Energy distribution function of relativistic beam electrons after its passing through plasma column for generating megawatt flux of THz radiation

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Introduction

Experiments are carried out at the GOL-PET facility to study the relaxation of the relativistic electron beam (20 kA/0.6 MeV/6μs) in plasma column due to the development of strong two-stream instability. The main aim of the experiments is to study physical mechanisms of the THz radiation generation in the beam-plasma system [1]. As a roll, these mechanisms are based on pumping the upper-hybrid waves during beam relaxation in plasma and their transformation into electromagnetic ones in various ways [2]. The ability of the REB to directly pump the electromagnetic wave was demonstrated for the first time in recent GOL-PET experiments [1]. In order to clearly distinguish these physical processes, one needs to measure the energy distribution function of the beam electrons after it passing through the plasma column. In this paper, the procedures to measure the currents of the electrons absorbed in the foils, and to evaluate energy distribution function of the beam electrons are described.

Experimental set up

Schematic of experiments for measuring the energy distribution function of the beam electrons is shown in figure 1. The beam is injected in a plasma column of 2-m length with required density (n~10^{15} cm^{-3}), confined in a multi-mirror magnetic trap (B~4 T). To measure this function in case of magnetized electrons a specially designed probe consisted of 10 successive aluminum foils. Such multi-foil analyzer was earlier applied to study the process plasma column heating by E-beam at the GOL-3 facility [3].

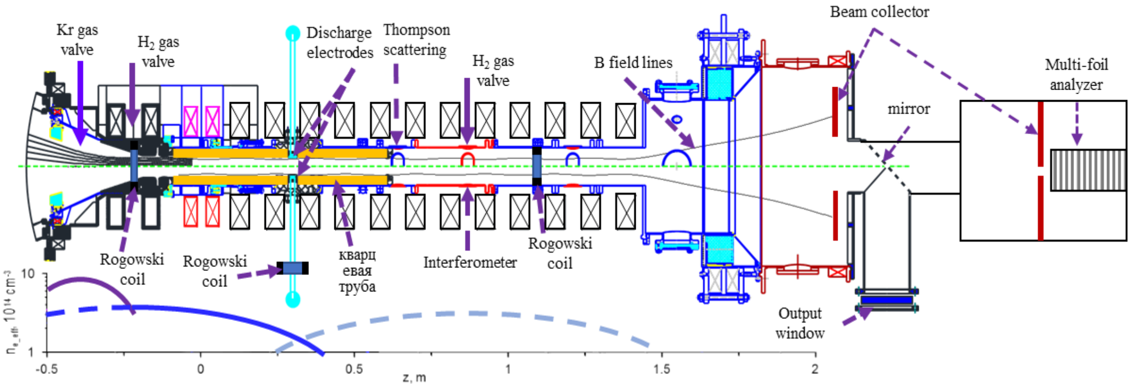

Figure 1. Schematic of the GOL-PET facility modified for measuring the electron energy distribution function.

Experimental results

Energy distribution function of the spent electrons was investigated in dependence on initial beam energy and gas puffing regime in carried out experiments. Beam currents at accelerator diode, at entrance to the plasma column and in plasma were measured by Rogowski coils. Measured characteristics of the beam for two different voltage values applied to accelerator diode presented in figure 2.

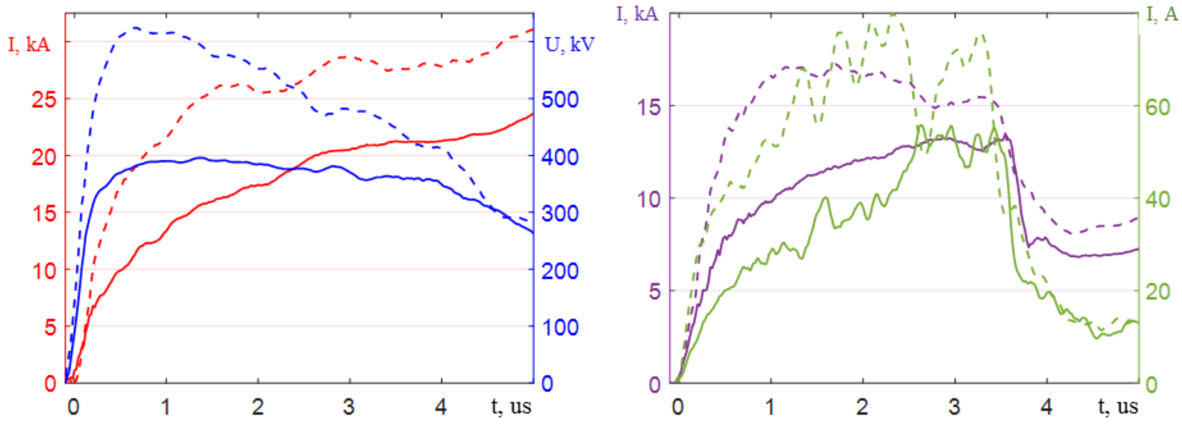

Figure 2. Current of the electron beam measured in experiments for two shots with different voltages applied to accelerator diode (blue lines): beam current at exit of the accelerator diode (red lines); beam current at entrance of the plasma column (violet lines); beam current absorbed in multi-foil analyzer (green lines).

