

# SIMULATING NOVEL COLLIMATION SCHEMES FOR HIGH-LUMINOSITY LHC WITH MERLIN++

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## Abstract

Due to the large stored beam energy in the HL-LHC, new collimation technologies must be used to protect the machine. Active halo control of the proton beam halo with a Hollow Electron Lens can give a kick to protons at the edge of the beam without affecting the core. Various modes of operation are possible, for example the electron lens can have a continuous current or it can be pulsed to different amplitudes for each passage of the proton beam. In this article we use Merlin++ simulations to show the performance of these modes for HL-LHC parameters. We also present recent simulations comparing scattering models in Merlin++.

## INTRODUCTION

The High Luminosity upgrade to the Large Hadron Collider (HL-LHC) [1] will increase the data collection capability of the LHC by a factor of 10. The upgraded components of HL-LHC should be installed by the end of the long shutdown 3 (LS3) in 2026. To achieve this, the beam current is increased and thus the stored energy of the beam increases by approximately a factor of 2. This puts significant extra demand on the collimation system to protect the rest of the machine. In addition the possibility of fast failures of the new crab cavity system introduces new risks to the collimators.

Active halo control is being considered for inclusion into HL-LHC to mitigate these new risks. This reduces the proton population in the tails of the beam distribution using fields rather than physical collimators. By doing so fewer protons are lost into the collimators in the time before the dump is triggered, for example in the event of a fast change in the orbit position. These methods have the advantage that they can cause effects closer to the core of beam without placing physical equipment at risk of damage from the beam.

Three methods of active halo control have been suggested: by narrow-band excitation using the LHC transverse damper [2], using tune modulation [3], and with a Hollow Electron Lens (HEL) [4].

## MERLIN++

Merlin++ [5] is an open-source accelerator simulation library written in C++11. It is designed to be modular and extensible to provide a large flexibility in its use for simulation tasks and to allow the easy addition of new physics processes. It has been used for a number of studies on a range of accelerators including the International Linear Collider (ILC) [6] and the LHC [7]. It is developed by a team

in the University of Manchester and the University of Huddersfield as part of the HL-LHC project. Its features include the ability to tracking particles and measuring optical parameters through typical accelerator lattices, as well as more advanced physics processes for collimation, HEL and synchrotron radiation studies.

## 5.02 Release

Merlin++ 5.02 was released in March 2019. The main focus of this release has been to improve the sustainability of the project as defined by the Software Sustainability Institute [8]. This has involved investigation into areas of the source code with the highest complexity, as measured by the McCabe cyclomatic complexity, and refactoring to resolve the problems found. For example, file-parsing code has been factored out from several places into a single shared class, the aperture class hierarchy has been redesigned, and the included random number generator has been removed in favour of the Mersenne Twister implementation in the C++11 standard library. There have also been significant improvements to the supporting material including a new website [9], new quick start guide and tutorials and improvements to the documentation.

A more detailed report on the sustainability of Merlin++ can be found in [10].

## SCATTERING

In [7] we have used data from the beam loss monitoring (BLM) system taken during LHC run 1 and 2 to validate Merlin++ for predicting loss maps, and have produced loss map calculations for the HL-LHC. Merlin++ implements two versions of the collimation scattering model. The first is based on the K2 [11] model from SixTrack [12], the current leading code for LHC collimation studies. The second is a new model of proton-nucleon scattering based on the Donnachie and Landshoff (D-L) description of Pomeron and Reggeon exchange [13]. Merlin++ also features three hybrid models, each using K2 in combination with one of the new versions of elastic, single diffractive and ionization components respectively. These can be used to assess the relative contributions of the upgrades.

Compared to the K2 model, Merlin++ contains several improvements. The cross sections for total, elastic and single diffractive proton-proton interactions have been upgraded from simple fits to the D-L model, fitted to data over a range of energies applicable to hadron colliders. Modelling of the ionization energy loss now takes straggling into account. The implementation of the advanced scattering models is discussed in detail in [14].

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Here we compare Merlin++'s scattering models, ranging from an emulation of the SixTrack/K2 model to the full updated Merlin++ model. For these simulations the HL-LHC version 1.2 lattice was used with  $\beta^*$  at IP1/5 set to 15 cm in each plane (round optics).

Loss maps show the distribution of proton losses around the ring. For simulation, we assume that losses are dominated by particles slowly drifting from the halo onto the primary collimators. We therefore start the simulation with a halo beam that hits the primary collimator with a small impact factor of 1  $\mu\text{m}$ ; here we use  $10^8$  initial particles. The scattered particles are then tracked for 200 turns. We use the scattering models described above when a proton interacts with a collimator jaw and consider other sections of beam pipe to be black absorbers. Losses are recorded in 10 cm bins.

