BEAM DELIVERY SIMULATION: BDSIM - DEVELOPMENT & OPTIMISATION*

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Abstract

Beam Delivery Simulation (BDSIM) is a Geant4 and C++ based particle tracking code that seamlessly tracks particles through accelerators and detectors, including the full range of particle interaction physics processes from Geant4. BDSIM has been successfully used to model beam loss and background conditions for many current and future linear accelerators such as the Accelerator Test Facility 2 (ATF2) and the International Linear Collider (ILC). Current developments extend its application for use with storage rings, in particular for the Large Hadron Collider (LHC) and the High Luminosity upgrade project (HL-LHC). This paper presents the latest results from using BDSIM to model the LHC as well as the developments underway to improve performance.

INTRODUCTION

For high energy particle accelerators, prediction of the beam loss throughout the machine are crucial to avoid damage as well as to achieve optimal performance. Beam loss and energy deposition simulations require both tracking particles through an accelerator lattice as well as simulating their interaction with the accelerator components. These features are usually simulated separately with dedicated codes and information passed between them. Particle tracking through the lattice alone gives discrete losses at the point where particles intercept the numerical definition of the beam aperture. A Monte-Carlo radiation transport code can then propagate the distribution of particles from the accelerator tracking code and simulate their full interaction with the accelerator components and therefore the energy deposition. However, this is normally confined to small areas of interest as such simulations are highly computationally intensive. Although the simulated beam losses from the accelerator tracking code may be inaccurate longitudinally, they are accurate in their absolute value of fractional partilce loss and so these codes have experienced much success in accurately predicting beam losses efficiently for large scale accelerators.

To determine beam loss with the greatest accuracy as well as predict and understand the background environment for detectors, a combined approach is required that allows both efficient transport of particles in the accelerator lattice as well as their interaction with surrounding material. BDSIM [1, 2] is a flexible, open source C++ particle tracking code that uses the Geant4 framework [3] and provides a solution. The full range of physics processes available in the Monte-Carlo radiation transport framework Geant4 is augmented with efficient tracking routines for typical accelerator components.

BDSIM parses simple ASCII input files using a MAD-like syntax that describe the accelerator lattice, geometry and simulation options in a flexible programmatic way. A Geant4 simulation is automatically generated by creating the accelerator lattice from either externally supplied geometry definitions or from an included library of generic components. In place of the typical 4th order Runga-Kutta magnetic field steppers included in Geant4, a set of fast, thick-lens, 6D tracking routines are used for fast tracking in-vacuum, significantly increasing the speed of the simulation.

This paper gives an overview of the latest code developments and recent usage examples. More information and the source code can be found on the bdsim website [4].

LHC SIMULATIONS

BDSIM was originally developed for the simulation of linear colliders such as the ILC and the Compact Linear Collider (CLIC) and many studies have been performed using it [5, 6], however it has been recently adapted to simulate circular accelerators such as the LHC and the HL-LHC [7,8]. Recently, a suite of Python utilities were written to allow simple conversion of lattices from various input formats to the BDSIM input format, which is of particular use with large lattices where automatic conversion is a necessity. These tools allow scripts to be created that can combine input information from various sources, such as a magnetic description of the magnets, sequence definition, aperture definitions and geometry information.

The LHC lattice was converted to the BDSIM input format using these tools and the model used to track particles. Under the Geant4 framework, particles are tracked down to zero energy (in accordance with production cuts) or they leave 'The World' volume, inside which all geometry must be contained. A particle of the correct energy on axis will never leave The World volume (in the absence of synchrotron radiation) and therefore the simulation would nevery end. To control the number of turns a primary particle can complete, a new Sensitive Detector class was written. Figure 1 shows the Twiss β amplitude functions calculated from tracking 500 protons in beam 1 of the LHC lattice for a single turn. Version 6.503 of the optics was used with

