HI-LUMI LHC COLLIMATION STUDIES WITH MERLIN CODE*

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Abstract

The collimation system is key to the successful operation of the LHC. Measurements and simulations of the previous run at 4 TeV have shown that the system is ready for the next step, running at 7 TeV, but at the same time some sensitive cleaning locations have been identified. In particular the dispersion suppressors downstream of the betatron cleaning region in IR7 are sensitive to single diffractive scattered protons from the collimator jaws. These particles can lead to magnet quenching. The MERLIN C++ library has been developed to exploit the functionality of an object oriented code, with improved collective effects and scattering routines. New single diffractive and elastic scattering routines, based on a fit of existing experimental data with the Regge theory of soft interactions of high energy scattering, is implemented in MERLIN. In this paper we present the impact of the new single diffractive scattering physics on the cleaning inefficiency of the LHC collimation system for the Achromatic Telescope Squeezing (ATS) PreSqueeze optics scheme, for the HL-LHC project. The results are compared with the same loss map calculated using a SixTrack+K2 like scattering routine.

INTRODUCTION

The LHC multi-stage collimation system has proven to be reliable during the first run with a beam energy of 3.5 and 4 TeV. The collimation studies are in a constant development to improve the physics models in the simulation and our ability to predict locations along the ring where magnet quenches could occur. The interaction models of protons with the bulk material of the collimators are particularly important. Elastic, single diffracted and Rutherford scattered protons survive the interaction and stay for many turns inside the beam pipe before being absorbed in the collimators on later turns or lost in the machine aperture. The understanding of limiting loss locations and of possible remedies are particularly important for future upgrade of the machine, when the stored beam energy will double from 362 MJ, for designed case, to more than 700 MJ, for HiLumi project.

In this paper we study the collimation cleaning performance of the optics scheme for the Hi-Lumi upgrade, the so-called *Achromatic Telescope Squeezing* (ATS) [1]. The ATS scheme is a way to strongly reduce β^* with a high control of the induced chromatic aberrations, off-momentum β beating and the spurious dispersion from the large crossing angles necessary to mitigate the beam-beam interaction. The MERLIN code [2] is a C++ accelerator library which is easy to extend and modify. The code has been benchmarked with the well known collimation version SixTrack+K2 and a good agreement has been found for locations and magnitude of the losses [3]. Previous results [4] have shown that Dispersion Suppressors (DS), downstream the betatron cleaning region of IR7, can suffer from large losses by protons with a large momentum deviation. Those protons have mainly experienced Single Diffraction (SD) dissociation with the collimators bulk material. An improved and accurate model has been developed by MERLIN group based on the Regge theory of soft diffraction dissociation [5, 6] . In this paper we present the first loss map results for PreSqueeze scheme with a SixTrack+K2 like scattering routine, we call here "MERLIN+K2", and a comparison with the improved single diffraction routine in MERLIN.

OPTICS AND SIMULATION SET-UP

The LHC optics and apertures definition is provided by the well known code MAD-X [7]. The Hl-LHC layouts uses larger aperture triplets to reduce further the β function in the high luminosity insertions (ATLAS and CMS) [1]. The beam squeezing consists in two main stages: an intermediate PreSqueeze at β^* of 44 cm, achieved with local optics changes in the IR matching sections, and after an additional squeeze to produce a β^* down to 10-15 cm, thanks to changes of the optics in the arcs adjacent to IRs. A more elaborated scheme adds the crab cavities to further increase the luminosity but it will not be discussed in this paper as this is not expected to affect the cleaning performance of the collimation system. The nominal collimator settings for optimum 7 TeV cleaning and triplet gaps that ensure adequate triplet aperture protection are assumed, see Tab. 1. In Fig. 1 we show the horizontal β function for the PreSqueeze and Squeeze ATS optics calculated by MERLIN. The dashed blue curve in the plot shows the beta beating, around ATLAS (IP1) and CMS (IP5), to achieve the low β^* values.

Table 1: Collimator Settings

Type	location	Setting[σ]
TCP	IR7	6
TCSG	IR7	7
TCLA	IR7	10
TCP	IR3	12
TCSG	IR3	15.6
TCLA	IR3	17.6
TCT	IR2-IR8	30
TCT	IR1-IR5	15
TCL	IR1-IR5	10
TCDQA	IR6	8
TCSG	IR6	7.5

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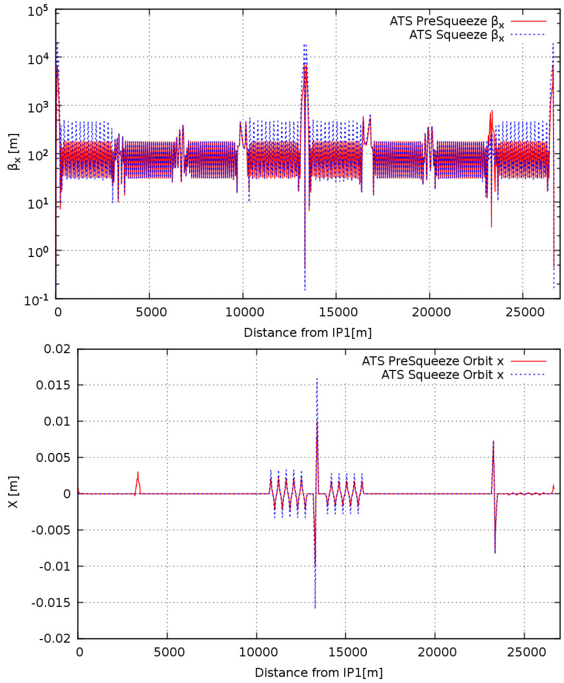

