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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 θ_{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 $70 \times 15 \times 5\ \text{mm}^3$ 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.

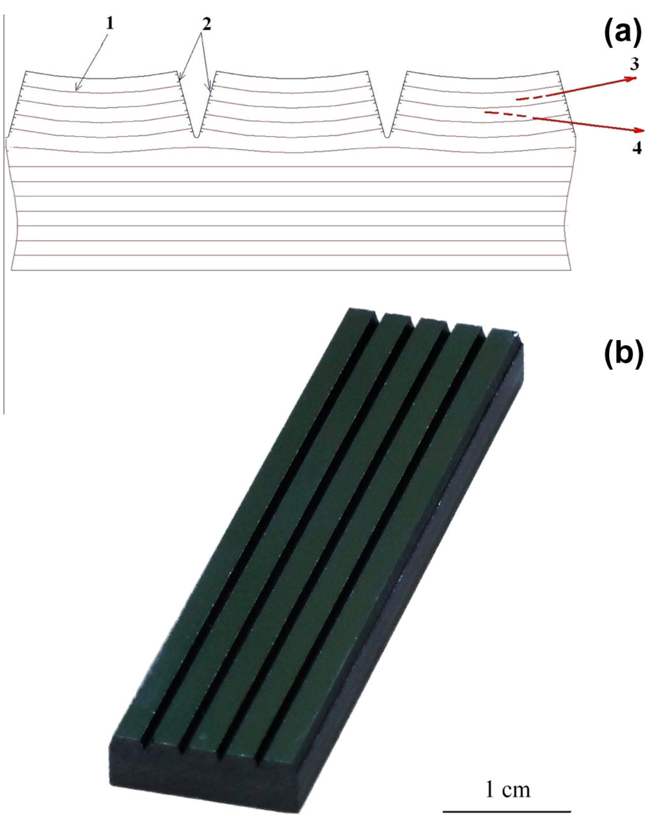

Fig. 1. (a) Schematic representation of bent multi-strips produced by the periodic grooves on the thick crystal surface. (1) Bent crystallographic planes, (2) rough surfaces of the grooves, (3) a particle deflected due to channeling and (4) a particle reflected by bent planes. (b) Photograph of the silicon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

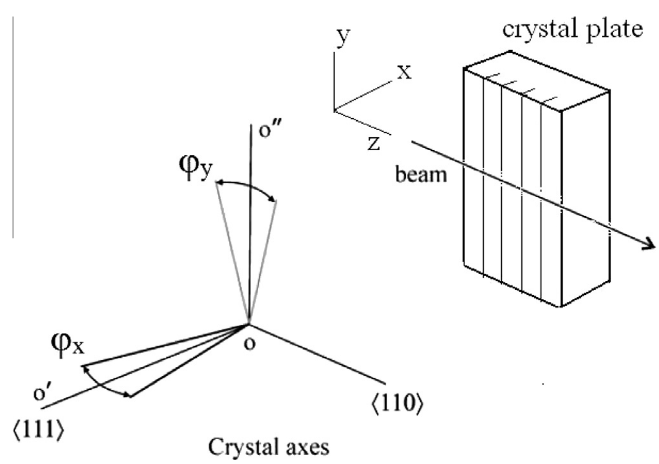

Fig. 2. Scheme of the multi-strip crystal installation relative to the beam. The entrance crystal face is normal to the ⟨1 1 0⟩ axis, whose direction is close to the beam direction. The (1 1 1) planes are parallel to the strip surface. They are bent due to the grooves. φ_x and φ_y are the horizontal 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.