JOINT INSTITUTE FOR NUCLEAR RESEARCH
Dzhelepov Laboratory of Nuclear Problems

FINAL REPORT ON THE START PROGRAM

Geometry simulation of the Zero-Degree Calorimeter at NICA-SPD using Geant4

Supervisor:
Dr. Katherin Shtejer Díaz

Student:

Thalia Rodríguez Martínez, Cuba

Higher Institute of Applied Sciences and Technologies, University of Havana

Participation period:

June 30 - August 17,
Summer Session 2024

Dubna, 2024

Table of Contents

Abstract

Geometry description is critical for many software tasks in any modern experiment: alignment, simulation, reconstruction and visualization. This report details the geometry simulation of the Zero-Degree Calorimeter (ZDC) which is an important component of the Spin Physics Detector (SPD) at the Nuclotron-based Ion Collider facility (NICA) currently under construction at the Joint Institute for Nuclear Research (JINR), Dubna. Using the latest version of the Geant4 toolkit, this work aims to replicate the particular design of the ZDC, which was engineered to be located at 13 m from the Interaction Point (IP) and placed in between the two beam pipes that are not parallel in that specific position. A precise ZDC geometry description was first created as a GDML solid in a FreeCAD workbench with the aim of being imported in Geant4. The main function of the ZDC consists of detecting neutral particles. Its finely segmented calorimeter design ensures to take part in polarimetry determination and luminosity measurements with high precision. This meticulous modeling of the ZDC's geometry takes into account its electromagnetic and hadronic modules, material composition, and the innovative “growing” design that enhances particle containment. The study also evaluates the detector's response to photons and neutrons with different energies. These results are benchmarked against the specifications outlined in the Technical Design Report (TDR) of the SPD collaboration.

Introduction

The Spin Physics Detector (SPD) is one of the two main experimental facilities to be installed in the Nuclotron based Ion Collider facility (NICA), which is currently under construction at the Joint Institute for Nuclear Research (JINR) in Dubna. The main goal of SPD is to study the nucleon structure and spin-related phenomena in longitudinally and transversely polarized collisions of protons and deuterons. A luminosity of 10^{32} $cm^{-2}s^{-1}$ and a maximum energy $\sqrt{s_{pp}}$ = 27 GeV is expected for p-p collisions. The SPD was designed assuring a coverage of 4π in solid angle, having a barrel part and two endcaps. [5]

The measurements of spin observables in polarized p-p and d-d collisions require a high precision polarimetry to obtain reliable values of the beam polarization and consequently the asymmetry measurements. Two detectors, located at each side of the endcaps of SPD are foreseen to provide local polarimetry and luminosity control: the beam-beam counter (BBC) and the Zero-Degree Calorimeter (ZDC).

The work developed during this period of the START program was focused on the detailed description of the ZDC geometry using the capabilities of the last version of Geant4 toolkit. This is an early stage of a broader project, aimed to develop computational methods in order to build a modular approach of the ZDC geometry based on the G4/GeoModel integration and subsequently integrate it in the SpdRoot framework.

1. Zero-Degree Calorimeter

The Zero Degree Calorimeter (ZDC) is a dedicated detector system used in collider experiments to measure neutral particles with high precision. Its design allows it to operate effectively in environments with strong magnetic fields, enabling it to focus on particles, such as neutrons, that are not deflected by these fields. The ZDC is strategically positioned within the collider infrastructure to maximize its detection capabilities and contribute to several critical measurements.

The ZDC is essential for several key functions in particle collision experiments. It provides accurate measurements of the collider's luminosity, a crucial parameter for understanding the rate of collisions. Furthermore, the ZDC is used for tagging spectator neutrons that do not participate in the collision but continue travelling at very small angles. In addition to these functions, the ZDC offers precise time tagging, which enhances the accuracy of event selection and reconstruction. It is also employed in local polarimetry studies based on forward neutrons. In this way, the longitudinal polarization settings can be verified. [5]

1.1 Geometric and design features

The ZDC is located approximately 13 meters from the Interaction Point (IP), positioned between the dipole magnets BV1E and BV2E1. This location was chosen to optimize its ability to detect particles traveling at very small angles symmetrically on both sides of the IP, which is crucial for balanced data collection. The detector is housed within the cryostat of the NICA magnets, imposing specific design constraints, such as the need to operate at cryogenic temperatures (~80 K) and within a confined space (Fig. 1) [5].

