PHYSICAL BASIS FOR THE USE OF LONG PULSE ELECTRON BEAM IN MULTI-MIRROR TRAP

V. Astrelin[1], A. Burdakov[1,2], I. Kandaurov[1], V. Postupaev[1,3], S. Sinitsky[1,3], and I. Timofeev[1]

[1]*Budker Institute of Nuclear Physics, Acad.Lavrentiev av. 11, Novosibirsk, 630090, Russia, Astrelin@inp.nsk.su*
[2]*Novosibirsk State Technical University, K.Marx av. 20, Novosibirsk, 630092, Russia*
[3]*Novosibirsk State University, Pirogova str. 2, Novosibirsk, 630090, Russia*

Recently high plasma parameters were reached in experiments on plasma heating in the multi-mirror open trap GOL-3. In these experiments deuterium plasma with density 10^{14}-10^{16} cm^{-3} in the 12-m trap with corrugated magnetic field of 4.8T/3.2T was heated by a relativistic electron beam of $eU \le 0.8$ MeV, $I \le 20$ kA, $j \sim 1$-2 kA/cm^2, pulse duration ~ 9 μs and angular spread $\theta \le 0.2$ rad. The electron temperature $T_e \sim 1$-4 keV and ion one to $T_i \sim 1$-2 keV were reached. After the beam pulse the electron temperature of the plasma quickly (~ 20 μs) decreased to ~100 eV. In turn, this leads to an increase in the rate of cooling of ions through the ion-electron collisions, which, together with particle losses determines the energy confinement time of plasma as 0.5-1 ms.

To increase the plasma parameters a prolonged heating of the plasma by the electron beam is proposed. The paper considers basic physical phenomena in the beam-plasma interaction and required parameters of the long-pulse beam. A choice of long pulse beam parameters is based on the obtained experimental results and scalings. Then estimates of the expected plasma parameters under the influence of the new beam have been done.

I. MAIN PHENOMENA IN PLASMA HEATING [1]

Below the phenomena in plasma heating by the electron beam in GOL-3 (Ref.1) are considered.

I.A. Collective beam-plasma interaction.

Values of plasma density n and magnetic field B in GOL-3 are the following ($n \sim 10^{14}$-10^{16} cm^{-3}, B = 4.8T/3.2T), so that Langmuir and electron Larmour frequencies are close

$$\omega_{pe} \sim (0.6-1.8)\cdot 10^{12} \sim \omega_{ce} \sim (0.6-0.8)\cdot 10^{12} \quad rad/s,$$

This doesn't allow applying theory results (e.g., Ref.2) to the beam-plasma processes directly. The experiments showed that the electron beam loses up to 40-50% of its initial energy [3]. Intensive oscillations in the wide spectrum of frequencies are excited near the plasma frequency and the double plasma frequency [4]. All this indicates that development of the plasma turbulence is observed.

Effective beam-plasma interaction occurs when the ratio of the beam density to plasma one is $n_b/n > 10^{-3}$. It corresponds to condition that growth rate of the beam-plasma instability Γ becomes greater than frequency of electron collisions ν_e in the plasma

$$\Gamma \approx \frac{n_b}{n\gamma < \Delta\theta^2 >}\omega_{pe} > \nu_e \approx \frac{4\sqrt{2\pi}\lambda e^4 Z^2 n}{3\sqrt{m_e}T_e^{3/2}}, \qquad (1)$$

here λ is a Coulomb logarithm; γ is relativistic factor; n, e, m_e and T_e are density, charge, mass and temperature (in energy units) of electrons, Z is charge of plasma ions, $<\Delta\theta^2>$ is mean square pitch angle of electrons. In case of developed instability, the interaction results in collective heating of plasma electrons[1], accompanied by suppression of longitudinal electron thermal conductivity in 10^2-10^3 times compared to classical one[5]. It is shown experimentally [6] that for the plasma density ~ 10^{15} cm^{-3} an electron temperature is proportional to the density of the beam energy

$$T_e \text{ [eV]} \sim 200\, Q \text{ [J/cm}^2\text{]}. \qquad (2)$$

I.B. Fast collective acceleration of ions and plasma cooling.

