Start Plasma Production in GOL-NB Multiple-Mirror Trap

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The GOL-NB project is a physics demonstration experiment on multiple-mirror plasma confinement that is currently under development in the Budker Institute of Nuclear Physics [1-3]. 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. GOL-NB will be a scaled-down physical model of a future fusion-grade open trap [4]. The main scientific task of the project is to demonstrate improved confinement with activation of the multiple-mirror configuration.

Currently, the start configuration of GOL-NB is assembled [5]. It includes both expander tanks, an arc source of start cold plasma, a multiple-mirror solenoid with 34 coils of 4 m length, and a short temporary section for the on-site commissioning of NBIs. The first plasma campaign was devoted to studies of the start plasma transport through the high-field section. This process imitates the initial filling of the central trap by the start plasma in the full configuration of GOL-NB. In the reported experiments, the magnetic induction in the high-field section was temporarily restricted by B_{max} = 1.8 T. The experiments were carried out with two configurations of the high-field section: the solenoidal and multiple-mirror ones, see Fig. 1.

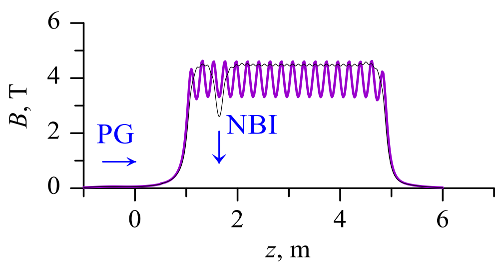

Fig. 1. Design axial profiles of the magnetic induction. Solenoidal and multiple-mirror regimes of operation are shown by thin and thick lines, respectively. Labels indicate locations of the plasma gun (PG) and neutral beam injectors (NBI).

Plasma parameters were studied with a four-electrode Langmuir probe that provided data on n, T_e and E_r (it used 6 locations along the high-field section), a diagnostic neutral beam, spectroscopy, high-speed imaging, *etc*.

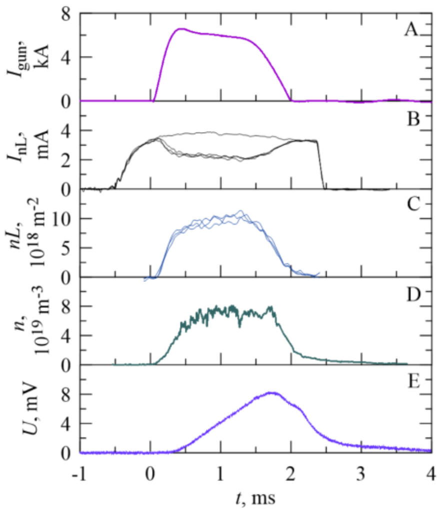

Fig. 2. Typical waveforms: A - plasma gun current I_{gun}, B – passing neutral beam monitor I_{nL} (three sequential plasma shots and one reference shot without plasma are shown), C – calculated line-integrated density nL from B, D – ion density from the Langmuir probe n at z = 2.02 m, E – photodiode signal U.

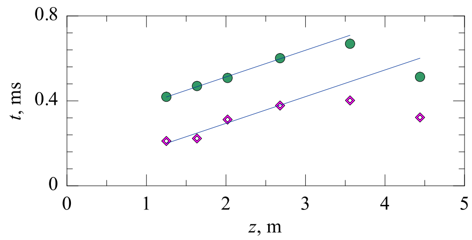

Fig. 3. Plasma expansion along the device in the multiple-mirror configuration.

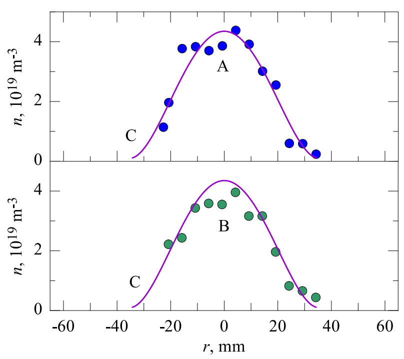

Fig. 4. Radial plasma density profiles at z = 356 см. Dots A – the solenoidal configuration, B – the multiple-mirror configuration, lines C are a symmetric polynomial fit to dots A (this curve is the same in both figure parts).

Figure 2 presents waveforms that characterize a typical discharge. The plasma gun current lasts about 2 ms. Plasma density demonstrated almost flattop during the gun operation time followed with fast density decay with the decrease of the gun current. The signal of the radiation monitor increases during the shot. Plasma density linearly depended on the initial gas pressure in 1 – 10 MPa range.

Plasma expansion rate was found from the probe measurements by two methods. Diamonds in Fig. 3 show moments of achieving 10% of local density maximum. Dots represent moments of maximum gradient of probe signals. Trend lines correspond to plasma expansion with the constant velocity of 0.8×10^8 m/s.

Theory predicted [6], that highly collisional plasma with $\lambda << l$ will penetrate a corrugated field almost freely with some energy loss due to longitudinal viscosity. Since then, this prediction was explicitly checked only in [7] with limited experimental information.

Direct comparisons of plasma flow in the solenoidal and in the multiple-mirror configurations demonstrated almost identical radial profiles and almost identical dependencies on the axial coordinate (Figs. 4 and 5). Solid curves C in Fig. 4 are the same fit of the data points A by a symmetric fourth-order polynomial. The difference in the line-integrated density nL was within the reproducibility of shots.

