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albertoadufour@gmail.com

MAXICC: Maximum Information Crystal Calorimetry for Future Colliders

Alberto Dufour

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Summary

This Summer Student project focuses on the development of the DAQ system for the MAXICC calorimeter prototype in view of the test beam scheduled for the end of September 2025. The test beam will be used to test the calorimeter prototype, currently under construction, composed of PWO crystals coupled to SiPMs for a total of 192 channels, as well as a Delay Wire Chamber (DWC) to track the position of incoming particles. The calorimeter will be read out using Caen FERS modules equipped with Citiroc-1A ASICs, while the DWC will be read by Caen V1742, which digitises the waveforms with a DRS4 chip. This report describes the characterisation of SiPMs and FERS, together with the implementation of a trigger logic ensuring correct event matching between the DRS and FERS DAQ based on EUDAQ, which will be implemented during the test beam.

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1 The IDEA Detector Concept

The FCC-ee is a proposed e^+e^- collider, with primary physics goals centered on precision measurements in the Higgs sector. It attempts to provide optimal performance on most of the physics accessible, while dealing with the constraints required by the accelerator. The Innovative Detector for E^+e^- Accelerator (IDEA) [1] is a new, innovative detector concept, specifically designed for FCC-ee. It is based on a sophisticated tracker and a crystal Dual-Readout (DR) electromagnetic calorimeter within a superconducting solenoid magnet, followed by a DR fiber calorimeter and then completed by a muon detection system placed within the iron yoke that closes the magnetic field.

To fully exploit the physics landscape of the FCC-ee, the performances of the calorimetry must be improved in several aspects compared to the solutions adopted so far. The IDEA project aims to develop a detector with excellent energy resolution for both electromagnetic and hadronic showers and high granularity, to enhance the final-state particle identification performance. This objective can be reached by implementing DR calorimetry.

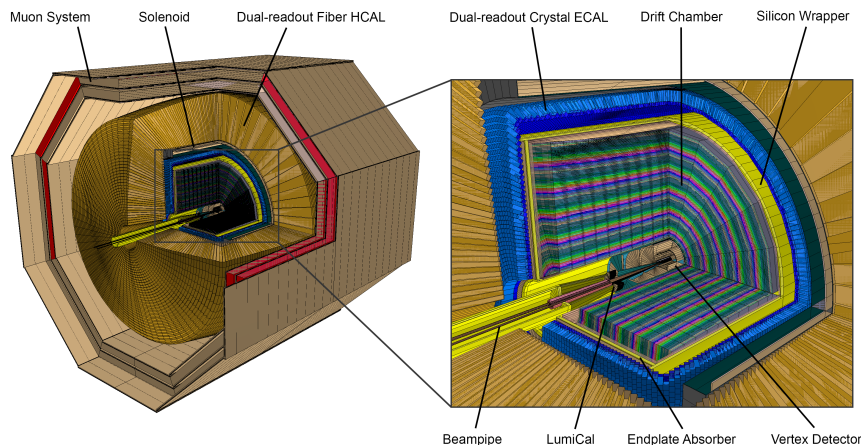


Figure 1: 3D cutout view of the IDEA baseline detector design with subdetector labels.

1.1 Dual-Readout Electromagnetic Calorimeter

A major problem in reconstructing the energy of the particles produced in an event is the presence, in hadronic showers, of two components, an electromagnetic one (electrons and photons) and a hadronic one, which produce different signals for the same energy loss. Each hadronic shower develops a different electromagnetic fraction, thus contributing to the energy shower measurement error.

Dual-readout (DR) calorimetry addresses this problem by measuring the showers simultaneously via two processes that are differently sensitive to the passage of non-relativistic particles (essentially the hadronic component) and relativistic particles (essentially the electromagnetic component). A scintillating material produces a signal in both cases, while a material that emits Cherenkov light is activated only by relativistic particles. From the

ratio between the two signals, it is possible to reconstruct the electromagnetic fraction of each shower, event by event, and cancel the effects of its fluctuation.

