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

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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, and the ability to reduce energy and particle flows onto plasma-facing components by leveraging a significant magnetic expansion ratio between the primary plasma and terminal plasma receivers. Linear magnetic systems for fusion applications are investigated in the Budker Institute of Nuclear Physics (BINP SB RAS) [1]. Recent experiments on the gas-dynamic trap GDT have demonstrated possibility of stable confinement of plasma with electron temperature up to 1 keV, density ~10^{19} m^{-3}, and beta parameter exceeding 0.5 [2]. Several projects of powerful sources of fusion neutrons based on linear magnetic systems have been proposed for fusion material testing, nuclear waste transmutation, thorium fuel burning study, and driving of hybrid fusion-fission reactor [3].

However, a critical downside of linear systems lies in their substantial longitudinal energy losses, which strongly restrict the achievable thermonuclear gain [4]. One possible solution to mitigate excessive longitudinal losses in linear magnetic is the use of a multiple-mirror magnetic field configuration [5]. 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. The instability of the plasma flow, leading to increased efficiency of longitudinal confinement by multiple-mirror sections, was experimentally observed at the GOL-3 facility [6] and later theoretically studied in [7].

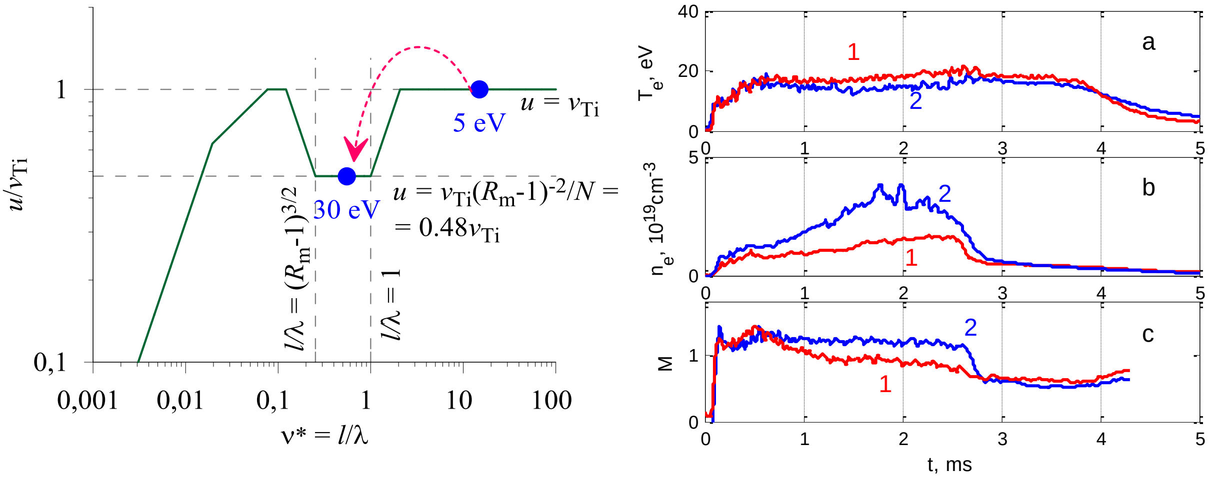

Fig.1 **left**: Evaluation of the plasma flow velocity through multiple-mirror section vs. plasma collisionality ν*. Number of local mirror traps N=13, mirror ratio R=1.4. The solid line was calculated from [8] theoretic estimates. Dots and arrow indicate the expected parameters for the stage of filling the trap with low-temperature starting plasma at $n = 3\times10^{19}$m^{-3} and T = 5 eV, and for the plasma during the heating stage at T = 30 eV.

Right: Dynamics of plasma parameters in the configuration with multiple-mirror (1, red) and uniform (2, blue) magnetic field. a) – plasma electron temperature, b) – plasma density, c) – Mach number. All measurements are done in section of strong magnetic field.

To investigate the physics of plasma confinement in a multi-mirror field, the GOL-NB facility was created at BINP SB RAS [9]. The facility consists of a gas-dynamic central cell with attached plug sections of strong magnetic field, each about 3 m long. Plasma in the facility is generated by a plasma gun located in the expander at one end of the facility and heated by the injection of fast hydrogen neutral beams.

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 (B = 4.5 T) and a corrugated (B = 3.2/4.8 T, corrugation period of 22 cm) magnetic field in the plug sections. The plasma parameters in the facility (plasma temperature of 15-20 eV, density of (1-3)$\times 10^{19}$ m^{-3}, length of local mirror trap of 22 cm) corresponded to the optimal conditions for multiple-mirror confinement (see fig.1 left).

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 (Fig.1 right), 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.

The next major milestone in the experiments will be to study the effects of multiple-mirror confinement in plasma with reduced collisionality (when the mean free path exceeds the length of the local traps in the plug sections). This kind of an extension of the parameters space is important for understanding of prospects of multiple-mirror systems at reactor-relevant conditions. To operate in this low-density plasma regime, the facility is currently being equipped with an ion cyclotron resonance plasma heating system.

The achieved results illustrate a capability of a multiple-mirror field to mitigate longitudinal losses in linear systems. The project of next-step facility which combines gas-dynamic trap with hot plasma (Te~1 keV) and superconducting multiple-mirror plugs is under development in the Budker INP [10].

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