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Mirroring of 400 GeV/c protons by an ultra-thin straight crystal

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ABSTRACT

Channeling is the confinement of the trajectory of a charged particle in a crystalline solid. Positively charged particles channeled between crystal planes oscillate with a certain *oscillation length*, which depends on particle energy. A crystal whose thickness is half the *oscillation length* for planar channeling may act as a mirror for charged particles. If the incident angle of the particle trajectory with the crystal plane is less than the critical angle for channeling, under-barrier particles undergo half an oscillation and exit the crystal with the reversal of their transverse momentum, i.e., the particles are "mirrored" by the crystal planes. Unlike the traditional scheme relying on millimeter-long curved crystals, particle mirroring enables beam steering in high-energy accelerators via interactions with micrometer-thin straight crystal. The main advantage of mirroring is the interaction with a minimal amount of material along the beam, thereby decreasing unwanted incoherent nuclear interactions. The effectiveness of the mirror effect for ultrarelativistic positive particles has been experimentally proven at external lines of CERN-SPS. The mirroring effect in a 26.5-μm-thick Si crystal has been studied in the experiment with a narrow beam of 400 GeV/c protons at the CERN-SPS. The reflection efficiency for a quasi-parallel beam is larger than 80%.

When a charged particle interacts with a crystal and its trajectory is inclined with respect to major atomic planes or strings by a small angle, a series of correlated collisions of the particles with atoms in the same plane (string) occurs and one can speak of *coherent interactions* of the particle with a crystal. In this case the Coulomb potentials of single atoms can be replaced by an average continuous potential of the plane (string) and the particle dynamics can be described by the interaction with the atomic plane (string) as a whole [1]. For an incident angle lower than the critical angle introduced by Lindhard, $\theta_c = \sqrt{2U_0/pv}$, a charged particle with momentum p and velocity v can be captured in the interplanar potential well with depth U_0, i.e., *channeling* of the particle takes place.

Coherent interactions are studied in straight crystals mainly with the purpose of high-intensity production of electromagnetic radiation such as *channeling radiation* [2] and *coherent bremsstrahlung* [3]. Coherent interactions result in more intense

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and, in some cases, more monochromatic radiation generation than would occur for the case of conventional bremsstrahlung in an amorphous material [4].

On the other hand, bent crystals can be exploited for particle beam steering because channeled particles, which are confined in the planar (axial) potential well, are adiabatically deflected through the whole curvature of the crystal [5]. This mechanism was demonstrated via either planar [6–8] or axial channeling [9]. The effect of volume reflection is another opportunity for particle steering [10]. A possible application of channeling in a bent crystal is halo-beam collimation of very high energy beams of modern hadron colliders [11,12]. The UA9 Collaboration demonstrated that crystal collimation is a viable way to reduce the beam losses in the SPS circular accelerator [12]. Two Si crystals should be installed soon in the LHC to test their use for the collider beam collimation.

Coherent interactions in straight and bent crystals were proven to work over a wide range of energies, from MeV [13] to TeV [14] for either negative [15,16] or positive particles [6,17], for heavy [17] and light [18–21] particles.

Tsyganov and Taratin suggested that not only a bent, but also a straight, crystal may serve for particle deflection, through the effect of particle "mirroring" [22], which occurs for positively charged particles because of a peculiarity of their dynamics. In fact, transverse motion of positively charged particles in the planar channeling regime is governed by a potential that can be described by the harmonic approximation ($\sim x^2$, where x is the distance from the potential minimum) [17]. For this reason, channeled particles oscillate during their motion with a characteristic *oscillation length*, $\lambda = \pi d_p/\theta_c$, d_p being the interplanar distance. In [22], it was shown that a positively charged particle beam aligned with atomic planes of a straight crystal as thick as $\lambda/2$ within an angle equal to $\pm\theta_c$, would reverse the transverse momentum of the particles, resulting in efficient mirroring of their trajectories.

Despite the fact that particle mirroring was hypothesized in 1995, it was proven to work only recently [23], thanks to the advent of sophisticated techniques for crystal fabrication [24]. In Ref. [23] the effect was demonstrated for non-relativistic protons of 2 MeV kinetic energy, while the most appealing applications concerning crystal-assisted manipulation of beam trajectories are those at ultrarelativistic energies, where an inexpensive and passive crystal would do the same job as a cumbersome superconducting magnet.

In this Letter we demonstrate that the effect of mirroring holds with ultrarelativistic 400 GeV/c protons in a suitably sized silicon crystal.

