Progress in Plasma Heating and Confinement at the Multimirror Trap GOL-3

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Abstract. Recent results on heating and confinement of plasma at the multimirror trap GOL-3 are presented. This facility is open trap for confinement of hot (0.1-1 keV) dense (10^{21}-10^{23} m^{-3}) plasma. The plasma heating is provided by a high-power electron beam (1 MeV, 30 kA, 8 μs) with energy content of up to 200 kJ. The upgrade to full-scale corrugation of a magnetic field was completed during last two years at the facility. In the 12-meter solenoid the multimirror sections of 4 m length were made at the both ends of the solenoid (B_{max}/B_{min} = 5,2 / 3,2 T, cell length is 22 cm). The modified source of preliminary plasma was put in operation for improvement of macroscopically stable beam transport through the plasma column. Search of optimal conditions for confinement of plasma with ~10^{21} m^{-3} density and high ion temperature, and also for macroscopically stable system "electron beam - plasma" was carried out in the new configuration of facility. As a result of the experiments the plasma with density of $(0.5\text{-}2)\cdot 10^{21}$ m^{-3}, $n_eT_e+n_iT_i = (0.5\text{-}2)\cdot 10^{21}$ keV/m^3 and confinement time up to 0.3 ms in the multimirror trap is obtained.

1. Introduction

Multimirror confinement of a hot dense plasma in a long open trap was proposed in [1,2] and is considered as one of approaches to nuclear fusion problem [3]. The multimirror trap consists of a set of mirrors which are connected to each other at their ends and have full length L which exceeds the mean free path of the particles λ. If, at the same time, the mirror cell length $l<\lambda$ then the free inertial plasma flow turns into slow diffusion along the corrugated magnetic field. As a result, the longitudinal confinement time increases essentially compared to classical single mirror trap (see review [4]). This effect allows a considerable reduction in the length and energy input in reactor based on multimirror confinement [3].

Now this concept is studied at the GOL-3 facility in Novosibirsk BINP [5]. Earlier main activity at this facility was focused on the physics of dense plasma heating by a high-power relativistic electron beam [6]. High efficiency of collective relaxation of the beam in the plasma and electron temperature up to 2 keV at 10^{21} m^{-3} density were reached, but energy confinement time was small. In order to increase this parameter the GOL-3 facility was modified into the multimirror trap. First experiments [7] have shown better energy confinement time comparing to single mirror configuration. At the same time macroscopic stability of the beam-plasma system in the corrugated field became more subtle, thus resulting in more frequent disruption events. This paper covers our new experiments with multimirror magnetic system. Main aims of the experiments were: study of physics of multimirror confinement of a sub-keV plasma; gradual improvement of the facility in order to reach broader range of operational parameters with macroscopically stable plasma.

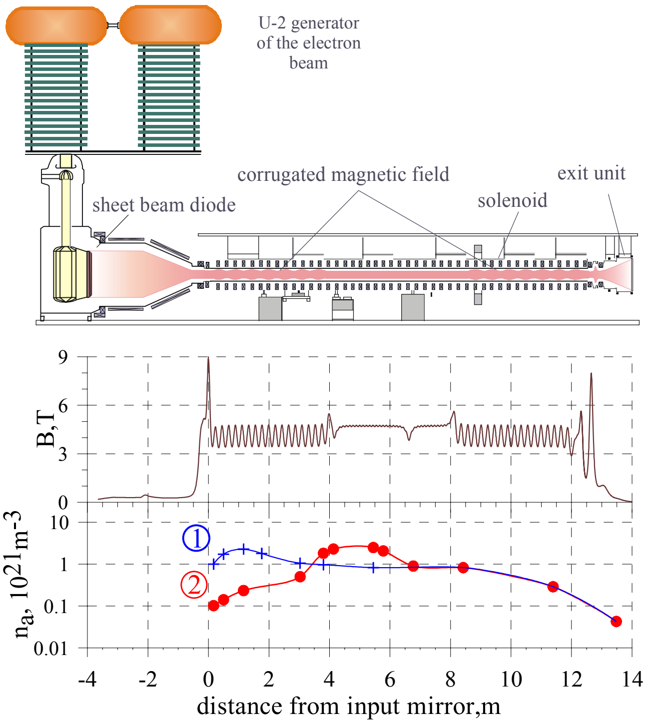

Fig.1. Layout of the GOL-3 facility. Magnetic field and initial deuterium concentration profiles for two regimes are shown as crosses and dots.

