# INTEGRATED SIMULATION TOOLS FOR COLLIMATION CLEANING IN HL-LHC*

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## *Abstract*

The Large Hadron Collider is designed to accommodate an unprecedented stored beam energy of 362 MJ in the nominal configuration and about the double in the high-luminosity upgrade HL-LHC that is presently under study. This requires an efficient collimation system to protect the superconducting magnets from quenches. During the design, it is therefore very important to accurately predict the expected beam loss distributions and cleaning efficiency. For this purpose, there are several ongoing efforts in improving the existing simulation tools or developing new ones. This paper gives a brief overview and status of the different available codes.

## INTRODUCTION

The High-Luminosity Large Hadron Collider (HL-LHC) is an ongoing upgrade project that aims to increase the performance of the LHC up to a yearly integrated luminosity of about 250 $\text{fb}^{-1}$ [1], which is about a factor 10 higher than achieved in LHC Run I (2010–2013). One very important contribution comes from increasing the bunch intensity by about a factor 2, which results in a stored beam energy of more than 700 MJ. This puts very high demands on the LHC collimation system to control beam losses and avoid quenches of superconducting magnets.

To assess the collimation performance, we need a detailed understanding of the cleaning of beam protons by the collimators. Protons lost in cold magnets have usually hit a collimator and afterward traveled some distance through the magnetic lattice of the ring—in many cases, protons are lost several turns after their first collimator impact. Therefore, we need simulation tools that model both the tracking through the magnetic lattice as well as the particle-matter interaction inside collimators. SixTrack with collimation, which we call here "classical SixTrack", was developed for exactly this purpose during the design of the LHC by combining the existing SixTrack [2, 3] with the K2 scattering routine [4, 5]. Recently, several efforts have been launched in order to develop simulation tools with improved accuracy in view of the increasing demands.

Two updates to the classical SixTrack are being developed at CERN: one is an update to K2 (which we call "new SixTrack"), while the other one, the SixTrack-FLUKA coupling, replaces K2 by an online call to a separate process of the particle-physics Monte-Carlo code FLUKA [6, 7]. In addition, independent simulation tools are being developed at the University of Manchester and Huddersfield (MERLIN) and Royal Holloway (BDSIM). The availability of several codes that are being developed independently increases the confidence in the final results and conclusions and offers the possibility of inter-code comparisons, which help in detecting possible errors and inconsistencies. This paper gives an overview of the different available tools, including the classical SixTrack, as well as some sample simulation results.

## CLASSICAL SIXTRACK WITH COLLIMATION

SixTrack is a thin-lens tracking code, that follows 6D trajectories of relativistic particles in circular accelerators in a symplectic manner. It accounts for magnetic non-linearities up to order 20 and the lattice input can be created using MAD-X, which provides a tight integration with the LHC magnetic imperfection model. SixTrack is used for dynamic aperture studies with high numeric stability, as well as for tune optimization. It is well-tested and experience with SixTrack has been accumulated over a few decades of code development at CERN [8]. It is still used both for the nominal LHC and its upgrades.

During the LHC design phase, the K2 Monte Carlo code [5] was included in SixTrack [4] to simulate the proton-matter interaction inside collimators. Ionization energy loss and multiple Coulomb scattering are included, as well as point-like processes: nuclear elastic scattering, nuclear inelastic scattering (where it is assumed that the proton disintegrates), single diffractive scattering, and Rutherford scattering. A particle is considered lost either when it hits the aperture—the particle coordinates are checked against a detailed aperture model with 10 cm longitudinal precision—or if it disintegrates in an inelastic interaction in a collimator. The simulation output contains all loss locations.

