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Deflection of positively charged heavy particles by the crystal miscut surface

A. Babaev [a,b,*], G. Cavoto [c], S.B. Dabagov [a,d,e]

[a] INFN Laboratori Nazionali di Frascati, Via E. Fermi 40, 00044 Frascati, Italy
[b] Institute of Physics and Technology, Tomsk Polytechnic University, Lenin Ave 30, Tomsk 634050, Russia
[c] INFN Sezione di Roma, Piazzale Aldo Moro 2, Rome 00185, Italy
[d] RAS P.N. Lebedev Institute, Moscow, Russia
[e] NRNU MEPhI, Kashirskoe highway 31, Moscow 115409, Russia

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ABSTRACT

The motion of relativistic nuclei which move near to a crystal surface was considered. The nuclei within a beam penetrate the crystal field at the small angle to the crystallographic planes, so the average field approximation and channeling phenomenology are valid. The crystal surface has a specific terrace-like form. It was shown the significant beam fraction could be deflected outwards from the surface due to quasichanneling.

1. Introduction

At present possible applications of crystals in accelerator physics are considered mostly for purposes of beam deflection and collimation. The usefulness of crystals is based on the channeling effect [1–4]. When charged particles enter a crystal at the small angle to crystallographic planes they move through the crystal along the channel formed by neighboring planes. This feature enables the motion direction of the channeled beam to be changed.

It is convenient to average the field of separate atoms placed on the crystallographic plane to describe the interaction of particles with the crystal field. For positively charged particles considered here, the averaged potential of a single plane has a maximum at the plane position. It decreases rapidly with increasing distance away from it and the electric field becomes negligible at the inter-planar distance. In the crystal field formed by these parallel potential barriers a channeled particle moves along the neighboring planes and simultaneously oscillates between them. Channeling is impossible if the incident angle θ_0 to the crystallographic planes exceeds the critical Lindhard angle $\theta_L = (2U_{ch,0}/E)^{1/2}$ (the expression is given for the ultrarelativistic case considered below), where $U_{ch,0}$ is the depth of the potential well between planes, E is the particle's full energy. Nevertheless, even if the particle's motion is not bound within a single channel, i.e. when the particle can cross planar potential borders, its motion can be still considered as the motion governed by the averaged potential. This kind of motion is known as quasichanneling. In the general case, in the situation of quasichanneling θ_0 slightly exceeds the critical angle θ_L.

In particular, channeling in a bent crystal ([5–7] and references therein), channeling in ultra-thin crystals [8], and channeling in a series of thin crystals [9] could be used in accelerator applications. In this work, a possible beam deflection by the lateral crystal surface when the beam propagates along this surface is considered. This situation could be realized when the crystal is mounted on the beam periphery similar to the scheme of beam collimation by a bent crystal [5,10].

The lateral crystal surface is usually characterized by a miscut angle θ_m, i.e. the angle between the crystal surface and crystallographic planes providing the channeling effect (Fig. 1a) [11,12]. The ordered crystal structure remains at the crystal surface layer [13,14]. Surface channeling, when the particle penetrates into the crystal through the lateral surface at the small glancing angle and successively is trapped into the channeling state, is also well-known phenomena [15]. It was shown the averaged planar potential approximation is applicable when the particle hits the lateral crystal surface at a small glancing angle to the crystallographic planes [16]. Hence, the surface with the miscut angle (miscut surface) could be considered as a terrace-like structure formed

* Corresponding author at: INFN Laboratori Nazionali di Frascati, Via E. Fermi 40, 00044 Frascati, Italy. Tel.: +39 3319825998; fax: +39 0694032427.
E-mail address: krass58ad@mail.ru (A. Babaev).

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by shortened channels and stair-step planes (Fig. 1b). The terrace length is Δz and the distance between them is the inter-planar distance a. The electric field of this structure is the deflecting field where one terrace stands out under another or is the channel field. Particle motion in the field of terrace-like structure was considered in [17] for protons and in [18] for positrons. In this work the simulations results for ultrarelativistic Pb nuclei are presented.

2. Theoretical considerations

It was shown in [17] that three kinds of motion are possible when the beam penetrates into the miscut layer along crystallographic planes: 1 – a particle can be deflected outward by a single terrace field from the surface before it enters a channel, 2 – a particle can enter a channel and can be successively trapped into a channeling motion regime, 3 – a particle can enter a channel but afterwards it will become quasichanneled (see in Fig. 1b). Quasichanneling provides multiple terrace deflection because the projectile can cross potential barriers between terraces. Multiple terrace deflection gives a maximum deflection angle exceeding that from a single crystal plane.

Let consider an ideal miscut surface where terraces have the same length $\Delta z = a/\tan\theta_m$ as shown in Fig. 1. When a particle penetrates the crystal field it initially moves in the deflecting terrace field (A in Fig. 1b). When it enters the channel it moves outward from the crystal and it has a deflection angle θ. If the deflection is enough the particle is quasichanneled. In this case it can cross the channel border at the initial Δz section of the channel, which is formed by the next upper terrace of the miscut layer. After that the particle moves in the deflecting terrace field, acquiring an additional deflection angle $\delta\theta$. It enters next channel having a larger deflection angle $\theta + \delta\theta > \theta$, so it can cross the channel border and so on. Hence, the particle suffers multiple terrace deflection being quasichanneled and is finally deflected at a noticeable angle.

