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Comparative results on the deflection of positively and negatively charged particles by multiple volume reflections in a multi-strip silicon deflector

W. Scandale[a,b,e], G. Arduini[a], M. Butcher[a], F. Cerutti[a], M. Garattini[a], S. Gilardoni[a], A. Lechner[a], R. Losito[a], A. Masi[a], A. Mereghetti[a], E. Metral[a], D. Mirarchi[a,j], S. Montesano[a], S. Redaelli[a], R. Rossi[a,e], P. Schoofs[a], G. Smirnov[a], E. Bagli[c], L. Bandiera[c], S. Baricordi[c], P. Dalpiaz[c], G. Germogli[c], V. Guidi[c], A. Mazzolari[c], D. Vincenzi[c], G. Claps[d], S. Dabagov[d,k,l], D. Hampai[d], F. Murtas[d], G. Cavoto[e], F. Iacoangeli[e], L. Ludovici[e], R. Santacesaria[e], P. Valente[e], F. Galluccio[f], A. G. Afonin[g], Yu. A. Chesnokov[g1)], A. A. Durum[g], V. A. Maisheev[g], Yu. E. Sandomirskiy[g], A. A. Yanovich[g], A. D. Kovalenko[h], A. M. Taratin[h], Yu. A. Gavrikov[i], Yu. M. Ivanov[i], L. P. Lapina[i], W. Ferguson[j], J. Fulcher[j], G. Hall[j], M. Pesaresi[j], M. Raymond[j], D. Bolognini[m,n], S. Hasan[m,n], M. Prest[m,n], E. Vallazza[o]

[a]CERN, European Organization for Nuclear Research, CH-1211 Geneva 23, Switzerland

[b]Laboratoire de l'Accelerateur Lineaire (LAL), Universite Paris Sud Orsay, 91898 Orsay France

[c]INFN Sezione di Ferrara, Dipartimento di Fisica, Universita' di Ferrara, 44122 Ferrara, Italy

[d]INFN LNF, 40 00044 Frascati (Roma), Italy

[e]INFN Sezione di Roma, 00185 Rome, Italy

[f]INFN Sezione di Napoli, 80126 Napoli, Italy

[g]Institute for High Energy Physics in National Research Centre "Kurchatov Institute", 142284 Protvino, Russia

[h]Joint Institute for Nuclear Research, 141980, Dubna, Russia

[i]Petersburg Nuclear Physics Institute in Natioanl Research Centre "Kurchatov Institute", 188300 Gatchina, Russia

[j]Imperial College, London, United Kingdom

[k]Lebedev Physical Institute of the RAS, 119991 Moscow, Russia

[l]National Research Nuclear University "MEPhI", 119991 Moscow, Russia

[m]Universita' dell'Insubria, 22100 Como, Italy

[n]INFN Sezione di Milano Bicocca, 20126 Milano, Italy

[o]INFN Sezione di Trieste, 34127 Trieste, Italy

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Bent silicon crystals in channeling mode are already used for beam extraction and collimation in particle accelerators. Volume reflection of beam particles is more efficient than beam channeling; however the mean deflection angle is rather small. An experiment on the deflection of a 400 GeV/c proton beam and a 150 GeV/c π^- beam at CERN using a multi-strip silicon deflector in reflection mode is described. The mean deflection angle of beam particles has been considerably increased due to sequential volume reflections realized in the deflector. This gives possibility for a successful usage of the multi-strip deflectors for beam collimation in high energy accelerators.

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Bent crystals have found applications in the beam extraction and beam collimation systems of large circular proton accelerators owing to high electric fields produced by the crystals [1–3]. These crystals were used mainly in the planar channeling mode. A new physical phenomenon, namely the reflection of a high-energy proton beam from the atomic planes of a bent silicon crystal, was recently observed and work started on the use of this phenomenon at accelerators [4–7]. Volume reflection is caused by an interaction between the incident proton and the potential of the bent crystal lattice and

1) e-mail: Yury.Chesnokov@ihep.ru

occurs in a short length interval in a region tangential to the bent atomic plane.

