GOL-NB Project: New Multiple-Mirror Trap with NBI-Heated Plasma

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I. INTRODUCTION

Existing modern concepts of fusion-grade open traps usually incorporate special end sections to improve axial confinement of plasma. These sections utilize either effect of ambipolar plasma potential (in projects of tandem-mirror-based reactors) or an effective friction force between a corrugated magnetic field and plasma stream (in projects of multiple-mirror reactors). In a multiple-mirror confinement system [1], 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 λ_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 on GOL-3 device [2]. The plasma was heated by a high-power electron beam; it was highly turbulent therefore. Confinement of turbulent plasma in GOL-3 is governed by several specific collective mechanisms that strongly differ the existing device from a classical trap that was considered by theory. This prevents us from the explicit demonstration of confinement scalings in a sufficient parameters range.

GOL-3 experiments have demonstrated an efficient multiple-mirror confinement at sub-fusion plasma parameters. Further advance to a fusion-grade device can be either along the existing paradigm of a turbulent plasma confinement or towards a new configuration featuring a central section for confinement of NBI-heated plasma and end multiple-mirror solenoids that will reduce plasma losses along the magnetic field.

In this paper, we discuss plans for a major reconfiguration and upgrade of the existing GOL-3 device. The main physical objective of new facility will be the direct demonstration of capacity of multiple-mirror end sections to reduce the end losses.

II. NEW PHYSICAL PROGRAM FOR GOL-3

Modern understanding of linear confinement systems was implemented in the GDMT project [3] that will integrate 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. In the pure GDT concept [4], an ambipolar potential forms that retards electrons and changes particle losses from the trap. The mean energy ε of an e-i pair that escapes the trap is $\varepsilon \approx 8T_e$, where T_e is the electron temperature of the warm plasma [4]. The lifetime of fast ions and fusion efficiency are determined by the electron temperature that in turn is maintained by the power balance between the drag for the fast ions and power loss through the mirrors. It can be increased if some method of reducing the power losses is implemented.

A fast-track verification of the main multiple-mirror scalings can be achieved at the existing GOL-3 facility. We plan to install a new low-field central trap in the middle of the existing solenoid. Plasma will be heated there by a 1.5 MW NBI system. Then the plasma will flow through the solenoids to end expander tanks. The solenoids can be reconfigured from a simple solenoidal configuration with 4.8 T field to a multiple-mirror one with 22 cm period and 1.4 mirror ratio - see Fig. 1.

In this project, we assume that all physics known from GDT experiments [4] will work, including classical slowing down of fast ions, absence of turbulence-related additional significant power losses, scalings for the rate of gasdynamic losses, and methods of MHD stabilization. Figure 2 demonstrates results from a simple energy balance model that includes main physical processes in the system. Here, the shaded area restricts the parameter space for the multiple-mirror confinement. Lower dashed line corresponds to a pure GDT configuration. The optimal density for start experiments is in the region of $(3-5)\times10^{19}$ m^{-3}. For this density, the temperature in the pure GDT regime will be already suitable for the multiple-mirror confinement. The temperature should grow with the activation of the multiple-mirror configuration. Two steps of research are proposed. During the first step, a classical multiple-mirror confinement will work in the solenoids. The expected plasma

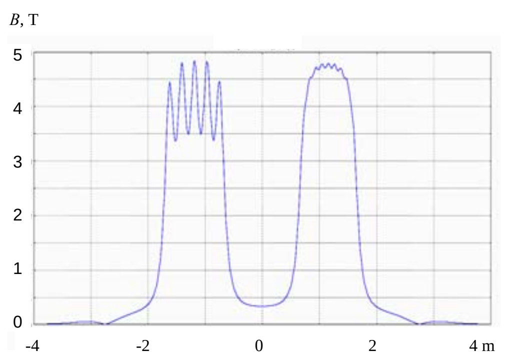

Fig. 1. The magnetic field profile at the axis for a configuration with the central trap for NBI heating, two solenoids and two expanders with cusps. The left solenoid is in the standard multiple-mirror mode, the right one operates as the simple solenoid.

