The GRAiNITA calorimeter

Sergey Barsuk[a], Oleg Bezshyyko[d], Ianina Boyarintseva[a,b], Andrey Boyarintsev[b], Dominique Breton[a], Hervé Chanal[c], Alexander M. Dubovik[b], Yingrui Hou[c], Denys Klekots[d,a], Andrii Kotenko[d], Giulia Hull[a], Jacques Lefrançois[a], Jihane Maalmi[a], Magali Magne[c], Stéphane Monteil[c], David Picard[c], Marie-Hélène Schune[a,1], Nazar Semkiv[d], Irina Tupitsyna[b], and Mykhailo Yeresko[c]

[a]Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France
[b]Institute for Scintillation Materials of the National Academy of Sciences of Ukraine, 60 Nauki Ave., Kharkiv 61072, Ukraine
[c]Université Clermont-Auvergne, CNRS/IN2P3, LP-Clermont, 63177 Aubiere, France
[d]Kyiv National Taras Shevchenko University, 01033 Kyiv, Ukraine

March 14, 2025

1 Scientific context

The Future Circular Collider (FCC-ee) [1] aims at collecting unprecedented large samples of Z, W, Higgs and top decays in an experimentally clean environment, allowing a completeness electroweak test of the Standard Model. Among the electroweak tests one finds a comprehensive Flavour programme at the Z^0 pole benefitting in particular of the abundant production of boosted τ leptons from Z decays and of all heavy-flavoured beauty and charm hadrons. By contrast with B-factories, these hadrons are also boosted, allowing the collection of very pure signal candidates samples reconstructed by hermetic detectors. Among the heavy-flavoured hadron decays of interest for advancing the knowledge on the CP symmetry breaking and the CKM profile, as well as the search for Beyond Standard Model (BSM) amplitudes, one finds the radiative decays (described by electroweak penguins in the SM) and the hadronic decay modes involving neutral pions in the final state. This physics case suggests very specific requirements to the calorimeter system, in particular excellent energy and angular resolutions. The novel detector concept presented in this expression of interest addresses these two requirements while meeting the high transverse granularity requirement useful to the physics of the jets at FCC-ee.

Another area of development related to the GRAiNITA project consists of the exploration of the well-established Pulse Shape Discrimination (PSD) of the nature of the incoming particles in crystal scintillators (electromagnetic vs hadrons), adapted to measure more accurately the calorimetric energy deposited by incident hadrons. The proof of concept is still to be made but this energy reconstruction technique, if the exploratory stage is successful, can lead new dual read-out calorimeter designs or adaptation of the existing designs.

2 The detector concept

The GRAiNITA electromagnetic calorimeter concept introduces a detection volume filled with millimetric grains of high-Z and high-density inorganic scintillator crystals, immersed in a bath of transparent high-density liquid. The multiple refractions of the light on the grains ensures the stochastic confinement of the light, as in the LiquidO detection technique [2]. The scintillation light is collected towards the photodetectors by means of Wave Length Shifting fibers, regularly distributed in the detection volume as for a conventional shashlik detector, allowing for a potentially large transverse granularity, necessary for the FCC-ee experiments. Due to this extremely fine sampling of the electromagnetic shower, an excellent energy resolution is expected. The main high-Z and high-density inorganic scintillator crystal considered for GRAiNITA is $ZnWO_4$ [3] that provides a light yield of 10000 photons per MeV. A considerable advantage of the use of this material is that $ZnWO_4$ can be successfully grown in the form of transparent granules of the desired size, with the method of spontaneous crystallization from a flux melt [3], reducing significantly the cost of the calorimeter. The characteristics of interest of $ZnWO_4$ are summarised in Table tab:properties.

Table 1: Properties of interest of the $ZnWO_4$ inorganic crystal.

	$ZnWO_4$
Effective Z	61
Density (g/cm^3)	7.87
Refractive index	2.0 - 2.3
Light yield (photons/MeV)	$\sim$ 9000
Peak emission wavelength (nm)	480
Decay time (μs)	20
Radiation length (cm)	1.20
Molière radius (cm)	1.98

Such a high energy-resolution granular calorimeter meets the general physics requirements of an FCC-ee experiment. It would moreover be particularly useful to address a comprehensive Flavour Physics program with decays involving electrons, photons or neutral pions in the final state. Since the Z^0 production rate at FCC-ee is of the order of 10^5 Hz and since these events should typically hit less than 1 % of the calorimeter cells, the 20 μs decay time of the $ZnWO_4$ should not be a concern. However the investigation of the possible use of other type of crystals is planned.

