Measurements of the Beam Angular Divergence at U-2 Accelerator

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Abstract. A detector of the electron angular distribution of a high-power microsecond E-beam has been constructed and applied for measuring in experiments. Functional properties of this detector are based on the regularities of transmission of magnetized electrons through cylindrical channels drilled in absorbing material. Simulations of motion, reflection and absorption of electrons in detector channels performed with code Geant4, have shown the possibility to measure an electron distribution function over their initial pitch-angles with angular resolution ~0.05 rad. Measurement results for electron angular distribution of the beam in the magnetic field 0.6 T that is generated by the accelerator U-2 are presented and discussed in the paper.

INTRODUCTION

For effective generation of THz-radiation in experiments on beam - plasma interaction [1] the relativistic electron beam with small angular divergence of the electrons and high current density is required. To produce such beams at the electron energy ~1MeV and current of about few tens of kA the creation of reliable diagnostics for measuring the angular divergence of the beam electrons in the guiding magnetic field is very important. To solve this task, two kinds of physical methods are available: contact and non-contact. Among of non-contact methods the laser scattering on the electrons [2] and measuring the diamagnetic effect of the beam [3] should be mentioned. The contact methods include, in particularly, two different measuring schemes. The first scheme is based on regularities of the transmission of magnetized electrons through cylindrical channels drilled in absorbing material [4]. Detectors for the second measuring scheme constitute a separate class so-called "pin-hole" detectors [5]. The design of our angular spread detector unites the advantages of both contact methods. As will be shown below, the principle of our detector operation and the method of the angular distribution function reconstruction utilizing the accurate simulations of all the electron processes inside the detector, provide its angular resolution about of 0.05 rad that is suitable for our experiments.

ANGULAR DIVERGENCE DETECTOR

Schematic of the detector for measuring the angular divergence of the beam electrons is presented in Fig. 1. It consists of the grounded entrance "pin-hole" collimator and a coaxial set of annular collectors i = 1,.., 7 with gradually decreasing inner diameters for measuring currents of absorbed electrons. The geometry of the tantalum entrance collimator should meet few physical requirements. To minimize the part of electrons reflected in forward direction from the inner cylindrical surface of the collimator (not to spoil the angular distribution of the electrons), the thickness of it (d_0 = 0.5 mm) should be much less than the characteristic Lamoure radius of the beam electrons $d_0 << \rho_L$ in the magnetic field (0.6 T) inside the detector. At the same time the thickness of the collimator must exceed the full absorption depth of the beam electrons with energies ~1 MeV in tantalum at their normal incidence to its surface. Moreover it should be sufficient to prevent the collimator destruction being exposed to few pulses of high-power electron beam irradiation. Without doubt to provide “pin-hole” operation of the detector the aperture radius of the entrance collimator (a_0 = 0.4 mm) should be also much less than ρ_L .

After passing the entrance collimator the beam electrons are absorbed in a set of measuring graphite collectors. They are insulated electrically from each other by means of dielectric shims with thickness of 2 mm and inner diameter of 8 mm that exceeds the diameters of the holes in adjacent collectors. This prevents the surface irradiation of the dielectric shims by the beam electrons. The currents of absorbed electrons in each collector are measured with resistive shunts, which signals are recorded by oscilloscope with frequency range 0÷200 MHz. The inner radius a_i of the hole in each $i^{\text{-th}}$ collector was chosen approximately equal to transverse Lamoure radius of the electrons with the specified pitch angle θ_i , which is supposed to be registered mostly with this collector. The hole length of the collectors d_i is chosen from the condition of full absorption of the electrons with energies of about 1 MeV in graphite, i.e. more than 4÷5 mm. Such design of the detector allows in a single shot to measure the currents of absorbed electrons and then basing on the calculated sensitivities of the detector channels to solve the inverse problem and to reconstruct the distribution function of the electrons on their pitch angles before detector.

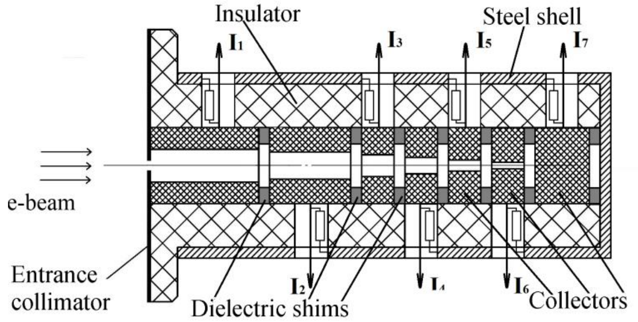

FIGURE 1. Schematic of the angular detector

Table 1.

