Nuclear Instruments and Methods in Physics Research B 269 (2011) 2098–2106

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Computer simulation of the radiation of electrons axially channeled in a thin Ge single crystal

B. Azadegan [a], S.B. Dabagov [b,c], W. Wagner [d,*]

[a] Sabzevar Tarbiat Moallem University, Sabzevar, Iran
[b] INFN Laboratori Nazionali di Frascati, Via E. Fermi 40, 00044 Frascati (RM), Italy
[c] RAS P.N. Lebedev Physical Institute, Leninsky Pr. 53, 119991 Moscow, Russia
[d] Helmholz-Zentrum Dresden-Rossendorf, P.O. Box 510119, 01314 Dresden, Germany

ARTICLE INFO

Article history:
Received 14 April 2011
Received in revised form 22 June 2011
Available online 3 July 2011

Keywords:
Channeling radiation
Axial channeling

ABSTRACT

The radiation emitted by axially channeled electrons has been investigated by computer simulations. Using the Doyle–Turner approximation for the atomic scattering factor and taking thermal vibrations of the crystal atoms into account, two-dimensional continuous potentials for the ⟨1 0 0⟩ and ⟨1 1 0⟩ crystallographic axes of a thin Ge single crystal have been calculated. The trajectories, velocities and accelerations of channeled electrons are obtained by solving numerically the classical equations of motion in three dimensions. In the framework of classical electrodynamics, these data allow realistic simulations of spectral-angular distributions and energy spectra of axial channeling radiation as well.

1. Introduction

The phenomenon of channeling radiation (CR) has been discovered in the middle of the 1970s. Relativistic charged particles emit CR during their interaction with the averaged transversely periodic field generated by symmetric structures in single crystals such as crystallographic axes and planes. The physics of CR has been explained by many authors (see, e.g., [1–3]). When the one-dimensional problem of planar CR may be well described nowadays, the two-dimensional nature of axial channeling left space for more precise investigations and a complete understanding of the photon spectra. In the framework of quantum mechanics, the channeled particle is considered as being bound in the transverse electrostatic potential of a crystallographic axis or plane, and CR occurs due to spontaneous transitions between the eigenstates of this potential. In the classical model, the scattering at the ordered crystal atoms becomes coherent what causes an oscillatory motion of channeled particles along the corresponding atomic rows or planes. Since this oscillatory motion is an accelerated one in the rest frame of the charged particle, it emits electromagnetic radiation which after transformation into the laboratory system gives X- or γ-rays.

Planar channeled particles with energies of units of MeV may usually occupy a limited number of bound states, and quantum calculations by means of the so-called many-beam formalism [2] provide good agreement with experimental data. Such procedure, however, becomes very complicated in the axial case because there are many quantum states of transverse motion even at medium particle energies. Therefore, the problem may approximately be treated by a classical approach.

Former computer simulations of the radiation of axially channeled electrons [4,5] based on the classical binary-collision approximation (BCA) and classical electrodynamics. Generally, by means of the BCA method [6], any trajectory of a particle through a single crystal may be generated from a (rather large) sequence of successive interactions with individual crystal atoms. Restricting such procedure to a major crystallographic axis (i.e., to an atomic row), the effect of axial channeling and CR may be studied. It is, however, well established that at sufficiently small angles of incidence of relativistic charged particles with respect to an atomic row (or plane) Lindhard's continuum approximation may be utilized for the transverse interaction potential [7]. As illustrated in Ref. [8], the sequence of correlated binary collisions along an atomic row transforms to some curved trajectory in the averaged potential of a (quasi-continuously charged) string.

A trivial picture associates axial electron channeling with a nice regular rosette motion around the atomic row. However, as already discussed in Ref. [9], this is a special case because the particle trajectories strongly depend on (i) the entrance conditions at the crystal surface and (ii) the shape of the interaction potential.

