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PLASMA CONFINEMENT IMPROVEMENT IN A LINEAR TRAP BY MULTIPLE-MIRROR PLUG SECTIONS

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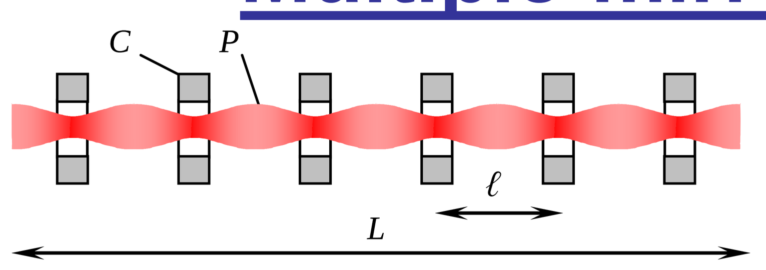
Main results

The use of multiple-mirror plugs is a way to increase plasma confinement efficiency in mirror traps. To investigate the physics of plasma confinement in a multi-mirror field, the GOL-NB facility was created at BINP SB RAS. In 2024, the first experiments were conducted on the facility to study the efficiency of multiple-mirror plasma confinement. The essence of the experiments was to compare the efficiency of plasma confinement in configurations with a uniform and a multiple-mirror magnetic field in the plug sections. A comparison of the two regimes showed that in the multi-mirror magnetic field, a reduction in the plasma outflow rate (Mach number), an increase in plasma temperature (both in the central section and in the plug sections), and a decrease in its density were observed, which qualitatively corresponds to theoretical predictions on the influence of the multiple-mirror magnetic field. This is a first demonstration of suppression of plasma flux from gas-dynamic trap by multiple-mirror plug cells.

