

Dual-Readout Calorimeter R&D in Korea

Hwidong Yoo (Yonsei Univ.)

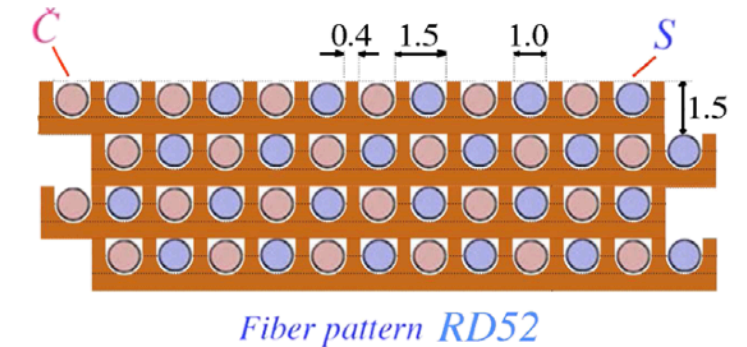
On behalf of the Korea
Dual-Readout Calorimeter R&D team

bECAL meeting,
May 9, 2023



Dual-Readout Calorimeter (DRC)

- DRC offers high-quality energy measurement for both EM particles and hadrons
- DRC consists of two different optical fibers (S, C) in a single component
- The main culprit of poor hadronic energy resolution is fluctuations of the EM shower components of hadron showers (f_{em})
- f_{em} can be determined using the measured values of scintillation and Cerenkov signals
- Excellent hadron energy resolution can be achieved by correcting the energy of hadron event-by-event



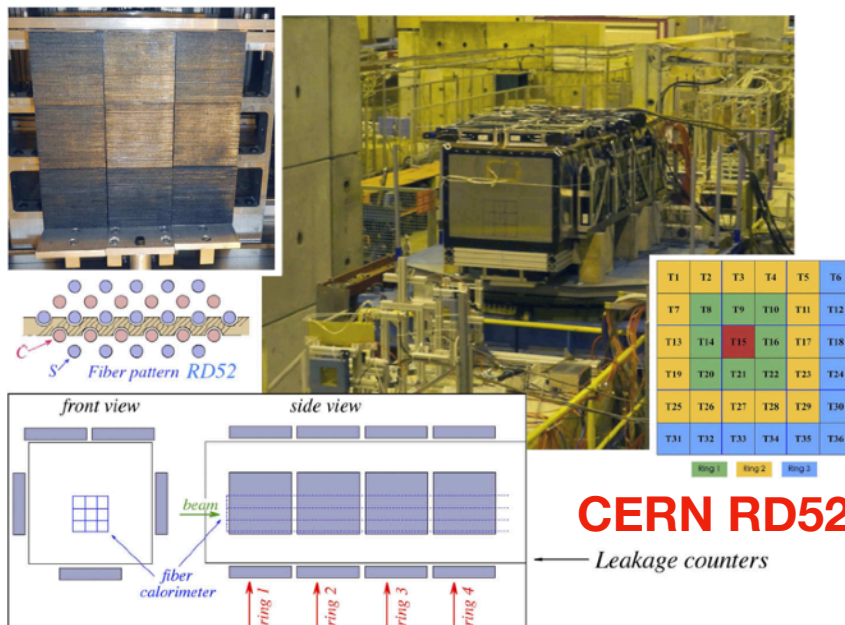
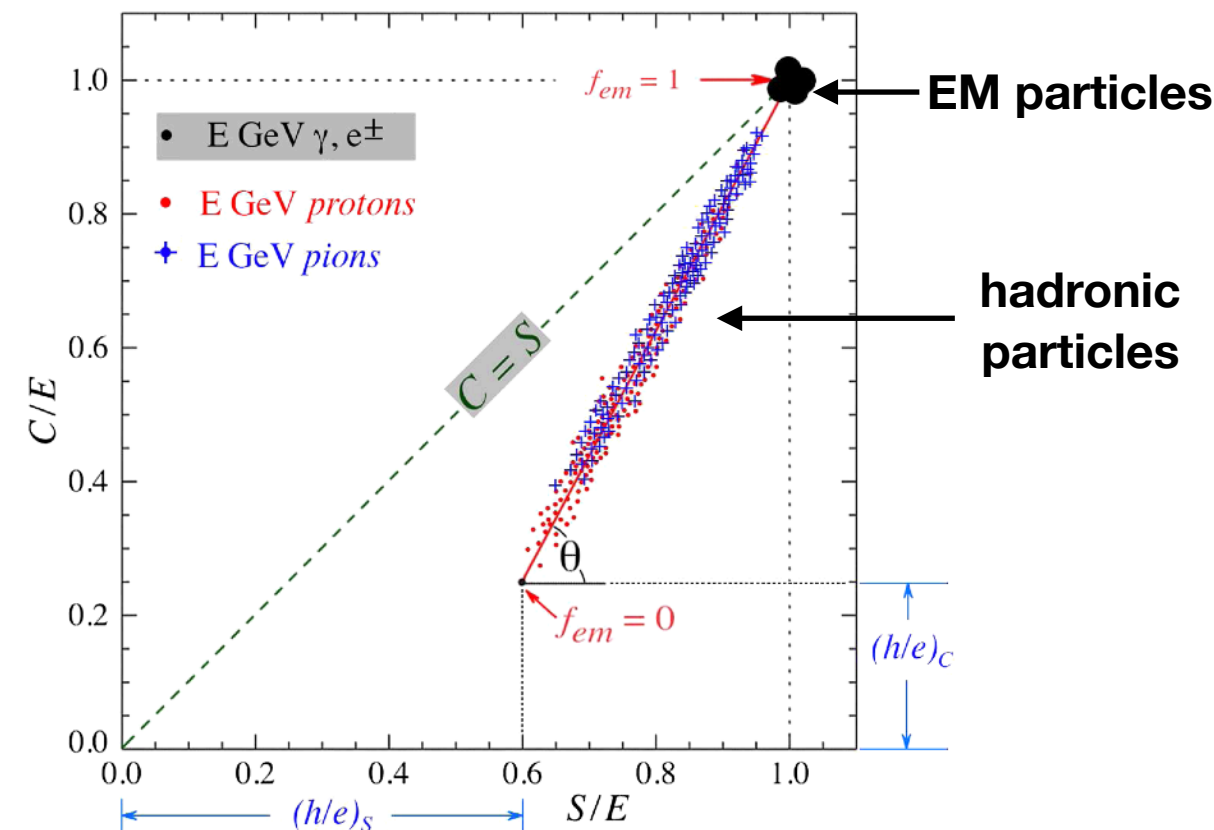
$$S = E \left[f_{em} + \frac{1}{(e/h)_S} (1 - f_{em}) \right],$$

$$C = E \left[f_{em} + \frac{1}{(e/h)_C} (1 - f_{em}) \right],$$

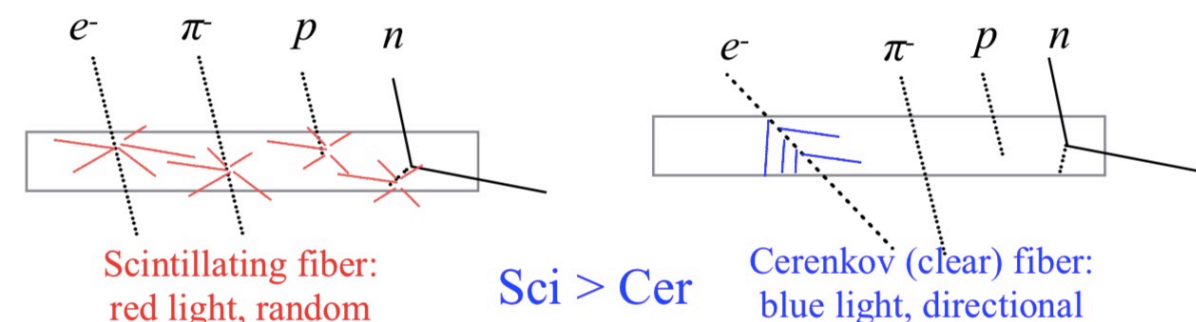
$$f_{em} = \frac{(h/e)_C - (C/S)(h/e)_S}{(C/S)[1 - (h/e)_S] - [1 - (h/e)_C]}.$$

$$E = \frac{S - \chi C}{1 - \chi}.$$

$$\cot \theta = \frac{1 - (h/e)_S}{1 - (h/e)_C} = \chi,$$

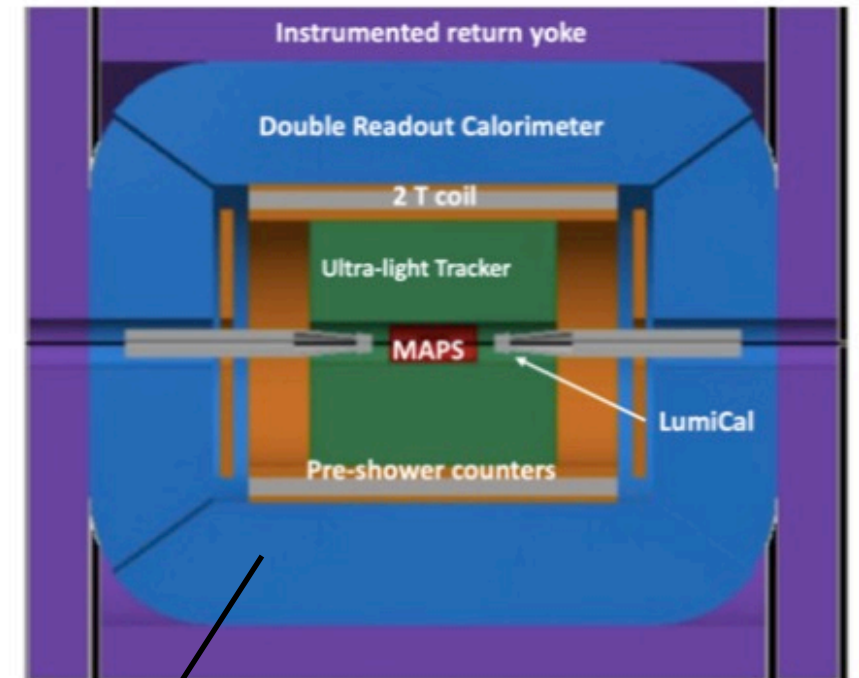
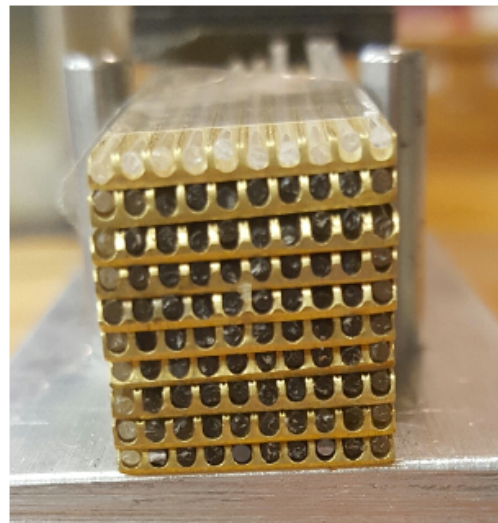


Signal generation: Scintillating & Cerenkov fibers

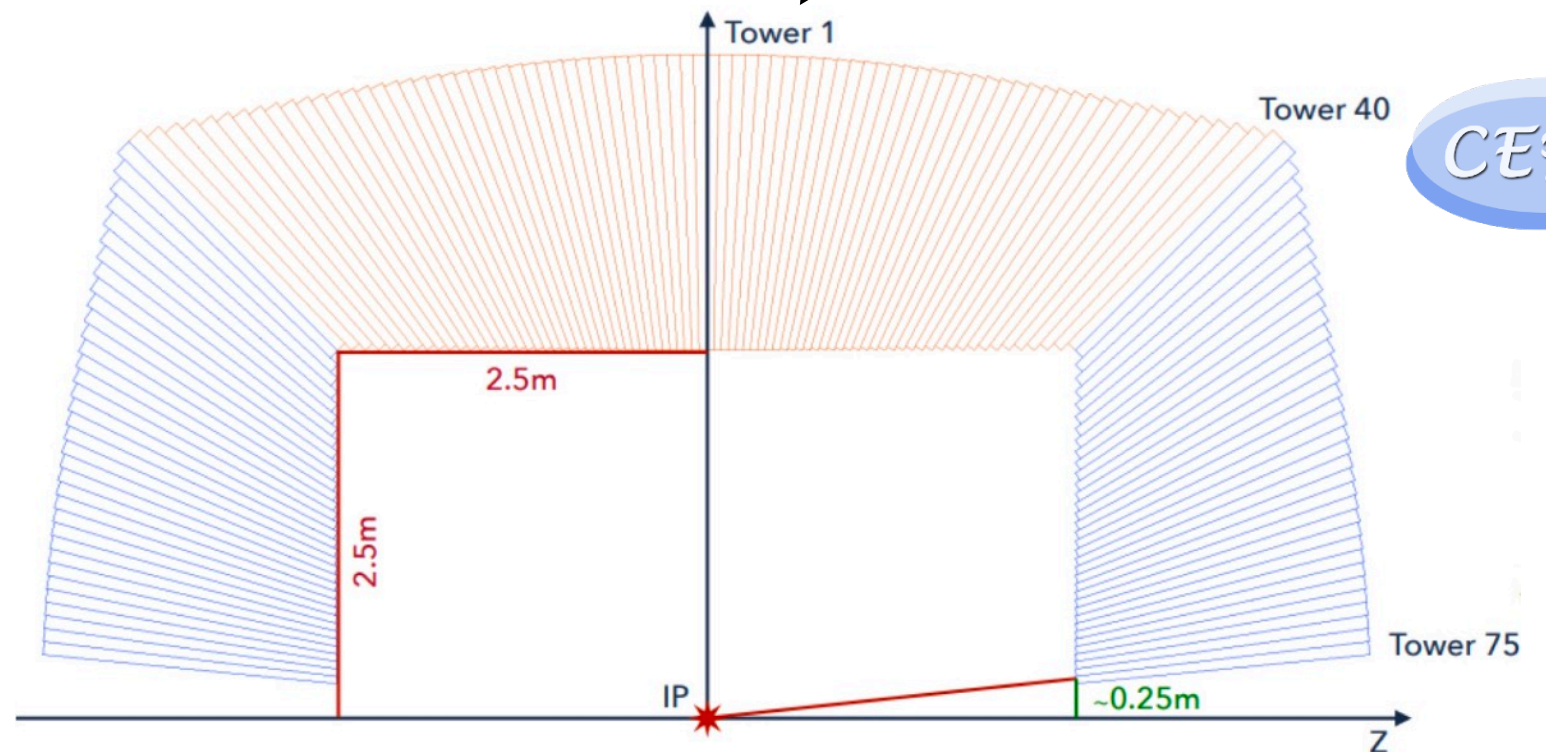
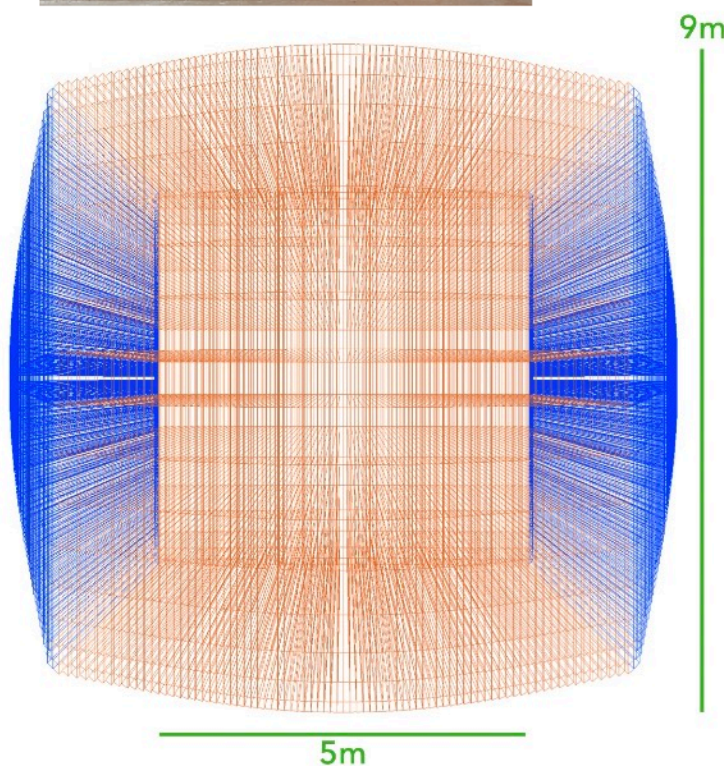


DRC Geometry and Module

- Korean team led the design of the Dual-Readout Calorimeter (DRC) for IDEA detector
- Included in the CDRs of both FCC-ee and CEPC, published at the end of 2018



IDEA



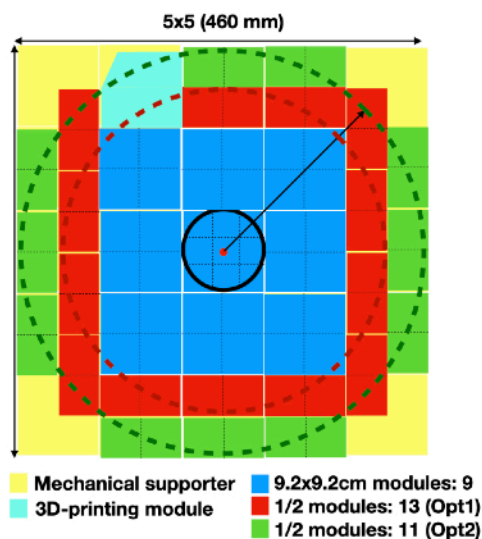
DRC International Collaboration

Prof. Hyonsuk Jo (KNU)
 Prof. Sanghoon Lim (PNU)
 Prof. Beomkyu Kim (SKKU)

Prof. Jason Lee (UoS)
 Prof. Sehwook Lee (KNU)
 Prof. Minsuk Kim (GWNu)
 Prof. Hwidong Yoo (YU)
 Prof. Suyong Choi (KU)
 Prof. Byunggu Cheon (HU)



