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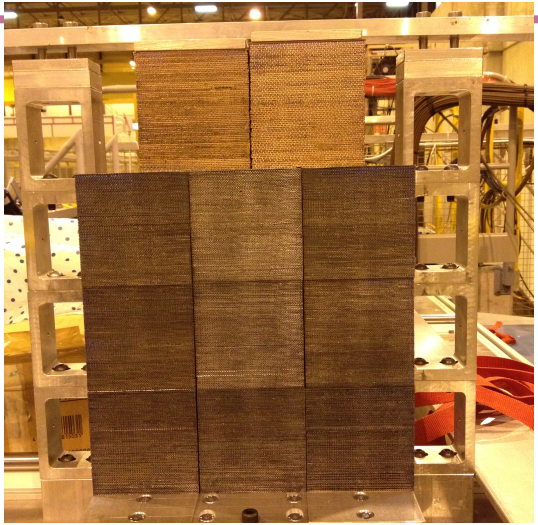
Dual-readout fibre prototypes: status and perspective

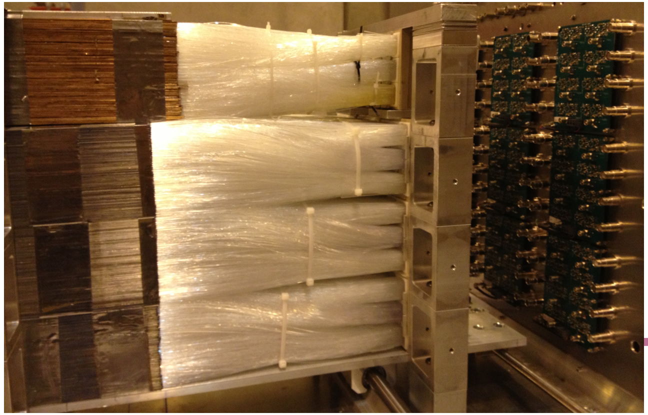
Gabriella Gaudio
on behalf of the IDEA Dual-Readout Calorimeter Collaboration
November, 8th 2021

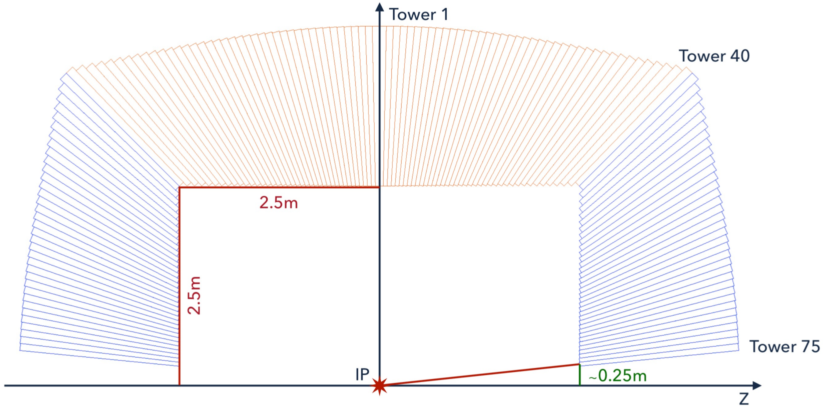
The 2021 International Workshop on the High Energy Circular Electron Positron Collider

Dual-Readout Calorimetry

RD52 prototypes (2012)







IDEA DR calorimeter

- Successfully pioneered SiPM readout to replace PMT
  → High granularity
- Studying scalable solution for
  - Mechanical construction
  - Sensors and RO system
- Full scale prototypes → Assess performance

R&D ingredients

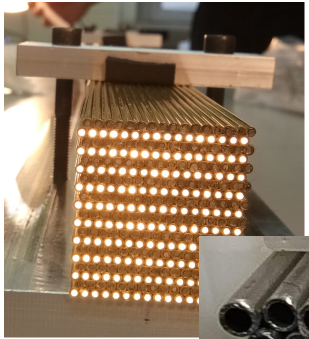
- Absorber
- Fibres
- Light sensor
- Readout system
- Integration

A few options are under study for each of these elements:
- optimize performance
- optimize scalability in term of personpower/time and costs

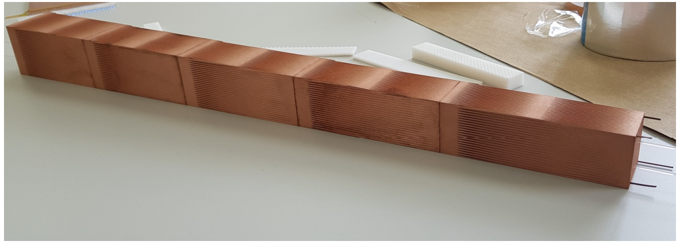
Mechanical construction aspects: status

- Absorber material
  - Copper
  - Brass
  - Stainless-steel
- Absorber structure
  - Plates
  - Capillary Tubes
  - Lego Assembly
  - 3D Printing

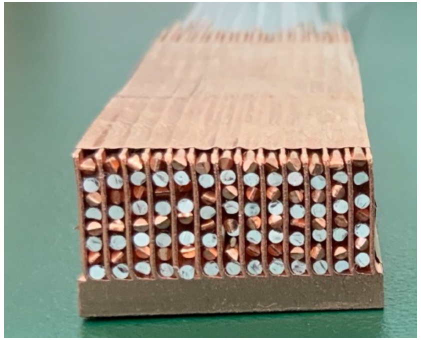
refurbishing Cu plates



capillary tube module (Brass / Stainless Steel)

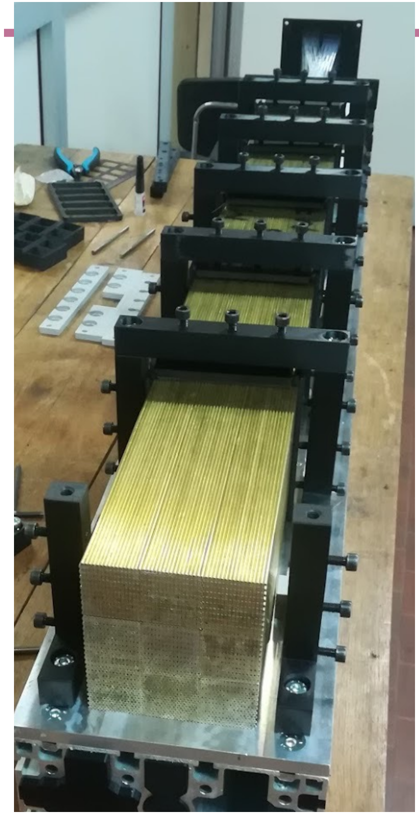


Cu 3D printing



Cu Lego

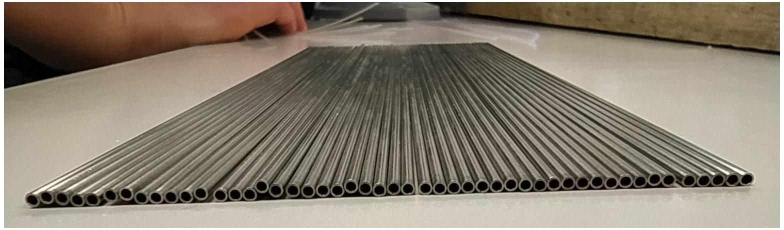
Capillary Module



100x100mm², 1 m long

- Hi-quality commercially available capillary tubes
- Quite easy and fast assembly system
- EM-size prototype
  - test the viability of this mechanical solution
  - scale up from 64 (previous test) to 320 SiPM readout
- Market survey for same-quality but cheaper capillary tube

