PROCEEDINGS OF SCIENCE

Simulation and test beam results of a capillary tube, dual-readout calorimeter

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The precision measurements planned at future lepton colliders require excellent energy resolution, especially in multi-jet events, to successfully separate Z, W, and Higgs decays. Over the past years the dual-readout method, which exploits complementary information from Scintillation and Cherenkov channels, has emerged as candidate to fulfil these requirements. Dedicated studies in simulation as well as test beam prototypes have investigated various detector geometries based on a fibre dual-readout calorimeter. One variation of the geometry, relying on capillary tubes, promises easy assembly with excellent geometrical accuracy at a moderate cost. In these proceedings we present the latest results from simulation of this newest prototype as well as compare this to recent test beam results. The simulation is also used to investigate the performance with a larger prototype fit for hadronic shower containment and the full 4π detector geometry using the capillary tube design.

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1. Introduction

The physics programme envisioned at the next generation of lepton colliders will require high precision detectors. The IDEA detector concept for a future e^+e^- collider, like the FCC-ee or CEPC, features a dual-readout calorimeter in its baseline design [1].

The dual-readout approach ([2]) aims to compensate detector performance effects from fluctuations in the electromagnetic fraction (f_{EM}) in hadron showers. These fluctuations limit the energy resolution and introduce non-linearities and non-Gaussianity in the reconstructed signal. The dual-readout method corrects for the fluctuations by measuring f_{EM} event-by-event, allowing for accurate energy reconstruction for hadrons of all energies. It requires two independent readout channels with different responses to the electromagnetic (EM) and non-EM part of a hadronic shower. Namely, a Cherenkov (C) and a scintillation (S) channel are used for the IDEA calorimeter. The C channel is only sensitive to the relativistic particles in the shower, mostly electrons and positrons, therefore providing a measurement of the EM component of the shower, whereas the S channel is sensitive to all charged particles. The combination of complementary information from these two channels restores a linear and Gaussian energy reconstruction which works for both EM and hadronic showers. More information on dual-readout calorimetry can be found in [2].

Figure 1 shows a sketch of the IDEA detector geometry (left) alongside a visualisation of the calorimeter barrel region. The calorimeter consists of towers, with most of the volume being the absorber material. The active material is embedded in the tower in the form of C and S fibres, which are placed longitudinally within the tower. Each tower is projective, such that they are wider in the back face than in the front. In the visualisation, the tower size has been artificially increased to emphasise this point. All fibres within one tower run parallel. There is no inherent longitudinal segmentation of the towers or the fibres.

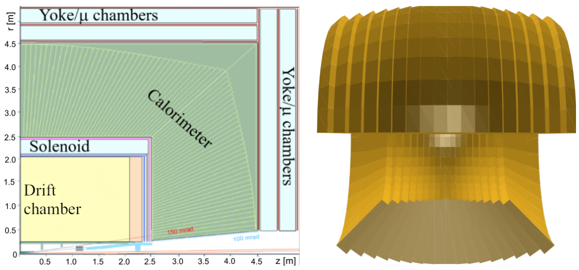

Figure 1: (left) Schematic of the IDEA detector concept for the FCC-ee [1]. (right) Visualisation of the barrel region with increased tower size to emphasise the shape of the projective towers.

2. Electromagnetic shower sized Prototype

2.1 Geometry

The construction of a 4π calorimeter will introduce many new challenges. To investigate a new assembly method and the feature of single-fibre silicon photomultiplier (SiPM) readout, a prototype with dimensions to contain a 100 GeV EM shower to 95 % was built. The assembly method, called 'Bucatini', consists of thin 'capillary' brass tubes, acting as absorber material, in which the fibres are embedded. The tubes have an outer diameter of 2 mm and an inner diameter of 1.1 mm with a length of 1 m. In total, 2880 tubes were stacked hexagonally, creating a prototype of dimensions $10 \times 10 \times 100\,\mathrm{cm}^3$. During construction and also for the readout, the prototype was subdivided into 3×3 towers, each containing 16×20 tubes. Photographs of the prototype are shown in Figure 2.