Multi-foil analyzer consists of ten successive aluminum foils. Each foil separately grounded through 3 Orm resistive shunt. In experiments voltage drop measured on these resistive shunts. Signals are recorded by oscilloscopes in the frequency range of 0÷200 MHz. Measured signals before the evaluation process were averaged at time window width 0.25 us. It should be noted that normed currents are used in the process of the energy distribution function evaluation. Normed currents obtained by dividing current from the each foils by the full current absorbed in analyzer. Measured signals are shown in figure 3.

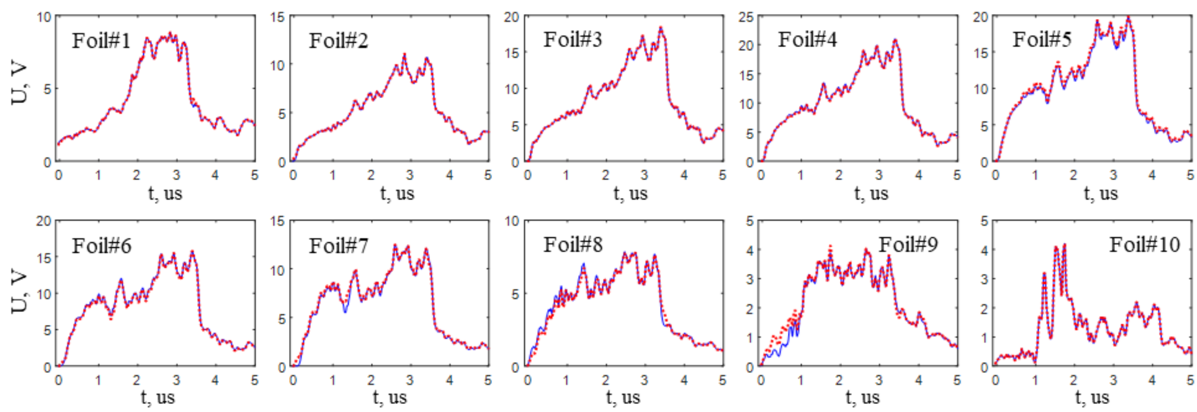

Figure 3. Waveform of the signals measured in multi-foil analyzer. Blue solid lines – measured signals. Red dashed lines - signals calculated based on energy distribution function.

Energy distribution

Current absorbed in *i-th* foil is given by the equation $I_i = \iint_{x_{i-1}}^{x_i} f(E) \cdot S_i(x,E) \cdot dx \cdot dE$. Where I_i – is normalized current; *f(E)* is energy distribution function and S_i is a sensitivity function describing probability of the electron to be absorbed in *i-th* foil. A number of x_i corresponds to the boundaries of the foils and x_0 equal to zero. Example of sensitivity functions in dependence of *x* for different values of E presented in figure 4b. Energy distribution function decomposes in a sum of the convenient basic functions $f(E) = \sum_{k=1}^{n} a_k \cdot V_k(E)$. Variation of the cosines function was chosen as basic functions $V_k(E)$.

$$V_k(x) = \begin{cases} 1 + \cos\left(2 * pi * \dfrac{E - {(E_{k+2} + E_k)}/{2}}{E_{k+2} - E_k}\right), & E \in [E_k, E_{k+2}] \\ 0, & E \notin [E_k, E_{k+2}] \end{cases}$$

Given functions are differential everywhere, smooth inside range $[E_k\ E_{k+2}]$, positive inside this range and equal to zero outside it. Decomposition allows one to solve linear equation system instead of integral one. $I_i = \sum_{k=1}^{n} A_{ik} \cdot a_k$, where $A_{ik} = \iint_{x_{i-1}}^{x_i} V_k(E) \cdot S_i(x,E) \cdot dx \cdot dE$. Coefficients a_i given by the equation $a_i = \sum_{k=1}^{n} A_{ik}^{-1} \cdot I_k$.

Main task of the energy distribution function evaluation is to calculate matrix A_{ik}^{-1}. Given task is ill-posted because of the sensitivity functions intersection and must be solved by one of the specialized methods. In our case it is method of the Tanabe-Huang [4]. In order to decrease calculation error, the minimization of the $\sum \frac{1}{\lambda}$ was executed by varying energy boundaries of the basic functions E_k. Where lambda are engine values of the matrix (A'·A). In figure 4a presented basic functions correspond to minimum of the $\sum \frac{1}{\lambda}$.

