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Dual-readout calorimeter development for future High-Energy Physics experiments

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The next generation of particle physics experiments, such as Future Circular Collider (FCC) and the Circular Electron-Positron Collider (CEPC), will require advanced detectors suitable for a broad range of high-precision measurements. Among these, we can mention studies of the production and decay channels of the Higgs boson, heavy-flavour physics and searches for processes beyond the Standard Model. From the calorimeter standpoint, the benchmark requests are the capability to resolve the hadronic decays of the Z and W bosons based on the invariant mass of the two jets, and precise tagging of heavy flavour object decays. The separation of Z and W bosons, which would prove essential in the identification of Higgs-related processes, entails a resolution for hadronic jets that has never been reached by detectors operating on running colliders. Dual-readout calorimeters have been designed explicitly for excellent energy resolution: the fibre-based design also enables high-granularity capabilities, and thus advanced software reconstruction techniques, through independent SiPM readout of each fibre. In this contribution, the experimental challenges on future detector calorimeters are addressed, and the dual-readout calorimetry technique is briefly illustrated. Remarkable effort was put on the development of prototypes, to demonstrate the feasibility of SiPM readout and the accessibility of expected physics performances required at future collider facilities. The construction technique of a currently under development prototype, designed for hadron shower containment, is illustrated, together with Geant4 simulation-based results.

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1. Introduction

Following the European Strategy for Particle Physics Update [1], European particle physics experiments after the High-Luminosity LHC era will first focus on precision measurements of the Higgs boson. In order to study in high detail its mass and couplings, high-energy electron-positron collisions will be exploited to benefit from the precise knowledge of energy in the centre-of-mass frame. Other major advantages of lepton colliders include the cleaner environment and lower pile-up with respect to hadron colliders, and reduced radiation damage, allowing for less stringent requirements on detector materials. The two main accelerator projects for e^+e^- collisions are the Future Circular Collider (FCC-ee), at CERN, and the Circular Electron-Positron Collider (CEPC), which would be hosted in China. Both projects feature similar characteristics: a $\sim$ 90 km long accelerator ring with up to four interaction points, to target both the energy and intensity frontiers. The two projects also include a second phase, consisting of proton-proton collisions (FCC-hh and SPPC), with energies one order of magnitude higher than the LHC.

Besides the aforementioned Higgs boson studies, the experimental conditions at FCC-ee/CEPC will also enable a wide range of Standard Model measurements. During the proposed $\sim$ 15 years of operation, the centre-of-mass frame energy will be increased from 90 GeV to 165 GeV, 240 GeV and 365 GeV, allowing for precise electro-weak W and Z bosons mass and width measurements, top-quark and other heavy-flavour physics studies such as bottom-quark and tau leptons. Both direct and indirect searches for weakly interactive particles beyond the Standard Model are included in the physics programme, in order to take advantage of both the very high-luminosity and clear final state topologies.

Calorimeters will play a central role in future collider detectors. Because of the relatively high branching fraction of W and Z bosons into two hadronic jets, an excellent energy resolution for these objects will be very important. The main target is the capability to separate the Higgs decays into two Z or two W bosons ($H \to ZZ^* \to 4j$, $H \to W^+W^- \to 4j$) from the $e^+e^- \to W^+W^-/ZZ \to 4j$ background based on the invariant mass of the two hadronic jets coming from the on-shell boson. The combined information of energy deposits in the calorimeter with track momenta and particle ID provided by advanced tracking detectors, known as particle-flow [2], will also improve the reconstruction of complicated final states, including τ leptons and b, c hadrons.

1.1 Detector concepts for FCC-ee/CEPC

Multiple technologies and methods have been proposed to achieve a resolution of 4-5% on $\sim$ 50 GeV hadron jets, which would be sufficient to statistically separate W and Z bosons masses. The CALICE collaboration [3] has been working for many years on the development of extremely finely-segmented calorimeters and compact readout integration to maximally exploit the particle-flow technique, targeting multi-dimensional imaging calorimeters. The idea behind this method is that, in a hadronic jet, only $\sim$ 10% of the total energy is carried by neutral hadrons that can only be measured in calorimeters, while the remaining component is carried by photons and charged particles, whose latter energy can be measured by track bending inside a magnetic field with higher precision. Excellent resolution on photon energies could be achieved using apposite electromagnetic calorimeters characterised by a high sampling fraction. Highly granular calorimeters are then required to separate energy deposits produced by particles that have already been measured in the inner tracker or electromagnetic calorimeter (ECAL) and subtract them from the remaining deposits in the hadronic calorimeter (HCAL). Several particle-flow-oriented calorimeter designs have been proposed for different detector layouts, with solutions applied to the International Linear Collider (ILC) detector concepts, and the CMS HGCal calorimeter upgrade for the HL-LHC phase. The CLD detector concept [4] for the FCC-ee features a silicon-based ECAL with tungsten passive layers and a steel-scintillator HCAL, with $\sim$ 160 and $\sim$ 9 millions readout channels, respectively, both optimised for software reconstruction in conjunction with track momenta measurement.

