JOINT INSTITUTE FOR NUCLEAR RESEARCH

Veksler and Baldin Laboratory of High Energy Physics

FINAL REPORT ON THE START PROGRAMME

Simulation of the SPD Beam-Beam Counter tile response

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Participation period: 15.02.2026 – 11.04.2026,
Winter Session 2026

Dubna, 2026

Abstract

The Spin Physics Detector (SPD) collaboration plans to install a universal detector at the southern interaction point of the NICA collider, currently under construction at the Joint Institute for Nuclear Research (Dubna), with the aim of investigating the spin structure of the proton and deuteron, as well as other spin-related processes and phenomena in collisions of polarized proton and deuteron beams at centre-of-mass energies of up to 27 GeV and luminosities of up to 10^{32} cm^{-2} s^{-1} [1].

To monitor beam polarization and measure luminosity, two planes of the Beam–Beam Counter (BBC) scintillation detector will be installed symmetrically with respect to the interaction point.

This work addresses the development of a Geant4 simulation model for a scintillator tile of the Beam-Beam Counter detector (BBC).

Contents

1. Introduction

According to astrophysical and cosmological data, visible baryonic matter accounts for approximately 5% of the total mass of the Universe. Despite significant advances in Quantum Chromodynamics (QCD), the question of why nucleons have their observed properties remains open. Understanding the structure and fundamental properties of the nucleon directly from quark and gluon dynamics is one of the central unsolved problems in QCD.

An important characteristic of nucleons is their spin, equal to $\hbar/2$. It governs fundamental phenomena such as the magnetic moments of protons and neutrons, various phases of matter at low temperatures, the properties of neutron stars, and the stability of the known Universe. Gluons, together with quarks, are the fundamental constituents of the nucleon. The nucleon spin depends on the intrinsic spins of valence and sea quarks (spin-1/2), gluons (spin-1), and their orbital angular momenta. Despite progress made in recent decades in understanding the quark contribution to nucleon spin, the gluon contribution remains poorly constrained, partly due to the absence of direct methods for determining the gluon content in high-energy processes.

The Spin Physics Detector (SPD) collaboration plans to install a universal detector at the southern interaction point of the NICA collider, currently under construction at the Joint Institute for Nuclear Research (JINR, Dubna). The experiment will study the spin structure of the proton and deuteron, as well as other spin-related processes, using polarized proton and deuteron beams at collision energies up to 27 GeV and luminosities up to 10^{32} cm^{-2}s^{-1} [1].

For beam polarization monitoring and luminosity measurement, two planes of the scintillation Beam-Beam Counter detector will be installed symmetrically with respect to the interaction point. Reliable operation of the BBC requires an accurate Geant4 simulation model that correctly describes the optical and geometric properties of its components.

2. SPD and BBC

The SPD experimental setup is designed as a universal 4π detector with particle identification and tracking capabilities. The Beam-Beam Counter will be positioned symmetrically with respect to the interaction point at a distance of 1716 mm from it (Fig. 1) [2].