A simple way to implement a dual-readout calorimeter is to use a scintillating material (for example, scintillating fibers) alternating with a material that emits Cherenkov light (for example, clear fibers). A major drawback of this approach is that it introduces dead volume, which leads to a loss of data and therefore a lower resolution. Alternatively, one can try to isolate and measure the Cherenkov light that is emitted in a scintillating material. The proposed IDEA electromagnetic calorimeter is composed of a dense scintillating crystal emitting both Cherenkov and scintillation light.

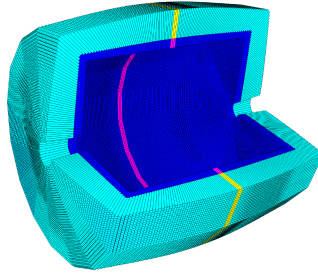


Figure 2: 3D cutout view of the dual-readout crystal calorimeter showing (dark blue) front crystal segments and (light blue) rear crystal segments.

2 MAXICC

The MAXICC project aims to assess the potential and feasibility of integrating a cost-effective, homogeneous, dual-readout segmented crystal electromagnetic calorimeter into the IDEA detector.

The current prototype design, scheduled for testing with an electron beam in late September 2025, consists of a 9×9 lead tungstate (PWO) crystal matrix, divided into two sections (front and rear) and coupled to SiPMs. Dual-readout functionality is achieved by using two distinct SiPMs for Cherenkov (C) and scintillation (S) light. One of the SiPMs is coupled to an optical filter that selects higher wavelengths, characteristic of Cherenkov emission, in order to isolate this signal from the scintillation light.

In this design, dual readout is implemented only in the rear section. Simulation studies indicate that hadronic showers typically develop after the first 5 cm of crystal: the front section prioritises finer transverse granularity, thus higher spatial resolution, over dual-readout.

2.1 PWO Crystals

Lead tungstate (PbWO_4 , often abbreviated PWO) is a dense scintillating crystal widely used in electromagnetic calorimeters for high-energy physics experiments, such as CERN CMS ECAL and ALICE PHOS. Its high density, short radiation length, fast scintillation time and small Molière radius make it well suited for compact detector designs capable of containing high-energy electromagnetic showers. Furthermore, PWO is relatively radiation hard, which

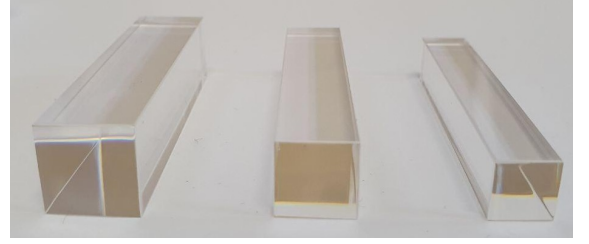
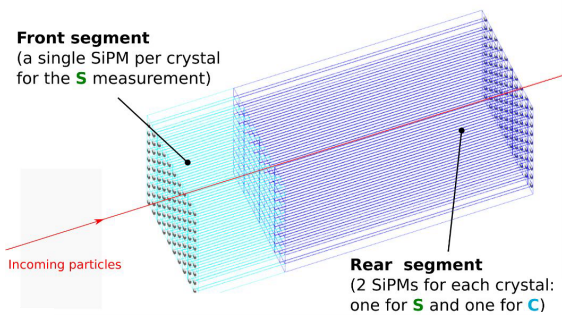


Figure 3: MAXICC prototype model (left), PWO crystals used in the final prototype (right).

is essential in the high-rate, high-radiation environments of modern (and even more for the future) colliders. Although its light yield is modest compared to other scintillators, it is sufficient when coupled with high-sensitivity photodetectors such as SiPMs. These characteristics lead to the choice of PWO over other crystals such as BSO and BGO.

The front section is composed of $10 \times 10 \times 50 \text{ mm}^3$ crystals, while the rear layer is composed of bigger $14 \times 14 \times 160 \text{ mm}^3$, which gives a much finer granularity compared to that of CMS ($\approx 22 \times 22 \times 230 \text{ mm}^3$ for the barrel [2]).

