Status of GOL-3 Multiple Mirror Trap Experiments

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Abstract. New experiments in two operational regimes of the GOL-3 Multiple Mirror Trap are considered. The plasma is confined in an 11-m-long solenoid with axially-periodical (corrugated) magnetic field that consists of 52 magnetic corrugation cells with $B_{max}/B_{min} = 4.8/3.2$ T. In the first regime, deuterium plasma of 10^{20}-10^{22} m^{-3} density is heated up to ~2 keV ion temperatures (at ~10^{21} m^{-3} density and confinement time ~1 ms) by a high power relativistic electron beam. Results of study of MHD stability of the beam-plasma system are presented. In the second regime, plasma heating and stabilization in the trap was provided by 20 MW, 100 keV electron beam. Possibility of plasma rotation control by the beam injection is shown. Results of study of collective beam-plasma interaction via electromagnetic emission are presented. This electron beam was used for plasma-material interaction studies in ELM-like conditions. First results from *in situ* optical diagnostics for vapor and droplet characterization are presented.

1. Introduction

The main physical goal of our studies is the development of physics and technology for a multiple-mirror fusion reactor concept that was originally proposed in early 1970ies [1]. In our previous experiments [2], an effective plasma confinement at the density of ~10^{21} m^{-3} and the temperature of ~2 keV in the 12-m-long solenoid with corrugated magnetic field was demonstrated; the enhancement of longitudinal plasma confinement due to collective effects was shown [3]. Based on those results, as well as on GDT data [4], a new scheme of the open-trap-based reactor was proposed [5]. The new project combines the features of the existing GOL-3 and GDT devices. Namely, the central GDT-like cell with sloshing ions produced by intense neutral beam injection is combined with the multiple-mirror end sections suppressing axial plasma losses. Such a combination became feasible due to recent advances in both GOL-3 and GDT devices. In particular, it was shown that reasonably small radial transport can be provided by introducing a sheared rotation of plasma edge even if the plasma is not formally MHD stable. This allows employing the multiple-mirror sections with unfavorable average field-line curvature thus avoiding introduction of the complicated MHD stabilizers.

Previously, we have experimentally demonstrated that the multiple-mirror confinement can be efficient at lower plasma densities in comparison with the theoretical estimates due to collective rather than binary scattering of ions [2]. This supports our vision that the multiple-mirror end solenoids can effectively suppress the axial losses at $\beta < 1$ in the central cell. Besides additional plasma heating, pulsed injection of electron beams can be used for plasma biasing for the regimes where traditional electrodes become ineffective.

2. Operational Regimes of GOL-3

2.1. Multiple Mirror Trap With Relativistic Electron Beam

In this regime the relativistic electron beam (REB) of 0.5 – 0.8 MeV, 20 – 30 kA, 8 μs was injected in an 11-m-long solenoid with axially-periodical (corrugated) magnetic field that consisted of 52 magnetic corrugation cells with $B_{max}/B_{min} = 4.8/3.2$ T (FIG.1).

