Determination of the Energy Characteristics of an Electron Beam Using a Light Scintillator

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Abstract—The possibility of using the effect of full energy release in a light scintillator when an electron beam passes through it to determine the energy characteristics of a low- and medium-energy beam (the “absorbed energy” method) is experimentally shown. Using scintillation detectors with thicknesses of 14.5, 20, 23.5, and 51.2 cm, the energy calibration of the quasi-monochromatic electron beam of the Pakhra FIAN accelerator was performed. For electron-beam energies of up to ~100 MeV and scintillation-detector thicknesses from 5 to 20 cm, the accuracy of determining the electron-beam energy may be 10–20%, respectively.

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INTRODUCTION

The energy characteristics of an electron beam include the maximum and average energy, as well as the energy spectrum. Synchrotron, Cherenkov, and transient radiations carry information on the energy parameters of the beam. The total energy of the beam is directly measured using the calorimetric method. The energy characteristics can be determined either by one of the methods or simultaneously by several methods [1].

This paper shows the possibility of determining the energy characteristics of an electron beam in the energy range of several hundred megaelectronvolts using the calorimetric method, in which a light scintillator is used. The essence of this method is to determine the characteristics of the beam by changing the thicknesses of scintillation detectors or to change the electron-beam energy at a fixed scintillator thickness to a value at which the trajectories of individual electrons completely fit into the detector volume. In this case, the average energy of beam electrons corresponds to the integral of the average ionization loss of the electron energy per unit path in the detector \( \langle E \rangle = kL \), where \( k = \Delta E/\Delta x \) (\( \Delta E/\Delta x \) is the average ionization loss of electrons per unit path in the detector), and \( L \) is the scintillation-detector thickness) [2].

EXPERIMENTAL APPARATUS

The research was performed on a quasi-monochromatic beam of secondary electrons of the Pakhra FIAN accelerator (Fig. 1). A copper plate with a thickness of 3 mm and a 3.2-mm diameter that was located on the “cut” of the magnet poles served as the converter [3]. The trigger signal \( T \) was a signal from the coincidence of signals of scintillation polystyrene counters \( S_1-S_3 \) and the anticoincidence counter \( A \) with a hole diameter of 10 mm (\( T = (S_1 \times S_2 \times S_3) A \)). The dimensions of the \( S_1-S_3 \) and \( A \) counters were 15 × 15 × 1 and 60 × 90 × 10 mm, respectively. The intensity of the secondary electron beam was \( \sim 10^2 \, e^-/s \).

Two polystyrene scintillation detectors (SDs) with dimensions of 20 × 20 × 20 cm (SD1) and 14.5 × 23.5 × 51.2 cm (SD2) were used (Fig. 2). The scintillators were viewed with an assembly of seven FEU-85 photomultiplier tubes (PMTs). PMT assemblies without grease were pressed tightly against the surface of the scintillators. The scintillators, with the exception of the area occupied by the PMT photocathodes, were wrapped with metallized Mylar and black paper.

The multichannel property based on the FEU-85 assembly is associated with the preservation of the value of light collection from the scintillator area, which is determined by the area of the FEU-49 photocathode, with a slight loss in the energy resolution, which however has the significantly higher speed that is required when working with an electron beam. In the future, it is planned to use SDs in an experiment with a significant low-energy electromagnetic background of \( \sim 10^4-10^5 \, \text{particles/s} \).

The SD amplitude was the sum of signals from all the PMTs of the assembly minus the constant component (“pedestal”) of the charge-to-digital converter.
Fig. 1. A schematic of a quasi-monochromatic secondary-electron beam from the Pakhra FIAN accelerator: (1) lead collimator; (2) cleaning magnet; (3) converter; (4) SP-57 magnet; (5) photon-beam absorber (“burial”); (6) collimator (Ø10 mm); (7) anticoincidence scintillation counter A; (8–10) trigger scintillation counters S1–S3; and (11) scintillation detector (SD).

(CDC) of each channel. It can be assumed that an insignificant current of secondary electrons \( I \sim 0.03 \text{nA} \) [4] almost does not affect the SD signal amplitude; no special study was performed.

The scheme of research is shown in Fig. 2. At the first stage (Fig. 2a), the energy characteristics of SD1 were investigated when the counter thickness along the beam was 20 cm; at the second stage (Fig. 2b), SD2 with a thickness of 14.5 cm was studied on the beam; at the third stage (Fig. 2c), SD2 with a thickness of 23.5 cm along the beam was studied; and at the last fourth stage (Fig. 2d), the characteristics of SD2 with a thickness of 51.2 cm along the beam were investigated.