Figure 1: Horizontal β function (top plot) and orbit (bottom plot) for PreSqueeze and ATS optics calculated with MERLIN

IMPROVED SINGLE DIFFRACTION MODEL

Single diffraction dissociation in pp interaction ($pp \rightarrow pX$) is a complex interaction which is phenomenologically described by Regge theory [8] . In this section we introduce the topic with references for further information. The SD interaction is characterised by one elastically scattered proton and one which breaks up into an unknown system X with an invariant mass of M_X, called missing mass. The variables used to describe this process are the squared centre-of-mass s, the four-momentum transfer t and M_X. The last variable is usually replaced with the scaled variable $\xi = M_X^2/s$. Different approaches have been attempted to reproduce with accuracy the available data on this process. Some of them rely on the flux renormalization [9], which however introduces unconventional features in conflict with the standard notion of Regge theory [5]. Here, instead, we use an extended model developed by Donnachie [5,6] using the conventional Regge theory alone. The model is divided into high and low missing mass regions. For $M_X < 3$GeV the system X is dominated by baryon resonances and it is modelled by a background with the additional contribution of the resonances. For higher missing masses the interaction is described by an exchange of a *pomeron* or a *reggeon* [5] between the elastically scattered proton and the system X. The interaction can be described by a sum of triple Regge exchange terms [5]. There are four main leading terms from the triple-reggeon vertex and an additional pion-exchange term [10] is added which is important at small t. The model is fitted with data coming from the main experiments at low (Akimov, Armitage, Albrow, Schamberger) and high energy s (UA4, UA8, CDF), see [9] and references therein. Although some of them are not particularly good, other survived only in integrated form and some others have been reconstructed, it is possible to get a reasonable agreement with the model [6]. In the main collimation codes the SD double differential cross section is represented by [11]

$$\frac{d^2\sigma}{dt \cdot dM_X^2} = \frac{SD_{const} \cdot e^{-b_{SD}(M_X)\cdot t}}{M_X^2}, \tag{1}$$

where $SD_{const} = 0.68$ mb is the single diffraction constant, and b_{SD} is the SD slope. The upper limit of M_X^2 is given by $M_X^2 = M_p^2 + 0.15s$ and M_p^2 is the lower one, where M_p is the proton mass. The SD slope is related with the slope of elastic process and takes different value in three different regions of the missing mass. The shape of the double differential cross section has an exponential like behaviour with different slopes. The model is simply extended to low missing mass and low t without taking into account any resonances or background contribution [11]. The new model implemented in MERLIN [6] is an attempt to improve significantly the scattering routine in collimation codes. The main idea is to produce a detailed model of the elastic and single diffraction interactions with a strong theoretical background.

LOSS MAP CALCULATION

For the loss map simulations we generate a horizontal beam halo characterised by a ring shape in normalised (x,x') phase space and Gaussian in the vertical coordinate. The radius is defined to intercept the primary collimators at a defined transverse offset between the jaw surface and the impact point, called the impact parameter. For the following simulations the impact parameter is set to 1μm. The halo is then transformed back in real coordinates before being tracked. The beam is injected in front of the horizontal primary collimator in the betatron cleaning region and tracked for 200 turns. The loss map are characterised by the local inefficiency defined as

$$\eta = \frac{N_{ABS}}{\Delta z \cdot N_{coll}^{Tot}}, \tag{2}$$

where Δz is the longitudinal resolution (10 cm). N_{ABS} is the number of particles absorbed in Δz and N_{coll}^{Tot} is the total loss in the collimators along the machine. For the collimator Δz is set to the collimator length and N_{ABS} are the total losses in the collimator. In Fig. 2 we show the loss map comparison for PreSqueeze optics scheme with a K2-like scattering routine (top plot) and the new SD routine (bottom plot). As expected the majority of the protons are lost in the collimation IR3-IR7 areas. The plot is colour coded: black spikes represent losses in the collimators, red spikes losses in warm elements of the accelerator, and most importantly blue spikes which indicate losses in the superconducting magnets. The black spikes on the incoming beam side of each detector are caused by the tertiary halo protons caught by the tertiary collimators. The absence of blue spikes at the

