EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

CERN – SL Division

CERN SL / 95–41 (DI)

High efficiency multi-pass proton beam extraction with a bent crystal at the SPS

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Abstract

Recent measurements of 120 GeV proton extraction by means of a bent silicon crystal at the CERN-SPS accelerator are summarized. The existence of multi-pass extraction has been proven by blocking first-pass extraction: using a crystal covered with an amorphous layer, extracted beam with high efficiency was observed, which provides a direct proof for the importance of the multi-pass mechanism. This opens new possibilities in the design and optimization of a bent crystal extraction scheme.

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(to be submitted to Phys. Lett. B)

Geneva, Switzerland
June 1995

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1. Introduction

Classical resonant extraction of a multi-TeV proton beam from circular accelerators requires a long, complex and expensive extraction channel, and would not allow collider operation simultaneously with extraction. The possibility of using channeling in a bent crystal to slowly extract the halo of one circulating proton beam, e.g. in the LHC, therefore remains an attractive, cost-efficient option to operate a fixed target facility parasitically during the collider runs [1]. In addition to this physics tool possibly provided, the directional properties of bent crystals have also been considered by accelerator physicists as one ingredient of the complex collimation system needed in order to protect the super conducting magnets of TeV hadron colliders [2].

Channeling and deflection of high energy proton beams in bent silicon crystals is well understood. If a parallel beam of e.g. 450 GeV protons is hitting the entrance face of such a bent crystal, deflection efficiencies of up to 50 % are achieved for a 2 mrad deflection angle [3]. The method is used routinely, e.g. for very asymmetric beam-splitting to provide beams for the CP violation experiment NA48 at CERN [4].

The principle of proton extraction with a bent crystal is also well established. The method has served a number of external target experiments at Serpukhov [5,6]. The large deflection angle imposed by the conditions in that accelerator makes it difficult, however, to study the details of the processes leading to the extraction. Efficiencies of some 10^{-3} have been obtained. The pulsed mode of these extractions additionally hampers detailed investigations.

Since a few years, experiments have been taking place at the CERN-SPS to investigate the extraction of 120 GeV protons with a bent silicon crystal. Here, the immediate aim is not to serve a particular user, but rather to study in detail the processes leading to extraction, estimate the potential of the technique and attempt to extrapolate to multi-TeV machines like the LHC. A first series of SPS experiments gave an encouraging extraction efficiency of about 10 %, but at the same time led to a number of unexpected observations, e.g. the large range of crystal alignment angles over which extracted beam is observed [7].

The parameters relevant for channeling and extraction of a circulating proton beam change considerably from the SPS to TeV accelerators. For example, the critical angle for planar channeling of protons in (110) silicon scales as $\sqrt{1/p}$ and is found to be 1.8 µrad at the LHC (7 TeV). More importantly, in the SPS experiments the typical impact parameters can to some extent be controlled and are found to be in the sub-micron range. It is very difficult to predict the impact parameters for the LHC, but it has to be anticipated that they will be very small and strongly dependent on the operating conditions of the collider.

For this reason, the question of “first-pass” or “multi-pass” extraction through the bent crystal is extremely important: are the protons extracted at their first encounter with the crystal, or is the extraction dominated by multiple scattering on the first pass and channeling at one of the later passes? If the multi-pass mechanism could be shown to dominate, the initial impact parameter distribution and therefore the precise conditions of the accelerator become much less important. Predictions for future accelerators would become possible.

The present paper describes recent experimental results obtained at the SPS using protons slowly diffusing onto two different bent crystals. One of them is a “perfect” crystal with a polished surface, leading to the highest extraction efficiencies observed so far. The other crystal is covered with an amorphous layer in order to prevent extraction at the first pass. Together with computer simulations, the experimental results presented here allow a better insight into the extraction mechanism and show the importance of multi-pass extraction even at the SPS.

2. Experiment at the SPS

The layout of the SPS experiments is schematically shown in Fig. 1. A 120 GeV/c coasting beam with an intensity of about $5 \cdot 10^{11}$ protons is used. The lifetime of the beam without external interference can be several hundred hours. The crystal is placed typically at a horizontal distance of 10 mm from the closed orbit, some 10 times the transverse beam size, where only a few halo particles are found initially. Then, the beam is excited horizontally with band limited white noise induced on a pair of electrostatic deflector plates (used as “dampers” in the feedback system of normal SPS operation). Typical kicks produced are of order 0.0005 to 0.005 µrad, and the kick strength can be varied by changing the noise power. Once the beam has diffused onto the crystal and a steady state is reached, beam lifetimes can vary from a few minutes to 50 hours depending on the kick strength used.

