Energy resolution of the GRAiNITA protoype detector

D. Klekots[a], S. Barsuk[b], O. Bezshyyko[a], A. Boyarintsev[c], I. Boyarintseva[b,c], D. Breton[b], H. Chanal[d], A. M. Dubovik[c], L. Golinka-Bezshyyko[a], Y. Hou[d], G. Hull[b], *Member, IEEE*, J. Lefrancois[b], J. Maalmi[b], M. Magne[d] S. Monteil[d], D. Picard[d], M.-H. Schune[b], I. Tupitsyna[c], M. Yeresko[d]

[a]Kyiv National Taras Shevchenko University, 01033 Kyiv, Ukraine
[b]Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France
[c]Institute for Scintillation Materials of the National Academy of Sciences of Ukrain, 61072 Kharkiv, Ukraine
[d]Université Clermont Auvergne, CNRS/IN2P3, LPCA, F-63000 Clermont-Ferrand, France

***Abstract*— We will present the outcomes of a GEANT4 simulation study of the energy resolution that can be achieved with a GRAiNITA detector.**

GRAiNITA is a new-generation sampling calorimeter based on the use of high-stopping power inorganic scintillator grains evenly distributed in a volume of high-density liquid, as absorber. As in a shashlik detector, the scintillation light produced by the grains, can be collected to the photodetectors by means of wavelength-shifting fibers.

The characterization of a GRAiNITA prototype, filled with $ZnWO_4$ grains, proved that a stochastic fluctuation of 1%/√E[GeV] on the energy resolution, due to photo-electron statistics, is at reach [1]. While this result is really encouraging, the estimation of the constant term contribution to the energy resolution, due the non-uniformity of the detector response and to the containment of the electromagnetic shower in the detection volume, remains crucial to demonstrate the real effectiveness of GRAiNITA.

***Index Terms*— Shashlyk calorimeter, Energy resolution, Opaque scintillator, $ZnWO_4$, FCC detector**

I. Introduction

IN order to perform precise flavour physics in future FCCe+e experiments, an excellent photon energy resolution will be necessary [2], and, for this reason, the newly introduced GRAiNITA detector [3],[4], seems to be an appealing candidate as electromagnetic calorimeter in the FCC e+e- context.

GRAiNITA is an extremely fine sampling calorimeter based on the opaque scintillation technique. The innovative idea consists in using high-Z scintillator grains (size ~ 1mm) in a bath of high-density liquid. The scintillation light is collected towards the photodetector with the use of evenly distributes wavelength shifting fibers running along the longitudinal axe of the detector.

In a previous communication, we reported on the detection properties of a GRAiNITA prototype, with size of 2.8 x 2.8 x 5 cm^3, equipped with $ZnWO_4$ grains and 16 O2(200) WLS fibers collecting the scintillation light on 16 SiPMs, fig.1. With the detection volume filled with grains and ethylene-glycol, we measured a light yield of ~400 photoelectrons, for the 40 MeV deposited in the detector by the cosmic muons. This result clearly indicates that a statistical contribution, to the energy resolution, of the order of $1\%/\sqrt{E}$ is at reach.

Anyway, another contribution to the energy resolution as to be taken into account: the statistical fluctuation between energy deposited in grains, and thus producing light, and the energy deposited in the heavy liquid, which is not measured. A previous simulation study [3] has shown that with 2-mm-grain size this effect results in a resolution of $2\%/\sqrt{E}$.

While these results are very encouraging, the influence of the constant term in the energy resolution expression:

$$\frac{\sigma_E}{E} = \frac{2\%}{\sqrt{E}} \oplus cst$$

may still represent a limiting factor, as this term is dominant for high energy photons. For the competitiveness of GRAiNITA, compared to a standard Shashlik calorimeter, the constant term should not exceed about 1-1.5%.

The uniformity of the detector response, depending on the vicinity of the track with respect to the WLS fibers, will have a clear impact on the constant term, as well as the containment of the electromagnetic shower in the module.

