Advancement and Innovation for Detectors at Accelerators

Subtask 8.4.2:

Development of highly granular dual-readout fibre-sampling calorimeter

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Università dell'Insubria and INFN-MI

On behalf of the IDEA Dual-Readout calorimeter collaboration

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101004761.

8.4.2 – Objectives

- **Development of highly-granular dual-readout fibre-sampling calorimeters**
  - **The beneficiaries**: INFN – Italy (PV, MI, PI, BO, CT and RM1), Sussex Univ. (UK) and CAEN
  - **Collaborators external to the program**: Kyungpook National University (Korea), Korea University (Korea) and Iowa State University (US)

The dual-readout fibre-sampling technique offers a way to overcome one of the limiting factors in hadron calorimetry, by cancelling, event by event, the effects of the electromagnetic fraction fluctuations in hadronic showers, and, with SiPM read-out, provides high granularity and excellent angular resolution. The production and mechanical assembly of the detector elements, the readout of $O(10^8)$ channels with an optimised scalable system, and the possibility to discriminate photon and electron showers from hadrons by time measurements will be investigated. The readout system will be developed in collaboration with CAEN in order to equip several 10×10 cm^2, 2 m long, prototypes to be qualified with test beams.

Milestone number[18]	Milestone title	Lead beneficiary	Due Date (in months)	Means of verification
MS35	Definition of the assembly method and of the ASIC specifications for a dual readout calorimeter	22 - INFN	23	Report (Task 8.4)

Report available here: https://aidainnova.web.cern.ch/milestones

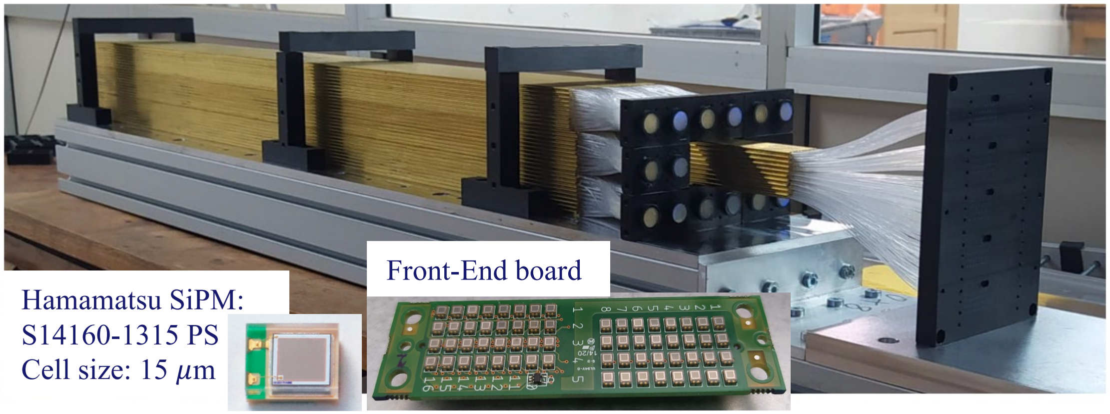
Now, fully committed to the demonstrator

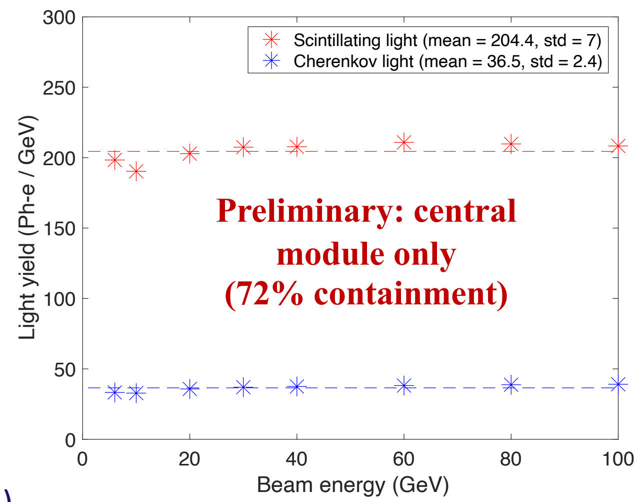
Deliverable Number[14]	Deliverable Title	WP number[9]	Lead beneficiary	Type[15]	Dissemination level[16]	Due Date (in months)[17]
D8.4	Construction and qualification with beam of 10×10 cm^2, 2 m long, prototypes	WP8	22 - INFN	Demonstrator	Public	46

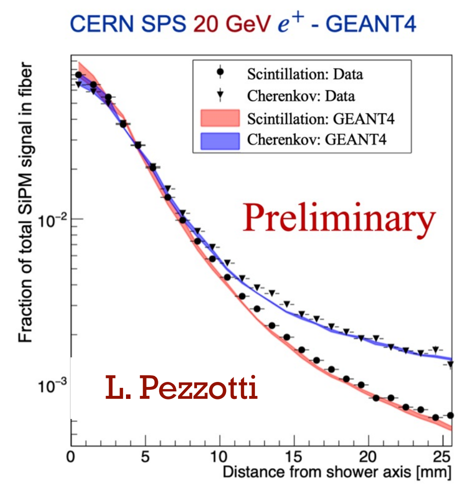
Outline

- Summary of the results reported in the Milestone M35
- Progress report on the activities on going to build the hadronic size demonstrator

