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Near 100% deflection efficiency in bent crystals using multiple volume reflection

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Abstract

Simulations of the trajectories of high-energy ions through several bent crystal layers show that ions can be reflected from each layer, resulting in a multiple volume reflection angle which is correspondingly increased in proportion to the number of layers. At certain configurations of a 20 layer structure we achieve a 100% deflection efficiency of high-energy ions through an angle which is 20 times greater than the critical angle. The range of entrance angles over which ions undergo volume reflection is 40 times greater than the critical angle. The use of several bent crystal layers to produce multiple volume reflection provides an alternative approach to beam steering which overcomes limitations of bent crystal channeling such as narrow angular acceptance and low deflection efficiency. This study shows that multiple volume reflection can be used for high efficiency collimation in high-energy colliders such as the LHC and ILC and for space and radiation shields based on bent crystals.
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1. Introduction

Bent crystal channelling is established as a means of deflecting, extracting and collimating charged particle beams in high-energy accelerators [1–6] and has been experimentally explored over six decades of energy from a few MeV [7] to ~1 TeV [3]. The technique is used on permanent basis in IHEP Protvino where crystal systems extract protons from the 70 GeV main ring with an efficiency of 85% at an intensity up to 4×10^{12} protons using Si crystals which are just 2 mm along the beam direction [6]. Bent crystals channel in good agreement with predictions up to the highest energies [8]. Crystal applications at the 7 TeV large Hadron Collider have been considered for beam collimation and extraction [9], *in situ* calibration of CMS and ATLAS calorimeters [10], and channeling forward protons for the measurement of diffractive scattering [11]. The use of large area bent crystals as a space shield to deflect high-energy, heavy ions (HZE ions) of all atomic numbers away from spacecraft was recently proposed [12].

Bent crystal channelling occurs for those ions incident on the surface within the planar channeling critical angle, $\pm\theta_c$ where

$$\theta_c = \sqrt{\frac{4Z_1Z_2e^2Nd_pCa_{TF}}{pv}} \tag{1}$$

Here Z_1 and Z_2 are the atomic numbers of the incident and lattice nuclei, N is the atomic density, d_p in the planar spacing, $C \cong \sqrt{3}$, a_{TF} is the Thomas–Fermi screening distance and p,v are the ion momentum and velocity. If the lattice curvature radius R is greater than a critical radius many ions incident on the entrance face are steered through the full curvature angle δ of the lattice and emerge aligned with the exit face. The critical radius R_c is given by

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$$R_c = \frac{pv}{\pi Z_1 Z_2 e^2 N d_p} \quad (2)$$

Volume reflection [13] occurs when the entrance beam becomes tangential to the curved lattice within the bulk of the crystal, rather than at the entrance face, resulting in reflection off the coherent field of curved lattice planes towards alignment with the entrance face. Volume reflection of MeV, GeV, and TeV protons and ions along the lattice curvature of bent layers was recently studied [14,15] using Monte Carlo simulations with the codes FLUX and CATCH. The Monte Carlo code FLUX [16] uses a binary collision model in conjunction with the Ziegler–Biersack–Littmark potential [17]. The code CATCH [18] is based on a continuum-model [19] with Moliere potential, taking into account the single and multiple scattering on crystal electrons and nuclei. The predictions of the two codes for volume reflection agreed well with each other. Protons and heavy ions have shown very similar behaviour in volume reflection over a wide range of energies, from 5 MeV to 1 TeV per nucleon, in different Si(1 1 0) and (1 1 1) crystal lattices [15]. The reflection angle θ_R of the transmitted beam increases as R increases because the path length over which an ion travels close enough to be repelled by the lattice field is larger. For $R/R_c > 30$, almost a straight lattice, θ_R tends to constant value of 1.4–1.6θ_c. When the curvature radius becomes very small at $R/R_c \sim 1$ there no net deflection. As shown in [15], the plot in terms of the critical angle and critical radius, i.e. θ_R/θ_c versus R/R_c, is not only universal over a wide energy range but also gives similar predictions with different screening functions.

In papers [20,21] enhanced volume reflection produced by a single bent crystal due to the repeated passage of ions in high-energy circular accelerators was studied with the aim of reducing the local background rate for beam collimation. In a ring, the successive volume reflections can appear in the same crystal due to particle circulation [20]. One may consider an ensemble of crystals possibly resulting in particle deflection at a large angle [23].

