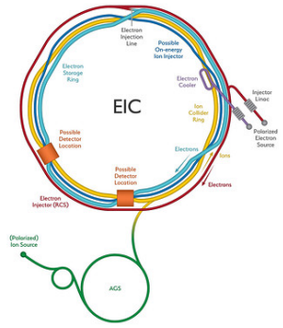


Dual-Readout Calorimeter R&D in Korea

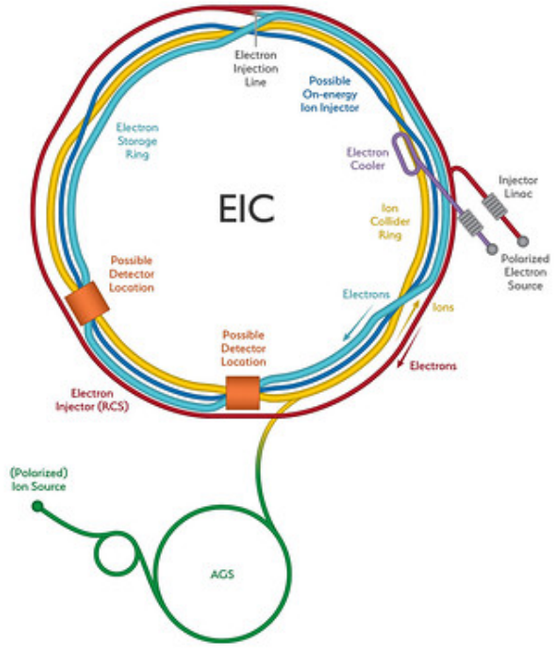
Hwidong Yoo (Yonsei Univ.)

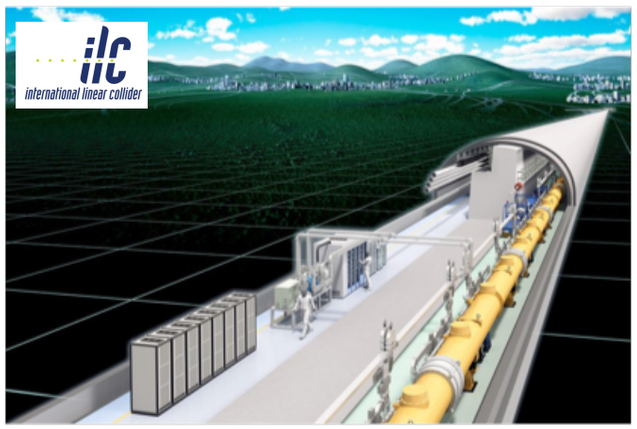
On behalf of the Korea
Dual-Readout Calorimeter R&D team

