JOINT INSTITUTE FOR NUCLEAR RESEARCH
Veksler and Baldin laboratory of High Energy Physics

FINAL REPORT ON THE START PROGRAMME

Integration of the SPD Zero Degree Calorimeter into SPDGeoModel framework

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Abstract

This report presents the integration of the Zero Degree Calorimeter (ZDC) geometry for the Spin Physics Detector (SPD) experiment into the SPDGeoModel framework. The work focused on developing a complete geometric description of both ZDC stages (stage 1 and stage 2) using the GeoModel toolkit. C++ classes were implemented to define the hierarchy of detector components. The resulting models accurately represent the modular design of both calorimeter stages. This successful integration provides a foundational geometry for the ZDC within the overall SPD detector, enabling its use in subsequent simulation studies and physics performance evaluations for the SPD collaboration at the NICA facility.

Keywords: ZDC, SPD, GeoModel.

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1 Introduction

Calorimetry is a ubiquitous detection principle in particle physics. Originally developed for the study of cosmic ray phenomena, it was refined to be used in accelerator-based particle physics experiments, primarily to measure the energy of electrons, photons, and hadrons [3].

The enrichment of experimental techniques driven by calorimetry is evidenced by the fact that different characteristics of calorimetric performance were decisive for notable discoveries in nuclear and particle physics, as well as astrophysics; examples include the discovery of the intermediate vector bosons, the observation of neutrino oscillation effects in Super-Kamiokande, and the experimental observation of the Higgs boson [4].

In this context, calorimetry is essential for the Spin Physics Detector (SPD), currently under construction at the Nuclotron-based Ion Collider Facility (NICA), belonging to the Joint Institute for Nuclear Research (JINR) [5]. It is designed to provide high-precision data to improve the current understanding of nucleon structure in general, and spin structure in particular, in a scarcely explored kinematic range, with the goal of accessing the gluonic content of nucleons [6].

The SPD is conceived as a universal 4π detector with advanced tracking and particle identification capabilities, based on modern technologies. It will operate with polarized proton and deuteron beams, reaching collision energies of up to 27 GeV and luminosities of up to 10^{32} cm^{-2} s^{-1} (in proton-proton collisions) [7]. It is equipped with two Zero Degree Calorimeter (ZDC) devices placed in the space between the BV1E separation dipole and the next BV2E1 dipole, inside the NICA magnet cryostat, symmetrically on both sides of the interaction point (IP), at about 13 m, as shown in Fig. 1. The strong magnetic field before the ZDC efficiently removes all charged particles, allowing a clean measurement of neutrals, so the device can work up to very high luminosities. Two stages have been proposed for the SPD detector commissioning in the NICA accelerator [1].

