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High-efficiency deflection of high energy protons due to channeling along the ⟨110⟩ axis of a bent silicon crystal

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ABSTRACT

A deflection efficiency of about 61% was observed for 400 GeV/c protons due to channeling, most strongly along the ⟨110⟩ axis of a bent silicon crystal. It is comparable with the deflection efficiency in planar channeling and considerably larger than in the case of the ⟨111⟩ axis. The measured probability of inelastic nuclear interactions of protons in channeling along the ⟨110⟩ axis is only about 10% of its amorphous level whereas in channeling along the (110) planes it is about 25%. High efficiency deflection and small beam losses make this axial orientation of a silicon crystal a useful tool for the beam steering of high energy charged particles.

1. Introduction

In the last twenty years, channeling has been exploited for steering [1], collimation [2–4] and extraction [2,5–7] of relativistic beams in circular accelerators, as well as splitting and focusing of extracted beams [8]. In the last decade, a significant boost to the research on particle-crystal interactions was provided by the fabrication of uniformly bent crystals with thickness along the beam direction suitable for experiments at high-energy. The novel generation of crystals has demonstrated the capability of efficiently steering positively charged [9,10] particle beams and to observe the deflection of negatively charged particle beams [11,12]. As well as efficient deflection, channeling has been shown to modify the probability of incoherent interactions with atomic nuclei with respect to an amorphous material of the same length [13]. In particular, the use of bent crystals as a primary collimator has been demonstrated to reduce the beam losses in the SPS proton synchrotron at CERN [14–16], leading to the installation of two bent crystals in the LHC collider [17]. The crystals installed in the LHC were successfully tested and shown to reduce the beam losses in the LHC ring with 6.5 TeV/c protons [18].

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As a charged particle traverses a crystal with a small angle with respect to one of the main crystallographic axes, the particle motion is governed by the potential of the atomic strings averaged along the axis [19], i.e. the particle is subject to axial channeling (AC). The maximum angle between the particle incident angle and the crystal axis, for which channeling occurs is called critical angle for channeling $\psi_{ac} = (4Ze^2/p\beta d)$ [19], where d is the distance between neighboring atoms in the atomic string, $p\beta$ the particle momentum-velocity, Z the atomic number of the crystal atoms and e the elementary charge. For a silicon crystal, ψ_{ac} is almost three times larger than the critical angle for channeling between atomic planes, i.e. planar channeling (PC) [20]. However, because the potential barrier separating the axial channels formed by neighboring atomic strings is rather low, the fraction of particles confined within a single axial channel is limited. As an example, for a silicon crystal, such a potential barrier is ∼ 6 eV for the $\langle 110\rangle$ direction and only 1 eV for the $\langle 111\rangle$. If a particle under AC has a transverse energy slightly higher than the potential well barrier, particles interacting with a bent crystal may be deflected by the multiple scattering on the atomic strings toward the bending direction, increasing the efficiency of AC. Indeed, as soon as a particle penetrates the crystal, the position of scattering centers shifts, causing the subsequent random scattering with atomic strings to acquire a preferential direction. Such an effect was experimentally demonstrated for positively [10,21] and negatively [12] charged particles.

As predicted in [22] high deflection efficiency and small beam losses due to inelastic interactions may be achieved using the axial channeling, most strongly along the $\langle 110\rangle$ axis of a silicon crystal. Despite that fact, experimental measurements on AC are limited to studies of the deflection efficiency of 400 GeV/c protons interacting with a $\langle 111\rangle$ silicon crystal [10,12,21], and measurement of the inelastic nuclear interaction (INI) frequency under AC was observed only for 15 GeV/c pions interacting with germanium crystals [23,24].

In this paper, we experimentally investigate the deflection efficiency and the inelastic interaction frequency of 400 GeV/c protons interacting with $\langle 111\rangle$ and $\langle 110\rangle$ bent silicon crystals under axial channeling at the H8 external line of the SPS at CERN.