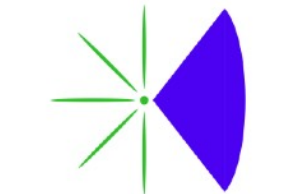
**Full-size
 prototype
 detector**



Prof. Yuji Enari

Japan

Korea



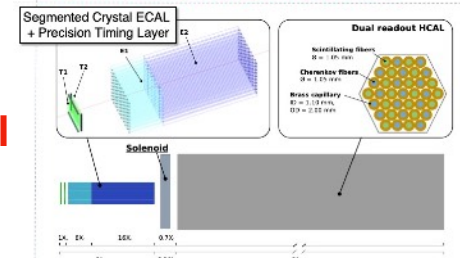
USA

Europe

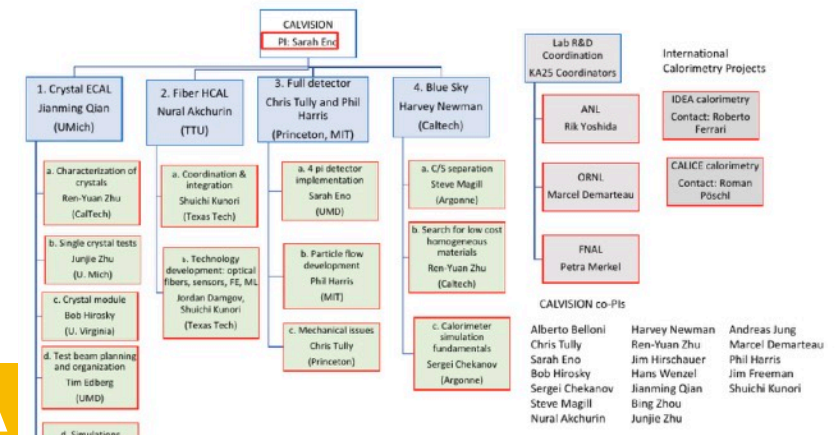


Prof. Paolo Giacomelli (Bologna)
 Prof. Romualdo Santoro (Insubria)
 Prof. Roberto Ferrari (Pavia)
 Prof. Franco Bedeschi (Pisa)
 Prof. Iacopo Vivarelli

Segmented Crystal Option of IDEA



DRC with crystal



A very high-level overview of planned activities follows



Prof. Sarah Eno

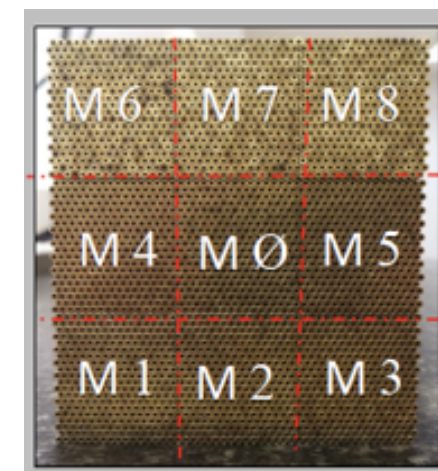


Prof. Richard Wigmans



Prof. John Hauptman

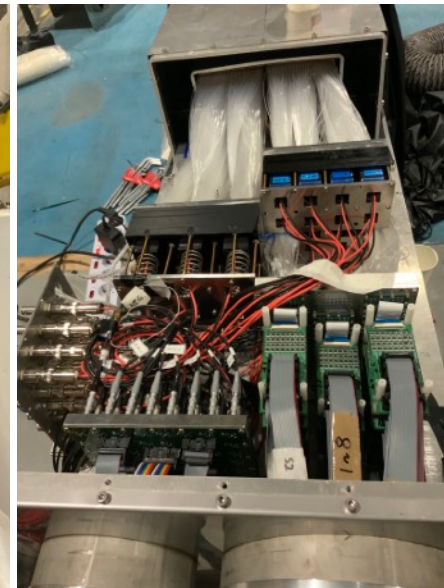
Bucatini prototype



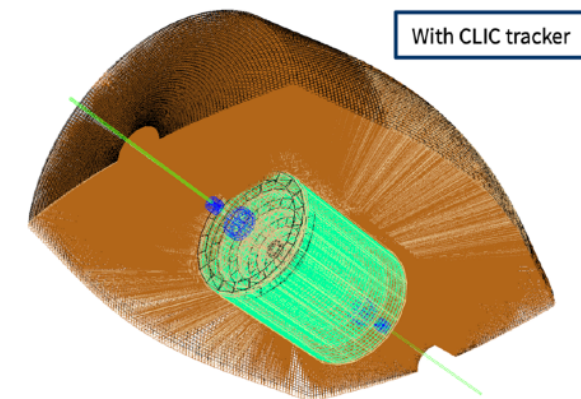
Status of DRC R&D in Korea

- We are doing all aspects of the DRC R&D

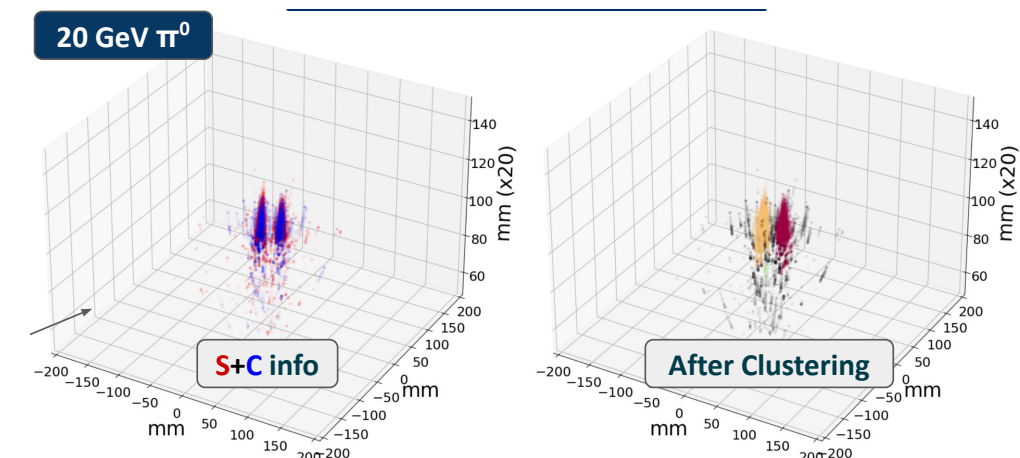
- Module building
- Electronics system
- DAQ system



- Data analysis framework
- Full GEANT4 simulation framework (standalone, key4hep)
- Longitudinal shower profile reconstruction
- Particle identification with ML technique



- We are world leading group for the DRC R&D



Test-beam (TB) 2022 Preparation

- Duration : Aug. 4th ~ 24th
- Measurement Goal

Module 1

- Shower depth
- Longitudinal shower profile
- Light attenuation length

Module 2

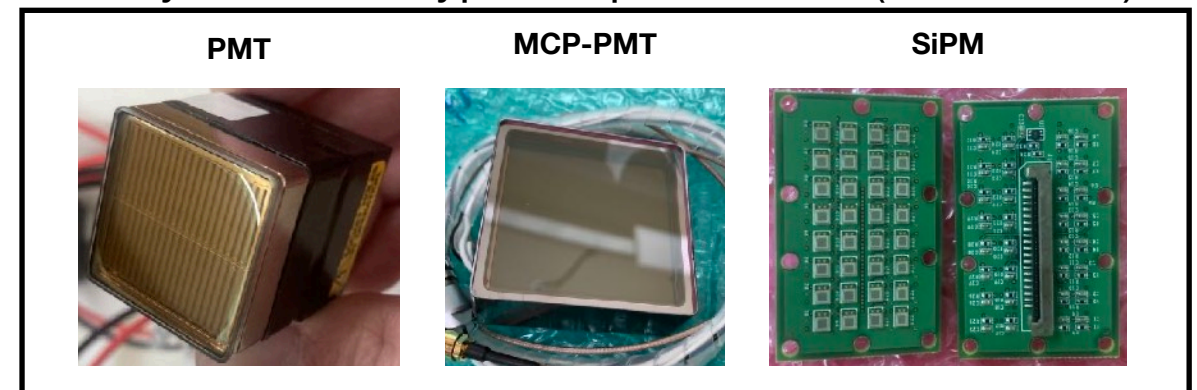
- Position resolution
- Lateral shower profile
- EM energy resolution
- Uniformity study

- Schedule of test beam preparation

- Location : CERN North area (H8)

- R&D Goal

- Readout system test (MCP-PMT & SiPM)
- Study of various type of optical fibers (scintillation)



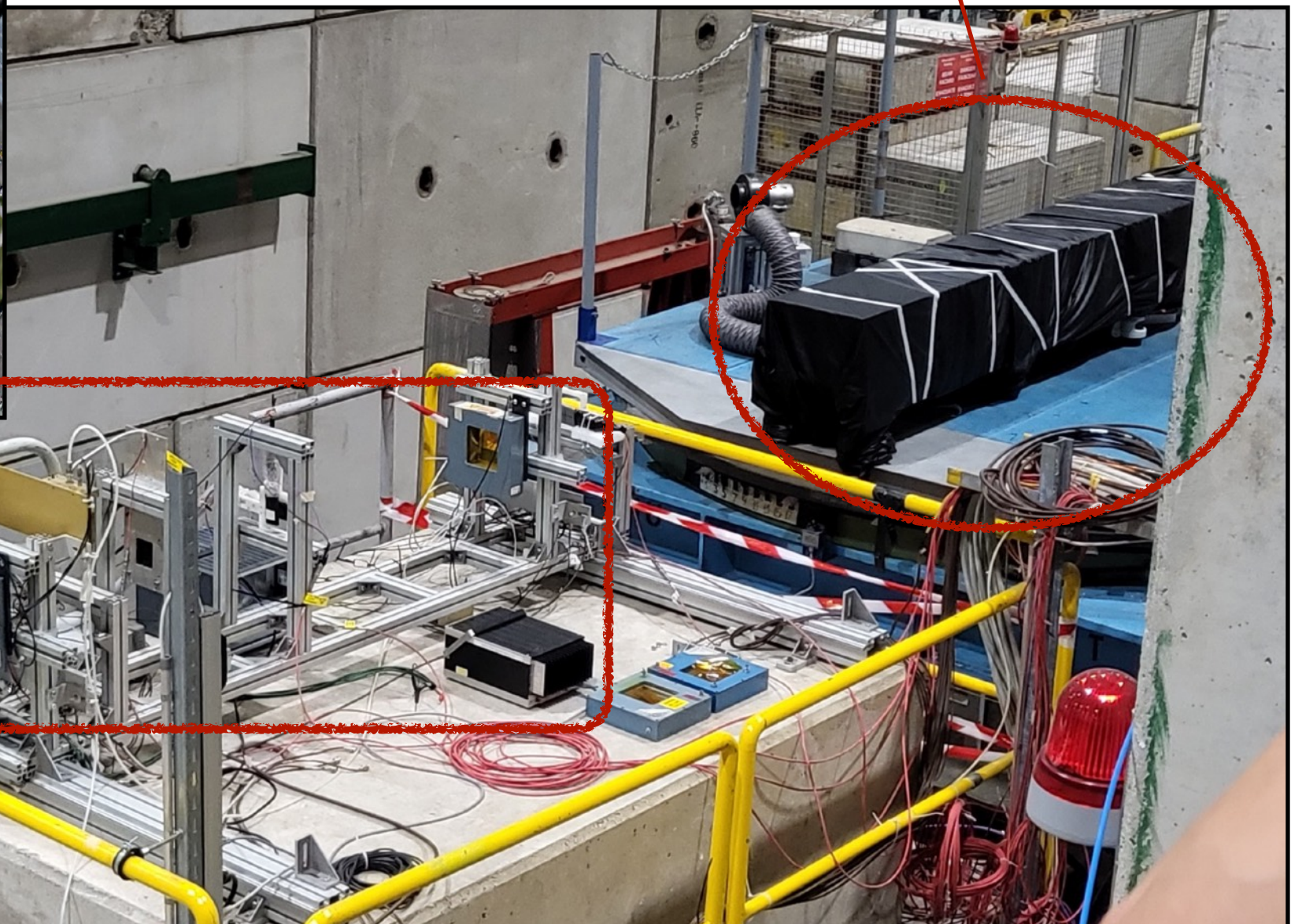
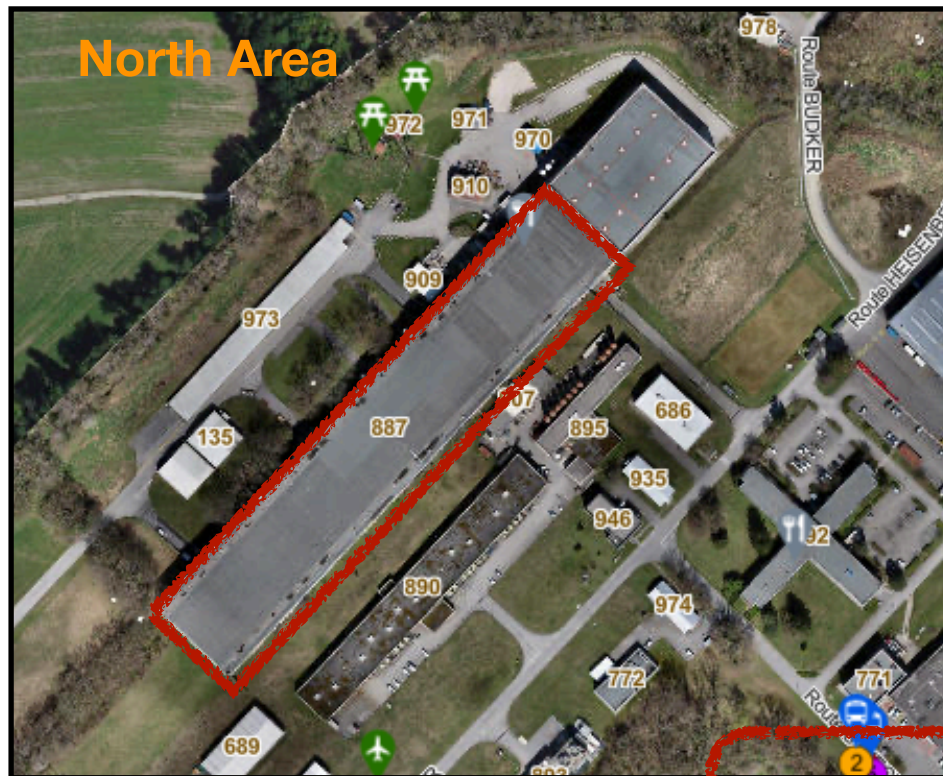
- Training Goal

- Training next generation experts for DRC HW

Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	
Module	Building Module (fiber+Cu)		Attach readout			Test Commissioning	Packing/ Shipping	Install @ CERN(H8)	-
DAQ	Test Mutichannel operation						Packing/ Shipping	Install @ CERN(H8)	-
Test beam							Packing/ Shipping	8/3 ~ install	Preparation & commissioning @ cern (~8.16)
								Taking test beam (8.17~8.24)	

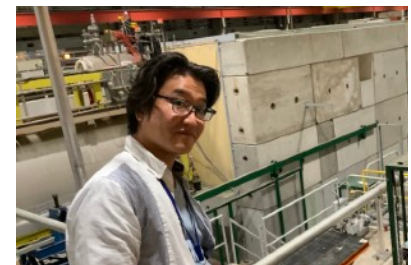
TB 2022 at CERN

- **Experimental hall**
 - During test beam, our experiments conducted at T4-H8 @ North Area

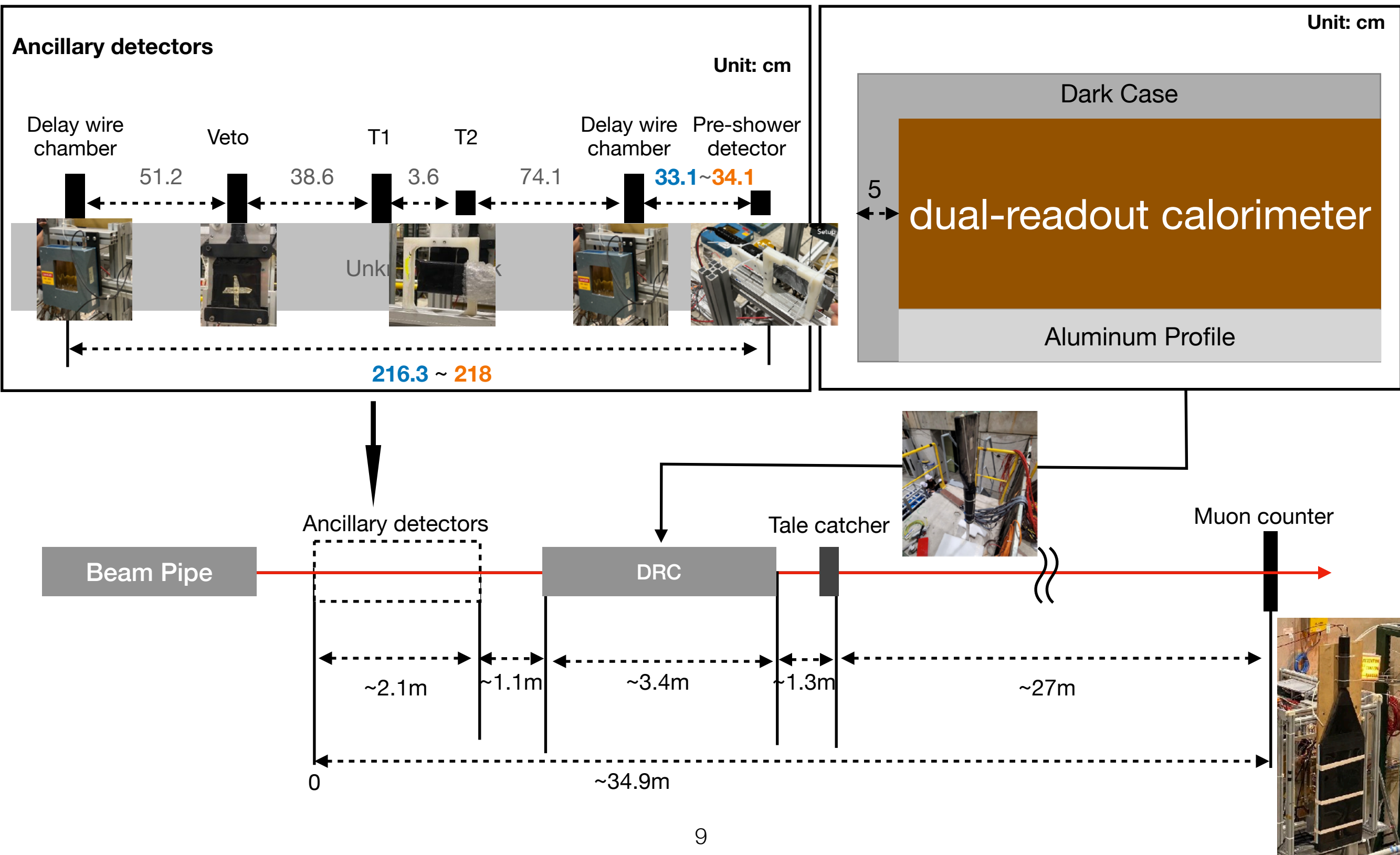


TB 2022: Participants

- 13 institutes 34 participants (including 23 students)

