Advances in Plasma Heating and Confinement in the GOL-3 Multiple-Mirror Trap

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Abstract. *The paper reviews recent experimental results from GOL-3. Currently efforts are focused on further development of a physical database for multiple-mirror confinement systems and also on an upgrade of plasma heating systems of GOL-3 device. In general, current GOL-3 parameters demonstrate good prospects of a multiple-mirror trap as a fusion reactor.*

1. Introduction

Fusion research program on the concept of a multiple-mirror confinement suggested by Budker, Mirnov and Ryutov [1] is developing in Budker Institute [2]. Multiple-mirror trap is a set of linked magnetic mirror cells which form corrugated magnetic field. At large enough density the plasma undergoes a kind of a “friction force” which slows its axial expansion along the system. At large enough number of mirror cells $N>>1$ the multimirror confinement time becomes suitable for a fusion reactor ([3] and references therein). Early small-scale experiments validated basic principles of multimirror confinement for plasma dominated by classical binary collisions. Significant drawbacks of the initial reactor proposals were extremely high density and pressure in the system.

In present a very important role of collective effects in multiple-mirror trap GOL-3 becomes evident. Generally, for most of magnetic confinement systems these effects are negative and decrease energy confinement time. A situation in multiple-mirror systems is quite different. The feature is a small free path length comparing to system length, in contrast to simple “classical” mirror trap as well as tokamaks, stellarators and other magnetic confinement systems. Development of turbulent processes during the plasma heating and confinement causes reduction of free path length. This makes possible to reduce a length of a corrugation cell l for reaching the best confinement condition $\lambda_{eff} \sim l$ (λ_{eff} is effective free path length in respect to scattering on turbulent fields). As a result the total system length can be considerably reduced comparing to purely classical system. Turbulence noticeably increases transverse particle transport, but up to a certain level this is tolerable because main problem of open traps is large axial energy and particle losses, which can be significantly reduced by turbulence. Plasma parameters in the GOL-3 facility at the heating by the electron beam were found much higher [4] than expected from classical estimates even in conditions of low beta and of thermal contact of the plasma with solid edges. Temperatures of 1÷4 keV at plasma density up to 10^{21} m^{-3} and energy confinement time ~1 ms were achieved. This becomes possible due to excitation of plasma turbulence that sufficiently decreases longitudinal losses thereby eliminate this weakness of open traps.

2. Role of Turbulence in Plasma Heating and Confinement in GOL-3

In basic configuration of GOL-3 the deuterium plasma with density of $10^{20}\div10^{22}$ m^{-3} is confined in a 12-meter-long solenoid, which comprises 52 corrugation cells with mirror ratio B_{max}/B_{min} = 4.8/3.2 T (see Fig. 1). The plasma in the solenoid is heated up to ~2 keV temperature by a high power relativistic electron beam (~0.8 MeV, ~20 kA, ~12 μs, ~120 kJ) injected through one of the ends [4].

As was shown earlier in theory and experiment the beam-plasma interaction can excite Langmuir turbulence under certain conditions. In our case it can be complicated by close electron cyclotron frequency. All this in presence of gradients of magnetic field and plasma density makes theoretical analysis of instabilities very hard. Nevertheless some main features of turbulent phenomena in the beam-heated multiple-mirror trap and their consequences were understood based on experimental findings. These features are:

- beam electrons lose in average up to 40% of their initial kinetic energy in the plasma during the beam-plasma interaction [5];
- effective heating of plasma electrons occurs in turbulent fields;
- axial electron thermal conductivity is suppressed in ~3 orders of magnitude [6,7];
- due to two last effects strong gradients of electron pressure arise in corrugated magnetic field during the beam pulse [8];
- fast collective acceleration of ions following by thermalization occurs together with appearance of total plasma flow along the system due to electron pressure gradients [7,8];
- interaction between trapped and transit ions in high-pressure-gradient zones excites an ion bounce instability [4,9] that increases exchange between two mentioned particle groups and suppresses axial plasma flow.