In this work we consider Pb nuclei beam of an energy of 270 GeV per unit charge. This energy is one of possible CERN energies used for crystal collimation experiments [10]. The beam hits the miscut surface of a (1 1 0) oriented Si crystal which is the typical object of a crystal collimator. For these conditions the critical Lindhard angle is θ_L = 12.7 µrad. The critical angle for the penetration through the planar potential barrier is $\theta_{\rm pl} = (2U_{0,\rm pl}/E)^{1/2} = 15.3$ µrad. If a particle moves from the vacuum to the lateral surface at a glancing angle $\theta_0 < \theta_{\rm pl}$ it cannot overcome the surface planar potential barrier $U_{\rm pl,0}$ (see in Fig. 1c) and it will be reflected from the surface. If $\theta_0 > \theta_{\rm pl}$, then the particle can penetrate into the crystal bulk [15].

The theory developed in [17] predicts that when a non-divergent beam hits an ideal miscut surface along crystallographic planes (shown in Fig. 1) there are two critical miscut angles defining the dominating kind of motion. The first critical miscut angle is $\theta_{m1} = 2\theta_{\rm pl}/\pi = 9.7$ µrad, the second one is $\theta_{m2} = \arctan(\theta_{\rm pl}/\alpha)$ where α is defined from the equation:

$$\frac{\cos\alpha}{\cos^2\alpha + \frac{\theta_{\rm pl}^2}{4\theta_L^2}\sin^2\alpha} = 1.$$

For the beam energy considered here θ_{m2} = 15.7 µrad. At miscut angles $\theta_m < \theta_{m1}$ the single terrace deflection is the main motion regime. The maximal deflection angle at single terrace deflection is $\theta_{\rm pl}$. At $\theta_{m1} < \theta_m < \theta_{m2}$ particles can be either channeled or quasichanneled. In this miscut angles range one should expect the multiple terrace deflection over angles $\theta > \theta_{\rm pl}$. At $\theta_m > \theta_{m2}$ only channeling motion exists.

3. Simulations

Simulations of the motion of 270 GeV per unit charge Pb nuclei in the (1 1 0) Si miscut surface layer were carried out following the algorithm, in general, described in [17,19]. Namely, to evaluate the particle trajectory the equation for transverse motion:

$$\gamma m \frac{d^2x}{dt^2} = -\frac{dU_{\rm cr}}{dx},$$

was solved numerically, where $U_{\rm cr}(x)$ is the crystal potential shown in Fig. 1c. The longitudinal motion (along the Z axis in Fig. 1) is free. Also, the Coulomb multiple scattering of nuclei was taken into account by the way described in [19,20]. The crystal of thickness l (the length of the longest, lowest plane in Fig. 1b) consists of 1 0 1 planes. It was shown in [17] this number of planes is enough to find features related to the multiple terrace deflection.

First of all we consider the three ranges of miscut angles pointed out in previous section. A non-divergent beam of Pb nuclei penetrates the miscut surface layer of the crystal along the crystallographic planes. The typical angular distributions of nuclei scattered by an ideal miscut surface at these conditions are shown in Fig. 2. In Fig. 2a the miscut angle is $\theta_m < \theta_{m1}$. Hence, channeling is absent, particles form single peak with the maximal deflection angle about of $\theta_{\rm pl}$ due to single terrace deflection. In Fig. 2b the miscut angle corresponds to $\theta_{m1} < \theta_m < \theta_{m2}$. In this case one can see the scattered beam is split into two beams: a beam of channeled particles and a beam of particles deflected from the surface by angles $\theta > \theta_{\rm pl}$. This shift of the peak in comparison with the case shown in Fig. 2a is due to multiple terrace deflection. In Fig. 2c, at a large miscut angle $\theta_m > \theta_{m2}$ the deflection outward from the surface disappears, only channeling exists.

It is convenient to characterize the effectiveness of multiple terrace deflection by the beam fraction deflected at $\theta > \theta_{\rm pl}$. This fraction is presented in Fig. 3 as a function of miscut angle θ_m. From this figure one can see multiple terrace deflection exists approximately for

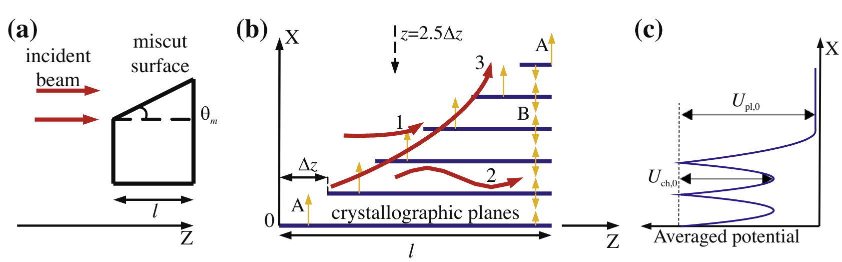

Fig. 1. Scheme of an ideal miscut surface and the averaged crystal field in the surface layer. (a) Ideal miscut surface – the top triangle part of the crystal. The incident beam propagates along crystallographic planes that constitute the miscut angle θ_m with the crystal surface. (b) Crystallographic planes of a miscut surface form a terrace-like structure. Thin arrows show the direction of the electric field in different regions: A – the deflecting terrace field where one terrace stands out under another, B – the channel field between planes. Numbers designate different possible kinds of motion: 1 – single plane deflection before particle enters the channel, 2 – channeling, 3 – multiple terrace deflection through quasichanneling. (c) Averaged potential as a function of transverse coordinate x at a distance $z = 2.5\Delta z$ from the frame origin (the position is shown in (b) by the dashed arrow). For the averaged (1 1 0) Si potential the depth of the channel well is $U_{\rm ch,0}$ = 21.9 eV, the height of the surface potential barrier is $U_{\rm pl,0}$ = 31.7 eV.