The probability of a single reflection is high, approaching 98 % for 400 GeV/c protons [6]. Because of the short characteristic length of the volume reflection process it is very efficient both for positive and for negative particles while channeling is considerably less efficient for negative particles in comparison with positive ones [8, 9]. Efficient channeling in very short crystals of μm length scale has been shown recently for 0.8 and 6 GeV electrons [10, 11]. The use of axially-aligned crystals can be considered as a promising option for channeling of negative particles [12, 13]. In this work we show that volume reflection in a sequence of crystals can effectively deflect both positive and negative multi-GeV particles through angles of about 0.1 mrad. This value of the deflection angle is sufficient for important accelerator applications [2, 3].

Analytical theory [7] predicts that, under the same conditions, the deflection angle for negative particles due to volume reflection is ~ 1.8 times smaller than that for positive particles. However, allowing for the $\sim (1/E)^{1/2}$ energy dependence of the reflection angle, in our case for (111) silicon crystals with a bending radius of 7 m, the theory yields similar values for protons and negative pions (Fig. 1). More specifically, the theoretical values for mean reflection angle and RMS have been determined to be 11.2 and 5.0 μrad, respectively, for 400 GeV/c protons, and 14.3 and 11.7 μrad, respectively, for 150 GeV/c negative pions.

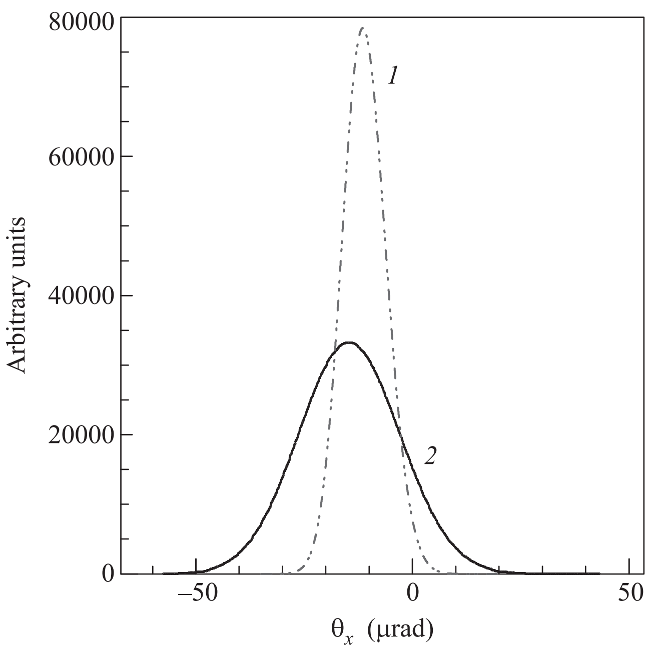

Fig. 1. The theoretical distributions of deflection angles due to volume reflection in a 2 mm silicon crystal bent along the (111) planes with a radius of 7 m for 400 GeV/c protons (*1*) and 150 GeV/c negative pions (*2*)

Accelerator physics problems like extraction and collimation require the reflection angle to be several times larger. In order to increase the reflection angle a few variants of multi-crystal devices have been tested in proton beams [14–18]. The design of an eight-strip crystal device used for this study is shown in Fig. 2. Details are described in [18]. The crystals were bent using the anisotropic properties of the crystal lattice. A transverse bend of 0.28 mrad appears when each strip is bent in the longitudinal direction by the metallic holder. Furthermore, since all strips are manufactured from one silicon wafer, good mutual alignment of individual strips holds in both the horizontal and vertical planes. The major faces of the crystal plate were parallel (111) crystalline planes, and the entry face was normal to the ⟨110⟩ crystalline axis. The separate crystal strips are 2 mm in width along the beam, 40 mm in length and 0.9 mm in thickness across the beam.

