FAST HEATING OF A DENSE PLASMA BY HIGH-POWER ELECTRON BEAM AT THE GOL-3-II FACILITY

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Abstract

Recent results on dense plasma heating by 200 kJ-electron beam at GOL-3-II facility are presented. The efficiency of collective electron beam deceleration up to 40% is achieved in 10^{15} cm^{-3} plasma. The characteristic electron temperature of ~ 2 keV at plasma density (1-2) $\times 10^{15}$ cm^{-3} is obtained. At the two-stage heating of a dense (~10^{16} cm^{-3}) plasma the electron temperature of 300-500 eV and the ion temperature of 100-200 eV are reached. Prospects of experiments on "wall" and multimirror plasma confinement at GOL-3-II facility are discussed.

1. INTRODUCTION

One of possible approaches to a fusion problem is a concept of a pulsed multi-mirror reactor [1,2]. The proposed pulsed fusion reactor with dense (n ~ 10^{17} cm^{-3}) high-β-plasma is based on a long (L ~ 200 m) solenoid with strong (B ~ 15 T) magnetic field. Plasma confinement along the magnetic field is provided by a large number of magnetic mirrors (multi-mirror trap). The radial equilibrium is maintained by the chamber walls (non-magnetic, «wall» confinement), while the only role of the magnetic field is to suppress the plasma heat conductivity. The crucial problem for the development of the multimirror reactor concept is producing of hot dense (~ 10^{17} cm^{-3}) plasma.

The fast heating of the plasma with $10^{15} \div 10^{17}$ cm^{-3} density during its collective interaction with a microsecond electron beam with an energy content over 100 kJ is being investigated at the GOL-3-II facility [3]. Production of ~ 1 keV plasma in the facility gives the possibility to study the multimirror and «wall» confinement of such a plasma [4]. The plasma that is already obtained and can in principle be obtained in this facility is of interest for a broad spectrum of applications, not only for controlled fusion, but for pulsed neutron source, X-ray flash sources, UV laser, plasma-wall interaction simulation etc. In this paper recent results performed at the GOL-3-II facility are presented.

2. GOL-3-II FACILITY

The layout of this facility is given in Fig.1 (detailed description is in [3]). The U-2 generator produces the electron beam with the energy content of ~ 200 kJ (1 MeV, 30 kA, 8 μs). The longitudinal magnetic field is up to 4.5 T in the uniform part of the solenoid and 9 T in its end mirrors. The plasma has a diameter 6 cm and 12 m length. Plasma density can be varied in $10^{14} \div 10^{17}$ cm^{-3} range and can be as of fixed density distribution along the device length and varied one.

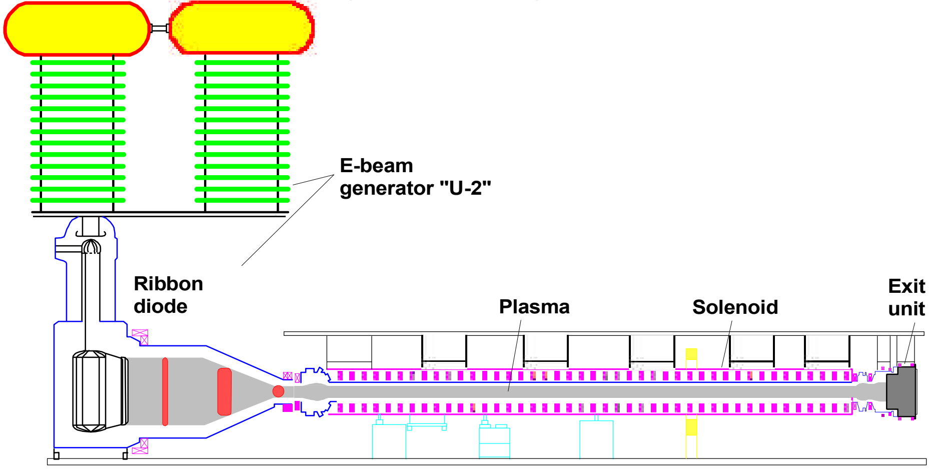

FIG. 1. Layout of GOL-3-II facility.

3. FEATURES OF BEAM-PLASMA INTERACTION

At the beam injection into a plasma the two-stream instability is developed resulting in beam energy losses and heating plasma electrons. The energy distribution of beam electrons changes due to their collective deceleration [3]. In new experiments, the collective plasma heating was optimized. The beam energy distribution is shown in Fig.2 for plasma density $(1 \div 2)\times10^{15}$ cm^{-3}.

