HIGH EFFICIENCY COLLIMATION WITH BENT CRYSTALS

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Abstract

A revolutionary collimation approach is being developed by the H8RD22 collaboration. The basic idea is to replace the amorphous jaws, which spread the beam halo in the whole solid angle, with bent crystals, which are able to deviate the halo particles in a given direction outside the beam core. Studies to investigate the bent crystal properties have been carried out over the past 2 years at the H8 beam line (CERN SPS) with a 400 GeV/c proton beam. The crucial result of these studies is the observation of the Volume Reflection effect, the coherent scattering of the whole beam on the crystalline planes which provides a small but very efficient (respectively, 14 μrad and 98% at 400 GeV/c) particle deflection. The high efficiency (which should increase at higher energy) combined with a large angular acceptance ($\sim$100 μrad) led to the development of multi-reflection systems to increase the deflection angle. Nowadays this system has reached the stage to be tested in a circular accelerator as a primary collimator to verify the effective collimation efficiency in a complex environment. The second phase of the LHC collimation could be the first application of this crystal based system.

INTRODUCTION

Bent crystals can be used for high energy beam steering exploiting their ordered atomic structure. The crystal in fact is able to confine the motion of a charged particle in the channel formed within two neighboring atomic planes [1]. If the particle trajectory is aligned with the crystal plane direction, it is subjected to coherent scattering with the plane instead of the usual multiple scattering. If the crystal is bent (with a mechanical holder) the particle is forced to follow the channel and its curvature being thus finally deflected by the crystal. This deflection ability can be used to create a primary collimator able to deviate the particles outside the beam in a given direction increasing the collimation efficiency. This intriguing idea has been already tested on circular accelerators (RHIC and TEVATRON) but without obtaining an unambiguous result. The H8RD22 collaboration is studying the last generation of bent crystals on an extracted beam with an innovative experimental approach in the crystal channeling field which is the single particle track reconstruction (with high resolution silicon microstrip detectors). In the following sections some important results, which summarize and explain the bent crystal behaviour, are shown together with a brief analysis on the possibility of the application to circular accelerators.

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MEASUREMENTS ON AN EXTRACTED BEAM

Three data taking periods have been carried out on the CERN SPS H8 beam line with a 400 GeV/c proton beam while one has been devoted to the studies with light particles. The data presented in this article have been collected during the May 2007 beam test whose experimental setup is shown in Fig. 1. The crystal is mounted on a high precision goniometer which allows to orient it with respect to the beam with a precision of 1 μrad. The tracking system consists of three silicon microstrip detectors (S4 is for redundancy) which measure both the horizontal and vertical particle position with a resolution of 5 μm. The system is optimized for the measurement of the particle angle before and after the crystal minimizing the angular dispersion due to multiple scattering.

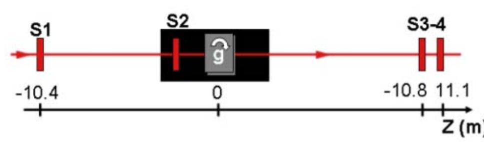

Figure 1: Experimental setup (of the May 2007 test): S indicates the silicon microstrip detectors and g the goniometer which rotates the crystal.

During the experiment both strip [2] and quasimosaic [3] crystal types have been tested showing a similar behavior; the data presented in the following refer to a strip crystal prepared by the INFN section of Ferrara. The plot in Fig. 2 shows the beam angular profile after the crystal as a function of its orientation with respect to the beam; there are different deflecting effects which can be identified. From left to right: (1) the crystal is misaligned, it behaves as an amorphous material; (2) the crystalline planes are aligned with respect to the beam at the crystal entry face and the channeling peak appears; (3) the tangency point between the channel and the beam moves inside the crystal itself where an elastic scattering with the potential barrier causes the reflection of the particle trajectories.

