# Studies of Plasma Confinement in GOL-3 Multi Mirror Trap

A.V. Burdakov 1), A.V. Arzhannikov 1), V.T. Astrelin 1), A.D. Beklemishev 1), V.S. Burmasov 1), G.E. Derevyankin 1), V.G. Ivanenko 1), I.A. Ivanov 1), M.V. Ivantsivsky 1), I.V. Kandaurov 1), V.V. Konyukhov 1), I.A. Kotelnikov 1), V.M. Kovenya 2), T.V. Kozlinskaya 3), K.N. Kuklin 3), S.A. Kuznetsov 1), A.G. Makarov 1), K.I. Mekler 1), V.S. Nikolaev 1), S.S. Popov 1), V.V. Postupaev 1), S.V. Polosatkin 1), A.F. Rovenskikh 1), A.A. Shoshin 1), I.V. Shvab 2), S.L. Sinitsky 1), Yu.S. Sulyaev 1), V.D. Stepanov 1), Yu.A. Trunev 1), L.N. Vyacheslavov 1), V.P. Zhukov 2), Ed.R. Zubairov 1)

1) Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia
2) Institute of Computational Technologies, Novosibirsk 630090, Russia
3) Novosibirsk State University, Novosibirsk 630090, Russia
E-mail: A.V.Burdakov@inp.nsk.su

**Abstract.** Experiments on multiple mirror plasma confinement are carried out at the GOL-3 facility in Novosibirsk. In present configuration of the device, a plasma with a density of $10^{20}\div10^{22}$ m$^{-3}$ is confined in a 12-meter-long solenoid, which comprises 55 corrugation cells with mirror ratio *Bmax*/*Bmin*=4.8/3.2 T. The plasma in the solenoid is heated up to 1-2 keV temperature by a high power relativistic electron beam (~1 MeV, ~30 kA, ~8 microseconds, ~120 kJ) injected through one of the ends. Conditions for plasma stabilisation are found in the experiment. Magnetic shear was shown to be the important factor for good plasma confinement in GOL-3. Sheared structure of the magnetic field is formed by axial guiding magnetic field of the solenoid and by azimuthal magnetic field, which is generated by axial currents in the plasma. Radial profile of rotation transformation factor was measured. The problem of MHD stability of the plasma heated by the electron beam was studied with 2-D (with helical symmetry) MHD and 3-D Reduced MHD models. Calculations show that tearing-like instability takes place and its typical development time is close to the experimentally observed one. Plasma confinement in the multi mirror configuration was studied. Comparison of the density dependence of global energy confinement time with the theory prediction for classical binary collisions indicates that optimal density for the best confinement is shifted to the lower densities. This fact is beneficial for multi-mirror-trap-based fusion reactor concept. Oscillations of local plasma parameters are observed in the separate cells of the trap. Such oscillations, in particular, result in periodic modulation of DD neutron flux. This phenomenon is associated with excitation of bounce oscillations of fast ions in separate cells caused by the plasma motion along the corrugated magnetic field. These oscillations provide an efficient exchange between populations of slightly trapped and slightly transit ions, therefore the plasma density required for efficient confinement in the multi-mirror system is reduced.

## 1. Introduction

Multi mirror confinement systems are developed in Budker Institute of Nuclear Physics from the early 70$^{th}$, after proposal of an idea of a multi mirror fusion reactor [1]. The plasma density in a multi mirror trap is substantially higher than that in other usual magnetic confinement systems. The improved longitudinal plasma confinement in a multi mirror system (as compared to the classical mirror trap) is achieved due to a frictional force that arises when a high-density plasma flows along a corrugated magnetic field. The main advantages of this approach are technical simplicity, absence of density and beta limits. The experiments on multiple mirror plasma confinement are carried out at the GOL-3 facility (Fig.1). The final aim of the experiments is development of a multi-mirror fusion reactor concept [1, 2].