To study the influence of the constant term on the possibly achievable energy resolution we then performed a GEANT4 simulation study of the energy resolution for a full size GRAiNITA demonstrator and the outcomes of this study will be discussed here.

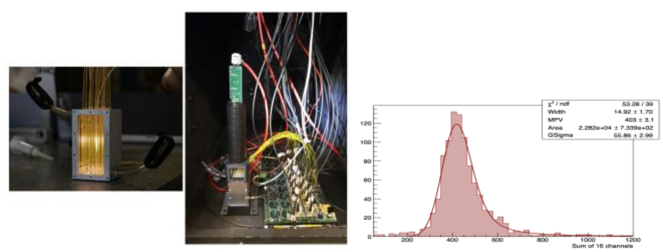

Fig. 1. *The 16-channels GRAiNITA prototype (left), the cosmic rays test bench (middle) and (right) fit using a Landau function convoluted with a Gaussian function of the sum of the signals recorded on the 16-channels when the ZnWO4 grains are immersed in ethylene-glycol.*

II. Simulation study

GEANT4 simulation study has been performed using gamma quanta as initial particle and using a GRAiNITA detector geometry corresponding to a full-size electromagnetic module demonstrator, with volume of 17x17x40 cm^3, filled with $ZnWO_4$ millimetric grains and heavy liquid and equipped with 576 WLS fiber elements. These dimensions, corresponding in depth to 25 X_0, should allow the detector to entirely contain a photon shower of at least 25 GeV.

For the simulation, the detection volume was divided in a series of strips, with size of 1x1x400 mm^3, as a single material having the same radiative properties as the mixture of the

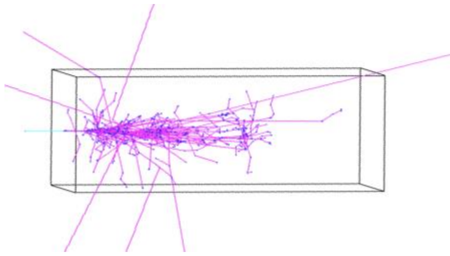

Fig. 2. *Shower produced by a 1-GeV gamma-ray hitting in the center of the detection volume*

scintillator grains ($ZnWO_4$) and heavy liquid (water-based sodium polytungstate solution). The total simulated detector volume then counted 168x168 singles strips. The WLS fibers are distributed in the volume with a square geometry and are located 7 mm apart to each other; the energy deposited in the strips that contain the fiber is not recorded in the simulation output. The shower produced by a 1-GeV photon hitting the GRAiNITA volume is shown in fig.2, as an example.

III. Constant term: the escape enegry

For the evaluation of the constant term, we firstly simulated the energy escaping form the detector volume as the difference between the projectile particle energy and the deposited energy, as a function of the positions of the primary hit. The results of

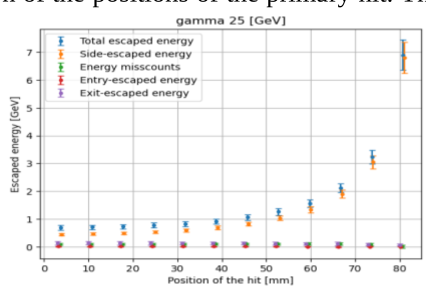

Fig. 3. *Escaped energy as a function of the primary hit position.*

the study, for 25 GeV gamma-rays, are shown in the fig.2 It is interesting to observe that the energy escape uncertainty remains below 1% for most of the points, except those impinging close to the detector edge. Even for a central entry position there is a contribution from leakage at the back of the module but this remains small. However, it was found that if the primary hit takes place close to the detector edge, the escaped energy is strongly correlated with the deposited one, and can be predicted.