This phenomenon is an energy transfer from electrons to ions during time interval much less than classic electron-ion collisions time. It was explained by an effect of electron pressure gradients caused by periodical space heterogeneity of electron heating and suppression of electron thermal conductivity. The phenomenon of collective ion acceleration has been found in the experiments [7]. The time of energy transfer is of order of the ion time span the length of one mirror cell.

After beam pulse ions loss their energy through electrons due to drag effect, mainly, because electron heat conductivity restores and electron temperature quickly decreases down to level of T_e ~ 100 eV. For ions heated to maximal temperature 1-2 keV an ion cooling time may be described by expression [8]

$$\tau_T^{i/e} = \frac{3m_i}{8\sqrt{2\pi m_e}} \frac{T_e^{3/2}}{\lambda n e^4 Z^2} \approx 5.7 \cdot 10^{18} \frac{m_i}{\sqrt{m_e}} \frac{T_e^{3/2}}{\lambda n Z^2} \qquad (3)$$

It gives $\tau_T^{i/e}$ ~ 0.5 ms for density $n \sim 10^{14}$ cm^{-3}. To suppress this loss channel and increase $\tau_T^{i/e}$, e.g. tenfold, it is necessary to support electron temperature at level of T_e ~ 500 eV during this time interval. Using long pulse electron beam of necessary power can provide it.

As for energy confinement time, we must take into account the particle losses and non uniformity of space distribution for energy of plasma. Therefore evaluation done above may be considered as a rough estimation only.

I.C. Providing of macroscopic MHD stability.

Magnetic field in GOL-3 has a helical structure due to external longitudinal field and azimuthal field of the beam current, return inductive current and plasma discharge current used for preliminary ionization of deuterium. To estimate a plasma stability, a local safety factor $q = (H_z/H_\varphi)\cdot(2\pi r/L)$ (where H_z and H_φ are longitudinal and azimuthal components of the magnetic field, r and L are plasma radius and column length) may be used.

In GOL-3 experiment the beam-plasma system is macroscopically stable if region of stability $q < 1$ is inside plasma column[9]. MHD stability may be obtained for GOL-3 by appropriated choice of plasma discharge current and its direction. As for experiments with long pulse beam, this question have to be investigated.

I.D. Longitudinal plasma confinement in the multi-mirror magnetic field.

Investigation of plasma confinement shows[9] that plasma energy life time satisfy to theoretical estimates for multi-mirror confinement if ion mean free path is close to length of one mirror cell. At the same time the classical mean free path of the particles is comparable and even exceeds full length of the trap. This means that frequency of ion-ion collisions is much more than the classical one. It was explained theoretically[10] by the bounce instability due to interaction of ions, flying through magnetic cells of the trap with trapped plasma ions.

II. CHOICE OF PARAMETERS OF MILLISECOND ELECTRON BEAM.

Based on the experimental results, we choose beam parameters the same as for GOL-3, but with power enough for providing T_e ~ 500 eV. We used the beam with j_b ~ (1-2) kA/cm^2 and eU = 800 keV for heating of plasma with density $n \sim 10^{14}$-10^{15} cm^{-3} up to T_e ~ 4-5 keV that corresponds to $n_b/\gamma n \sim 10^{-3}$ (see condition (1) for development of instability). As for choice of electron energy, from a technical point of view it is expedient to reduce it to 100-200 keV. Then, for electron energy eU = 150 keV the same ratio $n_b/\gamma n$ may be reached at j_b ~ (0.35-0.7) kA/cm^2. It corresponds to 15-fold decreasing of the beam power that may proportionally decrease a density of turbulence energy and electron temperature (see (2)). Therefore we restrict density of beam current as j_b ~ (0.5-1) kA/cm^2, i.e. 10-fold decreasing only, to support level of T_e as ~500 eV.

