

ELECTRON HEATING IN MIRROR BY END POTENTIAL PLATES

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Hot target plasma was obtained without additional heating in an open trap AMBAL-M from arc source located behind the mirror [1]. The plasma has a diameter of 20 cm, an average density of $6 \times 10^{12} \text{ cm}^{-3}$, an ion energy of 200 eV, and high electron temperature of 50 eV that is of the most importance. The present work is devoted to the elucidation of the main mechanism of electron heating up to so high temperature. It was determined that this efficient heating was related to the number of the experimental peculiarities. Our attention will be concentrated on these peculiarities.

In Fig.1 the experiment scheme is shown. The plasma is generated by the arc source [2] located behind the mirror. The source generates a narrow ring dense plasma jet. The inner diameter of the jet at the output of the source is 11 cm, the outer is 13 cm. Another feature of the source is that the arc source electrode potentials form a non-equilibrium radial electric field (Fig. 2). The nonuniform azimuthal drift causes the Kelvin-Helmholtz instability [3]. The development of the instability is accompanied by frequency modulation of radial electric field and stochastic heating of magnetized ions into the transverse degree of freedom [4].

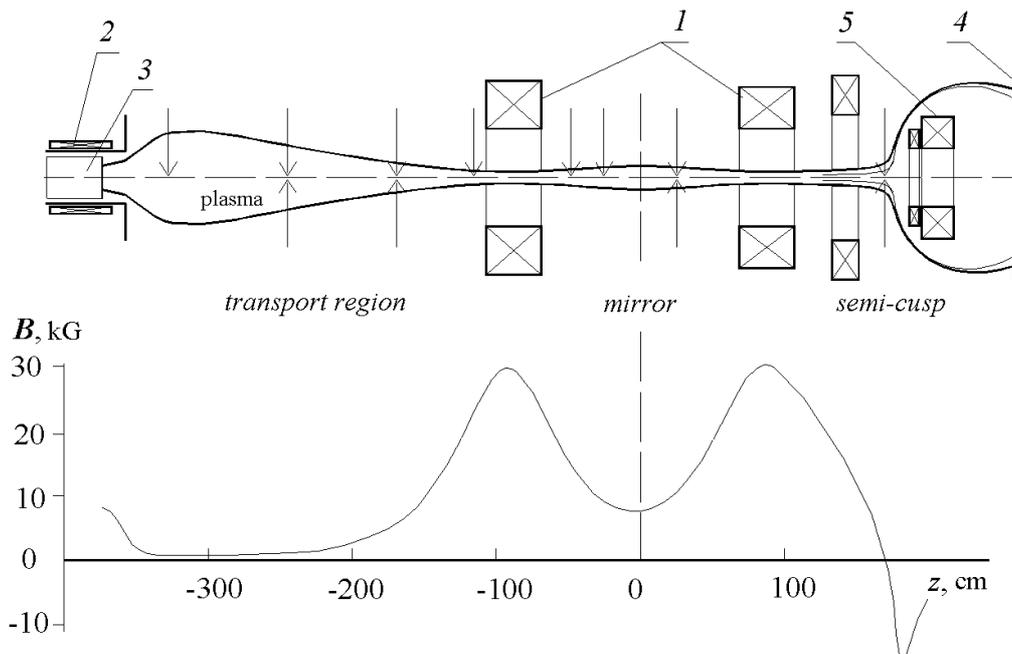


Fig. 1. Scheme of AMBAL-M experiments. 1— mirror coils, 2 — gun solenoid, 3 — plasma gun, 4 — plasma receiver, 5 — semi-cusp coil. The arrows from above show the coordinates of the cross sections where Langmuir probes were measured, from below — magnetic probes.

On moving to the mirror, the ions get heated, and the free path increases. The major part of the plasma flow is reflected, and plasma density decreases, and the plasma potential also decreases. A thermobarrier in the throat is realized [5, 1]. Ions in the mirror are kept by magnetic field, electrons — by magnetic field and ambipolar potential.

It was determined [6, 7] that in the transporting region an ion current of 1 kA flowed outside across magnetic field. The current flowing was determined to be provided by the following processes at plasma periphery: 1) nonambipolar transverse diffusion from ion-ion collisions; 2) transverse current suppressed essentially by magnetic field in positive radial electric field from electron-ion collisions, which is increased due to conductivity fluctuations; 3) longitudinal current from the extending outward grounded frame of the solenoid to the anode of the gun. The big value of the current is explained by the non-equilibrium radial electric field in plasma, given by the arc source electrode potentials, small transverse gradient value of the density change due to the narrow jet ($L_{\perp}/\rho_i \sim 4$), big square of plasma surface ($4 \times 10^4 \text{ cm}^2$) due to the weak magnetic field, and improved longitudinal confinement of plasma in the transporting region.

