Work Progress on GOL-NB Multiple-Mirror Trap

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I. INTRODUCTION

Recent advances in plasma parameters in axisymmetric mirror confinement systems have revived interest in reactor-scale projects of open traps. An open-trap-based fusion reactor can be made sensible if plasma losses through mirrors are significantly decreased. Special magnetic sections attached to a central confining core are usually considered for this purpose. Known technologies include multiple-mirrors, tandem mirrors, and helical mirrors. The current version of the conceptual next-generation GDMT project [1] use the multiple-mirror technology to increase the energy confinement time.

The GOL-NB project [2] is a technology demonstration experiment on multiple-mirror plasma confinement in the Budker Institute of Nuclear Physics, see Fig. 1. 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. The physical program and achievable plasma parameters were discussed in [3,4].

In this report, we present results of a preliminary experiment on start plasma transport through the multiple-mirror magnetic field and discuss the assembly status of GOL-NB.

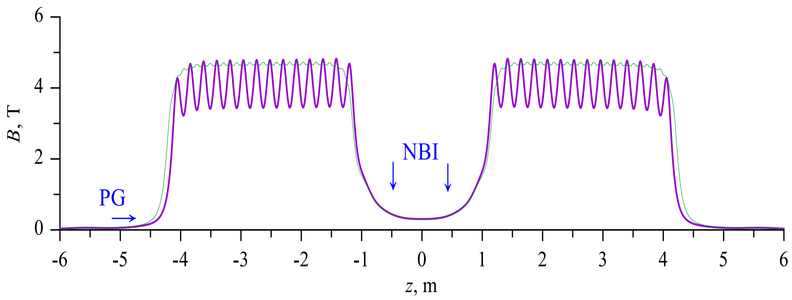

Fig. 1. Axial profile of the magnetic field in GOL-NB in the multiple-mirror (thick magenta line) and solenoidal (thin green line) configurations. Arrows show locations of the plasma gun (PG) and neutral beam injectors (NBI).

II. COLD PLASMA TRANSPORT IN MULTIPLE-MIRROR FIELD

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 [5,6].

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 $\lambda \ll l$. 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 $\lambda \approx l$ 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 $n_e \sim (1 - 4)\times10^{20}$ m^{-3}, $T_i \sim 1$ eV and $T_e \sim 3 - 10$ 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 ($B_{sol} = 0.6 - 4.5$ T) [7] and multiple-mirror [8] configurations (the corrugation ratio and period were $R \approx 1.5$ and $l = 22$ cm; field strength in maxima was the same as for the solenoidal configuration). Figure 2 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.

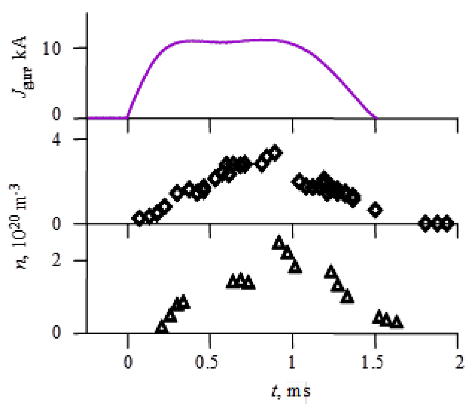

Fig. 2. Dynamics of density by DNBI attenuation at $z = 1.9$ m; the plasma gun current J_{gun} (top) and electron densities at the axis in the uniform (diamonds) and multiple-mirror (triangles) configurations at $B_{sol} \approx 4$ T and $R \approx 18$.

In general, the experiments confirmed the existing theory prediction on the availability of the used technique of the start plasma creation.

III. ASSEMBLY STATUS

The GOL-NB assembly schedule uses one of the engineering advantages of linear confinement systems. Fast start of commissioning of different subsystems and the first plasma can be achieved before readiness of the each component of magnetic and vacuum systems. Currently, the start configuration includes both expander tanks, an improved cold start plasma source, a multiple-mirror solenoid with 34 coils (instead of 2×28 coils in the final system), and a short temporary section for the on-site commissioning of NBIs – see Fig. 3. In contrast to the preliminary experiments discussed in Section II, the final version of the vacuum chamber was mounted. Two pumping modules provide the residual oil-free vacuum better than 10^{-4} Pa before the discharge initiation. The magnetic system presently operates at lower currents with $B_{\max}$ = 1.75 T due to limitation of the stray magnetic field strength in turbo pumps locations. Full magnetic field will be available after installation of magnetic shields to the pumps.

