

PLASMA TRANSPORT IN LINEAR AND HELICAL MULTIPLE-MIRROR SYSTEMS

A.V. BURDAKOV

Budker Institute of Nuclear Physics
Novosibirsk, Russian Federation
Email: A.V.Burdakov@inp.nsk.su

A.V. SUDNIKOV^{1,2}, A.D. BEKLEMISHEV^{1,2}, V.V. POSTUPAEV^{1,2}, V.I. BATKIN¹, V.S. BURMASOV¹, I.A. IVANOV^{1,2}, A.A. INZHEVATKINA², K.I. MEKLER¹, S.V. POLOSATKIN^{1,2}, E.N. SIDOROV¹, V.F. SKLYAROV^{1,2}, V.B. BOBYLEV¹, N.G. VASILYEVA¹, K.N. KUKLIN¹, A.F. ROVENSKIKH¹

¹ Budker Institute of Nuclear Physics

Novosibirsk, Russian Federation

² Novosibirsk State University

Novosibirsk, Russian Federation

Abstract

The challenge of creation of an open trap with the reactor-grade plasma is achievable if such trap will use specialized sections of the magnetic system for suppression of particle and energy losses along the magnetic field. Currently, two new experimental devices are under construction in the Budker Institute for studies of physics of plasma confinement in magnetic systems with multiple-mirror configurations. Linear topology of the traps enables early start of experiments with plasma before the completion of the magnetic and vacuum systems. In the paper, we will report experimental results on the transport of a low-temperature start plasma flow through a section with a multiple-mirror magnetic field as well as the direct comparison with the case of solenoidal magnetic field. In the final configuration of GOL-NB, that plasma stream will be used as the target for the capture of heating neutral beams. In 2017, new SMOLA helical multiple-mirror trap achieved the first plasma. In this trap, plasma rotation is used for creation of moving magnetic mirrors in the rotating frame of reference. An active plasma pumping by the moving magnetic mirrors can deliver an exponential dependence of the confinement efficiency on the system length. Modification of the plasma flow profile at helical mirror confinement was demonstrated in the experiment. Main results from the first experimental campaign will be discussed.

1. INTRODUCTION

Linear magnetic traps give interesting prospects as a ‘plan B’ for fusion plasma confinement due to their technological simplicity and relative ease of reproduction and construction. Advances plasma confinement in open magnetic mirrors features high relative pressure ($\beta \approx 60\%$), mean energy of hot ions of 12 keV and the electron temperature up to 0.9 keV in quasistationary regime [1–3]. At the same time, the mirror ratio in a simple open trap is limited by the achievable magnetic field and is supposed to be 15–20 in neutron source concepts [4]. Higher fusion gain in linear plasma devices is possible with improved longitudinal confinement [5]. Special magnetic sections attached to a central confining core are usually considered for this purpose. Possible technologies include tandem mirrors, static and dynamic multiple-mirrors. Combined with gas-dynamic central cell [6, 7] they can provide effective mirror ratios of the order of 100, which gives feasible fusion gain appropriate for hybrid systems.

The current version of the conceptual next-generation GDMT project use the multiple-mirror technology to increase the energy confinement time. Two possible ways of application of this technology are static or dynamic mirrors. Static multiple-mirror concept is proved to provide diffusive expansion of the plasma flow at the conditions when ion mean free path is comparable to the distance between individual mirrors, which is more favourable than plasma outflow at the sonic speed in simple mirrors [8]. Dynamic multiple-mirrors renew the idea of a plasma flow control with moving multiple magnetic mirrors [9]. Moving mirrors push the trapped particles in the desired direction. If the collisionality is moderate, momentum is effectively transferred from the mirrors to the trapped particles and from the trapped particles to the free ones. Recent analysis in [10] have shown that the modulation of the guiding magnetic field travelling in the laboratory reference frame may be achievable, but presumably restricts the usage of the superconducting magnetic system due to the mechanical stresses and coil quenching. Helical mirror idea [11, 12] is free of this drawback, because it utilizes the plasma rotation to create periodical variations of static helicoidal magnetic field moving upstream in plasma’s frame of reference.