The two bent crystals used for the present work, installed on separate goniometers and to be used alternatively, are shown in Fig. 1. The crystal shown in Fig. 1a has already been successfully used to extract protons from the SPS [7], but is now covered with a layer of amorphous silicon oxide (see below). Alternatively, a “U-shaped” crystal can be used (Fig. 1b). This crystal is cut out of a block of silicon, with “legs” at both ends, allowing to bend the crystal with two differential screws. The stiff ends avoid the unwanted curvature at the entrance and exit faces of the crystal, and careful adjustment of the two screws allows bending to 8.5 mrad without any longitudinal twist. For both crystals, the surface is cut parallel to the (110) planes.

The protons extracted by the bent crystal are measured in an arrangement of scintillation counters and a scintillator hodoscope, which are described with further details about the experimental procedure in ref. [7]. The number of protons circulating in the machine is continuously monitored, and the extraction efficiency is determined from the ratio of particles extracted by the number of protons lost in the accelerator (per second) in the steady state.

3. Channeling, first- and multi-pass extraction

The condition for 120 GeV/c protons to be channeled in the (110) planes of the silicon crystals used are given by the Lindhard critical angle, $\Psi_p = 13.6$ µrad [8]. Protons hitting the crystal under an angle smaller than Ψ_p may be channeled and, with an estimated probability of 35 %, extracted. The deflection efficiency for protons channeled in a bent silicon crystal has been measured in an external beam [3] and is well understood. Note that in such external beam applications, the full beam hits the crystal entrance face, may be channeled and deflected – the notion of an impact parameter is therefore irrelevant to this case (see Fig. 2).

First-pass extraction from an accelerator would correspond to this situation in an external beam line, the only difference being the small impact parameters of the protons onto the crystal, typically much below 1 µm (see also the following section). Therefore, for first-pass extraction the surface quality of the crystals is of paramount importance. Technology today allows to polish silicon crystals to a roughness of some 50 Å, however, to cut a crystal with its surface exactly parallel to the crystalline planes still poses problems — less than 100 µrad are typically obtained. This angle and the surface roughness would be even more crucial for a crystal to be at TeV energies. Moreover, good stability of the impact parameters and therefore the reproducibility of the extraction by a bent crystal would be difficult to achieve.

Multi-pass extraction has been predicted as a possible mechanism by several authors [9,10]. The term “multi-pass” refers to protons that are not channeled during their first encounter with the crystal, but rather scattered by a small angle. Thus these protons will continue to travel around the accelerator and have “further chances” at later turns to be channeled and extracted, when passing the crystal at larger impact parameters and within the critical angle (cf. Fig. 2). Clearly, for such multi-pass extraction the crystal surface properties are less crucial. It has been shown, however, that the accelerator parameters play a more important role in this case [11].

No direct experimental proof of the existence of this multi-pass mechanism existed so far, although some (model-dependent) conclusions were inferred from recent experimental results. For example, the observation of extracted protons over a very large range of crystal angles with respect to the closed orbit in the SPS experiment [7] seemed to indicate the importance of multi-pass extraction: for first-pass extraction, one would expect a sharp peak in the angular scan with a width of twice the critical angle, i.e. 28 µrad at the SPS.

Within the restrictions of an accelerator experiment, the possibility to reach large impact parameters, and therefore clean “first-pass” conditions, are limited: the only possibility found is to kick the beam strongly onto the crystal [12], but in this mode it is difficult to estimate an extraction efficiency. Furthermore, such a mode does not reflect the standard operational conditions and certainly can not be used for a parasitic extraction. Therefore, a different approach was taken here to experimentally prove the existence and possibly the importance of multi-pass extraction: a crystal as shown in Fig. 1a, with an amorphous layer of 30 µm Silicon oxide, was installed in the SPS. This layer should prevent any first-pass extraction, the impact parameters being much smaller than the thickness of the layer. The observation of an extracted beam with such a crystal would therefore demonstrate the existence of multi-pass extraction and provide a clean sample to study the multi-pass process separately and in detail.

