Heating and Confinement of Ions at Multimirror Trap GOL-3

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Abstract. Main results of researches on plasma heating and confinement of dense plasma in the multimirror trap GOL-3 are presented. Recently magnetic system of the facility was converted into completely multimirror one. This results in further improvement of energy confinement time of plasma with ion temperature ~1 keV. Collective plasma heating by ~120 kJ (~8 μs) relativistic electron beam results in T_e~2 keV at ~10^{21} m^{-3} density. High T_e exists for ~10 μs. To this time T_i reaches ~2 keV. Ion temperature keeps at the high level during ~1 ms. The energy confinement time sufficiently increases and a value of $n\tau_E$ =(1.5÷3)·10^{18} m^{-3}s.

1. Introduction

Multimirror confinement of hot dense plasma in a long open trap is studied at GOL-3 facility in Novosibirsk [1]. Initially multimirror confinement was proposed in [2,3] and it is considered as alternative approach to nuclear fusion [4]. The multimirror trap consists of a set of mirrors, which are connected to each other at their ends. Full solenoid length L exceeds mean free path of the particles λ. If, at the same time, the mirror cell length l<λ then the longitudinal confinement time increases essentially compared to classical single mirror trap (see review [5]). This paper covers our new experiments with multimirror magnetic system at the GOL-3 facility. Main aims of the experiments were: study of multimirror confinement of a dense hot plasma; gradual improvement of the facility in order to reach broader range of operational parameters with macroscopically stable plasma; study of mechanism of ion heating and confinement.

2. Modification of GOL-3 Facility

GOL-3 facility (Fig.1) is a long open trap intended for study of heating and confinement of a relatively dense (10^{21}÷10^{23} m^{-3}) plasma in axisymmetrical magnetic system [1]. The magnetic system consists of coils for transport and shaping of the electron beam, a 12-meter-long solenoid and an exit unit (which includes plasma creation system, expander and exit receiver of the beam and plasma). Solenoid consists of 55 cells of 22 cm length each with B_{max}/B_{min}= 4.8/3.2 T (Fig.2). Preliminary deuterium plasma of (0.2÷5)·10^{21} m^{-3} density is created by a special linear discharge along the whole device length. Axial distribution of the plasma density is formed by a set of fast gas-puff valves. The plasma heating is provided by a high-power electron beam (~1 MeV, 30 kA,

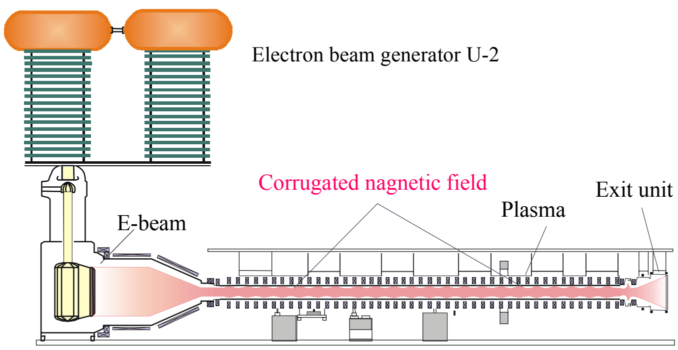

Fig.1. Layout of the GOL-3 facility.

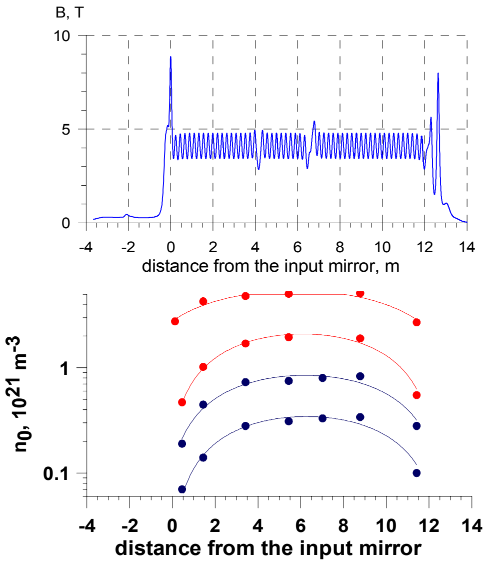

Fig.2. Magnetic field configuration (top). Axial distribution of the initial deuterium density n_0 (bottom). Four different regimes are shown.

