STUDIES OF PLASMA CONFINEMENT IN GOL-3 MULTI MIRROR TRAP

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Recent results of the experiments at GOL-3 facility are presented. Plasma with a density of $10^{14}…10^{16}$ cm^{-3} is confined in a 12-meter-long solenoid, which comprises 55 corrugation cells with mirror ratio B_{max}/B_{min}=4.8/3.2 T. The plasma is heated up to 2…4 keV temperature by a high power relativistic electron beam (~1 MeV, ~30 kA, ~8 μs, ~120 kJ) injected through one of the ends. Mechanism of experimentally observed fast ion heating, issues of plasma stability and confinement are discussed.
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1. INTRODUCTION

In multi mirror system [1], if plasma density is high enough, its expansion along the magnetic field becomes diffusion-like due to effective "friction force" between the magnetic field and plasma particles. The final aim of experiments carried out at the GOL-3 (Fig.1) is development of a multi mirror fusion reactor concept [1-3].

Recently analysis of classical theory based on Coulomb collisions was made. Result of estimation of confinement time for typical GOL-3 conditions (mirror ratio $k=1.5$, ion temperature ~1keV, total device length $L=12$m) is given in Fig.2. Optimal conditions for confinement corresponds to $\lambda_i\sim l$, were λ_i is mean free path and l is individual mirror cell length. Important remark is the following. Usually in mirror traps plasma microturbulence is exited and it leads to decrease of mean free path and confinement time. Feature of a multi mirror trap in respect to influences of non classical scattering of particles is the improvement of the longitudinal plasma confinement.

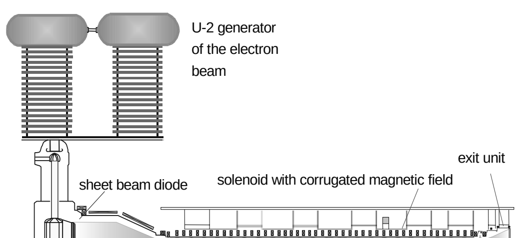

Fig.1. Layout of the GOL-3 facility. 12-meter-long solenoid consists of 55 cells of 22 cm length each with B_{max}/B_{min}=4.8/3.2 T. The plasma heating is provided by a high-power electron beam (~1 MeV, 30 kA, 8 μs) with total energy content of 120…150 kJ

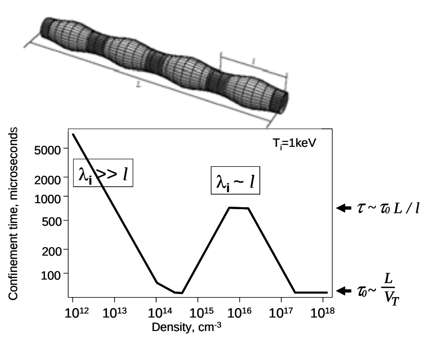

Fig.2. Calculation of confinement time τ on base of classical collisions

2. PLASMA HEATING

The plasma in multi mirror trap GOL-3 is heated as a result of interaction of high current relativistic electron beam with a dense (~10^{15} cm^{-3}) plasma. When the beam is injected into the plasma, collective beam–plasma interactions lead to the excitation of Langmuir turbulence. As a result, the energy of the relativistic electron beam is transferred primarily to the plasma electrons. The electron temperature rapidly reaches 2...4 keV at a density of $0.3\cdot10^{15}$cm^{-3} (see Fig.3).

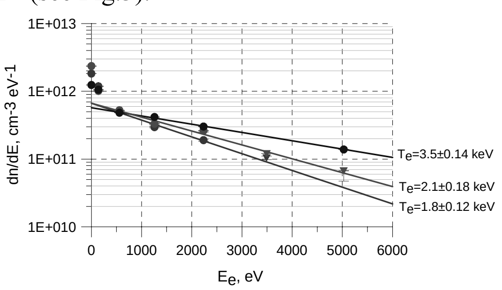

Fig.3. Results of measurements of electron temperature by Thomson scattering

To achieve such intense electron heating, it is necessary to suppress longitudinal electron heat conduction toward the system ends, at least, during the heating phase [4]. This phenomenon gives rise to high longitudinal gradients of the electron temperature and plasma pressure during the axially nonuniform plasma heating by a high-current relativistic electron beam. These gradients lead to two kinds of plasma macroscopic motions: local inside each cell and global along the system. Both these motions in a corrugated field lead to the electron energy transfer to ions much faster than the energy transfer due to binary collisions. As a result, ion temperature up to 2 keV at density ~10^{15} cm^{-3} is achieved.