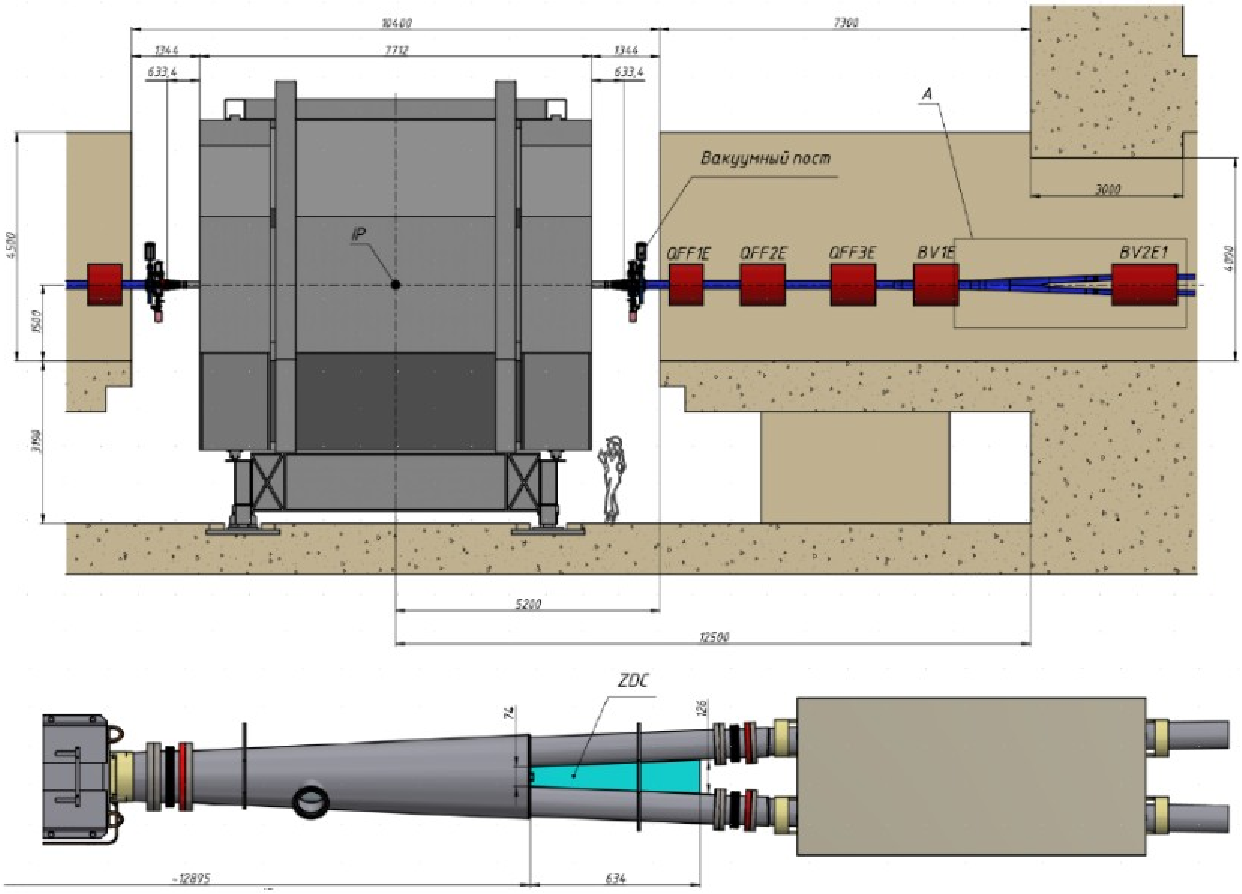


Figure 1: Placement of the ZDC on the right side of the interaction point. Top: general view. Bottom: zoom of the red inset labeled with the letter A, where the ZDC position is shown in the space between beam pipes.

The ZDC is constructed as a fine-segmented calorimeter, utilizing plastic scintillator tiles interleaved with tungsten absorber plates. This configuration enables the detector to effectively measure the energy of incoming particles. The readout system is based on Silicon Photomultipliers (SiPMs), which are directly coupled to the scintillator tiles, ensuring high detection efficiency. The calorimeter itself is divided into two sections: a front section that acts as an electromagnetic calorimeter for gamma-ray detection, and a rear section dedicated to neutron measurement (Fig. 2) [5].

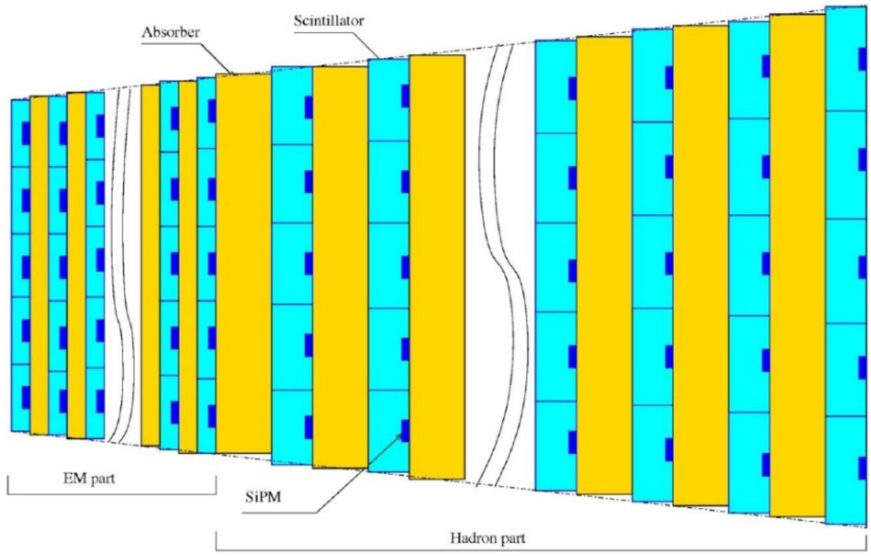


Figure 2: Schematic layout of the ZDC (taken from the TDR-SPD).

2. Geometry description to be used in ZDC simulations

The description of the geometry of this scintillation-type calorimeter detector was performed in a FreeCAD program. An effort was made to reflect the details of the physical structure of the device, as proposed in the TDR.. FreeCAD, an open-source, multi-platform computer-aided design (CAD) software, has become an indispensable tool for engineers and designers in various fields, including nuclear and particle physics. This parametric 3D software enables users to create complex models with high precision and flexibility, making it particularly suitable for particle detector design [6]. FreeCAD's main features include:

- parametric modeling, which facilitates easy design modifications through parameter adjustments;
- a modular architecture that allows for straightforward functionality extensions;
- compatibility with multiple file formats, including STEP, IGES, STL, and crucially GDML;
- a user-friendly interface that provides an accessible working environment for users of varying expertise levels.

The design process was divided into the following stages:

a) Definition of basic components (Fig. 3):

- Modeling of printed circuit boards (PCBs).
- Creation of Hamamatsu S13360-3050PE SiPM detectors.

- Design of scintillator plates.
- Modeling of tungsten absorber plates.

