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Experimental Results on Multiple Mirror Trap GOL-3

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Introduction

Recently the GOL-3 facility was upgraded to configuration with a long multimirror parts of the magnetic system. After the proposition a multimirror open trap [1] some small proof-of-principle experiments on confinement of plasma with rather low parameters (see review [2]) were carried out. Earlier the possibility of effective plasma heating by a high-power relativistic electron beam was demonstrated at the GOL-3 facility, the electron temperature of plasma was obtained up to 2-3 keV [3]. Therefore from the point of view of demonstration of thermonuclear prospects of multimirror traps is important to perform the experiments on confinement of plasma with high parameters. The experimental mode of the GOL-3 facility was selected so that the condition of longitudinal confinement of plasma was satisfied, namely the density of plasma is $(1\text{-}3)\times10^{15}$ cm^{-3}, that corresponds to temperature about 1 keV for a high effective confinement. In the performed series of experiments the main attention was focused on heating and confinement of ion component of plasma.

Experimental conditions on the GOL-3 facility

Multimirror trap GOL-3 is intended for studies of heating and confinement of a dense (10^{15}-10^{17} cm^{-3}) plasma [3]. The magnetic system of 17-m -length consists of coils for transport and compression of the electron beam, a 12-meter-long solenoid with ~4 m multimirror sections at the ends (B_{max}/B_{min}=5.2T/3.2T, 20 cells each) and exit plasma creation system. Initial plasma density with variable axial profile was formed by two pulse gas valves. The plasma heating is provided by a high-power electron beam (1 MeV, 30 kA, 8 µs, 120-150 kJ). Macroscopical stability of beam-plasma system was achieved by forming of the longitudinal net current with safety factor *q> 2-3.* Here we will discuss the experiments with initial deuterium distributions marked as 1,2,3 in Fig.1.

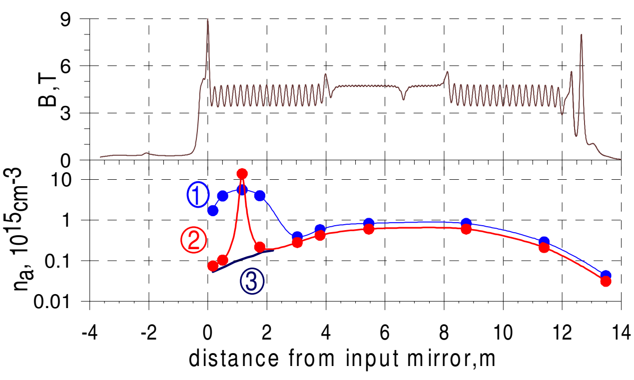

Fig.1. Magnetic field and initial D concentration.

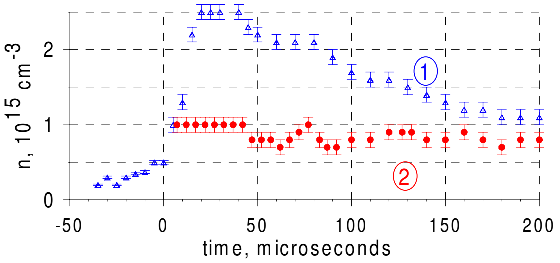

Fig.2. Density (Stark spectroscopy).

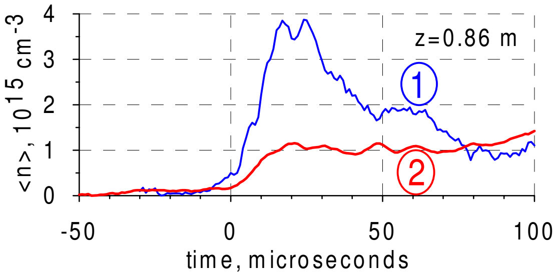

Fig.3. Averaged density (interferometry).

Dynamics of the plasma density

After the beginning of beam injection and plasma heating the density distribution in axial direction changes. Time evolution of plasma density was measured with two interferometers (Z=0.86 and 8.4 m), Thomson scattering of the ruby laser light (Z=1.9 m), Stark broadening of deuterium lines (Z=2.2 m). The density profile was measured by multipoint Thomson scattering of the Nd laser light (Z=4.2 m).

