DEVELOPMENT OF GRAINITA, A NEXT-GENERATION CALORIMETER TECHNOLOGY

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The development of research in fundamental particle physics comes with ever-increasing energies and improvements to the detectors used. According to the European strategy on particle physics [1], the building of the FCC is the top priority step in future accelerator development. Calorimeters are the only subdetectors for measuring neutral particles, being one of the largest detector subsystems, accounting for a significant portion of the detector's cost. For example, the gammas can only be detected with calorimeters, and at the same time, the resolution (both energy and spatial) of calorimeters is significantly worse compared to tracker systems. Good resolution is particularly important for flavor physics experiments running at the Z^0 resonance during the electron-positron stage of FCC. The rare decay modes from Z^0 resonance with gammas and neutral pions in final states rely on the calorimeter in the first place. Providing good energy resolution while maintaining a feasible cost is very important for future experiments.

GRAiNITA is a new technology of a sampling calorimeter, with promising improvements in resolution. Its approach combines scintillation grains of millimetric size with transparent heavy liquid evenly distributed in the volume. The light created by the scintillation is captured by the wavelength-shifting (WLS) fibers and transferred to the SiPM. Due to multiple reflections and refractions of the light on the optical interface of crystals and heavy liquid, the light is stochastically trapped close to the point it was created, and this allows for better resolution compared to the well-established shashlik-type calorimeter, which consists of alternating layers of scintillator and solid absorber. Also, because small-sized scintillating grains can be produced by the method of spontaneous crystallization from a flux melt [2], the building cost of the GRAiNITA calorimeter could be lower compared to calorimeters, which require growing large crystals.

The water-based solutions of sodium polytungstate were selected as a heavy liquid medium, with a density of about 2.85 g/cm^3. The presence of chemical elements with high atomic numbers makes it more effective in stopping electromagnetic showers. The $ZnWO_4$ was selected as the scintillator material. The analysis of $ZnWO_4$ measurements with a beta-ray source and beam-test results with protons from the ALTO research facility accelerator indicates the possibility of pulse shape discrimination in the $ZnWO_4$ scintillator, which could further improve particle identification in a collider experiment.

The beam test measurement at the CERN SPS H9 accelerator with the GRAINITA prototype has been conducted to estimate the worsening of the detector energy resolution due to the non-uniformity of light collection as a function of the distance between the scintillation light production site by a particle and the surrounding WLS fibers [3]. The experimental setup consists of a 28 × 28 × 55 mm^3 active volume with sixteen O-2(200) WLS fibers of 1 mm in diameter. The WLS fibers were located in the nodes of a square mesh with a 7 mm distance between fibers. The pion and muon beams were used. The number of detected photoelectrons, depending on the hit position, was measured with a step size of about 1 mm. A map of the scintillation light capturing sensitivity, depending on position, to the nearest WLS fibers was calculated from analysis of the beam test results.

To estimate the effect on energy resolution, the measured light detection efficiency data were combined with Geant4 simulation [4] results on shower development. The simulation setup consists of a 168 × 168 × 400 mm^3 box volume composed of scintillator and heavy liquid with mass fractions of ~20.77 % heavy liquid and ~79.23 % $ZnWO_4$, which correspond to the values in the beam-test setup. The WLS fibers were simulated as cylinders of 1 mm in diameter positioned similarly to the beam test setup. A simplified simulation setup is preferable for computation resources optimization, but further updates are planned to see fractions of energy deposited in the scintillator and absorber.

A 2D transverse energy deposition map for each event was built from the simulation output. The discretization step of the energy deposition map corresponds to the one of beam-test analysis. The energy readout for scintillators is proportional to the number of photoelectrons detected at SiPM. The different probability of the photon being captured, depending on where it was emitted with respect to the distance to the WLS fibers, would cause the nonuniformity of detector response and would affect energy resolution. To estimate this effect, the energy deposited for each event was weighted with the photon detection efficiency, and resulting value was considered as detected energy.

To estimate the energy resolution and how nonuniformity affects it, two types of simulations were conducted: with WLS fibers simulated and an actual beam test light detecting efficiency map, and with a flat map of constant efficiency without WLS fibers in the simulation.

The energy resolution ($R = \sigma_E/E$) of the calorimeter can be represented by the following formula

$$R = \sqrt{\left(\frac{A}{\sqrt{E}}\right)^2 + B^2}$$

Here $\boldsymbol{A/\sqrt{E}}$ is an energy-dependent term which corresponds to various stochastic effects in the detector (like statistic of the number of scintillation photons). **B** is the constant term; it describes resolution constraints by detector construction (such as previously mentioned non-uniformity). The stochastic and constant terms were estimated by fitting the energy resolution formula to the data for energies of primary gamma in the range from 1 GeV to 34 GeV. Results are represented in the Figure 1.

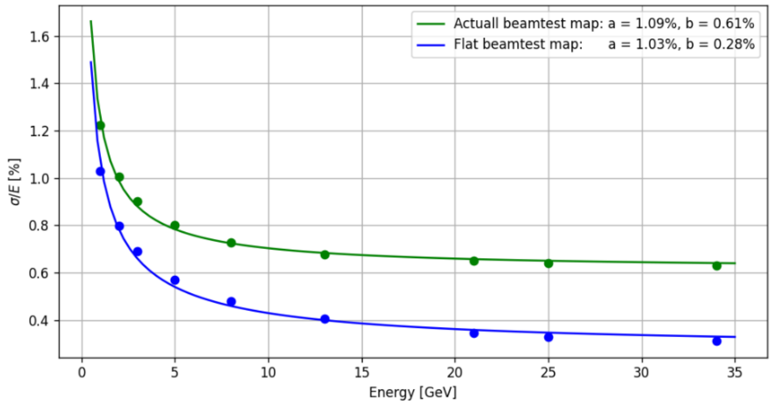

Figure 1: Dependence of energy resolution, calculated with the actually measured nonuniformity of light capturing efficiency (green curve), and with constant light capturing efficiency (blue curve).

Further analysis of the cause of the worsened energy resolution for lower energies in this simulation setup was conducted, and the cause is statistics 1-3 MeV gammas that escape from the detector volume.

The results of the beam test analysis and simulation indicate that constant term of the GRAiNITA calorimeter stays below 0.65% and stochastic term due to escape of secondary particles is about $1\%/\sqrt{E}$. Previous studies [5] also indicated the possibility to reach about $1\%/\sqrt{E}$ of stochastic term due to photo-electron statistics. The next steps of the GRAINITA calorimeter simulation would include the fraction of energy deposited in the liquid and scintillator, which could also affect the stochastic term.

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