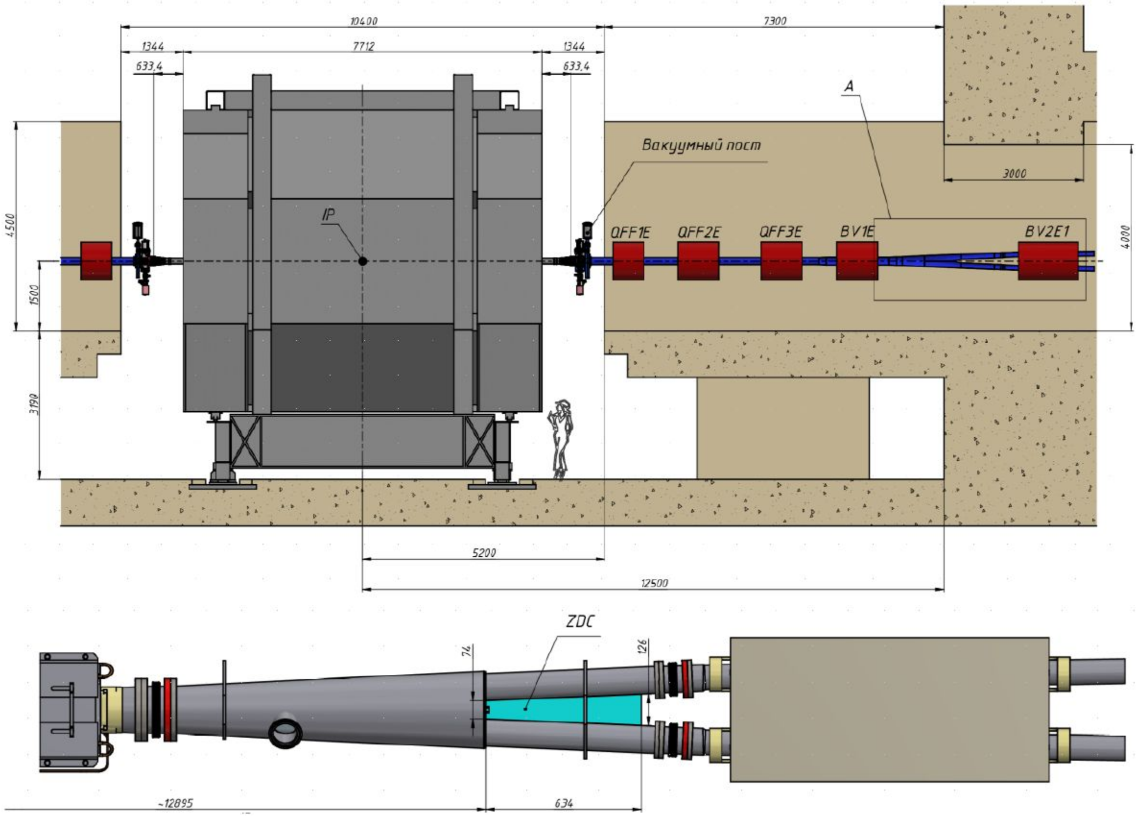

Figure 1: ZDC position on one side from the IP. The top figure shows the general view while the 5 times enlarged area A is shown in the bottom. The cryostat is not shown [1].

In modern experimental science, the design and construction of complex detectors, as well as the interpretation of the data they produce, is inconceivable without appropriate simulation. In fact, simulation has become crucial in high-energy physics (HEP) [8]. This is especially relevant for the development of the two stages of the SPD's ZDC, because its location presents the following challenges:

- Limited space between the two beam tubes,
- Insulation vacuum $\approx 10^{-6}$ Torr,
- Cryogenic temperature ≈ 80 K,
- Difficult accessibility [1].

In this work, the design of the ZDC detector based on GeoModel toolkit is developed for both stages, called stage 1 and stage 2. The geometrical ZDC model will be integrated in the Gaudi-based offline software SAMPO, which will be used for full simulation in SPD. Therefore the objectives of this project were:

1.1 Objectives

- The geometric description of the two stages of the SPD's ZDC with the GeoModel toolkit.
- The inclusion of both stages in the SPDGeoModel framework.

2 GeoModel

GeoModel is a comprehensive toolkit for creating and managing detector descriptions in High Energy Physics experiments. It provides geometrical primitives for describing detectors, along with tools for writing, accessing, manipulating, visualizing, and debugging detector geometry. As a pure C++ toolkit with minimal external dependencies, GeoModel is highly modular, allowing users to select only the necessary components [9].

The original GeoModelKernel library, used in the ATLAS experiment for over 20 years, represents detectors as a tree of nodes. These nodes include volumes, shapes, elements, materials, transforms, and parametric placements. Most nodes can be shared to conserve memory. The library features efficient alignment handling with multiple alignment constants maintained in a cache, and incorporates various memory-saving techniques that result in a very low memory footprint [10].