In Fig. 2 and 3 waveforms of density on various distances from an input mirror for two regimes (marked as 1 and 2 in Fig.1) are given. The electron density increases for 20-50μs, and then decreases with characteristic time of 50-200μs in dependence on coordinate and initial density of plasma. The shape of density reflects movement of plasma bunches in trap. By comparison of an axial structure of plasma density at the various moments of time it is possible to make the conclusion that velocity of expansion of the plasma in a multimirror trap is about $2x10^6$ cm/s, that is approximately 10 times less, than in a uniform magnetic field [4].

Transverse losses and edge plasma.

The edge plasma energy density was measured by a movable calorimeter. The plasma energy decreases strongly out of the beam crosssection and only small part of the beam energy is absorbed by limiters. This means that transverse heat losses are smaller than longitudinal ones. Edge plasma was studied also by spectroscopy. After the beam injection impurities come to edge plasma mainly from limiters. The temperature of silicon ions is ~100 eV.

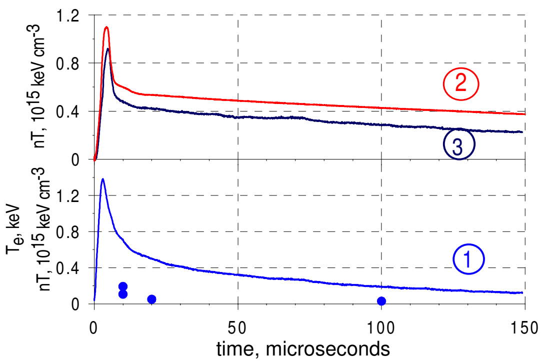

Fig.5. Electron temperature and nT.

Plasma pressure and electron temperature

Plasma pressure (nT) was measured by 25 diamagnetic loops placed along the plasma column. Dynamics of plasma pressure along the length depends on distribution of initial gas pressure. The waveforms of pressure at Z=2.09 m are shown in Fig.5 for various regimes. Curves 1, 2 and 3 correspond to the shot conditions marked in Fig.1. After the beginning of beam injection a pressure rises and reaches (1-2)x10^{15} keV/cm^{-3}, then quickly falls down by half and then slowly decreases with characteristic time of 100-200 μs. As previous measurements by Thomson scattering have shown, peak electron temperature reaches 1-2 keV. In Fig.5 electron temperatures for one of the regimes, measured by Thomson scattering of the ruby laser near to corresponding diamagnetic loop are given (points). In ~10 μs after the ending of a beam heating the electron temperature becomes of 200-300 eV at density of (0.8-1)x10^{15} cm^{-3}. Thus, in contrast with a conditions without a multimirror field [3,5], the plasma pressure is determined not only by pressure of Maxwellian electron components.

Heating and confinement of ions

First experiments on studying ion component of the plasma at the GOL-3 facility are carried out. For this purpose new diagnostics are prepared. The scintillation neutron detectors (Fig.6.) records neutrons and gamma radiation. Emission of particles begins at the time of beam passage. Duration of a radiation pulse is 100-300 μs, the shape of a waveform depends on distance from an input (3m and 6m on Fig.6). The total number of neutrons during a shot was determined by activation of the silver as (0.5-1)x10^6 m^{-1} at Z~2 m. Neutron flux obtained from measurements with the scintillation detectors is (1-5)x10^9 $s^{-1}m^{-1}$ and integration on the time this data is in agreement with activation detector data. Doppler broadening of lines was measured in a place with lowered density Z=2.15 m (see Fig.1). Time evolution of ion temperature for three shots in similar regimes measured by Doppler broadening of a D_α line is presented in Fig.7 .

The first experiments on registration of a spectrum of CX neutrals are carried out. The signal from one channel of the analyzer corresponding to ion energy of 3 keV is given in Fig.8. Emission of CX neutrals starts during the beam injection and lasts some hundreds of microseconds. The ion temperature to be estimated is in the range 0.5-1.2 keV.