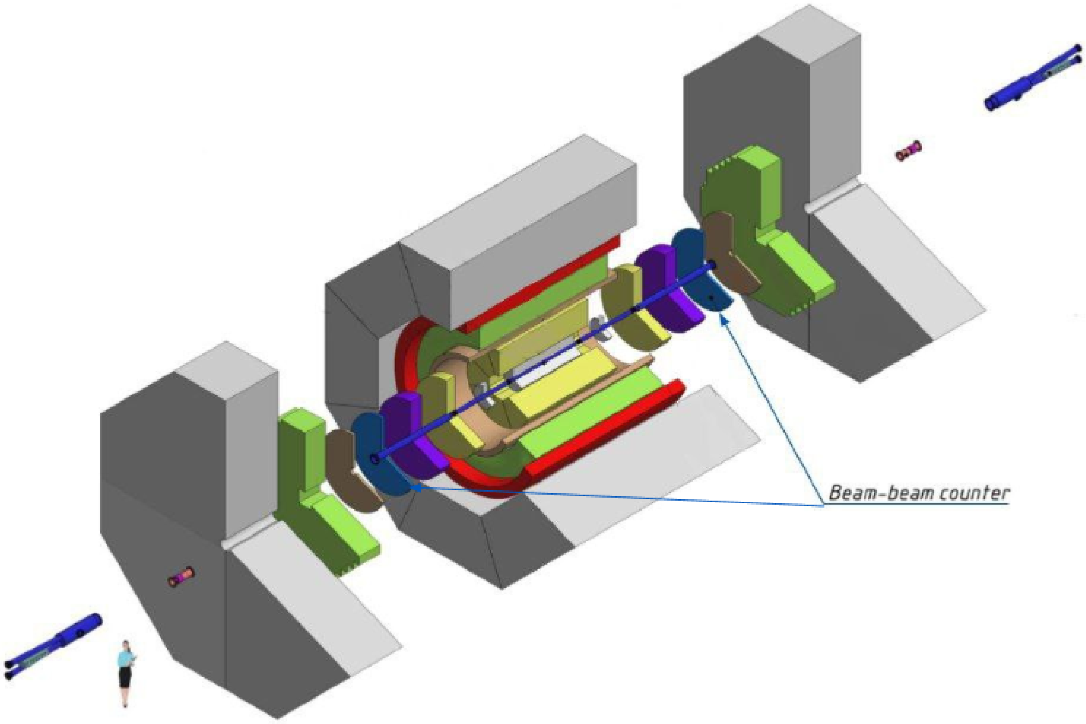


Figure 1: The layout of the SPD experiment with the BBC detector indicated

2.1. BBC Design

The BBC is a scintillation detector consisting of 16 sectors [2] (a drawing of a single sector is shown in Fig. 2). One sector comprises 13 rows (it is currently planned to omit the farthest row from the center). The first and second rows (from the center) contain one tile each, while the remaining rows contain two tiles each. The tiles are made of plastic scintillator composed of polystyrene (98.0–98.5%), p-terphenyl (1.5–2.0%), and POPOP (0.01–0.04%). Within each tile, grooves are made for wavelength-shifting fiber, which is necessary for re-emitting light from one wavelength range to another, as well as for transporting photons to the readout elements. The fiber is fixed inside the groove using an adhesive that is transparent to scintillation photons. The experiment will employ wavelength-shifting fiber of the Kuraray Y11 S-type with a single cladding and an outer diameter of 1 mm.

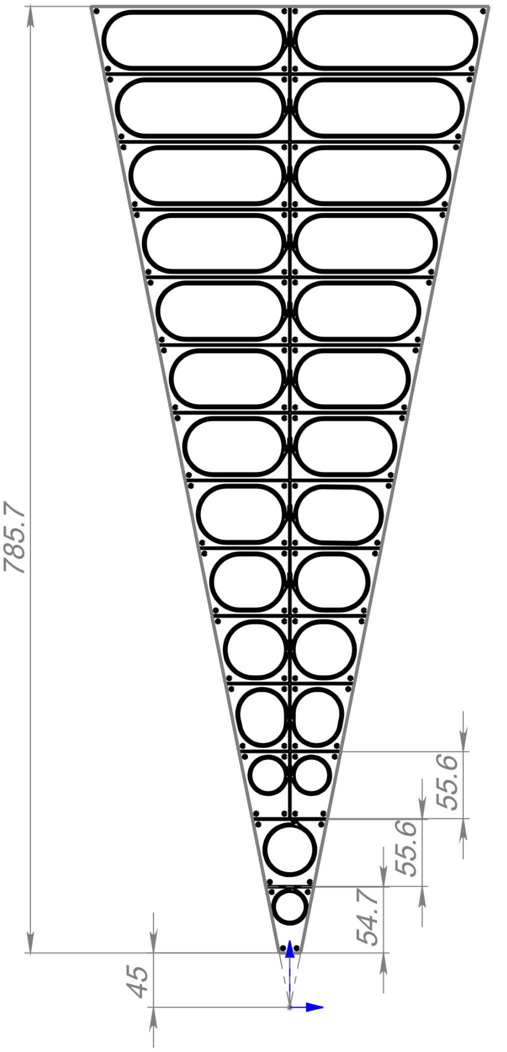


Figure 2: Sector drawing

2.2. Project Goals

- Develop a Geant4 simulation model of the BBC scintillation tile using standard Geant4 primitives.
- Comparison of the tile model with the experimental data obtained with an X-ray tube.

3. Geant4 Package

Geant4 (an acronym for GEometry ANd Tracking) is a software package designed for simulating the passage of elementary particles through matter using Monte Carlo methods [3]. Developed by the Geant4 Collaboration (CERN and other scientific institutions), this package is written in C++ using an object-oriented approach. The first versions of Geant4 were released in 1998 and have since been actively employed in high-energy physics, nuclear research, medical physics, and other fields.