Currently, two new experiments have been started in Budker INP to demonstrate the technologies of the static and dynamic multiple-mirror confinement for future linear magnetic traps. The GOL-NB project [6] is a technology demonstration experiment on multiple-mirror plasma confinement. The final configuration of the device will include a 2.5-m-long central gasdynamic trap with two attached multiple-mirror sections of 3 m each, and two end magnetic flux expanders that house a start plasma creation system, plasma receiver endplates, and a system of biased electrodes for plasma stabilization. Plasma will be heated by two 0.75 MW, 25 keV neutral beams. Concept exploration device SMOLA is a helical mirror which started operation in the end of 2017 in BINP [13]. The gun-generated cold or warm plasma with the maximum ion density of $n_i \sim 10^{19} \text{ m}^{-3}$ can be trapped in the expander cell between the high-field region of the plasma gun and the 2.3-m-long helical section. Independent feeds of the helical and solenoidal windings will allow operation with variable directions and strengths of these field components. Rotation is driven externally by the potentials of the plasma gun, endplates and limiters.

In this report, we present the first experimental results of these two linear devices.

2. EXPERIMENTAL SETUP

2.1. GOL-NB experiment

Detailed discussion of physics and hardware of GOL-NB can be found in [6]. Layout of the start configuration of the device is shown on Fig. 1. Simulations [14] predict that plasma temperature in the central trap will reach 70-100 eV in the multiple-mirror configuration comparing with 30 eV in the standard gas-dynamic regime (at mirror ratio $R = 15$, density $n = 3 \times 10^{19} \text{ m}^{-3}$ and 1.5 MW NBI).

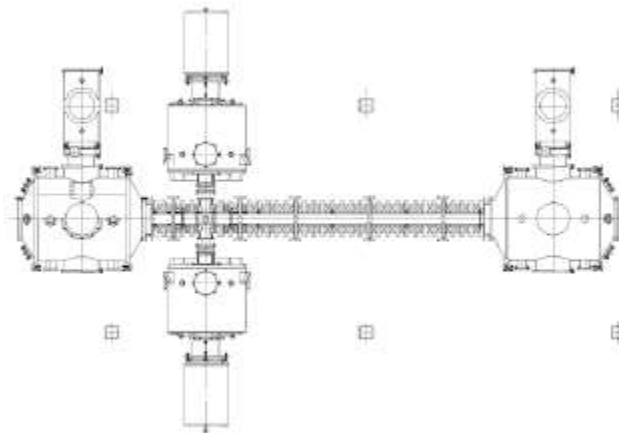


FIG. 1. Layout of the start configuration of GOL-NB device for the commissioning of main subsystems.

The first plasma series in the start configuration of GOL-NB was launched in the end of May 2018. Its main tasks are the initial acceptance tests of the plasma source and checks of performance of all new elements. Besides the absence of the central trap and shorter highfield sections, this configuration temporarily lacks all in-chamber biased electrodes for plasma stabilization. The high-field sections were in the solenoidal configuration. Both neutral beam injectors operated close to their design parameters. Attenuation of the neutral beam by the plasma flow reaches 30 - 40% that is close to the expected value for the current arrangement of the experiment. This value corresponds to the line-integrated plasma density $nL \sim 10^{19} \text{ m}^{-2}$ with the density at the axis $n(r=0) > 10^{20} \text{ m}^{-3}$. In the experiments, the plasma gun operated at the same magnetic field; we varied the field strength in the solenoid. Measurements of the attenuation of neutral beams by plasma have shown that we have the lossless compression of the plasma stream at $z \sim 0.5 \text{ m}$ at least up to $B_{max} = 1.75 \text{ T}$.

The influence of a multiple-mirror magnetic field on the plasma flow depends on the ratio of the ion free path length λ to the corrugation period l . If $\lambda \approx l$, a multiple-mirror magnetic field will significantly decelerate the plasma flow due to a friction force between populations of transiting and locally-trapped particles. In the extremes of “cold, dense” and “hot, rare” plasmas a corrugated field will not affect the flow. Additional details and references to the theory and previous experiments can be found in [8].

2.2. SMOLA experiment

The aim of the first experiments was to prove the concept itself, regardless of the efficiency. Some of subsystems were not installed yet or was operating in interim configurations. The layout of the device and the positions of the diagnostics are shown in Fig. 2.

