# Status of GOL-NB Project

V. V. Postupaev[1, 2, a)], V. I. Batkin[1, 2], A. D. Beklemishev[1, 2], A. V. Burdakov[1, 3],
V. S. Burmasov[1, 2], I. S. Chernoshtanov[1, 2], A. I. Gorbovsky[1], I. A. Ivanov[1, 2],
K. N. Kuklin[1], K. I. Mekler[1], A. F. Rovenskikh[1], E. N. Sidorov[1] and D. V. Yurov[1]

[1]*Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia*
[2]*Novosibirsk State University, 630090 Novosibirsk, Russia*
[3]*Novosibirsk State Technical University, 630092 Novosibirsk, Russia*

a)Corresponding author: V.V.Postupaev@inp.nsk.su

**Abstract.** Overview of the activity on the development of the new multiple-mirror trap GOL-NB to be built in Budker Institute will be presented. This device to be build in BINP in several years as a deep conversion of the existing GOL-3 facility. The device will consist of a central trap with two 0.75 MW neutral beams, two multiple-mirror solenoids, two expander tanks and a plasma gun that creates start plasma. Plasma will be NBI-heated and confined in the central trap that is essentially a compact version of the GDT device with the well-known physics. The multiple-mirror sections should decrease the power and particle losses along the magnetic field. The main physical task of GOL-NB is the direct performance demonstration of the multiple-mirror sections that will change the escaping plasma flow and equilibrium plasma parameters in the central trap depending on the magnetic configuration chosen. In this paper, we will discuss new results in scenario modeling and progress in the hardware, including neutral beam injection system and start plasma source. First experiments on transport of a $(1-4)\times10^{20}$ m$^{-3}$ cold plasma stream through the 3-meter-long solenoids with 0.5 – 4.5 T field are already completed thus demonstrating the performance of start plasma creation system..

## INTRODUCTION

The progress in the development of the GOL-NB multiple-mirror trap is discussed. This device will be created in BINP in several years as a deep conversion of the existing GOL-3 facility. The main physical task of GOL-NB will be the direct performance demonstration of multiple-mirror magnetic sections attached to a central confinement zone [1].

In a multiple-mirror confinement system [2], plasma expansion along a corrugated magnetic field is slowed down due to an effective friction force between populations of locally-trapped and transiting particles. Under optimum conditions (i.e. at the free path length of ions $\lambda_i$ is close to the corrugation period $l$), the particle confinement time τ scales as the square of the device length $L$: $\tau \approx R^2(L^2/\lambda_i v_{Ti})$, where $v_{Ti}$ is the ion thermal speed and $R = B_{max}/B_{min}$ is the mirror ratio.

The multiple-mirror approach to fusion was experimentally studied in Novosibirsk in the experiments with sub-fusion plasma in the GOL-3 facility [3]. The plasma was heated by a high-power electron beam; it was highly turbulent therefore. For more than four decades since the introduction of the multiple-mirror idea, GOL-3 was the only experiment that provided data on hot plasma confinement. GOL-3 experiments have demonstrated a better than expected confinement at sub-fusion plasma parameters. However, the use of the high-power electron beam for plasma heating challenges scalability of the system to truly reactor-grade steady-state parameters, though visions of such systems exist [4].

Currently, fusion prospects of multiple-mirrors are related to their use as special end sections attached to a main confinement system in order to reduce axial particle and energy losses. In this paper, we discuss current status and future plans of GOL-NB project.

## GOL-NB PHYSICS

Current mainstream in open magnetic systems for plasma confinement is implemented in the project of the next-generation GDMT device [5] that integrates features from both the gasdynamic (GDT) and multiple-mirror traps. NBI-heated two-component plasma will be confined in GDMT in a GDT-like central magnetic section. Two multiple-mirror end sections will slow down the axial plasma flow. The fusion efficiency depends on electron temperature that is maintained by the balance between the drag for the fast ions and power loss through the mirrors. The latter can be reduced by multiple-mirrors thus improving the confinement.