In past GOL-3 experiments on plasma heating by a high-current microsecond relativistic electron beam [3] the electron temperature of ~1 keV was achieved and after modernization of this device [4,5] the temperature grows to 2–3 keV at a density of ~$10^{21}$m$^{-3}$. Both the absolute value of the temperature and its nonuniform distribution along the device length during ~5 μs could not be explained by the assumption that the plasma energy is lost due to the classical electron heat conductivity. To explain these experimental results, it was assumed in [6] that an abnormally high electron-scattering frequency caused by a strong turbulence occurring in the course of electron-beam injection into the plasma, reduces the longitudinal electron heat conductivity by two to three orders of magnitude, as compared to the classical conductivity (this problem is considered also in [7,8]).

## 2. GOL-3 Facility

In present configuration of the device ([5], Fig.1) the plasma with a density of $10^{20}\div10^{22}$ m$^{-3}$ 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 in the solenoid is heated by a high power relativistic electron beam (~1 MeV, ~30 kA, ~8 microseconds, ~120 kJ) injected through one of the ends.

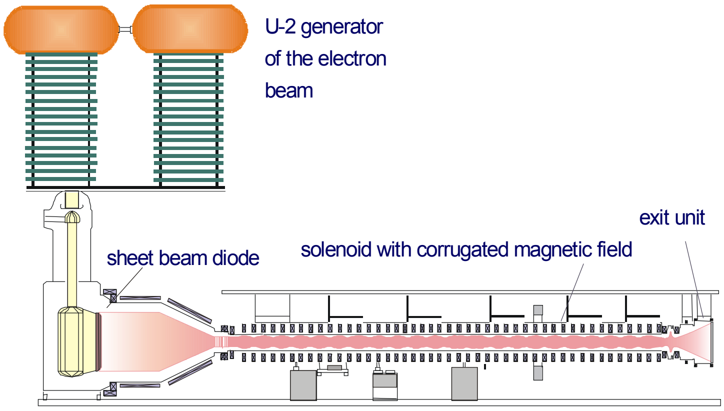


*FIG.1. Layout of the GOL-3 facility.*

The relativistic electron beam excites a high level turbulence in the plasma. The beam energy deposition is not uniform along the system. The axial profile of heating power and plasma pressure depends on local ratio of beam to plasma densities. Within the first meter of the plasma column, a sharp maximum of plasma pressure is observed, then it rapidly falls down and then the pressure decreases slower. As a result of the beam-plasma collective interaction, the efficient collision frequency of plasma electrons exceeds by a few orders the classical binary collision frequency. Consequence of this phenomenon is that the plasma longitudinal heat conductivity is decreased substantially. All the mentioned above phenomena result in high pressure gradients inside mirror cells along the magnetic field and macroscopic motion of the plasma. 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 [9]. 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.

Figure 2 shows the signal from a local neutron detector set 1 m from the entrance mirror. The evolution of neutron flux can be conventionally divided into three stages. In the fluctuation stage (0-50 μs), 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 (50-200 μs), the hot and cold ions intensively interchange their energy, the plasma temperature equalizes along the trap, and the ion temperature somewhat increases

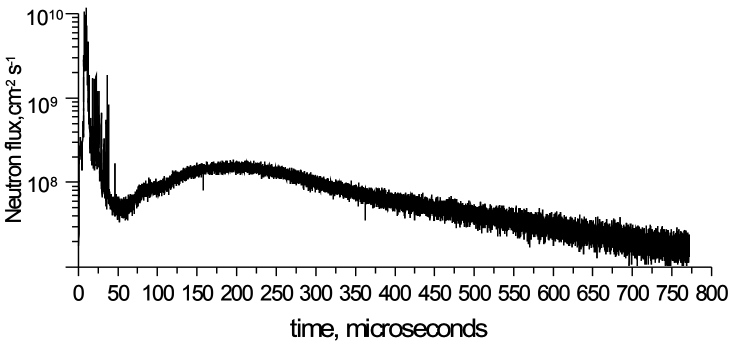


*FIG.2. Time evolution of intensity of neutron emission at 1 m from the input mirror.*

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. As a result, electron and ion plasma temperatures up to 2 keV at density $\sim 10^{21}$ m$^{-3}$ are achieved and the value $n\tau T \sim (1.5 \div 3) \cdot 10^{18}$ m$^{-3}$s·keV at $T_i \sim 1$ keV is attained.