Another class of collective phenomena is connected with formation of helical magnetic field by axial currents. Complex radial structure of currents is formed in the plasma with turbulent resistivity [10]. Sheared helical magnetic field is created in GOL-3 with a zero-azimuthal-field magnetic surface inside the plasma. Magnetic shear was shown to be the important factor for achievement of stable operation regimes and good plasma confinement in GOL-3.

Confinement in multiple-mirror trap is also improved by collective effects. Best energy confinement time in GOL-3 (~1 ms) corresponds to theory predictions but it is achieved at lower than predicted density. Good confinement at low density indicates that effective collision frequency in the plasma exceeds the classical value by a factor of few tens.
This simple listing of collective phenomena shows that plasma dynamics in multiple-mirror trap is mainly determined by turbulent processes.

Combined collective phenomena allow reaching high plasma parameters in GOL-3. Importance of these mechanisms is that optimal for the best confinement plasma density significantly decreases comparing to the classical model and therefore becomes more suitable for a feasible fusion reactor.

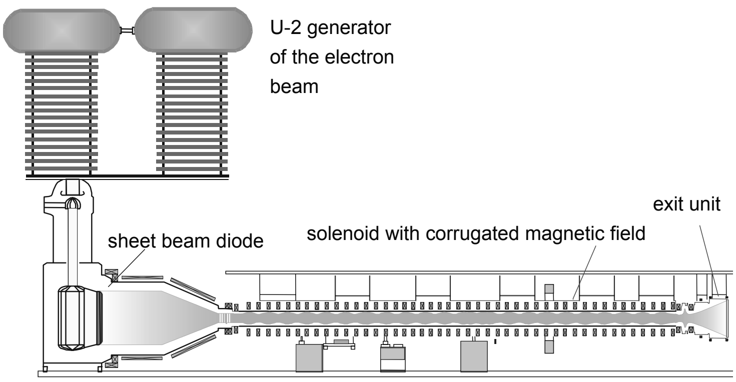

FIG. 1. Layout of GOL-3.

Conceptual reactor which includes collective effects can have sufficient advantages over the classical model. It can be stationary, operate at beta less than unity, and have more compact dimensions.

3. Strong Corrugation Regime at GOL-3

Usually GOL-3 operates with mirror ratio of the corrugated magnetic field equal to $R = 1.5$. At the same time the physical understanding of plasma confinement in a multimirror system will benefit if other than standard configurations of the magnetic field will be studied. Classical theory of plasma confinement in a multimirror trap predicts that particle confinement time should be proportional to a square of mirror ratio R at other parameters being equal. New experimental data is required for a margin of plasma stability in the modified system. In reality any change of the magnetic field profile in the experiment leads to related changes of some other important parameters, which govern plasma heating and confinement in the trap.

A special experiment with a change in magnetic configuration of the trap was done to validate the theory predictions. A high-mirror-ratio section was formed at first 2 meters of the solenoid with 5 cells at B_{max}/B_{min}=6.0/2.2 T and 44 cm length each (details are in [11]).

Oscillations of flux of D-D neutrons from near-the-end cells of the trap were found in previous experiments [4]. Period of oscillations equals to transit time of an ion through one corrugation cell. Current understanding of this effect is that the plasma motion along the corrugated magnetic field due to axial pressure gradient leads to electrostatic instability of bounce oscillations of slightly trapped ions [9]. Excitation of these oscillations leads to efficient exchange between populations of locally trapped and transit ions, therefore the axial plasma confinement in the multimirror system (which relies on a relatively short free path length for ions) improves.

Experiments have shown that transport of the electron beam through the plasma is stable. Collective plasma heating to sub-fusion temperatures and emission of neutrons from D-D reactions is observed. At the same time, the absolute values of energy content and confinement time of the plasma were less, than in optimum modes at regular corrugation of the magnetic field. Such decrease of parameters may be explained by non-optimal conditions of experiment, in particular increasing of transverse energy losses from the plasma.

