Mechanisms of high energy charged particles beams deflection by a bent crystal

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Annotation. From the single point of view we have considered various mechanisms of high energy charged particles beams bending by a bent crystal. These mechanisms are based on multiple scattering of fast particles on bent atomic strings (stochastic mechanism), planar channelling and reflection of particles from crystal atomic planes (the effect of volume reflection). The results of computer simulation which allow to make a comparison between these beams bending mechanisms are presented. The consideration is performed for both positively and negatively charged particles. It is shown that stochastic mechanism is the most effective for negatively charged particles beam bending. The results of simulation under conditions that have been used in last CERN experiments on observation of stochastic mechanism of positively and negatively charged particles beams bending are presented.

1. Introduction
When fast charged particles are moving in a crystal under a small angle to one of its axes or planes correlations between consecutive collisions of particles with lattice atoms appear. As a result of these correlations the particle motion in a crystal is basically defined by continuous potential of atomic strings or atomic crystal planes near to which particle is moving [1-3]. Strong intracrystalline fields allow to make on small distances an essential impact on beam particles characteristics, leading to considerable effects in scattering and radiation. Special interest represents high energy particles passage through the bent crystal because in this case an effective beam bending by a small sized crystal is possible. There are several mechanisms of high energy charged particles bending by a bent crystal, connected with finite motion (channeling) and infinite (above barrier) motion in relation to the bent atomic strings or crystal atomic planes [4-6]. Method of computer simulation of particles motion in bent crystal plays an important role at the research of these beams bending mechanisms (see for example [7-10] and references therein).

In the present work the method allowing to consider various mechanisms of high energy charged particles beams bending by a bent crystal from a single point of view is suggested. This method is based on the development of the simulation method of particles motion in the field of the bent crystal atomic strings offered in [10,11]. We have employed this developed method to a case of particles motion near crystal atomic planes. Thus crystal atomic planes are considered as the planes formed by crystal atomic strings, located periodically in a plane. On the basis of this method it is possible to consider from one point of view not only mechanisms of beams bending by a bent crystal, connected
with particles plane channeling, volume reflection and their multiple scattering on crystal atomic strings, but also to investigate intermediate cases.

2. The motion of high energy charged particles in bent crystal

Fast charged particle motion in a crystal near one of crystal axes is basically defined by continuous potential of crystal atomic string located parallel to this axis. In such field the particle can commit both finite (channeling), and infinite (above barrier motion in a perpendicular plane) in relation to atomic strings. Character of particle motion in a periodic field of atomic strings is rather complicated and it essentially depends on conditions of particle entrance into a crystal. Thus depending on entry conditions the particle can execute both regular (plane channeling in a periodic field of atomic strings) and chaotic (the phenomenon of dynamic chaos [12]) motion relatively to the atomic strings. Due to incoherent effects in scattering on thermal fluctuations of lattice atoms and on crystal electronic subsystem mutual transitions between various regimes of movement are possible. Such transitions are possible also due to curvature of crystal atomic strings. Therefore the important role at the research of fast particles motion in a bent crystal plays a method of numerical simulation.

The simulation in this article was carried out on the base of classical physics because the inequality \( N_e Z e^2 / \hbar c >> 1 \) in considerable case is fulfilled [3]. Here \( N_e \propto R / \psi a \) is a number of string atoms, with which particle effectively interacts passing the string, \( Z \) is the atomic nucleus charge, \( a \) is the lattice constant, \( R \) is the atomic potential screening radius and \( \psi \) is an angle between particle momentum and atomic string axes. The simulation consisted in numerical solving of two-dimensional motion equation

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\dot{v}_\perp(t) = -\frac{e^2}{\varepsilon} \frac{\partial}{\partial \rho} U(\rho),
\]

which describes particle motion in periodic crystal atomic strings potential energy in orthogonal to the strings axis plane. In equation (1) \( m \) is a particle mass, \( v_\perp(t) \) is its orthogonal velocity as a function of time, \( U(\rho) \) is continuous potential energy of atomic strings [1]. At equation (1) numerical solution the particle trajectory within elementary cell was partitioned in many path sections and in each of them the crystal was considered as straight. In the end of each path section the change in particle velocity generated by crystal bending and incoherent scattering on thermal fluctuations of lattice atoms and crystal electronic subsystem was taken into account.

3. Simulation of fast charged particles beams passage through a bent crystals at various entry conditions

The character of fast charged particles motion in a crystal essentially depends on conditions of particle entrance in a crystal. Thus depending on an incident beam orientation with respect to the crystal axes and planes various mechanisms of the charged particles beams bending by a bent crystal can be realized.