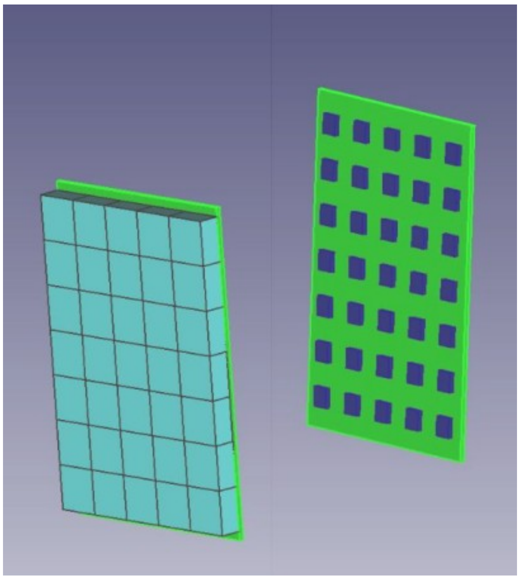


Figure 3: Left: Scintillator plate (light blue) with printed circuit board (PCB) frame (green). Right: Printed circuit board (green) with SiPM detectors (dark blue squares) arranged in a grid pattern.

b) Assembly of individual planes (Fig.4):

- Arrangement of components in a 7x5 matrix.
- Incorporation of size variations according to position in the calorimeter.

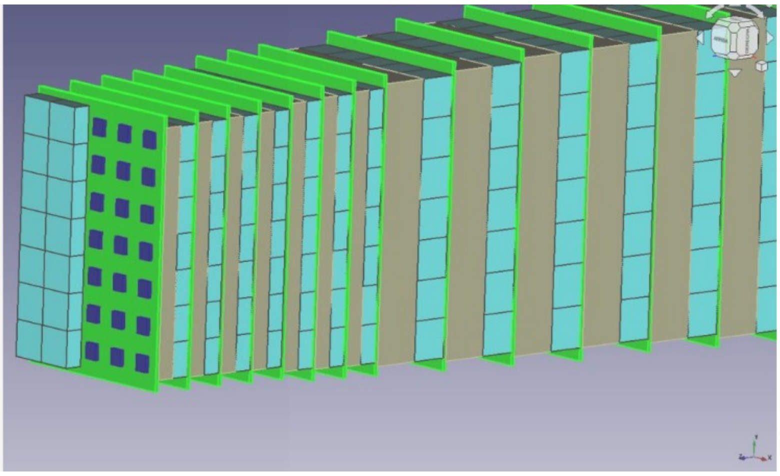


Figure 4: Assembly of individual planes: 3D model in FreeCAD showing the arrangement of absorptive plates (gray) and transparent sections to form the Zero-Degree Calorimeter (ZDC).

c) Integration of calorimeter sections (Fig. 5):

- Differentiation between electromagnetic and hadronic sections.
- Implementation of component thickness variations (10 mm for scintillators and 13 mm for absorbers in the hadronic section).

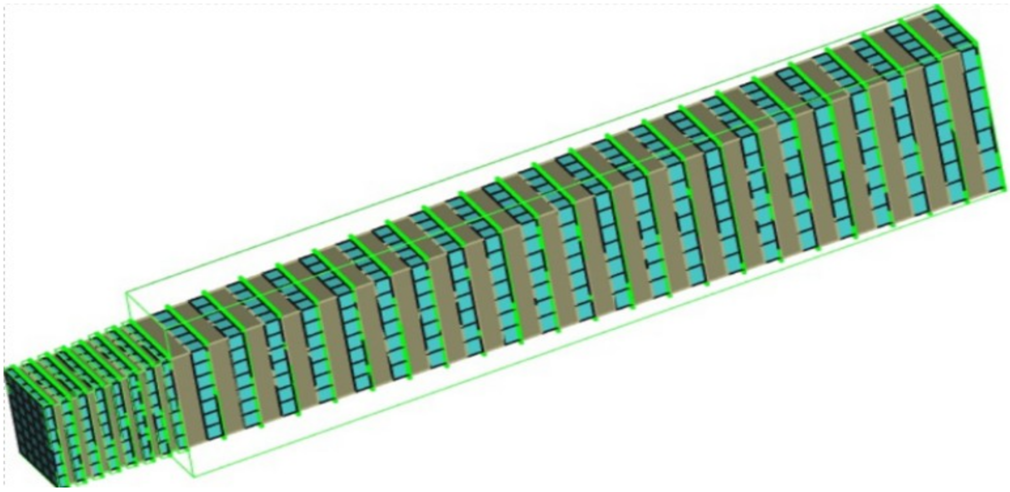


Figure 5: Integration of the calorimeter sections, consisting of 8 scintillating planes and 7 absorber planes in the EM part, and 27 alternating scintillating and absorber planes in the hadronic section.

2.1 Technical modeling details

- Dimensional precision: FreeCAD measurement tools were used to ensure exact dimensions of each component.
- Variable parameters: Parametric relationships were implemented to facilitate future adjustments in critical dimensions.

The software's possibility to generate output files in GDML (Geometry Description Markup Language) format is particularly valuable in the context of particle detector design. This feature enables a seamless transition between geometric design and particle physics simulation, as the GDML format is directly compatible with simulation tools such as GeoModel and Geant4. The synergy between FreeCAD, GeoModel, and Geant4, provided by the GDML format, establishes a coherent and efficient workflow. [4]

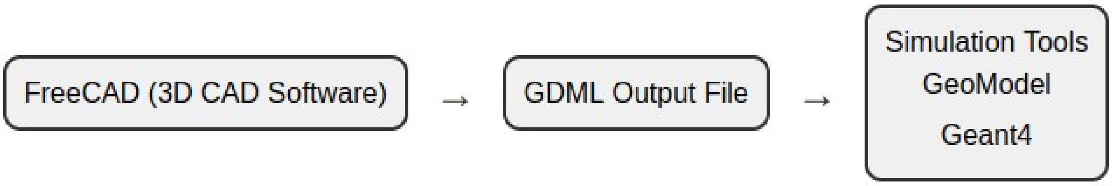


Figure 6: Workflow diagram.