## 3. Stable Operation Regimes of the Multi Mirror Trap GOL-3

Necessary condition for achievement of high performance regimes is the macroscopical stability of the plasma. Magnetic shear was shown to be the important factor for good plasma confinement in GOL-3 [10]. Sheared structure of the magnetic field is formed by axial guiding magnetic field of the solenoid and by azimuthal magnetic field, which is generated by axial currents in the plasma. Radial profile of local current density is created by three main sources of current, two of which are external (current of relativistic electron beam and current of the preliminary linear discharge) and the third internal source is the return current to the beam generator which also runs through the plasma.

An influence of helical structure of magnetic field on plasma heating and confinement of hot ($T_i \sim 1$ keV) plasma was demonstrated in special experiments shown in Fig.3. A preliminary plasma was created by a linear discharge. The discharge current oscillates. Thus, if we change a delay time between start of discharge current and start of beam pulse, we can vary configurations of azimuthal magnetic field and of magnetic shear. A stable plasma confinement is reached if the discharge current exceeds 3 kA and it is directed opposite to the beam current (case 3 in Fig.2). In this case the net current is directed opposite to the beam current too, and its value exceeds some specific value, ~2 kA for the regime under consideration.

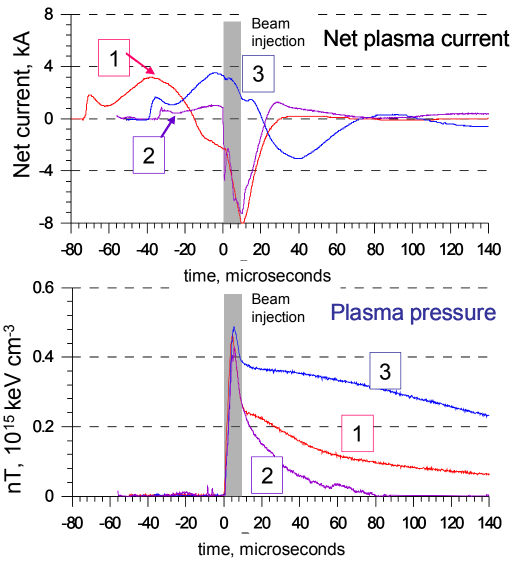


*FIG.3. Dependence of plasma heating efficiency and energy confinement time on direction of discharge plasma current: 1 – plasma current is parallel to beam current; 3 – plasma current is opposite to beam one; 2- is low discharge current.*

## 4. Measurements of Rotation Transformation Factor

Helicity of the magnetic field is usually described for linear systems with the safety

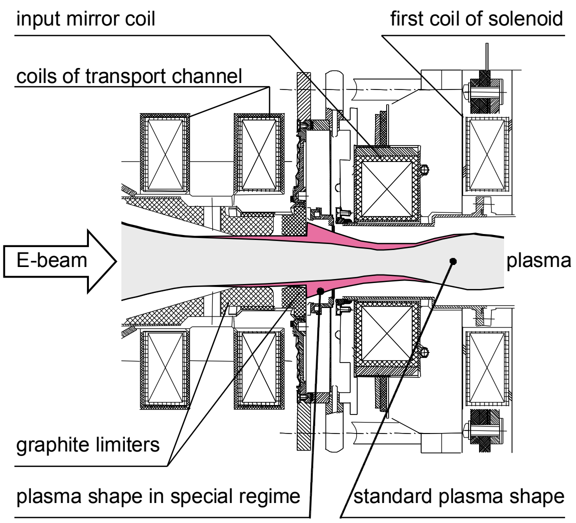


*FIG.4. Layout of the experiment for measurement of the radial distribution of the plasma current in the input mirror.*

