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# Deflection of high energy protons by multiple volume reflections in a modified multi-strip silicon deflector

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ABSTRACT

The effect of multiple volume reflections in one crystal was observed in each of several bent silicon strips for 400 GeV/c protons. This considerably increased the particle deflections. Some particles were also deflected due to channeling in one of the subsequent strips. As a result, the incident beam was strongly spread because of opposite directions of the deflections. A modified multi-strip deflector produced by periodic grooves on the surface of a thick silicon plate was used for these measurements. This technique provides perfect mutual alignment between crystal strips. Such multi-strip deflector may be effective for collider beam halo collimation and a study is planned at the CERN SPS circulating beam.


Bent crystals in planar channeling mode have been used for both extraction and collimation of the beams at large circular accelerators [1–3]. Volume reflection from bent atomic planes of a silicon crystal recently observed for high energy protons [4–7] may also be useful for accelerator beam control. It takes place in a bent crystal near the tangential intersection of the particle momentum with bent planes. The deflection angle of particles due to volume reflection $\theta_{VR}$ is limited by a value of about $1.5\theta_c$, where $\theta_c = (2U_o/pv)^{1/2}$ is the critical channeling angle, $U_o$ is the depth of the planar potential well, $p$ and $v$ are the particle momentum and velocity. For instance, protons can be deflected in a direction opposite to the crystal bend due to volume reflection by angles of 14 and 3.5 μrad when their momentum equals 400 GeV/c and 7 TeV/c respectively [7]. The probability of volume reflection is high, approaching 98% for 400 GeV/c protons [6]. However, the problems of accelerator beam extraction and collimation require considerably larger deflection angles of the circulated particles.

The deflection angles due to volume reflection may be increased using a sequence of bent crystals. If volume reflection can occur in

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each crystal of the sequence (multiple volume reflection) the deflection angles of particles increase proportionately with the number of crystals. Multiple volume reflection (MVR) was first realized for 400 GeV/c protons at the CERN SPS with two and five silicon crystals [8,9] which were bent in separate bending devices. It was necessary to align step-by-step the separate crystals to obtain volume reflection of protons in each of them. Afterwards, the silicon multi-strips (MST) were successfully used to obtain multiple volume reflections for 400 GeV/c and 70 GeV/c protons [10,11]. The MST were cut from one silicon plate and bent using a force applied in a common bending device. Nevertheless, the inaccuracy of alignment in these MST was large, about tens of microradians. As a rule, the edge strips were not sufficiently well aligned to contribute to multiple volume reflections.

In this paper the results of testing a new device to realize multiple volume reflection of particles in the sequence of bent silicon strips are presented. A schematic diagram of the crystal deflector and its photograph are shown in Fig. 1. The deflector was produced from a $70 \times 15 \times 5$ mm$^3$ silicon plate. The large faces of the crystal plate were parallel to the (1 1 1) crystal planes, while the entry face was normal to the ⟨1 1 0⟩ axis. Conversely to the method based on the use of external force produced by the holder, the method proposed (described in [12]) uses internal stresses created by the grooves on the surface of a thick crystal plate. The depth of the triangular grooves was about 1.1 mm in our case. The bending of 2 mm long separate strips, which are formed between the grooves, was produced by deformation of the surface layers due to the Twyman effect [13]. Because of the thick unbent base of the crystal deflector, mutual alignment of the surface strips, both angular and spatial, is significantly better than with the use of a bending device.