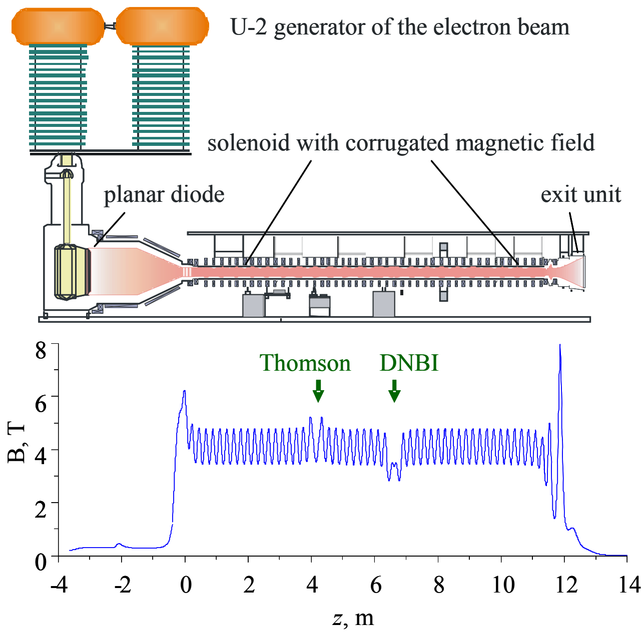

FIG. 1. Layout of the GOL-3 experiment (top) and axial dependence of the magnetic field (bottom). Axial coordinate z is measured from the centre of the high-field coil at the beam input side. Arrows at non-regularities of the magnetic structure indicate locations of Thomson scattering system and Diagnostic Neutral Beam Injector.

2.2. Configuration with 20 MW Electron Beam

The new version of intense long-pulsed electron beam source with plasma emitter has been developed at BINP for the experiments on beam injection in GOL-3 – see FIG. 2. The beam is formed in a planar diode-type electron optical system with 499 small round apertures arranged in a hexagonal pattern. Diode optics allows more than 100-fold beam compression in adiabatically converging magnetic field. The injector was installed in the end tank of GOL-3 multiple mirror trap, and tested to produce ~100 keV electron beam of power up to 20 MW in submillisecond pulse duration range. Application of pulse modulator has allowed to generate a series of 25 – 30 μs pulses during 200 – 300 μs.

In the experiments, the beam was injected into GOL-3 plasma chamber filled with deuterium gas with 10^{19} – 10^{21} m^{-3} density and transported in the corrugated magnetic field at mean magnetic field up to 1.4 T. The beam transport and compression were observed with several diagnostics including high speed visible and X-ray cameras.

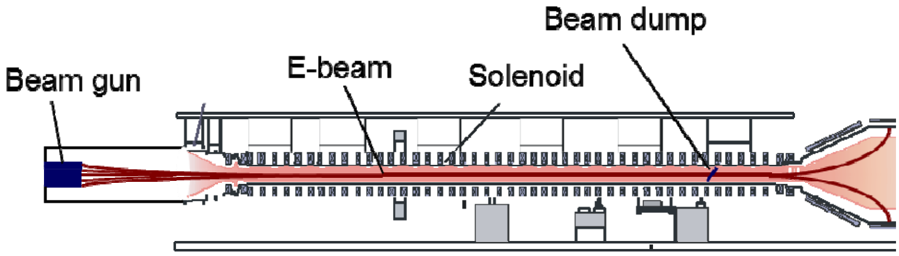

FIG.2. Layout of the GOL-3 experiment with 20 MW electron beam

The electron beam collectively interacts with plasma. It excites strong Langmuir turbulence. As a result of collective beam-plasma interaction beam energy losses, plasma heating, generation of electromagnetic radiation in plasma, suppression of conductivity and heat conductivity of plasma are appeared. During compression (50-200 times) powerful (>10 MW) E-beam in a magnetic field a reduction of the beam duration because of diode breakdown is observed. This problem needs more detailed study.

3. MHD stability of the beam-plasma system

MHD stability of the plasma should be noted as one of the key problems of the linear traps limiting plasma parameters. Plasma stability in GOL-3 is provided by controlling of the radial current profile that creates the required magnetic shear, and by controlling of the plasma potential that causes differential $\boldsymbol{E}\times\boldsymbol{B}$ rotation of the plasma column. Due to the linear topology of the device, the axial injection of the electron beam is used for both purposes. The beam-plasma interaction maintains a high-level microturbulence during the beam injection that in turn suppresses electric conductivity in the core and therefore expels the return current to the edge. This provides an unusual radial profile of the net current (that consists of the beam current, current of the preliminary discharge, and the return current) [6].

