SIMULATIONS OF CRYSTAL COLLIMATION FOR THE LHC

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Abstract

Bent crystals are promised to provide a path towards significant improvement of cleaning efficiency for high power collimation systems. In this paper a possible implementation of a crystal-enhanced collimation system is evaluated for the LHC. Simulation studies were performed with the same state-of the art tracking codes as used for the design of the conventional LHC collimation system. The numerical models are described and predictions for the local and global cleaning efficiency with a crystal-based LHC collimation system are presented during stable physics runs at the nominal 7 TeV energy. Open issues and further work towards a crystal collimation design for the LHC are discussed.

INTRODUCTION

The energy stored in the LHC (up to 360 MJ per beam [1]) makes the LHC beam very powerful and highly destructive. A tiny fraction of of this energy can provoke a quench in the superconducting magnets or even irreversible damage to the machine. For this reason collimation insertions are used to intercept and control unavoidable losses. The rate of expected losses assumed for the dimensioning of the collimation system corresponds to a beam lifetime of 0.2 hours [1].

Recent studies [2] assess a limitation of 40% of the nominal intensity for the Phase 1 of the collimation system, yet considering a machine without imperfections such as jaw flatness tolerances, tilt errors, machine alignment errors, non ideal closed orbits. When the imperfections are taken into account the machine luminosity is further reduced to a few percent of the nominal value.
The Phase 2 of the collimation system is being designed to improve the efficiency by means of metallic collimators to be used during stable physics runs and add collimators in the cryogenic region [3]. In parallel, advanced collimation studies are carried out to maximize ultimate performance of the LHC. Crystal collimation is one of these advanced options. The idea is to use the well-studied and tested crystal channeling effect in a bent crystal to increase the betatron amplitude of the halo particles, thus increasing the impact parameter on secondary collimators and possibly improving the collimation efficiency for the betatron halo. The crystal collimation option has been quantitavely investigated with detailed simulations and the results are discussed in this paper.

SIMULATION SETTINGS

A bent crystal gives a kick to an impinging particle if certain initial conditions are fulfilled. In detail, if the particle direction is aligned with the crystal planes within the critical angle of the crystal, the particle has a certain probability to be trapped between the potential planes of the atomic structure, and to be channeled along the full length of the crystal. The critical angle depends on the crystal material, its crystalline plane orientation and the transverse momentum of the particle. For a Si crystal with 110 orientation the critical angle varies between ∼8 and 2 μrad (respectively at LHC injection and collision energy). The resulting tight alignment requirements and the change in divergence of the beam halo during the energy ramp (see [4] for details) makes the use of the crystal possible only during stable physics runs. It follows that the crystal must be a complement and not a substitution of the existent collimation system, which in principle should be able to take over in case of crystal misalignment/misfunction.

Table 1: Aperture Setting for the IR7 Elements.

element	aperture setting [σ] crystal	aperture setting [σ] phase 1
C primary collimators	6.2	6.0
crystal collimator	6.0	-
secondary collimator	7.0	7.0
W absorbers	10.0	10.0

The simulations presented in this article investigate the possible configurations for a crystal-based collimation insertion during stable physics runs at the LHC nominal energy (7 TeV). Since the planar channeling provides a kick in one trasverse direction, while acting as a drift in the other direction, we studied independently the horizontal and vertical halo. Each simulation has been perfomed by tracking 8 milion particles for 500 turns. The longitudinal location of the crystal is set in the space presently available at the beginning of the IR7 insertion, together with the primary collimators.

The crystal analyzed is a Si crystal with orientation 110, curvature radius of 50 m and no amorphous layer. We scanned different lengths in order to explore a range of channeling angles between 10 and 200 μrad. We consider a perfect machine with the sextupoles switched off. The aperture settings for the IR7 elements both for the crystal option and the standard Phase 1 system are summarised in Table 1.The initial beam has no energy spread and its average impact parameter on the crystal front face is $\sim 1\mu$m. The results are compared with those for the standard Phase 1 system, having the same optics and same initial conditions.

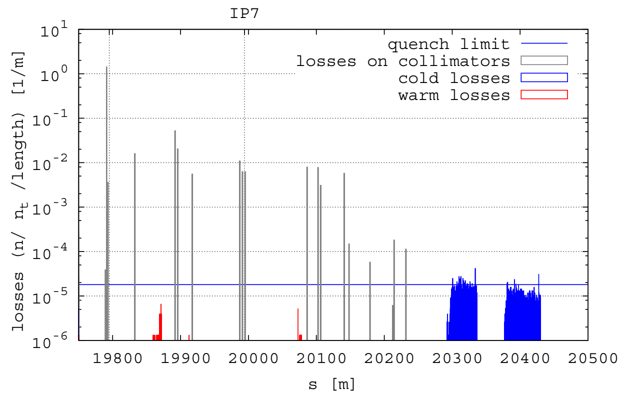

Figure 1: Loss map in case of standard collimation, horizontal halo, Phase 1. Zoom in the IR7 and dispersion suppression region.

