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`walter.scandale@cern.ch`

Progress of Crystal Channeling Technique for Beam Extraction and Collimation at IHEP

Yu.A.Chesnokov, A.G.Afonin, V.T.Baranov, V.M.Biryukov,
V.N.Chepegin, V.I.Kotov, V.I.Terekhov, E.F.Troyanov
Institute for High Energy Physics, Protvino, Russia
V.Guidi, G.Martinelli, M.Stefancich, D.Vincenzi
Ferrara University, Italy
Yu.M.Ivanov, *PNPI, Russia*
D.Trbojevic, *BNL, USA*
W.Scandale, *CERN, Switzerland*
M.B.H.Breese, *Surrey University, UK*

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Summary

We report progress achieved in crystal-assisted slow extraction and collimation of the 70-GeV proton beam in the U-70 accelerator at IHEP-Protvino. We recently obtained an extraction efficiency of 85.3±2.8% for a beam of $\sim 10^{12}$ proton directed towards very short crystals of ~2 mm length in spills of ~2 s duration. The experimental data follow very well the theoretical predictions obtained with Monte Carlo simulations. This success is important to devise a more efficient use of the U-70 accelerator in Protvino and suggests a possible way of implementing crystal-assisted slow extraction and collimation in other machines, such as the Tevatron, RHIC, the AGS, the SNS, COSY, and the LHC.

1 Introduction

The idea to deflect proton beams using bent crystals, originally proposed by Edouard Tsyganov in 1976 [1], was demonstrated shortly later, in 1979, by a Soviet-American team in Dubna on proton beams of a few GeV energy. The physics related to channneling mecha-

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nisms was studied in details, in the early 1980's, at St.Petersburg, in Dubna, at CERN, and at FNAL using proton beams of 1 to 800 GeV (see Refs.,e.g. in [2]).

Crystal-assisted extraction from accelerator was demonstrated for the first time in 1984 in Dubna at beam energies of 4-8 GeV and deeply tested at IHEP in Protvino starting from 1989 by exposing a silicon crystal bent by 85 mrad to the 70 GeV proton beam of U-70. The Protvino experiment eventually pioneered the first regular application of crystals for beam extraction: the Si crystal, originally installed in the vacuum chamber of U-70, served without replacement *over 10 years*, delivering beam for particle physicists all this time. However its channeling efficiency was never exceeding a fraction of %.

In the 1990's an important milestone was obtained at the CERN SPS. Protons diffusing from a 120 GeV beam were extracted at an angle of 8.5 mrad with a bent silicon crystal. Efficiencies of $\sim$10%, orders of magnitude higher than the values achieved previously, were measured for the first time [3]. The extraction studies at SPS clarified several aspects of the technique. In addition, the extraction results were found in fair agreement with Monte Carlo predictions (see Refs., e.g. in [2]). In the late 1990's another success came from the Tevatron extraction experiment where a crystal was channeling a 900-GeV proton beam with an efficiency of $\sim$30% [4]. During the FNAL test, the halo created by beam-beam interaction in the periphery of the circulating beam was extracted from the beam pipe without measurable effect on the background seen by the experimental detectors.

The dramatic increase of efficiency in the experiments at CERN and at FNAL is related to the fact that the bending angle of 8.5 mrad and 0.64 mrad respectively was much smaller than the 35-85 mrad in Dubna and IHEP. Also divergence and scattering were much less an issue at CERN and FNAL. The major difference was dechanneling.

In crystal extraction, the circulating particles can cross several times the crystal without nuclear interactions [5]. Unchanneled particles are slightly deflected by multiple scattering and eventually have new chances of being channeled on later turns. Indeed, the crystal size should be well matched to the beam energy to maximise the transmission efficiency. To clarify this mechanism an extraction experiment was started at IHEP Protvino at the end of 1997(see Ref.[6, 7] and References therein).

