New Experiments on the GOL-3 Multiple Mirror Trap

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Abstract. New physical results from recent experiments on collective plasma heating by a reduced-cross-section electron beam at GOL-3 are presented. Typical plasma parameters were ~10^{21} m^{-3}, 1-2 keV. Topics discussed are: new regime of device operation; efficiency of beam-plasma interaction and beam spectrum after passing the plasma; transverse energy losses, MHD activity and stabilization of the beam transport through the plasma; features of sub-THz emission at double plasma frequency; progress in electron beam generators for plasma heating. New GOL-3 experiments in general confirmed existing understanding of underlying physics for a new domain of operational parameters.

1. Introduction

Investigations on heating and confinement of dense plasma for development of a multiple-mirror confinement for fusion are carried out in GOL-3 [1, 2]. 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).

Plasma heating and confinement in the trap are of essentially turbulent nature. A keV-range electron temperature is obtained due to 1000-fold turbulent suppression of axial heat losses during the beam pulse 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} density. At the same time, it is clear that presence of turbulent fields in the plasma should lead to enhanced transverse losses. In the essentially new regime reported in this paper heating of the plasma was done by a reduced-cross-section electron beam of 13 mm diameter with the total current decreased tenfold comparing to the full-scale experiments (at the same current density of ~1 kA/cm^2). Main focus was on details of collective beam-plasma interaction.

2. Layout of Experiments with Thin Electron Beam

Details of the experiment are the following. Deuterium plasma of $(2\div8)\cdot10^{20}$ m^{-3} density is confined in a 12-meter-long solenoid, which produces axially periodical (corrugated) magnetic field (Fig. 1). The solenoid consists of 52 magnetic corrugation periods (cells of

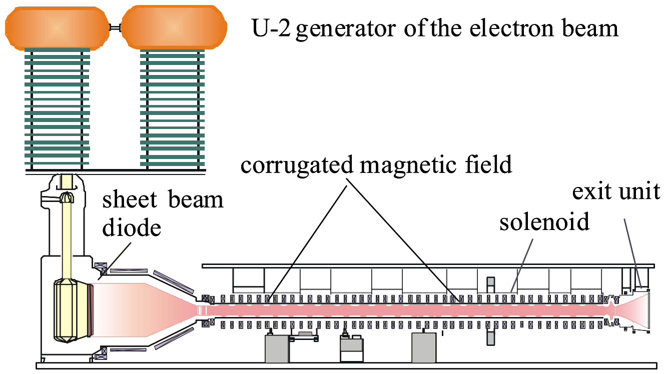

FIG. 1. Layout of GOL-3.

multimirror system) with 22 cm length each and mirror ratio R=1.5 (B_{max}/B_{min}= 4.8/3.2 T). The solenoid terminates in magnetic mirrors with a field of 8÷9 T. Initial density distribution along the axis is a bell-shaped profile, some dense gas is also puffed into a beam compression area – see Fig. 2. This profile slightly differs from the profile in standard configuration due to different gas flow in the vicinity of an input limiter.

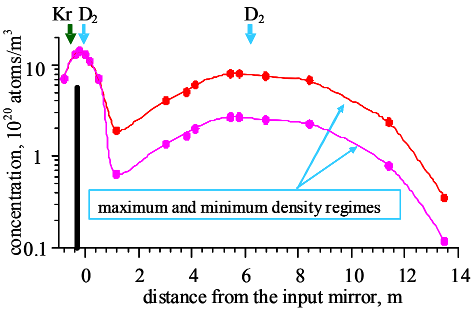

FIG. 2. Initial gas density profile. Bold line corresponds to location of input limiter.

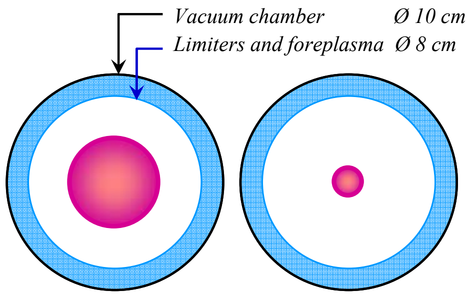

FIG. 3. Beam-heated cross-section of the plasma compared with vacuum chamber and limiters. Normal operation regime is at left, thin beam geometry is at right.