3 The first results

Measurements with a small prototype ($2.8 \times 2.8 \times 5.5$ cm^3) using green LED are experimentally confirming that, as expected, the signal remains confined in the vicinity of its production point [4]. From analysis of cosmic muons [4] and data from a muon test beam recorded in summer 2024 at CERN, with the same small prototype, it is clear that the collection of about 10000 photo-electrons per GeV is at reach with a GRAiNITA-like calorimeter. This result paves the way to a statistical fluctuation of $1\%/\sqrt{E}$ on the energy resolution due to photo-electron statistics (Fig. 1).

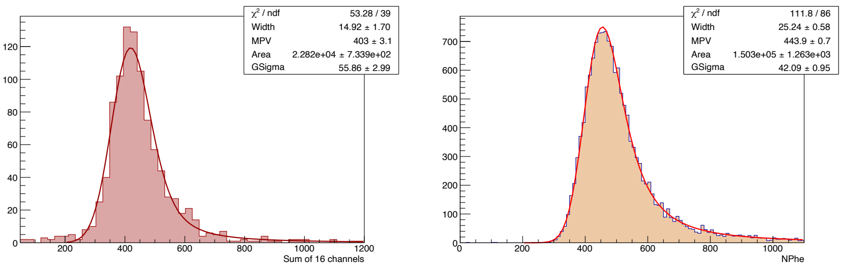

Figure 1: Number of photo-electrons recorded in a GRAiNITA small prototype where the $ZnWO_4$ grains are immersed in an heavy liquid to increase the density of the medium. Left: cosmic muons with $ZnWO_4$ grains immersed in ethylene-glycol (taken from [4]). Right: muon tracks from CERN test beam with $ZnWO_4$ grains immersed in LST_fastloat (density=2.8).

The test beam data, recorded in the H1 area of the SPS at CERN in June 2024, allowed to scan the prototype with minimum-ionising particles (muons and pions) crossing the apparatus from front to rear. The hit map distribution is shown in Fig. 2, and the fiber positions are clearly seen. The response of the prototype has been quantified to provide non-uniformity maps that have been subsequently inputed into accurate GEANT-4 simulations of the calorimeter concept. The analysis is still preliminary but the first results indicate that a less than 1% constant term contribution to the energy resolution is at reach.

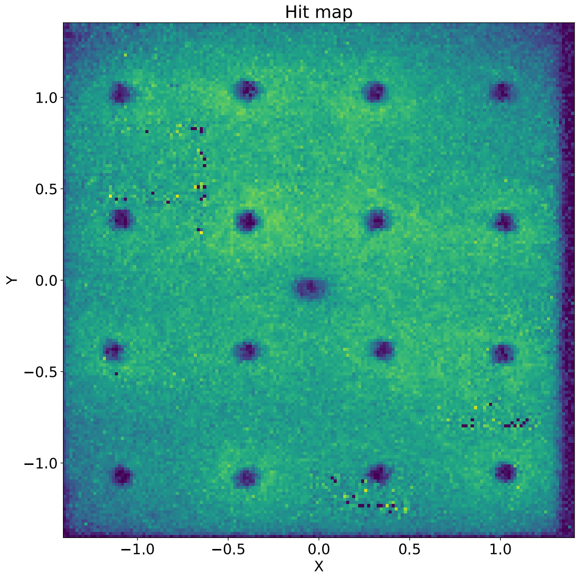

Figure 2: The number of hits in the GRAiNITA small prototype above a threshold of 200 photo-electrons read-out as a function of the incoming muon particle position. The positioning of the fibres is clearly seen, the fibers being 7mm apart. The depleted region in the middle corresponds to the clear fibre instrumented in the centre of the prototype to inject calibration light.