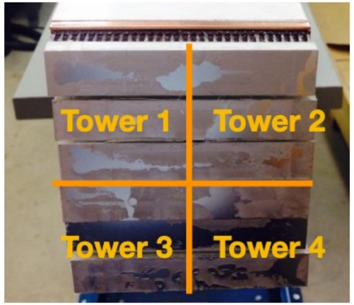
Qualified on TB
(see L. Pezzotti's talk)



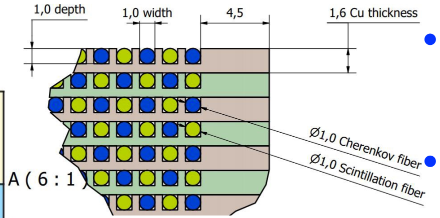
2μ RMS on OD
5μ RMS on ID
very clean cut
cost ~1€/m (under finalization)

Refurbishing Cu Plates

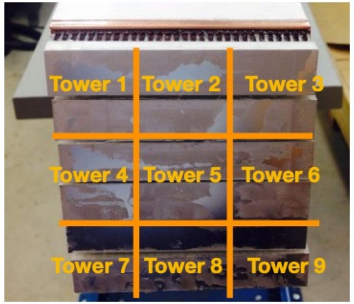
Module #1 (2x2)



Tower#1	Tower#2
Tower#3	Tower#4



Module #2 (3x3)



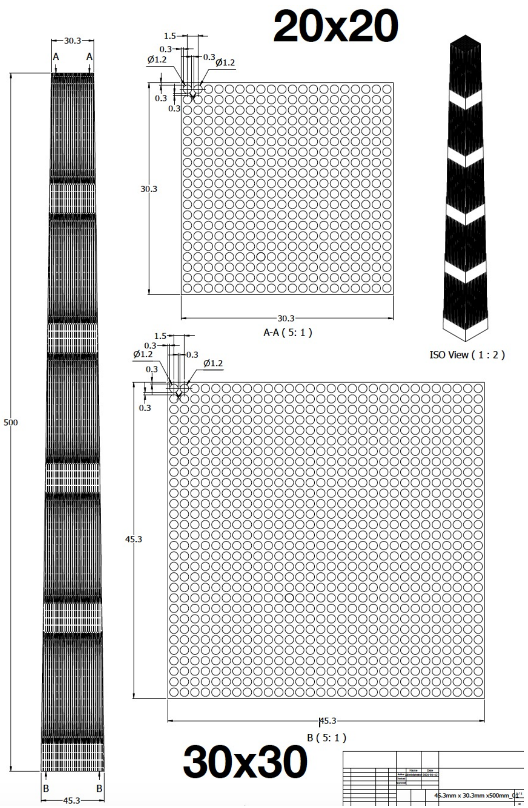
Tower#1	Tower#2	Tower#3
Tower#4	Tower#5	Tower#6
Tower#7	Tower#8	Tower#9

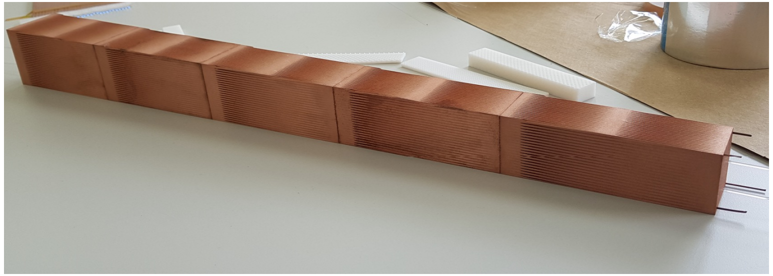
92x92mm^2, 2.5 m long

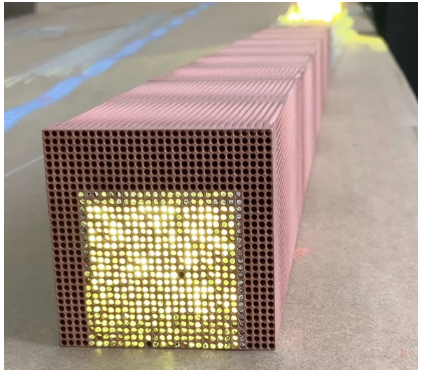
- Two modules has been prepared meant for Test Beam 2021 at SPS (postponed to 2022)
- Reusing two RD52 Cu module
  - disassemble, recuperate Cu plates
  - new fibres
- R&D Goal
  - Different light sensors under study (MPT, MCP-PMT and SiPM)
  - Study of various type of optical fibers (scintillation)
  - Time resolution (100 ps processing)

Cu 3D printing

- Exploiting 3D printing technique to obtain desired shape
  - 5 tiles 30.3 x 30.3 mm^2 (front), 45.3x45.4 mm^2 (back), 100 mm long
- 1st projective module
- Easy alignment of the tiles and fiber insertion
- Ultra-high cost







Cu Lego Module

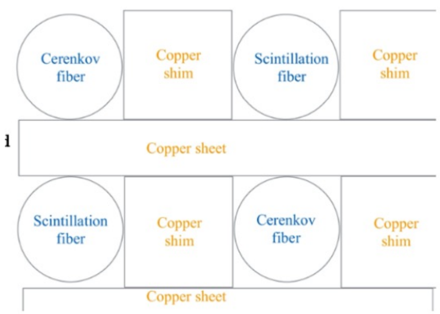


Figure 27: Direct stacking of copper shims and fibers. The shims bear the load.

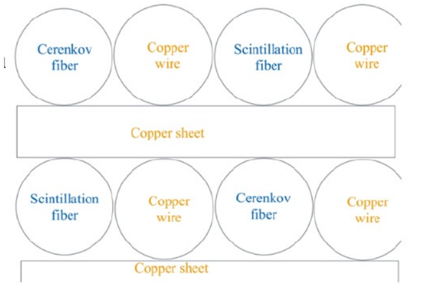
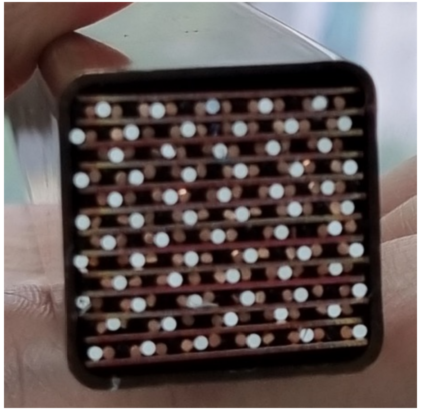
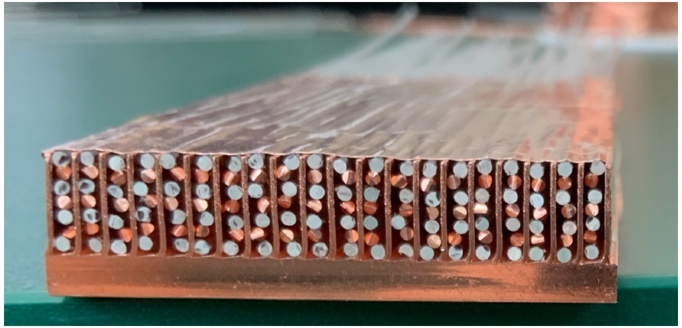


Figure 28: Direct stacking of copper wires (1.05mm diameter) and fibers on 0.5mm copper sheets. The slightly oversized copper wires carry the load.

