Transportation of Plasma Jet in GOL-NB Multiple-Mirror Trap

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Abstract. New experimental results on magnetic compression and transport of low-temperature arc plasma at ~3 m distance are presented. The magnetic compression ratio of the plasma stream varied from 5 to 60 at the initial plasma diameter about 5 cm. Theory predicts that the multiple-mirror magnetic field should not significantly decelerate and weaken the collisional low-temperature arc plasma. In the experiments, the transport efficiency of the plasma stream in the multiple-mirror configuration of the solenoid was compared with the same in a uniform solenoidal field. As the result, the plasma with (1-4)$\times10^{20}$ m^{-3} density at the axis was obtained at ~3 m distance from the arc plasma source. The experiments simulated the baseline scenario of GOL-NB filling by the start plasma. Finally, the experiments described in the paper validated the decisions made for the GOL-NB start plasma source.

INTRODUCTION

The idea of using sections with a corrugated magnetic field to improve plasma confinement in open traps was first proposed in [1]. Confinement systems with such magnetic configurations are known as multiple-mirrors. Experiments in GOL-3 have demonstrated 50-fold increase in the energy confinement time at transition to a multiple-mirror configuration [2,3]. Behavior of turbulent electron-beam-heated plasma with sub-fusion parameters in GOL-3 was governed by a complex chain of collective processes [4]. Later, multiple-mirror sections were integrated in the GDMT project [5] as components that improve the performance. Detailed design of the device will require a good physical database on multiple-mirror scalings that will be relevant to NBI-heated plasma in the central trap of GDMT with low level of turbulence. The GOL-NB project [6] is under development in Budker Institute of Nuclear Physics for this purpose.

Unlike previous generations of multiple-mirror traps, GOL-NB will focus on a quasi-stationary confinement of neutral-beam-heated plasma with moderate parameters: $n \sim 3\times10^{19}$ m^{-3} and $T \sim$ 30-100 eV. The plasma will be confined in the 2-m-long central trap of GOL-NB, which ends with two multiple-mirror solenoids. The solenoids are re-used parts of the GOL-3 magnetic system with 14 corrugation periods (elementary multiple-mirror cells) of 22 cm length. The solenoids will decrease particle and power losses along the magnetic field when multiple-mirror configuration is activated. Theory predicts that at high enough plasma density when ion free path length becomes comparable with the corrugation period, the particle confinement time τ increases comparing to free expansion in solenoidal magnetic field $\tau_0 \approx R^2L/v_{Ti}$: $\tau \approx N\tau_0$, where N is number of mirrors in each solenoidal section of length L and mirror ratio R [1,7,8]. Plasma heating in the GOL-NB will be provided by two 0.75 MW neutral beams [9] that should be captured by a low-temperature start plasma created by an arc plasma gun installed in magnetic expander. Numerical calculations [10] predict about doubling of density and temperature in multiple-mirror configuration in comparison with uniform long mirrors.

In this paper, we will present new experimental results on a magnetic compression and transport of a low-temperature arc plasma at ~3 m distance. The magnetic compression ratio varied from 5 to 60, the initial plasma stream diameter was about 5 cm that corresponds to anode diameter of the plasma gun. Theory predicts that the multiple-mirror magnetic field should not significantly decelerate and weaken the collisional low-temperature arc plasma stream, because ion free path length significantly less than the corrugation period that does not satisfy to multiple mirror confinement [1,7,8]. Later, the plasma stream will be used in GOL-NB experiments as the target for neutral beams capture. Experimental program requires that main parameters of the target plasma should be the same for the uniform and multiple-mirror field in solenoids. Previously we have reported the initial studies of plasma gun operation in a simple solenoidal configuration [11]. New experiments include the plasma stream transport in the corrugated magnetic field with the same parameters that will be used in GOL-NB later.