2. Experimental results and discussion

GOL-3 facility (Fig.l) is a long open trap intended for studies of heating and confinement of a relatively dense ($10^{21}\div10^{23}$ m^{-3}) plasma in axisymmetrical magnetic system [5]. The magnetic system consists of coils for transport and shaping of the electron beam, a 12-meter-long main solenoid and an exit unit (which includes plasma creation system, expander and exit receiver of the beam and plasma). Main solenoid operates with 4.9 T field and 8-9 T in end mirrors. Current design of the magnetic system enables operation in the multimirror mode with 22 cm cell length and B_{max}/B_{min}~1.5 on the part of the solenoid. Here we will discuss experiments with ~4 m multimirror sections at the plasma ends (20 cells each). The plasma heating is provided by a high-power electron beam (1 MeV, 30 kA, 8 µs) with total energy content of 120 kJ. Macroscopically stable beam transport was achieved with specially designed source of the preliminary plasma. The exit receiver operates under near-to-floating potential during the short period of the beam injection.

Scenario of the experiment was the following. At 30 µs before the beam injection the system of preliminary plasma creation is switched on and the linear discharge current up to 5 kA, opposite to the direction of the beam current is created. During this time the plasma is partly ionized, that it is seen, e.g., from D_α line emission. Then the electron beam is injected into this plasma (t=0 in Fig.2). Though the injected beam current achieves ~30 kA, net plasma current in the system practically does not change. This condition is also obligatory for maintenance of a beam and plasma stability in relation to the Kruskal-Shafranov instability.

The main purpose of the performed series of the experiments was search of modes with high ion temperature and improved confinement. The first results of the experiments in this direction were published in [10,11]. In the presented paper the results for new modes of operation of the GOL-3 facility are given. The axial structure of initial deuterium density is shown in Fig.1. Further we shall compare these modes designated in the Figure as regimes 1 and 2.

Typical distributions of the plasma pressure over the GOL-3 length are shown in Fig.2 for two mentioned regimes (measured by diamagnetic loops). Left part of the Figure corresponds approximately to distribution of local energy deposition from the electron beam to the plasma. Regime 2 with decreased density of the plasma at first 3 m gives much higher plasma pressure at the device entrance. The plasma pressure at last half of the facility remains the same. During the heating the beam energy is delivered mainly to the plasma electrons and T_e>>T_i at this time. As it was shown in [6] by Thomson scattering measurements, electron temperature could reach 2-3 keV. In the new multimirror configuration of the magnetic field the energy

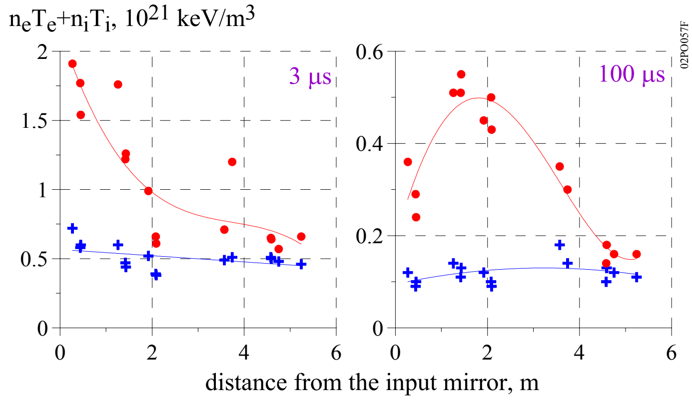

Fig.2. Distribution of the cross-section-averaged plasma pressure over first half of the facility for 3 µs (left) and 100 µs (right). Crosses correspond to regime 1, dots – to regime 2.

transfer from the plasma electrons to ions is possible also due to friction of expanding electron-hot plasma on ions, trapped in separate cells (physical details of this mechanism are discussed in [10]). After the end of beam heating the electron temperature decreases fast enough due to longitudinal electron thermal conductivity. In 10 µs it is 150-300 eV at Z=2 m. Since that the electron pressure becomes less than the total plasma pressure, measured by diamagnetic loops. This means that in the middle of the first multimirror section we have the plasma with $T_i>T_e$. As seen from the right part of Fig.2, the ion temperature remains in keV range for more than 0.1 ms. Regime with the ion-hot plasma at the GOL-3 facility was found for the first time.

