STATUS OF ACTIVITY ON THE GOL-NB MULTIPLE-MIRROR EXPERIMENT

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Abstract

A multiple-mirror confinement is an alternative concept in the fusion energy development that improves particle and energy confinement time in open traps (linear magnetic systems). The paper discusses the progress of the GOL-3 multiple-mirror experiment since the 27th IAEA Fusion Energy Conference (Ahmedabad, India, 2018). The first main topic is the study of the transport of cold collisional start plasma along the magnetic system in the cases of uniform and multiple-mirror magnetic field. The second topic is the completion of the device assembly in the full design configuration and start of the integrated commissioning in the beginning 2021. Features of the experimental device and the start set of diagnostics are also presented. In general, the on-going commissioning progress and results of the preliminary experiments in the start configuration are optimistic for the expected device performance.

1. INTRODUCTION

The paper presents current results from the GOL-NB experiment [1] that is a part of broader activities on developing the physics basis for a next-generation sub-fusion-grade GDMT linear confinement system [2,3] in the Budker Institute of Nuclear Physics. The current understanding of physics of open confinement systems requires a significant improvement of the longitudinal energy confinement time over the usual scalings in order to achieve reactor parameters. In the GDMT project, this will be done with special multiple-mirror magnetic sections that should decrease energy and particle losses from a central gasdynamic trap where the main plasma will be confined. The GOL-NB experiment is a low-cost device that includes all the main physical elements of the larger project. The multiple-mirror confinement idea was introduced quite long ago in [4,5] as the method of suppression of the longitudinal plasma expansion by a multiple-mirror magnetic field. The magnetic system features periodical change in the magnetic induction along the device axis that makes the plasma boundary corrugated – see Fig. 1. The system can be considered as many individual axisymmetric magnetic mirror traps joined in their high-field parts.

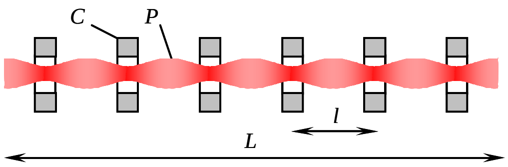

FIG. 1. A multiple-mirror confinement system: C – magnetic coils, P – plasma, L – full system length, l – elementary mirror cell length. Color intensity of the plasma surface indicates the local magnetic field strength.

The confinement physics is simple. There are three spatial scales: the elementary mirror cell length l, the total system length L and the ion free path length λ. The total number of the corrugation periods is evidently $N = L / l >> 1$. Two particle populations exist in each elementary mirror cell, the trapped and transiting ones. The collisional friction between the transiting and locally-trapped particle populations transfers momentum from the plasma flow to the magnetic field and therefore slows down the flow. The similar process is known for tokamaks where the toroidal plasma rotation slows down due to bulk plasma interaction with particles trapped in ripples of the toroidal field [6]. The multiple-mirror technique is effective at moderate collisionality $\lambda \approx l$. One can introduce the merit factor K as the increase in the particle confinement time τ comparing to a simple solenoid of the same length. In the case of medium magnetic corrugation $R - 1 = B_{max}/B_{min} - 1 \sim 1$ and moderate collisionality $\lambda \approx l$, the merit factor can be estimated as $K \approx L / \lambda = N >> 1$ [7]. This means, that τ scales quadratically with the multiple-mirror system length. The multiple-mirror confinement relies on collisions and particle scattering. Therefore, an additional scattering of particles in turbulent fields can even improve the longitudinal confinement in the rare-hot part of the parameter space. A recent review of achievements in the multiple-mirror confinement physics and technology can be found in [8].

The GOL-NB experiment is the successor of the highly productive GOL-3 multiple-mirror experiment in the Budker Institute of Nuclear Physics, which demonstrated the expected confinement improvement of turbulent sub-fusion plasma [9]. The GOL-3 device was a “brute force” experiment where plasma of $n_e \sim 10^{21}$ m^{-3} was collectively heated up to several keV with a high-power relativistic electron beam (~1 MeV, ~30 kA, ~10 μs). Due to short beam duration and primary significance of collective processes, the GOL-3 experiment lacked the ability to clearly isolate the multiple-mirror physics from other processes. Therefore, the major modification of the device with a completely new physical program was suggested in [10]. In the new GOL-NB experiment, a gasdynamic central trap is added in the middle of the multiple-mirror solenoid, the neutral beams injection (NBI) is the main plasma heating technique, the plasma lasts for several milliseconds that is enough for reaching the quasistationary state. The GOL-NB project relies on classical physics based on binary particles collisions that should make studies of multiple-mirror scalings simpler.