2.2 SiPMs

The SiPMs selected are Hamamatsu S14160: the 6015PS (or, alternatively, the 6010PS) for scintillation light, and the 6050HS for Cherenkov light. Since Cherenkov emission is less intense than scintillation, a higher Photon Detection Efficiency (PDE) is required, which also results in a higher gain. The $50 \mu\text{m}$ cells of the 6050HS provide a higher PDE compared to the 6015(10)PS, whereas the latter feature a higher cell density and therefore offer better energy resolution.

All these SiPMs have a $6 \times 6 \text{ mm}^2$ active area, the largest currently available on the market, thus maximising the detector active surface.

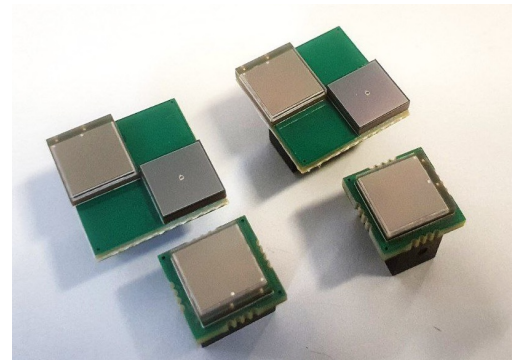
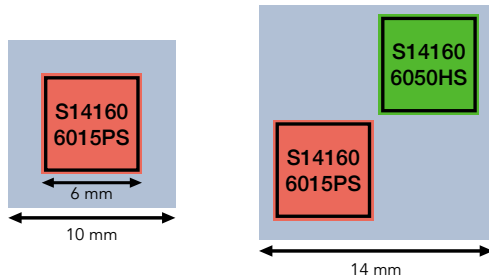


Figure 4: Diagram of the SiPM layout on the crystals (front and rear sections) (left), picture of the SiPMs used in the prototype (right).

3 Test Beam

The current status of the MAXICC project is the preparation for a test beam, scheduled for late September 2025, where the calorimeter prototype will be tested with high-energy electrons.

The test beam setup includes a Delay Wire Chamber (DWC) to track the position of incoming particles, placed upstream of the calorimeter. Data from these two detectors will be acquired using different technologies: the DWC signals will be digitised and processed with Caen V1742, which features a DRS4 chip, while the calorimeter will be read out by Front-End Readout Systems (FERS). The FERS will manage all 192 SiPM channels and process their signals through Citiroc-1A ASICs, which provide an output proportional to the integrated charge of each event.

The goal of my summer student project was the characterization of SiPMs and electronics (FERS) used in the prototype, as well as the development and commissioning of a data acquisition system based on the EUDAQ framework ¹, to be used at the forthcoming test beam.

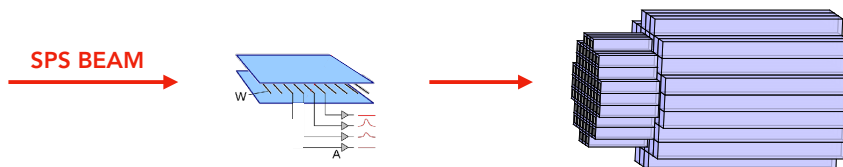


Figure 5: Schematic of the test beam setup: the SPS beam passes through the Delay Wire Chamber (left), used to track particle positions, before reaching the calorimeter prototype (right) to measure deposited energy.

3.1 SiPM Characterisation

The SiPMs of interest have been tested and characterised. A breakdown voltage scan was performed using a Keithley 2450 SourceMeter, by measuring the current passing through the SiPM while linearly varying the applied bias voltage (voltage ramp), thus obtaining the I(V) curve. By definition, the breakdown voltage corresponds to the peak of the derivative of this curve, as shown in Fig. 6.

SiPM	V_{br} (V)
6015 [front]	38.8
6010 [front]	38.9
6015 (6050) [rear]	38.9 (38.2)
6010 (6050) [rear]	38.8 (38.1)

Table 1: Breakdown voltages V_{br} measured for the SiPMs used.

