Available online at www.sciencedirect.com

ScienceDirect

ELSEVIER

Physics Letters B 658 (2008) 109–111

PHYSICS LETTERS B

www.elsevier.com/locate/physletb

Double volume reflection of a proton beam by a sequence of two bent crystals

Walter Scandale [a,*], Alberto Carnera [b,c], Gianantonio Della Mea [b,d], Davide De Salvador [b,c], Riccardo Milan [b], Alberto Vomiero [b,e], Stefano Baricordi [f], Pietro Dalpiaz [f], Massimiliano Fiorini [f], Vincenzo Guidi [f], Giuliano Martinelli [f], Andrea Mazzolari [f], Emiliano Milan [f], Giovanni Ambrosi [g], Philipp Azzarello [g], Roberto Battiston [g], Bruna Bertucci [g], William J. Burger [g], Maria Ionica [g], Paolo Zuccon [g], Gianluca Cavoto [h], Roberta Santacesaria [h], Paolo Valente [h], Erik Vallazza [i], Alexander G. Afonin [j], Vladimir T. Baranov [j], Yury A. Chesnokov [j], Vladilen I. Kotov [j], Vladimir A. Maisheev [j], Igor A. Yazynin [j], Sergey V. Afanasiev [k], Alexander D. Kovalenko [k], Alexander M. Taratin [k], Alexander S. Denisov [l], Yury A. Gavrikov [l], Yuri M. Ivanov [l], Vladimir G. Ivochkin [l], Sergey V. Kosyanenko [l], Lyubov P. Lapina [l], Anatoli A. Petrunin [l], Vyacheslav V. Skorobogatov [l], Vsevolod M. Suvorov [l], Davide Bolognini [m,n], Luca Foggetta [m,n], Said Hasan [m,n], Michela Prest [m,n]

[a] *CERN, European Organization for Nuclear Research, CH-1211 Geneva 23, Switzerland*
[b] *INFN Laboratori Nazionali di Legnaro, Viale Università 2, 35020 Legnaro (PD), Italy*
[c] *Dipartimento di Fisica, Università di Padova, Via Marzolo 8, 35131 Padova, Italy*
[d] *Dipartimento di Ingegneria dei Materiali e Tecnologie Industriali, Università di Trento, Via Mesiano 77, 38050 Trento, Italy*
[e] *INFM-CNR, Via Valotti 9, 25133 Brescia, Italy*
[f] *INFN Sezione di Ferrara, Dipartimento di Fisica, Università di Ferrara, Via Saragat 1, 44100 Ferrara, Italy*
[g] *INFN Sezione di Perugia & Università degli Studi di Perugia, Dipartimento di Fisica, Via Pascoli, 06123 Perugia, Italy*
[h] *INFN Sezione di Roma, Piazzale Aldo Moro 2, 00185 Rome, Italy*
[i] *INFN Sezione di Trieste, Via Valerio 2, 34127 Trieste, Italy*
[j] *Institute of High Energy Physics, Moscow Region, RU-142284 Protvino, Russia*
[k] *Joint Institute for Nuclear Research, Joliot-Curie 6, 141980, Dubna, Moscow Region, Russia*
[l] *Petersburg Nuclear Physics Institute, 188300 Gatchina, Leningrad Region, Russia*
[m] *Università dell'Insubria, via Valleggio 11, 22100 Como, Italy*
[n] *INFN Sezione di Milano Bicocca, Piazza della Scienza 3, 20126 Milano, Italy*

Received 14 July 2007; received in revised form 31 August 2007; accepted 18 October 2007

Available online 7 November 2007

Editor: M. Doser

Abstract

The doubling of the angle of beam deflection due to volume reflection of protons by a sequence of two bent silicon crystals was experimentally observed at the 400 GeV proton beam of the CERN SPS. A similar sequence of short bent crystals can be used as an efficient primary collimator for the Large Hadron Collider.

PACS: 29.27.-a; 61.85.+p

* Corresponding author.
E-mail address: walter.scandale@cern.ch (W. Scandale).

0370-2693/$ – see front matter
doi:10.1016/j.physletb.2007.10.070

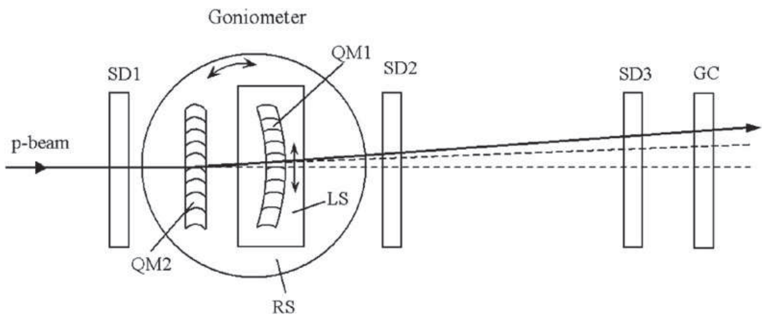

Fig. 1. Schematic top view of the experimental layout in the horizontal plane. QM1 and QM2 are two quasimosaic crystals installed on the rotational stage RS of the goniometer. The QM1 crystal is placed on the additional linear stage LS that allows to align QM1 with QM2. SD1, SD2, SD3 are silicon microstrip detectors, GC is a position sensitive gas chamber. The distances between the crystal and SD1, SD2, SD3 and GC equal to 0.5, 0.5, 64.8 and 70 m, respectively. The lines represents the trajectories of the protons after the crystals, the unperturbed beam (lower dashed) crossing the crystals both in amorphous position, the beam reflected by the first crystal only (upper dashed), and the double-reflected beam (solid).

