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ADVANCES IN TURBULENT PLASMA CONFINEMENT IN MULTIPLE-MIRROR TRAP GOL-3

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Main physical task for GOL-3 is the development of physics of a multiple-mirror plasma confinement for fusion [1]. Relatively high density and short plasma lifetime in the trap require a high-power heating system. Relativistic electron beam is used for this purpose. The plasma heating and confinement in the trap are of essentially turbulent nature. A keV-range electron temperature was obtained due to 1000-fold turbulent suppression of axial heat losses during the beam pulse [2] that is provided by Langmuir microturbulence, excited in the process of the beam relaxation in the plasma. The turbulence also creates sheared magnetic field which provides MHD stability [3]. In general, achieved plasma parameters support our vision of a multiple mirror trap as the alternative path to a fusion reactor with β~1 and $10^{21}\div10^{22}$ m^{-3} plasma density. This paper contains new experimental results with the beam of reduced cross-section.

DEVICE AND OPERATION REGIME

The plasma of $10^{20}\div10^{22}$ m^{-3} density is confined in a 12-meter-long solenoid, which produces axially periodical (corrugated) magnetic field. In the basic operation regime the solenoid consists of 52 magnetic cells with B_{max}/B_{min}=4.8/3.2 T (mirror ratio R=1.5). The plasma is heated up to ~2 keV (at ~10^{21} m^{-3} density and τ_E~1 ms) by a high-power relativistic electron beam (~0.8 MeV, ~20 kA, ~12 μs, ~120 kJ). A feature of new experiments is the reduction of diameters of the beam and of the heated plasma to 13 mm (see Fig.2). A small central part

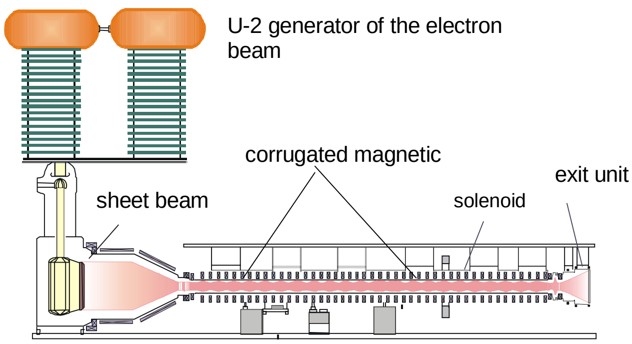

Fig. 1. Layout of GOL-3.

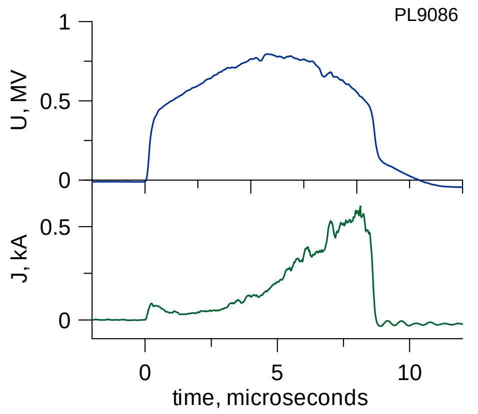

Fig. 2. Waveforms of the diode voltage and of the beam current (vacuum shot shown, in plasma shots the beam current reaches ~2 kA).

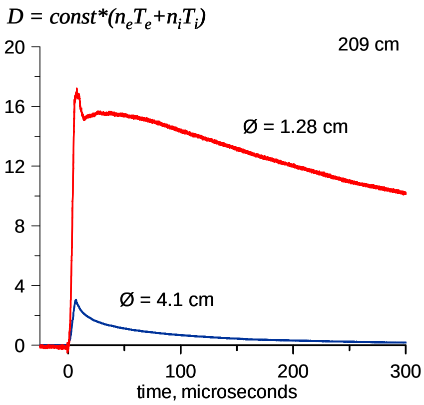

Fig. 3. Dynamics of plasma pressure from diamagnetic measurements for the cases of thin and standard electron beams at 209 cm distance from the input mirror. Waveforms are normalized for calculated vacuum cross-sections of the electron beam.

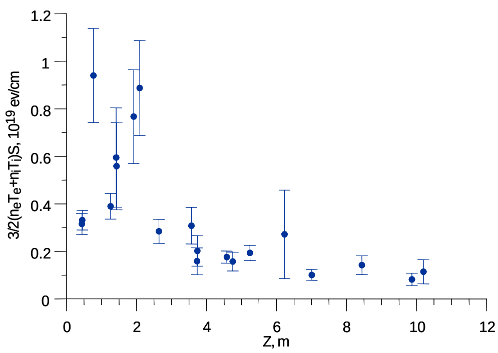

Fig. 4. Axial dependence of plasma energy content per unit length in the experiments with the thin beam. Statistical spread for a series of 20 shots is shown. Data were recalculated for 4 T magnetic field corresponding to the mean field in the corrugation cell.

was cut from the standard beam by means of a graphite limiter placed in the area of a final beam compression before the solenoid. Further in the text such beam will be referred as the thin beam. The current density of the thin beam in the plasma remained the same as for the full-sized one and quality of the thin beam improves because of smaller average pitch angle due to smaller own magnetic field at the beam edge.

EXPERIMENTS WITH THE THIN BEAM

Feature of this beam is that its current becomes essentially less than a limiting vacuum current. Thus experiments became possible not only with injection of the beam in the low-temperature start plasma, but also with the beam injection in the vacuum and in a non-ionized gas. Two latter cases are unavailable with the full-current electron beam. Besides it, at the reduction of the beam diameter the ratio of the hot plasma cross-section to its perimeter worsened. Accordingly, the role of transverse energy and particle losses increases comparing with the standard operation mode with a good confinement where transverse losses do not exceed 10% in global energy balance. Spatial distribution of axial currents flowing along the plasma changes also, i.e. helical structure of the magnetic field in the confinement area (on which quality of the plasma confinement in GOL-3 depends) changes too.

