BDSIM: RECENT DEVELOPMENTS AND NEW FEATURES BEYOND V1.0*

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Abstract

BDSIM is a program that creates a 3D model of an accelerator from an optical beam line description using a suite of high energy physics software including Geant4, CLHEP and ROOT. In one single simulation the passage of particles can be tracked accurately through an accelerator including the interaction with the accelerator material and subsequent secondary radiation production and transport. BDSIM is regularly used to simulate beam loss and energy deposition as well as machine detector interface studies. In this paper we present the latest developments beyond BDSIM V1.0 added for ongoing studies. For simulation of collimation systems several new additions are described including new element geometry, enhanced sensitivity and output information. The output has been further enhanced with aperture impact information and dose information from scoring meshes. As well as supporting the full suite of Geant4 physics lists, a new user interface is described allowing custom physics lists and user components to be easily included in BDSIM. New undulator, crystal collimator and wire-scanner elements are also described.

INTRODUCTION

A common desire is to accurately predict and understand beam losses in an accelerator. Such losses are simulated for many reasons including safe operation; minimising radioactivation; and to reduce experimental backgrounds. Such simulations are typically performed using multiple codes working in concert as each is specialised in a particular aspect required for such a simulation. Whilst successful, a more holistic approach has been found in BDSIM [1–4]. BDSIM builds a 3D radiation transport model using the open source Geant4 physics library [5]. Geant4 provides a large catalogue of physics processes and particles that are well validated due to their widespread use, and are regularly updated with the latest experimental data. BDSIM incorporates accelerator tracking routines in combination with a geometry library of common accelerator components. BDSIM allows creation of a full 3D model from an optical description in minutes. Presented here are the latest developments introduced for ongoing studies since V1.0.

SENSITIVITY AND SCORING

For any Geant4 or radiation transport model, a major component of the function of the code is reducing and refining the possible information available in the simulation. For each unit of simulation (an "event") a single or few initial particles are propagate through a model creating potentially millions of secondary particles that also must be tracked. Storing coordinates for every step of every particle is impractical, so a simulation must capture the relevant information.

Sensitive Detectors

BDSIM makes use of Geant4 "sensitive detectors" (SD), which are developer-definable classes that are attached to chosen volumes in the model and produce the desired information. The most ubiquitous is one to record energy deposition in materials. BDSIM has been augmented to include two new SDs. Firstly, a class was added to generate precise impact information and counts for collimators. As these are typically expected to intercept the beam, it is important to classify events based on collimator impacts.

A further addition is an SD to identify aperture impacts. Whilst BDSIM already records the first point a physics process was invoked (as opposed to just a step through a volume) and the final absorption point of a primary particle, it was useful to record where the primary first *left* the accelerator. This also makes comparison with other codes more conducive.

Since Geant4.10.3 it is possible to attach more than one SD class to any given volume, however the information generated by each class attached is not shared. In the case of energy deposition, the discrete energy loss is attributed randomly to a point between the end points of the step. If two SDs perform this action they will be inconsistent in their information. In the case of a collimator the extra collimator-specific information is generated as well as the regular energy deposition information. To overcome this, a new class was created that allows multiple SDs similar to Geant4, but each is called in order and has access to the previous SDs output information.

Originally, only the beam line geometry was sensitive. BDSIM now has the option of making everything sensitive to measure for example the energy deposition in the "world" volume (typically the surrounding air) as well as the energy leaving the boundary of the model. This allows the user to determine the fraction of energy deposited in each part of the model overall easily.

Scoring

Complimentary to sensitive detectors are scorers. These are classes that are attached to a volume and generate a single value for each event. The data is stored in a map from an integer index to the value. Geant4 provides a variety of scorers for various quantities that can be used.

BDSIM now makes use of the Geant4 scoring meshes. These are 3D repetitive solids that are kept in a parallel world, i.e. a secondary independent set of geometry that can be used at the same time as the original geometry (the "mass world"). The 3D mesh acts not only as a geometrical representation of a 3D histogram but also limits the step of each particle passing through even if the boundary does exist in the mass world. This is necessary for correct dose calculation.

