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Detector geometry management system designed for Super Tau Charm Facility offline software

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Abstract: In this paper, a geometry management system (GMS) is designed for the Offline Software of Super Tau Charm Facility (STCF) in China. Based on the eXtensible Markup Language (XML) and Detector Description Toolkit for High Energy Physics Experiments (DD4Hep), the system provides a consistent detector-geometry description for different offline applications, such as simulation, reconstruction and visualization. It is being used for detector optimization and performance evaluation with a customized full detector simulation package (FullSim). The paper presents the design, implementation, and performance of the GMS.

Keywords: Simulation methods and programs; Software architectures (event data models, frameworks and databases); Data processing methods; Performance of High Energy Physics Detectors

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Contents

1 Introduction

The Super Tau Charm Facility (STCF) [1] is a proposed high-luminosity electron-positron collider operating in the transition interval between nonperturbative and perturbative quantum chromodynamics (QCD). The facility is currently in the conceptual design stage of its research and development in China. Its designed peak luminosity exceeds $0.5 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with center-of-mass collision energy between 2 and 7 GeV. The facility has wide-ranging physics goals and will provide a unique platform to further study charmonium physics, charmed hadron physics, light hadrons, τ physics, QCD, and new physics. In the future, STCF will play a crucial role in the high-intensity frontier of elementary particle physics worldwide.

The Offline Software of Super Tau ChARm Facility (OSCAR) is developed based on the Software for Non-collider Physics ExpeRiment framework (SNiPER) [4], which is a light-weight, efficient and flexible framework that depends on only a few external packages such as Geant4 [5], ROOT [6] and Python. SNiPER supports both “Non-Collider Physics” and “Collider Physics” modes and has been adopted by the Jiangmen Underground Neutrino Observatory (JUNO) [7, 8] and the Large High Altitude Air Shower Observatory (LHAASO) [9] experiments. OSCAR is designed for the STCF experiment to facilitate the detector optimization, experimental performance studies, and potential physics discoveries. OSCAR includes generator, simulation, digitization, calibration, reconstruction, visualization, and analysis applications.

Offline applications require a detector geometry description. The geometry management system (GMS) should support the core functionality of providing a uniform detector geometry description to different offline applications. An inconsistent geometry description will lead to errors and incompatibility problems in the offline jobs of detector simulation chains. Thus, the geometry should be initialized from a single source and the consistency of detector geometry description for different applications should be ensured. Therefore, GMS is designed and developed to implement this functionality in OSCAR.

In this paper, we first introduce the STCF detector conceptual design and the requirements for detector geometry management. Next, we describe the implementation of the GMS in detail. Finally, we demonstrate the workflow of detector optimization and performance of the GMS with a test run.

2 STCF detector and geometry management requirements

The experimental apparatus at STCF includes a general-purpose detector that probes the final state products of positron-electron collisions. The conceptual design is shown in figure 1. With increasing radius from the beam-line, the sub-detectors are as follows: Vertex Detector (VTD), Main Drift Chamber (MDC), Particle Identification Detector (PID), Electromagnetic Calorimeter (ECAL), and Muon Counter (MUC). In addition, the detector system relies on two auxiliary devices: Machine-Detector Interface (MDI) and Superconducting magnet (SC).

As the innermost tracking detector, the VTD records the information near the collision point, and is used for vertex reconstruction, which improves the detection efficiency and momentum resolution of the charged tracks. The MDC surrounds the VTD in a cylindrical sensitive area, ensuring precise momentum and energy loss ($\mathrm{d}E/\mathrm{d}x$) measurements of the charged particles. The MDC is surrounded by the Particle IDentification (PID) system, which comprises two Cherenkov detectors: a Ring Imaging CHerenkov counter (RICH) in the barrel region and a Forward Time-Of-Flight detector (FTOF) in each end-cap region. The PID system aims to provide excellent particle identification for protons, muons, pions, and kaons. The ECAL, placed outside the PID system, measures the energy and position of the electromagnetic showers generated by photons or electrons. The outermost sub-detector is the MUC which is composed of sandwich-like structures of hadron absorbers and Resistive Plate Chamber (RPC) arrays. The MUC mainly distinguishes muons from other charged hadrons escaping from the ECAL, especially pions.