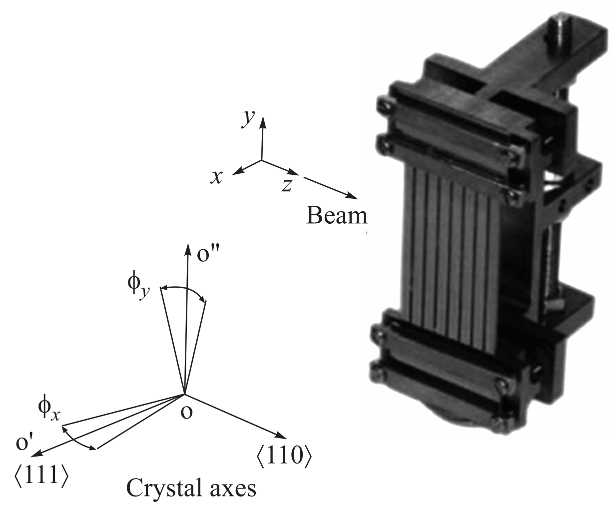

Fig. 2. A picture of the multi-strip crystal deflector and scheme of its installation in the goniometer

The experimental setup was as described in [19]. Four microstrip silicon detectors, two upstream and two downstream of the crystal, were used to measure the particle trajectories with an angular resolution of 3 μrad, which is limited by multiple scattering of the particles in the detectors and air. The angular divergence in the horizontal and vertical planes of the incident beam was about 10 μrad. A high precision goniometer allowed orientation of the multi-strip deflector both in the horizontal and vertical plane with an accuracy of 2 rad. The scheme of crystal installation in the goniometer is shown in Fig. 2.

In the first stage of the study, a scan of the horizontal orientation angles of the crystal deflector ϕ_x was performed. A two-dimensional color plot in Fig. 3 shows

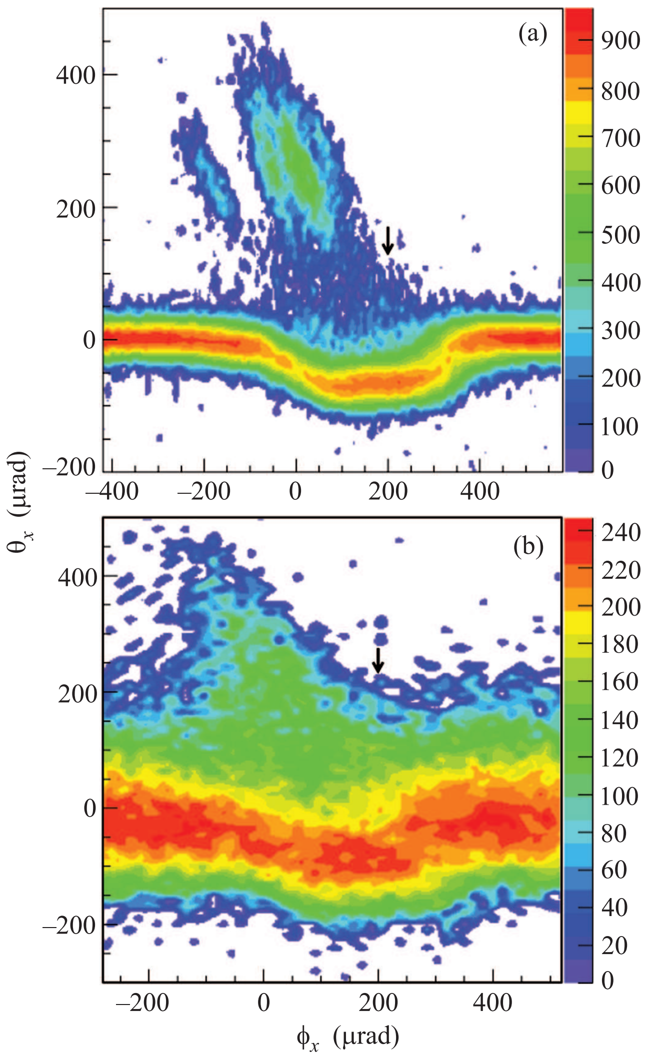

Fig. 3. The intensity distribution of a 400 GeV/c proton beam (a) and 150 GeV/c negative pion beam (b) passed through the eight-strip silicon deflector as a function of the particle deflection angle θ_x for different goniometer positions ϕ_x

the intensity distribution of the beam passed through the crystal as a function of the particle deflection angle θ_x and angular position of the goniometer ϕ_x. Fig. 3a corresponds to 400 GeV/c protons, and Fig. 3b corresponds to 150 GeV/c negative pions.