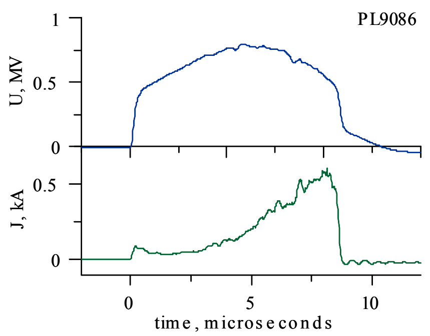

FIG. 4. Waveforms of the diode voltage and of the beam current (vacuum shot shown, in plasma shots the beam current is ~1.5 kA).

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 reduction of diameters of the beam and of heated plasma to 13 mm (see Fig. 3). A small central part was cut from the standard beam by means of a graphite limiter placed in the area of final beam compression before the solenoid. Further in the text such beam will be referred as the thin beam. Current density of the thin beam in the plasma remained at the same level of ~1 kA/cm^2 as for the full-sized one and quality of the thin beam is slightly better because of smaller average pitch angle due to smaller own magnetic field at the beam edge.

Typical parameters of the thin electron beam are shown in Fig. 4. Here we should remind that the thin beam was created by dumping of the main fraction of primary electron beam to a graphite limiter. Reliable measurements of the current can be done in clean vacuum conditions only. Plasma appearance mimic the beam current with plasma currents, so adequate waveforms of the beam current were obtained in special shots with low beam current - see Fig.4. Amplitude of the beam current in standard shots is higher and it can be estimated as ~1.5 kA from initial parts of the waveforms.

In shots into the preliminary plasma compensation of the beam plasma by the return plasma current is almost perfect in regimes with good confinement. The net current waveform follows the waveform of the discharge current – see Fig. 5. Waveforms of 8 Rogowski coils at different coordinates coincide within the calibration accuracy.

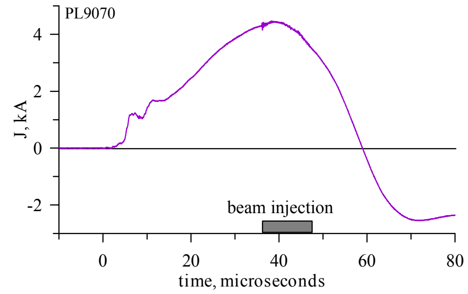

FIG. 5. Net plasma current. Preliminary plasma starts at t=0, the beam duration is shaded.

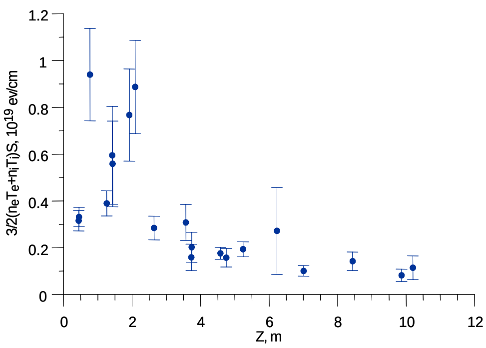

FIG. 6. Axial dependence of plasma energy content per unit length in the experiments with the thin beam. Statistical spread for a series of 20 shots is shown. Data were recalculated for 4 T magnetic field corresponding to the mean field in the corrugation cell.

3. Efficiency of Beam-Plasma Interaction

Feature of the thin beam is that its current becomes essentially less than a limiting vacuum current. Therefore experiments became possible not only with injection of the beam in the low-temperature start plasma, but also with the beam injection in vacuum and in a non-ionized gas. Two latter cases are unavailable with the full-current electron beam. Results of experiments with the thin beam appeared more interesting, than it was expected. Main specific parameters of plasma heating remain the same as for the full-scale experiments with some minor changes in axial profile of plasma pressure at first two meters of the plasma. At the rest of the plasma column the beam moves already in partially relaxed condition so plasma heating coincides with that observed with the standard beam, as it was expected (see Fig. 4).

Analysis of energy spectrum of electron flow from the plasma in the range of 0.1÷1 MeV was done with a multifoil absorbing analyzer [4]. This flow includes both beam electrons mainly decelerated in the plasma as well as accelerated plasma electrons. The analyzer was mounted in an exit expander tank at low magnetic field of 0.05 T in order to avoid destruction of the foils by high heat load. The electrons leaving the trap along the magnetic field lines are absorbed in a stack of thin foils at different depths depending on the initial energy of the electrons. Knowing distribution of current on the depth one can recover the initial electron spectrum. The inverse problem for this case was solved as a set of Lagrange coefficients calculated via minimization of the current discrepancy squared. To do that, we applied the Tanaba–Huang method [5] with the assumption of positive definiteness of spectrum. Stability of the chosen method to experimental errors and uncertainties of the electron absorption function was checked.