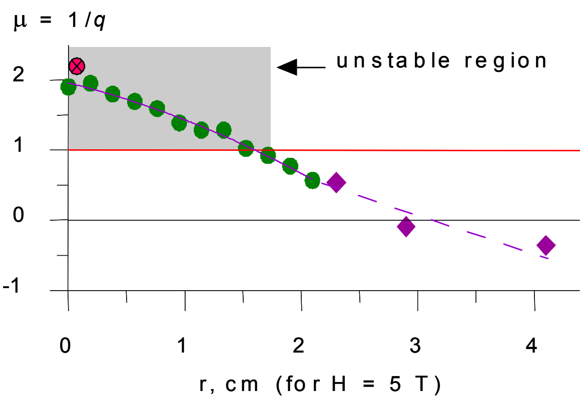


*FIG.5. Results of measurements of rotary transformation factor at 3.5 microseconds after the beam injection start. Dots is X-ray footprint, cross is current density at exit, diamonds - current measurements at the entrance.*

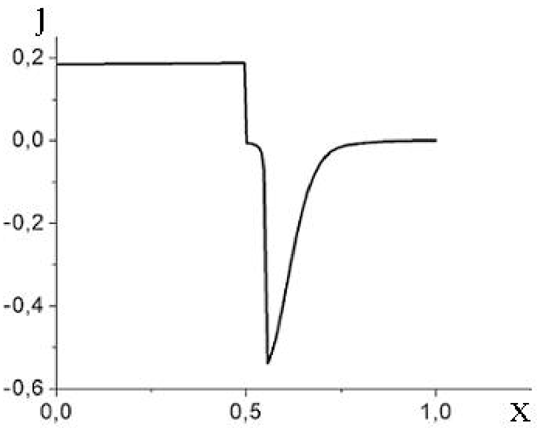


*FIG.6. Radial profile of the net current in modelling. This is the initial state for Fig.7.*

factor $q=(H_z/H_\varphi)\cdot(2\pi r/L)$ (where $H_z$ and $H_\varphi$ are longitudinal and azimuthal components of the magnetic field, $r$ and $L$ are plasma radius and column length). In the case of non-compensated beam current (up to 30 kA) $q$ is in the range 0.3-0.5 for GOL-3 conditions that may lead to the exitation of the external helical modes and the stability loss of the beam-plasma system.

First experimental proof of formation of helical magnetic field was providing by the X-ray footprint of the relativistic electron beam at the collector [10]. In a new experiment a time evolution of the beam and net current density on axis was carried out. A compact Rogovsky coil is placed at the axis of the collector for measurement of the net current density. Beam current density inside the coil is measured with collimated bremsstrahlung detector. Carbon foil covers coil entry in order to cutoff plasma current. Measured X-ray signal corresponds to beam current density rather well. When the foil is removed, net current density remains practically the same, but lasts a bit longer. This means that during the beam injection its current density at the axis is not compensated (that is due to turbulent decrease of conductivity) and corresponding paraxial q value is 0.3-0.5. Plasma current, which is possibly induced at the beam cutoff, damps rather quick. Distribution of current density on a plasma periphery was measured in a special experiment (see Fig.4). In this experiment the magnetic field in the transport channel was changed, so the plasma diameter was changed too. Graphite limiter cuts off some part of the plasma current corresponded to limiter diameter. Net current before and after the graphite limiter was measured, enabling therefore calculation of local current density.
Results of all these experiments (as at the entrance and also at the exit of plasma