As it is a very complicated task to design the STCF detector and requires collaboration between different working groups, the geometry description of sub-detectors should be independent so that groups can work separately. The GMS is designed to provide a unified software environment for designing sub-detectors, wherein each group can conveniently optimize its sub-detector to meet the requirement of the intended physics goals. The aspect of detector design and performance is a major concern for physicists, thus extensive detector simulations and optimizations are essential.

Before the final detector design, different technical solutions may be proposed and compared. For example, the VTD has two very different design options (see figure 2). In the μRWell [10] design (figure 2a), 3 layers of 100 μm-thick μRWell foil acting as an electron multiplier and charge collector constitute the main components of the detector. In the Inner Silicon Detector (ISD) design (figure 2b), silicon pixel detectors or silicon strip detectors serve as the critical components. The GMS should work with different detector designs and provide a simple way to switch between them.

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Therefore, the GMS should meet the requirements as summarized below:

(1) Provide a consistent geometry description for offline applications;

(2) Provide a unified and user-friendly software environment for detector designers and scientists;

(3) Support flexible geometry combinations of sub-detectors and easy switching among different designs;

(4) Easy to use.

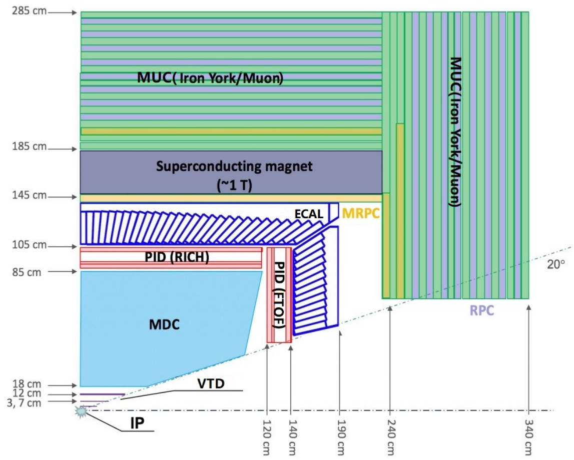
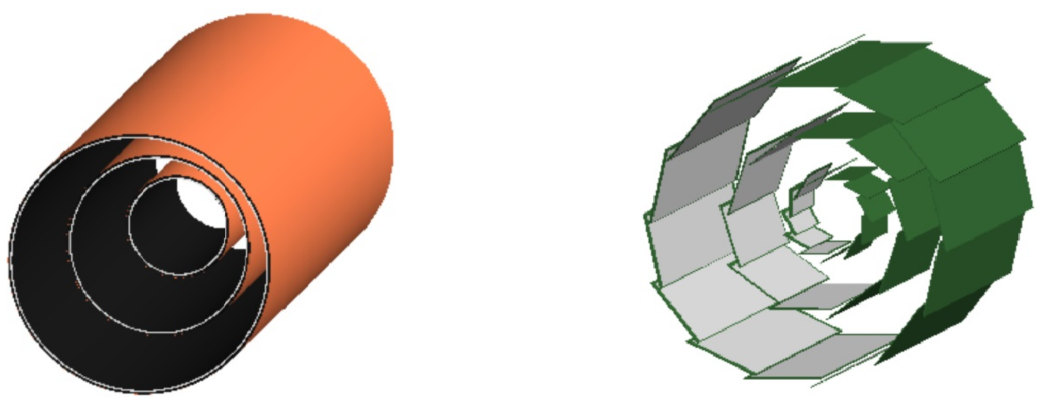


Figure 1. Conceptual design of the STCF detector. From the Interaction Point (IP) to the external space, the full detector comprises five sub-detectors: Vertex Detector (VTD), Main Drift Chamber (MDC), Particle IDentification system (PID), Electromagnetic Calorimeter (ECAL), and Muon Counter (MUC).



(a) μRWell design option.

(b) ISD design option.

Figure 2. Layouts of the two VTD detector designs: the μRWell design (left) and the inner silicon detector (ISD) design (right).