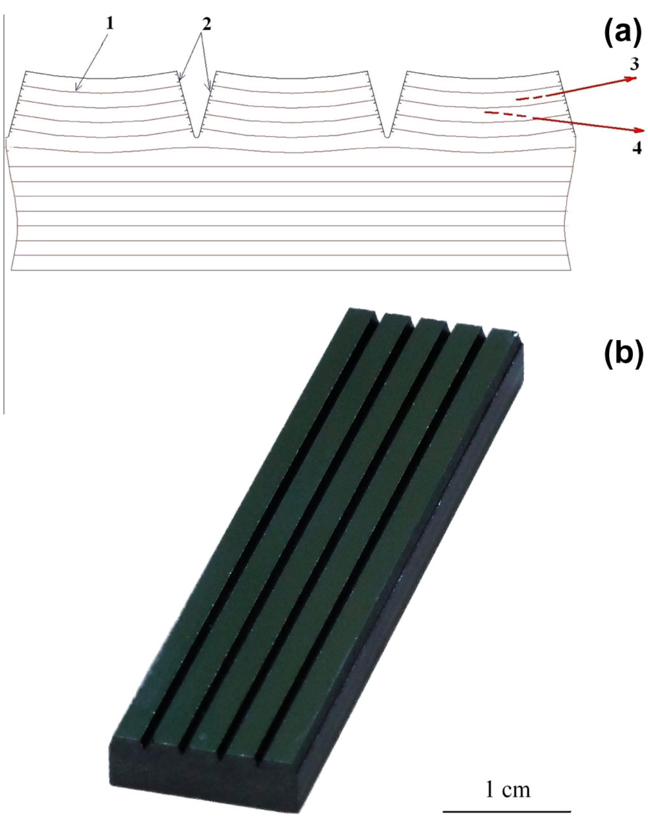


**Fig. 1.** (a) Schematic representation of bent multi-strips produced by the periodic grooves on the thick crystal surface. (1) Bent crystallographic planes, (2) rough surfaces of the grooves, (3) a particle deflected due to channeling and (4) a particle reflected by bent planes. (b) Photograph of the silicon crystal plate with the periodic grooves.

The experiment was performed with 400 GeV/c protons at the H8 external beam line of the CERN SPS. The experimental layout was similar to that described earlier in [14]. Five pairs of silicon microstrip detectors, two upstream and three downstream of the crystal, were used to measure incoming and outgoing angles of particles with an angular resolution in each arm of about 3 μrad [15]. The measured angular divergence in both horizontal and vertical planes of the incident beam was about 10 μrad. A high precision goniometer allowed orienting the multi-strip deflector in both orthogonal planes with an accuracy of 2 μrad. The scheme of the crystal alignment by the goniometer is shown in Fig. 2.

In the first stage of our study a scan of horizontal orientation angles $\varphi_x$ of the crystal deflector was performed. Fig. 3a shows the beam intensity distribution behind the crystal as a function of the particle deflection angles $\theta_x$ at different horizontal angles $\varphi_x$ of the goniometer (the intensity values are shown by different colors). Only particles hitting the crystal near its surface in the range $0 < x < 200$ μm were selected because the bend of the strip layers fast decreases with increasing distance from the surface.

At the beginning (left) as well as at the end of the angular scan the mean deflection angle equals zero due to scattering of particles in the crystal deflector as in an amorphous substance. For deflector orientations near $\varphi_x = 0$ incident particles are deflected by angles of about 200 μrad due to channeling. This deflection angle gives us the strip bend angle $\alpha = 200 \pm 10$ μrad, and the corresponding bend radius $R = 10$ m. There are no other maxima with the same deflection which means that all strips have about the same orientation. So, we may conclude that the method used for the MST production really provides a good mutual alignment of the strips. With increasing $\varphi_x$ the condition for volume reflection initially appears in the first strip and then in the subsequent ones. For this reason, the deflection angle due to VR increases and reaches the maximum value of $5\theta_{VR}$ when VR occurs sequentially in all five strips. In this interval of deflector orientations there is also some fraction of the beam deflected to the bend side due to channeling because particles can enter the channeling acceptance area after volume reflections in the previous strips.

Fig. 4a shows the deflection angle distribution of protons for the goniometer position marked by the arrow in Fig. 3a where multiple volume reflection occurs in all five strips (histogram 1). The efficiency of one side MVR deflection with $\theta_x > 0$ is about 90%. The efficiency of MVR deflection exceeding the RMS angle of multiple

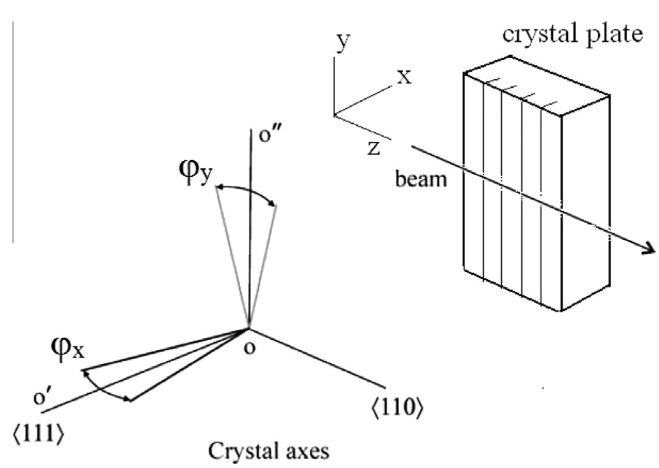


**Fig. 2.** Scheme of the multi-strip crystal installation relative to the beam. The entrance crystal face is normal to the ⟨1 1 0⟩ axis, whose direction is close to the beam direction. The (1 1 1) planes are parallel to the strip surface. They are bent due to the grooves. $\varphi_x$ and $\varphi_y$ are the horizontal and vertical angles of the crystal orientation to align the (1 1 1) planes and the ⟨1 1 0⟩ axis with the beam direction, respectively.