The classical equations of motion of an electron in the transverse plane read [9,10]

$$\frac{1}{2}m\dot{\rho}^2 + w(\rho) = E_\perp \qquad (1)$$
$$m\dot{\varphi}\rho^2 = L_z,$$

* Corresponding author.
E-mail address: w.wagner@hzdr.de (W. Wagner).

0168-583X/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.nimb.2011.06.018

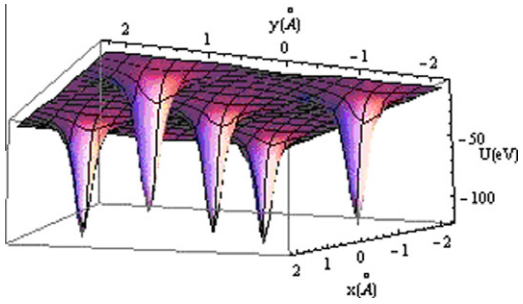

Fig. 1. Continuous potential of the ⟨1 0 0⟩ axis of a germanium single crystal for electron channeling.

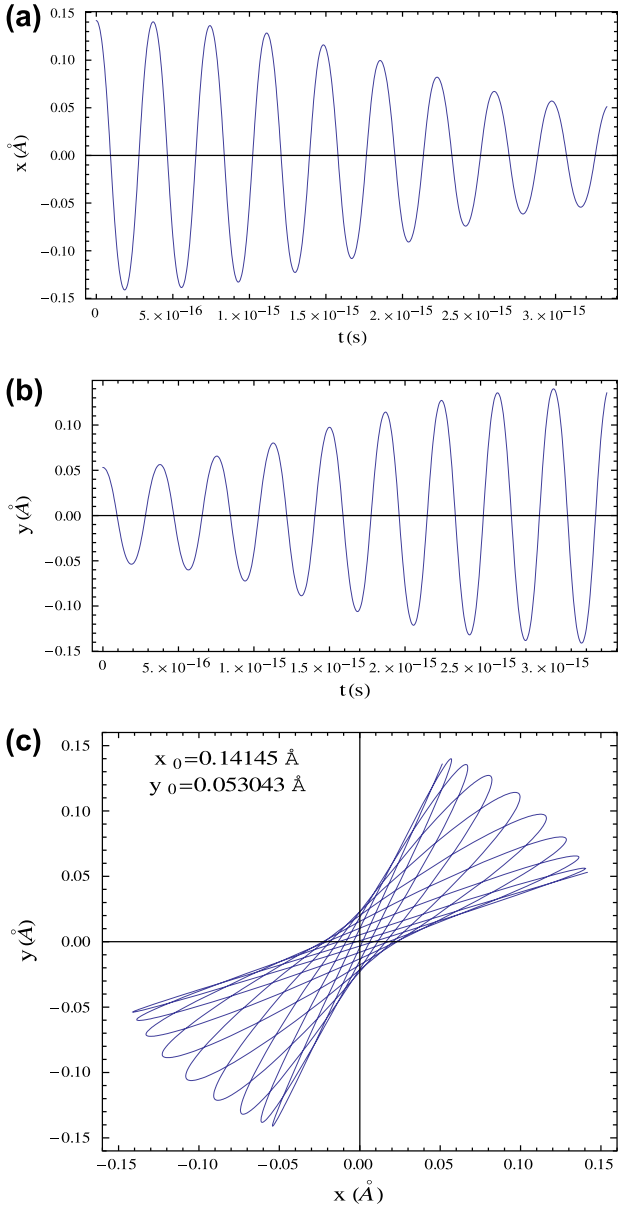

Fig. 2. Transverse trajectories $x(t)$ (a) and $y(t)$ (b) for electrons channeled along the ⟨1 0 0⟩ axis of a Ge single crystal. (c) Parametric plot of the electron trajectory through a 1 μm thick Ge crystal for the point of incidence with coordinates x_0 = 0.14145 Å and y_0 = 0.053043 Å.

