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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

Biryukov V.M. et al. Observation of the influence of the crystal surface defects on the characteristics of the high energy particle beam deflected with a bent monocrystal: IHEP Preprint 95-13. – Protvino, 1995. – p. 9 , figs. 7, tables 1, refs.: 7.

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. We have precisely measured the profiles of the beam bent by the crystal, with the use of nuclear emulsions. The inefficient layer measured for several crystals is as thick as $\simeq 50\mu$m. There was also observed a specific mosaics of crystals near the ends, which led to the bent beam angular perturbations exceeding the critical angle of channeling.

Аннотация

Баранов В.И. и др. Наблюдение влияния дефектов кристаллической поверхности на характеристики пучка частиц высоких энергий, отклоненного изогнутым монокристаллом: Препринт ИФВЭ 95-13. – Протвино, 1995. – 9 с., 7 рис., 1 табл., библиогр.: 7.

В настоящее время изогнутые монокристаллы широко применяются для управления пучками частиц высоких энергий. Некоторые задачи, например вывод частиц из сверхпроводящих коллайдеров, требуют высокого совершенства приповерхностных слоев кристалла. В настоящей работе прецизионно измерены профили отклоненного кристаллом пучка частиц с помощью ядерных фотоэмульсий. Измеренный для нескольких кристаллов неэффективный слой составил величину $\simeq 50\mu$m. Наблюдалась также специфическая мозаичность кристаллов вблизи торцов, проводящая к угловым искажениям отклоненного пучка, превосходящим критический угол каналирования.

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 in a close agreement with theoretical predictions, that is, silicon crystals in the bulk closely resemble 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.

It is known from measurements with X-ray diffraction that the width of near-surface amorphous layer in well polished crystal does not exceed $\sim 1\ \mu$m. However, it is unknown so far, how efficient the channeling of high energy particles in the crystal layer adjacent to its surface may be. In the present paper a direct measurement of the unchanneling layer width 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 was observed.

The measurements were carried out with the setup shown in Fig.1. The tested Si crystal was mounted in a goniometer placed near the magnet – corrector M2. The 70 GeV proton beam was brought onto the crystal by the magnet M1. The beam bent by the tested crystal was transported along the beam-line axis, where it was cleared from the background by the magnet M3 and M4. The crystal alignment was performed by feedback from the angular dependence of the signal on the scintillating counters S1 and S2.

Precise measurement of the bent-beam profile was performed with the use of a few layers of the nuclear photoemulsion, placed at different distances downstream the crystal. The beam pictures on the emulsions were handled with the microphotometer, or by direct counting of particle tracks with a microscope. The grain size (the track width) of the photoemulsion is about $\sim 0.5\ \mu m$, which is more than by an order better than resolution of typical coordinate detectors (microstrips and drift chambers).

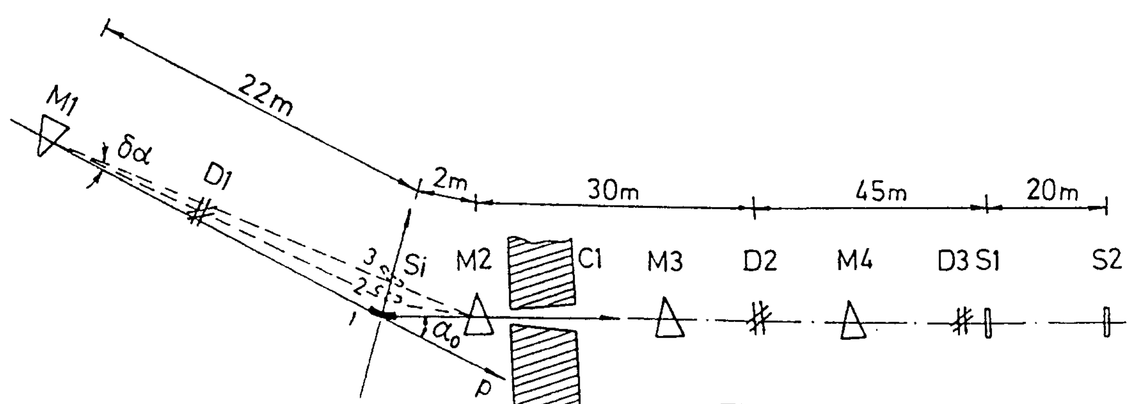

Fig. 1. The equipment layuot.

There were tested several crystals $\sim$ 5 cm long and of various thickness, ranging 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 long ($\sim$ 1 cm) straight parts to avoid deformation of faces caused by a bending stress. The incident protons had a divergence of $\sim$ 1 mrad, much greater than the Lindhard angle, to provide a uniform illumination of the crystal entrance.

