First results on the focusing of a 70-GeV proton beam by a curved single crystal

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A method for focusing a beam with a curved single crystal has been devised and implemented. Specifically, a 70-GeV proton beam was deflected and focused into a narrow line 200 μm wide by a silicon crystal 2 mm wide.

Curved single crystals are widely used to deflect beams of high-energy particles. Another important application may lie in the focusing of these beams. Several ways to solve this problem have been proposed. One is to focus the beam by a thin curved crystal oriented in the direction transverse with respect to crystallographic planes, as in Ref. 1. Strictly speaking, what was achieved in Ref. 1 was not a focusing of a parallel beam but a selection of particles whose trajectories intersected at a common line. Another possible approach is to make use of the deformation of planes which occurs in a thick crystal when it is squeezed. These methods suffer from the disadvantage that there is a background of an unchanneled component of the beam. In the present study we have realized a method for focusing a parallel beam to a line in which the beam is simultaneously turned through a significant angle. As a result, a pure focused beam can be obtained.

The idea underlying the method is that the surface of the exit end of the curved crystal is shaped in such a way that the tangents to the crystallographic planes at the surface pass through a common line. If the crystallographic planes are to be bent into a shape corresponding to a cylinder of radius R (Fig. 1), the line running through the centers of curvature (line OO') must be on the surface of the cylinder in accordance with which the end of the crystal is shaped. In the case of ideal curvature and shaping of a crystal, the size of the beam at the focus will be determined by the product of the focal length $L=\sqrt{4r^2-R^2}$ and twice the critical angle for channeling, ψ. Since this critical angle is quite small ($\psi=0.02$–0.002 for particles with energies from 100 GeV to 10 TeV in the case of planar channeling in silicon), and since the technological capabilities for bending and shaping crystals make it possible to achieve a focal length ~ 1 m, the beam dimensions attainable are a few tens of microns in the gigaelectron-volt energy range and a few microns in the teraelectron-volt range. The linear magnification during the focusing ($F=2L\psi/H$, where H is a characteristic width of the crystal, ~ 1 mm) can reach values of a few hundredths and a few thousandths, respectively.

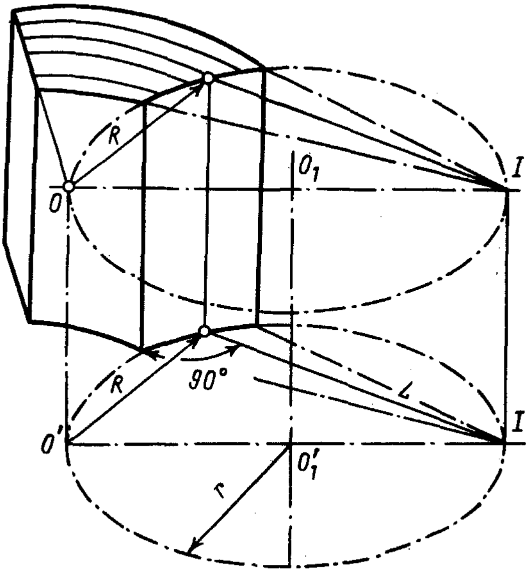

FIG. 1. Principle for focusing a beam by means of a crystal. OO'—The line running through the centers of curvature of the crystallographic planes; O_1O_1'—the axis of the cylinder of radius r in accordance with which the end of the crystal is shaped; II'—focus line, at which the tangents to the curved planes converge according to a known geometric theorem.

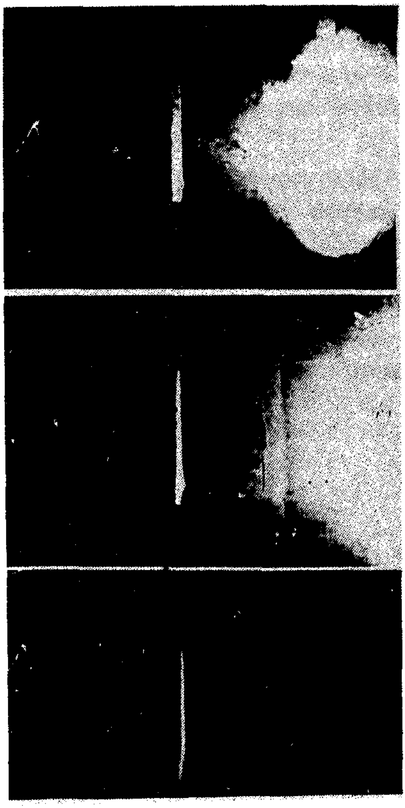

FIG. 2. Image of the turned beam on three emulsion layers, at distances of 0.7, 2, and 3.5 m from the crystal. (Visible at the right are the unturned beam, with a secondary-particle halo, and a feature corresponding to particles dechanneled in the curved part of the crystal.)

