ENERGY SPECTRUM OF ELECTRONS IN FLOW FROM PLASMA COLUMN HEATED BY REB AT GOL-3 FACILITY

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Efficiency of the beam–plasma interaction was investigated for the case of small radial size intense E-beam on the base of the energy spectrum measurements with multi-foil analyser. This shows good prospects of such beams for reactor applications.

I. INTRODUCTION

In recent years an essential progress has been done in experiments on heating dense plasma ($n \sim 10^{14}$-10^{15}cm^{-3}) by a high-power relativistic electron beam (REB) in the multimirror trap GOL-3. The beam generator U-2 has been switched to an operation mode in which REB is produced with the following parameters: the electron energy ~0.8 MeV, the beam current ~25 kA, the beam current density in the plasma ~2 kA/cm^2, the pulse duration ~10 μs, the total energy of the beam pulse ~150 kJ (Ref. 1). The magnetic configuration of the GOL-3 facility is a multimirror trap with the length 12 m consisting 55 cells with the mirror ratio of R = 4.8T/3.2 T(Ref. 2).

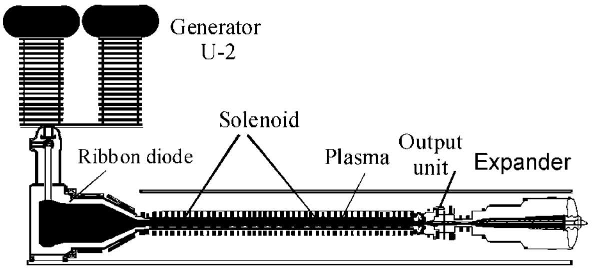

Fig. 1. Layout of the GOL-3 facility

The scheme of the GOL-3 facility[3] is presented in Fig.1. The electron beam with small angular divergence is generated by the magnetically insulated diode with a ribbon explosive emission cathode (5x75 cm^2 cross section) and slit foilless anode. After passing through the anode slit the beam is transported in a slit vacuum channel with a homogeneous magnetic field of 0.27 T to a transformer, where it changes the shape from ribbon to square one. After the transformation the beam is compressed by the guiding magnetic field rising from 0.3 T to 6 T at the entrance to the multimirror trap. Finally, after the compression the beam has a diameter of 4.4 cm in the plasma. The beam passed through the plasma column, is dumped in a collector located in a magnetic expander after the output magnetic mirror.

In the process of the beam-plasma interaction the high intensity Langmuir turbulence is created in consequence of two stream instability. Then the energy of the Langmuir waves is transferred from the long wavelength band resonant with the beam, to the short wavelength one where it is efficiently absorbed by the plasma electrons. As a result the average energy of the plasma electrons reached 2 keV at the density $n \sim 10^{15}$ cm^{-3}. The achievement of such energy is possible due to the effect of anomalously low electron thermal conductivity along the trap axis, provided by this turbulence[3]. Owing to this effect and the recently discovered mechanism of fast ion heating in a multimirror trap[1], the temperature of the plasma ions also increase up to 2 keV. The time of plasma energy confinement reaches 1 ms in these experiments.

In respect to the fusion prospects of such approach in the plasma heating it is important to investigate the possibility of decreasing the power of the beam from 20GW to 1 GW keeping the specific parameters of the beam on the same level. To do that the size of the beam in plasma was decreased to 1cm by cutting out only the central part of the beam cross section with a special limiter placed between transformer and the compression system. Such experiment also will make clear the role of the turbulence in transverse transport of the wave energy from the heated region of plasma to its outer part.

To study the peculiarities of the beam-plasma interaction for such “thin” beam we needed to investigate the energy spectrum of the electrons in the flow from the plasma column. For solving this task the multifoil analyser of the electron energy distribution was applied. The results of energy distribution measurements are presented and discussed in the paper.

