Bent crystal extraction from a 100 TeV proton collider

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The crystal-assisted extraction of particles from high-energy proton colliders is discussed. The results corresponding to the beam energy of 50 TeV are presented in more detail due to the FCC design study started at CERN. It is suggested to produce a horizontal dogleg with the Lambertson magnet in a straight section of the collider. In this case, the vertical deflection of about 100 μrad or even smaller in a bent crystal may be sufficient for the collider beam halo extraction. The optimal parameters of the crystal deflector and the extraction efficiency of a natural collider beam halo were estimated by simulation. The halo extraction may provide both the collimation for the collider and external beams for fixed target physics.

1. Introduction

The work was motivated by a recent proposal on the design of a 100 TeV proton collider coming from CERN [1]. The authors of the present paper are involved in the activity closely connected with multiTeV-range hadron collider projects such as SSC, LHC, VLHC and in the analysis of bent crystal usage for such projects [2–4].

Deflection of high energy charged particles channeled in a bent crystal has been predicted by Professor Eduard Tsyganov [5]. The prediction has soon been confirmed in an experiment on the deflection of a beam of 8.4 GeV protons at the synchrophasotron of the Laboratory of High Energies, JINR [6]. In 1984 a bent crystal was used for the first time to extract a circulating proton beam from the synchrophasotron [7]. It may be noted that 70 years ago the first director of this laboratory Academician Vladimir Veksler discovered the autophasing principle, which is very important for the accelerator technology.

The extraction of a particle beam from a cyclic accelerator by a bent crystal was later studied at IHEP [8], CERN [9,10] and FNAL [11]. The crystal extraction studies in CERN have been first performed with 120 GeV proton beam at the SPS with 3 and 4 cm long silicon crystals bent along the (110) planes by the angle of 8.5 mrad. The beam extraction efficiency up to 15% was observed. Later the same 4 mm long silicon crystal was used for the extraction of Pb nuclei with 270 GeV/c per charge. The observed extraction efficiency was about 10%. The crystal extraction systems have been developed in IHEP for a long time and now they work here providing several physical experiments with the extracted beams. The extraction efficiency of 70 GeV protons from U-70 in IHEP with 2 mm long silicon crystals bent by the angle of about 1 mrad reaches 85%.

The beam halo extraction by a bent crystal from high energy proton colliders LHC and SSC to perform simultaneous fixed target experiments has been proposed in [12,13]. Possible extraction schemes of 20 TeV protons from the SSC with a silicon crystal bent by the angle of 100 μrad has been suggested and simulation studies of its efficiency have been performed in the frame of the super fixed target (SFT) project at the SSC Laboratory [4]. The extraction of a natural beam halo from the Tevatron by a bent crystal has been studied by simulation in [14]. The first experiment on the beam halo extraction during collider operation has been performed at the Tevatron [11]. An extraction efficiency of up to 30% from the halo of a 900 GeV proton beam without impact on the collider experiments has been observed.

Detailed studies on channeling of high energy protons and π mesons in short bent silicon crystals have been performed in CERN during the last years. A short bent crystal used as a primary collimator instead of a solid target can deflect channelled protons and direct them onto the collimator–absorber far from its edge. As a result the possibility of back scattering from the absorber into the beam should be significantly reduced. Therefore, the collimation efficiency would be increased. The investigations of the crystal
assisted collimation at the circulating beams of protons and Pb nuclei at the CERN SPS in the frame of the UA9 experiment really showed that the off-momentum halo intensity was strongly reduced when the crystal deflector was in channeling conditions [15–19]. Recently two precise goniometers with 4 mm long silicon crystals bent by the angle of about 50 μrad were installed in the LHC to study the crystal assisted collimation.

However, it is much better to extract a natural halo by a bent crystal realizing the collider beam collimation. In addition to obvious advantages of possessing the extracted beam, the problem of the absorption of a very narrow beam deflected by a bent crystal may be avoided. Here we suggest including in the studies on the FCC project the consideration of possibilities of a natural beam halo extraction by a bent crystal using it as a primary collimator. A possible scheme of the extraction may be similar to the one suggested for the SSC and it is shown in Fig. 1. A horizontal dogleg is formed in a long straight section of the FCC where a bent crystal is installed at the beginning behind a magnet at the vertical distance of 6σv from the closed orbit. Halo particles deflected vertically by a full angle of the crystal bend enter the passive aperture of the Lambertson magnet and thus they are extracted. Other halo particles deflected with smaller angles hit a collimator–absorber installed upstream the Lambertson. In this paper the optimal parameters of the crystal deflector with the bend angles of 50 and 100 μrad and the extraction efficiency of a natural halo of 50 TeV proton beam were estimated by simulation.