THE EXPERIMENTAL DEVICE

The experimental system consists of solenoid, which can be switched in uniform or multiple-mirror configuration by changing the power feed circuit in the main part of solenoid, see Fig. 1. All coils have inner diameter Ø 0.16 m and are installed with 0.11 m spacing along the axis. The solenoid can be switched in the simple configuration with the uniform magnetic field of up to 4.5 T or in the multiple-mirror configuration with field in maxima of 4.5 T, in minima 3.3 T and the corrugation period of 0.22 m. At the left end of solenoid the arc plasma gun is placed in the magnetic expander. The first magnetic coil placed above the plasma gun changes plasma stream compression ratio $\boldsymbol{R} = \boldsymbol{B}_{\text{sol}}/\boldsymbol{B}_{\text{gun}} = 5 - 60$ by a separate current regulation. A small vacuum vessel with 30 liters volume is installed between the plasma gun and the solenoid. It is essential as a receiver for gas produced by the gun during its operation and decreasing of charge-exchange losses of plasma.

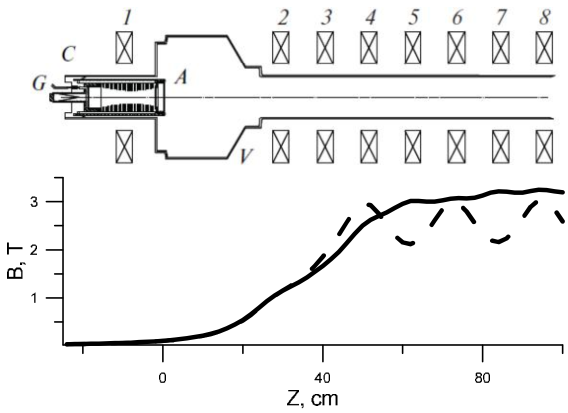

FIGURE 1. Entrance expander with plasma gun – top image, and axial magnetic field dependence vs. corrugation depth. Designations: A – anode of plasma gun, C – cathode, G – hydrogen puffing system, V – plasma expander, numbers 1-8 – magnetic coils.

The plasma expansion along the system is studied with a set of diagnostics. Full list and layout of diagnostics was discussed in [11]. Here we will mention two main systems. The first one is the diagnostic neutral beam injector [12] placed at coordinate $\boldsymbol{z} = 1.9$ m. The beam attenuation in plasma is measured by a 10-channel chord detector that covers all plasma diameter. Its instrumental resolution is 8 mm. The radial density profile is recovered from its data. The radial density profile is approximated by a Gaussian plus wide gas background. The second important diagnostics is a spectral system with spatial resolution placed at $\boldsymbol{z} = 2.9$ m [13]. Spatial distributions of several lines of light impurity ions were measured.

EXPERIMENTAL DATA

Figure 2 shows several signals of main diagnostics. They are measured in typical experiment with $\boldsymbol{B}_{\text{sol}} = 1.6$ T and $\boldsymbol{R} = 18$. The plasma gun current $J_{\text{gun}} \approx 12$ kA was not dependent practically from experimental conditions. The longitudinal plasma current flowed along the whole plasma system; it was maximal at the beginning of the gun