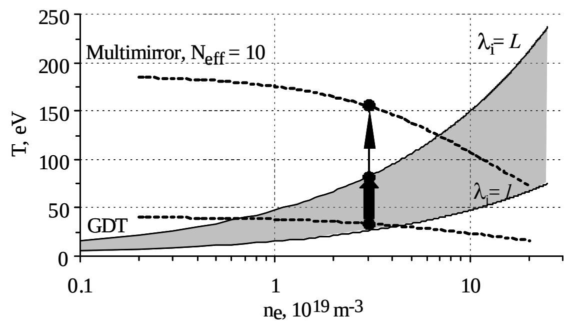

Fig. 2. Parameter space for the proposed experiment (calculated with a simple model for 1.5 MW NBI, plasma Ø 20 cm, B_{center} = 0.3 T, B_{mirror} = 4.5 T). Solid lines constrain the domain of multiple-mirror confinement. Lower dashed line indicates a pure GDT regime, upper dashed line corresponds to a maximal possible 10-fold reduction of axial losses.

parameters will correspond to the upper solid line in Fig. 2, i.e. we expect about twofold temperature growth. Advance to higher temperatures is possible if we will be able to implement a technology of a non-binary particle scattering in the solenoids.

Summarizing this Section, the baseline physical program includes the following [5]. Task 1: transform GOL-3 to the configuration with the central trap and two simple solenoids and demonstrate the GDT-like confinement. Task 2: demonstrate the temperature growth 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.

III. UPGRADE PLANS FOR GOL-3

The existing GOL-3 is a multipurpose plasma physics facility; current research programs cover the areas listed in the Introduction. The proposed upgrade of GOL-3 includes separation of the existing facility into two partly-independent devices that are more dedicated to specific physics. The first device GOL-3T will continue beam-plasma-related research. The rest of the existing 11-m-long solenoid will be adapted to an autonomous operation. For some time, this longer part of the solenoid will be used as a testbed for several new technologies for the next-step experiments in the multiple-mirror confinement, including new plasma creation system and two new 25 keV, 0.7 MW, 1 ms neutral beam injectors [6]. After that, new vacuum chamber, new pumping system, and new plasma creation system will replace the existing hardware in that section. During the next modernization step, the central trap and two end expander tanks will be connected to the solenoid. The neutral beam injectors will be mounted at the central trap. At this step, MHD stabilization will be provided by either the magnetic configuration or the plasma biasing. The plasma sustainment will be as long as NBI injection, i.e. 1 ms.

The further physical program supposes application of additional plasma heating methods and turbulence control in the multiple-mirror sections. This should improve plasma parameters and expand the available parameter space. The detailed hardware specifications for these steps will be completed later.

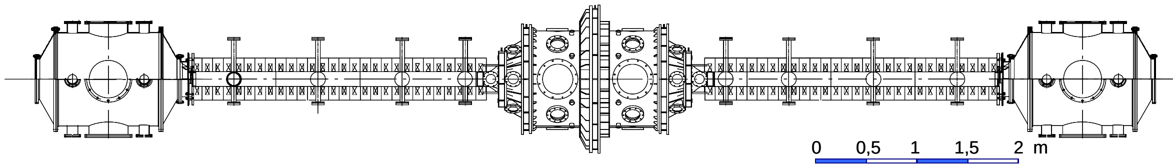

Fig. 3. Layout of GOL-NB after the proposed reconfiguration of GOL-3 (front view). The device consists of the central trap with 2 × 0.75 MW NBI, two multiple-mirror solenoids, two expander tanks and a plasma gun.

VI. SUMMARY

For more than four decades since the introduction of the idea of multiple-mirror plasma confinement, GOL-3 was the only physical facility that provided experimental data on confinement of hot plasma with sub-fusion parameters. Achievements in the GOL-3 program have demonstrated that the multiple-mirror approach works even better than it was initially expected for the case of turbulent beam-heated plasma. 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 [7].

In this paper, we introduce plans for the GOL-NB device that will be optimized for the multiple-mirror confinement studies. Two main ideas behind the proposed upgrade are the separation of plasma heating and confinement processes and the achievement of a quasi-stationary plasma state. In the proposed configuration, a new low-field central section with 1.5 MW NBI heating will be embedded in the center of the existing multiple-mirror solenoid. 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 section, the baseline plasma losses through mirrors will change. Preliminary calculations predict growth of the electron temperature from 30 eV up to 75 eV for 3×10^{19} m^{-3} density at a transition from a GDT-like confinement to a supposed multiple-mirror regime. Currently, design and modeling activities are carried out.

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