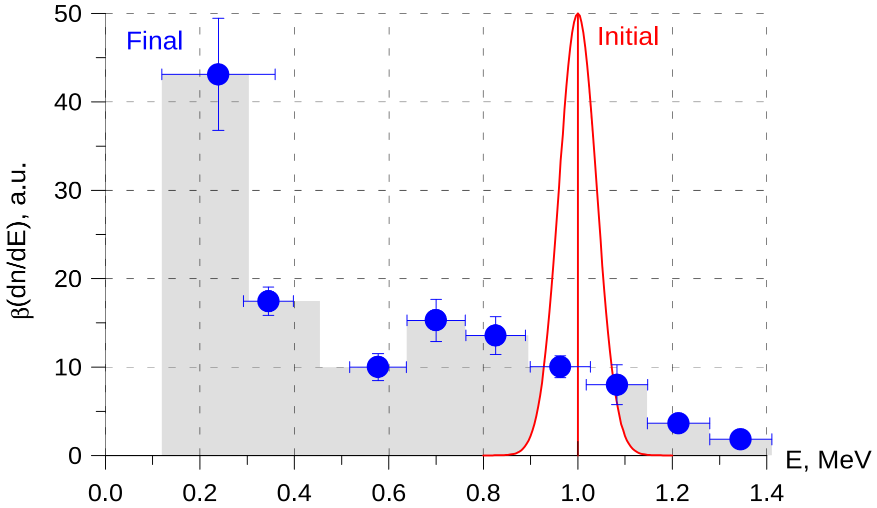

FIG. 2. Beam energy spectrum after interaction with the plasma (measured by magnetic analyzer in 4 μs after start, initial beam energy is 1.00 MeV)

The characteristic feature of beam relaxation in this experiment is that an output beam spectrum is quite unique for the beam-plasma systems. In contrast to the earlier experiments [5] substantially broader beam spectrum is observed. One can see in Fig.2 that after beam-plasma collective interaction there is no beam in the system output but there is a flux of electrons with a spectrum which decreases to high energies. The total energy losses of a beam passed through a 12 m long plasma column calculated by the observed spectra reaches 40%.

4. HEATING OF UNIFORM DISTRIBUTED PLASMA

Two effects are important for plasma heating by an electron beam. The first effect is a transformation of the beam energy into heating of plasma electrons. The second one is very essential increasing of the effective collision rate because of excitation of microturbulence in the plasma. At the GOL-3-II the last effect leads to suppression of longitudinal thermal conductivity by factor of 100-1000 [6] (detailed discussion of this effect and its influence on plasma heating is given in [4]). As a result, the electron temperature can reach 1.5-2 keV at optimal conditions.

The distribution of electron temperature over length of the plasma column calculated from diamagnetic measurements is presented on Fig.3. There are also points of T_e measured by Thomson scattering (0,53 μm, 15 J).

Finding the electron distribution function corresponding to energies 0.5÷5 keV was made by the analysis of spectrum of light scattered at an angle 8° simultaneously in three fixed directions: along the beam propagation, in opposite direction, and perpendicular to the beam axis. The low energy fraction (in range up to ~500 eV) was detected by a 90° scattering system. In the cases where the detected spectra do not correspond to the Maxwellian distribution, the terms "transverse" $T_\perp$ and "longitudinal" $T_\parallel$ temperatures mean the double value of the average energy of electron motion in the selected direction.

At a plasma density of $1\cdot10^{15}$ cm^{-3} the measured transverse temperature $T_\perp$ was (0.9±0.2) keV, at the longitudinal temperature of plasma electrons following the beam propagation was found to be (2.9±0.6) keV and for electrons moving in the opposite direction it was (1.7±0.4) keV. With the increase in plasma density the longitudinal temperature drops rapidly but the transverse temperature changes insignificantly. As a result, at $n=2.5\times10^{15}$ cm^{-3} they become equal approximately to 0.5 keV and the electrons become Maxwellian. With a further increase in density up to 6×10^{15} cm^{-3} the electrons remain Maxwellian and the electron temperature drops with the density.

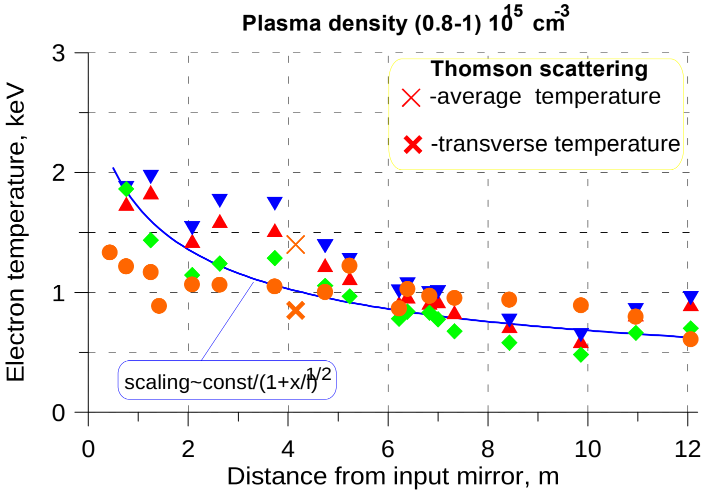

FIG. 3. Distribution of electron temperature over length of plasma column.