A different calorimeter design concept, but with a similar technique for hadron jets measurement, has been proposed for the ALLEGRO detector [5]. It is based on noble-liquid active material for the electromagnetic section, guaranteeing excellent energy resolution on electromagnetic showers, and a hadronic section consisting of alternating steel plates and scintillating tiles. In this case as well, imaging capabilities and particle-flow methods are expected to be essential for the improvement of hadron showers measurement.

A radically different approach to hadron calorimetry, which is better described in Section 2, is the dual-readout technique on which the IDEA detector [6] calorimeter is based. A single, longitudinally unsegmented calorimeter for both electromagnetic and hadronic shower measurements is employed, to improve the standalone detector energy resolution before further application of software reconstruction algorithms. A second option for this detector, consisting of a second, crystal-based calorimeter optimised for electromagnetic shower measurements and following the same dual-readout concept, is also being considered. The design of the IDEA detector will be better detailed in Section 3.

2. Dual-Readout calorimetry

The resolution on energy measurements for hadronic jets performed by currently operating calorimeters at collider experiments is limited by well-known characteristics of hadron shower physics and detector effects. Any hadron interacting with the calorimeter nuclei produces showers of particles and fragments from nuclear break-ups, mainly from spallation and neutron evaporation processes. A component of these subsequent particles consists of electromagnetic showers, from $\pi^0, \eta \to \gamma\gamma$ decays, whose fraction of energy with respect to the hadron shower-initiating object is called electromagnetic fraction (f_{em}). The f_{em} is subject to large and non-gaussian fluctuations, and also increases with the total energy, following[7]

$$f_{em} = 1 - \left(\frac{E}{E_0}\right)^{k-1} \tag{1}$$

with E_0 being a material-dependent scale factor related to the energy required for pion production, and $k \sim 0.8$. The distributions of f_{em} are also different depending on the nature of the impinging particle, with values averaging higher for pions and kaons and lower for protons and neutrons, due to baryonic number conservation.

Superimposed with fluctuations upon f_{em} are also event-per-event fluctuations in the amount of energy that is spent into the nuclear break-up, not resulting in electronic signals to be read by detectors, called *invisible energy*. Such an effect depends as well on the binding energy of the detector nuclei, and hence on the atomic properties of the calorimeter absorber which must be carefully chosen.

The occurrence of a non-accessible energy component specific to hadron interactions has, as a consequence, that most calorimeter's response to electromagnetic (e) and hadronic (h) components of a shower are different, a property called *non-compensation*. The response of non-compensating calorimeters is also energy dependent, based on the event f_{em}, therefore resulting intrinsically non-linear.

The dual-readout calorimetry technique [8] was specifically developed to overcome these sources of signal fluctuation in hadron showers. Signals emitted through two different physical processes are used to measure the f_{em} of each hadron shower, and its value can then be used to correct the calorimeter signal. Alongside with scintillation light emission (S), Čerenkov light (C) is used. The latter signal is mostly emitted by electrons and positrons also in hadron showers, therefore measuring the electromagnetic component. After calibrating with an electron beam, the signal produced by hadron-induced showers of energy E for the S (C) channel is

$$\begin{aligned} S &= E[f_{em} + (1 - f_{em})(h/e)_S] \\ C &= E[f_{em} + (1 - f_{em})(h/e)_C] \end{aligned} \tag{2}$$

with $(h/e)_S$ and $(h/e)_C$ representing the different non-compensation properties of the two independent signals. These values can be directly accessed through beam tests of the calorimeter, or through simulations. Solving equation 2 for f_{em} and measured energy E, one obtains

$$f_{em} = \frac{(h/e)_C - (C/S)(h/e)_S}{(C/S)[1 - (h/e)_S] - [1 - (h/e)_C]} \tag{3}$$

$$E = \frac{S - \chi C}{1 - \chi}, \quad \text{with} \quad \chi = \frac{1 - (h/e)_S}{1 - (h/e)_C}. \tag{4}$$

Among the main advantages of the dual-readout method is that the resulting reconstructed energy distribution is gaussian-shaped, and centred around the correct value. One can then optimise the design of the calorimeter, such as choosing sampling fraction, sampling frequency and materials, according to the needs of the measurements to be performed.