There are two possible application of crystal channeling in modern hadron accelerators: the slow extraction and the halo collimation. The benefits of a crystal-assisted extraction are fourfold. In hadron colliders this mode of extraction can in general be made compatible with the colliding mode of operation. The time structure of the extracted beam is practically flat, since the extraction mechanism is resonance-free. The size of the extracted beam is smaller and more round than in a resonant extraction. Finally polarized beams can be extracted without detrimental effects on the polarization. The benefits of crystal-assisted scraping we will discuss in the next section. These two major applications can be exploited in a broad range of energies, from sub-GeV cases (i.e. for medical accelerators) to multi-TeV machines (for high-energy research). Indeed, several projects are in progress to investigate them. Crystal collimation is studied at the Spallation Neutron Source (1 GeV) [8], at RHIC (100-250 GeV) [9] and at the Tevatron (1000 GeV) [10], whilst crystal-assisted slow extraction is considered for COSY (1-2 GeV) and AGS (25 GeV) [11]. In all cases, the critical issue is the channeling efficiency.

The results presented here and the simulations [12] suggest that channeling efficiencies over 80-90% can eventually be reached in the energy range from several hundred MeV to multi-TeV, provided the crystal parameters are well optimised for each case.

In section 2 we discuss the use of crystals as primary scraper. In section 3 we present recent results on channeling efficiency obtained at U-70. In section 4 we show high-intensity tests and in section 5 we investigate the effect of a large integrated dose of radiation. In section 6 we consider the case of crystal collimation at low energy. Finally in section 7 we draw some conclusions.

2 Crystal as a Scraper

The classic two-stage collimation system for loss localisation in accelerators typically uses a small scattering target as a primary element and a bulk absorber as secondary element [13]. Normally in colliders and storage rings the halo diffusion is rather slow, therefore the first touch of a halo particle with the aperture-restricting collimator is rather a glancing touch, with impact parameters of the order of a micron or less. Unfortunately, particles interacting near to the surface of a solid block can be scattered back in the beam pipe, hence they can be lost far from the cleaning area. The role of the primary element is to give a substantial angular kick to the incoming particles in order to increase the impact parameter on the secondary element, which is generally placed in the optimum position to intercept transverse or longitudinal beam halo.

An amorphous primary target scatters the impinging particles in all possible directions. Ideally, one would prefer to use a ”smart target” which kicks all particles in only one direction: for instance, only in radial plane, only outward, and only into the preferred angular range corresponding to the centre of the absorber (to exclude escapes). A bent crystal is the first idea for such a smart target: it traps particles and conveys them into the desired direction. Indeed, the scattering process on single atoms of an amorphous target becomes the selective and coherent scattering on atomic planes of an aligned mono-crystal. An ideal crystal with 100% channeling efficiency would serve as a kicker deflecting all the impinging particles deeply onto the secondary collimator for a safe absorption. A real crystal is not 100% efficient, therefore it can deflect only a fraction of the halo in the safe region. Instead, the rest of the particles are scattered as in an amorphous target and are possibly scraped by the edge region of the secondary collimator. The effect of a crystal as primary collimator is more and more beneficial as the channeling efficiency increases. This depends strongly on the quality of the crystal and on its length, which should be well matched to the energy of the incoming particles.

3 Experimental Results on Channeling Efficiency

In the last two years, we were able to produce and bend crystals with 50% channeling efficiency. We were also able to show that, when properly aligned, these crystals could be efficiently used as primary collimators, thereby reducing by a factor two the radiation level measured downstream of the collimation region of U-70 [6, 7].

To continue our investigations, in the year 2000, we installed and tested several new crystals in different straight sections of the U-70 ring.

Three of them were produced by different manufacturers with a new shape. They were made with narrow strips of silicon, oriented in the 111 mode, about 40 mm long in vertical direction and a fraction of mm long in the radial plane. Their azimuthal length was only of a few mm. A great care was used to polish them. They were bend by a metallic holder providing deflections of 0.8 to 1.5 mrad.

The advantages of "new-generation" crystals are threefold: (a) they can be made shorter than a usual bulk crystal, (b) they have no straight ends, since the bending mechanism is continuous, and (c) they have no amorphous material close to the beam (like the "legs" of U- and O-shaped deflectors). The new technology allows us to control very precisely the crystal length and the bending radius and to adapt them to the beam energy, to optimise the channeling efficiency.

