Radiative moderation of an electron beam in a silicon single crystal

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The attenuation due to radiative moderation of a beam of electrons with momenta ~ 26.6 GeV/c and angular spread $\sim \pm 1$ mrad by an oriented silicon single crystal of 0.34 radiation length thickness is measured. Electron beams with lower momenta ~ 7.5–17.5 GeV/c are obtained. A strong orientation dependence of the beam intensity is observed. The experimental results can be described satisfactorily by the well known formulas for bremsstrahlung in single crystals.

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1. INTRODUCTION

Electron or positron beams in modern proton accelerators permit the study of electromagnetic processes in matter to be advanced to the energy region of tens and hundreds of GeV inaccessible in existing electron accelerators. As a result in recent years there has been greatly increased interest in the theoretical and experimental problems of interaction of radiation with the ordered structure of single crystals. In the new energy region interesting experimental results have been obtained on the coherent bremsstrahlung of electrons in single crystals, on the production of electromagnetic showers in crystals, and on the spontaneous radiation of electrons and positrons channeled in crystals.

In this article we describe an experiment carried out at the Serpukhov 70-GeV proton accelerator on the radiative moderation of a beam of high-energy electrons in an oriented single crystal of silicon. The practical application of this effect to obtain electrons of reduced momenta is discussed.

2. EXPERIMENTAL APPARATUS

The experiment was performed in the high-energy electron beam 14E (Ref. 1) with use of apparatus of the existing physical installation PROZA.[2] The two-target system of beam generation in the accelerator ($p + N \to \pi^0 + X$, $\pi^0 \to 2\gamma$ in the hadron target and $\gamma \to e^- e^+$ in the conversion target) has been described elsewhere,[3] and a diagram of the magnet-and-counter arrangement for formation and monitoring of the beam is shown in Fig. 1.

The electron beam extracted from the accelerator was limited in aperture by collimators C_1 and C_2 and was captured into the beam channel by the leading objective of the lenses Q_1 and Q_2. The deflecting magnet M_1, which analyzes the particles in momentum in the horizontal plane, and the gap of the momentum collimator C_3 determined the central value and interval of the beam-electron momenta. The subsequent beam optics in the section from M_2 to Q_6 produced a quasimonochromatic beam.

Radiative moderation of the high-energy electrons was accomplished by a silicon single crystal CR mounted on a goniometer. The goniometer and crystal were placed in a beam pipe in the converging beam between the leading objective and the analyzing magnet in the beam. Formation of a beam of electrons of momentum reduced by the crystal was accomplished by decreasing the fields and gradients of the magnetic elements in the beam section between M_1 and Q_6 in proportion to the momentum. On reversal of the direction of the current in these magnetic elements, shower positrons were selected from the single crystal. The technique described has been used previously[2] to lower the momentum of the electrons in beam in 14E by means of radiative moderation in a plate of amorphous material.

The electron beam in the channel could be intercepted beyond magnet M_1 by a copper absorber BS_1 of thickness $77X_0$ and directly in front of collimator C_3 by a lead absorber BS_2 of thickness $4X_0$, where X_0 is a radiation length.

The beam intensity in the channel was monitored by an external scintillation telescope $S_{1\mu}$–$S_{2\mu}$ which measured the flux of muons produced when the proton beam hit the hadron target in the accelerator. The beam itself was monitored by scintillation counters S_1–S_2, which were 80 mm in diameter and 5 mm thick, and could be further defined by a counter S_3 of variable dimensions in the final focal plane.