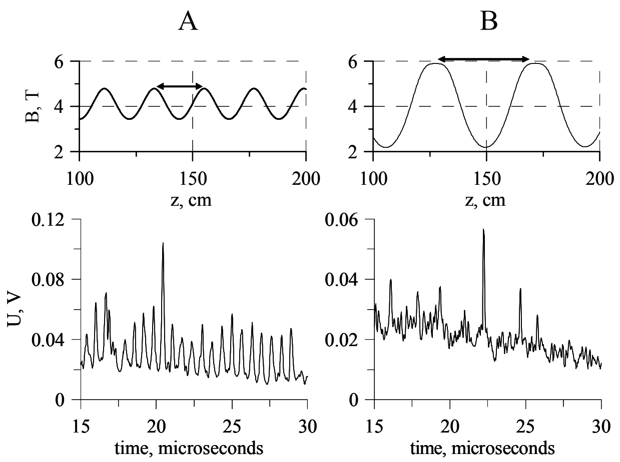

FIG. 2. Oscillations of local neutron flux. Cases A and B correspond to standard and strong corrugation, respectively. Top: magnetic field near the detector, arrows indicate the transit distance for oscillating ions. Bottom: fragments of waveforms of the local detector.

The important physical result from the experiments with strong corrugation of the magnetic field is change of the period between flashes of neutron emission in an initial part of the plasma. In full conformity with current views the frequency of bounce oscillations has decreased at the transition to strong corrugation – see Fig. 2.

4. Plasma Heating by Prolongated Electron Beam

Major mechanism which enables high plasma parameters in GOL-3 is suppressed electron heat flow along the axis which is provided by small-scale Langmuir turbulence developed as a result of two-stream instability. Fusion prospects of electron-beam technology of plasma heating in the multimirror trap depend on possibility of further increase of plasma parameters by the prolongation of the beam pulse. At more durable (~100 μs) beam pulse of ~0.1÷1 GW power one can expect the maintenance of the turbulence at the level appropriate for providing suppression of the electron heat transport. Additionaly the beam current can contribute to MHD stabilisation of plasma column [10].

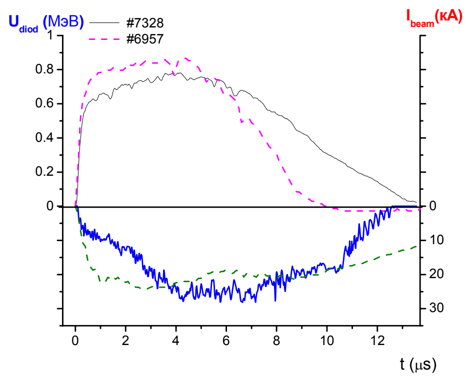

FIG. 3. Diode voltage and beam current before (dashed lines) and after (solid lines) prolongation of the electron beam.

As the first step in solving this task the 1.5-fold increase of duration of the high-power part of the electron beam generated by the accelerator U-2 was completed. Conditions of durable generation in magnetically insulated diode, stable transportation and compression in the magnetic field of the high-power electron beam were found. As the result the beam pulse duration was increased from 9 to 14 μs at the expense of some decrease of the diode voltage (see Fig. 3). As the prolongation of the pulse was reached due to the increase of the diode gap the beam current decreased from 30 to 25 kA. Total energy content of the beam at the collector remains practically unchanged.

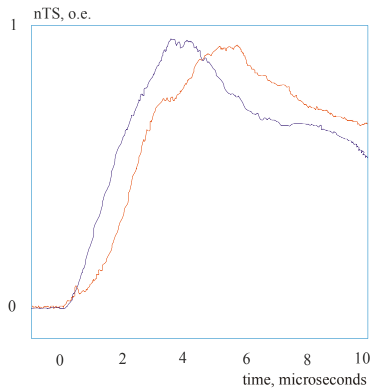

FIG. 4. Diamagnetism at Z = 44 cm in the same conditions for the beam of old and prolonged duration.

Experiments on plasma heating in GOL-3 were done under conditions described above in the Section 2. Here we will discuss the experiments with a bell-shaped distribution with a density peak of $(3÷8)\cdot10^{20}$ m^{-3} at the middle of solenoid and three-fold density decrease to the plasma edges.

