COMPARISON OF MERLIN/SIXTRACK FOR LHC COLLIMATION STUDIES

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Abstract

Simulations of the LHC collimation system have been carried out in previous years with the well known SixTrack code with collimation features. MERLIN is a C++ accelerator physics library that has been extended to perform collimation studies. The main features of the code are: its modular nature, allowing the user to easily implement new physics processes such as resistive wakefields and synchrotron radiation, improved scattering routines and the MPI protocol for parallel execution. MERLIN has been configured to use the same scattering routines as SixTrack in order to benchmark the code for the LHC collimation system. In this paper we present a detailed comparison between MERLIN and SixTrack for optics and cleaning inefficiency calculation.

INTRODUCTION

The Large Hadron Collider (LHC) is equipped with a sophisticated multi-stage collimation system to protect the machine from radiation damage, and the cold elements from quenching, due to the inevitable losses of high energy protons. The LHC has eight arcs and eight Interaction Regions (IRs) , four are dedicated to the detectors (IR1, IR2, IR5, IR8), one for the RF cavities (IR4) and one for the beam dump (IR6). The remaining two are used for the momentum (IR3) and betatron cleaning (IR7). The first is used to remove the off-momentum particles and the second as transverse betatron cleaning. In each collimation region there is a three level cleaning hierarchy and primary collimators (TCP) in IR7 represent the tightest apertures of the machine. In addition tertiary collimators (TCT) are installed at both sides of the detectors to protect them.

Advanced numerical tools have been developed over the past years to ensure a good prediction of the losses along the machine. The main elements of the loss map simulation are the proton tracking through the machine lattice and the scattering routines to model the interactions of the protons with the jaw material. Sixtrack is a 6D fully symplectic thin lens tracking code [1], it has been interfaced with the K2 Monte Carlo code [2] and it provides the basic tool to calculate the loss maps. A proton is considered lost when it touches the machine aperture or when it interacts inelastically with the bulk material of the collimator jaws. The LHC optics and apertures are defined by the well known code MAD-X [3]. MAD-X converts the thick lens optics into thin lens optics and generates the information required by SixTrack+K2 to run a collimation simulation. Future upgrades of the machine require a deep understanding of the collimation system, with more accurate scattering, tracking, and wakefield models. This requires a flexible code able to simulate new advanced collimation schemes and to introduce detailed beam dynamics effects. The MERLIN code [4] is a C++ accelerator library well suited for this aim. MERLIN, initially used for ILC beam delivery system studies, has been extended through HiLumi LHC to be used in large scale collimation simulations. It has an accurate fully parallel wakefield model, a new scattering physics model [5], magnetic and alignment errors of the machine elements and a parallel mpi protocol to run on clusters and many other speed enhancements [6]. For the loss map calculation MERLIN has been set up with a K2 like scattering physics model in order to get a reliable benchmark with SixTrack+K2. The simulations are done for the ideal machine without wakefields or any other collective effects. In this paper we present a numerical comparison of the the loss maps generated for the well studied LHC nominal optics case at 7 TeV as reported in the LHC Technical Design Report [7].

OPTICS AND SIMULATION SET-UP

MERLIN is a 6D thick lens tracking code but it is currently running without RF accelerating cavities. The full inclusion of longitudinal motion is under study and is planned to be available in the future. In MERLIN it is possible to write a dedicated lattice or import its parameters using the *MADInterface* class. The code calculates the optics functions and loads the aperture file and collimator gap settings. Different particle distributions can be chosen to generate the halo to be tracked. The lattice is constructed as a single, or a series of, beamlines: a beamline is composed of the lattice elements, and a specific tracker can be assigned to each. Different physics routines such as collimation, resistive wakefields and synchrotron radiation can then be attached to the tracker. The code checks the transverse positions of the particles during tracking, and if they are outside the corresponding element aperture, they are removed and their positions are recorded. The main beam parameters and collimation set up for the nominal optics case are listed in Table 1. Aperture wise, the most critical situation at top energy occurs with squeezed and separated beams before collision, when the beams are closest to the superconducting triplet aperture. Fig. 1 shows the beta function and dispersion in the CMS region (IR5), calculated by MAD-X and MERLIN, as an example of optical function calculation. The plot shows

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an excellent agreement for the optics parameters calculated with the two codes.