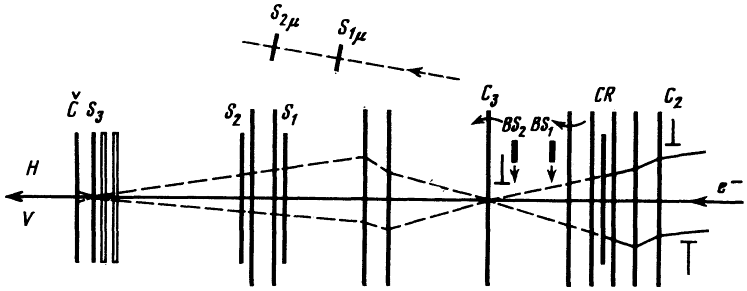

FIG. 1. Optical diagram of electron beam 14E and the experimental apparatus: H and V are the horizontally and vertically aligned longitudinal planes of the beam, C are collimators, Q are quadrupole lenses, M are deflecting magnets, CR is a silicon single crystal in a goniometer, S are scintillation counters, G are scintillation hodoscopes, $\check{C}$ is a hodoscope of total-absorption Čerenkov counters, BS are beam stoppers, and lenses Q_3–Q_4 and Q_7–Q_8 have been turned off.

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The beam profile in front of counter S_3 in the horizontal and vertical directions was monitored by one-coordinate scintillation hodoscopes G_1–G_2.

The energy and momentum of the particles at the exit of the beam channel were measured by a hodoscope $\check{C}$ of lead glass total-absorption Čerenkov counters. The energy resolution of this hodoscope for 40-GeV electrons was 5% (FWHM). The presence of amorphous material with a total thickness about $0.2X_0$ in the channel between Q_6 and $\check{C}$ broadened somewhat the electron energy distribution in the shaped beam toward the lower-energy region. However, in the experiment this circumstance did not distort the nature of the variation of the measured beam intensity with variation of the angular orientation of the single crystal.

3. CRYSTAL AND GONIOMETER

The experiment utilized a single-crystal silicon radiator in the shape of a disk 75 mm in diameter and $0.34X_0$ thick (for silicon $X_0 = 9$ cm) cut along the (100) planes. The radiator was mounted on the movable frame of a single-axis remotely controlled goniometer and could be inserted into the beam or removed from it.

The vertical and horizontal goniometric axes were located in the transverse plane of the beam. Rotation of the goniometer frame about the vertical axis was excluded, that is, the corresponding angle was given by $\Phi_V = \text{const}$. The range of angles of rotation of the frame about the horizontal axis was $\Phi_H \approx \pm 7°$. The accuracy of the apparatus and of the determination of this angle were ± 0.2 mrad or better.

The plate in the goniometer was adjusted on the basis of the crystallographic axes [100], [011], and [0$\bar{1}$1], the unit vectors of which we shall designate $\mathbf{b}_1$, $\mathbf{b}_2$, and $\mathbf{b}_3$. The vectors $\mathbf{b}_2$ and $\mathbf{b}_3$ coincided mechanically with the vertical and horizontal goniometric axes. The angle values $\Phi_V = \Phi_H = 0$ were taken for $\mathbf{b}_1$ oriented along the beam axis. According to the results of the experiment, the plate turned out to be rotated by an angle $\Phi_V = 7$ mrad, and the relative azimuthal rotation angle of the vector $\mathbf{b}_2$ and the vertical about $\mathbf{b}_1$ amounted to 53 mrad.

4. ELECTRON BEAMS

For the direct primary beam with the single-crystal radiator removed from it the channel was adjusted to the central value of electron momentum $p_0 = 26.6$ GeV/c and a standard spread $\sigma_p/p_0 \approx \pm 1\%$. The beam was restricted in the experiment by the aperture collimators of the channel to dimensions which excluded particles that passed around the radiator in its working position. The calculated angular distributions of electrons in the single crystal had standard deviations of about $\pm 0.60 \times 0.75$ mrad in the horizontal and vertical directions. The measured beam intensity was $3 \cdot 10^4$ electrons for $5 \cdot 10^{11}$ accelerated protons with an admixture of π^- and μ^- mesons less than 0.5%. The focal spot had a diameter of 25 mm.

