

REALISTIC CAD-BASED GEOMETRIES FOR ARBITRARY MAGNETS WITH BEAM DELIVERY SIMULATION (BDSIM)

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Abstract

Monte Carlo simulations are required to accurately evaluate beam losses and secondary radiation in particle accelerators and beamlines. Detailed Computer-Aided-Design (CAD) geometries are critical to provide the most realistic distribution of material masses but increase the model complexity and often lead to code duplication. Beam Delivery Simulation (BDSIM) and the Python package PYG4OMETRY enable handling such accelerator models within a single, simplified workflow to run complete simulations of primary and secondary particle tracking and interactions with matter using Geant4. Replacing geometries of straight magnets is trivial in BDSIM. However, for curved magnets, the procedure is significantly more complicated and time-consuming for the user. Additional capabilities have therefore been developed to facilitate the design of arbitrary bent magnets by associating externally modelled geometries to the magnet poles, yoke, and beampipe. Individual field descriptions can be associated with the yoke and vacuum pipe separately to provide fine-grained control of the magnet model. The implementation of these new features is described in detail and applied to the modelling of the CERN Proton Synchrotron (PS) combined function magnets.

INTRODUCTION

Accelerator systems are becoming increasingly complex in recent years. Medical hadron therapy installations are evolving towards more compact systems and the high-energy colliders are reaching new records of luminosity. Such systems require prior Monte Carlo simulations to predict the energy deposition and activation of specific elements and to design the concrete shielding.

Multiple Monte Carlo codes have been developed over the years for these kinds of studies such as Geant4 [1, 2], Fluka [3] or MCNPX [4]. However, these codes use numerical integration to simulate the tracking of the primary and the secondary particles inside the magnetic fields in the beamlines leading to less accurate tracking in many fields systems, such as accelerators. Therefore, a complete loss or activation study typically requires the results of previous simulations realised by tracking codes such as MAD-X [5] or Zgoubi [6], depending on the application. On the other hand, only the propagation of the primary beam is computed using these tracking codes. This leads to approximation in the loss patterns distribution given as input to the Monte Carlo codes, impacting the studies results.

As solution, we propose to use Beam Delivery Simulation (BDSIM) [7], a Geant4-based C++ library that provides

a full 3D model of any accelerator-based system. BDSIM includes the particle-matter interactions of Geant4 and the tracking of all particles through the beamline and its magnetic fields. It provides tunable default geometries for any accelerator-based elements allowing effortless beamline design. Figure 1 shows the default geometry for a sector dipole magnet (Sbend). Once the components of a system are defined, BDSIM builds the model based on a sequence of elements provided by the user. Identical components can be called multiple times in the sequence avoiding code duplication.

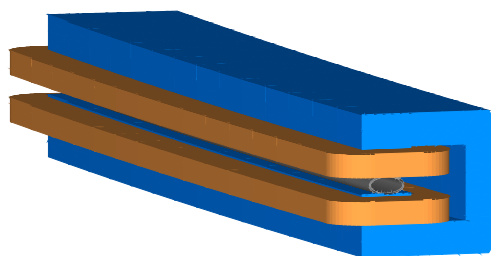


Figure 1: BDSIM model of an Sbend using the default geometry. The coils are represented in brown while, the yoke is represented in blue. An elliptical generic beampipe is represented in grey.

To improve the magnet realism, a user can import Computer-Aided-Design (CAD) files for the external geometry of the magnets. Unfortunately, in the current version of BDSIM, CAD-based external geometry cannot be directly applied to an Sbend. Furthermore, the magnets vacuum pipe design can only be chosen among some predefined default apertures. Therefore, a new feature has been developed to provide extra degrees of freedom to the user. With this feature, an Sbend can be implemented with one external geometry for the whole magnet using a CAD-based external geometry and a subpart of the provided external geometry can be defined as vacuum pipe.

This contribution details the new developments that have been realised in BDSIM for improving the customisation of the outer geometry of magnets and their vacuum pipe. This new feature is illustrated on the combined function magnets of the CERN Proton Synchrotron (PS).

EXTERNAL GEOMETRY CUSTOMISATION

User-defined external geometries are imported into a BDSIM model using Geometry Description Markup Language (GDML) files [8]. Users can create these GDML

files using the Python library PYG4OMETRY [9, 10] to convert CAD files inputs in GDML format or by constructing them from scratch using constructive solid geometry principles with Geant4-based or tessellated solids. If an outer geometry is defined for a simple element using a GDML file, BDSIM creates a default beampipe corresponding to the magnet dimension and adds the outer geometry to complete the magnet.