- Ingredients: housing, copper wall, copper plate
- Use ingredients available in a market as much as possible
  - housing (copper pipes)
  - structure/wall: copper wire or plates, skiving fin heatsink



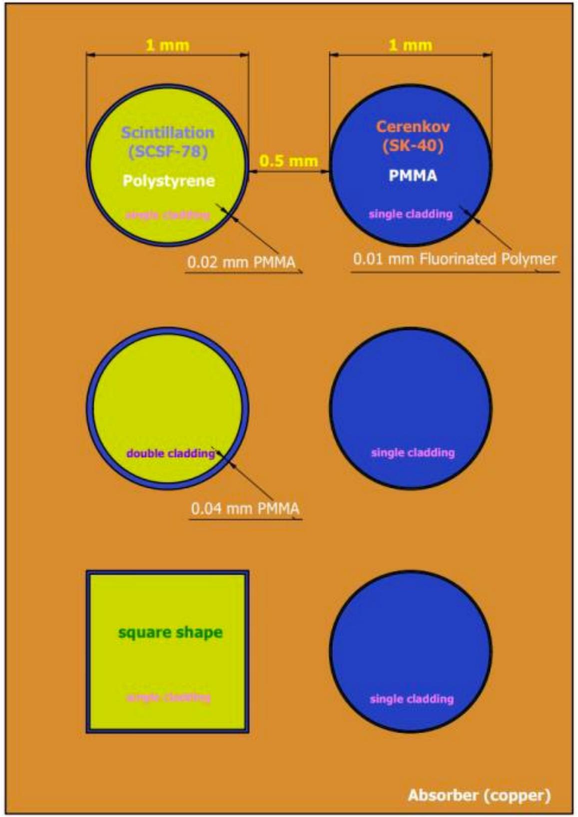
$45x45\ mm^2$, 50 cm long



R&D ingredients

- ✓ Absorber
- Fibres
- Light sensor
- Readout system
- Integration

Scintillanting and Cherenkov Fibres



- Scintillanting Fibres:
  - polystyrene-based core and a PMMA cladding.
  - Kuraray SCSF-78 (single and double cladding)
  - Saint-Gobain BCF-10 double cladding + other option under evaluation
- Cherenkov Fibres:
  - PMMA core + Fluorinated Polymer cladding
  - Mitsubishi, SK-40
  - Saint-Gobain Wavelength shifters

R&D ingredients

- ✓ Absorber
- ✓ Fibres
- Light sensor
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EM-Size capillary module

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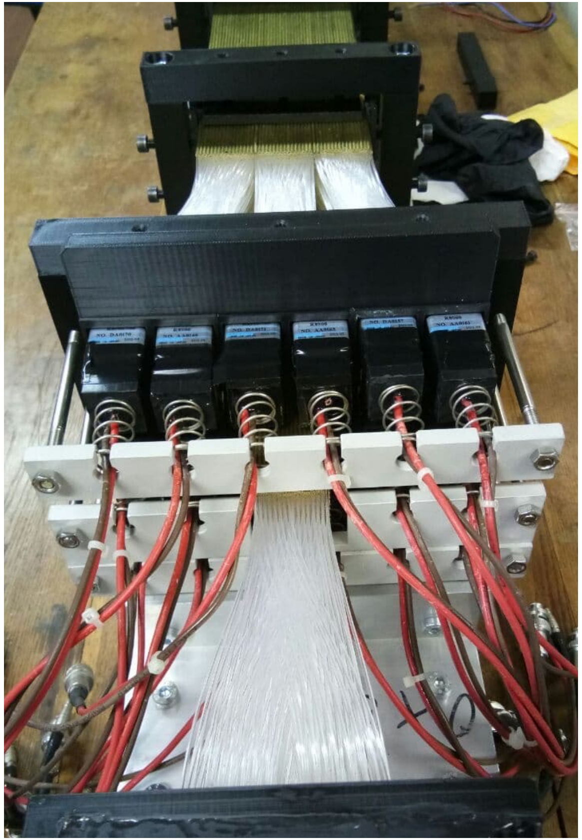
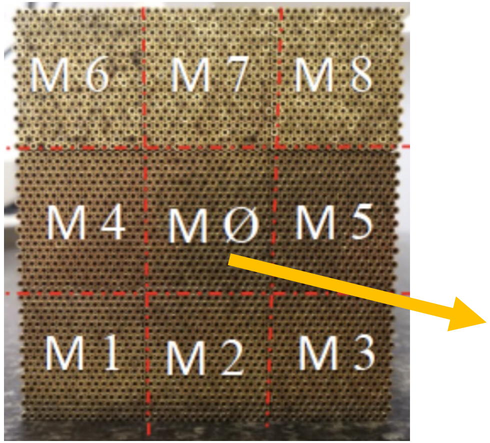
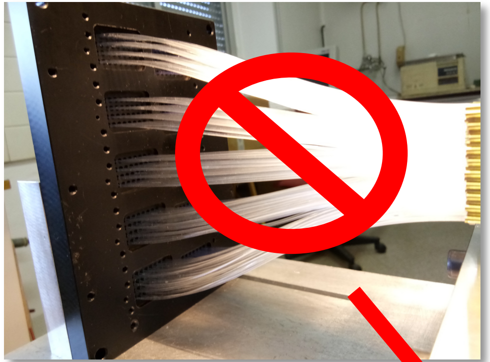


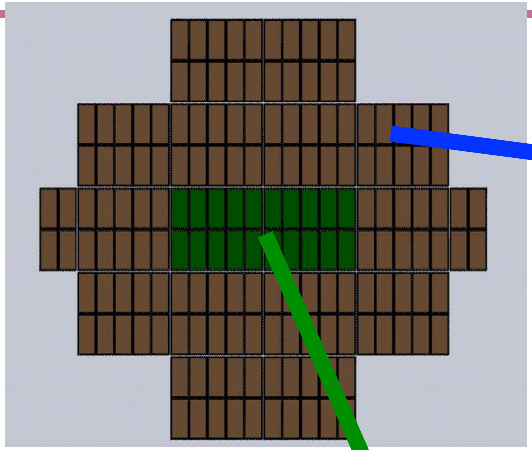


PMT readout:
Hamamatsu
R8900-100 cherenkov
R8900 Scintillation

SiPM readout:
Hamamatsu SiPM: S14160-1315 PS
Cell size: 15 µm

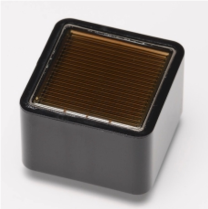
Sensors for next capillary tube prototype