Calibration beams of secondary electrons, that is, beams moderated in the radiator, were formed in the central-momentum range $p_0' \sim 17.5$–7.5 GeV/c with a constant gap of the momentum collimator of the channel. These beams had a momentum spread $\sigma_{p'}/p_0' \sim \pm 8\%$ and focal spots which reached $\sim 50 \times 70$ mm in the horizontal and vertical directions. This is explained by the mismatch of the beam optics as the result of multiple scattering and of the broad spectrum of radiation loss of electron energy in the radiator.

5. EXPERIMENTAL RESULTS AND DISCUSSION

In the main series of measurements we investigated the attenuation of a direct primary electron beam with momentum $p \approx 26.6 \pm 0.3$ GeV/c by the single-crystal radiator and the production of a flux of secondary electrons of lowered momenta $p' \approx 10 \pm 0.8$ GeV/c with variation of the radiator orientation angle Φ_H. The experimental results are given in Fig. 2 and show a change, selective in the orientation angle, of the intensity in the beam channel of both the primary and secondary electron beams.

The nature of the orientation dependences in Fig. 2 is explained by the initial adjustment of the single-crystal radiator in the primary electron beam. Figure 3 shows for this adjustment a map of the principal so-called reference lines.[4] The line FF' on the map corresponds to angular rotation of the radiator with respect to the axis of the primary beam in the experiment ($\Phi_H = \text{var}$, $\Phi_V = \text{const} = 7$ mrad). For values of the angle Φ_H at the points of intersection of this line with the reference lines one should observe peaks of coherent bremsstrahlung of the primary electrons and correspondingly dips and peaks in the orientation dependences in Fig. 2. The widths of these dips and peaks depend on the initial adjustment of the single-crystal radiator and also on the vertical and horizontal divergence angles of the primary electrons in the radiator and on the multiple scattering of the particles in the radiator.

The beams in the beam channel were simulated by Monte Carlo calculations. For the electrons in the crystal we took into account energy loss to bremsstrahlung in accordance with the well known relations[5,6] and multiple scattering. In these relations the atomic form factor of silicon was taken from Ref. 7 (the Moliere potential). For comparatively large angular divergences of the beam in a thick single crystal the spontaneous radiation of the channeled electrons is negligible. The development of an electromagnetic shower was not considered. The calculations were carried out with an accuracy of about $\pm 3\%$.

The modest attenuation of the flux of high-energy particles in the channel as the result of multiple scattering in the single-crystal radiator was verified in a beam of π^- mesons with momentum $p = 40$ GeV/c in the PROZA apparatus and amounted to about 6%. Here no dependence of the effect on the radiator-orientation angle was observed. The flux of shower positrons produced in the radiator with momenta $p' \approx 10 \pm 0.8$ GeV/c in the channel did not exceed 3% of the flux of electrons of the same momenta.

The calculated orientation curves and the experimental results in Fig. 2 are in satisfactory agreement. The curves had been normalized to the measured flux of direct primary beam electrons in terms of its calculated value. We note that according to the calculations the single-crystal plate thickness selected for generation of an intense beam of secondary