This integrated approach not only saves time in transitioning between design and simulation phases but also minimizes potential errors that could arise from manual geometry translation between different platforms. Furthermore, this methodology allows for rapid iteration between design and simulation. Geant4 simulations lead to modifications in the original FreeCAD design, which can be quickly incorporated into new simulations, thus accelerating the detector optimization process.

3. GEANT 4 simulation

Geant4 is a comprehensive software package intended to simulate particle interactions with matter. It offers a wide range of tools including tracking functionalities, geometry modeling, and physical models. Its set of physical processes covers electromagnetic, hadronic, and optical interactions, with support for various particles, materials, and energy ranges.

3.1 Geometry and materials

The simulation under study presents a calorimeter design, consisting of two main modules: an electromagnetic (EM) module and a hadronic (HAD) module. The geometry of this calorimeter is constructed using a hierarchical structure of volumes, starting from the world volume and progressing to the individual detector components. The following sections describe the overall structure, specific characteristics of the EM and HAD modules, innovative design elements, the materials used in the construction, and other relevant dimensions.

3.1.1 General structure

The calorimeter is housed within a world volume, which is filled with vacuum to simulate space-like conditions. This choice ensures minimal interactions outside the detector's active volumes, thereby reducing background noise and simplifying subsequent data analysis. The calorimeter itself is composed of two distinct modules: the EM module and the HAD module.

Electromagnetic Module (EM)

The EM module is composed of 8 layers, each containing a 5x7 grid of scintillating fibers. These fibers are arranged in a regular pattern and are separated by tungsten absorber plates. The total thickness of the EM module depends on the thickness of individual layers and absorber plates.

Hadronic Module (HAD)

The HAD module, designed to detect hadronic particles such as protons and neutrons, consists of 22 layers with a fiber arrangement similar to the EM module. Like the EM module, the layers in the HAD module are separated by tungsten absorber plates. The total thickness of the HAD module also depends on the specific thicknesses of the layers and absorbers used.

In the electromagnetic section of the detector, the total thickness is 83 mm, which encompasses all components and contributes to a compact design. The thickness in terms of radiation length, X0, is 10, indicating that the detector can efficiently manage electromagnetic cascades by reducing the energy of electrons to 1/e of their initial value. Additionally, the thickness in terms of nuclear interaction length, λi, is 0.4, suggesting that the electromagnetic section is not intended to stop hadronic particles, as this value indicates the depth required for a high probability of interaction. In contrast, the hadronic section has a total thickness of 528 mm, reflecting the need for a more robust design to effectively detect hadronic particles. The thickness in terms of nuclear interaction length for this section is 3.1, further emphasizing its capability to handle hadronic interactions.

The Geant4 implementation of the HAD module would be similar to that of the EM module, but with different parameters to reflect the larger number of layers and the different absorber thicknesses.

Hierarchical Structure:

Basic Components:

- SiPMs (formerly fibers): Boxes (G4Box)
- EM and HAD layers: Boxes (G4Box)
- Absorber plates: Boxes (G4Box)
- PCB: Boxes (G4Box)

Modules:

- EM Module: Box containing EM layers, absorbers, and PCBs
- HAD Module: Box containing HAD layers, absorbers, and PCBs

Calorimeter:

- Box containing both EM and HAD modules

World:

- Global volume containing the entire calorimeter

Construction Process:
Each volume is created through three steps:
a) G4Box for the solid volume
b) G4LogicalVolume for the logical volume
c) G4PVPlacement for physical positioning

Special Features:

- A gradual increase of the size of layers is implemented.

Assigned Materials:

- SiPMs: Doped silicon (simplified)
- Scintillating layers: Scintillating plastic
- Absorber plates: Tungsten
- PCB: FR-4 (composite material of fiberglass and epoxy resin)
- Modules and Calorimeter: Vacuum (default material)
- World: Vacuum

This design approach allows for better containment of particle showers as they develop deeper into the detector (Fig.7).

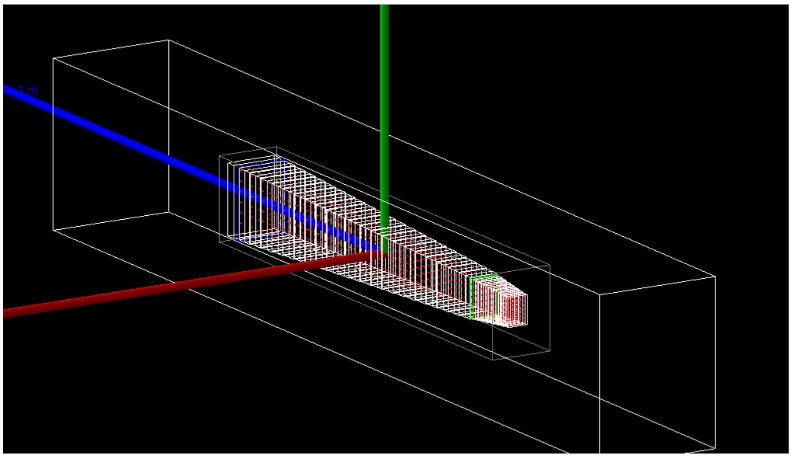


Figure 6: Geometry overview, simulated in Geant4.

This structure allows for a comprehensive simulation of particle interactions within the calorimeter, enabling accurate modeling of both electromagnetic and hadronic showers. The modular design facilitates easy modification and optimization of the detector geometry, which is crucial for fine-tuning the calorimeter's performance in various experimental scenarios.

