EXPERIMENTS WITH "THIN" ELECTRON BEAM AT GOL-3

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The latest experimental campaign at the GOL-3 multiple-mirror trap was mainly aimed at features of heating and stability of the electron-beam-heated turbulent plasma. The device itself is a long solenoid with axially-periodical (corrugated) magnetic field [1]. The plasma heating is provided by a high-power relativistic electron beam. Collective nature of the beam-plasma interaction results in high level of plasma microturbulence during the beam injection. Turbulent processes are also important for good confinement regimes to be achieved [2]. The feature of the operation regime is a significant reduction of full current and full cross-section of the electron beam. The beam heated plasma volume become therefore small comparing with the full plasma cross-section, the significance of transverse transport increases. First results from this regime were reported in [3]. This paper presents new data from this experimental regime, especially concerning stability of the beam-plasma system and features of operation with non-ionized gas at the beam start.

DEVICE AND OPERATION REGIME

In the basic operation regime the solenoid consists of 52 magnetic corrugation cells with B_{max}/B_{min}=4.8/3.2 T (the mirror ratio R=1.5). Deuterium plasma of $10^{20}\div10^{22}$ m^{-3} density is heated up to ~2 keV ion temperature (at ~10^{21} m^{-3} density and τ_E~1 ms) by a high power relativistic electron beam. Typical beam parameters in a standard configuration are ~0.8 MeV, ~20 kA, ~12 μs, ~120 kJ. Use of multimirror confinement scheme (the corrugated magnetic field) allows confining the hot plasma much longer, than in a simple solenoidal trap.

The discussed experiments feature a reduced-cross-section electron beam with the current decreased down to 1÷1.5 kA at the current density of ~1 kA/cm^2 (the same as in the "full-scale" experiments). The beam and hot plasma cross-section was reduced down to 13 mm.

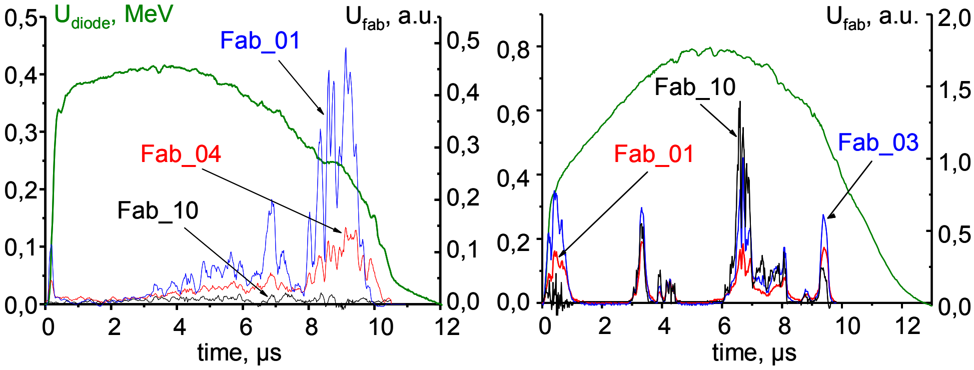

Fig. 1. Waveforms of the diode voltage (smooth envelopes) and of three channels of the multifoil analyzer of the beam spectrum. The left part is for a shot into vacuum, the right part is for a shot into the plasma.

EXPERIMENTS WITH THE THIN BEAM

Check of existence of turbulent thermal insulation of the plasma at the tenfold smaller current and power of the beam was the main physical task for the experiments on interaction of the reduced-cross-section beam with the plasma and neutral gas. In [3] we have shown that plasma heating within the beam cross-section remains almost the same as for the case of full-scale beam. Despite the beam transport through the plasma column was stable in general, some displacement of the beam-heated zone was observed. These displacements were different not only in different shots but also can change in the course of one experiment.