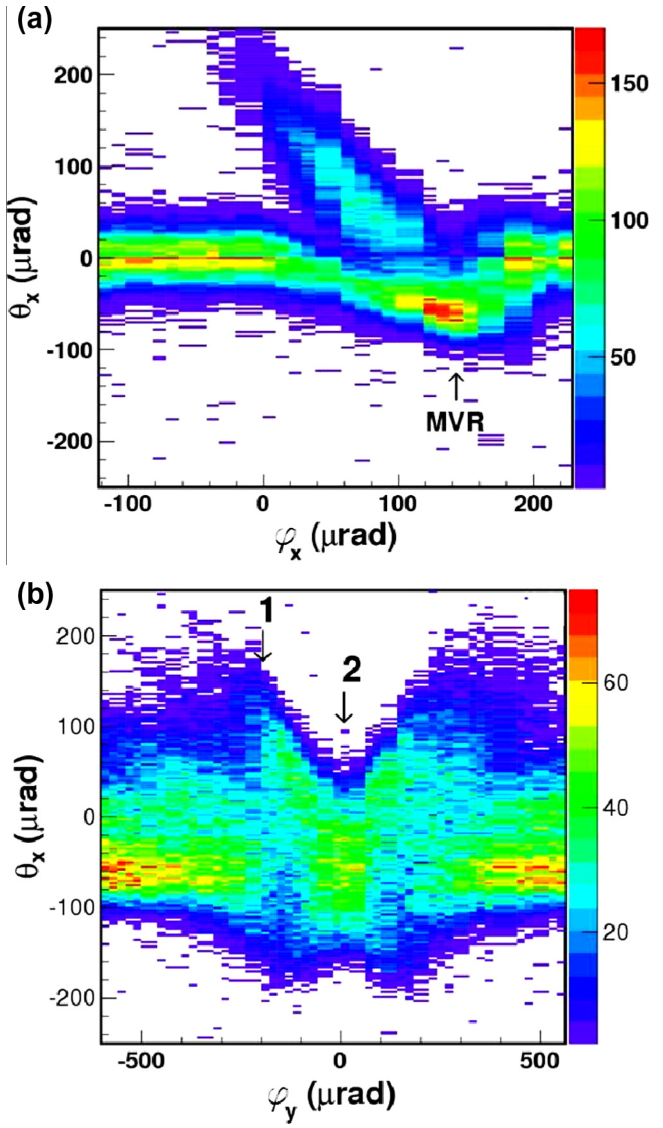


**Fig. 3.** The intensity distribution of the 400 GeV/c proton beam having passed through the five-strip silicon deflector in the deflection angles of particles $\theta_x$: (a) at the different horizontal angles of the goniometer $\varphi_x$. The arrow shows the goniometer position for which volume reflection of protons is realized in all strips. (b) At the different vertical angles of the goniometer $\varphi_y$, with $\varphi_x$ fixed in the position shown by the arrow in (a). The arrows 1–2 are at the goniometer positions for which different mechanisms of particle deflection occur.