The nomenclature for graph nodes follows that of GEANT4, though the concepts are not completely identical. GeoModel provides:

- `GeoElement` nodes representing chemical elements
- `GeoMaterial` nodes that aggregate elements with specific weight fractions
- Various shapes inheriting from `GeoShape`
- Logical volumes (`GeoLogVol`) that combine shapes and materials
- Physical volumes (`GeoPhysVol`) that contain logical volumes and may have children

The position of a physical volume is determined from transformation nodes located upstream in the tree structure. During tree traversal, the position is computed by composing the transformations encountered from the "world" volume to the specific physical volume. This memory-saving approach allows instances of physical volumes to be shared, enabling the same instance to represent multiple volumes in different positions. Similarly, instances of logical volumes, shapes, and materials can be shared. Memory management is handled through reference counting [11].

The hierarchical structure and relationships between these core components are illustrated in Fig. 2, which shows the flow from basic elements to complex detector geometry.

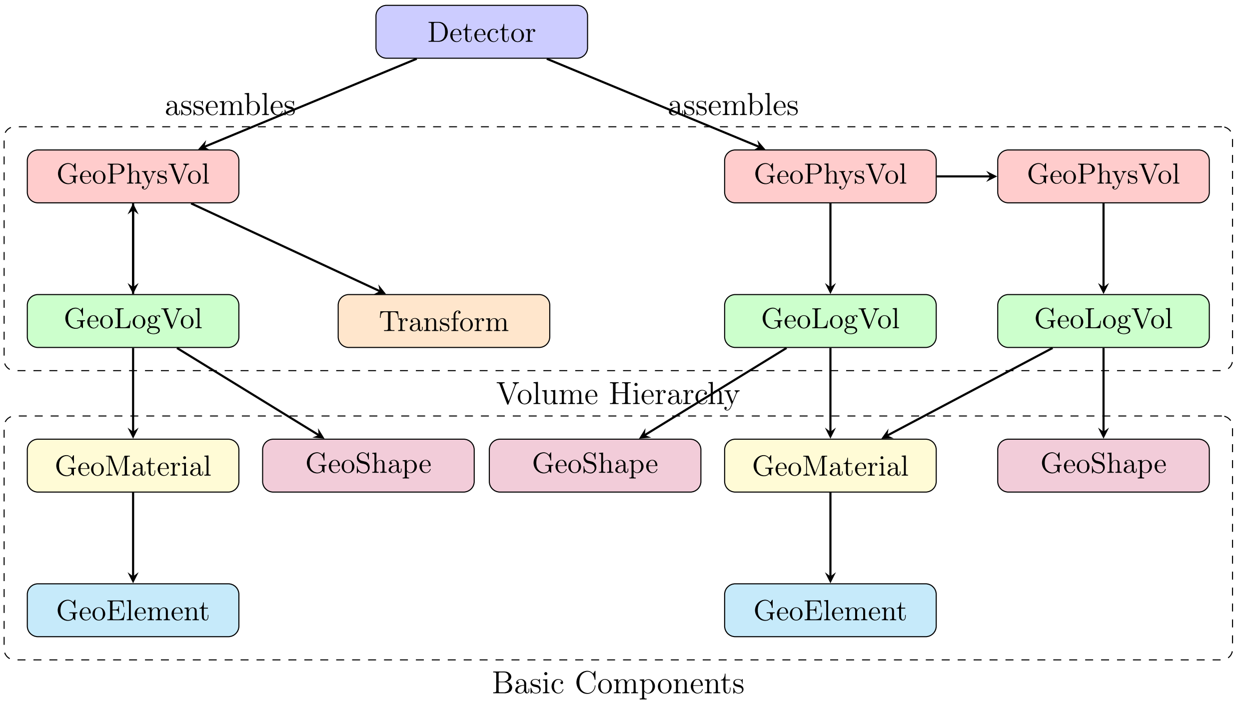

Figure 2: GeoModel architecture showing the hierarchical structure of detector geometry components. The diagram illustrates how basic components (chemical elements, materials, and shapes) are combined into logical volumes, which are then positioned as physical volumes within the detector assembly. Physical volumes can contain other physical volumes, creating a tree structure that defines the complete detector geometry.