Before undertaking experimental work, a study aimed to design a crystal with the correct size for mirroring 400 GeV/c protons was done. In [22], a study was performed for 900 GeV/c protons, thereby a new simulation was carried out using the Monte Carlo code DYNECHARM++ [25] to study particle trajectories and transverse momentum evolution of 400 GeV/c protons interacting with (100) planes of the Si crystal. The code is capable of evaluating the electrical characteristics of complex atomic structures and to simulate and track the particle trajectory within them. The calculation method relies on the expansion in Fourier series of the electrical characteristics of the periodic structures with the usage of form factors from X-ray measurements [26]. The core of the code relies on the full integration of particle trajectories under the continuum potential approximation. The maximum of the (100) potential well and the Lindhard angle estimated by means of the DYNECHARM++ code are ~ 11.8 eV and $\sim$7.6 μrad, respectively. Under the harmonic approximation, λ would be 57 μm. In fact, the planar potential well $U(x)$ is not perfectly harmonic [17]. Therefore, the particle trajectories are not characterized by a single oscillation length λ, but their oscillation period depends on the impact parameter with the atomic planes (see Fig. 1), lying between 50 μm and 61 μm.

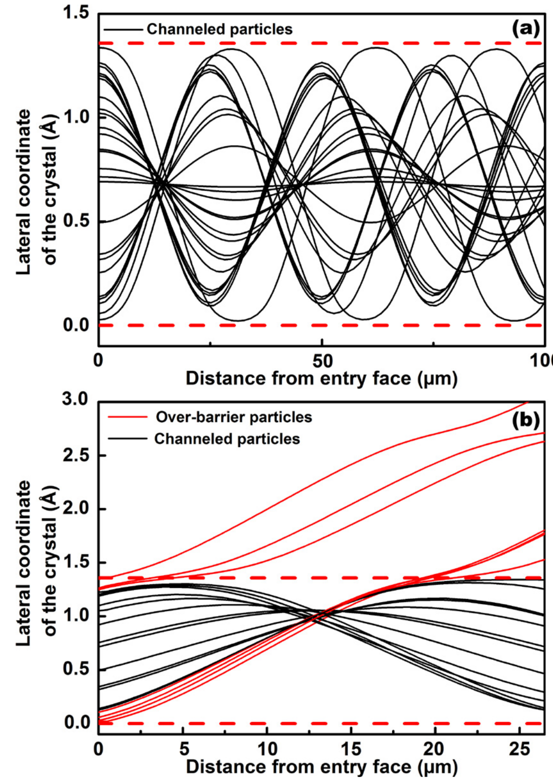

Fig. 1. (a) A graphic representation of a few trajectories of 400 GeV/c protons in a 100 μm Si crystal. At the entry face of the crystal the particle momenta are parallel to the (100) planes. Due to the lack of perfect symmetry in the approximately quadratic planar potential, each trajectory is characterized by an oscillation length λ that depends on the impact parameter at the entry face of the crystal. (b) A few trajectories of 400 GeV/c protons in the 26.5 μm thin crystal tilted by 4 μrad $\sim 1/2\theta_c$ with respect to the beam-to-crystal perfect alignment. Most of the particles are captured in the planar channeling regime (black trajectories). Trajectories in red pertain to the particles that are in over-barrier states at their entrance in the crystal. In order to highlight the coherent part of interaction between particles and the crystals, the simulation for (a) and (b) were performed without the contribution of incoherent scattering on nuclei and electrons. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

However, the imperfection in the harmonic approximation of $U(x)$ negligibly affects the first half-oscillation length, while it plays a significant role after few oscillations (see Fig. 1a).

The prime material for crystal fabrication was a (100) oriented Si wafer, which was then machined through techniques borrowed from silicon micromachining. A Si crystal with lateral sizes of 4×4 mm^2 was fabricated via anisotropic etching [27] (see Fig. 2a). All the wafer surfaces were coated with 100 nm silicon nitride deposited through low-pressure chemical vapor deposition, which was subsequently patterned through photolithography techniques to remove the coated film from selected areas. Photolithography also determines the lateral size of the crystal, which was optimized to obtain a thin silicon membrane surrounded by a bulky frame of 500 μm in order to assure easy handling and to prevent deformations of the crystal when it is mounted on a goniometer. The wafer was immersed in a KOH solution, resulting in thinning of the uncoated areas. A precise calibration of the silicon etching rate allowed stopping the thinning process once an ultra-thin silicon membrane with the desired thickness was left. Fig. 2b shows a picture of the manufactured Si membrane.

