OPTICS STUDY FOR A POSSIBLE CRYSTAL-BASED COLLIMATION SYSTEM FOR THE LHC

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Abstract

The use of bent crystals as primary collimators has been long proposed as an option to improve the cleaning efficiency of the LHC betatron and momentum collimation systems. These systems are presently based on two-stage collimation with amorphous scatterers and absorbers. Crystals are expected to help by channelling and extracting the halo particles with large angles, resulting in higher cleaning efficiency. Independent of ongoing studies for crystal qualifications (not reported here), it is important to understand the required deflection angles and the possible locations of absorbers for the LHC layout. Optics studies have been performed in order to specify the required angles for various LHC beam energies and possible locations of absorbers for the deflected halo beam. A possible layout for crystal-assisted collimation at the LHC is discussed, aiming for a solution which would not change the LHC layout but would make use of the existing collimator locations.

CRYSTAL BASED COLLIMATION FOR THE LHC

It has been shown that bent crystals can be used efficiently to extract beam particles out of an accelerator. This crystal extraction can be applied on the main beam but also on halo particles. The basic idea of crystal based collimation for the LHC is to use bent crystals for channelling and extracting the halo protons at 6 σ from the central beam orbit onto a special absorber where they hit with large offsets (impact parameters). Due to large extraction angles and high impact parameters the extracted halo protons can in principle be efficiently removed from the LHC beam. For example, a channelling and extraction efficiency of 90% would leave 10 times less load on the standard collimation system [2], enhancing its performance by a factor of 10. Other crystal effects like reflected beam [1] are presently being studied.

The approach of crystal based collimation is promising. However, its implementation and operation will face some challenges which are shortly summarized:

1. **Heat load to the absorber:** The peak loss rates of the LHC are specified to reach 1 MW for 1 s at injection energy and 500 kW for 10 s at top energy. The DC losses can reach 100 kW for many minutes. Assuming efficient crystal extraction most of this energy will be extracted to an absorber with potentially small spot size. The construction of such an absorber inside the LHC vacuum, its efficiency, cooling and robustness is a clear concern.
2. **Efficiency**: Even if the crystals extract 90% of the halo protons from the beam, the remaining 10% must be prevented from reaching the cold aperture in the super-conducting magnets. The LHC requires a cleaning inefficiency (fraction of particles allowed to leave the cleaning insertion) of better than 0.1% (global) and 0.002%/m (local). Any crystal based cleaning must therefore be complemented by a powerful and traditional second and third stage cleaning. Crystals in the LHC can only be placed at the locations close to primary collimators, replacing their functionality.
3. **Operational stability:** Crystal channelling depends on tight tolerances in the alignment between the direction of halo protons and the crystal channel. As LHC collimation is required during all phases of operation the channelling of halo particles must be kept continuously from injection, through the ramp and into collision. This cannot be guaranteed, especially in case of machine perturbations which would also induce low beam intensity lifetimes. In case channelling is lost, the crystal would operate as a thin primary collimator, only scattering and not extracting primary beam halo particles. Therefore, the standard collimation system downstream of primary collimators (secondary collimators and absorbers) must be kept at or close to nominal settings to provide efficient multi-stage cleaning in case channelling is lost. In particular it cannot be guaranteed that crystals will allow opening the secondary collimator gaps and reducing the collimator induced impedance.
4. **Machine protection:** The crystal extraction would provide a way to provide a strong kick to parts or all of the LHC beam. For example, due to wrong distance of the crystal to the beam (”wrong” set-up) significant beam can in principle be displaced to large betatron amplitudes, causing a severe risk to the integrity of the LHC accelerator. Even with a correct setting, several nominal bunches can be extracted onto the absorber during an asynchronous beam dump.