The block diagram of the measurements is shown in Fig. 3. Signals from S1–S3 with a duration of \( t = 10 \text{ns} \) were fed to the formers \( F_1–F_3 \) (the threshold voltage of all formers \( U_{\text{thr}-3} \) was 30 mV) and were then fed through delays \( D_1–D_3 \) to a coincidence circuit CC. A signal with a 100-ns duration from the anticoincidence counter \( A \), which was formed by the former \( F_3 \), was fed to the “Anti” input. The signal from the CC was a Start trigger signal for triggering the 8-input CDC, using which signals from the scintillation detector were written to the computer memory through the crate controller of the CAMAC system.

RESULTS

Figure 4 shows the typical dependence of the average amplitude of the 20-cm-thick SD1 on the energy of the secondary-electron beam, where it is seen that at an electron energy of 40 MeV the dependence changes abruptly. With a further increase in the electron energy the value of the registered energy changes slightly. This means that at a detector thickness of 20 cm, the average ionization loss of electrons was \( \langle E \rangle = (\Delta E/\Delta x) L = 2 \text{[MeV/cm]} \times 20 \text{[cm]} = 40 \text{MeV} \) and did not increase as the energy increased (for SDs that are used in this study, the ionization loss was \( \Delta E/\Delta x = 2 \text{MeV/cm [2]} \)).

Figure 5 shows the dependence of the average SD amplitude on the energy of the secondary electron beam for all measured thicknesses. It can be seen that dependence \( I \) determines the thicknesses of the SDs, when the electron tracks are inside the SD volume, and dependences 2–5 determine the situation where the electron tracks of the beam go beyond the SD. Therefore, dependence \( I \) can be called the “absorbed energy,” while the point at which the dependence sharply changes is the “inflection point.”

Figure 6 shows the dependence of the average amplitude of the SD signal on the scintillator thickness at four “inflection points” that are shown in Fig. 5. As is seen, the dependence has a linear character within the investigated SD thicknesses. However, when the dependence is extrapolated to the region of energies that are close to zero, the dependence ceases to be linear.

Figure 7 shows the final dependence of the electron-beam energy determined by this method \( (E_{\text{in}}) \) on the electron energy, which is determined by the estimation of the average ionization losses at the corresponding SD thickness \( (E_{c}) \). It can be seen that the...
The dependence is linear and within the limits of errors (in this case, the errors of the energy resolution include the influence of the copper converter that forms the electron beam and the energy resolution of the SD itself). In addition, the values of the beam energy that were determined experimentally with this method coincide with the energy values of the secondary-electron beam, which is formed on the basis of a bremsstrahlung photon beam by the magnetic system and detected by the SD (Figs. 1 and 4) [3].

The error of the electron energy value at any “inflection point” was determined by extrapolating the energy errors that were determined before and after the “inflection point” to the “inflection point” according to the relevant paths, “$E_{ab} - \sigma_{ab}$” and “$E_{ab} + \sigma_{ab}$” (Fig. 4). For a 20-cm-thick detector, the beam energy at the “inflection point” was $E_{ab} = 40 \pm 10$ MeV.

The preliminary calibration of both SDs that was performed on single cosmic muons using the “transmission” method [3] showed that the energy resolution of the 20-cm-thick SD is $\sigma = 9\%$ ($\sigma = \Delta E/E/2.35$, $\Delta E$ is the FWHM of the electron-beam energy spectrum, and $E$ is the average electron-beam energy [3]); the energy value is then $E_{ab} = 40 \pm 8$ MeV. This resolution is the resolution of the method and is determined by fluctuations in the average path length of the beam electrons on the SD thickness.

Figure 8 shows the dependence of the electron-beam energy resolution determined by this method on...
the thickness \(L\) of the scintillation detectors (the resolution of the detector itself is subtracted). In this figure, dependence 1 determines the energy resolution of the electron beam with allowance for the influence of the copper converter (Fig. 6); in dependence 2, the influence of the converter is subtracted. As is seen, the greatest influence of the converter is observed at the \(SD\) thicknesses \(L < \sim 40\) cm or \(L < \sim 1 X_0\) (\(X_0 \approx 40\) cm is the radiation length for polystyrene [2]). The accuracy of determining the beam energy improves with a decrease in the \(SD\) thickness.

It should be noted that the form of \(SD\) amplitude spectra varies qualitatively depending on the electron beam energy. Figure 9 shows the amplitude spectra for the 20-cm-thick \(SD\) (Fig. 4) at electron beam energies below the “inflection point” (\(E = 9\) MeV, Fig. 9a), close to the “inflection point” (\(E = 45\) MeV, Fig. 9b), and after the “inflection point” (\(E = 145\) MeV, Fig. 9b). It can be seen that for electron energies that exceed the energy that is lost by an electron in the \(SD\) thickness (Fig. 9c), the shape of the spectrum is actually determined by the Landau distribution [2].

