Characterization of multi-strip crystal deflector for high energy proton beams by synchrotron radiation topography with angular scanning

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Abstract. Currently, for extraction and collimation of proton beam at the large accelerators bent silicon single crystals are used. Recently the new device for multiple deflection of the proton beam was developed, it consists of several bent strips of silicon in the reflection mode. In the device the successive bending of silicon strips at the surface of a thick plate is achieved due to internal stresses in the material of the crystal due to the Twyman effect as a result of applying mechanical grooves. Method of X-ray topography at synchrotron radiation with angular scanning was applied for measurement of bending of the individual strips of the deflector and the crystal as a whole. The results of the measurement are compared with the results obtained in the proton beam.

1. Introduction

The bent crystals, due to the high values of the internal electric field, are increasingly used at large circular accelerators in the systems for the extraction and collimation of high-energy proton beams [1–6]. Such crystals have been used mainly in a mode of planar channeling. Recently, a new physical phenomenon has been experimentally discovered – reflection of the beam of high-energy protons by the bent atomic planes of the silicon crystal, and the use of this phenomenon at the accelerators has begun [7–10].

Volume reflection is caused by the interaction of the incident proton with the potential of the bent crystal lattice and occurs at a small length in the region, tangential to the curved atomic plane. The deflection angle of the particles at the reflection from crystallographic planes is limited to 1.5 θ_c, where $\theta_c = (2U_c/pv)^{1/2}$ – critical angle of channeling, U_c ~20 eV – the potential barrier of the planar channel (111) in silicon, p, v – momentum and velocity of the incoming particle. Protons with an energy of E = 400 GeV are deflected by the single strip in the direction, opposite to the bend, at an angle of 15 μrad [10]. Probability of a single reflection is high and at energies around 100 GeV approaches unity. To increase the angle of reflection and to make the use of the volume reflection practical for extraction and collimation of the proton beams it is necessary to increase the value of the deflection angle of the charged particles.

In experiments with accelerators of CERN and IHEP it has been shown that proton beams with energies of 400 and 70 GeV are effectively deflected by the reflection in the devices consisting of several aligned crystals due to multiple enhancement of the deflection angle [11–14]. In these devices separate silicon strips are installed in a metal holder which creates a bending moment for each crystal.

A disadvantage of the multi-crystal structures with successively arranged strips with bending by the mechanical holder, is a misalignment of the individual strips by about 50 μrad [13]. Therefore, for applications such as at the Large Hadron Collider (LHC), the device goes beyond the requirements for the system of localization of the LHC, which requires the crystals disoriented to no more than few μrad from each other, with the total bending of a few tens of μrad with a bending radius about 100 meters [15].

Thus, for ultrahigh-energy particle beams a chain of successive crystals with very similar parameters of bending of each of them is required. To create such a device there was recently proposed a new scheme of bending [16], which is based not on the external force exerted by the holder but caused by internal stresses created by the grooves mechanically applied on the surface of a thick crystal (figure 1). Bending of the crystal strips between the grooves is caused by deformation of their surface layers caused by the Twyman effect known in optics [17].