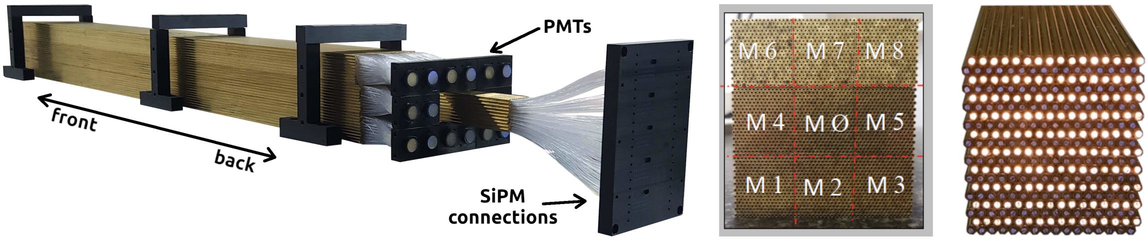

Figure 2: (left) Picture of the EM prototype with readout connections. (middle) Front face of prototype, subdivided into nine modules. (right) Alternating rows of C (illuminated) and S fibres. [3]

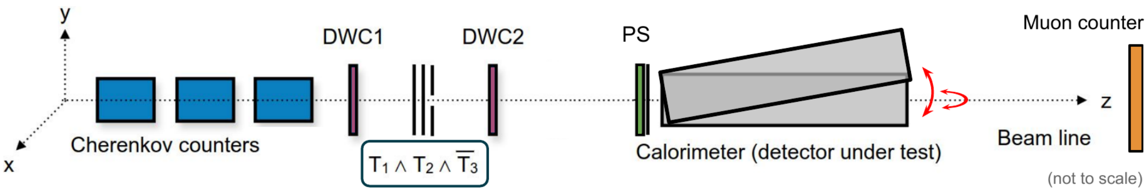

Figure 3: Sketch of the beam line setup for the 2023 SPS test beam (adapted from [3]).

The fibres are placed in a layout of alternating rows of C and S fibres. For the C channel, clear undoped SK-40 Mitsubishi fibres, with a core of polymethyl-methacrylate (PMMA) resin and a cladding of fluorinated polymer, are used. The S fibres are Saint-Gobain BCF-10, with a polystyrene core and PMMA cladding.

In the central tower, M_0, each fibre is equipped with one Hamamatsu SiPM (S14160-1315PS). The surrounding towers are readout with two Hamamatsu R8900 photomultiplier tubes (PMTs) each, one for the bundled C fibres of the tower, and one for the bundled S fibres.

2.2 2023 Test Beam

The EM prototype was put on test beam twice in 2021, once at DESY and once at the super proton synchrotron (SPS) at CERN. Details and results from these test beam can be found in [3].

These proceedings focus on another test beam campaign at SPS in 2023. This test beam allowed to address some of the issues encountered in 2021. Figure 3 shows a sketch of the test beam set up. Since the positron beam was contaminated with hadrons and muons, there were several ancillary detectors to allow for an effective positron selection. Three helium filled Cherenkov counters were placed upstream in the beam. The pressure inside the chambers was tuned for every energy to optimise positron-pion separation. Furthermore, a preshower detector, consisting of one X_0 of lead attached to a scintillator slab, was placed before the calorimeter, with only positrons having a significant interaction probability. Downstream of the calorimeter a muon veto was placed. Further auxiliary detectors include the delay wire chambers, used to determine the beam position. To trigger, three scintillation counters were available, one with a hole in the centre used to veto off-axis particles (physics trigger: $T_1 \wedge T_2 \wedge \bar{T}_3$). With respect to 2021, the setup allowed for easy rotation of the prototype, due to placing it on a rotating platform, and building a support structure, allowing to set a 2.5° vertical inclination.

With the highly granular readout in the central tower, the radial shower shapes were investigated in new conditions with respect to the 2021 test beam. Namely, the various rotation modes could be

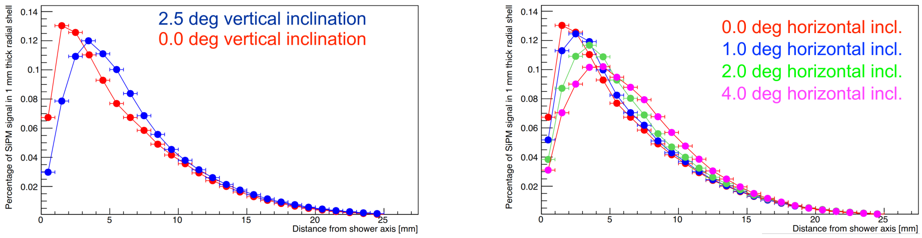

Figure 4: Radial shower profiles for runs with different vertical (left) and horizontal (right) rotations.

