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Nuclear Instruments and Methods in Physics Research B 227 (2005) 125–131
NIM B Beam Interactions with Materials & Atoms
www.elsevier.com/locate/nimb

Simulation of incoherent bremsstrahlung of high energy electrons and positrons in a crystal

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Received 17 December 2003; received in revised form 8 March 2004

Abstract

The simulation procedure for the intensity of incoherent radiation by the electron and positron beams in oriented crystal is developed. This procedure is based on the quasi-classical formulae of the bremsstrahlung theory. Substantial orientation dependence of the intensity of hard incoherent radiation manifests itself under the angles of incidence of electrons and positrons to one of crystallographic planes, close to the critical angle of planar channeling. It is demonstrated that the orientation dependences for the electrons and positrons substantially differ from each other. The results of simulation are in a good agreement with the experimental data.
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PACS: 02.70.−c; 41.60.−m; 61.85.+p
Keywords: Bremsstrahlung; Incoherent radiation; Semiclassical approximation; Simulation

1. Introduction

Under motion of fast charged particles in a crystal along one of crystallographic axes or planes the channeling phenomenon is possible, when the particles move in channels formed by atomic strings or planes in the crystal (see e.g. [1–3]). The redistribution of the particle flux in the crystal takes place under the channeling. Due to this fact both increase and decrease of yields of the processes connected with small impact parameters are possible. This is connected to the fact that positively charged channeling particles could not move too closely to the positively charged lattice constituents, so such particles would collide with the atomic nuclei in the crystal more rare than under absence of the channeling. For negatively charged particles the inverse effect takes place.

Under disorientation of the crystal on small angle to the incident beam the particles performing the above-barrier motion in relation to the atomic strings or planes in the crystal appears together with the channeled particles [3–5]. For the above-barrier particles some redistribution of the particle flux in the crystal also takes place. However, this effect has substantially different form than the redistribution of the flux of channeled particles. Namely, under above-barrier motion near atomic

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doi:10.1016/j.nimb.2004.03.016

planes in the crystal the positively charged particles "hang" for a relatively long time in the region of atomic nuclei location in the crystallographic planes, whereas negatively charged particles fly across this region faster than positively charged ones.

At last, if the angle of the crystal disorientation substantially exceeds the critical angle of channeling the effect of redistribution of the particle flux in the crystal is absent [3].

So, in the case of disorientation of the crystal by the angles of order of the critical channeling angle substantial orientation dependence of yields of the processes connected to small impact parameters must take place. Such orientation dependences have been observed earlier for the nuclear reactions yields, delta-electron yield, and a number of other processes (see e.g. [2,3,6,7]).

The present paper is devoted to the analysis of orientation dependence of the yield of incoherent radiation of relativistic electrons and positrons under motion of the particles in the crystal near one of crystallographic planes. The simulation procedure for this process based on the model in which the atomic planes in the crystal are treated as rows of atomic strings is presented. In the frames of this model the interaction of the particle with each atomic string is considered in the approximation of the uniform atomic string potential. Simulation is carried out for thin targets, when the effects of dechanneling and rechanneling of the particles are negligible.

2. Simulation procedure for incoherent radiation

Radiation of relativistic electron in matter develops in a large spatial region along the particle's momentum. This region is known as the coherence length [3,8]. If the electron collides with a large number of crystal atoms in the coherence length, the effective constant of the interaction of the electron with the lattice atoms may be large in comparison with the unit, so we could use the semiclassical description of the radiation process. In the dipole approximation the spectral density of bremsstrahlung is described by the formula (see Eq. (68.1) in [3])

$$\frac{\mathrm{d}E}{\mathrm{d}\omega} = \frac{e^2\omega}{2\pi c^4} \times \int_\delta^\infty \frac{\mathrm{d}q}{q^2}\left[1+\frac{(\hbar\omega)^2}{2\varepsilon\varepsilon'} - 2\frac{\delta}{q}\left(1-\frac{\delta}{q}\right)\right]\left|\vec{W}_q\right|^2, \tag{1}$$

where $q = \frac{\varepsilon}{\varepsilon'}(\omega - \vec{k}\vec{v})$, $\vec{k}$ is the wave vector of the radiated photon, ε is the energy of the initial electron, $\vec{v}$ is its velocity, $\varepsilon' = \varepsilon - \hbar\omega$, $\vec{W}_q = \int_{-\infty}^{\infty} \dot{\vec{v}}_\perp(t) e^{icqt}\,\mathrm{d}t$ is the Fourier component of the electron acceleration in the direction orthogonal to $\vec{v}$, $\delta = \frac{m^2c^3\omega}{2\varepsilon\varepsilon'}$.

For the case of radiation of the electron in the field of single atom (using the screened Coulomb potential $U(r) = Ze\frac{e^{-r/R}}{r}$ as the potential of the atom, where Z is the atomic number, R is Thomas–Fermi radius) we have

$$\vec{W}_q^{(1)}\left(\vec{\rho}_0\right) = \frac{2Ze^2c}{\varepsilon}\sqrt{q^2+R^{-2}}K_1\left(\rho_0\sqrt{q^2+R^{-2}}\right)\frac{\vec{\rho}_0}{\rho_0}, \tag{2}$$

where $K_1(x)$ is the modified Bessel function of the third kind, $\vec{\rho}_0$ is the impact parameter. Since the characteristic values of q making the main contribution to the integral (1) are $q \sim \delta \ll R^{-1}$, we can take $q = 0$ in Eq. (2),

$$\vec{W}^{(1)}\left(\vec{\rho}_0\right) = \frac{2Ze^2c}{\varepsilon R}K_1\left(\frac{\rho_0}{R}\right)\frac{\vec{\rho}_0}{\rho_0}. \tag{3}$$

Integrating over q, and over $\vec{\rho}_0$, we obtain with logarithmic accuracy the Bethe–Heitler result for radiation efficiency by the unit particle flux in the field of the atom

$$\hbar\omega\frac{\mathrm{d}\sigma_{\mathrm{BH}}}{\mathrm{d}\omega} = \int \frac{\mathrm{d}E}{\mathrm{d}\omega}\,\mathrm{d}^2\rho_0 = \frac{16}{3}\frac{Z^2e^6}{m^2c^2}\left(1+\frac{3}{4}\frac{(\hbar\omega)^2}{\varepsilon\varepsilon'}\right)\ln\left(\frac{mRc}{\hbar}\right). \tag{4}$$

Note that the integral over the impact parameter diverges at small values of ρ_0. The divergence results from the use of the dipole approximation, which is valid at $\rho_0 \geqslant \hbar/mc$. We take this constraint into account by introducing the lower limit of integration ($\rho_{\min} = \hbar/mc$ that is the Compton

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