8 μs) with total energy content of 120÷150 kJ. Main plasma diagnostics include magnetic measurements, 1.06 μm Thomson scattering, visible and VUV spectroscopy, VUV linear detector array, 1.15 μm interferometry, neutron detectors of different types, CX neutrals, etc.

Certain modernization of the facility was performed during last years. Goals of the modernization were transformation of the magnetic system in full corrugation mode and increase of power density in the electron beam.

3. Plasma Heating Stage

The relativistic electron beam interacts collectively with a plasma and excites a high level turbulence in it. As a result of collective interactions, the distribution function of heated plasma electrons becomes essentially nonequilibrium one. The major part of electrons is heated up to average energies (temperature) of 1÷2 keV. In this case the spatial anisotropy of the electron distribution function is observed: the mean energy of electrons in the axial direction exceeds by several times the electron energy in the radial direction. In addition, the electron spectrum is non-Maxwellian and it extends up to an energy of the heating beam [6]. These suprathermal electrons keep the major part of energy left by the beam in the plasma. The beam energy release is nonuniform along the system length. Fig.3 shows the axial distribution of specific plasma energy for two operation regimes. Dependence *a*) corresponds to the high temperature regime with rather low density (0.2÷0.5)$\cdot 10^{21}$ m^{-3}, *b*) corresponds to the high density regime (4÷5)$\cdot 10^{21}$ m^{-3}. It is seen that in the high temperature regime there is the pressure peak at a distance of about 1 m from the entrance mirror. In the high density regime this dependence is smoother.

As a result of the beam-plasma collective interaction the effective collision frequency of plasma electrons exceeds by three orders the classical Coulomb collision frequency. Consequences of this phenomenon [7] are in the fact that the plasma electrical conductivity and its longitudinal electron thermal conductivity decreased substantially. All the mentioned above phenomena enable a possibility to form the high pressure gradients along the magnetic field and macroscopic motion of a plasma. As a result, fast heating of ions is observed in GOL-3 [8].

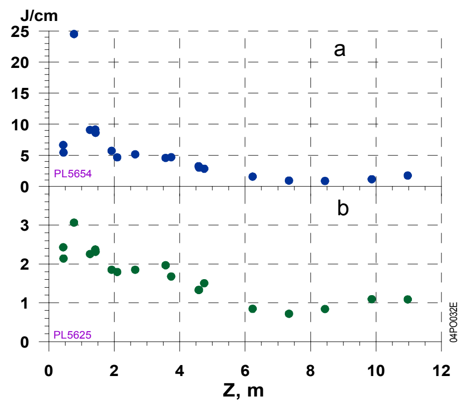

Fig.3. Axial distribution of plasma energy (multiplied to averaged cross section) at different initial density.

3.1. Fast Heating of Ions (Model and Experiment)

A model for explanation of fast ion heating in a multimirror trap was proposed (see [8]). It takes into account the following: a) a nonuniform plasma

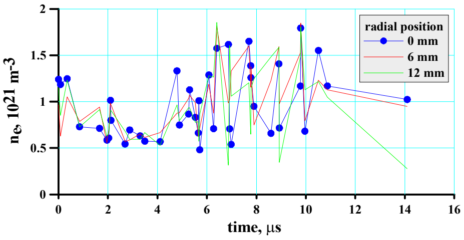

Fig.4. Results of shot-by-shot measurements of radial profile of the plasma density by Thomson scattering.

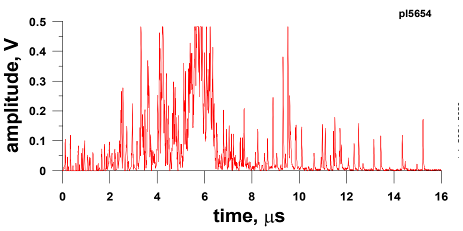

Fig.5. Initial phase of neutron emission, $n_0=0.3\cdot10^{21}m^{-3}$

heating (which depends on the n_b/n_p ratio, i.e. on the local magnetic field); b) suppression of heat transport during the beam-plasma interaction that enables one to create high pressure gradients; c) collective acceleration of plasma flows from the high-field part of corrugation cells to cell's 'bottom'; d) thermalization of the opposite ion flows. The model predicts occurrence of strong modulation of density and velocities of ions in cells of a trap after several microseconds of beam injection.