The challenges mentioned above must be addressed in detail in order to evaluate the real potential of crystal collimation for the LHC. As a first step a basic layout of crystal collimation must be worked out, given the constraints in the LHC. In particular one needs to 1) place the crystals close to the primary collimators and 2) to place dedicated absorbers to efficiently intercept the channelled beam. This fixes important design parameters like extraction angles, longitudinal distances, transverse offsets achievable, etc. This paper summarizes a first preliminary optics study.

BOUNDARY CONDITIONS

Any crystals in the LHC must be placed close to primary collimators in the cleaning insertions of the LHC, for the reasons discussed above. The optics requirements in IR3 and IR7 were quite demanding for multi-stage cleaning. As a result, the α at the primary collimators could not be made zero, a compromise needed to achieve a 200° phase advance over the cleaning insertion. As a result the crystals are placed at a location where halo particles have a divergence that depends on the beam energy. This is illustrated in Figure 1 for matched halo particles at 6 σ. The crystal alignment would have to follow the beam divergence during the ramp to maintain channelling.

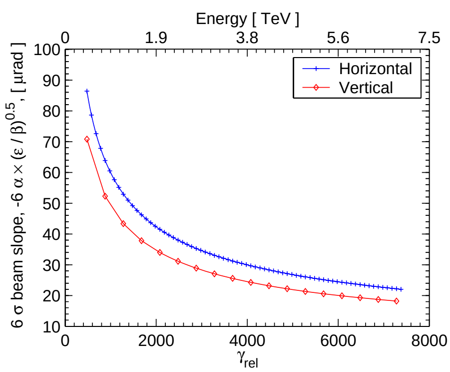

Figure 1: Horizontal (blue) and vertical (red) 6 σ beam divergence at the crystal locations versus beam energy.

Some additional constraints must be taken into account:

1) It is assumed that the machine layout is not changed. The crystals are put into the space reserved for one-sided scrapers next to the primary collimators. Absorbers for the channelled halo particles are placed at existing collimator locations.

2) Direct halo extraction before the first downstream magnet (separation dipole) would require 7 TeV extraction angles around 20 mrad, which is not considered feasible at the moment and is not pursued further.

3) The extracted beam should be absorbed as early as possible in the cleaning insertion in order to avoid that the exiting showers quench cold downstream magnets.

POSSIBLE LAYOUTS FOR CRYSTAL BASED BETATRON CLEANING

Solutions with the phase I collimation layout

Two horizontal (TCSG.B4L7, TCSG.6R7) and one vertical (TCSG.D4L7) secondary collimators (TCS's) are available in IR7 and could be used as absorbers with no changes of the present layout. Five Tungsten absorbers (TCLA's) are in principle available but are not considered here because they are located at the very end of IR7, immediately upstream of the cold arc. A linear tracking program has been set-up to determined the required crystal bending angles to obtain impacts at the aforementioned collimators.

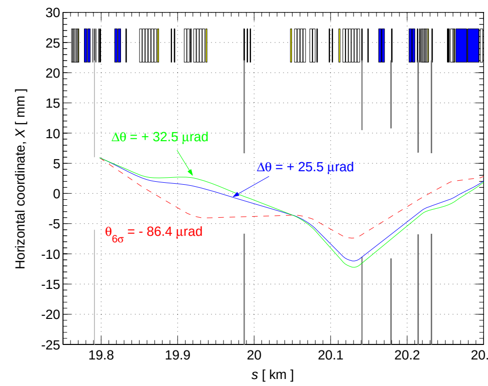

Figure 2: Horizontal trajectory of a 6 σ halo particle deflected by 25.5 μrad 32.5 μrad at the scraper location (injection).

Table 1: Crystal deflection in μrad required to have impacts of zero and 1 mm at existing secondary collimators.