The development path of the GOL-NB experiment demonstrated one of the engineering advantages of open traps (linear confinement systems). The device has modular design of the magnetic system that allows early start of plasma operations in the reduced configuration and following gradual increase of the device capabilities with newly-installed modules. We started with a 6-meter solenoid with the old vacuum chamber from GOL-3 and a prototype plasma gun for initial checks of the accessibility of the required parameters range in [11]. Then two end tanks of magnetic flux expanders with the final plasma source and several sets of in-vessel electrodes were added. The vacuum chamber was also replaced with the design one. In this configuration, the propagation of start plasma through the high-field section was studied [12]. Additionally, both neutral beam injectors were mounted to temporary ports for the initial commissioning. One of the beams was used as the diagnostic tool for the line-integrated density measurements. Finally, we finished the device assembly in the design configuration in 2020. The central trap was installed; the NBIs were relocated to the design ports in it. During this development path, the “first plasma” event was passed three times after the major configuration changes.

In the next Section, we describe the GOL-NB multiple-mirror trap and start set of diagnostics. Then, the final results from the start configuration will be discussed. The next Section is about the status of operations with the final configuration of GOL-NB. The paper finishes with a brief discussion and summary.

2. EXPERIMENTAL DEVICE AND DIAGNOSTICS

The GOL-NB experiment was designed as the device that should directly demonstrate the confinement properties of a multiple-mirror magnetic system. This task requires the capability of operation in three different magnetic configurations: as a classical gasdynamic trap with short magnetic mirrors of the length $l_m \ll \lambda$, as a trap with long mirrors $l_m = L \gg \lambda$ where plasma particles will experience collisions and partial backscattering in the high-field sections, and finally as a multiple-mirror system. The free path length λ is the key plasma property here that defines the required parameter space. The theory predicts the best multiple-mirror effect at moderate collisionality near $\lambda \approx l$ [7]; this regime was chosen for the reference experimental scenario. The device was designed with relatively small mirror ratio in the central trap, $R_c = B_{max}/B_c = 15$. This makes the longitudinal confinement bad with large axial particle and energy losses. Simultaneously, the same bad axial confinement should make other losses channels less significant in the energy balance. Therefore, effects of the activation of the multiple-mirror configuration should be observable. Simulations with 1-D kinetic code DOL predict that at $n = 3\times10^{19}$ m^{-3} and NBI power of 1.5 MW, plasma will be heated up to ~30 eV in the pure gasdynamic regime [13]. The multiple-mirror sections should reduce the longitudinal particle losses thus reducing the energy losses and shifting the quasistationary plasma pressure to higher value with the same heating power.

The experimental device was built with some technical compromises. We reused a part of the existing infrastructure of our previous GOL-3 facility and its magnetic coils (now used as coils for the high-field sections). This practically limits the available magnetic induction at 4.5 – 4.8 T and the total plasma duration at about 5 ms. The NBI injection energy is 25 keV that requires at least 0.3 T in the midplane for the reasonable Larmor radii of fast ions. Due to limitations set by the existing mechanical support structures, the injection angle was set to 90°. This decreased the beam capture efficiency comparing with the GDT experiment with oblique injection [14].