A set of special experiments was carried out at GOL-3 facility in order to study this mechanism of ion heating. The Thomson scattering system (10 J, 1.06 μm) was used to measure a 8-point radial distribution of the plasma density with 1 mm spatial resolution. Shot-to-shot spread of plasma density is below 10% during several first microseconds of the beam injection. Then the density spread becomes larger, up to $\delta n/n$~40% (Fig.4).

Measurements of a neutron emission intensity (Fig.5) show that first neutrons are detected in 2÷3 μ*s* after beginning of the beam injection and then a powerful flash of neutron radiation takes place in 4÷8 μ*s*.

3.2. Dynamics of a Plasma at the Heating Stage

Let us consider distributions of the pressure and intensity of neutron radiation along the trap length (Fig.6) in order to understand the mechanism of occurrence of modulations of the plasma local parameters, leading to the redistribution of the ion temperature along the plasma column length, and in particular, to an increase in temperature at some points of coordinates. As is seen from the data given above, there is a pressure peak at a distance of about 1 m from the input mirror. At this point the sharp maximum of the neutron emission is observed at the moment of the beam injection end.

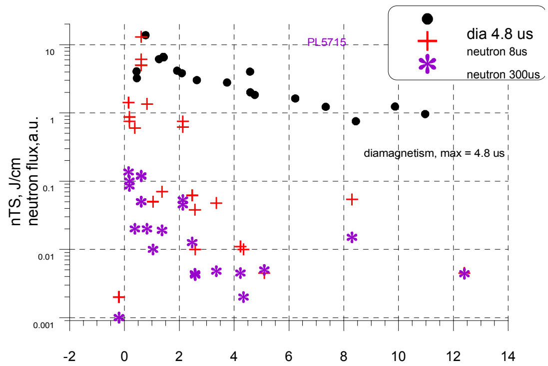

Fig.6. Comparison of axial distribution of plasma pressure (multiplied to averaged cross section) and DD neutrons power vs. initial deuterium density. Z=4.5 m.

After the end of the beam injection the plasma pressure equalizes along the trap length and corresponding redistribution of the neutron emission intensity along the trap length occurs. On average, at the point with the maximum flux of neutrons, the neutron flux decreases. Far from the maximum the neutron emission intensity increases slowly (in time scale of ~0.1 ms). Such a plasma behavior can be related to macroscopic motion of the plasma along the multimirror trap. Since in a multimirror trap such a process is of a diffusive nature, the plasma motion velocity in such a system is much lower than that corresponding to the free expansion of a hot plasma along the magnetic field. At some time the pressure profile as well as the neutron intensity become more uniform along the trap length. For illustration, Fig.6 shows distribution of the neutron emission in 0.3 ms after beginning of the beam injection. This moment of time corresponds already to the plasma confinement stage.

The plasma motion in the axial direction through the multimirror system and redistribution of its parameters along the radius is accompanied by excitation of oscillations inside the hot part of the plasma column. This is clearly displayed by the signals of neutron detectors as this diagnostics most sensitive to the plasma parameters. Excitation of the inner modes are also detected by other local diagnostics.

It is worth mentioning that one should also take into account an energy stored in the magnetic field of the beam current and plasma current (see [9, 10]). From the plasma heating viewpoint, helical modes possible in such a configuration lead both to occurrence of fluctuations and to additional heating of the plasma. The energy in the azimuthal magnetic field despite the fact that it is lower that in the hot plasma is enough for partial explanation of increase of the plasma temperature after end of the beam injection.

4. Stage of Plasma Confinement

Fig.7 shows the results of plasma pressure measurements with diamagnetic loops compared to the ion temperature obtained with the analysis of the Doppler broadening of the D_α line emitted from the hot central part of a plasma. These data are given for Z~2 m from the input mirror of the trap. As is seen from the diamagnetic measurements, the plasma pressure increases fast during the beam injection. As was shown in the earlier studies of the electron distribution function in a simple solenoid [11] and measurements results of the electron temperature by the 90° scattering in a multimirror trap, during injection of the beam the plasma electron component contribution into the pressure is dominant.