2. Channeling parameters and deflection efficiency

When a high-energy charged particle enters the crystal with a small angle relative to some crystallographic planes its motion is governed by the crystal potential averaged along the planes [20]. The potential U(x) is periodic in the transverse direction. The depth of the planar potential well for the (110) planes in silicon crystals \( U_o = 22.7 \text{ eV} \) with the Moliere approach for the atomic potential, see Fig. 2a. If the angle is smaller than the critical channeling angle \( \theta_c = (2U_o/p\nu)^{1/2} \),

\[
\theta_c = (2U_o/p\nu)^{1/2},
\]

where \( p \) and \( \nu \) are the particle momentum and velocity, the particle can be captured into the planar channeling regime oscillating between two neighboring crystal planes. For 50 TeV protons \( \theta_c = 1 \mu\text{rad} \) for the (110) silicon channel.

Collisions with atomic electrons and nuclei of the crystal change the transverse energies of particles and as a result they leave the channels. That is particle dechanneling takes place along the crystal length. The process has the exponential character, \( N_{ch}(z) \sim \exp(-z/L_d) \), where \( L_d \) is the dechanneling length. Collisions with atomic nuclei occur only for particles with large oscillation amplitudes in the planar channels. Therefore, multiple scattering by the crystal electrons determines the dechanneling length for the larger part of channelled particles. The electronic dechanneling

![Fig. 1. Possible scheme of the beam halo extraction from the FCC with a bent crystal. (a) The horizontal dogleg with a bent crystal upstream the Lambertson septum. (b) The cross-sectional view at the position of the crystal. A vertical beam halo intercepts crystal. (c) The cross-sectional view in the Lambertson septum. The extracted beam, which is the portion of the vertical beam halo that the bent crystal intercepts and deflects vertically, has been separated from the circulating beam and passes through the Lambertson hole.](image)

![Fig. 2. (a) Averaged potential of the (110) planar channel of a silicon crystal at room temperature in the Moliere approximation for the atomic potential, \( d_p = 1.92 \text{ Å} \) is the channel width. (b) Effective potential of the (110) channel of a Si crystal bent with \( R = 600 \text{ m} \) for 50 TeV protons.](image)
length measured in the (110) silicon crystal [21] was about 10 cm for 200 GeV protons. It is approximately proportional to the particle energy. Therefore, the dechanneling length for 50 TeV should be about 25 m.

Particle channeling is still possible if the crystal is bent with a radius larger than the critical one, \( R > R_c \) [5].

\[
R_c = \frac{p\nu}{Z_\text{eff}E_m},
\]  

where \( Z_\text{eff} \) is the charge of the particle, \( E_m \) is the maximum strength of the atomic electric field averaged along the planes. For the (110) silicon planes, \( E_m = 5.89 \text{ GV/cm} \) and \( R_c = 85 \text{ m} \) for 50 TeV protons. Channeling in bent crystals is described by an effective potential

\[
U_\text{eff}(x, R) = U(x) + \frac{p\nu}{R} x.
\]

The centrifugal term leads to a decrease of the potential well depth and its shift to the outer channel wall, see Fig. 2b. This potential transformation decreases the efficiency of particle capture into channeling. For parallel beam it is equal to the part of the channel width where a finite motion of particles is still possible (shown by the dot-dashed line in Fig. 2b). Besides, the decrease of the potential well depth reduces the dechanneling length. At \( R = R_c \) the potential well disappears.

Channeled particles can be deflected by the bend angle of the crystal. The deflection efficiency is determined by the probability of particle capture into the channeling regime \( P_d \) and the probability for the particles to pass through the entire crystal in the channeling regime

\[
P_d(x, R) = P_d(R) \exp\left(-xR/L_d(R)\right),
\]

where \( x \) is the bend angle of the crystal. In the parabolic approximation for the planar potential the capture probability \( P_d(R) = 1 - R/R_c \) for parallel beam and the dechanneling length \( L_d(R) = L_{dm}/(1 - R/R_c)^2 \), where \( L_{dm} \) is the dechanneling length in a straight crystal. At the beginning, the deflection efficiency increases with increasing \( R \) because the capture increases but then it decreases because the larger crystal length leads to a larger dechanneling. An optimal radius and length of the crystal exist for the particle deflection by an angle \( x \) [22]. The optimal crystal parameters may be analytically determined for the parabolic potential [23]. For realistic planar potentials the optimal parameters are found by simulation.