Geant4 enables the construction of detailed geometric and physical models of particle detectors, comprising numerous components of various shapes and materials. Furthermore, Geant4 supports the visualization of simulation results using the ROOT program [4], including the generation of graphs. The package also provides tools for event visualization-displaying the geometry of the simulated setup, as well as the tracks of primary and secondary particles-thereby facilitating the analysis of interaction processes.

Geant4 implements the simulation of particle interactions through a system of classes grouped by functionality.

4. Geant4 model of the BBC tile

4.1. Configuration of Materials

To simulate the scintillation process, it is necessary to include the G4OpticalPhysics package of physical processes. In addition, it is required to specify not only the chemical composition of the materials used but also their optical characteristics. Table 1 describes the optical parameters of the materials of the tile components for modeling the BBC prototype.

Table 1: Parameters of the scintillator material

Parameter name	**Description**	**Value**
Resolution Scale	Fraction of the energy spectrum involved in generation	1.0
Scintillation Yield	Light yield per unit energy loss	$1200\frac{1}{\mathrm{MeV}}$
Scintillation time constant 1	Decay time of the fast component of the scintillation flash	2.4 ns
Scintillation Yield 1	Fraction of the fast component in generation	1.0

4.2. Simulation of Particle Incidence on the Tile

One of the key stages in constructing a model of an experimental setup is the specification of the physical processes occurring in the detector during its operation. In Geant4, most of these processes are grouped into software packages, the selection of which depends on the specifics of the problem being simulated. In the case of a scintillation detector, the main ones are electromagnetic processes (in particular, ionization energy losses of charged particles when passing through the scintillator volume) and optical processes responsible for the propagation of optical photons.

The following physics modules were used for the BBC prototype simulation:

- **FTFP_BERT** — the physics list recommended for high-energy physics applications, including standard electromagnetic processes via `G4EmStandardPhysics_option4`;
- **G4OpticalPhysics** — an additional module for optical processes (not included in FTFP_BERT), connected separately to handle scintillation photon propagation.

4.3. Simulation configuration

The simulation was performed according to the scheme shown in Fig. 3. Geometric parameters of the tile are presented in Table 2. γ-quanta with energy sampled from the X-ray tube spectrum were generated over the entire surface of the tile in the direction perpendicular to its plane with a step of 1 mm (hereinafter referred to as the grid), with the energy spectrum corresponding to that of the X-ray tube. For each grid point, 10^4 events were simulated. In order to increase the uniformity of irradiation over the entire tile surface, the coordinates of the photon entry point in each event were additionally smeared by adding a random displacement within a circle of radius 2.5 mm relative to the grid point. The number of photons captured by the optical fiber (marked as photon counter in Fig. 3) was used as the response.

Table 2: Geometric Characteristics of the 5th Row Tile

Parameter	**Description**	**Value**	**Unit**
Trapezoid height	Height of the trapezoidal base	55.61	mm
Major base length	Length of the longer parallel side	64.26	mm
Minor base length	Length of the shorter parallel side	53.19	mm
Prism thickness	Depth (extrusion) of the prism	10.00	mm
Groove depth	Depth of the groove	8.00	mm
Fiber diameter	Fiber model diameter	1.00	mm

