



The SHADOWS calorimeter — A pointing calorimeter for future beam dump experiments

C.C. Delogu^a, V. Büscher^a, R. Degele^a, K. Geib^a, S. Ritter^a, S. Schönfelder^b, R. Wanke^a

^a Institute of Physics - Johannes Gutenberg Universität, Staudingerweg 7, 55128, Mainz, Germany

^b Detector Laboratory, PRISMA+ Cluster of Excellence - Johannes Gutenberg Universität, Staudingerweg 9, 55128, Mainz, Germany

ARTICLE INFO

Keywords:

Calorimetry
Pointing calorimeter
Feebly-interacting particles

ABSTRACT

This contribution presents advancements in the design and testing of an electromagnetic calorimeter intended for the detection of feebly interacting particles in future beam dump experiments. The calorimeter is designed to accurately reconstruct particle decays into photons, focusing on achieving precise energy and direction measurements. We propose a plastic scintillator-based calorimeter capable of providing the necessary resolution for these measurements. The pointing capability has been validated through GEANT4 simulations, optimizing scintillator granularity for effective shower direction reconstruction. Additionally, we detail the prototyping efforts and the first results of test beam measurements conducted at DESY.

1. Introduction

Future research on Feebly Interacting Particles (FIPs) will focus on reconstructing novel decay processes, such as the decay of Axion-Like Particles (ALPs) into two photons. An electromagnetic calorimeter designed for these studies should fulfill several functions. First, it must provide a sufficiently accurate energy measurement to perform particle identification. Achieving an energy resolution of $\frac{\sigma(E)}{E} \simeq 10\% - 15\% / \sqrt{E[\text{GeV}]}$ is sufficient for this application [1]. Second, the calorimeter should provide a measurement of the shower direction, to determine the masses of decaying particles in scenarios involving only neutral particles like $\text{ALP} \rightarrow \gamma\gamma$.

Such a detector was originally proposed for the SHADOWS Collaboration [1], and could now be employed at the SHIP experiment [2].

2. Design and simulation

The proposed technology is a sampling calorimeter, consisting of 9 mm ($\simeq 0.5X_0$) thick iron absorber plates, and 1 cm thick plastic scintillator strips as active material. The key aspect of the design is the choice of scintillator granularity. To be cost-effective, the plastic scintillator is segmented into strips, that alternate in the horizontal and vertical directions. The strips are positioned perpendicularly with respect to the incoming beam direction. For the simulation, the calorimeter cross section is $2.5 \times 2.5 \text{ m}^2$ (matching dimensions in the original SHADOWS proposal [1]), and a total length of 1 m corresponding to 40 layers and about 20 radiation lengths. Electromagnetic showers up to 10 GeV are contained within the calorimeter.

This detector has been simulated in GEANT4 [3], and the response to photons hitting at different angles and energies has been evaluated. The stochastic term of the energy resolution is about 11% for all incident angles. The shower direction is determined by calculating the barycenter of the energy deposits in each layer and fitting a line through these points to estimate the angle of the shower [1].

The reconstruction of the shower direction from the simulated data allows to determine the optimal granularity of the active material. As shown in Fig. 1, shower directions from photons hitting the calorimeter at low angles are well reconstructed only for scintillator strips with a width of 1 cm or less. For wider strips, photons with small incident angles are reconstructed as if they had hit the calorimeter perpendicularly. Strips narrower than 1 cm do not offer further advantages in shower direction reconstruction. Each layer is therefore segmented into 250 strips of $1 \times 1 \times 250 \text{ cm}^3$. Strips of this length cannot be read out directly, so the scintillation light of each strip is collected by wavelength-shifting (WLS) fibers, which are read out by a Silicon Photomultiplier (SiPM) on each side of the strip.

Such a calorimeter achieves a good angular resolution, independent of the incident angle of photons, reaching 12 mrad at 20 GeV (see Fig. 2).

3. Prototyping and test

To validate the design, a small calorimeter prototype was built and tested in early 2024 (Fig. 3). The prototype consists of 9 layers, each with an active area of $20 \times 20 \text{ cm}^2$, and a total of 180 channels. Co-extruded scintillator strips, $1 \times 1 \times 20 \text{ cm}^3$, are read out by 1 mm

* Corresponding author.

E-mail address: cdelogu@uni-mainz.de (C.C. Delogu).

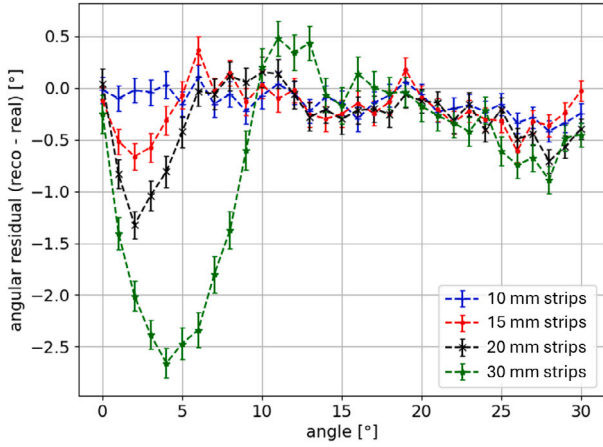


Fig. 1. Residuals between real and reconstructed shower directions as a function of the incident angle, for 2 GeV simulated photons and different strip widths.