4. Computer simulations

The diffusion of particles in our experiment is provided by random kicks from electrostatic plates [13]. Typically, the diffusion speed can reach maximum values in the order of 1 mm/minute, but is generally smaller in the SPS experiments. The diffusion created in this way is a stochastic process, and statistical parameters (e.g. mean values) can be calculated analytically. However, single particle properties like impact parameters and angles can only be assessed by Monte Carlo tracking simulations [13,14]. Here, a beam of typically 10’000 protons was followed through the SPS accelerator, with parameters close to the ones found in the experiment. Emittance growth due to induced voltage (white noise) on the damper plates was simulated, and the impact parameter and impact angle distributions resulting at the crystal position were recorded. An example is shown in Fig. 3 for a kick strength of 0.01 µrad. The impact parameters found in the simulation are very small — even for these kick amplitudes, which are at least 20 times larger than the ones used in the experiment. It has been shown [13] that for small kicks the mean impact parameter rises approximately linearly with the kick strength and scaling of the impact parameter distribution found in the simulation is thus permitted. The important result at this stage is that the mean impact parameter (of an approximately exponential distribution) for realistic kick strength in the SPS experiment is estimated to be of order 50 nm. Clearly, for the crystal with an amorphous layer (Fig. 1a), first-pass extraction is excluded under these conditions. (Note that in earlier publications [7,12], impact parameters of order 1 µm were assumed, based on a different diffusion mechanism).

In a second step of the simulation program [14], the proton distributions generated as described above, were used to investigate the passage through the crystal and the multi-pass behaviour. The geometrical shape of the crystal as measured with laser light reflection [7] was taken into account, and the multiple scattering of each particle traversing the amount of material corresponding to its impact parameter was calculated. Nuclear interactions and energy loss in the crystal were taken into account. The microscopic behaviour of proton channeling (and dechanneling) in a crystal was not considered important at this stage: These phenomena are independent of the accelerator parameters, the diffusion speed, etc.. However, the macroscopic behaviour (surface transmission, de-channeling) as confirmed in earlier experiments at 450 GeV/c [3] was implemented in the simulation. Tracking around the SPS and through the crystal shows that a large fraction of the protons have an impact parameter beyond the amorphous layer of 30 µm already at the second or third encounter. Therefore, it could be expected to observe multi-pass extraction even with this artificially increased "bad layer" on the crystal.

5. Experimental results with an amorphous layer

Results of the measurements using the bent silicon crystal shown in Fig. 1a, with its amorphous layer, are summarised in Table 1. Measurements were taken for different kick strengths and a crystal position 10 mm from the closed orbit. A typical angular scan obtained with this crystal is shown in Fig. 4a. The width of the scan is approximately 300 µrad, similar to the result found earlier, when the same crystal did not have an amorphous layer [7]. Note that to a large extent, this "angular acceptance" can be understood through the known unwanted vertical curvatures of a crystal bent in a device as shown in Fig. 1a. As a net effect, protons hitting the bent crystal at different vertical positions will "see" a different orientation of the crystalline planes. For a finite beam size, channeling can thus take place over a larger angular range than would be permitted by the critical angle and a flat crystal. This "anti-clastic" curvature has been measured both with laser light reflection from the surface [7] and by moving the beam in the SPS to different vertical positions [12].

The profiles of the extracted beam as measured with the hodoscope at the peak of the angular scan are shown in Fig. 4b. The profile width is also influenced by the vertical curvature, as has been shown by simulations [7], and is broadened in addition by multiple scattering in the crystal and in the material upstream of the hodoscope.

Evaluating the measured beam intensities and lifetimes in the SPS, together with the number of extracted protons per second, leads to an extraction efficiency of up to 7 % (cf. Table 1), similar to the one obtained without an amorphous layer on the crystal. Given the small impact parameters with respect to the 30 µm of amorphous material at the surface of the crystal, this result is clear experimental evidence for multi-pass extraction. Together with the simulations mentioned above, this result leads to the most likely conclusion that multi-pass extraction is the dominant process in the SPS extraction experiment, even when a crystal with a "perfect" surface is used.

6. Extraction efficiency with a "perfect" crystal

In order to avoid the unwanted curvature of the silicon crystal shown in Fig. 1a, a new crystal was produced at ESRF, the so-called "U-shaped" crystal, as shown in Fig. 1b. The crystal surface used for extraction is again cut parallel to the (110) plane to better than 100 µrad precision, and the surface is etched and polished, leading to a surface roughness of about 3 nm (r.m.s.). The beam entrance side of the crystal is flat, laser measurement show a vertical curvature of less than 5 µrad/mm.