The thickness of the crystal was characterized with infrared interferometry (Fogale T-MAP) and was found to be (26.5 ± 0.1) μm,

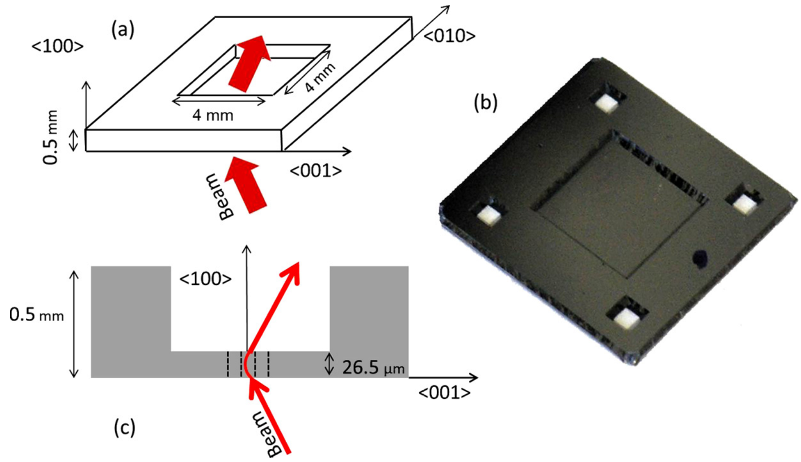

Fig. 2. (a) Sketch of the ultra-thin Si crystal that highlights the crystallographic orientations; the arrows indicate the direction of the mirrored proton beam, which impinges on an active area 4×4 mm^2 large and 26.5 μm thick, surrounded by a 500 μm thick frame. (b) Picture of the thin Si crystal. (c) Lateral view of the crystal, with crystallographic orientation highlighted; arrows represent the incidence and outgoing direction of particle beam mirrored by the Si (001) crystal planes (dashed lines).

which lies within the range of values foreseen for $\lambda/2$ for (001) Si planes used to deflect the particles as a crystal mirror (see Fig. 2c).

With the aim of testing the capability of the 26.5 μm Si crystal as a mirror, a simulation of interactions of 400 GeV/c protons with the crystal has been carried out. Fig. 1b shows the outcomes of the simulation, in particular some trajectories of 400 GeV/c protons in the crystal tilted by 4 μrad, $\sim 1/2\theta_c$, with respect to the perfect alignment of (001) planes with the beam, are displayed. The choice of $1/2\theta_c$ for the tilt angle was suggested in [22] as a compromise between large deflection efficiency (more than 50% for small beam divergence) and large deflection angle. Indeed, one notices that most of the particles are captured under planar channeling regime (black trajectories) and thereby they are reflected by an angle twice the angle of incidence. Trajectories in red pertain to particles in over-barrier states at the entry face of the crystal. At the exit face, most of the over-barrier particles acquire a non-zero component of transverse momentum and are deflected in a direction opposite to that of the channeled ones.

An experiment to test the feasibility of a crystalline mirror for 400 GeV/c protons was performed at the SPS-H8 extracted beamline in October 2012. 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 [29]. Pre-alignment of the sample was worked out by means of a laser system parallel to the beam direction. An "angular scan" of crystal planes with respect to the beam orientation was then performed to find the ideal region for the mirror effect. In order to excite the mirroring of protons by crystal planes, the crystal was rotated around the horizontal axis and, for each angular position, the particle distribution after interaction with the crystal was recorded.

A theoretical prediction of the outcomes of the scan is shown in Fig. 3a, where the simulated beam distribution after interaction with the crystal as a function of the incident angle is displayed. The effect of mirroring is observed within the whole angular range for channeling, that is $2\theta_c$ wide, and the crystal shows a perfect spatial symmetry upon reversal of the incident angle. Four regions