¹<https://github.com/eudaq/eudaq>

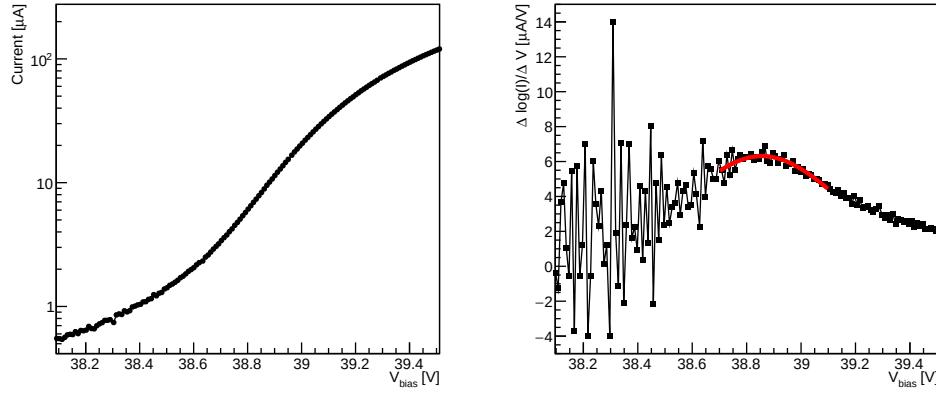


Figure 6: SiPM breakdown voltage characterisation: $I(V)$ curve (left) and derivative of the logarithm (right). The breakdown voltage is defined as the peak of the derivative.

3.2 FERS Characterisation

The FERS-5200² (Front-End Readout System) is a distributed and scalable platform powered by Citiroc-1A ASICs. Specifically designed for SiPM readout, each Citiroc-1A chip integrates 32 channels, using preamplifiers, shapers, and discriminators. The A5202 unit houses two of these ASICs to deliver a compact 64-channel solution, making it ideal for acquiring a large number of channels, as in the test beam DAQ for the MAXICC prototype.

The Citiroc-1A architecture provides critical features channel-by-channel gain trimming via an 8-bit DAC, allowing for precise uniformity correction across the SiPM array. Its dual-gain preamplifier chain ensures a wide dynamic range, capable of resolving everything from single photoelectrons to large energy depositions. When operated in Spectroscopy Mode, as will be for the calorimeter, the system leverages these features to perform charge measurement. On top of this, FERS conveniently provide on-board HV power supply for the SiPMs.

To read out the 192 channels of the calorimeter prototype, a system of three A5202 units will be employed, coordinated by a DT5215 Concentrator Board³. The concentrator board acts as the central data acquisition and synchronization hub, connecting to the front-end units via optical TDlinks and providing a single high-throughput interface to the host PC. Crucially, the DT5215 also manages the system-wide synchronization, distributing a common clock and trigger signals to all A5202 units, ensuring a coherent time reference for event building across the entire detector.

FERS feature multiple parameters which can be adjusted for data acquisition. Using Caen Janus software, some of these parameters were studied for the DAQ.

The setup used for this part features a LED used as a light source, shining directly on a SiPM mounted on a FERS unit. This configuration gives rise to Single PhotoElectron (SPE) spectra, as show in Figures 8 and 9.

²<https://www.caen.it/subfamilies/fers-5200/>

³<https://www.caen.it/products/dt5215/>



Figure 7: FERS A5202 board (left), DT5215 Concentrator Board (right).

The first notable feature is the dynamic range of the Citiroc. With the bias voltage fixed, the spectrum was fitted with a Gaussian (Fig. 8, left), while varying the gain (0–63) for both the Low Gain (LG) and High Gain (HG) channels of the FERS. As shown in Fig. 8 (right), the gain is nonlinear, and there is a range where the LG and HG channels overlap.