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3 Implementation

3.1 Geometry description package

The STCF detector is a composite system typically comprising more than 200,000 components of the five sub-detectors and two auxiliary devices. The geometry information of these large number of components needs to be delivered to different offline software applications with different formats. Therefore, the GMS should support easy transition between different formats of geometry and guarantee the consistency.

Several geometry description tools are extensively used in the high energy physics (HEP) experiments, including Geometry Description Makeup Language (GDML) [11], TGeometry of ROOT (TGeo) [12], and DD4Hep [3]. DD4Hep is adopted to satisfy our requirements for GMS. The DD4Hep toolkit was designed based on the experience of detector description in the Large Hadron Collider beauty (LHCb) experiment [13, 14]. The advantages of DD4Hep are listed as follows:

(1) The geometries of different sub-detectors can be independently constructed and easily assembled into a full detector. Therefore, detector designers can work on a specific sub-detector without affecting others;

(2) DD4Hep supports geometry conversion to Geant4 (G4) [5] geometry objects. Using this feature, Geant4-based detector simulation packages can be linked closely with GMS;

(3) DD4Hep provides a sophisticated 3D visualization plug-in to conveniently display and check detector designs;

(4) DD4hep offers full technical support and maintenance from the developers. It has been successfully applied in many high-energy physics experiments [15], such as LHCb, the Compact Linear Collider detector (CLICdp) and the Future Circular Collider (FCC).

3.2 Repository structure and construction of geometries

The detector geometry description usually requires parameters of the basic elements and materials, the sizes of volumes or structures, the positions and rotations of the detector components, as well as the visualization attributes. To hold and manage these parameters, a customized repository with hierarchical structure is designed in the GMS, as shown in figure 3. All parameters are stored in the compact files with eXtensible Markup Language (XML) [2], which is human readable and can be edited by any text editor: the library of elements and materials is shared by all sub-detectors; the parameters of sub-detectors are kept in standalone daughter XML files; the whole STCF detector description can be flexibly assembled by combining daughter XML files into a mother XML file; and the parameters of different design options are arranged in different XML files with specific version numbers, making it easy to switch between different sub-detector designs by changing the compact files with version numbers. This feature allows a flexible configuration for the assembly of different sub-detectors. A subversion (svn) server is set up to store the geometry repository so that the latest geometry can be conveniently updated or checked out by users via the internet.

As shown in figure 4, the workflow of the detector geometry initialization includes two steps. First, specialized C^{++} code fragments, called *detector constructors*, read and parse the geometry parameters from the XML-based repository and construct the *generic detector description model* (based on TGeo) in memory. Then, the *generic detector description model* is converted to G4 geometry representation by the TGeo-to-G4 conversion interface. Both the construction and conversion of the geometry rely on the mature DD4Hep functionalities and are encapsulated into the detector geometry construction service (DetGeoConsSvc, a SNiPER-type package) so that it can be dynamically loaded by applications when necessary. The geometry of the STCF detector is shown in figure 5.