Several techniques for achieving double readout have been proposed: the DREAM/RD52 collaboration [9][10], which also provided the proof-of-concept for this method, focused on scintillating and clear optical fibres for separating the two signals. Different approaches, such as separating the two signals in the same media through the different pulse shape, precise timing or light polarisation, have also been implemented.

3. IDEA detector dual-readout calorimeter

The Innovative Detector for Electron-Positron Accelerator (IDEA), shown in fig. 1, is one of the general-purpose experiments proposed for one of the interaction points at a future e^+e^- collider and has been included in both the FCC and CEPC Conceptual Design Reports [11][12].

The tracking system[13] features a silicon-based vertex detector with active pixels based on MAPS technology, targeting a spatial resolution at the micron level. It is followed by an ultra-light drift chamber specifically designed to minimise the number of multiple scatterings from low-energy tracks, providing momenta measurements and particle identification through cluster counting. The drift chamber is also surrounded by a silicon micro-strip detector layer. A 2 T magnetic field is provided by a very light and ultra-thin solenoidal coil, placed before the calorimeter.

Outside the tracker volume, the IDEA detector exploits a longitudinally unsegmented dual-readout calorimeter, based on alternating layers of scintillating and clear optical fibres, parallel to the radial direction. Excellent lateral granularity is guaranteed by a Silicon PhotoMultiplier (SiPM) readout of each fibre with a 1 mm^2 active area, while longitudinal information could be provided through timing measurement, targeting $O(\mathrm{cm})$ precision. Despite not being particle-flow oriented by design, imaging capabilities of this detector layout are under study[14], and software reconstruction including modern neural networks is expected to further improve the standalone calorimeter performance. A more recent proposal for the IDEA calorimeter, which also provides additional longitudinal segmentation[15], includes a dual-readout electromagnetic calorimeter based on crystals [16], shown in fig. 1, for enhanced resolution at a $2-3\%/\sqrt{E}$ level for electrons and photons. The presence of an additional calorimetry volume could require adapting the design of the following fibre hadronic section. The excellent energy measurements and the larger crystals lateral size with respect to fibres would lead to looser requirements on extreme lateral segmentation for the hadron detection, whose performance are still provided through dual-readout. A coarser granular calorimeter could then be used, limiting the amount of readout channels. Optimisation of electromagnetic and hadronic showers energy resolutions using different fibre and tube diameters are being developed through Geant4 simulations.

Finally, micro-Resistive WELL (μ-RWELL) micro-pattern gaseous detector technology[17] would be exploited as part of the muon system for the identification and momenta measurement of these particles. The same kind of detector would also be used as a pre-shower in case of a single, longitudinally unsegmented, calorimeter option.

4. Existing dual-readout calorimeter prototypes

The construction of small scale prototypes is required in the development phase of advanced detectors, in order to understand how to cope with challenges and reach the required physics performances. They are fundamental to identify the best techniques for construction and assembly, and to find solutions regarding the front-end electronics and readout systems. Prototypes of dual-readout calorimeters are also fundamental for validating the Geant4[18] and `DD4HEP`[19] simulations, from which the IDEA detector studies on precision measurement and sensitivities are based. While prototypes of this kind have been realised within the mentioned DREAM and RD52 collaborations, the high-granularity feature reached through SiPM readout association to fibres is still a novel technique and poses several challenges with its implementation.

The first dual-readout calorimeter prototype of this series, shown in fig. 2, was built in 2021 and tested with positron beams at the DESY laboratories in Germany, and at CERN SPS in 2021[20]. The same prototype was taken again to the SPS for further characterisation, including muons and pion beams, for studying the responses to different particles and also having a first look at hadron