GOL-NB is designed as a fast-track low-cost prototype that will share the main GDMT physics at lower plasma parameters. Therefore we adopt the GDMT-like general structure for GOL-NB. We also supposed that all known GDT physics will also work and all technical solutions found by GDT team can be reproduced for the new device. Its magnetic configuration is shown in Fig. 1. GDT-type central trap with the mirror ratio $R = 15$ for $B(z=0) = 0.3$ T will confine plasma heated by 1.5 MW, 25 keV NBI system. Two 3-meter-long solenoids can produce either a uniform magnetic field of 4.5 T thus creating “long mirrors” or a multiple-mirror field with 14 mirror cells with $l = 22$ cm, $B_{\text{max}} = 4.5$ T, $B_{\text{min}} = 3.4$ T, and $R = 1.4$.

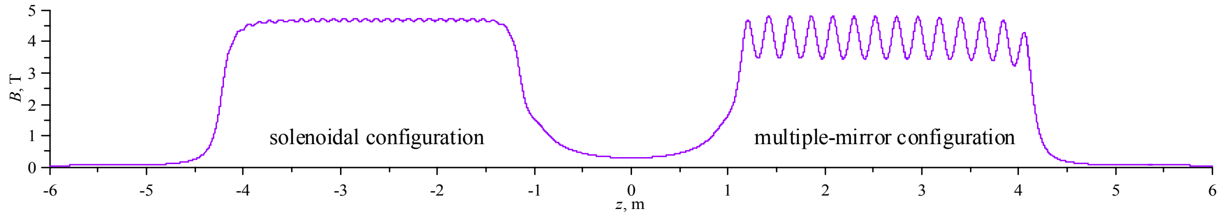
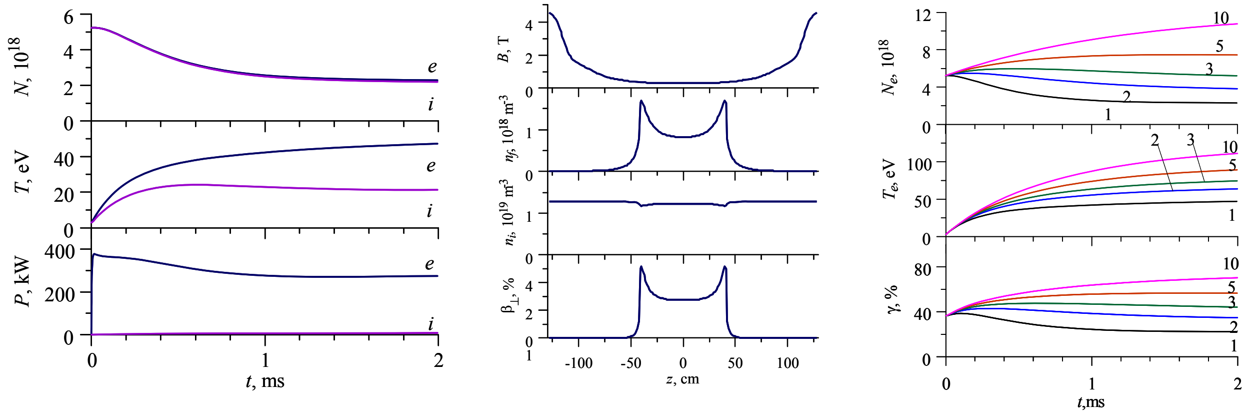


**FIGURE 1.** The magnetic field profile at the axis. The right solenoid is shown in the standard multiple-mirror mode, the left one is with the uniform field

As well as GDT [6], the central section will confine two-component plasma that will consist of thermalized warm plasma and fast beam ions. The warm plasma will be confined in gasdynamic regime. The requirement of warm plasma collisionality there will be satisfied automatically because of the condition $l \leq \lambda_{\text{i}} << L$ that is required for the multiple-mirror confinement. In GOL-NB, the central trap is simply a plasma source that provides a flux of moderately-hot plasma through mirrors. Captured beam ions will decelerate mainly in collisions with electrons down to thermalization. Restrictions on the layout of the equipment led to the decision to change the beam injection geometry comparing to both GDT and GDMT. For GOL-NB, oblique injection into the centerplane is impossible. A scheme with a displaced transverse injection in local mirror ratio $R(z=0.4) \approx 1.4$ was chosen instead. The multiple-mirror sections will slow down the axial plasma flow. After collisional escape from the central trap, plasma will flow through solenoidal sections. Then plasma flow will expand in decreasing magnetic field. The receiving endplates will be installed in low enough magnetic field (local $R \geq \sqrt{M/m} \approx 40$). High expansion ratio prevents penetration of the return flux of cold secondary electrons from the endplates into the confinement zone. This effectively restricts axial energy losses due to the requirement of plasma quasineutrality. Plasma parameters in the trap will be maintained by the balance between the drag for the fast ions and power loss through the mirrors. Depending on magnetic configuration, the balance will change thus allowing us study the multiple-mirror physics.