Results obtained with this new crystal are summarised in Table 2 and Fig. 5. The angular scan shown in Fig. 5a is clearly much narrower than the one obtained with the first crystal (Fig. 4a), reflecting the fact that the entrance face is no longer bent vertically. The beam profiles measured with the hodoscope are shown in Fig. 5b. The difference to Fig. 4b is particularly striking in the horizontal profile, which exhibits a width which is hardly broader than the crystal itself. Also, the background observed under the profiles of the extracted beam is considerably lower for this “perfect” surface than for the crystal with the amorphous layer (cf. Tables 1 and 2).

The extraction efficiency measured with this crystal varies slightly according to the kick strength applied at the damper, i.e. according to the beam lifetime in the SPS. Other parameters of the accelerator which are difficult to keep under control, might however also produce such small variations. The maximum extraction efficiency measured so far with this novel crystal design is found to be 15 % (cf. Table 2). We note that even with this crystal no clear first pass extraction is identified (e.g. there is no peak of 28 µrad width on top of the broad multi-pass distribution shown in the angular scan of Fig. 5a).

7. Conclusions and outlook

Proton extraction from the SPS with a bent silicon crystal has been pursued with two different crystals. The crystal with an “ideal” geometry and “perfect” surface consistently gives reproducible extraction efficiencies above 10 % and up to 15 %. The second crystal with an amorphous layer also provides an intense extracted beam: this is a clear proof that multi-pass extraction exists. Moreover, the fact that a considerable amount of protons can be extracted in a pure multi-pass mode is very encouraging for extrapolations towards the LHC for two reasons: first, the size of the impact parameters of the protons becomes less stringent — multiple scattering will occur whenever the protons reach the crystal surface. Second, the requirements on the crystal surface quality become less stringent — the surface acts as a scatterer rather than for channeling and extraction.

Given that the importance of the multi-pass effect is now established, one can try to increase the extraction efficiency relying on this effect. For example, it has been shown that the efficiency for pure multi-pass extraction depends strongly on accelerator parameters, in particular the β function at the crystal position and on the tune [11]. These parameters can be optimised, in simulations or in the experiment, in order to achieve the highest possible extraction efficiency. Another possibility has been suggested to increase the efficiency: the use of a scatterer placed at an appropriate location in the accelerator [6]. Scattering in such a device would increase the impact parameter at the crystal without deteriorating the impact angle distribution. We intend to study such a scheme both in simulations as well as in the experiment at the SPS, as a further step towards a high efficiency beam extraction option with a bent crystal.

Acknowledgements

We wish to thank R. Hustache and A. Paul of ESRF Grenoble for the careful cutting, polishing and bending of the crystals, and E.M. Hansen for the evaporation of the amorphous layer onto one of the crystals. The support of the SPS operations team as well as the beam-instrumentation, beam-transfer and controls groups of the CERN SL-Division is gratefully acknowledged.

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Tables

intensity (10^{11} p)	lifetime (hours)	extracted rate (10^5 protons/s)	background (%)	extr. efficiency (%)
5.9	33 ± 2	2.07 ± 0.02	13.9	3.6 ± 0.2
5.8	45 ± 10	1.54 ± 0.05	15.2	3.7 ± 0.8
4.4	28 ± 2	2.38 ± 0.03	13.0	4.8 ± 0.3
1.9	5.1 ± 0.2	8.78 ± 0.04	13.8	7.6 ± 0.3
0.6	1.8 ± 0.1	7.27 ± 0.05	13.3	7.4 ± 0.4

TABLE 1: Results obtained with the crystal with a 30 µm amorphous layer (Fig. 1a) for different lifetimes. The extraction efficiency is calculated including the linearly subtracted background, as obtained from the measured beam profiles. The uncertainty of the extraction efficiency is dominated by the error on the lifetime measurement.

intensity (10^{11} p)	lifetime (hours)	extracted rate (10^5 protons/s)	background (%)	extr. efficiency (%)
4.9	44 ± 8	3.45 ± 0.06	3.2	10.6 ± 2.6
0.13	0.7 ± 0.1	7.88 ± 0.07	4.0	15.4 ± 2.2
0.07	0.9 ± 0.1	2.67 ± 0.04	3.2	12.4 ± 1.4
0.16	0.6 ± 0.1	9.48 ± 0.06	3.1	13.0 ± 2.2

TABLE 2: As Table 1, but for the U-shaped crystal (cf. Fig. 1b).