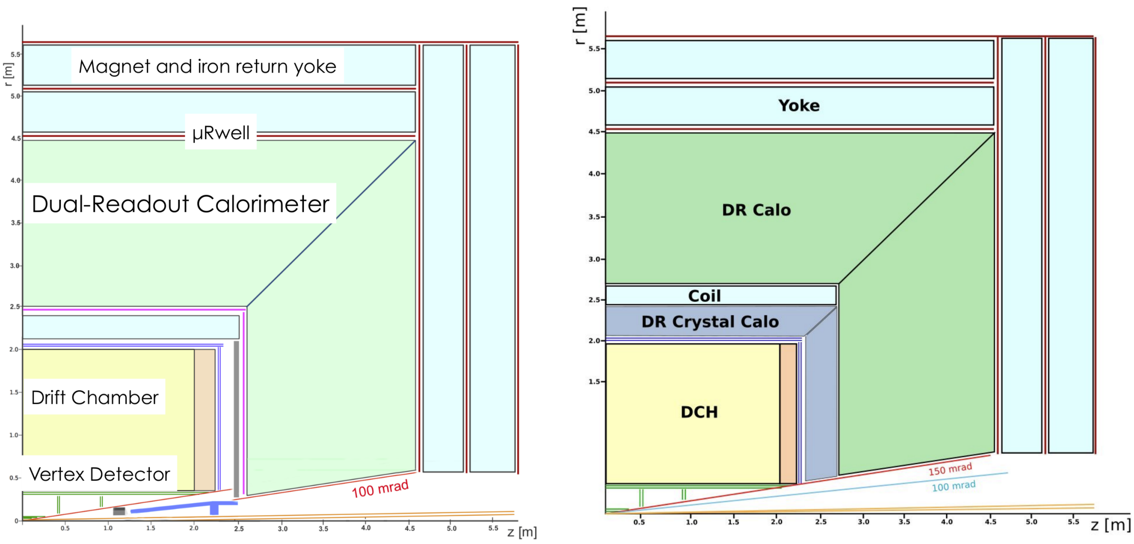

Figure 1: Drawing of the IDEA detector, without (left) or with (right) the crystal ECAL.

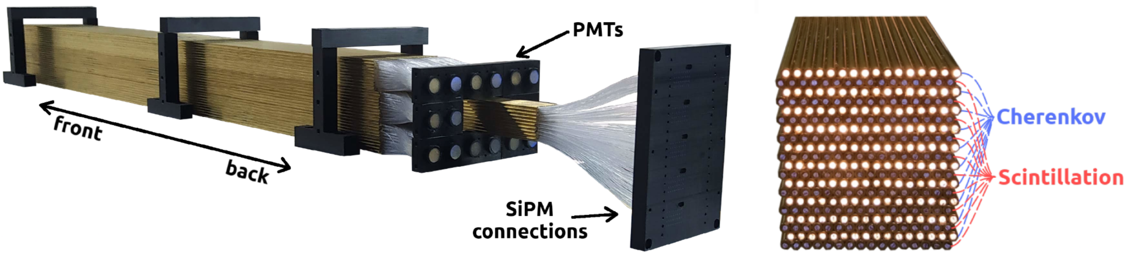

Figure 2: Pictures of the electromagnetic shower size prototype built in 2021. The side and back of the calorimeter is shown on the left, with the SiPM and PMT connections, while the front of one module is shown on the right. Clear optical fibres for Čerenkov light measurements were illuminated to show the alternating fibre layout.

shower cores. The construction technique that was identified consisted of a modular geometry based on smaller units, each made of 20 rows of brass capillary tubes, that formed the calorimeter absorber. The scintillating and clear fibres were then inserted in an alternating rows layout, with 16 fibres per row. The full prototype was made of nine modules (total size of $10 \times 10 \times 100$ cm^3), with only the central one that was readout with SiPMs, reaching 320 independent channels. At the time of prototype construction, SiPM packages small enough to be positioned right behind each fibre (with a diameter of 1 mm) were not available on the market, so the fibres were extracted from the back of the calorimeter and fed into an interface board, for easier connection to the front-end boards positioned behind the calorimeter. Hamamatsu S14160-1315PS SiPMs with a photosensitive area of 1.3×1.3 mm^2 and 15 μm pitch guaranteeing wide dynamic range were chosen to read both scintillation and Čerenkov photons[21]. The eight external modules were equipped with two photomultiplier tubes (PMT) each, for scintillating and clear (that will also be called Čerenkov in the following) fibres.

Results from the 2021 beam test [20] showed good linearity in the response to electromagnetic showers and excellent agreement of shower profile with Geant4 simulations mimicking the exper-

