PROCEEDINGS OF SCIENCE

HiDRa: High-resolution Calorimeter for e^+e^-

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The forthcoming generation of colliders demands advanced mass resolutions for the Higgs H, W and Z bosons when decaying into jets. Dual-readout calorimetry achieves this by making use of two independent measurements of the hadronic shower energy, leveraging the distinct factors of Cherenkov and scintillation light produced in a calorimeter equipped with two types of optical fibres. This allows for event-by-event compensation of the electromagnetic fraction.
In this context, we present HiDRa, a $65 \times 65 \times 250$ cm^3 dual-readout fibre calorimeter prototype currently under construction. The primary objective is to assess the performance in terms of linearity and resolution when exposed to a high-energy particle beam. The paper will focus on strategic choices made to offer scalable solutions for the mechanics and readout electronics. The insights gained from the evaluation of HiDRa will be key for the construction of a full 4π calorimeter at a future collider.

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1. Introduction

Calorimetry plays a crucial role in high-energy physics experiments, enabling the precise measurement of particle energies, including those of electrons, photons and hadrons. Significant challenges in achieving the high energy resolution required are due to the stochastic nature of energy deposition processes. In particular, the simultaneous detection of electromagnetic and hadronic components in hadron showers complicates the ability to accurately determine the total energy deposited, because the electromagnetic fraction varies from one event to the next, introducing a significant degradation in resolution. The dual-readout approach compensates for this fluctuation by measuring the scintillating and the Cherenkov light produced event by event. HiDRa (High-resolution highly granular Dual-Readout demonstrator) integrates the dual-readout approach in a solution compatible with typical 4π geometries, of interest for future leptonic colliders. It exploits a compact and cost-effective detector design that can be implemented using commercially available components. High granularity is achieved by measuring the light produced in small number of fibres (1 or 8), giving access to fine lateral segmentation of the shower that can further improve the accuracy of energy measurements and particle identification.

A fibre-based dual-readout calorimeter prototype ($10 \times 10 \times 100$ cm^3), built to largely contain electromagnetic showers ($\approx 95\%$) and partially read out by SiPMs, was tested on beam in 2021 at DESY (using electron beams up to 6 GeV) and at CERN-SPS using positron beams with energies from 10 GeV to 100 GeV. Details on the readout schema and calibration procedure used for SiPMs can be found in [2] and a complete review of all the SPS test beam results in [3]. The same module was tested again at the SPS in 2023 because the positron beam provided in 2021 was largely contaminated by muons and hadrons, and the poor statistics left after event selection (especially at higher energies), together with further problems with the setup, required heavy reliance on simulation to evaluate the detector performance [3]. The results available at the time of writing this paper are preliminary because the analysis is still in progress, however details on the methodology used in the analysis will be provided.

2. Electromagnetic-size prototype

The prototype under test consists of 9 modules, 8 of which are read out with PMTs (1 scintillating and 1 Cherenkov per module) and the central one (highly granular) with 320 SiPMs (one per fibre). The noise is measured after equalising and calibrating the response of all PMTs and SiPMs. Pedestals were collected in each run by using $\approx$ 10% of random triggers and the rms noise for the PMTs is the standard deviation of the Gaussian distribution after selecting these events ($\approx$ 120 MeV).

The 320 SiPMs used to equip the central module are connected to five A5202[1] readout boards. The signal produced by each SiPM feeds two amplifiers with different amplification factors: High Gain (HG) and Low Gain (LG), a special feature of the CITIROC1A chip. The HG gives access to the multiphoton spectra for each SiPM, which is useful for converting the signal from ADC to photolectrons (N_{pe}), but saturates the ADC at $\approx 140\ N_{pe}$ due to the settings in use. For this reason, the LG is crucial; it gives access to larger signals (low amplification factor) while sacrificing the multiphoton spectrum that is hidden by the ADC resolution. The data analysis uses information