To show this we will present results of simulation (see figures 1-3) of passages of positively (b) and negative (c) charged particles with 400 GeV energy through the bent silicon crystal with thickness of 1 cm at various entry conditions of an input of particles in a crystal with respect to the \(<11\bar{1}>\) axis. Simulation was performed for a 1000 particles beam which divergence was \( \psi_c / 2 \). The crystal bend was performed by z axis (which is parallel to the \(<11\bar{1}>\) axis) bending in the direction of the x axis (which is orthogonal to the (110) planes). The bend radius was 40 m. Broad spots in figures 1a, 2a, and 3a correspond to various entry conditions of the beam input in the crystal. The size of these spots corresponds to divergence of incident beam particles. The centers of these spots correspond to incidence of the beam along the \(<11\bar{1}>\) axis (figure 1a), crystal disorientation on angles
$\theta_x = 0, \theta_y = 10\psi_c$ (figure 2a) and disorientation on $\theta_x = 4\psi_c, \theta_y = 10\psi_c$ (figure 3a). The point on crossing of lines in the right part of the mentioned figures corresponds to the final direction of the $<111>$ crystal axis. Points are the results of simulation.

**Figure 1.** Angular distribution of 400 GeV charged particles before (a) and after (b, c) passing 1 cm Si bent crystal for the case of stochastic mechanism of beam deflection by a bent crystal.

The results of simulation that are presented in figure 1 illustrate the stochastic mechanism of the beam deflection by a bent crystal, connected with multiple scattering of particles on the bent atomic strings. Due to this mechanism practically all beam particles deflect towards the bend of the crystal axis on the angles considerably exceeding the critical axial channeling angle. Thus for positively charged particles the considerable part of beam particles due to multiple scattering on the bent atomic strings is captured in plane channels and then follows the bend of these planes. For negatively charged particles such mechanism of particle capture in plane channels in the considered case is not realized. At the same time, as figure 1c shows, the multiple scattering on the bent atomic strings leads to considerable beam deflection comparing to its initial position.

**Figure 2.** Angular distribution of 400 GeV charged particles before (a) and after (b, c) passing 1 cm Si bent crystal in planar channeling conditions.

The results of simulation with initial conditions that correspond to possibility of particles capture in plane channels at the beam input in the crystal are presented in figure 2. Thus the considerable part of positively charged particles captured in the channel follows the bend of crystal planes and bends on the crystal bend angle. The small exit of such particles from the bent plane channel is caused by
incoherent scattering on an electronic subsystem of a crystal and on atomic strings, forming crystal planes. For negatively charged particles there is no beam deflection in the considered case. Primarily it is connected with intensive multiple scattering of such particles on thermal fluctuations of lattice atoms that leads to significant instabilities in particles motion in plane channels.

Figure 3. Angular distribution of 400 GeV charged particles before (a) and after (b, c) passing 1 cm Si bent crystal for the case of volume reflection mechanism of beam deflection by the bent crystal.

The results of simulation presented in figure 3 correspond to above barrier particles motion at the beam input in the crystal concerning (110) planes under the angle exceeding the critical angle of plane channeling \( \theta_c \) (\( \theta_x \approx 8\theta_c \)). For positively charged particles the effect of their reflection from the bent crystal planes (see figure 3b) in this case takes place. Thus deflection of the major part of beam particles occurs on angles on the order of \( \theta_c \) in the direction opposite to the crystal planes bent direction. The similar effect takes place and for negatively charged particles. However, it is expressed much more weakly (see figure 3c), than for positively charged particles.

The possibility of stochastic mechanism of high energy positively and negatively charged particles beam deflection by a bent crystal was recently confirmed experimentally at CERN accelerator [13,14]. The results of computer simulation under these experimental conditions are represented in figure 4. These results of computer simulation are in good agreement with experimental data.

Figure 4. Angular distribution of 400 GeV protons after passing 2 mm Si bent crystal with 40 m curvature radius (a) and 150 GeV \( \pi^- \)-mesons after passing 1.172 mm Si bent crystal with 40 m curvature radius (b).
The results of simulation presented above and the results of simulation carried out at other conditions (different length of crystals, different crystal axes and planes orientations concerning to the incident beam etc.) show that for positively charged particles mechanism of planar channeling is the most effective for beam deflection in a bent crystal. Due to this mechanism deflection on angles much greater than $\theta_\psi$ are possible. Due to multiple scattering by bent atomic strings splitting of positively charged particles beams is possible (see figure 1b). After all, when positively charged particles beam reflection on bent atomic planes conditions are fulfilled the deflection is possible only on angles on the order of $\theta_\psi$.

For negatively charged particles the most effective mechanism of beam deflection is stochastic mechanism (see figure 1c). Due to this mechanism almost all beam particles are deflected on angles on the order of several critical angles of axial channeling $\psi_c$. Mechanisms of planar channeling and reflection on bent atomic planes leads to a weak beam deflection.

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