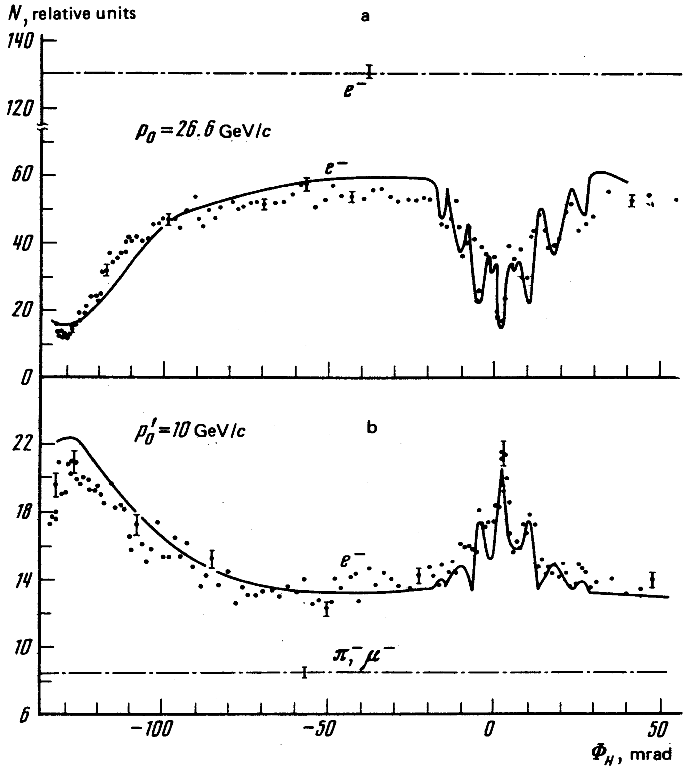

FIG. 2. Fluxes N of primary electrons (a) and secondary electrons (b) in the beam channel as functions of the orientation angle Φ_H of the single crystal: the points are experimental data with the single crystal placed in the primary beam; the dot-dash lines show the experimental fluxes of particles with the single crystal removed; the solid curves are theoretical; the experimental and calculated fluxes have been normalized to the primary-beam intensity with the single crystal removed; in individual experimental points we have indicated typical statistical errors; $N = S_1S_2$.

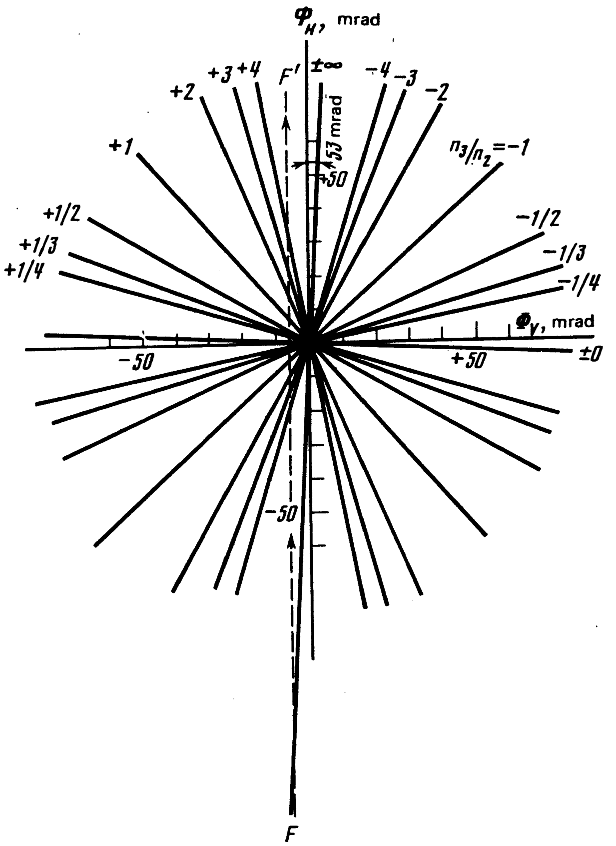

FIG. 3. Map of the principal reference lines for coherent bremsstrahlung from electrons in a silicon single-crystal radiator in the experiment: ϕ_H and ϕ_V are the orientation angles of the crystal with respect to the horizontal and vertical axes of the goniometer; n_2 and n_3 are the integer indices of the reciprocal-lattice points of the single crystal in the directions $\mathbf{b}_2 = [001]$ and $\mathbf{b}_3 = [0\bar{1}1]$; the straight line FF' is the variation of the angular orientation of the vector $\mathbf{b}_1 = [100]$ of the single crystal with respect to the beam axis in the experiment.

electrons with $p_0' \approx 10$ GeV/c is close to optimal under the experimental conditions (Fig. 4).

