Crystal Collimation Experiment on 70-GeV Proton Accelerator

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Abstract

The first proof-of-principle experiment on "crystal collimation" was performed with 70-GeV protons on IHEP accelerator. A bent crystal installed in the ring as a primary element upstream of a collimator has reduced the radiation levels downstream in the accelerator by a factor of two. The measurements agree with Monte Carlo predictions.

1 Introduction

Bent-crystal technique is well established for extracting high energy beams from accelerators. It was successfully applied at the energies up to 900 GeV[1], and simulations were able to predict the results correctly. Recent experiments at IHEP Protvino[2] have demonstrated that this technique can be quite efficient: 50-70% of the beam have been extracted using a thin (3-5 mm) *Si* channeling crystal with bending of 0.5-1.5 mrad, with intensity of the extracted 70-GeV beam up to 6×10^{11} protons per spill. At this intensity, no cooling measures were taken and no reduction in the efficiency observed. At IHEP Protvino this technique has been routinely used since 1987 to deliver a 70 GeV beam to particle physics experiments. One of the IHEP crystals did extract 70 GeV protons over 10 years since 1989 without replacement and without any degradation seen! It was shown in the experiments at BNL AGS and at CERN SPS that radiation damage in channeling crystals is sizable only at over (2-4)$\times10^{20}$ proton/cm^2.

The theory of crystal extraction is based mainly on detailed Monte Carlo simulations tracking the particles through a curved crystal lattice and the accelerator environment in a multipass mode. Our code CATCH was successfully tested in the extraction experiments at CERN, FNAL, and IHEP in 1992-99[3]. Monte Carlo predictions, suggesting a "multipass" mode of crystal extraction where efficiency is dominated by the multiplicity of particle encounters with a short crystal, have lead to the breakthrough in the extraction efficiency demonstrated at IHEP Protvino[2].

Crystal can channel a charged particle if it comes within so-called critical angle θ_c, about ± 150 μrad/$\sqrt{pv(GeV)}$ in silicon. This restricts crystal efficiency in divergent beams. However, if a crystal is installed in a circulating beam, particle may scatter in inefficient encounters and have new chances on later turns. To benefit from the "multi-pass" channeling, the crystal must be short enough to reduce beam losses in multiple encounters with it.

It should be promising to apply this bent-crystal technique for a beam halo scraping in accelerators and storage rings[4, 5]. A bent crystal, serving as a primary element, should bend halo particles onto a secondary collimator. A demonstration experiment of this kind was performed at IHEP where for the first time a significant reduction in the accelerator background was obtained with a bent crystal incorporated into beam cleaning system[2].

A crystal collimation system for a gold ion beam is now being installed at RHIC in collaboration with IHEP[6], and –upon success– it will serve there on permanent basis.

2 Crystal Deflector

Bending a short crystal to be installed in the accelerator vacuum chamber is not easy. The first crystal used in the course of our experiment of 1997-1999 was of Si(111) type and performed as a short plate of a big height, $0.5\times40\times7$ mm^3 (thickness, height, and length along the beam direction, respectively). It was bent transversally with a metal holder which had a hole of 20 mm size for beam passage, and gave the channeled protons a deflection of 1.7 mrad. Despite an angular distortion (a "twist") in that design, encouraging results on beam extraction were obtained in our first run in December 1997, Figure 1. The peak extraction efficiency reached about 20% and the extracted beam intensity was up to 1.9×10^{11} [7]. Here and later on in the paper, the extraction efficiency is defined as the ratio of the extracted beam intensity as measured in the external beamline to all the beam loss in the accelerator.

To further increase the extraction efficiency, further crystals (without twist) were made from a monolithic Si piece in a shape of "O" at the Petersburg Nuclear Physics Institute, as described in Ref. [8]. The crystals Si(110) used in our recent runs had the length along the beam direction of only 5 mm. The bent part of the crystal was just 3 mm long, and the straight ends were 1 mm each.

Such a crystal, with bending angle of 1.5 mrad, was successfully tested in March 1998 and has shown extraction efficiencies over 40% [8]. In the mean time we have changed the crystal location in order to use another septum magnet (with partition thickness of 2.5 mm instead of 8 mm as in the old scheme) where a smaller bending angle is required from a crystal. This change was also motivated by the intention to test even shorter crystals (two of them, 2.5 and 3.0 mm long, are already undergoing tests). The crystal used in this location was new, but of the same design and dimensions as earlier described[8]. The bending angle used in this run was 0.65 mrad.

