Progress in Crystal Extraction and Collimation

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Presented at HEACC (Tsukuba, March 25-30, 2001)

Abstract

Recent IHEP Protvino experiments show efficiencies of crystal-assisted slow extraction and collimation of 85.3±2.8%, at the intensities of the channeled beam on the order of 10^{12} proton per spill of ∼2 s duration. The obtained experimental data well follows the theory predictions. We compare the measurements against theory and outline the theoretical potential for further improvement in the efficiency of the technique. This success is important for the efficient use of IHEP accelerator and for implementation of crystal-assisted collimation at RHIC and slow extraction from AGS onto E952, now in preparation. Future applications, spanning in the energy from order of 1 GeV (scrapping in SNS, slow extraction from COSY and medical accelerators) to order of 1 TeV and beyond (scrapping in Tevatron, LHC, VLHC), can benefit from these studies.

1 Introduction

Two major applications of crystal channeling in modern hadron accelerators are slow extraction and halo collimation (see e.g. [2] and refs therein). The benefits of crystal extraction are fourfold. In hadron colliders this mode of extraction can 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. Finally polarized beams can be extracted without detrimental effects on the polarization. The benefits of crystal-assisted scraping we discuss in the next section.

These 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 being studied at RHIC (100-250 GeV) [3], for the Tevatron (1000 GeV) [4] and the LHC [5].
for the Spallation Neutron Source (1 GeV) [8], whilst crystal-assisted slow extraction is considered for COSY (1-2 GeV) and AGS (25 GeV) [12].

2 Crystal as a Scraper

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 [14]. 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.

Naturally, an amorphous target scatters particles in all possible directions. Ideally, one would prefer a "smart target" that 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 center of absorber (to exclude escapes). Bent crystal is the first idea for such a smart target: it traps particles and conveys them into the desired direction. In physics language, we replace the scattering on single atoms of amorphous target by the coherent scattering on atomic planes of aligned monocystal.

3 Channeling Efficiency

It’s been long argued theoretically that a breakthrough in crystal efficiency can be due to multiple character of particle encounters with a crystal installed in a circulating beam. To clarify this mechanism an extraction experiment was started at IHEP Protvino at the end of 1997 (see Ref.[6, 7] and refs therein).

In the last two years, we demonstrated crystal channeling with 50% efficiency. We also showed that 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, we installed and tested in U-70 ring several new crystals produced by different manufacturers with a new shape. The azimuthal length of the Si(111) crystals was only 1.8-4.0 mm, bending angle 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. The new technology allows us to control precisely the crystal length and bending radius.

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 built 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.

Fig.1 illustrates the beneficial effect of crystals when used as primary collimators. We present beam profiles in the radial plane downstream of the crystal, recorded with
Figure 1: Beam profiles measured at the collimator entry face: (a) crystal out; (b) crystal in, but misaligned; (c) crystal in the beam, aligned; (d) beam kicked by magnet.

the profile-meter of Ref.[6]. The coordinate $R$ represents the radial displacement referred to the collimator edge. 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. 1(a)). In the second case (Fig. 1(b)) the crystal is used as the primary scraper, whilst the amorphous target is retracted. No care is taken to align crystal with respect to the beam direction, hence its action on the incoming protons is very similar to that of an amorphous target. When properly aligned (see Fig. 1(c)), the crystal channels most of the incoming beam and displaces their distribution by about 10 mm inside the collimator edge. In the last case (see Fig. 1(d)), the beam is simply kicked by a magnet towards the secondary collimator, whilst the primary target is retracted.

The channeling efficiency is given by the ratio of the extracted beam intensity, as
Figure 2: Crystal extraction efficiency as measured for 70-GeV protons. Recent results (⋆, strips 1.8, 2.0, and 4 mm), 1999-2000 (□, O-shaped crystals 3 and 5 mm), and 1997 (⊗, strip 7 mm). Also shown (○) is Monte Carlo prediction [7] for a perfect crystal.

measured in the external beam line, to all the beam loss, as measured in the entire ring; see the diagnostics part of the experiment described in refs. [6, 7]. 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 4 mm long crystal reached 68% efficiency. In Fig.2 we plot the expected (the prediction published in [7]) and the measured channeling efficiencies together with data relative to an old O-shaped crystal. The agreement between measurements and simulations is excellent. Fig.2 shows the theoretical potential for channeling efficiencies of 90-95% when we manage a crystal deflector with the size optimal for our set-up.

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, also important are standing a high beam intensity and crystal lifetime. 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. We can measure 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. The number of hits per primary particle can vary from a few to more than hundred. Such analysis has shown that our crystals were irradiated up to $2 \times 10^{14}$ particles per spill of $\sim 1$ s duration. When averaged over machine cycles, the irradiation rate was as high as $2 \times 10^{13}$ proton hits/s.

Notice that this irradiation rate already exceeds the expected beam loss rate at the
Spallation Neutron Source. Indeed, the SNS Accumulator Ring should generate a 1 GeV proton flux of $60 \times 2 \times 10^{14}$ per second. At the expected rate of beam loss of 0.1% the halo flux will be $1.2 \times 10^{13}$ protons/s. Several crystals in use in U-70 have been exposed to high intensity beams for months. After the irradiation of $\sim 10^{20} \text{p/cm}^2$ the initial channelling efficiency was practically unaffected.

![Beam profile as measured on the collimator entry face with 1.3 GeV protons. In black is shown the simulated profile of channeled protons.](image)

**Figure 3:** Beam profile as measured on the collimator entry face with 1.3 GeV protons. In black is shown the simulated profile of channeled protons.

## 5 Collimation at 1.3 GeV

On the same location in U-70 with the same 1.8-mm crystal of Si(111) positioned $\sim 20$ m upstream of the ring collimator, we have repeated the crystal collimation experiment at the injection flattop of U-70, proton kinetic energy of 1.3 GeV. With the crystal aligned to the incoming halo particles, the radial beam profile at the collimator entry face showed a significant channeled peak far from the edge, Fig.3.

The expected width of the channeled peak is about 5 bins in the profile of Fig.3 in agreement with observations. About half of the protons intercepted by the collimator jaw, have been channeled there by a crystal; i.e., crystal doubled the amount of particles intercepted by the jaw. As only part (about 34%) of all particles scattered off the crystal have reached the jaw, we estimate the crystal deflection efficiency as 15-20%. The observed figure of efficiency could be well reproduced in computer simulations. This figure is orders of magnitude higher than previous world data for low-GeV energy range.

It is remarkable that the same crystal was efficiently channeling both at 70 GeV and at 1.3 GeV, thus demonstrating to be operational in a very wide energy range.
6 Conclusion

The crystal channeling efficiency has reached unprecedented high values both at top energy and at injection energy. 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 over $10^{20}$ proton/cm$^2$ and irradiation rates of $2 \times 10^{14}$ particles incident on crystal in spills of $\sim 2$ s duration without deterioration of their performances.

The efficiency results well match the figures theoretically expected for ideal crystals. As simulations show, extraction and collimation with channeling efficiencies over 90-95% is feasible. The obtained high figures provide a crucial support for the ideas to apply this technique in beam cleaning systems, for instance in RHIC and Tevatron. Earlier Tevatron scraping simulations [10] have shown that crystal scraper reduces accelerator-related background in CDF and D0 experiments by a factor of $\sim 10$. This year, first experimental data is expected from RHIC where crystal collimator [9] is installed. 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 [11].

This work was supported by INTAS-CERN grant 132-2000, RFBR grant 01-02-16229, and by the "Young researcher Project" of the University of Ferrara.

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