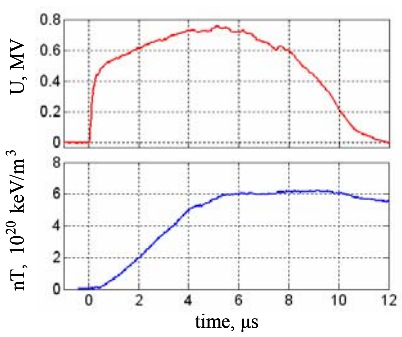

FIG. 5. Dynamics of plasma heating in central part of plasma column. Top: diode voltage, bottom: plasma pressure at Z = 4.75 m.

Growth of the plasma energy was measured with a set of 20 diamagnetic loops placed at different coordinates along the axis of the plasma column. In general axial distribution of the plasma pressure is similar to that with the beam of shorter duration. Shape of individual waveform depends on several parameters, including the coordinate along the plasma column.Figure 4 shows diamagnetic signals from a loop placed in the input part of the plasma at *Z* = 44 cm. Two shown cases differ in the beam duration only. Growth of the plasma pressure occurs during the high-power part of the beam pulse, and then the plasma cooling is observed despite the continuing beam injection. As was already mentioned, the main mechanism of the plasma cooling here is axial heat loss by electron thermal conductivity which is turbulently suppressed during the heating phase. When the beam power is insufficient for keeping the plasma turbulence at a high level, the suppression of axial heat loss decreases and fast cooling of plasma electrons occurs. Important feature of waveforms presented in Fig. 4 is extended duration of the plasma heating phase with the new beam. This means that such beam provides improved plasma heating even at lower average power without a degradation of peak plasma parameters.

Fast plasma cooling at the second half of the beam injection is observed in the edge parts of the plasma column only. Near the plasma midplane the energy and particle confinement are better. Typical diamagnetic signal from the central part of the plasma is shown in Fig. 5. Unlike Fig. 4, decreased heating efficiency stays high enough to keep the pressure at almost constant level up to the end of the beam injection.

Dynamics of diamagnetic signals and data from several other diagnostics indicate the possibility of substantional change of the beam-plasma interaction at approximately the peak power of the electron beam. Such change should result in the change of electron distribution function. Usually the electron distribution function is non-Maxwellian with large high-energy tails in the experiments with good efficiency of electron beam relaxation in the plasma.

Features of electron distribution function were studied with a Thomson scattering system positioned at Z = 415 cm. This system consists of a *Nd*-glass laser (1.058 μm, 30 J, 15 ns) and two registration systems for 90° and 8° scattering angles, which enable measurements within the energy range up to 20 keV [12]. Spectra of scattered light measured with 90°-subsystem are shown in Fig. 6 for several shots and two moments of time. The upper (energy) scale is obtained using the simple relation

$$\Delta\lambda \approx \lambda_0 \sin(\theta/2)(2E/mc^2)^{1/2},$$

where $\theta = 90°$ is the scattering angle. The distribution of plasma electrons is non-Maxwellian and anisotropic. A distinguishable excess of electrons with dominated longitudinal velocities over electrons with dominated transversal velocities in the range of $E \sim 1$ keV is clearly seen from the small angle Thomson scattering spectrum. High-energy tails and lower bulk temperature are more evident at the second part of the beam pulse in Fig. 6. We should note that interpretation of scattered spectra is model-dependent. During the period from 2 till 6 μs the difference in energies of "bulk" and "tail" components is not large, the distribution functions appear similar. Then, in the second half of the beam pulse, non-Maxwellian nature of the distribution function becomes more emphasized. Change in the electron distribution function occurs approximately at maximum plasma pressure mainly due to loss of a group

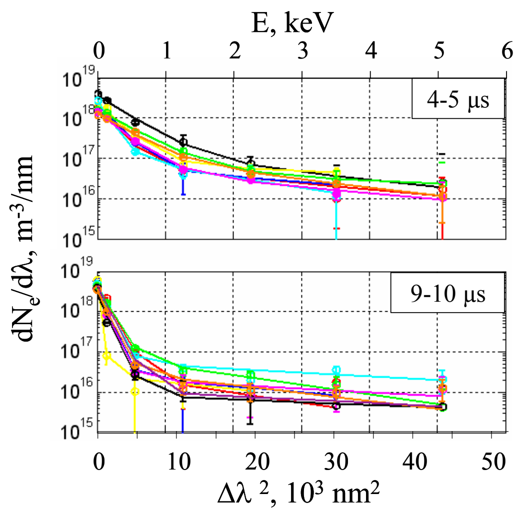

FIG. 6. Scattering spectra for 4÷5 (top) and 9÷10 μs after the beam start by 90° Thomson scattering.