Two crystals were assembled in Protvino: one 2 mm long was bent by 0.9 mrad, the other 4 mm long was bent by 1.5 mrad. The third crystal 1.8 mm long bent by 0.8 mrad was build and polished in the University of Ferrara (Italy). The two Russian crystals were used in extraction mode, whilst the Italian one was tested as a primary collimator.

The three crystals were exposed to 70 GeV proton beams and used to channel and extract halo particles.

In Figure 1 we show the shape of the deflected protons (the small spot to the right of the photo) and of the incident halo beam (the large spot to the left of the photo) as seen downstream of the 4 mm long crystal. The beam spots are recorded on photo-emulsions as described in Refs. [6, 7].

In Figure 2 we illustrate, in a schematic sequence, the beneficial effect of crystals when used as primary collimators. Indeed, we present beam profiles in the radial plane downstream of the crystal itself, recorded with the profile-meter of Ref.[6]. The coordinate R represents the radial displacement referred to the crystal edge. The coordinate I is proportional to the intensity of the out-coming particles, after the crystal traversal. In all plots (from 2(a) to 2(d)) the integral of I is arbitrarily set to the same value. Four cases are reported. In first one, an amorphous collimator is used as primary target whilst the close-by crystal is kept outside of the beam envelope. As expected, the beam profile is peaked at the collimator edge (Fig. 2(a)). In the second case (Fig. 2(b)) the crystal is used as the primary scraper, whilst the amorphous target is retracted. No care is taken to aligned crystal with respect to the beam direction, hence its action on the incoming protons is very similar to that of an amorphous target. Again the resulting beam profile is peaked at the crystal edge. When properly aligned (see Fig. 2(c)), the crystal channels most of the incoming beam and displaces their distribution by about 10 mm inside the crystal edge. In the last case (see Fig. 2(d)), the beam is simply kicked by a magnet towards the secondary collimator, whilst the primary target is retracted. The resulting beam profile is displaced towards inside and has a shape very similar to that of plot 2(c).

The channeling efficiency is given by the ratio of the extracted beam intensity, as measured in the external beam line, to all the beam loss, as measured in the entire ring. We obtained very high channeling efficiencies in *each* of the three new crystals: namely, both the 1.8 and 2 mm long crystals reached 85% efficiency, whilst the 4mm long crystal reached 68% efficiency. In Figure 3 we plot the expected and the measured channeling efficiencies together with data relative to an old O-shaped crystal. The agreement between measurements and simulations is excellent. The diagnostics part of the experiment is described in Ref. [6, 7].

These unprecedented results were indeed obtained in a steady manner over many runs. In particular, the 2 mm long crystal was regularly functioning to extract beams with a channelling efficiency of 85.3±2.8%.

4 High-intensity tests

Beside the channeling efficiency, there are other important issues to be addressed for a practical application of crystal-assisted extraction and collimation, like radiation damages and crystal lifetime.

In this section we will discuss collimation tests performed at U-70 with very high intensity beam. Crystals located in the region upstream of the U-70 cleaning area were irradiated with the entire circulating beam, spilled out in rather short time durations to simulate very dense halo collimation.

First, we would like to evaluate the irradiation dose hitting the crystal during a spill. Indeed, we can measure very precisely the beam intensity intentionally damped into the crystal. However, we can only estimate with computer simulations the total amount of particle hits during a spill, since unchanneled protons are simply scattered and may continue to circulate in the ring hitting the crystal many times before being either channeled,thereby removed from the circulation, or lost by nuclear interaction in the crystal or lost elsewhere in the ring. The number of hits per primary particle can vary from a few to more than hundred units, depending on channeling efficiency, crystal length and crystal alignment.