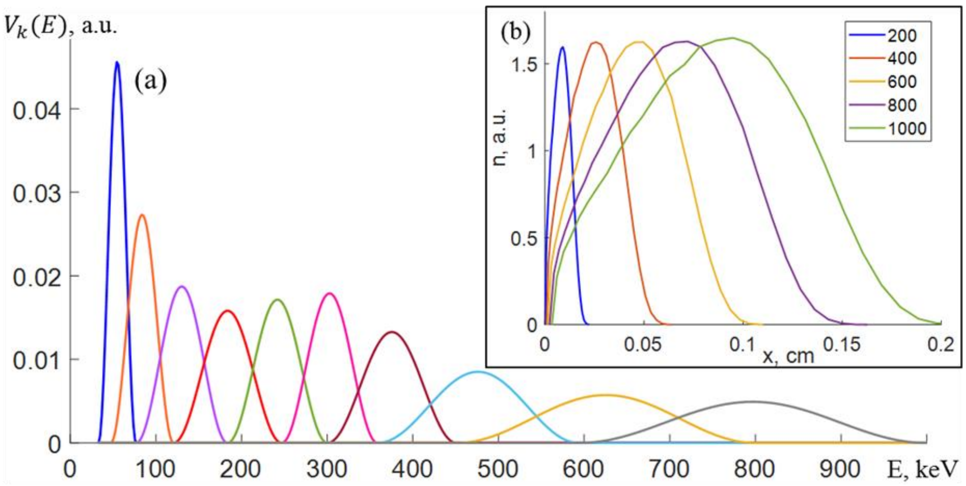

Figure 4. Characteristic functions necessary to evaluate energy distribution function. (a) – used basic function $V_k(E)$; (b) – portion of the electrons absorbed in aluminum foil at normal fall calculated for different initial energies.

Results discussion

Obtained energy distribution function of the relativistic electron beam in correlation with the results of studying the megawatt flux generation of the THz radiation at various plasma density distributions over the plasma column. As a result of the beam-plasma interaction several electron groups with low energies (localized near 50, 150 and 300 keV) are formed. There is no significant change in energy specter detected in dependence on gas puffing regime.

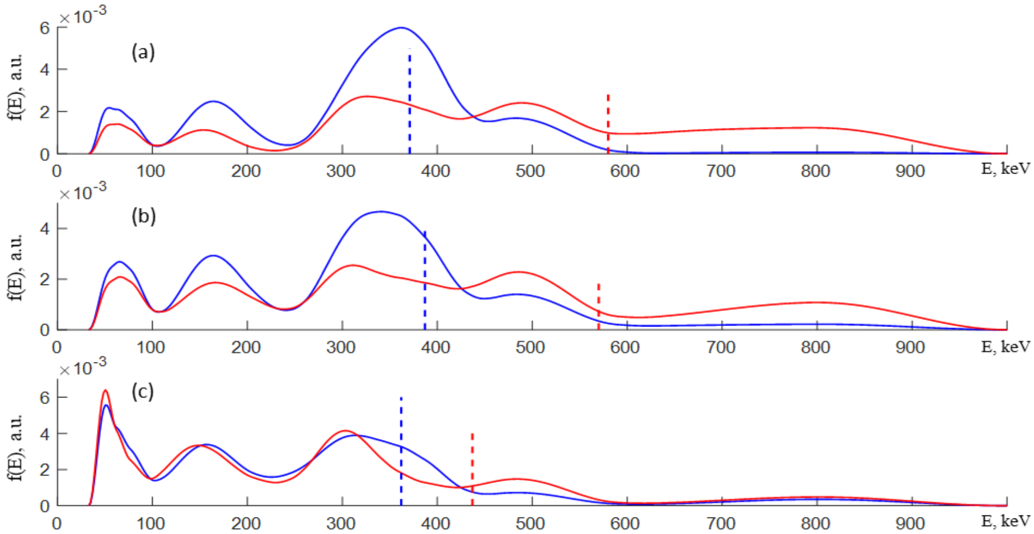

Figure 5. Energy distribution function of the beam electrons at different moments after starting its injection (a – 0.5 us; b – 1.5 us; c – 3.5 us) for different values of the diode voltage (vertical dashed lines).

Acknowledgment

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References

[1]. A.V. Arzhannikov, I.A. Ivanov, A.A. Kasatov, et al., “Well-directed flux of megawatt sub-mm radiation generated by a relativistic electron beam in a magnetized plasma with strong density gradients” //Plasma Physics and Controlled Fusion. 2020. T. 62. – №. 4. – C. 045002.

[2]. I.V. Timofeev, V.V. Annenkov and A.V. Arzhannikov. Regimes of enhanced electromagnetic emission in beam-plasma interactions // Phys. Plasmas 2015, Vol.22, P.113109.

[3]. Arzhannikov A. V., Makarov M. A., Sinitsky S. L., Stepanov V. D. Energy spectrum of electrons in flow from plasma column heated by REB at GOL-3 facility //Fusion Science and Technology. – 2011. – T. 59. – №. 1T. – C. 304-306.

[4]. T.S. Huang, D.A. Barker, S.P. Berger, Iterative image restoration. Apply. Opt., v. 14, N 5, (1975), p. 1165-1168.