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PLASMA HEATING AND CONFINEMENT AT THE GOL-3-II FACILITY

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Results of experiments on plasma heating and confinement in multimirror open trap GOL-3-II are presented. This facility is intended for heating and confinement of a relatively dense (10^{15}-10^{17} cm^{-3}) plasma in axially-symmetrical magnetic system. The plasma heating is provided by a high-power electron beam (1 MeV, 30 kA, 8 μs, 200 kJ). Results of the experiments with multimirror configuration of the device indicate that the confinement time of the plasma with $n_e \sim (0{,}5 \div 5)\cdot 10^{15} cm^{-3}$ and T_e ~1 keV increases more than order of magnitude in comparison with single mirror device.

1. Introduction

Concept of multimirror confinement of a dense plasma develops in Novosibirsk INP since proposal [1]. Main idea of the concept is that for collisional plasma the particle movement in a corrugated magnetic field becomes diffusive and the longitudinal confinement time increases compared to classical mirror trap (see review [2]). After the first experiments with alkaline plasma [3] were done, the activity was directed to the development of technique and physics of dense plasma heating by high-power relativistic electron beams. Recent progress at the new-generation GOL-3-II facility [4] 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 [5,6]. Energy confinement time τ_E is mainly determined by longitudinal thermal conductivity, which is suppressed during the heating time by beam induced microturbulence. With the end of the beam the thermal conductivity restores to its classical value and the confinement time decreases down to a few microseconds.

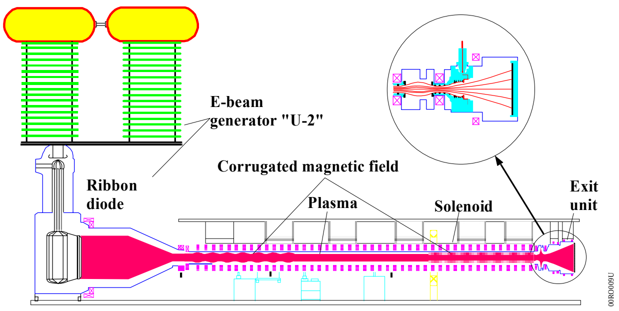

Fig.1 Layout of the GOL-3-II facility

The aim of our experiments is to confine 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: the magnetic field on part of the solenoid was reconfigured into multimirror (corrugated) one and plasma column was separated by vacuum gaps from the beam accelerator and exit beam receiver. Results on plasma heating and confinement in the new GOL-3-II configuration are presented.

2. GOL-3-II facility

GOL-3-II facility (Fig.1) 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 (8÷9) T in the 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 kJ. The plasma in GOL-3-II facility has 6 cm diameter and its density can be varied in $10^{14} \div 10^{17} cm^{-3}$ range. Total energy loss of the beam passed through 12-m-long plasma column with density of $(1 \div 2)\cdot 10^{15} cm^{-3}$ achieves 30-40% [5].

Magnetic system of the GOL-3-II facility is flexible enough and during the experiments several configurations with corrugated field were used (H_{max}/H_{min}~1.5 and 22 cm cell length). Here we will discuss the 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 shown in Fig.2).

Initial gas distribution in described experiments over the device length was uniform in the first configuration (with special input foil separating vacuum volume of the beam generator). Latest experiments were done with pulsed gas-puffing without the input foil (typical initial pressure distribution is shown in Fig.2). Triggering time and output of each gas-puff unit is adjusted separately to reach the required density profile over the device length.

By the next step modified was 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 has started to flow on the plasma periphery (unlike our previous experiments with practically uniform current distribution [5]). Important feature of new exit system is expander section (see Fig.1) with the graphite beam receiver of 60 cm diameter under floating potential, which is placed in a relatively weak magnetic field (~1:80 ratio to field in the exit mirror), similar to [7].

