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PRECISION MODELLING OF ENERGY DEPOSITION IN THE LHC USING BDSIM

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Abstract

A detailed model of the Large Hadron Collider (LHC) has been built using Beam Delivery Simulation (BDSIM) for studying beam loss patterns and is presented and discussed in this paper. BDSIM is a program which builds a Geant4 accelerator model from generic components bridging accelerator tracking routines and particle physics to seamlessly simulate the traversal of particles and any subsequent energy deposition in particle accelerators. The LHC model described here has been further refined with additional features to improve the accuracy of the model, including specific component geometries, tunnel geometry, and more. BDSIM has been extended so that more meaningful comparisons with other simulations and data can be made. Firstly, BDSIM can now record losses in the same way that SixTrack does: when a primary exceeds the limits of the aperture it is recorded as a loss. Secondly, by placing beam loss monitors (BLMs) within the BDSIM model and recording the simulated dose and energy deposition, it can be directly compared with real BLM data. These results are presented here and compared with SixTrack and BLM data from a typical fill in 2018.

INTRODUCTION

The Large Hadron Collider (LHC) at CERN is a synchrotron designed to explore the frontiers of particle physics. This necessitates the highest centre of mass energy for proton-proton collisions to date at 6.5 TeV, and a design energy of 7 TeV. This design energy corresponds to a stored beam energy of 386 MJ per beam [1]. Losing even a fraction of this stored energy can result in super-conducting magnets quenching or damage to the machine components. It is therefore of paramount importance to understand beam losses within the LHC, how they develop, and how to control them.

The LHC collimation system is designed to protect the machine from these massive stored energies, without which the inevitable beam losses would quickly lead to magnetic quenching and machine shutdown. High stored energies necessitates a complex, multi-stage system of increasing collimator aperture sizes situated in two IRs (betatron cleaning in IR7, and momentum cleaning in IR3). The main idea is that the large-amplitude particles should first hit the primary collimators (TCPs) with the tightest apertures in the cleaning insertions, followed by the secondary collimators (TCSGs), and then the absorbers (TCLAs). Supplementing this hierarchy are the tertiary collimators (TCTs), which are situated upstream of the experimental insertions and are designed to protect the super-conducting final focus quadrupoles as well as minimise machine-induced backgrounds.

The other key component for protecting the machine is the system of beam loss monitors (BLMs) which are placed around the ring at key locations, particularly in critical regions where beam loss may result in machine damage. In the event that the detected beam-loss is found to be larger than some threshold, a beam-dump is triggered.

The LHC collimation system is typically simulated with the CERN-developed simulation code SixTrack [2, 3]. SixTrack is a multipurpose 6D thin-lens tracking code with the capability to study the collimation system. This is achieved with use of an aperture description interpolated to 10 cm and the special treatment of primary protons within collimators where they may additionally undergo Monte Carlo physics processes. SixTrack's approach to particle losses consists of two aspects: any primary proton that exceeds the defined aperture definition is immediately considered lost, and secondly, any proton that undergoes an inelastic process in a collimator is also considered lost. In either scenario, any subsequent traversal of the proton or its products is not considered. However, a primary may undergo either an elastic or single diffractive event within the collimator and will be tracked onward through the accelerator.

The simulation of energy deposition in the LHC has typically been with the use of FLUKA [4]. FLUKA is a Monte Carlo particle physics code which can simulate particle-matter interactions all the way from the primary to any subsequent products and the energy deposition.

Beam Delivery Simulation (BDSIM) is a novel particle accelerator simulation code using ROOT [5], CLHEP [6] and Geant4 [7] to procedurally generate a full 3D particle accelerator [8]. From a simple ASCII description, BDSIM will build a particle accelerator from a set of predefined generic accelerator components. What sets BDSIM apart is that it can track both primaries and secondaries, as well as ensure the correct treatment of particle physics processes, which is directly as a result of BDSIM's use of the Monte Carlo particle physics library Geant4. Therefore BDSIM bridges the divide between conventional accelerator and particle physics codes, and therefore should be able to study beam losses in a more holistic fashion, resulting in a more detailed account of these processes.

BDSIM is in the process of being benchmarked against SixTrack and here we present a comparison between the two. In particular, SixTrack's unique approach to particle losses described above have been implemented in BDSIM, thus enabling a more direct comparison between the two simu-

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lation codes. Secondly, a novel comparison to real BLM data is now possible as BDSIM is now capable of scoring energy deposition in specific volumes, meaning that individual BLMs can be placed in one-to-one correspondence in the model as found in the real machine and compared [9]. Here preliminary results are presented and described for a run in 2018.

