Observation of the Influence of the Crystal Surface Defects on the Characteristics of the High Energy Particle Beam Deflected with a Bent Monocrystal

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Abstract

Nowadays bent crystals are widely applied for high energy beam steering. Some problems, like the extraction of particles from a large hadron collider, imply a high perfection of the crystal near-surface layer. In this work we have measured precisely the profiles of the beam bent by crystal, with use of nuclear emulsions. The inefficient layer measured for several crystals is as thick as $\simeq 50\mu$m. There was observed also a specific mosaics of crystals near the ends, which has led to the angular perturbations of the bent beam exceeding the critical angle of channeling.

I.

Nowadays the bent monocrystals are widely applied for high energy beam steering [1]. Experiments [2-4] have shown that deflection efficiency and dechanneling length for GeV particles are close to theoretical predictions, that is, silicon crystals in the bulk are close to ideal.

However, some problems like a particle extraction from a large hadron colliders, demand a high perfection of the near-surface layer of a crystal. The width of the layer inefficient for channeling, due to the crystal machining, affects the efficiency of particle extraction.

From measurements with X-ray diffraction it is known that the width of near-surface amorphous layer in good polished crystal does not exceed $\sim 1\mu$m. However, it is unknown so far, how efficient may be the channeling of high energy particles in the crystal layer adjacent to its surface. In the present work a direct measurement of the width of the unchanneling layer has been performed for several crystals of silicon and germanium. A specific kind of mosaicity near the crystal faces was observed, which lead to the angular perturbations of the bent beam in excess of the critical angle of channeling.

Precise measurement of the bent-beam profile was performed by use of a few layers of the nuclear photo emulsion, placed at different distances downstream of the crystal. The grain size (the track width) of the photoemulsion in use amounts about $\sim 0.5\mu m$, which is more than one order better than resolution of typical coordinate detectors (microstrips and drift chambers).

There were tested several crystals as long as ~ 5cm of various thickness, from 300 μm to 2 mm, bent at the angles of $\sim 10 \div 20$ mrad. The miscut angle of the crystal slabs was less than 1 arc minute. The crystal bending was made with a well-known "Serpukhov" device [5]. The crystal ends had the long ($\sim 1cm$) straight parts to avoid deformation of faces caused by a bending stress. The incident protons had a divergence $\sim$ 1 mrad much greater than Lindhard angle to assure a uniform illumination of the crystal entrance.

The first tested crystal as thick as 700μm has shown a strange result: the bent beam was splitted in two parallel parts (see Fig.1).

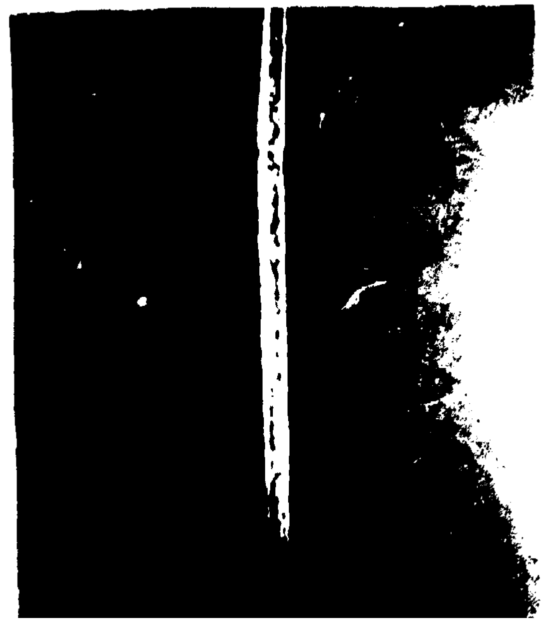

Figure. 1. The image the bent beam splitted in two parts (the distance from the crystal ~ 0.5m).

By dividing the variables (changing the bending angle, varying the lengths of the crystal straight ends, modifying the shape of the crystal faces) it was discovered that the cause of the angular perturbations was an unflat shape of the crystal exit face, where the master has bevelled the edges on each side for his convenience.

The different shapes of a crystal end face (cross-section in the plane of beam bending), and the qualitative scheme of the particle emerged angles, reconstructed with the use of several emulsions were shown in Fig.2.

The analysis of beam profiles on emulsions has shown that the sharp bumps on the face cause the 70 GeV beam deflection at $\alpha \sim 1$ mrad. This indicates on the crystal lattice distortions at a depth $h \sim (3R_c) \times \alpha = 50cm \times 1mrad = 0.5mm$. Here we adopt $(3R_c)$, the bending radius equal to the three critical ones, as the radius when an efficient channeling is possible (at smaller radii of planes deformation, the particles will be dechanneled and will not give such a correlated picture, as one sees from the figures).