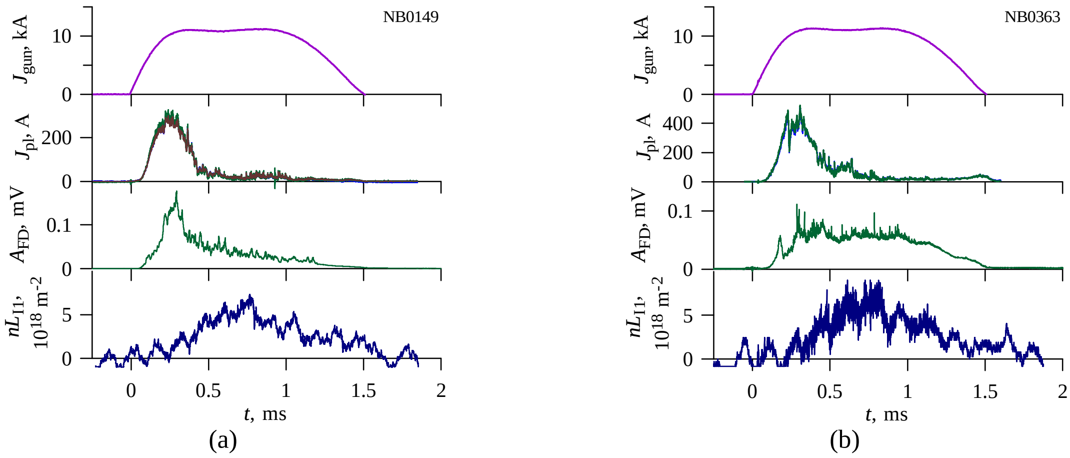

FIGURE 2. Typical diagram of diagnostic systems in experiments with homogenous (a) and multiple-mirror (b) magnetic field at the B_{sol} = 1.6 T and R = 18. From top to bottom: plasma gun current J_{gun}, current along the plasma chamber J_{pl}, calorimetric radiation detector signal A_{FD} at z = 0.9 m, and density integral from the 10.6 μm interferometer at z = 3.79 m.

discharge. All four Rogovsky coils gave identical signals. The value of longitudinal current depended on experimental conditions. At a low magnetic field in the gun, $B_{gun} \approx 0.1$ T, the current was about 10 A but with the field increase of up to $B_{gun} \approx 0.3$ T it reached 400 – 500 A. The existence of longitudinal current is the known feature of arc plasma sources. We found that change of uniform magnetic field to the multiple-mirror one did not significantly influence the current. A calorimetric radiation detector FDUK at z = 0.9 m indicated gradual growth of plasma brightness during the first phase of the discharge with current growth along the plasma. An infrared CO_2 interferometer at z = 3.79 m shows almost identical waveforms with similar typical times and values for plasma accumulation and decay in the uniform and multiple-mirror configurations.

At z = 2.96 m, the plasma profile was measured by visible spatial resolved spectrometer. In full GOL-NB configuration, the central trap with neutral beam injectors will be mounted at that distance. From the spectrum of plasma emission shown in Fig. 3 one can see that the plasma column consists of two zones. The first one is a cold halo that is identified by H_α emission area. The second one is hotter central core; it was identified by emission from ions of impurities (C, N, O) in different charge states. The existence of O^{4+} ions allows to plasma temperature estimate as $T_e \approx 10$ eV. So in agreement with DNBI and CO_2 interferometer data, the plasma parameters measured by spectroscopy did not differ in uniform and multiple-mirror configurations. Emission of higher charged ions faded during the mirror ratio increase from $R \approx 40$ up to 60. This shows that plasma temperature reduces at highest mirror ratios. The area of the existence of single charged ions reduced too. At all experimental conditions, the center of plasma column had maximal temperature.

The general data about the spatial parameters and the dynamics of plasma density were obtained by using 10-channel chord detector of fast atoms passed through plasma from DNBI at z = 1.9 m. It has pulse duration of