After the end of the beam, the anomalously low electron thermal conductivity of a plasma vanishes. The electron temperature drops and it equalizes along the plasma column length. The Thomson scattering measurements show that after the end of the beam, the «transverse» component of the electron temperature is of the order of 100 eV. The Thomson scattering measurements enable us to conclude that thermal electrons do not make the noticeable contribution into the total pressure of the plasma after the electron beam injection. The same conclusion can be made upon the analysis of axial distribution of the pressure (see Figs. 3, 6). Actually, the nonuniformity of the plasma pressure distribution along the system length remained rather long and much longer than the time of equalizing the electron temperature along the plasma column. Note, that in a simple solenoid, the plasma pressure was determined by the electron component and after the end of heating, the pressure axial profile was established in the trap, which corresponded to the electron thermal conductivity to the trap edges. In a multimirror trap, the situation is changed very essentially.

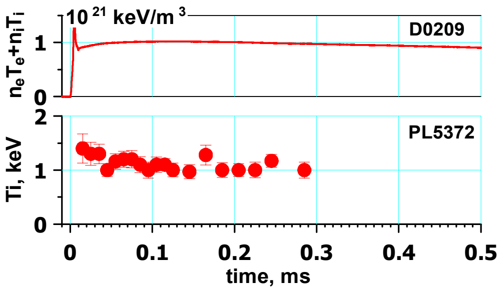

Fig.7. Dynamics of plasma pressure (Z=209 cm) and ion temperature. Initial deuterium density is $0.5\cdot10^{21}$ m^{-3}.

Fig.7 shows also the ion temperature. It is seen that at the initial plasma density of n_0=0.5·10^{21} m^{-3} in these experiments the dominant role in pressure is already played by the plasma ion component. Ion temperature is varied with changing of initial plasma density. At n_0=0.3·10^{21} m^{-3} it achieves 2 keV and keeps at the level of 1.5 keV during ~ 0.25 ms. Some similar conclusions can be made on the base of the analysis of the fast charge-exchange neutrals escaping plasma. Typical values of the ion temperature obtained in these measurements are ranging from 1 to 2 keV in the regimes with corrugated magnetic field at the deuterium initial densities of (0.3÷0.5)·10^{21} m^{-3}.

Fusion reactions proceed rather intensively in the heated plasma. Fig.8 shows time evolution for the emission of DD neutrons performed with the scintillator detector based of the stilbene crystal. The upper picture shows the total flux of neutrons and gammas. The lower figure shows only the neutron component separated with the digital Pulse Shape Discrimination (PSD) system. One can evaluate the ion temperature by the emission intensity. The ion temperature value is 1÷2 keV under assumption of the Maxwellian distribution function and uniform distribution of emission over cross-section of the plasma hot region. As is seen from the Figure, the neutron emission duration exceeds 1 ms.

Let us pay attention to some features of the time evolution for all the signals related to the ion temperature. First of all, the ion component is heated in time scale comparable with the beam duration (~10 μs), the hot ion component is confined in the trap for 0.3÷1 ms at the plasma density of ~10^{21} m^{-3}. At some certain points along the plasma column, some rather slow (~0.1 ms) changes in the ion temperature are observed. This is seen in the diamagnetic signals (an increase of pressure in 0.05÷0.1 ms after the beam injection), in the time dependence of the ion temperature, in the neutron emission intensity. The slow changes of plasma parameters, which are presently related to the plasma macroscopic motion, occurs as a result of formation of the pressure peak in the plasma and further equalizing of the pressure along the column length as well as with an additional heating of the plasma due to dissipation of the energy stored in the magnetic field of the longitudinal plasma currents (see [9, 10]).