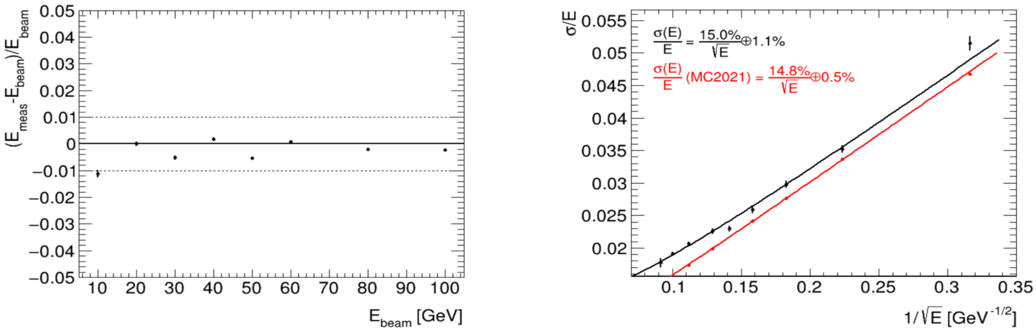

Figure 5: Positron linearity (left) and energy resolution (right) for the 2023 test beam at SPS

investigated with the data from dedicated runs. Figure 4 shows the shower profiles for various runs with different vertical (left) and horizontal (right) inclinations. The shower shape clearly shows a strong dependence on the rotation angle, becoming less centralised for larger rotations.

One of the main performance metrics for this prototype remains the energy linearity and the achievable resolution. Figure 5 shows the achieved positron linearity (left) and energy resolution (right) for this test beam campaign. As in [3], the linearity lies within 1 % over the full energy range. The energy resolution agrees with the results from [3], although at this test beam there is a large uncertainty on the beam energy (1–2 %), resulting in a larger constant term. Additionally, larger noise and SiPM saturation effects negatively impacted the result.

3. HiDra Prototype for hadronic containment

3.1 Geometry

Since the EM prototype cannot efficiently contain hadronic showers, a new, larger prototype is in the process of being built. The high resolution, highly granular dual-readout demonstrator (HiDra) prototype, also based on the Bucatini assembly method, will have dimensions of $65 \times 65 \times 250\,\mathrm{cm}^3$. Similarly to the EM prototype, it will consist of 80 independent modules, each with 16×64 tubes, with SiPM readout in the central region and PMT readout in the edge region. Figure 6 shows the layout of the modules and the readout.

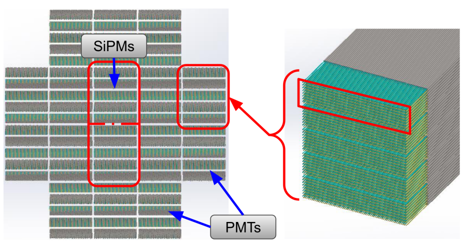

Figure 6: Geometry of the HiDra prototype with SiPM readout in the centre, and PMT readout in the surrounding modules [4].

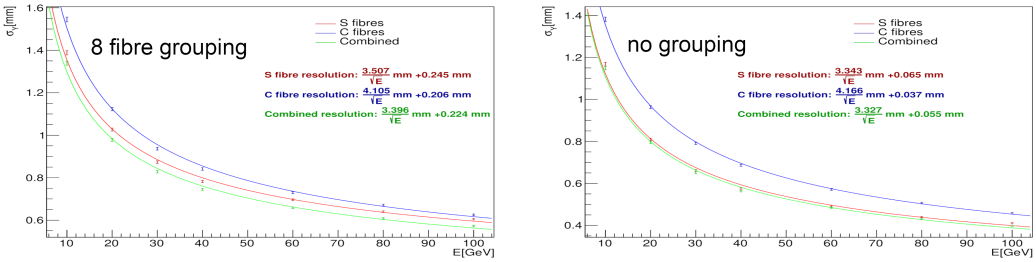

Figure 7: Spatial resolution in the direction of rows with (left) and without (right) grouping of the fibres.

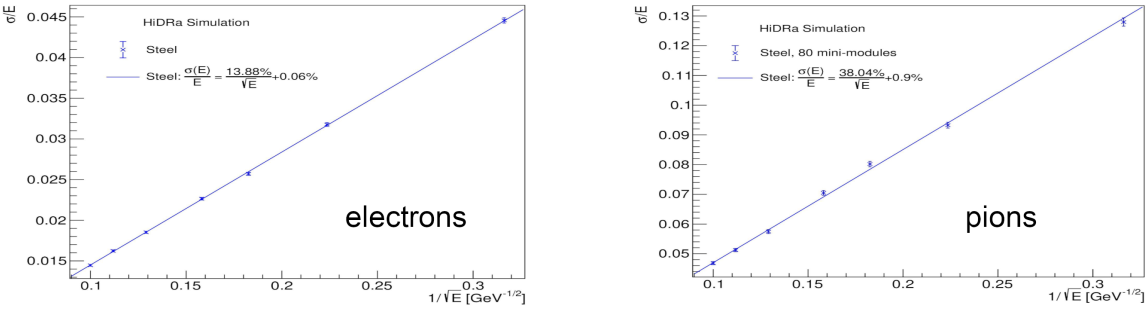

Figure 8: HiDra energy resolution for electrons (left) and hadrons (right) with linear fits.