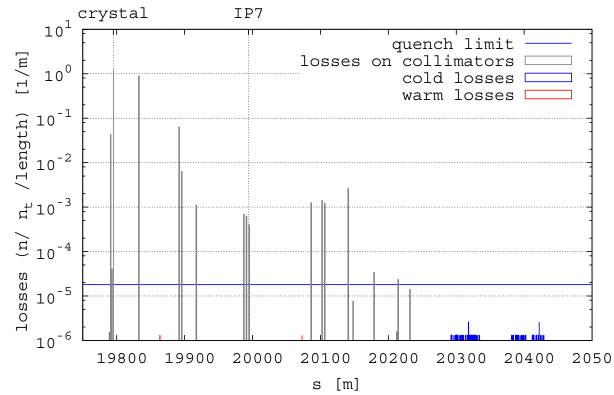

Figure 2: Loss map in case of crystal collimation, 40 μrad, channeling aligment, horizontal orientation. Zoom in the IR7 and dispersion suppression region.

SIMULATION RESULTS

Given that the energy stored in the halo is 8 orders of magnitude larger than the quench limit, the local losses around the ring must be evaluated at a very high precision level. Not only is it necessary to evaluate the escape rate of particles from the collimation system, but also critical to understand how losses are distributed along the machine. The quantity that we use to qualify our collimation system is the local cleaning inefficiency η

$$\eta = \frac{N_{abs}(dl)}{N_{Tot} \cdot dl} \tag{1}$$

e.g. the number of particles N_{abs} hitting the aperture in the longitudinal interval dl over the total number of particles absorbed by the collimation system N_{Tot}, normalized over the length. Considering the expected losses, the beam energy and the quench limit, we obtain a target local inefficiency of $1.7\,10^{-5}$1/m. To run detailed simulations we use a software package which includes a full 6d tracking code (Sixtrack [5]) and we evaluate the losses along the ring with a longitudinal precision of 10 cm. The plot of the local cleaning inefficiency versus the longitudinal position is usually called loss map.

Examples of loss maps for the horizontal case, without and with crystal collimation, are presented respectively in pictures 1 and 2 for the IR7-dispersion suppressor region: losses outside of this region are negligible. The vertical case is analogous. Figure 2 refers to the crystal option, with a crystal in perfect channeling position, channeling angle of 40 urad, which shows a massive decrease for cold losses: the cleaning inefficiency peak values, in the two cases, go from $4.2 \cdot 10^{-5}$ to $2.6 \cdot 10^{-6}$, showing about a factor 15 improvement. Figures 3 and 4 show the dependence of the local cleaning inefficiency peak value from the crystal orientation in cold region, together the maximum power load released in the IR7 warm insertion, along a length of 10 cm.

It is interesting to notice how these two variables naturally define an optimal range for the crystal bending angle:

Table 2: Range For an Optimal Channeling angle.

case	$\theta_{\mathbf{C-min}}$ [μrad]	$\theta_{\mathbf{C-Max}}$ [μrad]
horizontal	30	50
vertical	40	100

1. For channeling kicks beyond a critical value θ_{C-min} the maximum local inefficiency in cold regions does not improve anymore; this defines the minimum bending angle for maximum cleaning inefficiency ;
2. For channeling kicks up to a critical value θ_{C-Max} the loss peak in the warm insertion is stable, while it increases for large values; this defines the maximum bending angle for minimum radiation load to warm elements.

The angles θ_{C-min} and θ_{C-Max} (whose values are summarized in Table 2) define the range of optimal channeling angles. It is important to remember that our simulation results do no take into account the showers generated in the collimators; we assume that, for inelastic interactions, all the energy associated to the particle is absorbed at the interaction location. This assumption, that is a good approximation in case of metallic collimators, cannot be considered realistic for our graphite collimators. Even if a proton crosses the whole length of the collimator, the average lost energy is about 0.5 percent of the impacting one[6]; the rest is dispersed in showers. It is therefore important to understand how the inelastic losses redistribute within the IR7 insertion for the different scenarios. In Table 3 we present the collimator where the highest losses are concentrated, the relative number of inelastic interactions and the average impact parameter depending on the bending angle. It is found that, in 6 out of 7 cases within the optimal channeling range, the largest part of the primary halo is stopped at the first secondary collimator (TCSG.A6L7.B1). The rate of inelastic interactions is about 90%, and decreases for