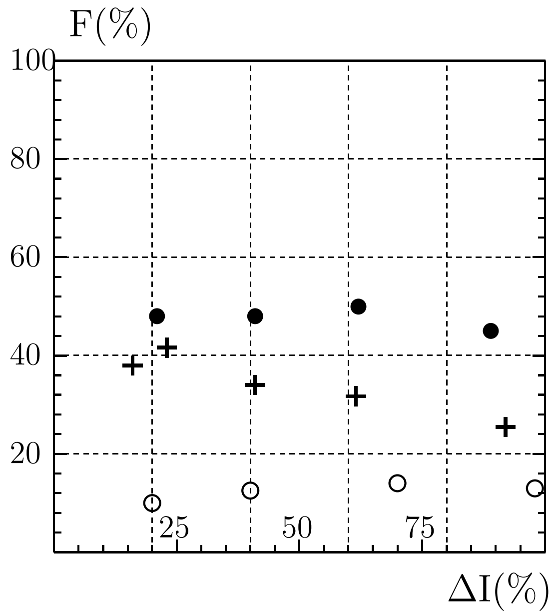

Figure 1: Spill-averaged efficiency of extraction as measured with 5-mm crystal 0.65 mrad bent (•), December 1998; 5-mm crystal 1.5 mrad bent (+), March 1998; 7-mm twisted crystal 1.7 mrad bent (o), December 1997; plotted against the beam fraction taken from the accelerator.

3 Study of Crystal Work in Slow-Extraction Mode

Experiments on crystal-assisted slow extraction and scraping are very similar on the part of crystal component, the only difference being the target of the channeled deflected beam — is it an external beamline or beam absorber. This is why we were able to study the crystal work first in the conditions of slow extraction where we could measure the amount and characteristics of the channeled beam more easiely.

The general schematics of beam extraction by a crystal is shown in Ref.[8]. As the small angles of deflection are insufficient for a direct extraction of the beam from the accelerator, a crystal served as a primary element in the existing scheme of slow extraction. Crystal was placed in straight section 106 of the accelerator upstream of a septum-magnet of slow-extraction system. The accuracy of the crystal horizontal and angular translations was 0.1 mm and 13.5 μrad, respectively. The horizontal emittance of the circulating proton beam was about 2π mm$\times$mrad, and the beam divergence at the crystal location was 0.6 mrad. A local distortion of the orbit by means of bump windings in magnets moved the beam slowly toward the crystal. To obtain a uniform rate of the beam at crystal, a monitor for close loop operation based on a photomultiplier with scintillator was used to automatically adjust the orbit distortion. We used also function generator to control current in bump windings.

The beam deflection to the septum and its transmission through the beam line of extraction were supervised with a complex system of beam diagnostics, including TV system, loss monitors, profilometers, intensity monitors[8]. All the diagnostics devices were firstly tested in fast-extraction mode and calibrated with beam transformers. The background conditions were periodically measured with and without crystal. According to the measurements, the fraction of background particles (e.g. elastically scattered protons) together with the apparatus noise did not exceed 4% of the useful signal level. This background was subtracted from the efficiency figures shown in the paper. The fraction of the beam directed to the crystal was defined as the difference between the measurements of the circulating beam intensity done with beam transformers before and after the beam extraction, with the systematic error of 1%. The extraction efficiency was evaluated in every cycle of acceleration.

4 Crystal Efficiency

The accelerator beam intensity during the experiment was about 1.3×10^{12} protons per cycle. The fraction of the circulating beam incident on the crystal ΔI was varied from 20 to 90%. The spill duration of the channeled beam in the feedback regime was on the order of 0.5 s. The plateau of the IHEP U-70 accelerator magnet cycle is 2 s long while the overall cycle of the machine is 9.6 s. Figure 1 shows the efficiency of extraction averaged over the spill, as measured in our three experiments of 1997-98. In the last one, the efficiency was about 50% even when all the accelerator beam was directed onto the crystal. The spill-averaged efficiency figures were reproducible with 1% accuracy from run to run. The dependence of the extracted beam intensity on orientation of the crystal was about the same as in Ref.[8] and not shown here. The highest intensity of the extracted beam, for 1.15×10^{12} protons incident at the crystal in a cycle, was equal to 5.2×10^{11}.