In the experiments with a high-power relativistic electron beam (0.5 – 0.8 MeV, 20 kA, 10 μs), the plasma core carries supercritical current density with the typical safety factor $q(0) \approx$ 0.3 – 0.5, but as a whole the plasma is stable with $q(a) \approx$ -4. Here negative sign of $q(a)$ means that helicities of the magnetic field in the core and at the edge are of different sign. The net plasma current is counter-directed to the beam current. This forms a system with a strong magnetic shear that stabilizes the plasma core in good confinement regimes. The magnetic configuration is stable if operation regime is set properly. Cold plasma shell outside the beam-heated turbulent zone is necessary for MHD stability of the beam-plasma system. In some cases when the cold plasma was not pre-created properly, the plasma lost stability and disruptions occurred.

Large-scaled instabilities during the injection of the beam were studied both in macroscopically stable shots and in disruptions. The most pronounced azimuthal mode in both regimes is the mode m = 1. Slow ($t \sim$ 10 μs) dynamics of the magnetic fluctuations is identical in the shots with the same gas density. Mode amplitudes are larger up to an order of magnitude in disruptions (FIG. 3).

At the same time, details of the spectra differ in stable and unstable shots. In stable experiments, transition to higher azimuthal modes with time was observed [7]. During the disruption, plasma cross-section became highly asymmetric; all spatial modes grew with roughly the same rate. Plasma touched limiter in less than 10 μs since the beam injection start - see FIG. 4.

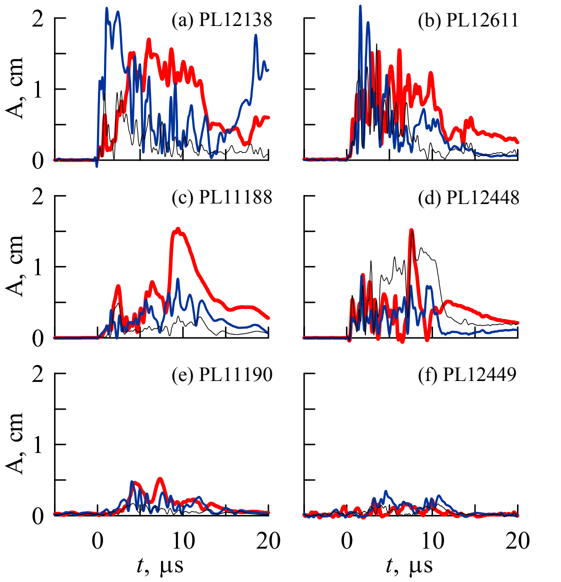

FIG. 3. Evolution of amplitudes of azimuthal modes m = 1 (thick lines), m = 2 (medium lines), and m = 3 (thin lines) in shots with disruptions (a)–(d) and in normal shots (e), (f). The beam injection started at t = 0.

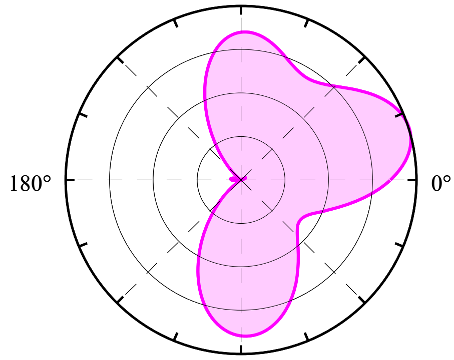

FIG. 4. Shape of reconstructed magnetic boundary in the disrupted shot PL11188 at t = 10 μs. Thick outer line corresponds to the limiter at a = 4 cm. Distances between thin circles are of 1 cm.

Longitudinal mode structure was identified basing on the phase shift between single azimuthal modes in cross-section $z = 514$ cm and signals from coils at $z = 288$ cm and $z = 464$ cm after the subtraction of the $m = 0$ mode. Mode $m = 1$ demonstrated good correlation with the typical correlation coefficient 0.7 – 0.8. Correlations of the higher modes were less pronounced. Phase shifts were the same for the stable and disrupted shots. Measured phase shift $\Delta\varphi/\Delta l \approx 0.57$ m^{-1} corresponds to the full turn at the device length, see FIG. 5. Therefore, we can conclude that the most intense observed magnetic perturbations mode is the well-known $n = 1$, $m = 1$. Most probably, that we observed the kink mode that became saturated by direct contact with the limiter.