IV. Constant term: the non-uniformity

For the estimation of the contribution of the uncertainty term due to non-uniformity, the energy deposited in each strip measured by the weight given by the following equation:

$$F = 1 - a\cos\left(\frac{2\pi x_s}{l}\right) - b\cos\left(\frac{2\pi y_s}{l}\right)$$

This corresponds to the efficiency of capturing the scintillation light by the wavelength-shifting fibers. Here x_s and y_s are the coordinates of the corresponding strip, according to the system originating from the center of the detector, and the z-axe of which is aligned with the direction of the fibers. In the formula l represents the distance between the fibers and is equal to 7 mm, while the amplitude terms, *a* and *b*, are placed equals to 0.07, as estimated from a previous beam tests performed with the LHCb calorimeter [5]. The histograms of the event-by-event measured energy is shown in fig.4.

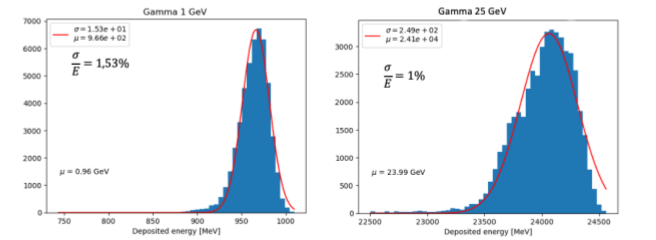

Fig. 4. *Histogram of the measured event-by-event energy for a 1-GeV (left) and a 25-GeV (right) photon energy shower, respectively.*

It is interesting to observe that the contribution of the constant term due to the non-uniformity of the light collection is at the level of 1% for 25-GeV-photons.

Fig.5 shows the efficiency maps in which each bin of the histogram represents the mean energy (over 1000 events) that has been deposited when the primary hit was taking place in the specific bin. It is interesting to underline that the two efficiency maps are very similar, in terms of distribution as well as amplitude.

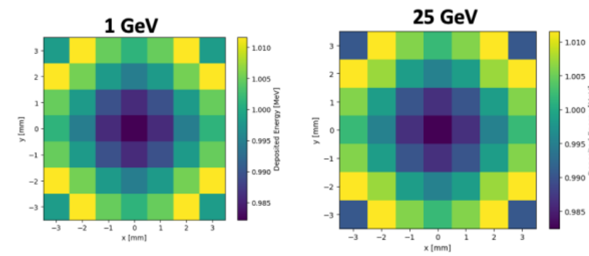

Fig. 5. *Efficiency maps for a 1-GeV (left) and a 25-GeV (right) photon energy shower. Values in each bin are normalized to the total mean value.*

V. Conclusion and future work

This simulation study showed that a constant term uncertainty of about 1% can be expected for the detection of a 25-GeV-photon shower, with the GRAiNITA calorimeter. This result, together with the excellent light yield measured with the $ZnWO_4$-filled GRAiNITA prototype, indicates that this detector has the potential to provide excellent energy resolution for photons thus fulfilling the requirement needed to perform the flavour physics program.

The characterization of the GRAiNITA prototype with a muon beam at CERN will represent the final step for the proof-of-concept for this innovative calorimeter, necessary to pursue the construction of a full-size demonstrator module capable to contain 25-GeV photons.

References

[1] S. Barsuk et al., “First characterization of a novel grain calorimeter: the GRAiNITA prototype”, JINST 19, P04008 (2024)
[2] S. Monteil, https://indico.cern.ch/event/1307378/contributions/5727835/
[3] G. Hull et al., “Proof of concept for a scintillator powder calorimeter” 2021 IEEE NSS-MIC, N-20-03
[4] G. Hull et al., "Development of the GRAiNITA prototype with $ZnWO_4$ and BGO crystal grains," *2023 IEEE NSS-MIC-RTSD* doi: 10.1109/NSSMICRTSD49126.2023.10338679.
[5] M. Prokudin, “Study of response uniformity of the LHCb ECAL”, NIMA, 598 (2009) 235-238