	Horizontal		Vertical
E [TeV] / b [mm]	B4L7	6R7	D4L7
0.45 / 0.0	101.0	25.2	26.3
0.45 / 1.0	110.5	32.5	45.0
7.0 / 0.0	27.0	8.5	8.5
7.0 / 1.0	36.5	15.0	27.3

We assume here that the crystals sit at 6 σ and the TCS's at 7 σ. Table 1 summarizes the required kicks to obtain impact parameters of $b = 0$ mm and $b = 1$ mm at the TCS's. Note that the required kicks at 7 TeV are smaller than at injection energy because the initial beam divergence is smaller (-86 μrad instead of -22 μrad). Also note that at injection kicks above $\approx$ 70 μrad are prevented because channelled particles would hit the aperture of warm quadrupoles. Figure 2 shows trajectories of channelled particles that hit the TCSG.B4L7 (horizontal case at injection). Gray lines indicate the gaps of horizontal collimators.

Table 1 shows that with the present phase I layout it is difficult to find crystal bending angles that are suitable for the whole LHC energy range, in particular for the horizontal case. The choice of an angle around 32 μrad could ensure impacts on the TCSG.6R7 collimator at injection and on the TCSG.B4L7 at 7 TeV. However, at injection losses would be concentrated far downstream of IR7, close to the cold magnets. The angles of Table 1 could be used as a guideline for useful scenarios for crystal studies and/or for low-intensity tests with the present layout rather than for designing a crystal-based proton betatron cleaning. The LHC ion collimation, which has less demanding constraints, could instead profit from the proposed scenarios that use only existing phase I collimators.

Optimization of crystal-based cleaning

Optimum locations of absorbers are studied in order to (1) minimize the crystal kick angles, (2) minimize the difference between required angles at injection and top energies and (3) move the absorber location as much as possi-

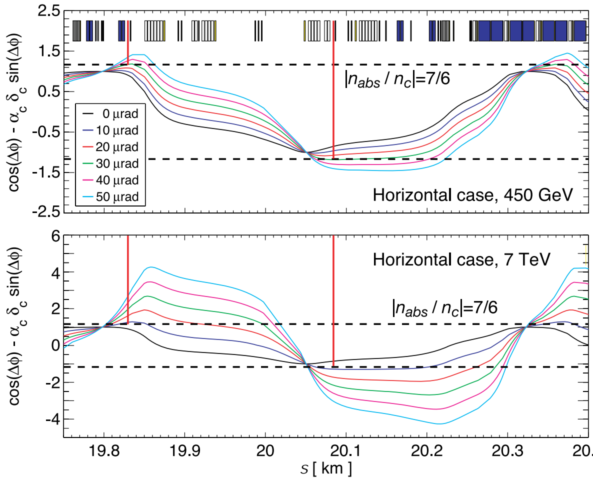

Figure 3: Normalized trajectory of a channelled particle versus s for various crystal kick angles, see Eq. (1).

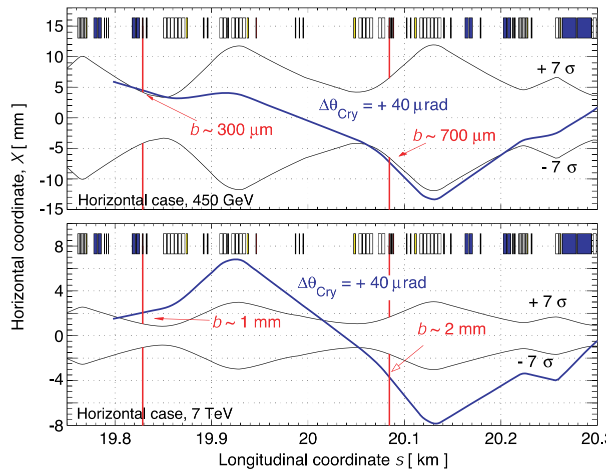

Figure 4: Horizontal trajectory for an kick angle of 40 μrad, which ensures impacts at the new absorbers (red lines).