[1] https://www.caen.it/products/a5202/

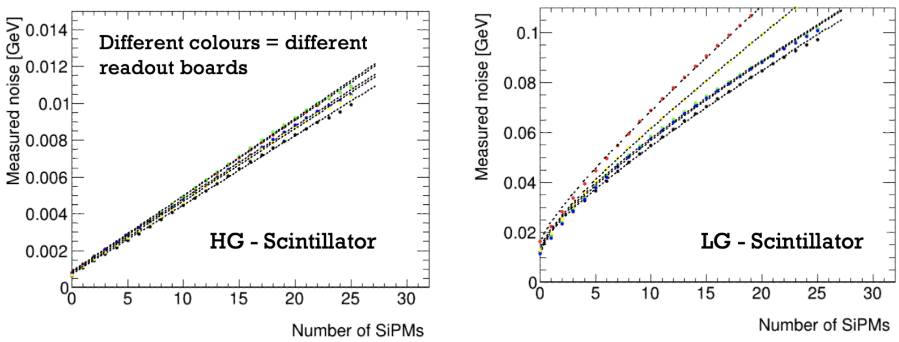

Figure 1: Noise as a function of the number of scintillating SiPMs from the same readout board. Different colours refers to different boards. High-Gain and Low-Gain results are shown on the left and right, respectively. Similar trends, with a different scaling factor, are observed for the Cherenkov channels.

from both gains requiring the calibration and noise estimation for the two readout chains. The trigger logic uses the AND condition of two signals: 1) the internal, produced when more than 3 SiPMs (over the 64 served by one A5202 board) exceed the discriminator threshold set at 2.5 N_{pe} and 2) the external one, issued when a particle passes through the trigger detectors (scintillators placed in front of the calorimeter). When these conditions are met, the signals of all SiPMs connected to the same readout board are saved on disk. Accordingly to this logic, if an external trigger is randomly generated (pedestal), it does not necessarily meet the internal trigger condition. For this reason, it produces empty data from the SiPMs and a series of zeros are set offline to maintain data synchronisation in the reconstructed events.

The rms noise induced by the the HG can be estimated using the width of the 1^{st} peak in the multiphoton spectra also visible with physics data. The average value is 2 MeV for Cherenkov channels and 0.6 MeV for scintillating channels, even if the same type of SiPM is used. The difference comes from the scaling factor used in the calibration. In addition, assuming uncorrelated noise between SiPMs, we would have expected a total noise of the order of 25 MeV and 8 MeV for the Cherenkov and scintillating channels respectively ($\sigma_0 \cdot \sqrt{N_{SIPM_{ch}}}$). Figure 1 shows the width of the 1^{st} peak obtained by adding contributions of a larger number of SiPMs. The plot shows a faster increase than expected, a clear indication that signals in the same board are correlated. The same trend is observed in all boards and for scintillating and Cherenkov channels. The approach used for the LG is different because the multiphoton is not visible. In this case, we measure the width of pedestals obtained after having selected events with HG signals falling in the 1^{st} peak. Again, the signals show a correlation and the trend is fitted with the following curve: $a + b \cdot \sqrt{N_{SiPM}} + c \cdot N_{SiPM}$. The total noise, at the different energies, is calculated as the sum in quadrature of the contributions from the PMTs and those from the average number of SiPMs (scintillating and Cherenkov) in each readout board with signals in the HG and LG regime. The result goes from $\approx$ 140 MeV to $\approx$ 280 MeV (120 MeV is always due to PMTs) because the number of SiPMs operating in LG regime increases with the energy.

Figure 2 (left) shows the energy resolution in response to positron beams after removing the noise. The same selection criterion described in [3] has been applied and the agreement with the Monte Carlo simulation is evident. There is still a difference in the constant term possibly due to the

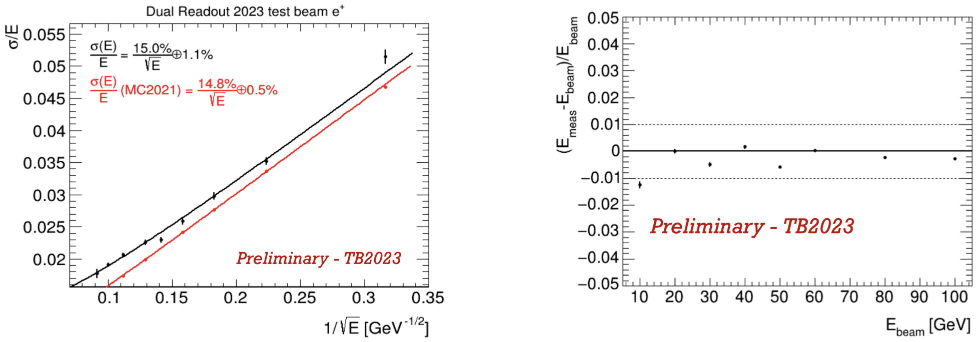

Figure 2: Resolution of the EM-prototype for positrons as a function of the reciprocal of the square root of the beam energy is shown on the left. The black points represent the data after noise subtraction (text for details), the blue ones correspond to the Monte Carlo simulation. The linearity of the energy response to positron is shown on the right.