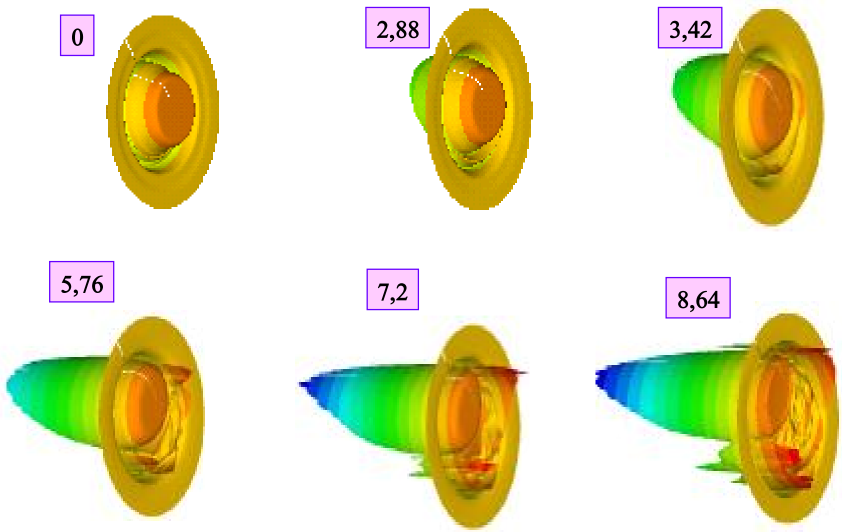


*FIG.7. Evolution of plasma currents at a tearing-like instability. Moments of time after beam start are given in microseconds. Beam duration is of 8 microseconds*

column) are summarized in Fig.5 for stable operation regime of GOL-3. Features of this regime are appearance of sheared helical magnetic field and formation of magnetic surface with azimuthal field equal to zero inside the plasma column ($q = \infty$ at some radius).

## 5. Computer Modelling

The problem of MHD stability of the plasma heated by the electron beam was studied with 2-D (with helical symmetry) MHD and 3-D Reduced MHD models. The presence of the beam leads to anomalously large resistivity within the beam area. The presence of the beam and the sharp decrease of the resistivity at the beam edge provide a current distribution shown in Fig.6. The safety factor for such distribution is below unity near the axis. Respectively inner modes of tearing instability can take place.

In 2-D modeling (Fig.7) we studied evolution of the mode $m$=1, $n$=1, which should dominate by our estimates. 2-D modeling shown, that:
I. Tearing-like instability really takes place and has a typical time coincidence to the experimental current disruption time;
II. The instability becomes visible already during the beam existence;
III. The current configuration is such, that the inner magnetic flux is larger, than the outer.

Results of 3-D modeling confirm qualitatively the results of the 2-D modeling. According to 3-D results the main dangerous modes are $m$=1, $n$=1 and $m$=1, $n$=0.

## 6. Plasma Confinement

The plasma confinement in GOL-3 facility was studied for the initial density in a range of $3{\cdot}10^{20}$-$5{\cdot}10^{21}$ m$^{-3}$. For the analysis of confinement time of plasma the data of all diagnostics were used, here we will consider mainly diamagnetic measurements.

The measured dependence of distribution of specific energy in plasma versus distance from an entrance mirror is given in Fig.8. 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 measured by

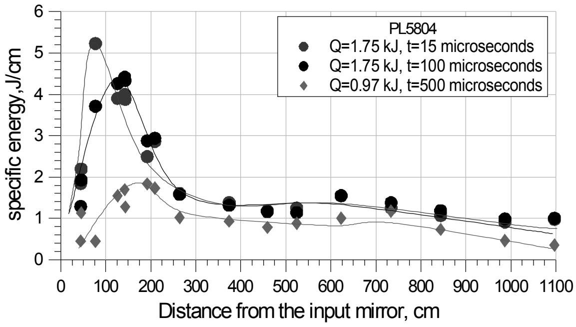


*FIG.8 Axial distribution of plasma energy at different instants.*

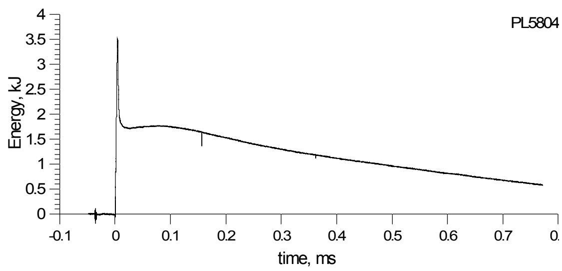


*FIG.9. Energy stored in plasma with density of $8 \cdot 10^{20}\ m^{-3}$.*

Thomson scattering during the beam injection reaches 2-4 keV, and ion temperature 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 axial energy distribution is changes. Sift of maximum of the energy stored in plasma is observed. Slow motion of the plasma along the trap because of the pressure gradient is observed. Especially it is appreciable on distances of 1-3 meters from the input mirror where plasma pressure increases. Later (500 microseconds) this process proceeds. From this data also follows that local confinement time of the plasma depends on coordinate along the axis of the system (see Fig.8).