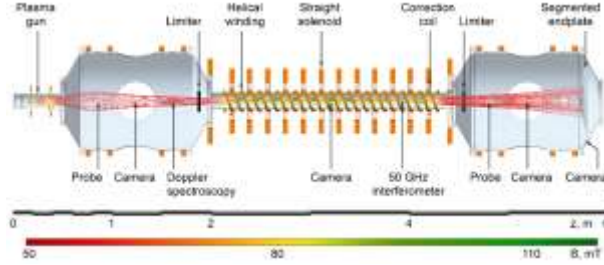


FIG. 2. Layout of the SMOLA helical mirror.

In these experiments, the influence of the magnetic configuration on the plasma stream parameters was studied. Hydrogen plasma with the density $\sim 10^{19} \text{ m}^{-3}$ and temperature 2 – 5 eV was generated by the plasma gun, based on the design of [17]. Ionization is performed by the electrons emitted from heated LaB_6 cathode. Potentials of the anode and cathode are independent and magnetically insulated by the guide field 0.06–0.2 T of each other and of the grounded vacuum chamber (Fig. 2). The plasma source always operated at the same parameters, providing the same plasma flow.

Plasma passed along the 2.3-m-long transport section with helical magnetic corrugation. The magnetic system of the transport section consisted of two separately-powered windings, which created the straight and the helical components of the magnetic field. In the first plasma campaign, we used a temporary solenoidal winding instead of that shown in Fig. 2. It provided lower magnetic field (up to 0.04 T) and had significant parasitic field strength modulation along the axis. After the transport section, the plasma stream passed to the exit magnetic expander featuring radially-segmented electrically-insulated endplates.

The plasma rotation was driven by the radial electric field of the plasma gun; external sources were not used to form the special profile of the radial electric field. Electric field of the gun corresponds to the negative charge on the plasma axis.

Significant dimensionless parameters were the following:

- pitch of the helical field to the ion mean free path $h / \lambda \sim 0.5 - 1$,
- mean corrugation $R_{mean} \sim 1.5 - 2$,
- ion gyroradius to the plasma radius $\rho / r \sim 0.1$,
- longitudinal velocity of the magnetic corrugation in the plasma's frame of reference to the ion thermal velocity $v_z / v_T \sim 1$.

3. COLD PLASMA TRANSPORT IN MULTIPLE-MIRROR FIELD

The experimental sequence for GOL-NB supposes the initial filling of the central trap with the low-temperature start plasma. Then the start plasma will be heated by NBIs. The first task requires a good plasma flow transport efficiency from the arc plasma gun through one of the multiple-mirror sections. Plasma parameters correspond to “cold, dense” regime. In theory, multiple-mirrors should not decelerate and weaken the flow of a highly collisional plasma with $\lambda \ll 1$. However, this prediction had no solid experimental verification. In contrast, the plasma heating phase relies on the effective inhibition of plasma losses along the magnetic field in $\lambda \approx 1$ regime.

Before start of the device assembly, experiments with a prototype plasma source in the existing section of the magnetic system were done. The plasma stream with $n_e \sim (1-4) \times 10^{20} \text{ m}^{-3}$, $T_i \sim 1 \text{ eV}$ and $T_e \sim 3 - 10 \text{ eV}$ was successfully compressed by the converging magnetic field and transported through a 3-m-long vacuum system thus imitating the process of start plasma creation in GOL-NB. We found no significant differences of plasma properties in solenoidal ($B_{sol} = 0.6 - 4.5 \text{ T}$) [15] and multiple-mirror [16] configurations (the corrugation ratio and period were $R \approx 1.5$ and $l = 22 \text{ cm}$; field strength in maxima was the same as for the solenoidal

configuration). Fig. 3 shows the dynamics of the linear densities measured by a diagnostic neutral beam. In general, the same conclusion can be made from the data from high-resolution imaging spectroscopy.

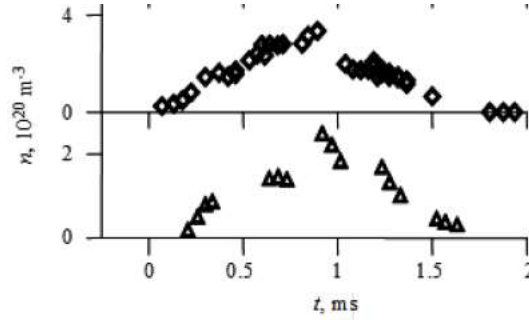


FIG. 3. Dynamics of density by DNBI attenuation at $z = 1.9$ m; electron densities at the axis in the uniform (diamonds) and multiple-mirror (triangles) configurations at $B_{sol} \approx 4$ T and $R \approx 18$.