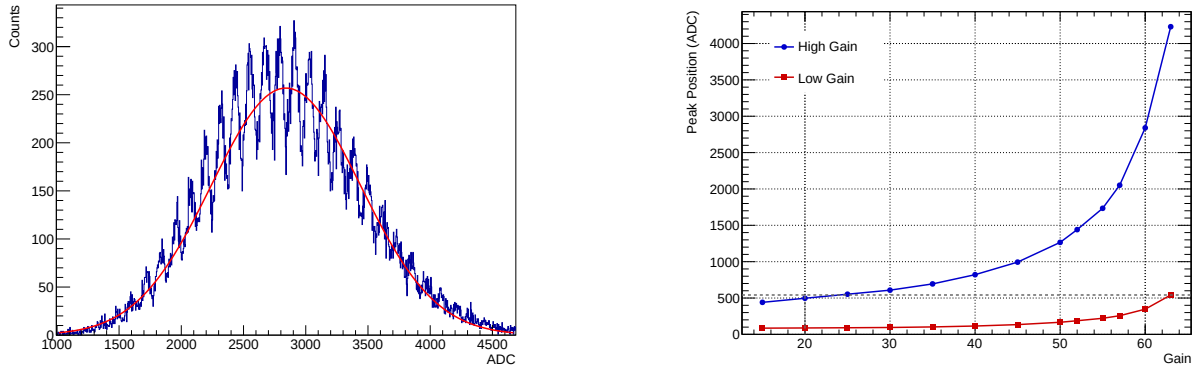


Figure 8: Spectrum from the LED setup, fitted with a Gaussian (left), peak position versus gain at fixed bias voltage (right).

Another interesting parameter studied is the shaping time. Having fixed both gain and bias voltage, a single photoelectron peak was chosen and fitted with a gaussian (in green, Fig. 9, left) to study the resolution (defined as the FWHM/mean of the peak) varying the discrete values of shaping time available: Fig. 9 (right) shows that there is a value (25 ns) that optimises the resolution. This value may vary for different SiPMs.

Furthermore, the resolution of the peak was studied varying the gain but no clear trend was observed, as expected.

3.3 Lab Setup at CERN LAB27

To develop the DAQ for the test beam, a new setup was required. The main goal is to implement a system capable of matching events read by the DRS (which will acquire data from the Delay Wire Chamber) with those read by the FERS (which acquire calorimeter data).

The setup consists of an array of 16 $3 \times 3 \times 57 \text{ mm}^3$ LYSO crystals, each wrapped in reflective material in order to prevent optical crosstalk between them (same modules used in

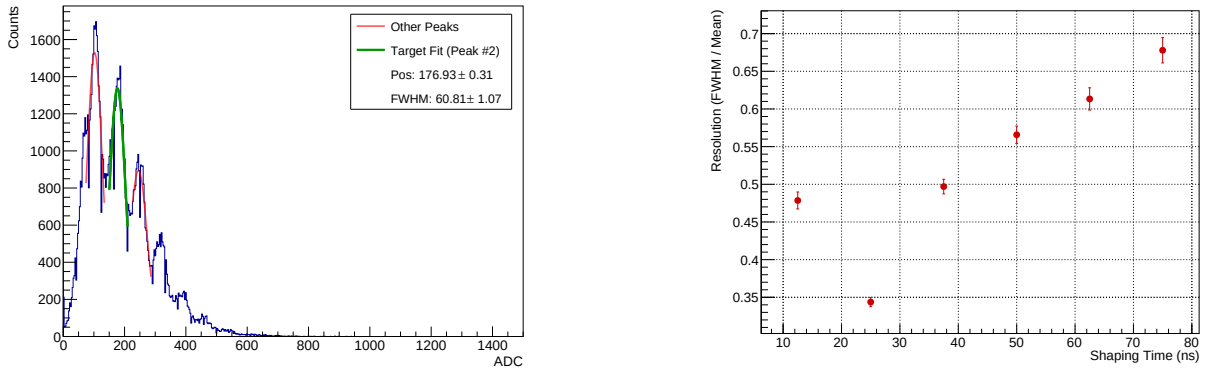


Figure 9: Spectrum obtained with the LED setup, fitted with a Gaussian (green) (left), resolution versus shaping time at fixed bias voltage and gain (right).