The crystals with classic flat faces (Fig.2a) did not show such strong effects (except for the places of accidental breaks on edges to cause sizable distortions). Fig.3 shows the bent

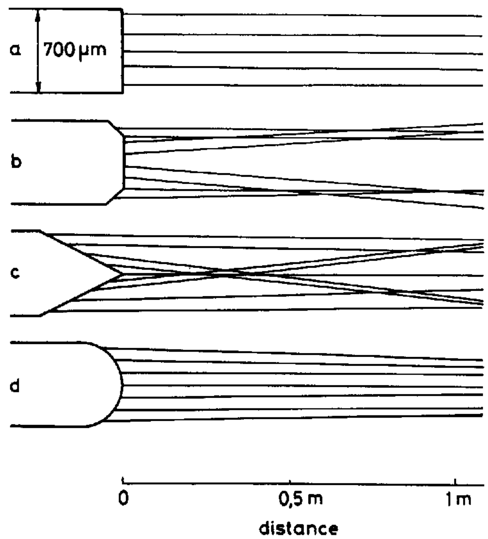

Figure. 2. Demonstration of the "shape effect".

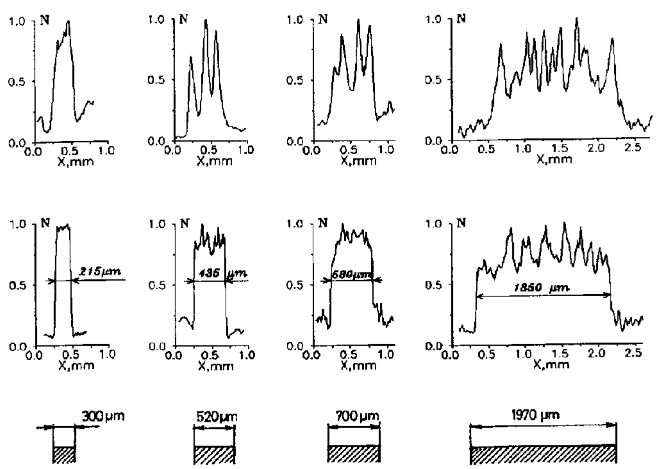

Figure. 3. The bent-beam profiles for several crystals with flat end faces at the distance of ~ 15cm (bottom) and ~ 1m (top). The bottom part of the Figure shows also the corresponding thicknesses of crystals.

beam profile evolution downstream of the crystals. There are presented the data from emulsions positioned ~15 cm (bottom profiles) and ~1 m (top profiles) apart the flat exit faces of the crystals, developed by the microphotometer. The further development of the beam image on the emulsions, by counting the particle tracks directly under microscope, has shown that the beam borders are very sharp, $< 10\mu$m, and its size is equal to the FWHM of the profiles handled by the microphotometer. From comparing the beam images on the nearest emulsions with the crystal thickness, it was found that all the tested crystals have a measurable unchanneling layer (see Table 1), which has the width in the range 40 to 60 μm. (Notice that a loss of the useful cross-section due to the miscut angle was smaller than $\sim 10\mu$m on each side of crystal).

The channeled beam in the plane of bending had no appreciable angular distortion as in the case with an unflat faces, but it was not ideally uniform, neither. At the distance of ~1 m from the crystal there was observed a fragmentation of the beam into separate zones as wide as $\sim 100\mu$m (see Fig.3 and 4a).

The observed angular distortions $\alpha \sim 100\mu$rad in this case are due to the lattice deformation at a depth of $h \sim (3R_c) \times (\sim 100\mu rad) = 50\mu m$ on the crystal end face. The visual image of typical fragmented beam in Fig.4a strongly reminds the character of the surface defects at the crystal face. The photograph of this face under microscope is shown in Fig.4b.

The side faces of the crystals were polished better (a surface roughness $< 0.05\mu$m), but also had several cracks as wide as $\leq 1\mu$m, like at the end faces. One may suppose that these cracks define the presence of an inefficient layer $\sim 50\mu$m observed in experiment.