Summary from the 2021 Test beam







- A EM-size prototype has been tested on beam in 2021 (@DESY and @CERN) with electrons from 1 to 100 GeV
- The prototype was made of brass capillary tubes (2 mm outer diameter) each hosting a fibre of 1 mm diameter: (10x10x100 cm³)
- There are 9 towers containing 16x20 capillaries with alternating scintillating and clear fibres
- The central tower is equipped with SiPMs while the surrounding towers are connected to PMTs (cost-saving reason)

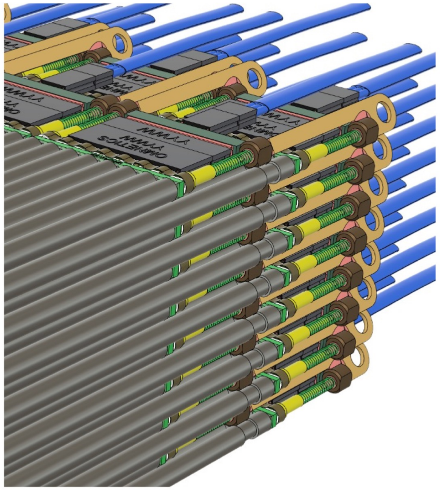
Calor2022 – *DOI: 10.3390/instruments6040059*

A performance paper is almost ready for the submission

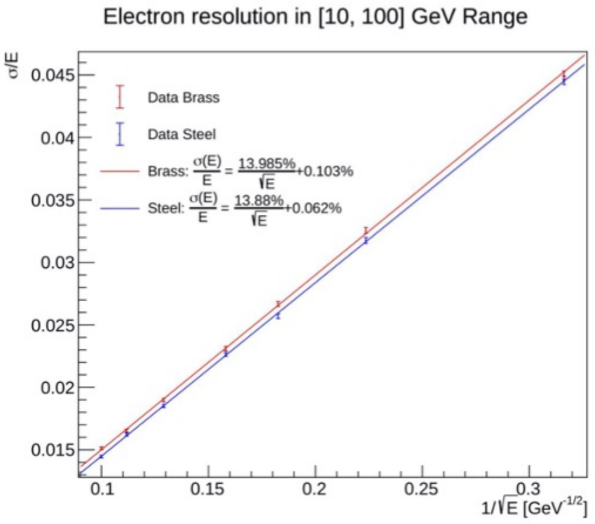
Design of a scalable solution

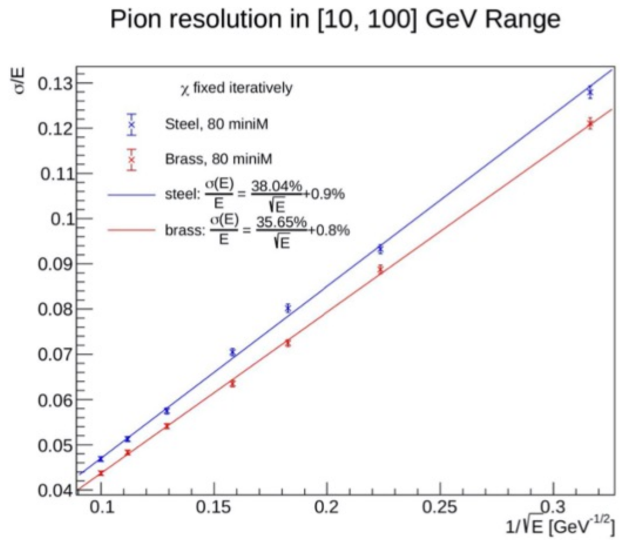
Challenging task requiring:

- Precise assembly procedure
- Compact components: almost no space in the rear part of the calorimeter
    - Sensors
    - Mechanical support
    - Services



- The scalable design is a compromise between integration constrains, costs and performance tuned with a Geant4 simulation
    - Baseline: steel tubes, 2mm diameter, 2.5 m long

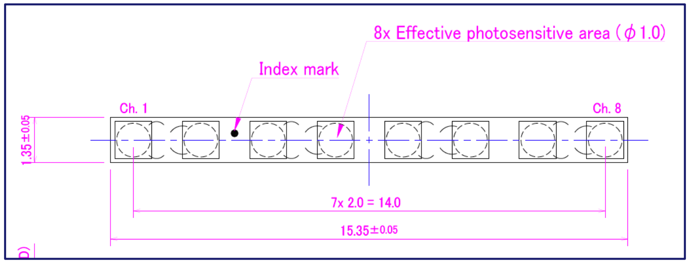




SiPM - requirements

- Compact package (almost no dead area)
- Large dynamic range:
  - Cherenkov (scintillating) light is expected to produce ≈ 5 p.e./GeV (≈ 28 p.e./GeV) in the SiPMs closest to the shower axis
  - Different options considered for Cherenkov and scintillating light to operate SiPMs in linear regime (occupancy less than 25 – 30 %)