#collector	1	2	3	4	5	6	7
Radius of collector a_i, mm	3	2	1.5	1	0.6	0.2	0
Length of collector hole d_i, mm	19	15	6	6	6	6	10

ELECTRON ABSORPTION IN ANNULAR COLLECTORS

In the first attempts to solve the inverse problem we developed simple quasi-analytical model basing on the assumptions that all the electrons incident on the surface of the graphite measuring collectors at any angle are absorbed. For the geometric sizes of collectors (see Table 1) we easily obtained the probabilities for the electrons with initial pith-angle θ and the energy E to be absorbed in $i^{\text{-th}}$ collector (S_i - sensitivity of the $i^{\text{-th}}$ channel), presented in the Fig. 2,a. But then it was noticed that in the range of small pitch-angles the coefficient of the electron reflection from the inner cylindrical surface of the collectors even made of graphite is close to 1. It means that multiple reflecting and scattering with the energy losses inside the detector should be taken into account. For the next approximation to real channel sensitivities we developed own Monte-Carlo code based on the tabulated results of calculated probability for the incident electron to be reflected from the collector matter at specified angle and energy. This probability was derived from “EMSH-2” – code [6] intended for calculating electromagnetic showers in the matter which has a shape of a single solid block or cylinder but not a ring. The last and the most accurate approximation for the sensitivities of the channels we have obtained by direct modeling of the electron motion, reflection and absorption inside the set of annular cylinders making our detector, with code Geant-4 [7]. The comparison of the sensitivities obtained by last two codes are presented in the Fig. 2,b. As it is seen from the figure the behavior of sensitivities obtained with EMSH2 and Geant4 in spite of some blur due to electron reflection from collectors remains practically the same as for the simplest model of full absorption and shows good selectivity of the detector channels.

MEASUREMENTS OF THE ANGULAR DIVEREGENCE AT THE EXIT OF U-2 ACCELERATOR

The detector of angular divergence was applied to measure the angular spread of the high-power E-beam at the accelerator U-2 [8]. This beam is used for injection into the plasma column confined in the magnetic trap GOL-3, to investigate the emission of THz radiation upon relaxation of intense relativistic electron beam in plasma. The electron beam is generated in the magnetically insulated ribbon diode of accelerator U-2 consisting of explosive emission cathode made of fibrous graphite material and the anode with a slit for the beam output. The beam cross-section has a shape of a ribbon with dimensions 75x5 cm near the cathode immersed in converging magnetic field with variable induction within 0.05÷0.2 T. Then the beam cross section is transformed to a quasi-circular one and after the compression in the magnetic field 5 T the beam has practically cylindrical shape with the diameter 4 cm, current ~20 kA in the magnetic trap with homogeneous longitudinal field 4 T. In the compression region the space charge of intense E-beam is compensated by injection of neutral gas Kr with density about 10^{15}-10^{16} cm^{-3}. In the experiments on measuring the angular divergence the detector was placed in the dispersing magnetic field after the compression region. To create homogeneous magnetic field 0.6 T inside the detector a special coil with profiled wounding was applied. According to magnetic measurements the induction along the detector axis was practically constant and equal to 0.6 T with accuracy better than 5%.

To achieve collinearity of the detector axis and the magnetic field line a special adjustment was carried out. For that purpose the tantalum entrance collimator was replaced by a graphite collimator with thickness of 6 mm and aperture diameter 1.2 mm which cuts out the cylindrical electron beam with the same diameter. All other collectors were removed. To register the beam imprint at the exit of the detector a thin film of Mylar covered with Al was used. During the beam pulse the stream of electrons (a small fraction of the beam) passed through a hole in a graphite collimator and produced imprint on this film. After that the detector was inclined until the centers of imprint and the detector coincide with an accuracy of ~0.1 mm. The estimates have shown that corresponding noncollinearity of $2\cdot10^{-3}$ rad can produce noticeable deviation only in the currents from 6^{-th} and 7^{-th} collectors on the level of 10-30% .

The next Fig. 3 shows the oscilloscope traces of the electron currents absorbed in the measuring collectors of the detector (I_1-I_7) together with the diode voltage (U_d), the beam current in the diode (I_d) and the current of circular beam before compression region (I_t) for the case when the magnetic field in the diode was 0.11 T (#10599). In the remaining part of magnetic system including the region of compression and detector location the magnetic field was not changed. As it is seen from the Fig. 3 the waveforms of collector currents have a strong oscillation in time, which is the result of chaotic pulsation of the emission current density on the cathode with space scale of few mm and time scale of ~10 ns, which was observed earlier in [9]. On these reason the signals were processed by the method of simple moving average on 50 points (Δt = 100ns) and then were used for the reconstruction of the angular distribution function - $f(\theta)$. The standard deviation of the currents from their moving average together with measurements errors formed the total error that is used in solution of inverse problem and produces the strip of events for the angular distribution function. The current in each channel can be expressed by this function and the sensitivity of the channel: $I_i = \int_0^{\pi/2} f(\theta) S_i(\theta) \sin(\theta) d\theta$. To solve the inverse problem $f(\theta)$ was presented as a linear combination of basic functions: $f(\theta) = \sum_1^7 a_k V_k(\theta)$, where we took: $V_k(\theta) = S_k(\theta)$. Because the matrix of transformation $L_{i,k} = \int_0^{\pi/2} S_i(\theta) S_k(\theta) \sin(\theta) d\theta$ is close to a singular and its inversion gives sometimes the negative values of $f(\theta)$, the coefficients a_k were found by iteration method of Tanabe-Huang [10] assuming the positive definiteness of the distribution function. The reliability of this solution was estimated by calculating the collector currents with the use of $f(\theta)$ and checking the coincidence with experimental values within standard deviation.