spread of $\approx$ 1% in the beam energy (estimate provided by CERN beam physicists). This hypothesis will be validated with dedicated Monte Carlo simulations.

The energy linearity of $\approx$ 1% is achieved in response to positrons of energies up to 100 GeV (Figure 2, right) after correcting the SiPM response for a small nonlinearity effect. The observed light yield is 290 N_{pe} / GeV and 62 N_{pe} / GeV for scintillating and clear fibres respectively. A small increase with respect to the previous test was observed due to the use of optical grease between SiPMs and fibres [3]. However, the correction requires precise calibration of all SiPMs because it relies on the number of cells fired in each SiPM, assuming that the sensor is uniformly illuminated. This sets an important requirement for the next generation of prototypes.

3. HiDRa: High-resolution highly granular Dual-Readout demonstrator

The experience gained with the electromagnetic-size prototype during the construction [4] and validation on beam-tests fully goes in the new demonstrator. HiDRa will be large enough to largely contain hadronic showers ($65 \times 65 \times 250$ cm^3) and the layout is shown in Figure 3. Even though the design fulfils the requirements of having all modules equipped with SiPMs, at this stage, for cost/performance reason, we are building standard modules (read out with PMTs) placed at the periphery of the demonstrator and highly granular modules (with SiPMs) placed in the centre. The modules are divided in minimodules, assembled with 16×64 stainless steel capillary tubes 2.5 m long. The capillaries have an outer diameter of 2 mm with an inner diameter of 1.1 mm. Scintillating and clear fibres with a diameter of 1 mm are inserted in the capillaries alternated in rows. The different types of fibres coming out from the standard minimodule are separated at the back and grouped to fit the surface of a PMT. A different strategy is used for the minimodules assembled in highly granular modules (Figure 3, right). In this case, the capillaries with clear fibres are shorter than the others and the fibres stop at the edge of the tubes, allowing each SiPM to be in contact with one fibre. In addition, the different length prevents the Cherenkov light from being contaminated by scintillating light, which is much more intense. Figure 3 (right) also shows the front-end boards (in green) and how the cables fit into the limited volume available on the back side of the minimodule. In the design, a big effort was made to define how to fix the large front-end board to the absorber,

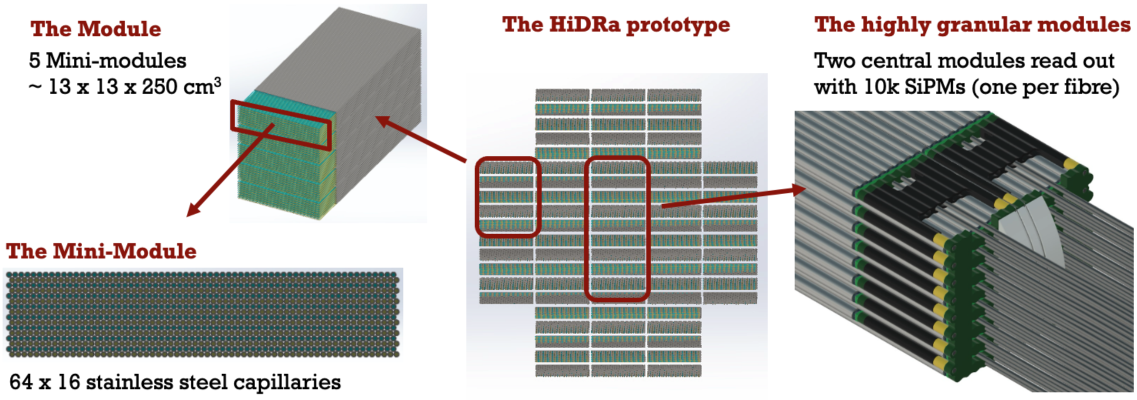

Figure 3: The schematic view of HiDRA is shown in the centre, the segmentation into modules and minimodules on the left and details of the mechanical integration of part of a highly granular minimodule on the right.