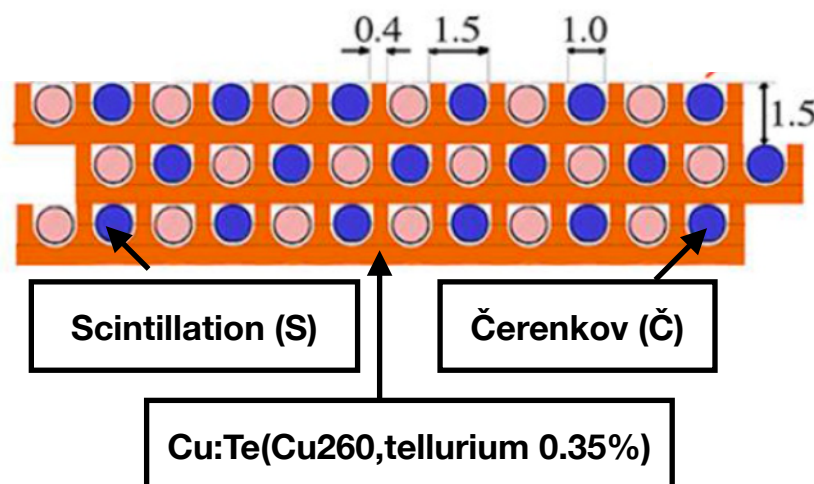


TB 2022: Apparatus Setup



TB 2022: Module Building

• Copper Plate & Fibers

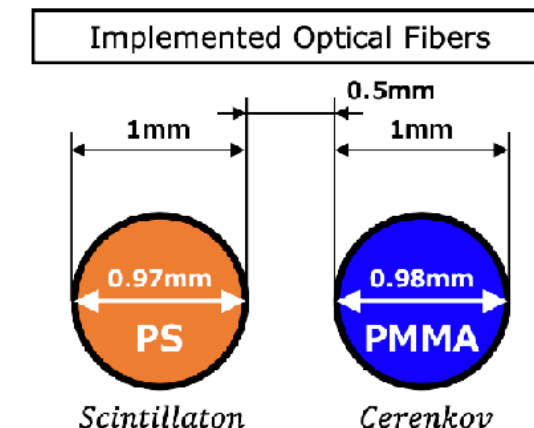


- Copper plate (60)

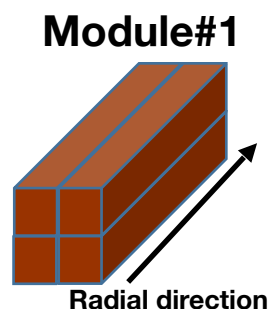
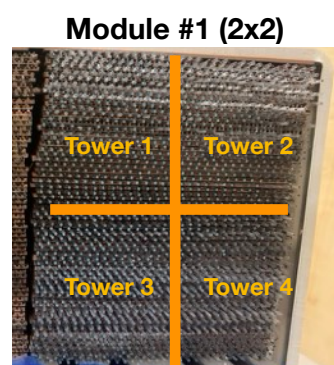
- Width : 10 cm
- Length : 2.5 m
- Thickness : ~1.6 mm
- Hole : 1 mm (diameter)
- Distance between hole : ~ 0.63 mm

- Optical fibers

- Scintillation fibers & Čerenkov fibers



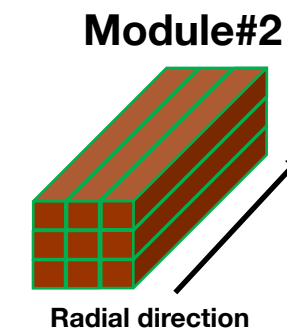
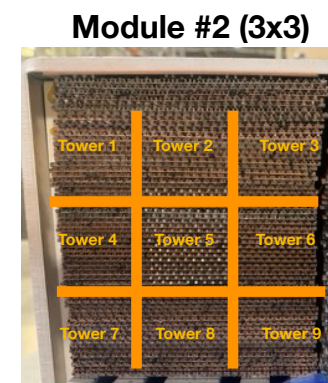
• Configuration of Fibers & Readout detector for Test Beam



Module#1	
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 / Double cladding	Round / Single cladding	Square / Single cladding
Čerenkov fibers	Round / Single cladding	Round / Single cladding	Round / Single cladding	Round / Single cladding
Readout detector (2*4 ch)	2 PMTs	2 PMTs	2 MCP-PMTs	2 PMTs

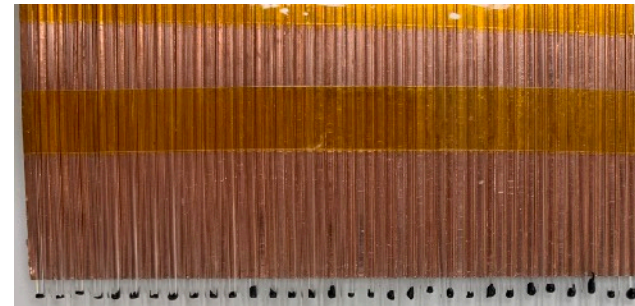
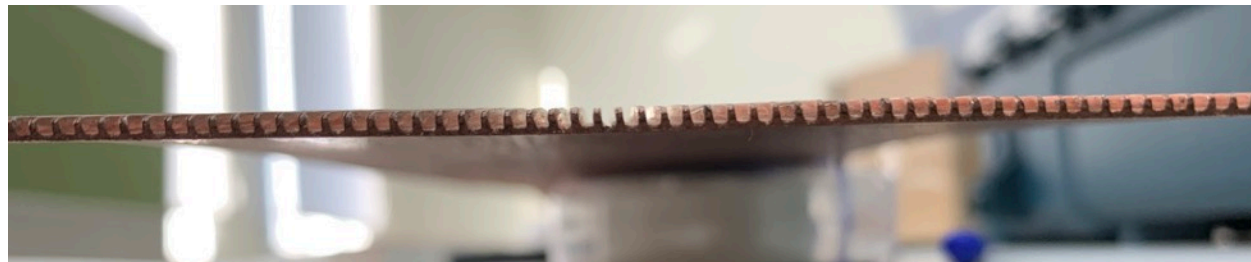


Module#2		
Tower#1	Tower#2	Tower#3
Tower#4	Tower#5	Tower#6
Tower#7	Tower#8	Tower#9

Combination of fibers for Module#2

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

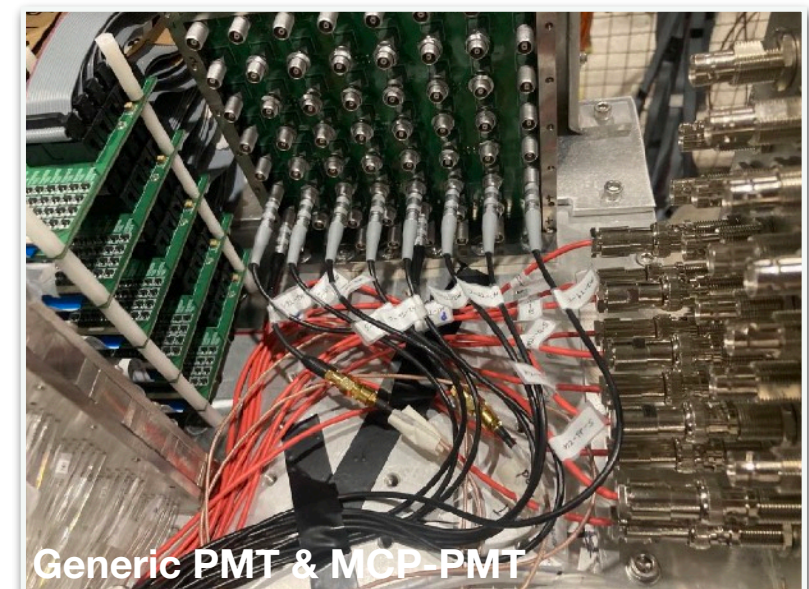
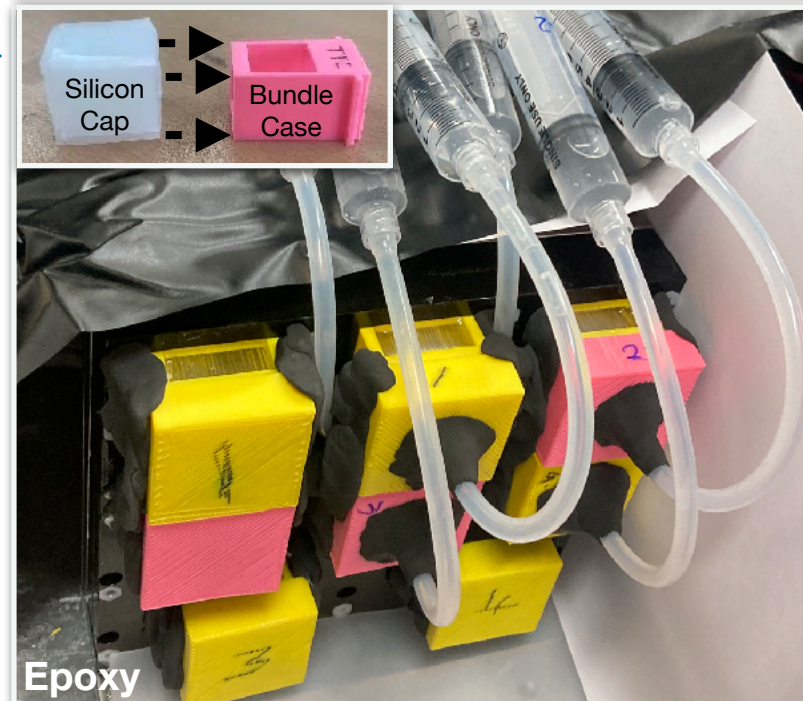
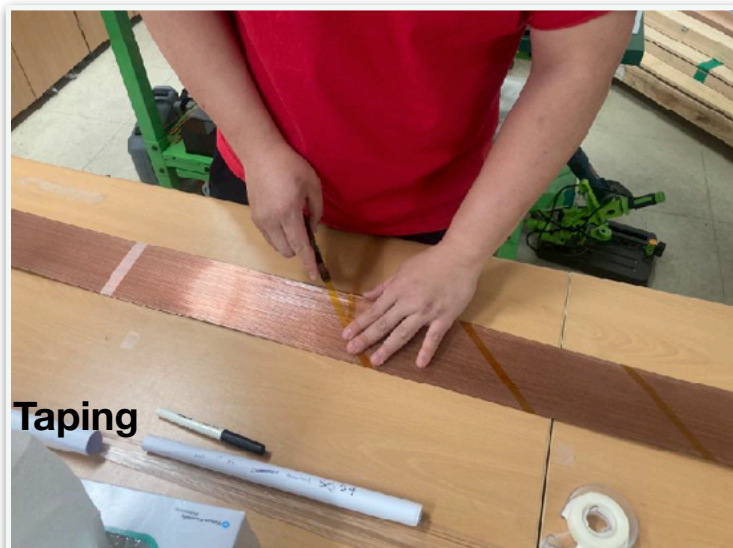
TB 2022: Module Building



Assembly

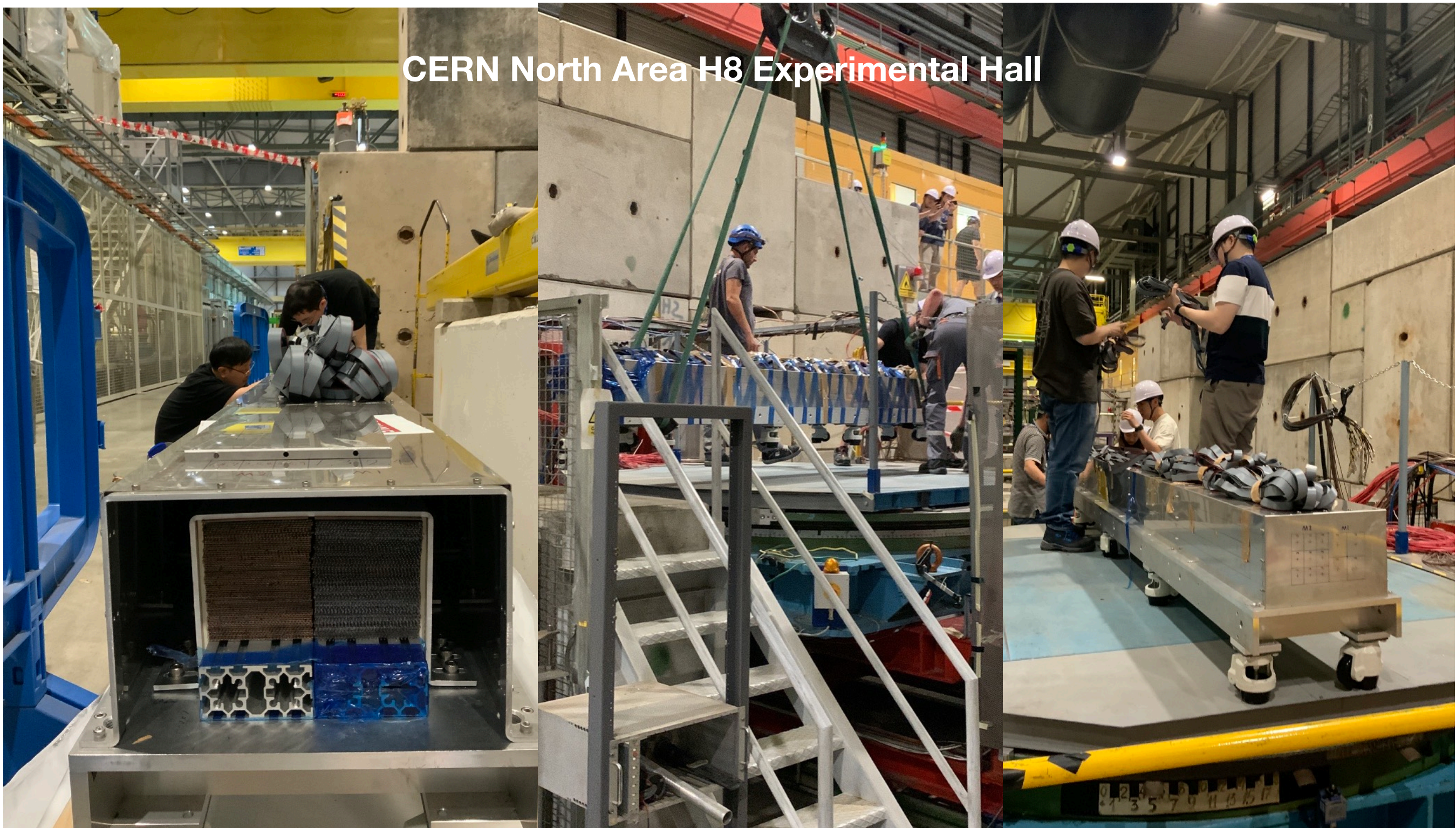
Bundling & Epoxy

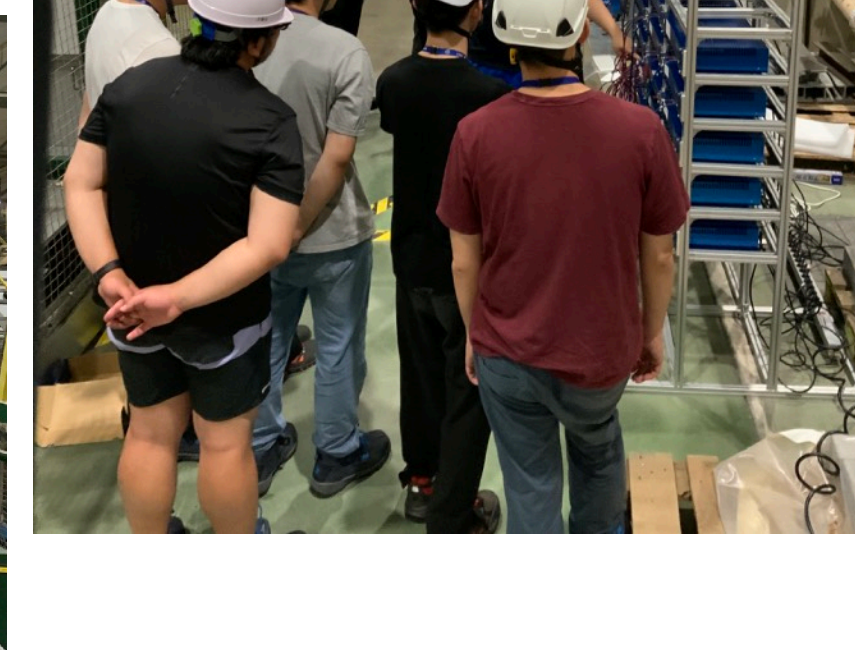
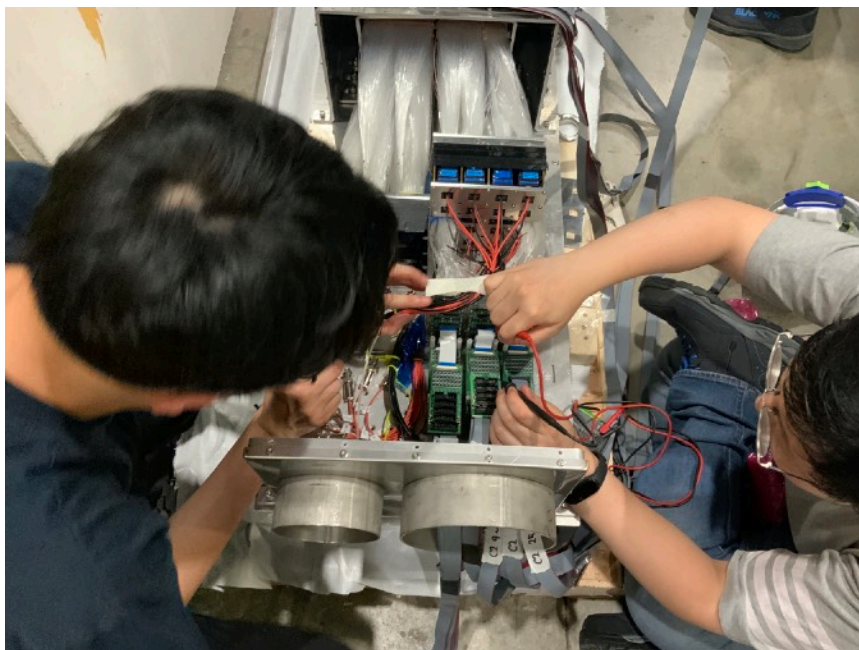
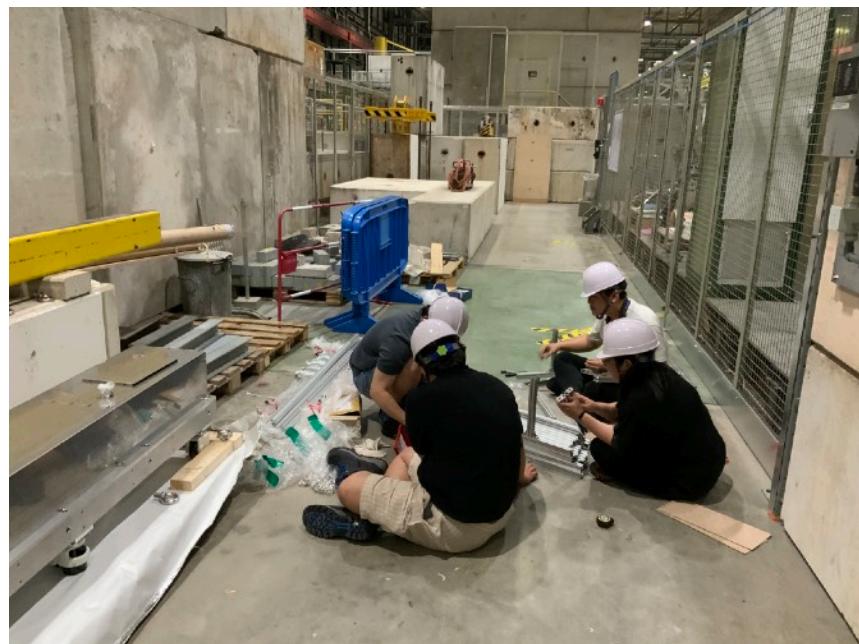
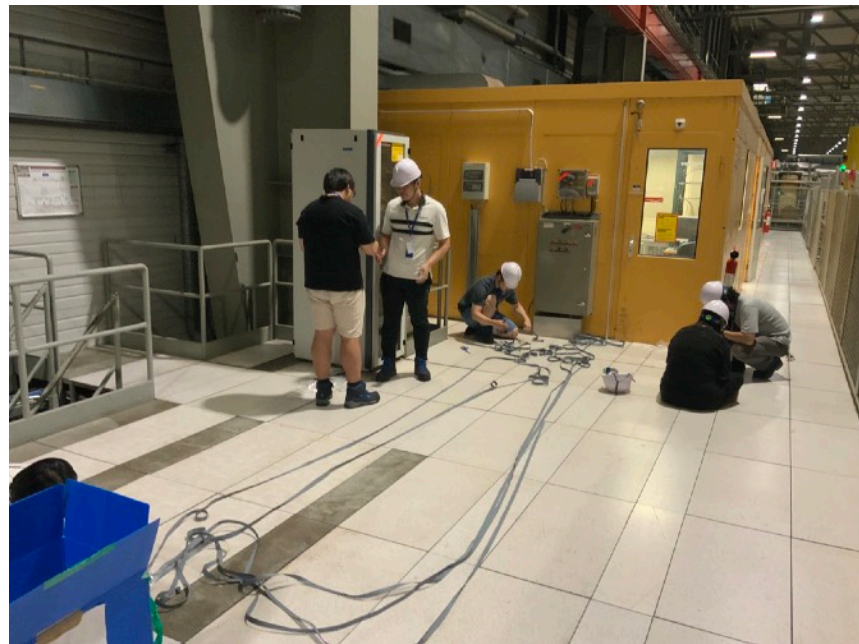
PMT Installation & Reflecton