Two sets of waveforms are shown in Fig. 1. The left part corresponds to a calibration shot into vacuum with the beam of decreased energy. Signals from the analyzer of the exit beam spectrum are continuous and last for expected duration despite being heavily spiked due to known microstructure of the beam. At the same time in a typical shot with the plasma the same signals undergo simultaneous breaks and recoveries. The quantity and duration of such breaks varies from shot to shot, while exit bremmstrahlung always remains continuous. The relaxation efficiency remains practically constant over those fragments of waveforms where such calculation is possible. Such situation can be naturally explained by the beam footprint displacement with the amplitude which is at least comparable with the analyzer aperture.

Signs of the beam displacement from the axis are also detected with other diagnostics. Simultaneous measurements in two radial points by a Thomson scattering system were done. At the stable beam transport should always be hotter than at the edge, such situation is presented in Fig. 2. Nevertheless reverse and other cases were also observed. Such behavior evidences for large shot-to-shot displacement of the beam position. The observed displacement of the beam at the Thomson scattering system location is still small enough and the beam remains within the preliminary plasma cross-section.

Direct comparison of the beam injection into preionized or neutral gas became possible for the first time at GOL-3. Earlier fast development of the Kruskal-Shafranov instability

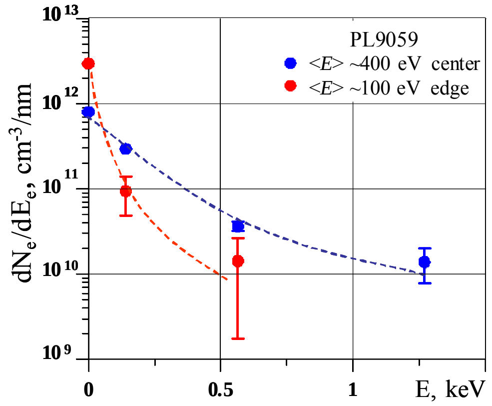

Fig. 2. Energy spectrum of plasma electrons measured by a Thomson scattering system simultaneously for the point at the axis (at the expected beam center) and 6 mm apart (at the expected edge of the beam-heated zone).

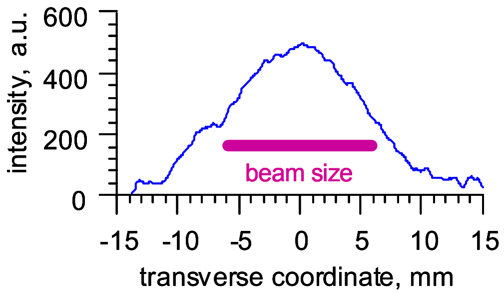

Fig. 3. Radial profile of OV 76.0 nm emission (beam shot into the gas).

occurred at the beam injection into a neutral gas with the beam dump to the wall. Efficiency of the beam relaxation in the gas is about twofold worse than in the plasma. The same twofold difference was observed for the peak energy which the beam leaves in the plasma. Similar conclusion on significant role of preliminary ionization was earlier made in the experiments [4] with shorter plasma column in uniform magnetic field. Experiments with the non-ionized gas enable studies of formation of the return current which in turn creates the edge plasma. Observed time-integrated VUV profile is broader than the expected one (see, e.g., Fig. 3). Interesting that ionization of the gas and formation of the edge plasma occur not only within the expected beam cross-section but in the whole cross-section of the vacuum chamber. Therefore evolution of the beam-plasma system at later stages of the experiment is similar to that observed in the experiments with the preliminary plasma.

STABILIZATION OF THE ELECTRON BEAM

As was already mentioned in [3], some displacements of the electron beam from the axis were observed. These displacements do not lead to the beam dump to the wall; this means that amplitude of the displacement was limited. This differs the case from the Kruskal-Shafranov instability which was observed earlier in unstable GOL-3 operation regimes.