BDSIM LHC MODEL

The BDSIM model of the LHC was converted from a MADX optical description [10, 11] of the 2018 $\beta^* = 30$ cm, "end-of-squeeze" optics, and then supplemented with extra geometrical details. Mostly importantly, an aperture description interpolated to a precision of 10 cm and the collimator openings and materials were programmatically set to the correct values for the given run, in both cases identical to those used for the SixTrack simulation. Furthermore, the magnet geometries, cold two-beampipe geometries in the arcs, and the warm, single beampipe geometries around the IRs were set, including their approximate widths were used. Whilst the geometries are a simplification, they are very quick for a single user to prepare. Finally, an infinitely absorbing tunnel with the correct transverse cross sections was automatically generated and placed around the beamline using BDSIM. The tunnel is infinite absorbing to improve simulation time and minimise cross-talk between distant sections of the machine.

Beam loss monitors were placed in one-to-one correspondence with those found in the machine, but only ionisation chambers and those which are attached to quadrupoles and collimators. In all, 1172 BLMs were placed along the length of the ring. The BLMs are simple cylinders 50 cm in length and 9 cm in diameter, shown in Fig. 1, which corresponds to a sensitive volume twice as large as in reality, as well as consisting entirely of aluminium, compared with aluminium and nitrogen in reality [12]. A more detailed BLM model is being prepared, but these characterisations can be considered acceptable at this stage as they should be sufficient for comparing detected BLM dose with energy deposition within the surrounding components.

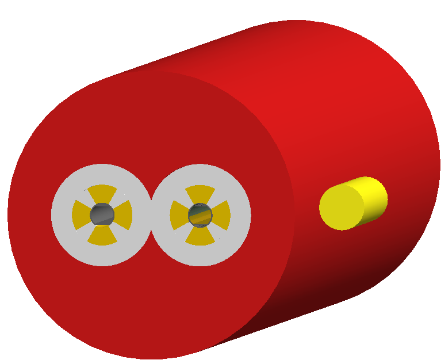

Figure 1: LHC quadrupole geometry with attached beam loss monitor in yellow.

In total, 900,000 primaries were simulated in BDSIM. The primary halo distribution was generated to overlap with the collimator jaws (5.5σ) with realistic impact parameters. Both the BLM dosage and the aperture impacts were recorded in the same simulation. For the SixTrack simulation 6.4×10^6 protons were simulated using the same optical configuration as in BDSIM. Finally, the BLM data was taken from a special 2018 qualification run, where the beam was deliberately impacted upon the collimator jaws to give as clean a loss map as possible.

RESULTS

The full set of comparisons situated at IR7 between BDSIM, SixTrack and BLM data is shown in Fig. 2. Excellent agreement between the collimators is shown between all five sources, and the familiar collimator hierarchy is faithfully reproduced throughout. However, there are two others aspects of the loss maps which are also notable, the warm sections between the collimators, and the cold dispersion suppressor which follows IR7.

The total absence of the warm section aperture primary losses as in (a) and (b), in comparison with the ample BLM data and energy deposition shows the dependence on secondary products in this region. The simulated and real BLM data can be seen to be in good agreement, although the rates are slightly lower in the simulated scenario. It is clear by looking at the total energy deposition that the BLMs in this region go only a small way to capturing the features—particularly noteworthy are the warm spikes immediately following the primary collimators which are completely absent from all the other loss maps.

The SixTrack simulation (a) predicts a relatively large number of primary losses in the cold, dispersion suppressor region, which contrasts with BDSIM's primary losses (b) where very little can be found. BDSIM BLMs (d) go some way to capturing the features found in the real BLM loss maps (c), but the full BDSIM energy deposition loss map (e) appears to be the closest to capturing the features in the BLM data—for example detecting the cold losses just after 20.2 km which are detected in the BLMs, but totally absent from SixTrack.

The correlation between component energy deposition and BLM dose is shown in Fig. 3. The distribution is split into two populations, energy deposition with elements which is detected in the nearby BLM, and energy deposition within elements which is not at all detected in the nearby BLM. Further investigation is required here to investigate the possiblity that some BLMs are unusually blind to nearby losses.

The aforementioned disparities can possibly be explained in a number of ways. The BDSIM component geometries are built from a set of generic components, it may be necessary to further refine these models to accurately capture the energy deposition in this region. Accurate field maps may also be necessary. Additionally, the BLM as used in BDSIM, an aluminium cylinder, is fairly crude—a more accurate geometry as well as a realistic detector response may

