First Results on Dense Plasma Confinement at the Multimirror Open Trap GOL-3-II

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Abstract. First results of experiments on plasma confinement in multimirror open trap GOL-3-II are presented. This facility is an open trap with total length of 17 m intended for 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). New phase of the experiments is aimed to confinement of high-β thermalized plasma. Two essential modifications of the facility have been done. First, plasma column was separated by vacuum sections from the beam accelerator and exit beam receiver. Second, the magnetic field on part of the solenoid was reconfigured into multimirror system with $H_{max}/H_{min}\sim1.5$ and 22 cm cell length. Results of the experiments at modified 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 $T_e \sim 1$ keV increases more than order of magnitude.

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 (device length exceeds free path length) the particle movement in a corrugated magnetic field becomes diffusive with typical scaling $z^2 \sim (\lambda v_{Ti})t$ and the longitudinal confinement time increases compared to classical mirror trap due to additional «friction force» between «trapped» and «transit» particles (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. Ions remain relatively cold.

The aim of new phase 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. First results on improved plasma confinement are presented.

2. GOL-3-II Facility and its Modification

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].
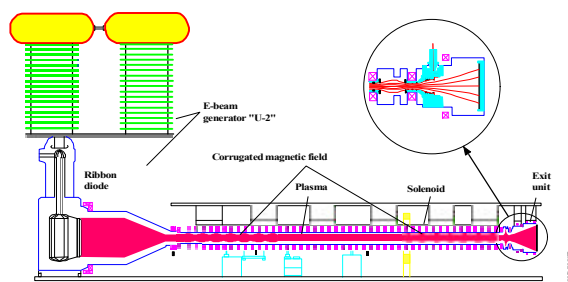
FIG.1 Layout of the GOL-3-II facility.

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 ($H_{max}/H_{min} \sim 1.5$ 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), see 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).

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]). As a result of selection of the discharge operation regimes and electrode geometry one managed to find the conditions, in which formation of currents ensuring the plasma stabilization is possible. 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]. This keeps specific heat load to front surface of the receiver well below the threshold of britte destruction of the graphite. Gas pressure in the expander section kept low.

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

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., [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
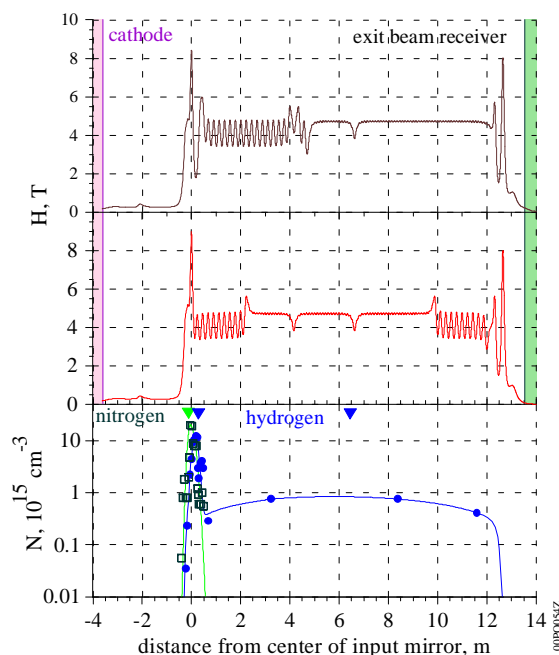
constant pressure within $(0.2\div1)\cdot10^{15}\,\text{cm}^{-3}$ interval and fast decrease of a heating efficiency with the further density growth. Plasma pressure is determined by electron temperature at low densities, then transition to $T_e\approx T_i$ occurs (FIG. 3 shows measured for the midlpane 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

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

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 (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 $(1.5\div2)\cdot10^{15}\,\text{cm}^{-3}$.