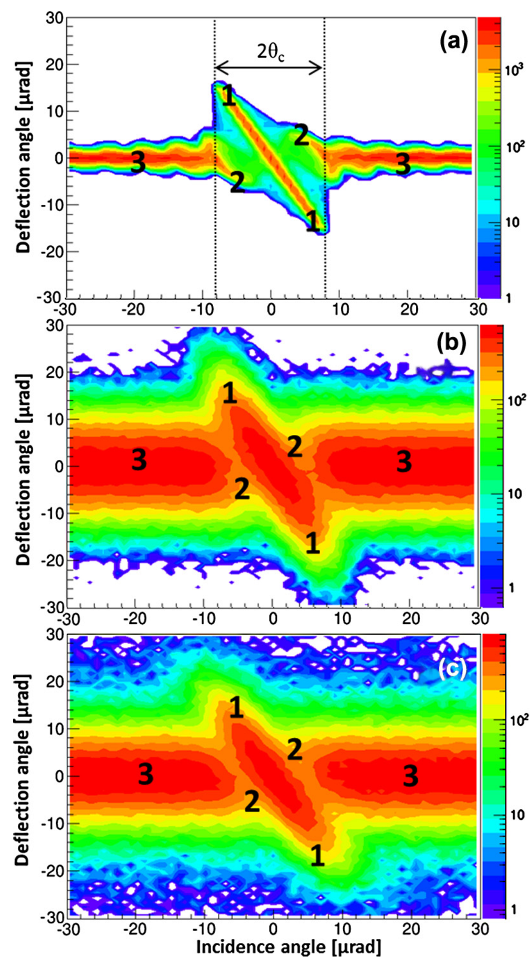

Fig. 3. Deflected beam distribution in the direction orthogonal to (001) crystal planes vs. incidence angle of the beam. (a) Simulation for a parallel beam of 400 GeV/c interacting with the crystal; (b) the same after the convolution with the finite resolution of the experimental apparatus. (c) Experimentally recorded distribution of the beam vs. tilt angle with the crystal.

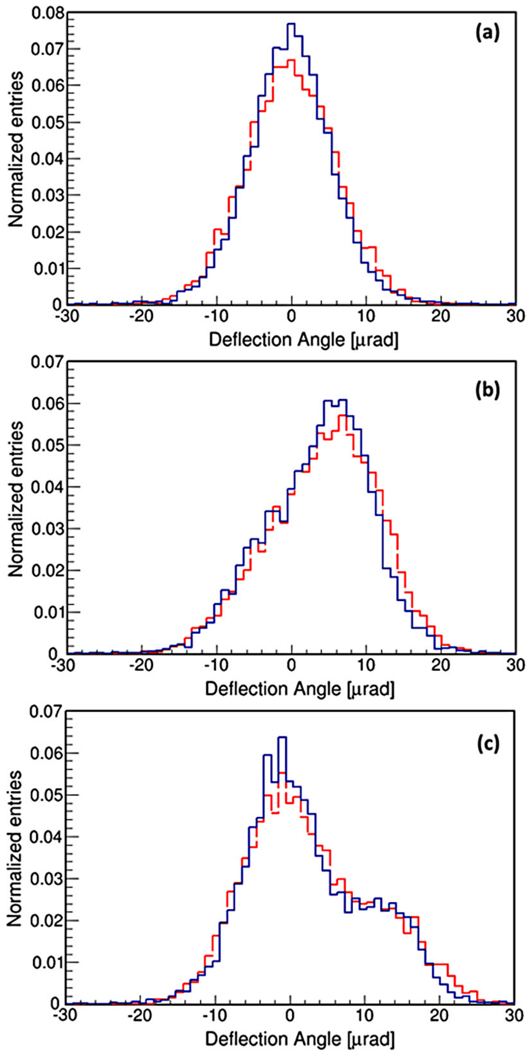

Fig. 4. The distributions of angular deflection of 400 GeV/c protons in a (001) Si crystal 26.5 μm observed in experiments (solid) and obtained by Monte Carlo simulation taking into account the angular resolution (dashed) for three different angles of incidence. Tilt angles are 0 μrad (a), 4 μrad $\sim \theta_c/2$ (b) and 8 μrad $\sim \theta_c$ (c).

can be identified. In region (1) beam deflection occurs via particle mirroring through interaction with the (001) crystal planes. The region (2) corresponds to the deflection experienced by over-barrier particles within the angular acceptance for channeling. In regions (3) all the particles move in over-barrier conditions and are scattered almost incoherently as would be the case for an amorphous. Indeed, the presence of the oscillations in the pattern of regions (3) suggests that the crystal planes are still capable of deflecting over-barrier particles to some extent. In any case such deflection is very small and quickly decreases with the incident angle.

For a better comparison with the experiment, a convolution between the simulated profile and the experimental resolutions for incident and deflection angles has been computed (see shown Fig. 3b). The effect of the finite resolution is to spread out the beam distribution and to eliminate the clear distinction between region (1) and (2) of under- and above-barrier particles within the $2\theta_c$ angular acceptance for the mirror.