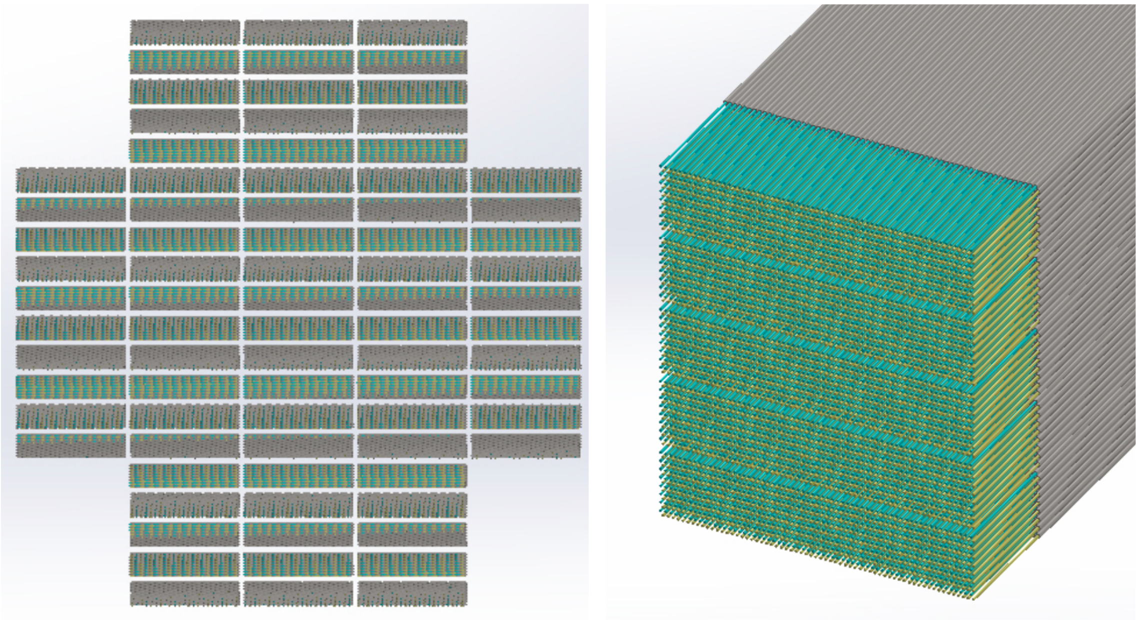

Figure 3: Sketch of the HiDRa prototype. Front view (left) and detail of a module, made of five "mini-modules". Čerenkov and scintillating fibres are blue and yellow coloured, respectively.

imental setup. Limited energy resolution was observed and motivated by non-optimal calorimeter rotation with respect to the positron beam, which was due to access issues in the experimental area. The Geant4 simulation with an appropriate test setup indicates that a resolution of $14.7\%/\sqrt{E}$ could be achieved. Encouraging preliminary results from the following 2023 test beam, which are ongoing at time of writing, suggest that this results is in reach.

5. HiDRa: hadronic shower prototype

The High-Resolution highly granular Dual-Readout demonstrator (HiDRa) is a project, funded with a grant under the Italian INFN CSN5, for the construction of a dual-readout calorimeter prototype suitable for the (almost) complete containment of hadron showers. At the time of writing this prototype is under construction at the Pavia laboratories (Italy), with the collaboration of other Italian groups. The main goal of this project is to identify a scalable construction method for larger calorimeter sizes, and at the same time reach optimal resolution on hadron energy measurements. It also allows to start facing problems related to the compactness of readout and front-end electronics, which are an essential part of the development of a complex system such as the IDEA calorimeter.

Figure 3 shows the final layout of the HiDRa prototype. It features a similar concept with respect to the previous one, based on a modular geometry of multiple smaller units. The fundamental unit, called the mini-module, consists of 16 rows of stainless steel capillary tubes, with 64 tubes per row. Alternating rows of scintillating and clear optical fibres are placed inside the capillaries. The full prototype will be made of 80 mini-modules, reaching total dimensions of $\sim 65 \times 65 \times 2500$ mm^3. Geant4-based simulations of this prototype show that an expected energy containment for pion-induced showers with energies in [10, 100] GeV range is about 93%. Of the 80 minimodules, 10 in the centre of the calorimeter will feature SiPM readout, in order to gradually increase the number of channels and the readout system complexity. SiPMs with custom packages from Hamamatsu were chosen, with different characteristics for scintillating and Čerenkov fibres, listed in table 1. For scintillating fibres, a 10 μm pitch SiPM solution (S16676-10) was selected to improve the dynamic range. The lower photon detection efficiency was not considered a problem, due to the large photon yields in these fibres. An opposite solution was preferred for Čerenkov channels, where the amount of emitted photons is significantly lower. SiPMs with 15 μm pitch (S16676-15) and higher photon detection efficiency were then selected. As for the 2021 em-prototype, all the remaining mini-modules will be equipped with two PMTs, for the collection of either scintillation or Čerenkov light from 512 fibres each. Hamamatsu R8900 PMTs for scintillating fibres and R8900-100 for Čerenkov ones from the previous RD52 calorimeter prototype are used in the external mini-modules. As the number of required PMTs is larger than the RD52 one, and the mentioned PMTs are no more in production, R11265-203 from the same company and having similar characteristics will be bought.

Table 1: Details of the chosen SiPMs for the HiDRa prototype.