This structured approach enables the creation of complex detector geometries while maintaining computational efficiency through component sharing and optimized memory management. The ability to share instances of physical volumes, logical volumes, shapes, and materials significantly reduces memory usage, which is crucial for large-scale detector simulations.

3 SPDGeoModel

Building upon the foundational principles of the GeoModel toolkit, the SPDGeoModel project is specifically designed to create the complete geometry description of the SPD.

The project structure is organized to systematically manage the detector's geometry. Key components include:

- **Managers:**
  - `GeoMaterialManager`: Defines and provides access to all materials used in the SPD via a singleton pattern.
  - `GeoEnvelopeManager`: Creates mother volumes for detectors, places them within the world volume, and offers volume access through a singleton pattern.

- **Plugins:** Contains GeoConstruction classes for each subdetector. These classes are responsible for creating physical and logical volumes and integrating them into their respective mother volumes, ultimately generating the geometry file [12].

This structured approach ensures that the SPD geometry is accurately represented, efficiently managed, and readily integrable with simulation frameworks like Geant4. The use of singleton patterns in managers guarantees consistent access to materials and volumes across the entire detector description, facilitating both development and simulation processes.

4 ZDC geometry

Both ZDC stages, according to their design, are classified as sampling calorimeters [3]. The geometry of both stages, as well as their component materials, are detailed below.

4.1 Stage 1 ZDC Geometry

The stage 1 ZDC is structured into seven modules, each of which is composed of:

- Absorber layer
- Reflective sheet
- Scintillator layer
- Another reflective sheet
- PCB layer
- Insulating layer

Each scintillator layer is segmented into 31 cells, as shown in Fig. 3, and the SiPMs are installed on the printed circuit board (PCB). The first module (veto) consists only of a scintillator layer with its respective reflective sheets and insulating layer, without segmentation. The first scintillator layer has a greater thickness than the remaining scintillator layers [2].

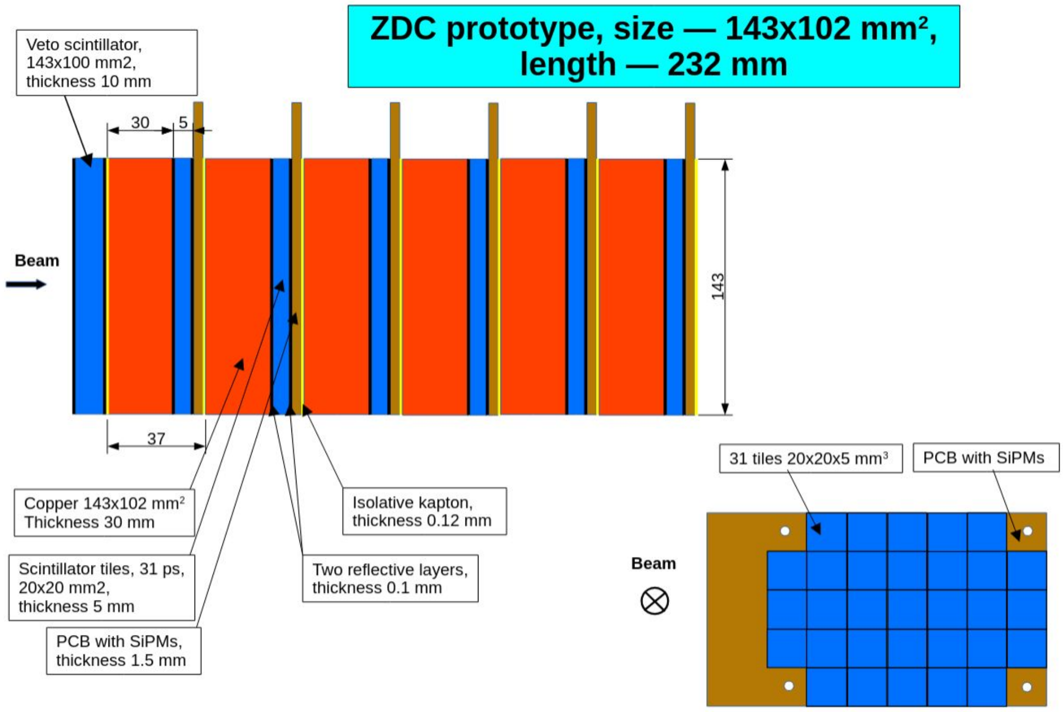

Figure 3: Module distribution of the SPD stage 1 ZDC [2].