ble upstream within the warm insertion. A semi-analytical relation has been worked out to find optimum absorber locations. It is assumed that immediately downstream of the crystal the coordinates of halo particles are given by

$$\begin{pmatrix} x_c \\ x'_c \end{pmatrix}_{\rm aft} = \begin{pmatrix} x_c \\ (x'_c)_{\rm bef} + \Delta x'_c \end{pmatrix} = \begin{pmatrix} n_c\sqrt{\epsilon\beta_c} \\ -n_c\alpha_c\sqrt{\epsilon/\beta_c}\,(1+\delta_c) \end{pmatrix},$$

where $\Delta x'_c$ is the crystal kick, α_c and β_c are the horizontal Twiss functions at the crystal, ϵ is the beam emittance and n_c is the normalized crystal aperture in σ. The normalized crystal kick is defined as $\delta_c = -\Delta x'_c/n_c/\alpha_c\sqrt{\beta_c/\epsilon}$. In order to intercept the trajectories of channelled particles ($x_{\rm ch}(s)$), absorbers must be placed at longitudinal positions s that fulfill the following condition:

$$\frac{x_{\rm ch}(s)}{n_c\sqrt{\epsilon\beta(s)}} = [\cos(\Delta\phi(s)) - \alpha_c\delta_c\sin(\Delta\phi(s))] > \frac{n_{\rm abs}}{n_c}, \quad (1)$$

where $n_{\rm abs}$ is the normalized half-gaps of the absorbers and $\Delta\phi(s)$ is the betatron phase advance with respect to the crystal location. A tracking program has been setup to find the s-locations that satisfy Eq. (1). As a working condition, we have assumed the ratio $n_{\rm abs}/n_c = 7/6$, as for primary and secondary collimators of the present two-stage system. In Fig. 3 the right-hand-side of Eq. (1) is given as a function of s along IR7 for different values of crystal kicks. The vertical red line indicate possible locations for absorbers that ensure absorption both at injection and at top energy. The choice of 40 μrad could be suitable for both energies, as it is shown in Fig. 4. The proposed location use space reservation for collimation upgrades and would therefore not require major layout changes. The similar exercise is repeated for the vertical case. The proposed optimum locations for both planes are listed in Table 2. With the proposed layout, the first impact of channelled particles occur at the beginning of the warm insertion. This figure would change for different values of the $n_{\rm abs}/n_c$ ratio.

Table 2: Proposed locations of additional absorbers.

Location	s [m]	$b_{\rm inj}$ [mm]	$b_{\rm 7TeV}$ [mm]
Horizontal, crystal kick = 40 μrad			
TCSG.B6L7	-165.48	0.3	1.0
TCSM.A5R7	90.26	0.7	2.0
Vertical, crystal kick = 50 μrad			
TCSM.B5L7	-100.26	0.5	2.3
TCSM.B5R7	94.26	- -	3.3

CONCLUSION

The challenges for implementing a crystal based collimation system for the LHC have been discussed. Taking into account the existing boundary conditions in the LHC, basic crystal collimation layouts have been presented for the present phase I system and for an optimized IR7 design with additional dedicated absorbers. It was found that the most promising solution for proton requires bending angles of 40 to 50 μrad and two additional absorbers per plane. The impact on the layout is minimum because available space reservations are used for the new absorbers. The proposed basic crystal collimation layout can be used for detailed analysis of a possible crystal based LHC collimation systems. The LHC ion collimation might especially profit from crystal enhanced collimation with the proposed layouts. Future studies must include simulations of the crystal interaction with protons (channelled and scattered particles), a detailed model of the absorber, analysis of energy deposition along the cleaning insertion and operational aspects. Only then it can be decided if crystals are a viable solution for enhancing and improving the proton and/or ion collimation at the LHC.

REFERENCES

[1] W. Scandale et al. ”First Observation of Proton Reflection from Bent Crystals”. These proceedings.

[2] R. Assmann. ”The Final Collimation System for the LHC”. These proceedings.