3.1.2 Materials selection

The ZDC structure is based on a modular design that integrates several key materials:

1. *Tungsten (W) Absorber Plates:*
   - Tungsten, with atomic number 74 and density of 19.3 g/cm³, is used as the primary absorber material. Its high density and atomic number make it ideal for initiating and developing electromagnetic and hadronic cascades, allowing precise measurement of incident particle energy.
2. *Plastic Scintillator Plates:*

   - Composed mainly of carbon (97.49%), hydrogen (2.5%), and traces of oxygen (0.01%), with a density of 1.05 g/cm³. This material converts particle energy into detectable light signals. The Birks constant of 0.126 mm/MeV optimizes the scintillator response.

3. *FR-4 Printed Circuit Boards (PCB):*
   - FR-4, with a density of 1.85 g/cm³, composed of carbon (43%), hydrogen (3%), and oxygen (54%), provides the necessary structural support and electrical connections for signal acquisition.

4. *Silicon Photomultipliers (SiPM):*

Simplified in the simulation as a composition of silicon (95%), oxygen (3%), and aluminum (2%), with a density of 2.33 g/cm³. These solid-state devices offer high efficiency in detecting light signals produced by the scintillators.

The layered configuration of these materials allows for efficient detection and precise measurement of neutral particle energy. Tungsten initiates particle cascades, the plastic scintillator converts energy into light, SiPMs detect these light signals, and the PCB provides the necessary structure and connections for data acquisition.

The combination of dense absorber material, efficient scintillators, and sensitive photodetectors enables the ZDC to provide crucial information about collision centrality and energy flow in heavy-ion experiments.

Dimensions

The dimensions of the key components of the calorimeter are as follows:

- **Fibers:** Each scintillating fiber measures 3 mm x 3 mm x 0.5 mm.
- **Initial Layer Size:** The initial layer size is determined by the number of fibers and their spacing, with subsequent layers increasing in size according to the "growing" design principle.
- **EM Absorber Thickness:** The tungsten absorber plates in the EM module are 5 mm thick each, reaching a total absorber thickness of 35 mm.
- **HAD Absorber Thickness:** In the HAD module, the tungsten absorber plates are 13 mm thick each, having a total absorber thickness of 286 mm.
- **Total Calorimeter Size:** The total thickness of the calorimeter counting all layers (scintillator, absorber and PCB plates) together, is 611 mm, which means $\lambda_i = 3.5$ in terms of track lengths.

3.2 Event generation

The simulation utilizes Geant4's *PrimaryGeneratorAction* class to generate primary particles, employing the G4ParticleGun C++ class to create individual particles for each event. The characteristics of the primary particle generation are:

Neutrons and photons of 1 GeV and 12 GeV each are simulated. The primary particle generator in this Geant4 simulation implements a beam with a customizable transverse profile. The initial position of the particles was random uniformly distributed ((fRndmBeam)) in the front plane of the detector, with the direction parallel to the longitudinal axis of the ZDC detector.

The generation of one particle per event facilitates detailed tracking of each interaction. This approach allows for a granular analysis of how cascades develop and how energy is deposited in different parts of the calorimeter, crucial information for refining energy reconstruction algorithms.

3.3 Physics Lists

3.3.1 Physics Configuration for Photon

In our simulation of incident photons at 1 and 12 GeV, we have configured the physics considering the fundamental electromagnetic processes that govern the interaction of photons with matter at these energies. To achieve this, a custom EM physics package of Geant4 (**G4EmStandardPhysics_option4**) was defined, which includes the best models of standard, low and intermediate-energy, thus ensuring a high precision electromagnetic calorimetry [1].

To enhance the quality of the simulation, specific optimizations were made. Production cuts were reduced to 0.01 mm, allowing for better spatial resolution. This means that more subtle interactions can be detected and simulated. Finally, the step function was optimized to 0.2 mm and 0.1 mm, facilitating precise tracking of particle trajectories.

The justification for this configuration is based on the expected behavior of electromagnetic cascades.

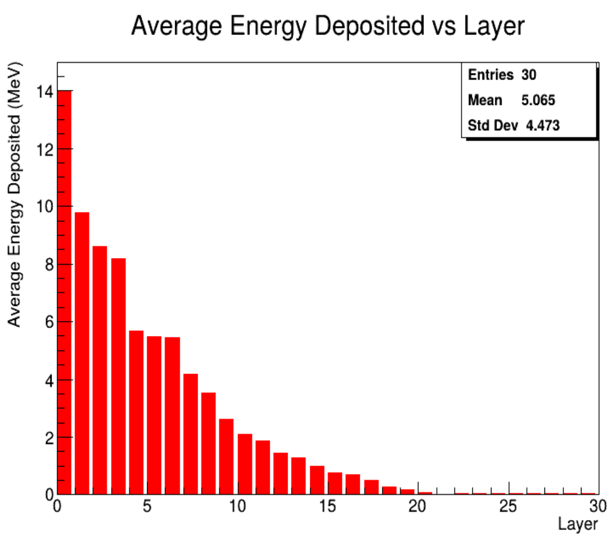
3.3.2 Physics Configuration for Neutrons

For neutrons of 1 and 12 GeV, a particular physics configuration was implemented with a physics list combining optimized models for a wide range of energies. Physics models for inelastic interactions were complemented with the integration of Fritiof and Bertini cascade model [2].

4. Analysis of the results

4.1 Longitudinal Energy Deposition Profiles

The analysis of the results from the Zero-Degree Calorimeter simulation shows a contrast in the longitudinal profile of the energy deposition of neutrons and photons.