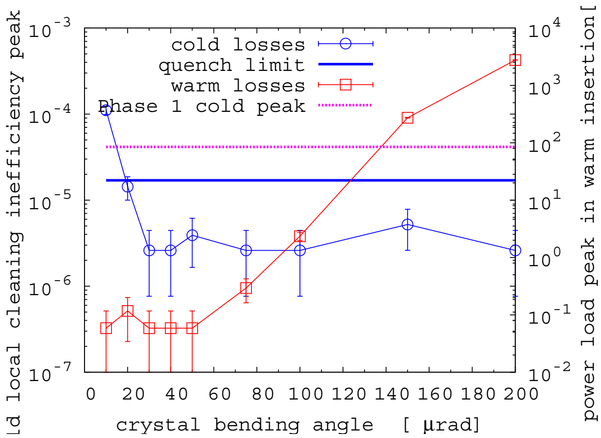

Figure 3: Maximum local cleaning inefficiency for different channeling angles.The crystal is perfectly aligned in channeling position, horizontal case.

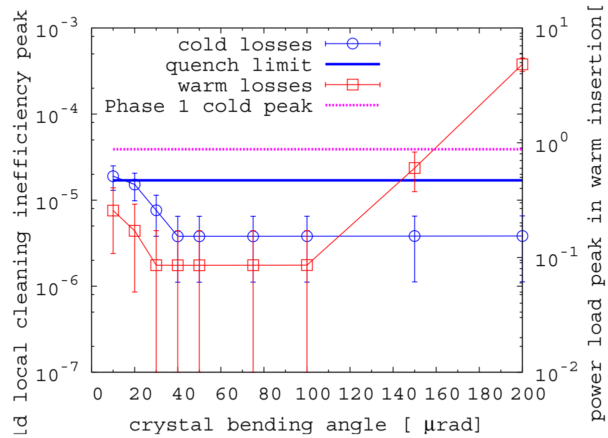

Figure 4: Maximum local cleaning inefficiency for different channeling angles. The crystal is perfectly aligned in channeling position, vertical case.

Table 3: Number of inelastic interactions on the highest loaded secondary collimator versus the channeling angle θ_c. The name, longitudinal position and average impact parameter are also shown.

θ_C [μrad]	name	position [m]	$\frac{N_{abs}}{N_{tot}}$	b [mm]
		horizontal case		
010	TCSG.6R7.B1	345.84	0.912	4.024
020	TCSG.B5R7.B1	291.24	0.388	0.016
030	TCSG.B5L7.B1	96.73	0.907	1.005
040	TCSG.A6L7.B1	37.50	0.893	0.066
050	TCSG.A6L7.B1	37.50	0.889	0.352
075	TCSG.A6L7.B1	37.50	0.895	1.065
100	TCSG.A6L7.B1	37.50	0.893	1.773
150	TCSG.A6L7.B1	37.50	0.886	3.171
200	TCSG.A6L7.B1	37.50	0.880	4.552
		vertical case		
010	TCSG.D4L7.B1	122.06	0.777	0.081
020	TCSG.A6L7.B1	37.50	0.783	0.021
030	TCSG.A6L7.B1	37.50	0.909	0.245
040	TCSG.A6L7.B1	37.50	0.907	0.475
050	TCSG.A6L7.B1	37.50	0.906	0.703
075	TCSG.A6L7.B1	37.50	0.903	1.267
100	TCSG.A6L7.B1	37.50	0.900	1.825
150	TCSG.A6L7.B1	37.50	0.893	2.922
200	TCSG.A6L7.B1	37.50	0.887	4.003

larger channeling angles (while the warm losses increase). This means that the main shower source is shifted downstream by at least 37.5 m with respect ot the Phase 1 system, where the most hit collimators are the primary ones. A detailed evaluation of the energy deposition must be done with the use of dedicated programs, in order to check that the downstream equipment (quadrupole, electronics in the UJ76 insertions, ...) is not affected.

CONCLUSIONS

A crystal collimation solution for the LHC has been worked out, showing that a perfect crystal in channeling mode can provide an increase of a factor 15 with respect to the standard Phase 1 collimation system. This solution is compatible with the present layout in IR7. On the contrary, simulations of crystals in volume reflection mode did not show any improvement.

Optimal channeling angles have been found for horizontal and vertical cleaning. Fundamental problems (like the heat load in the secondary collimator which is directly hit by the channeled beam) have not been addressed in detail yet. The main particle shower source is shifted about 40 m downstream, further studies must add crystal imperfections (miscut angle, amorphous layer, deformation from heating) to the simulations for estabilishing realistic performance estimates. Experiments in SPS and Tevatron [7][8] are also required to validate the model used.

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