2.1. General description of GOL-NB

Figure 2 shows the general layout of GOL-NB and profiles of magnetic induction in the solenoidal and in the multiple-mirror configurations [1]. The GOL-NB device includes the central gasdynamic trap of about 2.5 m long, two high-field multiple-mirror sections mounted laterally to it, and two end magnetic flux expanders. Each of the multiple-mirror sections can generate either the uniform solenoidal field with $B = 4.5$ T or the multiple-mirror field with the same maximal induction, 13 corrugation periods of 22 cm length and corrugation depth 1.4. A typical experimental scenario will be the following. A low-temperature start plasma of $n = 10^{19}$ - 10^{20} m^{-3},

$T \approx 5$ eV will be created by an arc plasma gun located in the low-field part of one of the expanders. The plasma flow will pass through the first high-field section and fill the central trap. Then plasma will be heated in the central trap by two 25 keV, 0.75 MW neutral beams. Our preliminary simulations had shown that in the pure gasdynamic operation mode, plasma temperature will weakly depend on its density due to partial absorption of the beams power [13]. Plasma stability will be provided by the line-tying to the plasma gun during the initial filling stage and by the so-called vortex confinement technique [15] during the heating.

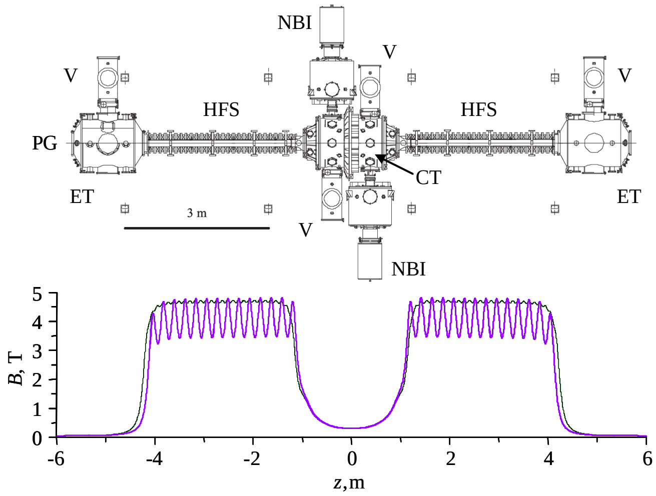

FIG. 2. The layout of GOL-NB (top view) and profiles of magnetic induction in the solenoidal configuration (thin line) and in the multiple-mirror regime (thick line). Labels are: CT – the central gasdynamic trap, HFS – the high-field section, ET – the tank of the magnetic flux expander, PG – the plasma gun, V – a vacuum pumping module, NBI – the neutral beam injector. Locations of structural columns are shown.

2.2. Magnetic system and power supply

The magnetic system of GOL-NB consists of three functional groups of coils. Each of the high-field sections includes 28 coils [16] with 15.6 cm bore made of unannealed copper tape. The coils are spaced by 11 cm. All coils are powered in the solenoidal regime. In this case, the field ripples at the axis are about 5%. Switching to the multiple-mirror regime requires manual reconfiguration of feeder cables. In this regime, only odd coils are powered and modulation of the magnetic field at the axis becomes 40% with the corrugation period of 22 cm – see Fig. 2. In order to obtain the required induction, the current density in the multiple-mirror regime is up to 250 A/mm^2. The field in the central trap is formed with a set of 5 coils that are attached directly to the vacuum vessel. The largest central coil has 1.3 m inner diameter. The accuracy of the magnetic field is provided by the proper tolerances of the central trap fabrication. The reference magnetic configuration is with the $B_c = 0.3$ T in the midplane. The field in the central trap can be increased up to 0.6 T in the backup scenario. With the latter option, the Larmor radii of fast ions will be smaller and (due to higher field) thresholds of some hot-ion instabilities will be higher, but simultaneously the mirror ratio decreases by half thus doubling the axial losses.

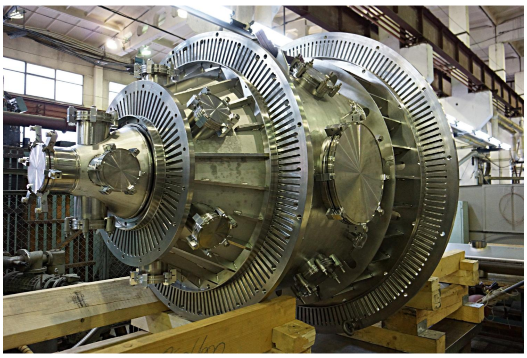

FIG. 3. The vacuum vessel of the central trap during the factory vacuum leak inspection.