Parameter	S16676-15(ES1) (C fibres)	S16676-10(ES1) (S fibres)
Photosensitive area diameter (mm)	1	1
Pixel pitch (μm)	15	10
Number of pixels	3443	7772
Recommended operating voltage (Vop)	+4 V	+5 V
PDE at the Vop (%)	32	18
Direct cross-talk at the Vop (%)	< 1	< 1
Dark count rate (kHz)	60 (200 max)	60 (200 max)
Gain (10^5)	3.6	1.8

Regarding the choice of materials for both the active and passive components, the same clear optical fibres that were successfully used for previous prototypes, Mitsubishi ESKA SK40-1500, were chosen. These fibres have a 1 mm outer diameter, with a 10% tolerance. As for scintillating fibres, BCF-12 from Saint-Gobain were chosen. They show an emission peak with wavelength in the blue light range and a $\sim$ 7 m attenuation length on average. Tests of the optical properties of these fibres, such as light attenuation as a function of wavelength and the output light, are currently being performed parallel to the prototype construction. Capillary tubes with an outer diameter of 2 mm and an inner one of 1.1 mm were selected, guaranteeing enough space for fibres to be directly coupled with SiPMs through optical grease. It was decided to not increase the outer diameter over the em-prototype one, as it would have drastically reduced the sampling fraction and hence the electromagnetic resolution. Sampling fractions for a brass absorber (the em-prototype) and a stainless steel one (for the hadronic prototype) as a function of the capillary outer diameter are shown in fig. 4, for scintillating and Čerenkov fibres, respectively.

The prototype construction starts with the selection of steel capillaries, which are required to be within specifications to not undermine the mini-module shape and stability. Tubes are rolled on a table to check the straightness, removing ones with kinks and other deformations. After this first

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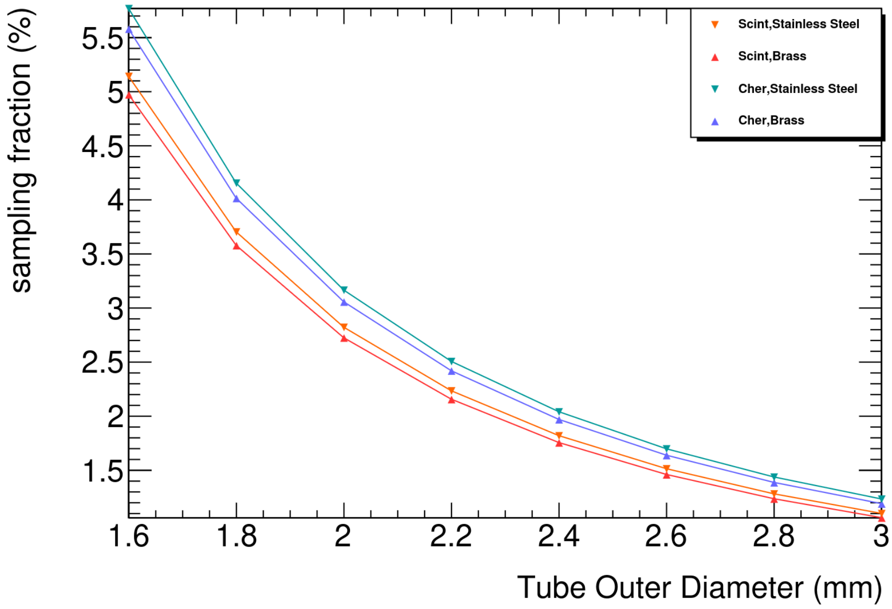

Figure 4: Analytical calculation of the sampling fraction for a calorimeter with capillary tube design, as a function of the tube outer diameter. The fibre diameter and the tube inner radius were fixed to 1 mm and 1.1 mm.

basic selection, 64 tubes are aligned on a reference tool with the exact module width and length. Dirt and other production leftovers, which would prevent the correct gluing of tube layers, are simply removed by rubbing with ethyl alcohol. Bi-component Araldite 2011 is deposited on the aligned tubes that form one of the mini-module rows (fig. 5). A vacuum system tool suspended on a crane is used for the handling of the capillaries, to place each layer upon the previous ones. Finally, after the tube glueing a semi-automatic quality check on the completed mini-module is performed, using a gauge supported by a 3D movement machine. The height of the mini-module, which is positioned on a granite table that has already been measured as a reference to eliminate mechanical deformation of the tool, is regularly checked for studying eventual mechanical issues. Figure 6 shows one completed mini-module on the granite table, and the measured height of one mini-module. Optical fibres are then manually inserted inside each of the capillaries, and bundled into the PMTs supports on the back of the mini-modules.

