MERLIN SIMULATIONS OF THE LHC COLLIMATION SYSTEM WITH 6.5 TeV BEAMS

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Abstract

The accelerator physics code MERLIN has been extended in many areas to make detailed studies of the LHC collimation system and calculate loss maps from beam halo losses. Large scale tracking simulations have been produced for the 2015 run configuration at 6.5 TeV. We present results of cleaning inefficiency simulations of the LHC's multi-stage collimation system along with a detailed comparison between MERLIN, SixTrack, and measured beam losses.

INTRODUCTION

The Large Hadron Collider (LHC) uses a multi-stage collimation system aimed at efficiently cleaning the beam halo, providing passive protection and limiting background at experimental apparatus [1, 2]. Its main design requirement is to protect superconducting magnets from beam losses which may induce quenches. The performance of the collimation system is qualified by loss maps, i.e. the local cleaning inefficiency which expresses the probability that a proton interacting with the collimation system around the ring is lost in a given location. In measurements, the cleaning performance can be assessed with dedicated low-intensity tests where beams are lost in a controlled way to probe the collimation system performance. This is also estimated by means of numerical simulations, which take into account the machine working point and the interaction of beam particles with the material of the collimator jaws, responsible for the cleaning.

Advanced numerical tools have been developed over the past years to ensure a good prediction of the losses along the machine, which combine proton tracking through the machine lattice and scattering routines. MERLIN [3] has been improved for this application, and it is now compared with SixTrack [4]. In addition to previous comparisons [5], in this paper we present simulations of the machine configuration at higher energy and comparisons to measured loss patterns.

MERLIN

MERLIN is a C++ accelerator physics library, originally developed to model beam delivery system of linear colliders [6], and more recently used to simulate the collimation system of the LHC [7]. Currently MERLIN is used for designing the FCC collimation system [8], investigating novel schemes such as HL-LHC hollow electron lens collimation [9], as well as LHC collimator upgrade material studies [10].

A standard MERLIN simulation consists of constructing an accelerator model, a particle beam, and defining physics processes that are assigned to a tracker. MERLIN provides 6D thick lens tracking using a choice of either `TRANSPORT` or `SYMPLECTIC` integrator classes. For full 6D simulations the `klystron` control class is used to set RF cavity voltages. A matched beam may be defined at any point in the accelerator using calculated lattice functions. A number of input distribution types are available, and users may create their own. Details of the MERLIN simulation setup are beyond the scope of this paper. It is just noted that recent developments of the MERLIN simulations setup [11] include full treatment of 6D dynamics and the treatment of novel materials presently under consideration for the HL-LHC collimation upgrade [12]. Composite materials, which may be defined as mixtures of existing or user-defined materials or other composites, have been implemented in order to study the effect of novel collimator jaw materials on scattering and loss maps [10].

In this paper we present results of numerical simulations of collimation cleaning and of beam losses around LHC using MERLIN, for the first time, as a multiturn tracking code that accounts for six-dimensional phase space in a symplectic manner. As a benchmark of the new simulation setup for the LHC collimation system deployed for Run II, we compare loss maps and inelastic and single diffractive losses in each collimator, as simulated in SixTrack and MERLIN. We also include loss map measurements taken in Run II for the LHC lattice, with specific focus on the betatron collimation insertion in IR 7.

SIMULATION SETUP

Simulations were performed using the 2015 machine configuration at 6.5 TeV, whith beta functions at IPs $\beta^*_{1,5}$ = 11 m, $\beta^*_{2,8}$ = 10 m. The collimator settings are detailed in Table 1 for primary (TCP), secondary (TCSG) and tertiary (TCT) collimators. Shower absorbers (TCLAs) in the betatron (IR 7) and momentum (IR 3) cleaning insertions and some protection collimators are also listed. The simulation

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inputs in SixTrack and MERLIN are the same and the parameters of the initial distribution are adjusted to reproduce similar impact on the primary collimators. Simulations were performed for the anti-clockwise beam 2.

Table 1: Collimator Half Gaps Expressed in Units of Beam Standard Deviation, Calculated for a Normalized Emittance of 3.5 mm-mrad

Region	Collimators	Half-gap
IR3	TCP / TCSG / TCLA	15σ / 18σ / 20σ
IR7	TCP / TCSG / TCLA	5.5σ / 8σ / 14σ
IR6	TCDQ / TCSP	9.1σ / 9.1σ
IP1/ 2/ 5/ 8	TCT	$37\ \sigma$

LOSS MAP COMPARISON

The beam loss distribution around the ring is estimated by using beam loss monitors (BLMs) [13]. These are ionization chambers located all around the ring to detect beam losses by means of the secondary particle showers emitted when a proton interacts with the vacuum chamber and the surrounding materials. The BLM system provides an interlock mechanism that can trigger an emergency beam dump in the case of high losses in cold or sensitive areas of the machine. By exciting the beam to provoke losses, loss maps may be generated studying the BLM signals around the ring for a given integration time. This is done regularly at the LHC as part of the system validation, using the transverse damper to excite individual bunches in dedicated low-intensity fills.