Fig. 4 shows the dependence of the central density n_l (DNBI data) on the compression ratio. At low compression ratios $R < 10$, the plasma flow from the arc source passed through the system almost freely. At higher compression ratios, rarefaction of the stream in the compression zone was observed. The plasma diameter was almost independent on the compression ratio though it experienced large shot-to-shot spread.

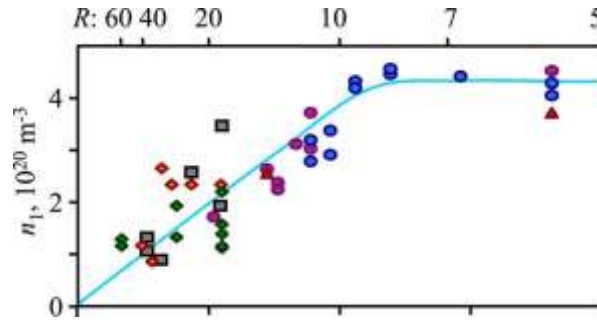


FIG. 4. Dynamics of density by DNBI attenuation at $z = 1.9$ m; electron densities at the axis in the uniform (diamonds) and multiple-mirror (triangles) configurations at $B_{sol} \approx 4$ T and $R \approx 18$.

4. DEMONSTRATION OF THE HELICAL CONFINEMENT

In the first experiments on helical confinement the magnetic corrugations moved oppositely the plasma flow. Two significant effects were expected in this case: flow suppression at the plasma periphery with higher magnetic corrugation along the field line, and radial plasma contraction [18]. Both of these effects lead to the radial contraction of the discharge.

An experiment with the opposite direction of the rotation was also performed to exclude an effect of the static multiple mirror confinement. Due to $v_z / v_{Ti} \sim 1$, the helical field component should not have influenced the flow significantly.

Main discharge parameters (Fig. 5a, 5b), plasma density, its shape, and visible spectrum of the plasma before helical mirror (Fig. 5e) do not depend on the presence of the helical component of the magnetic field. Density profile in the entrance expander also does not significantly change by the configuration of the magnetic field in helical plug (Fig. 6a).

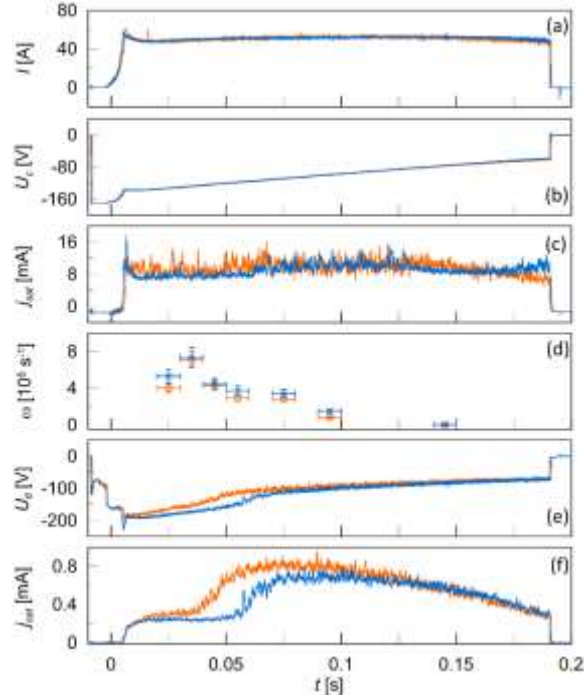


FIG. 5. Typical plasma parameters in shots without (SM1936, red color) and with (SM1937, blue color) the helical corrugation. From top to bottom:

- a) the plasma gun current,
- b) the voltage between the cathode and the anode,
- c) the ion saturation current of the Langmuir probe at the axis in the entrance tank at $z = 0.4$ m,
- d) the rotation velocity in the entrance tank,
- e) the potential of the central endplate,
- f) the ion saturation current of the Langmuir probe at the axis in the entrance tank at $z = 4.34$ m,
- g) the raw signal of the 50 GHz interferometer at $z = 3.48$ m.