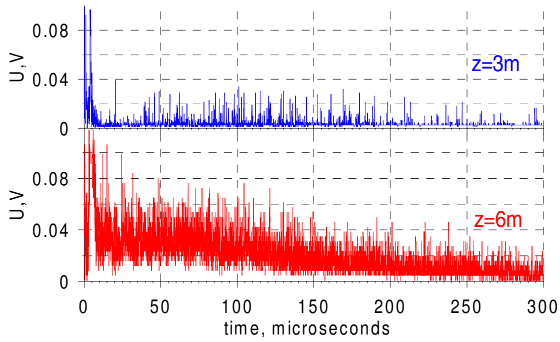

Fig. 6. Signals of neutron detectors.

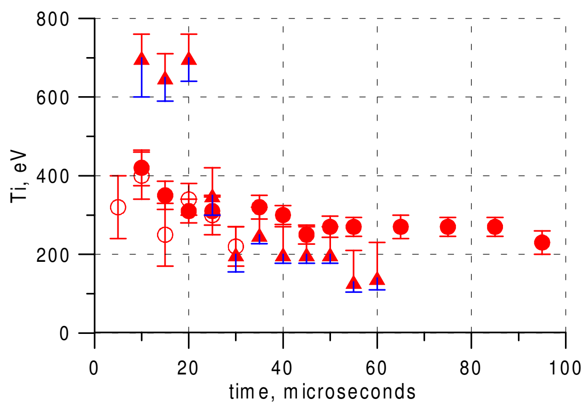

Fig.7. Ion temperature (Doppler broadening).

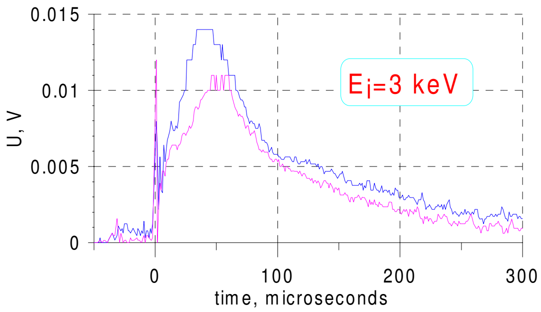

Fig.8. Waveforms of CX neutrals.

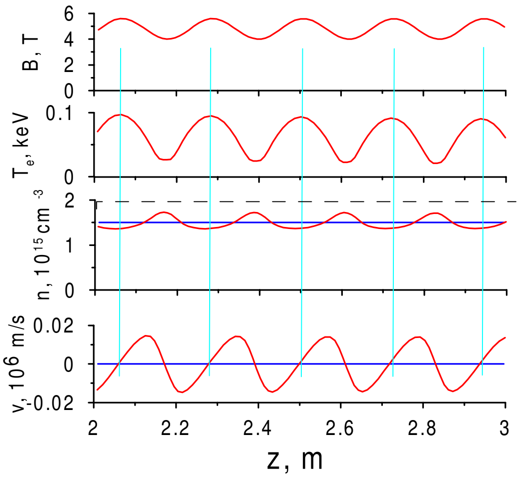

Fig.9. ISW-code results (1 μs).

Discussion and numerical simulation.

Estimations shows that ion heating is much faster than classical electron-ion collision time. A suggested explanation is the following. Collective interaction of the high-power electron beam with the plasma leads to effective electron heating, suppression of electron heat conductivity, dependence of electron temperature on magnetic field and as result to motion of plasma with $v \sim c_s$. Additionally the friction between ions appears in multimirror trap and decelerates the plasma flow. As result energy of free expansion of ions thermalizes. Numerical simulation by 1D two-component hydrodynamic code ISW shows (Fig.9) that periodical spatial modulation of electron temperature and pressure causes ion acceleration and then they mix in mirror cells (f. p. l. of ions is comparable to the cell length). This mechanism is more efficient than electron-ion binary collisions, because it takes about one ion-ion collision.

Conclusion

In 12-meter multiple mirror trap GOL-3 the macroscopical stability of system electron beam – plasma of 10^{15} cm^{-3} density was achieved. The first measurements of ion temperature have shown that ion components of plasma is heated during collective relaxation of a powerful electron beam, ion temperature reaches of 0.5-1.2 keV and exists in a trap more than 100 μs. Emission of fusion neutrons is observed.

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