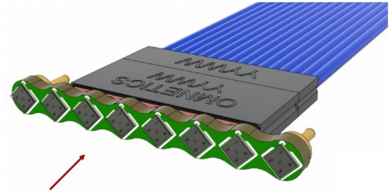


PMT readout:
Hamamatsu
R8900 discontinued

R11265-200 (UBA)
R11265-203 (UBA, UV glass)

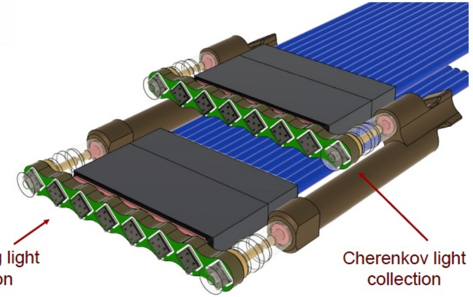


Packaging for S14160-1315 not compatible with tube pitch



FEE-board + SiPMs
Segmentation optimised to exploit grouping

Pair of FEE-boards joint together with clips



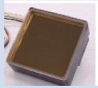
Scintillating light collection

Cherenkov light collection

development with hamamatsu
module MPPC 8ch, active area 1mm diam.
wire bonding without connectors

Plate-based calo sensors: SiPM, PMT, MCP-PMT

MCP-PMT: excellent timing performance

MCP-PMT	Window size	Light / pour size	Q.E. (Bialkali)	max. HV (V)	Rise time (ns)	photo
PLANACON XP85012	53x53 mm^2	scintillation / 25 um	~7% at 550 nm	2400	0.6	
PLANACON XP85112		Cerenkov / 10 um	~21% at 400 nm	2800	0.5	

https://www.photonis.com/products/planacon

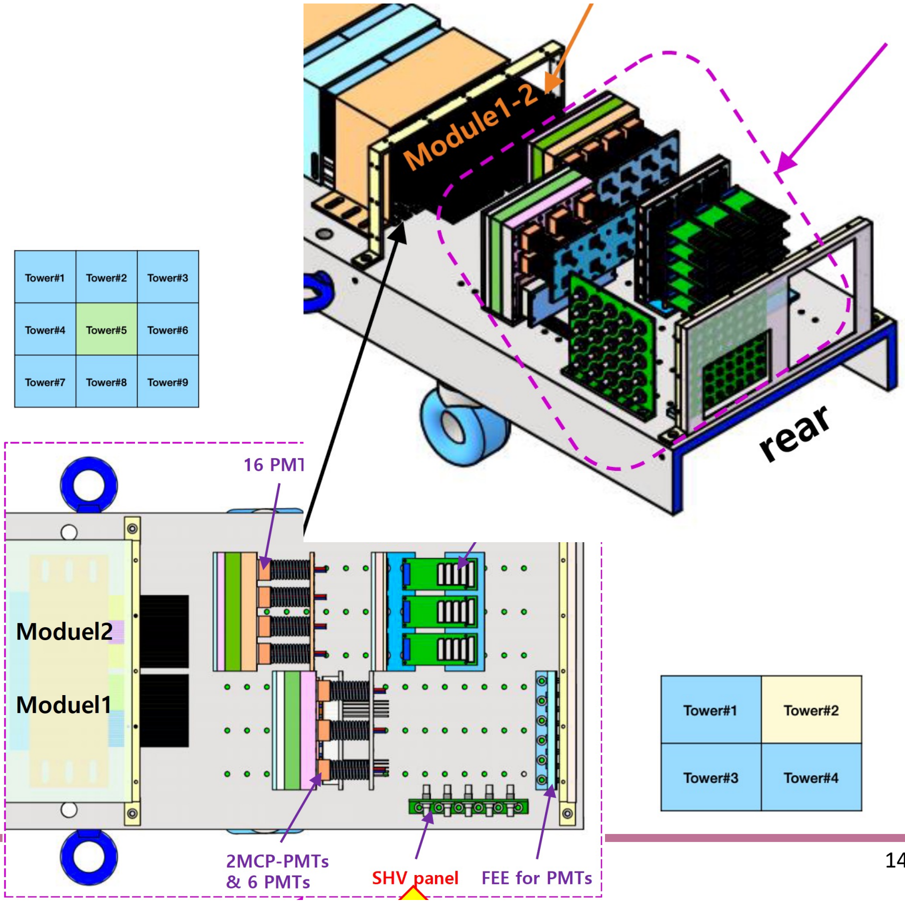
PMT: window size and timing performance

PMT	Window size	Q.E. (Super bialkali, SBA)		max. HV (V)	rise time (ns)	photo
		Ck.	Sc.			
R11265-100	23x23 mm^2	~35% at 400 nm	~7% at 550 nm	1000	1.3	

https://www.hamamatsu.com

The biggest number of pixels (16675) have been chosen
to avoid the saturation effect of photon counting for the scintillation lights.

SiPM	Photo-sensitive area	pixel size	Photo detection eff. (Silicone resin)		number of pixels	photo
S14160-1310PS	1.3x1.3 (1.69 mm^2)	10 µm	~15% at 400 nm	~17% at 550 nm	16675	

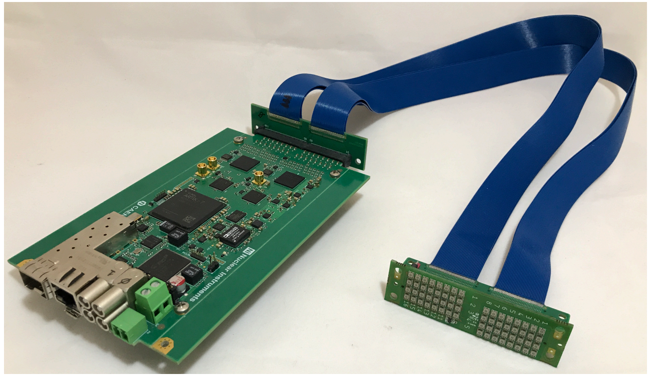


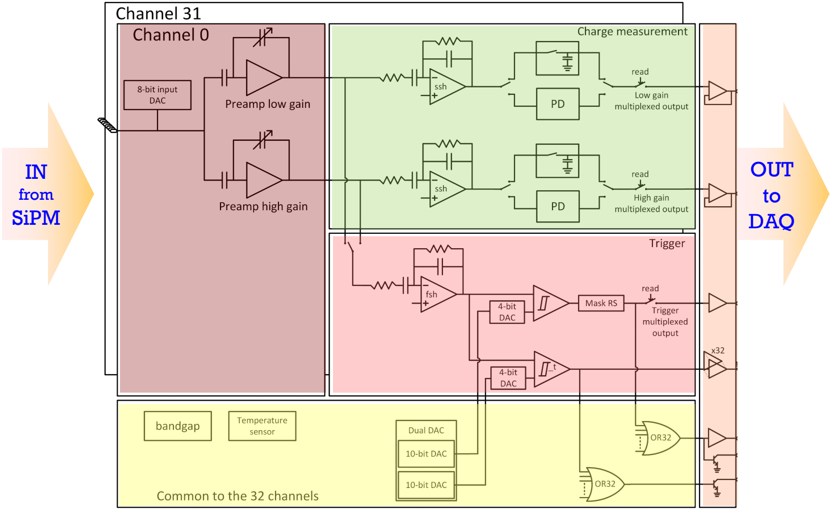
R&D ingredients

- ✓ Absorber
- ✓ Fibres
- ✓ Light sensor
- Readout system
- Integration

Citiroc1A based readout

- 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)