In addition to the plasma pressure dynamics and plasma temperature measurements, we measured the dynamics of radial profile of plasma density. To this aim, we used the new system of the Thomson scattering based on the *Nd* laser (1.06 μm) operated in a multipulse Q-modulation regime. This system enabled measurements of the radial profile of the plasma density with the resolution of 1 mm in every 10÷20 μs in about 20 points in time in one shot. Measurements have shown that as a result of formation of the initial plasma and after completion of turbulent processes at the plasma heating stage, some plasma profile is established. Its minimum ("valley") size corresponds to the size of the heating electron beam. The density profile in the beam cross-section does not change in practice during over 0.1 ms. Some slow density variations in the periphery are observed.

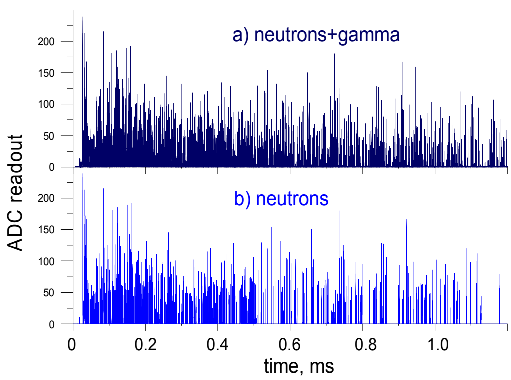

Fig.8. Generation of fusion neutrons (digital PSD stilbene detector at Z=4.3 m). Initial deuterium density is 1.9·10^{21} m^{-3}.

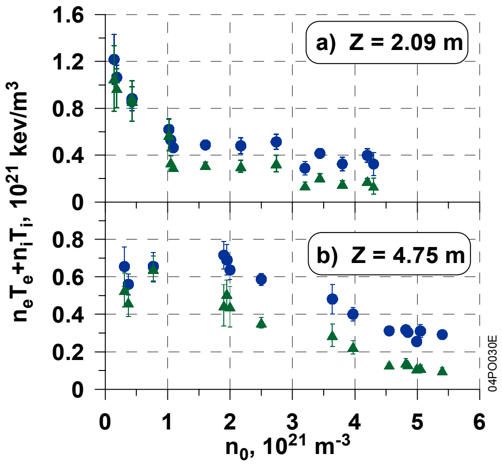

Fig.9. Plasma pressure vs. initial deuterium density. Z=2.09 m and 4,75 m. Circles – 10 μs, diamonds – 150 μs after the beam injection.

Conclusion of this section is that a stable plasma is generated with a density of ~10^{21} m^{-3}, ion temperature of 1÷2 keV and lifetime of ~1 ms as a result of heating by the relativistic electron beam in a corrugated trap.

4.2. Dependence of Plasma Parameters on Density and Their Axial Distribution

In a series of experiments we obtained the dependence of basic plasma parameters on the initial distribution of deuterium along the system length. Initial pressure of the gas was varied by changing of a pressure in the pulse valves (see Fig.2). Fig.9 shows the results of plasma pressure measurements by the diamagnetic loops at two distances from the input mirror. Each plot shows results for two moments of time. The time moment of 10 μ*s* after the beginning of beam injection characterizes the plasma pressure after completion of the fast heating of electrons and ions. The beam ends 2÷3 μs earlier and part at suprathermal electrons leaves the trap to this time. Therefore value of plasma pressure at *t*=10 μs is less than the peak one (see, e.q., Fig.7). The pressure measurements at the time moment 150 μs correlate with energy confinement time. It is seen that dependencies on the plasma density are different for the entrance plasma (*Z*~2 m) and for the plasma in the center of the facility (*Z*~5 m). At the device entrance, the dependence is strong but in the central section of the trap the plasma pressure is practically independent on density up to the density of $2{\cdot}10^{21}$ m^{-3}. After that, it drops slowly.

Let us draw attention to the density-confinement time dependence. In a high temperature regime corresponding to the density lower than $2{\cdot}10^{21}$ m^{-3}, the plasma lifetime is also longer. In these regimes, the "diamagnetic" $n\tau_E=(1.5\div3)\cdot10^{18}$ m^{-3} s corresponds to the confinement time of a plasma in a multimirror trap under optimum confinement conditions. With the increase of the plasma density, the ion temperature and lifetime decrease. These results of diamagnetic measurements are also confirmed by measurements of a neutron flux from the plasma (see Fig.10). The neutron flux intensity is stronger dependent of the density. This results from the dependence of the neutron yield on the density and temperature. As follows from the neutron measurements, with an increase in plasma density, the ion temperature decreases.

