# Obtaining of Hot Plasma in a Mirror by an Arc Source

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Hot plasma was obtained without additional heating in an open magnetic trap AMBAL-M from arc source located behind the mirror [1]. The plasma has a diameter of 20 cm, an average density of $6 \times 10^{12}$ cm$^{-3}$, an ion energy of 200 eV, and high electron temperature of 50 eV that is of the most importance.A number of works were dedicated to the study of this plasma [2-6]. The present paper is a general one.

In Fig.1 the experiment scheme is shown. The plasma is generated by the arc source [7] 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].

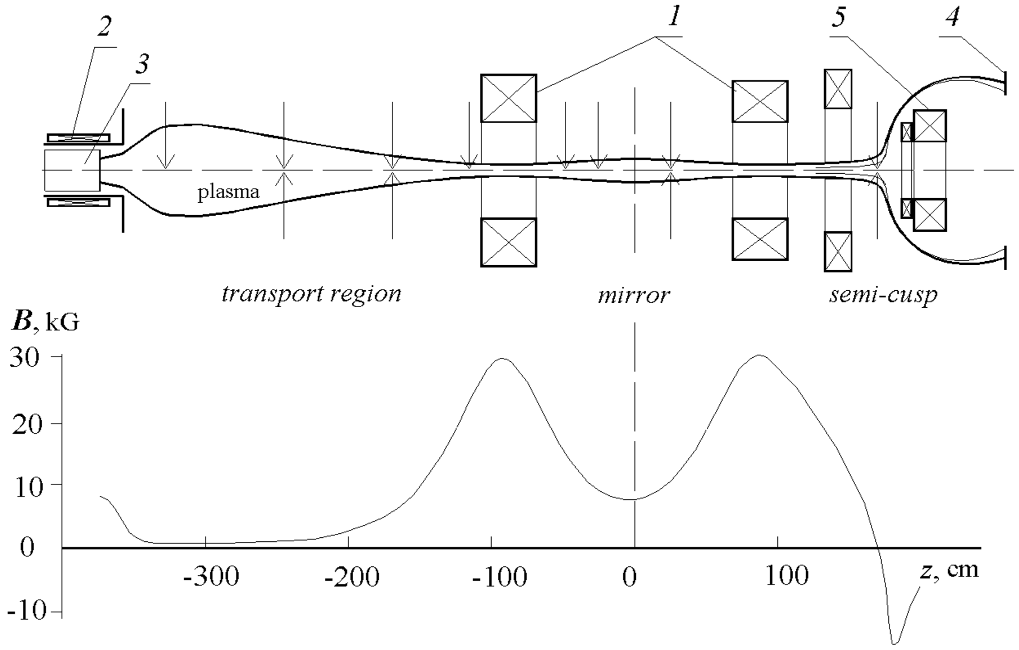

*Fig. 1. Scheme of AMBAL-M experiments. 1— mirror coils, 2 — gun solenoid, 3 — plasma gun, 4 — plasma receiver, 5 — semi-cusp coil. The arrows from above show the coordinates of the cross sections where Langmuir probes were measured, from below — magnetic probes.*

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. Ions in the mirror are kept by magnetic field, electrons — by magnetic field and ambipolar potential.

It was determined 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 ($4 \times 10^4$ 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. The current was determined to be a part of the source arc current. 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 throat area (Fig. 3).

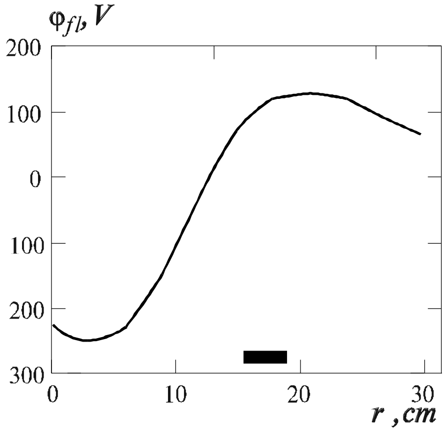

*Fig. 2. Radial profile of plasma potential in the transport region (z = -243cm). Position of the gas-discharge channel is marked with the bold line segment*