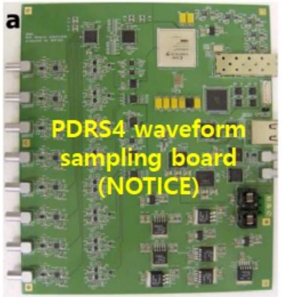


DRS based readout

DRS4

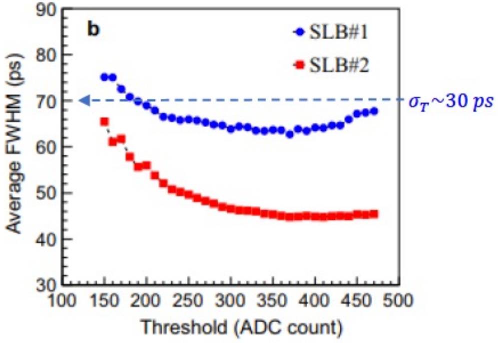
Specification of DRS4 chip NIM A 623 (2010) 86, Stefan Ritt et al.
- DRS (Domino Ring Sampler) based on SCA (Switched Capacitor Arrays)
- Number of channel (input + trigger): 8 + 1 ch
- Sampling frequency: 1~5 GS/S (1 ns ~ 200 ps/sampling depth)
- Number of sampling depth: 10 bits
- Power consumption: max. ~40 mW/ch
  max. 19.2 W for 60 DRS chips (480 ch)

Preamp board based on DRS4



NIM A830 (2016) 119 H. Kim et al.

Average FWHM with DRS4 & SiPMs



Operation Mode

Trigger mode	Data Type	Data Size	Control Bus	Expected Trigger Rate (kHz)
Waveform & Bin event modes	**Waveform data** during gate open and **ADC peak and its time values** over the threshold	16 bits per channel (64 kBytes/32ch)	USB3 (~1 GBps)	**~0.1 kHz**
Fast DAQ & Bin event modes	**ADC peak and its time values** over the threshold	8 bits per channel (256 Bytes/32ch)	USB3 (~1 GBps)	**~25 kHz**
Bin event mode	**Pedestal data** during periods in between beam spills (**pedestal trigger mode (every 1 ms)** with external beam trigger)			

AARDVARC based readout

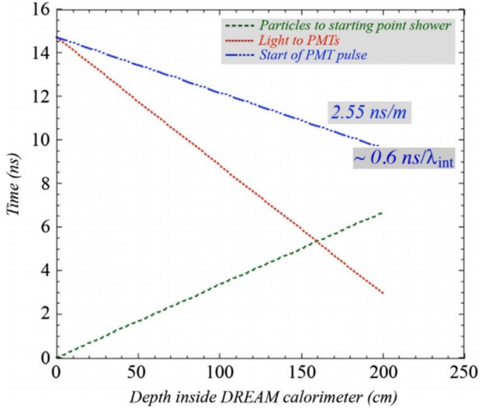
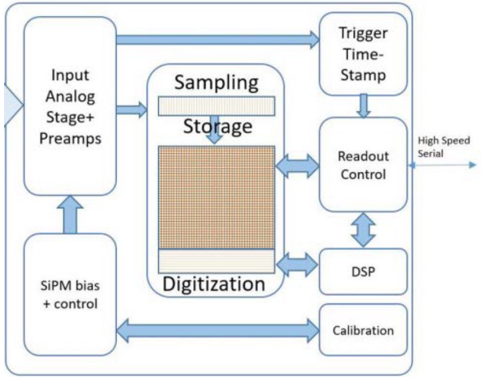


Fig. 8. Dependence of the starting time of the PMT signals on the average depth (z) inside the calorimeter where the light is produced (the dash-dotted line). This time is measured with respect to the moment the particles entered the calorimeter. Also shown are the time it takes the particles to travel to z (the dashed line) and the time it takes the light to travel from z to the PMT (the dotted line).

Timing information is a key element for PID in a longitudinally unsegmented fiber calorimeter



Parameter	Spec
Sampling Rate	1-2 GSa/s
ABW	> 600MHz
Depth	2k Sa
Trigger Buffer	~3 us*
Deadtime	0**
Channels	64
Supply/Range	2.5
ADC bits	12
Timing accuracy	80-120ps
Technology	250 nm CMOS
Power	TBD

HDSCoC
Produced by Nalu Scientific

System on Chip with a built in SiPM biasing

- On chip calibration
- Serial interface
- On chip feature extraction
- Virtually dead-timeless
- 32 ch proto chip fabricated
- Phase II SBIR awaiting award
- Next steps: packaging and eval

R&D ingredients

- ✓ Absorber
- ✓ Fibres
- ✓ Light sensor
- ✓ Readout system
- Integration

HiDRa module

- High-Resolution Highly Granular Dual-Readout Demonstrator
- Financed by INFN CSNV Grant: 2022 – 2024 (three years)
- Total request: ~ 900 k€ (dominated by material and sensors)
- Organization:
  - P.I.: Roberto Ferrari (PV)
  - WP 1: Mechanics and fibre characterisation (MI, PI, PV)
  - WP 2: Light sensors (analog and digital SiPMs) (BO, CT, MI, TIFPA)
  - WP 3: FEE and DAQ development (BO, CT, MI, PV, TIFPA)
  - WP 4: Performance assessment (MI, PV, RM1)