In Figure 4 we shows the vertical distribution of primary and secondary hits in two different crystals, computed for a primary beam intensity of 2×10^{14} particles extracted in spills of $\sim$1 s duration. The primary beam is originally directed towards the centre of the crystal (in Fig. 4 H indicates the vertical position), whilst the successive hits are spread-out in the vertical direction, due to multiple scattering and betatron oscillation from turn to turn. In a 3 mm O-shaped crystal the vertical spread is ±2.5 mm, whilst in a 1.2 mm strip crystal the vertical spread is ±12 mm. In all cases the hit distribution is symmetric around the centre of the crystal and determines the spot size of the channeled beam.

The primary flux of protons hitting the crystal during our test already *exceeds* the expected beam loss rate at the world planned highest-intensity proton machines, i.e. the Spallation Neutron Source. Indeed, the nominal intensity and repartition rate in the SNS Accumulator Ring should generate a 1 GeV proton flux of $60\times2\times10^{14}$ per second. At the expected rate of beam loss of 0.1–1% the halo flux will be of $(1.2–12)\times10^{13}$ protons/s, i.e. at least two times less than in the U-70 dump experiment. This seems to indicate that strip-type crystals, with high channeling efficiency, may well tolerate high flux of protons as large as those expected to hit the SNS beam collimation system, even at the nominal intensity.

A second crystal 5 mm long also located upstream of the U-70 cleaning area was exposed for several minutes to even higher radiation flux. Beams of up to 10^{13} protons at 70 GeV were directed towards the crystal in spills of 50 ms, with a repetition period of 9.6 s. Although it was impossible to characterise the crystal efficiency in such a short time, we could test the channelling properties after the exposure of the crystal, in an external beam line. The deflected beam, observed with photo-emulsion, was perfectly normal, without breaks, nor significant tails eventually produced by dechanneled particles. This is a good indication of the absence of radiation damages.

5 Integrated doses

Several crystals in use in U-70 have been exposed to high intensity beams for months, thereby accumulating very large integrated doses [7]. In Figure 5 we show the achieved radiation density accumulated in a 5 mm long O-shaped crystal, in one month of operation (about 10^5 machine cycles) with $\sim 5\times 10^{11}$ extracted protons in every spill. The number of protons per square centimetre is plotted as a function of the radial position R from the crystal face. The highest dose is seen at the crystal edge close the beam. As reported in [7], after this irradiation of $\sim 10^{20}$p/cm^2 the initial channelling efficiency of about 43% was practically unaffected. Figure 5 also shows that the radiation flux strongly depends on channeling efficiency. If the crystal is misaligned, the circulating halo particles are not immediately channeled and can hit the crystal a larger number of times. As a consequence the radiation dose increases. On the other hand, if we manage to extract particles with higher efficiency, channeling becomes the major factor limiting the particle circulation in the ring, therefore the radiation dose and the consequent damage is reduced. Thus more efficient crystals would have longer lifetime in the beam.

The radiation level achieved during our test is still below the world highest results obtained in BNL at 28 GeV [14] and in CERN at 450 GeV [15], where (4–5)$\times 10^{20}$ proton/cm^2 were directed on crystals. The CERN experiment showed that at the achieved threshold of 5×10^{20} p/cm^2 the crystal lost only 30% of its deflection efficiency, which means ~100 years lifetime in the intense beam of NA48 experiment.

6 Crystal collimation at 1.32 GeV

We studied crystal channeling at low energy with the 1.8 mm strip-crystal build by the University of Ferrara, which is positioned ~20 m upstream of the collimator area, in the U-70 ring. The experiment was made at the injection plateau, with proton of 1.32 GeV kinetic energy.

The crystal was carefully aligned in the direction of the incoming halo particles, which were deflected and intercepted at the entry face of the secondary collimator jaw. The radial beam profile at the exit of the crystal showed a significant channeled peak intensity at about 7 mm from the crystal-face, see Figure 6. With a misaligned crystal instead the profile was similar to the ones shown in Figure 2 (a, b).