The first tested crystal 700 μm thick has shown a strange result: the bent beam was splitted in two parallel parts (Fig.2).

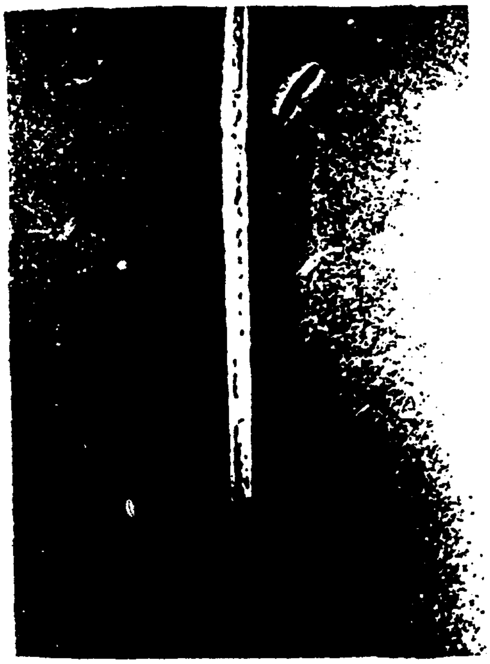

Fig. 2. The image of the bent beam splitted in two parts (the distance from the crystal $\sim$ 0.5m).

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 had bevelled the edges on each side for his convenience.

Trapezoidal (due to bevelled edges) shape of the end face of this crystal and the qualitative drawing of the angular perturbations of the bent beam are shown in Fig.3b.

To even a greater extent the "shape-effect" is demonstrated in Fig.4, where the crystal face edges were bewelled in the shape of triangle, so the crystal cross-section is rectangular in the upper part (Fig.3a), then it gradually becomes a trapeze (Fig.3b) in the middle, to finally become a sharp triangle at the bottom (Fig.3c). As Fig.4 shows, the beam profile on emulsion is alike to the shape of the crystal face. One sees that particles experience a focusing effect near the sharp edges at the crystal face. In case of a semicircular end face (Fig.3d), the whole beam gradually converges to a nondistinct crossover at $\sim$2 m downstream the crystal. It is possible that the shaping of the crystal face to some circular form can become another method of a beam focusing from parallel to point (in addition to the methods discussed in [6]).

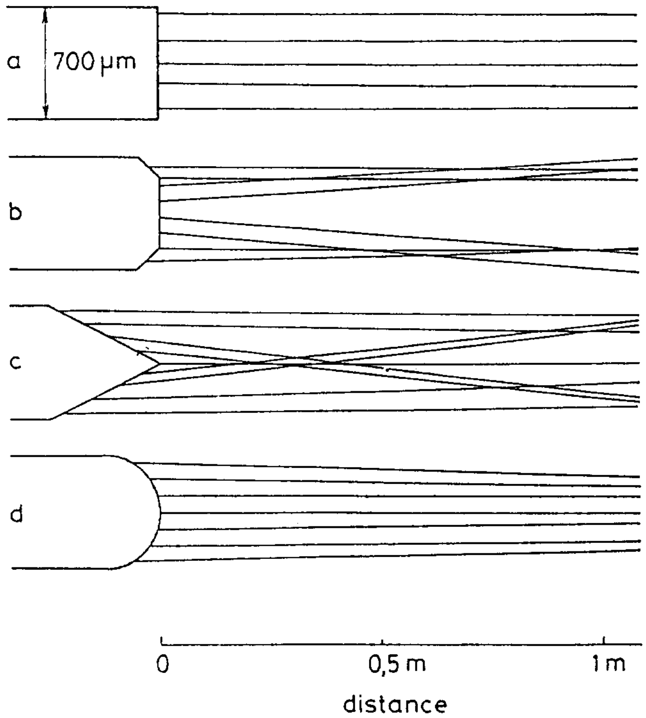

Fig. 3. Different shapes of the crystal end face (cross-section in the plane of beam bending) and the qualitative scheme of the particle emerged angles, reconstructed with the use of several emulsions: a) classic rectangular face; b) trapeze face; c) triangular face; d) semicircular face.

The analysis of beam profiles on emulsions has shown that the sharp bumps on the face cause the 70 GeV beam deflection of by $\alpha \sim 1$ mrad. This indicates to the crystal lattice distortions at a depth $h \sim (3R_c) \times \alpha = 50\ cm \times 1\ mrad = 0.5\ mm$. Here $(3R_c)$ is taken to be the bending radius equal to the three critical ones, wherein 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 in figs.).