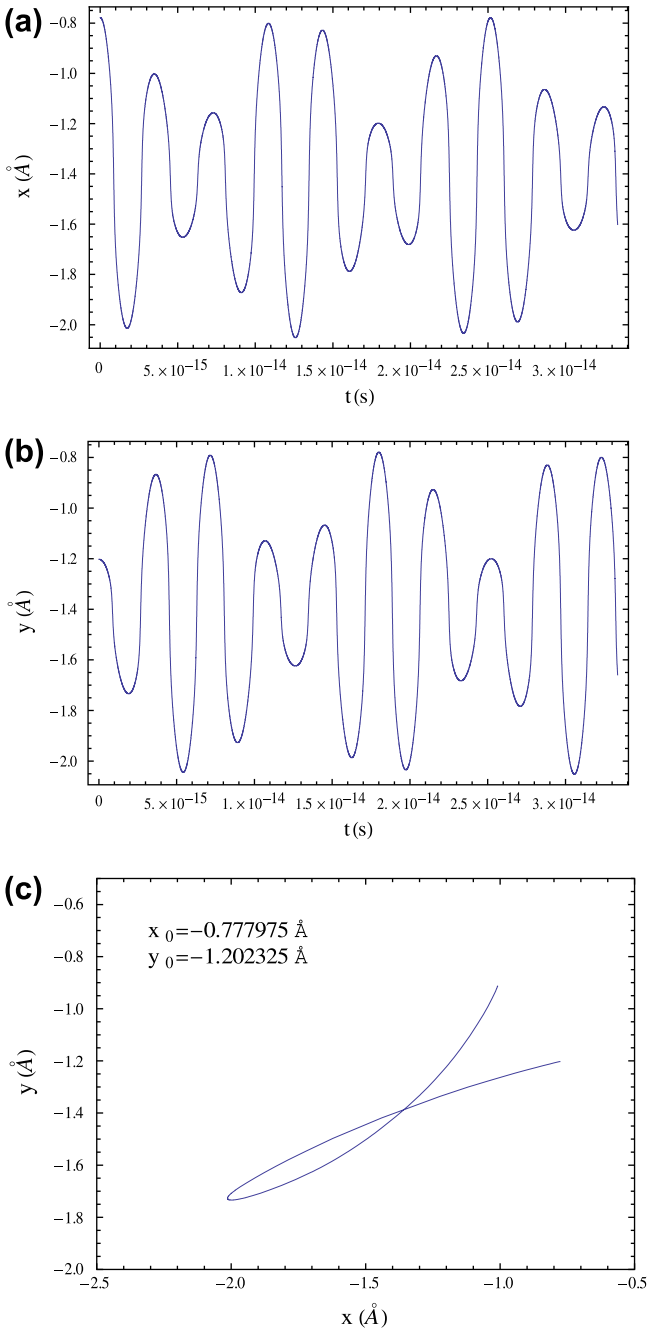

Fig. 3. Transverse trajectories $x(t)$ (a) and $y(t)$ (b) for electrons channeled along the ⟨1 0 0⟩ axis of a Ge single crystal. (c) Parametric plot of the electron trajectory through a 1 μm thick Ge crystal for the point of incidence with coordinates x_0 = −0.7779 Å and y_0 = −1.2023 Å.

where ρ and φ denote polar coordinates with respect to the z-axis chosen in direction of the crystallographic axis considered, m is the relativistic mass, $E_\perp$ is the transverse energy, L_z is the angular momentum of the particle, and $w(\rho)$ means the effective potential given by

$$w(\rho) = u(\rho) + \frac{L_Z^2}{2m\rho^2}. \tag{2}$$

With reference to [7], the transverse continuous potential of an atomic row at distance ρ may be written

$$u(\rho) = \frac{1}{d}\int_{-d/2}^{d/2} V(\sqrt{\rho^2 + z^2})dz, \tag{3}$$