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**Crystal Deflector for Highly-efficient Channelling Extraction
of a Proton Beam from Accelerators**

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The design and manufacturing details of a new crystal deflector for proton beams are reported. The technique allows one to manufacture a very short deflector along the beam direction (2 mm). Thanks to that, multiple encounters of circulating particles with the crystal are possible with a reduced probability of multiple scattering and nuclear interactions per encounter. Thus, drastic increase in efficiency for particle extraction out of the accelerator was attained (85%) on a 70-GeV proton beam. We show the characteristics of the crystal-deflector and the technology behind it.

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1. Introduction

During the last decade, the use of bent crystals for beam extraction in circular accelerators has been intensively investigated in several laboratories for high-energy physics [1,2,3]. The potential advantages of the method are at least threefold. The required devices are of low cost. It seems possible to operate the crystal in a circular collider even during a luminosity run or simultaneously with internal targets. The extracted flux of particles is inherently stable, since no resonant blow-up of the beam is needed to direct the beam onto the crystal for extraction. The crystal has a minimal "septum width", that is the crystal depth required to deviate particles from their impinging trajectory, hence it seems potentially very convenient even for application in a beam-loss localisation system as a coherent scatterer [4].

In the frame of the CERN-INTAS collaboration 2000-132, we recently achieved a substantial progress experimenting crystal-assisted beam deflection at the 70-GeV accelerator in the IHEP at Protvino. Extraction efficiency of the order of 85% was repeatedly obtained for an impinging intensity as high as 10^{12} protons [4]. The key reason of this successful operation was the use of very short crystals for extraction. The crystal length was selected close to the optimal value foreseen by the physics of proton channeling [5,6]. During extraction, the circulating particles may encounter the crystal many times, suffering a very small divergence at each pass due to reduced probability of scattering and nuclear interaction in the crystal. Multiple passage of particles allowed the protons to be eventually channeled by the crystal planes, leading to the experimentally recorded high efficiency.

Fig. 1 shows the theoretical prediction [7] of extraction efficiency as a function of the crystal length, for an impinging proton beam of 70-GeV, together with the experimental values determined in the campaign of measurements through 1997-2001 with crystals of different size and design. The trend is clear from both theory and experiments: the shorter the crystal, the higher the efficiency. The theoretical plot also indicates the value of the crystal length optimal for 70-GeV protons, which is slightly less than 1 mm. Indeed, such a short length for a crystal deflector is very difficult to be implemented. In this paper, we discuss the design and manufacturing of the crystal deflector that led to the successful execution of the experiments.

2. Crystal bending system

The first designs of short crystals appeared in the literature in 1998 [3]. It consisted of an "O-shaped" deflector cut from a monolithic piece of oriented silicon. Here the bend was obtained by compressing the crystal at its middle part. Indeed, this method is not suitable for an efficient deflection with a crystal shorter than 5 mm. Any attempt to shorten this length resulted in a reduced bending efficiency as shown in Fig. 1 for the 3-mm long "O-shaped" crystal sample. The "O-shaped" crystal is not good below 5 mm because the legs of the "O" must have enough thickness to ensure a proper shape for the deflector; if the whole length is below 5 mm, the legs take too much of it, and the bent middle part (which actually deflects the particles) becomes relatively short compared to the legs.

Therefore, a new design to produce a suitably short sample was needed. A possibility is the use of the anisotropic properties of a crystal lattice. From the theory of elasticity it is known (see e.g.[8]) that bending a crystal plate in the longitudinal direction causes some

"anticlastic bending" or twists to appear in the orthogonal direction. In that case, a crystal plate obtains the shape of either a saddle, or a barrel, or a pure cylinder depending on the anisotropic properties of the material. The surface equation for the crystal plate in the ideal case of the method of moments discussed in Ref.[9] is:

$$y = \frac{1}{2R_{\parallel}} z^2 - kx^2 \quad (1)$$

where y is the direction tangent to the incident beam on the centre of the crystal, x is oriented along the thickness (crystalline direction (111) of silicon) and z is oriented along the height. $1/R_{\parallel}$ and $1/R_{\perp}$ are the so called main curvatures of the bent surface $1/R_{\perp}$: is the curvature experienced by channelled protons and $1/R_{\parallel}$ is the curvature along the z direction, as depicted in Fig. 2. Parameter k is a coefficient related to the actual anisotropy of the material, which is bound up to $1/R_{\perp}$, i.e., $|k|=1/(2R_{\perp})$; its sign determines the shape of the surface: $k>0$ leads to the equation of a hyperbolic paraboloid (saddle), $k<0$ gives the equation of an elliptical paraboloid (barrel), and $k=0$ is for a parabolic cylinder. Eq. (1) is rigorous for an infinite crystal plate. In the case of a finite crystal, Eq. (1) provides a second-order approximation of the real case. Parameters k and R_{\perp} must be determined experimentally.