From HiDRa project for CSNV

HiDRa2

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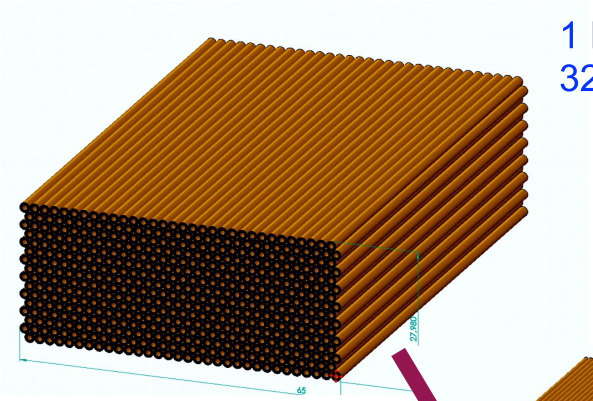
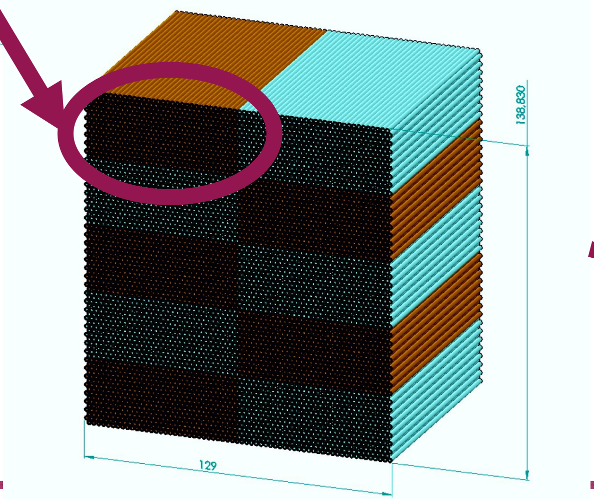


1 Mini-Module (MM):
32 x 16 channel (512 ch)



1 Module:
2 x 5 MMs
→ 10 FEE boards
(8-channel grouping)
~ 13 x13 x 200 cm^3

17 modules, ~ 65 x 65 x 200 cm^3

- 2 central modules with SiPMs
  → ~ 10 k SiPMs, ~ 20 FEE boards
- all others with PMTs
  → ~ 150 PMTs

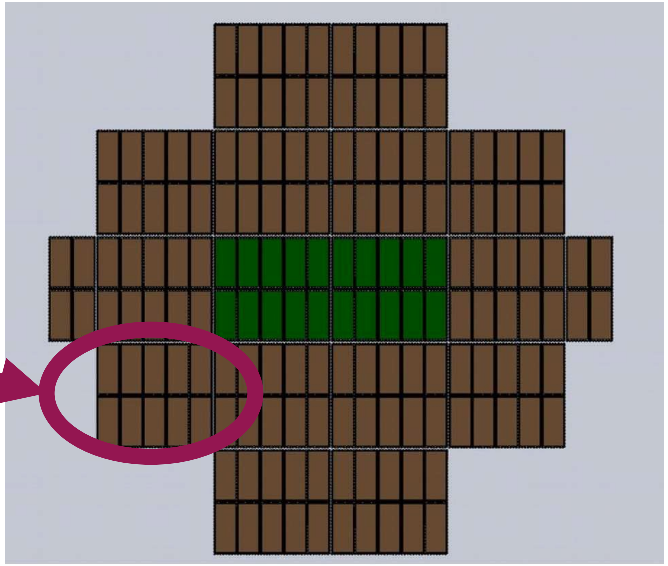
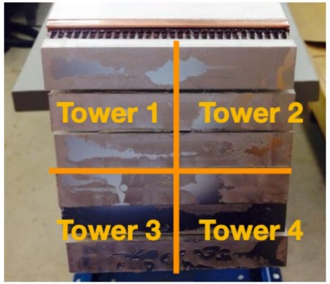


Plate-based (+3D printing) calo (Korea)

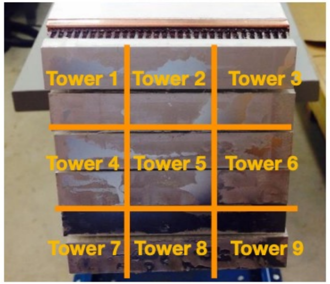
"Short-term plan"

Module #1 (2x2)

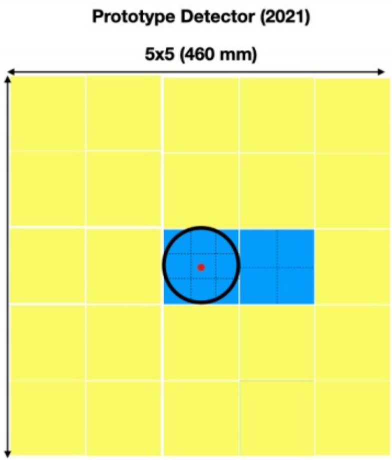


Tower#1	Tower#2
Tower#3	Tower#4

Module #2 (3x3)

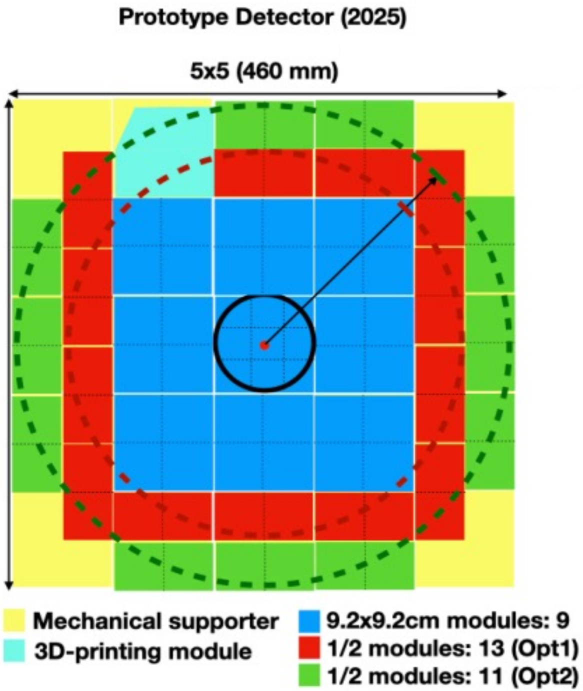


Tower#1	Tower#2	Tower#3
Tower#4	Tower#5	Tower#6
Tower#7	Tower#8	Tower#9



Building more and more modules 2022-2025

"Mid-term plan"



Outlook

- Complementary R&D programs are ongoing in Europe, Korea and US
- Optimization on choice of detector construction, sensors, RO chip and DAQ schema
- Two full containment modules, based on different technique are funded by Korea and INFN
  - scalable technique for construction and RO
  - final assessment of EM and Hadronic performance

Additional Material

Scintillanting Fibres

Specific Properties of Standard Formulations

Fiber	Emission Color	Emission Peak, nm	Decay Time, ns	# of Photons per MeV**	Characteristics / Applications
BCF-10	blue	432	2.7	~8000	General purpose; optimized for diameters >250µm
BCF-12	blue	435	3.2	~8000	Improved transmission for use in long lengths
BCF-20	green	492	2.7	~8000	Fast green scintillator
BCF-60	green	530	7	~7100	3HF formulation for increased hardness
BCF-91A	green	494	12	n/a	Shifts blue to green
BCF-92	green	492	2.7	n/a	Fast blue to green shifter
BCF-98	n/a	n/a	n/a	n/a	Clear waveguide

** For Minimum Ionizing Particle (MIP), corrected for PMT sensitivity

Type	Luminescence			Absorption Peak (nm)	Attenuation length^2 (m)	Characteristics
	Color	Spectra	Peaks (nm)			
SCSF-78	Blue		450	2.8	>4.0	High luminescence High attenuation length
SCSF-81	Blue	Refer to catalogue	437	2.4	>3.5	High attenuation length
SCSF-3HF (1500)	Green		530	7	>4.5	Radiation resistance