The simulated loss maps generated by MERLIN and SixTrack are compared to the measured loss maps in Fig. 1. The plot is colour coded: black spikes represent losses in the collimator jaws, red spikes losses in warm elements of the accelerator, and most importantly blue spikes which indicate losses in the superconducting magnets. The top plot shows the BLM signals caused by losses provoked, during operation, in beam 2 in the horizontal plane.

A quantitative comparison between the measured pattern and simualtion results cannot be done without additional energy deposition simulations to reproduce the BLM signal per proton lost in the machine aperture. Thus, only a qualitative comparison can be done, paying attention to possible cross-talk between monitors.

As the beam travels from right to left on these figures, the standard collimation hierarchy is observed with losses mainly in IR 7 (betatron losses), IR 3 (off-momentum losses) and IR 6 (dump protection system). Losses in IR 7 can be observed in greater detail in Fig. 2. The highest losses occur at the primary collimators and the loss levels decay along IR 7, as expected from the three-stage cleaning hierarchy. A small tail, a few orders of magnitude lower than the TCP loss, leaks to the cold magnets in the dispersion suppressor (DS) downstream of IR 7. The location of the highest local cold losses in the ring is the limiting location for the LHC intensity reach from collimation cleaning. While the two simulated

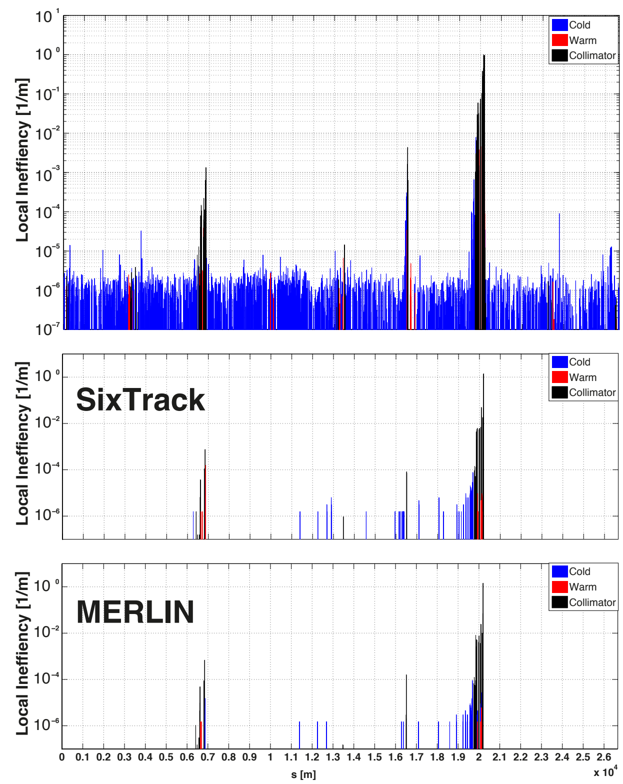

Figure 1: Beam loss distribution around the LHC. On top losses measured with BLMs from a qualification loss map of the betatron collimation system on September 2015 compared to simulations performed with SixTrack (centre) and MERLIN (bottom).

loss maps agree well with the prediction of protons lost in the aperture, some qualitative differences can be observed between simulations and measurements. The measurement indicates a much denser loss pattern, with higher losses in the warm section, but also in the cold arc. This is caused by the shower development, as discussed in [14].

Differences between the two codes are small. Losses in collimators are similar, and the most noticable difference is the magnitude of losses in the DS downstream of the IR 7 collimators.

IMPACT OF ADVANCED SCATTERING

The MERLIN scattering routine includes a recently improved fit through all available experimental data to calculate the single diffractive proton nucleon cross section [15], and the resulting value is slightly smaller than the one used in SixTrack. This is manifested in the loss maps as fewer losses in the DS region in MERLIN than in SixTrack. The percentage of losses in collimators, cold and warm apertures after 200 turns is shown in Table. 2. MERLIN estimates a larger proportion of losses in the collimators. The integrated inefficiencies observed in the two DS regions are $5.9 \cdot 10^{-4}$ and $2.7 \cdot 10^{-4}$ for SixTrack and $3.7 \cdot 10^{-4}$ and $1.8 \cdot 10^{-4}$ for MERLIN.

