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

[1,2,3]S.V. POLOSATKIN, [1,2]V.I. BATKIN, [1,3]A.V. BURDAKOV, [1,2]I.A. IVANOV, [1]R.G. GOROKHOVSKY, [1,2]P.V.KALININ, [1]K.N.KUKLIN, [1,2]N.A. MELNIKOV, [1]K.I. MEKLER, [1]A.V.NIKISHIN, [1,2]V.V. POSTUPAEV, [1]A.F.ROVENSKIKH, [1]E.N.SIDOROV, [1,2]D.I.SKOVORODIN, [1]E.N. SKURATOV

[1]Budker Institute of Nuclear Physics, Novosibirsk, Russian Federation
[2]Novosibirsk State University, Novosibirsk, Russian Federation
[3]Novosibirsk State Technical University, Novosibirsk, Russian Federation
Email: s.v.polosatkin@inp.nsk.su

Abstract

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 (B = 4.5 T) and a corrugated (B = 3.2/4.8 T, corrugation period of 22 cm) 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.

1. INTRODUCTION

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 [5,6]. 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[7] and later theoretically studied in [8].

The need to confirm the effectiveness of this approach at plasma parameters close to those required in a fusion reactor, as well as to study of anomalous scattering during plasma flow through a multiple-mirror magnetic field, served as the motivation for the construction of the GOL-NB facility in the Budker Institute of Nuclear Physics. The first results of experimental investigations of multiple-mirror confinement at GOL-NB facility are presented in the paper.

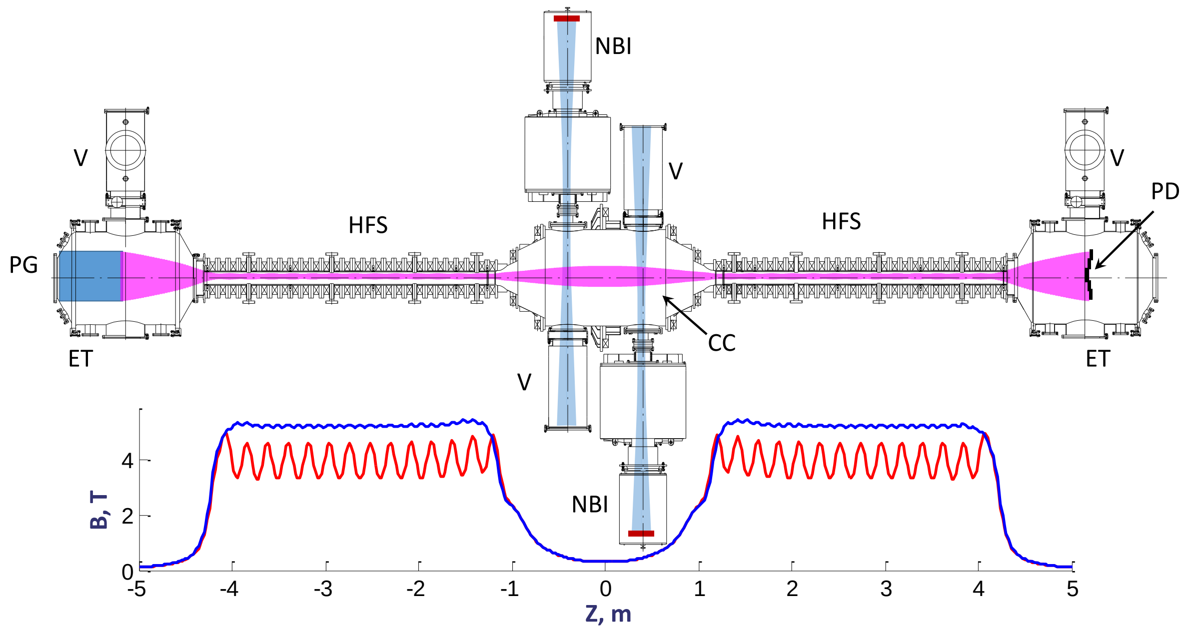

FIG. 1. The layout of the GOL-NB facility. CC – central cell, HFS – high field sections, NBI – neutral beam injectors, PG – plasma gun, PD – plasma dump, ET – expander tanks, V – vacuum pumping units. Magnetic field for both solenoidal (blue) and multiple-mirror (red) configurations are shown.