Table 1 shows a list of the materials and dimensions of the components for each module.

Table 1: Materials and dimensions of the components for each module of the SPD stage 1 ZDC.

Component	Material	Dimension (mm)
Absorber	Copper	143x102x30
Reflective sheet	Polypropylene	143x102x0.1
Scintillator tile	Polystyrene	20x20x5
PCB	G10	143x102x1.5
Insulator	Kapton	143x102x0.12
First scintillator layer	Polystyrene	143x100x10

4.2 Stage 2 ZDC Geometry

The stage 2 ZDC consists of an electromagnetic section and a hadronic section. It is composed of 30 modules, where each module consists of an absorber layer (Wolfram), a scintillator layer (Polystyrene), and a PCB (G10). The first module (veto) consists only of the scintillator layer and the PCB.

The PCB contains the SiPMs (3x3 mm^2), the scintillator tiles, and the tungsten absorber layer. The SiPMs and scintillator tiles are organized into a 5x7 matrix.

The plane sizes increase from the front to the back of the calorimeter, along with the increase in the gap between the beam pipes. Tile sizes increase accordingly. The electromagnetic section comprises the first 8 modules; the thickness of the scintillator and absorber layers is 5 mm. The hadronic section comprises the remaining 22 modules; the thicknesses of the scintillator and absorber layers are 10 mm and 13 mm, respectively. The thickness of each PCB layer throughout the entire calorimeter is 1 mm [1].

A detailed geometric description has been provided for both stages of the ZDC. The material composition, dimensional specifications, and structural organization are now defined for the seven modules of the stage 1 ZDC and the 30 modules of the stage 2 ZDC, enabling their implementation in SPDGeoModel.

5 Geometry Implementation in SPDGeoModel

For the implementation of the geometry for both ZDC stages, five C++ classes were created:

- ZDCGeoConstruction
- ZDCStage1FirstLayerGeoConstruction
- ZDCStage1ModuleGeoConstruction
- ZDCStage2EMGeoConstruction
- ZDCStage2HADGeoConstruction

All of them follow the steps explained below:

5.1 Material Definition and Volume Creation

In each of the implemented classes, functions were created that return the physical volume for every component described, following this procedure: By creating an instance of `getManager`, a method from `GeoMaterialManager`, access to the materials used in the SPD is granted, allowing the materials for each component of both ZDC stages to be obtained. With the `GeoBox` class, all solid volumes are created. For the ZDC stage 1, the dimensions were simply defined as private variables in the header file and provided as arguments for creating the shape of each component. However, for the ZDC stage 2, the dimension along the y-axis was provided as an argument due to the variation in layer height along the calorimeter. Consequently, the function `getYSize` was created, which returns the height along the y-axis for the desired layer when its z-position is given as an argument. Then, having both the material and the shape, the logical volumes were defined through the `GeoLogVol` class. In this way, each function can return the physical volume via `GeoPhysVol` by being assigned the logical volume. Listing 1 and Listing 2 show an example of the described procedure for the ZDCStage1ModuleGeoConstruction and ZDCStage2EMGeoConstruction classes, respectively.