To test the diagnostics the “thin” electron beam with half energy (~0.4 MeV) and nearly half current density was injected in the magnetic trap with technical vacuum (residual gas pressure $3\cdot10^{-3}$ Pa). Applying the mentioned procedure of spectrum determination we found that the electron distribution function consists of two narrow spikes, the first one is located near the energy of the injected beam (decelerated beam electrons) and the second is at the lower boundary of the investigated energy range 0.03 MeV (accelerated plasma electrons). At these conditions due to 10 μs pulse duration such beam easily produces plasma from the residual gas but the interaction with it is not effective because of insufficient current density of the beam. The average energy losses of the beam electron do not exceed 10%. If to raise the diode voltage to 0.8 MeV and hence the beam current density to ~1 kA/cm^2 in the trap, the experiments have shown that such beam effectively interacts with self produced plasma and the average energy loss of the beam reaches 20%.

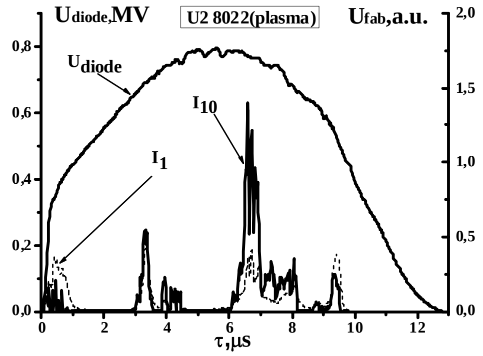

FIG. 7. Waveforms of diode voltage and currents from first and last foils.

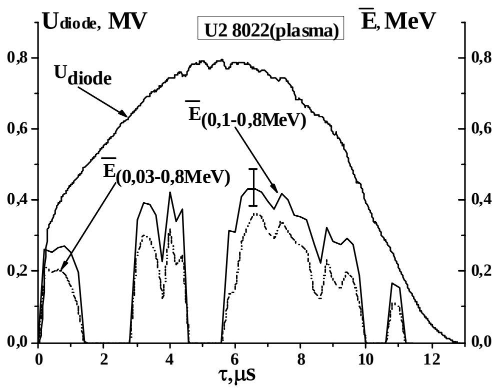

FIG. 7. Diode voltage and mean energy of electrons in the ranges 0.1÷0.8 MeV (solid line) and 0.03÷0.8 MeV. In time intervals, where the total current from the foils was less than experimental error, the average energy was taken zero.

The loss of energy for such beam at its injection in preliminary prepared plasma with $(0.4\div1)\cdot10^{21}$ m^{-3} density becomes even greater. Waveforms of foil currents and of the diode voltage for typical shot are shown in Fig. 7. The foil currents are strongly modulated that is explained by filamentation of the beam current combined with movement of these filaments. In time intervals when the foil currents are non-zero one can determine energy spectrum - see Fig. 8. For these periods electron distribution function rises roughly monotonously with the decrease of the electron energy in the range 0.03÷0.8 MeV and no signs of the beam spike within the errors of the solution can be detected there. So the beam-plasma interaction at such parameters of the beam is so effective that the beam energy loss (in the range 0.1÷0.8 MeV) exceeds 50% and distribution function of the beam electrons diffuses so much that it reaches non-Maxwellian electron tails accelerated by Langmuir turbulence.

4. Transverse Losses and Stabilization of Beam Transport

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 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 [3]. 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.

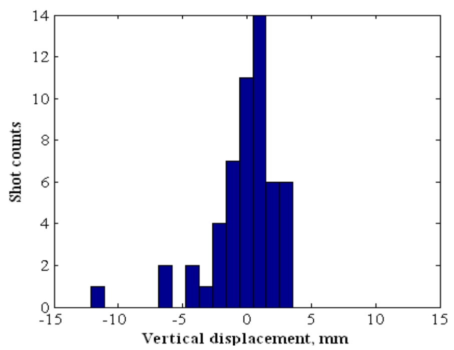

FIG. 8. VUV measurements of the electron beam displacements.