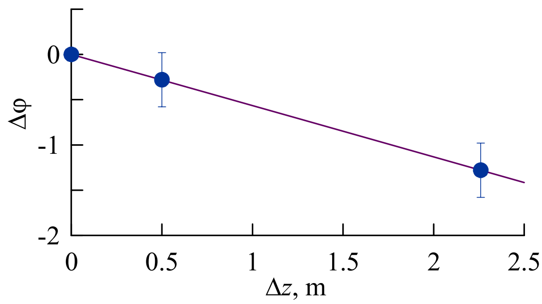

FIG. 5. Dependence of the phase on the coil distance relatively to the 16-channell array.

4. Charge injection in GOL-3

Control of the radial profile of plasma potential is an important tool that is used for confinement improvement in different experiments, in particular, in the GDT trap [8]. In GDT, plasma potential is controlled by biasing radial limiter and an endplate. In GOL–3 experiments, an alternative method of potential control with charge injection into plasma by the electron beam was studied recently.

In addition to collective plasma heating, the electron beam carries an electric charge that changes plasma potential within the beam-heated cross-section. A classical high-temperature plasma has high electric conductivity. Therefore, good compensation of an externally-injected charge occurs. However, under conditions of an intense beam-plasma interaction, the beam-induced plasma turbulence leads to enhanced scattering of electrons that in turn suppresses both electric and thermal conduction [9]. The beam therefore can be used as a tool to control the plasma electrical conductivity and its ability to carry an excessive negative electric charge.

In previous GOL-3 experiments, measurements revealed the reversed rotation of magnetic plasma boundary perturbations during the beam injection time that was interpreted as $E\times B$ drift with a negative potential at the axis during the beam injection and a positive one after it. Excess charge density was maintained by the anomalous resistivity of the plasma inside the beam cross-section. New data on the plasma rotation was obtained with a multipulse injection regime of the sub-ms electron beam. Up to 7 beam pulses of 30 μs each and 1:1 duty factor were injected in GOL-3. The first pulse was injected into deuterium gas; it created the plasma. The next pulses are injected in the already existing plasma. The main difference is in the initial resistivity of the plasma column for each pulse that changes conditions of the return current propagation.

Rotation direction inversion was observed in every individual beam pulse provided the current above some threshold value (FIG. 6). Between the pulses, the excessive negative charge was carried away by axial currents and the “natural” rotation direction restored.

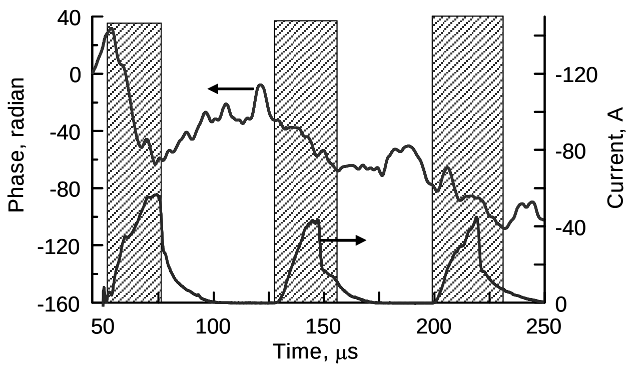

FIG. 6. Inversion of the rotation of the magnetic fluctuations during the injection of the multiple-pulse beam.

At the same time, correlation of the rotation of the magnetic fluctuations with the directed motion of plasma ions is still questionable. Doppler spectrometry of the C^+ impurity ions did not revealed evident correlation of the mean velocity of the outer plasma layers with magnetic fluctuations propagation.

