DYNAMICS OF ELECTRON DISTRIBUTION FUNCTION IN MULTIPLE MIRROR TRAP GOL-3

V.V. Postupaev[1,2], A.V. Arzhannikov[1,2], V.T. Astrelin[1,2], V.V. Belykh[2], A.V. Burdakov[1,3], V.S. Burmasov[1,2], I.A. Ivanov[1,2], M.V. Ivantsivskiy[1,3], M.V. Kolosov[2], A.S. Krygina[2], K.N. Kuklin[1], K.I. Mekler[1], S.V. Polosatkin[1,2], S.S. Popov[1,2], A.F. Rovenskikh[1], A.A. Shoshin[1,2], N.V. Sorokina[3], S.L. Sinitsky[1,2], Yu.S. Sulyaev[1,2], Yu.A. Trunev[1], L.N. Vyacheslavov[1], Ed.R. Zubairov[1]

[1]*Budker Institute of Nuclear Physics, Novosibirsk, Russia*
[2]*Novosibirsk State University, Novosibirsk, Russia*
[3]*Novosibirsk State Technical University, Novosibirsk, Russia*

Essential progress in experiments on dense plasma heating by a high-power electron beam was achieved at the GOL-3 facility. The electron beam with ~0.8 MeV energy, ~30 kA current, ~8 μs pulse duration, and ~150 kJ total energy content heated deuterium plasma of ~10^{21} m^{-3} density up to 2-3 keV temperature [1]. The confinement time in these experiments was ~1 ms. The high electron temperature in the linear trap was obtained due to 1000-fold suppression of longitudinal electron thermal conductivity during the beam pulse that is provided by a microturbulence, the latter is excited in the process of the beam relaxation in the plasma [2].

The achieved plasma parameters support our vision of a multiple mirror trap as the alternative path to a fusion reactor. The key physical problem for a multimirror-based reactor is keeping turbulent suppression of axial heat flow during the entire plasma burning pulse by injection of a long-pulse electron beam. Such a beam should sustain turbulence level strong enough to suppress electron transport along magnetic field. In the presented experiments two-fold increase in the beam duration (up to ~12 μs) allows us to study dynamics of the electron distribution function during beam-plasma interaction.

OPERATION REGIME AND DIAGNOSTICS

Two significant parameters were different in the present experiments comparing to the standard scenario [1] listed above. The beam generator was modified in order to get longer beam generation. In new diode configuration the beam duration increases at the expense of the beam current (Fig. 1), total energy content remains the same. The beam current density in

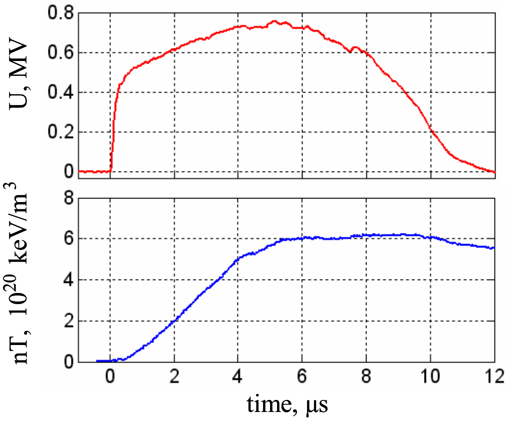

Fig.1. Dynamics of plasma heating. Top: diode voltage, bottom: plasma pressure at $Z = 4.75$ m (60 cm from the Thomson system).

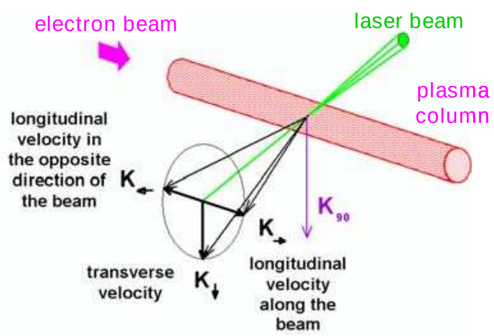

Fig.2. Geometry of Thomson 90° and small-angle scattering.

the plasma therefore somewhat decreases, correspondingly decreases the beam-plasma interaction efficiency and plasma heating.

The second feature of this regime is initial axial density profile with the density minimum near the midplane, which was required for a stable operation of a new NBI system (discussed in [3]) but is not optimal for beam-plasma coupling.

The shape of electron distribution function is studied with a Thomson scattering system employing 90° and 8° scattering angles, which enables measurements within the energy range up to 20 keV [4]. The 90°-subsystem is sensitive to transverse component of electron velocities. Subsystem of 8° scattering allows selection of a desired component of a velocity vector (see Fig.2) and enables separate measurements of both longitudinal and transverse components in each shot. Both subsystems operate within the standard $\alpha \ll 1$ scattering regime. Measuring point is Z = 4.15 m from the beam injection point.

OBSERVED DYNAMICS OF ELECTRON DISTRIBUTION FUNCTION

Typical evolution of the plasma diamagnetic pressure near the Thomson scattering location during the beam pulse is shown in bottom of Fig. 1. Growth of the plasma pressure continues during the first half of the beam pulse. Then the plasma heating saturates despite the beam injection continues at reduced power. The main physical task of this paper is to measure electron distribution function and to track its evolution during the beam pulse.