Compact package



Used for the 2021 prototype

Options considered for the hadronic-size prototype

Parameter	S14160-1315PS	S16676-15(ES1)	S16676-10(ES1)
Effective photosensitive area (mm2)	1.3 x 1.3	1 x 1	1 x 1
Pixel pitch (mu)	15	15	10
Number of pixels	7284	3443	7772
Recommended operating voltage (Vop)	+4 V	+4 V	+5 V
PDE at the Vop (%)	32	32	18
Direct cross talk at the Vop (%)	<1	<1	<1
Dark count rate (kHz)	120 (360 max)	60 (200 max)	60 (200 max)
Gain (10^5)	3.6	3.6	1.8

ASIC – requirements

Main specifications	
Readout strategy	Charge integration
Number of channels	32 / 64
Sensitivity	0.5 p.e. (@ 2 * 10^5 SiPM gain)
Dynamic Range	0 – 320 pC (i.e. 10000 p.e. @ 2 * 10^5 SiPM Gain)
Timing resolution	< 50 ps rms (single p.e.)
Power consumption	< 500 mW
Full frame readout	Internal / external trigger (one of the two or both)
Additional features	
Single channel HV adjustment	
Single channel gain tuning	
Single channel threshold setting (required for timing and internal trigger)	
Trigger mask (required for internal trigger)	
Signal latency (≈100 ns)	
Internal TDC (optional)	

Charge integration plus timing information

ASIC – requirements

Charge integration plus timing information

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Trigger mask (required for internal trigger)	
Signal latency (≈100 ns)	
Internal TDC (optional)	

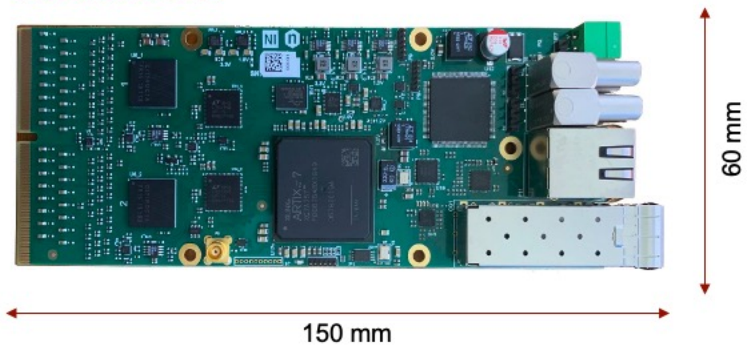
Waveform sampling plus feature extraction

Main specifications	
Readout strategy	Waveform sampling
Number of channels	32 / 64
Sampling frequency (GHz)	5 - 10
Input Bandwidth (GHz)	> 1
Buffer length (samples)	> 4k
Feature extraction	i.e. total charge, ToA, ToT, current-peak time …
Full frame readout	Internal / external trigger (one of the two or both)

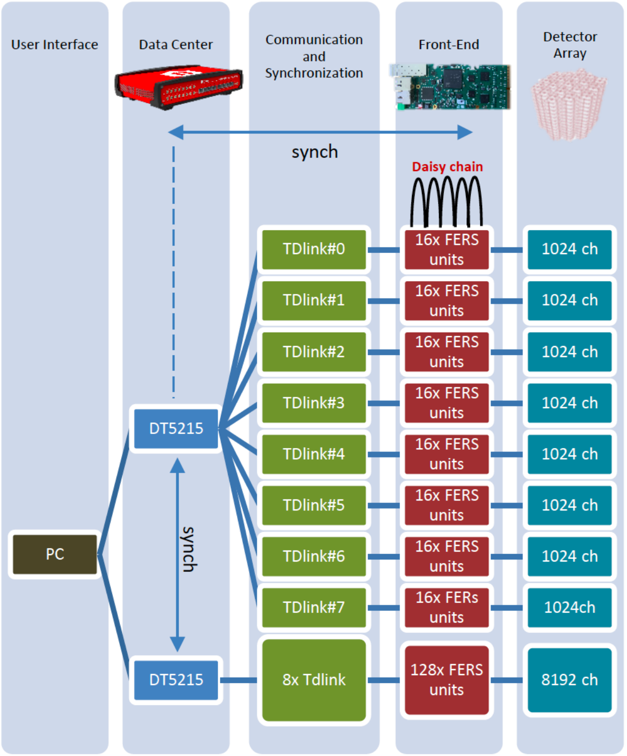
Scalable readout system

- The Caen FERS system (5200) is our baseline, compliant with the Citiroc1A and the Radioroc (hopefully soon). Alternatives will be also considered

FERS: A5202

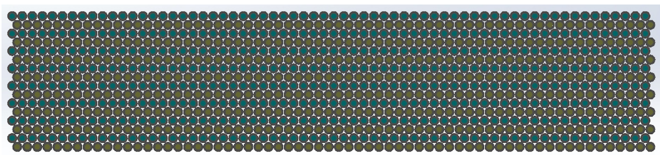


- Two Citiroc1A for reading out up to 64 SiPMs
- One (20 – 85V) HV power supply with temperature compensation
- Two 12-bit ADCs to measure the charge in all channels
- Timing measured with 64 TDCs implemented on FPGA (LSB = 500 ps)
- 2 High resolution TDCs (LSB = 50 ps)
- Optical link interface for readout (6.25 Gbit/s)



