FAST AND ACCURATE ACCELERATOR MODELLING WITH FLUKA CAD GEOMETRY WORKFLOW

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Abstract

Accurate geometric representation is essential in accelerator beam-matter interaction Monte-Carlo simulations, yet conventional Constructive Solid Geometry (CSG) modeling of beamline elements or tunnels remains time-consuming and error-prone. Recent FLUKA developments [1–3] offer a robust alternative to manual CSG implementation by introducing a CAD-based (Computer Aided Design) workflow. The new approach supports CAE (Computer Aided Engineering) volumetric meshes and the direct import of meshes generated in Gmsh, Ansys, or Abaqus [4–6]. This workflow is expected to accelerate model development, particularly for complex geometries. Benchmark comparisons will be presented between FLUKA conventional CSG geometries, FLUKA CAE-mesh geometries, and an independent development carried out in Geant4 to support CAD surface meshes [7]: the results demonstrate that while CAE meshes introduce a modest performance penalty, they provide substantial gains in accuracy, maintainability, and interoperability across design and simulation environments.

INTRODUCTION

In high-energy particle experiments, nuclear physics, and accelerator science, the fidelity of Monte Carlo simulations is fundamentally limited by the accuracy of the underlying geometric model. As modern accelerator designs evolve toward increasingly complex and large configurations, manual Combinatorial Solid Geometry descriptions have become both time-consuming and prone to systematic errors. Consequently, the field is undergoing a necessary transition toward automated, high-fidelity geometry workflows based on CAD and CAE methodologies.

This shift reflects not only the growing geometric complexity of modern accelerator infrastructure but also the practical need to maintain consistency between simulation models and rapidly evolving hardware prototypes. In this context, geometry handling is no longer a purely technical step but a critical component of simulation reliability. At the core of this transition lies the FLUKA geometry kernel, which must efficiently answer two basic queries: the identification of the volume containing each particle, as well as the subsequent volume along its trajectory. The computational speed and precision of these operations are directly determined by the chosen geometric representation. While CSG provides a mathematically well-defined and historically robust framework, its scalability becomes increasingly limited for complex accelerator components.

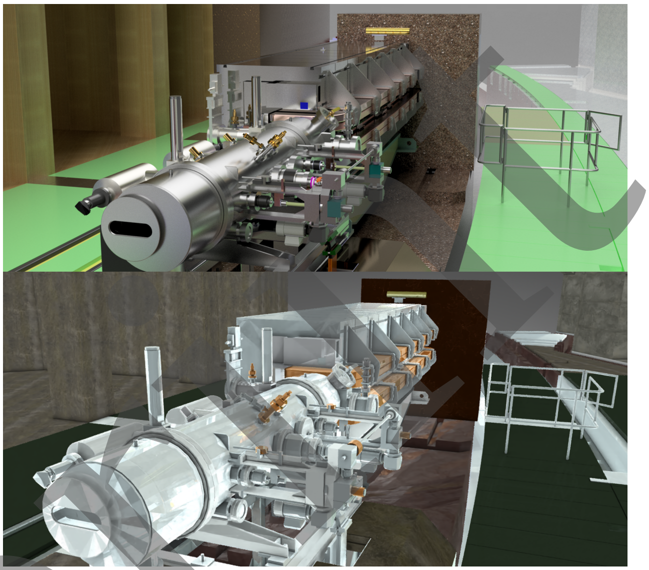

Figure 1: Example of PS geometry implementation for an extraction septa, a dipole magnet, a beam loss monitor, shielding and tunnel infrastructure. (Top) CAD model rendering with Autodesk Fusion 360 [8]. (Bottom) Imported geometry rendering in Flair [9] using the FARM4 path-tracing engine. Various materials were assigned for visual clarity.

In contrast, mesh-based representations introduce a fundamentally different approach. Tessellated surface meshes, typically obtained either directly (e.g., STL, 3MF) or through the discretisation of CAD boundary representations such as STEP, consist of polygonal facets approximating the geometry in a more precise way. Unlike CSG these meshes are not guaranteed to be strictly watertight or manifold, and may contain gaps or inconsistencies that lead to ambiguities in particle tracking.

The introduction of a CAD-to-CAE workflow since FLUKA v4-5.0 represents a significant advancement in this context. Multiple unstructured mesh geometries can be directly imported using standard formats (TetGen, Abaqus, ANSYS and Nastran), with all elements internally mapped to first-order tetrahedra to ensure consistency in tracking. To enable this capability, the core geometry construction, tracking, and scoring algorithms in FLUKA have been extended to support unstructured meshes. On the user side, CAD geometries can be converted using either commercial tools such as ANSYS [5] or open-source solutions like Gmsh [4]. In this context, a complementary meshing script is provided to FLUKA users [10], which leverages open-source tools,

