NEW IDEAS FOR CRYSTAL COLLIMATION*

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Abstract

Both channeling and volume reflection (VR) effects are used for proton beam deflection by bent crystal. We propose the modifications of both these two effects to drastically improve the deflection efficiency. For the channeling it is a narrow plane cut [1] increasing the fraction of channeled particles up to 98-99%. In order to simplify the fabrication technology we suggest to use a buried amorphous layer instead of a crystal cut [2]. We also suggest to use the multiple volume reflection in one crystal (MVROC) [3], instead of single one because the MVROC increases the deflection angle in 5 times in comparison with VR.

The cut method can be applied with high efficiency for the extraction of high intensity proton beam from the Recycler Ring (FNAL) [5] as well as the MVROC will provide very good deflection parameters for the future LHC crystal-based collimation system. We also argue that the channeling effect is not efficient in the LHC case because of large angular divergence of halo beam particles caused by the elastic nuclear scattering on residual gas.

INTRODUCTION

Bent crystals possess wide capabilities for accelerator physics. Very strong intracrystal electric fields applied with accuracy of Angstrom provide high deflection efficiency. The main advantages of crystals are very compact size, low price of production and simplicity of installation and exploitation. Additionally, they can efficiently deflect the beams of different types of charged particles, of very different energies (from hundreds MeV up to tens TeV and higher) and of different beam angular divergence. The latter parameter is critical for the proper effect choice.

For small beam angular divergence the channeling effect provides rather high performance. For the best case the deflection efficiency exceeds 80%. For multiturn case it can exceed 95%. If the angular divergence is large, the volume reflection will be efficient. It provides less deflection efficiency than the channeling but the angular acceptance of it is much higher.

The efficiency of the channeling can also decrease because of the miscut angle characterizing nonparallelity of the channeling planes and crystal surface. It is shown in [4] that for UA9 experiment [6] the nuclear reactions rate in crystal increases by a factor of 4.5. So, we should consider both the beam impact parameter and angular divergence for effect choice. If the beam impact parameter is rather large for most of particles not to enter in the miscut influence zone and the beam angular divergence is less than the critical angle for the channeling, the latter will provide good deflection efficiency. Otherwise the VR must be chosen.

In this paper we will consider bent crystal application for two opposite cases relevant to two different machines: the future LHC crystal-based collimation system and the 8GeV proton beam extraction from the Recycler Ring at Fermi National Accelerator Laboratory (FNAL) [5]. As we will show below the volume reflection should be chosen in the LHC case while the channeling in the case of the Recycler Ring. Also we suggest for both cases some modifications: a narrow plane cut increasing the channeling efficiency up to 98-99% [1] for channeling and multiple volume reflection in one crystal (MVROC) instead of "single" one.

MVROC FOR LHC COLLIMATION

In order to solve the future LHC collimation problem it is very important to understand the main source of halo formation. Knowing the latter we can calculate the beam profile as well as both the impact parameter and angular divergence distributions in the beam collimation zone (6σ). Then we can exactly choose the proper deflection effect. The main mechanisms of beam loss are inelastic, diffractive and elastic scattering in interaction points (IP) and on residual gas. We can exclude as halo particle production reasons the inelastic and diffractive scattering on gas and in IP because of large scattering angles and energy losses. So, only elastic scattering on residual gas and in interaction points should be considered.

It is known that β-function of interaction points is 2-3 orders less than the average value. That's why the scattering at the same angle increases the amplitude of betatron oscillations for gas 10 times more than for IP:

$$X = \sqrt{\beta_{avr}\epsilon} = \sqrt{\beta_{avr}\beta\theta^2}, \quad (1)$$

where X is an amplitude of betatron oscillations, β_{avr} is average beta function, ϵ is emittance after scattering, β is β-function in a scattering point, θ is a scattering angle. According to (1) the multiple Coulomb scattering on residual gas gives emittance increase of less than initial LHC beam emittance. So, we can exclude the multiple coulomb scattering. The single coulomb scattering at large angles can be excluded because of very small probability and scattering angle of such events insufficient to achieve 6σ. Thus, only elastic nuclear scattering stands for examination.