It turns out that the first case applies to Si (111), therefore the crystal plate takes the shape of a saddle as sketched in Fig.2. The orthogonal bending of a narrow crystal plate was used for beam deflection. The technical advantages of such a deflecting system vs. the "O-shaped" deflector are manifold: it may be easily made shorter along the beam, has no straight sections in bending, and needs no additional material around the "legs".

The bending crystals were manufactured at the Semiconductors and Sensors Laboratory of the University of Ferrara as narrow strips, about 2-mm thick in the direction of the beam. The metal holder showed in Fig. 3 imparts the right curvature to the samples. A strip of monocrystalline silicon was bent in the longitudinal direction by an angle of about 100 mrad in the orthogonal direction: as a consequence the strips were bent in the beam direction by about 1 mrad. The quality of the strip bending was preliminary checked by the laser system described in Ref. [8]. Then the crystals were tested directly in the experiments on the 70-GeV high-energy accelerator at Protvino.

3. Sample preparation.

The starting material consisted of prime-grade, (111) oriented, 525- μ m-thick silicon wafers. The crystals were sliced to form $0.5 \times 2 \times 50$ mm³ (thickness (x), and length (y), height (z), respectively) by means of a mechanical dicing saw. The length of 2 mm was to be exposed to steer the protons in the collider and was determined according to the previous considerations on efficiency. The (111) crystalline direction was intended for alignment toward the radial direction in the accelerator.

A crucial methodology for the achievement of high-performance crystal extractors was to impart a chemical treatment to the surface of the crystal. The preparation of the sample is required to remove the defects induced by the saw at the beam entry and exit facets of the silicon crystals. Indeed, mechanical slicing of the samples induces a large amount of scratches, dislocations, line defects and anomalies that would reduce the overall channelling

efficiency of the crystal. According to the experience gained through previous runs at the accelerator, it came out that a superficial layer as thick as 30 μm was ineffective for channeling. We attributed this effect to the presence of in-depth lattice imperfections induced during the slicing.

Thus, we attempted the removal of such a layer by a sequence of room-temperature chemical treatments to the surfaces [10]. To avoid an unwanted sample thinning, the largest surfaces were protected by Apiezon wax while the others were left uncoated. The prime treatment was a wet planar etching (HF, HNO₃ and CH₃COOH (2:15:5) and the timing was such to obtain an etching depth of about 30 μm . The samples were prepared and treated in clean-room environment (class 100) to avoid material contamination, which would otherwise modify the etch rates locally and the finishing of the etch ground.

Preliminary, the first process stages were aimed at the removal of pollutants such as greasy or metallic compounds. The wafers were degreased in trichloro-ethylene, acetone and then isopropanol. A two-stage cleaning procedure was then carried out to remove organic and metallic impurities from the surface of the wafers. The samples were cleaned in solution of water, hydrogen peroxide and ammonium hydroxide (5:1:1) at 75 oC for 10 min. After a short dipping in diluted HF (10% in weight), the wafers were washed in water, hydrogen peroxide and hydrochloric acid (4:1:1) at 75 oC for 10 min. The specimens were cut from the coated wafer through a diamond-blade saw avoiding any alignment with major crystalline axes.

Finally, the entry and exit facets were ready for the prime chemical etching to remove the mechanical damages induced by the blade. The wax coating was eventually removed according to standard procedure and the resulting samples were once more subject to a complete cleaning process.

4. Tests with high-energy protons

The new crystal-deflectors were first tested in an external proton beam of 70 GeV. Fig. 4 schematically shows the experimental set-up. The incident proton beam was monitored by scintillation counters S1, S2. The crystal holder in the beam line could be tilted through a goniometer around the axis orthogonal to the proton beam and to the (111) orientation of the crystal. The rotation of the goniometer can be imparted in steps of 5 μrad each. The optimum crystal orientation was obtained by tilting the crystal sample through the goniometer and determining the maximum counting rate of the remote scintillation counters S3, S4.

Precise measurement of the profiles of the bent beam was done with nuclear photo-emulsions placed outside the vacuum chamber, 7 m far from the crystal.