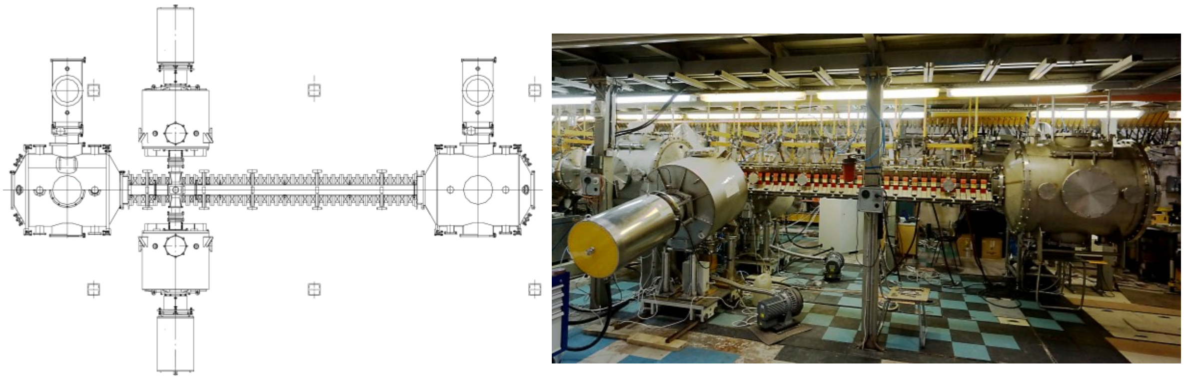

Fig. 3. Layout and photo of the start configuration for the commissioning of main subsystems. Spacing between the structural columns is 3 m.

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 high-field 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. Figure 4 shows typical waveforms from the discharge done with lowered magnetic field in the solenoid. 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 $nL \sim 10^{19}$ m^{-2} with the density at the axis $n_{(r=0)} > 10^{20}$ m^{-3}.

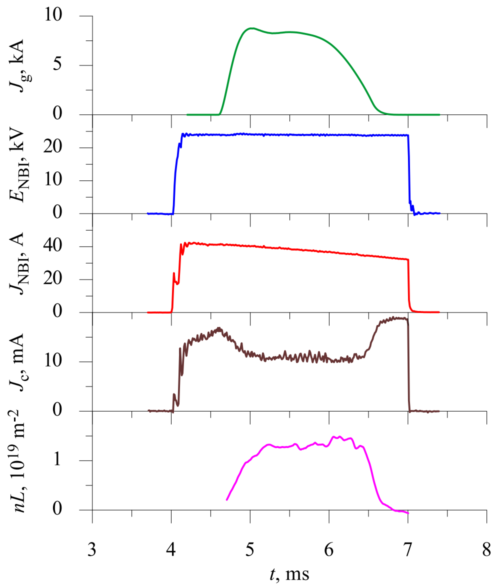

Fig. 4. Typical waveforms, top to bottom: plasma gun current, energy and current of the ion source in one neutral beam, current of a passing beam detector, calculated linear plasma density

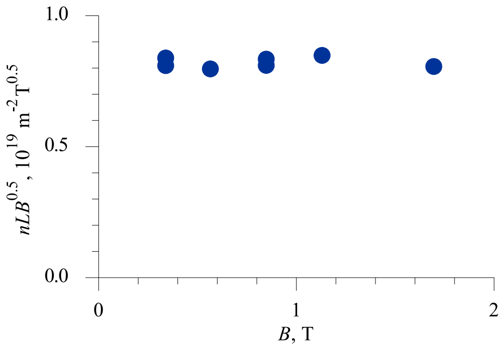

Fig. 5. Dependence of the plasma flow parameters on the magnetic field strength.

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 $z \sim 0.5$ m at least up to $B_{max} = 1.75$ T (see Fig. 5).

IV. SUMMARY

The start configuration of the GOL-NB open trap started the first plasma campaign in the Budker Institute of Nuclear Physics. 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. Success of the GOL-NB program will support the existing vision of a linear fusion reactor.

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