Listing 1 Implementation of the physical volume for a scintillator tile in a ZDC stage 1 module.

```
// Build physical volume for Scintillator Tile
GeoPhysVol* SPDGeom::ZDCStage1ModuleGeoConstruction::buildScintillatorTilePV()
{
  // Get material
  //
  auto matmanager = GeoMaterialManager::getManager();
  auto materialPolystyrene = matmanager->getMaterial("std::Polystyrene");

  // Construct volume
  //
  auto shape = new GeoBox(m_scintillatorTile_xsize * 0.5,
  m_scintillatorTile_xsize * 0.5, m_scintillator_zsize * 0.5);
  auto logical = new GeoLogVol("/SPD/ZDC/Module/Scintillator/Tile/Polystyrene",
  shape, materialPolystyrene);
  return new GeoPhysVol(logical);
}
```

Listing 2 Implementation of the physical volume for the absorber layer in the electromagnetic section of the ZDC stage 2.

```
//  Build physical volume for wolfram layer
GeoPhysVol* SPDGeom::ZDCStage2EMGeoConstruction::buildWolframPV(double YSize)
{
  // Get material
  //
  auto matmanager = GeoMaterialManager::getManager();
  auto materialWolfram = matmanager->getMaterial("std::Wolfram");

  // Construct volume
  //
  auto shape = new GeoBox(m_xsize * 0.5, YSize * 0.5, m_wolfram_zsize * 0.5);
  auto logical = new GeoLogVol("/SPD/ZDC/EM/Absorber/Wolfram", shape,
  materialWolfram);
  return new GeoPhysVol(logical);
}
```

5.2 Placement of Physical Volumes

In the `build` function of the stage 1 ZDC classes, the components of the first module and of a single one of the remaining modules were placed, respectively. The position of the components relative to the z-axis was considered. For this purpose, the functions defined previously for creating the physical volumes were called. These volumes were named, identified with an ID, positioned, and added to the physical volume (envelope) that the `build` function receives as an argument.

In the `build` function of the stage 2 ZDC classes, it was necessary to call the functions for creating the physical volumes inside a `for` loop, due to the variation in the y-dimension of each component. Similarly, the physical volumes were named, labeled with an ID, positioned, and added to the envelope received as an argument by the `build` function.

5.3 ZDCGeoConstruction

The ZDCGeoConstruction.cpp file consists of a `build` function, where a conditional statement was established to select which ZDC stage is assembled. For stage 1, using a `for` loop that shifts along the z-axis according to the ZDC structure, the module created in ZDCStage1ModuleGeoConstruction is added six times to the envelope. The first module, created in ZDCStage1FirstLayerGeoConstruction, is also added to the envelope, thus completing the assembly of the ZDC for stage 1. For stage 2, the electromagnetic section and the hadronic section, created in ZDCStage2EMGeoConstruction and ZDCStage2HADGeoConstruction respectively, are added to the envelope. In the header file ZDCGeoConstruction.h, modifying the variable `m_Stage` determines which ZDC stage will be assembled.

In the ZDCGeoPlugin class, by creating an instance of `getManager`, a method belonging to `GeoEnvelopeManager`, the shape of the ZDC is obtained. From this shape, along with the Air material (defined in `GeoMaterialManager`), the physical volume for the ZDC envelope is constructed. This envelope is provided as an argument to the `build` function of the ZDCGeoConstruction class. The resulting physical volume, which contains the internal ZDC structure, is used to place the two ZDCs symmetrically with respect to the interaction point (IP) in the `SPDGeoModel` world. The hierarchy of the classes implemented in the ZDCPlugin is illustrated in Fig. 4, and the code for ZDCGeoPlugin.cpp is shown in Listing 3.