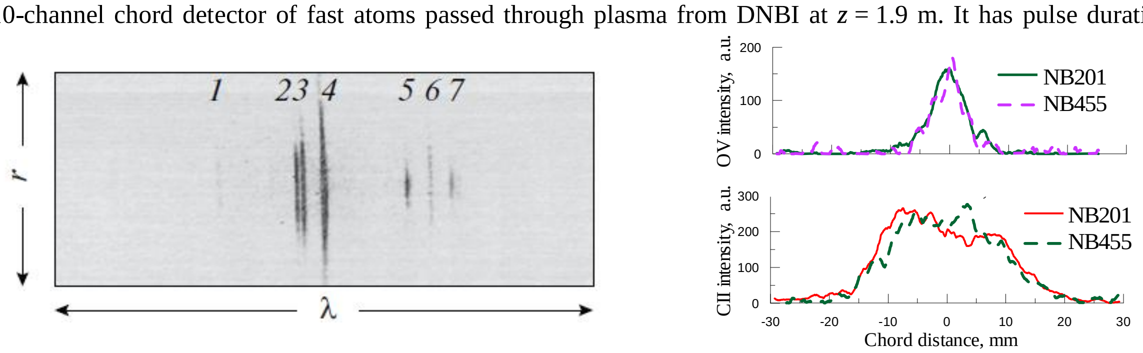

FIGURE 3. Left: typical frame of the spectral system (z =2.96 m). Wavelength changes with horizontal coordinate; the spatial coordinate is vertical. The value of blackening corresponds to emission intensity. Lines: 1 – OII 664.15 nm, 2 and 3 – CII 658.29 and 657.81 nm, 4 – H_α 656.28 nm, 5 – OV 650.02 nm, 6 – NII 648.25 nm, 7 – NIII 646.70 nm. Right: dependencies of several spectral lines intensity vs. chord radius for two experiments NB201 (uniform field, $B_{gun} \approx 0.1$ T, $B_{sol} \approx 3$ T, $R \approx 31$) and NB455 (multiple-mirror, $B_{gun} \approx 0.1$ T, $B_{sol} \approx 3$ T, $R \approx 31$). The spectra were measured at t = 0.4 ms.

about 0.4 ms. The full plasma duration was studied in a series of a few dozens repeatable shots. In the Fig. 4, the plasma density in the center of plasma column measured by this method is presented. Each symbol in the diagram is a separate plasma shot. The amplitude of the Gaussian fit was settled as plasma density. The calculated width of the Gaussian corresponds to that by spectral measurements. One can see that in multiple-mirror and uniform configurations the plasma density at the axis was the same. A reasonable agreement of the DNBI and the CO_2 interferometer data is found.

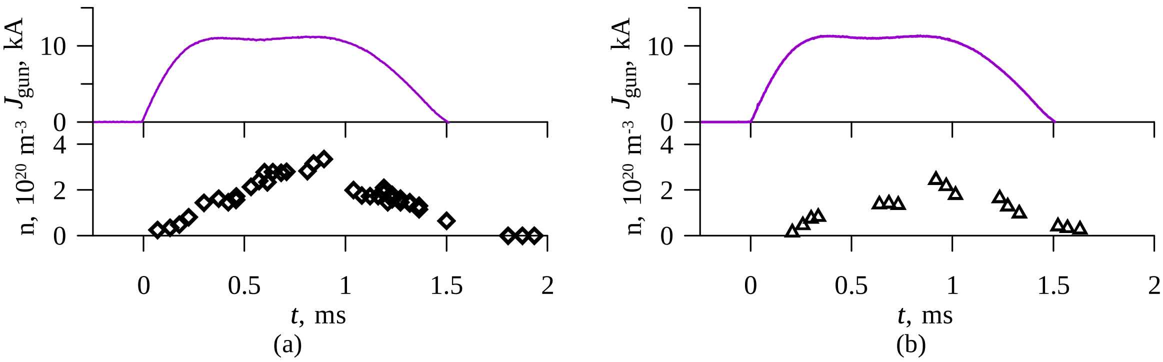

FIGURE 4. Electron plasma density at the system axis measured at z = 190 cm with homogenous (a) and multiple-mirror (b) magnetic field at the $B_{sol} \approx 4$ T and $R \approx 18$. From top to bottom: plasma gun current J_{gun}, plasma density at the axis n.

SUMMARY

In conclusion, one can note that the experiments demonstrated the efficiency of a new scheme of a low-temperature start plasma creation for the future GOL-NB device. The plasma stream was effectively generated by the arc plasma source and then it was compressed in a converging magnetic field and transported along the magnetic field over a long distance. At the plasma jet transport in a uniform and multiple-mirror magnetic field with mean induction of 0.5–5 T, the plasma density at the axis at the distance of 3 m was $(1–4)\times10^{20}$ m^{-3}. The mirror ratio with respect to the anode of the arc source was varied from 5 to 60. The experiments simulated the baseline scenario of GOL-NB filling by the start plasma. These experiments confirmed the correctness of the chosen technical solutions.

As a side note, we should mention that the reported results will be useful also for a physical program of the SMOLA device with helical magnetic field [14] that is under development in BINP currently. In SMOLA, a cold plasma stream will pass through a 3-m-long magnetic system with superimposed fields of solenoidal and bispiral windings that create a different configuration with periodic modulation of the magnetic field strength.

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