TB 2022: Installation

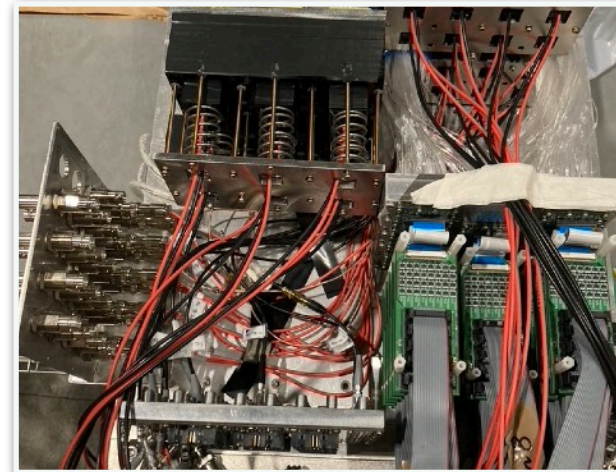
CERN North Area H8 Experimental Hall





TB 2022: Readout System

- Module 1
 - Read out information
PMT (6ch) + MCP-PMT (2ch)
- Module 2
 - Read out information
PMT (16ch) + SiPM (416ch, T.5)



MCP-PMT	Window size	light	Quantum Efficiency (Q.E.)	max. HV (V)	Rise time (ns)	Pulse width (ns)	photo
PLANACON XP85012	53x53 mm ²	scintillation	~7% at 550 nm	2400	0.6	1.8	
PLANACON XP85112		Cerenkov	~21% at 400 nm	2800	0.5	0.7	

PMT	Window size	Q.E. for Ck.	Q.E. for Sc.	max. HV (V)	Time response (ns)			photo
					anode pulse rise time	electron transit time	Transit time spread (FWHM)	
R8900 series (old)	23.5x23.5 mm ²	35% at 420 nm	~7% at 550 nm	1000	2.2	11.9	0.75	
R11265-100 (new)	23x23 mm ²	~35% at 400 nm	~7% at 550 nm		1.3	5.8	0.27	

SiPM	photosensitive area	photo detection efficiency (PDE)		operating voltage	Gain at V _{BD} +5V	Linearity of Q.E.	number of pixels	geo. Fill factor
S14160-1310PS	1.3x1.3 (1.69 mm ²)	~15% at 400 nm	~17% at 550 nm	V _{breaking Down} + 5 V	~1.75x10 ⁵	~2x10 ¹⁰ /sec as incident photons	16675	31 % (0.524 mm ²)
fiber (Φ1 mm)	0.785 mm ²						~7745 (effectively)	

TB 2022: DAQ System

- **DAQ System**

- 15 DAQ Board + 1 TCB Board

- DAQ Board

- One board can cover 32 channels

- DRS4 chip

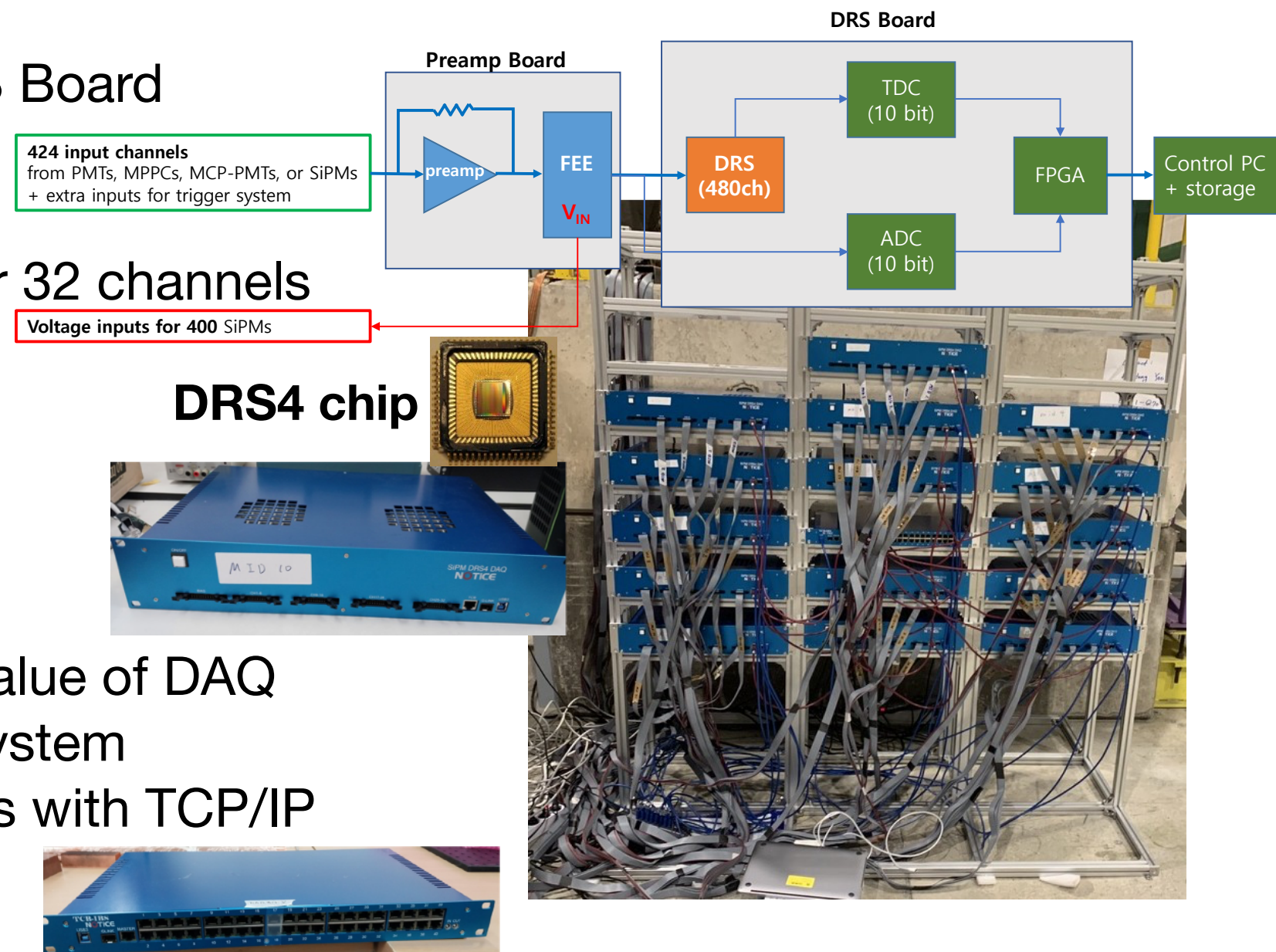
- 16 pin Ribbon cable

- TCB Board

- Control the setting value of DAQ boards and the trigger system

- Connect DAQ boards with TCP/IP cable, cover 40 ch DAQ

- All boards connected with PC using USB3 line



	PMT	MCP-PMT	Auxiliary detector	SiPM
channels	22	4	11	400
DAQ		2		13

TB 2022: Storage System

Beam

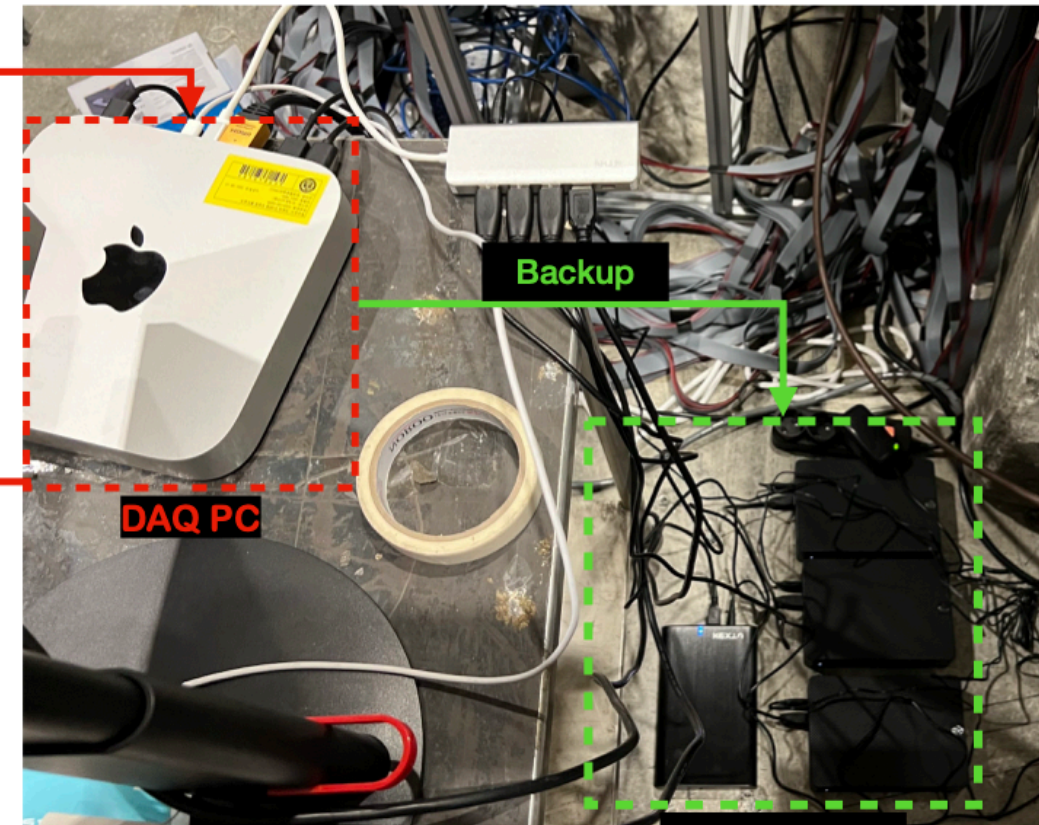
Aux. & DRC detectors

Signal

Data



DAQ



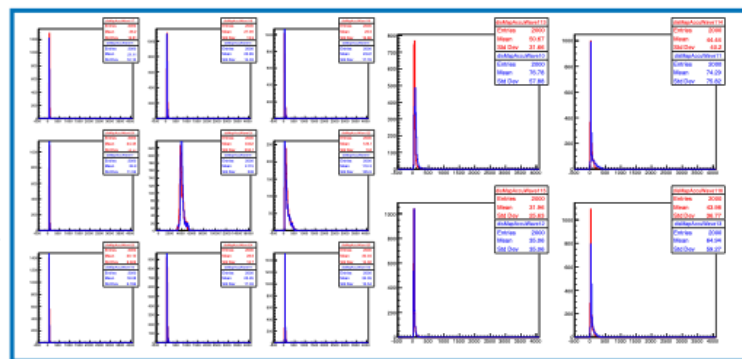
Backup

DAQ PC

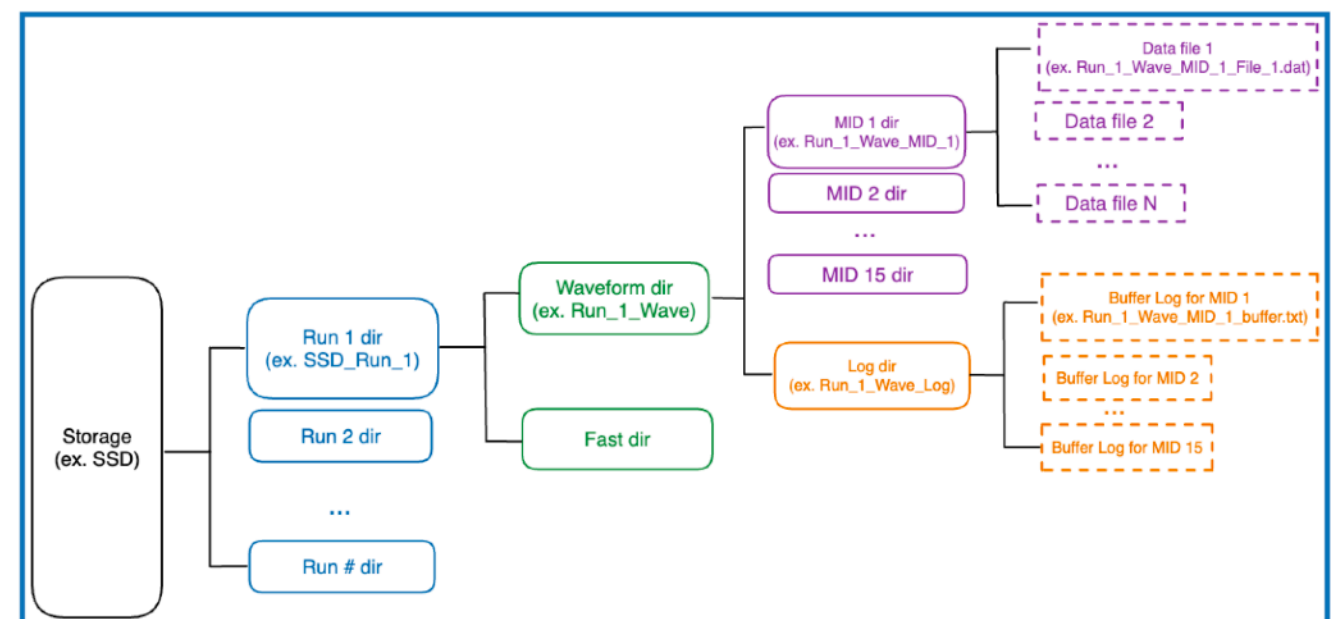
External HDD

DQM data

In control Room



Draw DQM plots



TB 2022: Program

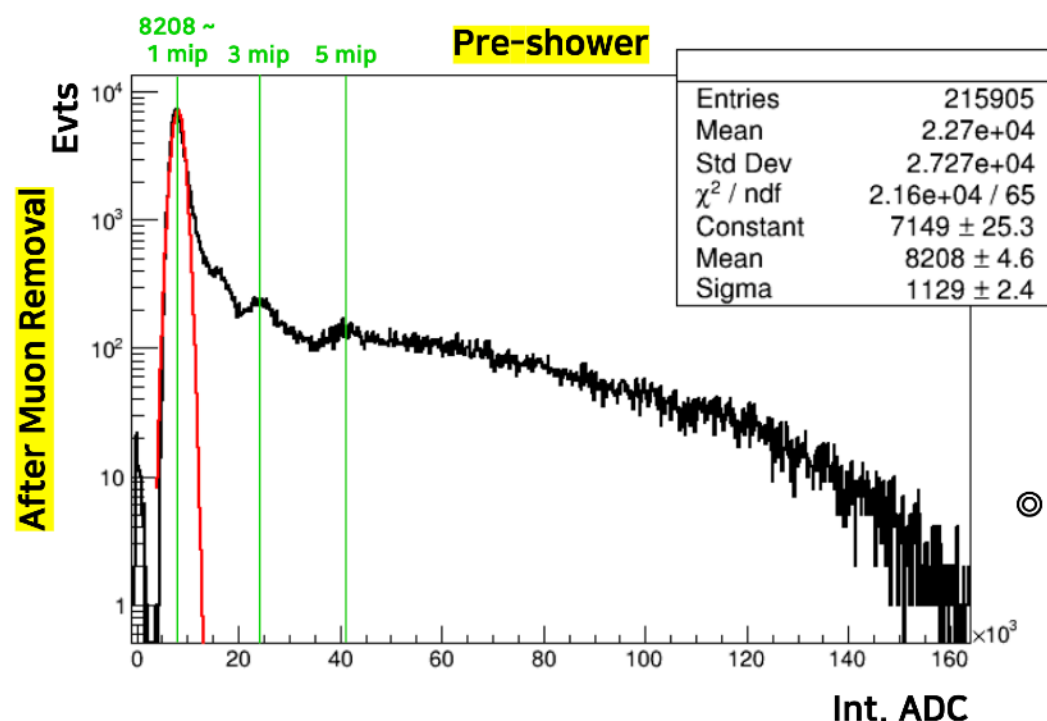
Aim	Module	Description
Finding towers (scanning tower position)	M1, M2	- Using positron beam (20 GeV) - 1cm vertical & horizontal scan - Find boundary of tower!
Gain tests	M1, M2	- Check signal level w.r.t. HV
Calibration	M1, M2	- Using positron 20 GeV, finding optimized HV (similar response ADC S and C)
Resolution	M2	- Energy resolution - position resolution
Cerenkov channel response	M1	- Using position 20 GeV, rotating & moving module
Longitudinal shower profile	M1	- Using position 20 GeV, varied lead blocks (variation of radiation length)

TB 2022: Runs

- During the test beam, we took data 84hours, and ~23M events were taken as fast mode and 4.6M events as waveform mode!