Simulation of particle passage through a crystal has been performed using the model [24]. The particle trajectories were calculated in the averaged potential of the crystal bent planes. The Moliere approximation of the atomic potential was used. The change of the transverse velocity of a particle due to multiple scattering on the crystal electrons and nuclei was calculated using realistic distributions of electrons and nuclei in the channels at every step along the trajectory, which was much smaller than the spatial period of the particle oscillations in the channel. The ionization energy losses of particles were found from the Landau distribution. The events of elastic and inelastic nuclear interactions with the crystal nuclei were considered. The nuclear cross-sections for elastic and inelastic nuclear interactions with the (110) planes by the angle \( \alpha = 50 \text{ mrad} \) were used. The distances from the closed orbit were \( Y_{\text{ex}} = \beta_y R_c = 7 \sigma_y \) for the crystal and absorber, respectively. The RMS beam size \( \sigma_y = 0.14 \text{ mm} \) for the vertical beta-function \( \beta_y = 500 \text{ m} \) and the normalized emittance \( \epsilon_{\text{nm}} = 2.2 \times 10^{-6} \) planned for the FCC. The FCC beam halo particles begin hitting the crystal due to a random increase of their betatron oscillation amplitudes according to an exponential diffusive law with \( \lambda = 0.1 \mu\text{m} \) per turn. Linear 6-dimensional transfer matrix \( M(6,6) \) were used to transport particles between the azimuths.

The dependence of the extraction efficiency \( P_{\text{ex}} \) of 50 TeV protons from the FCC on the crystal length obtained by simulation is shown in Fig. 3. It was assumed that the (110) crystal planes at its entrance are perfectly aligned with the beam envelope. The maximum extraction efficiency of about 93% is observed for a crystal length of about 3 cm. For the beam halo extraction with the deflection angle \( \alpha = 100 \text{ mrad} \) the optimal crystal length is larger, 6 cm. Fig. 4 shows the dependence of the extraction efficiency on the crystal orientation. The full dependence width is about 3 mrad. An extraction efficiency larger than 90% may be obtained in the angular interval smaller than 1 mrad. That means the goniometer step should be about 0.1 mrad.

High energy charged particles can also be deflected in a bent crystal due to volume reflection [28,29]. This effect can be observed for particles entering the crystal at angles with respect to the plane direction larger than the critical angle. The deflection due to volume reflection is not larger than 1.5 \( \theta_0 \) but the efficiency is high, up to 98%. The halo particles deflected due to volume reflection perform a smaller number of passages through the crystal to reach the absorber aperture than for amorphous orientations of the crystal. Therefore, the particle losses in the crystal due to nuclear interactions are smaller in this case. Fig. 5 shows the dependence of the fraction of 50 TeV protons lost due to inelastic nuclear interactions in the silicon crystal on its orientation angle obtained by simulation. The angular range of volume reflection is
wide and equal to the crystal bend angle. This simplifies the crystal alignment with the beam envelope.

Fig. 6 shows the distribution of impact parameters of 50 TeV protons with the collimator–absorber when the crystal bend angle is 100 μrad. The channeling peak is very narrow of about 1 mm. The peak position depends on the beta-function value and is about 50 mm from the absorber edge for the considered case (the absorber edge is located at 7σr from the closed orbit). An absorber position straight before the Lambertson magnet will be optimal. The vertical size of the collimator should be sufficient to absorb the tail of the deflected particles (hatched part of the distribution in Fig. 6) and its horizontal size should be optimized to realize the collimator cooling. The channelled particles pass by the collimator and are extracted from the FCC through the passive aperture of the Lambertson magnet.

Similar simulation on the beam halo extraction using a silicon crystal with the bend angle 50 μrad and with the same effective bend radius R/Rc = 7 have been performed for 450 GeV and 7 TeV protons which correspond to the energies of injection and collider operation of the LHC. Table 1 shows the maximum value of the beam halo extraction efficiency. It decreases from 450 GeV to 50 TeV by about 3%. The corresponding efficiency losses due to inelastic nuclear interactions in the crystal increase only by a factor of two whereas the crystal length increases by a factor of 100. This is because a strong reduction of multiple scattering in the first unsuccessful passages of circulating particles through the crystal occurs when the particle energy increases. As a consequence, the probability to be captured into the channelling regime in the repeated passages through the crystal increases for the particles with larger energies.

4. Conclusion

Our estimations show that the extraction of a natural beam halo from a collider of 50 TeV protons using a bent crystal is possible and may be efficient if a precise goniometer with the angular accuracy of 0.1 μrad can be realized. The consideration of synchrotron oscillations of halo particles should increase the divergence of the beam incident onto the crystal therefore it should be included in future simulation studies.

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