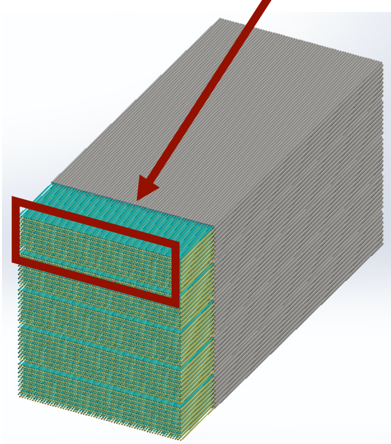
Prototype with hadronic containment: HiDRa

The Mini-Module



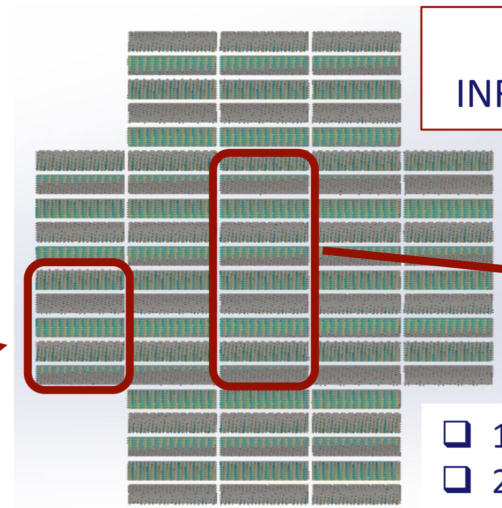
64 x 16 capillaries

The Module



5 Mini-modules
~ 13 x 13 x 250 cm^3

The hadronic prototype

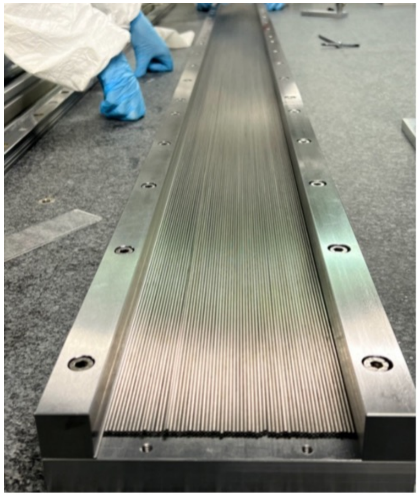


HiDRa
INFN-funded R&D project

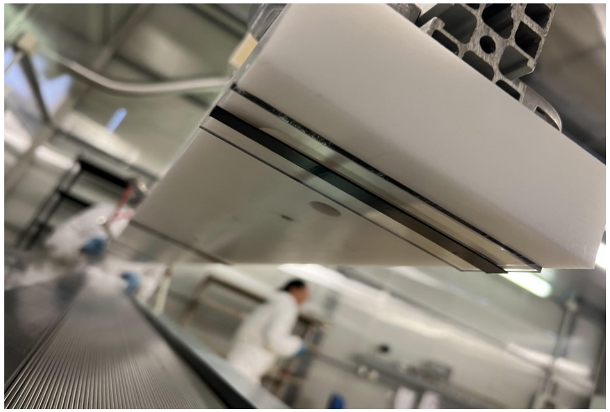
The highly granular modules

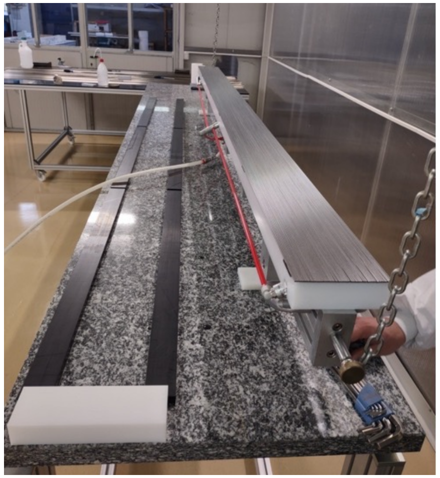
- 16 modules in total
- 2 central modules equipped with SiPMs
- 14 modules equipped with PMTs
- ~ 65 x 65 x 250 cm^3

Construction technique for the mini-module



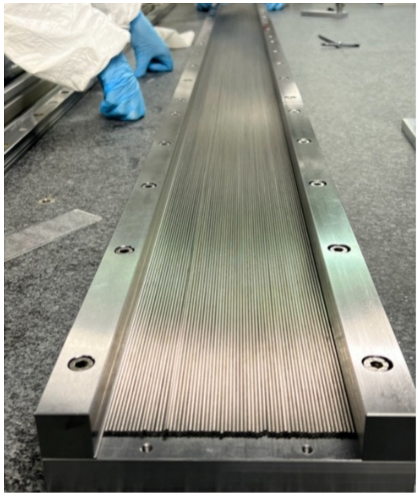
Assembly reference structure anchored to the granite table with the 1st layer of tubes in place





