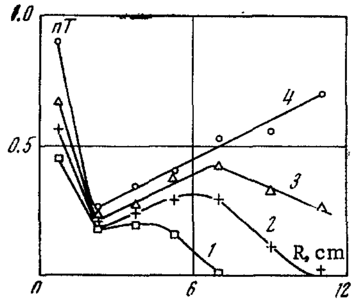

Fig. 2

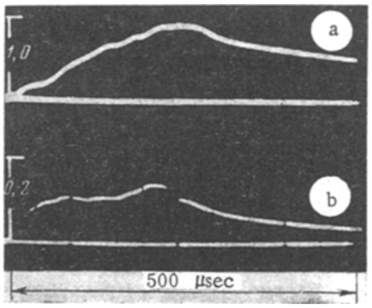

Fig. 3

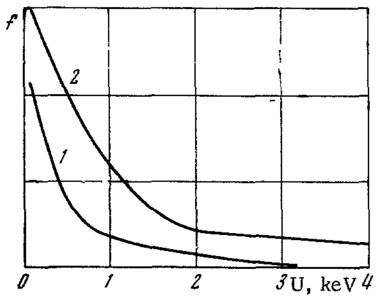

Fig. 4

Similar measurements of $nT_{\perp}(R)$ were made for different beam currents (5, 10, 20 A: curves 1-3) at a constant energy of 30 keV. It is seen in Fig. 5 that the hot component of the plasma reaches the maximum diaphragm at all beam currents. An increase in the beam current essentially affects the energy density of the hot plasma in zones close to the beam while the difference begins to level out starting $R \approx 2$ cm. The dependence on the current disappears at $R \approx 6$ cm and the energy density begins to decrease monotonically. These distributions show that a certain increase in the energy content observed in the experiment with an increase in the beam current occurs owing to the regions close to the beam. The filling of the peripheral zones of the trap does not depend on the beam current.

Oscillograms of the time dependence of the energy content at different beam currents for an energy of 30 keV are presented in Fig. 6. At a current of 5 A (Fig. 6a) the accumulation of plasma energy takes place for a long time, while at a current of 20 A (Fig. 6b) the accumulation occurs much faster and to a higher level because of the increase in density in the central zone (Fig. 5). The difference in the drop in the diamagnetic signal after the current is turned off attracts attention. On the oscillogram of Fig. 6a there is a slow decay of the plasma while on the oscillogram of Fig. 6b the decay takes place faster at first down to the level on the oscillogram of Fig. 6a, starting with which the decay occurs with the same time constant.

From this it can be concluded that the electrons of the central zones have considerably lower transverse energies and escape faster from the trap, while the number of long-lived particles and the spectral composition do not depend on the beam current. The oscillograms of the diamagnetic signals obtained for currents of 20 and 5 A with confinement of the plasma by a diaphragm with a radius of 4.5 cm (Fig. 6c,d) can serve as more reliable experimental proof of such a space-energy structure of the hot component of the plasma. The oscillograms do not differ in form (except for fluctuations), but differ about twofold in amplitude. Important for both oscillograms is the rapid drop in diamagnetism after the beam is turned off, which indicates the relatively low energy of the plasma electrons in zones close to the beam. From a comparison of the oscillograms of Fig. 6a,d for a current of 5 A it is seen that the contribution from the central zones is small and the energy content is determined by the peripheral zones which are filled with more energetic electrons but at a lower density.

For an understanding of the specifics of the accumulation of a hot plasma in a mirror machine as a function of the beam current it is necessary to trace the escape of the energetic electrons from the plasma near the beam into the loss cone. Distribution functions of such electrons in longitudinal energies f at a beam energy of 30 keV and currents of 5, 10, and 20 A (curves 1-3) are presented in Fig. 7. They show that with an increase in the beam current the total flux of plasma electrons into the loss cone increases with a considerable increase in their average energy. Thus, the weak dependence of the energy content of the plasma on the beam current correlates with the excape of fast particles along the magnetic field.

The experiments conducted showed that the nature of the accumulation of the hot component of the plasma in the trap depends essentially on whether the beam current or beam energy is varied. The space-energy structure of the hot plasma, the average particle energy, and the energy content of the plasma are sensitive to a change in the initial beam energy and react weakly to a change in the beam current. The losses of energetic plasma particles along the magnetic field from the region near the beam decrease with an increase in the initial beam energy while the losses of fast particles increase with an increase in the beam current.

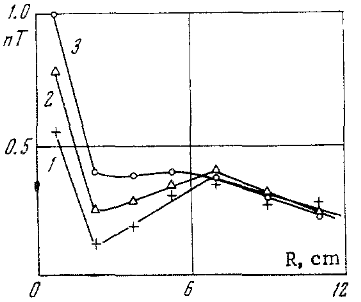

Fig. 5

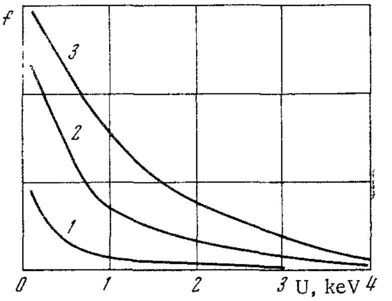

Fig. 7

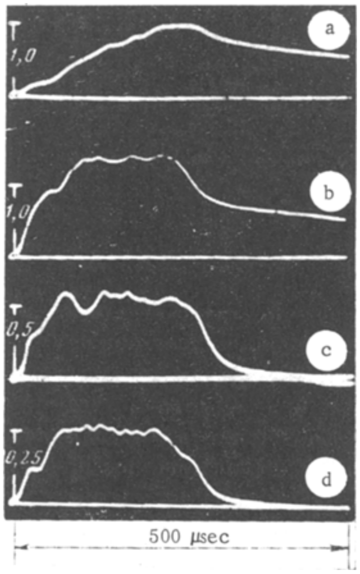

Fig. 6

All the relationships connected with a change in the initial beam energy which were obtained testify in a new aspect in favor of the diffusion model of beam heating proposed in [9].