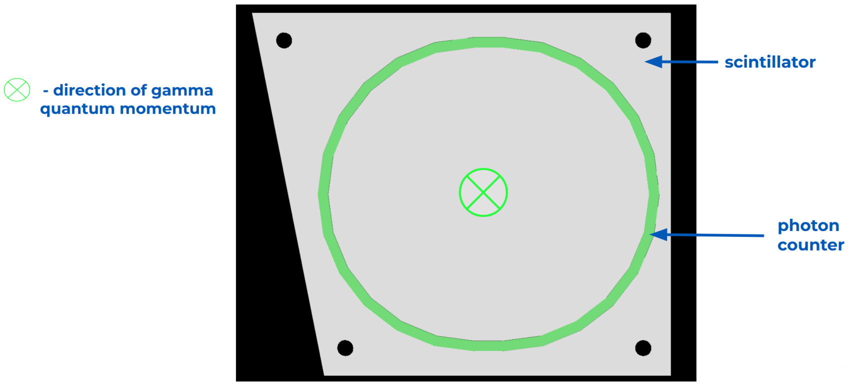


Figure 3: Simulation configuration

5. Results and discussion

5.1. Experimental setup

An experiment was conducted in the laboratory in which a tile was irradiated with X-rays. The purpose of the measurements was to study the average/maximum response of the tile to particles as a function of the interaction point position. To this end, the position of the X-ray tube was varied in steps of 1 mm, and the output current from the silicon photomultipliers and subsequent front-end electronics was measured. A photo of the setup is shown in Fig. 4. The setup employs an AMPTEK Mini-X X-ray tube (indicated by the arrow), a NEMA17 stepper motor, an Arduino CNC Shield microcontroller, and a CAEN DT5202 power supply. The entire assembly is placed in a light-tight box [5].

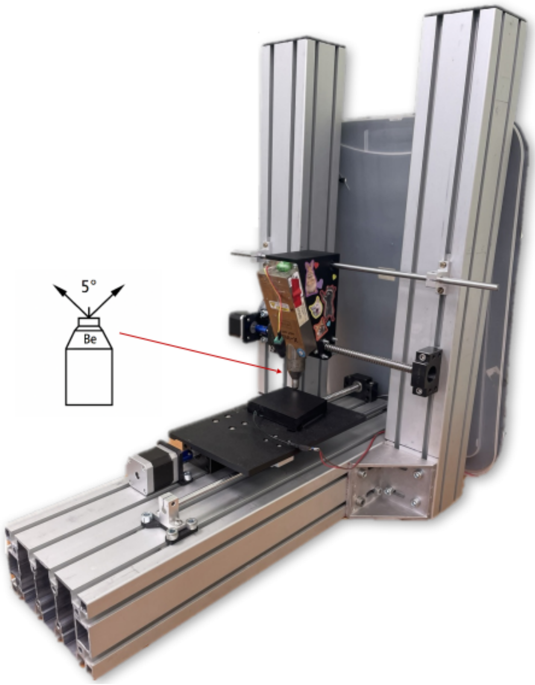
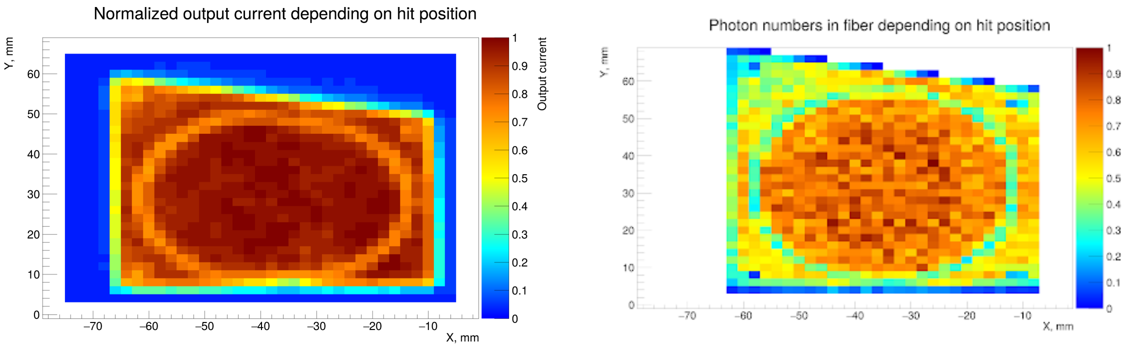


Figure 4: Photo of the experimental setup

5.2. First comparison of results

In Geant4, accurate simulation of photon propagation in a medium requires explicit definition of the optical surface parameters at the interface between two adjacent media. In the first model developed, the photon reflection coefficient for propagation from the scintillator into air was set to 0.9. The optical fiber model was placed inside the groove, and the remaining space was filled with vacuum. Based on the experimental and simulation results, the data presented in Fig. 5 were obtained (both histograms are normalized to the maximum).



(a) (b)

Figure 5: (a) - experimental data, (b) - simulation data

A clear difference in the uniformity of the response is observed. For its quantitative assessment, the histograms were normalized to each other. The result of the division is shown in Fig. 6. It was found that photons generated near the edge of the scintillator reach the fiber with a lower probability. Edge effects (top, bottom, right) are also clearly pronounced. The cause of these effects has not yet been explained. It is hypothesized that this phenomenon is related to inaccuracies in the translation of coordinates from the experimental reference frame to the simulation reference frame. A detailed study requires obtaining new experimental data.