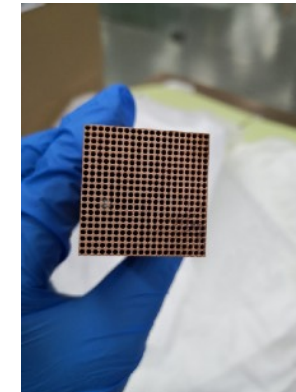
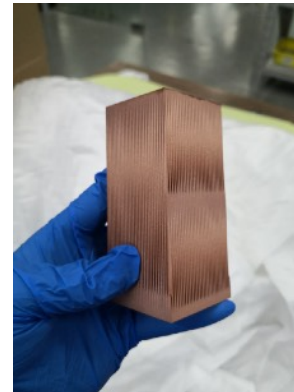
Total wave	Total Fast	Total Time (min)	Total Time (hour)
4,657,849	23,248,704	5,046	84



Prompt data analysis on-going

Module Building R&D

- 3D printing



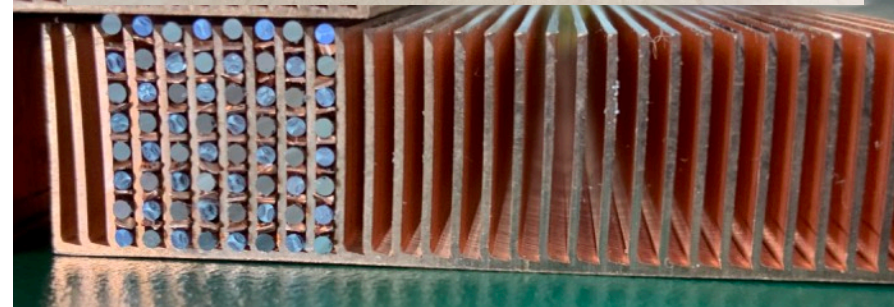
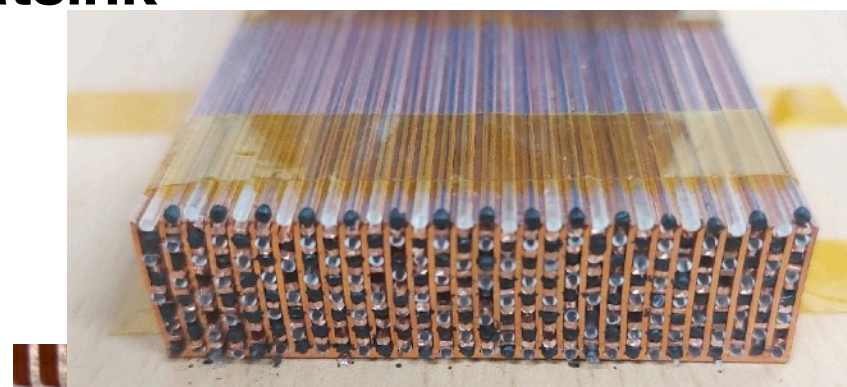
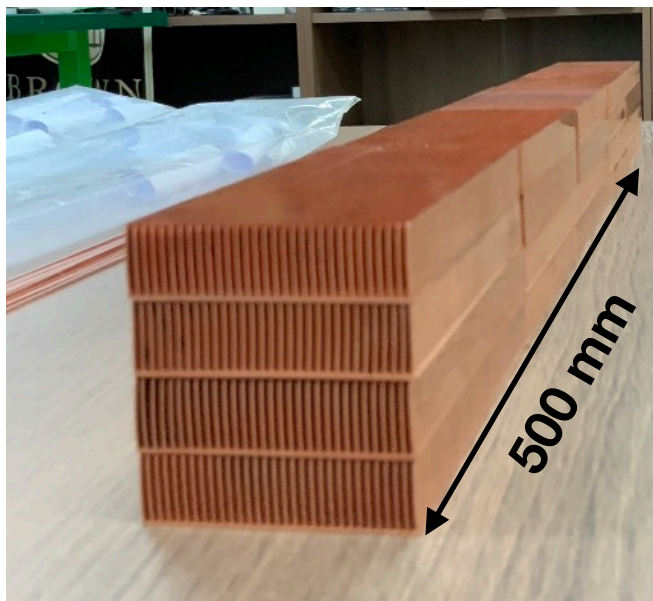
It has very perfect accuracy, but the cost is very high

- LEGO-like (Copper pipe)



It has very good accuracy, and pretty low cost

- Skiving Fin Heatsink



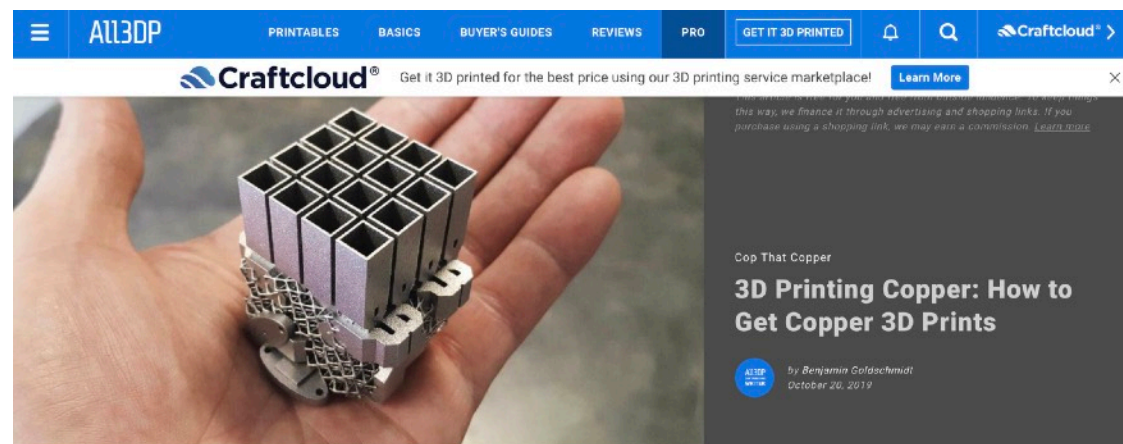
It has very excellent accuracy, and cost is low

Possibility for mass production!



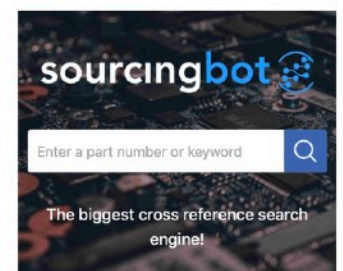
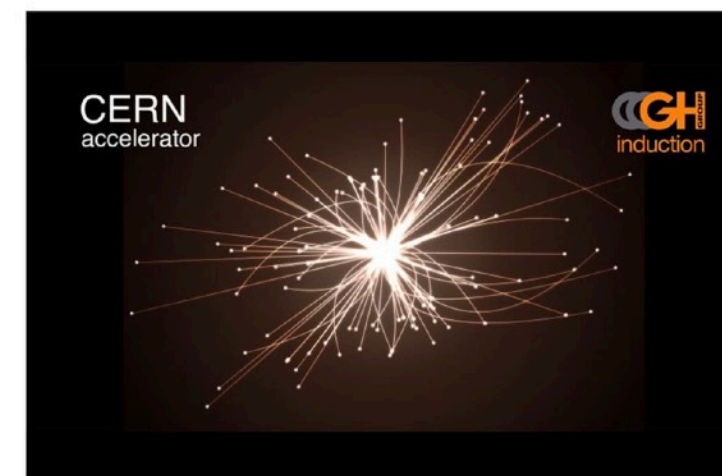
3D Copper Printing Technology

- Copper is not easy to be used for 3D metal printing
 - But technology is being developed very fast ...

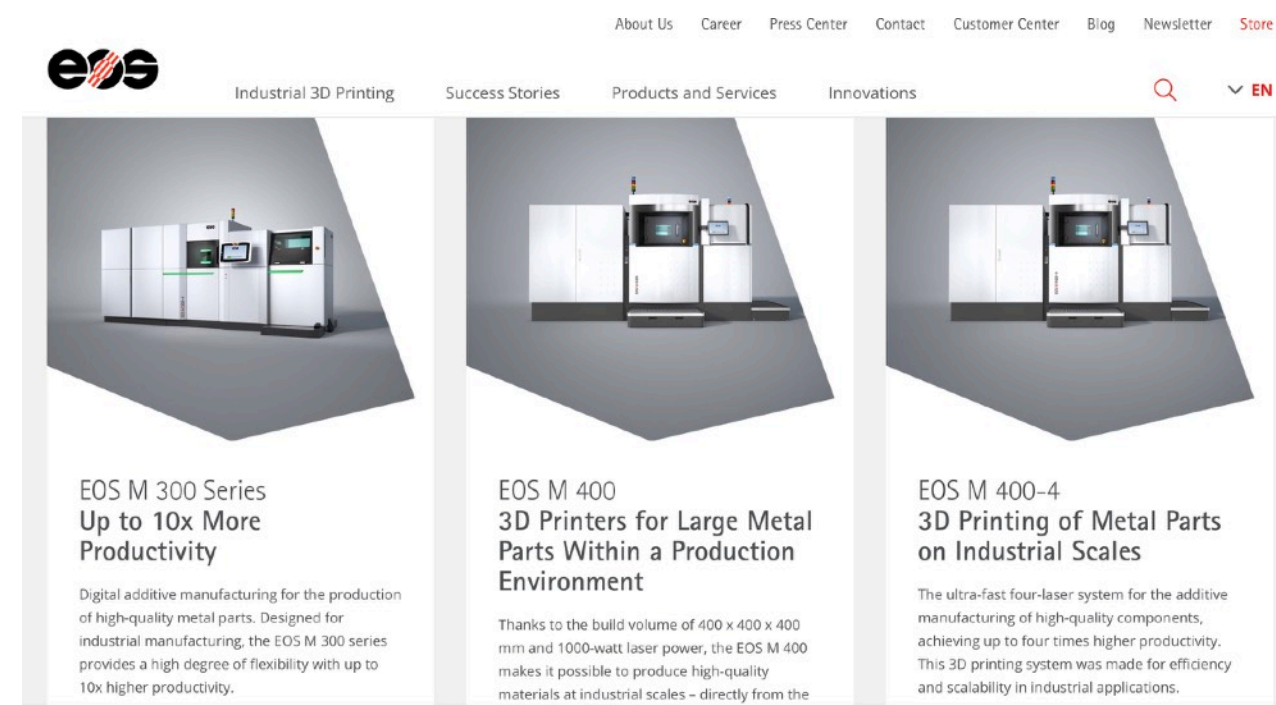
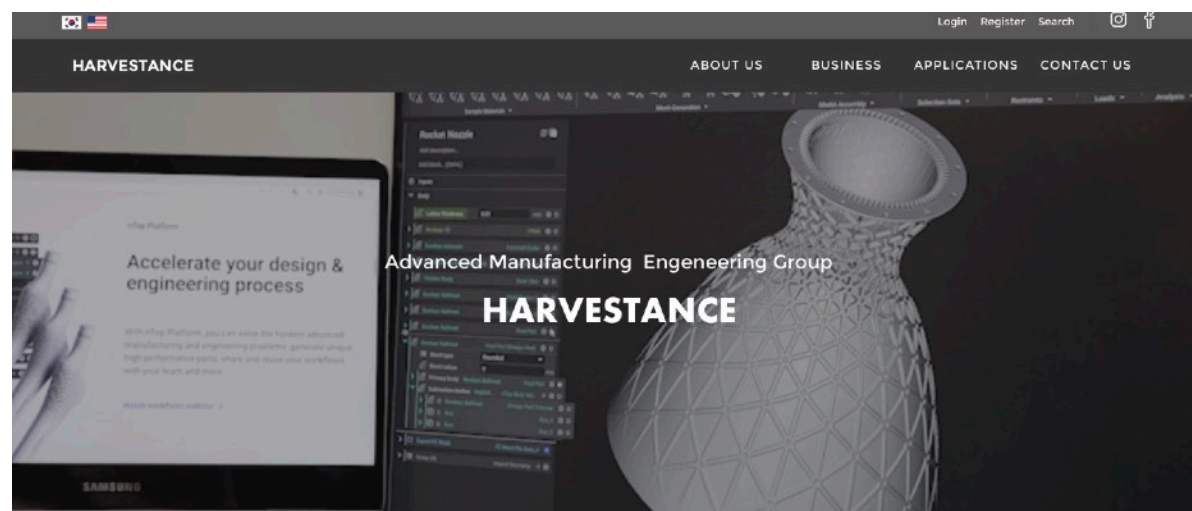


CERN exploring GH Induction's copper 3D printing

30.7.2019 Reading Time: 4min read

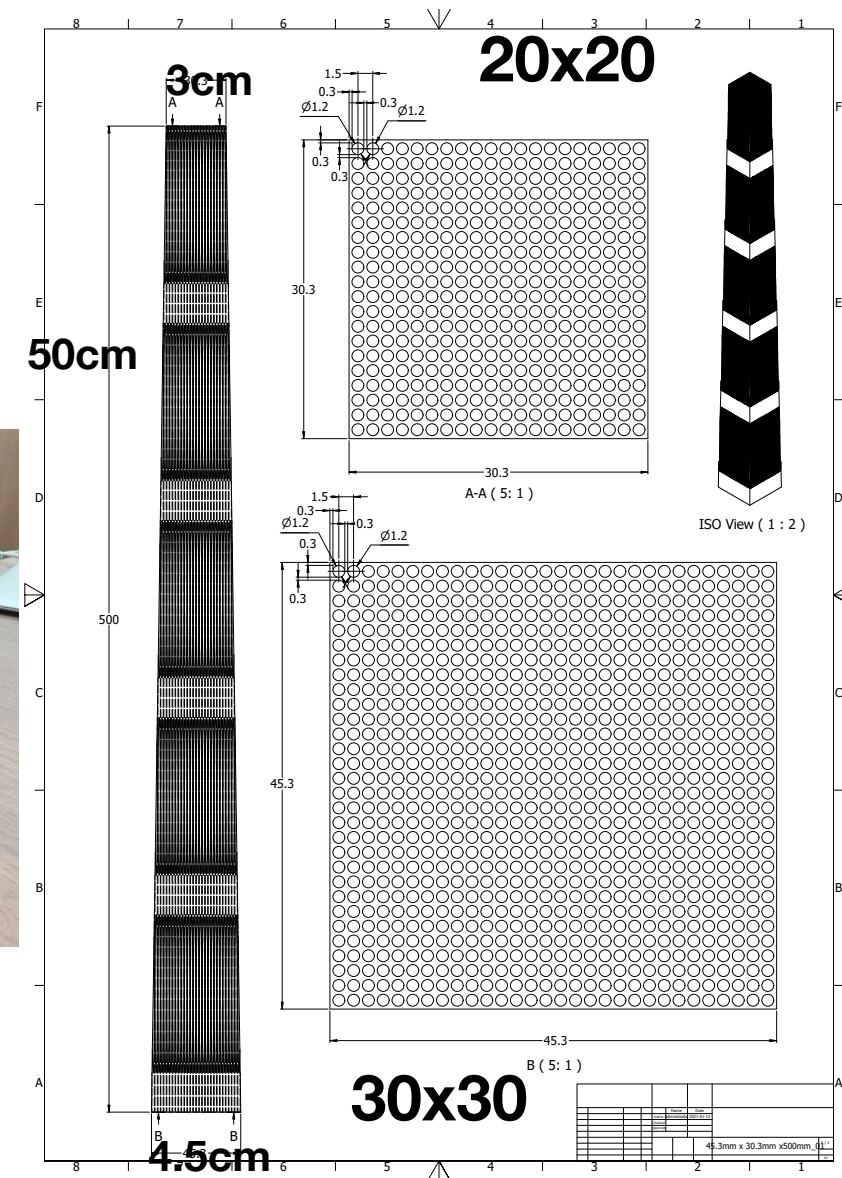
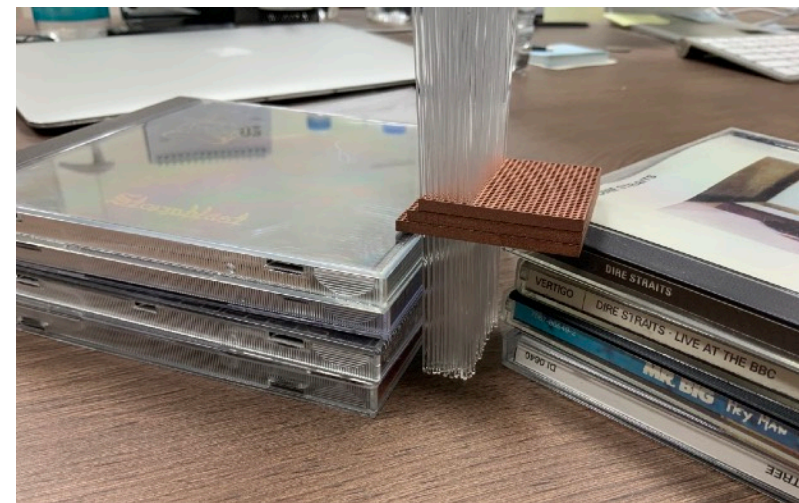
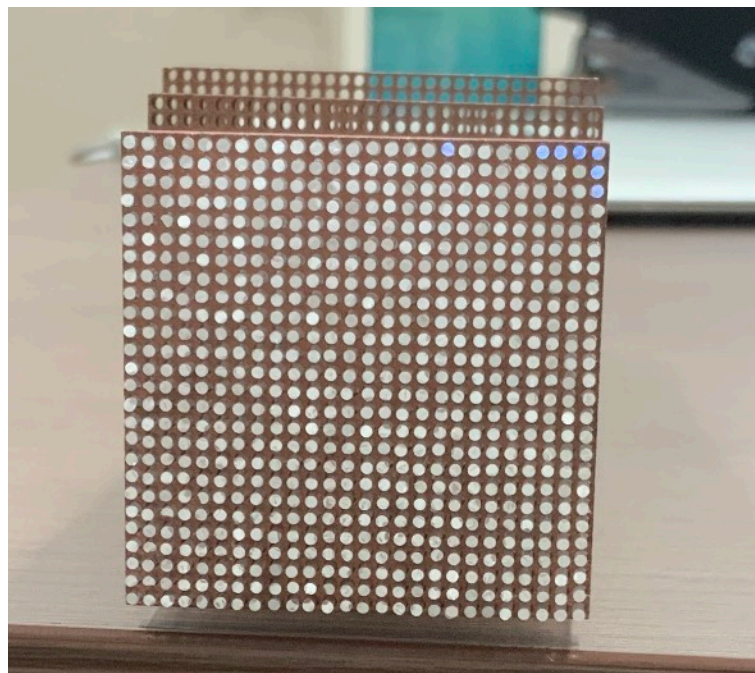
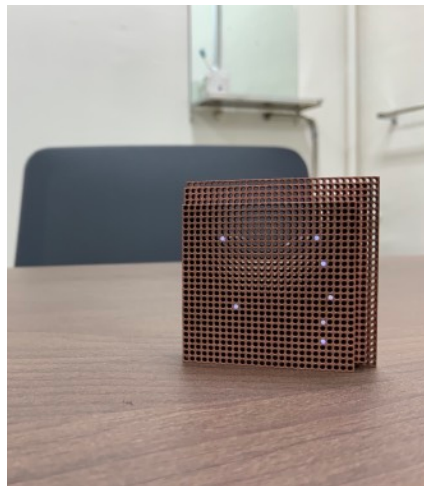
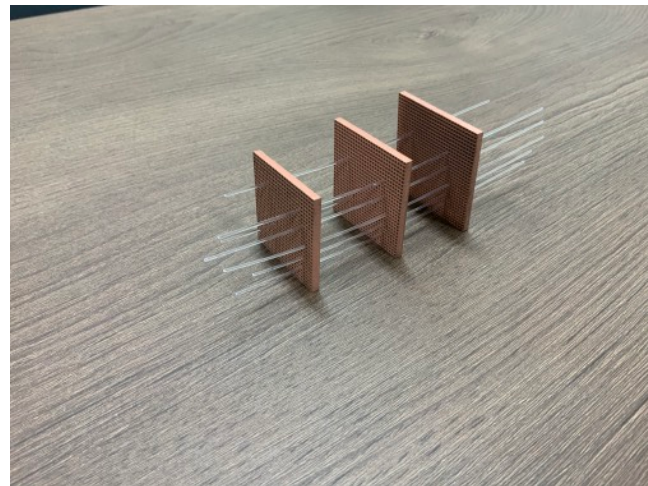