The main operation point was chosen from the condition $\lambda_{\text{i}} \approx l$. This corresponds to the density $n \approx 3\times10^{19}$ m$^{-3}$ from initial estimates with a simple energy balance model [1]. Recently, more advanced simulations [7] with the kinetic code DOL [8] provided more detailed analysis of experimental scenarios. Figure 2 shows dynamics of main plasma parameters for the baseline scenario (start parameters were $n = 3\times10^{19}$ m$^{-3}$, $P = 1.5$ MW, $E = 25$ keV) at varied efficiency of multiple-mirrors. Simulations revealed the importance of a plasma fueling system that for the case of Fig. 2 should provide a steady flux of cold plasma with the equivalent current of 1 kA.

In this project, we assume that methods of MHD stabilization used in GDT experiments [6] will also work in GOL-NB case. In the initial configuration, the stabilization will be provided by plasma biasing. A set of biased electrodes will create differential plasma rotation that saturates interchange instability at a safe level. Plasma in GOL-NB is less susceptible to kinetic instabilities than classical mirror devices due to high collisionality that populates the loss cones and makes electron and ion distribution functions more spherically symmetric. Preliminary analysis of the baseline scenario reveals that this configuration will be stable in respect for the Alfvén ion cyclotron and the drift-cyclotron loss-cone instabilities.



(a) (b) (c)

**FIGURE 2.** (a) Dynamics of basic parameters in the reference scenario without the multiple-mirrors, top to bottom: total number of particles in the trap $N$, temperature $T$, and power from fast ions to warm plasma $P$. Indices $e$ and $i$ denote parameters of electrons and ions of warm plasma. (b) Axial profiles for the baseline scenario without the multiple-mirrors at $t = 2$ ms, top to bottom: magnetic field at the axis $B$, fast ions density $n_{\mathrm{f}}$, warm ions density $n_{\mathrm{i}}$, and relative transverse pressure of fast ions $\beta_{\perp}$. (c) Dynamics of plasma parameters at different suppression of plasma flow by multiple-mirror field (indicated by numbers near curves, unity corresponds to no confinement improvement), top to bottom: total number of electrons in the trap $N_{\mathrm{e}}$, electron temperature $T$, and beam capture efficiency γ

## GOL-NB HARDWARE AND RESEARCH PROGRAM

Layout of GOL-NB is shown in Fig. 3. The project was optimized under the existing funding constraints that led to some important compromises in its technical and physical parameters. The device will reuse some infrastructure and hardware from GOL-3. It will occupy a part of current GOL-3 experimental area. The central trap is designed for 0.6 T maximum field in the midplane. Multiple-mirror sections will reuse 56 magnetic coils from GOL-3 with a new vacuum chamber inside. All coils use room temperature copper conductors with passive cooling. Depending on the coil type, its location and operation regime, half-periods of currents vary from 25 to 90 ms. Peak current density in solenoid coils reaches 250 A/mm$^2$ in the multiple-mirror configuration.

In-vacuum systems include a start plasma source, a set of passive and active (biased) limiters and end plasma receivers. The arc plasma source that will create start plasma will be located in the axial port of the expander tank. A system of limiters will provide plasma biasing in order to achieve its controllable differential rotation in a vortex confinement configuration. The arc plasma source can be biased as a whole in respect to the vacuum vessel walls. Recently a plasma stream from a prototype source was transported through ~3 m distance in test experiments that imitate the conditions of GOL-NB multiple-mirror sections [9] without the central trap. The mirror ratio with respect to the arc source anode was varied in the range from 5 to 60. The density at the axis reached $(1 - 4)\times10^{20}$ m$^{-3}$ in the solenoidal sections. Power supply of the magnetic system will be provided with the existing 15 MJ capacitor bank that will require minor modifications. Two 0.75 MW 25 keV injectors [10] are now in the commissioning stage. Four pumping units are already assembled. Each injector includes a beam source with geometric focusing and a gas charge exchange neutralizer. The ion source uses arc discharge plasma generator and plasma expander with multipole magnetic walls.