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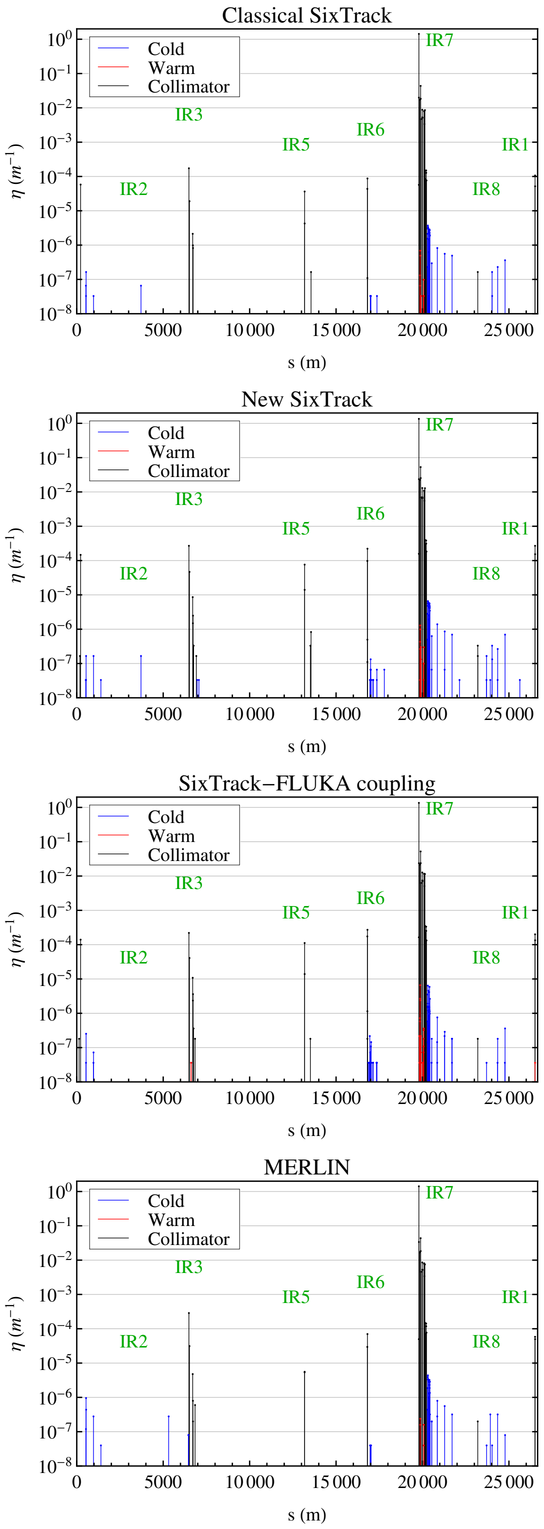

Figure 1: Cleaning inefficiencies around the LHC obtained with the different simulation tools, assuming the same nominal machine configuration [9] and an initial halo in the horizontal plane in beam 1. Bins of 5 m have been used for the aperture losses, while collimators have their natural length as bin length.

The simulation starts with a distribution of halo particles, which already have sufficient betatron amplitudes to hit the primary collimators. Tracking also the core, including the diffusive processes that send particles onto the collimators, would make the computing time unfeasible. The starting distribution, which relies on assumptions from other input calculations, thus determines directly the impact parameters.

An example of the simulation output is shown at the top of Fig. 1. It illustrates the distribution of losses around the ring for the case of 7 TeV proton beams in the LHC, using a nominal machine configuration (i.e. $\beta^{*}$=55 cm, nominal collimator settings as in Ref. [9]). As can be seen, the main loss location is the collimation insertion in IR7, and the highest cold losses are found just downstream in the IR7 dispersion suppressor. Significant losses are also intercepted by collimators in other parts of the ring, such as the momentum collimators in IR3 or the tertiary collimators in front of the experiments.

## NEW SIXTRACK WITH COLLIMATION

The new version of SixTrack uses the same tracking as the classical one but includes several updates to K2. Details can be found in Ref. [10]. The changes concern the proton-proton single diffractive cross section, considering a recent parametrization based on the renormalized pomeron flux exchange, the proton-nucleus inelastic and total cross sections, using recent data from the Particle Data Group, and the proton-proton elastic cross section, based on TOTEM data. Furthermore, the carbon material properties have been revised based on the composite material used in the collimators. The ionization energy loss and the multiple Coulomb scattering models have also been improved. Finally, routines for treating crystal collimation are also incorporated [11].

The second plot from the top in Fig. 1 shows the loss distribution obtained with new SixTrack for the nominal machine configuration. It is qualitatively similar to the result with classical SixTrack, but when looking at individual loss locations, significant differences can be observed. In particular, higher losses are found in the IR7 DS and at the TCTs.