Spectra of scattered light are shown in figure 3 (observed with 8° subsystem) and figure 4 (with 90°-subsystem) for several shots and three moments of time. The upper (energy) scales are obtained using simple relation $\Delta\lambda \approx \sin\theta/2 \cdot \lambda_0 \cdot \left(2E/mc^2\right)$, where θ=8° or θ=90° are scattering angles. 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~1 keV is clearly seen from the small

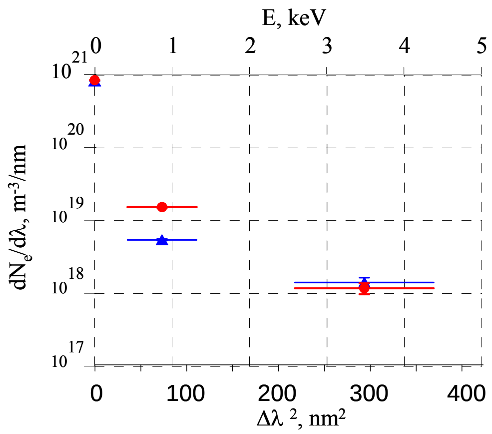

Fig.3. Transverse (blue triangles) and longitudinal (red dots) spectra for 6.4 μs by 8° Thomson scattering.

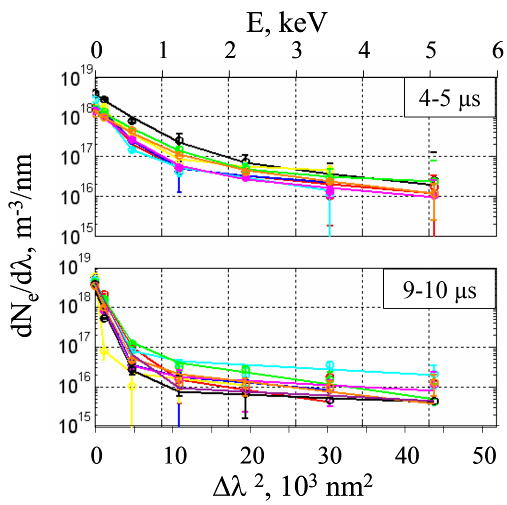

Fig.4. Scattering spectra for 4÷5 (top) and 9÷10 μs after the beam start by 90° Thomson scattering.

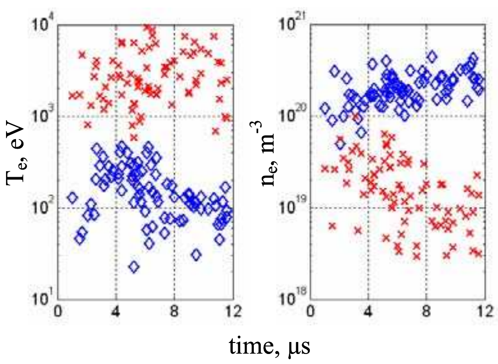

Fig.5. Temperature (left) and density (right) of two Gaussian components used for fit.

angle Thomson scattering spectrum. High-energy tails and lower bulk temperature are more evident at the second part of the beam pulse in figure 4. Double-Gaussian fit is used for the following analysis. We should note that interpretation of scattered spectra is model-dependent and here for a simplicity we use isotropic distribution function.

Evolution of parameters of the two fitted Gaussians is shown in Fig.5. During the period from 2 till 6 μs the difference in energies of “cold” and “hot” 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. Referring to figure 4 one can see that change in the electron distribution function occurs mainly due to loss of a group of 1-3 keV electrons from the trap. Comparison of Thomson and diamagnetic data shows, that the change of shape of electron distribution function occurs approximately at maximum plasma pressure. Here we should note that Thomson scattering data has rather large shot-to-shot spread, which only partly can be attributed to irreproducibility of the experiment or to errors in procedures. Possibly, such broad spread indicates considerable variations in the local plasma parameters due to the beam current microstructure which is known to exist. The characteristic size of scattering volume of 90° subsystem comprises only 1% of plasma diameter.

DISCUSSION

Non-Maxwellian shape of electron distribution function is common feature for the beam-plasma systems. Collective beam-plasma interaction pumps mainly high-energy tails and present measurements confirm it. The main result of this work is observed fast dynamics of hot electrons. The quick loss of 1-3 keV electrons from the trap happens at approximately the peak of plasma pressure. Transition of shape from top to bottom parts of Fig.4 occurs within 1 μs. This is about an order of magnitude faster than the Coulomb scattering of such electrons into the loss cone. Fast escape of 1-3 keV electrons from the trap indicates also that source of such electrons decreases simultaneously or shortly before. As we know (see, e.g. [1,5]) at this time fast collective heating of ions occurs in the corrugated magnetic field of GOL-3. This process features large axial gradients of plasma parameters and density fluctuations, which might be the reason for heating saturation. 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.

SUMMARY

Dynamics of electron distribution function was measured in GOL-3 experiments during the beam injection. Electron distribution is non-Maxwellian with the evident evolution and a significant shot-to-shot spread in the ratio of “low-energy” and “high-energy” components. Fast extinction of electrons with a few keV energies from the plasma can be accounted for a high level of microturbulence in the plasma during the last half of the beam with simultaneous decrease of pumping source for such electrons. During this period the beam power and/or quality is insufficient for further plasma heating, but the beam is still suitable as a tool for sustaining of a high effective electron collision rate, thus keeping axial heat losses collectively dumped.

ACKNOWLEDGEMENTS

The work was partially supported by Russian Science Support Foundation, RFBR 07-08-00682, 08-01-00622, 08-02-01197, CRDF Y4-P-08-09, RNP.2.2.2.3.1003.

REFERENCES

1. A. V. Burdakov, *et al*., Fusion Science and Technology, 51, No.2T, 106 (2007).
2. A. V. Arzhannikov, *et al*., Fusion Technology, 35, No.1T, 223 (1999).
3. V. V. Postupaev, *et al*., *this Conference*, paper P4.103.
4. S. S. Popov, *et al*., Plasma Physics Reports, 34, No. 3, 212 (2008).
5. A. V. Arzhannikov, *et al*., Plasma Physics Reports, 31, No. 6, 462 (2005).