A focusing experiment was carried out on a 70-GeV proton beam of the accelerator of the Institute of High-Energy Physics. In this experiment, a silicon single crystal with dimensions $H \times V \times Z = 2 \times 15 \times 70$ mm (respectively the width, height, and length along the beam) in the (111) orientation was used. This crystal was bent into a shape corresponding to a cylinder of radius $R = 2.7$ m over a distance of 65 mm. The end of the crystal was shaped in accordance with a cylinder of radius $r = 2.2$ m, so the focal length was $L = 3.5$ m. A beam with a size $\sigma_x = 2$ mm and a small angular divergence $\sigma_\alpha = 0.1$ mrad was incident on the crystal. Scintillation counters measured the intensity of the direct beam and that of the beam turned through an angle of 24 mrad by the test crystal. In the optimum orientation, the crystal deflected 3% of the particles of the direct beam (for the specified properties of the beam and the crystal, this value agrees with the calculated value). A focusing effect was detected by means of a nuclear emulsion. Several layers of emulsion were held at various distances from the exit end of the crystal. Figure 2 illustrates the focusing of the turned beam. Figure 3a shows the beam envelope constructed from the results of a study of the exposed emulsion layers on a microdensitometer, in comparison with the calculated envelope. Figure 3b shows the measured beam profile at the crossover. Its size ($2\sigma_x = 200\ \mu$m) agrees within 15% with the calculated value. The beam halo might be due primarily to deformation of the crystal during the bending and the deviation from an ideal shape. We hope to correct this defect in future work. The contrast of the focus (the effect-to-background ratio) is 100 according to an examination of the emulsion layers.

This focusing method might be useful for producing pure beams of micron size in the teraelectron-volt energy range in accelerators of a future generation. Here it would be sufficient to transmit an image of the beam deflected by the crystal to the experimental apparatus with the help of unit optics.

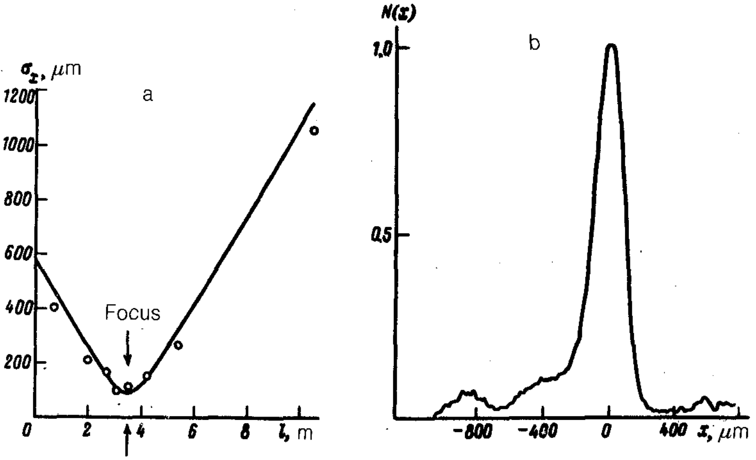

FIG. 3. a: Envelope of the beam focused by the single crystal. Points—Experimental; line—calculated for the case of ideal focusing. b: Beam profile at the crossover (3.5 m for the crystal). The microdensitometer resolution is 15 μm.

Another important application of a crystal focusing device would be reversing the direction of particles (focusing from a point into a parallel beam). With the focusing crystal a few meters away from an internal accelerator target in the form of filament, one could focus and deflect a large fraction ($\sim 50\%$) of the secondary particles generated at this target. Estimates suggest that this method would make it possible to produce beams of secondary particles with an intensity $\sim 10^8$ particles per second at colliders presently under construction.

[1] V. A. Andreev, V. V. Baublis, N. F. Bondar' *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **41**, 408 (1985) [JETP Lett. **41**, 500 (1985)].

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