## SIXTRACK AND FLUKA COUPLING

FLUKA [6, 7] is a general purpose Monte Carlo code which describes the interaction of particles whilst traveling through matter. It is routinely used at CERN, in particular for LHC calculations assessing energy deposition in the accelerator components, background to experiments, induced radioactivity, and radiation to electronics.

Aiming to coherently exploit its state-of-the-art physics models, it was coupled to SixTrack in order to describe all kinds of interactions taking place in beam intercepting devices (like SPS scrapers and LHC collimators) [12]. The 3D geometry of the latter ones is explicitly modeled in FLUKA, replacing the respective item in the SixTrack lattice. The two codes are compiled separately and run synchronously, exchanging particles through a network port at user selected interfaces along the accelerator element sequence.

For the LHC case, each collimator seen by the simulated beam implies an upstream and downstream interface. Preliminary results obtained by the coupling for the nominal machine configuration are shown in the third plot from the top in Fig. 1. The displayed pattern looks consistent with the previous ones, while local discrepancies call for a more detailed investigation.

## MERLIN

MERLIN is a thick-lens particle tracking code in the form of a C++ physics library, which provides many features and is simple to extend and modify. Initially developed for the ILC beam delivery system and then extended to simulate damping rings, it has been further developed as part of the HL-LHC project to perform large scale collimation simulations. A MAD-X interface has been introduced in the code to import optics, imperfections of magnetic elements, a fully parallel wakefield model, and a parallel MPI protocol to run on clusters, along with many other speed enhancements [13].

The code takes into account the full 6D phase space but it is currently running with no RF cavities in the simulation. This is foreseen to be included in the future. To model collimator dynamics, MERLIN has been equipped with a K2-like scattering routine for code benchmarking and a good agreement has been found with the classical SixTrack [14]. A new improved scattering routine based on the Regge-exchange model has been developed to improve the elastic and single diffraction processes along with a new ionisation routine. The impact of the updated single diffractive scattering has been evaluated for the HL-LHC optics [15]. The bottom plot of Fig. 1 shows a loss map obtained with MERLIN, using K2 scattering, which is in overall good agreement with the other codes.

## BDSIM

Beam Delivery Simulation (BDSIM) is a flexible, open source C++ code to simulate beam losses in particle accelerators that combines fast, thick-lens, 6D tracking routines with the full range of particle interaction physics processes available in Geant4 [16]. This enables the study of collimator cleaning, including both primary losses at apertures and the subsequent energy deposition of secondaries in the downstream beamline. With over a decade of development, BDSIM has been applied to simulate backgrounds for the International Linear Collider (ILC), Compact Linear Collider (CLIC) and the Accelerator Test Facility 2 (ATF2) [17].

Recently, the functionality of BDSIM has been extended to simulate circular colliders such as the LHC. A new cross-platform build system and suite of python utilities for lattice conversion and output analysis has been added. Novel conversion tools allow lattice descriptions in other formats such as both MAD-X input and Twiss output to be read by BDSIM as recently demonstrated with lattices as complicated as the LHC [18]. Already existing interfaces to other codes such as PLACET are being further developed to provide efficient simulation of collective effects such as wakefields during tracking. Tracking and optics comparison between the BDSIM LHC model and that of SixTrack and MERLIN are currently underway as well as extending the fast in-vacuum tracking routines to be fully symplectic.

## SUMMARY

With the increasing demands on the LHC collimation system in future upgrade scenarios, several efforts are ongoing within the HL-LHC project to develop improved simulation tools including both magnetic tracking and particle-matter interaction in collimators: an improved version of SixTrack+K2 and SixTrack coupled to FLUKA at CERN, MERLIN at UMAN and Huddersfield, and BDSIM at Royal Holloway. This rich flora of independent simulation tools allows inter-code comparisons, which can help in finding possible inconsistencies, as well as self-maintained simulation setups in different collaborating institutes.

We have presented preliminary simulation results of the nominal LHC configuration from several of the codes and the results show overall a good agreement. When looking at some specific loss locations, some differences can be noted, which have to be further studied in detail in order to be fully understood. Such a study could help in deepening the understanding of the dynamics of collimation simulations and the delicate interplay between optics, aperture and different scattering processes in the collimators. This might allow to further improve the simulation models and increase the confidence in the simulation results of collimation performance in HL-LHC.

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