OBSERVATION OF PROTON REFLECTION ON BENT SILICON CRYSTALS AT THE CERN SPS

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Abstract

We report the observation of the so-called volume reflection effect with 400 GeV/c protons interacting with bent silicon crystals in the H8 beam line performed by the H8RDD22 Collaboration at the CERN SPS. The volume reflection is an effect of the same nature of the particle channeling among the crystalline planes of a bent crystal. The reflection occurs at the tangency point of a particle trajectory with the bent crystalline planes where the transverse component of the particle momentum is reversed. The measurements were realized with a high spatial resolution detector mainly based on silicon microstrips showing the effect on particle trajectories of bent silicon crystals in several configurations. The proton beam was deviated in a direction opposite to that of channeling by 12-14 μrad, which is 1.3 times the critical angle, with an efficiency greater than 97% in a range of the proton-to-crystal incident angle as wide as the bending angle of crystallographic planes. This evidence opens new perspectives for manipulation of high-energy beams, e.g., for collimation and extraction in the new-generation of hadron colliders or as a method for high-energy experiments in the region close to the circulating beam.

INTRODUCTION

Channeling [1] is the confinement between crystalline planes occurring when particles hit a crystal with momentum nearly parallel to the atomic planes and transverse kinetic energy not exceeding the well depth U_0 of the crystal potential. The potential well depth determines the critical angle for channeling of a particle with respect to the crystal planes, $\theta_C = \sqrt{\frac{2U_0}{E}}$, where E is the particle energy. For a moderate bending of the crystals, the interplanar potential wells are preserved and the channeling remains effective.

A particle with a transverse component of the momentum such that it cannot be channeled at the entry face of the crystal, proceeds until its momentum direction is tangent to one of the bent crystal planes. Here its transverse direction can be elastically reversed by interaction with the potential barrier (*volume reflection*). At high energies volume reflection becomes the dominant effect and almost all the particles are then subject to it, resulting in a transverse kick that deflects them externally with respect to the centre of curvature of the crystalline planes. Numerical simulations predict that relativistic protons interacting with a bent silicon crystal may be reflected with a deflection angle about 1.5 θ_C.

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The use of bent crystals for halo collimation in hadron colliders has already been proposed [2]. A primary collimator should efficiently deflect halo particles away from the beam core toward a downstream massive absorber. While an amorphous target only scatters halo particles and the angular distribution of particles becomes wider but its maximum does not shift, a bent crystal, on the contrary, deflects halo particles by an angle, which can be large, and most of the particles hit the absorber far from its edge. Thus, a bent crystal can be used as a primary collimator taking advantage of the high efficiency of the volume reflection, as reported in [3].

In this paper we describe the analysis of data collected by the H8-RD22 experiments at the external line H8 at CERN-SPS where protons of momentum p=400 GeV/c were interacting with different types of bent silicon crystals. Deflection angles due to the channeling and to the volume reflection are reported and measurements of the probabilities of the various processes are given.

EXPERIMENTAL SETUP

The study of particle deflection phenomena on bent crystals requires a particle beam with an extremely low divergence, a high resolution telescope to track particles upstream and and downstream the crystal and a high precision goniometer to align the crystals with a high degree of repeatability.

Two different types of crystal have been fabricated and used in the experiment: strip and quasi-mosaic crystals. Silicon strips (in the following indicated with ST4) have been realized at the Sensors and Semiconductors Laboratory at Università di Ferrara in collaboration with IHEP [4]. Prime materials are (110) and (111) oriented 4” silicon wafers. The crystals are mounted on a specifically designed holder [5] which bends the strip and, thanks to anticlastic forces, give rises to a secondary curvature. The second type of crystals (in the following indicated as QM2) has been prepared exploiting the elastic-quasimosaicity effect at the Petersburg Nuclear Physics Institute [6].

The mechanical holders are fixed on the goniometer system, that is moved by a remote control system. Each crystal is aligned with respect to the beam with a level of repeatability within 1.5 μrad. The basic idea of the experiment is then to track each single particle that crosses the crystal and to determine the single pass efficiencies for the various processes. The tracking system consists of two types of silicon ([7, 8]) microstrip detectors with excellent spatial resolution (10-40 μm) and of a fast parallel plate gas chamber, in addition to scintillation counters used for triggering.

The experiment has been carried out on a 400 GeV/c momentum primary proton beam at the external CERN SPS beamline H8. The 2σ beamspot at the crystal position has a 5 mm diameter in the horizontal plane and 4 mm in the vertical plane with a very small divergence (nominally 3 μrad) . The primary beam intensity is very high (20×10^{11} proton-per-pulse), but it is reduced down to $10^4 - 10^5$ ppp without affecting significantly its divergence. This intensity is relatively low and allows the tracking of every single particle. High statistics runs were recorded with all detectors, while varying the crystal angle ϕ with respect to the beam (angular scan). Usually about 10-15 accelerator cycles were enough to accumulate a sufficient statistics.