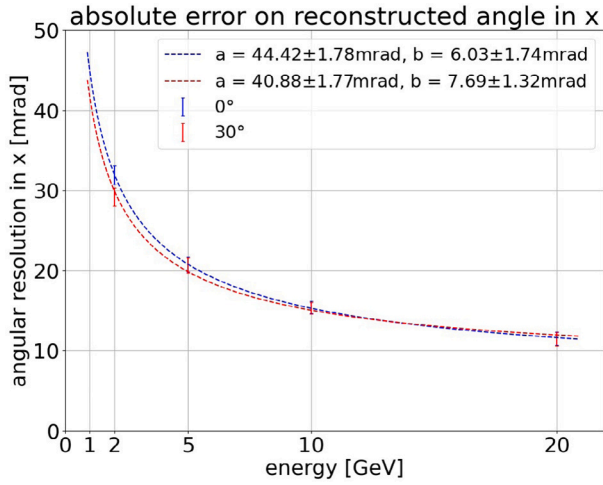


Fig. 2. Angular resolution in the x -direction, obtained using the strips aligned along the x -axis, for different simulated photon incident angles, fitted to $\sigma(\theta) = \frac{a}{E} \oplus b$. Similar performance is found in the y -direction, using the strips aligned along the y -axis.

diameter WLS fibers from Kuraray (YS2) and Hamamatsu $1.3 \times 1.3 \text{ mm}^2$ SiPMs (S13360-1325PE). Due to the reduced dimensions of the prototype, each strip is read out by a single SiPM. The strips are fixed into place on 4 mm thick iron plates. The modularity of the design allows to insert multiple iron plates, to test different setups in terms of radiation lengths.

The prototype was tested at DESY in March 2024, with an electron beam in the 1 to 5 GeV range. The calorimeter was tilted by five different angles from 0° to 20° , and the insertion of one or more iron layers allowed to change the radiation length in different sets of measurements.

Data analysis is still ongoing, however first results show that simulation and test beam data are in good agreement. The simulation has been adapted to reflect the change in absorber thickness (from 9 mm in the baseline design to 4 mm in the prototype). Fig. 4 shows a preliminary study on the angular resolution of the prototype, where the test beam data are compared to the simulation of the full detector.

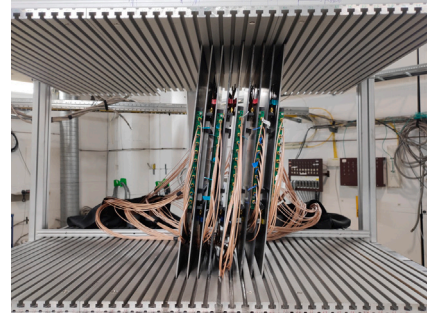


Fig. 3. Layers of iron and scintillator strips in the prototype. In this configuration, the prototype contains 1 Iron layer per active layer, for a total of $2 X_0$, and is tilted by 2.7° with respect to the beam. The electron beam comes from the right.

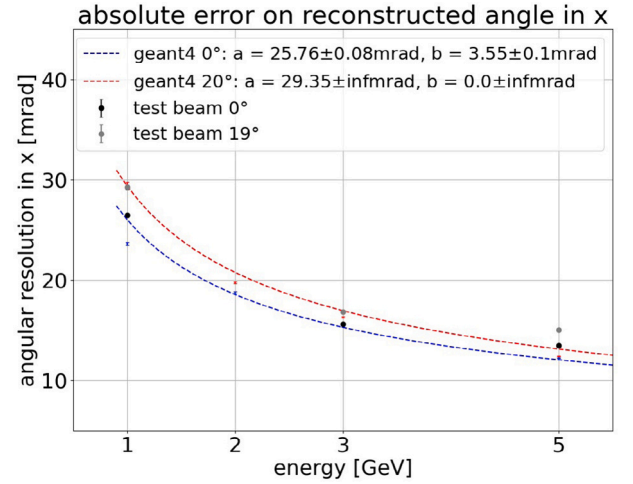


Fig. 4. Angular resolution in x , for a GEANT4 simulation of the prototype (dashed lines) and with test beam data (dots). Fitted to $\sigma(\theta) = \frac{a}{E} \oplus b$. A slight performance drop at 5 GeV in test beam data is due to shower leakage.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF). We would like to thank the local staff for their assistance during the test beam time.

References

- [1] M. Alvggi, et al., SHADOWS Collaboration, SHADOWS Technical Proposal, CERN, Geneva, 2023, URL: <https://cds.cern.ch/record/2878470>.
- [2] R. Albanese, et al., SHiP Collaboration, BDF/SHiP at the ECN3 High-Intensity Beam Facility, Technical Report, CERN, Geneva, 2023, URL: <https://cds.cern.ch/record/2878604>.
- [3] S. Agostinelli, et al., GEANT4 Collaboration, GEANT4—a simulation toolkit, Nucl. Instrum. Methods A 506 (2003) 250–303, [http://dx.doi.org/10.1016/S0168-9002\(03\)01368-8](http://dx.doi.org/10.1016/S0168-9002(03)01368-8).