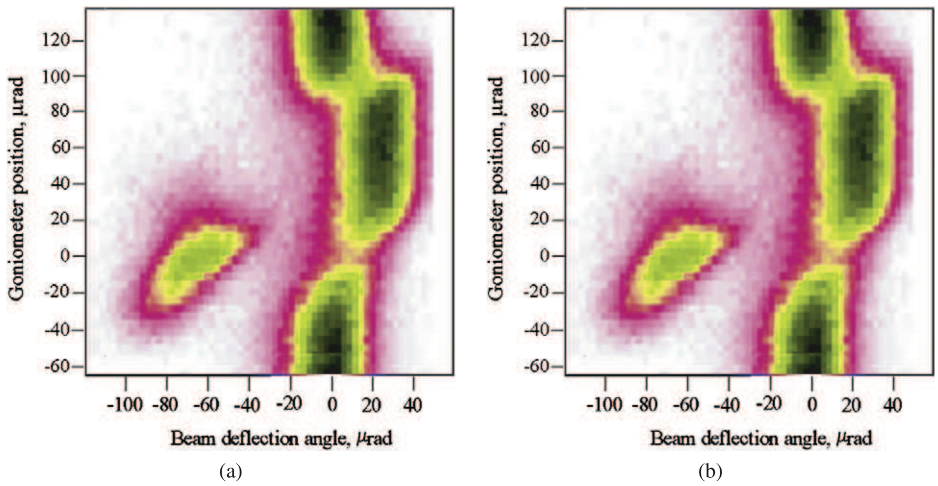

Fig. 2. Angular scans performed before (a) and after (b) the fine alignment of the crystals. On the y-axis the angular position of the goniometer is shown while on the x-axis the beam deflection angle of the particle measured with the GC detector is reported. The origin of the x-axis corresponds to the direction of the incident beam. The origin of the y-axis corresponds to the angular position of the goniometer when the channeling effect in QM2 crystal is maximal. In (a) both channeling peaks due to QM1 and QM2 are visible. In (b) the two channeling peaks coincides at about the same goniometer angle and are followed by the double reflection. The color scale indicates the beam intensity at a given deflection angle for various angular positions of the goniometer.

Deflection of channeled particles in a bent crystal is a well-established phenomenon and it is used in experiments with high-energy charged particle beams. Under certain conditions non-channeled particles can be deflected because of the reversal of their transverse momentum by the bent atomic planes in the crystal volume [1,2]. In a recent experiment at CERN it was found that volume reflection has an efficiency larger than 95% for the deflection of a 400 GeV proton beam at an angle of about 14 μrad [3].

However, larger deflection angles would be more appropriate for a realistic use of such crystals in the Large Hadron Collider (LHC) collimation system. This encouraged us to study sequential reflections of particles in short bent crystals. Using crystals similar to that described in [2] and the same beam and experimental setup described in [3,4] we have carried out an experiment on double volume reflection in two crystals, the results of which are reported in this Letter.

Fig. 1 shows schematically the experimental layout [4]. Two silicon plates QM1 and QM2 with (111) atomic planes bent of $\sim$70 μrad along the plate thickness of $\sim$0.8 mm were installed on a high precision goniometer. The (111) planes of QM1 plate were fan-shaped in a way that made possible to align them with respect to the QM2 plate within the proton beam spot using the transverse linear motion of the QM1 support. The silicon strip detector SD1 before the crystals was used to select a fraction of the incident beam, the silicon strip detectors (SD2 and SD3) and position sensitive gas chamber (GC) were used to measure the angles of the particles exiting the crystals.

In Fig. 2 the angular scans performed before (a) and after (b) the fine relative alignment of the two crystals are shown. The color on the plots shows the relative beam intensity measured for the various deflection angles reported on the x-axis while on the y-axis the goniometer angle is reported.