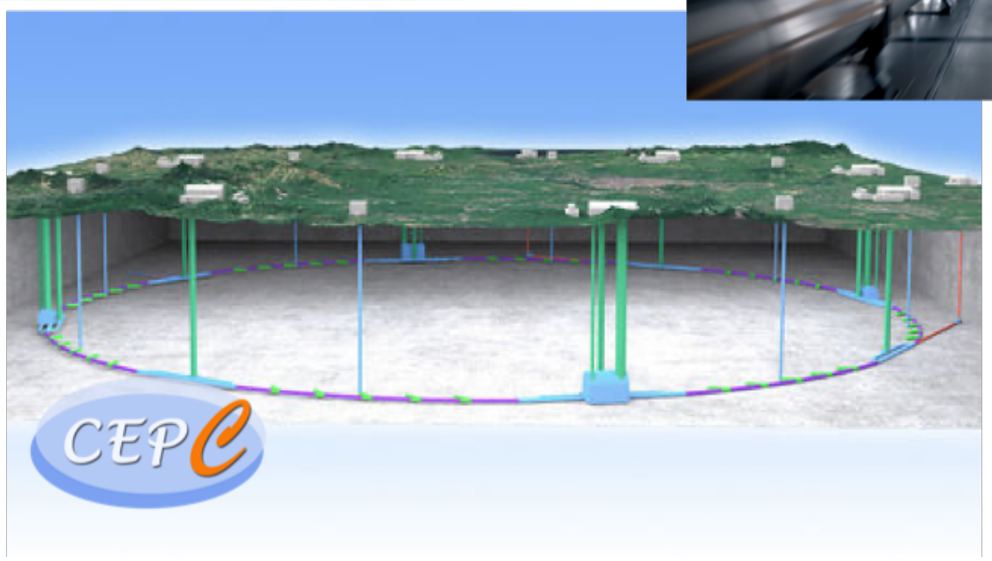
APCTP EIC workshop,
November 3, 2022

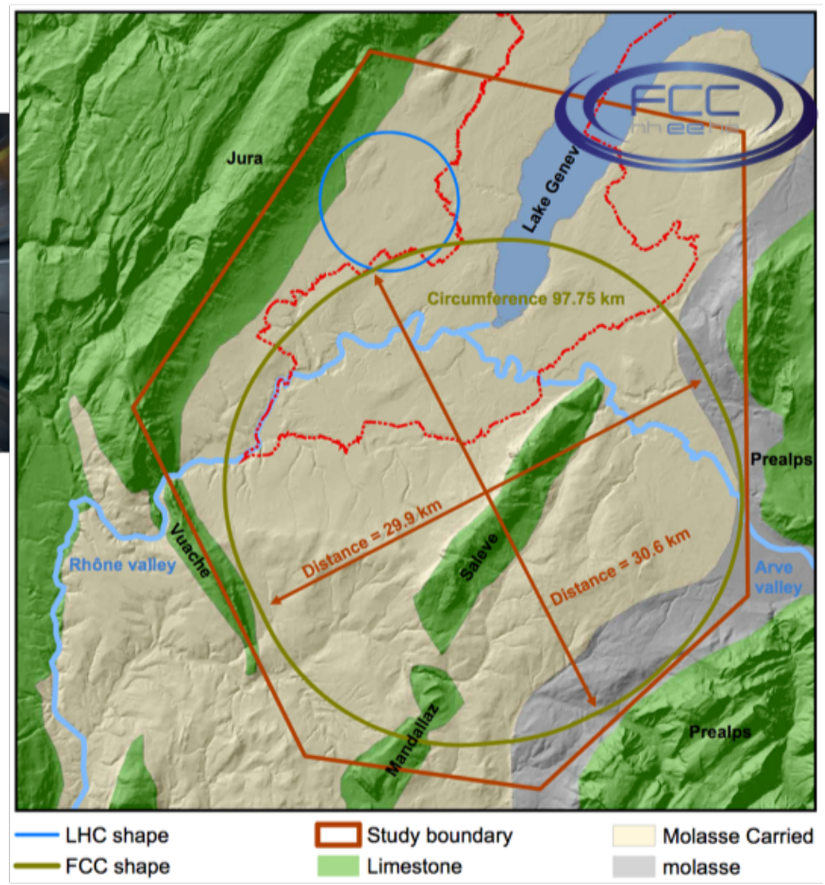
Future Collider Projects in HEP

- Many next generation experiments are under discussion
  - Linear colliders: ILC (Japan), CLIC (CERN)
  - Circular colliders: FCC-ee/eh/hh, muon collider (CERN), CEPC/SPPC (China)
  - HI colliders: EIC (US)



