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GENERATION OF BREMSSTRAHLUNG BY AN ELECTRON BEAM

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The problem of generation of x- and γ-radiations in interaction of an electron beam with a layer of a substance having a large Z is considered theoretically. Energy and angular spectra of bremsstrahlung are obtained for various energies of the electron beam.

Introduction. It is most advisable and economical to use a charged-particle accelerator to obtain several types of radiation (of electrons, positrons, and γ-quanta). This can be attained by converting one type of radiation into another. Consequently, it is of interest to know the specific features of generation of x- and γ-radiations by an intense electron beam. It is known that accelerated electrons emit γ-quanta in the field of the atomic nuclei of the target. The losses of the energy of electrons in breamsstrahlung are proportional to Z^2 [1], and therefore substances with a large atomic number are used as converters. When electrons have an energy of more than several tens of megaelectron volts, bremsstrahlung is emitted forward in the direction of beam propagation. The thickness of the target is selected to be close to the total electron range. The theoretical model used makes it possible to determine the characteristics of the radiation in relation to the initial parameters of the beam (angular and energy distributions of the electrons).

1. Physical Model and Processes of Interaction of Particles with the Target Material. A physical model that describes the passage of particles through the target is constructed on consideration of the processes of interaction of a single test particle with the scattering centers of the medium. This is the well-known approximation of pairwise collisions [2], in which it is assumed that an incident particle interacts simultaneously with just one scattering center (nucleus or electron) of the target. The interaction occurs at a point and instantly. The electron beam has an intensity such that the electrons in it are separated by a distance greatly exceeding the characteristic length of screening of the Coulomb interaction for the target material. Consequently, each electron of the beam interacts with the target independently, and collective phenomena are unlikely to occur. After penetration of the electron into the target the effect of the electromagnetic and electric self-fields of thermalized electrons in such a beam on the process of interaction can be neglected because of screening. This is true of beams with a current of up to units of kiloamperes. The target is a polycrystal, i.e., the atoms are located randomly in it.

When a beam of electrons of rather high energy (~50 MeV) passes through the target, secondary particles (electrons, positrons, and γ-quanta) arise, which redistribute a portion of the energy of the primary electrons throughout the target. Positrons appear in the process of formation of electron-positron pairs by γ-quanta in the field of atomic nuclei. A special feature of the interaction of an electron beam with a target with a large Z is generation of rather intense bremsstrahlung. The cross sections for elementary events of interaction of electrons and positrons with atoms of the substance are rather large and therefore they experience a host of collisions even over small stretches of the path in the substance. The basic mechanisms of the interaction of these particles with the substance are elastic scattering on electrons and nuclei, excitation and ionization of atoms of the medium, and bremsstrahlung of γ-quanta. For positrons the process of annihilation is also taken into account. The Coulomb character of the interaction of electrons and positrons with nuclei and electrons of the medium is responsible for the large probability of small-angle scattering. Elastic scattering on nuclei of the target is Z times more efficient than energy losses on electrons. Consequently, these particles change their direction of motion many times before

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they entirely lose their energy. Bremsstrahlung by electrons and positrons on nuclei of the target becomes important in the region of large and average energies. Thus, for example, for tungsten with an energy of 10 MeV the losses in bremsstrahlung equal the losses in ionization, and they exceed the latter by an order of magnitude at an energy of 100 MeV.

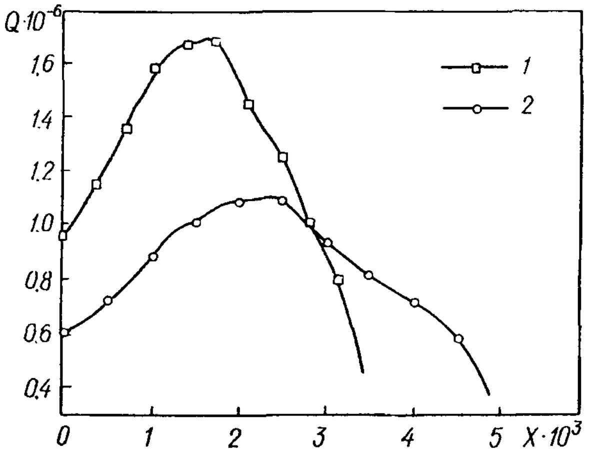
On their path γ-quanta experience considerably fewer collisions than electrons and positrons. The basic processes of their interaction with the substance are the photoelectric effect, Compton scattering, and formation of electron-positron pairs. In the considered energy range of 0.001-50 MeV all three processes are important. A special feature of the Compton effect is preservation of the γ-quantum, whereas it disappears in the photoelectric effect and during formation of pairs.