Fig. 5 comparatively shows the results of the tests for the chemically polished deflectors vs. those for the unpolished samples. The profile of the beam bent by a chemically polished crystal is more uniform and sharp. Its width corresponds to the crystal thickness once the beam divergence within the critical angle of channeling (equal to 20 μrad for 70 GeV protons) has been taken into account. On the other hand, the beam bent by a mechanically polished crystal exhibits irregularities corresponding to an angular distortion of the order of 100 μrad .

After testing in an external beam, the crystals were installed in the IHEP U-70 accelerator ring to extract circulating beams. The crystals with chemically polished faces have shown the best efficiency for beam extraction — up to about 85% [4].

New crystals can be applied for beam extraction and collimation of beams at accelerators in a broad range of energies as shown in Ref.[4]. One of the major applications would be the use in the collimation system of large colliders such as the CERN-LHC.

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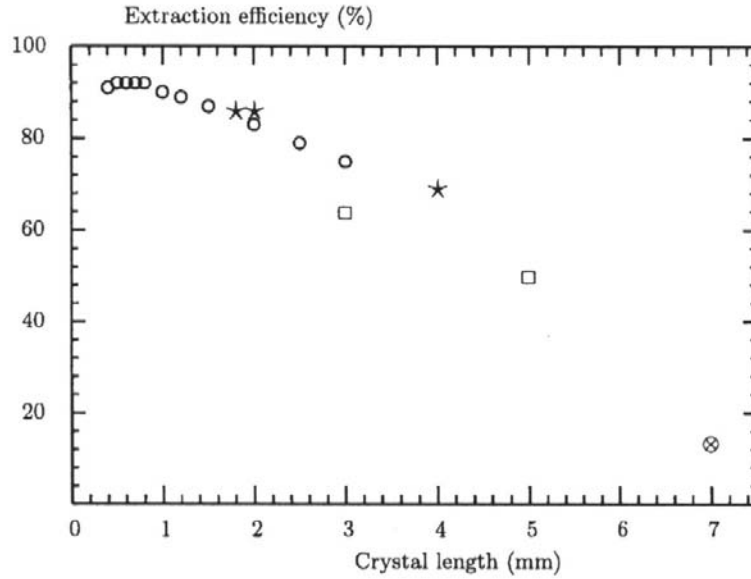


Figure 1 Crystal extraction efficiency as measured for 70-GeV protons. Recent results [4] (☆, strips, 1.8, 2.0, and 4 mm long), results of 1999-2000 [7] (□, “O-shaped” crystals 3 and 5 mm), and of 1997 (⊗, strip 7 mm). Also shown (○) is the Monte Carlo prediction [7] for a perfect crystal with 0.9 mrad bending. The size of the markers corresponds to the errors of simulations and measurements (about 2.8%).

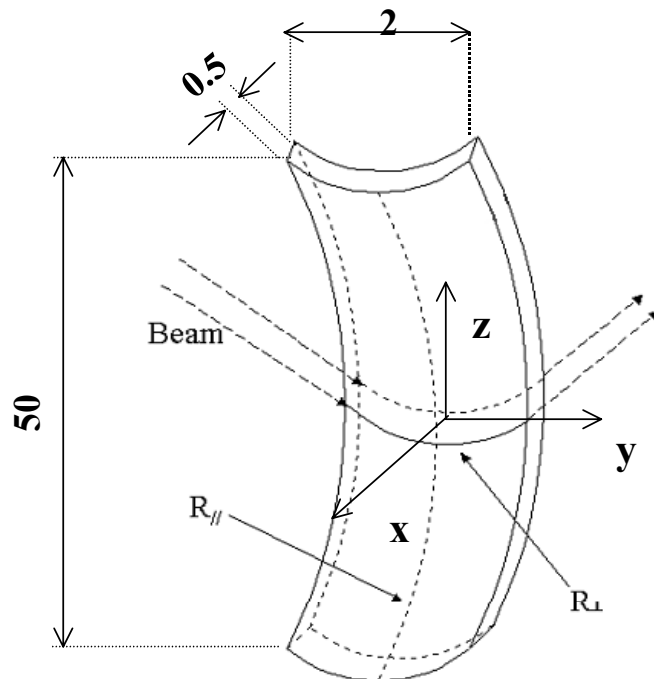


Figure 2 Scheme of the bent crystal plate (not in scale). Dimensions are expressed in mm, y is the direction tangent to the incident beam on the centre of the crystal, x is oriented along the thickness (crystalline direction (111) of silicon) and z is oriented along the height.