At n≈2.5×10^{15} cm^{-3} the free path length of the plasma electrons becomes comparable with the longitudinal size of the magnetic trap and at n≈1.5×10^{15} cm^{-3} it is already much larger than the device length due to simultaneous decrease of density and growth of temperature. In this case, the electron distribution function is formed by turbulent fields arising as a result of beam-plasma interaction and it is non-Maxwellian. Value of electron temperature and its nonuniform distribution along the plasma column can be only as a result of the very low heat conductivity of a beam-heated turbulent plasma.

5. TWO-STAGE DENSE PLASMA HEATING

Under the conditions described above (uniform plasma density along the device) quite strong heating of plasma electrons is observed, but the ion temperature achieves only 20÷30 eV. For a substantial increase in the ion temperature and probably for obtaining plasma with β>1 a method of two-stage heating of a dense plasma is being developed on the device [7,8]. In this case, in the background "rare" plasma which is heated directly by an electron beam due to collective interactions, a dense bunch is formed. As a result, hot electrons of the "rare" plasma transfer their energy to electrons and ions of the dense bunch by binary collisions.

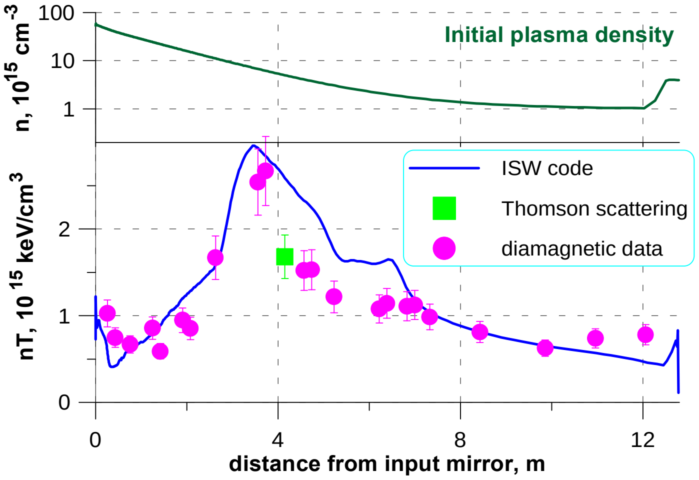

FIG. 4. Plasma pressure distribution over length, t=5.4 μs.

New experiments in this direction are also started on the GOL-3-II device. In the beginning of the device the deuterium cloud of a few meters in length is formed (see Fig. 4). The primary beam energy deposition occurs in the part of the device with plasma density of ~10^{15} cm^{-3}. Then the energy redistribution occurs and as a result the dense plasma is heated. The distribution of plasma pressure over the device length, for the end of electron beam injection, is shown on Fig.4. Peak of pressure is on 4 m distance at density of $\sim10^{16}$ cm^{-3} and the electron temperature of 300÷500 eV. Ion temperature measured by spectroscopy increases more slowly and at 15 μs reaches of 100÷200 eV. So, in these experiments higher parameters of the dense plasma were obtained on comparison with previous ones.

6. PROSPECTS OF GOL-3-II EXPERIMENTS

In order to improve the parameters of a dense plasma it is planned not only to optimize the conditions of its heating but also to improve confinement of the dense plasma bunch. Further growth of parameters of the dense plasma is limited by its fast expansion along the magnetic field and longitudinal heat losses from the plasma. Next steps of our experiments will be focused on improvement of confinement of the dense plasma.

Following the initial multimirror concept, we started the experiments with the corrugated magnetic field. As a first step a 4.5 m-long section of the solenoid is reconfigured into multimirror system (cell length 22 cm, 20 cells, H_{max}=4.5 T, H_{max}/H_{min}=1.5). First experiments in this configuration are performed. The conditions for macroscopic stable propagation of an electron beam through the device in this geometry have been found. The change of magnetic configuration from uniform to multimirror one leads to some restrictions in operating regimes of GOL-3-II facility (mainly due to more delicate operation of the preliminary plasma creation system). Our further plans include an activity on decreasing of longitudinal heat losses and next experiments with multimirror configuration. For $\beta\sim1$ experiments it is planned to mount at the device the short (~1 m) section with lower magnetic field («magnetic pit») where a dense plasma will be confined similarly as in a «gasdynamic» trap. Besides it, it is planned to surround the dense plasma bunch from the both sides along the device by sections of corrugated magnetic field. In the case of success of these experiments this will enable one to start experiments on the multimirror and "wall" confinement of plasma.

7. CONCLUSION

(1) High level (up to 30÷40%) of collisionless energy losses of 200 kJ-relativistic electron beam in the plasma of 10^{15} cm^{-3} density has been achieved.

(2) Effective heating of a plasma with this density up to Te~2 keV due to collective beam-plasma interaction has been obtained.

(3) Plasma with density $\approx5\cdot10^{15}$ cm^{-3} is heated up to 0.5 keV electron temperature and up to 0.1÷0.2 keV ion temperature by a two-stage scheme.

(4) There are good prospects for performance at GOL-3-II facility of experiments on multimirror and «wall» confinement of hot dense plasma.

ACKNOWLEDGMENTS

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