5. Electromagnetic emission from plasma with beam-induced turbulence

Studies of electromagnetic emission from a beam-plasma system have considerable interest for astrophysics because they can clarify generation mechanisms of radio waves in space at fundamental electron plasma frequency (f_p) and in the vicinity of second harmonic plasma frequency ($2f_p$), see [10] and following papers. These types of plasma emissions have been investigated in laboratory beam–plasma experiments in the case of non-relativistic weak electron beams in past two decades (see, e.g. [11]). In GOL-3, sub-THz plasma emission was studied in both mentioned configurations of the experiment [12-14].

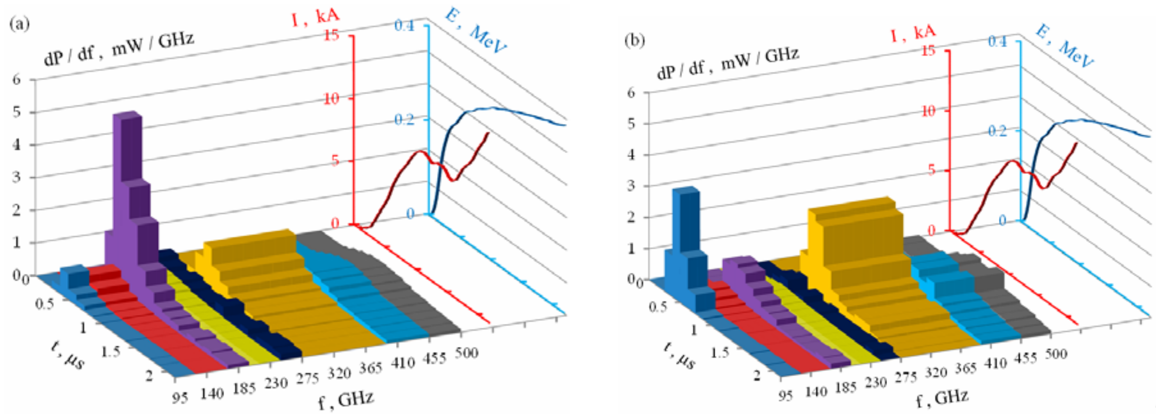

FIG. 7. Dynamics of the spectral power density of electromagnetic emission from the plasma with the polarization parallel (a), and perpendicular (b), to the magnetic field in the plasma.

In the described series of experiments, we used the relativistic electron beam. Electromagnetic emission was observed at z = 1.9 m, the local magnetic field was 3 T. The density of about 2×10^{20} m^{-3} was measured in the same cross-section by the Thomson scattering diagnostics in eight bars across the plasma diameter. During the beam injection, the density within the beam cross-section increased up to 4×10^{20} m^{-3} with shot-to-shot variation within 30%.

Figure 7 presents temporal dynamics of the spectral power density obtained by polarization-selective polychromator. Presented data was averaged over 7 shots performed at the same beam and plasma parameters. In these particular conditions, the sub-THz emission existed during the first two microseconds. This emission has three spectral domains: near f_1 = 100 GHz and f_2 = 190 GHz, and in the range of f_3 = 270 – 400 GHz.

We identify that the observed emission in the f_1 and f_2 frequency bands was produced by the conversion of the electron plasma oscillations and the upper-hybrid oscillations into the electromagnetic radiation. In these cases, the most likely mechanism is the linear conversion of the plasma oscillations into the electromagnetic waves on strong gradients of the plasma density [15]. In turn, the upper-hybrid plasma oscillations are pumped by the electron beam and (or) by a high energy tail of the electron distribution function. Fast decreasing of the radiation intensity to zero after t = 1 μs can be explained by the fast growth in the plasma density. The polarization was primarily directed transverse to the magnetic field for the frequency f_1 and parallel to the magnetic field for the frequency f_2.

The frequency interval f_3 approximately followed changes in the double upper-hybrid frequency with variation of the plasma density. The polarization was mainly perpendicular to the magnetic field. It allows us to associate the emission in the frequency interval f_3 with the nonlinear the coalescence of two upper-hybrid waves. Computer simulations of this process gave similar radiation polarization [16]. Strong decrease in the emission from the heated plasma after t = 2 μs can be explained by decreasing level of the plasma turbulence W/nT at gradual growth of the temperature and density.