Magnetic systems of the end magnetic expanders consist of four coils each. With those coils, we can control the magnetic expansion/compression ratio at the plasma receiver endplates, and additionally the shape of the plasma boundary near the last high-field coil where limiters are mounted at both sides. All coils are powered from a 6 kV sectioned capacitor battery with the total stored energy up to 12.5 MJ [17]. The duration of the current in different coils varies from 25 to 90 ms, depending on their inductances and number of capacitors in the connected section of the battery. At such timescales, induced eddy currents significantly change the magnetic field inside the vacuum vessels of the central trap and expanders. Grooves were milled on the coils-mounting flanges to decrease this effect – see Fig. 3. An additional magnetic shielding was provided to turbomolecular pumps, NBIs, and some other hardware because of large magnetic field outside the device.

2.3. Vacuum system

The largest parts of the vacuum system are the central trap and the end expanders tanks that have 1 m inner diameters. The central trap carries full mechanical load from the magnetic coils. The aperture of the vacuum chamber in the high-field section is 13 cm; it is limited by apertures of the high-field coils. This chamber is loaded by the atmospheric pressure only; all mechanical forces are taken by the high-field solenoid itself. GOL-NB has ISO K/KF flanges for several reasons, including the requirement to minimize the volume of conductive materials in the vicinity of pulsed magnetic coils. All main vacuum components (except for electrodes contacting with plasma) are made of 12X18H10T non-magnetic stainless steel (close analog of AISI 321). The pumping is provided with four pumping modules, that are attached to the central trap opposite NBIs and to both expander tanks (see Fig. 2). Every module is a self-sufficient unit with 3000 l/s turbomolecular pump backed with an oil-free scroll pump. The real pumping speed of the module measured with pulsed hydrogen injection into the expander tank is above 2500 l/s. Initial vacuum in the system between shots is better than 10^{-4} Pa. The walls are conditioned daily in several discharges of the plasma gun before the main experimental series. Currently, no additional high-pumping-speed systems are installed for neutrals density control during the plasma heating phase, although several options are discussed.

2.4. Start plasma creation system

The first step in the experimental scenario is filling the central trap with low-temperature start plasma generated by the plasma gun that has integrated design with one of the plasma receivers – see Fig. 4 [12]. The gun is an arc source of a washer stack type that was modified comparing with the prototype currently used in the GDT experiment [18]. The hollow cathode, the anode and “floating” washers are made of molybdenum. The gun is powered from a forming line charged typically to 2.5 – 3.5 kV. The discharge current of 2 ms duration can be varied within 6 – 15 kA, depending on the gas feed and the required plasma stream parameters. The gun operates in 0.1 – 0.2 T field that is created either by the magnetic system of GOL-NB or by two own coils used in standalone operations. After exiting the gun, the plasma stream is injected into the high-field section. During this magnetic compression, the plasma flux expectably decreases as $\Phi(z) = \Phi(0)\times(B(0)/B(z))^{1/2}$ [12].

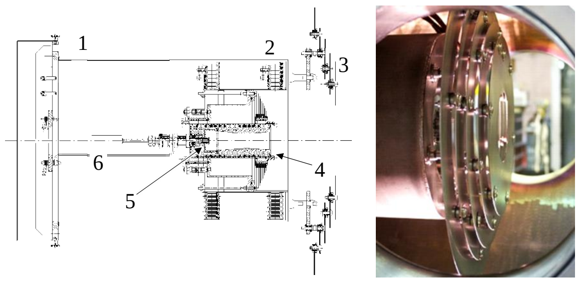

FIG. 4. Left: layout of the plasma gun with the sectioned endplates installed, 1 – vacuum case, 2 – coils for local magnetic field, 3 – five-electrode plasma receiver, 4 – plasma gun anode, 5 – plasma gun cathode, 6 – gas valve. Right: photo of this unit inside the expander tank.

2.5. Neutral beam injectors

Plasma will be heated by two NBIs that will provide 1.5 MW combined at 25 keV [19]. The beams pulse duration can be up to 5 ms. In the commissioning with the start configuration of GOL-NB, the NBIs demonstrated the design performance of ion sources [12]. One beam was used for line-integrated density measurements. Now the beams were moved to the design positions and attached to the central trap. An additional magnetic shielding was installed. The beams performance optimization in these conditions started.

