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Heating of Ions at the Multiple Mirror Trap GOL-3

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1. Introduction.

The physics of plasma confinement in a multiple mirror magnetic system is studied at the GOL-3 facility in Novosibirsk [1]. Plasma motion in a corrugated magnetic field becomes diffusive with typical scaling $z^2 \sim (\lambda v_{Ti})t$ (λ is the mean free path, v_{Ti} is the ion thermal velocity), energy confinement time is higher than for a simple mirror trap [2]. This approach to fusion features high plasma density with reasonably low energy confinement time comparing to other magnetic confinement schemes. A high power relativistic electron beam is used for fast plasma heating in the GOL-3 facility. Effective collective relaxation of the beam due to development of a two-stream instability was achieved and investigated during initial stages of the GOL-3 experiments [3].

During the last years the facility was step-by-step re-configured to a multimirror system. Experiments have shown that ion temperature with a multiple mirror configuration of the magnetic field is much higher than for plasma heating in a simple solenoid. Details of physics of fast heating of ions are discussed in the paper.

2. GOL-3 Facility and Diagnostics.

Main physical objective of the GOL-3 program is study of plasma heating by a high-power electron beam and its confinement in axisymmetrical corrugated magnetic field. The whole magnetic system of the facility is 17 m long. It consists of coils for transport and compression of the electron beam, a 12-meter-long solenoid with corrugated field and exit expander. Solenoid consists of 55 cells of 22-cm length each with B_{max}/B_{min}=5.2/3.2 T. In special experiments some cells were operated with decreased to 1.2-2.2 T magnetic field.

Initial deuterium plasma of $(0.2\text{-}5)\cdot 10^{21}$ m^{-3} density is created by a special linear discharge along the whole device length. Axial distribution of the plasma density is formed by a set of fast gas-puff valves. Initial ionization degree is about 30-70% (depends on initial local gas density), this is enough for safe transport and relaxation of the electron beam. In these experiments three different axial density profiles were used (see Fig.1). First one was with quasi-uniform density with $n=0.5\cdot 10^{21}$ m^{-3}, others were with additional relatively short high

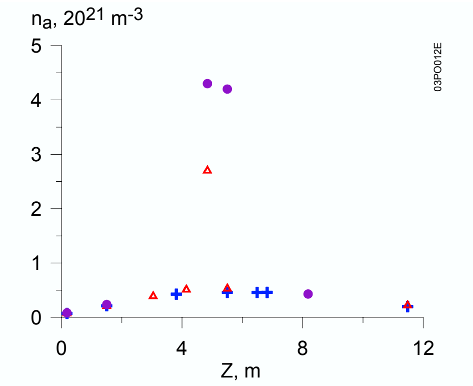

Fig.1. Initial axial density distribution. Crosses – only basic D_2 puffing, circles and triangles – additional dense region is created.

density region. The high-density plasma was placed just after the hottest (initial) part of the plasma column in order to increase yield of *DD* neutrons.

Then the high power relativistic electron beam heated this initial plasma. Typical beam parameters for these experiments were: energy ~1 MeV, current ~30 kA (current density in the plasma ~1 kA/cm^2), duration ~6 μs and energy content 120-150 kJ.

Main plasma diagnostics include magnetic measurements, 1.06 μm Thomson scattering, visible and VUV spectroscopy, VUV linear detector array, 1.15 μm interferometry, neutron detectors of different types, CX neutrals, *etc*.

3. Plasma Confinement in Multimirror System.

Two essential modifications of the GOL-3 facility were made during last year. First of all, all 12 m of the solenoid were switched in the multimirror configurations. Secondly, some modernization of the beam generation and transport part of the facility was made. The input beam diameter was decreased to 5 cm in order to increase energy density in the beam and simultaneously increase distance from the plasma to limiters in the minima of corrugated field.