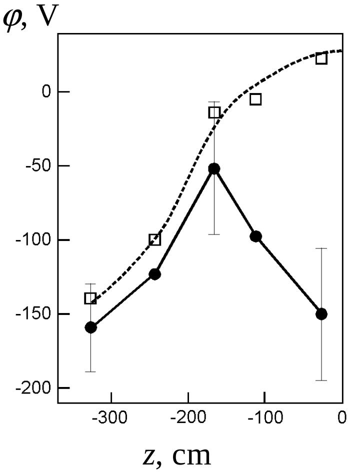

*Fig. 3. Profile of plasma potential (dashed line) and floating potential of probe (solid line) along a magnetic field line on which the significant longitudinal electron current flows.*

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

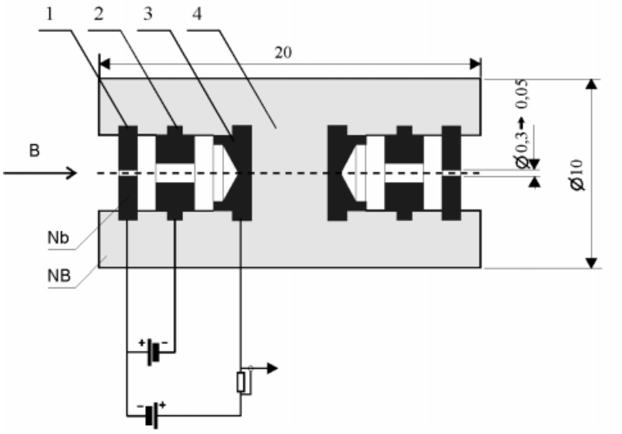

*Fig. 4. Schematic of the energy analyzer: (1) input diaphragm, (2) analyzing diaphragm, (3) collector, and (4) insulating case.*

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 by electron energy analyzer (a probe with small inlet and electrostatic repelled lens, Fig.4). The function of electron distribution over the longitudinal energy has a plateau in the energy range of 150-300 eV in the current-carrying channel of the mirror system and is Maxwellian (with a temperature of 60 eV) outside this channel.

According to the Pastukhov’s formula [8] 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.

Let us consider the electron flow of $\mathcal{E} = 100$ эВ energy in a equilibrium plasma of $T = 50$ eV. These electrons pass the mirror in $t_{\text{fly}} \sim 0{,}3$ µs. The typical collision time $\tau_1^e = \dfrac{\sqrt{m}}{\pi\sqrt{2}\,e^4}\cdot\dfrac{\mathcal{E}^{3/2}}{\lambda\, n_i}$ ~ 3 µs. At $\mathcal{E} > 2T$, the energy exchange time is $\tau_\varepsilon \sim \tau_1^e$. So, due to Coulomb collisions during the time of electrons passing the mirror, the energy is transferred from the flow electrons to the captured ones, and the heating value is $P = I\,\mathcal{E}\,t_{\text{fly}}/\tau_\varepsilon \sim 10$ kW. It was determined that the heating power weakly depends on flow electrons energy in the energy range of 100 - 300 eV. 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 hole. These force lines of magnetic field do not project into gas-discharge channel with high emission ability and low temperature. So, it was determined that the main mechanism of trapped electrons heating is direct energy transfer from flow electrons as the result of the Coulomb collisions.

Let us pay attention to the accumulated energy in an electron beam formed in a transporting area. At current of 1 kA and mean electron energy of 200 eV, the electron beam power is 200 kW. This value is high enough for the arc plasma source used in this experiment. In our early experiments [9] on efficient usage of arc plasma source for obtaining of dense plasma in a mirror system, the whole stream power was also 200 kW. Therefore, the energy accumulated in a radial electric field near the source was efficiently transferred into the directed energy of electrons which heat the captured electrons in the mirror efficiently.

The main mechanisms of heating and confinement are considered. A number of experimental peculiarities allowed to obtain hot dense plasma in an open magnetic trap from arc source located behind the mirror are determined. Influence of a narrow ring dense plasma jet on transverse current is indicated. Influence of a non-equilibrium radial electric field formed by arc source electrode potentials on Kelvin-Helmholtz instability development, stochastic heating of magnetized ions, formation of longitudinal electric field, longitudinal current, and population of fast electrons is shown. «Non-joule» non-turbulent effective heating of electrons by the current has been first identified and investigated. It is found that, 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.

Two of the specific features of the magnetic mirror device manifest themselves in these experiments. First, the plasma behavior is well described by classical phenomena, i.e., by collisional processes. Second, the possibility of controlling over the potential radial profile allows us to vary the plasma heating and confinement.

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