One obtains that for sufficient scattering angle (at IP) the probability is 5 orders less than for the distribution maximum. More accurate estimates give that about 10^4 particles enter the collimation zone per second. It is at least two or-

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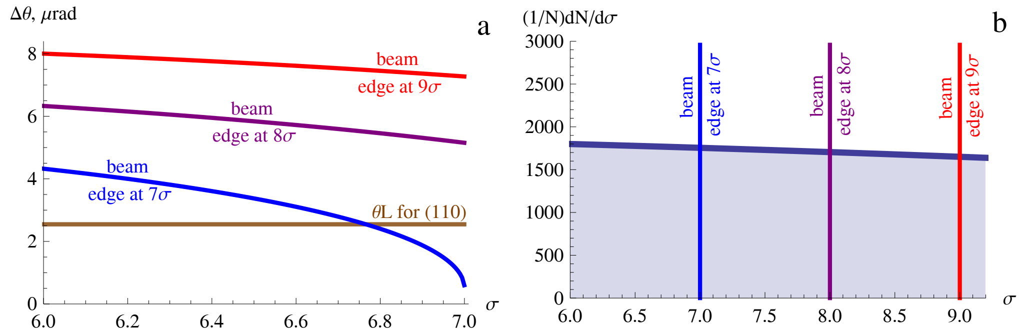

Figure 1: Elastic nuclear scattering on residual gas (LHC): beam profile (a) and angular divergence distribution (b).

ders less than the LHC quench limit. So, the elastic nuclear scattering in IP can be excluded.

Thus, we consider only elastic nuclear scattering on residual gas. In this case even small scattering angle (several μrad) is sufficient for particle to enter the collimation zone because of high β-function (about 10^2m). The R.M.S. scattering angle is about 40 μrad that is more than enough to achieve 6σ. The distribution of differential cross section at small angles is exponential, so we can simply obtain the beam profile shown in Fig. 1a. Here the beam intensity at 6, 7, 8σ remains almost the same. So, for channeling we can neglect the miscut angle influence.

The angular divergence distribution (see Fig. 1b) obtained from the beam profile shows that the crystal incident angle for the LHC is much higher than the channeling critical angle. That's why the channeling is not applicable in this case. Only volume reflection can be applied at the LHC. But the deflection angle of VR is very low - 7 times less than we can expect from the channeling. The solution of this problem can be obtained by MVROC [3] with deflection from several bent *skew* crystal planes (not from a single one as at VR). When these reflections almost compensate each other in the vertical direction, in the horizontal one they will sum.

The deflection angle for it can be 5 times larger than for VR and the angular acceptance and deflection efficiency will also increase [3]. Here we notice that the deflection efficiency of the MVROC is a bit less than of the channeling but large enough for the LHC collimation purposes.

The MVROC was observed for proton beam at U-70 accelerator in Protvino (Russia) and at SPS (CERN) for both protons and negative charged pions. In all cases high deflection efficiency was obtained. So, we suggest the MVROC as the main candidate for the application at the future LHC crystal-based collimation system.

CRYSTAL CUT FOR THE RECYCLER RING

There is an opposite situation for the project of high intensity 8GeV proton beam extraction from the Recycler Ring [5]. This beam is planned to be extracted in the Main Injector for application for neutrino and muon experiments.

According to our simulations, the angular divergence of the beam is small enough for capture of most particles in the channeling regime and the beam impact parameter is large enough to neglect the miscut angle influence (Fig. 3a). That's why the channeling effect choice is evident.

Additionally, because of low beam energy the angle of amorphous scattering on crystal exceeds the volume reflection angle. Moreover for farther use of the beam in another machine the particle deflection must be of similar angles. So, we can say that the volume reflection is not applicable for the Recycler Ring (like the channeling for the LHC).

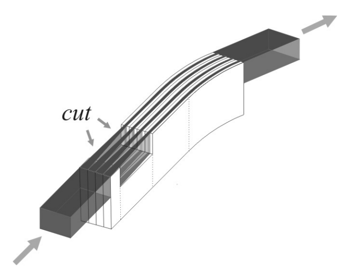

Figure 2: Narrow plane cut.

The main problem is very high intensity of the beam. So, a reasonable question of the crystal radiation damage can be asked. Thereby, one should minimize the number of particle passages of crystal. Additionally, the beam losses during the extraction must be minimized in order to achieve the high final beam intensities in the future neutrino and muon experiments. All these problems can be solved by application of the narrow plane cut (Fig. 2) [1]. When particle enters the cut it loses the potential energy because it simply becomes far away from crystal plane electric fields. For the optimal cut parameters [1] the particle escaping the cut will obtain the potential energy less than the loss, so, the final transverse energy will decrease.

