LHC COLLIMATION AND ENERGY DEPOSITION STUDIES USING BEAM DELIVERY SIMULATION (BDSIM)

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Abstract

Beam Delivery Simulation (BDSIM) is a program that uses a suite of high energy physics software including Geant4, CLHEP and ROOT, that seamlessly tracks particles through accelerators and detectors utilising the full range of particles and physics processes from Geant4. A comparison of the collimator cleaning efficiency and energy deposition throughout the full length of the Large Hadron Collider (LHC) with the established SixTrack simulations of the CERN collimation group is presented. The propagation of the full hadronic showers from collimators provides unparalleled detail in energy deposition maps and these are compared with the data from beam loss monitors that measure radiation outside the magnet body.

INTRODUCTION

The LHC at CERN is leading the energy frontier in particle physics and recently was used to discover the Higgs Boson [1]. The accelerator is designed to provide two proton beams at 7 TeV with a stored energy of 362 MJ per beam. Operation started at 3.5 TeV in 2010 and 2011, was subsequently raised to 4 TeV in 2012 and is currently at 6.5 TeV in 2015, with the future goal of reaching the design parameters. With each increase in energy, the stored energy also increases. The beams are highly destructive and any beam losses must be strictly controlled. Furthermore, the majority of the magnets in the accelerator are superconducting and kept at ~1.4 K. A localised fractional beam loss in one magnet of as little as 10^{-9} would cause the superconducting magnet to quench and become normal conducting and fail to guide the beam. Aside from possible damage, recovery from a quench is a lengthy process that reduces the operational time and therefore the recorded data.

To control the beam losses, a multi-stage collimation system is used to absorb inevitable beam loss in a safe manner. The collimation system is primarily required to protect the accelerator and general purpose detectors (GPDs) and secondarily, to reduce experimental background.

The collimation system performance must be predictable and therefore CERN has developed a simulation toolchain for this purpose [2, 3]. SixTrack is used to track a halo distribution for up to 200 turns. When a particle intercepts a collimator, a separate piece of software simulates the most relevant physics processes for a proton intercepting the collimator material. If the proton remains intact, the tracking is continued. After tracking, a program called BeamLossPattern is used to apply the aperture model and calculate the point of loss for a particular trajectory. Finally, for select areas of interest, the proton losses can be passed to a FLUKA model for energy deposition and radiation studies.

The current toolchain has successfully predicted beam losses sufficiently accurately to protect the LHC during its operation, however, the current toolchain cannot simulate the outcome past when a proton meets the aperture. Beam loss simulations using a Beam Delivery Simulation (BDSIM) model of the LHC are presented. BDSIM [4] constructs a 3D model in Geant4 [5] and uses the available physics processes in Geant4 to simulate the interaction of the protons and subsequent secondaries with the accelerator.

BDSIM has been recently developed and used to simulate energy deposition maps for the LHC [6]. Here, the latest developments and results from these simulations are presented.

MODEL PREPARATION & VALIDATION

Initially, MADX is used to calculate the optical functions and provide all available parameters from the LHC optics [7], including magnet strengths, Twiss parameters, beam offsets, in a single output MADX TFS format file. To prepare a BDSIM model, the magnetic description of the accelerator from MADX is used by a Python utility, *pybdsim* [4], to create the BDSIM input files. This provides a definition of all elements and their sequence. The input beam distribution and other options pertinent to the desired simulation are appended by hand afterwards.

Aperture Preparation

In addition to the magnetic description, the aperture throughout the accelerator is a crucial part of the simulation as it defines where particles are 'lost'. The collimation group aperture model is used with 10 cm resolution along curvilinear s.

The aperture model does not correspond exactly with the optical information from MADX as many of components such as beam screens are different lengths to the surrouding mangnets. The aperture model specifies the aperture at a distance along the accelerator with the majority of information specifed via markers rather than related to a specific magnet or beam line element by name. Conversely, BDSIM requires aperture information for each element as it must know how to build each element before the simulation begins and cannot be done in analysis afterwards. A Python utility was written to locate the nearest marker for a given

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ISBN 978-3-95450-147-2

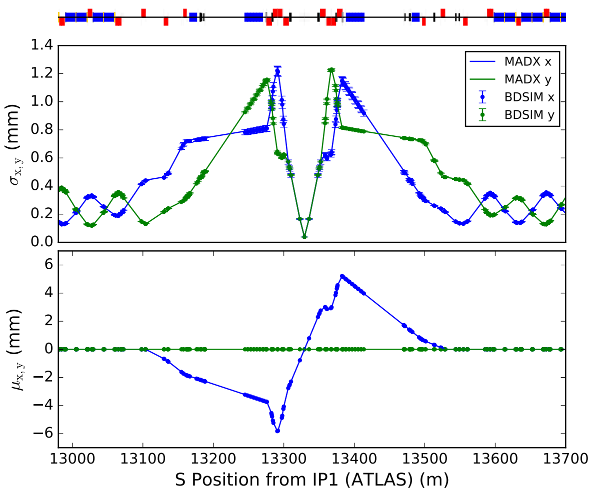

Figure 1: An example section of optical comparison and validation for insertion region 5.