In this model the electron beam is not only a source of Langmuir waves but also a source of particles involved in the process of acceleration. The lifetime of these particles in the trap can be represented in the form $\tau \sim (1/\tau_D + 1/\tau_S)^{-1}$, where τ_D is the time of diffusion of the fast particles to the boundary of the plasma and τ_S is the time of escape into the loss cone. Because of the different dependence of these times on the particle velocity ($\tau_D \propto V$, while $\tau_S \propto V^3$) it can be shown that with an increase in the energy of the beam particles τ_S is greater than τ_D. In this case the lifetime τ will be determined mainly by τ_D and the particles will diffuse along the radius for a longer time and acquire energy in accordance with $T_e \propto \tau^{2/5}$, with the transverse dimensions of the plasma also increasing.

At low beam energies the opposite case is possible, when $\tau_S < \tau_D$ and the lifetime will be determined by τ_S. In this case the average energy and transverse dimensions of the plasma decrease while the escape of fast particles into the loss cone increases. These effects, observed in the experiments described above, are reflected in Fig. 2, 3, and 4. The dependence of the energy density of the hot plasma on the radius at high beam energies is also in agreement with theory ($nT_\perp \propto R$).

The diffusional theory of beam heating does not give direct indications relative to the dependence of the heating efficiency on the beam current. Within the framework of this theory one can only state general reasons why the beam current is not directly connected with the acceleration mechanism. The effect of saturation of the energy content in the peripheral zones of the trap with an increase in the beam current can be considered as an experimental fact not contradicting the theory.

The accumulation of the hot component of the plasma is determined by the supply of electrons from the beam to the region near the beam and by the escape of energetic particles from this region into the loss cone and, on the other hand, by the efficiency of the accelerating mechanism. As the beam current increases the number of energetic electrons near the beam increases and the flux of these particles into the loss cone simultaneously intensifies. Beginning with a certain value of the beam current an equilibrium is established between these fluxes. For this reason the efficiency of the accelerating mechanism does not depend on the beam current, which is observed as the effect of saturation of the energy content in the peripheral zones of the trap.

The experiments conducted and the comparison of the results obtained with the diffusional theory of beam heating indicate that the hot component of the plasma under the conditions of these experiments ($\omega_{pe} \gg \omega_{He}$, where ω_{pe} is the electron plasma frequency and ω_{Ge} is the electron cyclotron frequency) is formed from the electrons of the beam.

The authors are grateful to L. I. Rudakov for valuable remarks.

LITERATURE CITED

1. I. Alexeff, R. V. Neidigh, W. F. Peed, E. D. Shipley, and E. G. Harris, "Hot-electron plasma by beam – plasma interaction," Phys. Rev. Lett., 10, No. 7 (1963).
2. L. D. Smullin and W. D. Getty, "Characteristics of the beam – plasma discharge," in: Plasma Physics and Controlled Nuclear Fusion Research, Vol. 2, Vienna (1966).
3. P. I. Blinov, L. P. Zakatov, A. G. Plakhov, R. V. Chikin, and V. V. Shapkin, "Effect of mirror ratio on plasma heating by an electron beam in a mirror machine," ZhETF, Pis'ma, 2, No. 9 (1965).
4. E. Z. Tarumov, Yu. L. Bakshaev, V. L. Borzenko, V. S. Pen'kina, and V. I. Rozanova, "Study of a hydrogen plasma containing 'hot' electrons," Zh. Eksperim. Teor. Fiz., 52, No. 1 (1967).
5. L. P. Zakatov, A. G. Plakhov, D. D. Ryutov, and V. V. Shapkin, "Study of the high-temperature electron component of a plasma formed in a plasma – beam system," Zh. Eksperim. Teor. Fiz., 54, No. 4 (1968).
6. P. I. Blinov and M. V. Ivkin, "Distribution of 'hot' electrons during heating of a plasma by an electron beam in a mirror machine," Zh. Eksperim. Teor. Fiz., 57, No. 11 (1969).
7. A. G. Plakhov, D. D. Ryutov, and V. V. Shapkin, "Study of the mechanism of beam heating of a plasma in a SN-24 L-2 mirror machine," in: Proceedings of Conference on Plasma Physics and Controlled Nuclear Fusion Research, Novosibirsk, 1968, Vol. 2, Internat. Atomic Energy Agency, Vienna (1969).
8. L. P. Zakatov and A. G. Plakhov, "Retardation of a powerful electron beam in a dense plasma," Zh. Eksperim. Teor. Fiz., 60, No. 2 (1971).
9. D. D. Ryutov, "Contribution to the theory of beam heating of a plasma in an open trap," Nucl. Fusion, 9, No. 4 (1969).