Parallel to the construction, a great effort is being put into the mechanical integration of the front-end electronics. The expected extremely large amount of SiPMs to read on the IDEA calorimeter, about 80 million channels, represents a challenge to the readout architecture. To reduce as much as possible the cabling outside the calorimeter, very compact front-end boards are required. For the high-granularity core of the HiDRa prototype, signals from 8 same-type fibres are grouped into one readout channel. To achieve this, grouping boards are directly connected to SiPMs, and perform an analogical sum of the signals. It has been observed through the same Geant4 simulation that such a grouping has a marginal impact on the spatial resolution for positron beams if the dimension of a single channel is significantly lower than the Molière radius of electromagnetic showers. Using 2 mm tubes, the total width of a channel is then 16 mm, while the estimated Molière

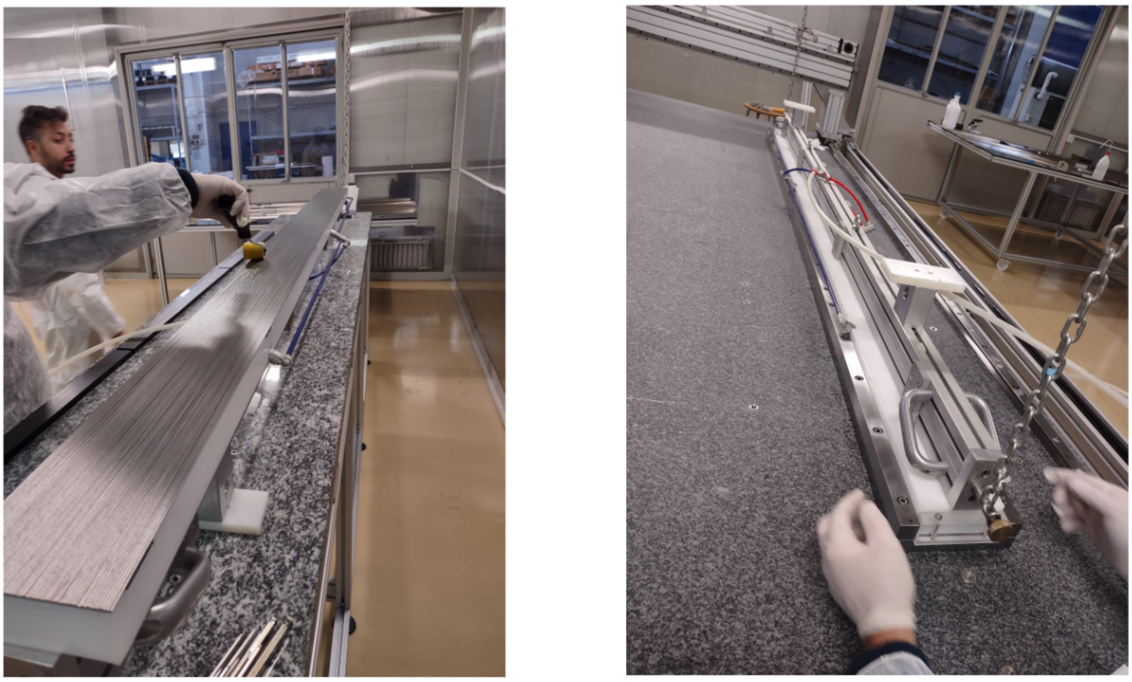

Figure 5: Pictures of the calorimeter mini-modules construction. On the left, the capillaries were aligned on the reference tool, and the vacuum system allows to turn the whole row upside down for the glueing. On the right side, the same vacuum system is used to move the tubes and deposit them on the previous layers.

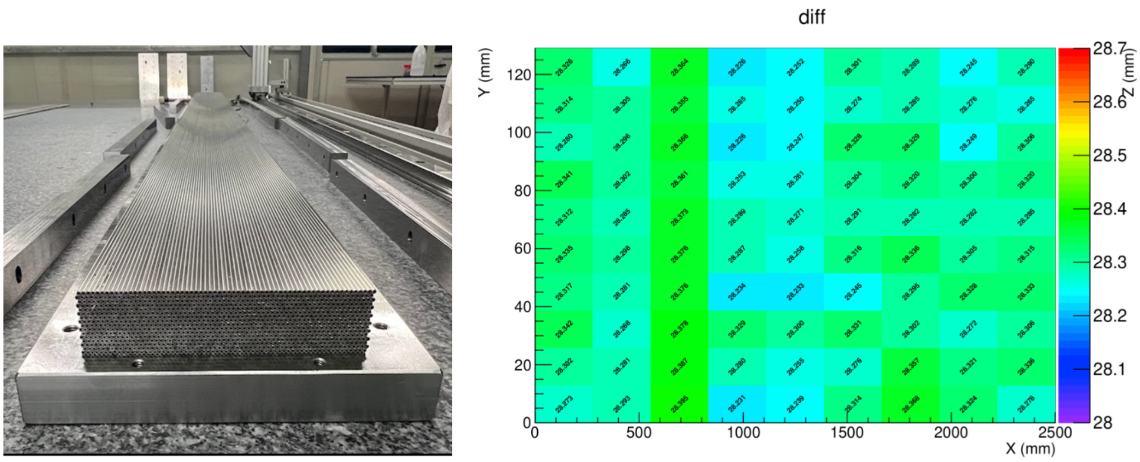

Figure 6: A completed mini-module with 16 capillary rows (left) and the Z-axis measurements taken using a gauge supported by a 3D movement machine. The bin content represents the difference of the mini-module height over the reference table.