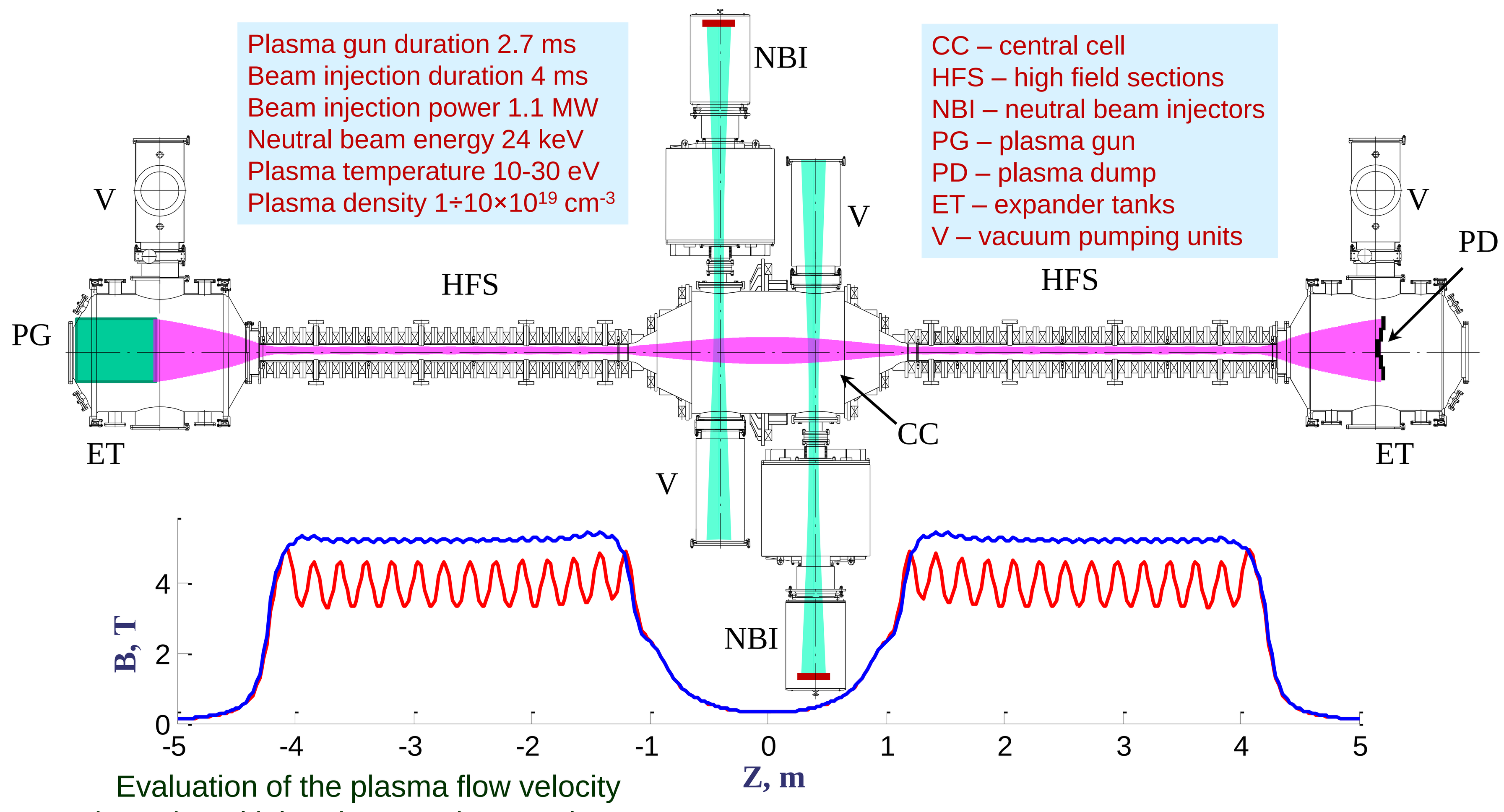
Multiple-mirror confinement



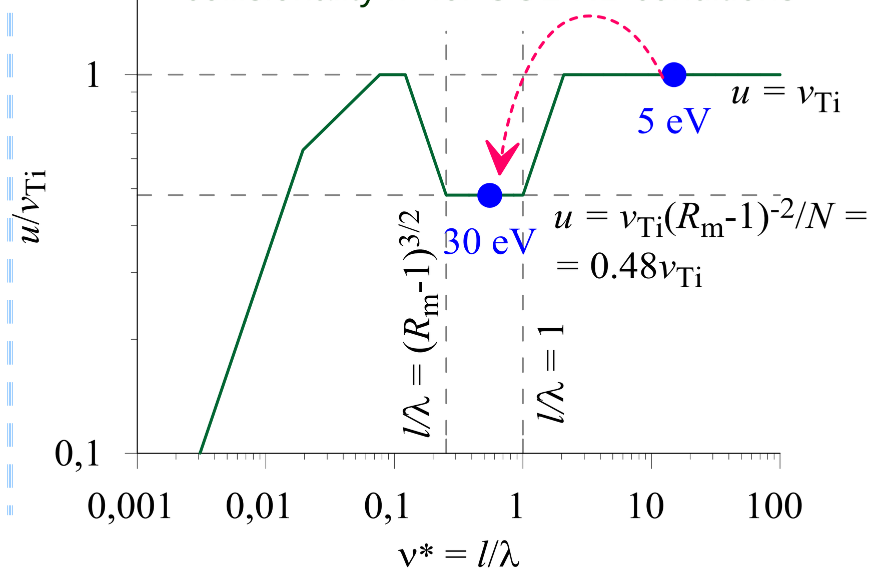
Linear magnetic systems offer several potential benefits for fusion plasma confinement, such as straightforward coil geometries, effective utilization of the magnetic field, the capacity to maintain plasma under high pressures.

However, a critical downside of linear systems lies in their substantial longitudinal energy losses, which strongly restrict the achievable thermonuclear gain. One possible solution to mitigate excessive longitudinal losses in linear magnetic is the use of a multiple-mirror magnetic field configuration. The principle of plasma confinement in a multiple-mirror magnetic field is based on the friction between passing particles and particles confined in local magnetic traps of the system. As a result, the momentum from the plasma flow is transferred to the magnetic field, leading to a reduction in the plasma loss rate from the trap. Ion scattering in local traps can occur both due to binary collisions and due to electric field fluctuations arising from unstable plasma flow or induced by external influences on the plasma. In the case of binary collisions, multiple-mirror confinement is effective if a free path length of ion in the plasma is close to a length of a local mirror trap ($\lambda_{ii} \sim \ell$).