The user may now define arbitrary meshes as well as a selection of scorers to be used for individual meshes including energy, particle species and time coordinate filters. Aside from the common particle count, deposited charge count and deposited energy count, scorers for dose are also available including a user supplied calibration factor to convert the cell flux.

The scoring implementation is also used for new beam loss monitors (BLMs) that are small customisable volumes that can be placed alongside the accelerator to mimic real detectors that integrate a signal. Similarly, multiple scorers can be attached to a given BLM, however Geant4 requires that scorers are attached to a volume through a single sensitive detector to hold them. BDSIM automatically makes the unique combinations of scorers required and files the information correctly into the output irrespective of which particular SD was used.

These additional classes allow BDSIM to provide a much richer understanding of a model as well as allow users to more easily compare to real experiments and monitors.

EXTENDED OUTPUT INFORMATION

Due to the increased level of information available from new sensitivity and scoring, the ROOT [6] output data files from BDSIM were extended with optional parts to cover these features. Additionally, a much greater level of control was implemented over the output to prevent escalation of the output structure and size.

For both collimators and aperture impacts, new specialised information was added allowing analysis and correlation of collimator impacts, scatters, aperture losses and energy deposition already recorded.

The structure of the output is event-by-event where one event is the minimal unit of simulation and completely independent of all others. The strategy employed by the included *rebdsim* tool is to always analyse all events in a file but optionally weight or filter them based on some criteria of data other than the desired variable in that file. A key requirement of such analysis is that a suitable variable describing the desired feature is available. For this purpose, several summary variables are now recorded such as the number of collimators interacted with and sums of energy deposited in
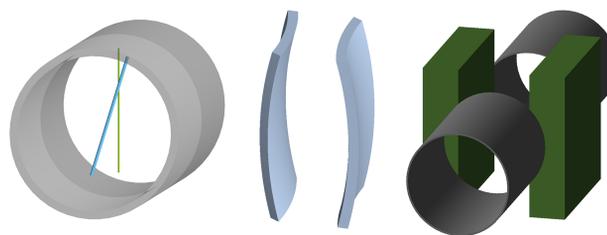

Figure 1: Visualisation of new elements in BDSIM showing (left to right) two wire-scanners in a beam pipe, two curved crystal collimators and a *jcol* jaw collimator.
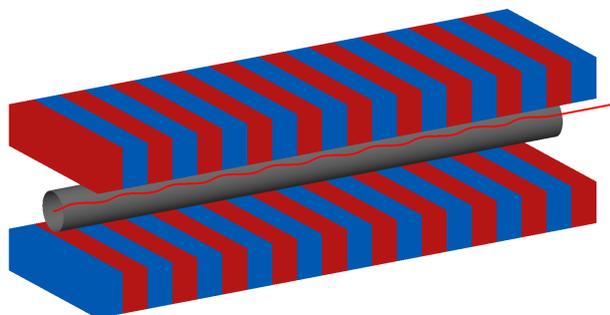

Figure 2: Example of an undulator in BDSIM. A single charged particle can be seen oscillating through the field of the undulator. Synchrotron radiation was disabled for this visualisation.

various parts of the model. These make problems such as finding where the energy deposition from particles that hit one collimator as well as make it through a second collimator possible and easy.

Such complex questions are only trivially answered if the correct summary variables are present. New worked examples document how to prepare such analyses and make best use of the summary variables.

NEW BEAM LINE ELEMENTS

To aid ongoing studies for the Large Hadron Collider [7] and the European X-ray Free-Electron-Laser (XFEL) [8], several new beam line elements were added. Simplest are the geometries for a "jaw" collimator (*jcol*) with two side pieces but no connecting aperture that can be rotated and a bent crystal collimator. The crystal collimator uses the crystal channelling physics in Geant4 allowing high energy charged particles to be steered by the crystal. These are shown in Fig. 1.

