First Experiments on Injection of High-Power Long Pulse Electron Beam in Multiple-Mirror Trap GOL-3

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1.Introduction

GOL-3 is the facility intended for studies of physics of fast collective plasma heating by a high-current electron beam and for studies of physics of multiple-mirror confinement [1] of high-temperature plasma in corrugated magnetic field. The main feature of plasma behavior in the facility is the key role of collective and non-linear processes.

Motivation of the experiment is the following. During the last years the several key physical phenomena (including enhanced confinement, fast collective heating of ions, suppression of electron heat transport and some other) were identified in the experiments with plasma heating by ~20 GW ~10 µs electron beam [2]. In general, achieved plasma parameters (plasma temperature ~1 keV at 10^{21} m^{-3}, energy confinement time ~1 ms) support our vision of a multiple-mirror trap as the alternative path to a fusion reactor with ß~1 and $10^{20}\div10^{21}$ m^{-3} plasma density. A project of a new linear trap with multiple-mirror end plugs based in particular on GOL-3 results is in progress in BINP [3, 4]. The main problem to be solved by the new facility is in increase of the plasma sustainment time. New approach to fusion reactor suggests application of a long pulse or continuous ~10 MW electron beam injection for control of plasma turbulence. Development of the required long pulse electron beam technology has been started.

2.Modeling

One of the key issues related to the design of the beam injector the cathode capable to emit a current density of the order of tens of A/cm^2 and the required total current of ~1 kA with a pulse duration in the millisecond range, and an electrode structure that enables the extraction and acceleration of high current high brightness electron beam. Among different

Fig. 1. Simulation of an electron beamlet in a single diode aperture. The left side is the cathode with a cathode plasma, the right one is the anode with a stream of plasma. Diameter of the cathode aperture is of 3 mm, anode one is 4.4 mm, the diode gap is 12 mm, the voltage is 100 kV, the electron current density averaged over the cathode aperture is 63 A/cm^2, the ion current density at the anode is ~1 A/cm^2, the diode current is 1.1 kA. The maximum pitch angle of electrons is ~0.07 rad. The magnetic field is 0.05 T.

types of cathodes suitable for producing such a beam, the plasma cathode looks promising because it can provide a long beam extraction, high current density and survival at poor vacuum conditions. It seems rather natural decision to use a plasma cathode for the electron beam injection into a plasma trap. The extraction and acceleration of high perveance electron beam with required brightness can be achieved in multiple aperture electron optic system, where the total beam current is the sum of the currents of many beamlets [5].

Other problem to be solved is impact of a high-power plasma flow from the trap to the electron beam source. Both effects should be taking into account in modeling of multiaperture plasma diode. Algorithms for computation of shape of plasma boundaries in the low-temperature approximation of uniform emission from the surface were developed earlier for modeling of diodes with plasma electrodes. To account effects of thermal and directional movement of the plasma flow to characteristics of a diode, the problem of potential distribution in the gap between cathode and anode plasmas was solved and the results were applied in the computer code POISSON-2 for simulation of beam formation in systems with plasma emitters. The model also takes into account restriction of the emission fluxes orificing

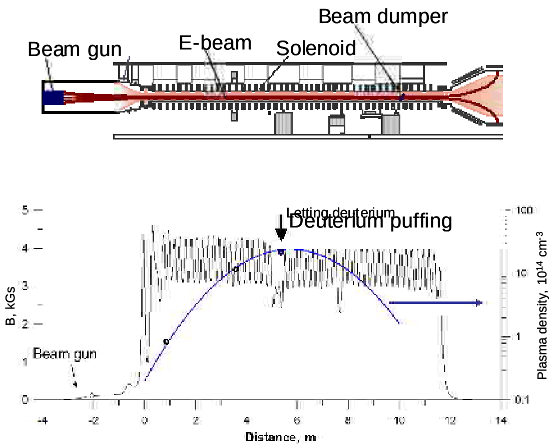

Fig.2. Experimental layout. Above: scheme of multi-mirror trap GOL-3. Below: magnetic field B_z and initial gas density n.

by the cathode and the anode apertures, leading to heterogeneity of emission of the plasma surface. Formation of an electron beamlet from a single cathode aperture of a plasma-cathode-based multiaperture source was simulated in the axisymmetric approximation. Conditions of the electron beam formation at the source with the design parameters (100 kV, 1 kA, 100 μs or more) were determined with features that allow 100-fold compression of the beam by guiding magnetic field, see Fig.1. In the numerical simulation of the diode exposed by he incident plasma flow a lossless motion of particles accelerated in the diode gap through the cathode and anode apertures without leaking to metal electrodes of the diode was achieved.