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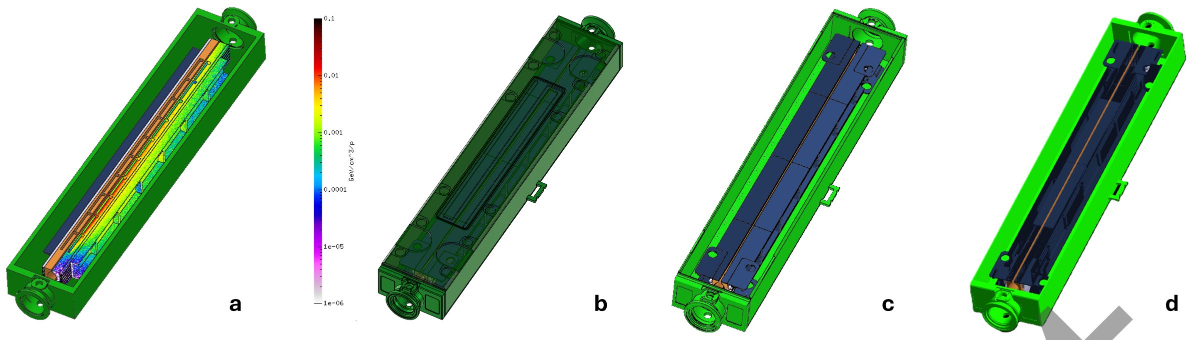

Figure 2: Tertiary collimator assembly geometry implementation. a) Simplified CSG implementation of collimator assembly with USRBIN scoring on the right jaw (top part of vacuum tank is fully transparent); b) CAD model of the assembly with semi-transparent top part of vacuum tank, c) FLUKA UMESH geometry; d) Geant4 tessellated solids geometry.

including Gmsh, and facilitates the handling of imperfect CAD inputs through remeshing procedures, thereby enabling robust geometry preparation even for challenging engineering models. A representative example of such complexity is shown in Fig. 1, illustrating the complete implementation of a Proton Synchrotron beamline section and surrounding tunnel infrastructure. The comparison between the original CAD model and its direct import into FLUKA highlights the capability of the CAD-to-CAE workflow to preserve geometric fidelity at the highest level.

To estimate the impact of different geometry representations, benchmark comparisons are performed between classical CSG models, FLUKA CAE-based volumetric meshes, and Geant4 tessellated solids based on the same initial CAD model. The study focuses on energy deposition in an LHC collimator setup under proton beam impact. The results indicate that, despite a moderate computational overhead, CAE meshes offer clear advantages in geometric fidelity and model robustness. Also notably, certain classes of geometries — such as those with free-form surfaces and non-trivial topology — are fundamentally incompatible with CSG representations without excessive approximation. This confirms the CAD-based workflow as a practical and scalable approach for accelerator modeling in FLUKA.

CSG & CAE SIMULATION BENCHMARK

To compare the performance of different geometry implementation methods, we selected a medium-complexity model of the LHC tertiary collimator. The unstructured mesh of the collimator jaw is provided with the FLUKA package as an example geometry. For a quantitative comparison, averaged energy-deposition profiles along both jaws were scored in all studies using the same Cartesian scoring mesh. All compared cases used the same beam conditions and material assignment. The impact scenario was defined by two 450 GeV proton pencil beams striking the collimator jaws at an impact depth of 100 µm, with the jaws set to a gap of 4 mm.

Figure 2 shows the different geometry variants considered in this benchmark. The simplified FLUKA CSG geometry (Fig. 2a) reproduces the main features of the vacuum tank and jaw assembly. For clarity, the energy-scoring results are shown only for the right jaw. The full CAD model of the collimator components, shown in Fig. 2b, illustrates the actual geometric complexity of the system. An unstructured mesh representation of the collimator (Fig. 2c) was generated with the complementary meshing tool available to FLUKA users [10] and imported in Abaqus format. Finally, a similar workflow was carried out using the Geant4 native CAD support: a model (Fig. 2d) was built from CAD geometry generated from the exterior faces of 3D regions of Abaqus mesh and then converted into tessellated solids using FreeCAD [11].

The computational performance was evaluated by focusing on geometry tracking, comparing the native implementations of FLUKA and Geant4. To ensure a fair comparison, the v5 framework [3] was adopted, allowing the use of FLUKA hadronic physics in both simulations, while electromagnetic interactions were suppressed through high production thresholds and mesh-based scoring was excluded from the benchmark. Table 1 reports results relative to the FLUKA CSG configuration (hadronic physics only). The findings indicate that transitioning from CSG to an unstructured mesh entails a computational overhead of approximately 20%. In contrast, the native Geant4 CAD support exhibits an additional overhead of about 40% relative to the FLUKA implementation. It is to be noted that the FLUKA native CAD support will also become directly available in the v5 framework.

Table 1: Performance comparison between FLUKA CSG (reference), FLUKA unstructured meshes, and the G4 tessellated solids support.

Study	**FLUKA CSG**	**FLUKA UM**	**G4 (Tess.)**
Time diff.	-	×1.22	×1.67

After sufficient statistics had been simulated in all cases (statistical uncertainty below 1%), the energy-deposition profile was evaluated. As shown in Fig. 3, the three geometry implementations are in excellent overall agreement. The small difference observed for the Geant4 result is expected, since FLUKA and Geant4 use different geometry-tracking kernels and different physics models; the Geant4 calculations were performed with the FTFP_BERT_HP_EMY physics list.

