Progress in Crystal Extraction and Collimation

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Abstract

Recent IHEP Protvino experiments show efficiencies of crystal-assisted slowextraction and collimation of 85.3±2.8%, at the intensities of thechanneled beam on the order of 10^{12} proton per spillof $\sim$2 s duration.The obtained experimental data wellfollows the theory predictions. We compare the measurements against theoryand outline the theoretical potential for further improvement in theefficiency of the technique. This success is important for the efficient useof IHEP accelerator and for implementation of crystal-assisted collimationat RHIC and slow extraction from AGS onto E952, now in preparation.Future applications, spanning in the energy from order of 1 GeV (scraping inSNS, slow extractio from COSY and medical accelerators)to order of 1 TeV and beyond (scraping inTevatron, LHC, VLHC), can benefit from these studies.

1 INTRODUCTION

Two major applications of crystal channeling in modern hadronaccelerators are slow extraction and halo collimation(see e.g. [1] and refs therein).The benefits of crystal extraction are fourfold.In hadron colliders this mode of extraction can be made compatiblewith 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 withoutdetrimental 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 studiedat RHIC (100-250 GeV) [2],for the Tevatron (1000 GeV) [3]and the LHC [4],for the Spallation Neutron Source (1 GeV) [5],whilstcrystal-assisted slow extraction is consideredfor COSY (1-2 GeV)and AGS (25 GeV) [6].

2 CRYSTAL AS A SCRAPER

Classic two-stage collimation system for loss localisationin accelerators typically uses a small scattering target as a primaryelement and a bulk absorber as secondary element [7].The role of the primary element is to give a substantial angular kickto the incoming particles in order to increase the impact parameteron the secondary element, which is generally placed in the optimum positiontointercept 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 inonly one direction: for instance, only in radial plane, only outward,and only into the preferred angular range corresponding to the center ofabsorber (to exclude escapes).Bent crystal is the first idea for such a smart target:it traps particles and conveys them into the desireddirection.In physics language, we replace the scattering on single atomsof amorphous target by the coherent scattering on atomic planes ofaligned monocrystal.

3 CHANNELING FFICIENCY

It’s been long argued theoretically[8]that a breakthrough in crystal efficiency can be due tomultiple character of particle encounters with a crystalinstalled in a circulating beam.To clarify this mechanism an extraction experiment was started at IHEP Protvinoat the end of 1997 (see Ref.[9, 10]and refs therein).In the last two years, we demonstrated crystal channeling with50% efficiency.We also showed that these crystals couldbe efficiently used as primary collimators, thereby reducingby a factor two theradiation level measured downstream of the collimation region of U-70[9, 10].To continue our investigations,we installed and tested in U-70 ring several new crystalsproduced 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 ne technology allows us to control precisely the crystallength and bending radius.Two crystals were assembled in Protvino:one 2 mm long was bent by 0.9 mrad, the other 4 mmlong was bent by 1.5 mrad.The third crystal 1.8 mm long bent by 0.8 mrad was built and polishedin the University of Ferrara (Italy).The two Russian crystals were used in extraction mode,whilst the Italian one wastested as a primary collimator.The three crystals were exposed to 70 GeV proton beams andused to channel and extract halo particles.

Fig.1 illustratesthe beneficial effect of crystalswhen used as primary collimators.We present beam profiles in the radial planedownstream of the crystal itself,recorded with the profile-meter of Ref.[9]. The coordinate$R$ represents the radial displacement referredto the crystal edge.Four cases are reported.In first one, an amorphous collimator is used as primary targetwhilst the close-by crystal is kept outside of the beam envelope.As expected, the beam profile is peaked

