Passage of fast charged particles through bent crystals and nanotubes

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Abstract

The present work deals with the analysis of the different deflection mechanisms of high-energy charged particles by bent atomic strings. Conditions for realization of deflection and splitting effects for a high-energy charged particle beam in a bent crystal due to donut scattering mechanism are considered. It is shown the possibility of charged particle beam deflection by a bent nanotube due to axial channeling mechanism. Conditions for realization of this effect are discussed. The influence of the particle charge sign, its magnitude and of the incoherent process by thermal oscillations of the strings atoms and by electrons of the target on the beam deflection efficiency are considered. Computer simulation results for relativistic charged particle beam passage through straight and bent crystals and bent nanotubes are presented.

Keywords: High-energy particle; Beam deflection; Bent crystal; Nanotube; Channeling; Simulation; Splitting of the beam; Charged particles

1. Introduction

In [1,2], the possibility of deflection of high-energy charged particle beams by multiple scattering by atomic strings of a bent crystal was noted. The effect takes place both for positively and negatively charged particles not bound to atomic strings. This beam deflection mechanism differs from the beam deflection mechanism proposed by Tsyganov [3], which is connected with the phenomenon of planar channeling of particles in bent crystal planes.

In [4] it was made an analysis of the different deflection mechanisms of high-energy charged particles in a beam incident upon a bent crystal along a crystalline axis. For conditions of beam-crystal interaction considered in [4], the deflection mechanism dealt with multiple scattering by atomic strings and the deflection mechanism dealt with axial channeling are realized simultaneously. This obstructs the analysis of conditions for these mechanisms. In the present paper, beam interaction with bent target is considered for conditions when the deflection mechanisms dealt with multiple scattering by strings and with axial channeling are realized separately. This makes it possible to

provide an analysis of conditions for realization of these beam deflection mechanisms. Effect of beam splitting into several separate fractions is considered. The influence of the particle charge, both in magnitude and sign, and of incoherent scattering processes by thermal oscillations of crystal's atoms and by the electrons on the beam deflection efficiency is shown. Computer simulations of the passage of high-energy charged particle beams through straight and bent crystals and through bent nanotubes are represented.

2. Beam deflection and splitting due to donut scattering in a bent crystal

The motion of a fast charged particle near a crystallographic axis (z-axis) is determined mainly by the continuous string potential, which is the crystal potential averaged along the z-axis [5,6]. In such potential, particles may perform finite (channeling) as well as infinite (over-barrier) motion in plane orthogonal to the z-axis. Possibility for hyperchanneling of positively charged particles is sufficiently different for motion near different crystallographic directions. For motion near $\langle 1\,1\,0\rangle$ axis of Si crystal (case of [4]), the potential barrier of proton hyperchanneling is 6 eV and hyperchanneling region is about 42% of the whole plane orthogonal to $\langle 1\,1\,0\rangle$ axis; in the case of proton motion near $\langle 1\,1\,1\rangle$ axis of Si crystal the hyperchanneling region is less than 18%, and the potential barrier of hyperchanneling is only 0.8 eV (see for instance Figs. 3 and 4 of [7]). In this case, practically all particles of a beam perform over-barrier motion in the field of atomic strings, and thus exist only one beam deflection mechanism in this case – the mechanism based on multiple scattering of particles on crystal atomic strings. In the present section we will consider relativistic beam interaction with crystal just for incidence on Si crystal along the $\langle 1\,1\,1\rangle$ axis. Fig. 1 presents computer simulation results for charged particle angular distributions resulting from multiple scattering of particles on atomic strings in a straight crystal. The simulation was performed with account of real geometry of atomic strings and with account of incoherent scattering processes by thermal oscillations of crystal atoms and by target electrons. Simulation results show that particle scattering on atomic strings occurs mainly along azimuthal angle φ in plane orthogonal to z-axis. This effect is named donut scattering effect (see for instance [1]). Donut scattering is shown on Fig. 1 in progress with growth of crystal length for two different values of initial angle ψ (ψ is angle between particle velocity and crystal axis direction). From Fig. 1 it may be seen the dependence of the multiple scattering features with angle ψ and with particle charge magnitude and sign. It will be shown below that such dependences sufficiently influence the charged particle beam passage through a bent crystal.