2.6. Internal electrodes

Several systems of in-vessel electrodes are installed, including two plasma receivers (endplates), four circular limiters and protective electrodes mounted on the outer shell of the plasma gun. The plasma receivers are five-electrode assemblies installed in the middle of the expander tanks; one of them is integrated with the plasma gun (Fig. 4). The limiters are assemblies of a main central electrode that sets the plasma boundary, and five arcing-prevention electrodes with increasing apertures from each side. The limiters are placed near the mirrors in the central trap outside the reflection points of fast beam ions and in the expander tanks in the decreasing magnetic field. All electrodes in contact with the plasma are made of molybdenum and can be biased up to 500 V. This gives us the flexibility to control the differential $E{\times}B$ plasma rotation and radial distribution of axial currents.

2.7. Diagnostics and data acquisition

Up to date, a limited set of diagnostics was available for studies of the start plasma properties. The main instruments were movable four-electrode asymmetric Langmuir probes [12] that provided data on ion density, electron temperature and radial electric field. The line-integrated density was measured by attenuation of the neutral beam. Several PMM-46-based vacuum sensors provided data on the gas pressure dynamics with ~0.5 ms temporal resolution. Additional diagnostics are X-ray-to-near-infrared FDUK-100UV photodiodes, broadband and narrowband visible spectrometry, several fast single-frame and video cameras, a Mirnov probe, *etc*. Currently, several new systems are under development. The neutral beams are relocated to the central trap, so a 10-keV diagnostic NBI will be installed in the exit high-field section (the right one in Fig. 2). The existing power supply of this beam provides 0.5 ms pulses; an upgrade to full plasma duration is planned. The magnetic diagnostics will be expanded with arrays of Mirnov coils in the high-field sections and azimuthal and axial two-coordinate arrays in the central trap. A 10.6 μm Michelson interferometer for density measurements in the entrance high-field section (the left one in Fig. 2) is in the assembly and adjustment phase.

A major new diagnostical system will be a two-part CXRS spectroscopy that will analyze H_α line emitted at 45° from the neutral beams charge-exchange zone. The first part of this system will use the MDR-12 grating spectrometer with fast CCD camera. It will observe the spatial distribution of H_α emission. The camera will simultaneously record a central core of the line emitted by neutralized ions of bulk plasma, Doppler-broadened wings emitted by neutralized fast ions and Doppler-shifted line emitted by the injected beam atoms. The second part of CXRS system is a fast CCD camera with a high-contrast interference filter with $\Delta\lambda_{1/2} = 3.5$ nm transmission window. This camera will observe the spatial evolution of H_α emission near the turning plane of fast ions. Joint operation of both systems will allow studies of processes of fast ions accumulation and bulk plasma heating.

A neutral particle analyzer (NPA) is intended for measurement of the energy distribution of fast ions confined in the central trap. Its design replicates schemes of the analyzers previously built for MST and C-2 facilities [20] except for the option of mass separation of detected ions. Incoming neutrals get ionized in the solid 10-nm-thick stripping foil, then accelerated by electric field, passed through a bending magnet and counted by a linear detector array. The soft iron vacuum case shields from stray magnetic field. The analyzer is equipped by Bayard-Alpert type ion source for on-site calibration and checking of the foil consistency. Fifteen detection channels cover the energy range of fast protons from 2 up to 25 keV with the energy resolution about 15%. The analyzer will be mounted at 90° in the same plane with NBI; it can be tilted lengthwise and crosswise magnetic field lines for studies of the radial distribution and angular spread of fast ions confined in the facility.

The timings and data acquisition are provided by hardware and software that are migrated from our previous GOL-3 experiment [21] except for several systems that has their own microprocessor-based controls.