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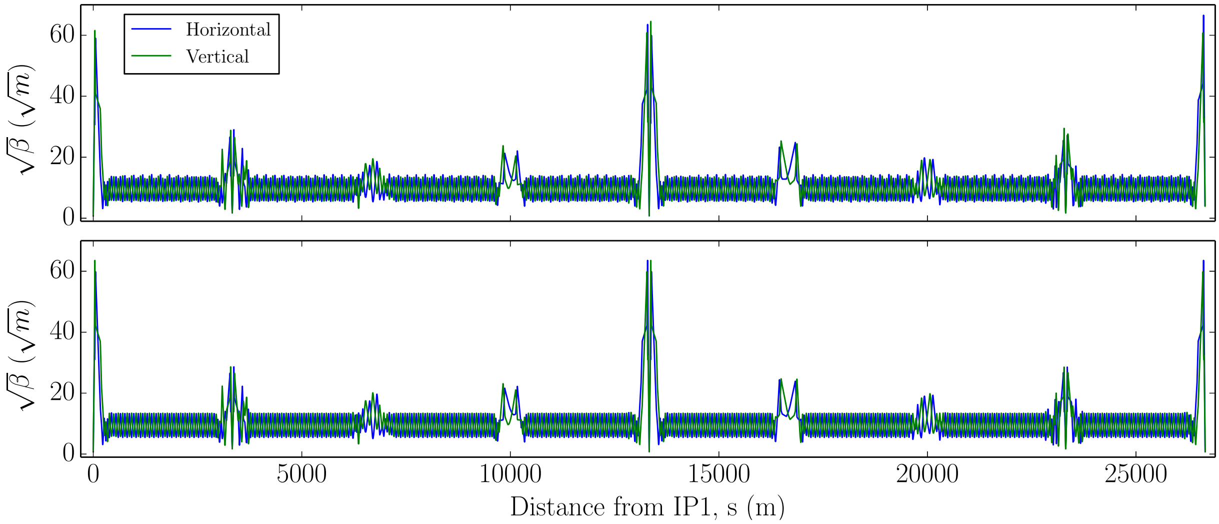

Figure 1: Horizontal and vertical β amplitude functions for the LHC beam 1 for the 2012 4 TeV calculated with both BDSIM (*top*) and MADX (*bottom*), showing very good agreement.

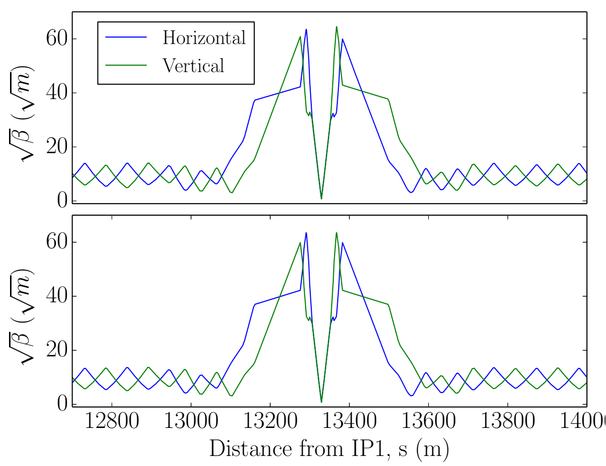

Figure 2: A zoom of the β amplitude functions for the LHC beam 1 for the 2012 4 TeV calculated with both BDSIM (*top*) and MADX (*bottom*) around IP5.

β = 0.3 m at IP1 & IP5 for the 2012 4 TeV physics run. Figure 2 shows these functions about IP5 where a low β waist exists.

These results show very good agreement both visually and numerically with the Twiss output from MADX. Further studies are ongoing to compare these results with that of SixTrack and Merlin [9]. The analysis was performed using the integrated ROOT output from BDSIM.

OPTIMISATION FOR CIRCULAR COLLIDERS

To further develop BDSIM to simulate circular colliders, the efficiency and speed of the code are being considerably improved. Recent improvements have reduced the typical simulation time by a factor of ~30, however further improvement is required.

For a circular collider, particles must be simulated for many hundreds of turns of the lattice, unlike a linear collider that is inherently single pass, for which BDSIM was originally developed. The code must therefore be a similar order of magnitude more efficient for a comparable simulation to be computed. BDSIM has been extensively profiled and it has been found that the largest gain in efficiency can be found in the voxel navigation and step length proposal algorithms of the Geant4 framework. These are used to determine which volume the particle will next intersect as well as the optimal step length to track the particle through inside a given volume respectively. While, these are heavily optimised for a detector simulation where they are necessary, an accelerator lattice presents quite a different scenario where the geometry is mostly sequential and the most likely next volume is known a priori. Modifications to these specific algorithms are being investigated for optimisation in the case of a highly sequential geometry.