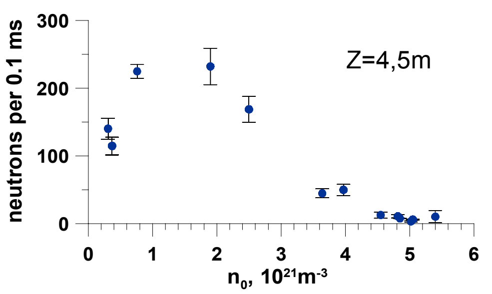

Fig. 10. DD neutrons yeld vs. initial density. Z=4.5 m. Stilbene detector with dPSD. Number of neutrons for interval 50÷150 μs after the beam injection.

Let us consider the axial distribution of plasma parameters (Fig.3) and transverse losses (Fig.11) for revealing the reasons of occurrence of the plasma lifetime-density dependence. Energy content of the plasma (J/cm) is given for direct comparison with the transverse losses. It is seen that in the high temperature regime, the transverse losses remain to be lower than longitudinal ones. In the context of these considerations, the plasma transverse losses

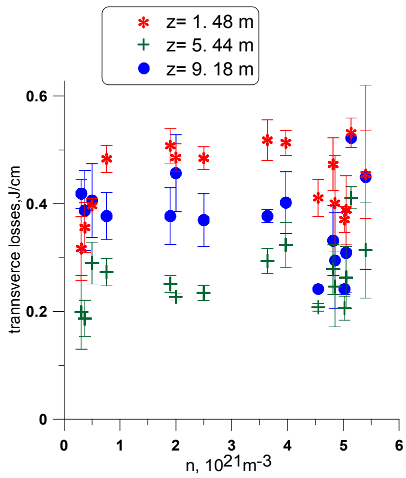

Fig.11. Transverse losses measured by wall calorimeter.

are determined as the losses to the vacuum chamber wall, i.e. the losses for radiation and charge exchange neutrals. For finding out the fractions of these losses, the radiation power from a plasma have been measured in the visible and VUV ranges. The measurements by the absolutely calibrated VUV spectrometer enable the conclusion that the main source of radiation losses is the linear radiation of light impurities in the VUV. In the high temperature regime, the total losses for radiation make a substantial fraction and probably the dominant fraction of the transverse energy losses from the plasma. In this regime, the transverse losses are small and the plasma confinement corresponds to its calculated value for the multimirror confinement.

At high density of a plasma the fraction of transverse losses increases and moreover, the losses to limiters become probable, i.e. the plasma escape across the magnetic field with its further loss at limiters. Such a behavior of a plasma is related now to a decrease in the longitudinal current flowing along the plasma column with an increase of plasma density. The decrease in the net current leads to the decrease in the magnetic field shear and probably to the increase in the role of the plasma MHD instability at high densities. Special experiments (see [9, 10]) confirm this assumption and, at the same time, shows the way of damping such instabilities. Namely, in order to increase the plasma lifetime, it is necessary to increase the discharge current in the plasma and therefore to increase the magnetic field shear.

5. Progress in Plasma Parameters at the GOL-3 Facility

The final aim of experiments carried out at GOL-3 facility is a proof of a perspective of the multimirror trap for the thermonuclear reactor. In the last few years, the device was step by step transformed into the multimirror trap with full corrugation. In addition, the energy density in the heating electron beam was increased that led to improvement in plasma heating. The major efforts in the experiments were directed to the search for conditions optimum for obtaining the macrosopically stable plasma. The results of GOL-3 facility improvement are illustrated by Fig.12 with the best shots for various configurations of the magnetic fields. It is seen that at the shift to the fully corrugated magnetic field, the confinement time increases substantially and plasma parameters increase also with the improvement of heating and optimization of confinement.