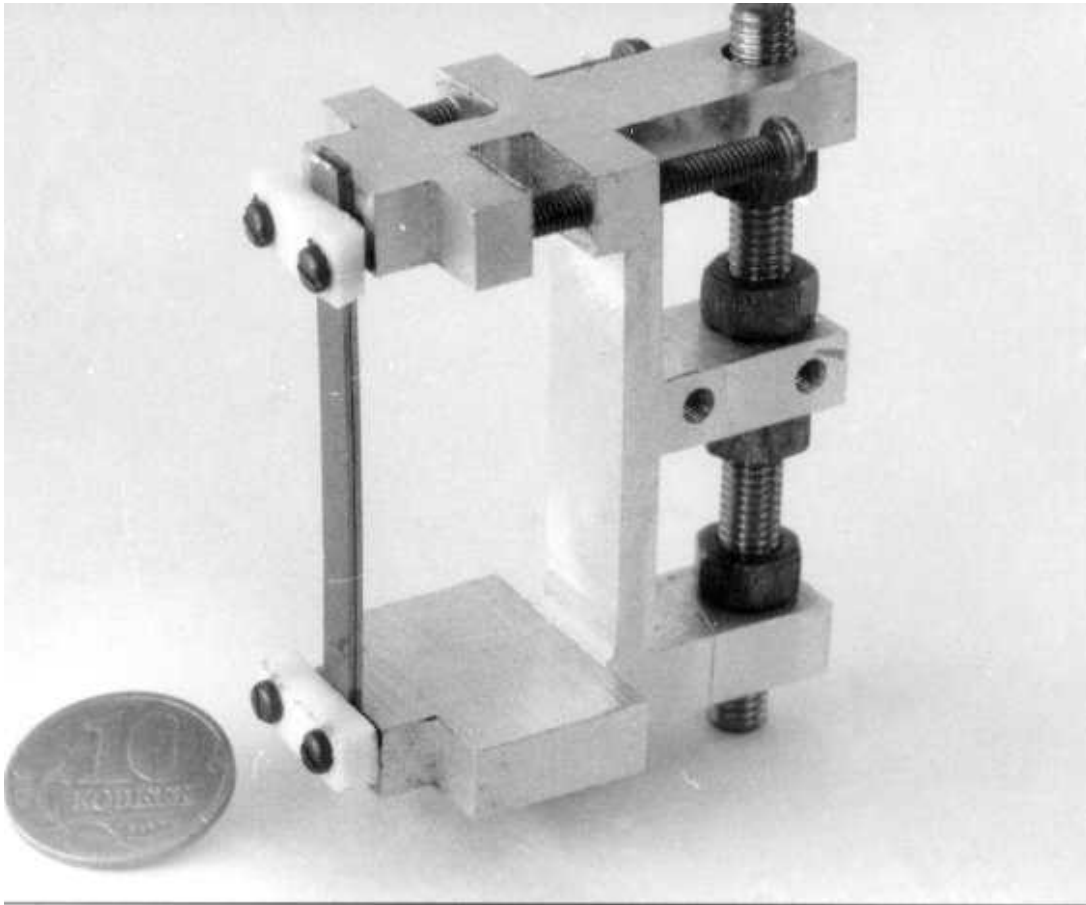


Figure 3 Photo of crystal bending device (on the left is a narrow crystal strip).

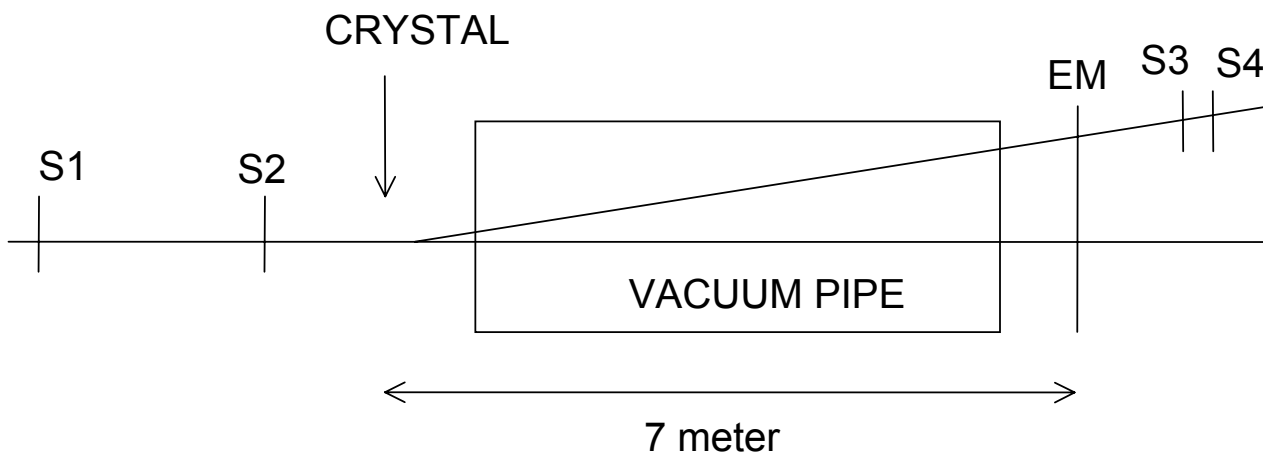


Figure 4 Experimental set-up for checking the crystal deflector quality. S1, S2, S3, S4 are scintillator counters, EM is a nuclear emulsion layer.

