EXPERIMENTS WITH GRADUAL-ENERGY-GROWTH ELECTRON BEAM AT GOL-3

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The paper presents experimental data on plasma heating in a new regime of GOL-3 operation. Unlike previous experiments, the new regime features significant growth of energy of electrons in a relativistic electron beam during the beam pulse.

The new dynamics of beam energy during the shot changes dynamics of plasma heating. A pronounced feature of previous GOL-3 experiments on plasma heating in the corrugated magnetic field was early transition to the plasma cooling stage, which in some regimes occurred much earlier than the beam injection stopped. In the gradual-energy-growth regime, plasma heating continues for a longer period until the beam power decreases significantly. Some other features will also be discussed.

Experiments in the new regime allow us to partially verify feasibility of plasma heating with the electron beam at lowered beam parameters. This is important for the next planned step in GOL-3 program.

I. INTRODUCTION

Collective plasma heating by a relativistic electron beam was chosen as the primary method of plasma heating in the multiple-mirror trap GOL-3. In a standard operation regime of the U-2 accelerator the waveform of the accelerating voltage is optimized for maximum beam energy per shot. Usually, this optimization results in weakly changing voltage within the main part of a beam pulse (see, e.g., Ref. 1 and Fig.1). All other previous experiments, including those at the first stage of GOL-3 (Ref. 2) and at several smaller devices that used relativistic beams of 50-100 ns duration, were conducted with decreasing beam energy.

The paper presents experimental data on plasma heating in the new regime, which features significant voltage growth during a beam pulse. Special design of the U-2 accelerator based on LC cells instead of usual Marx scheme allows shaping of the output voltage for some extent (see details of the new beam generation regime in the special paper [3]).

The beam-plasma interaction within the parameter space typical for GOL-3 experiments features several important nonlinear and collective processes. The goal of the discussed experiments was to check a possibility of significantly reducing the beam power while keeping the plasma parameters at a high level. Such data is important for considering fusion prospects of a multiple-mirror reactor with an electron beam. [4]

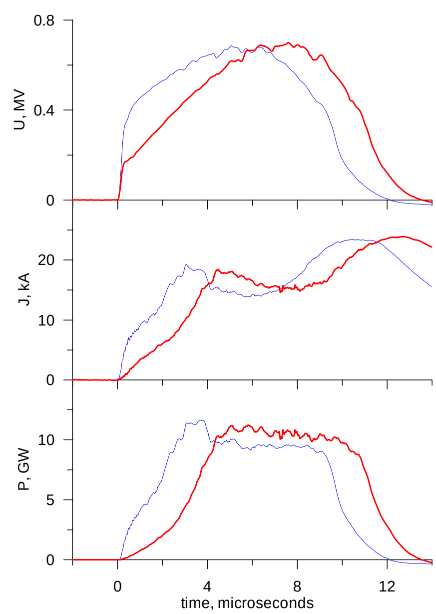

Fig. 1. Main parameters of the electron beam for two cases: standard regime (thin lines) and operation with gradual energy growth (thick lines). Shown are typical waveforms for the diode voltage (top), beam current (middle) and beam power (bottom).

II. OPERATION REGIME AND DIAGNOSTICS

Deuterium plasma is confined in a 12-meter-long solenoid, which has 52 corrugation periods (cells of multimirror system) of 22 cm length each; the field in maxima is 4.8 T and that in minima is 3.2 T. The mirror ratio of the corrugated field is 1.5. The solenoid ends with magnetic mirrors with a field of 8÷9 T. In the experiments being discussed the deuterium plasma was of $(5\div8)\cdot10^{20}$ m^{-3} density with a bell-shaped axial density profile (due to used gas-puffing technology where some dense gas was also puffed into the beam compression area).

The plasma heating is provided by the high-power electron beam. The main beam parameters are: energy ~0.7 MeV, current ~20 kA, pulse duration ~12 μs, and initial energy content ~80 kJ. Comparison of plasma heating in two regimes will be discussed. The regimes differ in dynamics of the beam voltage and the beam power in the first half of the beam pulse (see Fig. 1).

Standard set of GOL-3 diagnostics was used. In this paper we focus on diamagnetic measurements which give general understanding of plasma heating differences in two regimes. Other diagnostics give consistent data including non-Maxwellian electron distribution function by Thomson scattering.

III. EXPERIMENTAL DATA

New dynamics of the beam energy during the shot significantly changes the dynamics of plasma heating. A pronounced feature of previous GOL-3 experiments on plasma heating in the corrugated magnetic field was early transition to the plasma cooling stage, which in some regimes occurred much earlier than the beam injection stopped. In the gradual-energy-growth regime, plasma heating continues for a longer period until the beam power decreases significantly.

Plasma heating is highly non-uniform along the axis. That was naturally explained by concurrence of several processes, including gradual degradation of the beam quality, change of ratio of the beam electron density to plasma density, particle and energy transport, etc.

Two shots with the same energy content of the beam and same other initial parameters were chosen. Figure 2 shows diamagnetic waveforms for three locations. Coordinate Z = 77 cm corresponds to the peak plasma heating point, Z = 209 cm is an approximate boundary between the hottest initial part of the plasma column and the rest of the plasma, and Z = 475 cm is a typical location within the rest of the plasma.

At Z = 77 cm a very intensive plasma heating occurs in the standard regime with sharp pressure peak in axial direction. Fast pressure growth changes into fast decay as early as in the beginning of the beam pulse. Such change can be attributed to the detected change of electron distribution function which was measured by Thomson scattering.[5] In the gradual-energy-growth regime the pressure peak also appears at this coordinate, but the pressure continues to grow much longer.