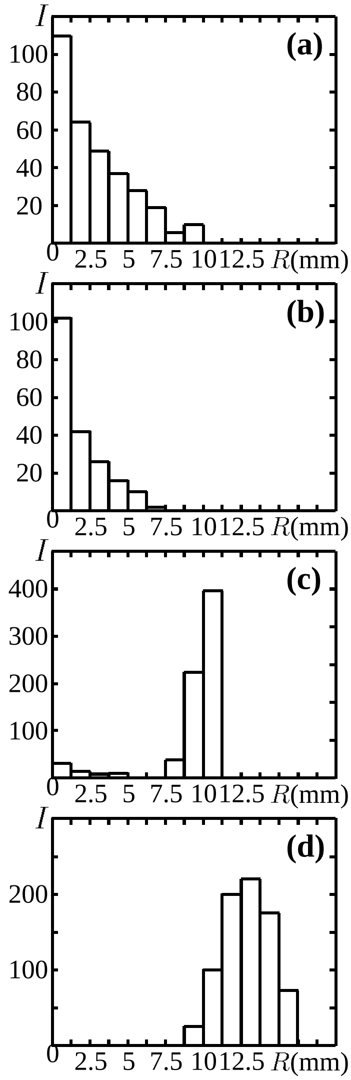

Figure 1: Beam profiles measured at the collimator entry face:(a) crystal out;(b) crystal in, but misaligned;(c) crystal in the beam, aligned;(d) bea kicked by magnet.

at the collimator edge (Fig. 1(a)).In the second case (Fig. 1(b)) thecrystal is used as the primary scraper,whilst the amorphous target is retracted.No care is taken toalign crystal with respect to the beam direction,hence its action on the incoming protons is very similar to thatof an amorphous target.When properly aligned (see Fig. 1(c)), the crystal channels mostof the incoming beam and displaces their distribution byabout 10 mm inside the crystal 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 bythe ratio of the extracted bea intensity, as measured inthe external beam line, to all the beam loss, as measured in the entire ring;see the diagnostics part of the experiment describedin refs. [9, 10].We obtained very high channeling efficiencies in *each* of thethree new crystals: namely, both the 1.8 an 2

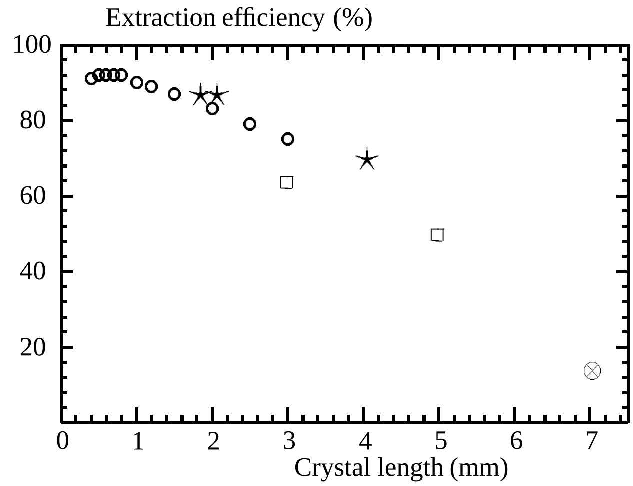

Figure 2: Crystal extraction efficiency as measured for 70-GeV protons.Recent results (★, strips 1.8, 2.0, and 4 mm),1999-2000 (□, O-shaped crystals 3 and 5 mm),and 1997 (⊗, strip 7 mm).Also shown (o) is Monte Carlo prediction [7]for a perfect crystal.

mm long crystals reached85% efficiency, whilst the 4mm long crystalreached 68% efficiency.In Fig.2 we plot the expected (the prediction published in[10]) and the measured channelingefficiencies 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 efficienciesof 90-95% when we manage a crystal deflector with the size optimalfor our set-up.These unprecedented results were indeed obtained in a steady mannerover many runs. In particular, the 2 mm long crystal was regularlyfunctioning to extract beams with a channelling efficiency of 85.3±2.8%.