2. AC mechanism

Charged particles interacting with an aligned crystal under AC are mainly deflected by two phenomena, hyperchanneling [25] and the randomization of transverse momenta of the particles because of multiple scattering by atomic strings [26]. Hyperchanneling consists in the confinement of the particle trajectory between the potential well barriers separating neighboring atomic planes. Due to the low potential barrier, such a phenomenon is possible only for a few percent of the incident particles. On the contrary, when particles scatter on atomic strings, the deflection due to the randomization of transverse particle momentum affects all the particles not under hyperchanneling and is possible if the crystal bending angle (α) is lower than a characteristic value α_{ts} [27]

$$\alpha < \alpha_{ts} = \frac{2R\psi_{ac}^2}{l_0} \tag{1}$$

where R is crystal bending radius, $l_0 = 4/(\pi^2 n d R_a \psi_{ac})$ the minimum encounter length between the incident particle and a nucleus, n being the concentration of atoms in the crystal and R_a the atomic screening radius.

Although Eq. (1) proved to be a good condition for the observation of the particle deflection due to incoherent scattering [10,12,21], it does not furnish an estimate of the best crystal length at a fixed bending angle. A useful parameter introduced to account for the maximum crystal length for efficient particle steering at the full bending angle $\alpha = L/R$ is the relaxation length l_r [21], i.e. the length within which the fraction of particles in the AC regime are reduced to $1/e$ and escape from AC to skew planes. In order to efficiently deflect under AC a crystal has to fulfill the inequality [21]

$$L < l_r \tag{2}$$

Up to now, an analytic equation for the calculation of l_r does not exist. The dependence of the l_r on R was worked out only for a 400 GeV/c proton beam interacting with a $\langle 111\rangle$ Si crystal [21] and included the incoherent scattering on nuclei and electrons.

Table 1
Parameters of the $\langle 111\rangle$ and $\langle 110\rangle$ bent Si crystals, with R the crystal bending radius, L the crystal length along the beam direction, α_{pl} the channeling mean deflection angle.

	$\langle 111\rangle$	$\langle 110\rangle$
Plane	$(1\bar{1}0)$	$(1\bar{1}0)$
Axis	$\langle 111\rangle$	$\langle 110\rangle$
L (mm)	1.941 ± 0.002	1.881 ± 0.002
R (m)	32 ± 2	35 ± 2
α_{pl} (μrad)	63 ± 1	54 ± 1

3. Experimental measurements

The experimental setup was based on a particle telescope [28], consisting of ten planes of silicon microstrip sensors, arranged as five pairs, each measuring two orthogonal coordinates, with an active area of 3.8 × 3.8 cm^2. The telescope provided excellent angular and spatial resolution for measuring the trajectories of incident and outgoing particles. The apparatus had a long baseline, of approximately 10 m in each arm, and achieved an angular resolution in the incoming arm of 2.5 μrad and a total angular resolution on the difference of the two arms of 5.2 μrad, with performance limited by multiple scattering in the sensor layers. The crystal was mounted on a high-precision goniometer with an angular resolution of about 1 μrad. This instrument allowed three degrees of freedom, one linear and two rotational movements, to align the crystal along either the horizontal or vertical directions. Two pairs of scintillators were placed after the target outside the beampipe in order to measure the secondary particles produced by the nuclear interactions of protons with the silicon crystals. Prealignment of the samples was achieved by means of a laser system parallel to the beam direction.

The targets were two silicon crystals produced according to the method described in Refs. [29–31]. The crystals were mounted on mechanical holders that impart a controlled deformation to the primary and the anticlastic curvatures [5,32]. The crystal parameters are reported in Table 1. Both the crystals have a ∼ 2 mm length and the same bent $\langle 1\bar{1}0\rangle$ axis orthogonal to the beam direction. Therefore, both crystals make use of a $(1\bar{1}0)$ bent plane for PC. However, the bent axes parallel to the beam direction are different, being respectively $\langle 111\rangle$ and $\langle 110\rangle$. As a consequence the use of such crystals allows comparison of the AC features for two different crystal axes under the same experimental condition. The crystal torsion due to the mechanical holder was compensated in the data analysis for both the crystals [33].

The INI frequency for a particle interacting with a crystal under AC (n_{ac}) can be expressed in units of the INI frequency for a particle interacting with an amorphous material (n_{am}). In the experiment, we tagged as nuclear interacting particles (N_{ini}) the incoming particles that interact with the crystals and produced a signal in both the scintillators. Subtracting the background events that produce a coincidence in the scintillators ($N_{bg,ini}$) from the