Ion component of plasma was studied by diagnostics of fusion neutrons, gamma radiation, fast CX neutrals and by Doppler broadening of lines. Products of fusion reactions were registered by the activation silver detector, detector with plastic scintillator recording neutrons by recoil protons and gamma detector with BGO crystal. In Figure 3 signals of scintillation detector for two modes of operation of the GOL-3 facility are given. The detector was placed at distance of 1.5 m from the entrance mirror in the axial direction and 3 m from the axis of the trap. It records radiation of plasma with density $(1\text{-}2)\cdot10^{21}$ m^{-3} in the regime 1 and $(0.3\text{-}0.5)\cdot10^{21}$ m^{-3} in the second one within its field of view. It is apparently from the figure, that the intensity of neutron radiation has increased at transition to regime 2 in 20-40 times, the value of a specific neutron flux increases up to $4\cdot10^{10}$ s$^{-1}\cdot$m^{-1}. It corresponds to the ion temperature of 1-2 keV. This data is in the consent with the ion temperature obtained from the diamagnetic measurements. Neutron emission starts during the beam injection and lasts of about 0.3 ms.

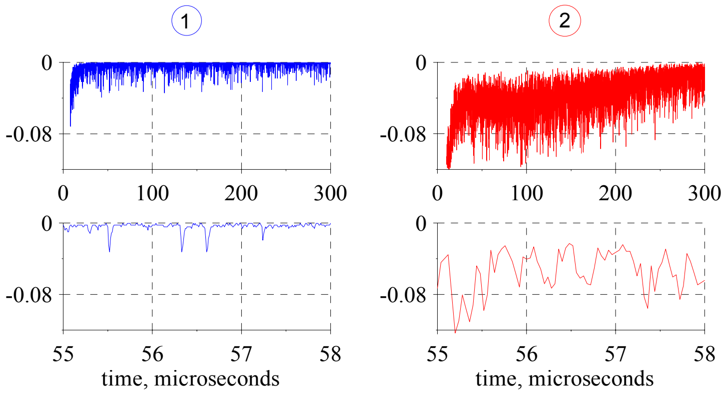

Fig.3. Signals of scintillation neutron detector. Two regimes are shown: parts 1 and 2 correspond to two distributions of initial concentration of the deuterium atoms, given in Fig.1. On the bottom of signals are shown with higher resolution. In regime 1 signals from separate particles are resolved, in regime 2 intensity of radiation is much higher, therefore overlapping of scintillation pulses is observed.

Doppler broadening of spectral lines was measured in a region with lowered density (Z=2.15 m) (see Fig.1). For this purpose a high-resolution spectral system with the double grating spectrograph DFS-24 was used. The theory predicts that shape of spectral line depends on the plasma density and ion temperature. In the conditions of the GOL-3 facility for the plasma density $\leq10^{21}$ m^{-3}, the contour of spectral line strongly depends only on the ion temperature. Centre of a spectral line shows the temperature in the

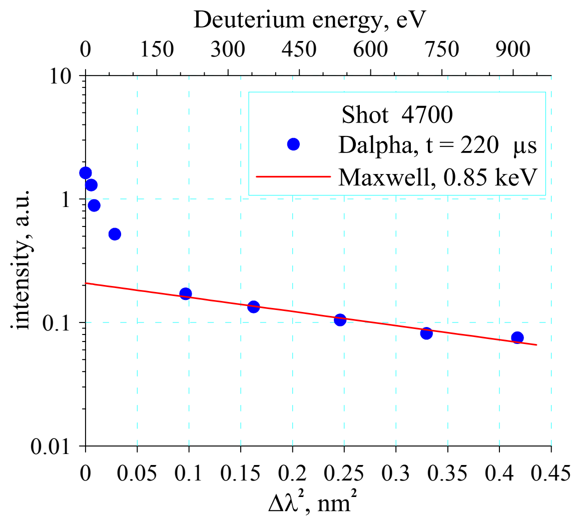

Fig.4. Contour of D_α line measured at 0.22 ms after the beam injection with calculated Doppler contour for 0.85 keV deuterium.