Thus, most of particles will be captured in the regime of stable channeling motion. Because of low transverse energy they will oscillate far away from zone of nuclear scattering. So, most of them will achieve the end of the crystal in the channeling regime with high probability.

The width of the cut must be very small. It is proportional to the root square of the beam energy and achieves

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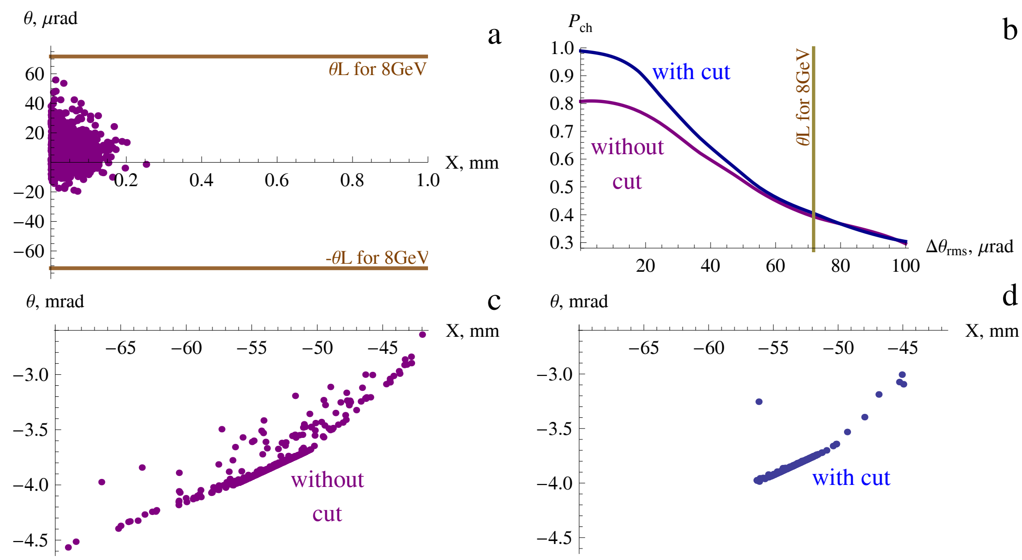

Figure 3: Beam extraction from the Recycler Ring: phase space at the 1^{st} crystal entrance (a), the channeling efficiency *vs* R.M.S. incident angle (b), phase spaces of the extracted beam without cut (c) and with cut (d). Crystal parameters: (110) silicon crystal of 1mm length and thickness, deflection angle 0,5mrad.

about 1μm at 8GeV. It is very difficult technologically to make such crystal. Much simpler is to make the amorphous layer [2] instead of the cut. The R.M.S. scattering angle is negligible at such narrow layer. So, the crystal lattice disturbance is equivalent to the cut.

Now let us consider the cut effect performance for 8GeV beam of the Recycler Ring. In Fig. 3b the dependence of the channeling efficiency on the R.M.S. incident angle obtained by our simulations is shown. The efficiency in the case with cut is more than without it. This difference decreases with the incident angle rise. But in Fig. 3a the incident angular divergence is small enough for high performance of the cut method. So, we can conclude that there are good conditions for the first experiment with crystal cut.

The phase spaces of the extracted beam from the Recycler Ring are shown in Fig. 3c-d. This result (and Fig. 3a) was obtained with our simulation code of particle motion in crystal combined with the program for the simulation of beam dynamics in accelerator - ”STRUCT” [7], developed in FNAL. One can see here that the phase space is much narrower for the cut case. Thus, the latter will considerably improve the quality of obtained proton beam. In addition, the fraction of particles extracted after the first crystal passage exceeded 95% (compare a bit more than 80% without cut). So, the limiting intensity of the extracted beam increases considerably.

Finally, the beam losses decreased in 4 times due to the cut method. It allowed to increase the extraction efficiency from 94-95% up to 98-99%.

CONCLUSION

The application of bent crystals for two different machines was considered. The main deflection effect was chosen: volume reflection for the LHC and channeling for the Recycler Ring. The new methods considerably increasing the deflection efficiency were proposed. In the first case it is the MVROC increasing 5 times the deflection angle being almost independent from the incident angle. In the second one it is the cut method decreasing the beam losses up to 4 times, increasing the extraction efficiency from 94-95% up to 98-99% and providing much higher intensity of the beam. All these improvements provide the high performance of future high energy accelerators.

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