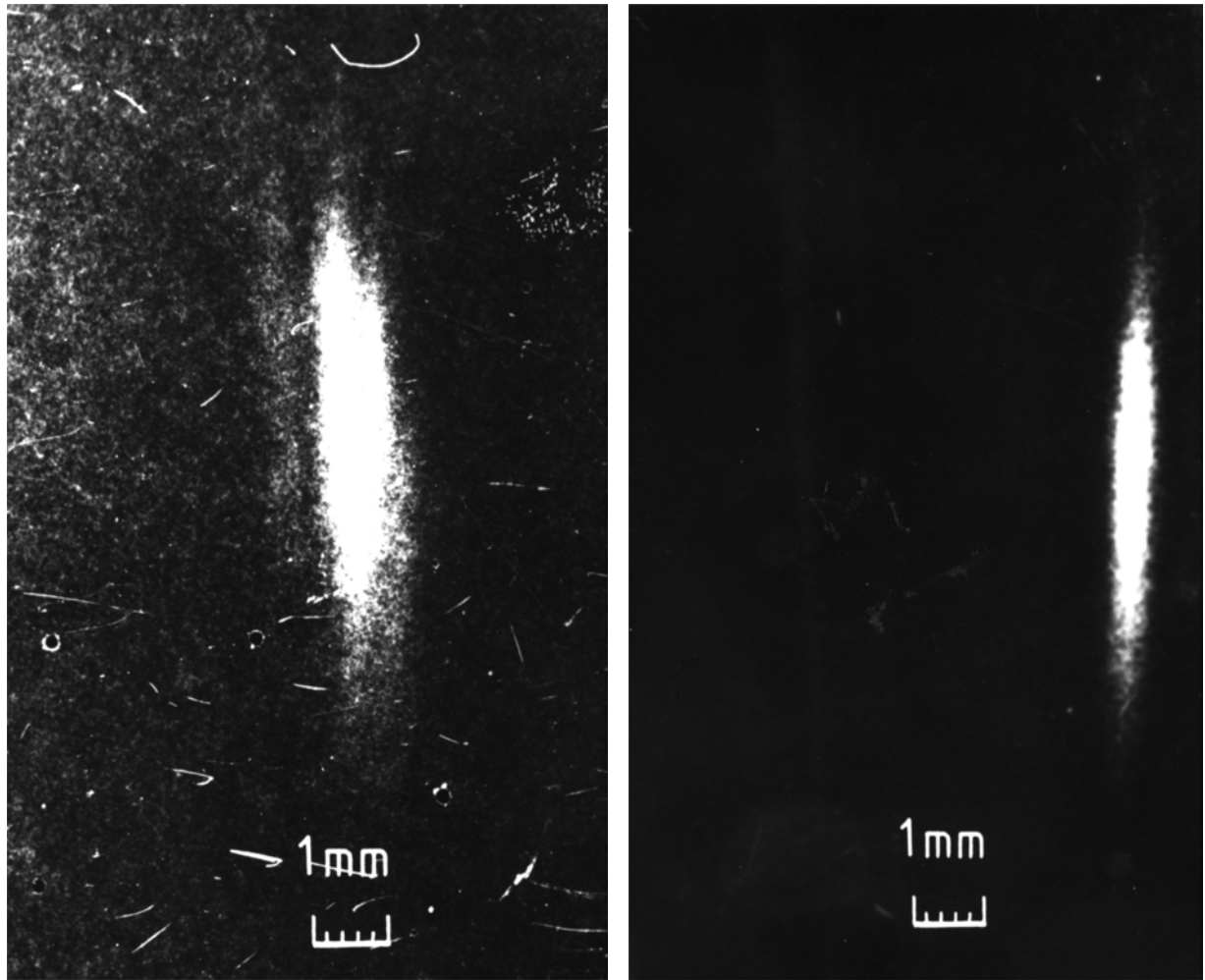


Figure 5 Image of the beam deflected through mechanically treated (left) and chemically polished crystals (right).