Beam deflection as whole is possible in a bent crystal due to donut scattering mechanism. The condition for this is [8]

$$\alpha = \frac{l_\perp}{R\psi_c}\frac{L}{R\psi_c} < 1, \tag{1}$$

where L is the crystal thickness, R is the curvature radius of the bent crystal, $l_\perp$ is the characteristic length of transverse momentum equalization over azimuthal angle due to multiple scattering by the atomic strings, and ψ_c is the critical angle of axial channeling. For $\psi \leqslant \psi_c$, according to [5], $l_\perp \approx (\psi_c n\,\mathrm{d} a_{TF})^{-1}$, where n is the atomic density and a_{TF} is the screening radius of the atomic potential.

Together with the effect of beam deflection, for particle motion near the crystal axis a beam splitting effect is possible [1,9]. In [4] it was shown, that splitting effect is a result of donut scattering too and the necessary conditions for this effect are

$$\alpha' = \left(\frac{l_\perp}{R\psi_c}\right)^2 \ll 1, \tag{2.1}$$

$$\alpha = \frac{l_\perp}{R\psi_c}\frac{L}{R\psi_c} \gg 1. \tag{2.2}$$

Fig. 2 presents computer simulation results for π^-, p^+, U^{+92} beams with energy of 450 GeV passing along the $\langle 1\,1\,1\rangle$ axis of a bent silicon crystal for different values of the parameter α. These simulation results make possible to see in detail beam deflection and splitting dynamics, and to verify