3. RESULTS OF FINAL EXPERIMENTS IN THE START CONFIGURATION OF GOL-NB

The experimental scenario described in Section 2.1 strongly relies on one specific feature of the multiple-mirror confinement. The theory predicts [7] that sections with the corrugated magnetic field will not significantly slow down transport of the cold start plasma thus enabling the initial population of the central trap from a plasma source located at the end of the magnetic system. Despite the evident prediction, no direct experimental results were previously published for a collisional plasma flow in a multiple-mirror system. Therefore, one of the first steps in the physical program of GOL-NB was to study the process of the start plasma propagation in the high-field section. This was initially done in a transitional configuration in [22] and then the detailed studies were continued in the so-called start configuration of GOL-NB, which is shown in Fig. 5. The system uses both expander tanks *1* and *7*, the full-size right high-field section *6*, a short left high-field section *3*, and a short temporary section *5* for NBIs attachment. The total length of the high-field solenoid was about 4 m. The magnetic shields were not yet ready, therefore the magnetic induction was decreased to 50% of the nominal one.

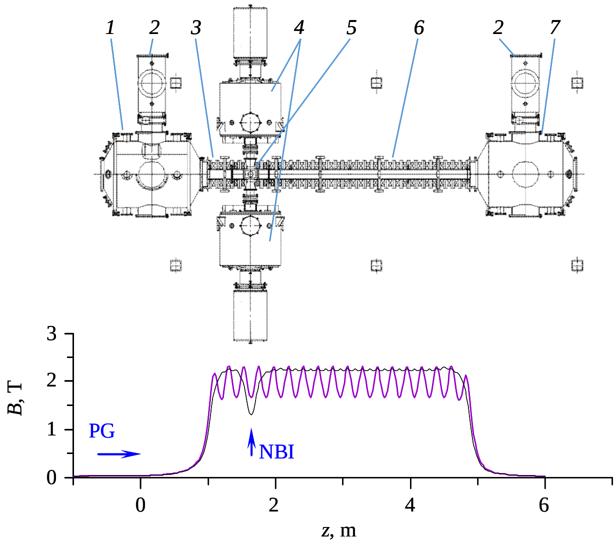

FIG. 5. Layout of the start configuration of GOL-NB (top) and the axial profile of the magnetic induction: 1 – magnetic expander with the plasma gun, 2 – pumping units, 3 – short high-field section, 4 – NBIs, 5 – temporary section for NBI attachment, 6 – standard high-field section, 7 – exit magnetic expander with the plasma receiver endplates. Solenoidal and multiple-mirror regimes of operation are shown by thin and thick lines, respectively.

In [12] we demonstrated that start plasma propagation occurs similarly in solenoidal and multiple-mirror configurations. The efficiency of plasma transport strongly depended on configuration and biasing of in-vessel limiters and plasma receiver endplates. However, plasma significantly decayed to the end of the high-field section comparing with the density at the entrance to it. In the last experimental session, we confirmed those probe data with the diagnostic neutral beam, which was mounted at the coordinate z = 4.4 m – see Fig. 6. The reason for plasma decay during its transport along the system was identified; it was mainly caused by hydrogen gas that was trapped by the plasma stream in the plasma gun area and then moved with the plasma through the system. An optimization of the plasma gun operation regime and triggering sequence improved the density at the exit of the high-field section. After that, works on the device assembly in the design configuration started.

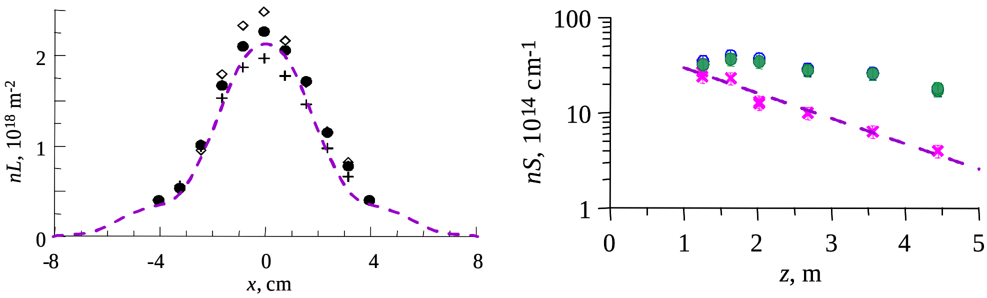

FIG. 6. Left: dependence of the line-integrated density nL on the chord radius x from DNBI data (three shots are shown by different symbols) compared with a fit of the Langmuir probe data (shown by the dashed line). Right: dependence of number of ions per unit length on the axial coordinate before (crosses and exponential fit [12]) and after (dots) optimization of the plasma gun operation regime in the multiple-mirror configuration.