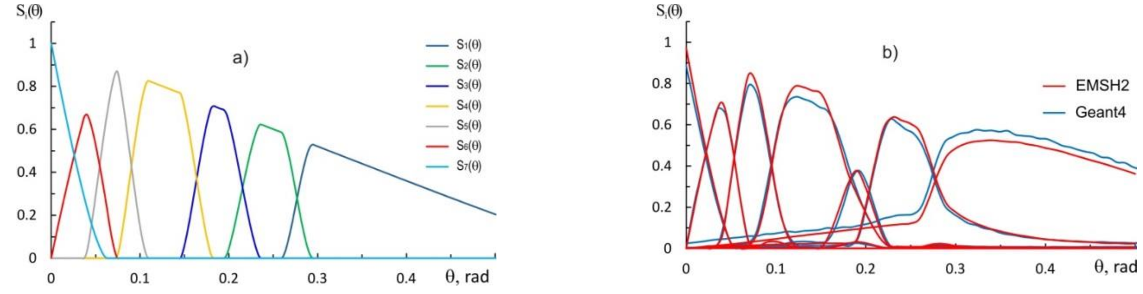

FIGURE 2. Sensitivities of the channels to the electron pitch angle obtained with full absorption model (a), EMSH2 and Geant4 codes (b) for the electrons with energy 0.6 MeV in the magnetic field 0.6 T

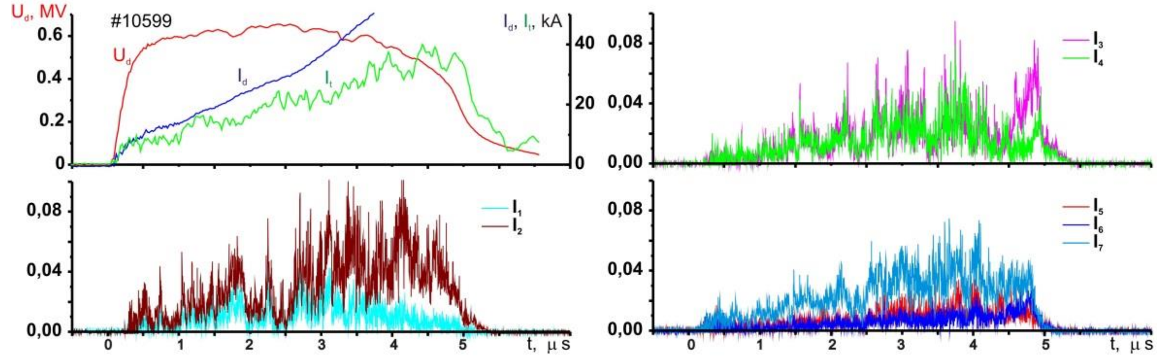

FIGURE 3. Signals of the diode voltage, the beam current and the collector currents for the diode magnetic field 0.11 T

The example of the reconstructed angular distribution function for the beam electrons in the shot #10599 at t = 1.5 μs after the beam start is shown in the Fig. 4,a. As one can see from the figure the distribution function starts from zero and reaches its maximum inside the range of investigated angles that can be determined by misalignment of the detector axis and the magnetic field line or mismatch of the detector and the beam centers. So we have carefully measured the angle between the axis of the detector and the magnetic field which was equal to 2 mrad and after that we have recalculated sensitivities of all collectors taking into account the tilt angle. The result of the reconstructing the distribution function for tilted detector is shown in the Fig. 4,b. After the treatment of data obtained in the series of shots with angular measurements we have established the following facts:

1. The RMS angle of the distribution function averaged during the beam pulse practically does not depend on the density of neutralizing gas within the limits 10^{15}-10^{16} cm^{-3} in compression region;
2. The RMS angle strongly depends on the diode magnetic field: for the fields 0.065 T, 0.088 T and 0.11 T the RMS angle is close to 0.16, 0.13 and 0.11 respectively that corresponds to the theory [11] and computer simulations.

FIGURE 4. 1- angular distribution function, 2- strip of events for two cases: a) the detector axis is parallel to the magnetic field, b) it was inclined at the angle 2 mrad

So, the design of the angular detector together with the complicated computer calculations of the cannel sensitivities allowed us to measure the angular distribution of the beam electrons and to investigate the dependencies of it on the diode magnetic field and the pressure of the neutralizing gas.

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