Results of experiments with the thin beam appeared more interesting, than it was expected. The plasma heating within some interval at first two meters from the beam injection point appeared better, than it was expected at simple recalculation for the new diameter of the electron beam (see Fig. 3). We should notice that for the thin beam there is a pressure maximum in axial distribution over the plasma length at this coordinate while for a full-sized beam this maximum is displaced closer to the input mirror and has smaller amplitude. At the rest of the plasma column the beam moves through the plasma already in partially relaxed condition so the plasma heating coincides with that was observed with the standard beam, as it was expected (see Fig. 4).

At ≈2 kA/cm^2 current density of the beam the safety factor $q(0) \approx 0.3$, so the beam-plasma system should be unstable. Displacement of the beam from its expected position was really observed in the experiment. This was detected by radial profiles of attenuation of a probing neutral beam and by spatial distribution of VUV emission of oxygen impurity ions. The beam appeared displaced to different points of plasma section from shot to shot. Thus the beam transportation through the plasma was steady as a whole, i.e. the beam dump to the chamber wall with fast plasma decay was not observed. Energy confinement was good in general. The observable phenomena can testify that the instability really develops, but displacement of the beam saturates because of self-organization of the plasma and formation of globally stable specific structure of return plasma currents in it. Special experiments with puffing of dense high-Z gas demonstrated stabilization of the beam footprint due to improved conductivity of the expander plasma.

EXIT BEAM ENERGY SPECTRUM

Energy spectrum of electrons at the output of the beam from the plasma determines the degree of the beam relaxation in energy and its average energy losses. It also allows estimating the energy density of resonant with the beam Langmuir fluctuations. The energy spectrum was measured with simple and reliable diagnostics, based on an energy dependence of range of electrons in an absorber. Electrons passed the trap were dumped in a stack of metal foils. Having measured the currents from the foils one can reconstruct the energy spectrum of incident electrons.

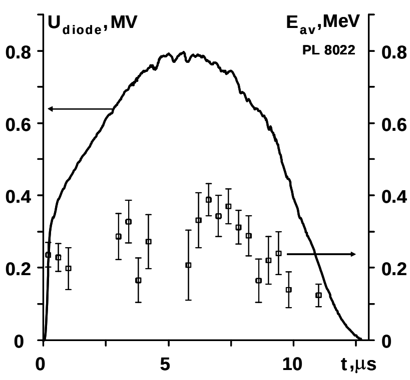

Fig. 5. Time dependencies of the initial beam energy (the diode voltage) and average energy of electrons in the range 0.1÷0.8 MeV at the plasma exit.

Intense relaxation of the beam in the plasma is accompanied by essential broadening of the energy spectrum and its shift to lower energies of electrons. A group of electrons with energies in the range 30÷100 keV is observed; this group consists of both strongly decelerated electrons of the beam and accelerated electrons of the plasma. The density of this group is comparable to the beam density. Average loss of the beam energy in the plasma estimated from the energy spectrum in the range 0.1÷0.8 MeV exceeds the level of 50% (see Fig. 5). At the beam injection into a neutral gas the plasma heating efficiency decreases, the average loss of the beam energy is somewhat lower and does not exceed 35÷40 %.

SUBTERAHERTZ EMISSION FROM THE PLASMA

A distinctive feature of a plasma with a developed Langmuir turbulence is possibility of electromagnetic radiation emission in the vicinity of the double plasma frequency. In this process the $2\omega_p$ photon appears as a result of nonlinear merging of two Langmuir plasmons. For $10^{20}\div10^{21}$ m^{-3} density range the linear frequency of $2\omega_p$ emission is within the range 180÷565 GHz. We have developed a four-channel radiometric system with channels preset to 280, 315, 350 and 380 GHz. Emission of sub-THz radiation was experimentally observed during the period of electron beam injection (Fig. 6). Sharp spikes of emission with duration ~5 ns were detected against a slower background envelope along with spectrum transformation at the final stage of the beam injection. Such peaks may evidence an existence of transient localized events in the plasma like a collapse of Langmuir caverns earlier predicted in [4] and found in [5]. At present, we continue experiments for clarifying details of underlying mechanism of sub-THz emission and study its power spectrum in different operational regimes of the GOL-3 facility.

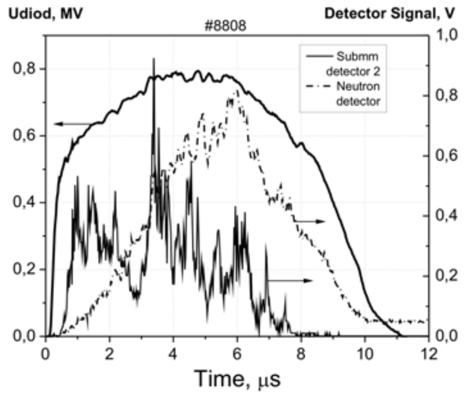

Fig. 6. Typical waveforms: voltage of the electron beam generator and signals of neutron and sub-THz detectors.

SUMMARY

Experiments with the thin beam at the multiple-mirror trap GOL-3 in general confirmed existing understanding of underlying physics. Efficiency of the beam relaxation reached ~50% due to better quality of the paraxial part of the electron beam. Sub-THz plasma emission at double plasma frequency was measured. Control of Kruskal-Shafranov instability with a change of electric coupling of the plasma with the exit receiver was demonstrated.

ACKNOWLEDGEMENTS

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