Start of Plasma Operations in GOL-NB with Central Trap

V. V. Postupaev, V. I. Batkin, A. V. Burdakov, V. S. Burmasov, I. A. Ivanov, K. N. Kuklin, N. A. Melnikov, K. I. Mekler, A. V. Nikishin, A. F. Rovenskikh, and E. N. Sidorov

Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia

Modern concepts of fusion-grade linear confinement systems involve the use of special magnetic sections with a multiple-mirror structure of the magnetic field for an improvement in axial confinement [1,2]. The multiple-mirror magnetic field improves the confinement due to the friction force arising from collisions of transiting and locally-trapped particle populations in every elementary mirror cell [3-5]; a recent review paper can be found in [6].

The GOL-NB device [7,8] is a moderate-scale linear confinement system (open trap) that combines a central gasdynamic trap with two attached multiple-mirror sections and two end magnetic flux expanders – Fig. 1. The main physical task of the experiment is to validate the theory predictions on the confinement improvement with the activation of the multiple-mirror sections in regimes with moderate collisionality. Other goals are to demonstrate effective plasma stabilization methods in the non-*min-B* magnetic configuration and to find an experimental technique that will extend good multiple-mirror confinement into the low-collisionality domain. Modular design of GOL-NB enabled early start of experiments in a reduced configuration. The goal of the first plasma campaign was the direct comparison of propagation of $(0.1 - 2)\times10^{20}$ m^{-3}, 4-6 eV start plasma from an arc gun through the high-field section. We confirmed the theory prediction that collisional plasma propagates similarly in solenoidal and multiple-mirror regimes [9].

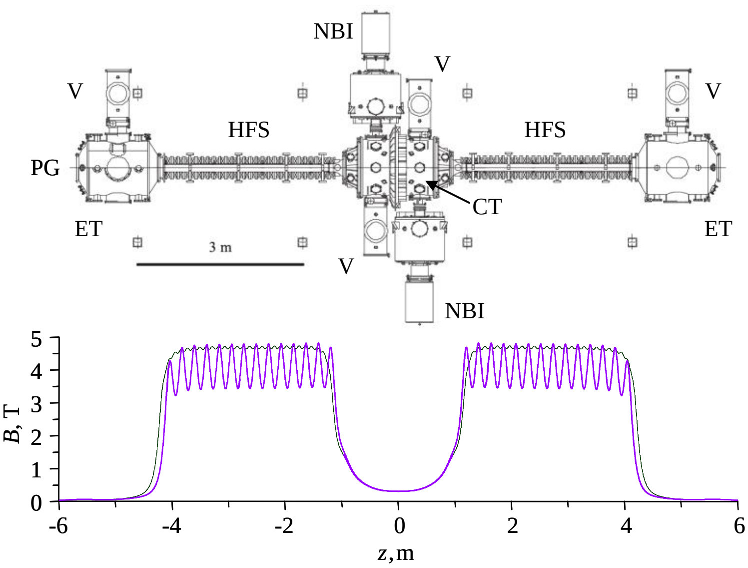

Fig. 1. The layout of GOL-NB (top view) and profiles of magnetic induction in the solenoidal (thin line) and in the multiple-mirror (thick line) configurations. CT: the central gasdynamic trap, HFS: the high-field section, ET: the tank of the magnetic flux expander, PG: the plasma gun, V: a vacuum pumping module, NBI: the neutral beam injector.

A major upgrade of the device began in February 2020. The main central module that is a 2.5-m-long gasdynamic trap with the mirror ratio up to R = 15 was

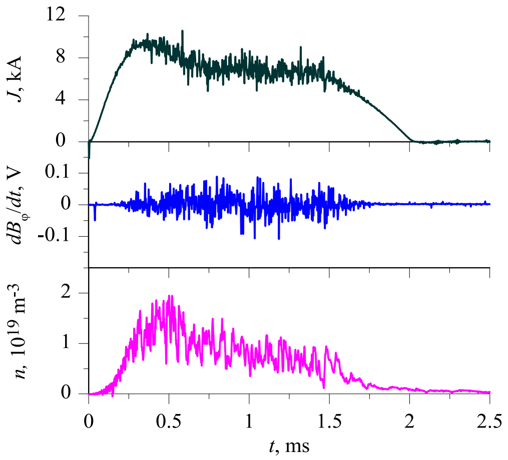

Fig. 2. Dynamics of the plasma flow before entering the central trap, top to bottom: the plasma gun current, signal of a Mirnov coil, density from a Langmuir probe measurements at $r = 0.5$ cm.