We briefly conclude as follows. In the course of the studies we have observed:

A). The "shape effect", which is the fact that a nonflatness of the end face shape leads to a strong angular perturbation (much greater than Lindhard angle) of the beam downstream of the crystal. A convex surface leads to particle focusing, while a concave surface leads to defocusing. We emphasize that this effect, observed in bent crystals, is due to just the end face shape of a crystal, and does not depend on the crystal bending angle.

B). The effect of beam fragmentation, that is, of local angular perturbations of the beam of order of the critical angle of channeling, which occurs even at a flat face if the surface is polished with worse accuracy. On the background of local angular distortions, no global effects were seen, as opposed to the case of a nonflat face. It is not excluded that a violation of the plane parallelity may be present with a flat face also, as a result of an edge effect. This point requires a further study, since it is quite important for bending highly-parallel beams (for instance, for a beam extraction from supercolliders).

C). The presence of an unchanneling layer near the side faces $\sim 50\mu$m, defined by the quality of the surface polishing.

Further investigation should show how far can the parameters of the bent beams be improved with a better accuracy of the surface polishing.

One should expect at higher energies ~ 1 TeV the beam fragmentation to be hardly seen, because the oscillation period of the channeled particle $\lambda \sim 100\mu$m starts to exceed the depth of the lattice deformation at a face of crystal. But the thickness of the inefficient layer may increase with energy.

As shown in [7], the problem of a non-zero inefficient layer is important for a crystal extraction of protons from a large hadron colliders.

The presence of an inefficient layer $\sim 50\mu$m may sizably decrease (by 50%) the efficiency of proton extraction from a multy-TeV collider; the layer with a thickness greater than a hundred μm reduces the efficiency by almost an order.

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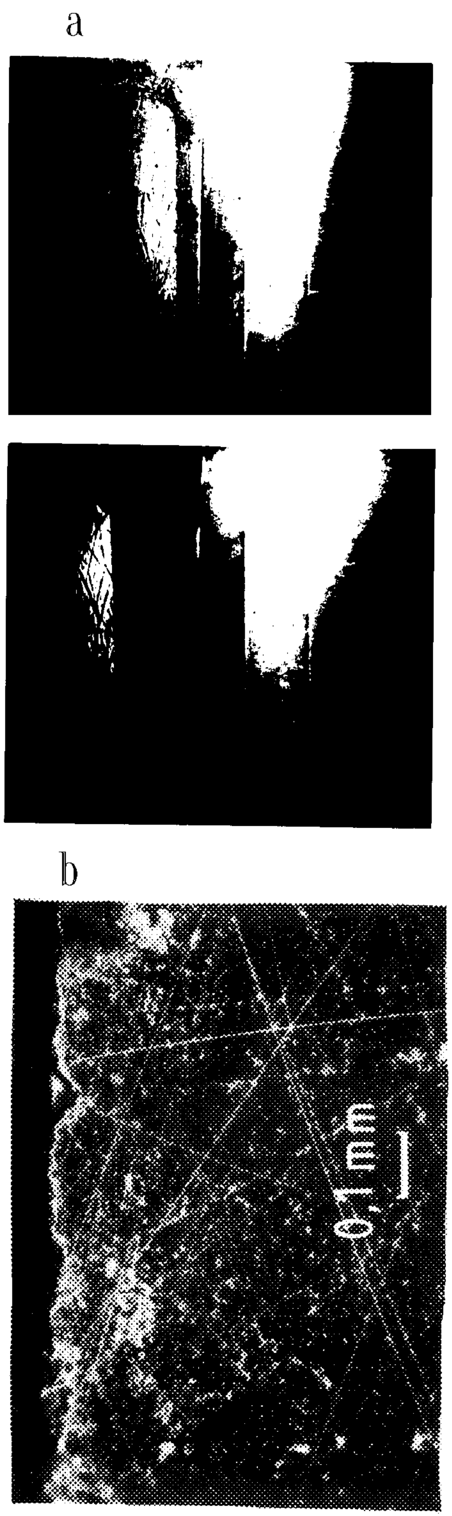

Figure. 4. b)– The amplified-with-microscope photograph of the crystal flat end face for the thickness of 1970 μm. a)– The images of the beam bent with this crystal, at the distance $\sim$1 m (bottom), and at ~ 0.5m (top).

Table I

Characteristics of crystals and size of the bent beams.

Type of crystal	Length mm	Thick-ness μm	Beam size μm	Inefficient layer μm
Si(110)	25	300	215	42
Si(111)	30	520	435	42
Ge(110)	17	600	510	45
Si(111)	47	650	550	50
Si(111)	80	700	580	60
Si(111)	28	1970	1850	60

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