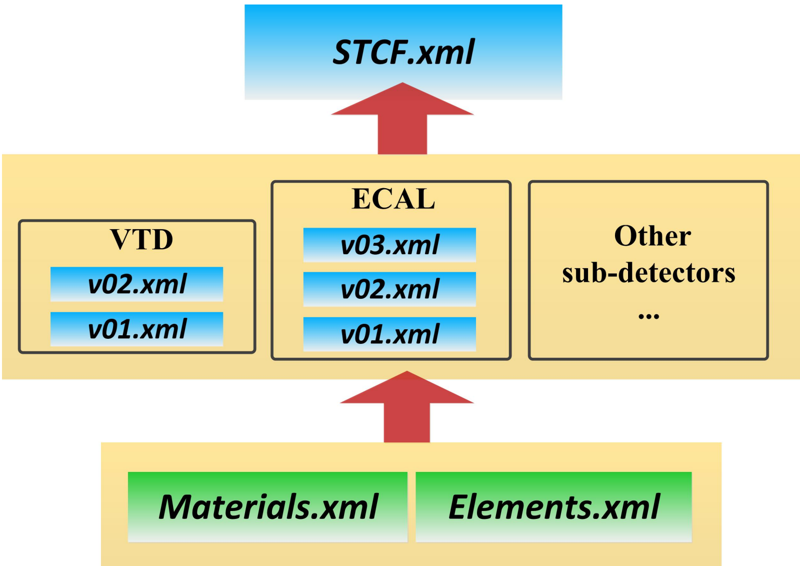

Figure 3. Structure of the geometry parameters repository. The library of elements and materials is shared by all sub-detectors. Different sub-detector designs are separately managed in different XML files; if a sub-detector has more than one designs, the parameters for different designs are stored in different XML files with version numbers. A mother XML file can include several daughter XML files.

3.3 Design of geometry management system

The design and data flow of GMS in OSCAR are shown in figure 6. Pivotal functionalities are encapsulated in SNiPER-type packages so that they can be dynamically loaded when running jobs. Using geometry parameters in the XML-based repository, the detector geometry is firstly constructed and automatically converted to G4 geometry via DetGeoConsSvc (introduced in figure 4). The full detector simulation package (FullSim) utilizes the G4 geometry provided by DetGeoConsSvc to simulate the response of the detector.

In the offline chain, detector simulation is based on Geant4, while the reconstruction, visualization and analysis are heavily dependent on ROOT. To provide consistent geometry information to these applications, a geometry analysis manager (GeoAnaMgr, a SNiPER-type package, introduced in figure 7) is developed to retrieve the G4 geometry and convert it back to TGeo at the end of the simulation. The geometry in TGeo format is written into a ROOT file for further use as input to reconstruction, visualization, and analysis applications. The geometry and event data are designed to be bundled together in the same output file to avoid inconsistency of the geometry in simulation and other offline jobs.

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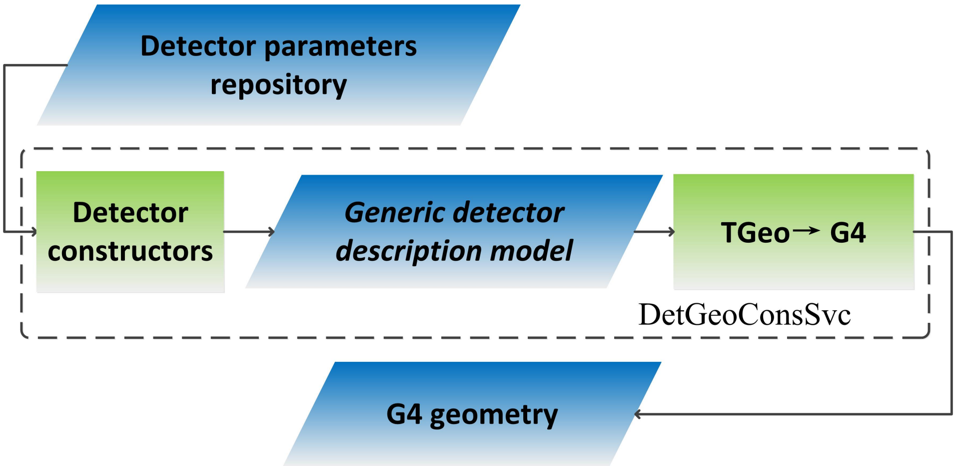
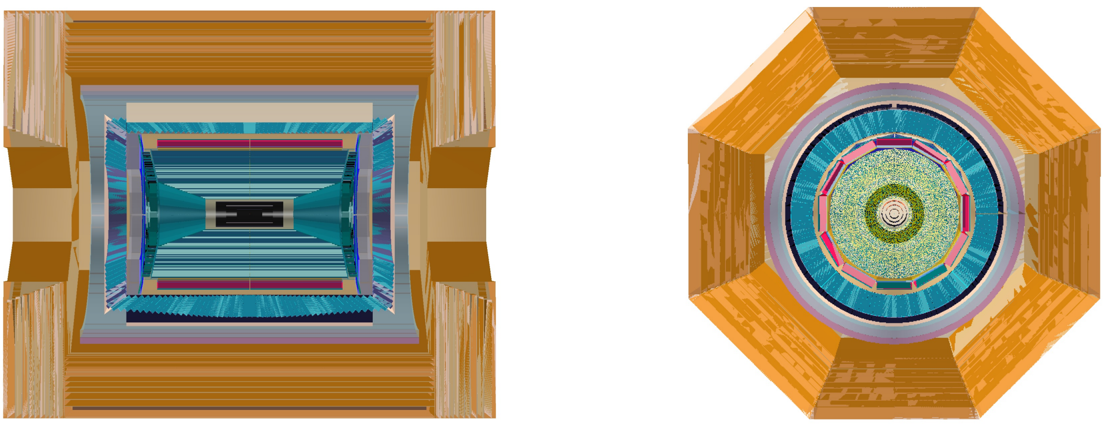