The crystals with classic flat faces (Fig.3a) did not show such strong effects (except for the places of accidental breaks on edges to cause noticeable distortions). Fig.5 shows the bent beam profile evolution downstream 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. When comparing the beam images on the nearest emulsions with the crystal thickness, all the tested crystals were bound to have a measurable unchanneling layer (see Table), whose width ranges from 40 to 60 μm. (Note that a loss of the useful cross-section due to the miscut angle was smaller than $\sim 10\ \mu$m on each side of the crystal).

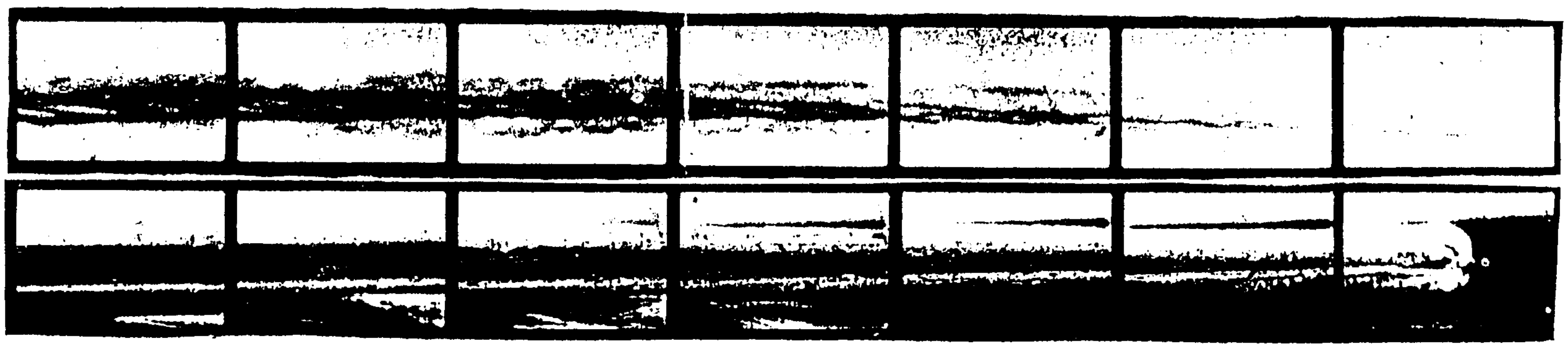

Fig. 4. The photo of the triangular end face of the crystal (left) and the image of the beam bent with this crystal at the distance of ~ 0.4m (right).