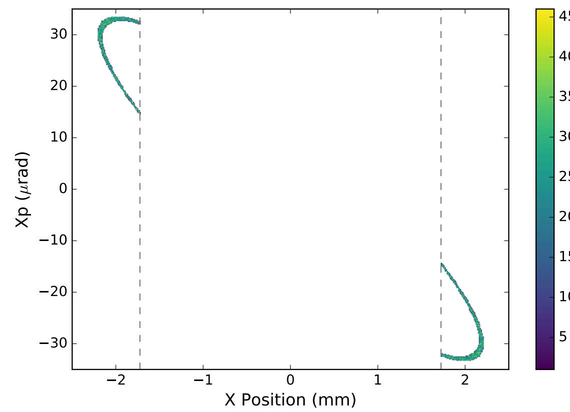

Figure 2: An exaggerated example halo distribution with closed collimators and a large width. The dashed vertical lines represent the boundaries of the collimator jaw.

element and interpolate between them. Additionally, there are many null values that had to be filtered out.

The collimation group aperture model and the MADX model are used in combination with precidence to the collimation group model to specify the correct aperture while *pybdsim* creates the BDSIM model element by element from the optics TFS file.

Validation

Once constructed, the model must be validated to ensure the correct propagation of particles through the accelerator. The core beam, a 4D Gaussian generated according to the Twiss parameters, was simulated for a single turn of the lattice. BDSIM 'samplers' that record the particle distribution were placed after every element and the mean, standard deviation, centroids and Twiss parameters of the distribution at each plane were calculated. The beam size is compared to that predicted by MADX as shown in Fig. 1 and agrees well. Importantly, the centroid offsets representing the collision bumps are well reproduced.

Halo Distribution

To improve the efficiency of simulating the collimator system performance, only a small fraction of the total beam phase is simulated - the halo. This is an annulus in phase space where the maximum extent is aligned with the jaw of the primary collimators that are closest to the beam. Horizontal and vertical collimation performance are simulated separately where the orthogonal dimension not being simulated is Gaussian. The halo distribution consists of an annulus in phase space described by N $\times$ σ_{twiss}, where N is the number of σ that the first collimator in inerstion region 7 (IR7) is set to - here 5.7 σ.

A further increase in efficiency and accuracy can be gained by selecting from this distribution only the particles whose spatial position is greater than the start of the collimator jaw, resulting in two lobes in phase space. This guarantees that every particle impacts at least the first collimator, although given the high energy, a large fraction may penetrate though this collimator.

In the presented simulations, the horizontal (x,xp) distribution is a cut annulus halo at $5.7 \pm 0.015\,\sigma$ with $x > 5.7\,\sigma$. The vertical (y,yp) distribution is Gaussian according to the Twiss parameters.

RESULTS

A total of 1.3×10^6 primary particles were simulated in the 3.5 TeV beam 1 optics LHC BDSIM model using a 500 node farm, taking ~10,000 cpu hours and producing ~1 TB of ROOT format data. From these primaries, 2.1306×10^{11} energy deposition 'hits' were recorded and are shown as a function of curvilinear s position in Fig. 3. The model is constructed from the first collimator in IR7 ('TCP.D6L7.B1') at 19789.48 m from IP1 and this is where the input distribution starts also. The LHC optics begin at IP1 and the energy deposition maps have been wrapped about this point for comparison with other simulations.

The BDSIM simulation produces near-continuous energy deposition throughout the lattice with occasional spikes that mirror those from the SixTrack simulations. SixTrack can only simulate primary protons so the beam losses are much more discrete in form than the energy deposition in the BDSIM simulation. An expanded view of the collimation system in IR7 is shown in Fig. 4. This area is of most interest as it defines the operational limits of beam loss. Here, the general form agrees well with SixTrack, but is more continuous. The two broad sections of cold losses at $s = 20300, 20400$ m appear to be present in the BDSIM simulations, although their form is modulated by the gaps in the lattice corresponding to less mass in drift sections than in other magnets that registers the energy deposition. This would seem to indicate that these areas of higher loss are not entirely due to primary impacts alone, but also from secondary radiation.