PMT / MCP_PMT

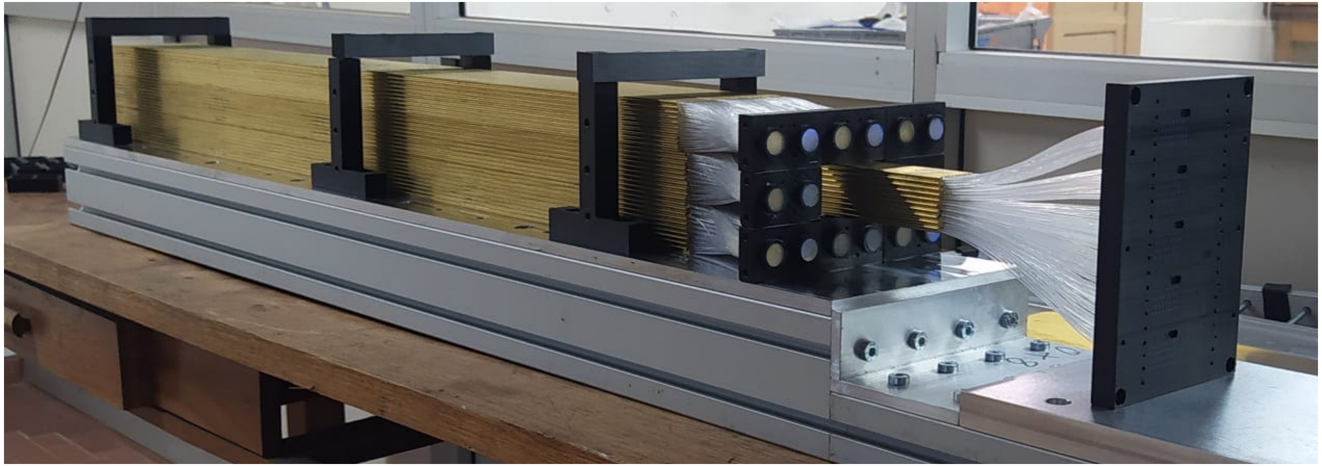
Description	
Window options	Schott 8337B or equivalent, UVFS (-Q)
Photocathode	Bialkali
Multiplier structure	MCP chevron (2), 25 µm pore, 40:1 L:D ratio
Anode structure	8×8 array, 5.9 / 6.5 mm (size / pitch)
Active area	53×53 mm
Package open-area-ratio	80%

Photocathode characteristics	Min	Typ	Max	Unit
Spectral range:	200		650	nm
Maximum sensitivity at		380		nm
Sensitivity:				
Luminous *	50	60		µA/lm
Blue *	7.5	8.5		µA/lmF
Radiant, at peak		70		mA/W
Quantum Efficiency		22		%
Characteristics	**Min**	**Typ**	**Max**	**Unit**
Overall Voltage for 10^5 Gain *		1800	2400	V
Total anode dark current @ 10^5 gain *		2	10	nA
Rise time		0.6		ns
Pulse width		1.8		ns

Recommended Voltage Divider (not included)

Type No.	Spectral response		Ⓐ	Ⓑ	Ⓒ	Maximum ratings		Cathode characteristics					
	Range (nm)	Peak wavelength (nm)	Photocathode material	Window material	Dynode structure / stages	Supply voltage between anode and cathode (V)	Average anode output current (mA)	Luminous Min. (µA/lm)	Luminous Typ. (µA/lm)	Blue sensitivity index (CS 5-58) Typ.	Red/white ratio (R-68) Typ.	Ⓓ Quntum efficiency Typ. (%)	Ⓔ Radiant Typ. (mA/W)
R11265U-100	300 to 650	400	SBA	K	MC/12	1000	0.1	90	105	13.5	—	35	110
R11265U-200	300 to 650	400	UBA	K	MC/12	1000	0.1	110	135	15.5	—	43	130

Capillary-tube based Prototype

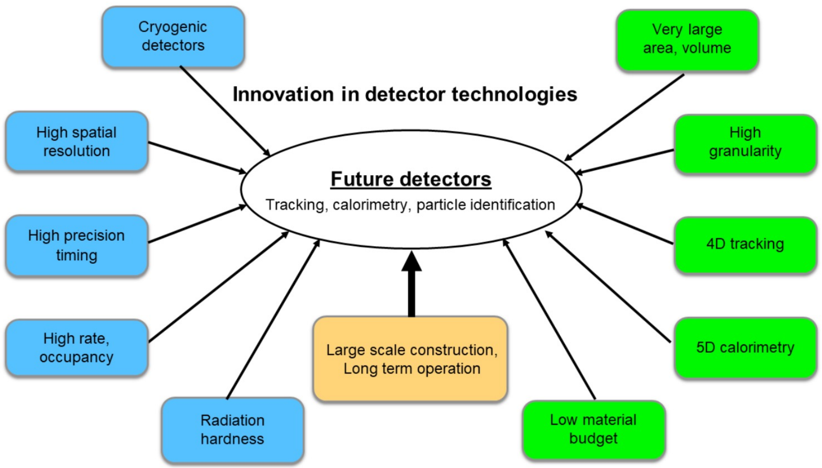


10×10 cm^2 divided in 9 towers, 1m long
16x20 capillary each (160 C + 160 S)

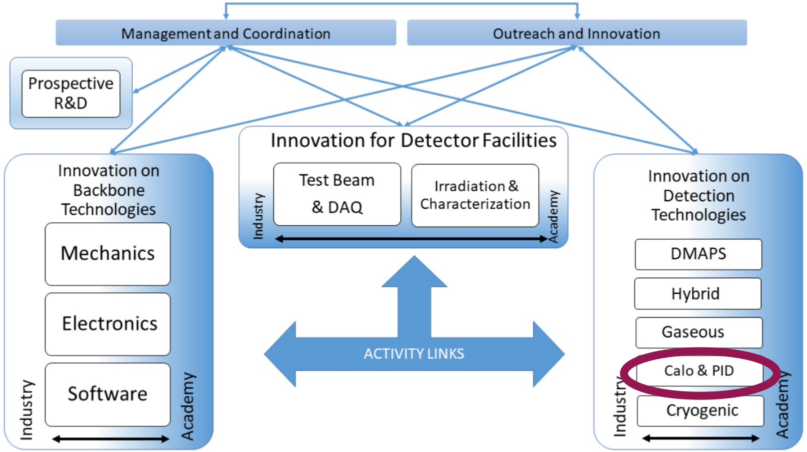
Capillary:
2mm outer diameter, 1mm inner diameter
Material: brass CuZn37

Readout:
- 1 central tower read out by SiPMs
- 8 surrounding towers read out by PMTs (à la RD_52)