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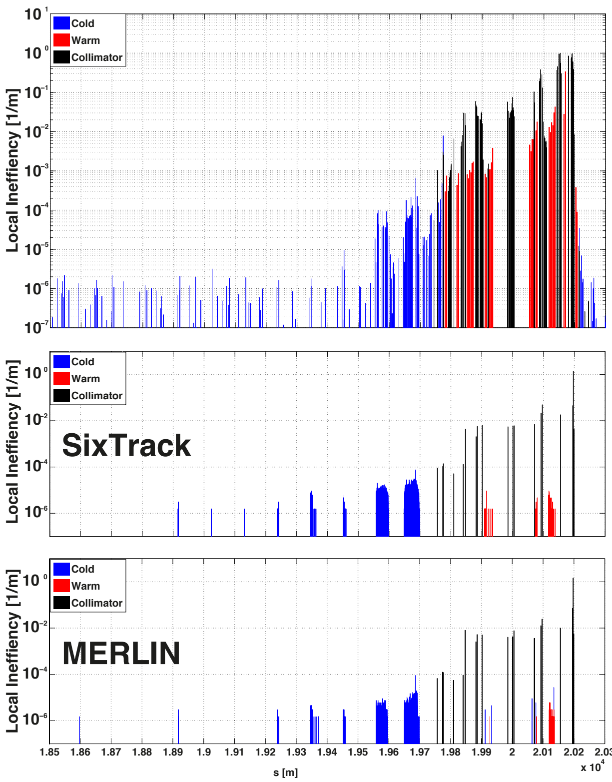

Figure 2: Loss locations in IR 7 (zoom of Fig. 1) from measurement (top), SixTrack (centre) and MERLIN (bottom).

Table 2: Percentage Losses for MERLIN and SixTrack for a $6.4 \cdot 10^6$ Proton Loss Map Simulation

Code	Collimator	Cold	Warm
MERLIN	99.9623	0.0362	0.0015
SixTrack	99.9017	0.0927	0.0055

The number of inelastic and single diffractive interactions in named collimators in IR 7 predicted by MERLIN and SixTrack are shown in Fig. 3. Again, it can be seen that MERLIN predicts higher inelastic losses in the horizontal primary collimator in IR 7. On the contrary, the new single diffractive scattering model in MERLIN leads to lower SD events in the collimation system, reflected in the much lower cold losses, typically dominated by this class of events.

CONCLUSION

MERLIN has been benchmarked with SixTrack and a good agreement has been found for the loss maps calculated for the machine configuration at higher energy. The code also shows good qualitative agreement with the measured loss map from the 6.5 TeV flat top configuration of the LHC. The improved model of single diffractive scattering leads to a smaller proton-nucleon cross section in MERLIN when compared to SixTrack. This manifests itself as a reduction in the predicted losses in the dispersion suppressor region

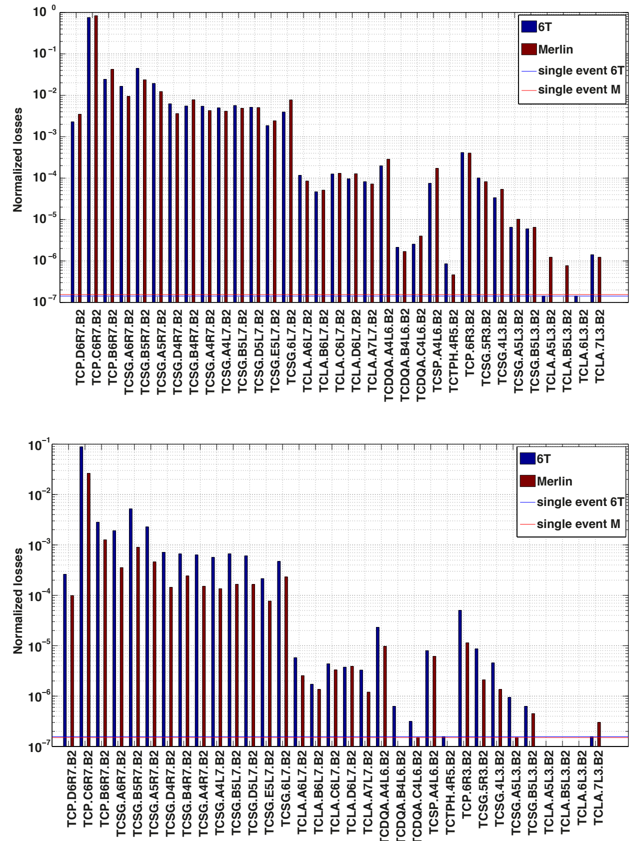

Figure 3: Inelastic (above) and single diffractive (below) losses at named collimators in MERLIN and SixTrack.

following the betatron collimation insertion region. More detailed comparison with measurement should be envisaged to address, if possible, which code better reproduces the measured loss patterns at the LHC.

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