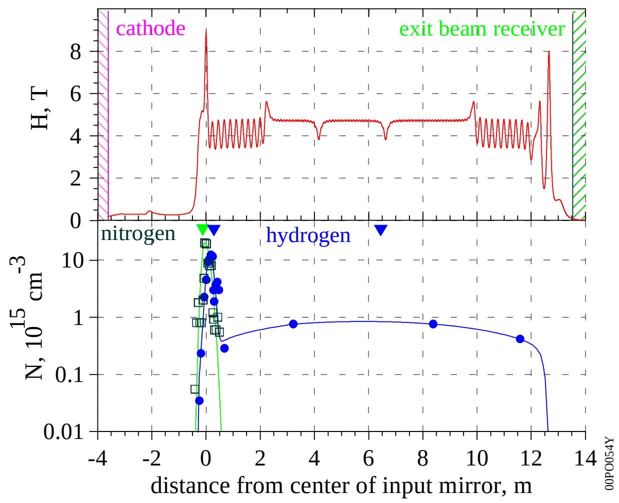

Fig.2. Magnetic field along the device (top) and initial distribution of hydrogen (dots) and nitrogen (squares)

3. Plasma heating

Theory predicts an essential influence of the magnetic field on the process of beam-plasma interaction (see, e.g., [8]). Therefore the plasma heating was studied in the experiments with 4.5-m corrugated section. Generally dependence of the final plasma pressure on the initial gas density is similar to that in uniform magnetic field [5,6]. Features of this dependence are almost constant pressure within $(0.2\div1)\cdot10^{15}$ cm^{-3} interval and fast decrease of a heating efficiency with further density growth. Plasma pressure is determined by electron temperature at low densities, then transition to $T_e\approx T_i$ occurs (Fig. 3 shows measured for the midplane of corrugated section).

Absolute achieved values of the plasma pressure and temperature for this regime are lower than for the case of uniform magnetic field. This might be attributed partly to worse ratio of the beam to the plasma densities in midplanes of the cells, to the larger total volume of the plasma and to changes in beam-wave synchronism and in spectrum of plasma microturbulence. 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 $(1.5\div2)\cdot10^{15}$ cm^{-3}.

As it was before mentioned, τ_E 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 the observed pressure wave with ~10^7cm/s velocity and finally expands into the trap, causing fast cooling of the plasma [5]. This expansion is observed by 1,15 μm interferometry, H_α stark broadening and diamagnetic measurements. 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.

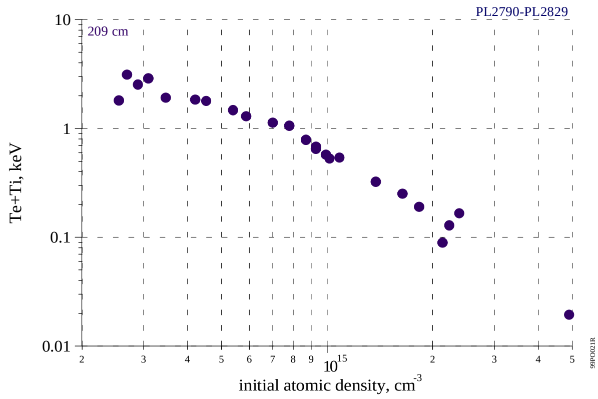

Fig.3. Dependence of plasma temperature on density (diamagnetic measurements)

4. Plasma confinement in multimirror magnetic field

This confinement has been studied in "foilless" mode of GOL-3-II operation. Operation of the preliminary discharge in this regime is highly sensitive to pressure distribution in the vicinity of the input mirror. Dense gas in this area is required both to provide some transverse electrical conductivity (after pre-ionization by fast electrons emitted from exit discharge unit) and to serve as source of background ions for proper compensation of space charge of the beam at final part of its ~40-fold compression in the magnetic field.

Experiments in the foilless regime were done with the symmetric configuration with two 2-m sections of the corrugated magnetic field at the device ends. This mode of operation differs from discussed above by absence of the dense cold foil plasma. τ_E in this regime increases, and due to constant density the plasma remains hot far longer than with the foil.