The mean deflection angle equals zero at the beginning (left) and at the end (right) of the scan due to scattering of particles in the crystal deflector as in an amorphous substance. The particle deflection maxima visible at $\theta_x > 0$ near the central region of the scan occurs due to channeling. Two separate maxima of the beam intensity are explained by misalignment of crystals in the sequence. Further in the angular region, deflections with $\theta x < 0$ occur due to multiple volume reflections of particles traversing the full sequence of strips.

Figs. 4a and b show the distribution of protons and negative pions in the horizontal deflection angle θ_x for

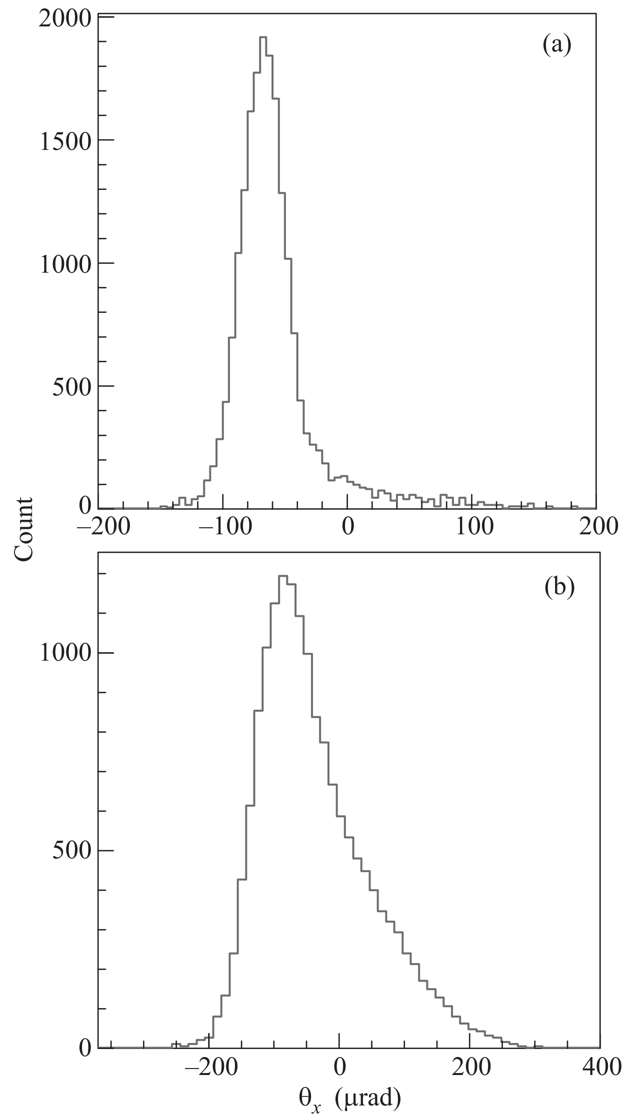

Fig. 4. The distributions of horizontal deflection angles θ_x in the conditions of sequential volume reflections in the multi-strip deflector marked by the arrows in Fig. 3: (a) – for protons, (b) – for negative pions

a fixed goniometer position indicated in Figs. 3a and b by the vertical arrows where multiple volume reflection (MVR) of particles occurs. The efficiency of one side MVR deflection ($\theta_x < 0$) is about 94 % for positive particles and about 71 % for negative particles.