2. **Monte Carlo Method of Simulation of Bremsstrahlung Generation.** With the use of known cross sections for different processes, the Monte Carlo method makes it possible to model random particle trajectories in a substance that are similar to the actual ones [3]. The method is effective in the formation of secondary particles and makes it possible to obtain diverse information about their characteristics. The Monte Carlo method uses random numbers for sampling separate elements of the trajectories of particles (the length of a portion of the trajectory, the energy lost over this portion, the scattering angle) from the corresponding probabilistic distributions.

To simulate electron and positron trajectories, a model of grouping of collisions is used [4]. All the collisions of electrons and positrons with atoms of the target are subdivided into two classes: "close" and "distant." "Distant" collisions are associated with small energy transfers and small scattering angles and are described by the theory of multiple scattering. "Close" collisions are associated with large energy transfers and scattering angles and are considered as separate events. Let us assume that a charged particle is located at the point r′ and moves in a certain direction Ω. To describe the interaction of electrons and positrons with atoms of the target, macroscopic cross sections are employed. Such a cross section Σ_t at the point r can be represented in the form of the sum $\Sigma_t = \Sigma_{en} + \Sigma_{ee} + \Sigma_{br}$. For positrons this sum must also be supplemented with the macroscopic cross section for annihilation Σ_{an}. The mean free path up to a "close" collision in a homogeneous medium is sampled from the following expression: $l = -\ln \xi/\Sigma_t$. As a result, the particle turns out to be at a certain point r′. The angle of scattering and the transferred energy at the point of a "close" collision are sampled from the differential cross sections for the corresponding processes. A large number of "distant" collisions occur over the length l. The energy loss in this case is determined in the continuous-deceleration approximation [1]. The overall angle accumulated by the charged particle over the length l is sampled from the distribution of the angles in the theory of multiple scattering [5]. After a "close" collision the charged particle moves in a certain new direction Ω' with a new energy. The simulation procedure is repeated from the determination of the total macroscopic cross section Σ_t at the point r′, and the mean free path covered until the next "close" collision is sampled. The secondary electrons appearing are traced similarly.

A model of individual collisions is used for the description of the transfer of γ-quanta [3]. According to this model, at each nodal point of the trajectory of a γ-quantum one of the possible elementary processes of interaction occurs, after which the γ-quantum changes its state, i.e., it moves in a new direction with a new energy until the occurrence of the next collision or until the γ-quantum is absorbed. In this case all the points of the collision of the γ-quantum with atomic electrons as a result of the processes of the photoelectric effect, formation of pairs, and the Compton effect are the nodes of the trajectory. The total macroscopic cross section Σ_t^γ for the interaction of γ-quanta with the substance can be represented in the form of a sum: $\Sigma_t^\gamma = \Sigma_{ph} + \Sigma_C + \Sigma_{ep}$. The mean free path in a homogeneous medium is determined from the relation $l_\gamma = -\ln \xi/\Sigma_t^\gamma$. The angle of scattering and the transferred energy at each nodal point are sampled from the corresponding differential cross sections for the processes of interaction.

3. **Results of Calculations.** The technique set forth above was used for investigation of the special features of bremsstrahlung generation by an electron beam. A layer of tungsten was used as the target. A numerical experiment was carried out for two values of the kinetic energy E of a monoenergetic electron beam equal to 30 and 50 MeV. It was assumed that the beam was incident normally on the target. The power density of the beam was 10^4 MW/m^2. The distribution of the absorbed energy for the two cases investigated is presented in Fig. 1. The thickness of the target d was equal to $3.5 \cdot 10^{-3}$ and $5 \cdot 10^{-3}$ m, respectively. The flux density F_e of the electrons



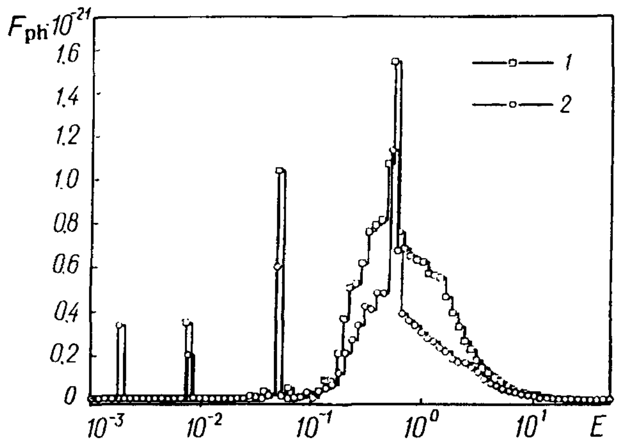


Fig. 1. Profiles of energy release by an electron beam in a tungsten target: 1) $d = 3.5\cdot10^{-3}$; $E = 30$; $F_e = 2.1\cdot10^{21}$; 2) $5\cdot10^{-3}$; 50; $1.2\cdot10^{21}$. Q, MW/m^3; X, m; d, m; E, MeV; F_e, el./(m^2·sec·MeV).