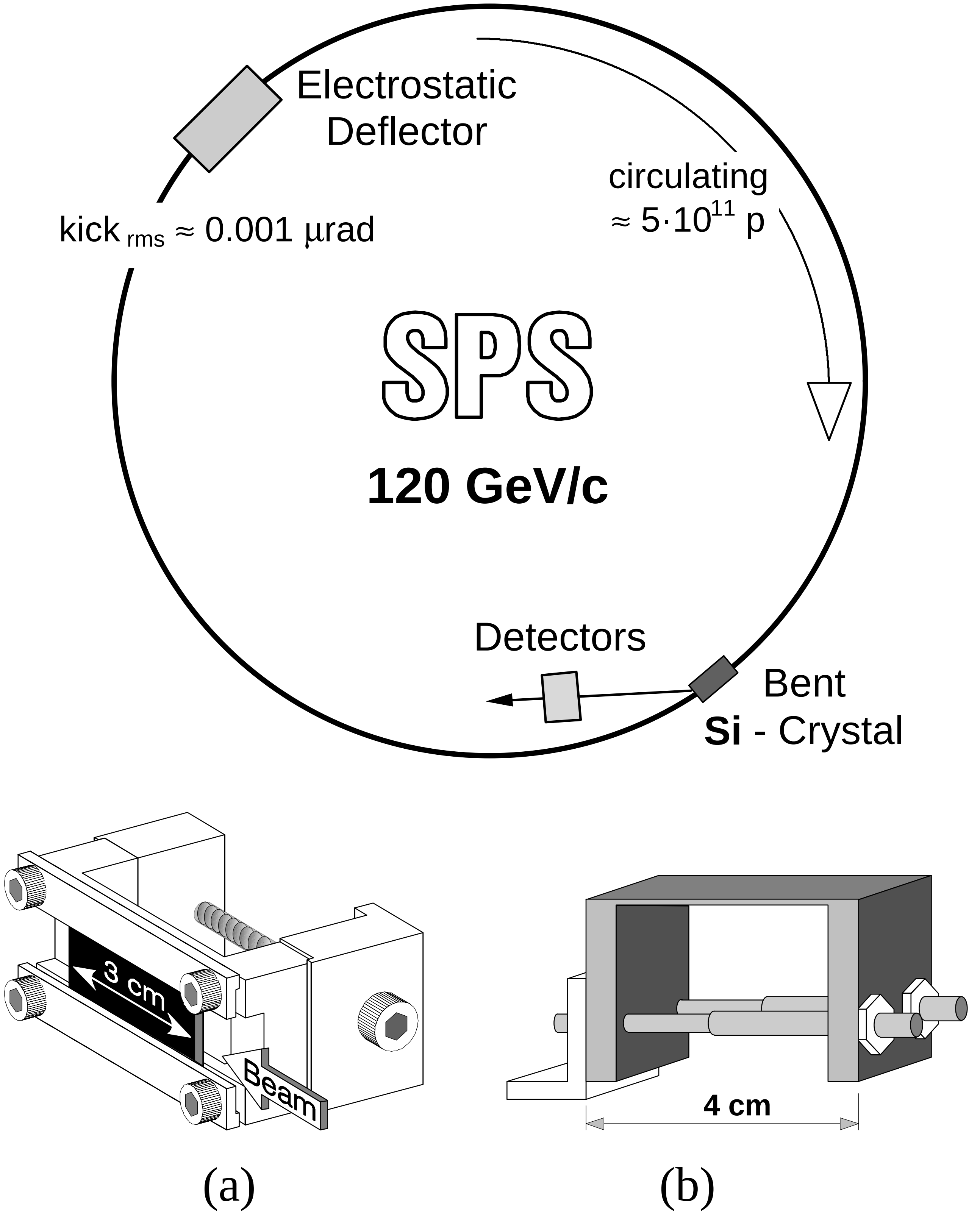

FIGURE 1: Schematic layout of the extraction experiment with a bent crystal at the SPS — Inserted are drawings of the two (110) silicon crystals used: (a) a 3 cm long crystal bent in a classical bending device, with a 30 µm thick amorphous layer of silicon oxide and (b) a 4 cm long "U-shaped" crystal and bender, cut out of one block of silicon. The latter has a "perfect" crystalline surface.