Time $t = 0$ s corresponds to the discharge initiation by the hydrogen flow start.

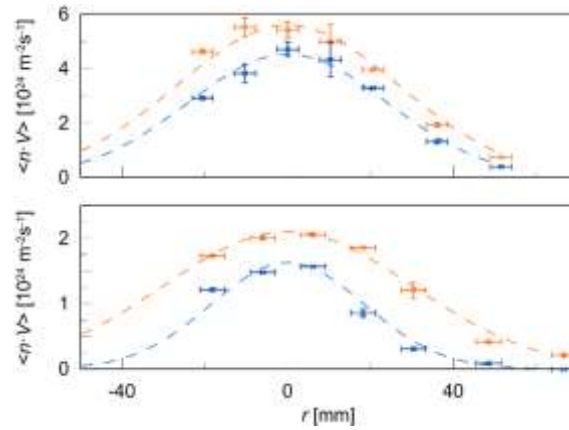


FIG. 6. Particle flux density profiles averaged for 0.07 – 0.1 s interval before (a) and after (b) the transport section are shown for configurations with (crosses) and without (circles) the helical field corrugation. Smooth lines are Gaussian fits. The radial scale was recalculated for a magnetic flux tube coordinates at the position of the interferometer.

At the same time, direct comparison of the experimental signals show significant difference between plasma parameters at the exit from the helical section with and without helical field (Fig. 5c, 5f, 5g) in quasi-stationary phase. Difference becomes negligible when rotation velocity drops to zero. We observed minor changes at the axis and significant decrease of the density in the periphery. This is consistent with theory predictions of the helical mirror confinement and inwards pinching. The plasma stream width at the half-maximum at the exit

from the helical mirror was 70 ± 5 mm in the solenoidal configuration, whereas it decreased to 43 ± 8 mm with the helical field in the deceleration regime – see Fig. 6(b). Changes of the plasma radius in the entrance tank were within the measurement accuracy (73 ± 4 mm vs. 66 ± 5 mm), albeit this difference is in the correct direction. One can note that the plasma radius in the magnetic flux coordinates increased by $\approx 13\%$ due to the transversal transport in the solenoidal configuration; on the contrary, the plasma radius decreased in the helical field by $\approx 30\%$. The interferometry data was averaged over ~ 25 discharges in each regime. Line averaged plasma density at the exit is suppressed by the factor of 1.25 compared to the regime with straight field lines.

In the series with the reversal of the magnetic field direction in all coils, the magnetic mirrors moved with the plasma flow at approximately the same velocity. No influence of the helical field was expected for our set of experimental parameters, exactly as we got from the experiment.

5. SUMMARY

The start configuration of the GOL-NB open trap started the first plasma campaign in the Budker INP. The trap is a low-cost scaled-down supporting experiment that should improve the knowledge base required for the next step fusion-grade GDMT project. It combines physics and technology from two different branches of open traps with a central section for gas-dynamic plasma confinement and two attached multiple-mirror solenoids that decrease particle and energy losses along the magnetic field. In general, the experiments confirmed the existing theory prediction on the availability of the used technique of the start plasma creation.

Experiments in the first plasma campaign in the SMOLA helical mirror trap evidently demonstrated the plasma flow suppression with activation of the helical winding in the flow reduction mode. The reported experiments were done at self-consistent floating potentials of all in-vessel electrodes without the controlled biasing (except for the plasma gun) and with the first-stage solenoidal winding, which has a large modulation of the magnetic field along the axis. In the current configuration, the axial modulation of the solenoidal magnetic field introduces some effects of the multiple-mirror confinement, which may slow down the plasma flow even without the helical component. This complicates the direct comparison of the reported experiment with theory predictions.

Even at these conditions, we observed two main effects predicted by theory: the decrease of the plasma flow through the transport section and its radial contraction. We expect stronger and more controllable effect in the final configuration of SMOLA. Integration of helical mirror sections into the existing GDMT project of the next-generation open trap should improve its equivalent fusion gain factor from $Q_{DT} = 0.25$ in the original project [5] to the approximately unity in the revised configuration that is currently under discussion in BINP. The required magnetic technologies for a reactor-grade system are less demanding than that already suggested for stellarator-based fusion plants.

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