To reduce the complexity of the SiPM readout in the highly granular HiDra core, individual fibre information will no longer be available. Instead, the signal from eight SiPMs are grouped via analogical sum on the front-end boards. The grouping of the fibres occurs along the rows such that C and S channels are not mixed.

3.2 Simulation Results

While HiDra is still under construction, there have been extensive simulation studies performed in Geant4 with this geometry.

With a relatively large central region being read out fibre-by-fibre, first studies on the spatial resolution can be conducted. The shower barycentre is reconstructed as the average of the energy weighted fibre position. Figure 7 compares the spatial resolution in direction of rows with (left) and without (right) grouping of the fibres to bundles of eight[1]. The effect of the grouping is negligible. Over a wide energy range, sub-mm precision in the barycentre reconstruction is possible.

With the HiDra simulation the hadronic performance can be studied for the first time. Figure 8 shows the energy resolution for single electron (left) and pion (right) events. The electron resolution is in line with the expectation from the test beam results, with an improvement due to higher energy containment. For pions, a resolution of $38\,\%/\sqrt{E} + 0.9\,\%$ is achieved. Despite HiDra's size, this result is still limited by leakage, mostly in lateral direction, as the simulation has shown.

4. Full 4π IDEA Calorimeter

While the construction of the full 4π detector is still in the far future, the full geometry with capillary tubes has been implemented in the DD4hep simulation framework. In the current

[1]For the grouped reconstruction, the position between the 4^{th} and 5^{th} tube was used.

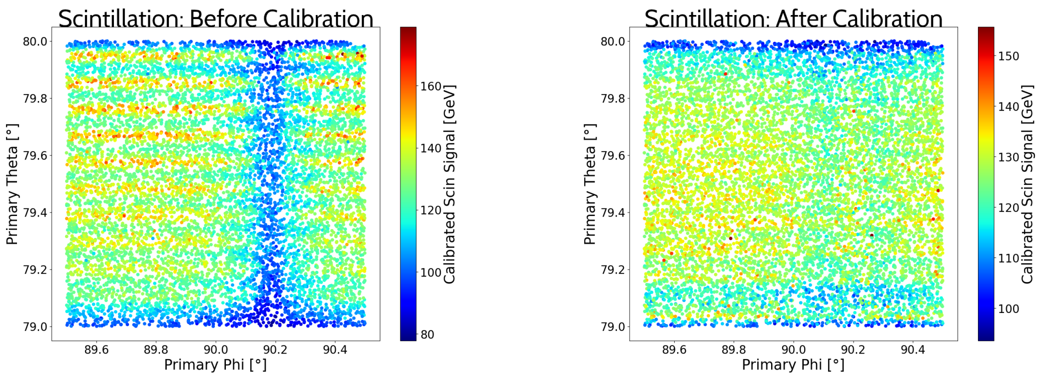

Figure 9: Signal modulation in the S channel before (left) and after (right) applying a correction procedure.

implementation, there is no inclination angle between particles coming from the interaction point and the alternating row structure of the fibres. Therefore, this geometry is susceptible to the energy modulation based on the impact point observed in [3]. Figure 9 shows the effect of applying the R_{max} calibration procedure detailed in [3] on the example for 120 GeV electron events shot over the range of one tower for the S channel. This correction procedure achieves decent results, except in the edge region, where the support structure for the towers marks the non-sensitive region. Nonetheless, further improvement to reduce the modulation are currently being investigated.

5. Conclusion

New results from the latest test beam campaign and from simulation have been shown. The energy resolution of the prototype meets the expectations set by the simulation results from 2021. The HiDra performance is yet to be tested on beam, but the simulation results are promising. The current full detector simulation reveals significant energy modulation due to the alternating fibre structure, which calls for further calibration investigations.

Acknowledgments

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References

[1] G. Gaudio, *The IDEA detector concept for FCCee*, *PoS* **ICHEP2022** (2022) 337.

[2] S. Lee, M. Livan and R. Wigmans, *Dual-Readout Calorimetry*, *Reviews of Modern Physics* **90** (2018) 025002 [1712.05494].

[3] N. Ampilogov et al., *Exposing a fibre-based dual-readout calorimeter to a positron beam*, *Journal of Instrumentation* **18** (2023) P09021.

[4] A. Pareti, *Status of dual-readout calorimetry for future high-energy physics experiments*, *Journal of Instrumentation* **19** (2024) C04029.