Figure 9 shows evolution of total energy stored in the plasma. This data was obtained from diamagnetic measurements shown in Fig.8. Initial fast growth of the energy corresponds to the plasma heating by the beam. At this time almost all the plasma energy belongs to electrons. The electron temperature keeps at a high level due to highly turbulent electron collisions during the heating phase. After end of the beam the plasma electrons fast cool down and simultaneously transfer a part of stored energy to plasma ions through a mechanism of fast collective ion heating. During some time thermalization of ion distribution function occurs, this shows up as a growth of the total diamagnetic energy of the plasma. At this stage and some later ion temperature is much higher than electron temperature. Then (after thermalization of ions) at the cooling stage we can found the global energy confinement time using decay time of the total plasma energy.

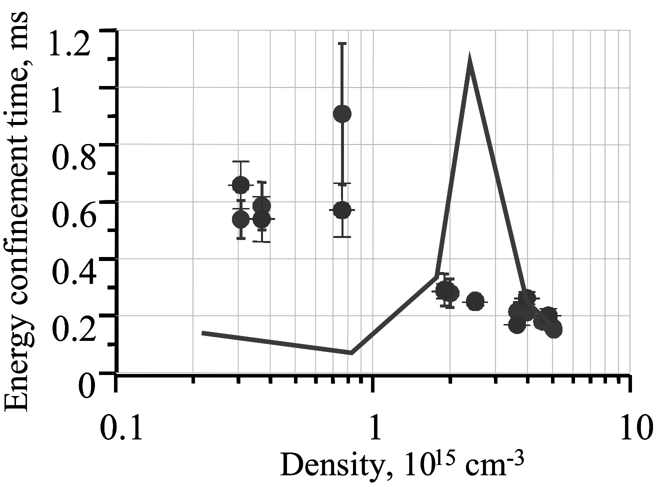


*FIG.10. Energy confinement time vs initial density. Solid line shows prediction of the classical theory.*

Dependence of the plasma confinement time on initial density is presented in Fig.10. The theoretical dependence [11] of the confinement time on initial density also is shown. Apparently there is a significant discrepancy of prediction of the theory and the experimental results at density below $3 \cdot 10^{21}\ m^{-3}$. At these densities and the temperature the classical mean free path of the particles becomes comparable and

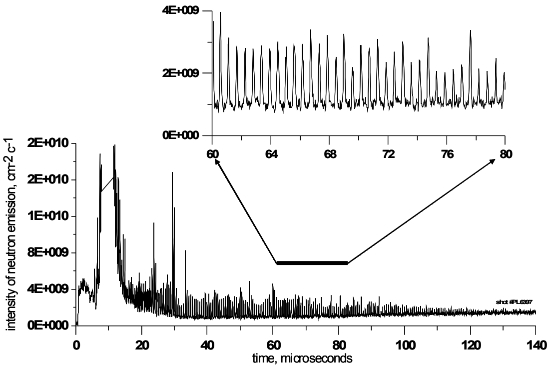


*FIG.11. Periodic oscillation of the neutron flux near the end of multi mirror trap.*

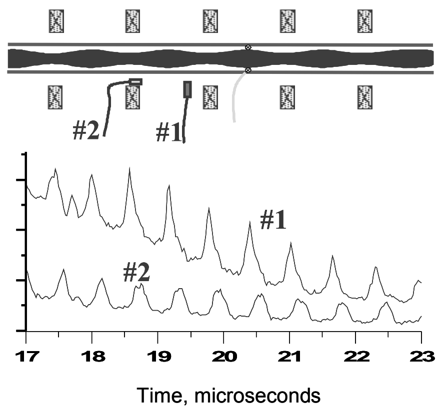


*FIG.12. Phase shift of neutron emission in a separate cell of the trap. Signals of two local neutron detectors placed near local maximum of the magnetic field are shown.*

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 exceeds the classical one and due to this the effective mean free path of particles $\lambda_{eff}$ may become about the length of a separate cell of multi mirror trap $l$. Therefore conditions for the best confinement in multi mirror trap ($\lambda_{eff}\sim l$) may be satisfied. The effective collision rate should be at least the order of magnitude higher than classical one.