Figure 4. Workflow of the detector geometry initialization. First, the geometry parameters in the repository are parsed by detector constructors, after which the generic detector description model is constructed in memory. Then the generic detector description model is converted to G4 geometry. The functionality of the geometry initialization is encapsulated in DetGeoConsSvc.



(a) (b)

Figure 5. Full detector described by the GMS and printed using the default 3D visualization plugin of DD4Hep. 2D sections are viewed from different directions: (a) Z-R view and (b) X-Y view.

As described in figure 7, GeoAnaMgr is a SNiPER-type package based on two available automatic geometry-conversion interfaces: *GDML writer* of Geant4 and *TGDMLParse* of ROOT. To convert the G4 geometry to TGeo, the G4 geometry in simulation is first exported to a GDML file by using *GDML writer*, and then the GDML representation is converted to TGeo by *TGDMLParse*.

3.4 Outlook

The GMS works closely with the Fullsim package. At the end of the simulation, the detector geometry is saved in a ROOT file as TGeo format. Now a prototype service is designed to extract the geometry information from TGeo geometry and provide it to offline applications including

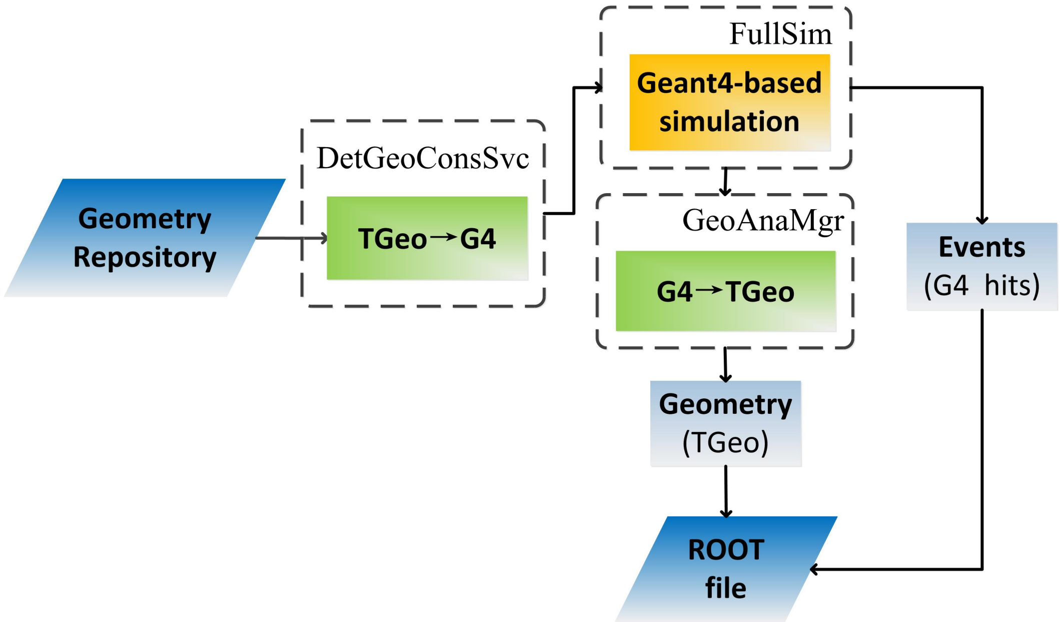


Figure 6. Overview of the GMS and data flow. DetGeoConsSvc reads the geometry parameters from XML files and provides G4 geometry objects for the simulation (FullSim). At the end of the simulation, GeoAnaMgr converts the G4 geometry to TGeo for further use in other applications.