4 The R&D program for the next four years

The main goal of the R&D program for the coming years is to build and characterize a full-size electromagnetic module demonstrator, with dimensions of 17x17x40 cm^3 filled with ZnWO4 grains. This prototype, filled in addition with fastfloat heavy liquid (density=2.8), corresponds to a depth of 25 X_0, allowing a 25-GeV photon shower to be entirely contained. The prototype will first be characterized with cosmic muons, such that the demonstrator be ready for the reopening of the muon and electron beams at CERN after the long shutdown planned between 2026 and 2028. The validation with high-energy particles (electrons, muons and pions) is mandatory to prove that this cutting-edge GRAiNITA technology is competitive and meets the FCC-ee physics requirements.

4.1 Construction of the demonstrator and characterisation of the grains

The construction of a full-size GRAiNITA demonstrator requires about 45 kg of ZnWO4 grains. These can be produced by the ISMA institute (Ukraine) with the method of spontaneous crystallization from a flux melt. The use of grains in a calorimeter is not conventional and a large production of scintillator grains has never been achieved before. It will therefore be crucial to continuously characterize the grains, both in terms of light yield and optical properties, to achieve a steady production quality. Alternative producers have been identified to mitigate the risks related to the critical situation in Ukraine. The mechanical structure will be designed with the aim of finding the best technical solution to fill the volume with grains and liquid. The detector will be assembled in IJCLab's mechanics workshop.

4.2 Design of the Read-Out electronics

The GRAiNITA demonstrator will be equipped with 576 WaveLength Shifting fiber elements. In order to reduce the number of output channels and thus the production cost of the detector, they will be grouped in bunches of 16 and coupled to 36 large-area SiPMs. The latter will be hosted on a board (to be designed) which will also contain the channel amplifiers. The 36 amplified signals will then be sent to a WaveCatcher digitizer, optimised for the studied crystal shaping times and pulse shape discrimination.

4.3 Experimental tests foreseen

- The GRAiNITA demonstrator will be tested with cosmic rays on test benches equipped with two plastic scintillators as external trigger. These initial tests will serve to optimise on one hand the mechanical design of the prototype by studying the system of collection of the light and to commission the front-end read-out. When the test beams will become available again worldwide, the response to high-energy electrons and pions will be studied. High-energy muon beams must be used to characterise the non-uniformity of the response as an important contribution to the constant term of the energy resolution.

- The design of a PSD technique to improve the precision hadron energy measurement will require as well some experimental tests. In particular, the implementation of a realistic optical model of the PSD response requires direct measurements of the scintillation properties of the crystals in response to low energy protons, for which the literature is scarce or non-existing. Test beam periods are envisaged at the ALTO facility (Orsay).

5 EoI to join a detector concept

The GRAiNITA R&D would benefit of being embodied in a larger detector concept, when it will come to assess the global physics performance on benchmark physics modes. The IDEA detector concept would be a right fit since it features dual read-out calorimeter designs.

References

[1] FCC collaboration, *FCC-ee: The Lepton Collider: Future Circular Collider Conceptual Design Report Volume 2*, *Eur. Phys. J. ST* **228** (2019) 261.

[2] A. Cabrera, A. Abusleme, J. dos Anjos, T.J.C. Bezerra, M. Bongrand, C. Bourgeois et al., *Neutrino physics with an opaque detector*, *Communications Physics* **4** (2021) .

[3] G. Hull, I. Boiaryntseva, J. Lefrançois, I. Tupitsyna, A.-M. Dubovik, S. Barsuk et al., "ZnWO4 grains characterisation for GRAiNITA – a new-generation calorimeter - IEEE 2022 contribution ." `https://hal.science/hal-04269276/file/Poster.pdf`.

[4] S. Barsuk, O. Bezshyyko, I. Boyarintseva, A. Boyarintsev, D. Breton, H. Chanal et al., *First characterization of a novel grain calorimeter: the grainita prototype*, *Journal of Instrumentation* **19** (2024) P04008.

Attestation de validation de l'EoI

GRAiNITA (contact FCC-IN2P3 S MONTEIL)

par les DU des laboratoires concernés

Ces validations ne constituent pas un engagement des laboratoires à mettre en œuvre tout ou partie de ces EoI et/ou à fournir des ressources, mais juste à témoigner que l'EoI a pu être lue par le DU, et que le DU ne s'oppose pas à ce que l'EoI soit soumise avec des personnels de son laboratoire comme signataires.

LPCA / Dominique PALLIN / 17-03-25

IJCLAB / Achille STOCCHI /


Par délégation,

Fadi Ibrahim

Directeur Adjoint d'IJCLab