Table 1: Beam Parameters and Main Collimator Set-up

Parameter	Nominal
Energy	7 TeV
ϵ_n	3.5 mm-mrad
β^*(IR1-5)	55 cm
β^*(IR2-8)	10 m
TCP (IR3-IR7)	15 - 6 σ
TCSG (IR3-IR7)	18 - 7 σ
TCL (IR3-IR7)	20 - 10 σ
TCT (IR2-IR8)	25 - 25 σ

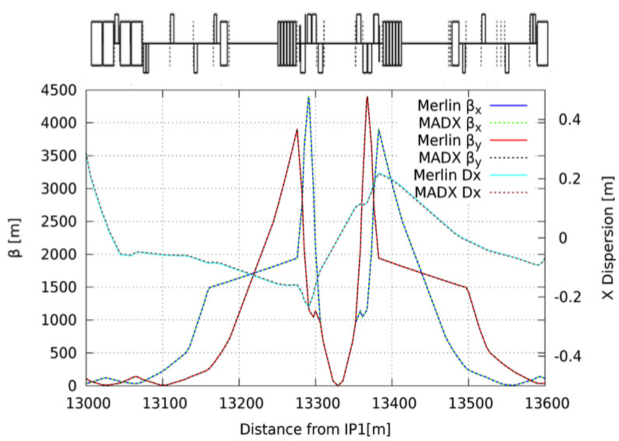

Figure 1: Horizontal beta function for nominal optics calculated with MAD-X and MERLIN.

LOSS MAP CALCULATION

MERLIN and SixTrack+K2 are used to simulate the distribution of the lost particles along the ring for the nominal optics and ideal machine. These studies identify the possible areas where the machine needs extra shielding and the installation of additional collimators. 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. For this reason it is necessary to work with accurate optics along with a detailed machine aperture and a good model of the scattering physics inside the collimators. For the loss map simulations we generate a horizontal beam halo which is characterised by a ring shape in the normalised horizontal phase space, and a Gaussian distribution in the vertical coordinate. The halo is then back transformed into real coordinates before being tracked. The beam is injected in front of the primary horizontal collimator in the betatron cleaning region and tracked for 200 turns. The transverse offset between the jaw surface and the impact point, called the impact parameter, is set to 1μm. The loss maps are characterised by the local inefficiency defined as

$$\eta = \frac{N_{ABS}}{\Delta z \cdot N_{coll}^{Tot}}, \qquad (1)$$

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 whole machine. For the collimator Δz is set to the collimator length and N_{ABS} are the total losses in the collimator.

The Dispersion Suppressors (DS) which match the optics of the arcs with the Long Straight Sections (LSS) are particularly sensitive areas. Indeed, protons which experience single diffractive scattering in the bulk material of the collimator emerge with a transverse kick and a lower energy. Protons entering the DS, where the dispersion rises rapidly, experience a higher transverse betatron oscillation and can be lost in these cold areas (see Fig. 2). In Fig. 2 and Fig. 3 we show the horizontal loss map comparison for the whole LHC, and the betatron cleaning region in IR7, respectively, both at 7 TeV using beam 1 nominal optics. After simulating $6.4 \cdot 10^6$ protons, SixTrack calculates $6.1 \cdot 10^6$ losses and MERLIN $5.2 \cdot 10^6$ losses. As expected the majority of the protons are lost in the collimation regions in IR3 and IR7. The losses before and after detector areas are protons intercepted by tertiary collimators, designed to protect the detectors and the focusing triplet quadrupoles from damage. Both codes show cold losses in the arcs between IR8-IR1 and IR1-IR2. These predictions allow us to understand where possible quenching events may occur, and also indicate how to modify the collimator set up along the accelerator in order to improve collimation. In Fig. 4 (top plot) we present a comparison of collimator losses in IR7, green spikes represent losses in MERLIN, and black spikes losses in SixTrack. There is very good agreement in all collimators, with a few percent difference in the primaries and secondaries, and lower than 15% for all remaining absorbers (TCLA). In IR3 and other collimators along the ring, the difference between inefficiencies is around 50%. Unexpected behaviour is only observed in the TCL downstream of IR1 where MERLIN observes no losses, whereas SixTrack gives a local inefficiency of around $5.5 \cdot 10^{-6}$ m^{-1}. This apparent discrepancy is being investigated. The bottom plot in Fig. 4 represents the cold losses in the DS downstream of IR7, blue spikes are calculated by SixTrack and the green spikes by MERLIN. The shape and magnitude of the losses are similar, the integrated inefficiencies observed in the DS1 and DS2 are 0.041 and 0.044 for SixTrack and 0.046 and 0.037 for MERLIN. Regarding warm losses, which are mainly located among the collimators in IR7 (see Fig. 3), MERLIN predicts a lower loss than SixTrack, with an integrated inefficiency of $7.56 \cdot 10^{-6}$, compared to $4.64 \cdot 10^{-5}$, as calculated by SixTrack. The above mentioned discrepancies are under study in order to better understand their origin. However, given the high complexity of the simulation and the differences between the codes, the results show a very good agreement.