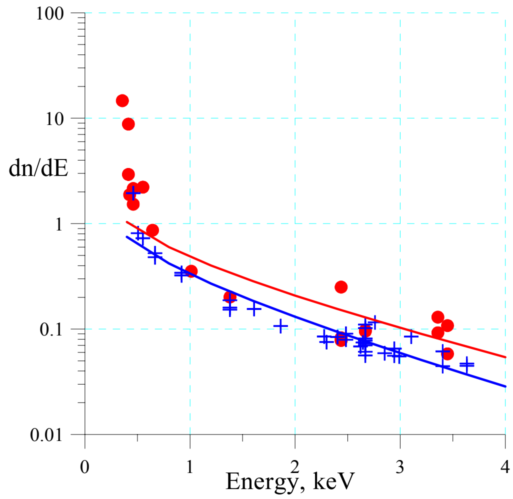

Fig.5 Energy distribution of CX neutrals leaving plasma at 50 μs after the beam injection (crosses) and 15 μs after the beam injection (dots). Lines - Maxwellian distribution for 1.7 keV (lower curve) and 2 keV (upper curve).

plasma edge and wings – the ion temperature in the plasma core. Fig.4 shows the contour of D_α spectral line measured at 0.22 ms after beginning of beam injection versus kinetic energy of radiating atoms. Experimental conditions correspond to regime 2. Dots show the measured contour and the straight line corresponds to radiation of deuterium atoms with temperature 0.85 keV. At earlier time the wings of the spectral line measured by the spectral system weakly differ from the horizontal line therefore the temperature is estimated as exceeding 1 keV.

The first experiments on registration of a spectrum of charge exchange (CX) neutrals are carried out. Analyzer of fast CX neutrals is placed at Z=3.1 m from the entrance mirror. Emission of CX neutrals starts during the beam injection and lasts for some hundreds of microseconds. Energy spectrum of CX neutrals measured with the help of analyzer is shown in Fig.5. Crosses correspond to regime described in [11], circles – to regime 2. In both regimes the initial plasma density near the analyzer was the same. To derive the energy distribution of CX neutrals in plasma core, the loss of the neutrals in a plasma edge was taken into account. From the calculated ion energy distribution the ion temperature is estimated in the range of 1.6±0.3 keV.

3. Summary.

The basic results obtained on the 12-meter multimirror trap GOL-3 during last years are the following.

1. Technology of preliminary plasma creation by linear discharge in the metal chamber of the multimirror trap with corrugated magnetic field is developed. The discharge current achieves of 5 kA.
2. The relativistic electron beam effectively heats the plasma in the trap with corrugated magnetic field. Longitudinal gradients of the plasma density and of the magnetic field strength do not influence on the efficient energy transmission from the electron beam to the plasma.
3. Macroscopically stable plasma in axisymmetric multimirror trap is obtained. Confinement time of hot plasma with density $(0.5\text{-}2)\cdot 10^{21}$ m^{-3} achieves ~0.3 ms.
4. Previously the effect of suppression of longitudinal electron thermal conductivity is discovered at the GOL-3 facility [11]. Direct measurements prove existence of thermal insulation of the plasma during the beam injection [10, 13]. Heating of the plasma electrons up to temperature of ~2 keV is achieved.

5. Plasma β reaches 20-40% in separate cells of the multimirror trap [9, 13].
6. New mechanism of fast ion heating during a collective relaxation of an electron beam in a corrugated magnetic field is offered. In this mechanism the ions are collectively accelerated by the electron pressure in each multimirror cell, and then are thermalized in the trap.
7. The ion temperature exceeding 1 keV is obtained at plasma density of $(0.3\text{-}1)\cdot 10^{21}$ m^{-3} and fusion neutrons are registered.

Recent results on the GOL-3 facility indicate the availability of the linear multimirror trap as an alternative approach to the thermonuclear reactor.

This work was partially supported by RFBR, project 00-02-17649.

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