In the experiments with the thin beam its transversal motion was observed with several diagnostics (see [6] for more details). In the sequence of shots the beam was shifted to different points of plasma cross section and the beam displacement does not go out its size Fig. 8. At the same time the bremsstrahlung images of the beam footprint at the collector show similar behavior. Moreover the X-ray size of the beam is close to the expected one. From this appears that beam transportation through the plasma is steady as a whole, i.e. the beam dump to the chamber wall and plasma limiters (8 cm diameter) with fast plasma decay was not observed.

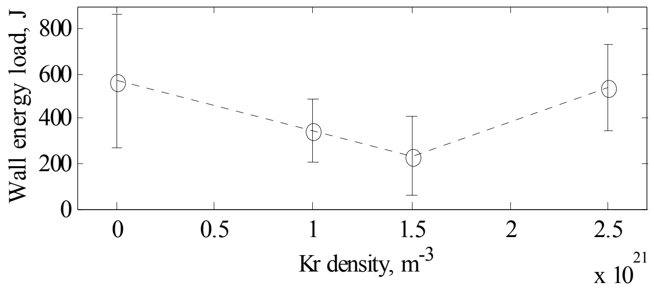

FIG. 9. Dependence of transverse losses on krypton density. Statistical spread is shown.

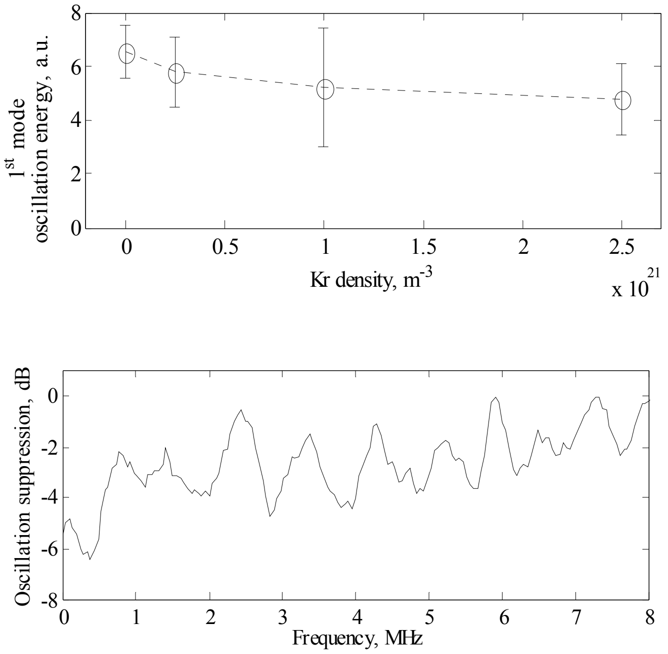

FIG. 10. Suppression of MHD activity in the middle of solenoid. Top is the dependence of integral amplitude of oscillations on Kr density. Bottom is the difference spectrum for heavy gas density ~$2.5 \cdot 10^{21}$ m^{-3} compared to no gas case.

Observations testify that the instability really develops, but displacement of the beam saturates. Previous GOL-3 experience allows supposing formation of globally stable specific structure of return plasma currents which can provide global plasma stability.

Plasma energy losses across the magnetic field were measured with a set of wall-equivalent bolometers. Unlike experiments with the full-scale electron beam (where transverse losses were below 10% in global energy balance), the transverse losses in the described regime are noticeable and depend on gas pressure near the exit beam collector in the end expander tank (Fig. 9). Minimal transversal energy losses correspond to density of the heavy gas about 10^{21} m^{-3}.

This effect could be explained by the stabilization of the beam oscillations by the heavy gas cloud in the beam receiver unit. Such process should affect the perturbations of current flow in the plasma column, which were studied by the set of Mirnov coils. Dependence of the integral amplitude of the magnetic surfaces oscillations with the azimuthal mode **m** = 1 on the heavy gas density was observed experimentally (Fig. 10). One can see the suppression of the oscillations in the broad band of frequencies except the set of harmonics that probably correspond to the integer longitudal wave numbers, which are not affected by the conditions in the exit unit because they have nodes in this point.

Experiments demonstrated evident improvement of the beam stability with the optimal gas-puffing. 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.