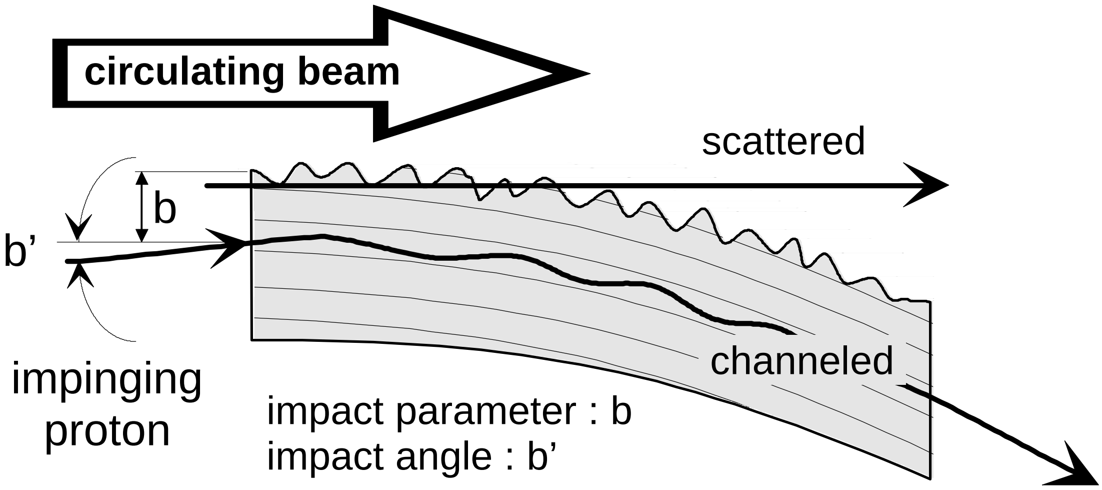

FIGURE 2: Illustration of the proton impact onto the crystal.

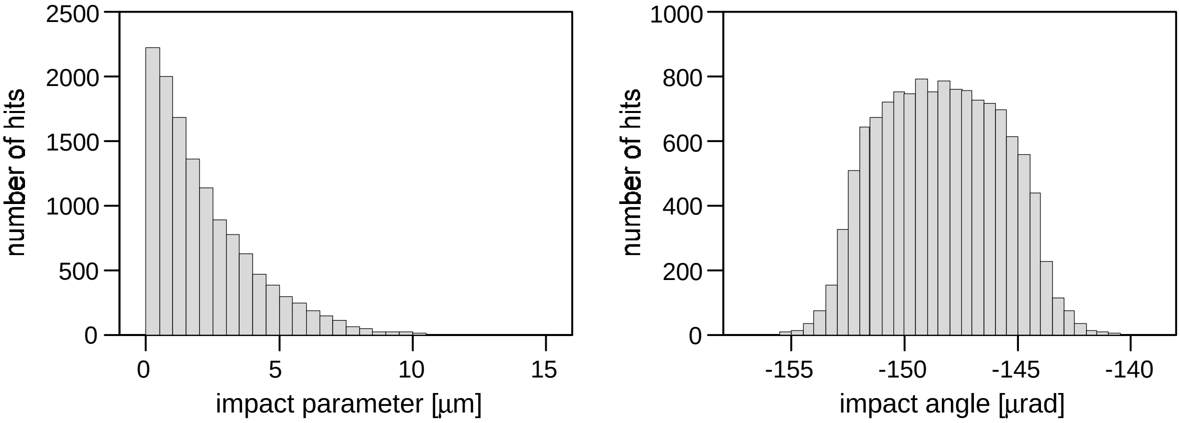

FIGURE 3: Results of the simulation program: (a) impact parameters and (b) impact angles resulting from the diffusion process are shown.