Then, a total beam current is determined by beam cross section. In GOL-3 experiments with thin electron beam of ~1.5 cm in diameter[6] the measured electron temperature remained almost the same as for the beam with diameter of ~ 4 cm and with the same density of current.

Consequently, the electron beam with cross section S_b ~ 2 cm^2 and current 1-2 kA at energy ~ 150 keV may be used effectively for plasma heating. So as the electron beam is injected into magnetized plasma in GOL-3, the required high current density of the beam can be obtained by magnetic compression of the beam with lower density of current. We propose to use 50-fold compression of the beam. It corresponds to its generation in a magnetic field of ~0.1 T with current density of 10-20 A/cm^2 and pitch angles lower than 0.03 rad. The angle divergence doesn't exceed 0.2 rad in the compressed beam that is enough for plasma heating experiment. This value of compression determines the conditions for the generation of the beam, which seem reasonable and technically achievable.

Generation of the long pulse electron beam will be realized in a source with plasma emitter, and multiaperture electrodes of electron optic system. The prototype injector is developed at BINP[11].

Below we present theoretical estimations of plasma heating by low-energetic electron beam based on non-linear theory of beam-plasma interaction and results of numerical simulations[12].

III. SIMULATIONS OF TURBULENT PLASMA HEATING.

Let us explore collective relaxation of low-energetic electron beams in plasma using 1D hybrid simulations. In the present form the model is able to simulate beam-plasma interactions up to the stage of steady-state turbulence. This stage is characterized by the constant pump power, which is saturated due to nonlinear effects of beam trapping[12]. So, the aim of our simulations is to study how the relaxation efficiency depends on beam parameters at the stage of turbulence excitation and to explain why we are going to use low-energetic beams in future experiments.

We define the relaxation efficiency as the ratio of the beam energy losses to the initial beam energy. Let us consider the problem of beam injection for the following parameters: $n = 4\cdot10^{14}$ cm^{-3}, j_b = 490 A/cm^2, E = 150 keV. Fig. 1a shows that relaxation of the beam appears to be more efficient compared to the beam with the same power, but the increased energy 300 keV. Moreover, in both cases a saturation of Langmuir turbulence is achieved in a short time (8-10 ns) with relaxation efficiency 20-30%. Fig.1b demonstrates electron temperature profiles taken at the moment $t = 9.5$ ns. It is seen that the peak of the beam energy release moves to the injector and becomes more localized as we decrease the energy of beam particles. The value of electron temperature is high enough (0.4-0.8 keV) but in a narrow region. Profiles of plasma heating, however, are very sensitive to the macroscopic inhomogeneities of plasma density. Simulations with the nonuniform density profile (Fig. 1c), which is more appropriate to the experimental conditions, reveal that beam-plasma instability appears to be suppressed by large density gradients, and efficient plasma heating peaks in the locally uniform regions (Fig. 1d). It is also observed that this effect plays an important role at the late stages of turbulence evolution, when large-scale density fluctuations are formed even in the initially homogeneous plasma due to nonuniform plasma heating.