Fig. 3 shows the angular profile of the beam for two different crystal orientations. In the top plot the crystal is in the channeling regime, so that a fraction of the particles are deflected with an angle of about 230 μrad. In the bottom plot the crystal is in the volume reflection regime: if compared to the amorphous position (white histogram) the beam is shifted of 13 μrad. Volume reflection has been discovered in computer simulation [4] and experimentally observed at high energy by the H8RD22 collaboration [5];

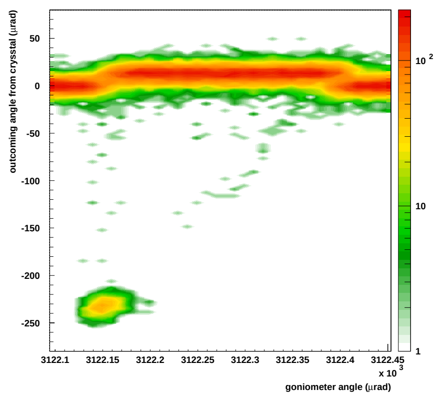

Figure 2: The beam angular profile after the crystal as a function of its orientation. The crystal is a strip one: 70 mm (vertical) x 0.5 mm (horizontal) x 2 mm (along the beam) with a bending radius of 9 m.

its high efficiency and large angular acceptance make it an attractive alternative with respect to channeling for collimation. To increase the deflection angle the collaboration is developing multi crystal assemblies in which consecutive reflections multiply the deflection angle; the first successful attempt can be found in [6].

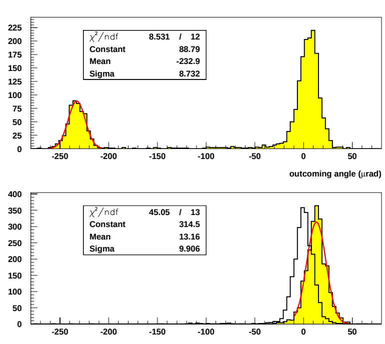

Figure 3: The beam angular profile after the crystal: top) in the channeling regime, bottom) in the volume reflection one (the white plot represents the amorphous regime).

The channeling deflection angle depends on the ratio between the crystal length and the bending radius; for example the 220 μrad deflection shown in Fig. 3 has been given by a crystal of 2 mm with a bending radius of 9 m. If the bending radius is reduced, a larger deflection angle can be achieved with the same material thickness; this is the case shown in Fig. 4 where the same strip crystal is bent with a bending radius of 4 m. The channeling deflection angle becomes 450 μrad (which is equivalent to a magnetic field of more than 300 T). The volume reflection angular acceptance corresponding to the channeling angle is larger while its deflection angle slightly decreases.

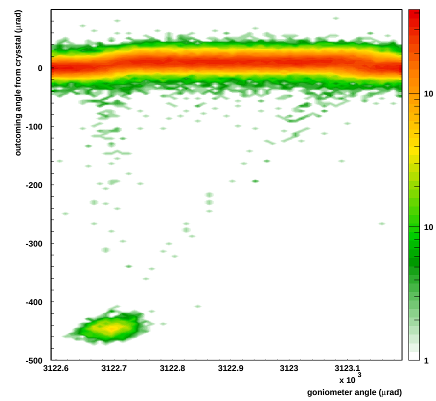

Figure 4: The beam angular profile as a function of the crystal orientation for the same crystal of Fig. 2 but with a bending radius of 4 m.

The comparison between Figs. 2 and 4 underlines a smaller channeling efficiency and also a worse separation between the amorphous and reflection regions in the second case (smaller bending radius). An accurate analysis demonstrates that these effects are not due to fundamental physics laws but depend on a secondary mechanical effect. When the crystal is bent, in fact, a torsion along the vertical axis appears; according to this, the particles impinging on the crystal experience a different crystal orientation as a function of their impact point. This produces an intrinsic limit on the reachable alignment with respect to the beam. Since the detection system allows to measure both the particles incoming angle to the crystal and the impact point on the crystal surface, the angle between the particle trajectory and the channel direction can be computed for each particle. Fig. 5 shows the particle outcoming angle from the crystal as a function of the misalignment with respect to the crystal itself. The separation of the different regions is sharper and the channeling peak extends on a smaller horizontal region. This means that for a perfect alignment (shown in Fig. 6) the channeling efficiency results to be higher with respect to the one measured without any correction; in this case it is greater than 75% in agreement with the theoretical prediction. Moreover, being the torsion problem a mechanical one, it can be checked in real time and solved acting on the holder.