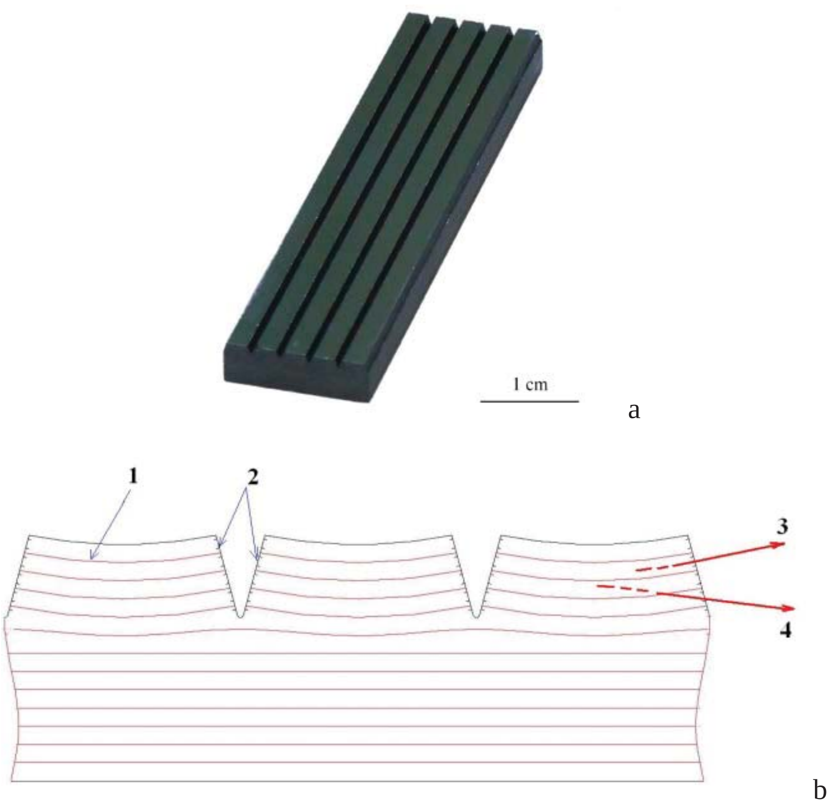


Figure 1. Silicon plate with grooves (a) and the supposed layout of the bent crystal planes due to the Twyman effect (b). 1 – bent crystallographic plane, 2 – rough surfaces of grooves, 3 – beam deflected by channeling, 4 – reflected beam of particles.

A recent experiment [18] at the SPS accelerator of CERN has shown that by using this crystal device it is possible to deflect the beam of protons with energy of 400 GeV. However, for use of such device at LHC with beam energy of 7 TeV detailed information on the size and shape of the bent crystal strips is needed to be known. Calculation of the deformation caused by surface treatment is difficult, so that data on the deflector can only be obtained experimentally. The aim of this work is to study the silicon deflector using diffraction of synchrotron radiation, which is sensitive to small local bending of the crystal.

2. Method

Method of the investigation of the deflector must meet several requirements. Firstly, it should be local, since the deflector is bent unequally in different points of the crystal. Secondly, the method should characterize the bent crystal quantitatively, i.e. rocking curves of the crystal should be measured in its different regions. Method of X-ray topography at synchrotron radiation with angular scanning, which satisfies these requirements, was proposed in [19]. The method consists in to obtaining a series of digital topographic images of the crystal at different angles of incidence of radiation on the investigated crystal, which allows one to restore local rocking curve at each point of the image. In the present study, this method has been implemented at the "Mediana" station of the Kurchatov synchrotron radiation source [20]. The sample was a silicon plate with the surface treated with chemical mechanical polishing, (111) orientation, thickness of 5 mm, size 71 × 16 mm, with 4 triangular shaped grooves of about 1 mm depth made along its long side. The beam incident on the sample was formed by an asymmetric silicon monochromator in (511) reflection. The sample was mounted in a symmetric Bragg reflection (333), so the non-dispersive plane-wave conditions were realized (figure 2). The wavelength was 0.72 Å, the Bragg angle was 20°, the depth of X-ray absorption of 100 microns. Estimated rocking curve of the sample had a width at half maximum (FWHM) 3 μrad. The sample was oriented so that the grooves lie perpendicular to the diffraction plane, so bending in the plane perpendicular to the grooves was registered. Images were recorded by area detector of 4008 × 2672 dimensions with a pixel size of 8.9 microns. The crystal was rotated with piezo actuator by steps of 0.7 μrad in the direction shown in figure 2, an image of the crystal was recorded at each position.