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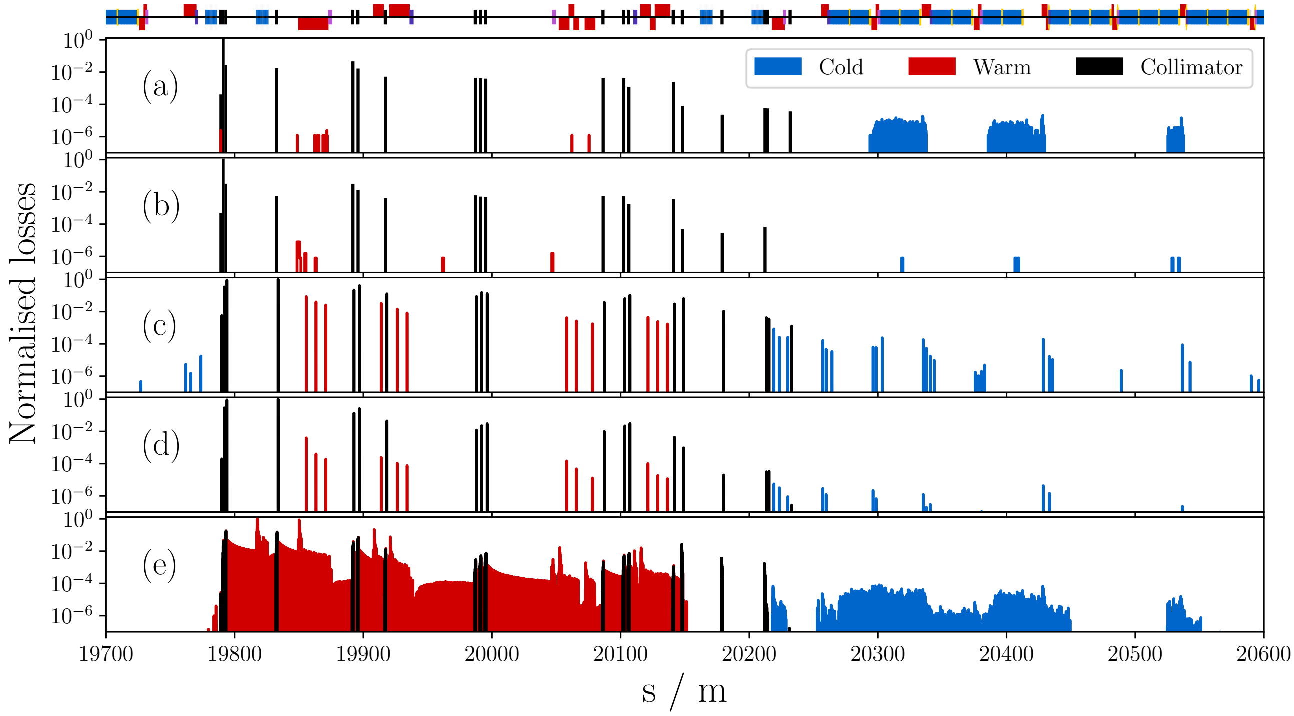

Figure 2: Colour-coded comparisons between SixTrack losses (a), BDSIM SixTrack-style losses (b), real BLM dose (c), simulated BDSIM BLM dose (d), and total BDSIM energy deposition (e). The machine is displayed along the top of the figure, and in all cases the losses are normalised with respect to the respective maximum loss.

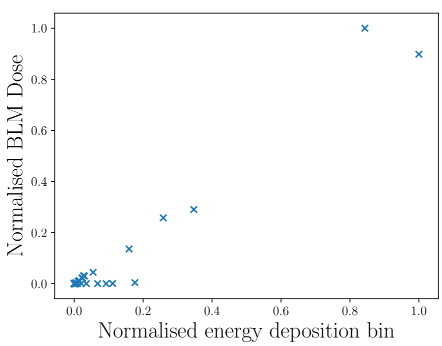

Figure 3: Normalised component energy deposition versus normalised BLM dose. The energy deposition is simply the recorded energy deposition in the nearest 10 cm long section.

be necessary to bridge the gap between the simulated and real BLM doses. Lastly, the difference between SixTrack and BDSIM SixTrack-style losses should first be explained as a matter of relatively small statistics, and then perhaps as resulting from tracking differences; SixTrack is fully symplectic and BDSIM is not. This difference between SixTrack and BDSIM primary losses is also possibly explained by the treatment of the particle physics interactions within the collimators, there appear to be far more inelastic collisions within BDSIM's collimators than in SixTrack, which may suggest to meaningful differences between Geant4 and SixTrack's implementation of the particle-matter interactions.

CONCLUSION

A detailed model of the LHC has been built in BDSIM and a novel approach to studying beam losses has been demonstrated by placing BLMs within the model and measuring the dose. Many of the features of the BLMs have been recreated, though it is possible that more detailed component models and detector simulations will be necessary to capture the remaining details.

Added to this, BDSIM can now record losses in a similar way to how SixTrack does, thus enabling more meaningful comparisons between the two codes. Promising early results of this comparison have been presented here where, again, the key features are recreated. To more meaningfully compare the two codes it will be necessary to simulate more primaries, and perhaps also symplecticify BDSIM's tracking.

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