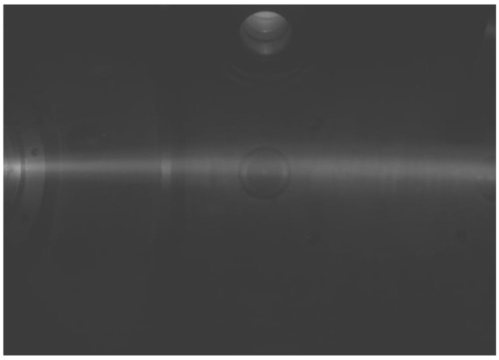

Fig. 3. Photo of the start plasma in the central trap.

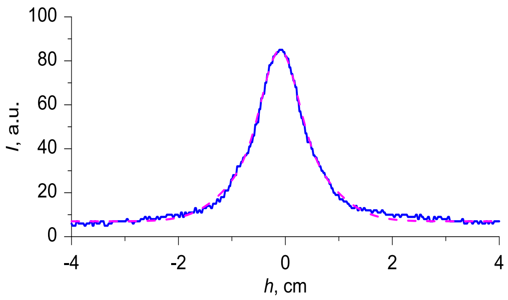

Fig. 4. Profile of the plasma brightness in the central trap for the experiment shown in Fig. 3. The solid line is the experiment, the dashed line is a bi-gaussian fit with a background due to reflections from walls, *h* is chord radius.

installed. Two 0.75 MW, 25 keV neutral beams were relocated to their design positions. The first experiments in the design configuration were aimed at understanding of the device performance and integrated commissioning. We achieved the design values of the magnetic field and vacuum.

Figure 2 shows dynamics of a typical discharge with a Langmuir probe located close to the central trap. Comparing with the previous results from the start configuration of GOL-NB [9], magnetic induction in the high-field sections was increased from 1.8 T to the nominal value of 4.5 T. Correspondingly, the plasma stream decreased in diameter. The ratio of magnetic induction at the anode of the plasma gun to that in the high-field section was about 1:100. This regime is not the optimal one in the terms of the noise in the plasma gun discharge and in the overall particle flow into the central trap; this high-compression-ratio mode of operation interested us as the way to observe a possible cross-field expansion of the plasma flow.

The image and the brightness profile of the stat plasma in the central trap are shown in Figs. 3 and 4. Preliminary Langmuir probe measurements demonstrated the expected asymmetry of the plasma flow before and after the central trap (Fig. 5). Currently, only limited experimental series with plasma was done with an insufficient accuracy of the profiles measurements. In general, images from different parts of GOL-NB (Figs 3 and 6) show no significant plasma broadening comparing to the expected flow along the magnetic field lines, though some changes in the profiles are observed.

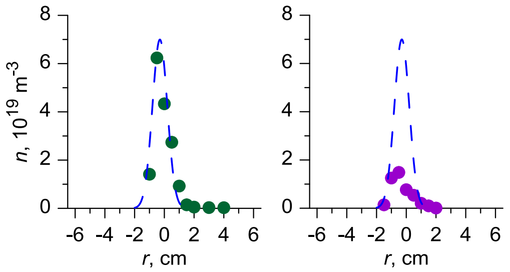

Fig. 5. Density profiles from Langmuir probes at the discharge flattop before (left) and after (right) the central trap. Dashed Gaussian curves are the same for both panels.