Our previous study [15] has shown that the use of several curved layers offers the possibility of greatly expanding the range of their applications by extending both the volume reflection angle and the entrance angular range over which single and multiple volume reflection occur. Multiple volume reflection produced highly efficient deflection over a wide range of entrance angles at high energies, so providing an alternative approach to the design of a space shield or radiation protection at accelerators based on curved crystals. Schemes capable of deflecting with high efficiency a larger range of entrance angles of HZE ions using bent crystal shields were devised, also relevant to applications of bent crystals as a means of collimating and extracting beams from accelerators. We refer to [15] for a detailed study of the angular deflection and dispersion of high-energy ions by multiple volume reflection through several bent crystals layers.

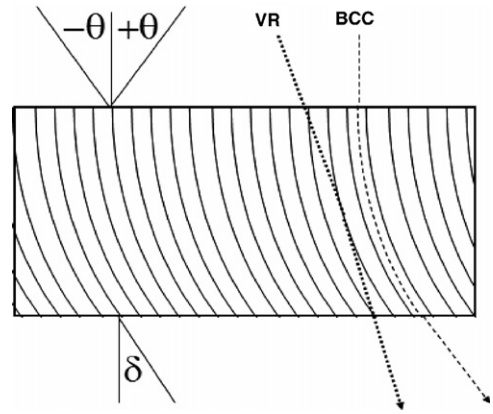

Fig. 1. Geometry for bent crystal channeling (BCC) and volume reflection (VR) through a lattice which is curved through an angle of δ. The surface lattice planes are aligned at $\theta = 0.0°$.

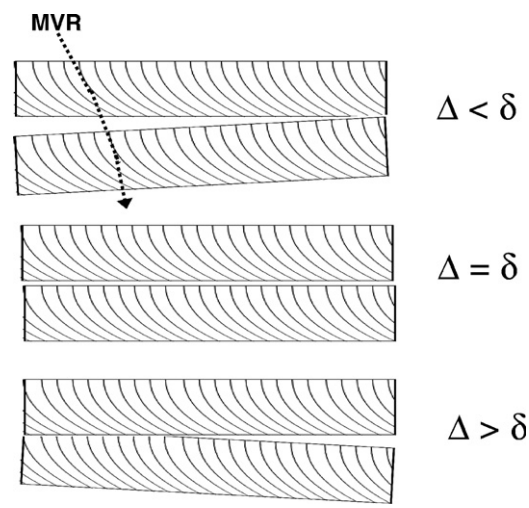

Fig. 2. Geometry for stacking several curved layers together to produce multiple volume reflection (MVR).

Fig. 1 shows the bent crystal coordinate system used here. The beam entrance angle to the channeling planes of the entrance surface is θ and the lattice is curved through an angle δ. Ions which enter the surface planes within $\pm\theta_c$ undergo bent crystal channeling and most are deflected through an angle of δ. Ions which enter the front surface within the angle subtended by the lattice curvature undergo volume reflection and are deflected by up to $+2\theta_c$ to a more positive exit angle. Fig. 2 shows the coordinate system used for stacking two or more curved layers together, each of which is rotated by an angle of Δ with respect to that above it. A value of $\Delta = 0.0°$ is equivalent to a single continuous layer curved through an angle of 2δ. For $\Delta = \delta$ the second layer has an identical angular alignment to the first layer.

2. Results

The purpose of this study is to look for layer structures which produce multiple volume reflection with the highest

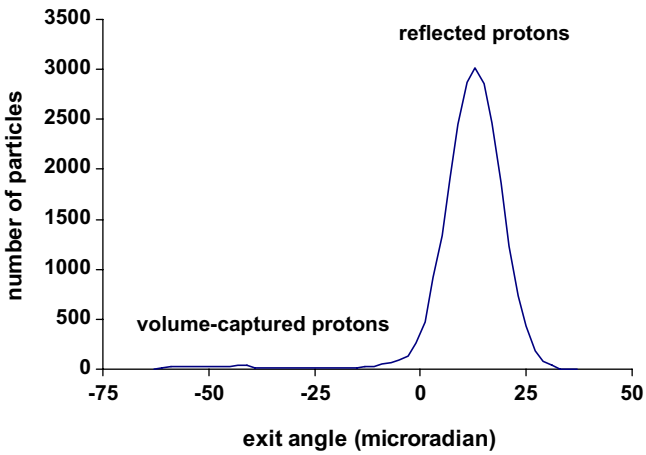

Fig. 3. Angular distribution of 400 GeV protons reflected off a single Si(1 1 1) crystal.

possible efficiency of beam deflection through large angles, with possible applications at the high energy frontier accelerators like the 7 TeV Large Hadron Collider. The code CATCH is used to simulate the passage of 400 and 7000 GeV protons through curved crystal layers.

