FUTURE PROSPECTIVE FOR BENT CRYSTALS IN ACCELERATORS

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Abstract

Crystals are medium where atoms are arranged in specific positions, repeating the pattern of the unit cell over the whole volume. This internal highly regular and periodic nanostructure is cause of phenomena otherwise impossible in amorphous material, where atoms are placed randomly. Indeed, in specific conditions incoming particles and photons interact with whole groups of atoms disposed along planes or strings. Such is the case of channeling, where the particles travel inside the crystal following the lattice planes or axes orientation. The effect was first observed in 1963 [1] and a great progress has been achieved in both theory and applications. Nowadays, a great interest is focused on the deflection of positive ultrarelativistic particles via planar channeling in a bent crystal. Indeed, the curvature of lattice planes acts on channeled particles in a similar manner as a waveguide. For particles of momentum $10^{2\text{-}3}$ GeV, the steering power of this method vastly exceed state of art magnetic dipole, providing deflection equivalent to up to $10^{2\text{-}3}$ Tesla in a compact device with zero-energy consumption. Consequently, novel schemes of beam manipulation have been proposed for LHC beams. Crystal-assisted collimation was experimented with both proton and ion beam. Future accelerators such as a muon accelerator may exploit this technology as well.

CHANNELING THEORY

The theoretical framework for planar channeling was first devised by Lindhard in 1965 [2]. He calculated that for trajectories in close alignment with lattice planes, subsequent elastic scattering with single atoms are correlated with each other thanks to the highly ordered crystal structure. Thus, the sum of every events can be efficiently described as the interaction with the whole atomic planes. This effect can be calculated by integrating the screened electrostatic potential of each atom on the atomic planes. The result is a one-dimensional smooth continuous potential along the dimension perpendicular to the lattice planes. Channeling occurs for incoming particles whose transversal energy (derived from momentum component perpendicular to lattice planes) is lower than the potential well depth. Only particles in close alignment with planes are bounded to the planar continuous potential, the maximum angle being defined as *critical angle* or *Lindhart angle* and corresponding to

$$\boldsymbol{\theta_C} = \sqrt{\frac{\boldsymbol{2U_0}}{\boldsymbol{pv}}}, \tag{1}$$

where U_0 is the depth of the continuous potential, p is the particle momentum and v its speed.

For positively charged particles, the maxima of the potential are located along the nuclei on the atomic planes while the minima are located between adjacent planes. Consequently, channeled positive particles are forced to propagate in a region of the crystal far from nuclei and with low electronic density. Hence, nuclear interactions are strongly suppressed with consequent reduction of inelastic scattering and energy loss. Indeed, usually scattering with nuclei occurs mainly only for channeled particles impinging the crystal near the lattice planes or with large transverse energy and usually quickly remove particles from channeled state. The remaining particles interact mainly with valence electrons. As particle momentum increases, electronic scattering scarcely affects channeled particles, which can maintain their state for a long distance. For protons and ions of LHC primary beam, dechanneling length is in the order of 10^{-1} m.

The bending state of the lattice plane modifies the continuous potential, introducing a centrifugal force in the non-inertial reference frame co-moving with the particle. This apparent force is proportional to the crystal curvature and the particle momentum and affect the continuous potential well by reducing its depth. Hence, as curvature is increased the continuous potential is gradually weakened, until the centrifugal force overcome the potential and channeling becomes impossible. This maximum bending is indicated by the *critical radius* R_c.

$$\boldsymbol{R_c} = \frac{\boldsymbol{pv}}{\boldsymbol{e\varepsilon_{max}}}, \tag{2}$$

where $\boldsymbol{\varepsilon_{max}}$ is the maximal electric field across two adjacent atomic planes. For radius of curvature several times larger than the critical one, channeling tends to remain stable similarly to the flat crystal case. A channeled particle travelling a length l along planes bent to a radius of curvature R will result deflected of an angle $\theta = 1/R$.

CRYSTAL ASSISTED COLLIMATION

A beam circulating in a synchrotron will inevitably loose a small portion of particles from the nominal trajectory, which will form a halo around the beam. If left uncontrolled, these stray projectiles would progressively increase the background in experiments and eventually lead to failure and serious damage of the accelerator. The capacity of blocking such particles is a major factor in defining the maximum luminosity of an accelerator. Such task is not trivial, especially in case of particle with very large momentum such as at LHC. Collimation of LHC is currently carried out with a series of tens of centimetres long slabs, made of light or dense materials. The first type elastically