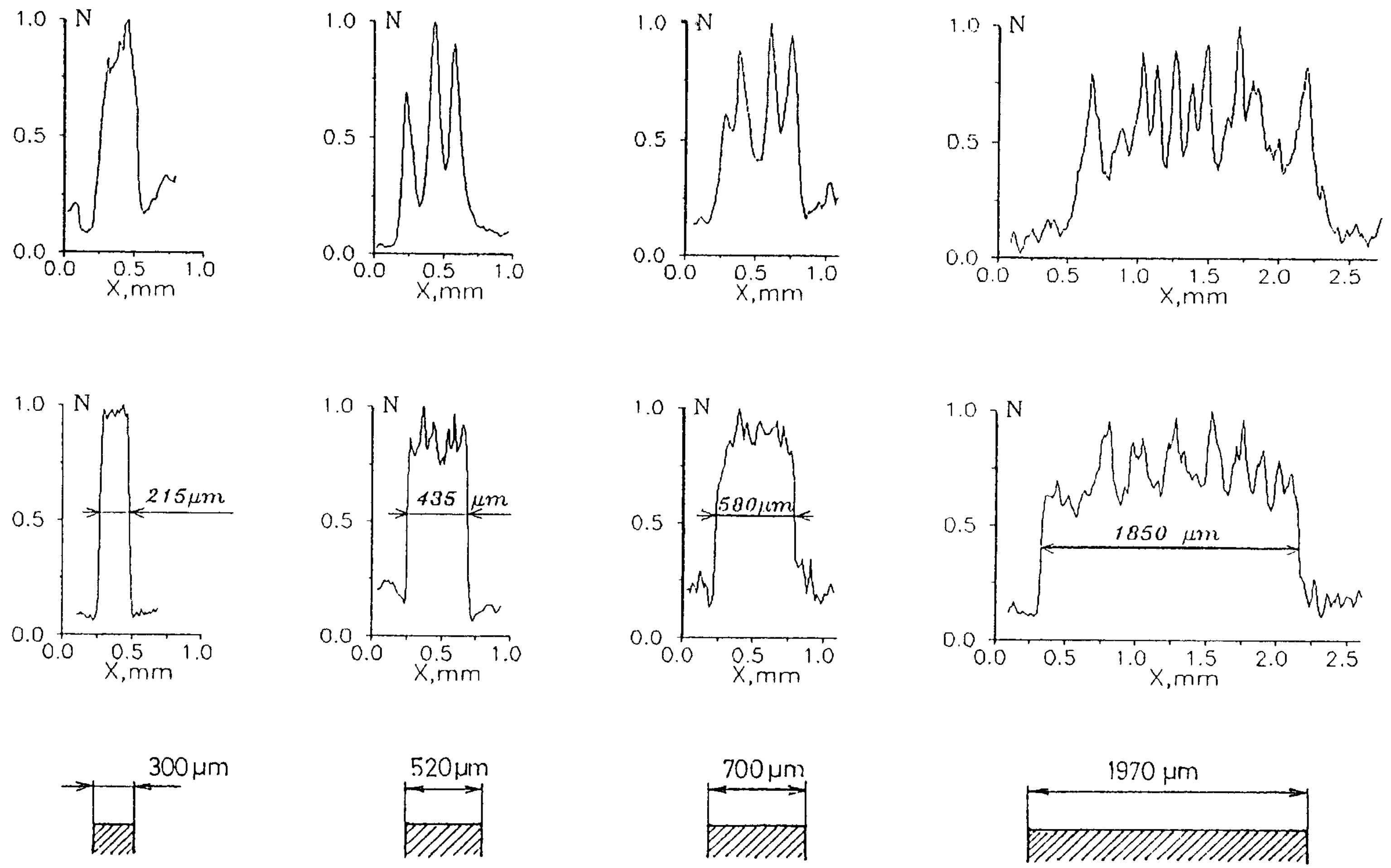

Fig. 5. The bent-beam profiles for several crystals with flat end faces at the distance of ~ 15 cm (bottom) and ~ 1 m (top). The bottom part of the Figure shows also the corresponding thicknesses of crystals.

Table 1. Characteristics of crystals and the bent beams sizes.

Type of crystal	Length mm	Thickness 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

The channeled beam in the plane of bending had no appreciable angular distortion as in the case with 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 ~ 100 μm (wide see Fig.5 and 6a,c,e).

The observed angular distortions of $\alpha \sim 100$ μrad in this case are due to the lattice deformation at the depth of $h \sim (3R_c) \times (\sim 100\ \mu rad) = 50\ \mu m$ on the crystal end face. The visual image of the fragmented beam in Figs.6a,c,e strongly reminds the character of the surface defects at the crystal faces. The photographs of these faces under microscope are shown in Figs.6b,d,f.

The side faces of the crystals were polished better (a surface roughness < 0.05 μm), but also had several cracks ≤ 1 μm (Fig.7), like at the end faces. One may suppose that is due to these cracks the presence of an inefficient layer ~ 50 μm observed in the experiment.

We can briefly conclude the following.

A. The "shape effect" is that a nonflatness of the end face shape leads to a strong angular perturbation (much greater than Lindhard angle) of the beam downstream the crystal. A convex surface leads to particle focusing, while a concave surface leads to defocusing. Emphasize that this effect, observed in bent crystals, is just due to the end face shape of the 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 the order of the critical angle of channeling, which occurs even at a flat face if the surface is not polished perfectly.