- We contact a local 3D consultant company in Korea



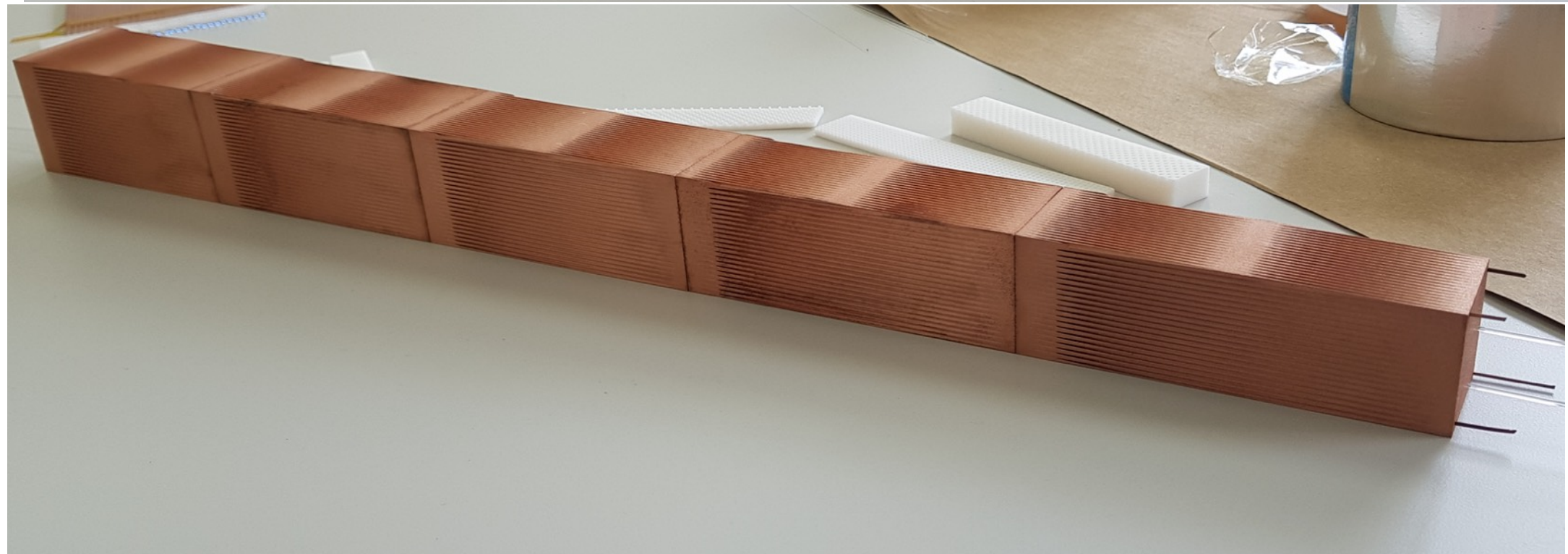
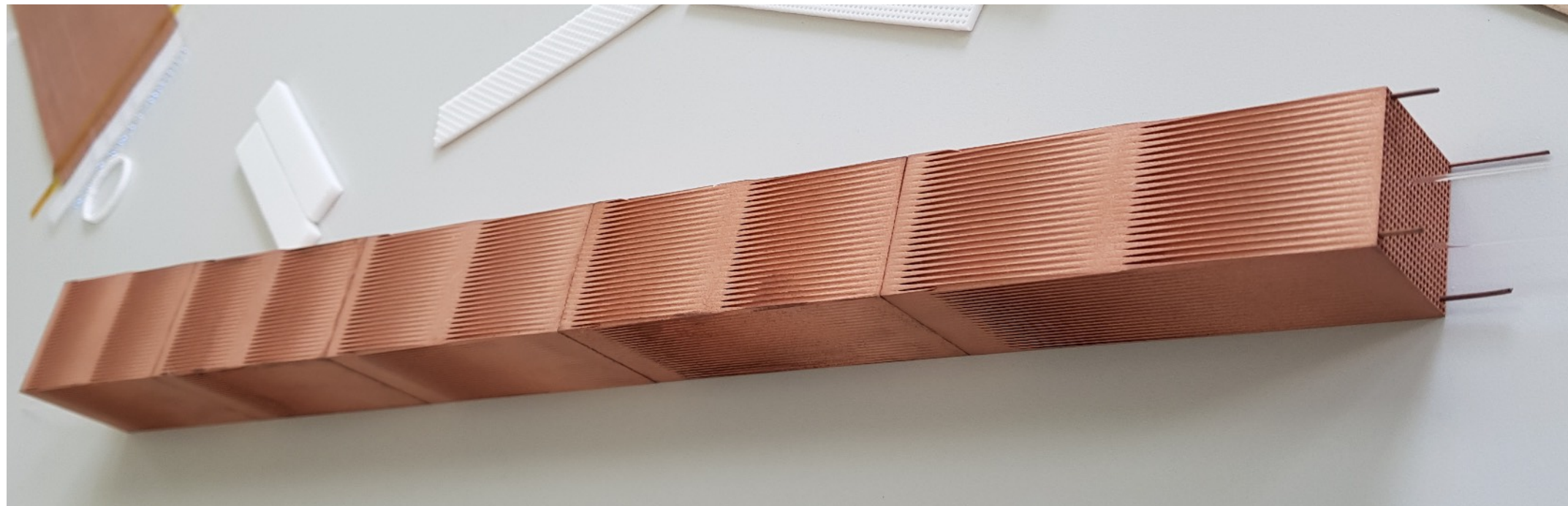
Toward Prototype 3D Module

- Under test and design: check alignment of holes and very successful!
- Ordered five 3D-printed copper blocks (10 cm length each) for the prototype module



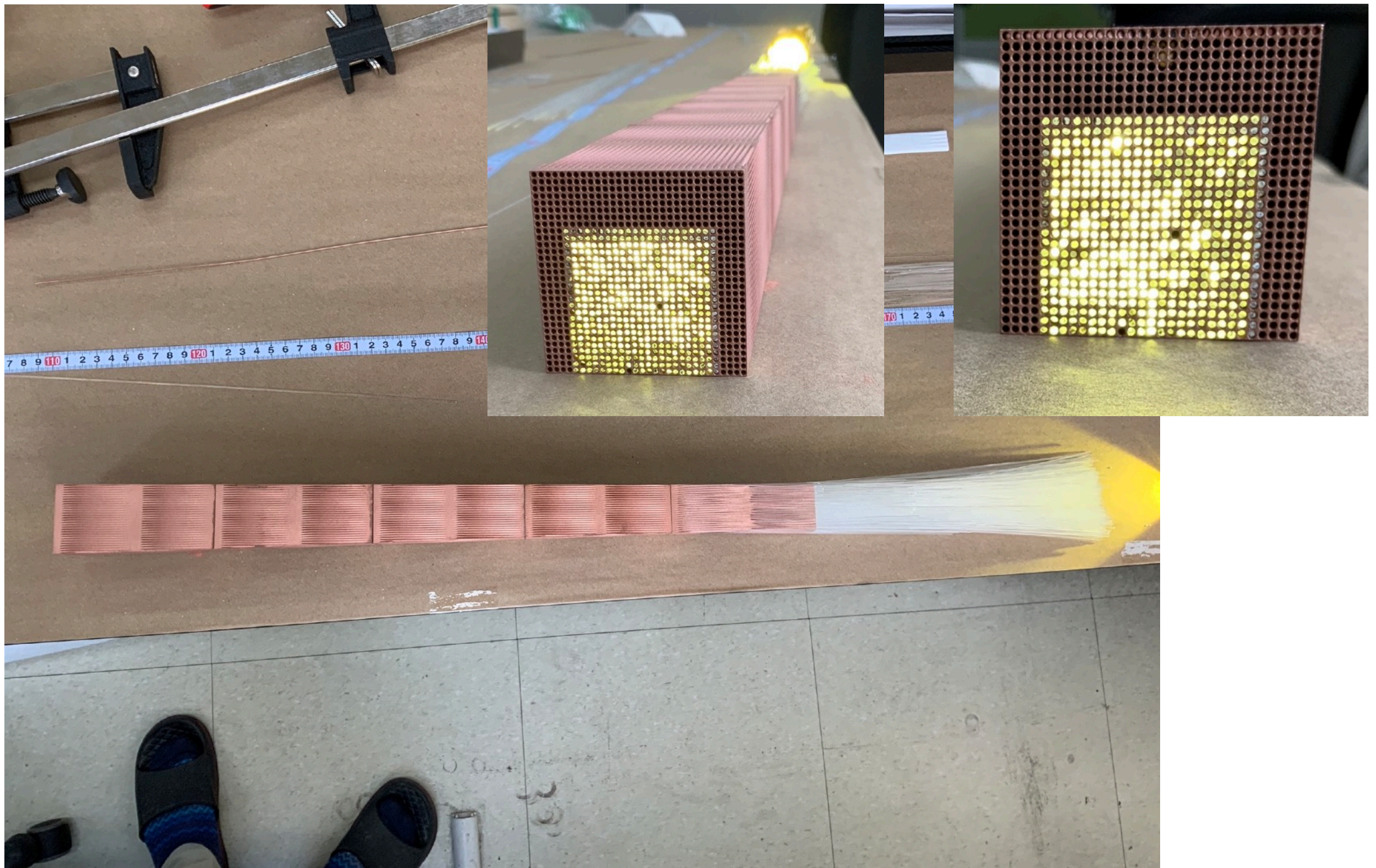
Prototype 3DP Module

- 1st projective DRC module ever!

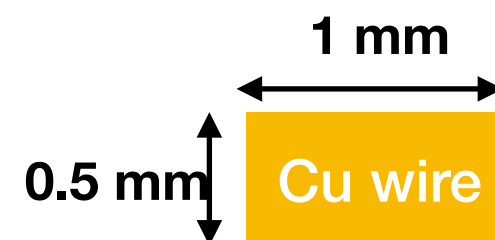
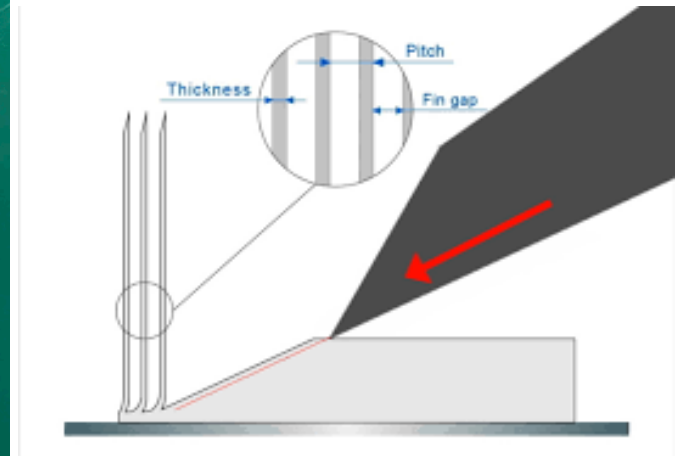
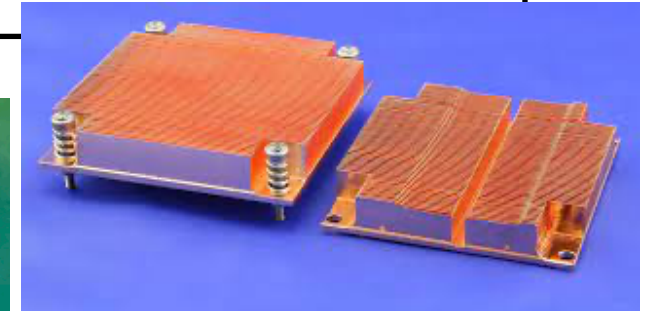
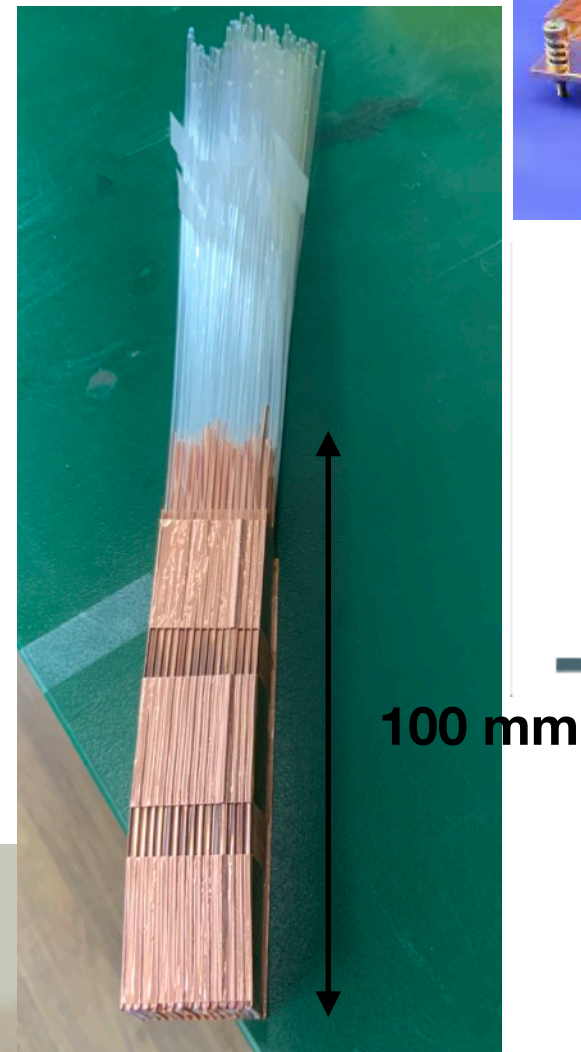
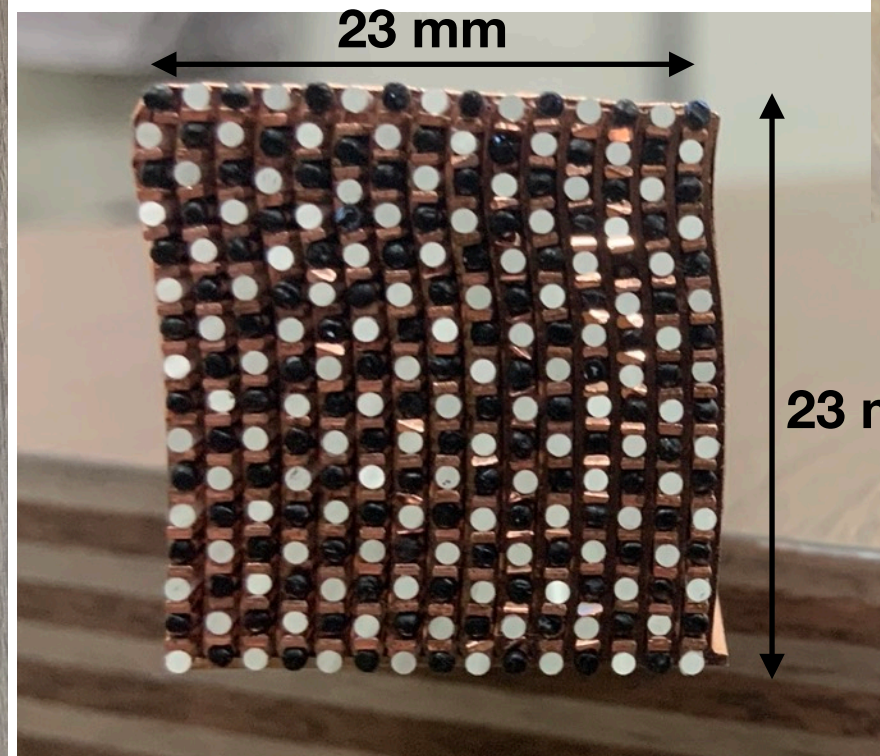
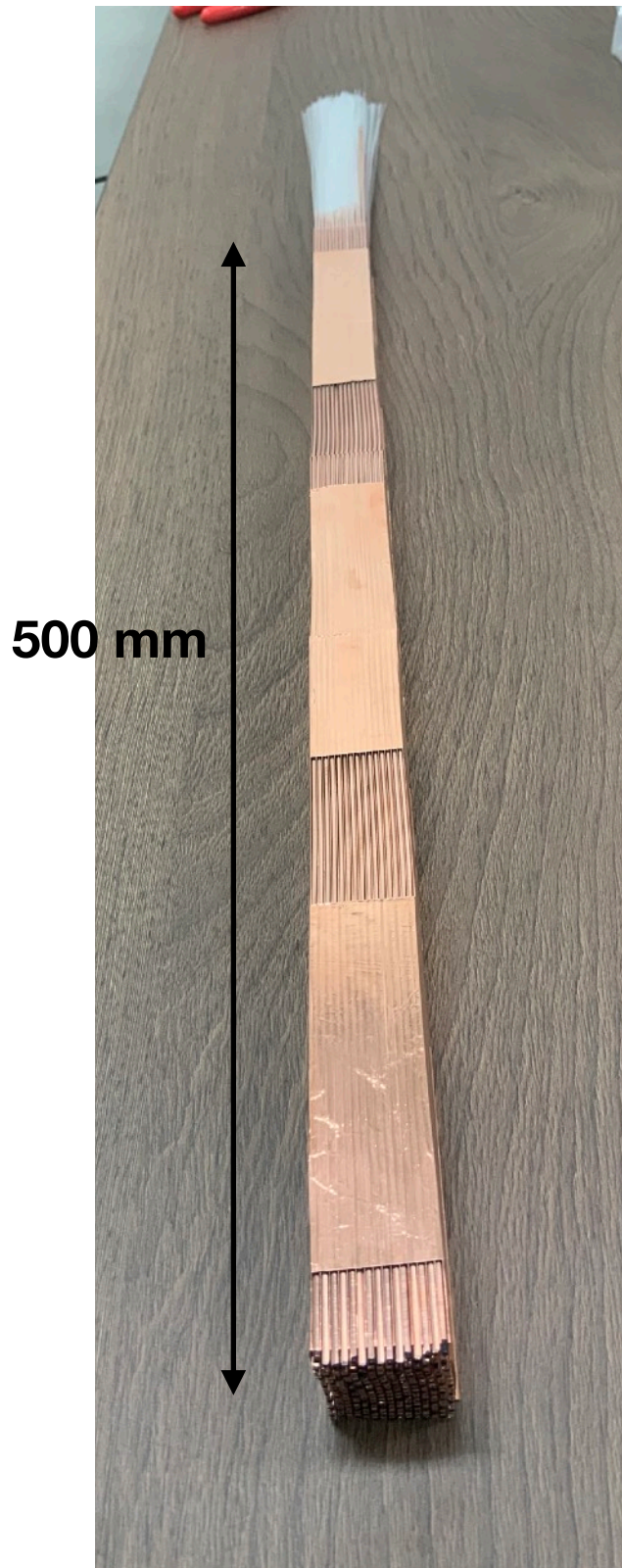