Up to date the experiments in the foilless regime were done with considerably reduced energy content of the electron beam, so the current plasma parameters in this regime are yet lower. Features of time evolution of the plasma pressure are: better τ_E, equalisation of the pressure in the central part of the device, absence of the pressure waves, different behaviour in the corrugated sections. Feature of this regime is also absence of fast pressure waves, which where typical for the experiments with the input foil [6]. The electron temperature is up to 250 eV at $1.5\cdot10^{15}$ cm^{-3} density at 14 μs after the beam start (Thomson scattering data at 180 cm from the input).

The main result of the latest experiments at the GOL-3-II facility is substantial increase of the τ_E , up to about 100 μs. Fig.4 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 $2\cdot10^{15}$ cm^{-3} plasma in the 12-m-long uniform field, best shot with $2\cdot10^{15}$ cm^{-3} plasma and 4.5 m corrugated section at input (foilless mode), and a shot with 10^{15} cm^{-3} plasma, 2+2 m corrugation, foilles regime and exit expander (energy content of the beam was lowered). Further experiments are planned with increase of the energy content of the beam up to its nominal value.

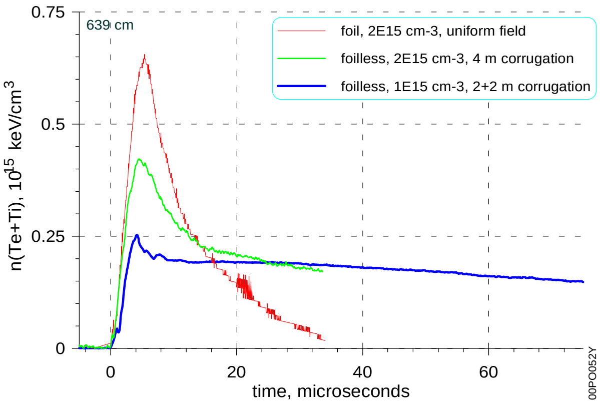

Fig.4. Plasma pressure in central part of the facility (different magnetic configurations)

The effect of corrugation of the magnetic field was also observed in experiment with puffing hydrogen cloud with a length about of 2 m. On a border of the cloud, which is inside multimirror section, a peak of pressure is created as a result of heating of the cloud by a main plasma, similarly to that as it occured in two-stage heating of a dense plasma in a uniform magnetic field [9]. However, in contrast to these experiments, now no fast movements, no fast decay of hot plasma bunch is registered. The explanation of this phenomenon can be an appearance of additional "friction" force in the corrugated magnetic field, as it should be in multimirror trap.

One of the basic physical problems in the GOL-3-II experiments is the macroscopic stability of plasma with current created by electron beam in the long plasma column. High enough plasma density (n_b/n_p~10^{-4}) and temperature eliminates some instability modes usual for intensive beams in a weak plasma. Nevertheless upper value of net current in our system is limited by well-known Shafranov-Kruskal criterion q>1, where q is safety factor. The 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). Operation in the multimirror regimes somewhat lowers the instability threshold due to lower average magnetic field in the corrugated sections. As the τ_E became longer in the latest experiments, the role of slower instability modes increases. We have no clear evidence of new problems with plasma stability at longer times, but some processes out of our control exist and have to be studied.

6. Conclusion

Success in physics and technology of fast plasma heating by a high-power electron beam marks the completion of the first phase of the GOL-3 program [4,5]. Further activity will be aimed at the improvement of plasma parameters using the concept of multimirror confinement. Recent experiments at the GOL-3-II facility were done in different multimirror configurations with up to 20 "cells". Additional efforts were taken in order to decrease longitudinal heat losses from the plasma. Macroscopically stable beam transport through the device is achieved. Main result of the latest experiments at the GOL-3-II facility is substantial increase of the energy confinement time.

Acknowledgments

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