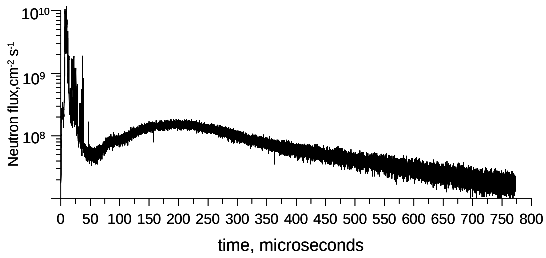

Fig.4. Time evolution of intensity of neutron emission at 1 m from the entrance mirror

The mechanism for fast ion heating considered here should lead to the excitation of large-amplitude waves of the plasma density. Such density waves were measured directly by Thomson scattering. The local neutron detectors allow one to trace the plasma evolution over a long time (see Fig. 4). The plasma evolution can be conventionally divided into three stages. In the fluctuation stage, a fraction of the ion component acquires energy (mainly a longitudinal one) due to the effect of fast ion heating in the multi mirror trap. In the second (transient) stage, the hot and cold ions intensively interchange their energy, the plasma temperature equalizes along the trap, and the ion temperature somewhat increases due to the thermalization of the directed energy of the fast ions. The third stage is the confinement of the cooling plasma in the multi mirror trap.

3. PLASMA CONFINEMENT

The plasma confinement in GOL-3 facility was studied for the initial density in a range of $3 \cdot 10^{14}$-$5 \cdot 10^{15}$ cm^{-3}. For the analysis of confinement time of plasma the data of all diagnostics were used, here we will consider mainly diamagnetic measurements.

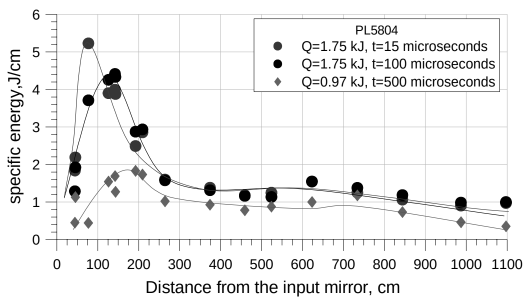

Fig.5. Axial distribution of plasma energy at different time moment

The measured dependence of distribution of specific energy in plasma versus distance from an entrance mirror is given in Fig.5. At 15 microseconds after the beam injection the energy deposition has a maximum at distance about 1 meter from an entrance mirror. In this place the peak of intensity of neutron emission is observed, the electron temperature during injection of a beam reaches of 2…4 keV, and ion temperature after an establishment of Maxwellian distributions also has a maximum of 2…4 keV. At large distances from the entrance mirror the temperature decreases to~1keV.

At 100 microseconds after the beam injection the energy distribution on length is changes. Sift of maximum of the energy stored in plasma is observed. Slow motion of plasma along the trap because of the pressure gradient is observed. Especially it is appreciable on distances of 1…3 meters from an input mirror where plasma pressure increases. Later (500 microseconds) this process proceeds. From this data also follow, that local confinement time of the plasma depends on coordinate along the axis of the system (see Fig.5.).

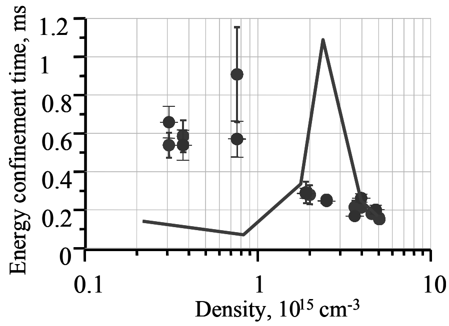

Fig.6. Energy confinement time vs initial density. Solid line shows prediction of the classical theory

Dependence of the global confinement time on initial density is presented in Fig.6. The theoretical dependence of the confinement time on initial density also shown. Apparently there is a significant divergence of prediction of the theory and the experimental results at density below $3 \cdot 10^{15}$ cm^{-3}. At these densities and the temperature the classical mean free path of the particles becomes comparable and even exceeds full length of the trap. In these conditions life time of particles should be of the order of time-of-flight of particles through full length of the system. This is not observed in the experiment. It is natural to assume, that effective ion collision rate considerably exceed the classical one, and due to this the effective mean free path of particles λ_{eff} may become about length of a separate cell multi mirror trap *l*. therefore conditions for the best confinement in multi mirror trap (λ_{eff}~ *l*) may be satisfied. The effective cross section should be at least the order of magnitude higher than classical one.