6. Observation of metal erosion under transient heat load produced by long pulse electron beam

The duration and power density (0.1 – 0.5 ms, 0.5 – 10 MJ/m^2) of new electron beam is very close to the parameters of the ITER ELMs. During irradiations at these conditions surface start to melt and can produce dust particle. Material erosion and parameters of dust particles is important for prediction of the ITER plasma-facing components lifetime and tritium retention. Experiments with irradiation of tungsten samples by the electron beam under ITER ELMs conditions were performed.

In the experiments carried out on the GOL-3 device several *in situ* diagnostic techniques for ablated material are employed. They include optical spectroscopy, laser scattering as well as imaging of droplets emission during and after heat load with the use of high speed photo camera. The spectroscopy shows dense line spectra of the target metal (tungsten or stainless steel) and characteristic scales for variation of the ablation plume parameters in the direction normal to the metal surface. Thomson scattering system is capable to measure plasma density at 15 spatial points across the ablation plume parallel to the metal surface two times during the heating pulse (see FIG. 8). Observations show dynamics of the plume profile during and after heat load but quantitative calculation of plasma density requires additional measurements to estimate contribution of the Rayleigh and Mie scattering into the total scattering signal. Imaging with 7 μs exposure shows that that dust particles are emitted from the metal surface during and after heating pulse. Multiple dust particles emitted with velocities decreasing with the delay from heating pulse are observed.

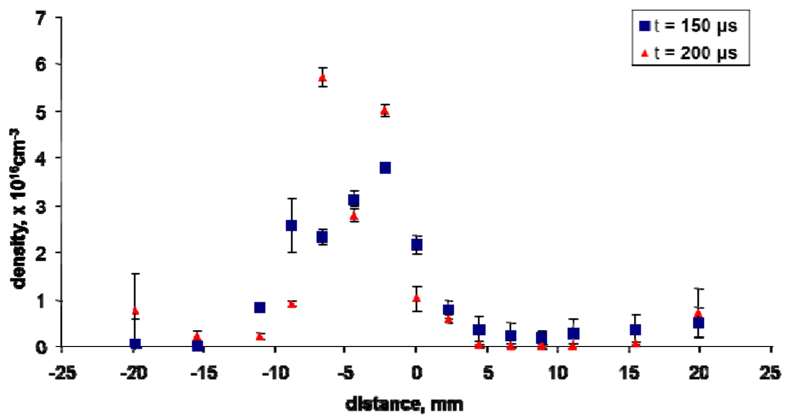

FIG. 8. Surface plasma density profile in PSI experiment measured by Thomson scattering. Two pulses laser beam (10 J, 30 ns, 1053 nm) passed at a distance of 9 mm from the surface of the W target.

7. Summary

Multiple-mirror Trap GOL-3 with relativistic electron beam:

- Energy confinement time (~1 ms at the density of ~10^{21} m^{-3} and electron and ion temperatures up to 2 keV) corresponds to theoretical value taking into account ion scattering on fluctuating fields.
- MHD stabilization is provided by sheared magnetic field. In stable operation regimes a displacement of hot plasma is less than 0.1 of plasma radius.

- On the basis of GOL-3 and GDT achievements, the project of advanced axisymmetric trap GDMT is proposed.

Multiple-mirror Trap GOL-3 with 20 MW electron beam:
- Plasma heating by the beam at 10^{19} – 10^{20} m^{-3} plasma density was observed by several diagnostics.
- Spectrum of intense microwave generation indicates to strong turbulence exited due to collective beam-plasma interaction.
- Possibility of charge injection and control of plasma rotation is shown.
- Plasma-surface interaction experiments demonstrate new possibility to study of surface plasma, gas and dust by spectroscopic and laser diagnostics.

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