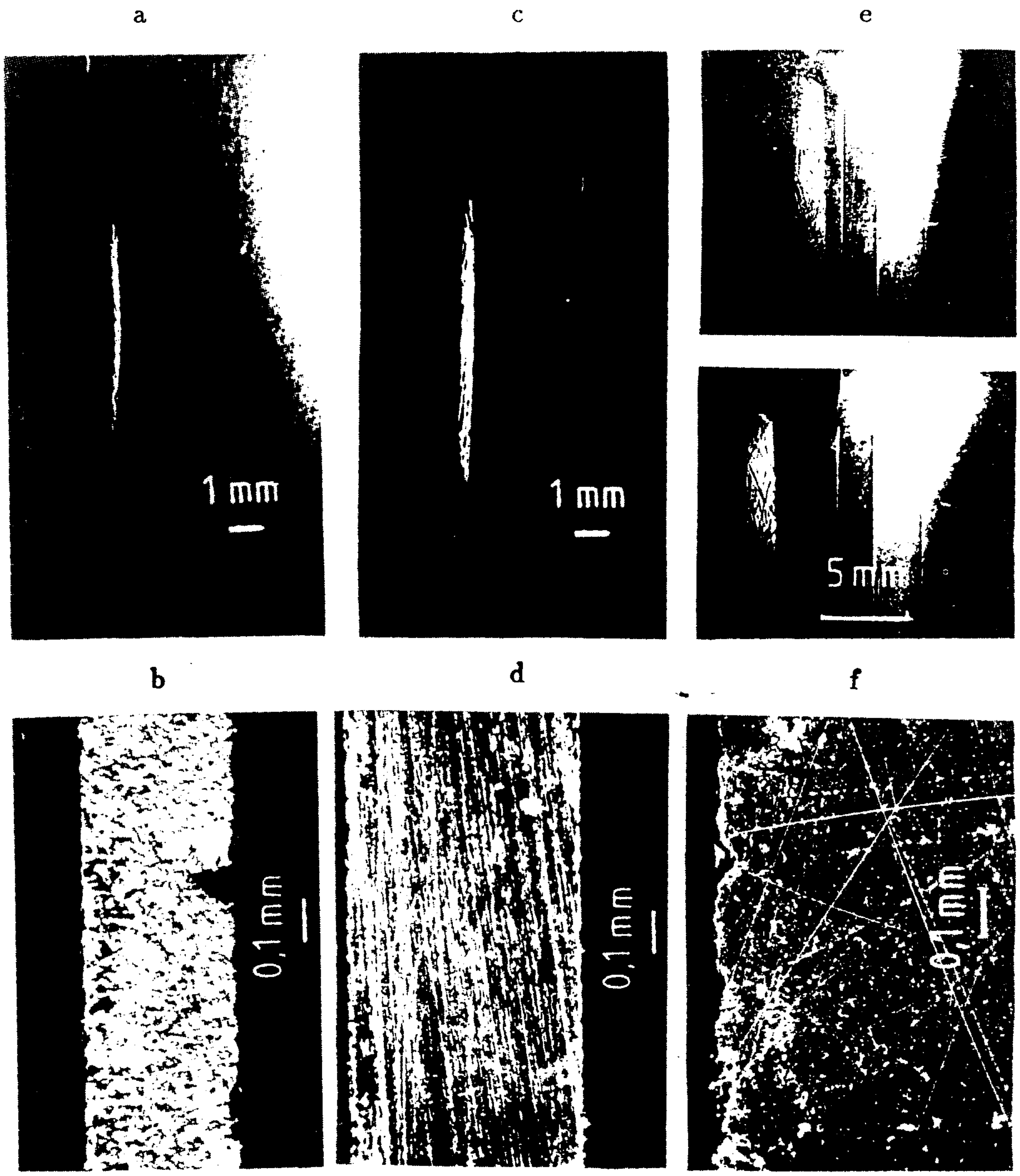

Fig. 6. b,d,f) – the amplified-with-microscope photographs of the crystal flat end faces for the thickness of 300, 520 and 1970 μm. a,c,e) – the images of the beams bent with these crystals at the distance ~1 m. The top of (e) shows also the beam image at ~ 0.5 m.

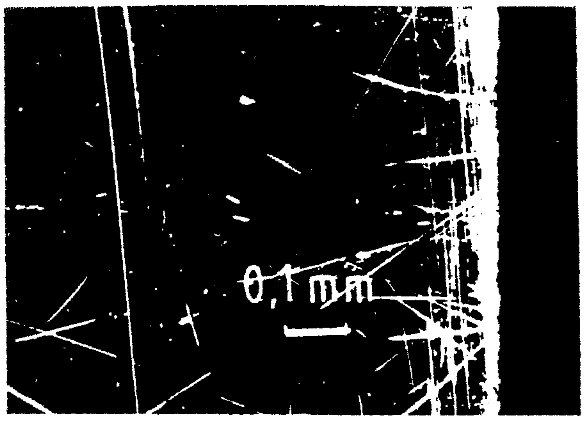

Fig. 7. The amplified photograph of a fragment of the side face of one of the crystals.

Against the background of local angular distortions, no global effects have been observed, as opposed to the case with the nonflat face. It is not excluded that a violation of the plane parallelity may also be present with a flat face, as a result of an edge effect.

This point requires a further study, since it is quite important for bent 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 is dipposed to show how far the parameters of the bent beams can be improved with a higher accuracy surface polishing. A detailed quantitative information on the angular distributions of the bent particles with the use of the microstrip detectors may be also obtained.

One should expect the beam fragmentation to be hardly noticeable, at higher energies ~ 1 TeV 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 is shown in [7], the problem of a non-zero inefficient layer is important for a crystal extraction of protons from large hadron colliders. The presence of an inefficient layer $\sim 50\ \mu$m may markedly decrease (by 50%) the efficiency of proton extraction from a multi-TeV collider; the layer with thickness greater than a hundred μm reduces the efficiency by almost an order.

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