BDSIM builds hard-edged components in a sequence. To achieve a curved magnet with a complex cross-section including poles and coils, BDSIM splits up the curved element into many small straight sections based on a maximum allowable aperture error — 1mm by default. Moreover, each component contains an “outer” yoke geometry and a beam pipe. Then, if an outer geometry is externally supplied, this conflicts with the splitting into many smaller sections that BDSIM does.

For example, in the case of an S-bend, the combination of many straight segments with corresponding angled faces to create the bending angle of the magnet is used. As previously described, if a GDML file is provided for its external geometry, the outer geometry is implemented for all its inner elements composing it, preventing using a CAD-based file to define S-bends external geometry. Figure 2 shows how an S-bend is currently represented in BDSIM when a GDML file is provided for its external geometry.

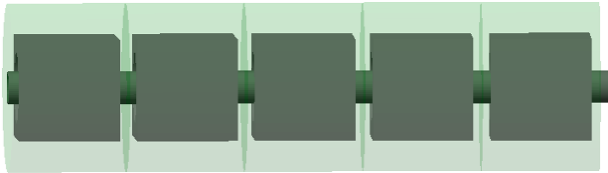


Figure 2: S-bend construction in BDSIM. The outer geometry provided by the user (intentionally shorter than the straight sections for illustrative purposes) is implemented for all the straight elements composing it. The magnet container logical volume is represented in light green.

Two developments in BDSIM characterise the new feature. The first development improves the user’s control of S-bends geometry by allowing the use of one GDML file for their outer geometry definition independently of the number of its inner components. When the new feature is activated, a new S-bend is created following two different steps. A regular S-bend is first built without any outer geometry; hence only the vacuum pipes of its inner elements are created. These vacuum pipes become the skeleton of the new element. As it is based on a regular S-bend, the correct magnetic field, entry and exit face angles, and total curvature are implemented. The combined pipe is then placed inside a Geant4 logical volume of adequate dimension. Finally, the outer geometry GDML is read, and the logical volumes inside its container logical volume are placed inside the new magnet logical volume. To correctly fit the elements and avoid overlaps, the transverse dimension of the magnet logical volume is tuned to accept the outer geometry. The magnetic return fields

of the vacuum pipes are then propagated inside the outer geometry. Figure 3 shows how the new feature is applied to an S-bend in BDSIM.



Figure 3: S-bend construction in BDSIM using the new feature. The outer geometry provided as one continuous piece by the user is implemented for the S-bend assembly. The magnet container logical volume is represented in light green.

VACUUM PIPE CUSTOMISATION

The second new development implemented in BDSIM gives the user more possibilities for the vacuum pipe customisation of any magnets. So far, BDSIM only provided the option to use default apertures for the pipe of common shapes. Some more complex geometries are also already modelled, as with the “lhclleft” and “lhcrigh” outer geometry types, which provide detailed magnet and beampipe geometries appropriate for the CERN Large Hadron Collider (LHC). On the other hand, the user cannot deviate from such default geometries leading to difficulties in efficiently simulating specific processes such as the pencil beam scanning or the beam extraction in high-energy accelerators which require aperture variation along the magnet length. The only solution for these situations was the implementation of the complete geometry of an element in BDSIM using a GDML file and associating a field map to it. This method is illustrated in Ref. [11]. This method can be time-consuming and complex for the user as the entire magnet and beampipe geometry must be defined in a GDML file and the corresponding magnetic field must be computed and mapped. The new feature allows to use one or several volumes of the external geometry GDML as beampipe for the magnet. The names of the chosen logical volumes must then be provided as component geometry option. The magnetic field that would be associated to the default pipe is then placed inside these chosen volumes but is still defined with respect to the reference trajectory of the beamline element. The default beampipe created by BDSIM is then removed from the magnet construction by using the aperture type “none”.

APPLICATION TO THE CERN PS EXTRACTION

Both new developments have been applied to the CERN Proton Synchrotron (PS) extraction magnet MU16. The MU16 extraction magnet consists of two combined dipole magnets, one focusing and one defocusing, encapsulated around a complex vacuum pipe composed of the extraction and the circulating parts. Figure 4 shows the visualisation of the step file of the MU16 geometry.

The MU16 magnet GDML file has been created using PYG4OMETRY discarding the minor details of the CAD files.

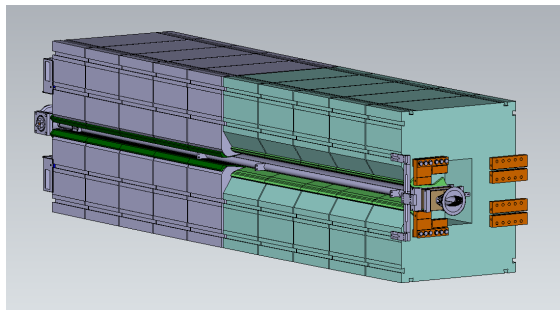


Figure 4: CAD representation of the MU16 extraction magnet showing the two half-units, the beampipe and the coils.