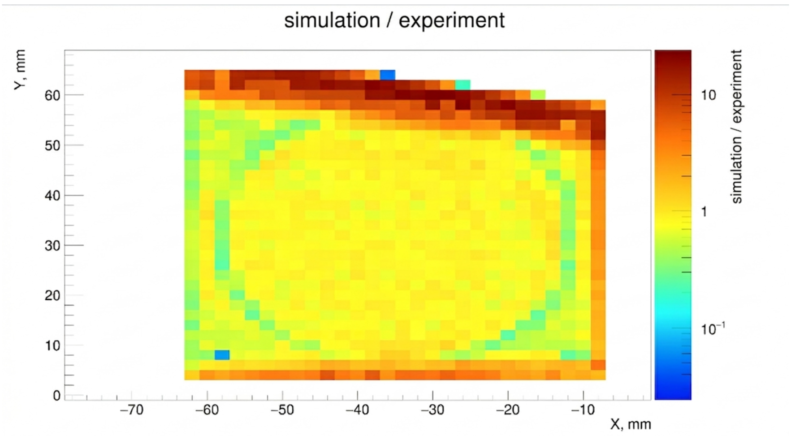
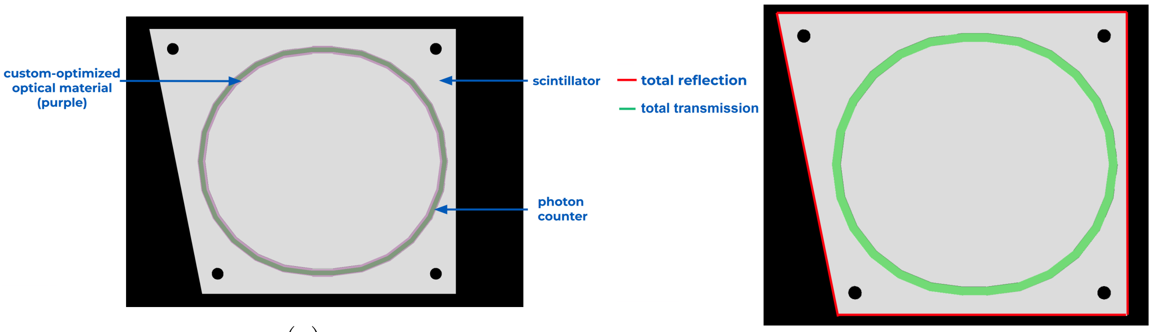


Figure 6: Histograms ratio

5.3. Result of the updated model

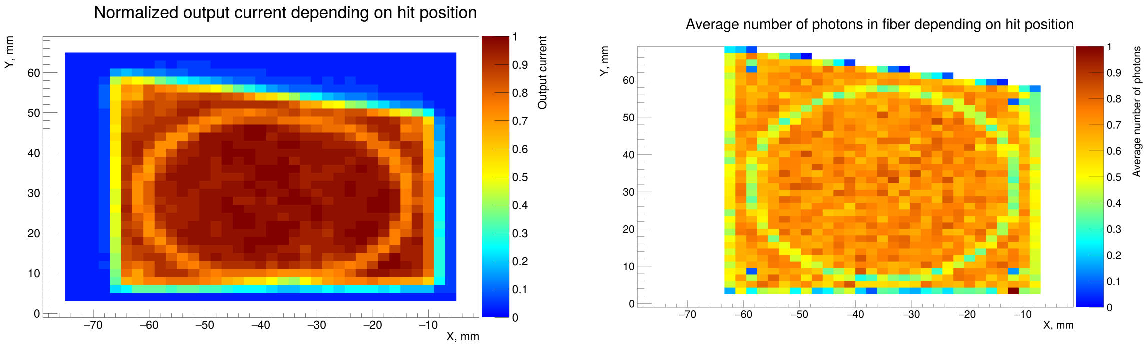
To bring the simulation closer to the experiment, a new model is proposed, shown in Fig. 7 (a). In contrast to the first model, the entire groove of the tile is filled with a special material (indicated in purple), whose optical properties are equivalent to those of the scintillator, with the sole exception that this material does not emit photons. Additionally, the photon reflection coefficient at the inner surface of the tile at the tile–air interface has been changed and set to 1.0. Thus, photons can leave the tile or enter the optical fiber only through the surface of the groove (Fig. 7 (b) illustrates the above). In such a simulation, regardless of the point at which the particle traverses the scintillator, all emitted photons will be collected by the fiber.