The mean reflection angle is 68 μrad and RMS deviation is 16.5 μrad for protons. The mean reflection angle is 78 μrad and the RMS deviation is 38.4 μrad for negative pions. The analytical theory predicts, in the case of a sequence of 8 crystals, a mean angle of $11.2\,\mu\text{rad} \times 8 = 89\,\mu\text{rad}$ and an RMS $= 14.2\,\mu$rad for protons, and a mean angle $14.3\,\mu\text{rad} \times 8 = 114\,\mu\text{rad}$ and an RMS $= 33\,\mu$rad for negative pions. The measured reflection angles are about 80 % of the theoretical values assuming volume reflection on eight strips. This can be explained by the misalignment of two strips for which volume reflection is not realized for the deflector orientation considered.

An additional way of increasing the reflection angle or RMS was achieved at the next stage of the work. In [20] it was explained theoretically that multiple volume reflections of particles in one bent crystal (MVR OC) can be realized due to the contributions of skew crystalline planes at crystal orientations near the crystallographic axis. This possibility was convincingly confirmed experimentally in an extracted beam [13, 17, 21] and verified in a circulating beam [22]. As noted above, in our case the entrance face of the multi-crystal used was cut normal to the $\langle 110 \rangle$ axis. After installation of the crystal in the position of planar reflection (in the position indicated by an arrow in Figs. 3a and b) the horizontal angle ϕ_x of the goniometer was fixed, and then scanning started about the vertical angle ϕ_y (see Fig. 2) in the region close to the crystalline axis.

The results of the scan are shown in Fig. 5 for both protons and negative pions. Fig. 6 shows the distributions of horizontal deflection angles θ_x for the case when the multi-strip deflector orientation corresponds to $\phi_y = 0$ marked by the arrows in Fig. 5: (a) – for protons, (b) – for negative pions. In this case, the beam axis and the $\langle 110 \rangle$ crystallographic axis are in the same plane. Particles undergo multiple potential scattering (doughnut scattering) by the $\langle 110 \rangle$ atomic strings in a few first strips. This gives them some vertical momentum, which is sufficient to realize the MVR OC effect for these particles in a few subsequent strips. The distributions displayed in Fig. 6 show a substantial increase in mean deflection angle, which becomes 102 μrad with an RMS of 79 μrad for protons, and 64 μrad with an RMS of 106 μrad for negative pions. In these conditions, the efficiency of one side deflection ($\theta_x < 0$) is about 88 % for protons and about 70 % for negative pions. As a whole, the multi-strip deflector with orientation near the crystallographic axis allowed to increase the angular beam size considerably in comparison with scattering in an amorphous position, which is very important for accelerator beam collimation.

In summary, the experimental results obtained show the possibility of the application of multiple volume re-