Measured and calculated secondary-electron fluxes in the channel in the momentum range $p_0' \sim 17.5$–7.5 GeV/c are shown in Fig. 5. In Fig. 6 we have given calculated momentum spectra of secondary electrons at the exit of the single-crystal radiator with variation of its thickness, under the experimental conditions. These spectra show that with optimal crystal thicknesses $\sim(0.15$–$0.65)X_0$, in the indicated range of p_0' values we can correspondingly expect increases of the secondary-electron fluxes in the channel in comparison with the measured fluxes. This increase is expected to be by 1.1–1.5 times in the energetic part and by a factor of two in the soft part of the momentum range.

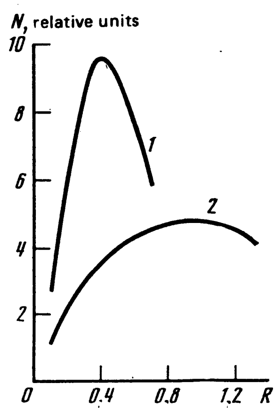

FIG. 4. Calculated secondary-electrons flux N for $p_0' = 10$ GeV/c as a function of the thickness R of the single crystal in radiation lengths in the beam channel (primary-electron momentum $p_0 = 26.6$ GeV/c): curve 1—$\phi_H = -131$ mrad; curve 2—single crystal disoriented; $N = S_1S_2$.

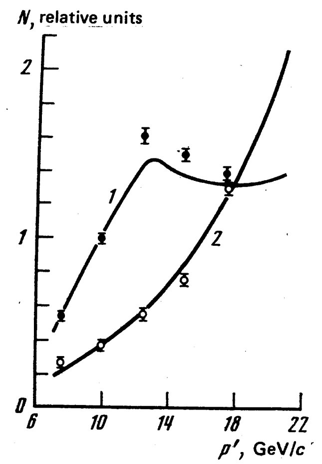

FIG. 5. Secondary-electron fluxes N for various momenta p_0' in the beam channel (primary-electron momentum $p_0 = 26.6$ GeV/c): curve 1—$\Phi_H = -131$ mrad; curve 2—single crystal disoriented; the solid and hollow circles show the experimental data, while the smooth curves have been calculated; $N = S_1S_2$.

The background conditions of the experiment were investigated on the basis of the variation of the beam intensity on movement of the conversion target in the accelerator into a nonworking position, introduction of absorbers into the beams, and by measurements with total-absorption Čerenkov counters. At the maxima of the intensity of secondary beams with momenta $p_0' \sim 7.5$–15 GeV/c (for $\phi_H = -131$ and $+2$ mrad) we observed a background flux $N_b/N_{e'} \sim 0.7$–1 which consisted mainly of π^- and μ^- mesons from the hadron target in the accelerator. The redefining of these beams by a scintillation counter 20 mm in diameter at the focal spot (counter S_3 in Fig. 1) decreased their intensity by an order of magnitude. Here the momentum spread of the electrons in the redefined beams was decreased by 2–2.5 times, while the background ratio was improved to values $N_b/N_{e'} \sim 0.2$–0.3. In the redefined electron beams with momenta $p_0' \gtrsim 17.5$ GeV/c the electromagnetic background rose significantly: $N_b/N_{e'} \gtrsim 3$. This rise was due to the location of the magnetic elements of the beam channel and to its simple optics. Characteristic energy (and momentum) spectra of the particles in the beams, obtained by means of total-absorption Čerenkov counters, are illustrated in Fig. 7.

Under identical conditions in the beam channel the silicon crystal of thickness $0.34X_0$ oriented in an electron beam with momentum $p_0 = 26.6$ GeV/c, in comparison with the amorphous lead plate of optimal thickness $\sim 0.6X_0$ used in Ref. 2, permitted a gain in the intensity of the reduced-momentum electron beams at $p_0' \sim 7$–15 GeV/c by 1.5–2 times with lower background levels and smaller undesirable multiple-scattering effects in the radiator.