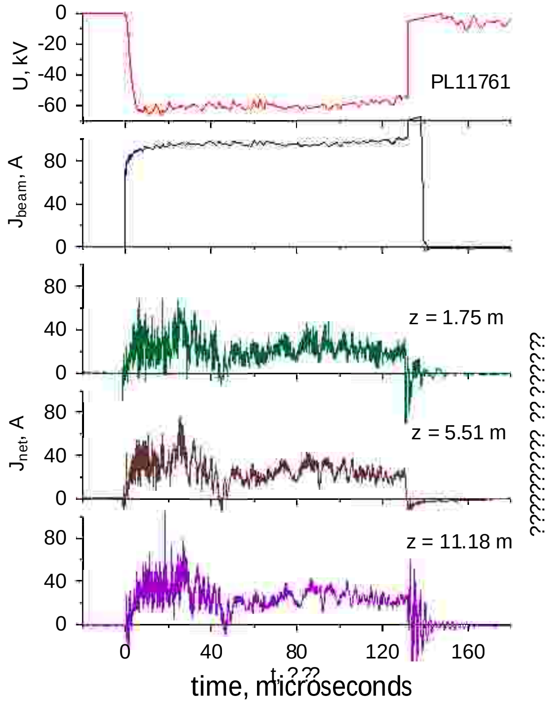

Fig.3. Above: accelerating voltage. Below: waveforms of net current in different cross-sections.

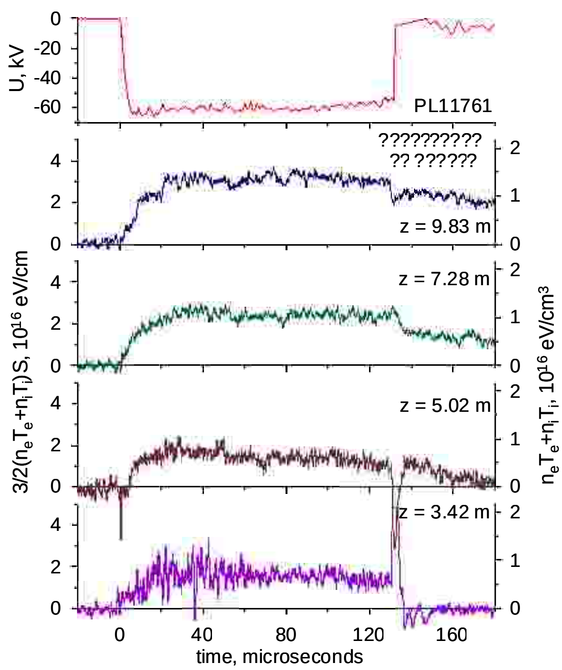

Fig.4. Diamagnetism of plasma in different cross-sections. Operating mode: ne ~ $(0.5\text{-}0.9)\times10^{20}$ m^{-3}, <B> = 0.31 T.

3. Experiment

A source of the high-power electron beam of a new type, based on a plasma emitter, was developed and installed into the end expander tank of GOL-3 for injection into 12-meter long solenoid of GOL-3 (Fig2) [5]. The beam with the emission current density of up to 20 A/cm^2 was formed in a multiple-aperture diode electron optic system at 100 kV accelerating voltage. The maximum achieved beam power was 10 MW.

Magnetic field has 52 corrugation periods (cells of multimirror system) with 22 cm length, the field in maxima is 4.8 T, and in minima is 3.2 T. Typical experimental scenario is the following. Several gas-puff valves create required axial deuterium density distribution in a metal vacuum chamber Ø10 cm, placed inside the solenoid. After that the electron beam is injected into this plasma. In the experiments the beam was compressed in 50÷200 times and then transported through the 12-meter-long trap prefilled with deuterium of up to 10^{20} m^{-3} density.

Stability of transportation of the beam was specified by measurement of radial profile of beam after its passing 15-meters plasma column and by radial image in visible with temporal resolution. Global instabilities of beam das not observed. Current registered in different point along the trap by Rogowski coils were in reasonably good agreement, in most case registered current was lower than the beam current in diode as Jnet ~ 1/3 Jb (Fig3.), the beam current was partially neutralized by counter flow of the plasma current. A part of the beam could be lost in compression area between an entrance (an input) mirror and the diode.

Beam injection in gas leads to its ionization and plasma heating. Plasma pressure (diamagnetism) was increased during ~ 20 microseconds and then it is stabilized (Fig.4). Typical mean energy of electron-ion pair is 100-150 eV. Thomson scattering also indicate increasing electron temperature up to 20-50 eV, during beam injection Soft X-ray emission increased. After the end of the beam pulse diamagnetism and soft X-ray decreased with characteristic time of 1 msec.

4. Summary

The new technology of high-power electron beam injection for plasma heating based on plasma emitter and multi-aperture diode was developed. The electron beam gun (10 MW, 100 kV, 0.1-0.5 ms) was integrated into the multiple-mirror trap GOL-3.

Beam compression by the magnetic field (up to 200 fold) and its stable transportation in the 15-meter-long trap was demonstrated. Plasma heating by the beam at 10^{19}-10^{21} m^{-3} density was observed by several diagnostics. The beam duration allows us to study plasma properties in a quasistationary state for the first time in GOL-3. Distribution function of plasma electrons is a non-Maxwellian as is usual for beam-plasma experiments.

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