STABILIZATION OF RELATIVISTIC ELECTRON BEAM BY DENSE PLASMA CLOUD IN GOL-3 EXPANDER

I. A. Ivanov[1,2], A. V. Burdakov[1,3], V. G. Ivanenko[1], M. A. Makarov[1], K. I. Mekler[1], S. V. Polosatkin[1,2], V. V. Postupaev[1,2],
A. F. Rovenskikh[1], S. L. Sinitsky[1,2], A. V. Sudnikov[1,2], A.A. Shoshin[1] and I.M. Shchudlo[3]

[1] Budker Institute of Nuclear Physics, 11 Lavrentjev Avenue, Novosibirsk 630090, Russia
[2] Novosibirsk State University, 2 Pirogova Street, Novosibirsk 630090, Russia
[3] Novosibirsk State Technical University, 20 Karl Marx Avenue, Novosibirsk 630092, Russia
e-mail: I.A.Ivanov@inp.nsk.su

The paper presents new experimental results from the GOL-3 facility on stabilization of some beam instability modes by controlled conditions at an exit beam receiver. In the experiments the space near the beam collector in the exit expander was filled with krypton. Position and shape of the beam footprint at the exit collector was imaged using the beam bremsstrahlung. The beam shape changes were detected by a set of magnetic probes. Improvement of the beam stability due to krypton puffing was achieved. Possible mechanisms of such stabilization are discussed.

I. INTRODUCTION

Fast plasma heating up to fusion temperatures is required for a reactor based on a multi-mirror trap.[1,2] Collective relaxation of a relativistic electron beam is usually considered as a heating method for such systems which efficiency was demonstrated. Experiments on plasma heating to sub-fusion temperatures in GOL-3 reveal several new collective effects that significantly change plasma properties.[3] Among them are: turbulent collision rate of plasma electrons (that affects resistivity and axial electron heat transport)[4] and fast collective heating of ions.[5]

Drawbacks of the beam heating scheme are additional problems with maintaining the beam and plasma stability that originates from a high level of turbulence during the beam injection. Stable transport of the beam requires careful selection of operation scenario. A necessary condition for macroscopically stable beam transport is good compensation of the beam current by a return plasma current. This is done with a special design of the plasma creation unit with the exit beam collector. Due to high-level turbulence in the beam-heated zone the return current flows mainly through cold edge plasma. Physics related with axial currents is discussed in Ref. 6.

New experimental campaign at GOL-3 devoted to studies of the beam-plasma interaction at reduced cross-section of the electron beam evidences displacements of the beam off the axis.[7,8] At the same time plasma confinement was good in the best shots but statistically unstable. We came to conclusion that the beam becomes boundary stable due to changed spatial structure of currents in the plasma that in turn depends on the ratio of the beam-heated area to full plasma cross-section.

The paper presents new experimental results from the GOL-3 facility on stabilization of some instability modes. Possible reasons for the beam instability are: decompensation by current density ($q < 1$ within the beam cross-section[6]); beam asymmetry at the input into the plasma; asymmetry of the return plasma current. Proposed stabilization technique improves plasma conductivity near the beam receiver for more uniform and smooth generation of the return current.

II. EXPERIMENT AND DIAGNOSTICS

GOL-3 is a multi-mirror trap with total plasma length of 12 m. The solenoid provides an axially-modulated magnetic field with B_{max}/B_{min}=4.8/3.2 T and corrugation period 22 cm. The plasma density in current experiments is $2\cdot10^{20}\div10^{21}$ m^{-3}. The beam parameters were the following[7]: energy up to 0.8 MeV, current density in 4 T magnetic field ~1 kA/cm^2, diameter 13 mm and duration 10÷12 μs. In standard experimental scenario at maximum of the magnetic field the vacuum chamber is filled with deuterium of a required density, then low-temperature preliminary plasma is produced from this gas by a linear discharge and finally the beam is injected into the plasma.

Stability of the beam-plasma system strongly depends on the net plasma current. Generally the well-known Kruskal-Shafranov criterion can be used:

$$q = \left(B_z \middle/ B_\varphi \right) \cdot \left(2\pi r \middle/ L \right) > 1,$$

where q is safety factor, B_z and B_φ are components of the magnetic field, r and L are radius and total length of the plasma. In our case formal q value near the axis could be as low as 0.3 even at zero net current due to lack of compensation of the beam current by the return current within hot plasma core.[6] In a standard GOL-3 operation regime with the beam diameter of 6 cm, plasma stability is provided by a strong magnetic shear which exists inside the plasma.[6] Smaller beam diameter in the discussed experiments means that boundary transition zone from the plasma core to its edge can occupy a relatively large space changing therefore conditions of the stability.