Prototype 3DP Module

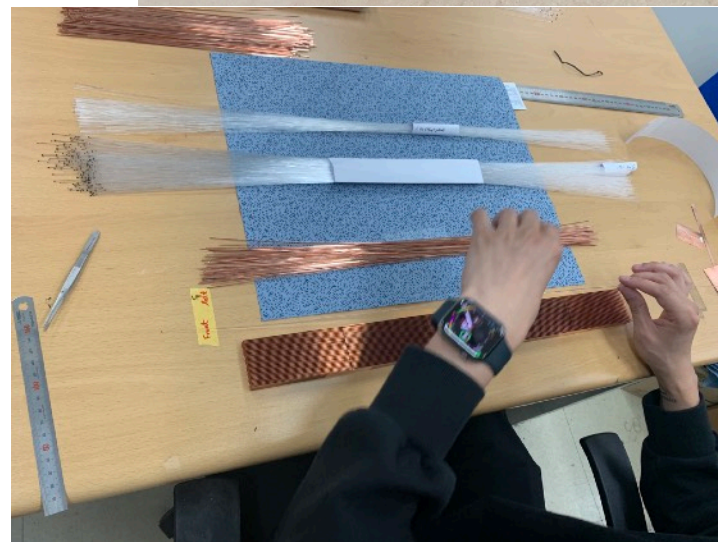
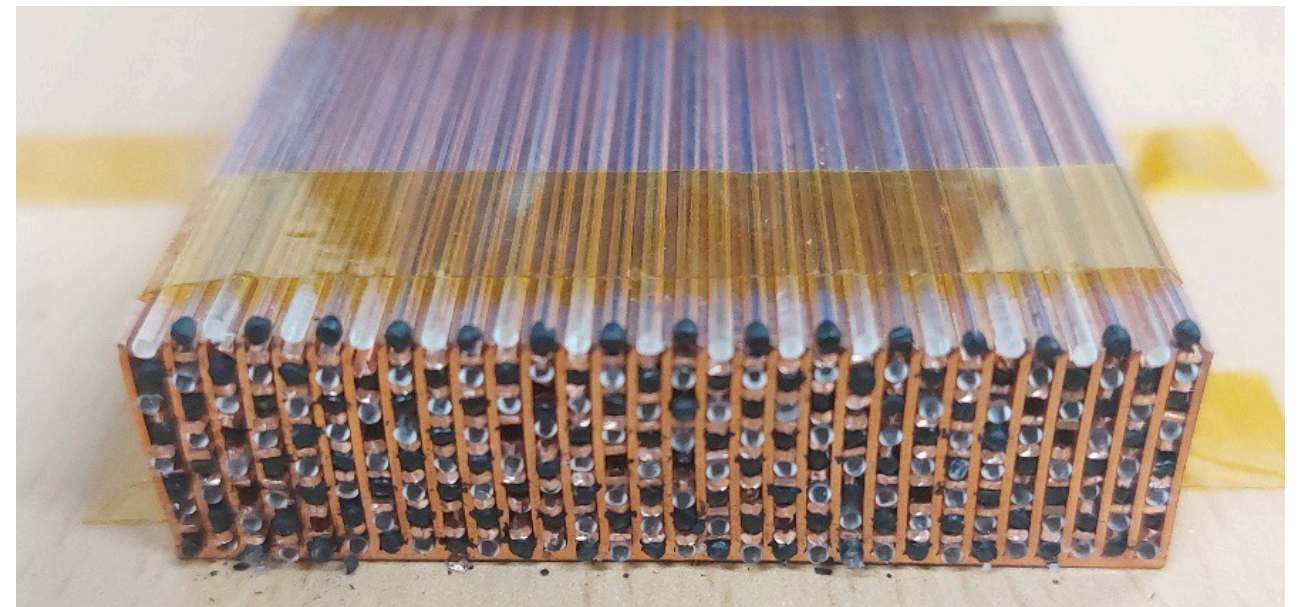
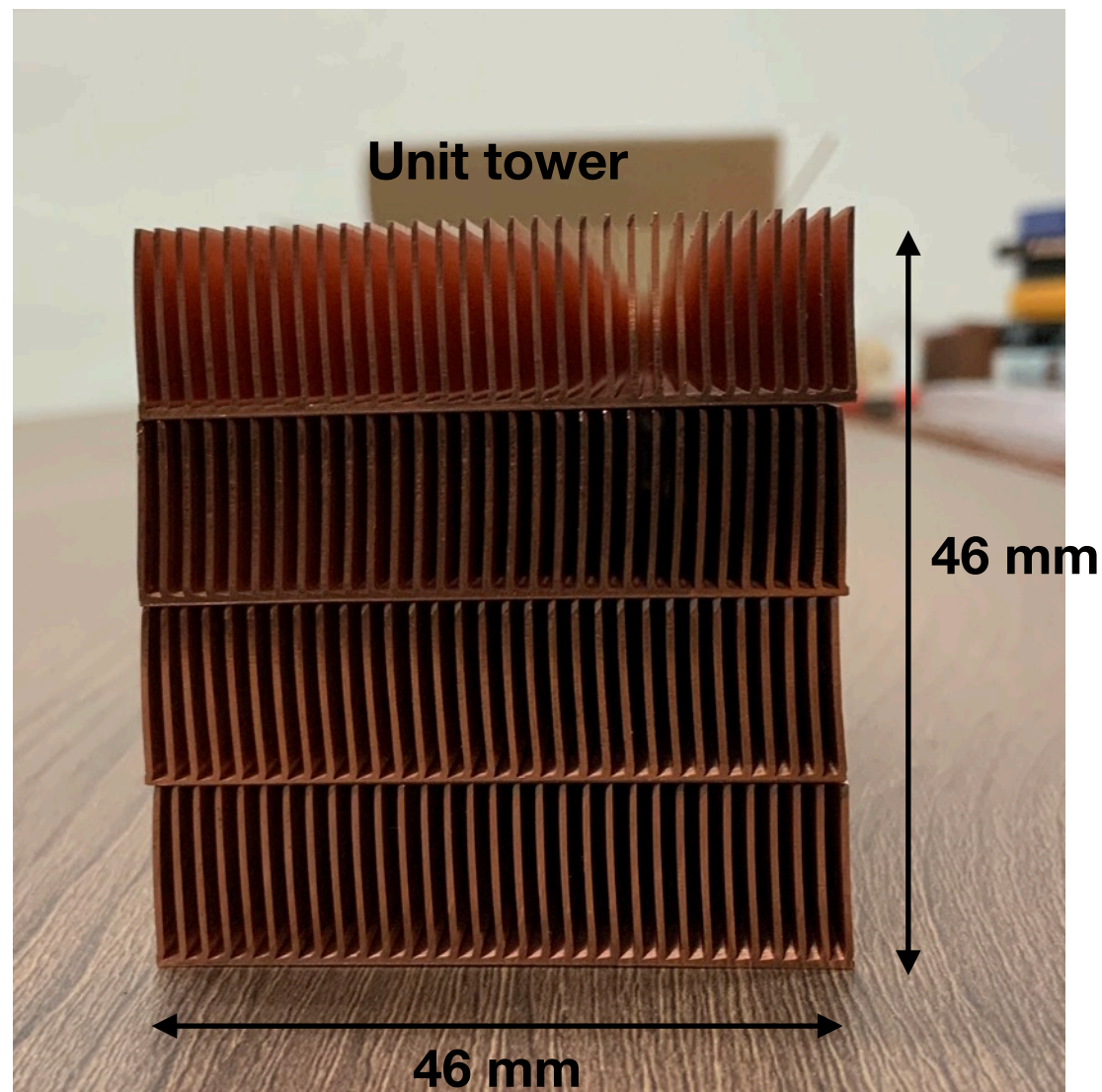
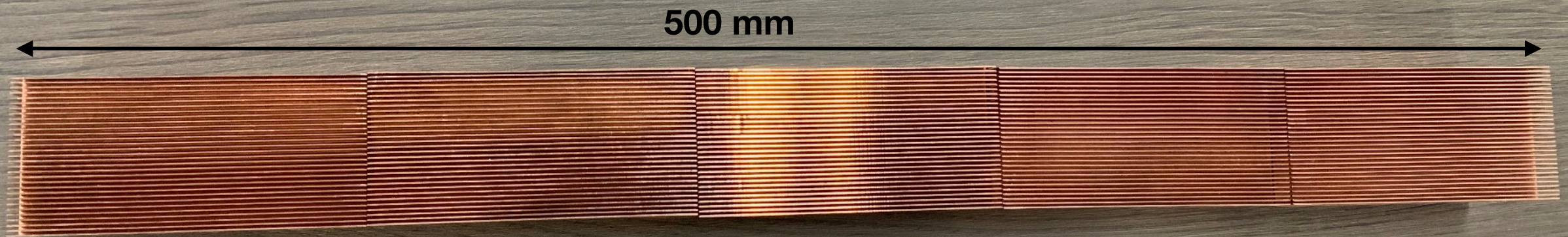
- Insert fibers into entire holes: well aligned!



SF Heatsink R&D

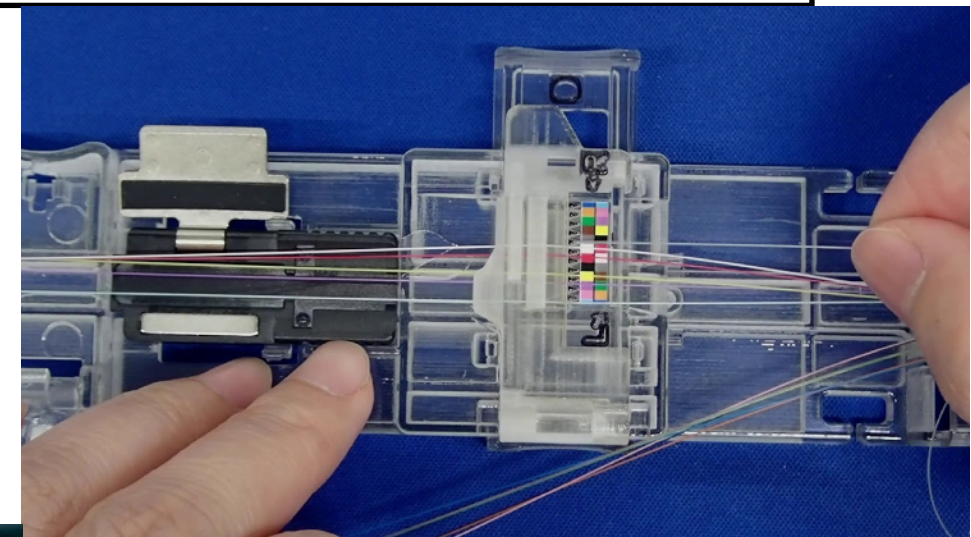
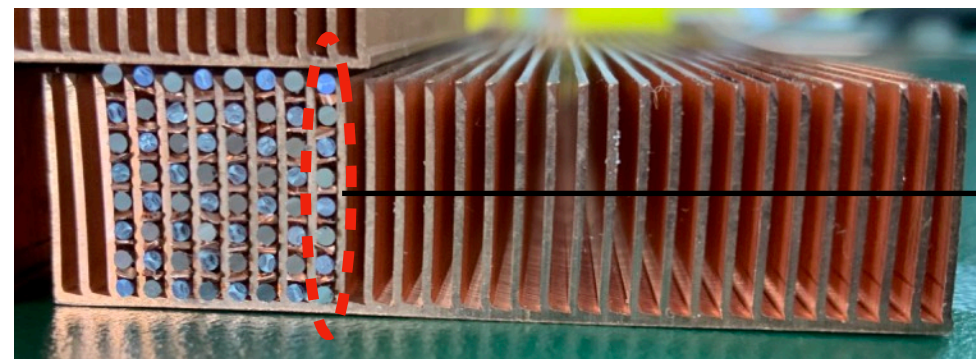
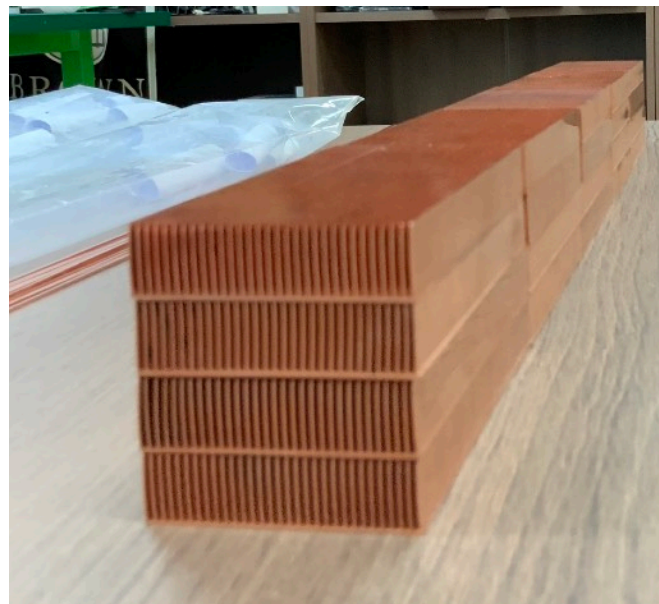


SF Heatsink: Prototype



Advantage of SF Heatsink

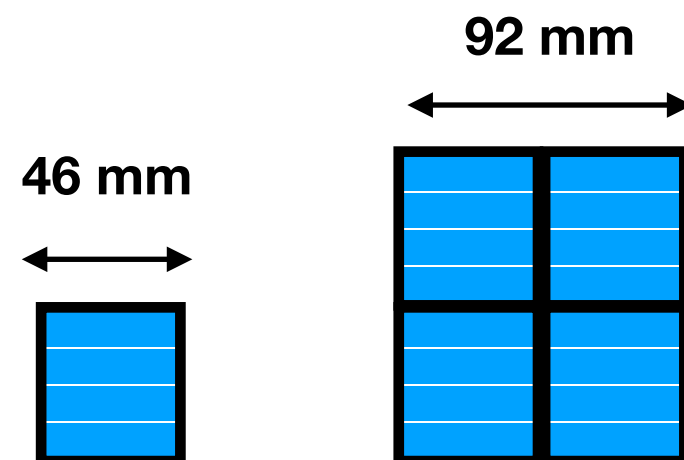
- Possibility for mass production



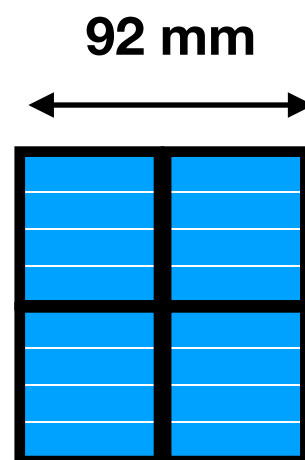
Ribbonizing



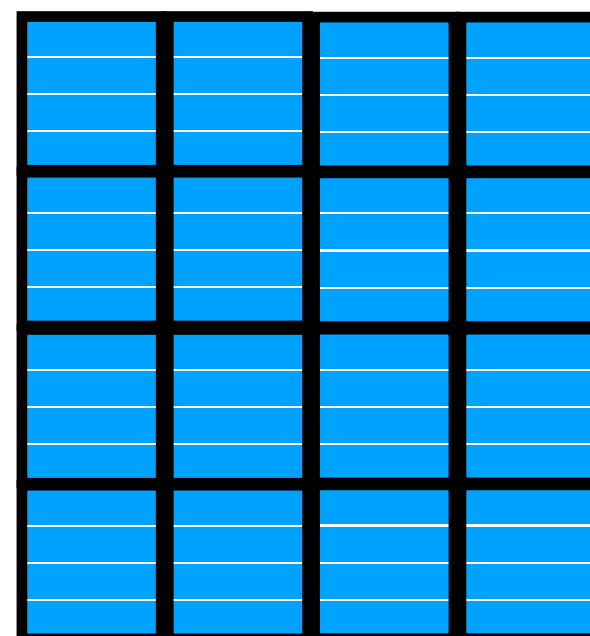
- Easy to configure various units including super-module assembly



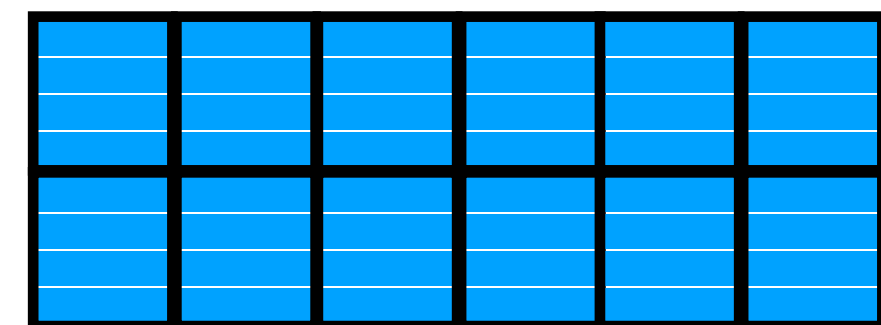
Tower
(1 x 4)



Module
(2 x 8)



Ex. Super-module 1 (4 x 16)



