FIRST EXPERIMENTS WITH MULTIMIRROR CONFINEMENT AT THE GOL-3-II FACILITY

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1. INTRODUCTION

Concept of a multimirror confinement of a dense plasma is developing in Novosibirsk INP since proposal [1]. Main idea of the concept is that the particle movement in a corrugated magnetic field becomes diffusion-like one and the longitudinal confinement time increases compared to classical mirror trap. After the first experiments with alcaline plasma [2] were done, the activity was directed to research of fast plasma heating by high-power relativistic electron beams. Recent progress at the GOL-3-II facility results in achievement of high efficiency of collective relaxation of the beam in the plasma. Electron temperature of the plasma is up to 2÷3 keV at 10^{15} cm^{-3} density [3]. Energy confinement time is mainly determined by the longitudinal thermal conductivity (which itself is suppressed by beam-induced microturbulence). With the end of the beam injection the thermal conductivity restores to its classical value and confinement time decreases to few microseconds. Ions remain relatively cold.

New phase of our experiments is aimed to confinement of high-β thermalized plasma. This means that energy confinement time should be considerably increased to get hot ions. Two essential modifications of the facility have been done: added sections of corrugated magnetic field and plasma column was separated by vacuum sections from the beam accelerator and exit beam receiver. First results on improved plasma confinement are presented.

2. EXPERIMENTAL DEVICE

GOL-3-II facility is a long open trap intended for studies of heating and confinement of a relatively dense (10^{15}-10^{17} cm^{-3}) plasma in axially-symmetrical magnetic system [4]. The magnetic system is 12-meter-long solenoid with 4.7 T field in the main part and 9 T in end mirrors. The plasma heating is provided by a high-power electron beam (1 MeV, 30 kA, 8 μs) with the total energy content of up to 200 k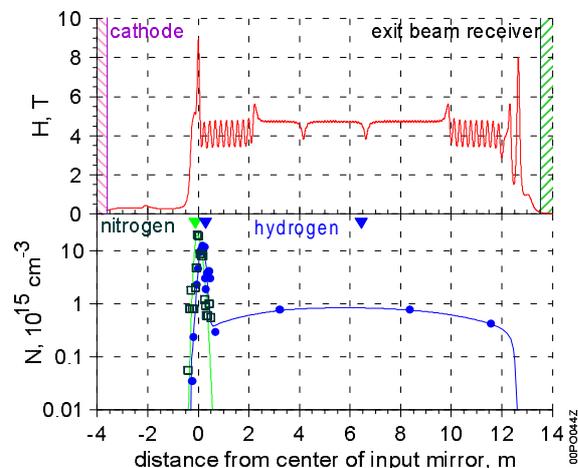J. The plasma in GOL-3-II facility has 6 cm diameter and its density can be varied in 10^{14}÷10^{17} cm^{-3} range. Total energy loss of the beam passed through 12-m-long plasma column with density of $(1÷2)\cdot10^{15}$ cm^{-3} achieves 30-40% [3].

During the experiments several configurations with corrugated field were used. Design of the magnetic system enables operation in the multimirror mode with H_{max}/H_{min}~1.5 and 22 cm cell length. Here we will discuss experiments with ~4.5 m corrugated section (20 cells) in the beginning of the plasma column and with ~2 m sections at the plasma ends (10 cells each). Configuration of the field is shown in Fig.1 for symmetric version. Initial gas distribution over the device length was uniform in the first configuration (with special input foil separating vacuum

Fig.1. Magnetic field along the device (top) and initial distribution of hydrogen (dots) and nitrogen (squares).

volume of the beam generator). Latest experiments were done with pulsed gas-puff without the input foil (initial pressure distribution for this case is shown in Fig.1, the nitrogen is required for proper operation of the beam generator). Additionally an expander section was added to the facility with the exit beam receiver moved downstream to 0.1 T magnetic field (~1:80 ratio to the field in the exit mirror). This lowers heat load to the receiver below the threshold of brittle destruction of the graphite and intensive creation of a surface plasma.