At 1.32 GeV kinetic energy the divergence of the channeled beam has a full width of 0.28 mrad. This corresponds to ~6 mm width on the front-face of the collimator, or about 5 bins in the profile of Figure 6. This is in a rather good agreement with our observations. In comparing the beam profile channeled by a well aligned crystal with that produced by an amorphous target we had the evidence that about half of the protons intercepted by the collimator jaw have been channeled there by a bent crystal; in other words, the crystal has almost doubled the amount of particles intercepted by the jaw. From the analysis of the beam losses around the ring we could evaluate that about 34% of the particles hitting the crystal were either scattered or channeled towards the collimation system. From the analysis of the radial profiles we estimated that indeed half of the particles were scattered and half of them channeled. From this, we could estimate that the crystal deflection efficiency is of the order of 15-20%. In the the past, efficiencies of at most 1% were obtained. In our case the strip-crystal was as long as about one dechanneling length. Taking into account this fact and the effect of the "surface acceptance" (see ref.[2]), the observed figure of efficiency could be well reproduced in computer simulations.

It is remarkable that the same crystal has efficiently channeling and really helping in cleaning halo particles both at 70 GeV and at 1.3 GeV, thus demonstrating to be operational in a very wide energy range.

7 Conclusion

Short strips of silicon crystals, bent by metallic holders with an almost constant radius, have been used to channel protons in the U-70 ring. Their channeling efficiency reached unprecedented high values both at top energy and at injection energy. For instance, the same 2 mm long crystal was used to channel 70 GeV protons with an efficiency of 85.3±2.8% during several weeks of operation and 1.32 GeV protons with an efficiency of 15-20% during some test runs. Crystals with a similar design were able to stand radiation doses of $\sim 10^{20}$ proton/cm^2 without deterioration of their performances.

These results give us a strong motivation to pursue our studies in view of proposing crystal-assisted collimation of beams in a broad energy range in order to evaluate the potential benefits for beam collimation systems in the new-generation accelerators, from spallation sources to large hadron colliders.

The technique presented here is potentially applicable also in LHC for instance to improve the efficiency of the LHC cleaning system by embedding bent crystals in the primary collimators. This application however may still require a substantial effort to optimise the crystal shape and to check its effectiveness in the TeV range of energy.

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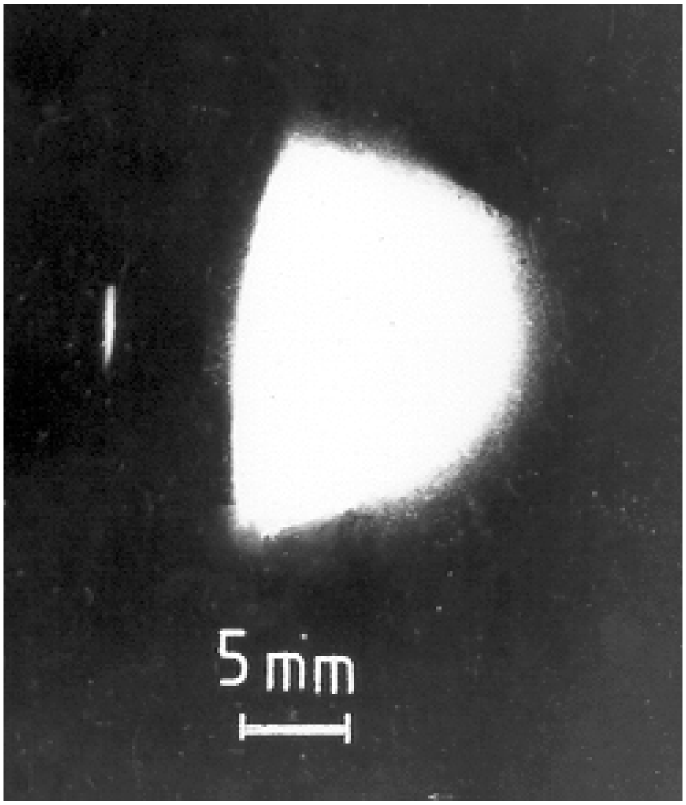

Figure 1: Photograph of the deflected (left) and incident (right) beams as seen downstream of the crystal. Prior to the test, the crystal was exposed in the ring to 50-ms pulses of very intense beam (dump of 10^{13} protons, resulting in $\sim 10^{14}$ proton hits per pulse). No damage of crystal was seen in the test, after this extreme exposure.