A special assembly was installed in the exit expander tank which provides the following functions (see Fig.1):

- footprint of the beam can be imaged in its bremsstrahlung with 7 μs temporal resolution;
- dense gas (krypton) can be puffed directly in front of the receiver surface.

Density of puffed gas was changed by delay of the plasma in respect to the gas-puffing (see Fig.2). Further we will refer to this delay time rather than to gas density in order to reference shots without the gas-puffing system ($t = 0$).

Bremsstrahlung from the target surface is projected onto CsI scintillator (∅20 cm × 1 cm). Visible image is recorded by CCD. Spatial resolution of the X-ray imager is 5 mm on target. Magnetic fluctuations are measured by Mirnov probes which enable reconstruction of azimithal and axial mode structure up to ~10 MHz frequency. Temperature of Kr plasma was measured by an imaging survey spectrometer by ratio of CII lines (589 nm and 658 nm). Other standard plasma diagnostics were also used.

III. EXPERIMENTAL RESULTS

In general krypton puffing improved stability of the beam-plasma system. Optimum of krypton density near the receiver is $(1\div1.5)\cdot10^{21}$ m^{-3}. This improvement is of statistical nature. That means that in both regimes (with and without the gas puffing) we had good shots. The difference is that with the optimal gas-puffing we had much less events with big problems in transport or in confinement.

Typical beam footprints on the beam receiver are shown in Fig. 3 (the imager fields of view are slightly different). The beam is at the axis and of good symmetry in the gas-puffing case. Some results of computer processing are presented in Fig.4, which shows the optimum in gas density for the delays 30÷40 ms.

A similar dependence can be seen in Fig. 5 for transverse energy losses to the wall near the exit end of the plasma. Mean full transverse losses decrease from ~600 J for no puffing case down to 250÷350 J for optimal krypton density.

Improvement of the beam stability in the vacuum chamber is also seen from Mirnov data. Figure 6 presents MHD spectra for the same two cases and the difference.

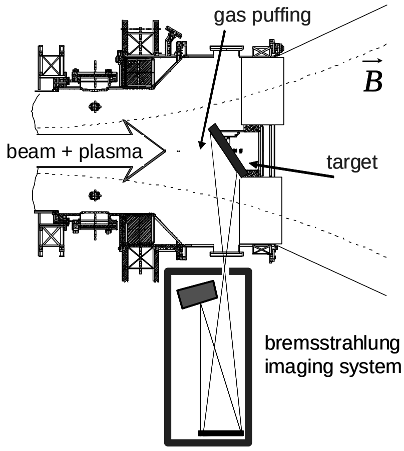

Fig. 1. Layout of new target assembly at GOL-3.

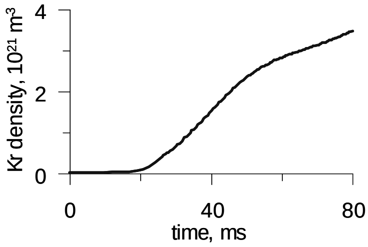

Fig. 2. Dependence of krypton density on timing.

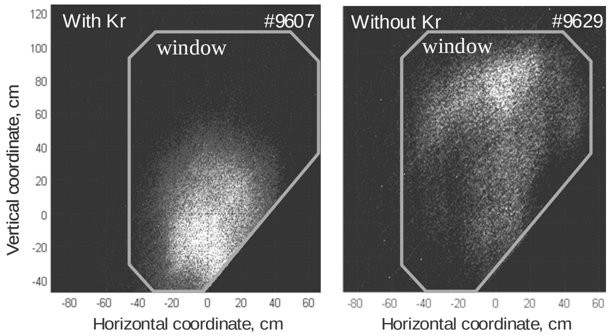

Fig. 3. X-ray images of the beam footprint with and without the gas puffing. Camera field of views are shown.

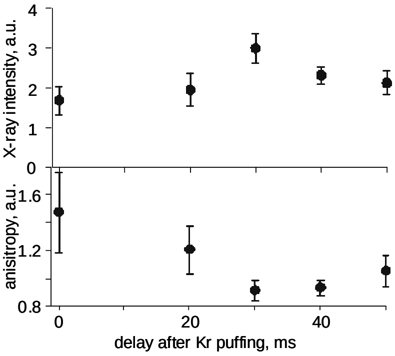

Fig. 4. Dependencies of image brightness (top) and asymmetry (bottom) on krypton delay time.

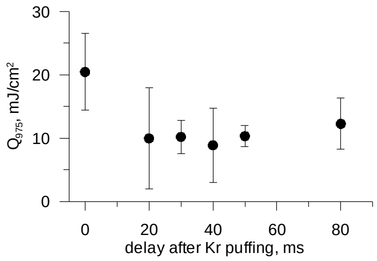

Fig. 5. Dependence of transverse losses at Z = 975 cm on Kr puffing delay. Dispersion is shown. Statistics are ~100 shots for 0 and 20 ms each and 3-8 shots for rest dots.