Fig. 3 illustrates single volume reflection showing a simulated angular distribution of 400 GeV protons reflected off a single Si(1 1 1) crystal bent with $R = 10$ m. The crystal is bent through 100 μrad and tilted 50 μrad away from the bend direction so the protons become tangential to the (1 1 1) planes halfway along the crystal curvature. The typical features of the distribution are a peak of reflected protons (deflected in the opposite direction to the atomic plane bending) and a tail of volume captured protons which undergoes bent crystal channeling (deflected towards the atomic plane bending). The volume capture process [22] makes the volume reflection efficiency less than 100%. In Fig. 3, the volume reflected peak has a most probable deflection angle of 13 μrad and contains 97.5% of the beam while the tail has the remaining 2.5%.

Volume reflection was recently observed for 1 GeV (Gatchina), 70 GeV (Protvino) and 400 GeV (CERN) protons in silicon [23–25]. In [26] CATCH predictions are compared with these experimental results in some detail, with good agreement found in general. E.g. earlier CATCH predicted (EPAC June 2006, [20]) for 400 GeV protons a reflection angle of 13 μrad in a Si(1 1 1) crystal bent with $R = 10$ m, with 96% protons reflected. The reflection angle measured at CERN was 13 μrad in Si(1 1 1) crystal bent with $R = 11.6$ m, while reflection efficiency exceeded 95% [25]. This agreement makes us more confident in the predictions reported for the multiple volume reflections below.

With two curved layers stacked together, the second layer further reflects the beam and doubles the reflection angle. The use of several bent crystal layers to produce multiple volume reflection (MVR) provides an alternative approach for beam deflection to bent crystal channeling [15]. By using 10–20 layers for MVR one can achieve deflections sufficient for many interesting accelerator applications.

However, with every reflection in a layer some particles undergo volume capture. Therefore, the number of volume-captured particles in the tail would increase with every additional layer, and the efficiency of multiple volume reflection (i.e. the number of particles in the reflected peak) would decrease linearly with the number of layers N.

In order to increase the efficiency of the MVR process each subsequent layer should try to reflect all the distribution of particles passing through the layer above, including the tail. The easiest way to realize it is to have parallel identical layers, $\Delta = \delta$. Simulations show that in this case the MVR angle grows linearly with N while the efficiency remains constant. The efficiency is mostly limited by the volume capture in the last layer.

The probability of volume capture is a linear function of R [1,27] because the path length over which an ion travels close enough to have a significant probability of becoming channeled by the lattice is proportional to R. Similarly, the reflection angle θ_R decreases as R decreases although it saturates at $R \gg R_c$ [15]. However, a decrease in a single reflection angle θ_R can be compensated by an increase in the number of layers while the probability of volume capture remains low. Therefore, in order to reduce the reflection inefficiency it is better to use a small curvature radius of $R \approx 4$–$6\ R_c$. Fig. 4 shows the angular distribution of 400 GeV protons reflected off 10 parallel identical Si(1 1 0) crystal layers, $\Delta = \delta$, each 0.8 mm thick and bent through 200 μrad with $R = 4$ m (6 R_c, where $R_c = 0.67$ m at 400 GeV). As a result of multiple volume reflection the beam was deflected through an angle of 100 μrad. The bent peak has a symmetric shape with an rms width of 16 μrad, or $2\theta_c$ (at 400 GeV, $\theta_c \approx 8$ μrad in Si(1 1 0) planes). Truly remarkable is the bending efficiency, with 98% of 400 GeV protons with a deflection angle $\theta > 0$.

The benefits of the MVR technique for deflection of particle beams become evident when compared with bent crystal channeling. Fig. 4 shows also a 400 GeV beam which is bent through 100 μrad by a channeling crystal of 8 mm length (the same thickness as the MVR layer structure

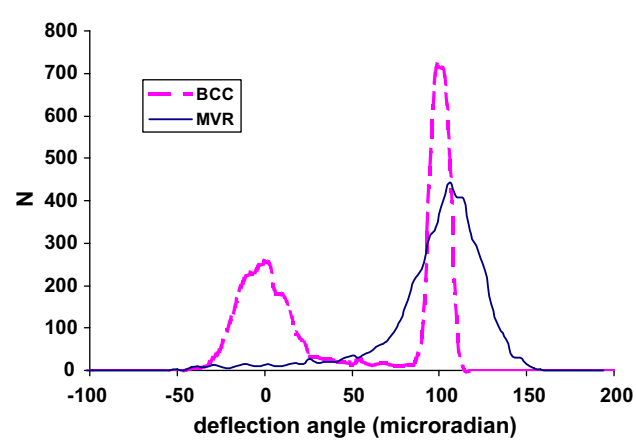

Fig. 4. Angular distribution of 400 GeV protons volume reflected (MVR) and channeled (BCC) in Si(1 1 0) crystal.