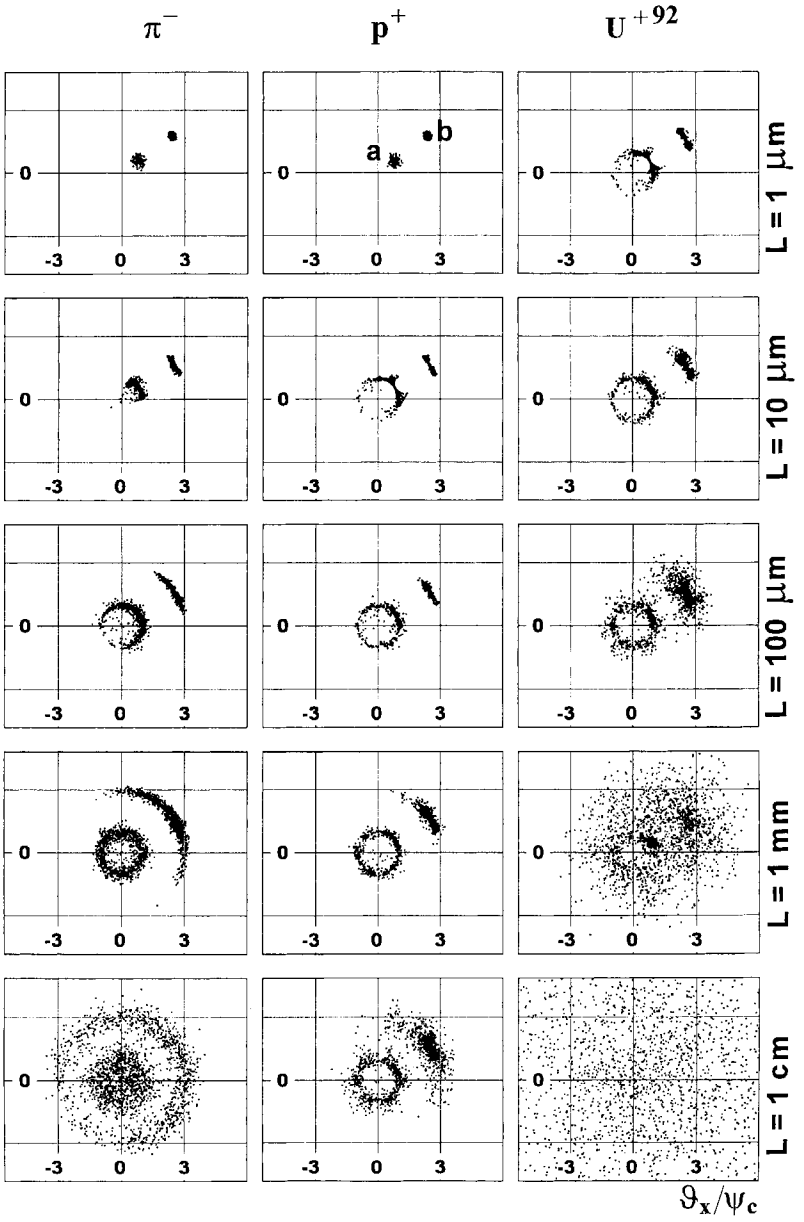

Fig. 1. The angular distributions of π^- – pions, protons and uranium ions (+92) with energy 450 GeV for beam scattering by straight silicon crystals of different thicknesses. Beam incidence angles with respect to $\langle 111 \rangle$ axis are $\psi = \psi_c(\psi_x = 0.8\psi_c, \psi_y = 0.6\psi_c)$ for spot marked by **a** and $\psi = 3\psi_c(\psi_x = 2.4\psi_c, \psi_y = 1.8\psi_c)$ for spot marked by **b**. Values on coordinate axes are in units of ψ_c. ϑ_X, ϑ_Y are angles of particle scattering in the plane orthogonal to crystal axis direction. Simulation statistics is 2×1000 particles.

conditions (1), (2.1) and (2.2). The simulation was performed with account of real geometry of atomic strings and with account of incoherent scattering processes by thermal oscillations of crystal atoms and by target electrons. For the construction of Fig. 2, beam spot (beam diameter divided by measurement base length) was assumed to be 1/20 of crystal bend angle.