of 1-3 keV electrons from the trap. Change of shape of electron distribution function may indicate that during the second part of the beam a level of the beam-induced microturbulence is not high enough to provide further plasma heating, but the anomalous scattering of electrons into the loss cone still exists for at least mentioned group of particles. Details of dynamics of electron distribution function are discussed in [13].

5. New Approach to Long-Pulse Electron Beam for Plasma Heating

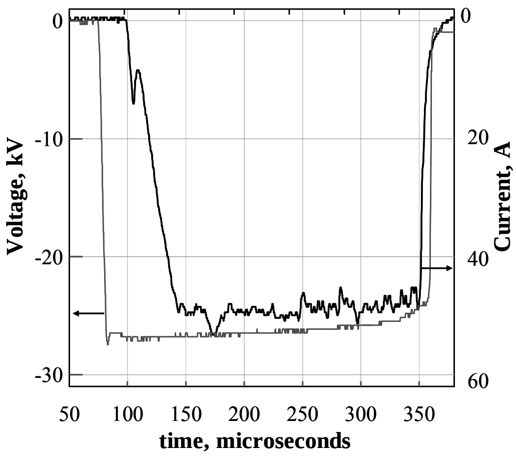

FIG. 7. Typical waveforms of the beam current and accelerating voltage.

Advance towards the creation of multiple-mirror fusion reactor requires the development of new tools and techniques purposed for heating and maintenance of plasma stability. First of all, duration of the electron beam pulse must be increased at least by an order of magnitude in comparison with that currently existing, with the retention of high current density and high brightness of the beam. The use of electron emitter based on controllable gas-discharge plasma seems a promising solution of the problem. Accordingly, development of a suitable technology of generation of electron beams in devices with a plasma cathode is required. The aim of the work is the development of an electron beam source with a pulse length in a range of 100 μs, accelerating voltage ~150 kV, current density of 1–2 kA/cm^2 and ~100 kJ beam energy content.

A special test bench was created for checking the concept of plasma electron emitter on the basis of high-current arc discharge and for the analysis of the technology of long-pulse electron beam generation. The stand comprises the electron beam source itself and the appropriate power-supply systems, vacuum system, etc. The value of the magnetic field is up to 0.1 T at the beam extraction region, then it rises along the beam transport line and reaches its maximum up to 2 T at a distance ~30 cm from the beam source.

The first experiments demonstrated that the arc plasma emitter can provide electron emission current density ~ 100 A/cm^2 in axial magnetic field ~ 0.1 T with the beam pulse duration at submillisecond range [14]. The mean electric field strength in the accelerating gap exceeded 100 kV/cm. Typical waveforms of the beam are shown in Fig. 7. Beam pulse duration and maximum current in these experiments were limited by the capabilities of the utilized power-supply systems only. The accelerated beam was transported without current loss in increasing magnetic field and maximal beam current density in the magnetic mirror up to ~ 0.5 kA/cm^2 was achieved in first experiments.

The results of the test experiments seem encouraging for developing the beam source with the higher parameters. New electron beam source with 150 kV voltage and beam current of up to 1 kA is currently designed for GOL-3.

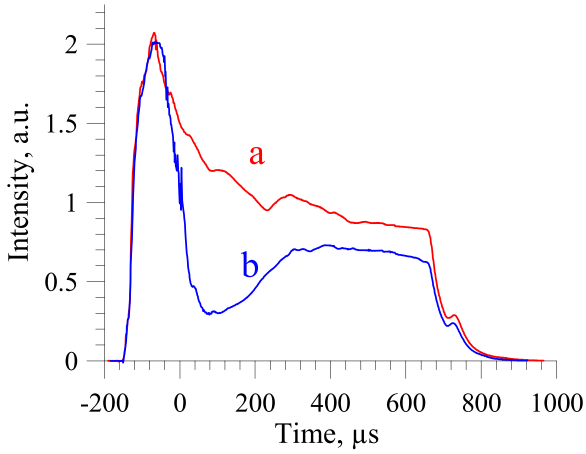

FIG. 8. Neutral beam attenuation by GOL-3 plasma, central collector of the profilometer: (a) NBI in vacuum, (b) NBI into plasma. t = 0 corresponds to the moment of electron beam injection.