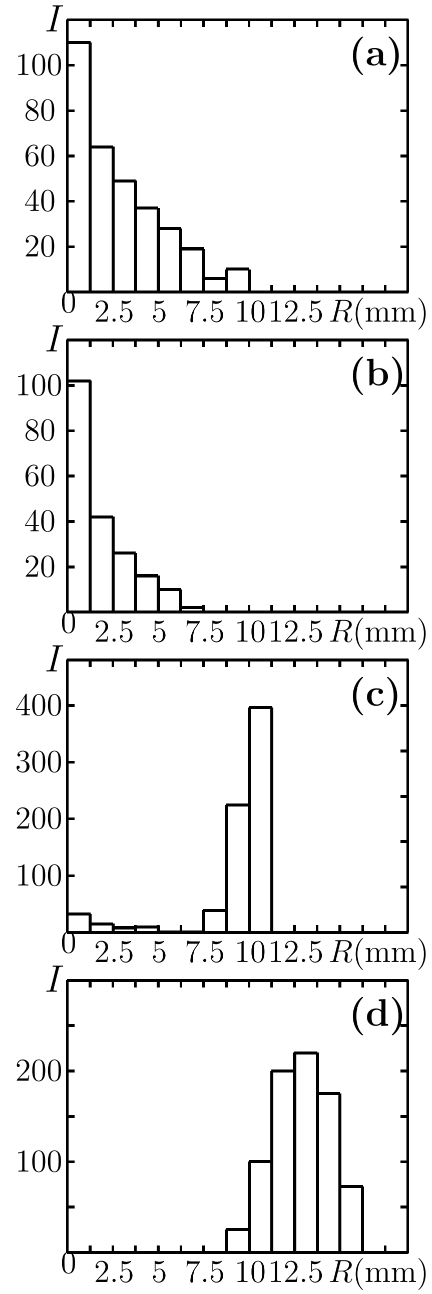

Figure 2: Beam profiles measured at the collimator entry face: (a) crystal is out, beam scraped by collimator alone; (b) crystal is in the beam, but misaligned; (c) crystal is in the beam, aligned; (d) crystal is out, beam is kicked by magnet.