4. STATUS OF THE FULL-SCALE GOL-NB ASSEMBLY

The assembly of GOL-NB in the design configuration shown in Fig. 2 is completed. Both NBIs and all four pumping modules are attached to the facility with the additional magnetic shielding installed. The magnetic system was tested at the nominal field. All in-vessel electrodes are installed. First integrated commissioning experiments passed successfully. The start plasma passed from the plasma gun to the central trap (Fig. 7) and then with decreased density – to the exit expander with the end receiver. The NBIs conditioning started.

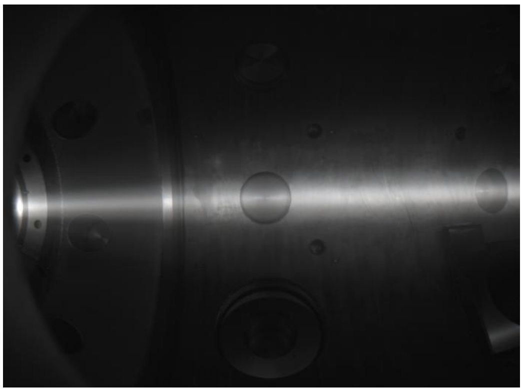

FIG. 7. The start plasma in the central trap.

In general, the GOL-NB multiple-mirror trap is ready for the beginning of its scientific program. Several first experimental sessions will be mostly technical in order to learn the best operation regimes and perform necessary checks and calibrations of diagnostics. The first major physical challenge will be reaching the stable plasma transition from the initial low-temperature state to the beam-heated state. The axisymmetric magnetic system of GOL-NB does not satisfy the well-known Rosenbluth-Longmire “minimum *B*” MHD stability criterion. Therefore, additional stabilization techniques will be required. Several possible methods are known for axisymmetric mirror devices [23], some of them will be tested in GOL-NB. The second problem is the density control. Simulations [13] predicted that a gas feed at the rate of 1 – 2 equivalent kA will be required to reach stable density. The gas will be injected near the limiters in the central trap. Currently, a real efficiency of ionization of this gas by the plasma flow escaping the trap and the gas flux into the confinement zone are problems that should be solved experimentally taking the real-life gas desorption from the walls into account.

5. DISCUSSION AND SUMMARY

The main scientific task of GOL-NB is the direct demonstration of plasma parameters improvement in the central trap at activation of the multiple-mirror configuration of the high-field sections. This is the first device with the magnetic system that includes the central trap for plasma confinement and two attached multiple-mirror sections for improving the energy and particle confinement. The assembly of GOL-NB is completed; the device is ready for the experiments. With the start configuration of GOL-NB, we confirmed the theory prediction on low influence of a corrugated magnetic field on propagation of highly-collisional plasma flow.

GOL-NB is the representative of classical multiple-mirror configurations, which provide slowing down plasma expansion along the axis due to momentum transfer at collisional interaction of transiting and locally-trapped populations. Recently, an old idea of active multiple-mirror confinement was reconsidered in two different approaches: with moving magnetic mirrors [24] and with rotating plasma in a helical mirror configuration [25,26]. Modular design of GOL-NB allows incorporation of an active section of a limited length into the magnetic structure that will expand the device capabilities when the main scientific goal will be achieved first. Other possible ways of improving plasma parameters are auxiliary heating systems and an upgrade of the multiple-mirror sections. Currently, we reused coils from the GOL-3 solenoid, which limits us in the magnetic induction and fixes the mirror ratio. Both higher magnetic field in mirrors and larger mirror ratio should improve the efficiency of the system at the fixed length and fixed number of corrugation periods. The next important problem relevant to fusion reactors is a possibility of an effective confinement in low collisionality regimes. The solution here can be related to an active forcing of an enhanced ion scattering in cells of a multiple-mirror system. All the ideas listed in this paragraph are currently being discussed, but no decision has been taken on them.

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