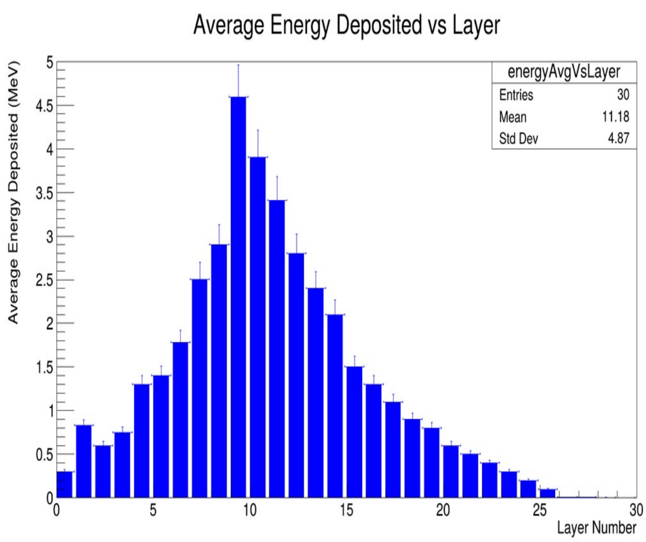


Figure 8: Energy Deposition Profiles for 1 GeV Photons (Left) and 1 GeV Neutrons (Right) in the Zero-Degree Calorimeter.

Photons of 1 GeV deposit most of their energy in the first layers of the detector, forming a well-defined electromagnetic cascade. This behavior is characteristic of the dominant electromagnetic processes at this energy.

In contrast, 1 GeV neutrons undergo inelastic scattering and nuclear processes with the detector material nuclei. As a result, neutrons produce a more extended hadronic cascade, with peak of the energy deposition taking place in the first layers of hadronic part of the calorimeter.

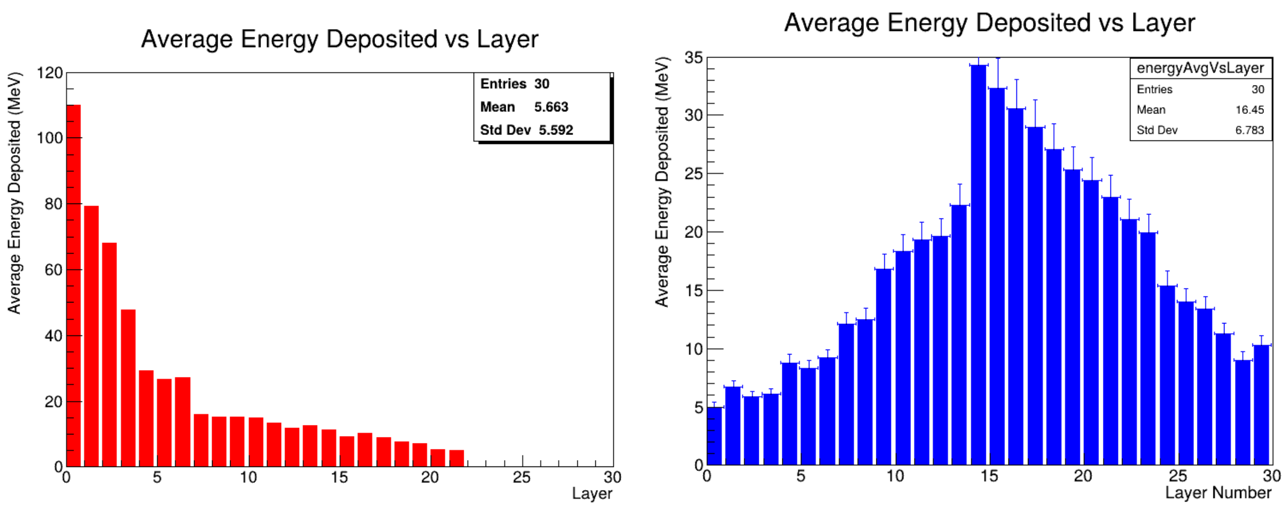


Figure 9: Energy Deposition Profiles for 12 GeV Photons (Left) and 12 GeV Neutrons (Right) in the Zero-Degree Calorimeter.

At the higher energy of 12 GeV, the energy deposition of photons is even more concentrated in the first layers of the detector, resulting in more intense electromagnetic cascades.

In the case of neutrons, the energy deposition at 12 GeV also shows a more gradual and uniform distribution across the detector layers, forming a more extended hadronic cascade compared to the neutrons at 1 GeV.

The results demonstrated different energy deposition patterns between electromagnetic and hadronic particles, validating the detector's design principles. Electromagnetic particles showed energy deposition primarily in the front layers, while hadronic particles deposited their energy more deeply in the detector, aligning with the expected behavior for this type of calorimeter. The analysis of the simulation shows that the longitudinal energy deposition profiles of photons and neutrons are clearly differentiated, which can be a valuable tool for the separation of these particles in the Zero-Degree Calorimeter.

4.2 Calculation of Deposited Energy Fraction

In sampling calorimeters, only small part of the deposited energy is measured. The fraction of how much energy is deposited varies event from event, in particular for neutrons. This fraction, assumed as the energy deposited with regard to the total energy available in each layer was collected in our simulation for each particle at both energies, 1 and 12 GeV. This allows us to estimate the energy efficiency per layer. This is shown in figures 10 and 11.