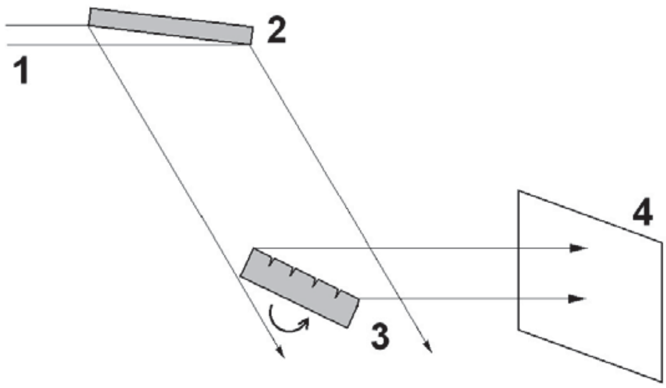
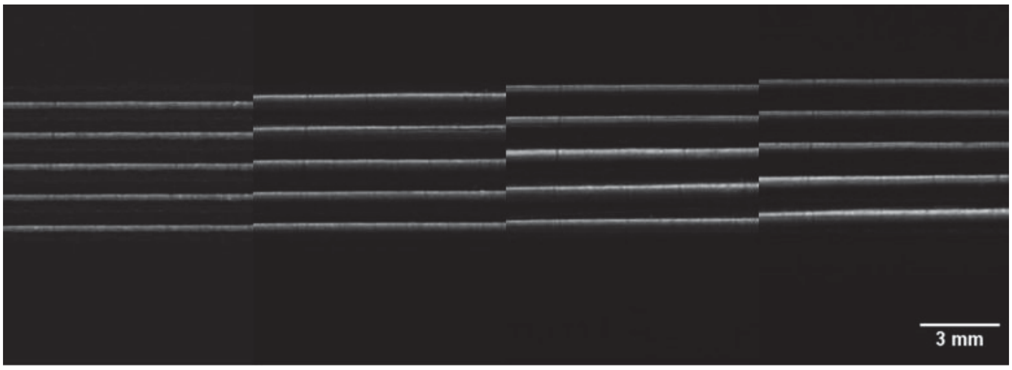


Figure 2. Scheme of the experiment: 1– radiation beam from the source, 2– monochromator crystal, 3– sample, 4– area detector.

3. Results

Figure 3 shows the topographs of the crystal obtained at different values of the angle of the sample. It can be seen that in the studied angular range of 200 μrad, grooves were always in reflecting position, indicating a strong broadening of the rocking curve of silicon in the grooves. When the crystal was rotated counterclockwise (figure 2), different regions of the crystal consecutively entered the reflecting position. In the topographs obtained at the increasing angle of rotation, the crystal region which reflected the X-ray beam, appeared at the lower end of each strip and moved to its top end. The uneven appearance of reflections on different strips is also observed, movement of the most bright parts of the crystal from the top down is visually traced.



a b c d

Figure 3. Topographs of the sample obtained at the position of the crystal of 0 (a), 81.2 μrad (b), 97.3 μrad (c), 105 μrad (d).

In order to quantitatively characterize the bending of the crystal the integration region of the size of 3618 × 12 pixels was taken in the topographs, at that the width of the image of the single strip was about 90 pixels. Integration region was shifted in the direction across the strips, so the intensity of crystal reflection of the chosen region was obtained as the dependence from its position on the crystal and from the angle of rotation of the crystal. Thus the rocking curves were reconstructed for different parts of the crystal. The rocking curves for a single strip are shown in figure 4. Attention is drawn to the fact that the rocking curves corresponding to the areas at the edges of the strips that are near the grooves, are greatly broadened with respect to the estimated width of the rocking curve (3 μrad). This means that the material close to the grooves has a strongly disturbed crystal structure. As the distance from the groove grows, the width of the rocking curve becomes closer to that expected for a perfect crystal structure. Peak point position of the curves is a quantitative measure of bending of the crystal, so the angular distance between the extreme peaks of one strip in the average equal to 66 μrad. With strip width of 2.4 mm this corresponds to average curvature radius of ~40 m, and the crystal planes parallel to the surface are concave as shown in figure 1. Figure 5 shows the dependence of the local maxima of the rocking curves on the coordinate across the crystal. It can be seen that the strips are slightly turned relative to each other, the overall bending of the crystal is 15 μrad. The bending is directed in the opposite to the bending of each strip, i.e. the entire crystal is convex.