GOL-NB facility



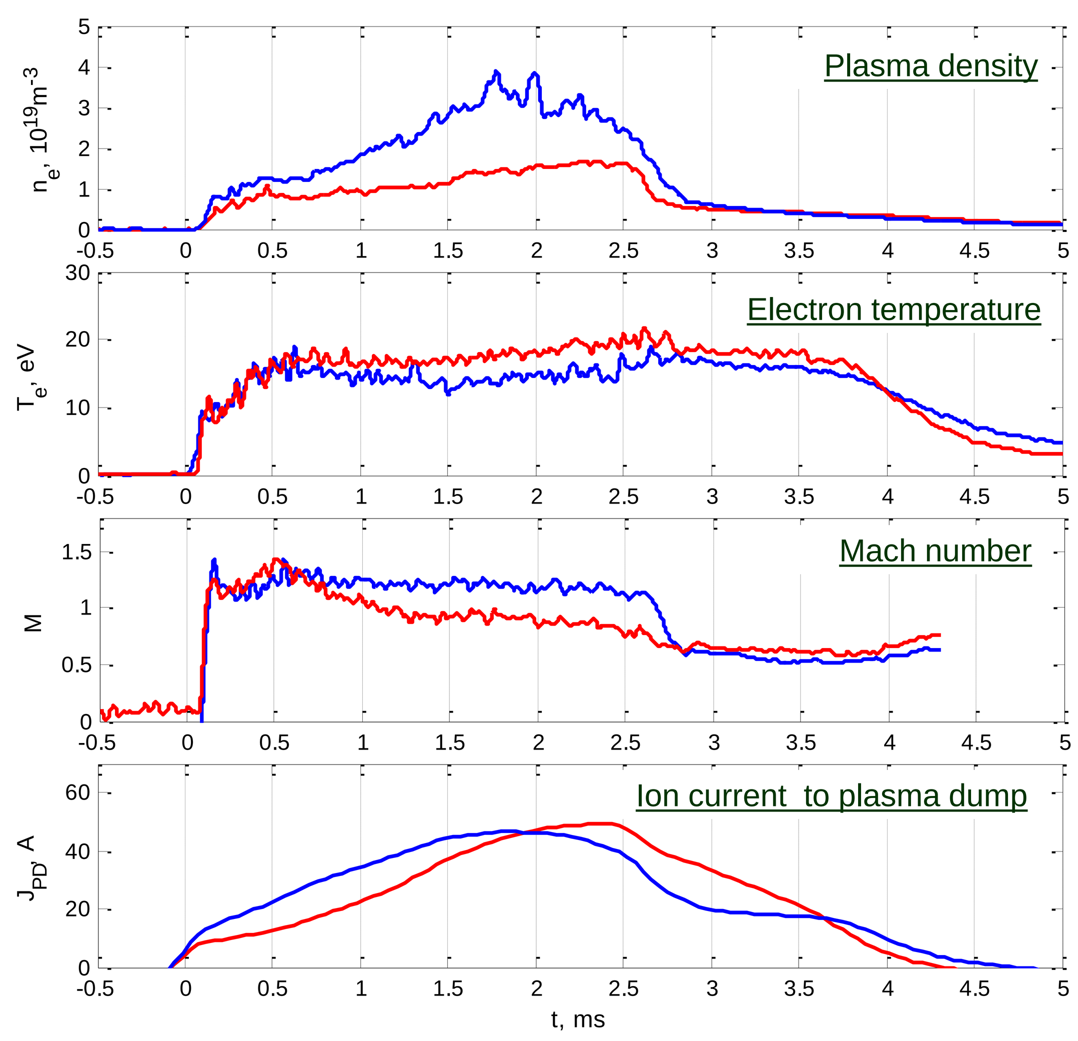
Evaluation of the plasma flow velocity through multiple-mirror section vs. plasma collisionality n* for GOL-NB conditions



