ENERGY TRANSFER FROM ELECTRON BEAM TO DENSE PLASMA CLOUD AT THE GOL-3-II FACILITY

A.V. Arzhannikov, V.T. Astrelin, A.V. Burdakov, V.S. Koidan, K.I. Mekler, P.I. Melnikov, S.V. Polosatkin, **V.V. Postupaev**, A.F. Rovenskikh and S.L. Sinitsky

Budker Institute of Nuclear Physics, 630090, Novosibirsk, Russia

Activity at the GOL-3-II facility is mainly directed to production of hot dense (10^{15} - 10^{17} cm^{-3}) plasma in long open trap in order to study then multimirror and «wall» confinement of such a plasma [1]. The plasma in GOL-3-II facility has 6 cm diameter and 12 m length. Plasma density can be varied in 10^{14}÷10^{17} cm^{-3} range and can be as of uniform distribution along the device length and nonuniform one. The longitudinal magnetic field is up to 4.5 T in regular section of a solenoid and 9 T in its end mirrors. Configuration of the magnetic field can be varied at the facility.

At the beam injection into the plasma a two-stream instability is developed resulting in the beam energy loss and in heating of plasma electrons. In described experiments energy content of the injected beam was up to 200 kJ (1 MeV, 30 kA, 8 μs). Total energy loss of the beam passed through 12-m-long plasma column with density of (1÷2)·10^{15} cm^{-3} achieves 30-40%. Feature of the beam relaxation under conditions of the GOL-3-II device is that output spectrum of the beam is quite unique for beam-plasma systems. In contrast to earlier obtained spectra (see [2]), output beam spectrum at the GOL-3-II is observed to have substantially stronger spreading. Actually, after beam-plasma collective interaction there is no beam on the device exit but there is a flux of electrons with a decreasing spectrum to high energies.

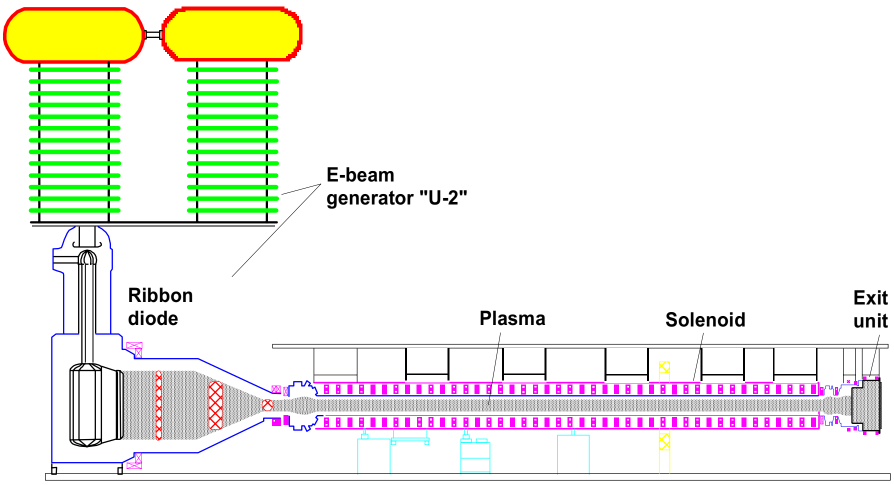

Fig.1. Layout of GOL-3-II device.

Two effects are important for plasma heating by an electron beam. First effect is transformation of the beam energy into heating of plasma electrons due to two-stream instability. Second one is sufficient increasing of effective colli-

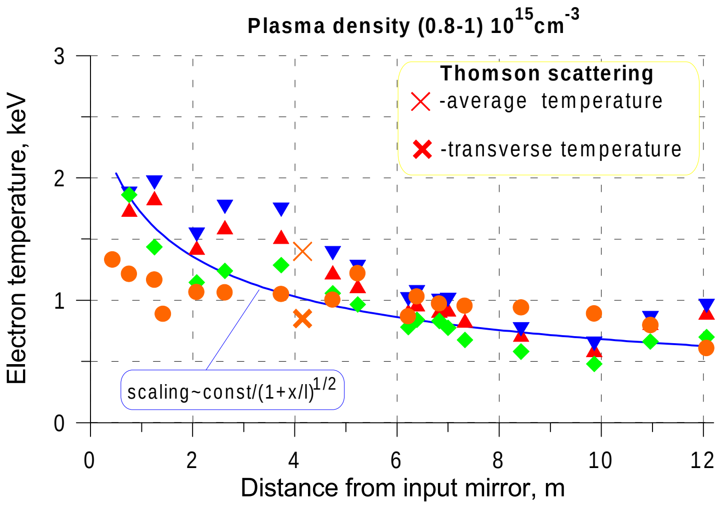

Fig.2. Distribution of electron temperature over length of plasma column.