CMS MTD BTL [3]). One crystal was selected by covering the others with dark tape, thus isolating a single bar for the measurement. At the two open ends of this crystal bar, two SiPMs were placed: one connected to a custom SiPM readout board with a transimpedance amplifier readout with the DRS, and the other to the FERS. In this way, two channels are read out with the different technologies that will be used for the DWC and the calorimeter in the test beam, both coupled to the same scintillator and therefore detecting the same event.

The choice of LYSO was particularly advantageous because of its well-known intrinsic radioactivity. LYSO contains lutetium, whose isotope ^{176}Lu undergoes β^- decay, emitting an electron followed by de-excitation gamma rays with energies of 307 keV, 202 keV, and 88 keV. The crystal could therefore be used simultaneously as a scintillator and as a gamma-ray source.

The event trigger is generated using an integral differentiator applied to the signal sent to the DRS.

3.4 Event Matching: Trigger Logic

Dead time management proved to be crucial, since any event lost by either of the two channels would result in an event mismatch. To avoid this, a dedicated trigger logic was implemented, making use of a coincidence unit, a fan-in fan-out module, a dual timer and a trigger unit. The DAQ is vetoed by the FERS RUN-ON signal, preventing the DRS from acquiring data until the FERS starts acquisition. Additionally, the DAQ is vetoed by the DRS BUSY signal, which lasts longer than the FERS acquisition time ($\approx 110 \mu\text{s}$ vs. $\approx 10 \mu\text{s}$). A manual DAQ rate limit was also implemented using the dual timer, which introduces a fixed dead time in the trigger chain.

Using this logic, the two channels acquired exactly the same number of events. To test the event matching, a correlation plot was constructed. A charge histogram was generated for the DRS events by integrating the waveforms: the baseline was estimated by averaging the initial portion of each waveform and subtracted, and the integral was then calculated as

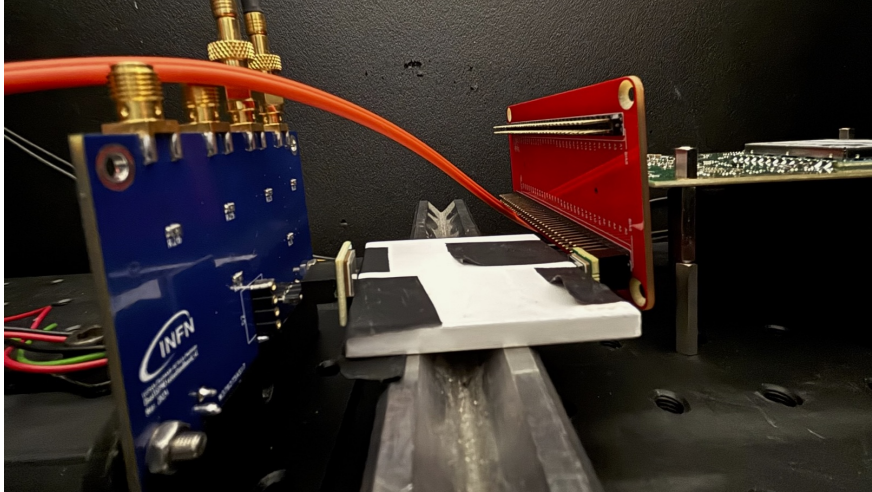


Figure 10: LAB27 setup. Central LYSO crystal array (white). Right: SiPM connected to the FERS board. Left: SiPM connected to a PCB, then connected to the DRS.

the sum of the waveform bins. The resulting histogram, shown in Fig. 11 (center), can be compared with those obtained from FERS events. As illustrated by the correlation plots in Fig. 12 (left and center), the correlation is nearly linear. A change in slope is observed near zero, since the DRS determines the trigger, and near the upper end, due to DRS saturation. Furthermore, the correlation was tested by taking the average of the two channels for each event, which is expected to improve the resolution (ideally by a factor of $\sqrt{2}$). To perform this averaging, the DRS data had to be converted to 8K ADC counts, matching the FERS scale. This was achieved by fitting the 307 keV peak in both spectra (as shown in Fig. 11, left and center) and rescaling the DRS accordingly. The average spectrum, shown in Fig. 11 (right), demonstrates a clear improvement in resolution. The Low Gain channel is consistent with the expected $\sqrt{2}$ improvement, while the High Gain channel shows only a minor improvement, likely because the FERS channel itself is saturating, which introduces distortions.