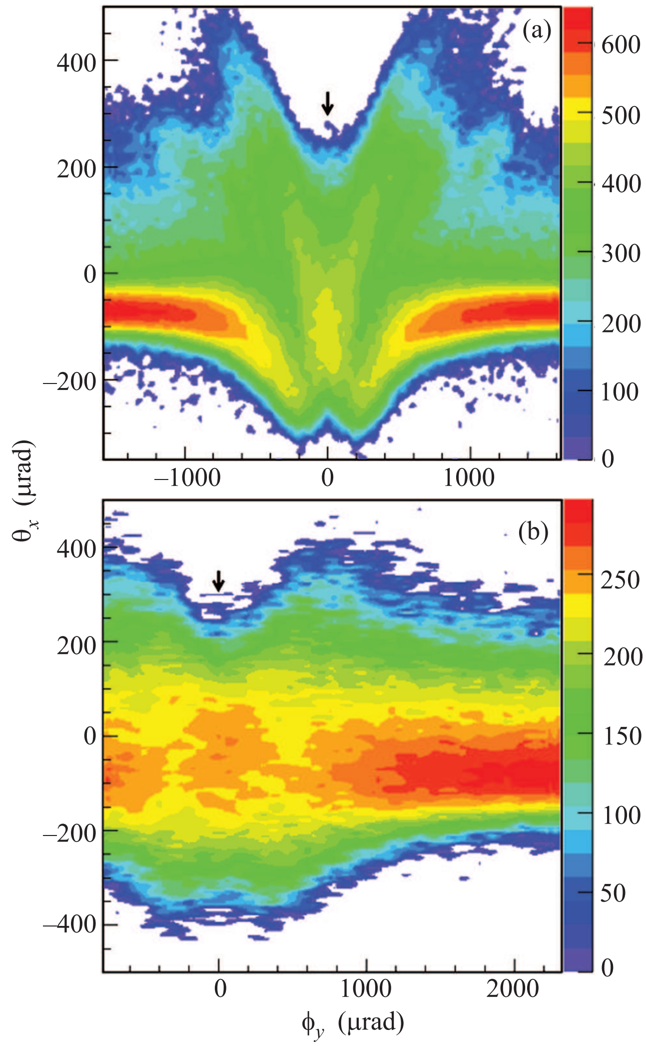

Fig. 5. The intensity distribution of a 400 GeV/ c proton beam (a) and 150 GeV/c negative pion beam (b) passed through the eight-strip silicon deflector as a function of the particle deflection angle θ_x for different goniometer positions ϕ_y

flections of particles in multi-strip crystal devices for beam collimation in high energy accelerators. This possibility is especially important for beams of negatively charged particles because of their low channeling efficiency. In the present study, the deflection angles of negative particles due to volume reflection were considerably increased in comparison with usage of one bent crystal in our previous experiments [8, 13].

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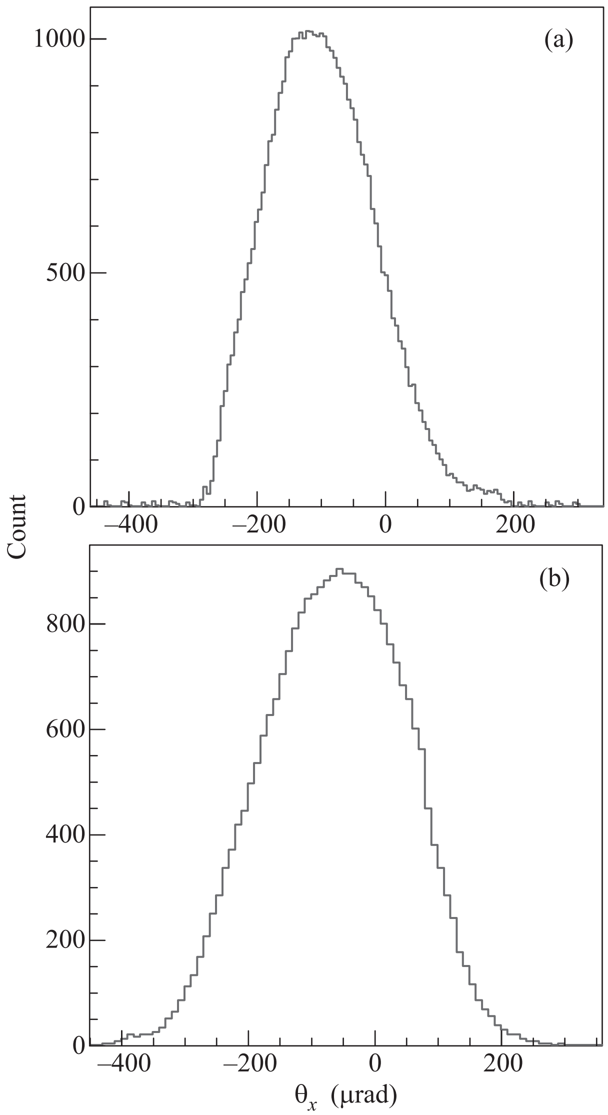

Fig. 6. The distributions of horizontal deflection angles θ_x for the case when the multi-strip deflector orientation corresponds to $\phi_y = 0$ marked by the arrows in Fig. 5: (a) – for protons, (b) – for negative pions

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