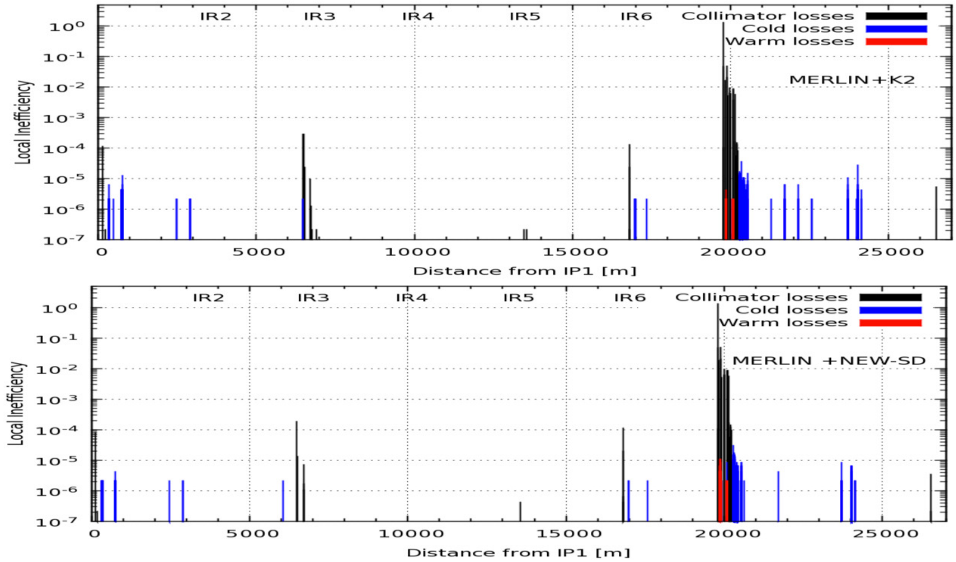

Figure 2: Loss map for PreSqueeze: case calculated with MERLIN+K2 (top) and MERLIN+new-SD (bottom). In black the losses in the collimators, in blue losses in the SC magnets and in red losses in warm elements.

triplet location, consistently found with both versions of the scattering, indicates that the proposed settings are effective in protecting the triplets for the pre-squeezed optics.
The results for the K2-like scattering routine show high cold spikes downstream IR7, and in the arc 78 and 81. The same behaviour has been observed by SixTrack+K2 simulation for the fully squeezed ATS scheme [4]. As shown in Fig. 2 and Fig. 3, the collimator inefficiencies in the various IRs have the same amplitudes for both the models. The new scattering routine loss map shows a smaller amplitude for the cold spikes upstream IR7 and in the arc 78 and 81. A closer look at the loss maps in the zoom of IR7, in Fig. 3, shows an inefficiency decreasing to around 60% in dispersion suppressors and a four times increase of warm losses among collimators. This study proves that also for the pre-squeezed optics, the limiting loss locations for betatron cleaning occur at the IR7 DSs. This result is consistently found for different optics configurations in the experimental regions provided that tertiary collimators protect locally the triplet. An appropriate collimation upgrade scenarios is foreseen to address this limitation for HL-LHC [12]. It is important to characterize well the limiting loss locations that are driven by SD. Therefore, the results achieved with the new version of our scattering are considered encouraging but the observed difference compares to the other model require a better understanding.

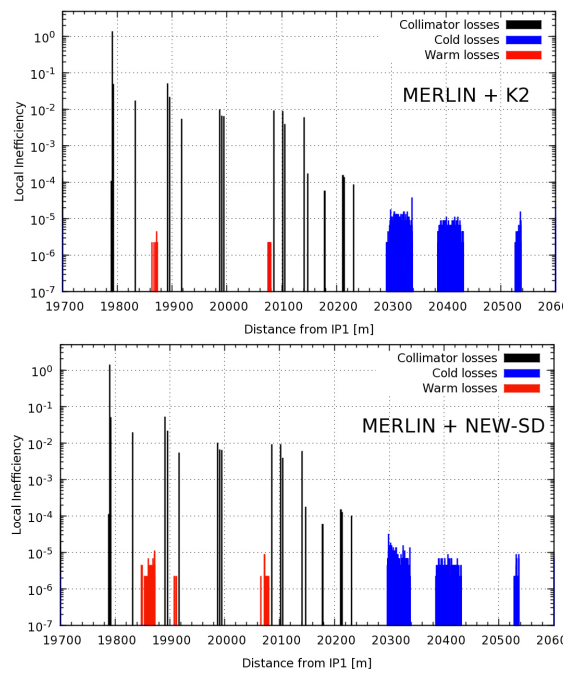

Figure 3: Horizontal loss map comparison for IR7. The amplitude of the collimator spikes are very well reproduced.The new SD routine show a lower amplitude for cold losses and strong increase of the warm.

CONCLUSION

In conclusion MERLIN has been used to calculate for the first time the PreSqueeze ATS loss map for the HiLumi LHC upgrade. The results indicate that the proposed settings are effective in protecting the triplets for the pre-squeezed optics. The results for the new-SD routine show a reduction of cold losses along with an increase of warm losses. Further studies on the standard optics at different energies and comparisons with the available experimental data are ongoing to investigate in more detail the observed differences.

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