which comprises 10×0.8 mm layers). The incident beam was very parallel, of 8 μrad rms width which is about θ_c, and thus very favorable for crystal channeling. Even so, the channeling crystal has bent only 51% of protons, that is, its inefficiency was 49%. For the same beam, the 10 layer reflector in Fig. 4 had an inefficiency of only ~2% or 25 times lower than for bent crystal channeling. Another important feature is that the angular acceptance of the MVR layer structure is 200 μrad full width, or ~12 times the $2\theta_c$ acceptance angle of the channeling crystal. The beam bent by MVR is just a factor of ~2–3 broader than the very narrow channeled beam. This means that a MVR-bent beam can be quite suitable for accelerator applications.

The angular acceptance of the MVR layer structure is not limited by any fundamental physical aspects in contrast to bent crystal channeling. The efficiency of the MVR technique is limited only by the volume capture process. The probability of volume capture reduces with energy E as $E^{-3/2}$ [1,27]. Below we show that the volume capture can be strongly suppressed by using crystals with variable curvature.

It is known from 70 GeV experiments on volume capture [1] and from theory [28] that the gradient of crystal curvature affects the volume capture probability. With $1/R$ increasing along the beam path in the crystal, the volume capture rate decreases, and with $1/R$ decreasing the volume capture rate increases [1,28]. This is because the volume captured particles occupy the very top of the potential well and are easily affected by variations of the effective potential well. If the crystal curvature increases linearly from $(1\text{-}a)/R$ to $(1 + a)/R$ over its length L, the analytical formula predicts that the volume capture rate decreases by $w \approx a\lambda/L$ where λ is the oscillation period (60 μm in Si at 400 GeV) of a channeled particle in crystal [28]. In order to fully suppress the 2.5% volume capture probability observed in single volume reflection at 400 GeV in Fig. 3, one has to apply a curvature variation of $a \geqslant 0.33$, according to the formula. The effective potential well then shrinks by $\geqslant 6$ eV over the crystal length, thus quickly releasing most of the volume captured particles.

We studied particle trajectories in crystals with variable curvature. The mean curvature along the crystal was kept constant, while the local value was a linear function of the coordinate. A strong gradient of curvature results in a significantly suppressed volume capture rate. For 400 GeV protons in 10 layers of Si(1 1 0) the volume capture rate was suppressed by a factor of 5 for $a = 0.6$ and this 10 layer structure bent 99.6% of 400 GeV protons at an angle $\theta > 0$. The inefficiency of MVR technique thus reduces to a mere 0.4%, which is more than 100 times smaller than that of the channeling crystal. The rms width of the bent beam increased to $3\theta_c$ because of reflection variations with curvature.

One interesting application of the new technique is beam collimation, for instance in the 7 TeV Large Hadron Collider. In simulations we have studied a large number of crystal layer structures with different curvatures and curvature gradients to find the best efficiency at 7 TeV. Fig. 5 shows a 7 TeV proton beam bent through an angle of about 40 μrad which could serve well for collimation purpose in the LHC [29]. Here a structure comprising 20 Si(110) layers, each bent through 65 μrad with $R = 50$ m (4.3 R_c, where $R_c = 11.7$ m at 7 TeV), has deflected 7 TeV protons with an efficiency of 99.95%. Each layer has a gradient of curvature of $a = 0.4$ which suppressed the volume capture rate by a factor of 20 compared to the same reflectors with constant curvature. This tremendous efficiency by far outperforms the capabilities of channeling crystals. Note that the angular acceptance of this MVR layer structure is 65 μrad, which is ~20 times greater than the acceptance of bent crystal channeling of $2\theta_c$. Such perfect deflection efficiency over a very broad angular acceptance makes MVR ideal for collimation.

Essentially, a deflection efficiency of ~100% is obtained in a single encounter of a particle with the multi-layered structure. In collimation techniques based on bent crystal channeling, fairly high efficiency is achieved because of a high number of particle encounters with a single crystal installed in the accelerator ring. Still, the expected channeling efficiency of ~90–95% in these techniques at TeV-range colliders [9,30] cannot compete with ~100% of MVR. The inefficiency of 5–10% compared to inefficiency of ~0.05% means that beam losses differ by a factor of 100–200, a huge value.