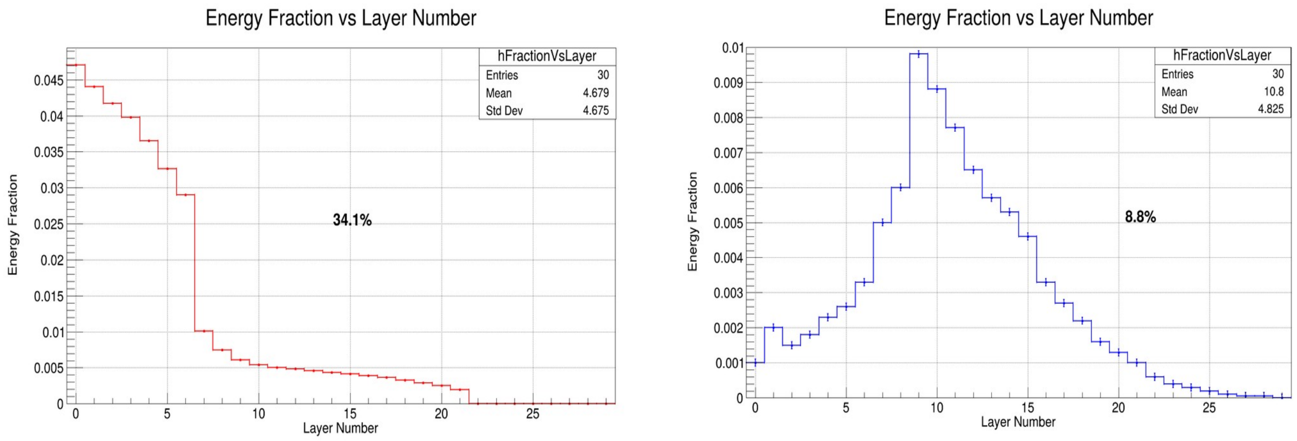


Figure 10: Energy Fraction vs Layer Number for 1 GeV Photons and Neutrons.

The graphs show the distribution of energy fraction per layer, where each point represents what fraction of the total deposited energy corresponds to each layer for 1 GeV photons and neutrons. Photons deposit larger fractions of energy in the early layers (around 0.045 or 4.5% per layer) with a steep drop-off. Neutrons (blue) exhibit different behavior, with a deposition maximum around layer 10 (approximately 0.01 or 1% of the total energy). The total percentages of 34.1% and 8.8% for photons and neutrons, respectively, represent the sum of the fractions over a specific range of layers, indicating different interaction patterns for each type of particle. This low deposited energy fraction, especially for neutrons, indicates significant energy leakage from the detector, which effectively hampers accurate identification of the incident particles.

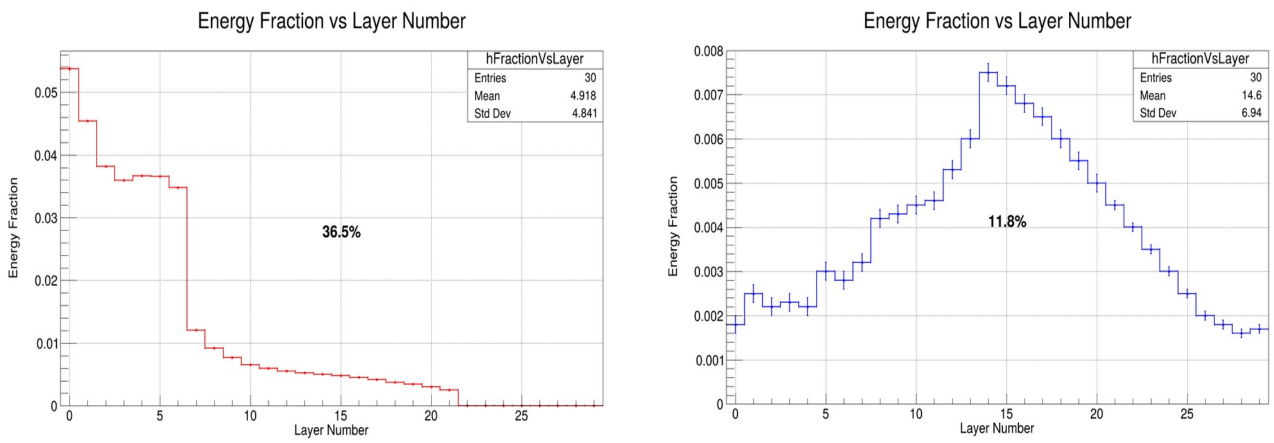


Figure 11: Energy Fraction vs Layer Number for 12 GeV Photons and Neutrons.

12 GeV photons (red) maintain a similar pattern but with a slightly higher energy fraction (36.5%) in the early layers compared to the 1 GeV case (34.1%). 12 GeV neutrons (blue) show a later deposition peak (layer 15) and a higher total fraction (11.8%) compared to 1 GeV (8.8%).

The large leakage percentage reduces the chances of precisely tagging incoming particles, and this should be investigated in the future analyses.

4.3 Energy Resolution Performance

The energy resolution is calculated for each individual detector layer to evaluate its performance. It is defined as the ratio of the Full Width at Half Maximum (FWHM) of the energy distribution to the mean (or most probable value) of that distribution, expressed as a percentage. The formula for calculating the resolution is:

$$\textit{Resolution} = (\textit{Mean} / \textit{FWHM}) \times 100\%$$

To determine the FWHM, we first fit the energy deposition histogram for each layer using either a Landau distribution or a Gaussian function, selecting the fit that best describes the data based on the chi-squared statistic. The mean and the standard deviation obtained from the best fit are then used to compute the FWHM, which is essential for calculating the resolution. The average energy resolution is calculated considering all the valid layers of the detector. Additionally, the statistical error of this average value is determined, which is important to understand the uncertainty associated with the measurement [3].

The report presents the results of the energy resolution for photons and neutrons at different energies. According to the data shown, the energy resolution worsens as the energy of the particles increases.

Particle Energy Resolution and Uncertainty Measurements

Particle Type	Energy (GeV)	Resolution (%)	Uncertainty (%)
Photons	1	11.3445	± 1.29358
Photons	12	15.836	± 4.50776
Neutrons	1	13.2335	± 5.29296
Neutrons	12	27.8866	± 10.1827

Table 1: Comparative Analysis of Energy Resolution and Uncertainty Measurements for Photons and Neutrons at Different Energy Levels.