Parts of the plasma column outside the high-heating-rate zone experience less difference in the pressure dynamics. For almost 80% of the plasma the final pressure is the same with the only minor difference in its dynamics due to the difference in the beam power at the beginning of the beam pulse. This act is important because it means that lowered beam power and lowered energy of the electrons in new regime are still sufficient for initiation of effective beam-plasma interaction.

Figure 3 shows the evolution of “diamagnetic” plasma energy for two regimes. During the beam pulse the difference is due to the energy stored at first two meters of the plasma column that almost disappears after

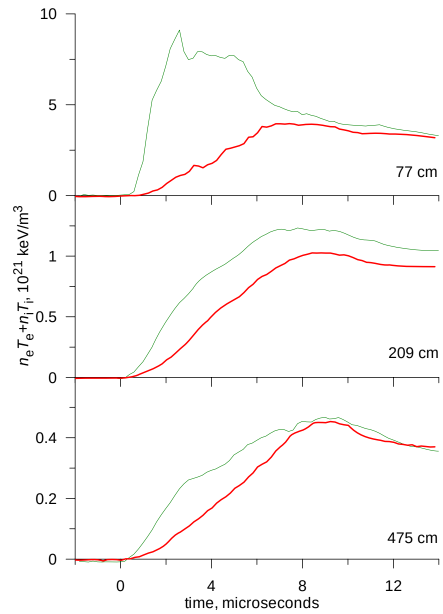

Fig. 2. Dynamics of diamagnetic energy at coordinates 77 cm (top), 209 cm (middle) and 475 cm (bottom) for two cases: standard regime (thin lines) and operation with gradual energy growth (thick lines).

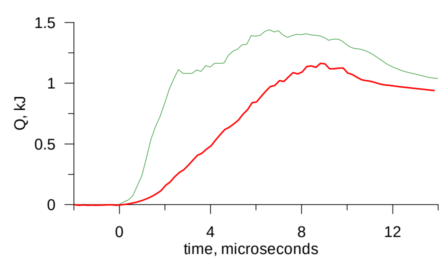

Fig. 3. Dynamics of stored plasma energy by diamagnetic measurements. Standard regime is shown by the thin line; operation with gradual energy growth is shown by the thick line.

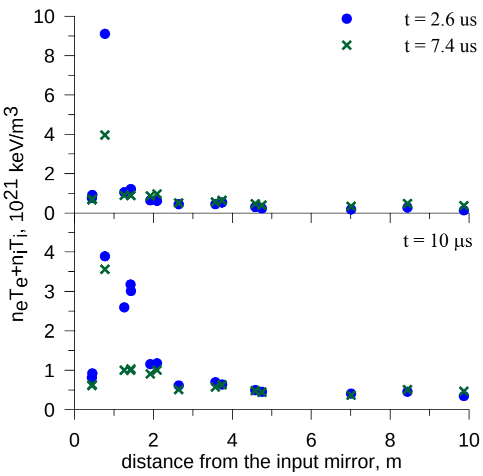

Fig. 4. Axial profiles of the plasma pressure for two moments of time. Dots are for the standard regime, crosses are for operation with gradual energy growth. Upper plot is for the peak of pressure at Z = 77 cm (upper waveforms in Fig. 2, note the different time). Bottom plot corresponds to 10 μs (between the peak plasma energy and end of the beam injection).

the beam injection ends. Subsequent plasma cooling periods are similar.

Axial profile of the plasma pressure changes during the beam pulse (Fig. 4). Initially fast growth of the pressure is observed in both regimes in the "hot spot" near Z = 77 cm (top part of Fig. 4). Intensive microwave emission at double plasma frequency is observed from this point [6] that serves as indicator of existence of strong Langmuir turbulence. The fact that in standard regime this stage lasts shorter may indicate that the turbulence and arising pressure gradients modify the plasma strongly enough to break the interaction that is sensitive to a particle-wave synchronism. In the gradual-energy-growth regime this stage of pressure growth in all parts of the plasma lasts for longer, probably due to the "softer" regime of heating due to lower beam power. At later periods of the beam injection the plasma pressure continues growing at the rest of the plasma column. Both regimes result in practically the same heating of the plasma column past $Z \sim 2$ m. The difference is in the section before $Z \sim 2$ m, where a peak of so-called "two-stage heating" is observed, which is provided mainly by energy and fast electrons transport along the magnetic field from the "hot spot".

Resulting energy content of the plasma is somewhat lower for the new regime. This fact is less important than demonstrated capability of steady plasma heating without overheated zones and without early transition to cooling. The "hot spot" plasma heating albeit providing very good local plasma parameters can be considered as a transient process, which is not particularly favorable for plasma heating with a quasistationary electron beam.

IV. SUMMARY AND DISCUSSION

Fusion prospects of a multiple-mirror system with an electron beam [4] depend on feasibility of realization of effective beam-plasma interaction at a reasonable power of the electron beam. The beam should bear at least two important functions: providing collective heating of plasma electrons in order to reduce drag losses of fast ions and maintaining a high level of Langmuir turbulence which reduces axial heat losses.[7]

The special experiments were performed at GOL-3 with slow growth of the beam power and energy of the beam electrons in the first half of the beam pulse. The plasma pressure increased almost linearly despite the much lower beam power in the beginning. Achieved plasma parameters are comparable with the old regime.

New experiments allow us to partially verify feasibility of plasma heating with the electron beam at lowered beam parameters. This is important for the next planned step in GOL-3 program.

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