As the beam moves radially toward the crystal, the proton incidence angle drifts at the crystal. For this reason the extraction efficiency varies in time during the spill, especially for a large beam fraction used. The peak extraction efficiency in a spill was always greater than 60%. The absolute extraction efficiency as obtained in our Monte Carlo simulations agree with the measurements to accuracy of about 5% for spill-averaged figures.

5 Crystal Collimation Experiment

Bent crystal, situated in the halo of a circulating beam, can be the primary element in a scraping system, thus serving as an 'active' collimator. In this case, the only difference from extraction is that channeled particles are bent onto a secondary collimator instead of the extraction beamline. The bent particles are then intercepted (with sufficiently big impact parameter) at the secondary element and absorbed there.

We have performed the first demonstration experiment on crystal-assisted collimation. A bent crystal, with the same dimensions as the extraction crystals described above and with bending angle of 1 mrad, was positioned upstream of a secondary collimator (stainless steel absorber 4 cm wide, 18 cm high, 250 cm long) "FEP" and closer to the beam in the horizontal plane. As the horizontal betatron tune is 9.73 in our accelerator, it was most convenient to intercept the bent beam at FEP not immediately

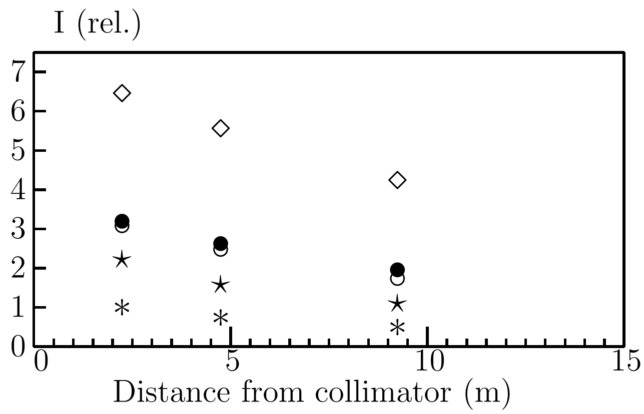

Figure 2: Radiation levels as monitored at three places along the ring in the vicinity of FEP, for different cases (bottom up): $*$ - beam kicked onto absorber by a kicker magnet; $\star$ - aligned crystal as primary; $\circ$ - FEP works as primary; $\bullet$ - misaligned crystal as primary; $\diamond$ - Si target downstream of FEP is primary.

on the first turn, but after 3 turns in the accelerator. In this case the deflection angle of 1 mrad transforms into more than 20 mm horizontal offset, and so the bent beam enters the FEP collimator at some ∼15 mm from the FEP edge. The optimal horizontal position of the crystal w.r.t. the FEP edge was found to be ∼10 mm.

Radiation levels were monitored at three places along the ring in the vicinity of FEP, from ∼2 to ∼10 meters downstream of the backward edge of the collimator. Several different cases have been studied.

- The whole accelerator beam was kicked into the middle of the FEP face by a kicker magnet. That's an ideal case for a beam interception and absorption, so the resulting radiation levels (nonzero due to escape of some primary and secondary particles from the FEP body) can be considered as a kind of pedestal for the results obtained then with several actual scraping methods. These lowest levels are shown in Figure 2 by ($*$) marks.

- When FEP was a primary element scraping the beam halo continously, the halo particles were entering FEP very close to its edge (at sub-micron depths) so the escape of particles from FEP body because of outscattering was very important. This resulted in higher radiation levels ($\circ$) as shown in Figure 2.

- A bent silicon crystal was introduced then about 60 cm upstream of the forward edge of FEP. Crystal served as a primary element of the scraping system, being closer to the circulating beam than FEP, with the offset of about 5-15 mm in the radial plane. When the crystal was misaligned, it was acting as an amorphous target scattering particles. The collimator downstream could intercept some of the scattered particles. The radiation levels measured ($\bullet$) in this setting were not so different from the preceding case of direct (by FEP) scraping of the beam halo.