5. Microwave Emission at Double Plasma Frequency

Current theory of induced electromagnetic emission from turbulent plasma gives two main processes for microwave radiation during the beam-plasma interaction at GOL-3:

- plasmon scattering on plasma density fluctuations, which yields the electromagnetic emission at plasma frequency (“ω_p process”);
- plasmon-plasmon merging, which results in production of photons in the vicinity of double plasma frequency (“$2\omega_p$ process”).

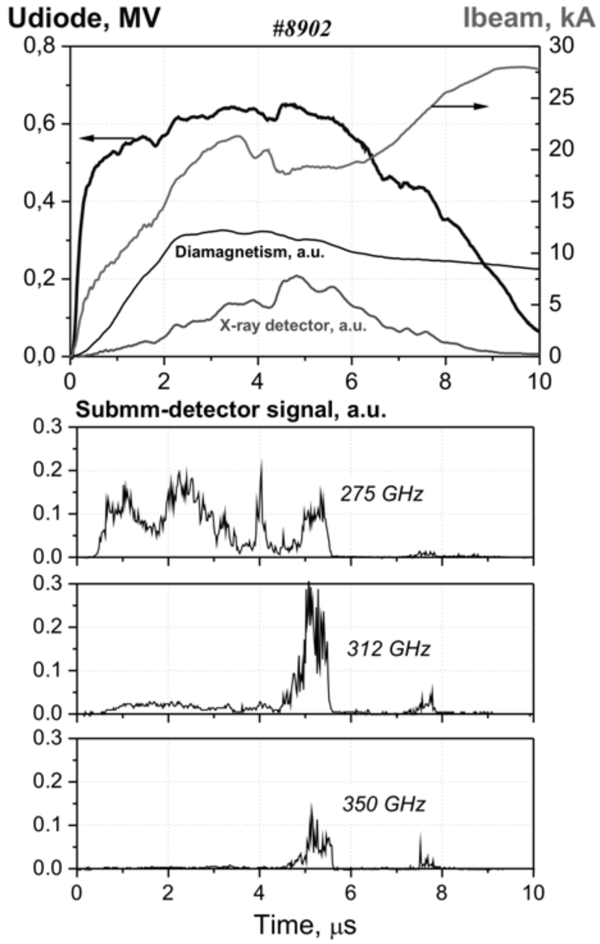

FIG. 11. Typical waveforms of the diode voltage, beam current, plasma diamagnetism and X-ray emission (top), and microwave signals (bottom) at initial plasma density $2.5\cdot10^{20}$ m^{-3}.

Investigations of $2\omega_p$ emission were performed at a distance of around 80 cm from the beam injection plane that corresponded to the region of maximum efficiency for the beam-plasma interaction. In this work we employed an original 4-channel quasi-optical radiometric system [7]. In the discussed experiments the channels were of ~40 GHz bandwidth and 20÷30 dB out-of-band attenuation at 35÷38 GHz frequency shift of adjacent transmission bands.

For standard regimes of REB-plasma heating a series of radiometric measurements of $2\omega_p$ emission from GOL-3 plasma was carried out. The experiments revealed a significant level of emission during the period of beam injection with total duration 7÷10 μs (Fig. 11), which in some cases exceeded a saturation level of Shottky detectors. Retrieved via experiment geometry, a specific power of emission was estimated on the level of ~10^2 W/cm^3. It is essential that radiometric signals disappear after termination of the beam injection, as well as were zero for test experiments with the beam injection into vacuum. That decisively excludes cyclotron harmonics from the consideration.

The experiments demonstrated a good concordance between the estimated value of the initial plasma density and the maximum of the power spectral density of emission associated with the “$2\omega_p$ process”. We also observed the phenomena of detuning and broadening of the $2\omega_p$ emission spectrum typically 4÷5 μs after starting the beam injection that is explained by modulation of the plasma density that develops during the beam-plasma interaction [8].

Checks of polarization of $2\omega_p$ emission via a grid-polarizer mounted at the radiometry system entry show predominance by a factor of 2÷3 for radiation polarized transversely to the magnetic field. It points out at a significant level of excitation of transverse plasma waves.