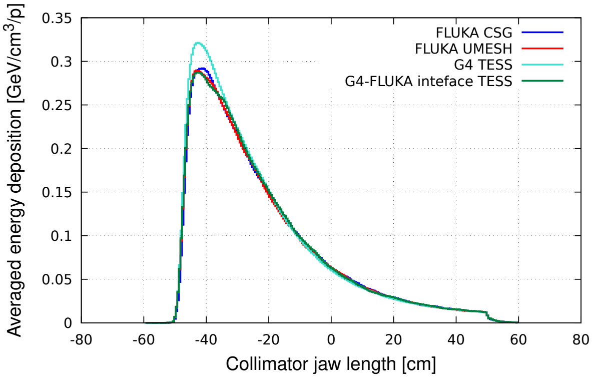

Figure 3: Comparison of average energy deposition inside the collimator jaws for all simulation methods.

Further, this hypothesis was confirmed by running Geant4 model with the FLUKA hadronic interface and the same tessellated geometry.

NON-TRIVIAL TOPOLOGIES

An important limitation of CSG arises for geometries with free-form surfaces and non-trivial topology. Although CSG is well-suited for models built from analytic primitives, it becomes inefficient and inaccurate when the real geometry contains smoothly varying three-dimensional boundaries, curved sweep paths, or complex internal interfaces. In such cases, an exact representation is generally not feasible without decomposing the model into a large number of auxiliary bodies and Boolean operations, which leads to excessive approximation and poor performance.

A representative example is provided by the family of curved canted-cosine-theta magnets [12], of which the prototype dipole magnet [13] designed and manufactured at CERN is shown in Fig. 4. Its conductor layout and internal magnetic structure contain continuous curved features that are almost impossible to reproduce with standard CSG bodies. Similar challenges also arise in fusion devices, where coils and nearby structural components often have highly complex shapes with non-trivial topology. This is not only a geometry-description issue but also a transport issue. In our study, off-momentum particles with large angular deviation were tracked in a 4.5 T magnetic field inside the toroidal volume and intercepted by inner yoke walls. In this regime, the exact shape of the inner aperture and yoke boundary determines the impact position, incidence angle, and local material path length. As a result, simplified CSG approximations can shift the predicted loss location and affect the calculated energy deposition.

This example shows that, for beam-loss studies in realistic accelerator magnets, CAD- or mesh-based geometry descriptions may be necessary. Their advantage is not only improved geometric realism, but also improved physics reliability whenever particle trajectories are sensitive to detailed free-form boundaries.

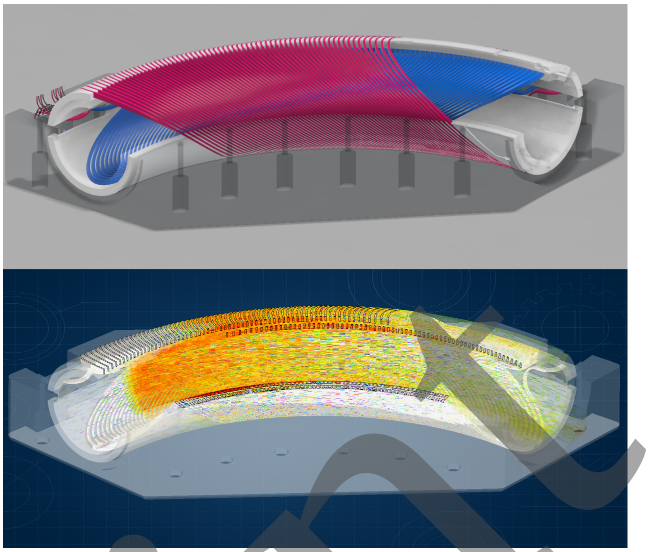

Figure 4: CCT dipole magnet geometry. (Top) Cut of CAD model which exposes the complexity of twisted coils nested inside channels of toroidal yokes. (Bottom) FLUKA energy deposition inside an unstructured mesh produced with the complementary meshing tool [10].

SUMMARY AND OUTLOOK

A CAD-to-FLUKA workflow for accelerator applications was presented and benchmarked against conventional geometry descriptions. Using an LHC tertiary collimator as a representative example, FLUKA CSG, FLUKA unstructured-mesh, and Geant4 tessellated-solid models were compared under equivalent beam-impact conditions. The energy-deposition profiles showed very good overall agreement.

The computational comparison indicated that the main overhead is introduced by fine Cartesian scoring, while the additional cost of switching from CSG to an unstructured-mesh description in FLUKA is modest. This suggests that CAD- or mesh-based geometry can be used in realistic transport studies without prohibitive performance penalties and save significant time needed for CSG description.

The study also underlines that some classes of geometries, especially those with free-form surfaces and non-trivial topology, cannot be represented accurately in CSG without excessive approximation. This is particularly relevant for devices such as curved canted-cosine-theta magnets and, more generally, for fusion components with complex coil shapes. For such systems, CAD-derived models are not only more convenient but can be required for physically reliable loss and energy-deposition predictions.

Future work will target one-to-one cross-code benchmarks, improved mesh description with high order elements, and further automation of CAD import and mesh preparation.

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