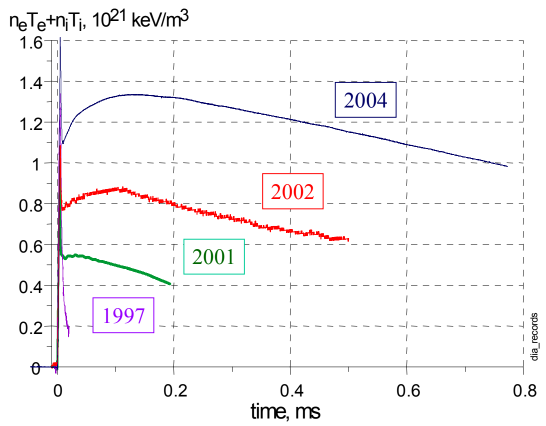

Fig. 12. The best shots for various configurations of the magnetic field. Experimental conditions:
1997 - uniform field, $0.9{\cdot}10^{21}$ m^{-3}, H, 3.73 m;
2001 – 4 m corrugated ends, $0.3{\cdot}10^{21}$ m^{-3}, D, 2.08 m;
2002 - full corrugation, $0.8{\cdot}10^{21}$ m^{-3}, D, 3.57 m;
2004 - full corrugation, $1.5{\cdot}10^{21}$ m^{-3}, D, improved heating, 2.08 m.

6. Conclusion

1. Conditions for stable creation of preliminary plasma and its effective heating in the range $(0.2 \div 6) \cdot 10^{21}$ m^{-3} are experimentally found.

2. Electron and ion plasma temperatures up to 2 keV at density $\sim 10^{21}$ m^{-3} are achieved.

3. Macroscopical stability and long confinement of the dense plasma in multimirror system is obtained.

4. The value $n\tau_E \sim (1.5 \div 3) \cdot 10^{18}$ m^{-3} s at ion temperature ~1 keV is attained.

5. Transition to full corrugation of the magnetic field and increase of specific parameters of heating E-beam results in essential increase of plasma parameters in the multimirror trap GOL-3.

Acknowledgements

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References

[1] KOIDAN, V.S., et al., "Multimirror Open Trap GOL-3: recent results", Transactions of Fusion Science and Technology **43**, No.1T (2003) 30-36.
[2] BUDKER, G.I., et al., "Influence of Corrugation of Magnetic Field on Expansion and Cooling Down of Dense Plasma", JETP Letters, **14** (1971) 320-322 (in Russian).
[3] LOGAN, B.G., et al., "Multiple-Mirror Confinement of Plasmas", Phys. Rev. Letters **28** (1972) 144-147.
[4] RYUTOV, D.D., "Open-Ended Traps", Sov. Phys. Uspekhi, **31** (1988) 301.
[5] LICHTENBERG, A.J., MIRNOV, V.V., "Multiple Mirror Plasma Confinement", Reviews of Plasma Physics, **19** (Kadomtsev, B.B., Ed.), Consultant Bureau/Plenum Press, New York (1996).
[6] ARZHANNIKOV, A.V., et al., "Recent Results on the GOL-3-II Facility", Transactions of Fusion Technology, **35**, No.1T (1999) 112-118.
[7] ASTRELIN, V.T., et al., "Generation of Plasma Acoustic Waves and Suppression of Heat Transport during Plasma Heating by an Electron Beam", Plasma Physics Reports **24**, No.5 (1998) 414-425.
[8] BURDAKOV, A.V., et al., " Experimental Results on Multiple Mirror Trap GOL-3", Controlled Fusion and Plasma Physics (Proc. 29th EPS Int. Conf. Montreux, 2002); Contributed Papers (CD-ROM file P5-057).
[9] BURDAKOV, A.V., et al., "Fast Heating of Ions in GOL-3 Multiple Mirror Trap", Controlled Fusion and Plasma Physics (Proc. 31th EPS Int. Conf. London, 2004); Contributed Papers (CD-ROM file P4-156).
[10] POSTUPAEV, V.V., et al., "Role of q profile for plasma confinement in the multimirror trap GOL-3", Transactions of Fusion Science and Technology, **47**, No.1T (2005) (in press).
[11] BURDAKOV, A.V. et al., «Experiments on the Collective Interaction of a Microsecond Relativistic Electron Beam with a Plasma in the GOL-3 Facility», Journal of Experimental and Theoretical Physics **82**, No.6 (1996) 1120-1128.