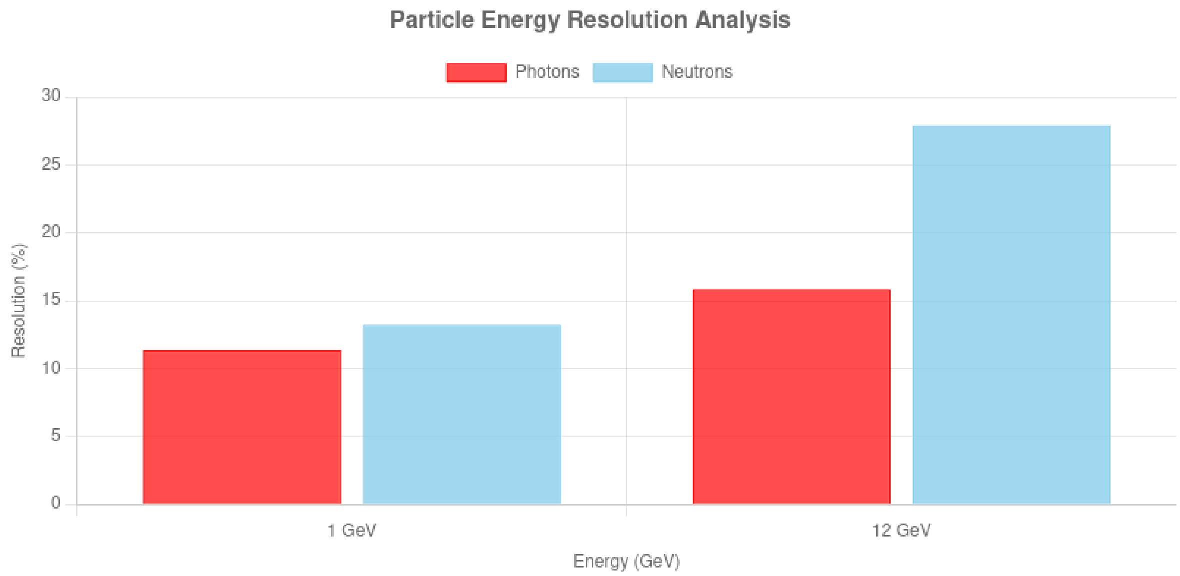


Figure 12: Energy Resolution Comparison Between Photons and Neutrons at 1 GeV and 12 GeV.

For photons, the resolution is 11.3% at 1 GeV and increases up to 15.8% at 12 GeV. On the other hand, for neutrons the resolution is worse, ranging from 13.2% at 1 GeV to 27.9% at 12 GeV. This indicates a better ability to detect the energy of photons than neutrons, especially at higher energies.

Additionally, the uncertainty associated with these simulations is reported, which also increases with the energy of the particles. For photons, the uncertainty ranges from 1.2% at 1 GeV to 4.5% at 12 GeV, while for neutrons it varies from 5.3% at 1 GeV to 10.2% at 12 GeV. While the reported energy resolutions are relatively low, it is important to note that these are preliminary results, and the collaboration is continuously studying and working to improve the performance of the detector.

Conclusions

A detailed model of the ZDC geometry was created using the information provided in the Technical Report and the Conceptual Design Report of the SPD. The implementation of FreeCAD software significantly enhanced our understanding of its geometric structure, which consists of the electromagnetic and hadronic modules, thus achieving the first specific objective of detailing the detector's geometry.

Using version 11.3.0 of the Geant4 toolkit, the detector's response to photons and neutrons with different energies was studied. The simulation results showed different longitudinal energy distributions for neutrons and photons, providing a solid basis for neutron/photon separation in future analyses, validating these results against the specifications in the SPD Technical Design Report, thus achieving the third specific objective.

This work represents an initial stage of a broader project aimed at developing computational methods to construct a modular approach to the ZDC geometry based on G4/GeoModel integration, with subsequent incorporation into the SpdRoot framework. The results obtained not only validate the proposed design but also establish a solid foundation for future optimizations and more detailed analyses of the detector, significantly contributing to the development of the SPD experiment within the NICA complex.

Acknowledgements

I would like to thank all the people who made not only this work possible but also supported me on this journey. I am grateful to my friends in Cuba who always believed in me, and to the new friends who accompanied me on my adventures: Deniel, Abel, my new brother Jorge Joe, as well as the sweetest person I have ever met, Madelaine, and a very cheerful person who showed me that Russia can be beautiful, Anya.

I cannot forget to mention a special person, Ana Laura, who, even though I was far away, helped me wake up early when I needed to work, as if she were close by. I would also like to thank my family for their support in many ways: my parents, Tamara and Roberto, for being the support that any daughter needs to take on new challenges in life, and my sister, Thaila, for always giving me kind advice over the phone. Special thanks to Cesar Ceballos Melian, who has seen wonderful things in me since he met me, even when I didn't know they existed.

Last but not least, I want to thank my mentors: Professor Fernando Guzman, to whom I will be eternally grateful for introducing me to this research topic, and my supervisor Katherin, from whom I have learned so much. She guided me through my first research experience in a very sweet yet demanding way. It is truly an honor to have such a researcher as my first mentor in such a prestigious place as JINR.

Thank you to the organizers of START Program for this wonderful opportunity.

Bibliographical References

[1] J. Allison et al., Geant4 Developments and Applications, IEEE Trans. Nucl. Sci. 53 (2006) 270-278.

[2] J. Allison et al., Recent Developments in Geant4, Nucl. Instrum. Meth. A 835 (2016) 186-225.

[3] S. Agostinelli et al., Geant4 – A Simulation Toolkit, Nucl. Instrum. Meth. A 506 (2003) 250-303.

[4] J. Boudreau and V. Tsulaia, The GeoModel Toolkit for Detector Description, Computing in High Energy and Nuclear Physics. Proceedings, Conference, CHEP'04, Interlaken, Switzerland, Sept. 27 – Oct. 1, 2004 (2005) 353-356.

[5] V. Abazov et al. [SPD Collaboration], Technical Design Report of the Spin Physics Detector at NICA, arXiv:2404.08317 (2024).

[6] J. Riegel, W. Mayer and Y. van Havre (2001-2017). FreeCAD (Version 0.16.6712) [Software] Available from http://www.freecad.org.