Special measurements of an effective charge of plasma have shown that such scattering can not be provided by scattering on impurity ions. Therefore we conclude that scattering of plasma ions in the trap is determined by scattering of particles on turbulence. One of possible mechanisms of improvement of longitudinal confinement is excitation of bounce oscillations near ends of the trap ([12] and section 7). 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**.**

## 7. 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.11. Period of oscillations agrees well with the predicted period for bounce oscillations [12]:

$$\omega \sim V_{T_i}/l,$$

where $V_{Ti}$ is ion thermal velocity.

Phase shift of neutron emission in separate sell is observed and this observation confirms nature of oscillation (Fig.12).

These oscillations make efficient exchange between populations of trapped and transit ions, therefore longitudinal plasma confinement near the ends of the multi mirror system (which relies on relatively short free path length for ions) improves.

## 8. Conclusion

- The electron temperature reaches 2–4 keV at a density of $0.3\cdot10^{15}cm^{-3}$ during the 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 $\sim10^{15}$ $cm^{-3}$.
- 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 particle loss.
- Global plasma stabilization in GOL-3 is achieved by the control of magnetic shear.

## Acknowledgments

The work was partially supported by RFBR 05-01-00146, 05-02-17160, 04-01-00244 and 05-08-33664 projects.

## References

[1] BUDKER, G.I., et al., "Influence of Corrugated Magnetic Field to Expansion and Cooling of Dense Plasma", JETP Letters **14** (1971) 320-322 (in Russian).
[2] RYUTOV, D.D., "Open-Ended Traps", Sov. Phys. Uspekhi **31** (1988) 301.
[3] BURDAKOV, A.V., et al, "Experiments on collective interaction of microsecond relativistic electron beam with plasma on GOL-3", JETP **82** (1996) 1120-1128.
[4] ARZHANNIKOV, A.V., et al., "Recent results on plasma heating and improved confinement at the GOL-3-II facility ", Fusion Technology **39**(1T) (2001) 17-24.
[5] KOIDAN, V.S., et al., "Progress in Multimirror Trap GOL-3", Fusion Technology **47**(1T) (2005) 35 - 42.
[6] BURDAKOV, A.V., and POSTUPAEV, V.V., "Features of Heat Transport at Beam Plasma Heating in Experiments on the GOL-3 Facility", Preprint No. 92-9, BINP, Novosibirsk, (1992) (in Russian).
[7] ASTRELIN, V.T., et al. "Generation of Ion-Acoustic Waves and Suppression of Heat Transport during Plasma Heating by an Electron Beam", Plasma Phys. Rep. **24** (1998) 414-425.
[8] ARZHANNIKOV, A.V., et al., "Direct Observation of Anomalously Low Longitudinal Electron Heat Conductivity in the Course of Collective Relaxation of a High-Current Relativistic Electron Beam in Plasma", JETP Letters **77**(7) (2003) 358–361.
[9] ARZHANNIKOV, A.V., et al., "Study of the Mechanism for Fast Ion Heating in the GOL-3 Multimirror Magnetic Confinement System", Plasma Physics Reports **31**(6) (2005) 462-475.
[10] POSTUPAEV, V.V., et al. "Role of q-Profile for Plasma Confinement in the Multimirror Trap GOL-3", Fusion Technology **47(**1T) (2005) 84-91.
[11] KOTELNIKOV, I.A., "New results in the theory of multiple mirror plasma confinement", Fusion Science and Technology **51**(1T) (2007) *in print.*
[12] BEKLEMISHEV, A.D., "Bounce Instability in a Multi Mirror Trap", Fusion Science and Technology **51**(1T) (2007) *in print.*