Vacuum + double-sided tape for tube handling

Construction technique for the mini-module



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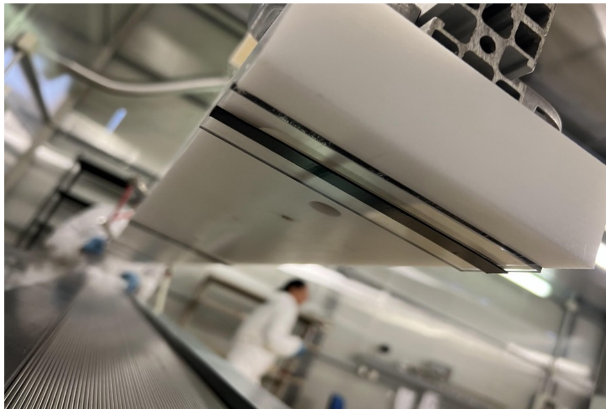
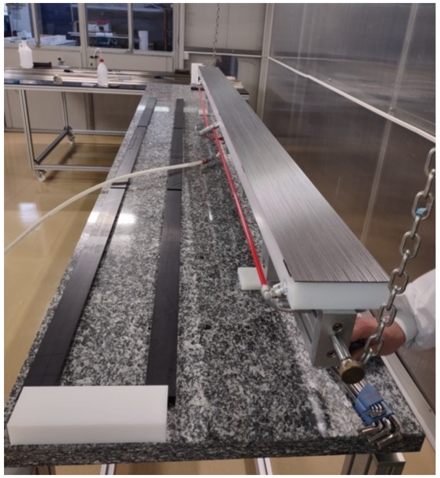
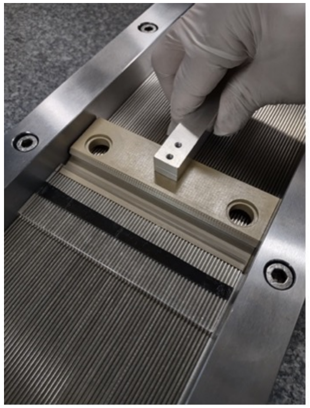


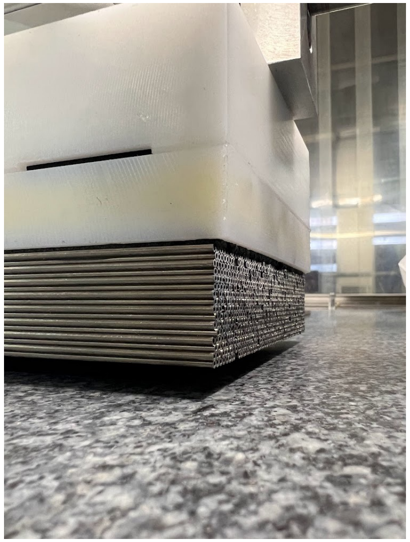
Vacuum + double-sided tape for tube handling

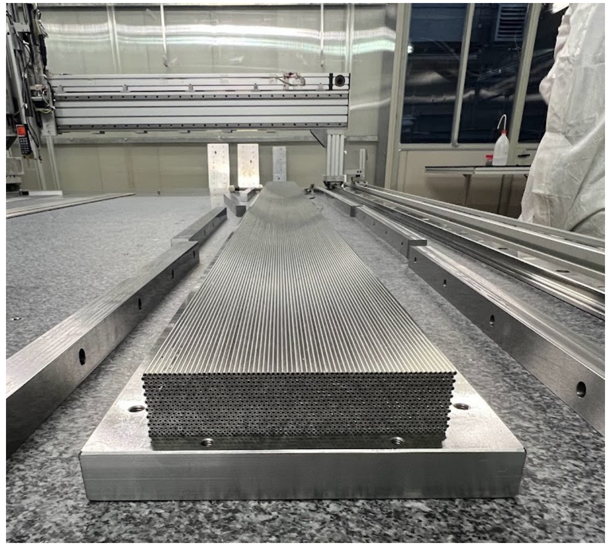




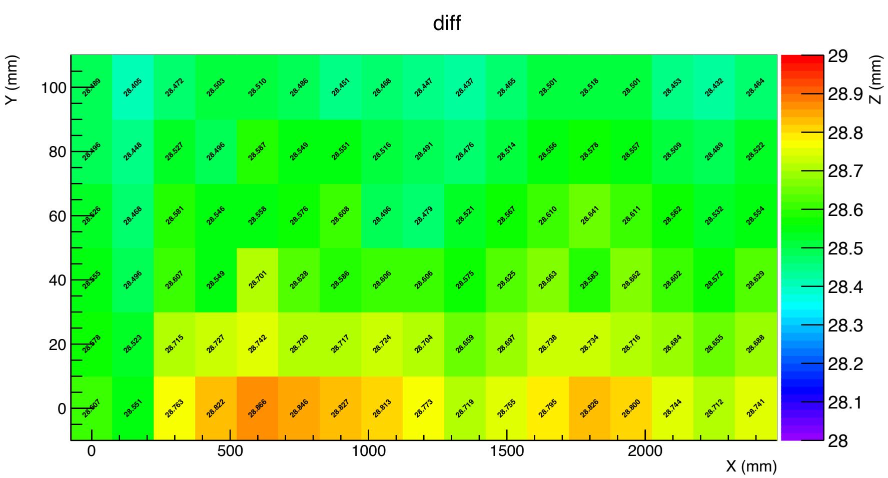
Glue dispensing and tube alignment and positioning