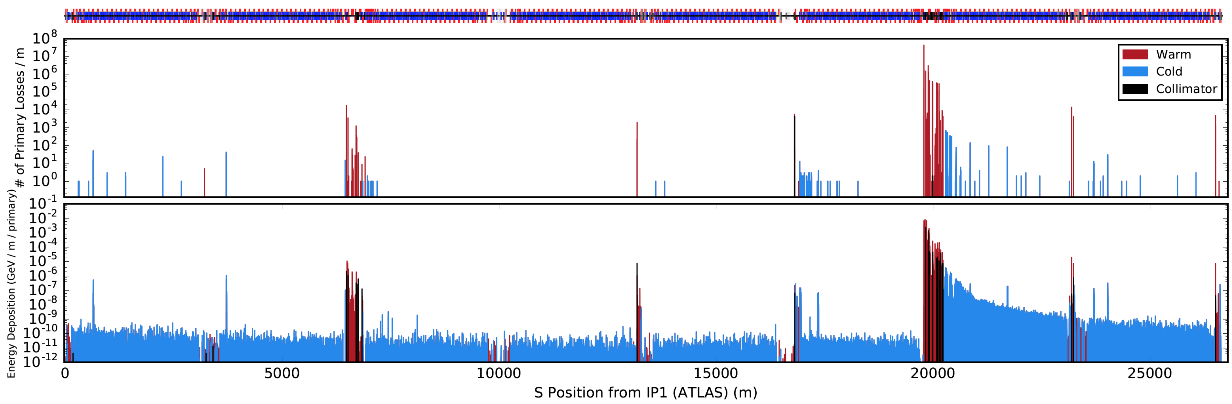

Figure 3: Comparison of SixTrack and BDSIM simulations for 3.5 TeV beam 1 optics. The top figure shows the proton losses as simulated using the SixTrack CERN toolchain and the bottom the energy deposition as simulated by BDSIM. Both are colour coded as to the location of the loss / energy deposition.

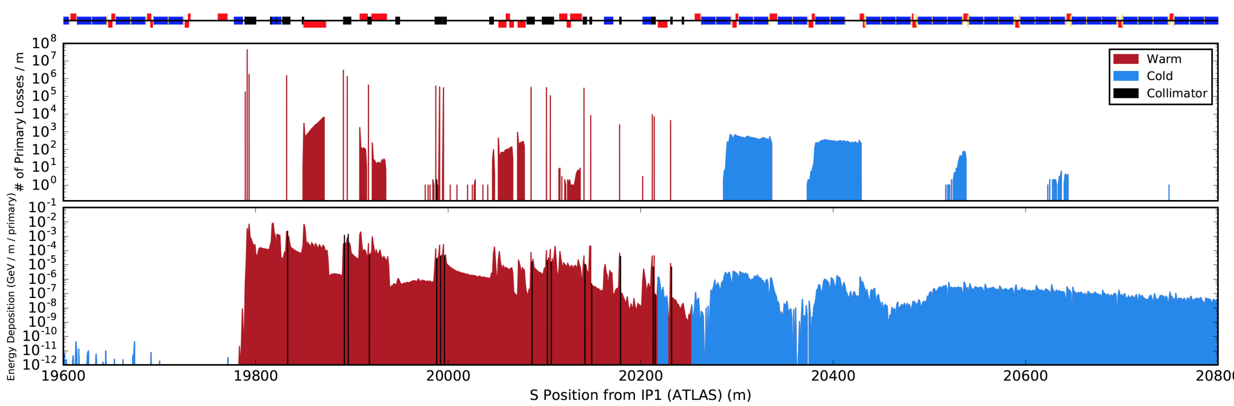

Figure 4: Energy deposition map for 3.5 TeV beam 1 optics. An expanded view showing insertion region 7 where the collimation system is located.

CONCLUSION & OUTLOOK

The most recent energy deposition maps with the most accurate BDSIM model yet are presented. Currently, only a qualitative comparison is possible, but upcoming event by event output in BDSIM will allow a complete statistical comparison between the SixTrack simulations and those from BDSIM [4]. These new features will also provide more accurate trajectory histories for each event to provide primary impact and absorption points in addition to energy deposition.

Currently under investigation are energy deposition maps from directly injecting SixTrack losses into the BDSIM model [4]. Coordinates of impacts on the aperture can be given to BDSIM to start the primary proton from and BDSIM can then simulate the subsequent interaction and secondaries. This will allow carefully validated SixTrack hits maps to be translated into energy deposition maps. Furthermore, these can be compared the energy deposition maps presented here to highlight any possible differences in the models or simulations. This will very clearly show any differences in aperture throughtout the model.

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ISBN 978-3-95450-147-2