(a) (b)

Figure 7: (a) - New simulation configuration, (b) - Reflection illustration

The simulation of interaction with gamma quanta was performed analogously to the previous model. The simulation result is shown in Fig. 8 (both histograms are normalized to the maximum).



(a) (b)

Figure 8: (a) - experimental data, (b) - new simulation data

The uniformity of the response across the surface is immediately evident. To assess its quality, the ratio of the histograms was also obtained (Fig. 9). Outside the groove and the edges, the ratio is close to unity, which qualitatively indicates the correctness of the model's performance.

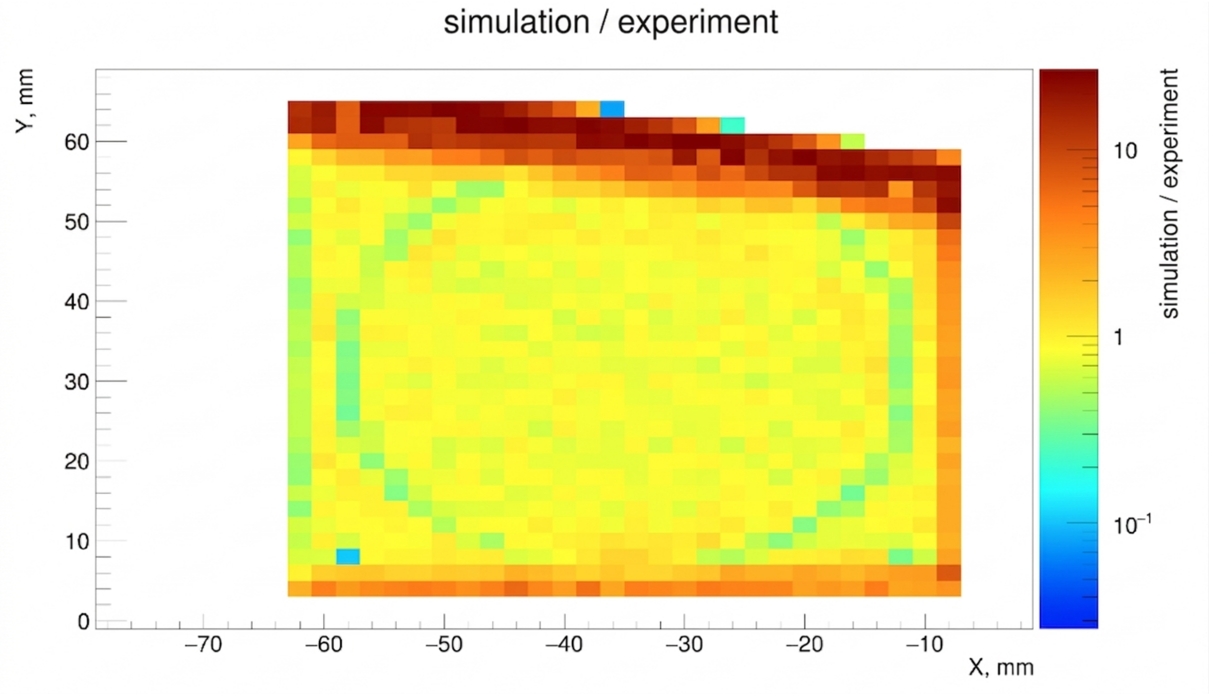


Figure 9: Histograms ratio (new simulation)

6. Conclusions

The result of this work is a Geant4 model of the scintillator tile of the BBC detector for the SPD experiment, which qualitatively describes the detector's performance. Further improvement of simulation accuracy necessitates validation of the model against independent experimental data.

Further stages of work:

1. Validation with new experimental data;
2. Parameterization of the optical fiber;
3. Configuration of the models for the entire detector tiles;
4. Threshold adjustment and digitization of hits.

Once the model of the entire wheel is created, it can be used for Monte Carlo simulations of the processes expected in the SPD experiment prior to the start of the experiment. This will help to form an understanding of the detector's performance as well as the expected results in advance.

Acknowledgments

The author would like to thank Dr. V. P. Ladygin for supervision and guidance throughout the project. The work was carried out within the framework of the JINR START Programme, Winter Session 2026.

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