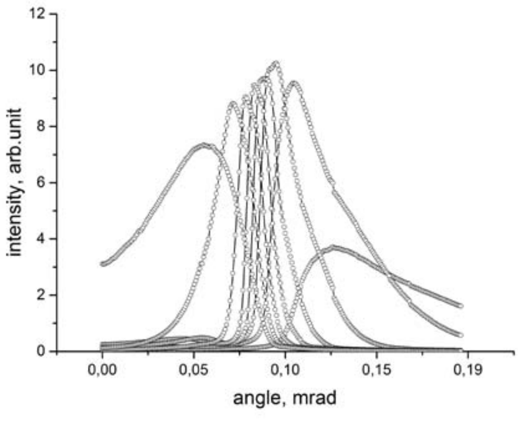


Figure 4. The rocking curves of the crystal within the same strip.

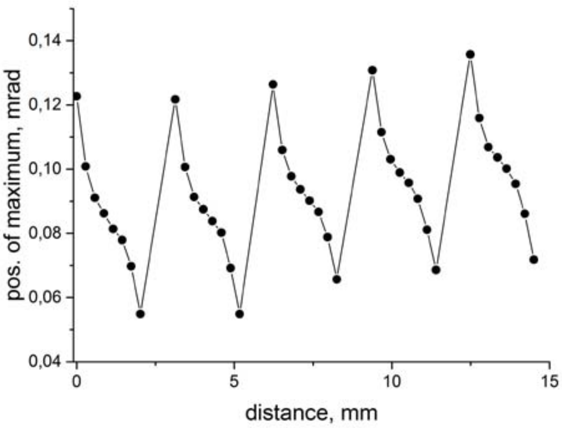


Figure 5. Dependence of the position of local maxima of the rocking curves on the coordinate across the crystal.

Using the data of figure 5 it is possible to receive the local values of radius of curvature of a separate bent crystal strip $R(l)= dl/d\alpha$. Changes of radius versus the coordinate are shown in figure 6. It is visible, that at length l ~ 1 mm (it is just a characteristic length of process of reflection of 7 TeV protons $R{\cdot}\theta_c$ ~ 1 mm) the radius is constant and equal to 80 m that is close to requirements of the LHC at 7 TeV energy. The fact of turn of the separate bent strips relative to each other by an angle of 3.7 μrad is also positive because this angle is equal approximately to reflection angle of 7 TeV protons. In this case, orientation offset of consecutive stripes will match the trajectory of the deflected particles, and operation of the crystal device will be improved.

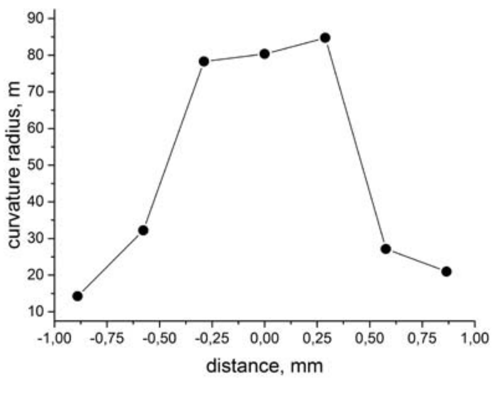


Figure 6. The curvature radius of separate crystal strip versus the coordinate.

4. Summary

Thus, with the help of synchrotron radiation topography distortion of the crystal lattice in a multi-strip deflector was observed. These distortions lead to the appearance of macroscopic stress, causing bending of the crystal. Bending of the crystal was observed at the scale of each strip and the crystal as a whole. The measured parameters of deformed crystalline strips well explain the data of experiment on deflection of the 400 GeV proton beam [18], where the beam is effectively deflected by successive reflections on five strips. The angular region of the proton deflection complies with the bending angle of the stripes, measured here with the help of x-rays.

Thus, the method of X-ray topography with angular scanning performed at synchrotron radiation makes it possible to characterize the deflector prior to its use at the high-energy beams of protons at large accelerators and can be used in the development of manufacturing technology of the deflector. We hope, that using a method of X-ray topography one can optimize the multi-crystal deflectors and for higher energy of protons which it is planned to reach by the future machines, such as FCC in CERN and SPPC in China with the energy up to 100 TeV.

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