3. PLASMA HEATING IN CORRUGATED MAGNETIC FIELD

Theory predicts an essential influence of the magnetic field on the process of beam-plasma interaction (see, e.g., [5]). Therefore the plasma heating was studied in first set of experiments with 4-m corrugated section in the beginning of the plasma column. Generally dependence of final plasma pressure on the plasma density is similar to that in uniform magnetic field - see Fig.2 (shown for midplanes of the corrugated section by squares and for the plasma column by dots). Features of this dependence are almost constant pressure within $(0.2 \div 2) \cdot 10^{15}$ cm^{-3} interval and fast decrease of heating efficiency with further density growth. Plasma pressure is determined by electron temperature at low densities, then transition to $T_e = T_i$ occurs due to fast decrease of the temperature with growth of the density.
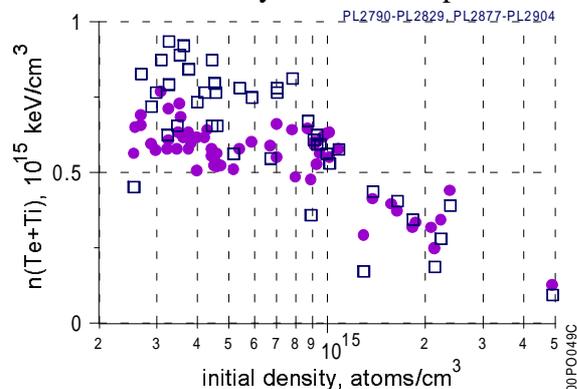

Fig.2. Dependence of plasma pressure on the initial gas density (diamagnetic data).
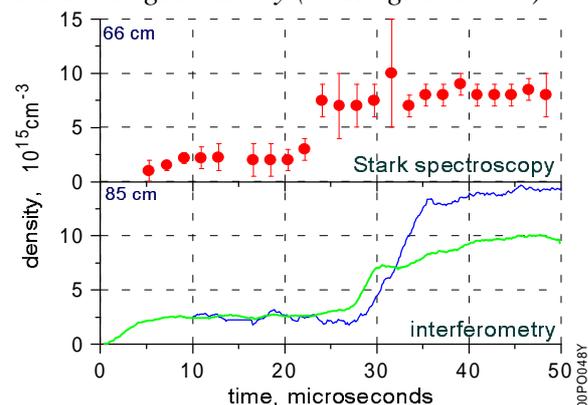
Fig.3. Expansion of a dense foil plasma.

Absolute achieved values for this regime are lower than for the case of uniform magnetic field. This might be attributed partly to worse ratio of beam to plasma densities in midplanes of the cells, to larger total volume of the plasma and to changes in beam-wave synchronism and in spectrum of plasma microturbulence (last two are sensitive to «magnetic» addition to plasma frequency). Free path length decreases very fast with increase in plasma density and device operates in regime of «classical» multimirror trap only in narrow interval of $(1.5 \div 2) \cdot 10^{15}$ cm^{-3}. As before, energy confinement time in this regime was determined by the longitudinal heat loss to the input foil, which produces dense bunch of a cold plasma. This foil plasma initiates observed pressure wave with ~10^7 cm/s velocity and finally expands into the trap, causing fast cooling of the plasma - Fig.3. Useful duration of the experiment is therefore limited by 10-20 μs, thus the foil plasma must be excluded in order to reach longer lifetime of the hot plasma.