DATA ANALYSIS

The positions of proton tracks on the silicon microstrip detector layers are reconstructed and the beam profiles are obtained (Fig.1). The angular position of the channeled and volume reflected portion of the beam with the respect to the unperturbed beam and the efficiencies of such processes are therefore measured for all the crystals tested during the data taking.

The particle trajectory direction θ after the interaction with the crystal is reconstructed using the information of two stations of detectors, one positioned upstream and very close to the crystal and the other located 65 m downstream. θ is defined by joining the average of horizontal positions determined at the detector layers in the two stations.

The events shown in the scan summary plot in Fig.2 are obtained selecting those particles that hit the central part of the crystal. The "amorphous" position zones at the beginning and at the end of the scan correspond to crystal angles at which the beam goes through the crystal with no perturbation besides the multiple scattering effect ("unperturbed" beam). From the angular distribution of the unperturbed beam component (Fig.1(a)), subtracting the effect of multiple scattering we determine the RMS beam divergence at the crystal to be $7.1 \pm 0.4 \mu$rad.

The region where channeling occurs ($\phi \sim 65\mu$rad) follows the "amorphous" region, showing a clear accumulation of deflected tracks. Subsequently the volume reflection phenomenon occurs in a region comprised in the $70 < \phi < 250\mu$rad interval. It is evident that the volume reflection causes a shift of the proton beam to the opposite direction with respect to the channeling. While such a shift is smaller, it occurs for a much wider angular range and with a higher probability.

The low intensity band in the channeling region corresponds to the *dechanneling* phenomenon due to the particles which start to be channeled at the entry face of the crystal but exit before reaching the end of the crystal. In the volume reflection region a diagonal low intensity band corresponds to the *volume capture* occurring when particles, initially not channeled, due to multiple scattering on the nuclei of the crystal, get trapped between the lattice planes at an intermediate position along the crystal length and are therefore only partially bent.

The value of the peak position and the width of the distribution for the unperturbed (θ_{un}, σ_{un}), channeling (θ_{ch},σ_{ch}) and volume reflection (θ_{vr},σ_{vr}) portions of the beam are then extracted with a fit, using a Gaussian parametrization for each component (Fig.1)

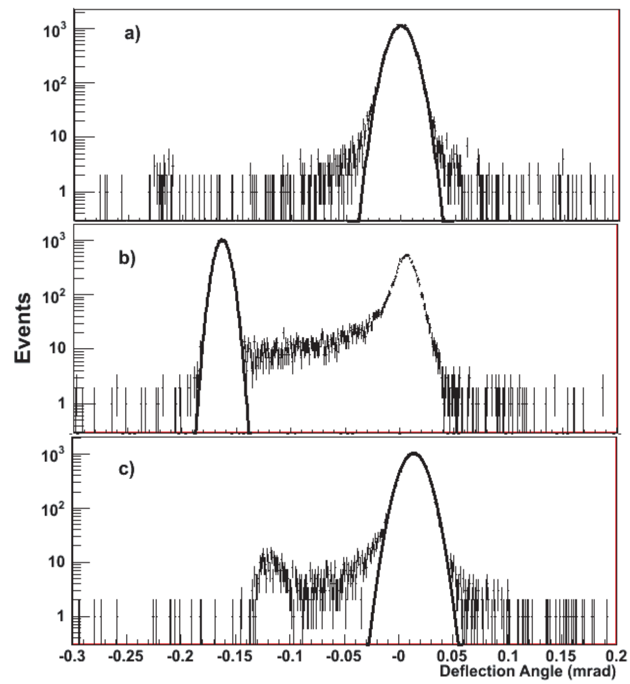

Figure 1: Beam profiles in different crystal positions: a) "amorphous" region, b) "channeling" region, c) volume reflection region.

Efficiency measurements

The various phenomena of particle deflections can be characterized by a probability ("efficiency") that we can estimate from our data by comparing the fraction of particles in the various region of the angular scan.

We define the number of protons in the unperturbed beam N_{un} as the number of protons within $\pm 3\sigma_{un}$ around θ_{un}. To determine an appropriate normalization each run of the scan has been normalized to an equal number of events, using the number of collected triggers. We define the number of protons in the unperturbed beam N_{un} as the number of protons within $\pm 3\sigma_{un}$ around θ_{un}. We evaluate $P_{ch} = \frac{N_{ch}}{N_{un}}$ for the runs in the channeling region where N_{ch} is the number of protons within $\pm 3\sigma_{ch}$ around θ_{ch}.