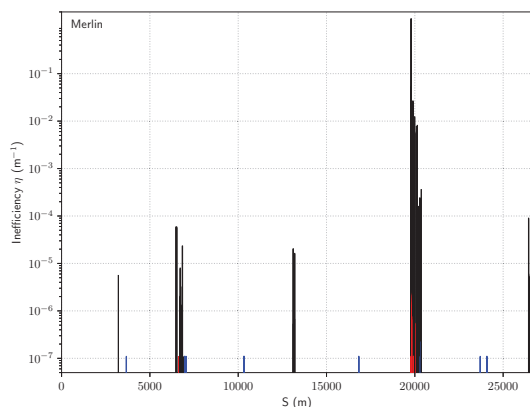


Figure 1: Loss map for HL-LHC full ring with Merlin++ scattering.

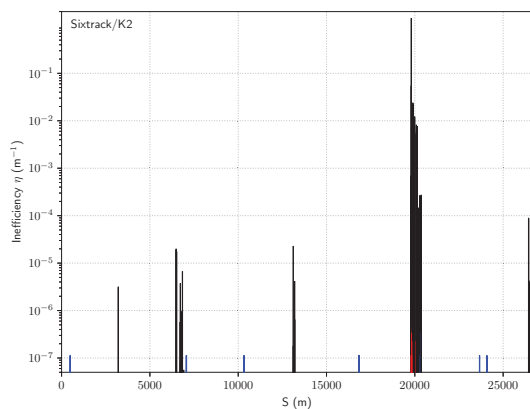


Figure 2: Loss map for HL-LHC full with SixTrack/K2 style scattering.

Figure 1 shows the losses for a horizontal halo in beam 1 using the Merlin++ scattering model. Losses in collimators are shown in black, warm magnets in red and cold magnets in blue. The collimation regions in IR3 (6665 m) and IR7

(19994 m) are clearly visible, along with losses on the TCTs in experimental regions and some losses in the cold magnets in the arcs. The same simulation using the SixTrack/K2 style scattering is shown in Fig. 2 and the predictions appear very similar. In both models it can be seen that the TCLDs do a good job of reducing losses in the IR7 dispersion suppressor and other cold regions around the ring.

We can see in greater detail the difference between scattering models by zooming in to the main collimation region IR7. Figures 3 and 4 show the loss maps for the Merlin++ and SixTrack/K2 models. The Merlin++ scattering shows increased losses in the warm region after the primary collimators, and slightly reduced losses in the dispersion suppressor region.

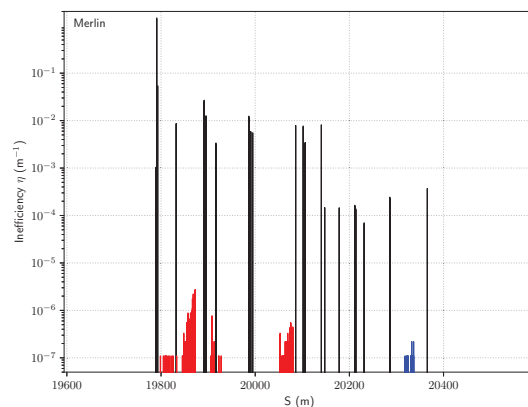


Figure 3: Loss map for IR7 with Merlin++ scattering.

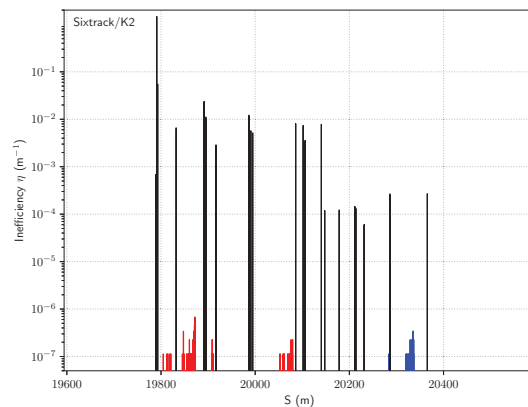


Figure 4: Loss map for IR7 with SixTrack style scattering.

Table 1 shows the absolute number of particles lost in the collimators, warm and cold regions, for each of the scattering models. Both models predict that losses are well within acceptable limits.