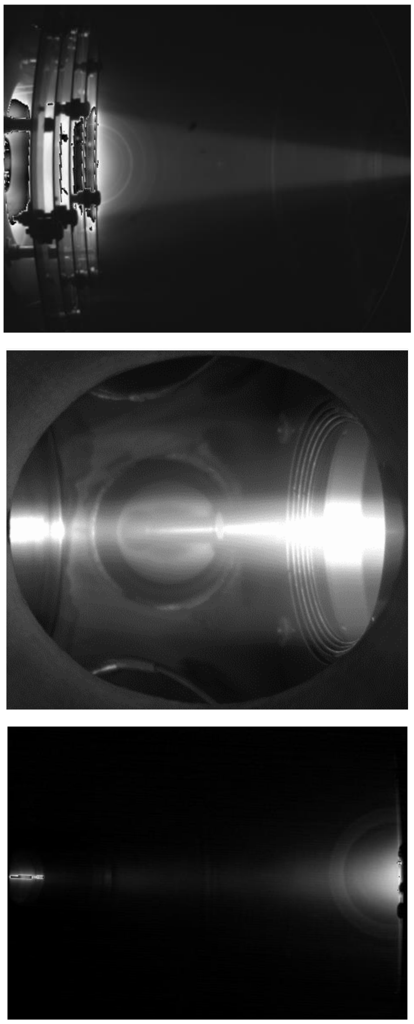

Fig. 6. Plasma images: (top) the plasma gun, endplates and converging plasma flow before entering the high-field section; (middle) exit from the high-field section into the central trap with limiters; (bottom) flow to the exit receiver in the right magnetic expander. Light reflections from walls contribute to image brightness.

Currently, plasma diameter is less than diameters of limiters installed in the central trap and in both expander tanks. Each limiter is a multiple-electrode system (see the middle part of Fig. 6) that can be biased to apply electric potential to the plasma periphery. We expect that with the neutral beams heating, plasma will expand in diameter due to large Larmor radii of fast ions.

The most important physical challenge for GOL-NB is reaching the MHD stability of plasma. Sections with a multiple-mirror magnetic field are suggested for a significant reduction of the longitudinal losses of particles and energy from a central trap. However, these sections simultaneously disable the classical plasma stabilization method by "average minimum *B*" [10] due to the small contribution of stabilizing end elements to the stability integral. Therefore, application of other stabilization methods (see the review [11]) is required. The magnetic configuration of GOL-NB is MHD unstable because of the "magnetic hill" at the axis.

A typical scenario of the GOL-NB includes the initial filling of the central trap by the start plasma, the confinement of NBI-heated plasma and the transition between them. Two major differences should be mentioned. The first one is the difference in radial plasma sizes; in the confinement phase, plasma diameter will expand to limiters. The second difference is the electric connection to the endplates that must be broken at the confinement stage in order to suppress classical electron thermal conductivity to the endplates (see [12] for details). The stabilization of the low-temperature start plasma will be provided by the line-tying into the hot cathode of the plasma gun and by the creation of differential plasma rotation by biased plasma receivers and other in-vessel electrodes. The first results of preliminary experiments on the GOL-NB start configuration [9] showed that transportation efficiency of a plasma flow through a long high-field section depends on potentials of the in-vessel electrodes. At the confinement phase, a so-called “vortex confinement” technique [13] will be used. This method worked at a relative plasma pressure of β = 60% in GDT experiments [14]. The technology uses the effects of finite Larmor radius, therefore it can be effective for a reasonably heated plasma. One more option for improving the plasma stability is a magnetic shear that can be created by axial currents between differently-biased symmetric electrodes. Due to topological differences, magnetic shear in an open trap is less effective than in tokamaks, but it still can stabilize plasma (like in [15]). The task of ensuring stability at all stages of the experiment, including the transition from a low-temperature start plasma to the heating stage, seems feasible.

The summary for the paper is the following. The GOL-NB device that combines a central gasdynamic trap for plasma confinement and multiple-mirror sections that should suppress particle and energy losses along the magnetic field was completed. The nominal parameters of the magnetic system were achieved. The start plasma flow was successfully transported from the arc plasma gun to the opposite receiver endplates.

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