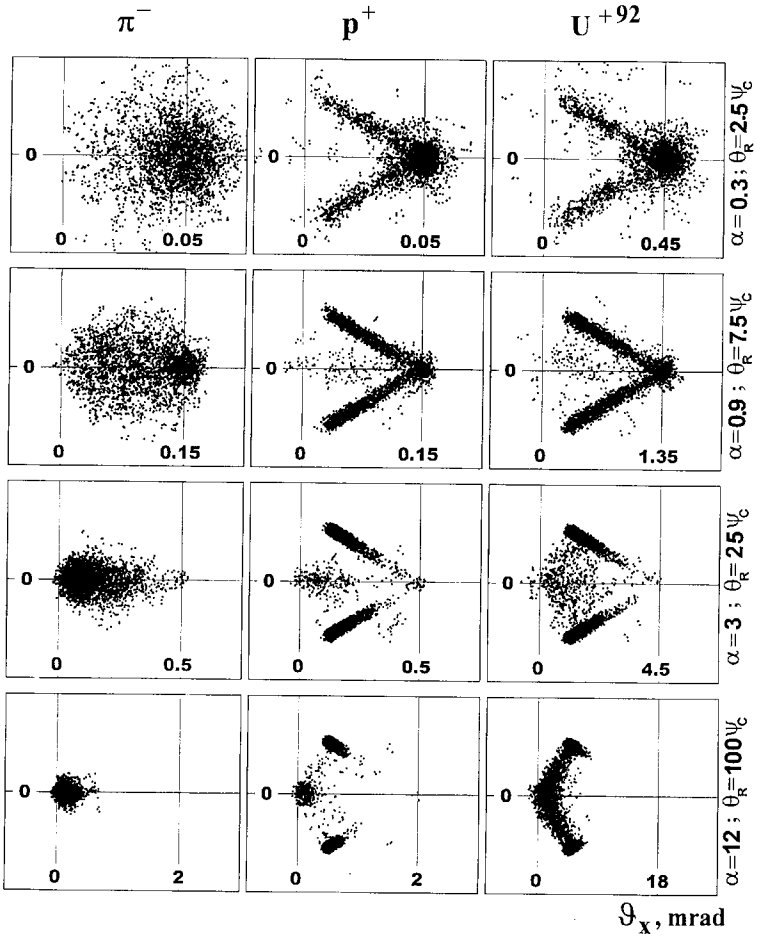

Fig. 2. The angular distributions of π^- – pions, protons and uranium ions (+92) with energy 450 GeV for beam passage through bent silicon crystal near $\langle 1\,1\,1\rangle$ axis. Crystal curvature radius is $R = 50$ m for π^-, p^+ and $R = 50$ cm for U^{+92}; crystal lengths are $L = 2.5$ mm ($\alpha = 0.3$), 7.5 mm ($\alpha = 0.9$), 2.5 cm ($\alpha = 3$), 10 cm ($\alpha = 12$) for π^-, p^+ and $L = 0.225$ mm ($\alpha = 0.3$), 0.675 mm ($\alpha = 0.9$), 2.25 mm ($\alpha = 3$), 9 mm ($\alpha = 12$) for U^{+92}. The coordinates of the initial beam center are $(\vartheta_X, \vartheta_Y) = (0, 0)$; the initial beam divergence is $0.1\psi_c$; initial beam spot is $(1/20)\theta_R$ ($\theta_R = L/R$). Values on coordinate axes are in mrad. ϑ_X, ϑ_Y are angles of particle scattering in the plane orthogonal to initial crystal axis direction. The simulation statistics corresponds to 1000 particles.

Let us now discuss the simulation results. In the case of $\alpha = 0.3$, the beam as whole follows the crystal axis bend, for all particle types (π^-, p^+, U^{+92}). Differences in the angular distributions of negatively and positively charged particles are seen. These differences are due to charge sign dependence in donut scattering of particles in region of small angles ψ ($\psi \geqslant \psi_c$). As one can see from Fig. 1, azimuthal distributions of negatively charged particles are smooth, when distributions of positively charged particles have spots. These spots dealt with planes which branch from crystal axis. In bent crystal such spots lead to formation of "branches" in the beam angular distribution. These branches are formed in half-plane co-directed with centrifugal force, which influences particles in a bent crystal [10].

For $\alpha = 0.9$, beam continues to follow crystal axis bend. But a part of particles begins to lose axis bend. From Fig. 1 one can see that with ψ growth, characteristic length $l_\perp$ growth sharply. In a bent crystal, for particles with $\psi > \psi_c$ the process of

transverse momentum equalization over azimuthal angle becomes impossible [7]. Such particles move away of axis and form tail in beam angular distribution along bending direction.

For $\alpha = 3$, beam deflection as a whole along crystal axis is stopped. Only isolated particles continue to follow crystal bend. For positively charged particles stopping of beam axial deflection means stopping of particles inflow to plane channels. The already formed branches of positively charged particle beams begin to move away one from another under bend action. Condition (2.2) of beam splitting begins to be fulfilled. Difference in the angular distributions of protons and uranium ions become to be seen. This difference is due to stronger incoherent scattering of uranium ions because of their higher charge. It leads to quicker dechanneling of ions from bent plane channels and to formation of alternative branches in their angular distributions.

Finally, in case $\alpha = 12$, the necessary condition (2.1) and (2.2) of beam splitting by bent crystal is fulfilled. In the angular distribution of the proton beam one can clearly see three localized fractions. Thus the splitting of the beam takes place in this case. At the same time, angular distributions of negatively charged pion and uranium ion beams do not demonstrate beam splitting. So, condition (2.1) and (2.2) is not a sufficient condition for beam splitting. Strong incoherent scattering of uranium ions results in strong plane dechanneling, which results in binding of ion beam fractions analogous to proton beam fractions. Absence of negatively charged particles capture by plane channels for small ψ angle region ($\psi \sim \psi_c$) results in the absence of beam fractions in their angular distribution analogous to proton beam fractions. Location, number and value of splitted proton beam fractions are determined by direction, number and force of plane channels, which branch from crystallographic axis (compare Fig. 2 of this paper and Fig. 3 of [4]).