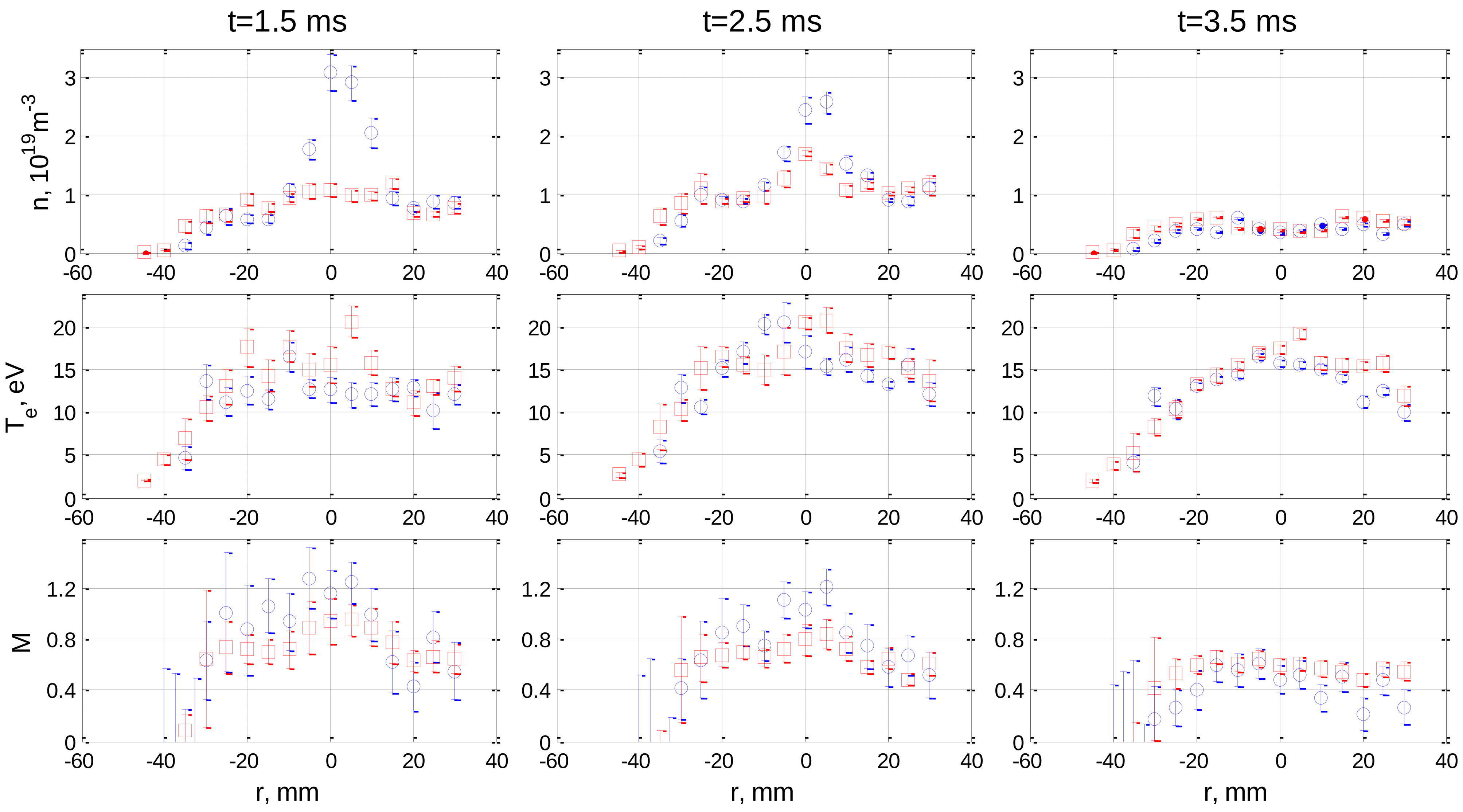
The GOL-NB facility is a linear axisymmetric open trap with high field pug sections. The essence of the experiments is to compare the efficiency of plasma confinement in the configurations with a uniform and a multiple-mirror magnetic field in the plug sections. The plasma parameters in the facility (plasma temperature of 15-20 eV, density of (1-3)×10[19] m[-3], length of local mirror trap of 22 cm) corresponded to the optimal conditions for multiple-mirror confinement. A theory predict two-fold suppression of plasma flow by the multiple-mirror sections compared to the flow through a short magnetic mirror.