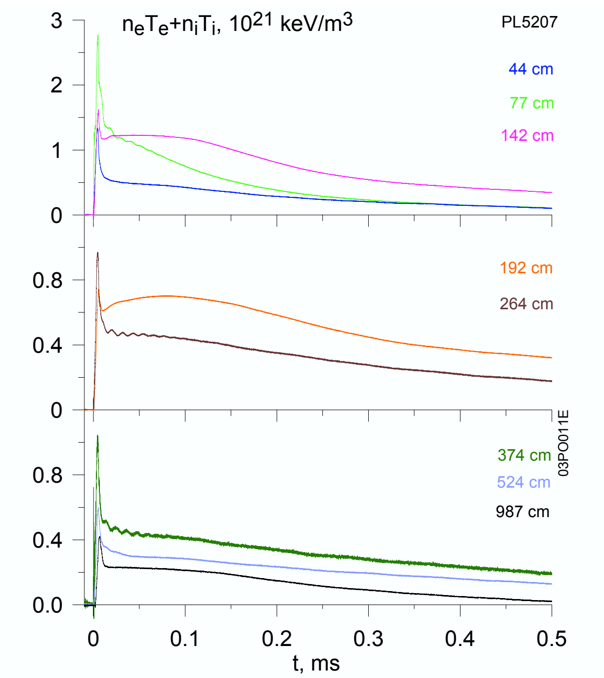

Fig.2. Typical evolution of the pressure at different parts of the plasma column. Numbers indicate coordinates of diamagnetic loops.

Initial collective plasma heating by ~120 kJ relativistic electron beam results in T_e~2 keV at ~10^{21} m^{-3} density, practically the same as for the uniform magnetic field [3]. Typical waveforms of the diamagnetic signals are shown in Fig.2. The beam energy release in the plasma is maximal at the first 1-2 meters, then heating efficiency become lower. After the end of the heating (~6-7 μs) energy redistribution along the magnetic field occurs. This results in some increase of plasma pressure at coordinates 1.4-2.5 m (such increase can be explained by T_e equalization along the initial part of

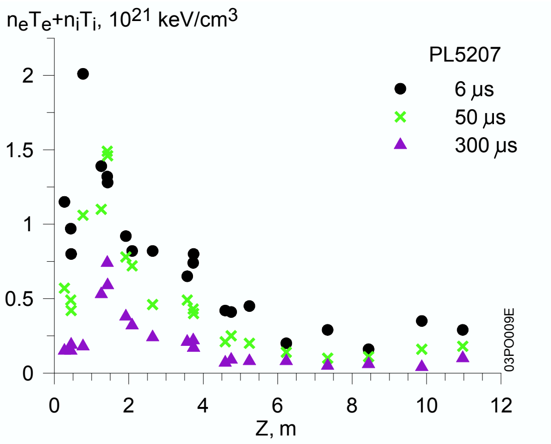

Fig.3. Axial profiles of the plasma pressure for 6, 50 and 300 μs after the heating start (the beam duration here is 6.2 μs)

the device with the existing density profile). Changes in axial profile of the plasma pressure are seen in Fig.3. Lower plasma temperature at Z>6 m can be caused by decreased transport coefficients due to the effect of multimirror confinement. Energy confinement time in the new configuration increases at least in an order of magnitude to >0.3 ms. The plasma is macroscopically stable. Details of plasma heating and stability are discussed in a separate paper [4]. Expansion of the plasma along the magnetic field is much less than C_s, this is typical for multimirror confinement.

At the end of the electron beam a fast heating of ions up to T_i~1.5 keV is observed. In a few microseconds later the electrons cool down and T_i>>T_e. Collective mechanism of such fast ion heating was proposed in [5] (details of the mechanism are discussed in paper [6]). Direct measurements confirm anomalously low longitudinal electron heat conductivity during the heating phase [7]. This anomaly results in fast buildup of large temperature and pressure gradients in the electron-hot plasma along the magnetic field (dT_e/dz~3 keV/m is measured). In the supposed mechanism the ions are accelerated due to longitudinal gradient of pressure of hot electrons in each cell of corrugated magnetic field. Then thermalization of opposite flows of plasma occurs.