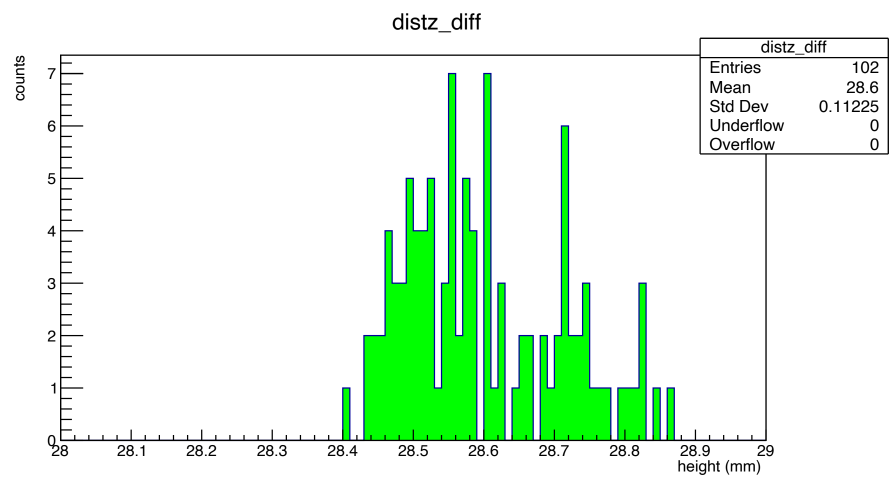
Construction technique for the mini-module





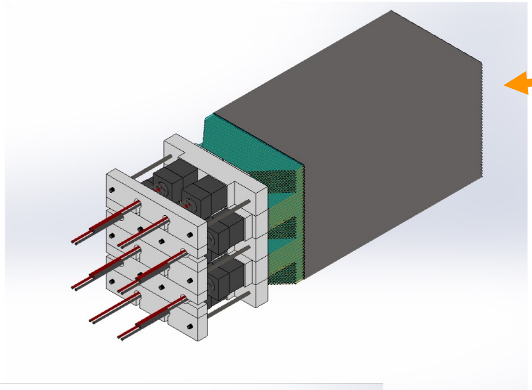
Tube average OD: 2.026 mm
Nominal height: 28.351 mm

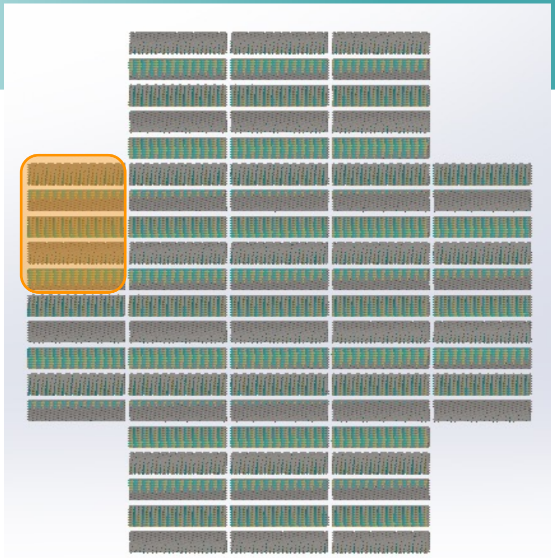


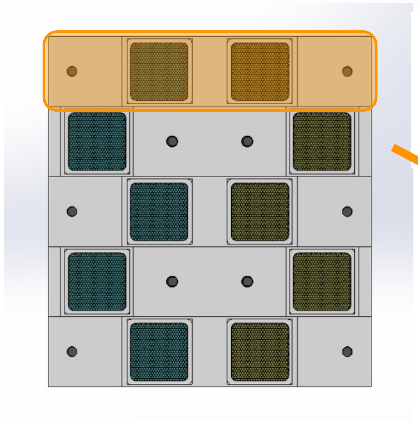


Photodetector integration: PMTs

The Module = 5 mini-modules



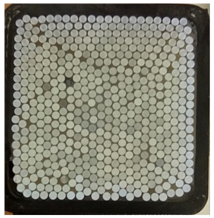


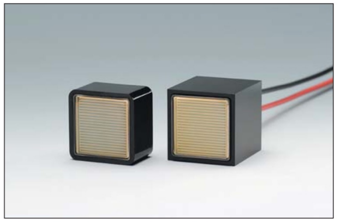


Each minimodule is readout with 2 PMTs (one for Cherenkov and one for scintillation)