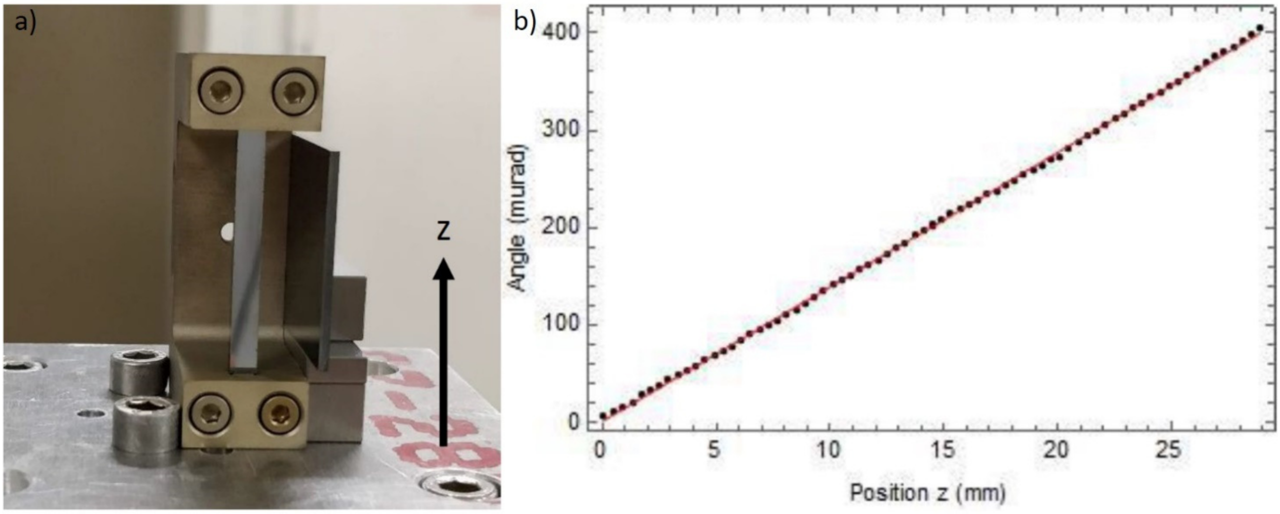

Figure 1: a) holder with bent crystal during measure at ID11, ESRF. On the left of the holder a flat crystal is used as reference to remove angular shift caused by translations during measures b) Plot of RCs angular shift measured along z direction to measure torsion.

scatters the beam halo away from the beam, while the latter dissipate the energy of incoming particles. One drawback of this method is the generation of secondary particles in the collimators, especially in case of ionic beams. Another issue lies in the random angular distribution of the scattered beam halo, which affects the efficiency in intercepting it onto the absorber. A few millimetres long bent crystal would allow to avoid such inconveniences. In first place, production of secondary particles would be suppressed thanks to the reduced amount of material intercepted by the halo and to the scarcity of inelastic interaction by channeled particles. Moreover, particles would be deflected at a precise angle and would thus be more easily intercepted and stopped by the absorbers. An extensive research was carried out on the subject by UA9 collaboration, which lead to the definition of the optimal parameter for a bent crystal for LHC collimation. Indeed, in order to achieve maximum efficiency, such crystal must follow a series of strict constrain on both size, material, lattice parameters and bending condition [3].

Two bending parameters are of particular interest: the homogeneity of curvature over the specimen and the absence of torsion. The first is necessary in order to deflect particles of the same quantity, independently from where they impact on the crystal. The presence of torsion tilts the lattice planes orientation along direction perpendicular to the curvature, thus its presence prevents to achieve alignment of the entire sample with the beam halo.

At the Laboratory of Sensor and Semiconductor of the University of Ferrara, several prototypes have been produced in order to achieve all the features required for installation on LHC. Silicon crystal samples of size 2x4x55 mm^3 are bent using titanium holder. The contact surfaces of the holder have been precisely machined at two opposite angles to induce bending along the 55 mm long direction. As elastic reaction, the sample takes the shape of a saddle, producing a so-called anticlastic curvature along the 4 mm direction. Particles will be channeled along this curvature to collimate the incoming particles.

A full and detailed pre-characterization of the crystal bending before installation on LHC is critical, in order to guarantee an optimal functionality. X-ray's diffraction is a powerful tool to attain such information. Indeed, the phenomena occurs only when x-rays impact at a very precise angle (Bragg angle) on lattice planes, and consequently is very sensible to variation of lattice plane orientation. The measure of the variation of the diffracted x-rays intensity in function of the angle between x-rays and lattice plane is called Rocking Curve (RC). The center of a RC indicates when a precise Bragg angle between lattice planes and x-rays is achieved. The angular shift between RC obtained at different positions on the crystal can be used to calculate the curvature or torsion of a sample. The measured width of the RC, deconvoluted with its theoretical value (Darwin width) and x-rays angular divergence, indicate the curvature of the diffracting lattice plane. A thoroughly investigation of one prototype was carried out at ID11 beamline of ESRF, in Grenoble. Synchrotrons are an exceptional source of x-rays radiation, outperforming laboratory instruments in both intensity and energy of the x-rays beam provided. The high flux allows to collimate the beam to few tens of microns (50x50 μm^2), increasing the spatial resolution of the measures. The high photon energy (80 keV) enables direct probing of the crystal bulk, hence to perform measurements in Laue configuration, with x-rays crossing the whole sample thickness along the anticlastic curvature direction (Fig. 1a).

The anticlastic curvature was measured from the width of the RCs: a uniform curvature was measured, corresponding to a particle deflection of 51±4 μrad on all the 740 RCs acquired. An analysis of the torsion was also carried out, by measuring angular shift of the rocking curves along the 55 mm dimension of the sample with 400 μm step (Fig. 1b), obtaining a value of 13.8 μrad, with precision of 0.2 μrad. The reliability of the measure was enhanced thanks to the use of a reference sample. In perfect and flat crystal features RC angular position are not position-dependent, thus any shift measured would be caused by mechanical imprecision of the motors. The bent crystal RC angular position were calculated relatively to the one of the reference sample, effectively avoiding any translation related error. This technique was previously used in [4] and allowed to define nanoscopic deformation in the sample in question.

These measures were consistent with the characterizations performed at the laboratory of Ferrara, providing a solid validation for the characterization of future prototypes with laboratory instrumentation as well.

CONCLUSION

Two different application of relativistic positive particles planar channeling in bent crystal have been presented along with the results of curvature characterization carried out via x-rays diffraction. In particular, for each case a different method has been presented. For the prototype of LHC collimation, a thoroughly analysis has been performed at the synchrotron beamline ID11 of ESRF, in Grenoble. This allowed to acquire very reliable data to validate the laboratory instrumentation in Ferrara.

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