II. MULTIFOIL ANALYSER

To measure the energy spectrum of magnetized electrons in the range of 100 -1000 keV, a multi-foil analyzer has been proposed and tested[4]. In our experiments the electron beam after passing through the plasma column came to a collector located at the exit vacuum chamber (expander) with a divergent magnetic field. To avoid destruction of the foils by the electron beam and plasma flow from the trap, the analyzer was placed in a low magnetic field of 0.05 T. In front of the analyzer, a collimator cutting the beam cross section to the diameter of 3.5 cm was mounted. The analyzer consists of an entry grounded 9 μm thick Al foil separating the analyzer from the plasma in the expander, set of nine measuring foils of different thicknesses (100-400 μm Al), and a collector. The measuring foils and the collector are grounded through resistors, R ~ 3 Ohm. The electrons with various energies leaving the trap along the magnetic field lines are decelerated and scattered in the material of the foils and finally are absorbed at different depths of the aluminium depending on the initial energy of the electrons. The distribution function of electron absorption in Al $K(X/R_0(E),E)$ vs. depth X in terms of $R_0(E)$ (maximal range of electrons with the energy E), was calculated before by using Monte-Carlo code EMSH[5] for the interval 10-2000keV. Measuring currents $J_i(t)$ from each foil and the collector and applying the calculated function $K(X/R_0(E),E)$, one can obtain the energy distribution for the incident electrons $\varphi(E)$ from the system of integral equations:

$$\begin{cases} J_i = J_0 \int\limits_{E_{\min}}^{E_{\max}} \varphi(E)dE \int\limits_{X_i}^{X_{i+1}} K\left(X/R_0(E),E\right)dX, i = 1...N \\ \int\limits_{E_{\min}}^{E_{\max}} \varphi(E)dE = 1 \end{cases},$$

where X_i are the foil boundary coordinates, $E_{min} \div E_{max}$ (0.06 ÷ 1 MeV) denotes the electron energy interval, J_0 is the total current in the analyzer aperture. For sampling the distribution function $\varphi(E)$ was represented as a series of model basis functions $\Phi_j(E)$, which are triangles in our case:

$$\varphi(E) = \sum_{j=1}^{N} a_j \Phi_j(E).$$

A solution of the system of equations is found as a set of Lagrange coefficients a_j calculated via minimization of the current discrepancy squared. To do that, we applied the Tanaba - Huang method[6] with the assumption of spectrum positive definiteness. Before the experimental data processing we checked that the chosen method is stable to inaccuracies of the current measurements and uncertainty of the distribution function of the electron absorption. In such a way we obtained the energy spectrum for all electrons outgoing from the multimirror trap, including the decelerated beam electrons and accelerated plasma ones.

III. SPECTRAL MEASUREMENTS

To test the diagnostics the "thin" electron beam with half energy (~ 400 keV) and nearly half current density was injected in the magnetic trap with technical vacuum (residual gas pressure 3x10^{-3} Pa). The traces of the foil currents and the diode voltage for this case are shown in the Fig. 2. Applying the procedure of spectrum determination we found that the electron distribution function consists of two narrow spikes, the first one is located near the energy of the injected beam (decelerated beam electrons) and the second is at the lower boundary of the investigated energy range (accelerated plasma electrons). At these conditions due to 10μs pulse duration such beam easily produces plasma from the residual gas but the beam-plasma interaction is not effective because of low current density of the beam. The average energy losses of the beam electron do not exceed 10%. If to raise the diode voltage to 800keV and hence the beam current density to kA/cm^2 in the trap, the experiments have shown that such beam effectively interacts with self produced plasma and the average energy loss of the beam reaches 20%.

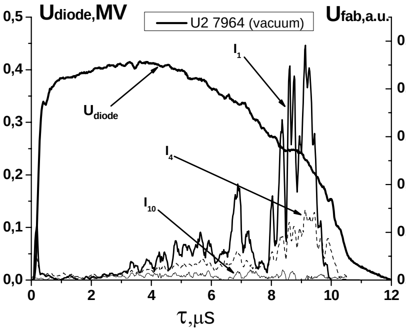

Fig.2. Oscilloscope traces of the diode voltage and currents from 1st, 4th and 10th measuring foils

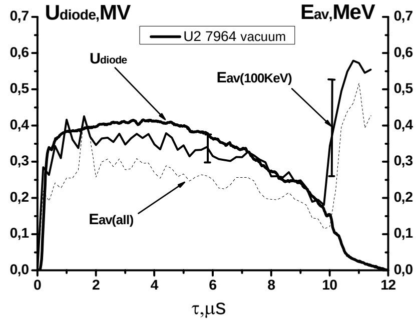

Fig.3. Temporal dynamic of average energy of the electrons in the range 100-800keV (solid line) and in the range 30-800keV (dotted line).