4. FOILLESS MODE OF OPERATION

Operation of the GOL-3-II facility without input foil leads to major changes in a technology of creation of a preliminary (background) plasma. First of all, the system of steady gas supply with palladium leak was replaced by a set of pulsed gas-puff units. Triggering time and output of each such unit is adjusted separately to reach the required density profile over device length. Typical example of the initial density distribution is shown in Fig.1. Gas flow into the beam generator and volume of the exit beam receiver must be kept low, so no «true» uniform-
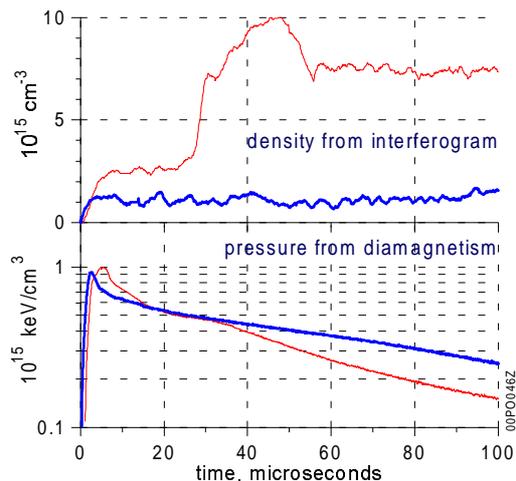
Fig.4. Comparison of regime with the entrance foil (thin) with foilless operation (thick)
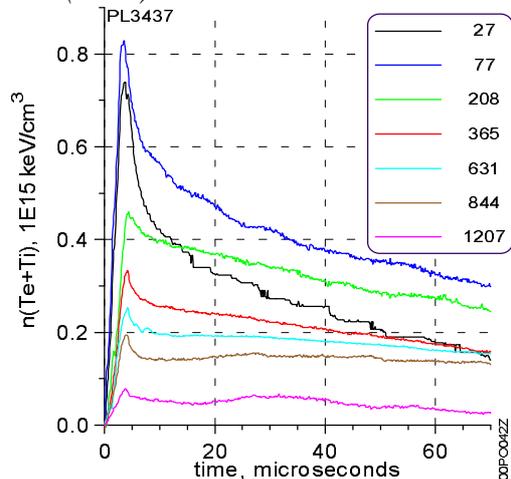

Fig.5. Dynamics of the plasma pressure in the system with two 2 m end sections of corrugated field. Numbers are coordinates in cm.

ity of the plasma density can be achieved (nevertheless, for our experiments with the plasma bunches of $\sim 10^{17}$ cm^{-3} density, uniformity is good enough in terms of efficient beam relaxation in the background plasma). Next modification was of a high-voltage system of linear discharge which creates preliminary plasma. The electrodes were placed just outside the boundary of the beam, thus current of the preliminary discharge flows on the plasma periphery (unlike our previous experiments with practically uniform current distribution).

Experiments in the foilless regime were done with symmetric configuration with two 2-m sections of corrugated magnetic field at the device ends. Foilless mode of operation differs from discussed above by absence of the dense cold foil plasma - see Fig.4. Some growth of the density is observed at ~ 80-100 μs from the beam start and may be originated from the input section of the device, but total value of this growth is much less then with the foil. Energy confinement time in this regime increases, and due to constant density the plasma remains hot far longer than with the foil.

Up to date experiments in the foilless regime were done with considerably reduced energy content of the electron beam, so current plasma parameters in this regime are yet lower. Typical time evolution of the plasma pressure in different points along the plasma column is shown in Fig.5. Features of these waveforms are: longer energy confinement time, equalisation of the pressure in the central part of the device, absence of the pressure waves, diff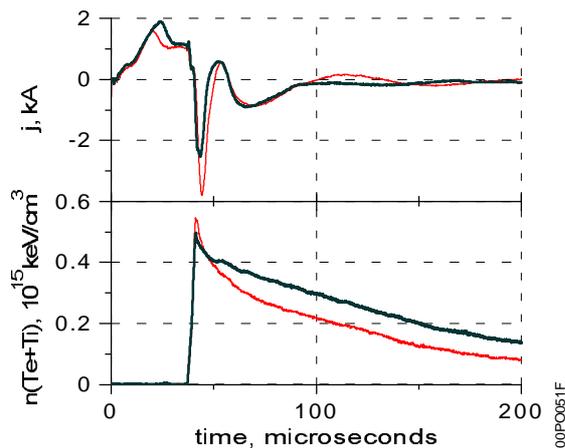erent behaviour in the corrugated sections. The electron temperature is up to 250 eV at $1.5 \cdot 10^{15}$ cm^{-3} density at 14 μs after the beam start (Thomson scattering data at 180 cm from the input).