sion rate because of excitation of a microturbulence in the plasma [2]. At the GOL-3-II conditions the last effect leads to suppression of longitudinal thermal conductivity by factor of 100-1000 [3]. As a result, electron temperature can reach 1.5-2 keV at optimal conditions.

Distribution of electron temperature over length of the plasma column estimated from diamagnetic measurements is presented in Fig. 2. There are points of T_e measured by Thomson scattering. This distribution shows typical relaxation length of the beam. In this case, the electron distribution function is formed by turbulent fields and non-classical transport and it is of non-Maxwellian type. This fact was measured by Thomson scattering technique.

A system of Thomson scattering of the second harmonic of the *Nd* laser light was used to find the energy distribution of plasma electrons. Pulse of laser light (15 J, 10 ns) was focused onto the axis of plasma column at a distance of 4 m from the beam input into the plasma. Finding the electron distribution function over velocities corresponding to energies ranging from 0.5 to 5 keV was made by the analysis of spectrum of radiation scattered at an angle 8° simultaneously in three fixed directions: along the beam transportation, in opposite direction, and perpendicular to the beam axis. In addition, low energy fraction (below 500 eV) of electron distribution function was detected by 90° scattering system. In the cases when detected spectra do not correspond to Maxwellian distribution, terms "transverse" $T_\perp$ and "longitudinal" $T_{||}$ temperatures mean double value of the average energy of electron motion in the selected direction that for the Maxwellian distribution corresponds to standard definition of temperature. In the experiments evolution of electron distribution function was studied at varied plasma density and fixed beam energy content of 170±10 kJ.

At the plasma density of $1 \cdot 10^{15}$ cm^{-3} measured transverse temperature $T_\perp$ was 0.9±0.2 keV (Fig. 2). At the same time, longitudinal temperature of plasma electrons following the beam propagation was found to be 2.9±0.6 keV and for electrons moving in opposite direction it was 1.7±0.4 keV. Thus, temperature of electrons co-directed with the beam turns to be 4 times higher than the transversal one.

With increase in density of the plasma its pressure $nT_{\perp}$ remains to be about the same at variation of plasma density within $(1\div5)\cdot10^{15}$ cm^{-3}. The longitudinal temperature drops faster than the transverse one. As a result, at $2.5\cdot10^{15}$ cm^{-3} density both temperatures equal approximately to 0.5 keV and electron distribution function becomes Maxwellian. With further increase in density up to $6\cdot10^{15}$ cm^{-3} the electron distribution function remains to be Maxwellian and electron temperature decreases inversely to the density. Presence of density threshold in the dependence of electron distribution function on plasma density is natural considering influence of binary Coulomb collisions. Under these conditions, electron temperature is inversely proportional on density ($T \propto 1/n$). Then, the classical mean free path of electrons determined in terms of density and temperature as $\lambda \propto T^2/n$ becomes strongly dependent on plasma density $\lambda \propto 1/n^3$. If one takes into account that at lower density mean longitudinal energy grows even faster, the free path length depends in this region even stronger on density. Free path length of the plasma electrons becomes comparable with longitudinal size of the magnetic trap at $n \approx 2.5\cdot10^{15}$ cm^{-3} and at $n \approx 1.5\cdot10^{15}$ cm^{-3} it is already much larger than the device length. In this case, the electron distribution function is formed by turbulent fields occurred as a result of beam-plasma interaction and it is non-Maxwellian.

Under experimental conditions described above (plasma of 10^{15} cm^{-3} density along the whole device) quite strong heating of plasma electrons was observed. Ion temperature reaches only $20\div30$ eV. For substantial increase of the ion temperature a method of a two-stage heating of a dense plasma is being developed on the facility [4]. In this case in the background "rare" plasma which is heated directly by an electron beam due to collective interactions, deuterium cloud of a few meters in length and density of $\sim10^{16}$ cm^{-3} is created in the beginning of the device. Hot electrons of "rare" plasma transfer their energy to electrons and ions of the dense bunch by binary collisions. As a result, the dense plasma gets electron temperature of $300 \div 500$ eV and ion temperature increases up to $100 \div 200$ eV (see Figs. 3 and 4).