APPLICATION TO CIRCULAR ACCELERATORS

The studies performed on the H8 beam line inspired two different strategies for the "crystal based" collimation: a single oriented crystal to channel the halo outside the beam and a multi-crystal assembly which deflects the halo particles with a series of consecutive reflections. In both cases the crystal should replace the primary amorphous collimator in a multi-stage collimation system (as shown in Fig. 7)

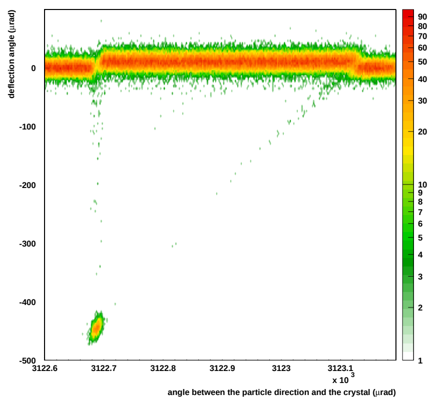

Figure 5: The beam angular profile after the crystal as a function of the angle between the particle trajectory and the crystalline plane direction reconstructed with the silicon detectors information.

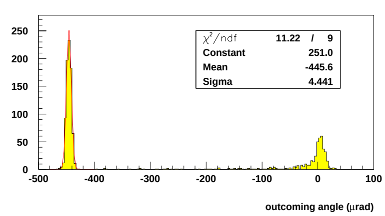

Figure 6: The beam angular distribution after the crystal for a perfect alignment with respect to the crystal channel.

increasing the collimation efficiency and reducing the contribution to the machine impedance.

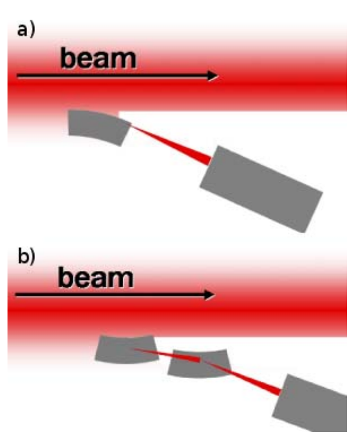

Figure 7: Pictorial representation of the crystal based collimation: a) single crystal in channeling; b) multi-crystals in reflection.

The results obtained on the extracted beam cannot establish which crystal configuration is more efficient once it is installed in the complex environment of a circular accelerator. There are two main features, in fact, which distinguish a circular beam from an extracted one:

1) the average impact parameter of the halo particles on the crystal surface can be very close to the crystal edge (from 100 to 200 nm) and the detector resolution cannot resolve such a thin region in a H8 like experiment;

2) particles which are not deflected at the first crossing of the crystal survive in the accelerator and have other chances to be steered by the crystal itself on the following turn; this effect which can increase the total collimation efficiency, is called multi-turn effect.

A preliminary comparison between channeling and volume reflection can be done without the aim of establishing which one is the most appropriate for collimation.

The channeling effect is attractive as it can provide large deflection angles with a simple mechanical assembly; the deflection angle and the efficiency are almost independent from the beam while the angular acceptance is limited by the critical angle which scales as the square root of the energy. A small angular acceptance requires a better alignment precision and beam stability; it limits the efficacy of the multi-turn effect and it prevents the use of crystals where the halo divergence is greater than the critical angle [8]. Volume reflection appears as the natural answer for a larger angular acceptance providing at the same time a very high efficiency at high energy; the difficulty of a small deflection angle can be overcome through multireflection. However this system is more complicated from the mechanical point of view and its behaviour in presence of a small impact parameter and of the multiturn effect remains to be tested.

CONCLUSION

The studies of the H8RD22 collaboration on bent crystals provide a complete knowledge of their behaviour. The application in the collimation field is a possibility that has to be investigated. While the tests on an extracted beam line are fundamental to improve the technology and to understand its limits and advantages, a test on a circular accelerator is mandatory to say the last word on crystal collimation.

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