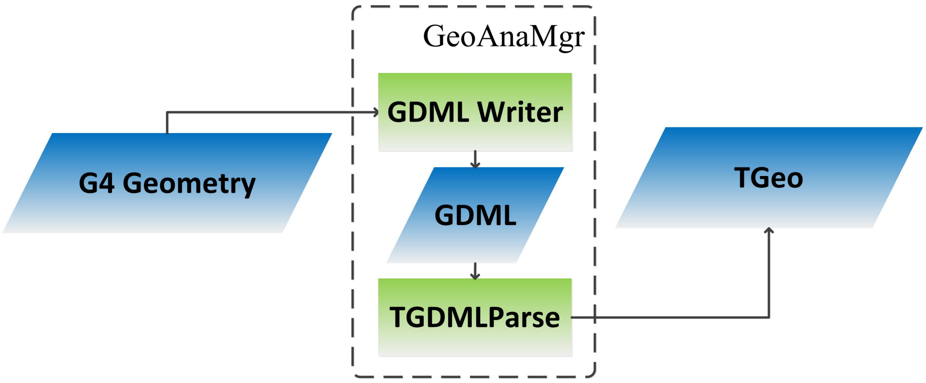


Figure 7. Schematic and data flow of the GeoAnaMgr. The main function of the GeoAnaMgr is to convert the G4 geometry in simulation to TGeo. The data flow in the dotted-line frame shows the conversion process from G4 geometry to TGeo.

reconstruction, visualization, and analysis. In the future, the service will be redeveloped and customized to support more features.

4 Performance of geometry management system

4.1 Detector optimization

At present, detector designers can use GMS and the FullSim package to evaluate and optimize the detector design. To make the simulation reflect the experimental setup, the detector must be set in a realistic scenario with the other sub-detectors and auxiliary components, which can be achieved by the GMS.

As an example, optimization of the ECAL is performed to test the workflow of the overall system. The sensitive volumes of ECAL mainly comprise two parts, the barrel and the end-caps, as shown in figure 8. A wedge-shaped cesium iodide (CsI) crystal constitutes the basic unit of the detector and is shown in figure 8d. The shape and size of the sensitive unit influences the detector performance. With the GMS, physicists can easily change the shape or size of the CsI crystal in XML-based repository and study the effects of geometry on the energy and spatial resolution.

The energy and spatial resolutions of different CsI crystal designs as functions of incident energy are shown in figure 9. Larger crystal size improves the energy resolution, while smaller crystal size improves the spatial resolution. Therefore, physicists need to balance both the energy and spatial resolutions when designing the CsI crystal units of ECAL.