2. GOL-NB FACILITY

The GOL-NB facility [9] is a linear axisymmetric open trap with multiple-mirror end plugs for plasma confinement. The main objective of experiments conducted on this facility is to investigate plasma confinement in a multiple-mirror magnetic field, which is periodically modulated along the axis. The GOL NB facility consists of a 2.4 m long central cell with a central field strength of B = 0.3 T, and attached sections with strong fields (plugs), each approximately 3 m long. The magnetic configuration of the plugs can be switched between uniform magnetic field (B = 4.5 T) and multiple-mirror magnetic field (13 cells with a length of 22 cm and B_{max}/B_{min}=4.8/3.2 T). The layout of the facility and magnetic field for the solenoidal and multiple-mirror configurations are shown in figure 1. Plasma in the facility is created by a plasma gun located in the expander at one end of the facility and is heated by the injection of fast hydrogen atom beams (neutral beams, NBI) [10].

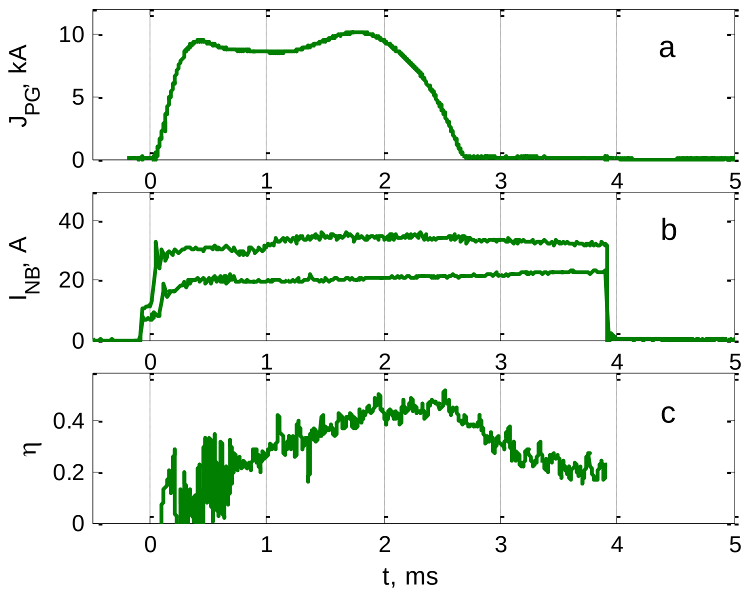

FIG. 2. Waveforms of GOL-NB operation. a) – current of plasma gun, b) – current of ions in the neutral beam injectors (efficiency of conversion of the ions to neutrals is about 80%), c) – capture of the neutral beams on the central chord of injection