To facilitate comparisons with other codes as well as improve compatibility, the thick lens, 6D tracking routines are in the process of being factorised into a tracking library. This will allow particles to be tracked solely using the tracking routines without a geometry description and without the aforementioned voxel navigation overheads in Geant4. This will also allow the user to select between these tracking routines and symplectic ones to be included in future. As part of an ongoing upgrade to the interface with other codes such as PLACET, an interface is being written that allows particles to be transferred from the tracking-routine-only lattice to that of the Geant4, which will provide a significant increase in efficiency and allow the many physics processes available in Geant4 to be used to accurately simulate the scattering of a particle from a collimator jaw. The transfer of particles in close proximity to the beam pipe from the tracking-routine-only lattice to the full Geant4 lattice

ISBN 978-3-95450-132-8

within BDSIM is envisioned to allow the full propagation of the primary and secondaries to be computed.

AWAKE

The AWAKE collaboration [10] are developing an experimental beam-line at CERN to demonstrate proton-driven plasma-wakefield acceleration. BDSIM is being used to build a detailed simulation of the AWAKE electron spectrometer system [11]. This involves simulating optical processes and components such as scintillator screens. The baseline AWAKE spectrometer design uses a phosphor screen to convert high energy electrons to visible light. To include this screen in the simulation chain, a scintillator screen accelerator component class is being developed, including optical photon physics. The simulation output of the screen in terms of photon count and angular distribution as a function of screen thickness agree reasonably well - for details see [11]. This additional functionality will eventually be included in the main branch of the code.

In future, other upstream components such as OTR screens will also be included in the simulated beam line in order to be able to predict and control background levels at the scintillator screen.

GEOMETRY LIBRARY

The simulation of the physical elements of the beamline (bending magnets, quadrupoles, sextupoles,...) was initially relatively simple, with the geometry of such elements based on cylindrical bodies representing the magnet body, beam pipe and vacuum chamber. Recently, a more detailed geometry for the magnetic elements is being implemented. The improvements include details of the external shape of the magnets including the corresponding number of poles that compose the magnet, reserving an empty space between them, where particles or radiation may propagate much further along the lattice. Figure 3 shows this schematcially for a quadrupole. The aim is to simulate more realistic interactions of the beam losses with the material of the magnet, taking into account filled with material regions and empty regions. This will be of particular relevance in the development of laserwire diagnostics and other Compton-photon based diagnostics, whose specification is highly dependent on their detector background environment. The different beamline elements are characterised with just a few parameters that define the size of the magnet and the number of poles. Simplified LHC cryomodules as well as a generic rf-cryomodule are also under construction.

CONCLUSIONS

We report the recent development of BDSIM, which has seen significant progress in optimisation as well as many new features. A suite of Python tools was used to convert the LHC lattice for simulation and comparison of the optical functions with other simulation codes. Further validation and beam loss studies are under way. BDSIM is being actively developed to improve efficiency as required for beam loss simulations of the HL-LHC. Extra functionality has been added to allow scintillator screens to be simulated as well as a more physically accurate library of normal conducting magnets. BDSIM is being actively developed and extended providing a flexible, open source code that is being used to simulate many different accelerators. This is essential for adoption by users who wish to simulate beam loss and instrumentation sensitive to beam losses.

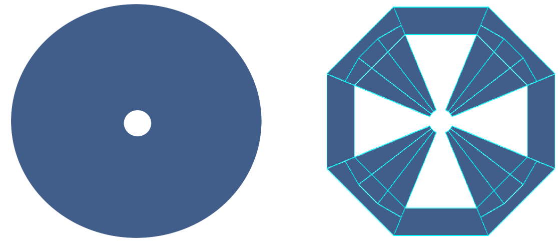

Figure 3: Evolution of the geometry of a quadrupole from its original design (left) to the more detailed design (right).

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