We conclude that scattering of plasma ions in the trap is determined by scattering of particles on turbulence. Now the nature of occurrence of micro fields in the plasma, resulting in improvement of confinement, is not clear. One of the possible mechanisms of improvement of longitudinal confinement is excitation of bounce oscillations near ends of the trap. Anyway, the fact of improvement of plasma confinement at moderate density is positive from the point of view of prospects of a multi mirror trap as fusion reactor**.**

4. BOUNCE OSCILLATIONS OF FAST IONS IN SEPARATE CELLS

A plasma motion along the corrugated magnetic field leads to excitation of bounce oscillations of fast ions in some separate cells near ends of the system. Such oscillations result in periodic modulation of flux of DD neutrons, which was measured with a set of compact local detectors - see Fig.7. Period of oscillations agrees well with the predicted period for bounce oscillations $\omega \sim \frac{V_{T_i}}{l}$, where V_{Ti} is ion thermal velocity. In the experiment a phase shift of neutron emission in separate sell is observed and this observation confirms nature of oscillation. These oscillations make efficient exchange between populations of trapped and transit ions, therefore the plasma confinement in the multi mirror system (which relies on relatively short free path length for ions) improves.

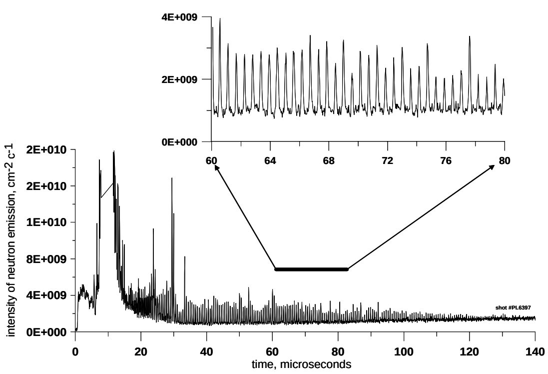

Fig.7. Periodic oscillation of the neutron flux. These oscillations are explained by excitation of bounce oscillations of fast ions in a cell of multi mirror trap

5. CONCLUSION

The electron temperature reaches 2…4 keV at a density of $0.3{\cdot}10^{15}$ cm^{-3} during collective beam-plasma interaction. Electron heat conductance is suppressed by three orders of magnitude.

Phenomenon of fast ion heating leads to increase of ion temperature up to ~2 keV at a density of ~10^{15} cm^{-3}.

Best energy confinement time (~1 ms) corresponds to theory but it is achieved at lower density, than it was predicted. This fact is beneficial for multi mirror trap based fusion reactor concept.

New class of plasma oscillations in the cells of multi mirror trap GOL-3 is observed. The oscillations are identified as bounce instability which can decrease the axial losses.

ACKNOWLEDGEMENTS

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ИЗУЧЕНИЕ УДЕРЖАНИЯ ПЛАЗМЫ В МНОГОПРОБОЧНОЙ ЛОВУШКЕ ГОЛ-3

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Представлены недавние результаты экспериментов на установке ГОЛ-3. Плазма с плотностью $10^{14}…10^{16}$ см$^{-3}$ удерживается в 12-метровом соленоиде, состоящем из 55 ячеек с пробочным отношением B_{max}/B_{min}=4.8/3.2 Тл. Плазма нагревается мощным релятивистским электронным пучком (~1 МэВ, ~30 кА, ~8 мкс, ~120 кДж) до температуры 2…4 кэВ. Обсуждаются механизм быстрого нагрева ионов, вопросы устойчивости и удержания плазмы.

ВИВЧЕННЯ УТРИМАННЯ ПЛАЗМИ В БАГАТОПРОБКОВІЙ ПАСТЦІ ГОЛ-3

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Представлено недавні результати експериментів на установці ГОЛ-3. Плазма з густиною $10^{14}…10^{16}$см$^{-3}$ утримується в 12-метровому соленоїді, який складається з 55 осередків із пробковим відношенням B_{max}/B_{min}=4.8/3.2Тл. Плазма нагрівається могутнім релятивістським електронним пучком (~1 МеВ, ~30 кА, ~8 мкс, ~120 кДж) до температури 2...4 кеВ. Обговорюються механізм швидкого нагрівання іонів, питання стійкості й утримання плазми.