The SixTrack+K2 code is usually run as 1000 jobs with

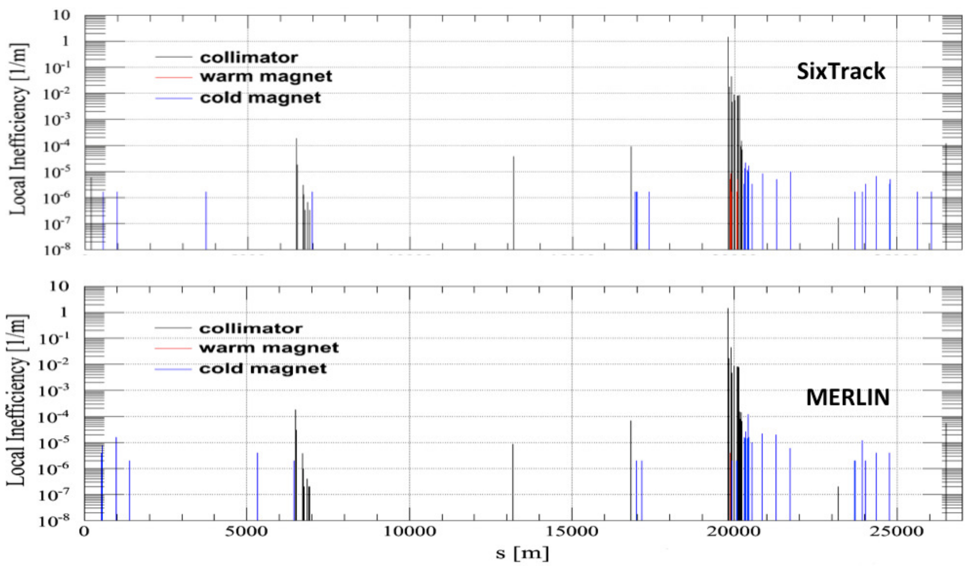

Figure 2: Loss map for the nominal case calculated with MERLIN (bottom) and SixTrack+K2 (top). In black the losses in the collimators, in blue the losses in the SC magnets and in red the losses in the warm elements.

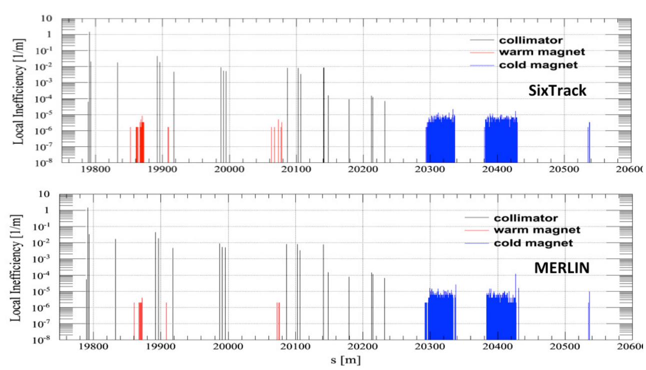

Figure 3: Horizontal loss map: zoom in IR7, Merlin(bottom) - SixTrack+K2(top).

6400 particles per job, for which the average computational time is around 2/3 hours per job. MERLIN takes around 35 minutes to run a job with 6400 particles on a single node. The speed of MERLIN makes it the ideal tool to run a large scale LHC collimation simulation, with many particles and high resolution,with a minimal running time.

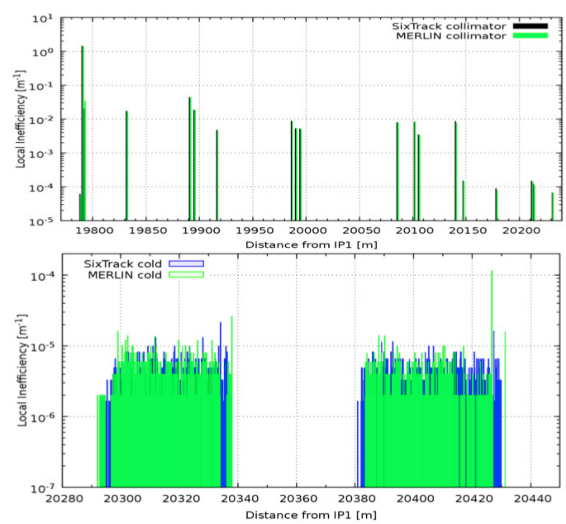

Figure 4: Collimator loss comparison in IR7(top): SixTrack in black and MERLIN in green. Cold Losses comparison in the dispersion suppressor downstream IR7(bottom): SixTrack in blue and MERLIN in green.

CONCLUSION

In conclusion, the MERLIN code has been benchmarked with the well known collimation version of the SixTrack+K2 code and a good agreement has been found for the loss map calculated for the nominal optics. Studies are still in progress but the overall results show that MERLIN is ready to produce reliable loss maps. This work is part of the effort of the collimation community to develop complementary and improved tools for the HL-LHC project. Future investigations will focus on a new detailed scattering physics routine and new collimation schemes related to the Hi-Lumi project such as new collimator material and hollow electron lenses.

ACKNOWLEDGMENT

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