## HOLLOW ELECTRON LENS

Effective active halo control needs to produce a sufficient effect on particles with high transverse amplitudes, while at the same time not causing detrimental effects to the core of

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Table 1: Lost Particles by Mode and Region for 100 Million Initial Particles

Mode	Total	Collimator	Warm	Cold
Merlin++	91558820	91557414	1363	43
SixTrack/K2	88844242	88844035	153	54
SixTrack/K2 + new elastic	88766488	88766252	200	36
SixTrack/K2 + new ionisation	91529486	91529193	240	53
SixTrack/K2 + new SD	88845262	88844093	1143	26

the beam. The HEL achieves this by using a hollow cylindrically symmetric beam of electrons co-propagating with the proton beam. For small amplitude protons in the hollow core of the electron beam, the transverse field contributions cancel out, leaving no net field. Protons with a higher amplitude, either coinciding with or outside the electron beam, feel electrostatic and magnetic focusing forces. The dimensions of the HEL can be adjusted with a solenoid field to control at which amplitude it starts acting. The HEL can then be used to enhance diffusion of these protons on to the primary collimators.

The HEL can be run in a number of modes, either on continuously (DC) or modulated sinusoidally (AC), on individual turns (turn-skip) or randomly (diffusive). The deflection per turn from the HEL is small, so its action is best understood by considering dynamic behaviour over many turns. Figure 5 shows the Poincaré section of the HL-LHC beam with the HEL disabled. Stable motion can be seen across the whole 10 sigma shown.

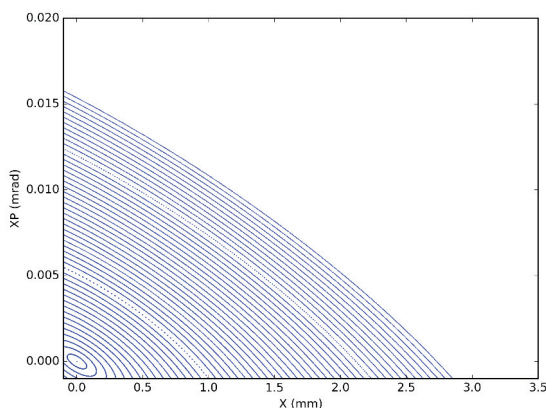


Figure 5: Poincaré section up to 10 sigma with the HEL off.

In DC mode there is a change to the focusing for high amplitude particles. In Fig. 6 this can be seen to perturb the orbits of high amplitude particles, introducing islands in phase-space.

In diffusive mode different kicks are given to the beam at each turn, effectively adding random noise to the dynamics.

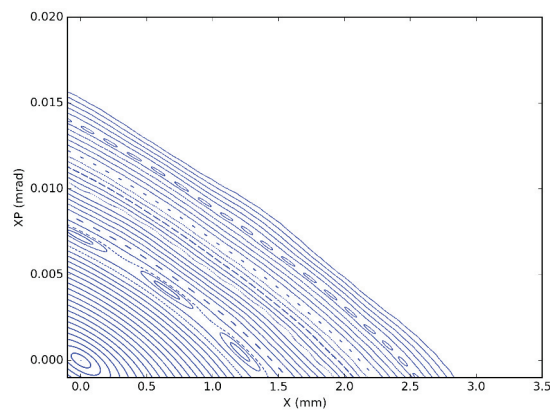


Figure 6: Poincaré section up to 10 sigma with the HEL in DC mode.

In Fig. 7 it can be seen that high amplitude particles experience chaotic motion, which will eventually drive them onto the collimators.

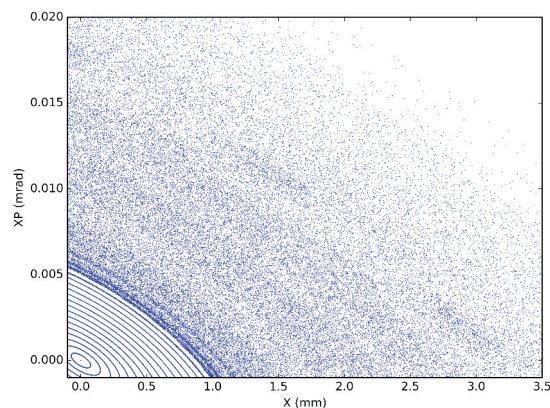


Figure 7: Poincaré section up to 10 sigma with the HEL in diffusive mode.

The HEL classes in Merlin++ have recently been refactored to improve parameter storage and to generalise radius ratio scaling. Work is ongoing to verify simulations to measurements taken at RHIC at Brookhaven National Lab.

## ACKNOWLEDGEMENTS

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