In the Serpukhov accelerator the high-energy electron beams 14E (Ref. 1) and 2E (Ref. 3) are generated by means of a single target system in two magnetic beam-optics channels. The channels have a common leading section in which the goniometer and single crystal are mounted. This enabled us to confirm the principal results of the experiment, which were re-verified by measurements in the electron beam 2E; this beam was produced by more refined magnetic optics. Here also reduced-momentum electron beams[8] for calibration of particle detectors were obtained.

6. CONCLUSION

In the experiment described we observed a significant increase of the probability of radiative moderation of quasimonochromatic electrons with momentum ~ 26.6 GeV/c and an appreciable angular spread $\sim \pm 1$ mrad in a thin $(0.34X_0)$ oriented silicon crystal. The effect depended strongly on the crystal orientation angle. The experimental results on attenuation of the beam intensity and on production of electrons of lowered momenta are described satisfactorily by calculations employing the well known relations for bremsstrahlung in single crystals. No special features were observed for the multiple scattering of high-energy particles in the single crystal.

The experiment demonstrated the possibility of adjustment of the crystal on the basis of the orientation effect of attenuation of the electron beam intensity and generation of electrons of reduced momenta. The use of a single crystal for production of electron beams of reduced momenta provided an appreciable gain in the intensity of these beams in comparison with the use of an amorphous plate. Thin oriented crystal can be used for suppression of a directional electron-positron background. It is also of interest to study the possibility of use of single-crystal plates as shower-producing absorbers in total-absorption detectors with orientational properties.

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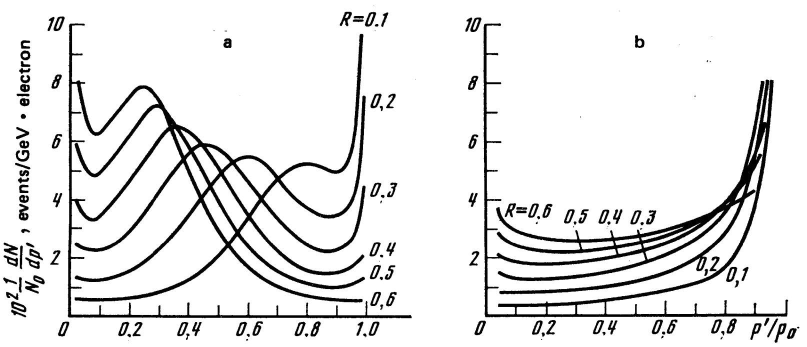

FIG. 6. Calculated momentum spectra of secondary electrons at the exit of the silicon crystal for various crystal thicknesses R in radiation lengths, under the conditions of the experiment (primary electron momentum $p_0 = 26.6$ GeV/c): (a)—$\Phi_H = -131$ mrad; (b)—single crystal disoriented; N_0 and N are fluxes of primary and secondary electrons.

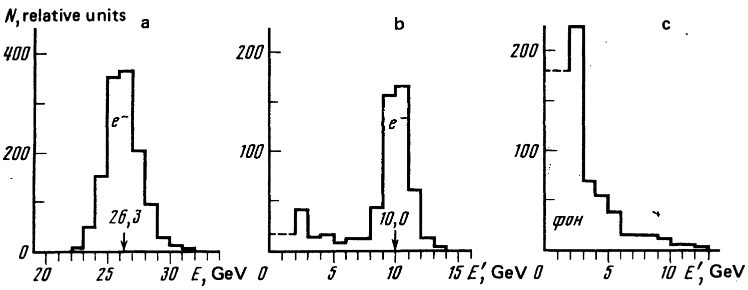

FIG. 7. Energy spectra of electrons obtained by means of total-absorption Čerenkov counters in the direct primary beam, (a), and in the secondary beam, (b) and (c) ($p_0 = 26.6$ GeV/c, $p_0' = 10$ GeV/c; N and E are the flux and energy of the particles; the trigger is $S_1 S_2 S_3$ and the diameter of counter S_3 was 20 mm; the spectra are given without correction for the energy resolution of the Čerenkov counters).

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