Fig.4 shows evolution of VUV emission from the plasma measured by linear array detector. After the start of heating the plasma density comes to full ionization with n_e=(0.7-0.8)·10^{21} m^{-3}. Oscillations of edge VUV emission can be interpreted as rotation of edge azimuthal modes (identified are modes m=2 and m=6). Assuming that rotation is caused by $\boldsymbol{E}\times\boldsymbol{B}$ drift, the radial electric field at the edge of beam-heated plasma can be estimated as E~120 V/cm. This value is in a reasonable agreement with the electron temperature at this time.

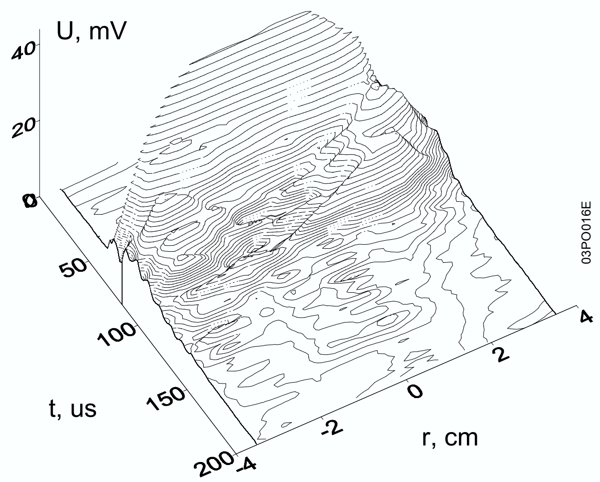

Fig.4. Evolution of VUV emission from the plasma at Z~2.2 m. Initial plasma starts at 10 μs, beam heating starts at 50 μs.

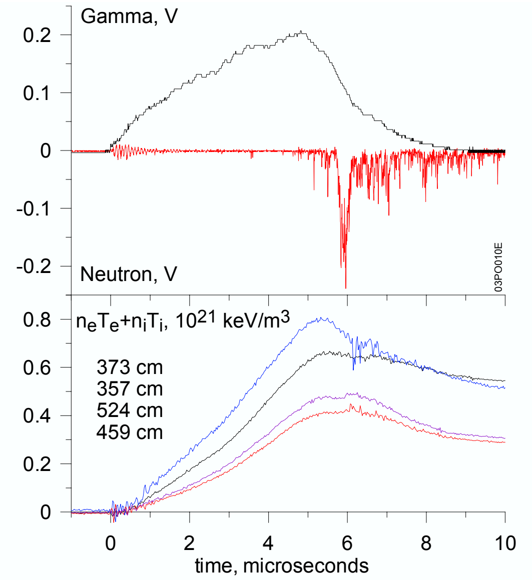

Fig.5. Typical waveforms, top to bottom: hard bremsstrahlung from the beam receiver, neutron detector at Z=4 m, four diamagnetic loops at coordinates near 4 m.

4. Start of Emission of Fusion Neutrons.

Emission of *DD* neutrons in the discussed regime lasts ~1.5 ms (details see in [4]). Here we will discuss start of neutron emission. Fig.5 shows waveform of hard bremsstrahlung (which can be used as rough monitor of the beam power) and signal of stilbene digital PSD neutron detector. Almost no signal is seen at the neutron detector up to ~6 μs (i.e. to the moment of maximum of the plasma pressure). Then burst of neutron emission appears, followed by steadily decreasing neutron flux for ~1.5 ms. At the end of the first burst of neutron emission some high frequency activity appears at signals of several magnetic loops, placed within region of maximal neutron emission. Fast broadening of VUV emission profile comparing to the diameter of the electron beam is also detected at the last half of the beam injection (Fig.4). All these facts indicate that some fast MHD process (most likely the one discussed in [5,6]), leading to fast collective heating of ions, occurs at this time.

5. Conclusion.

Experiments with complete multiple mirror configuration of the magnetic field at the GOL-3 facility have shown significant increase of energy confined time comparing with configurations with simple solenoid or short multimirror sections. In current regime of operation T_i>>T_e, emission of fusion neutrons is observed for ~1.5 ms. Experimental signs of existence of fast MHD process at final stages of plasma heating, which could be responsible for collective heating of ions, are observed.

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