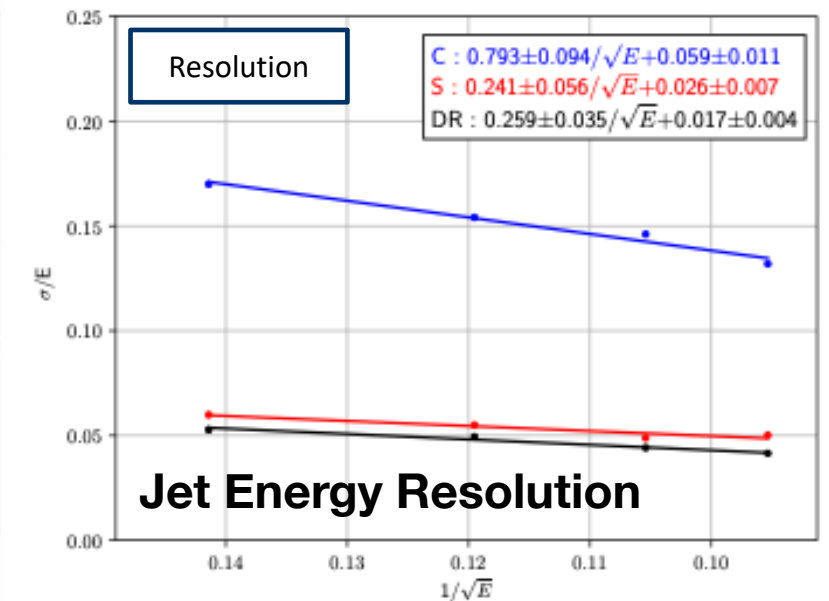
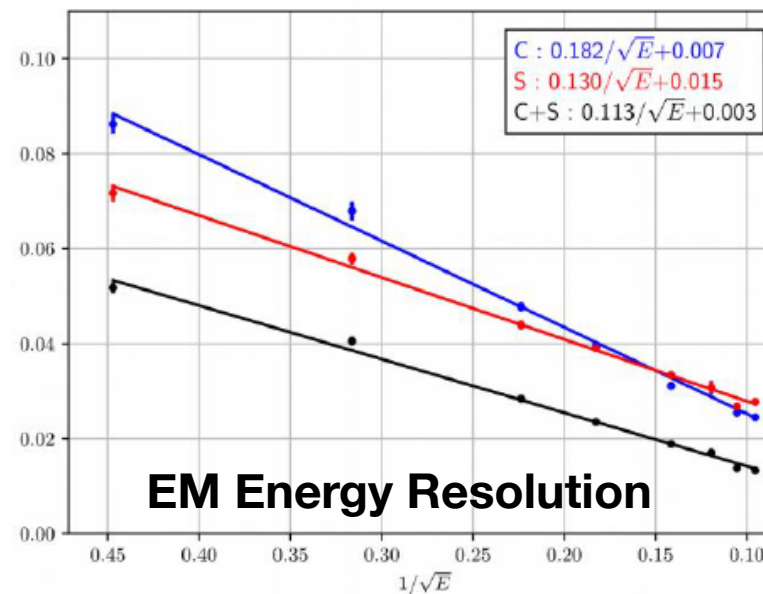
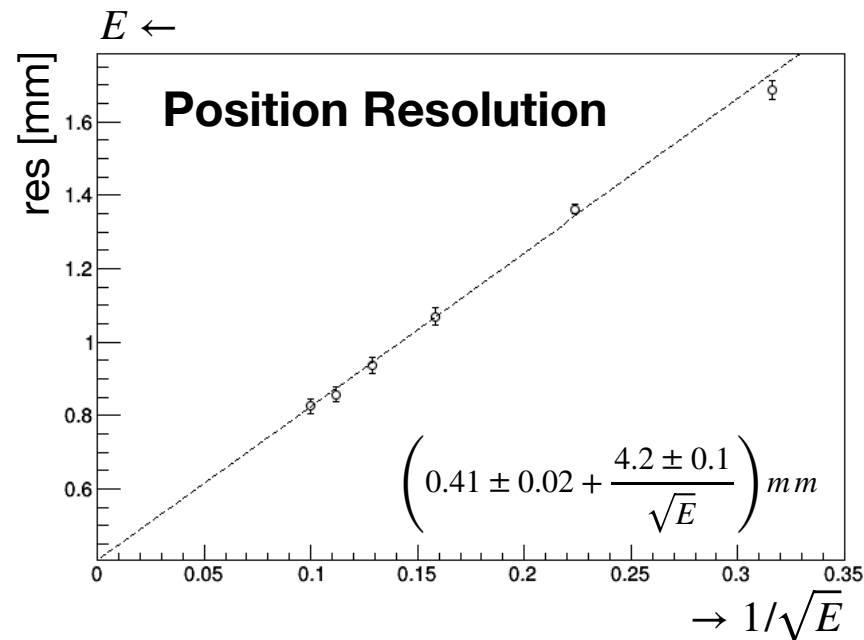
Ex. Super-module 2
(6 x 8)

Toward Detector Construction

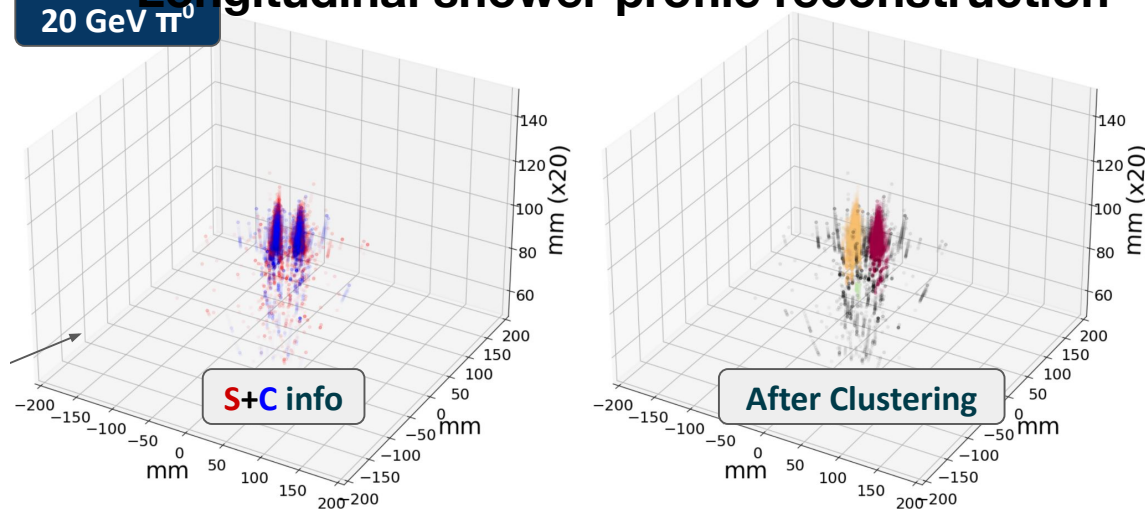
- Things to propose in TDR => need to demonstrate feasibility of the 4pi detector construction

	Cost	Preparation	Assembly	Accuracy
Cutting	Low	Difficult	Difficult	Fair
Bucatini (Italy)	Moderate	Difficult	Easy	Excellent
3D printing	Ultra high	Easiest	Easiest	Perfect
LEGO-like	Very low	Easy	Easy	Fair
LEGO-like 2 (SF Heatsink)	Low	Easy	Easy	Excellent

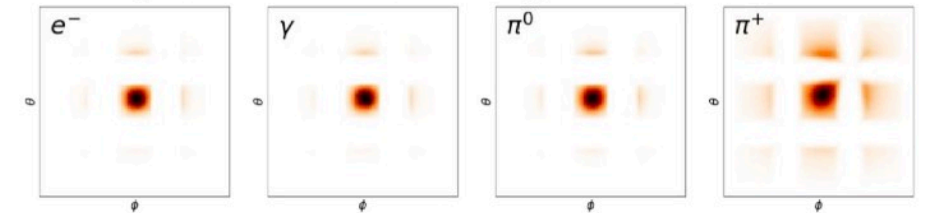
Simulation R&D



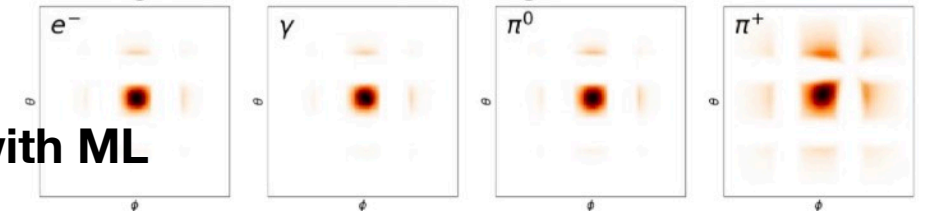
Longitudinal shower profile reconstruction



Average scintillation channel image



Average Cerenkov channel image



Particle IDs with ML

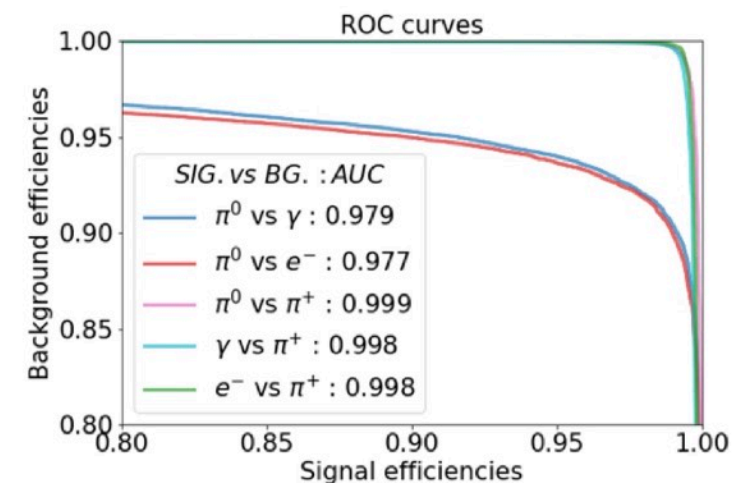
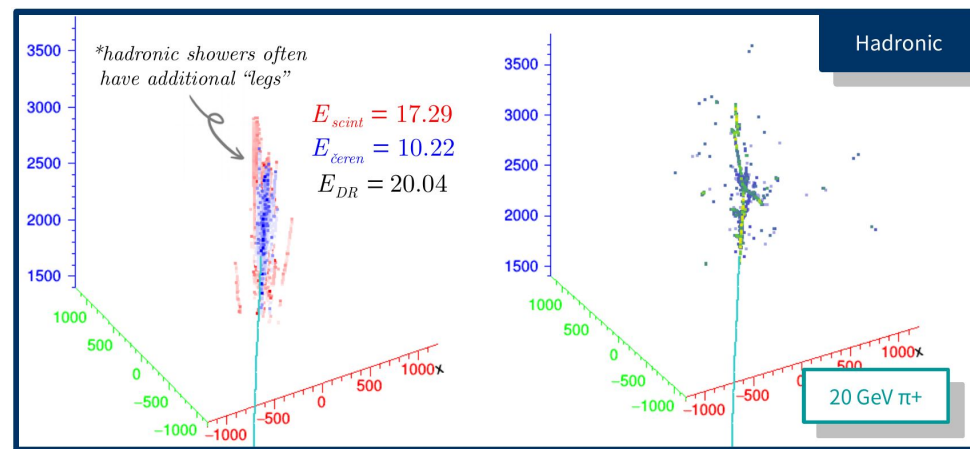
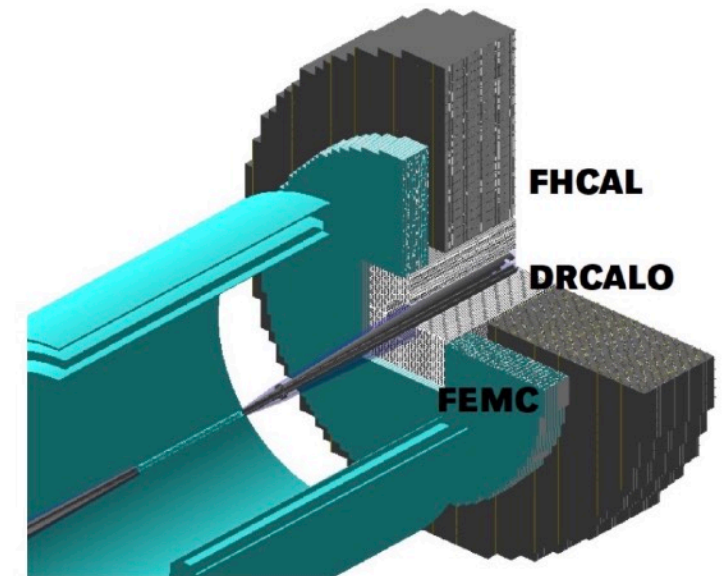


Image Classification 10-100 GeV AUC

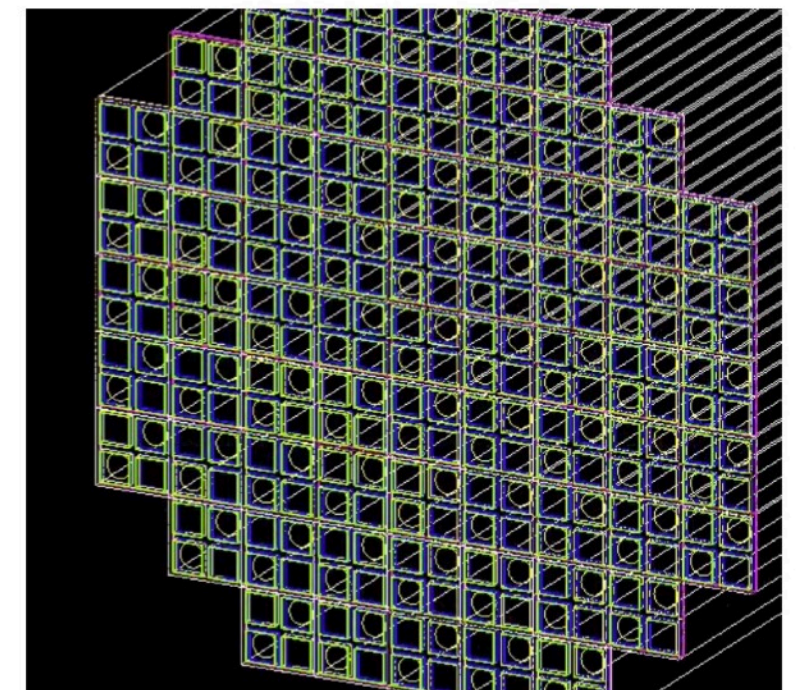
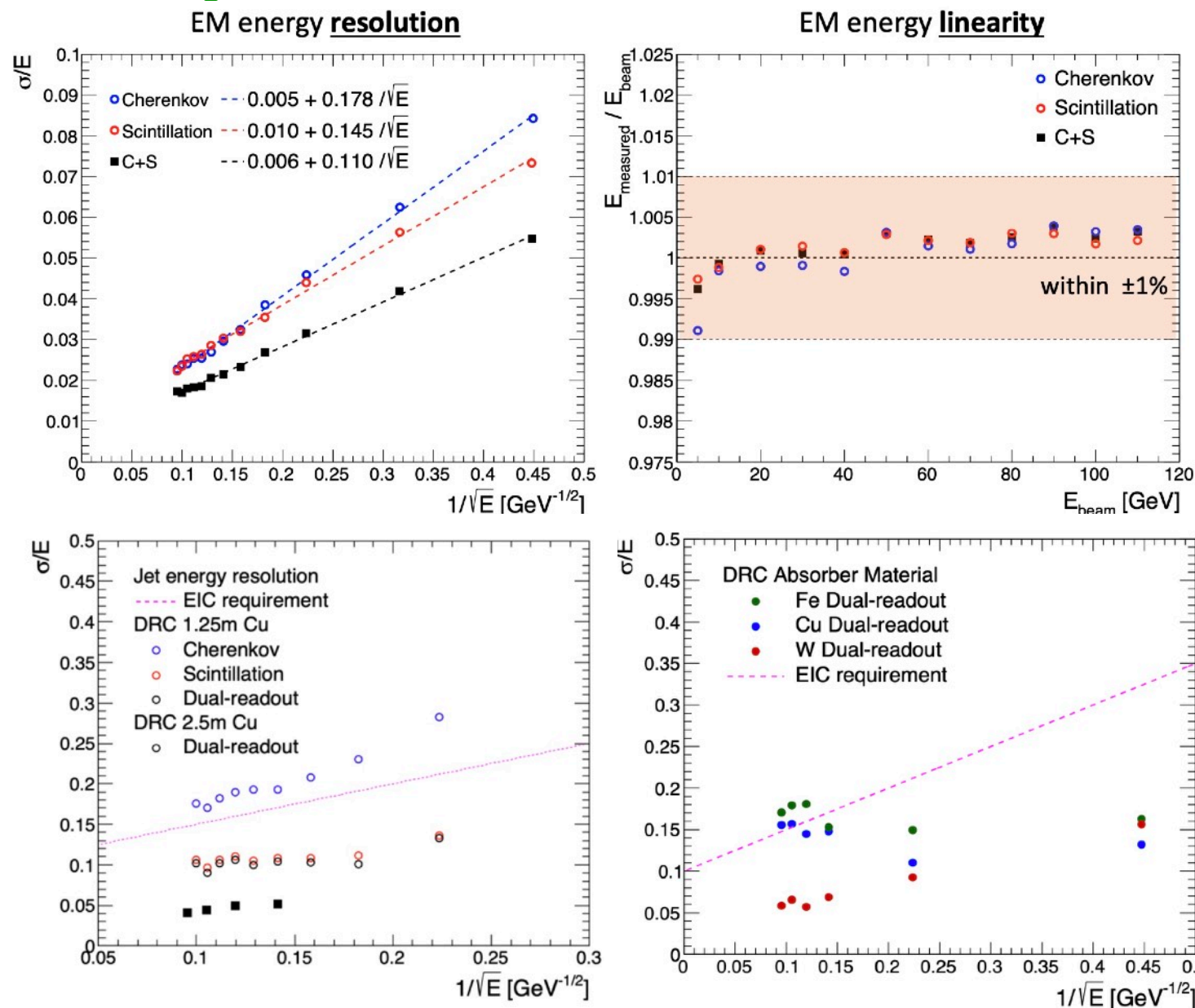
	γ	e^-	π^0	π^+	K_L^0	K^+	n	p
p	0.999	0.999	0.999	0.663	0.683	0.611	0.608	
n	0.999	0.999	0.999	0.694	0.624	0.649		0.608
K^+	0.999	0.999	0.999	0.553	0.616		0.649	0.611
K_L^0	0.999	0.999	0.999	0.630		0.616	0.624	0.683
π^+	0.998	0.998	0.999		0.630	0.553	0.694	0.663
π^0	0.979	0.978		0.999	0.999	0.999	0.999	0.999
e^-	0.610		0.978	0.998	0.999	0.999	0.999	0.999
γ		0.610	0.979	0.998	0.999	0.999	0.999	0.999

Simulation Study for EIC

- Initial design and feasibility study for ECCE
 - DRC pre-design is implemented in Fun4All framework
 - Various absorbers (Cu, W, Fe) tested with shorter length design



GEANT4 display with inlay DRC in EIC-ECCE



End of towers in EIC framework

Summary

- Dual-Readout Calorimeter R&D project for future e^+e^- collider in Korea is very active
- Two modules have been built and tested at CERN recently
- Toward TDR of FCC-ee and CEPC, full-size prototype detector is building
- Test-beam experiments are planned annually
- Experience and expertise from the DRC R&D project will be quite helpful for barrel ECAL detector building