Thus, the results of computer simulation confirm the possibility of charge particle beam deflection and splitting for beam passage near a crystal axis of a bent crystal. Analysis of simulation results confirm reliability of condition (1) for beam deflection and of necessary condition (2.1)

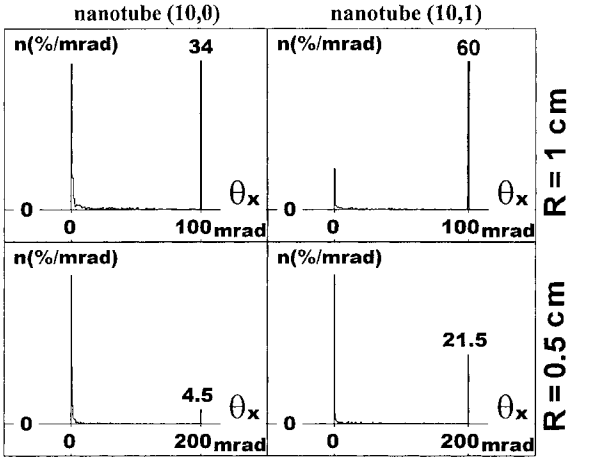

Fig. 3. The horizontal profile of a proton beam with energy 1 GeV after passage through bent nanotubes (10,0) and (10,1) with thickness 1 mm and curvature radii $R = 1$ and 0.5 cm. Numbers above right peaks correspond to fraction of particles, which were deflected to whole angle of nanotube bend (in % of beam particles, which were initially captured by nanotube channel). The simulation statistics is 1000 particles.

and (2.2) for beam splitting by bent crystal. This verifies the existence of beam deflection and splitting mechanism based on particle donut scattering in a bent crystal. In [4,9] it was shown that based on such mechanism theoretical estimations and results of computer simulations are in agreement with experiment data [1,11].

3. Beam deflection due to axial channeling in bent nanotube

Those particles, which are in conditions of axial channeling, will follow axial channel bend in the same manner as in the case of planar beam deflection by a bent crystal. Axial channel is not destroyed by crystal bend in case (same as for bent planar channel case [3,10])

$$R > \frac{\varepsilon}{U_H} \frac{a}{2}. \tag{3}$$

Here ε is the particle energy, a is a typical width of the potential well and U_H is its depth. For particle motion near crystal axis U_H is of the order of several eV, which limits the possibilities of such deflection mechanism.

In the early 90s, new structures were predicted and discovered – carbon nanotubes [12]. Nanotubes can be represented (see for instance [13]) as an aggregate of carbon atom strings, which form a cylindrical surface with about 1 nm diameter. Thus, the problem of particle motion in nanotube field near it axis is similar to the problem of particle motion in field of crystal atomic strings. So, it is possible to use for description of particle interaction with nanotube the methods, which are used in the theory of fast charged particle passage through crystal near crystallographic axis. Atomic strings of nanotube form deep two-dimensional potential hole with minimum in centre of nanotube. The value of the potential barrier for protons is about 100 eV in this case (see Figs. 1 and 2 of [13]). Thus, channelling phenomenon is possible for the particle motion along nanotube axis. So, for bent nanotube the beam deflection is possible. According to (3), critical radius of nanotube bending for proton beam with 1 GeV energy is about $R = 5$ mm (such bending is not a problem for nanotubes). So, it is possible to realise beam deflection by bent nanotubes for angles, which sufficiently exceed deflection angles accessible due to bent crystals. Surface potential of nanotube is sufficiently depends of nanotube geometry (compare Figs. 1 and 2 of [13]). This results in differences in beam deflections for different nanotubes. Fig. 3 presents results of computer simulations for axial channeling of a proton beam with energy 1 GeV in a bent nanotubes (10,0) and (10,1) (definition of nanotube indexes see for instance in [14]). Simulation results confirm the possibility of large deflections angles of relativistic proton beams for small lengths of nanotubes. One can see also a practical absence of incoherent scattering influence on proton beam channeling in nanotube, which results in the absence of particle dechanneling during deflection process.

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