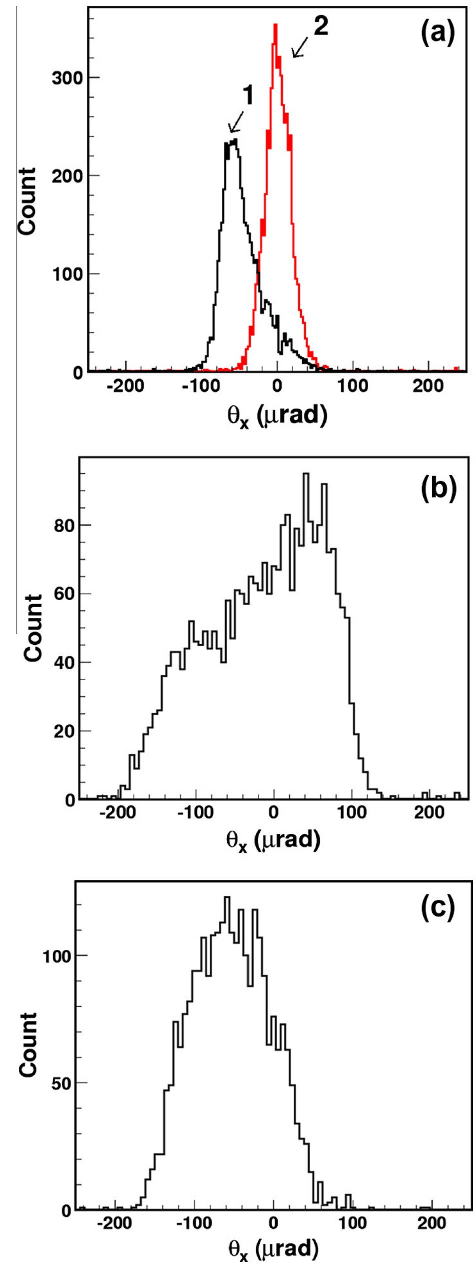


**Fig. 4.** The horizontal deflection angle distributions of 400 GeV/c protons. (a) Histogram 1 for the case shown by the arrow in Fig. 3a when particle volume reflections are realized in all five strips, histogram 2 in the case of multiple scattering for amorphous crystal orientation. (b) For the case shown by the arrow 1 in Fig. 3b when multiple volume reflections in one crystal are realized in the few first strips and deflection due to channeling in the subsequent one. (c) For the case shown by the arrow 2 in Fig. 3b when the ⟨1 1 0⟩ axis is aligned with the beam.

scattering for the amorphous crystal orientation shown by histogram 2 ($\theta_x$ > 25 μrad) is about 80%. The MVR maximum position is about 62 μrad, which agrees well with the theoretical prediction for this five strip deflector $\theta_{MVR} = 5\theta_{VR} = 5 \times 13 = 65$ μrad [7].

There are possibilities to increase the deflection angles of protons in our surface multi-strip deflector. It was predicted in [16] that particles entering a bent crystal with a small angle with respect to a crystal axis can be deflected due to a series of volume reflections by different planes crossing the axis. Besides volume reflection by the crystal plane normal to the bending plane, which was considered above, particles can be also reflected by skew crystal planes. This effect of multiple volume reflections in one crystal (MVR OC) should increase few times the deflection angles of particles. The MVR OC effect was confirmed by an experiment [17] with an external beam of 400 GeV/c protons from the CERN SPS and then at the circulating proton beam of the IHEP synchrotron [18].

As already mentioned, the entry face of our deflector was cut normal to the ⟨1 1 0⟩ axis. After the deflector installation the angle between the ⟨1 1 0⟩ axis and the beam direction was not fixed. As a rule it should be large. The previous scan of horizontal orientation angles $\varphi_x$ allowed us to find the effects of channeling and volume reflection by the normal (1 1 1) crystallographic plane. Now the vertical orientation angle $\varphi_y$ had to be scanned to find the angular area close to the axis direction. This scan was performed with the horizontal orientation angle fixed in the MVR position marked by the arrow in Fig. 3a. Fig. 3b shows the beam intensity distribution observed behind the crystal as a function of the deflection angles $\theta_x$ at different vertical angles $\varphi_y$ of the goniometer. The intensity distribution is symmetric relative to $\varphi_y = 0$ where the ⟨1 1 0⟩ axis direction is parallel to the beam direction. The particle deflection angles increase when the crystal axis direction becomes close to the beam direction. Simulations performed using the computer code SCRAPER [19] for such a crystal deflector give good qualitative agreement for both scans.

Fig. 4b shows the deflection angle distribution for the crystal orientation marked by arrow 1 in Fig. 3b when the beam broadening is maximal. The RMS proton deflection is about 80 μrad, which is more than 3 times larger than for the amorphous orientation. The deflections in the VR direction increase because the MVR OC effect is realized in a few strips, which considerably increases the effective reflection angle in all of these strips. Because of these MVR OC deflections in a few previous strips some particles enter the channeling acceptance area and are captured by the bent planar channels. The resulting deflections of these protons towards the bending side are about $\varphi_x - \alpha$.

Fig. 4c shows the deflection angle distribution for the crystal orientation when the ⟨1 1 0⟩ axis direction coincides with the beam direction (shown by arrow 2 in Fig. 3b). In this case, particles undergo multiple potential scattering by the ⟨1 1 0⟩ atomic strings in a few first strips (doughnut scattering [20–22]). This gives them some vertical momentum, which is sufficient to experience the action of both the (1 1 1) vertical and skew planes. Only then the MVR OC effect can occur for these particles in a few subsequent strips. As a result the mean particle deflection is about 57 μrad, which is larger than for the MVR case shown in Fig. 4a.

Our experiment showed that the bent strips produced by the periodic grooves on the crystal surface really have good mutual alignment, which allows to achieve volume reflection of incident particles in all strips (multiple volume reflection). It was also shown that the effect of multiple volume reflections of particles in one crystal (MVR OC) is realized for the deflector orientations when the direction of its main crystallographic axis is close to the incident beam direction. This regime can allow the use of the multi-strip deflector as a primary collimator because the deflections realized for the beam halo particles are sufficient to direct them onto the secondary absorber. The efficiency of such a primary collimator is planned to be studied at the circulating beam of the CERN SPS.

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