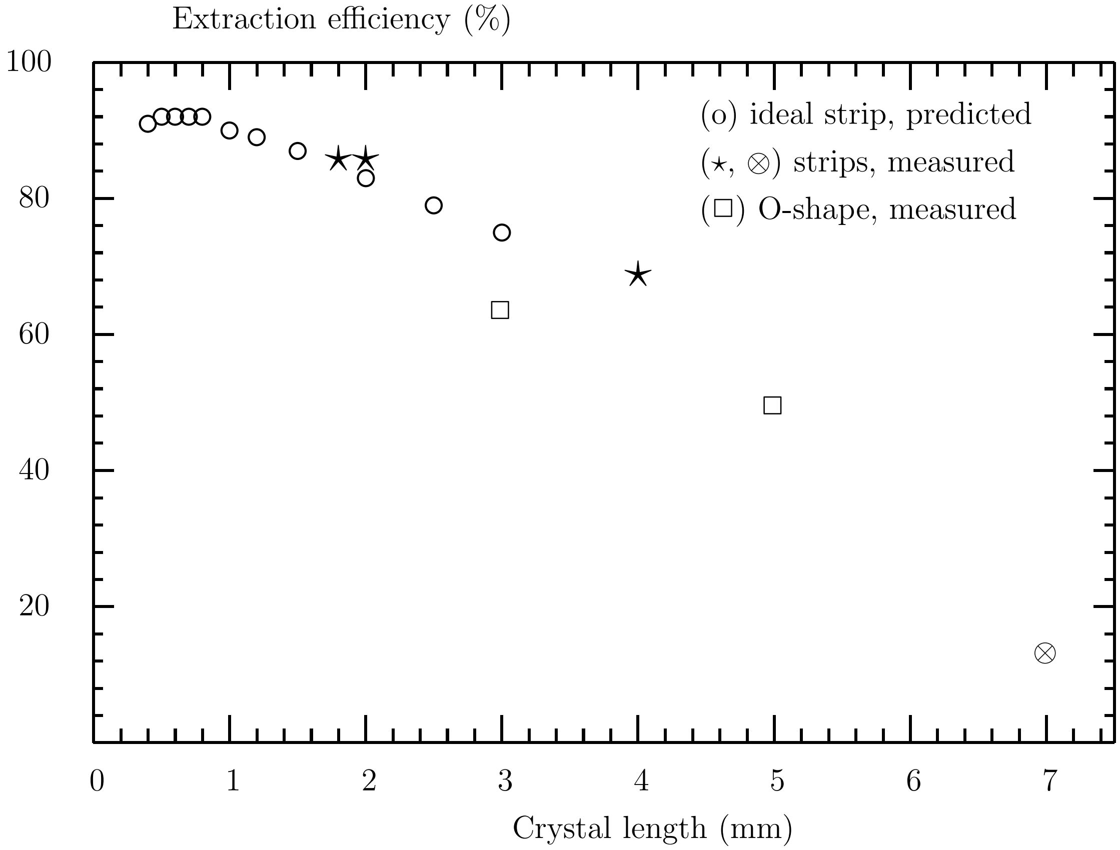

Figure 3: Crystal extraction efficiency as measured for 70-GeV protons at IHEP Protvino. Experimental results of 2000 (⋆, strips 1.8, 2.0, and 4 mm along the beam), 1999-2000 (□, O-shaped crystals 3 mm and 5 mm), and 1997 (⊗, strip 7 mm). Also shown is Monte Carlo prediction (o) from EPAC'2000 [7] for a "strip" deflector with perfect bending of 0.9 mrad.

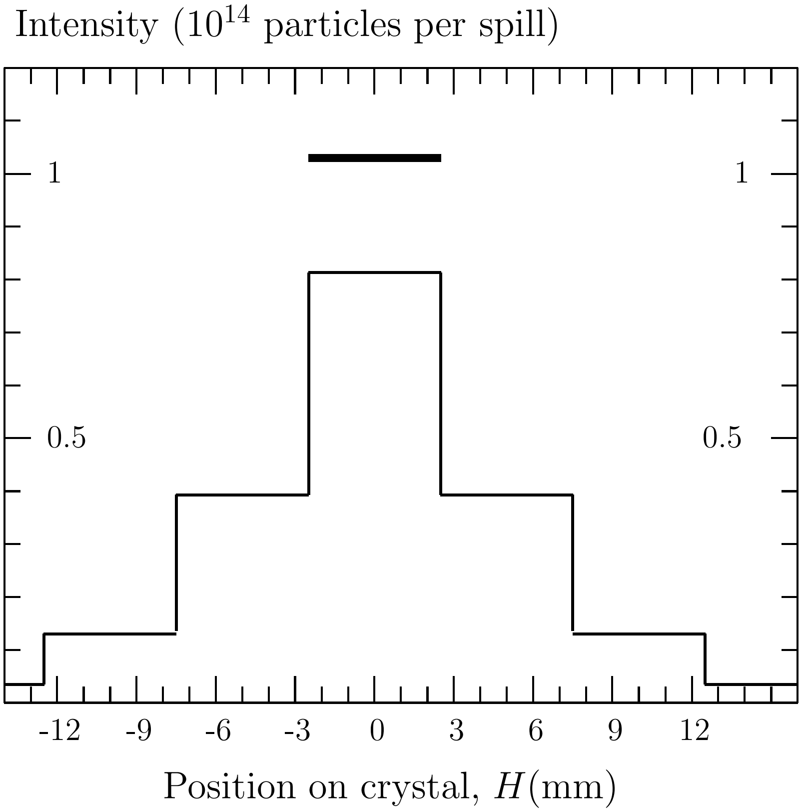

Figure 4: Intensity of proton hits at the crystal per spill of ∼1 s duration, as obtained in the run March 2000. This figure takes into account the number of hits on crystal per incident proton (∼100 for short crystal). The thick line at the top shows the intensity achieved at the 5-mm-high, 3-mm-long O-shaped crystal. The thin line below shows the intensity achieved at the 40-mm-high, 1.2-mm-long crystal ("strip").