The fact that efficient deflection occurs in a single encounter may become important in many different types of accelerators, like linear machines (e.g. International Linear Collider), machines with a short beam lifetime (e.g. muon or short cycle machines), and in high intensity beams with a fast developing instability.

The possibility to have an efficiency of ~100% makes MVR attractive for high intensity beam applications where beam losses are sensitive issues which rule out the use of bent crystal channeling.

At the world highest energy of 7 TeV, the crystal material along the beam direction in the above example becomes as long as 6.5 cm. Some protons undergo inelastic nuclear interactions in the crystal layers. For these protons, Fig. 5 shows also the proton deflection angle at the moment of nuclear interaction. One can see that these protons are bent on average by one half of the bending angle of non-interacted protons, and their bending efficiency is a remarkably high 95%. This is very different behaviour compared to both an amorphous target and from bent crystal channeling where products of nuclear interactions move in a forward direction. With MVR applied for collimation, not only the primary particles are bent towards an absorber but also the debris of particles that interacted with crystal nuclei are bent towards an absorber with great efficiency.

Our simulations rely on the availability of suitable multiple bent crystal layers. Two types of multiple layer structures can be considered. First, for lower energies a similar approach to that previously used to produce bent layers

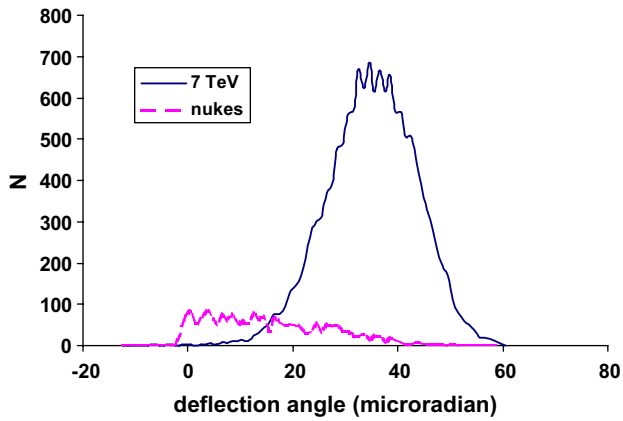

Fig. 5. Angular distribution of the protons volume reflected (7 TeV) and of the protons interacted ("nukes") in the 20-layer Si(110) crystal.

suitable for bending MeV ions can be produced by growing a graded silicon-germanium epitaxial layer [7], in which the Ge fraction varies from zero at the epilayer interface to a maximum at the surface [7,31,32]. 10 μm layers with $R \sim 30$ mm uniformly curved lattice were recently produced [33], capable of bending ions with energies up to a few GeV/n. This process may be extended to growing sequential curved layers, one on top of the next, so long as the cumulative lattice strain does not exceed a critical value. The second approach, more applicable to higher energies, is to align separate curved layers, whether in the form of individual bent wafers or as large area bent crystal shields as described in [12]. Hopefully, channeling nanostructures can be engineered in some ways that enhance beam reflection in periodic structures [34] and further improve the potential of its applications.

3. Conclusions

The technique of multiple volume reflection in several curved crystal layers can be a perfect beam instrument for deflecting particle beams through a large angle with 100% efficiency at high energy and with a very broad angular acceptance. This technique outperforms bent channeling crystals in terms of efficiency and angular acceptance by several orders of magnitude. It overcomes two major limitations of bent crystal channeling: narrow angular acceptance limited by the critical angle, and an efficiency which is significantly below 100%, limited by the thickness of atomic planes and strings in the crystal lattice. Similar behaviour in multiple volume reflection was observed over a wide range of energies, from 5 MeV to 7 TeV per nucleon for protons and heavy ions with two computer codes, FLUX and CATCH.

This result may boost bent crystal applications in the accelerator world. While bent channeling crystals promise an improvement in collimation efficiency by an order of magnitude at TeV range colliders, multi-crystal reflectors can give an improvement by three orders of magnitude. This would be very important for collimation in the Large Hadron Collider and may help to upgrade the LHC in future to a higher luminosity.

Apart from accelerator applications, multiple volume reflection is an attractive mechanism for a space shield producing highly efficient deflection of ions with energies of MeV and GeV per nucleon. Here, highly efficient deflection over a wide entrance angular range at high energies is of paramount importance for the design of a space shield for radiation protection based on curved crystals.

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