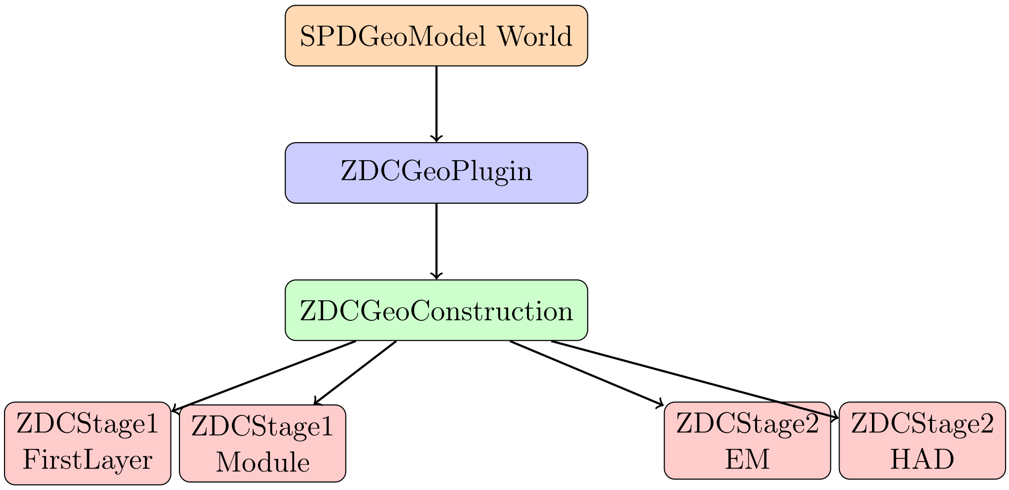

Figure 4: Class hierarchy implemented in the ZDCPlugin for geometry construction. The diagram shows the parent-child relationships between the main geometry classes, with ZDCGeoConstruction orchestrating the assembly of the four specialized component classes.

Listing 3 Implementation of ZDCGeoPlugin.cpp, created by Dr. Evgueni Tcherniaev.

```cpp
// Instantiate material and envelope managers
//
auto matmanager = GeoMaterialManager::getManager();
auto envmanager = GeoEnvelopeManager::getManager();

// Get material
//
auto air = matmanager->getMaterial("std::Air");

// Construct physical volumes for envelopes
//
auto shapeZDC = envmanager->getShape("ZDCal");
auto logZDC = new GeoLogVol("/SPD/ZDC", shapeZDC, air);
auto physZDC = new GeoPhysVol(logZDC);

// Build internal structure of envelopes
//
auto constructorZDC = new SPDGeom::ZDCGeoConstruction();
constructorZDC->build(physZDC);

// Place envelopes into the world
//
int copyNumber = 0;
world->add(new GeoNameTag("ZDCPos")); // set volume name
copyNumber = envmanager->getId("ZDCalPos");
world->add(new GeoIdentifierTag(copyNumber)); // set volume copy number
world->add(envmanager->getPosition("ZDCalPos")); // set volume position
world->add(physZDC); // place volume

world->add(new GeoNameTag("ZDCNeg"));
copyNumber = envmanager->getId("ZDCalNeg");
world->add(new GeoIdentifierTag(copyNumber));
world->add(envmanager->getPosition("ZDCalNeg"));
world->add(physZDC);
```

For further information regarding the implemented geometry code for both ZDC stages, the following resource can be consulted: this link.

5.4 Results

The obtained GeoModel geometries for stage 1 and stage 2 of the ZDC are shown in Fig. 5 and Fig. 7, as well as their sensitive volumes in Fig. 6 and Fig. 8. In both cases, the absorber layers are represented in red, the scintillator tiles in blue, the SiPMs in yellow, the PCB in green, and the unsegmented first scintillator layer of the stage 1 ZDC is shown in cyan.

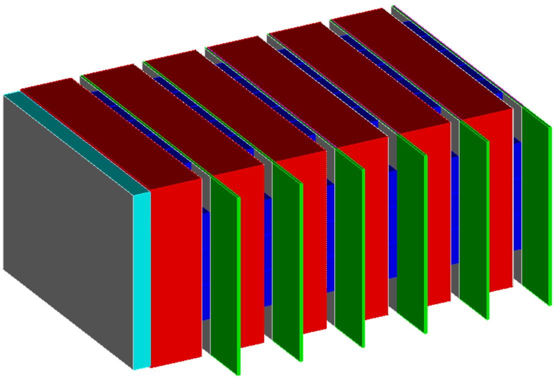

Figure 5: Geometry of the stage 1 ZDC created in GeoModel. Visualized with GeoModel's FullSimLight package.