The loss of energy for such beam at its injection in preliminary prepared plasma with density n~4x10^{14}-10^{15}cm^{-3} becomes even greater. The traces of the foil currents and the diode voltage for typical shot are shown in the Fig. 4. As it is seen the foil currents are strongly modulated. Its modulation is explained by the beam current filamentation at the exit of plasma column (the displacement of these filaments is registered independently by X-ray obscure diagnostics). In the time intervals when the foil currents are not zero we have made energy spectrum determination that gives the results shown in the Fig. 5, 6. At these time intervals the energy distribution function of the outgoing electrons (see Fig. 6) rises roughly monotonously with the decrease of the electron energy in the range 30-800keV and no signs of the beam spike within the errors of the solution can be detected there. So the beam-plasma interaction at such parameters of the beam is so effective that the beam energy loss (in the range 100-800 keV) exceeds 50% and the distribution function of the beam electrons diffuse so much that it reaches the nonmaxwellian tails of the plasma electrons accelerated by the electric fields of the Langmuir turbulence. In comparison with the case of “thick” beam (the beam diameter is 4.4cm), where the energy losses were about 40% (Ref. 7), the efficiency of beam-plasma interaction is higher for the “thin” beam which is confirmed by the measurements of the plasma diamagnetism. It can be explained by the lower angular divergence of the central part of the beam cross section.

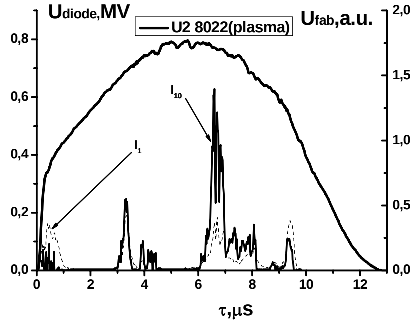

Fig.4. Oscilloscope traces of the diode voltage and currents from 1st, 4th and 10th measuring foils

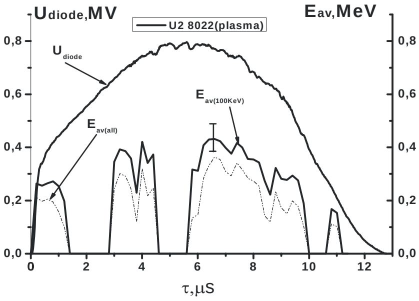

Fig. 5. The diode voltage and the average energy of the electrons in the range 100-800keV (solid line) and in the range 30-800keV (dotted line).

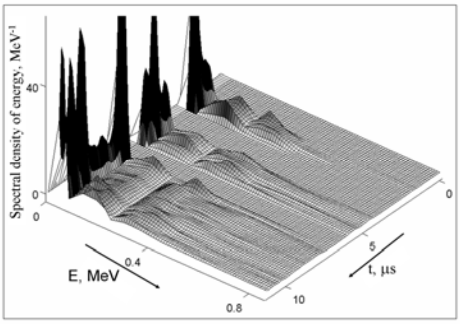

Fig.6. Energy spectrum of the electrons at the exit of the REB from plasma.

IV. CONCLUSIONS

Applying the multifoil analyser permitted to obtain the reliable energy spectrum of the electron flow outgoing from the plasma heated and confined in the multimirror trap GOL-3. These measurements confirmed the possibility to heat plasma electrons effectively by REB appropriate density even at a small beam diameter (about 1cm) and the beam current. The transverse transport of the waves and particles due to the strong Langmuir turbulence do not affect much on the process of REB relaxation in dense plasma.

ACKNOWLEDGMENTS

This work is partially supported Russian Ministry of Education and Science, Grant No. 2.1.1/3983, by Project No. 30 of Presidium RAS.

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