AIDA innova



Work Packages



WP 8.4.2
Development of highly-granular dual-readout fiber-sampling calorimeters

INFN - Univ. Sussex - CAEN

Start: April 1st, 2021
Duration: 4 years

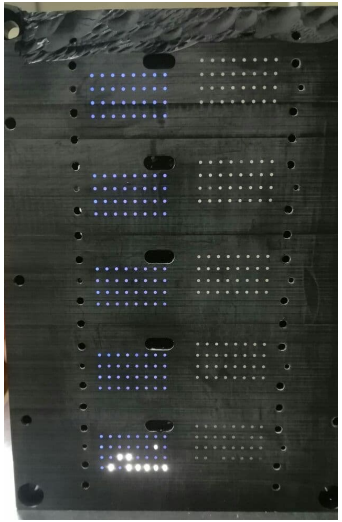
Full costs budget
AIDAinnova = ~ 30 M€

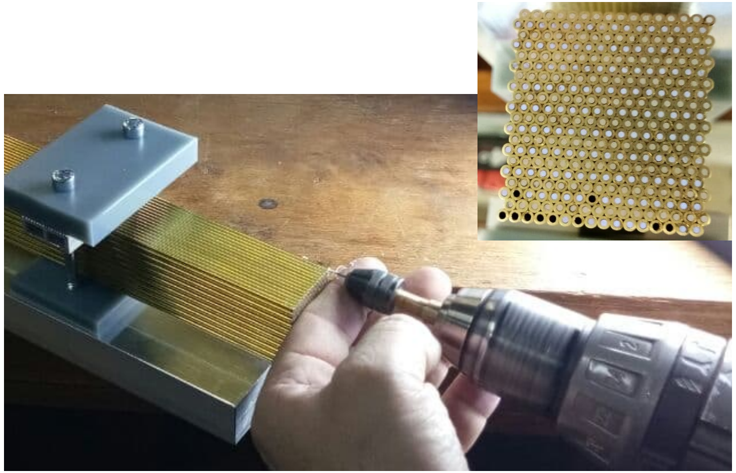
Reloading fibers

While milling the SiPM interface surface , the machine stopped, hitting the surface itself

10 S fibers broken between module and interface

- ➢Fibers reloaded
- ➢Glued
- ➢Damages Recovered





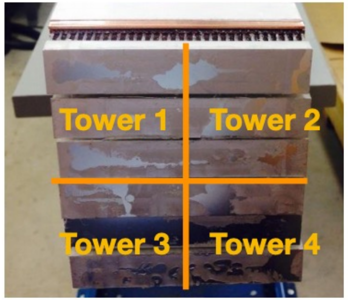
Drilling

Precise Drilling

Plate-based prototype: fiber and readout config

INFN
Istituto Nazionale di Fisica Nucleare

Module #1 (2x2)



Tower#1	Tower#2
Tower#3	Tower#4

Combination of fibers for Module#1

	Tower #1	Tower #2	Tower #3	Tower #4
Scintillation fibers	Round / Single cladding	Round / Single cladding	Round / Double cladding	Square / Single cladding
Cherenkov fibers	Round / Single cladding			
Readout detector (2*4 ch)	2 PMTs	2 MCP-PMTs	2 PMTs	2 PMTs

Module #2 (3x3)

Tower#1	Tower#2	Tower#3
Tower#4	Tower#5	Tower#6
Tower#7	Tower#8	Tower#9

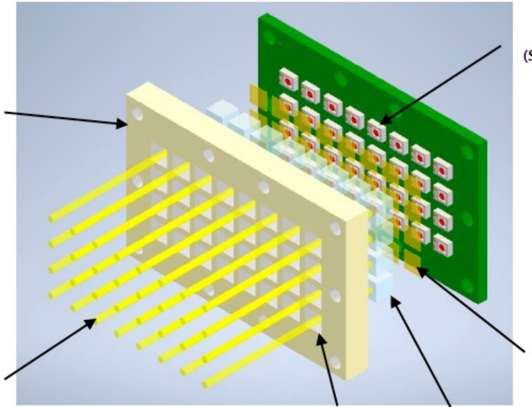
Combination of fibers for Module#2

	Tower #1~4 and #6~9	Tower #5
Scintillation fibers	Round / Single cladding	
Cherenkov fibers	Round / Single cladding	
Readout detector (400+16 ch)	16 PMTs	400 SiPMs

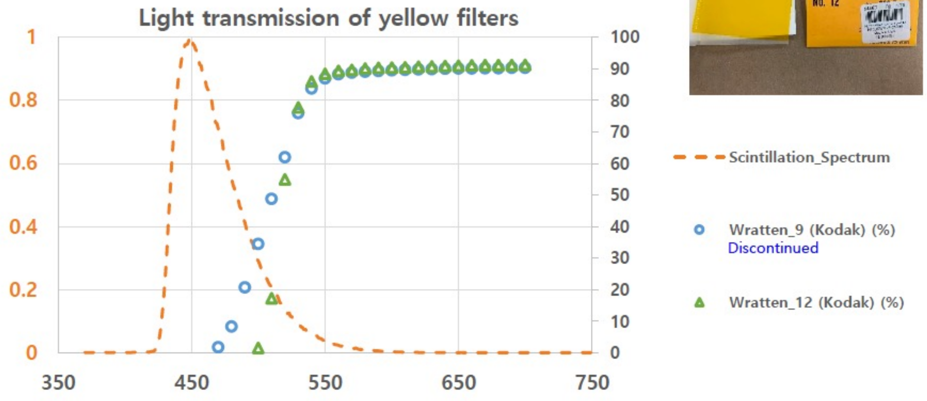
In the dual readout calorimeter, an **optical cookie** is used for light transmission and detector safety between the fiber and the readout detector.

For the scintillation light, the light yield less than 500 nm is too high, so a yellow filter is used to reduce the light transmission.

SiPM board for 32 scintillation fibers

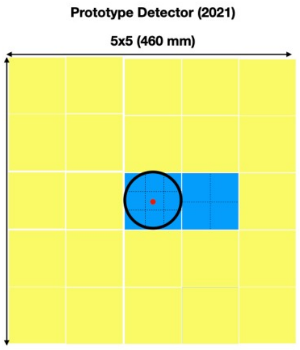


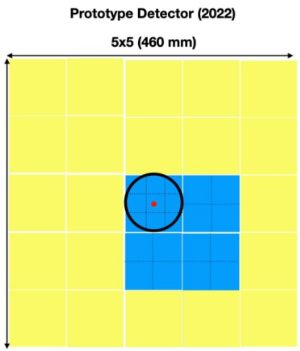
Light Shielding Wall can prevent the cross-talk in between light yield from each fiber.

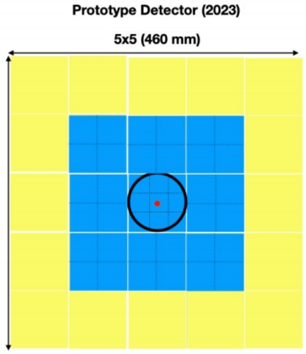


Note that changing the yellow filter from #9 to #12,
-> reduced transmission near 500 nm wavelength
-> similar light transmission over 530 nm

Plate-based prototype – roadmap to full containment







Aim to assemble the modules at CERN and do test beam every year