The external geometry of each combined magnet is composed of 5 blocks of two possible types, “open” or “closed”. Therefore, the external magnet geometry is realised by combining the model of each block several times with different orientation. The PYG4OMETRY model of the two types of blocks is shown in Fig. 5.

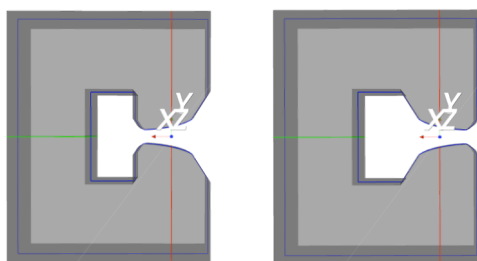


Figure 5: PYG4OMETRY models of the open and closed magnet blocks.

Figure 6 shows the CAD representation of the vacuum extraction pipe and the PYG4OMETRY models for each of its different inner parts. The four elements are combined using Boolean unions to create the final vacuum pipe.

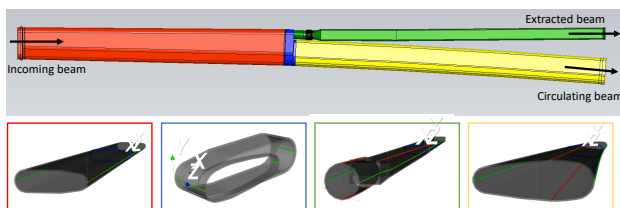


Figure 6: CAD representation of the vacuum extraction chamber. Each color corresponds to a different part of the chamber that has been separately modelled in PYG4OMETRY before being combined.

Finally, a GDML file is written for each of the two combined dipoles of MU16. The MU16 extraction magnet is therefore implemented in BDSIM by a sequence of two Sbends using the new developments [12]. Figure 7 shows the BDSIM model of the MU16 extraction magnet.

The other Sbends of the PS have also been modelled using the new feature capabilities. The only distinction with respect to the modelling of MU16 was that their beampipe was generated by BDSIM itself using its elliptical default

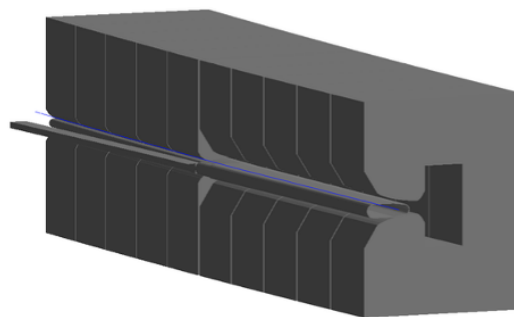


Figure 7: BDSIM model of MU16 composed of two combined dipoles each with a different GDML for their external part. The circulating primary beam can be observed in blue.

aperture. A close-up of the complete BDSIM model of the PS is shown in Fig. 8.

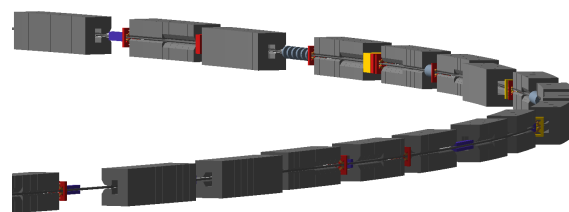


Figure 8: Close-up of the PS BDSIM model whose Sbends have been modelled using the new feature capabilities.

The use of more realistic external geometries in combination with the primary and secondary particle tracking allows BDSIM to become a powerful tool to reach new levels of accuracy in energy deposition, activation and shielding design studies [13, 14]. Different machine regimes and critical failure cases can be directly studied with one model, from the optics to the energy deposition in the magnets and walls for machine protection and radioprotection purposes.

CONCLUSION AND OUTLOOKS

A new feature has been implemented in BDSIM to improve the efficiency and flexibility of the BDSIM model definition. This feature aims to give additional degrees of freedom to the user for the magnet geometry design. The new developments allow a GDML-provided external geometry to be used for the entire modelling of an Sbend magnet with the possibility to define specific volumes of the magnet geometry to be considered the vacuum pipe and encapsulate the correspondent magnetic field. The new feature has been applied to the modelling of the PS extraction and combined dipole magnets by characterising the external geometry of the magnet and its beampipe based on a CAD file. Such new capabilities will improve the efficiency of the BDSIM modelling and, therefore, the accuracy of the results while also decreasing the time required for the model construction.

ACKNOWLEDGMENT

This work has received funding from the Walloon Region (SPW-EER) PIT Prother-wal program under grant agreement No. 7289.

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