Several causes of the observed instability are possible. One of them is an asymmetry of return plasma current. In the discussed experiments the exit beam receiver was placed in the low-field part of the exit expander in order to decrease the specific energy load to its surface down to allowable level. Such placement of the receiver complicates formation of the return current through the plasma column, therefore the return current can became non-axisymmetrical. This in turn can provide displacement of the beam as a whole and loss of its shape.

A special experimental series with varied conditions of formation of the return current was completed to check this assumption. For this purpose a heavy gas (krypton) was puffed in the vicinity of the beam receiver. Net puffed mass and gas distribution along the axis were varied in the experiments.

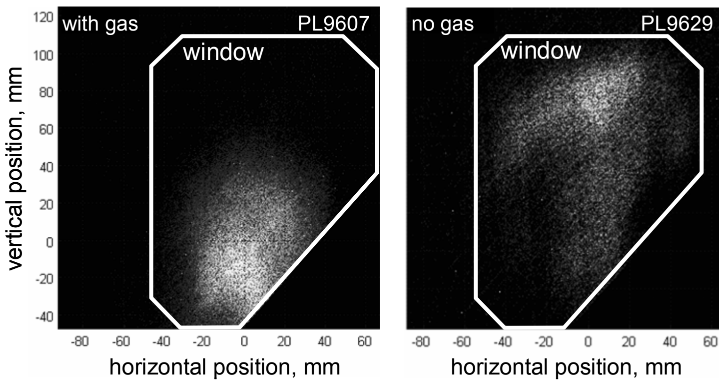

Fig. 4. Hard X-ray image of the exit beam footprint. Exposure is 1 μs. Left part: krypton was puffed near the receiver. Right part: no gas-puffing. White contour shows the field-of-view of the X-ray imager which is restricted by the device structure.

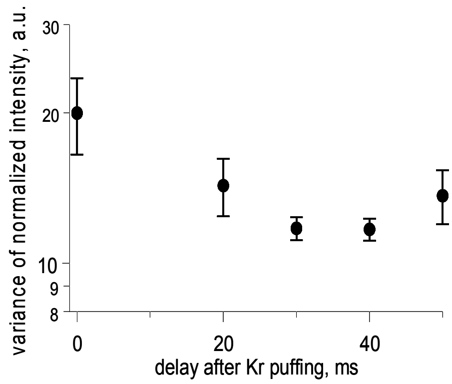

Fig. 5. Dependence of asymmetry of the X-ray image of the beam footprint on the delay of the beam start after the krypton puffing.

Displacement of the footprint from the expected position and change of its shape were detected with an X-ray imaging system in own bremsstrahlung of the beam. Right part of Fig. 4 shows a typical image of the footprint which is distorted and non-symmetric. Krypton puffing near the beam receiver improves the footprint shape. The gas-puffing technology results not in absolute but in statistical improvement of the beam transport. Averaged over large series of shots improvement of stability of the beam-plasma system occurs with the reduced deviations of the beam shape and position in optimal gas-puffed regimes (see Fig.5). Similar statistical improvement is also visible from several other diagnostics, including magnetics and wall bolometers.

SUMMARY

Experiments with the thin beam at the multiple-mirror trap GOL-3 in general confirmed existing understanding of underlying physics at tenfold-decreased beam power and plasma cross-section. Initial preionization of the plasma is important for effective beam-plasma interaction. The beam with $q < 1$ partially loses stability but stays within the plasma. Conditions for generation of the return current are important for stable beam transport through the plasma column. Improvement of the stability was demonstrated.

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REFERENCES

[1] *A. Burdakov, et al.,* Fusion Science and Technology, **55** (No. 2T), 63 (2009).
[2] *V. V. Postupaev, et al.* Fusion Science and Technology, **47** (No.1T), 84 (2005).
[3] *V. V. Postupaev, et al.,* 36th EPS Conf. on Plasma Phys., P-4.151 (2009).
[4] *A.V. Arzhannikov, et al.,* 8th Intern. Conf. on High-Power Particle Beams, Novosibirsk, **1**, 14 (1990).