6. First Experiments with NBI at GOL-3

A next step in the development of multimirror systems should provide significantly longer plasma lifetime. This requires development of new techniques of plasma heating in addition to existing high-power relativistic electron beam. Neutral beam injection is considered to be effective for auxiliary plasma heating in GOL-3. Special interest is in joint use of long-pulse electron beam for heat conductivity suppression and high-power neutral beam injection (NBI) for creation of population of fast ions in plasma.

High density, short lifetime, small plasma radius and high gas pressure near the wall are the challenges which complicate NBI use in GOL-3. First experiments with neutral beam injection were directed to adaptation of the technique for use in the conditions of GOL-3 and to study of fast ion confinement in turbulent plasma of multiple-mirror trap. Neutral beam injector based on START-2 design was mounted in the central part of the solenoid for normal injection. At first experiments the energy of accelerated atoms was 15÷18 keV, power was 0.45÷0.55 MW, and pulse duration was 0.8 ms. Beam passage across the plasma column was monitored by a current profilometer. This permits us to study radial distribution of the plasma density by attenuation of the neutral beam.

The feature of GOL-3 is high enough concentration ($\approx 10^{21}$ m^{-3}) of gas puffing. This results in additional losses of injected neutrals in transport line. In order to reduce such losses GOL-3 was put into a special operation mode, with the plasma and the gas densities in the vicinity of atomic injector decreased to 10^{20} m^{-3} while near needle valves it reached $1.8 \cdot 10^{21}$ m^{-3}.

The experience of neutral beam injection is successful in general. The rate of beam atoms, trapped into the plasma, reached 84%. Beam loss due to ionization of neutrals in the gas on the way to plasma column is below 20%. In the future we plan to increase NB power and additional geometric focusing of the beam.

7. Summary

Collective effects play important and positive role for a plasma confinement in a multi-mirror trap with a plasma heated by a high power relativistic electron beam. These effects lead to such consequences as effective beam relaxation in the plasma due to two-stream instability, strong suppression of axial electron heat flux due to enhanced particle scattering on beam-excited turbulence, effect of fast energy transfer from electrons to ions due to non-uniform collective acceleration of ions under electron pressure, excitation of density fluctuations in the mirror cells by axial plasma flow causing enhanced scattering of transiting ions which slows down plasma flow, MHD stabilization by a turbulence-shaped magnetic shear.

Combined effect of mentioned collective phenomena results in high plasma parameters in GOL-3. Electron temperature reaches 2÷4 keV at a density of $3\cdot10^{20}$ m^{-3}. Fast ion heating leads to increase of ion temperature up to ~2 keV at a density of ~10^{21} m^{-3}. Achieved energy confinement time (~1 ms) corresponds to theory taking into account collective processes.

Practical significance of collective processes is that the plasma in a reactor-scale trap can be maintained at much lower density than existed estimates based on classical binary collisions. The best confinement regime can be realized at density levels suitable for $\beta \leq 1$ operation that greatly improves engineering and physical feasibility of multiple-mirror concept for fusion reactor. The reactor therefore might be stationary, operate at beta less than unity and have dimensions less than supposed by the original model.

The data from experiments with strong corrugation and with the prolongated electron beam confirm the basic conclusions. The most important result from the presented series of experiments is the conclusion about maintenance of suppression of axial electron heat flow during full duration of prolongated electron beam.

Development of technologies of plasma heating is required for further increase of plasma parameters in the multiple-mirror trap. First experiments on neutral beam injection are carried out; experimental activity on new approach to generation of high-power electron beams is in progress.

Acknowledgement

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