The degree of changes in the spectrum can be estimated by using the coefficient \(\beta\) method [5]. The ratio \(\beta = \alpha_{\text{right}}/\alpha_{\text{left}}\) is calculated for each spectrum, where \(\alpha_{\text{right}} = \sum_{i=m+1}^{k_{\text{max}}} N_i\) and \(\alpha_{\text{left}} = \sum_{i=k_{\text{min}}} N_i\) are the numbers of events in the right and left parts of the spectrum, respectively, with respect to the channel \(m\), which determines the channel of the average amplitude in the spectrum; \(N_i\) is the number of events in the \(i\)th channel of the spectrum; and \(k_{\text{min}}\) and \(k_{\text{max}}\) are the numbers of the minimum and maximum channels of the spectrum with nonzero numbers of events.

Figure 10 shows the dependence of the coefficient \(\beta\) on the electron beam energy. It can be seen that as the beam energy increases the spectrum begins to change; the maximum change in the spectrum is achieved at \(E_e \approx 28\) MeV. The inflection point at which \(\beta = 1\) corresponds to \(E_e \approx 40\) MeV. This means that at this point, the electron tracks are optimally fitted to the \(SD\) thickness. Otherwise, tracks that correspond to lower energy releases (the left side of the spectrum, Fig. 9a) or tracks corresponding to higher energy releases (the right side of the spectrum, Fig. 9c) will prevail.

In this study, polystyrene-based \(SDs\) (\(\rho \approx 1\) g/cm\(^3\) [2]) were used; however, the use of \(SDs\) of a denser mate-
DETERMINATION OF THE ENERGY CHARACTERISTICS

The presented "absorbed energy" method, which is associated with the attainment of the full energy release of particles in a scintillation detector made of a light material, makes it possible to determine the energy of an electron beam and can be used in experiments. The field of use is preferred at energies of hundreds of mega-electronvolts and scintillation-detector thicknesses of presumably up to ~100 cm (~2.5\(X_0\)), i.e., before the region of the start of the development of an electromagnetic shower. At energies of tens of mega-electronvolts and SD thicknesses of up to ~20 cm (~0.5\(X_0\)), the accuracy of determining the electron-beam energy may be ~10–20\%, which is close to the accuracy of determining the beam energy using conventional methods, e.g., with a Cherenkov total-absorption spectrometer [6].

CONCLUSIONS

The presented "absorbed energy" method, which is associated with the attainment of the full energy release of particles in a scintillation detector made of a light material, makes it possible to determine the energy of an electron beam and can be used in experiments. The field of use is preferred at energies of hundreds of mega-electronvolts and scintillation-detector thicknesses of presumably up to ~100 cm (~2.5\(X_0\)), i.e., before the region of the start of the development of an electromagnetic shower. At energies of tens of mega-electronvolts and SD thicknesses of up to ~20 cm (~0.5\(X_0\)), the accuracy of determining the electron-beam energy may be ~10–20\%, which is close to the accuracy of determining the beam energy using conventional methods, e.g., with a Cherenkov total-absorption spectrometer [6].

REFERENCES

1. Moskalev, V.A. and Sergeev, G.I., Izmerenie parametrov puchkov zaryazhennykh chastits (Measurement of Parameters of Charged Particle Beams), Moscow: Energoatomizdat, 1991.
2. Kalinovskii, A.N., Mokhov, N.V., and Nikitin, Yu.P., Prokhodzenie chastits vysokih energii cherez veschestvo (Passage of High-Energy Particles through Matter), Moscow: Energoatomizdat, 1985.
3. Alekseev, V.I., Baskov, V.A., Dronov, V.A., L’vov, A.I., Krechetov, Yu.F., Malinovskiy, E.I., Pavlyuchenko, L.N., Polyansky, V.V., and Sidorin, S.S., Instrum. Exp. Tech., 2019, vol. 62, no. 2, pp. 143–149. https://doi.org/10.1134/S0020441219020143
4. Alekseev, V.I., Baskov, V.A., Dalkarov, O.D., Kol’zov, A.V., L’vov, A.I., Mamonov, I.A., Pavlyuchenko, L.N., and Polyansky, V.V., Bull. Lebedev Phys. Inst., 2019, vol. 46, no. 11, pp. 355–359. https://doi.org/10.3103/S1068335619110071
5. Baskov, V.A., Kim, V.V., and Khablo, V.A., Instrum. Exp. Tech., 2010, vol. 53, no. 4, pp. 477–483. https://doi.org/10.1134/S0020441210040020
6. Alekseev, V.I., Baskov, V.A., Dronov, V.A., L’vov, A.I., Kol’tsov, A.V., Krechetov, Yu.F., Malinovskii, E.I., and Polyanskiy, V.V., Bull. Lebedev Phys. Inst., 2019, vol. 46, no. 9, pp. 289–293. https://doi.org/10.3103/S1068335619090057

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