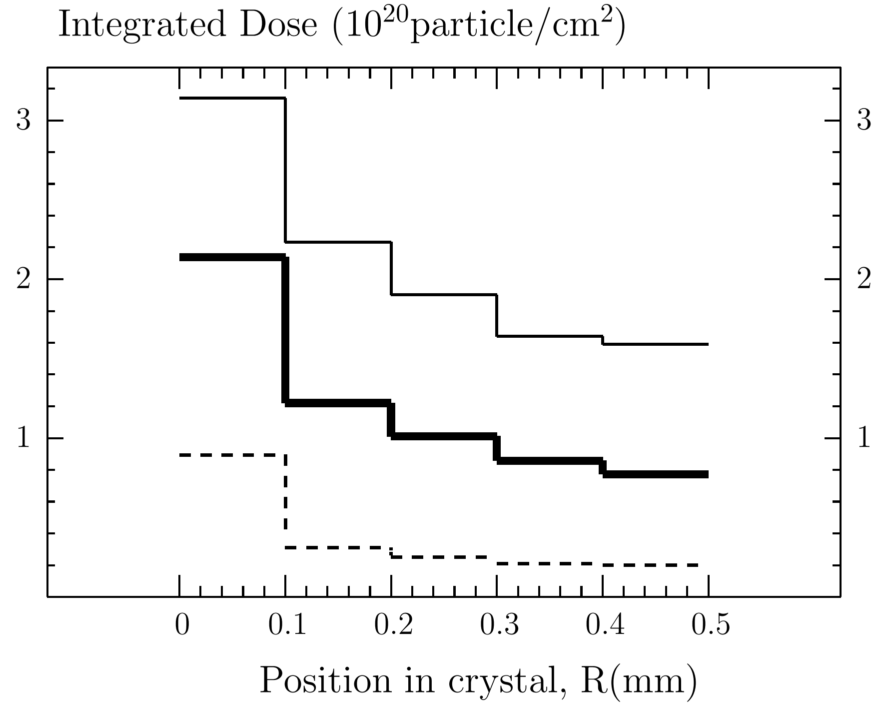

Figure 5: Irradiation of the crystal entry face (O-shaped crystal) in proton hits/cm^2, after 10^5 machine cycles (∼1 month of accelerator run) with dump of 10^{12} proton/cycle. Shown for extraction efficiency 43% (thick line, middle); for misaligned crystal (thin line, top); for extraction efficiency 73% (dashed, bottom).

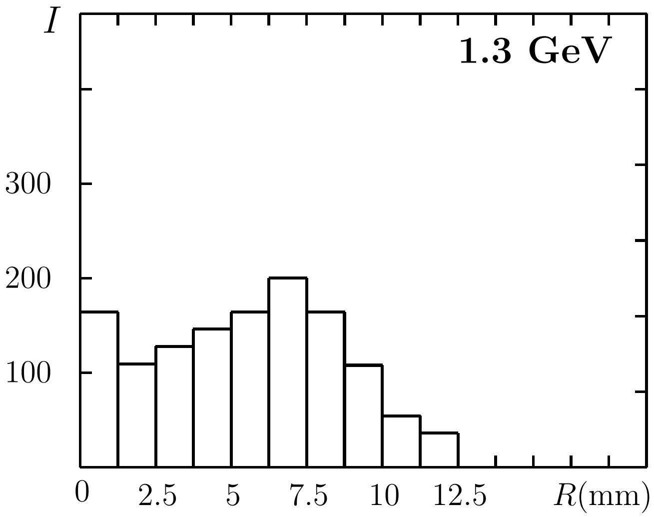

Figure 6: Beam profile as measured on the collimator entry face with 1.3 GeV protons. Crystal of Si(111), 1.8 mm long, was aligned to the beam and positioned ∼20 m upstream of the collimator.