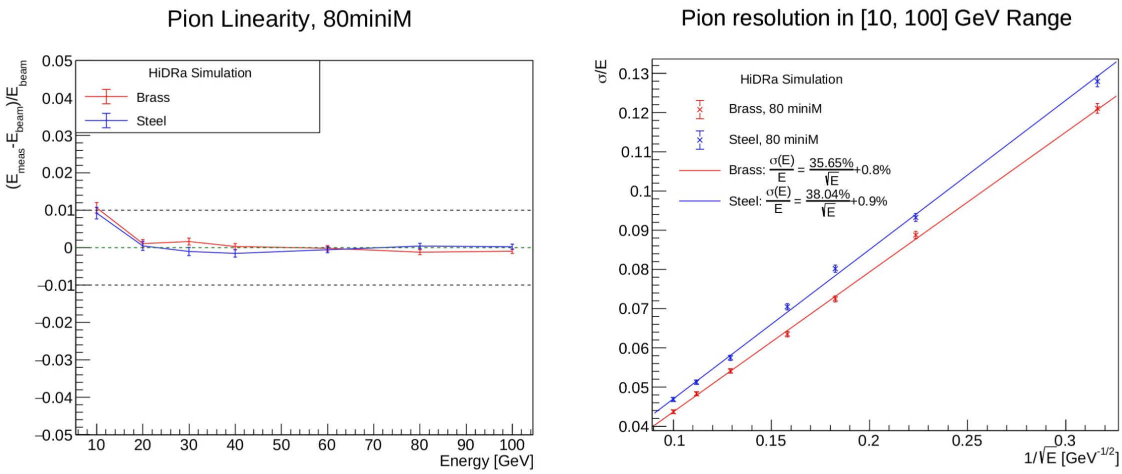

Figure 7: Geant4 simulation-based results for the HiDRa prototype with a π^+ beam, with energies between 10 and 100 GeV. On the left, the difference between the true and the reconstructed energies is shown, demonstrating the potential of the dual-readout technique. The reconstructed energy was corrected for the average containment, to take into account the limited detector volume. On the right, the energy resolution for two different absorber materials, brass and steel. While the brass absorber seems to guarantee slightly better performance, the difference was judged not large enough to motivate a significant increase in the prototype costs. Stainless steel was therefore selected as an absorber for HiDRa.

radius in HiDRa is $\sim$ 24.7 mm. Two CAEN FERS-5200 readout systems, able to read up to 64 channels each, are used to collect all signals from mini-modules for the charge measurements.

The construction of the HiDRa prototype started in November 2023, and at the time of writing 21 mini-modules were completed. A beam test of the prototype is expected by the end of 2024, with the number of mini-modules that will be available. Figure 7 shows the expected hadron energy measurements for charged pions within a [10, 100] GeV range, obtained through a Geant4 simulation with the full HiDRa (80 mini-modules). Once taken into account the mean contained energy inside the calorimeter volume, the dual-readout technique allows the correct reconstruction of beam energy and good resolution. The same simulation also shows encouraging results when more modules are added to the calorimeter, increasing the total lateral dimension. Using a simulated calorimeter with 1.3×1.3 m^2 cross size and the HiDRa geometry, a resolution of $33\%/\sqrt{E}$, very close to the target IDEA standalone calorimeter performances, is obtained.

6. Conclusions

The development of a dual-readout calorimeter, with very fine lateral and longitudinal segmentation, for the IDEA detector at FCC/CEPC requires addressing a number of complications. One of the possible layouts for such a detector, consisting of capillary tube absorber with alternating scintillating and clear optical fibre rows, is being investigated as an affordable and simple assembly solution. A calorimeter prototype with this design, sufficiently large to contain hadron showers, is currently under construction. It will be used to demonstrate that the target performances for hadron calorimetry can be achieved, and the feasibility of SiPM readout for imaging purposes. The prototype will also allow the development of compact solutions for the front-end electronics and readout systems with an increasing number of channels, more than ten thousand already in HiDRa. The construction, which started in late 2023, is underway and expected to last for the whole 2024. A characterisation of the prototype with beam tests will be performed by the end of 2024 and later, providing final validation of the detector response to electromagnetic and hadron showers. Based on the results of these studies, the Geant4/DD4HEP full-simulation of the IDEA will be updated, to guarantee reliable performance studies with deep understanding of the detector.

Acknowledgments

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