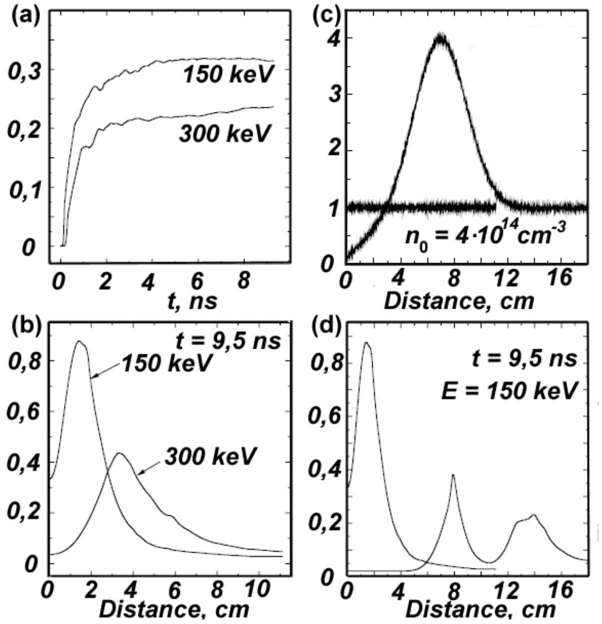

Fig.1. (a) Relaxation efficiency for beams with different energies; (b) electron temperature profiles in the uniform plasma, keV; (c) profiles of plasma density, n/n_0; (d) comparison of temperature profiles in uniform and non-uniform plasma, keV.

IV. SUMMARY

1. Analyses showed that the main channel of energy losses is longitudinal one through electrons. So, the decision on use additional long pulse electron beam was made. We expect to keep suppression of heat conductivity and to decrease cooling of ions.
2. Estimates and numerical modeling let us choose the beam parameters so that to provide expected results.
3. The key problem is to elaborate a generator of electron beam with necessary characteristics.

ACKNOWLEDGMENTS

This work is partially supported by RFBR Grants No. 08-01-00622, 08-08-00827, 10-08-00707 and 10-02-01317; Russian Ministry of Education and Science, Grant No. 2.1.1/3983, 2.1.1./3465, P2309, P276, 02.518.11.7113; by Project No. 30, 33 of Presidium RAS; by Joint Integration Project of Presidium SB RAS No 34, 113.

REFERENCES

1. V. S. KOIDAN, et al. "Progress in multimirror trap GOL-3", *Transactions of Fusion Technology*, 47, No.1T, 35 (2005).
2. B. N. BREIZMAN, "Collective interaction of relativistic electron beams with plasma," *in Reviews of Plasma Physics*, Consultants Bureau, N.Y., 15, 58 (1990).
3. S. L. SINITSKY, et al. "Plasma Heating in the Multimirror Trap GOL-3 by Elongated Pulse REB", *Proceedings of the 17th Intern. Conf. on High-Power Particle Beams*, China, 211 (2008).
4. V. F. SKLYAROV, et al. "Investigation of submillimetre radiation emission spectrum on the GOL-3 facility", *Abstracts of XXXVII International (Zvenigorod) Conference on Plasma Physics and Controlled Fusion*, Zvenigorod, 56 (2010).
5. V. T. ASTRELIN, et al. "Generation of Ion-Acoustic Waves and Suppression of Heat Transport during Plasma Heating by an Electron Beam", *Plasma Physics Reports*, 24, No.5, 414 (1998).
6. V.V. POSTUPAEV, (*private communication*).
7. A.V. ARZHANNIKOV, et al. "Direct observation of anomalous small thermoconductivity during collective relaxation of high-current relativistic electron beam in plasma", *JETP Letters*, 77, No.7, 358 (2003).
8. B.A. TRUBNIKOV, "Collisions of particles in fully ionized plasma", in *Reviews of Plasma Physics*, (*Russian "Voprosy teorii plasmy"*), GosAtomIzdat, Moscow, 1, 98 (1963).
9. A.V. BURDAKOV et al. "Status and Prospects of GOL-3 Multiple Mirror Trap", *Fusion Science and Technology*, 55, No.2T, 63 (2009).
10. A.D. BEKLEMISHEV, "Bounce instability in a multiple-mirror trap", *Fusion Science and Technology*, 51, No.2T, 180 (2007).
11. I.V. KANDAUROV et al. "Submillisecond electron beam for plasma heating in multi-mirror trap GOL-3" (*this issue*).
12. I.V. TIMOFEEV, et al. "Simulations of turbulent plasma heating by powerful electron beams" (*this issue*).