The event matching was demonstrated to be successful and reliable at all tested up to ≈ 1.4 kHz.

4 Outlook

The DAQ setup demonstrated reliable synchronization between DRS and FERS events, ensuring that each detected event is correctly matched across the two systems. The system can be readily adapted to accommodate all required SiPM channels, making it suitable for the full calorimeter prototype. During these studies, several key properties of the FERS were characterised, providing insight into its dynamic range, gain settings, and overall performance. Finally, all SiPMs of interest (Hamamatsu 6010 and 6015 for scintillation light, 6050 for Cherenkov light) were successfully tested and their breakdown voltage was characterised. The immediate next steps involve integrating all SiPMs (once they become available) and

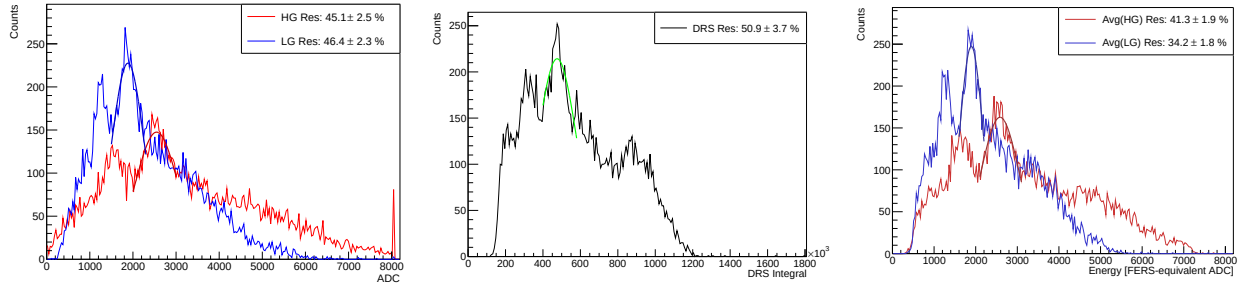


Figure 11: Spectra obtained with the setup shown in Fig. 10. From left to right: FERS spectra (HG and LG), DRS spectrum (obtained integrating DRS waveforms), averaged spectra, normalised to 8K bits.

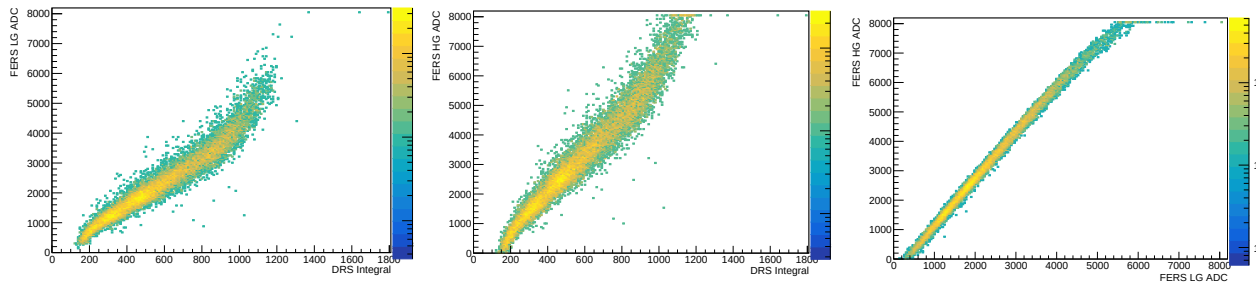


Figure 12: Correlation plots for spectra obtained in Fig. 11. From left to right: DRS vs. FERS LG, DRS vs. FERS HG, FERS LG vs. HG. All three show good correlation.

coupling them to the PWO crystals of the calorimeter prototype. The test beam will then be finalised by implementing the the Delay Wire Chamber. These steps will allow the system to operate under realistic conditions and provide the data necessary to evaluate the performance of the Dual Readout calorimeter.

References

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