5. ISSUES OF PLASMA STABILITY

Fastest global instability of the beam and the plasma in our experiments is common for many plasma facilities the Shafranov-Kruskal instability of a net plasma current. Critical net current for the case with uniform spatial distribution was ~15 kA (which is well below the beam current of ~30 kA). Stable beam transportation through the plasma with anomalous resistance during the beam injection was achieved by combination of proper parameters of the initial plasma discharge and return plasma current (forced by the «floating» exit beam receiver) - see [6]. Operation in the multimirror regimes somewhat lowers the instability threshold due to lower average magnetic field in the corrugated sections.

As the energy confinement time became longer in the latest experiments, the role of slower instability modes increases. We have no clear evidence of a new problems with plasma stability at longer times, but some processes out of our current control exist. As an example

Fig.6. Regimes with different confinement.

Fig.6 shows waveforms of the net current and plasma pressure in two sequential shots. Current of the preliminary discharge (beam starts at ~40 μs), parameters of the beam and peak plasma pressure are practically the same, the net current during and after the beam injection is far below the instability threshold, but at ~45÷60 μs in one shot plasma loses third part of its energy. Probable reasons for the difference might be change in radial structure of the return plasma current (different radial profiles of shear) and dense cold high-Z plasma appearing at the limiters. Parameters of the cold surface plasma depend on energy deposition into the limiters and that case can be sensitive to total energy content of the beam.

6. CONCLUSION

Success in physics and technology of fast plasma heating by a high-power electron beam marks completion of the first phase of the GOL-3 programme [3]. Further activity will be aimed at improvement of the plasma parameters using the concept of multimirror confinement. Magnetic system of the GOL-3-II facility was transformed to multimirror one, experiments were done in different configurations with up to 20 magnetic mirror «cells». Additional efforts were taken in order to decrease the longitudinal heat losses from the plasma (foilless mode of operation, exit expander section). Macroscopically stable beam transport through the device is
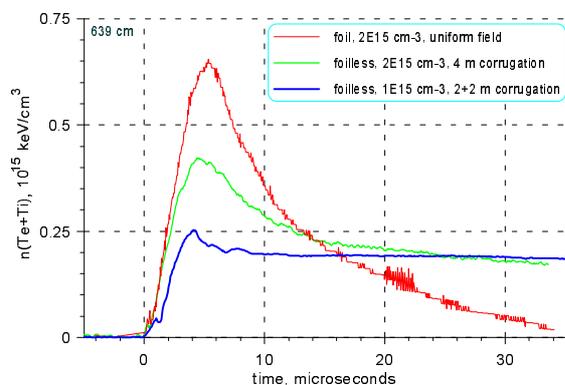

Fig.7. Plasma pressure in central part of the facility (different magnetic configurations).

achieved. The main result of the latest experiments at GOL-3-II facility is substantial increase of the energy confinement time. Figure 7 shows the plasma pressure in the midplane of the solenoid for three different regimes. Shots plotted are (top to bottom at peak value): best shot with $2 \cdot 10^{15}$ cm^{-3} plasma in the 12-m-long uniform field, best shot with $2 \cdot 10^{15}$ cm^{-3} plasma and 4 m corrugated section at input (foilless mode), and a shot with 10^{15} cm^{-3} plasma, 2+2 m corrugation, foilless regime and exit expander (energy content of the beam was lowered). In the last case the plasma pressure even grows a bit at ~20 μs due to thermal conductivity and temperature equalisation along the device. Further experiments are planned with increase of the enegry content of the beam up to its nominal value. *This work was carried out under financial support of Ministry of Science of Russia and RFBR project 00-02-17649.*

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