Operation of GOL-NB in full configuration shown in the upper part of Fig. 3 will be possible after completion of the central trap with its magnetic system. Before this, the initial configuration of GOL-NB will be assembled with a short dummy section of vacuum chamber mounted between two multiple-mirror sections that is shown in the bottom part of Fig. 3. In this configuration, performance checks of the start plasma source as well as of other technical systems will be done. Later the full configuration will be assembled. The neutral beam injectors will be mounted at the central trap.

The baseline physical program in full configuration includes the following. Task 1: demonstrate a stable GDT-like confinement in the central trap. Task 2: demonstrate the confinement improvement in the multiple-mirror configuration. Task 3: extend the achievable parameter space to higher temperatures with control of the particle free path length. Task 4: improve the plasma parameters with other plasma heating methods. GOL-NB can be put into operation in a few years after the authorization to start the on-site activities.

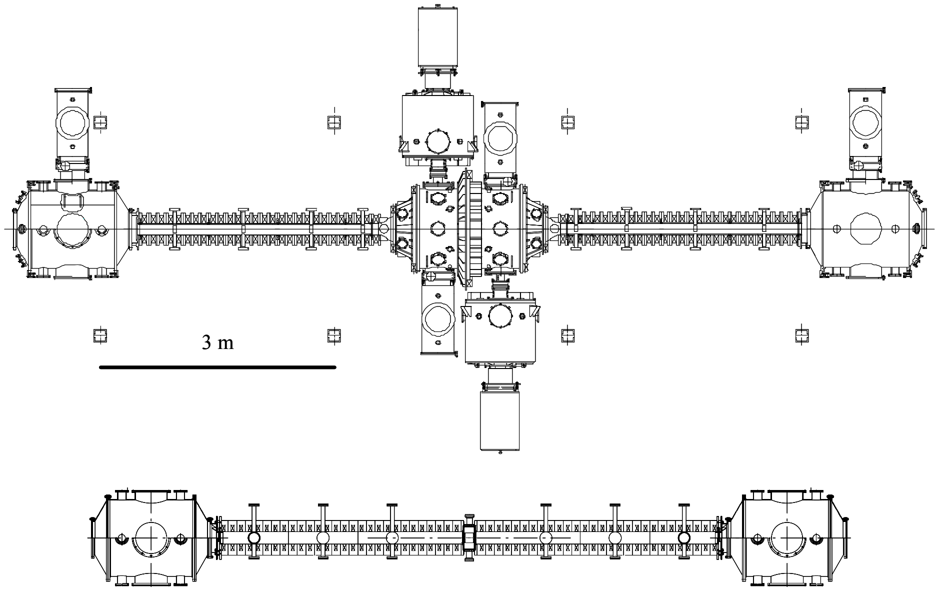


**FIGURE 3.** Top: layout of GOL-NB after completion of the proposed reconfiguration of GOL-3 (top view). The device consists of the central trap with two neutral beams, two multiple-mirror solenoids, two expander tanks (one with a plasma gun), and four pumping units. Spacing between structural columns is shown for scale. Bottom: side view of the first stage GOL-NB-1 configuration that will be temporarily used for the initial commissioning of main subsystems.

## SUMMARY

New linear trap GOL-NB will be created in Budker Institute of Nuclear Physics in a timeframe of several years. This device will combine physics of two existing linear magnetic configurations, namely gas-dynamic in the central trap and multiple-mirror in attached high-field solenoids. Plasma of $3\times10^{19}$ $m^{-3}$ density will be heated by 1.5 MW neutral beams. The central section will work as a miniaturized GDT trap with the same well-established physics. Depending on the magnetic configuration of the adjacent multiple-mirror solenoids, the baseline plasma losses through mirrors will change thus changing the confinement. We expect several-fold growth of plasma pressure in the central trap after the transition to the multiple-mirror configuration. The other option for axial confinement improvement is an active system with helical magnetic field [11]. GOL-NB is designed as a low-cost supporting experiment that should improve the knowledge base required for the fusion-grade next step GDMT project.

## ACKNOWLEDGMENTS

The authors are grateful to GOL-3 team, GDT team, and BINP plasma theory group for their valuable discussions and comments. This work was funded by Russian Federal Agency for Scientific Organizations.

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