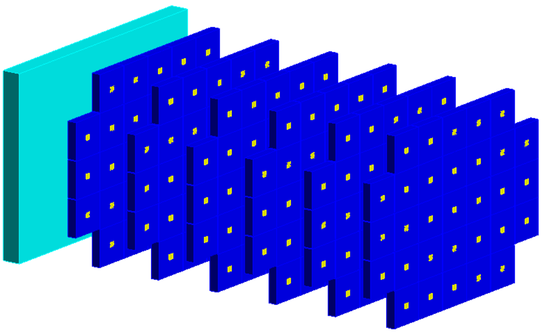

Figure 6: First scintillator layer (cyan) and the remaining scintillator tiles (blue) with their SiPMs (yellow) for the stage 1 ZDC geometry created in GeoModel. Visualized with GeoModel's FullSimLight package.

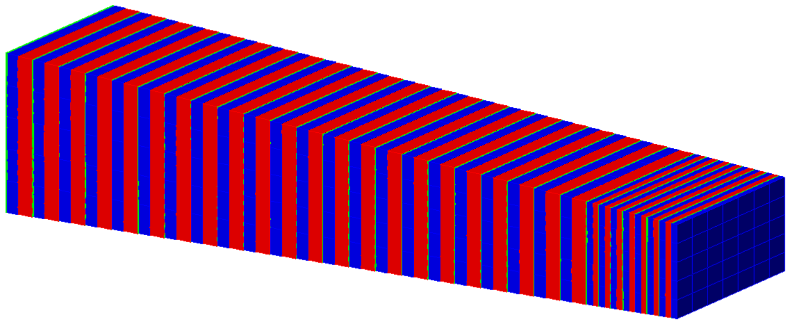

Figure 7: Geometry of the stage 2 ZDC created in GeoModel. Visualized with GeoModel's FullSimLight package.

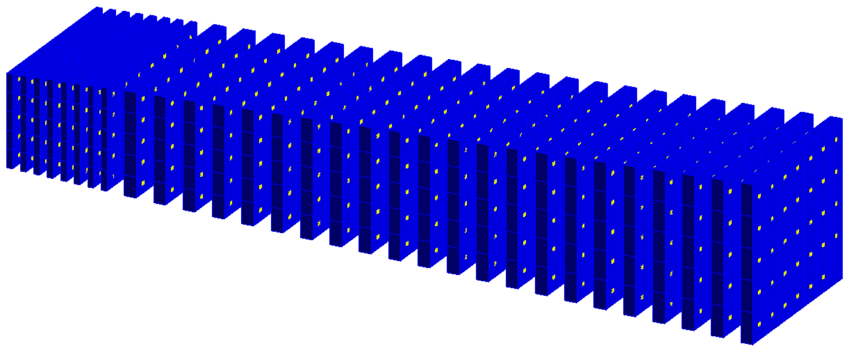

Figure 8: Scintillator tiles (blue) with their SiPMs (yellow) for the stage 2 ZDC geometry created in GeoModel. Visualized with GeoModel's FullSimLight package.

6 Conclusions

This report has documented the successful integration of the Zero Degree Calorimeter geometry into the SPDGeoModel framework. The work conducted during the START Programme has established a solid foundation for the geometric description of both ZDC stages within the SPD experiment.

Based on the objectives outlined at the beginning of this project, the following conclusions are drawn:

- The geometric description of both stages of the SPD's ZDC has been successfully implemented using the GeoModel toolkit.
- Both ZDC stages have been fully integrated into the SPDGeoModel framework. The ZDC geometry is now properly positioned within the overall SPD detector design and can be inserted in the Gaudi-based offline software SAMPO for simulation purposes in the SPD experiment.

The completion of these objectives represents a significant step forward in the development of the SPD detector simulation capabilities, providing the necessary geometric foundation for future studies of detector performance and physics analyses.

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