Fig. 2. Energy spectrum of photons that emerged from the target: 1) $d = 3.5\cdot10^{-3}$; $E = 30$; $F_e = 2.1\cdot10^{21}$; 2) $5\cdot10^{-3}$; 50; $1.2\cdot10^{21}$. F_{ph}, phot./(m^2·sec·MeV).

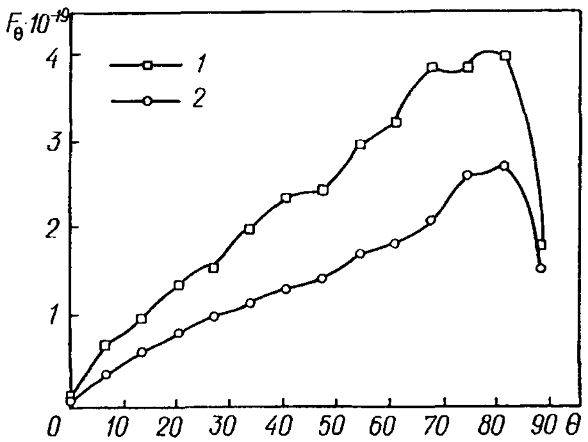


Fig. 3. Angular spectrum of photons that emerged from the target: 1) $d = 3.5\cdot10^{-3}$; $E = 30$; $F_e = 2.1\cdot10^{21}$; 2) $5\cdot10^{-3}$; 50; $1.2\cdot10^{21}$. F_θ, phot./(m^2·sec·deg); θ, deg.

incident on the target was $2.1\cdot10^{21}$ and $1.2\cdot10^{21}$ el./(m^2·sec) for the two values of the kinetic energy E. In calculation of the energy contribution of the electron beam to the target the redistribution of energy by secondary electrons, positrons, and photons was taken into account. In the two cases considered, 44.5 and 41.4% of the initial kinetic energy of the electron beam was absorbed in the target; 56.3 and 61.1% of the beam energy was transformed into bremsstrahlung, respectively. A portion of the bremsstrahlung was absorbed prior to exit from the target.

For the same energy of the beam we obtained an energy spectrum of the bremsstrahlung that emerged from the tungsten target (Fig. 2). It is seen that the maximum of the bremsstrahlung corresponds to an energy of approxinately 600 keV. In the low-energy portion of the spectrum a number of characteristic lines are observed that appear as a result of processes of photoelectric relaxation of atomic shells of tungsten after ionization. The line located near 50 keV corresponds to the $2p$-$1s$ transition. The line at 8 keV corresponds to the $3s$-$2p$ transition. And finally, the line at 2 keV corresponds to the $4p$-$3s$ transition.

The angular spectrum of the bremsstrahlung that emerges from the target is presented in Fig. 3. The angle θ is reckoned from the target surface. It is seen that a large portion of the photons emerges from the target at an angle of about 80°.

Thus, the Monte Carlo model created makes it possible to carry out a numerical experiment on the passage of an electron-photon avalanche through a target.

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NOTATION

Z, charge of the target nucleus; r and r′, radius vectors of the collision point; Ω and Ω', vectors of the direction of particle motion; Σ_t, total macroscopic cross section for interaction of an electron or a positron; Σ_{en} and Σ_{ee}, macroscopic cross sections for elastic scattering of electrons or positrons on nuclei and electrons of the target in "close" collisions; Σ_{br}, macroscopic cross section for bremsstrahlung by electrons or positrons; Σ_{an}, macroscopic cross section for annihilation of a position; l, mean free path between "close" collisions; ξ, random numbers uniformly distributed within the interval [0, 1]; Σ_t^γ, total macroscopic cross section for interaction of γ-quanta; Σ_{ph}, Σ_c, and Σ_{ep}, macroscopic cross sections of the photoelectric effect, the Compton effect, and creation of pairs; l_γ, mean free path of a photon; d, target thickness; E, kinetic energy of the electrons of the beam; F_e, density of the flux of electrons; F_{ph} and F_θ, spectral functions of the energy and angular distributions of photons; θ, angle with the target surface; Q, energy release power density; X, coordinate over the target depth. Subscripts: t, total cross section; en, scattering of an electron on a nucleus; ee, scattering of an electron on an electron; br, bremsstrahlung; an, annihilation; e, electron; θ, angle; ph, photoelectric effect; C, Compton effect; ep, electron-positron pair. Superscript: γ, photon.

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