Fibre and PMT holder built with 3D-printing technique

Fibre grouping and PMT coupling



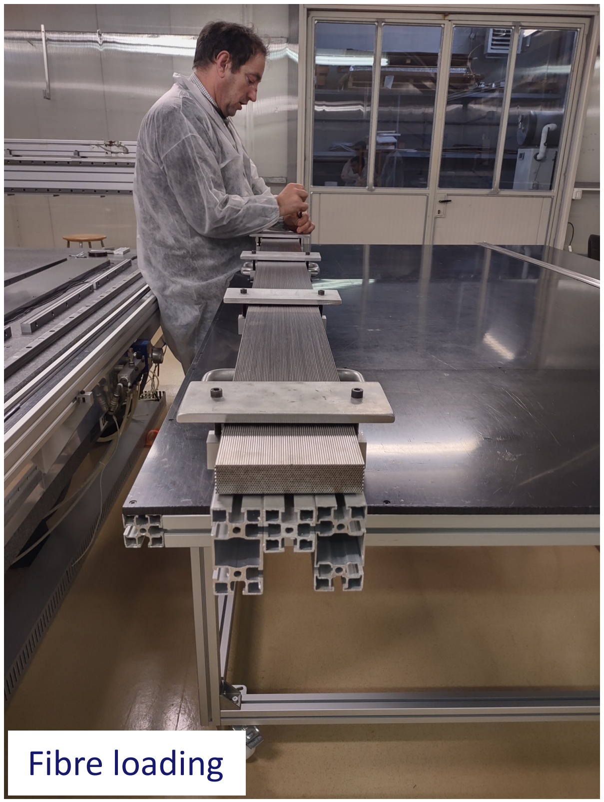


Left: R11265U series, Right: H11934 series

Hamamatsu PMT:

- R8900 (out of stock)
- R11265U-200
- R11265-203 (extended UV photodetection efficiency – Cherenkov light)

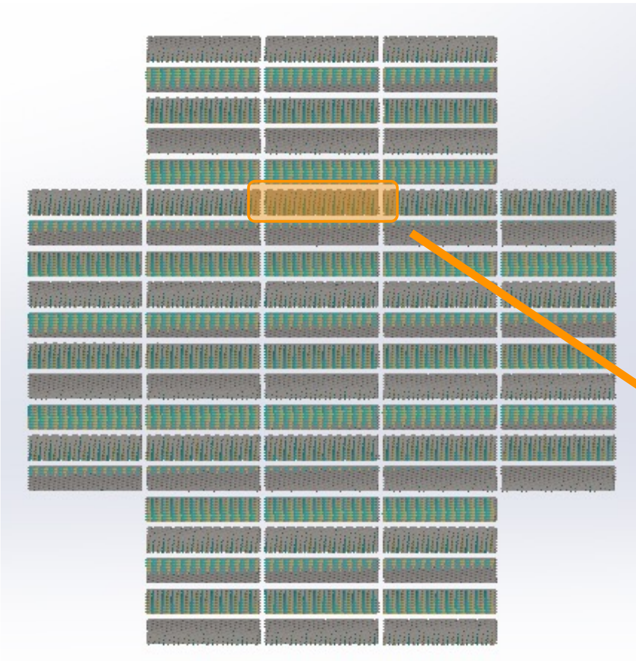
Preparation for fibre loading

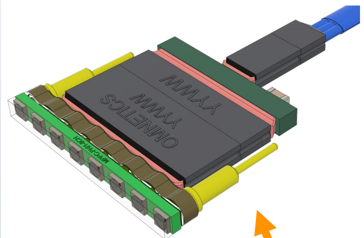


Fibre loading

Fibre gluing technique

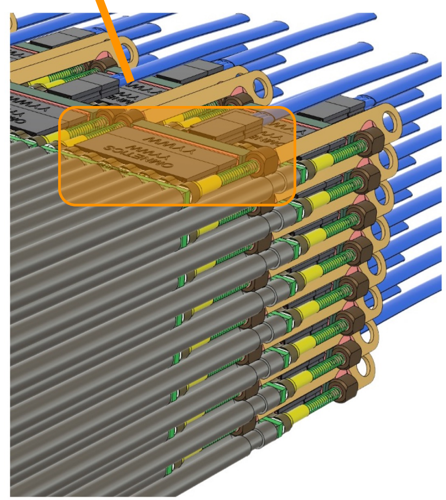
Photodetector integration: highly granular module