keeping the micro-pcb (used for the shorter capillaries) in place without using external mechanical supports that would create dead area. In fact, two metal wires, 100 µm thick, running all along the absorber and fixed at the front face of the calorimeter will hold the large pcb in position. Transverse alignment will be ensured by pins held in place with the long capillaries. We are aware that the full procedure requires precise tube assembly, indeed Figure 4 shows one of the minimodules produced and the tool used to measure the mechanical precision. The results obtained are in agreement with our expectation. In fact, the right-hand plot shows a deviation of the order of 10 µm with respect to the nominal value, all along the minimodule.

Due to the limited space available and to reduce the number of channels to be read out, it was decided to sum the analogue signals from the 8 sensors mounted on one SiPM-bar and connected to the same type of fibres. This decision reduces all the services required to operate 8 SiPMs to just two coaxial cables, but imposes strict requirements on the selection of SiPMs used to equip one bar. In fact, the same high voltage will be applied to all of them and only sensors with breakdown voltage differences not exceeding 100 mV will be used for the same SiPM-bar. Two different Hamamatsu SiPM models are used in HiDRa: the S16676-15(ES1) for Cherenkov and the S16676-10(ES1) for scintillating light. Each module consists of 8 SiPMs, $1{\times}1$ mm^2, spaced by 2 mm, to match the centre of the capillaries in the row. The choice of using a different size of microcells is a compromise between detection efficiency and dynamic range to better match the requirements set by the light produced in the shower. For Cherenkov signals, SiPMs with microcells of 15 µm pitch and a PDE of about 32%, similar to those used in the electromagnetic prototype, are used. For scintillating fibres, where more light is expected, microcells with a pitch of 10 µm and a PDE of about 18% will be used. Both the reduced PDE and the larger dynamic range of the SiPMs used for the scintillating fibres will allow the sensor to operate in linear regime, avoiding the need to correct for non-linearity. This choice enables the possibility to sum signals from the 8 SiPMs in the bar. Twenty A5202 readout boards will be used for the highly granular modules (1280 channels in total) that, considering the grouping, will allow to operate the 10 thousand SiPMs needed to equip the 2 highly granular modules of the HiDRa demonstrator.

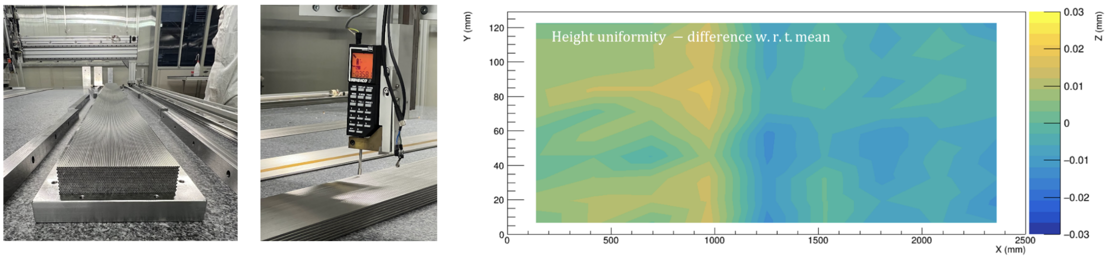

Figure 4: A minimodule immediately after the assembly is shown on the left, the automatic tool used to measure the height in the centre and a plot with the mechanical precision on the right.

4. Conclusion

The electromagnetic-size prototype, built and tested on beam in 2021 and 2023, provided a good number of information for the HiDRa demonstrator. The collaboration has a reliable Monte Carlo simulation capable of describing the detector performance response to electromagnetic showers. We optimised the requirements for the SiPMs after a good understanding of the yield of both scintillating and Cherenkov light collection and we defined the strategy needed to equalise and calibrate the prototype readout with SiPMs and PMTs. The production of the new demonstrator is progressing well, half of the standard modules have been produced and tested on beam in August 2024, while the start of the production of the highly granular minimodules is expected to happen at the beginning of 2025.

5. Acknowledgments

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References

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