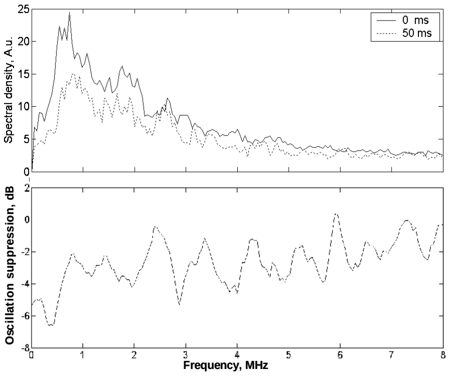

Fig. 6. Suppression of MHD activity of plasma at distance 6 m from the solenoid entrance. Top: spectra without puffing (solid line) and at 50 ms delay (dotted line). Bottom: the difference spectrum.

Decrease of magnetic perturbations is up to 6 dB in the low-frequency part of the spectrum. The difference spectrum features peaks of lower suppression at harmonics of 0.8 MHz. This frequency approximately corresponds to double Alfven transit time. Therefore the reasonable interpretation of measured spectra is the following. Improvement of the plasma coupling with the exit electrode "frozens" amplitudes of the beam vibrations except for axial modes with the node at the receiver surface (such modes already have zero displacements there).

IV. DISCUSSION AND SUMMARY

Change of diameter of the electron beam from standard 4÷6 cm down to 1.3 cm with corresponding 10-fold decrease of the beam current[7] revealed marginal stability of the beam-plasma system. Excursions of the beam off the axis were observed by different diagnostics. Bad electrical plasma coupling with the exit receiver placed in the expander tank was supposed to be the reason for this. Such bad contact can cause asymmetry of return plasma currents and therefore destroy sheared structure of the magnetic field that is important for a good confinement in GOL-3 (see Ref. 6). To solve the problem a heavy dense gas (krypton) was injected near the receiver. It increases mass of the plasma near the surface and provides better symmetry of plasma currents.

Experiments demonstrated evident improvement of the beam stability. This improvement is however statistical. Good shots can be found in both regimes, but under optimal gas puffing we see no near-to-catastrophic events with heavy distortion of the beam shape and fast plasma loss.

Optimal krypton density for our case is ~10^{21} m^{-3} that is much higher that ~10^{20} m^{-3} plasma density near the receiver. At this density the exit beam shape and position improve, transverse plasma losses decrease twofold, MHD activity reduces. Further increase of krypton density leads to slow degradation, possibly due to decrease of krypton temperature from ~5 eV in the optimal regime down to ~3 eV at larger studied delays.

ACKNOWLEDGMENTS

The work was supported by Russian Ministry of Education and Science, Grants 2.1.1/3983, 2.1.1/3465, P2309, P276, 02.518.11.7113; Russian Academy of Science, Projects 30, 33, 34, 113; Russian Foundation for Basic Research 08-01-00622a, 10-02-01317a, 10-08-00707a, Human Capital Foundation project 192.

REFERENCES

1. G. I. BUDKER, V. V. MIRNOV, D. D. RYUTOV, "Influence of Corrugated Magnetic Field to Expansion and Cooling of Dense Plasma", *JETP Letters*, **14**, p. 212 (1971).
2. V. V. MIRNOV, A. J. LICHTENBERG, "Multiple Mirror Plasma Confinement", *Reviews of Plasma Physics*, New York, **19**, p. 53 (1996).
3. A. BURDAKOV, et al., "Status and Prospects of GOL-3 Multiple-Mirror Trap", *Fusion Science and Technology*, **55** (No. 2T), p. 63 (2009).
4. V. T. ASTRELIN, et al., "Generation of Ion-Acoustic Waves and Suppression of Heat Transport during Plasma Heating by an Electron Beam", *Plasma Physics Reports*, **24**, p. 414 (1998).
5. A. V. ARZHANNIKOV, et al., "Study of the Mechanism for Fast Ion Heating in the GOL-3 Multimirror Magnetic Confinement System", *Plasma Physics Reports*, **31**, p. 462 (2005).
6. V. V. POSTUPAEV, et al., "Role of *q* Profile for Plasma Confinement in the Multimirror Trap GOL-3", *Fusion Science and Technology*, **47** (No.1T), p. 84 (2005).
7. V. V. POSTUPAEV, et al., "Experiments with "Thin" Electron Beam at GOL-3", *Fusion Science and Technology, this issue* (2011).
8. N. SOROKINA, et al., "Study of plasma on the GOL-3 facility by imaging VUV spectroscopy", *Fusion Science and Technology, this issue* (2011).