As ions flow outside in the transporting area and there is no runoff to an isolated gun, the electrons flow out into the mirror along the field to provide quasineutrality. The current shorting is realized by a conducting vacuum chamber. Longitudinal electron current of 1 kA in the plasma was found and investigated [8]. The current was determined to be a part of the source arc current [6]. When coming to the mirror the longitudinal current becomes displaced to the centre and flows mainly along the magnetic field force lines with radii of about 1/2 the gas discharge channel radius. The plasma potential was found to increase on these force lines when coming closer to the mirror and the thermobarrier was not found in the

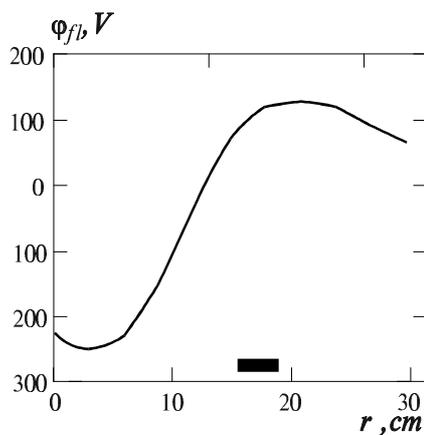


Fig. 2. Radial profile of plasma potential in the transport region ($z = -243\text{cm}$). Position of the gas-discharge channel is marked with the bold line segment.

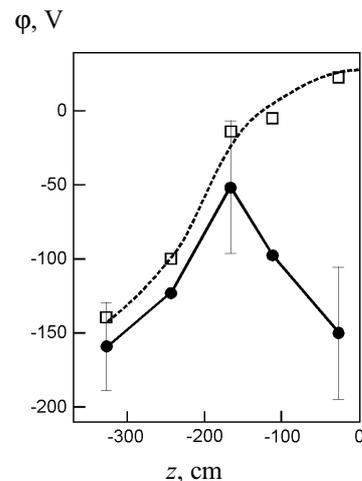


Fig. 3. Profile of plasma potential (dashed line) and floating potential of probe (solid line) along a magnetic field line on which the significant longitudinal electron current flows.

throat area (Fig. 3). This field formation could be possibly related to potential non-equilibrium cross profile as a result of the transverse diffusion of plasma. The need for longitudinal electron current flowing in the area of low plasma density could also cause the field formation. The potential increases 150 V on the length of 2 m. It is clear that a collisionless acceleration of electrons with initial temperature of 10 eV by this electric field in a homogeneous magnetic field could cause formation of almost monochromatic electron beam with longitudinal energy of 150 V. The solving of Vlasov's equation shows that the presence of increasing magnetic field leads to the electron spectrum widening at longitudinal energy. The cause is the transition of energy from longitudinal to transverse due to adiabatic invariant conservation. The absence of sharp boundary of electron runaway in the accelerating electric field could result even the more significant widening of the electron spectrum. When coming closer to the mirror the plasma density decreased, the boundary of the runaway area is shifted to the area of the lower velocities, and the more electrons become involved into the runaway process. The fast electron beam relaxation to the plateau state is also possible due to development of Langmuir instability. Therefore, the found longitudinal electric field forms the population of fast electrons which transports the current in the mirror. The fast electron flow in the mirror was experimentally registered [9] by electron energy analyzer (a probe with small inlet and electrostatic repelled lens). The function of electron distribution over the longitudinal energy looks like a plateau in the energy range of 150-300 eV.

According to the Pastukhov's formula [10] the energy losses of the trapped electrons from the mirror are estimated to be 20 kW. Both electron heating from the more hot ions (3 kW) and Joule heating concerning Spitzer conductivity (1 kW) are not enough for balance. Assuming the electrons to scatter more quickly by waves than by Coulomb collisions, the Joule heating power increases, but loss power carried out by the flow also increases, and the energy balance is not established.

In case of current being transferred by not all electrons but the small population of fast electrons, the electron heating by the current is stronger. That can be easily shown qualitatively. Let the current be transferred by all electrons. Their density is equal to n , the flow velocity — u , heat (chaotic) velocity v_T , and $u \ll v_T$. In a time τ determined by the velocity of the relative movement, i.e. heat velocity, the electrons lose the longitudinal momentum $nm u$. Friction force is $nm v / \tau$ and the power is $nm u^2 / \tau \sim j^2 / n \tau \sim 1/n$, where $j = enu$. Let the same current be now transferred by the part of electrons with the density of n_f ($n_f \ll n$) and the velocity of u_f ($u \ll u_f \sim v_T$). The current electrons lose the same longitudinal momentum $n_f m u_f$ in the same time interval τ . The friction force is the same — $n_f m u_f / \tau$, but the power generated increases considerably $n_f m v_f^2 / \tau \sim j^2 / n_f \tau \sim 1/n_f$. The precise calculations

confirm the significant heating of the electrons kept in the mirror by the fast electron flow which carries the current. This heating mechanism allows to close the energy balance. The fast electron flow heats the trapped electrons effectively (due to an ambipolar potential and the high velocity of the flow electrons) as a result of the Coulomb collisions. Presence of strong current does not affect the hot ions lifetime as the fast electron density is negligibly low, and therefore the power transferred that is carried out quickly by the flow from the mirror is also low. Absence of thermobarrier in the throat does not affect the plasma parameters in the mirror. Though the potential minimum is far from the mirror in the transporting region, the electrons on these force lines still are in deep potential well. These force lines of magnetic field do not project into gas-discharge channel with high emission ability and low temperature.

«Non-joule» non-turbulent effective heating of electrons by the current has been first identified and investigated. The plasma state obtained is close to the one which can be described basing on the classical (collisional) phenomena. It was determined that non-equilibrium profile of radial electric field set by the arc source electrode potentials has the major influence on realization of this efficient heating mechanism.

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