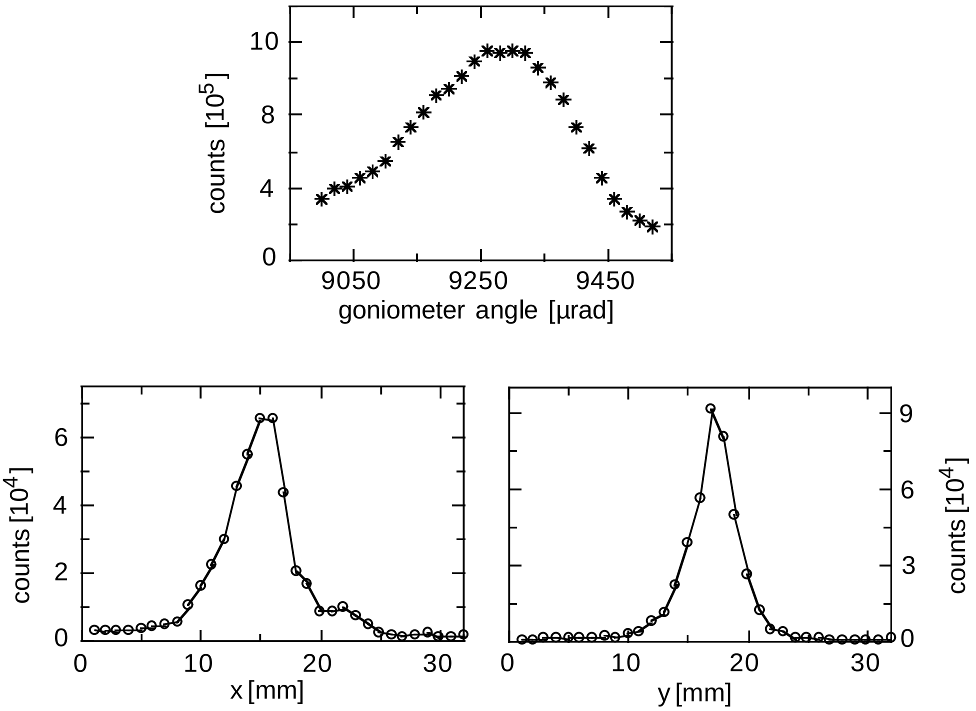

FIGURE 4: Typical angular scan (top) and horizontal and vertical beam profiles obtained using the crystal with an amorphous layer (cf. Fig. 1a).

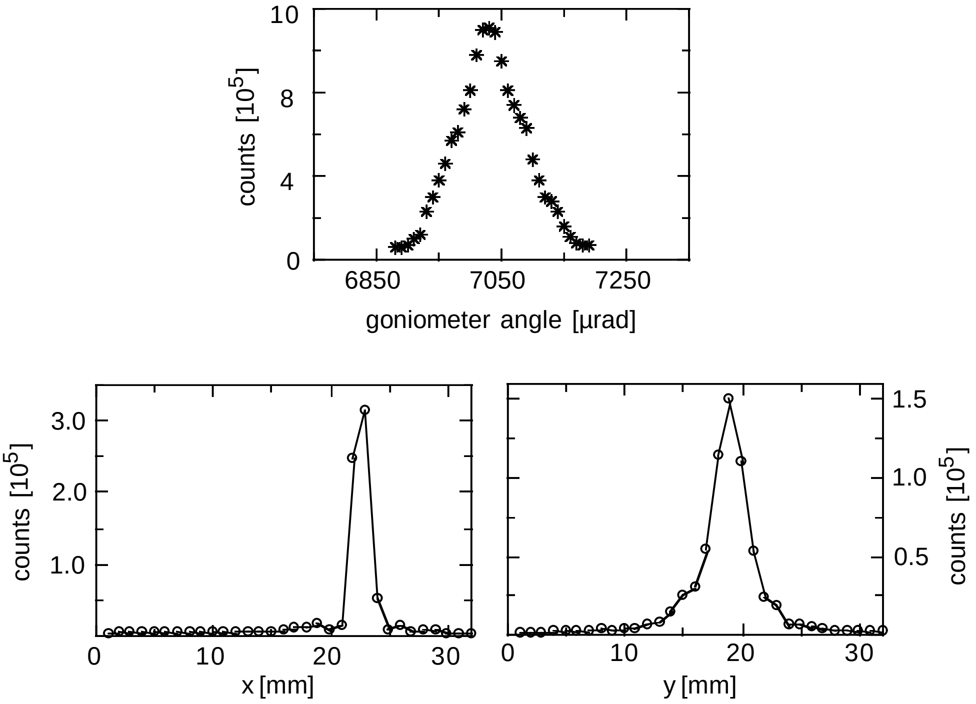

FIGURE 5: Angular scan (top) and beam profiles obtained with the crystal shown in Fig. 1b.