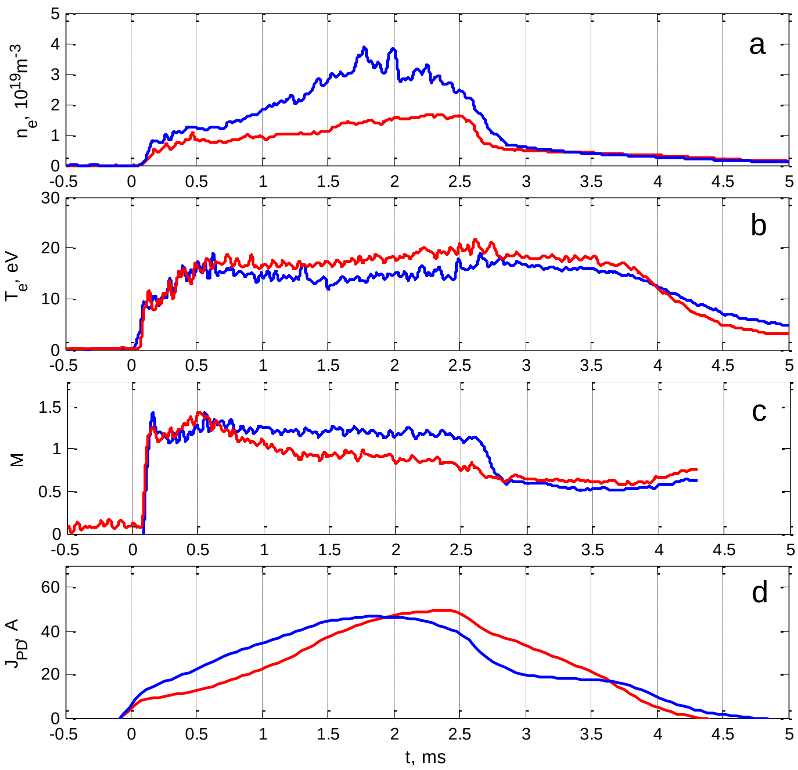

FIG. 3. Dynamics of plasma parameters in the configuration with multiple-mirror (red) and uniform (blue) magnetic field. a) – plasma density, b) –plasma electron temperature, c) – Mach number, d) – ion current to the plasma dump. All measurements are done in section of strong magnetic field.

Two neutral beam injectors (NBI) with a total power of 1.1 MW inject fast neutrals with an energy of 24 keV into the plasma across the magnetic field of the facility at coordinates z = ±0.4 m (the longitudinal coordinate z is measured from the centre plane of the trap). As they pass through the plasma, the injected fast atoms are ionized due to collisions with plasma electrons and ions.

The resulting fast ions are then captured in the central cell of the facility and heat the plasma electrons. The plasma gun pulse duration is 2.7 ms, and the fast neutral injection duration is 4 ms. In the regular operation scenario, beam injection was initiated simultaneously with the start of the plasma gun operation. Typical waveforms of GOL-NB operation is shown in figure 2.

3. COMPARISON OF UNIFORM AND MULTIPLE-MIRROR CONFIGURATIONS

For comparison of the two configurations, plasma parameters (density, temperature, and Mach number) were measured in both regimes at the coordinate of 1.37 m (in the first cell of the high-field section on the side opposite to the plasma gun) using triple and Mach probe. Dynamics of these parameters on the axis of the facility is shown in figure 3(a-c). Additionally, an ion current to the plasma dump (figure 3d). It can be seen that systematic differences in the plasma parameters and the nature of the plasma flow are indeed observed. In the multiple-mirror configuration, the plasma in the near-axis region is less dense and hotter, and also has a lower flow velocity during the operation of the plasma gun. The cooling and decay of the plasma after the termination of the heating beams proceed more slowly in the multiple-mirror configuration than in the uniform one.

The increase in electron temperature is confirmed by temperature measurements from the Thomson scattering system in the central cell of the device. Despite a noticeable scatter in the measurement results within each series, in the multiple-mirror regime, the electron temperature was systematically higher than in the uniform magnetic field regime (see figure 4).

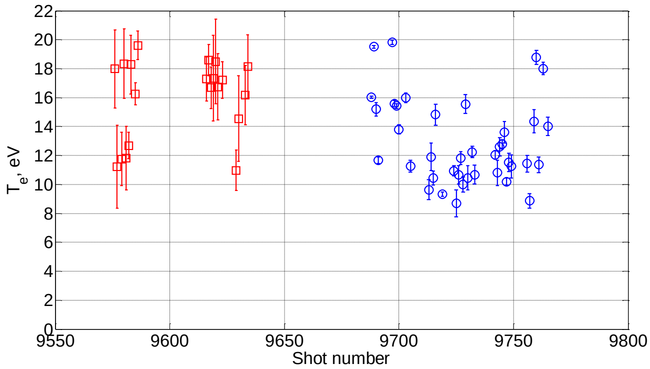

FIG. 4. A dataset from Thomson scattering measurements of the on-axis electron temperature T_e, taken at a time of t=2.5 ms. The red squares and the blue dots show the multiple-mirror and uniform field configurations, respectively. No data filtering based on the device's operating mode was performed.