Finally, Fig. 3c displays the experimental deflection distribution of the beam vs. angle of incidence of particle trajectories with the crystal planes. There is a good agreement between the patterns in Figs. 3b–c, providing a proof of the observation of the mirror effect for 400 GeV/c protons.

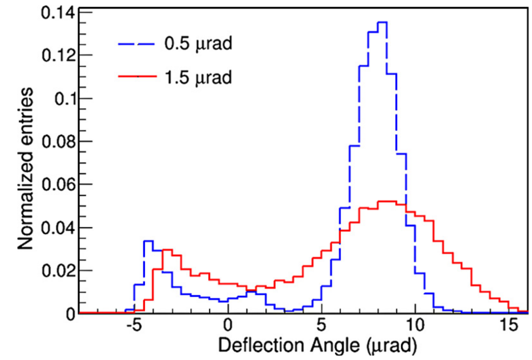

Fig. 5. Angular distributions of 400 GeV/c protons after interaction with a (001) Si crystal 26.5 μm thick in the ideal condition for mirroring (tilt angle $\sim \theta_c/2$) for two different beam divergences σ, equal to 0.5 μrad (dashed line) and 1.5 μrad (solid line) obtained by simulation. The experimental angular resolution has not been taken into account.

Fig. 4 gives a more quantitative comparison between the experiment and simulation. The angular distributions of protons passed through the crystal are shown here for three significant angles of incidence: 0 μrad (perfect alignment with (001) planes), 4 μrad $\approx \theta_c/2$ and 8 μrad $\approx \theta_c$. Good agreement between the experimental results and simulation can be seen in all three cases. The distribution maximum shift by the angle of about θ_c is observed for the incident angle equal to $\theta_c/2$, which is the most appropriate orientation to realize the mirror effect in the crystal.

The finite angular resolution of the telescope does not allow estimating the deflection efficiency of the crystal mirror, which can anyway be done by simulation. Fig. 5 shows the angular distributions of 400 GeV/c protons passed through a (001) Si crystal 26.5 μm thick for the ideal orientation (tilt angle of about $\theta_c/2$) obtained by simulation (a convolution with the angular resolution of the telescope was not performed). Two different beam divergences, σ, have been chosen ($\sigma = 0.5$ μrad (dashed line) and $\sigma = 1.5$ μrad (solid line)). The deflection efficiency was estimated as $\varepsilon = N(\Delta\vartheta > 0)/N_{tot}$, where $N(\Delta\vartheta > 0)$ is the number of particles with deflection angle $\Delta\vartheta$ larger than 0 μrad and N_{tot} is the total number of particles. It turned out $\varepsilon = 85.5\%$ at $\sigma = 0.5$ μrad and 83% at $\sigma = 1.5$ μrad.

In summary, it has been experimentally proven that a properly sized ultra-thin crystal can be used for mirroring of ultrarelativistic positively charged-particles. It was shown that the deflecting angle achievable through the mirror effect is of the order of θ_c as for volume reflection, while the angular acceptance is the same as for channeling. The main advantage of mirroring is to involve a minimal amount of material for interaction of the particles with the crystal. For comparison, in channeling or volume-reflection experiments with ultra-high energy protons, 1–2 mm long bent crystals are used [9,30]. Therefore, the usage of a crystal of a few tens of microns thickness would decrease the unwanted nuclear interactions by two orders of magnitude. Moreover, the deflection efficiency for a quasi-parallel beam has been demonstrated to be close to 90%. These features together make the mirror effect attractive for efficient manipulation of high-energy particles. A crystal-based collimator for a particle accelerator equipped with a crystal mirror not only would reduce the rate of nuclear interactions but also would avoid any problem related to the non-zero angle of the crystalline planes with the geometrical surface of the crystal (the so-called *miscut*) [31], thus decreasing further the particle losses during the first encounters with the crystal collimator.

Another advantage of a crystal mirror is the non-necessity for an external mechanical device for crystal bending [32], thereby circumventing the problem of crystal torsion and its compensation [33]. Moreover, if a deflection of the order of θ_c would not be sufficient for an effective beam steerer, multiple mirroring can be envisaged through the usage of an array of properly oriented crystal mirrors, in analogy to the case of multiple volume reflection [34]. However, the smaller angular acceptance for mirror compared with volume reflection does require a high precision alignment system such as that in Ref. [35].

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