Comparison of uniform and multiple-mirror configurations

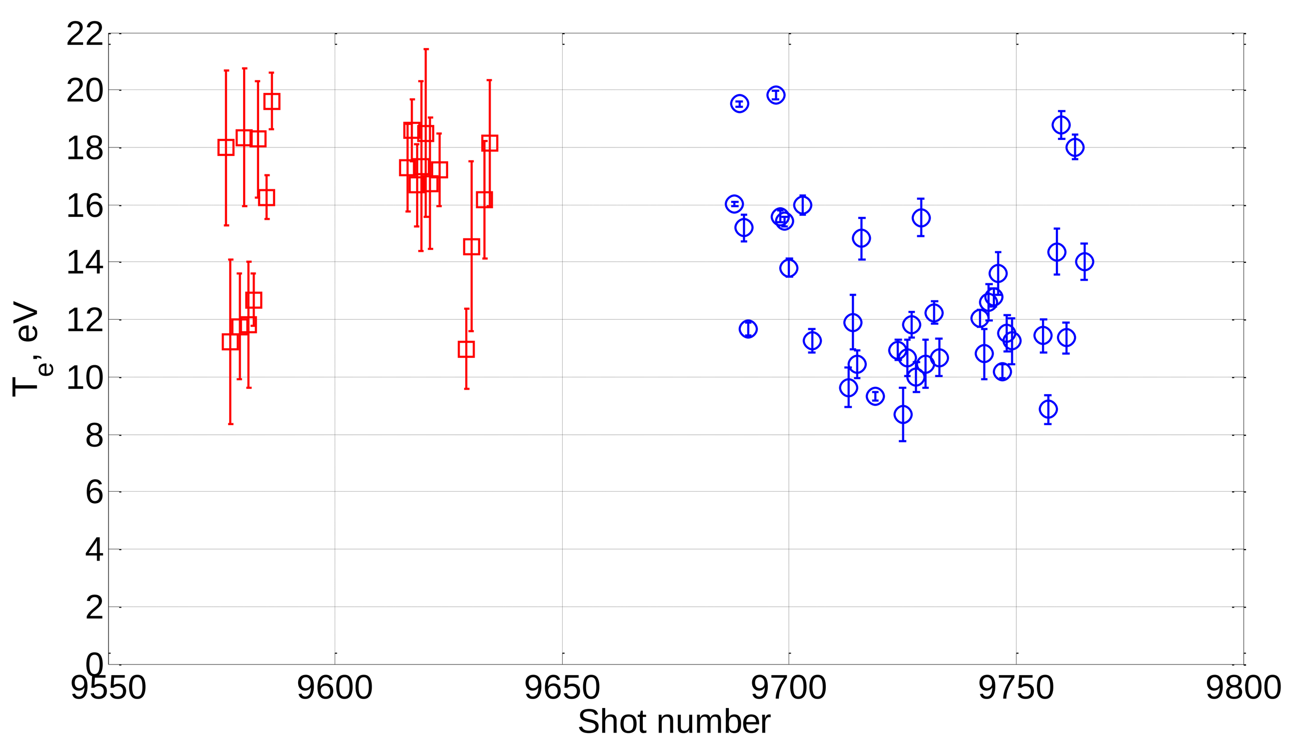
Dynamics of the plasma parameters (z=137 cm)



Radial distribution of plasma parameters (z=137 cm)



Electron temperature measurement using Thomson scattering system (z=-40 cm)



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DISCUSSION

This suppression factor for the longitudinal flow operates only within a relatively narrow range of plasma collisionality. In the presence of radial plasma parameter gradients, the condition for optimal multiple-mirror confinement is satisfied only within a certain radial zone of the plasma column.

The actual device is a much more complex system where other factors affecting plasma confinement quality exist. Significant factors include substantial transverse loss channels for fast ions due to charge exchange on the residual gas, reducing the efficiency of beam heating, considerable transverse particle losses from the confinement region with an effective diffusion coefficient on the order of Bohm diffusion, and the presence of several electrodes in contact with the plasma, to which potentials are applied and from which longitudinal currents flow. All this leads to the measured plasma parameters in the experiment differing from those expected based on calculations with idealized models. Additionally, it should be noted that even in the long magnetic mirror with uniform field, some braking of the plasma flow can occur due to the transfer of part of the directed momentum in collisions and resonant charge exchange events with neutral gas.

The neutral gas pressure is measured in both strong-field sections with a time resolution of less than 1 ms; at the end of the plasma lifetime, it rises to a value on the order of 0.1 Pa, which is already significant. Interaction with the gas, especially resonant charge exchange, cools the plasma as it flows along the strong-field section.

Nevertheless, a significant difference in the parameters of the plasma flow was recorded in the experiment when switching from one magnetic configuration to another. The main result was the demonstration that when switching to the multiple-mirror configuration, the plasma flow velocity decreases, its temperature increases, and the density decreases compared to the case of the uniform field. At the same time, in the central trap, the plasma density also decreases, and its temperature increases. This observation also corresponds to the expected behavior of the plasma as it flows from the plasma source through the multiple-mirror system into the central trap.