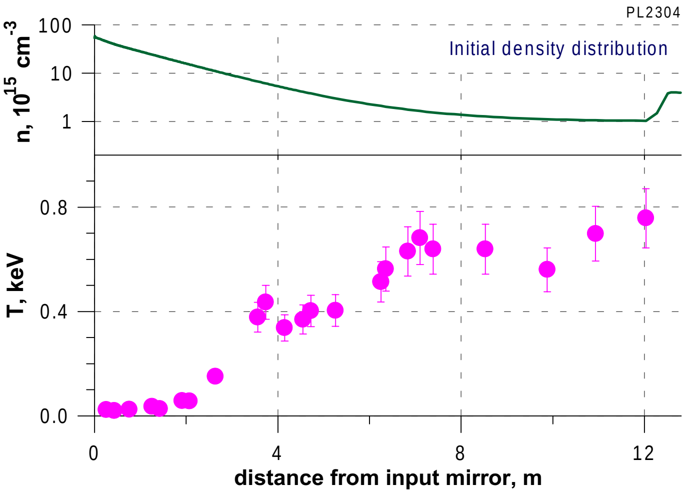

Fig.3. Electron temperature along the plasma column according to diamagnetic data.

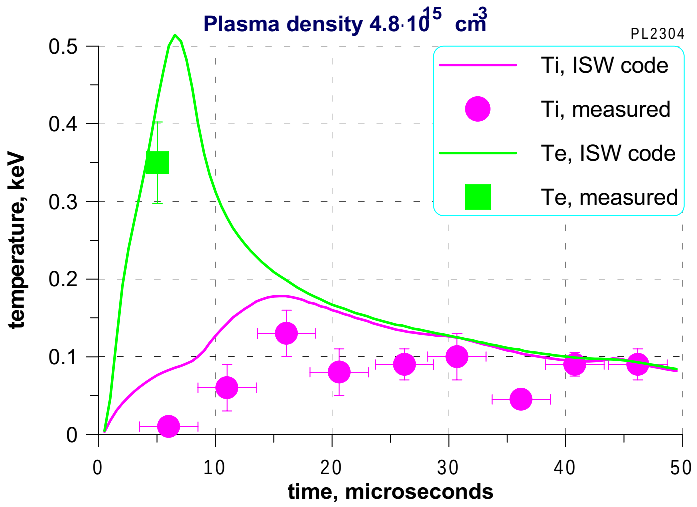

Fig.4. Dynamics of electron and ion temperature near z = 4 m (local density $4.8 \cdot 10^{15}$ cm^{-3}).

In order to improve parameters of the dense plasma it is planned not only to optimise its heating but also to improve the bunch confinement. To this aim, it is planned to mount in the device short (~1 m) section with lower magnetic field ("magnetic pit") where a dense plasma will be confined similarly as in a "gasdynamic" trap. Calculations show that it is possible to obtain ~1 keV and $\beta \geq 1$ plasma. This gives possibility to start experiments on multimirror and "wall" confinement of hot dense plasma.

CONCLUSION

1) High level (up to 30÷40%) of collisionless energy loss of 200 kJ relativistic electron beam in the plasma of 10^{15} cm^{-3} density is achieved at the GOL-3-II facility.

2) Effective heating of a plasma with this density up to $T_e \approx 2.0$ keV due to collective beam-plasma interaction is obtained.

3) Plasma with density $\approx 5 \cdot 10^{15}$ cm^{-3} is heated up to 0.5 keV of electron temperature and up to 0.1÷0.2 keV of ion temperature by two-stage scheme.

4) There are good prospects for production at the GOL-3-II facility of hot dense plasma with parameters suitable for experiments on multimirror and «wall» confinement and for other applications.

Acknowledgements: This work was carried out under financial support of Ministry of Science of Russia.

References

[1] M.A. Agafonov et al.: Plasma Phys. and Contr. Fusion, **38**, A93 (1996)
[2] A.V. Burdakov et al.: JETP, **82**, 1120 (1996)
[3] V.T. Astrelin et al.: Plasma Phys. Reports, **24**, 414 (1998)
[4] V.T. Astrelin et al.: JETP, **86**, 489 (1998)