4 HIGH-INTENSITY TESTS

Beside the channeling efficiency, also important arestanding a high beam intensity andcrystal lifetime.Crystals located in the region upstream of the U-70 cleaning area wereirradiated with the entire circulating beam, spilled out in rathershort time durations to simulate very dense halo collimation.We can measure preciselythe beam intensity intentionally damped intothe crystal. However, we can only estimate with computer simulationsthe total amount of particle hits during a spill, sinceunchanneled protons are simply scattered andmay continue to circulate in the ring hitting the crystal many times.The number of hits per primary particle can vary from a fewto more than hundred.Such analysis has shown thatour crystals were irradiated up to2×10^{14} particlesper spill of ∼1 s duration.When averaged over machine cycles,the irradiation rate was as high as2×10^{13} proton hits/s.Notice that this irradiation ratealready *exceeds* the expected beamloss rate at the Spallation Neutron Source. Indeed,the SNS Accumulator Ring should generate a 1 GeVproton fluxof $60\times2\times10^{14}$ per second. At the expected rate ofbeam loss of 0.1% the halo flux will be1.2×10^{13} protons/s.Several crystals in use in U-70 have been exposed to high intensity beamsfor months.After the irradiation of $\sim 10^{20}$p/cm^{2}the initial channelling efficiency was practically unaffected.

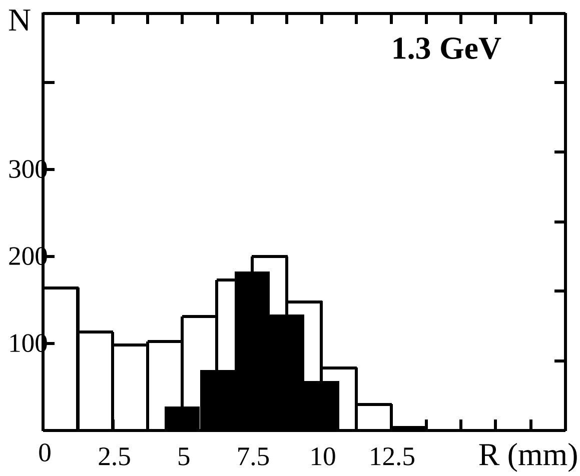

Figure 3: Beam profile as measured on the collimator entry facewith 1.3 GeV protons.In black is shown the simulated profile of channeled protons.

5 COLLIMATION AT 1.3 GEV

On the same location in U-70with the same 1.8-mm crystal of Si(111)positioned ∼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 faceshowed a significant channeled peak far from the edge, Fig.3.The expected width of the channeled peakis about 5 bins in the profileof 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., crystaldoubled the amount of particles intercepted by the jaw.As only part (about 34%) of all particles scattered off the crystalhave reached the jaw, we estimate thecrystal deflection efficiency as 15-20%.The observedfigure of efficiency could be well reproduced in computer simulations.This figure is orders of magnitude higher than prevous world datafor low-GeV energy range.It is remarkable that the same crystal was efficiently channelingboth 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 valuesboth at top energy and at injection energy.The same 2 mm long crystal was used to channel 70 GeV protonswith an efficiency of 85.3±2.8% during several weeks of operationand 1.32 GeV protons with an efficiency of 15-20% during some test runs.Crystals with a similar design were able to stand radiation dosesover 10^{20} proton/cm^{2}and irradiation rates of 2×10^{14} particlesincident on crystal in spills of ∼2 s durationwithout deterioration of their performances.The efficiency results well match the figures theoretically expectedfor ideal crystals. As simulations show, extractionand collimation with channeling efficiencies over 90-95% is feasible.The obtained high figures providea crucial support for the ideas to apply this technique in beam cleaningsystems, for instance in RHIC and Tevatron.Earlier Tevatron scraping simulations [3] have shown that crystalscraper reduces accelerator-related background in CDF and D0experiments by a factor of ∼10.This year, first experimental data is expected from RHICwhere crystal collimator [2] is installed.The technique presented here is potentially applicable also in LHC forinstance to improve the efficiency of the LHC cleaning system by embeddingbent crystals in the primary collimators[4].This work is supported by INTAS-CERN grant.

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