Dependencies of the cross-section-integrated

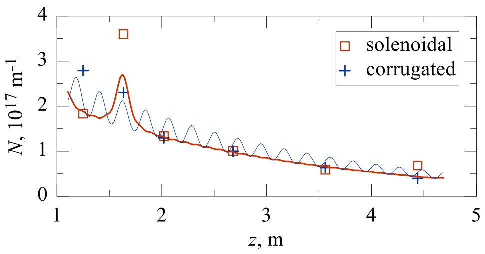

Fig. 5. Number of particles per unit length on the axial coordinate for the solenoidal and the multiple-mirror configurations. Solid lines are model functions.

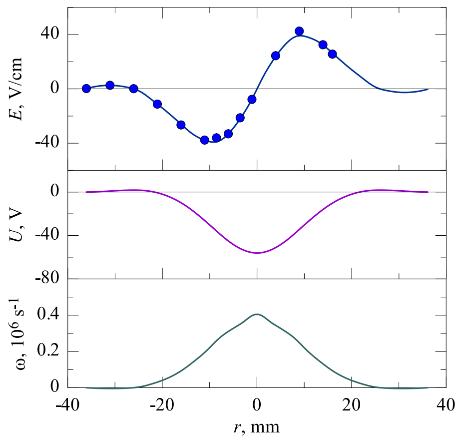

Fig. 6. Radial profiles at z = 1.25 m in the solenoidal configuration, top to bottom: measured radial electric field E and its fit by an antisymmetric function, plasma potential relative to the wall U, and frequency of $E{\times}B$ rotation ω.

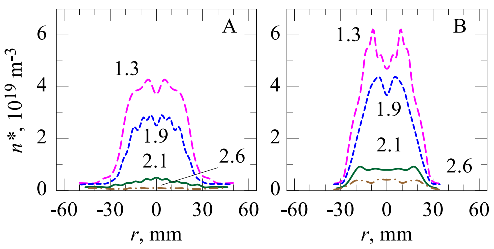

Fig. 7. Evolution of radial density profiles in the multiple-mirror configuration at z = 3.56 m with the endplate at a floating potential (A) and with -46 V bias (B). Other labels are time in ms. See comment in the text on the meaning of n^*.

density (number of particles per unit length) is shown in Fig. 5 for both magnetic configurations. Solid lines are model functions

$$N(z) = N(0)\frac{B(0)}{B(z)}\exp\left(-\frac{z}{z_0}\right),$$

that correspond to movement of a non-compressible fluid along the flux tube of variable diameter with constant loss rate at a typical scale of z_0 = 2.2 m.

Figure 6 shows the measured radial electric field profile in the beginning of the high-field section, its fit by an antisymmetric function and calculated profiles of the potential and frequency of $E{\times}B$ rotation. Near the axis, potential of the anode plane is translated along the magnetic field by longitudinal currents. Radial currents and convection contribute to observed broadening of the profile with respect to the expected flux tube projection. In the halo at $r \sim 30$ mm, plasma acquires the natural positive ambipolar potential. It reached ~10 V, i.e., about two electron temperatures, in the middle part of the high-field section.

Usual way of obtaining plasma stability in an open trap is a proper choice of its magnetic configuration that should satisfy the “minimum B” rule. A different stabilization technique was accepted for GOL-NB. We will rely on the so-called “vortex confinement” technique that was proposed in [8] for the GDT gasdynamic trap and actively used since then in the experiments with high plasma pressure up to β = 60%. In the vortex confinement, the most dangerous interchange instabilities are saturated at a low level by the differential $E\times B$ rotation with the negative plasma potential in respect to the wall. The radial electric field will be created by proper biased ring endplates and limiters. Additionally, the plasma gun translates potential of the required polarity along the magnetic field during its operation.

Figure 7 shows fits to radial density profiles in the multiple-mirror configuration with the endplate at a floating potential and with -46 V bias for four time moments, which are the flattop (t = 1.3 ms), moments just before and after termination of the gun current (t = 1.9 and 2.1 ms) and the plasma decay phase (t = 2.6 ms). Plasma temperature rapidly changes at the transition from the flattop to the decay. Therefore, we recalculated probe signals into the density n^* with the assumption of a constant temperature. This significantly undervalues the density during the decay, but enables comparisons of radial density distributions in different regimes. Two differences of plasma flow in different magnetic configurations can be seen in the figure. Plasma density increased by about 50% with the active biasing. More important, plasma decayed slower after termination of the gun current. A kind of a plateau with steep slopes remains at $t > 2$ ms.

The first plasma campaign was completed in the start configuration of the GOL-NB multiple-mirror trap. The cold plasma stream was generated by the arc gun, compressed in the converging magnetic field and then transported through the 4-m-long high-field section. The main technical result is the achievement of suitable parameters of this start plasma, which will fill the central gasdynamic trap in the final configuration of GOL-NB. The main physical result is the confirmation of the old theory prediction on a weak influence of a magnetic field corrugation on a collisional plasma flow. This confirmation is important for the GOL-NB project, which relies on the difference in the confinement properties of the multiple-mirror sections for highly collisional and moderately collisional plasmas.

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