Figure 5 shows the radial profiles of the main plasma parameters at z = 1.37 m. Three characteristic time points are displayed, corresponding to the plasma accumulation stage, the density maximum, and the plasma decay stage after the termination of the discharge current in the gun.

The most pronounced difference in the density profiles is the density in the near-axis plasma region, which corresponds to the diameter of the primary plasma flow from the gun. In the uniform configuration, this part of the profile has a significantly higher density. This is also evident from the dynamics of the signals in Figure 3.

4. DISCUSSION

In the simplest theoretical model, where longitudinal plasma losses dominate and transverse losses can be neglected, a roughly two-fold reduction in the plasma flow velocity escaping from the central trap compared to the flow through a short magnetic mirror could be expected for the specific parameters of the GOL-NB magnetic system in the multiple-mirror configuration.

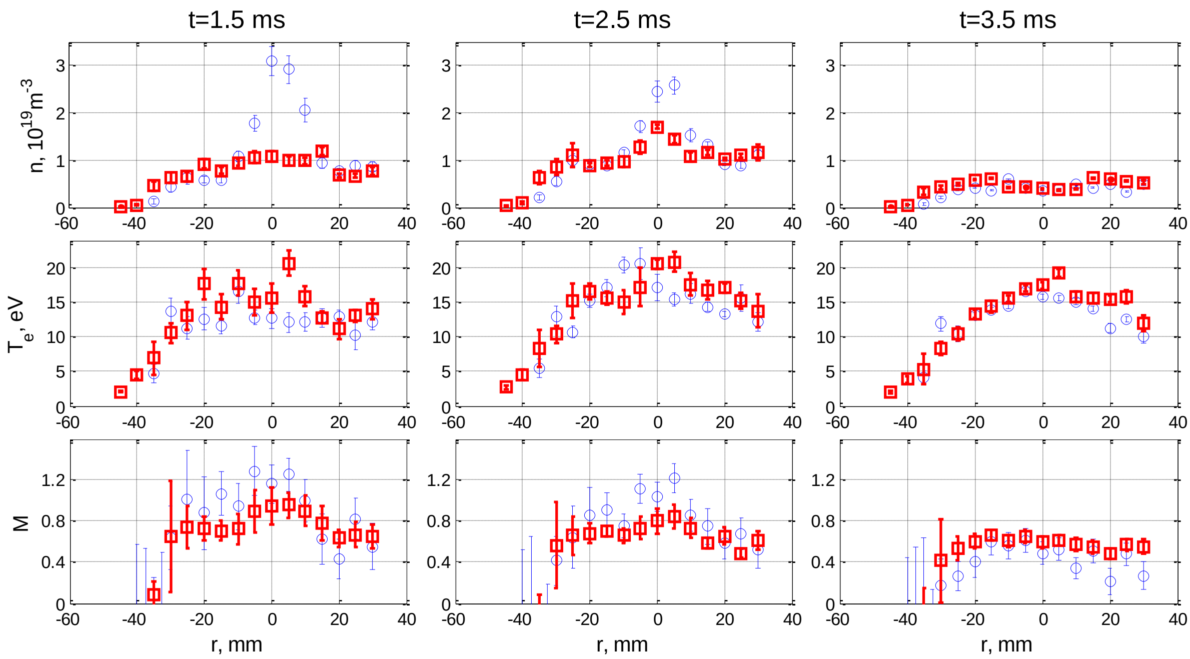

FIG. 5. Radial profiles of the plasma parameters (plasma density n, electron temperature T_e, and Mach number M) for different time points from plasma gun start. The red squares and the blue dots correspond to the multiple-mirror and uniform field configurations, respectively.

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 behaviour of the plasma as it flows from the plasma source through the multiple-mirror system into the central trap.

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