The evaluation of the volume reflection efficiency (P_{vr}) has been carried out similarly to the channeling case. The protons N_{vr} (N_{un}) are counted within $\pm 3\sigma_{vr}$ ($\pm 3\sigma_{un}$) around θ_{vr} (θ_{un}) and $P_{vr} = \frac{N_{vr}}{N_{un}}$.

From the measured P_{ch} values we extrapolate the maximal channeling efficiency and we determine the mean value of P_{vr} averaged over the volume reflection region. The results for two of the tested crystals are given in Tab.1. The definitions of the number of events N_j counted within $\pm 3\sigma$

of each distribution rely on the Gaussian assumption for the beam shape. This is the dominant component of the systematic uncertainty and to estimate it, we have reevaluated the efficiency using a different number of σ to calculate N_j and checking the stability of the measurement as a function of ϕ.

Deflection angle measurements

In the region around the maximal channeling we determine the crystal angle ϕ_{max} at which the channeling efficiency is maximal. From the fraction of tracks contained in the channeled beam in different runs we extrapolate ϕ_{max}. Given the liner relation between θ_{ch} and ϕ we then determine θ_{ch}^{max} and define the *channeling deflection angle* as the difference $\theta_{ch}^{max} - \theta_{un}$. θ_{un} is estimated from an average in the runs corresponding to the amorphous positions of the crystal.

For the volume reflection we define the *deflection angle at volume reflection* as $\theta_{vr} - \theta_{un}$. In this case θ_{vr} is determined as an average over the peak positions in the volume reflection region. Results of such measurements are given in Tab.1 for the various crystals. Systematic uncertainties on $\theta_{ch}^{max} - \theta_{un}$ measurements come primarily from torsional effect along the vertical axis of the crystal while $\theta_{vr} - \theta_{un}$ measurement is mainly affected by the model of dechanneling and volume capture effects that affects the extraction of θ_{vr} These results are in very good agreement with MonteCarlo simulation of the interaction of protons with bent silicon crystals.

Table 1: Results on deflection angles and efficiency for two of the tested crystals. Statistical errors from the fit and systematic errors are given.

$\theta_{ch}^{max} - \theta_{un}$ (μrad)	ST4	$-162.0 \pm 0.1 \pm 1.1$
	QM2	$-68.6 \pm 0.20 \pm 0.20$
$\theta_{vr} - \theta_{un}$ (μrad)	ST4	$13.91 \pm 0.06 \pm 0.50$
	QM2	$12.02 \pm 0.02 \pm 0.40$
P_{ch} (%)	ST4	$56.2 \pm 0.5 \pm 2.0$
	QM2	$51.9 \pm 0.5 \pm 1.6$
P_{vr} (%)	ST4	$98.17 \pm 0.04 \pm 0.50$
	QM2	$98.31 \pm 0.04 \pm 0.50$

CONCLUSIONS

Observing 400 GeV$/c$ proton beam deflection of about 13 μrad on various bent silicon crystals, we have interpreted it as due to volume reflection, measuring its efficiency to be more than 98% on two different types of crystals. This results is very encouraging for the development of new technique of beam collimation at future hadron colliders, since it exhibits superior performance compared to channeling in terms of efficiency and angular acceptance. A short bent crystal may be employed as a smart deflector to aid halo collimation in high-intensity hadron colliders

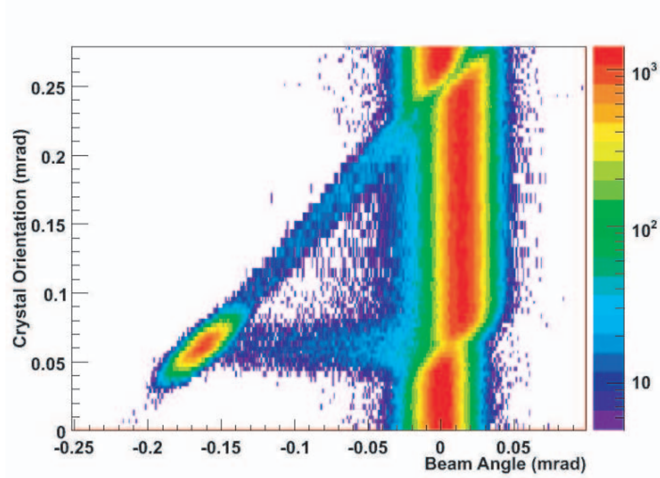

Figure 2: Angular scan of the ST4 crystal selecting only the middle horizontal part of the beam. On the ordinate axis the crystal rotation angle ϕ; on the abscissae axis the particle angle θ.

or as a device to separate low-angle scattering events in diffractive physics.

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