For the XFEL model, a new undulator beam line element was added. This allows in-flight generation of the incoherent synchrotron radiation using the Geant4 synchrotron radiation physics in combination with the specified field. A typical undulator element in BDSIM is shown in Fig. 2.

Diagnostics were added in the form of a wire-scanner element and the ability to create beam loss monitors. The wire-scanner element creates a wire of a chosen material and shape inside a beam pipe as shown in Fig. 1 and Geant4
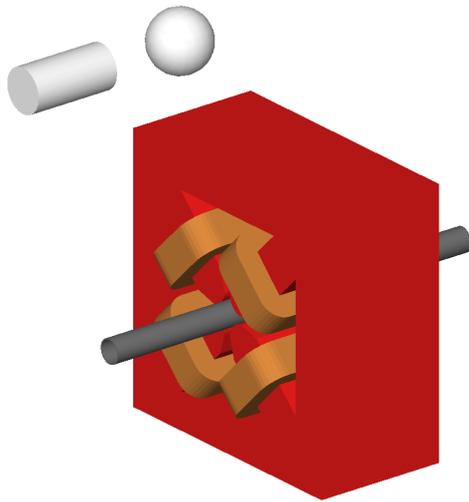
Figure 3: Visualisation of two generic single volume beam loss monitors alongside a quadrupole and beam pipe in BD-SIM. Here, a sphere and a cylinder are shown.

provides the requisite physics processes for the interaction with the material. This allows energy deposition and beam losses due to wire-scanners to be accurately identified.

The beam loss monitors currently consist of either user-supplied geometry or a simple cylinder, cube or sphere as shown in Fig. 3. These can be placed in many ways, such as in global Cartesian coordinates or curvilinear coordinates following the beam line where automatic rotation and translation are calculated. This includes placement relative to beam line elements identified by name.

CUSTOMISATION INTERFACE

Despite providing a large variety of customisable components, it is always foreseeable that a user may desire their own component that does not generally apply to other accelerators. The most ideal way to achieve this is to add a new C++ class to BDSIM for the desired element. However, complete integration requires modification of the parser and the component factory, which if undertaken by a user would prohibit them from updating to a newer version. In the past some collaborative groups have integrated their models into BDSIM, however it is preferable for a cleaner interface to exist.

Two major changes were made to BDSIM to revise this usage. Firstly, the CMake input for the build system was completed such that a user may write their own C++ program and easily make use of and link against BDSIM's code. Secondly, the *main* function of the program was restructured into a class that can be constructed and initialised from a users C++ program. This allows BDSIM to be created, then customised by the user before being fully initialised wherein the model is constructed. The BDSIM class has an interface to wholly replace the physics list or modify it as well as register new custom beam line components to BDSIM that will be recognised by input syntax.

These modifications make it simple to make use of BD-SIM but also extend it to include a specialised physics list or completely custom beam line components.

In addition to the CMake extension, ROOT dictionaries have now been added for all analysis classes making it possible for the user to completely reproduce the BDSIM analysis carried out by *rebdsim* but also to fully customise their analysis whilst making best use of the existing BDSIM classes and features.

MAGNET FRINGE FIELDS

In BDSIM, dipole fringe fields are implemented as thin elements for the integrated kick to match other tracking codes. Dipole fringe fields are crucial in low energy transport as well as when strong pole-face rotations are present. The implementation of dipole fringe fields has been extended to include thick horizontal and vertical kicker magnets as well for the most accurate transportation.

Furthermore, the integrator for the solenoid element has been rewritten and also includes hard-edge fringe fields.

CONCLUSION AND OUTLOOK

Several key developments in BDSIM for active study areas have been described as well as their implementation. BDSIM provides a unique ability to create a radiation simulation from an optical description with minimal effort. The generic models can now be customised to an even greater degree of detail to accurately predict experimental background and beam loss throughout an accelerator.

Further development of BLM response as well as a generic detector description are planned to aid comparison with experimental data. Such simplified detectors will be highly useful when investigating the possible locations of a new detector or experiment beside an accelerator.

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