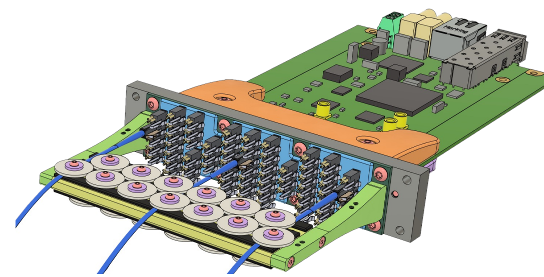




The front-end board with signal grouping

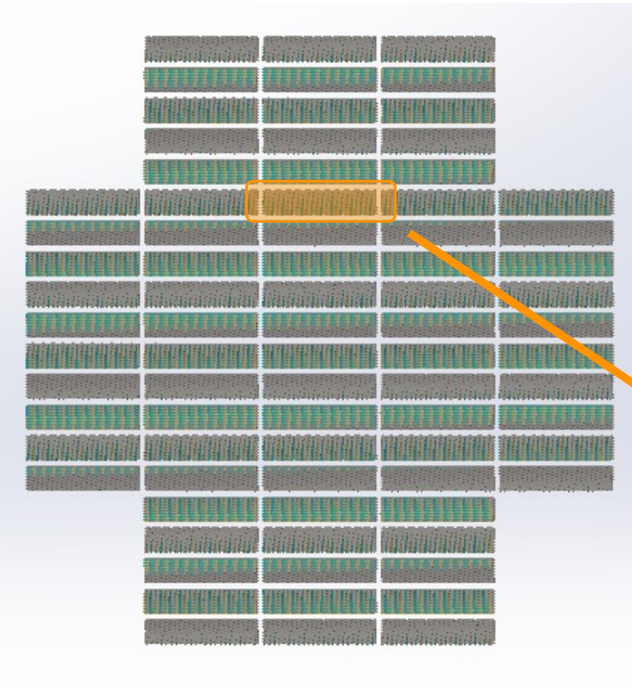
The mini-module

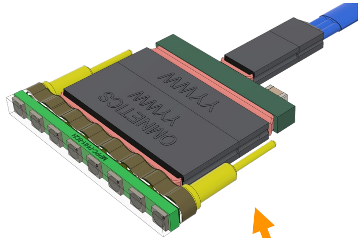




1 readout board serves 64 front-end boards with grouping: half mini-module

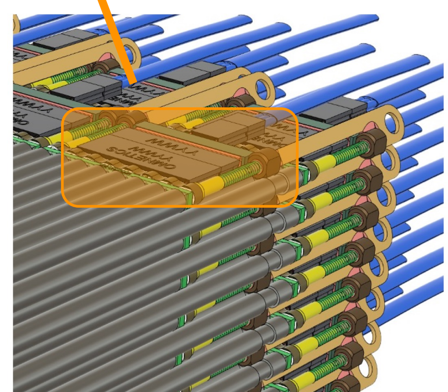
Photodetector integration: highly granular module

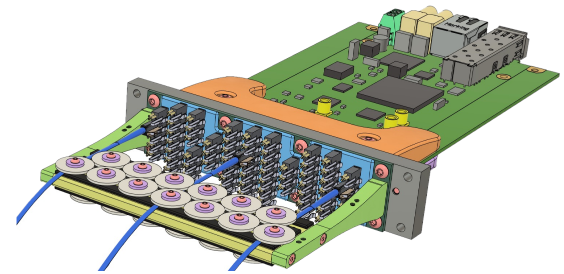




The front-end board with signal grouping

The mini-module





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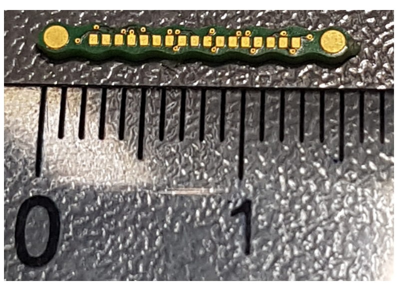
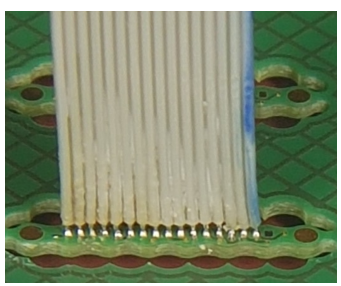
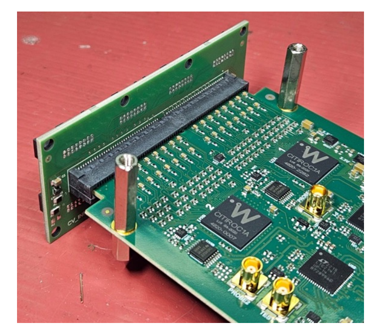


The front-end board



cable soldering



Patch-panel and readout board

What next?

- The Milestone 35 has been submitted (https://aidainnova.web.cern.ch/milestones)
  - Definition of assembly method and ASIC specifications
- A performance paper summarising the 2021 TB data is almost ready. It covers:
  - Calibration, Linearity, EM energy resolution and Data-Geant4 comparison
- A test beam is planned at CERN this year with the EM-size prototype. We will focus on
  - Increased statistic at high energy
  - Additional studies on the energy resolution dependence on the angle of the impinging particles
- The first mini-module has been assembled and the mechanical precision is within specification. The material procurement to build the Had-size prototype is started (i.e. tubes, fibres, PMTs)
- The photodetector integration with the highly granular module still needs to be finalised
  - The first batch of SiPMs with front-end board will be qualified soon
  - Integration test with dummy components is needed to freeze out the design
- Simulation studies are progressing to further constrain the specifications or to add new requirements (i.e. new features to better exploit ML techniques and PFA)