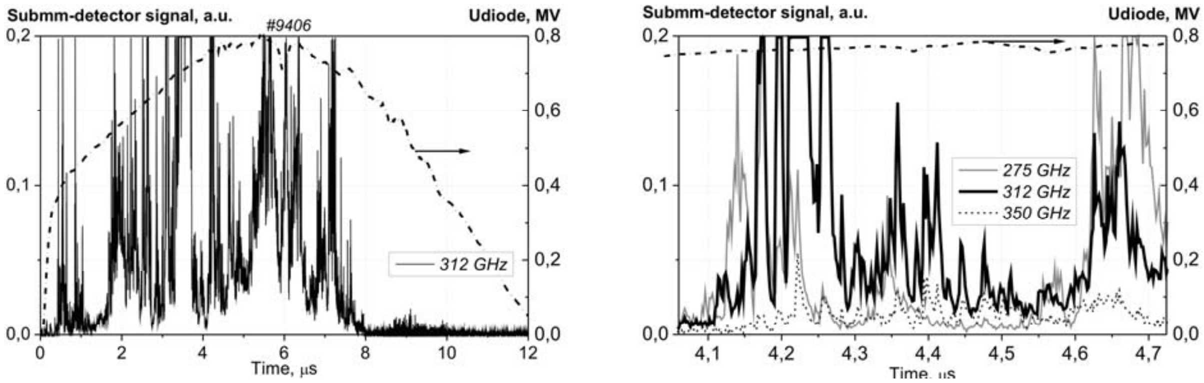

FIG. 12. An example of fine temporal structure of microwave emission in the experiments with the thin beam. Right diagram shows a fragment from the left one.

Analysis of microwave signal time behavior revealed presence of sharp spikes of emission with 2÷10 ns duration against a background envelope [9]. The spikes exhibit fast spectral detuning and are admittedly associated with dynamic density wells (caverns) which emerge at the final stage of Langmuir turbulence. It's noteworthy that the fine temporal structure of emission was distinctively enhanced for the experiments with decreased cross-section of the electron beam (Fig. 12), as compared to the case of a full-size beam. This fact is associated with a smaller total number of caverns per a beam-plasma-interaction region that results on average in stronger amplitude excursion of microwave signals when caverns dynamically evolve.

6. Progress in electron beam generators for plasma heating

The prototype of long pulse electron beam injector is being developed in BINP for to test a possibility to elongate the plasma electrons heating and to slow down cooling of plasma ions. The designed beam parameters are the following: energy of electrons up to 150 keV, pulse duration of >0.1 ms and beam current up to few hundred amperes. The injector is intended to operate in an external axial magnetic field of 0.1 T with following 50-fold compression by the guiding magnetic field to current density ~1 kA/cm^2. A diode of injector consists of a cathode plasma box and the flat anode. The frontal plate of the plasma box constitutes the emission electrode (cathode of the diode) with 36 circular emission openings aligned precisely with the openings in the accelerating electrode (anode of electron-optical system, EOS). An arc discharge generator is placed inside the box and the hydrogen plasma inside cathode apertures serves as an emitter. The results of first experiments are shown on the Fig. 13 for the case of no magnetic field.

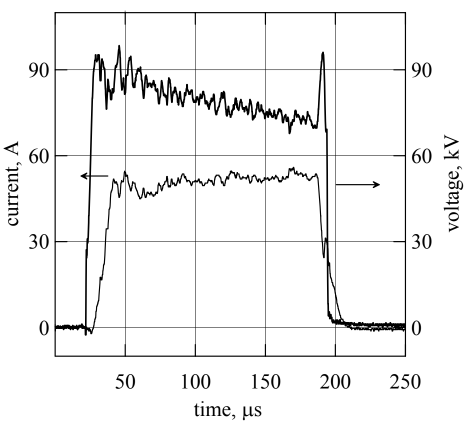

FIG. 13. Typical waveforms of the beam voltage and emission current for 36-aperture EOS.

The next steps to reach the required beam parameters are the following: switching on the magnetic field, increasing of diode voltage and current with simultaneous providing of electric strength of diode gap. Then minimization of the electron velocities divergence and compression of the beam in a magnetic field would be done. The work is in progress.

7. Summary

New GOL-3 experiments with plasma heating by the thin beam in general confirmed existing understanding of underlying physics for a new domain of operational parameters. Main plasma parameters (plasma temperature ~1 keV, energy confinement time ~1 ms) are high enough for the next step of development of the multiple-mirror confinement concept. As the upgrade we plan to use millisecond-range electron beam with energy of electrons ~100 keV and current density in the plasma ~1 kA/cm^2 for plasma heating. Now the appropriate technology is under development in Budker Institute of Nuclear Physics.

Acknowledgements

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