As it was before mentioned, the 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 the observed pressure wave with $\sim10^7\,\text{cm/s}$ velocity and finally expands into the trap, causing fast cooling of the plasma [5]. This expansion is observed by several diagnostics - FIG.4. 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. Plasma Confinement in Multimirror Magnetic Field

This confinement has been studied in «foilless» mode of GOL-3-II operation. Operation 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 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 the device length (shown in FIG.2). 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
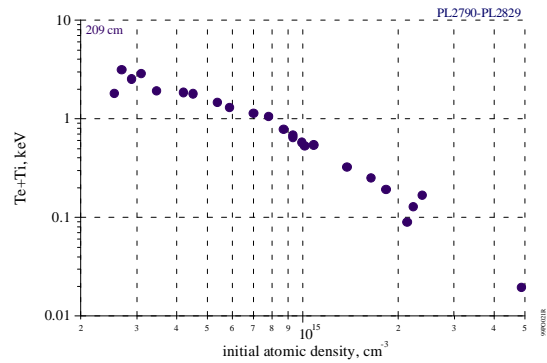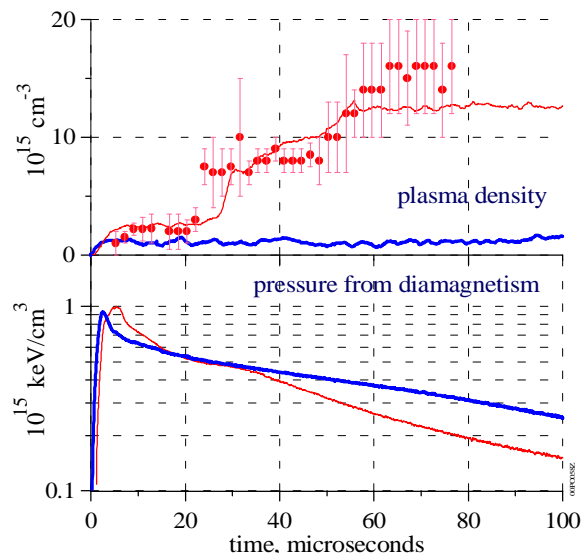

FIG.4. Comparison of regime with the entrance foil (thin) with foilless operation (thick). Top - plasma density, solid lines - data from 1.15 μm interferometry (86 cm from the input), dots - Stark broadening of H_α line. Bottom - data from diamagnetic measurements.

device ends. This mode of operation differs from discussed above by absence of the dense cold foil plasma (see FIG.4). Energy cofinement time 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: longer energy confinement time, 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 $1.5 \cdot 10^{15}$ 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 energy confinement time. FIG.5 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 4.5 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

FIG.5. Plasma pressure in central part of the facility (different magnetic configurations).

content of the beam was lowered). Further experiments are planned with increase of the energy content of the beam up to its nominal value.

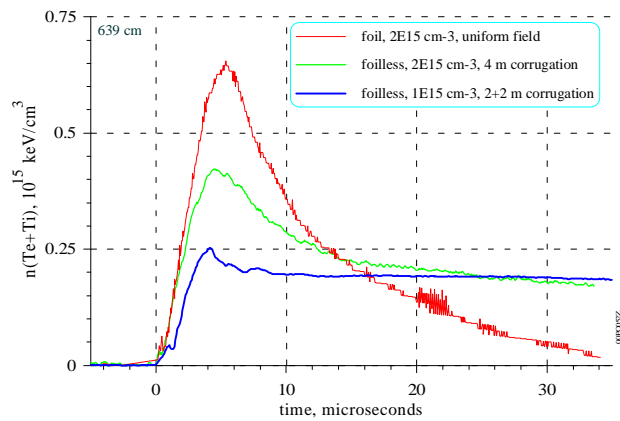The effect of corrugation of the magnetic field was also observed in experiment with puffing hydrogen cloud with a length about of 2 m. On a border of the cloud, which is inside multimirror section, a peak of pressure is created as a result of heating of the cloud by a main plasma, similarly to that 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.

5. Issues of plasma stability

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 ($n_b/n_p \sim 10^{-4}$) 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 - 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) - see [4,5]. 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 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. Recently 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 longitudinal heat losses from the plasma (foilless mode of operation, exit expander section). Macroscopically stable beam transport through the device is achieved. Main result of the latest experiments at the GOL-3-II facility is the substantial increase of the energy confinement time. Further experiments are planned with increase of the energy content of the beam up to its nominal value.

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