The channeling peaks for both QM2 and QM1 crystals are visible as the two isolated spots at negative values of the beam deflection angles in Fig. 2(a). This scan was obtained before the alignment and therefore the two peaks appear at different angular positions of the goniometer. The mean deflection angles of the channeled protons are measured with the SD2 and SD3 detectors to be (68.6 ± 0.9) μrad and (78.1 ± 4.8) μrad for the QM2 and the QM1 crystal, respectively: they are equal to the bending angles of the (111) atomic planes in the crystals. The

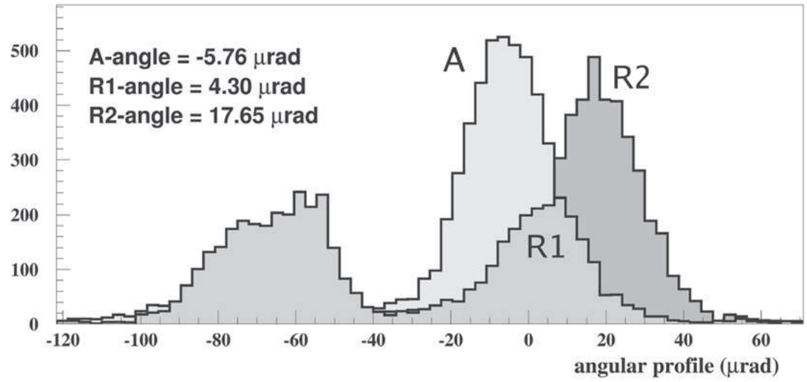

Fig. 3. The beam profiles corresponding to amorphous scattering of protons in both crystals (A), the reflection case in one of the crystal (R1) and in both crystals—double reflection (R3). The peak to the left associated to R1 is due to channeling.

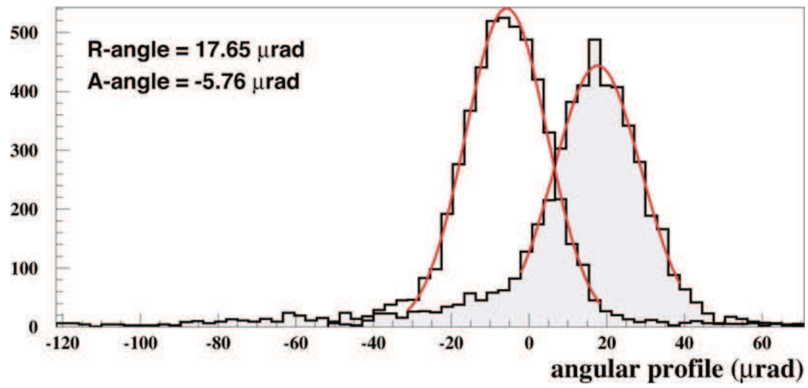

Fig. 4. The beam profiles corresponding to amorphous scattering of protons and to double reflection in both crystals are interpolated with a Gaussian.

region of the scan with the proton beam deflected to the opposite direction with respect to the channeled protons is due to the volume reflection effect. The deflection angle and efficiency of a single reflection are found to be (11.70 ± 0.51) μrad and $(98.27 \pm 0.50)\%$, respectively for QM2 and (11.90 ± 0.59) μrad and $(97.80 \pm 0.64\ )\%$ for QM1. The efficiency was defined as the ratio of the proton number within $\pm 3\sigma$ around the distribution maximum for the crystal orientation corresponding to volume reflection of protons to the same value for the orientation with amorphous scattering of protons in the crystal. Both values were normalized on the same number of protons hitting the crystal. It is clear in Fig. 2(a) that the volume reflection regions corresponding to the QM2 and QM1 crystals are partly superimposed resulting in the deflection of the proton beam at larger angles than in the case of a single reflection.

The angle and efficiency of double reflection were accurately measured with finely aligned crystals, and the result is shown in Fig. 2(b). In this measurement the channeling peaks and the volume reflection regions for both crystals fully coincide. Fig. 3 shows the beam profiles for three different cases corresponding to either amorphous scattering, single or double reflections of protons in the crystals. The deflection angle of the double reflected beam is extracted with Gaussian fits to the beam profile distributions obtained with the SD2 and SD3, detectors, as shown in Fig. 4, and it is found to be equal to $23.23 \pm 0.18(\text{stat}) \pm 0.09(\text{syst})$ μrad, that is twice larger than in single reflection. The efficiency of double reflection is equal to $96.73 \pm 0.38(\text{stat}) \pm 0.50(\text{syst})\%$. The systematic uncertainties on the deflection angle and efficiency measurements are mainly related to the Gaussian model used to describe the beam profiles.

Thus, the experiment demonstrated a feasibility of multiple volume reflections in a sequence of short bent crystals with high efficiency and with beam deflection angle proportional to the number of reflections. This result opens new ways to develop crystal optics for the manipulation of high-energy charged particle beams.

Acknowledgements

This work was partly supported by Russian Foundation for Basic Research (grant No. 06-02-16912), “Elementary Particle Physics and Fundamental Nuclear Physics” Program of Russian Academy of Sciences, INFN-NTA-HCCC program, the INTAS-CERN Foundation (grant No. 05-103-7525), and the MIUR 2006028442 project.

References

[1] A.M. Taratin, S.A. Vorobiev, Nucl. Instrum. Methods B 26 (1987) 512.
[2] Yu.M. Ivanov, et al., Phys. Rev. Lett. 97 (2006) 144801.
[3] W. Scandale, et al., Phys. Rev. Lett. 98 (2007) 154801.
[4] M. Fiorini, et al., in: EPAC Proceedings, Edinburgh, 2006, p. 1538.