- When the crystal was aligned to the best angle w.r.t. the incident beam, a substantial number of halo particles was channeled and deflected into the depth of

FEP for best absorption. The monitored radiation levels with aligned crystal serving as primary element are shown ($\star$) in Figure 2. One can conclude that about one half of the halo was extracted and forwarded to a safe place (i.e. the middle of FEP face) for absorption, reducing the radiation background in the ring correspondingly.

- Finally, another case studied was a silicon target (amorphous) positioned downstream of FEP as a primary element. In this case the machine was not protected from the scattered particles originating in the target, so the radiation levels achieved ($\diamond$) were the highest.

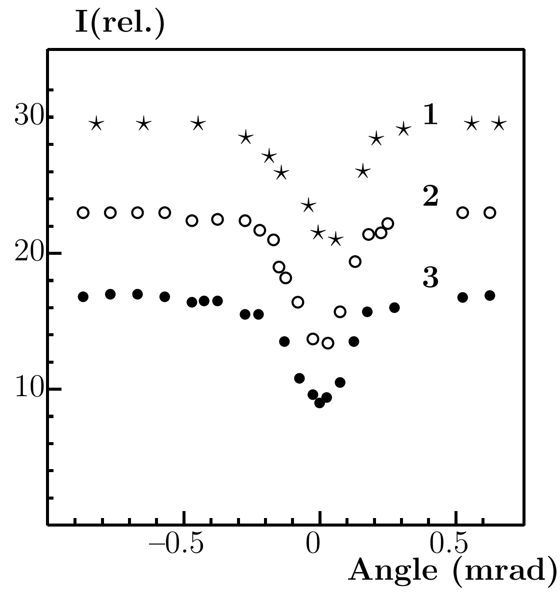

Figure 3: Measured irradiation in detectors 1, 2, 3 as function of crystal angle.

Figure 3 shows how the radiation level depends on the angular alignment of the crystal. At the best crystal angle, preferable for channeling, the radiation levels decrease by up to factor of ∼two in the places of monitoring. This is explained by the fact that ∼50% of the incident beam is channeled by the crystal and deflected to the depth of FEP where absorbed. In the case when crystal was out and the beam was scraped directly by FEP, the radiation at the monitors was at about the same level as in the case of disaligned crystal.

We were able to check the crystal efficiency figure by alternative means, measuring the profile and intensity of the particles incident at the FEP entry face. The channeled beam had a narrow profile and was well distanced from the FEP edge, as shows Figure 4 where this profile is shown in comparison with the profile of the accelerator beam deflected onto FEP by a kicker magnet. From comparison of the two profiles, from crystal and from kicker, we again derived the crystal efficiency, which was found to be about 50%, in agreement with the radiation monitoring figures and with the earlier shown figures of extraction efficiency with crystal in straight section 106.

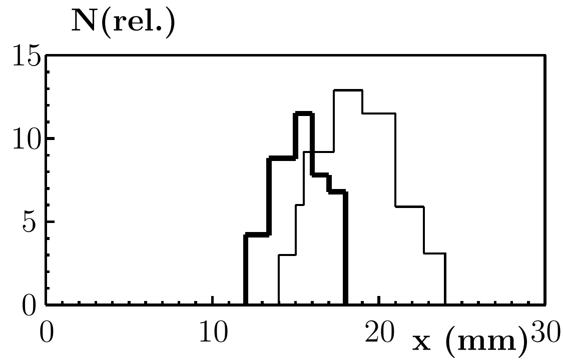

Figure 4: Profiles measured at FEP entry face: the channeled beam (thick line) and the beam (thin line) deflected by kicker magnet.

6 Conclusions

The crystal-assisted method of beam steering (for scraping or slow extraction) demonstrates peak efficiencies in the order of 60-70% and shows reliable, reproducible and predictable work. Crystal can channel at least 5-6$\times 10^{11}$ ppp with no cooling measures taken and no degradation seen.

In our experiment this technique was for the first time demonstrated for scraping of the beam halo. Such application has been studied by computer simulation for several machines, notably RHIC [6] and Tevatron [9]. We have shown that radiation levels in accelerator can be significantly decreased by means of channeling crystal incorporated into beam cleaning system as a primary element.

We continue tests with crystals as short as down to 1 mm, where Monte Carlo predicts 80-90% efficiency of steering. We study different techniques to prepare bent crystal lattices with required size, one of the most interesting approaches is described in Ref.[10].

7 Acknowledgements

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