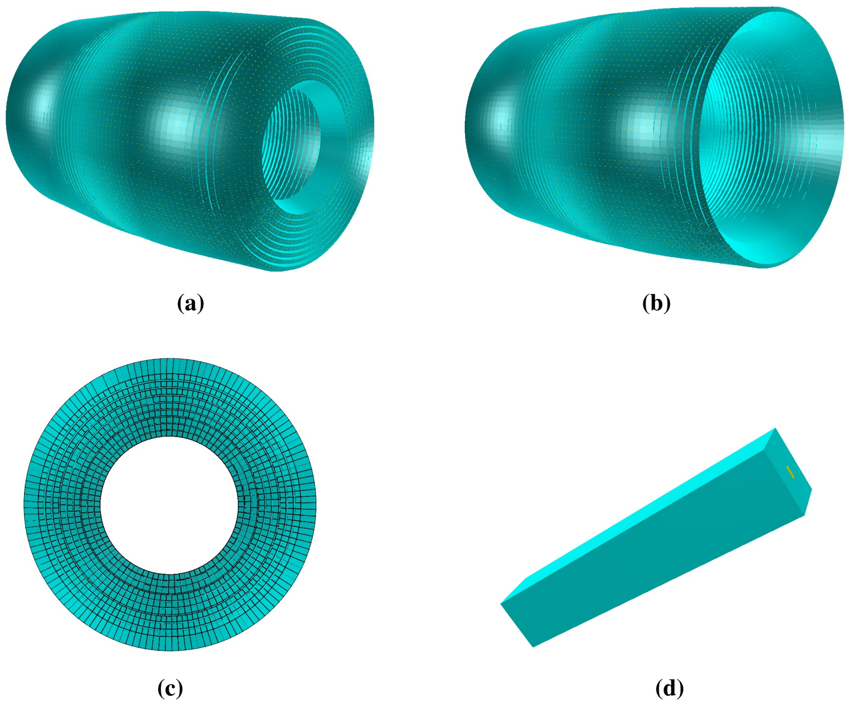


Figure 8. The Layout of the ECAL: (a) the full sensitive volumes of ECAL; (b) the barrel part of ECAL; (c) the end-cap part of ECAL; (d) a single wedge-shaped CsI crystal.

4.2 Software performance

Based on the present design of the STCF detector, we test the time required for the geometry construction on a Dell R440 server with two Intel Xeon Silver 4116 CPUs. The geometry construction includes two steps: TGeo-based detector geometry initialization in memory; and TGeo geometry conversion to G4 geometry. The time taken for the two steps are 1.12 and 0.16 s, respectively (total time: 1.28 s), which are listed in table 1. The first step takes most of the run time because DetGeoConsSvc needs to read compact parameters in sequence from the geometry parameters repository.

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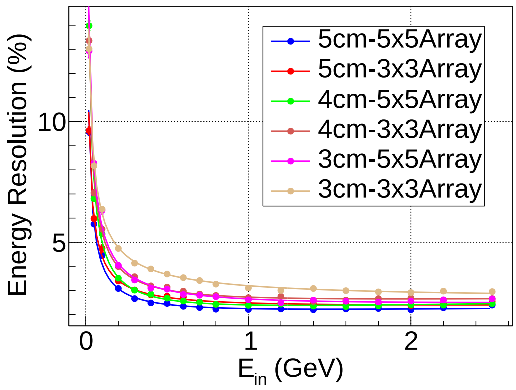
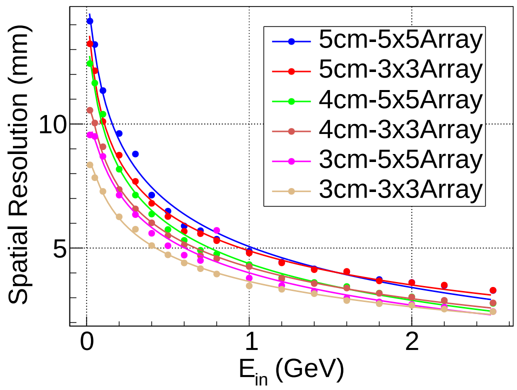


(a)



(b)

Figure 9. Performance of ECAL simulated using GMS and FullSim package. Panels (a) and (b) panels plot the energy and spatial resolutions versus incident energy under different crystal sizes, respectively. The crystal sizes of different designs are indicated in the plot. For instance, 5 cm-5×5 Array means the side length of the end face of the crystal is 5 cm and each EMC shower is reconstructed with a 5×5 crystals array. All the crystal designs have the same longitudinal length of 28 cm.

However, the total time is acceptable. The XML and ROOT file sizes of the same STCF detector design are also compared in table 2.

Table 1. Time consumption of the detector geometry construction.

Steps	Geometry construction	Geometry conversion	Total
Time consumption	1.12 s	0.16 s	1.28 s

Table 2. Comparison of XML and ROOT file sizes.

File	XML	ROOT
Size	100 KB	4 MB

5 Conclusion

In this paper, a GMS was developed in OSCAR to provide a consistent geometry description for different offline applications and to set up a unified and user-friendly software environment for detector designers. In addition, a flexible geometry assembly of sub-detectors and an easy switching among different detector design options were achieved. Several packages were developed to make the workflow of the system easy and efficient. Moreover, performance evaluation and design optimization for STCF detectors were performed using the FullSim package along with the GMS. In the future, the GMS will be redesigned and re-developed to serve a wide range of applications, including reconstruction, visualization, and analysis.

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