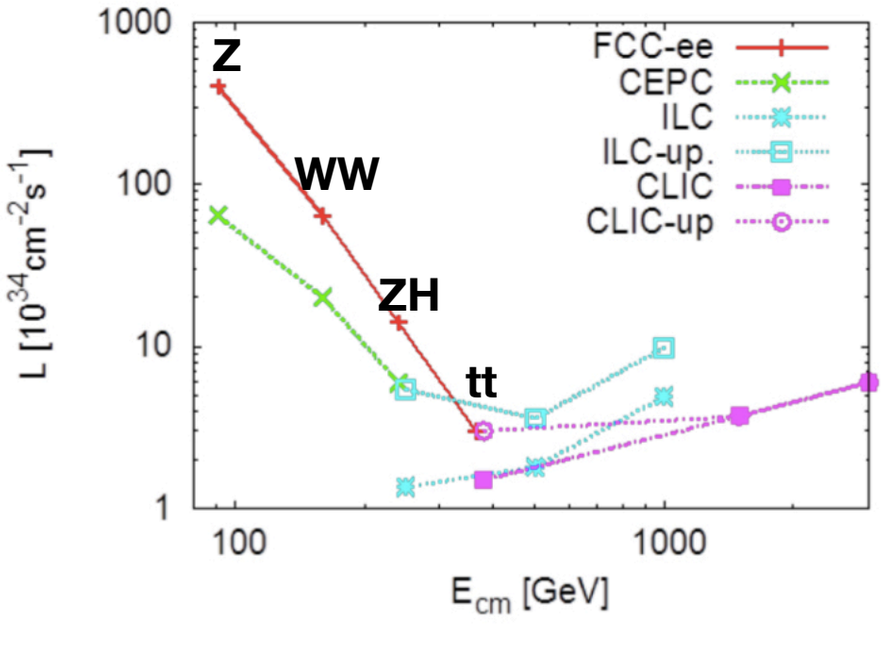


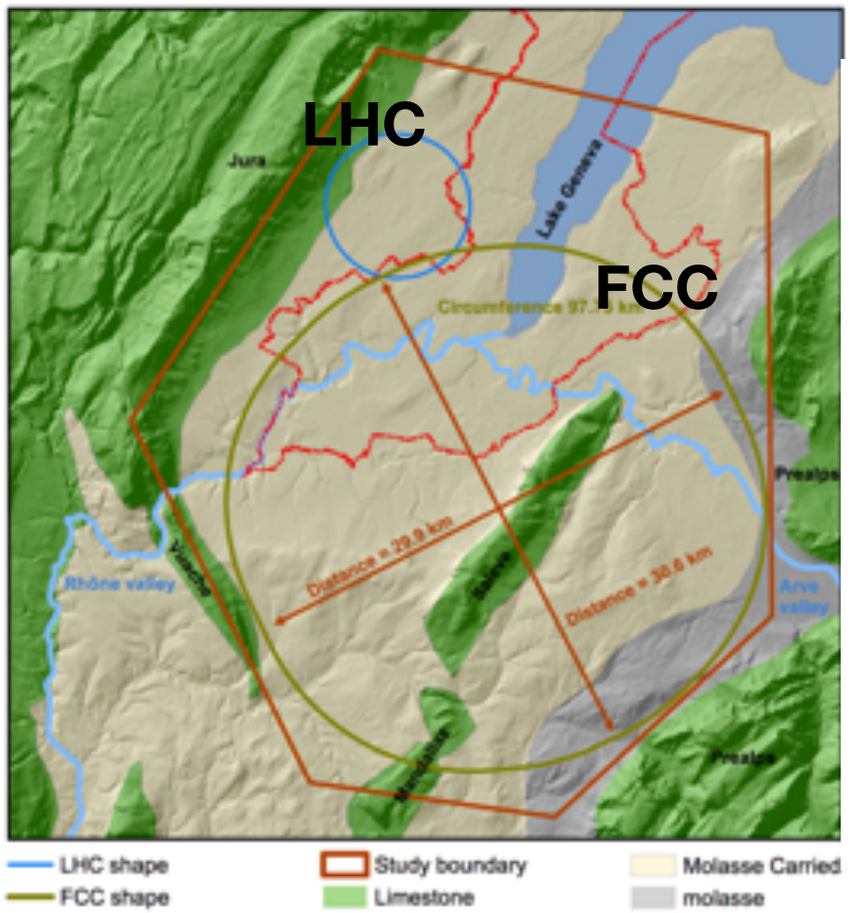


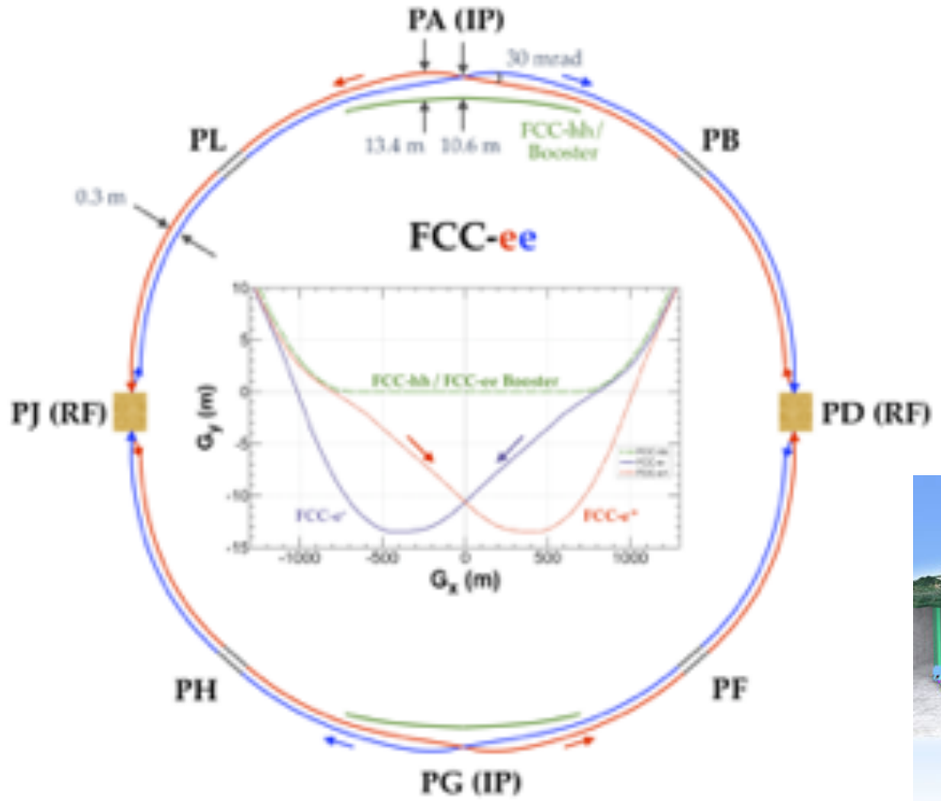


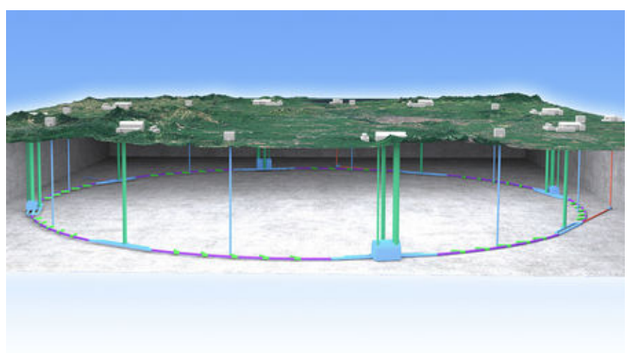
CEPC, FCC-ee Projects

- Programs in two phases
  - Phase 1: FCC-ee (Z, W, H, tt) as Higgs, EW and top factory
  - Phase 2: FCC-hh (~100 TeV) as natural continuation at energy frontier (ion and eh options)



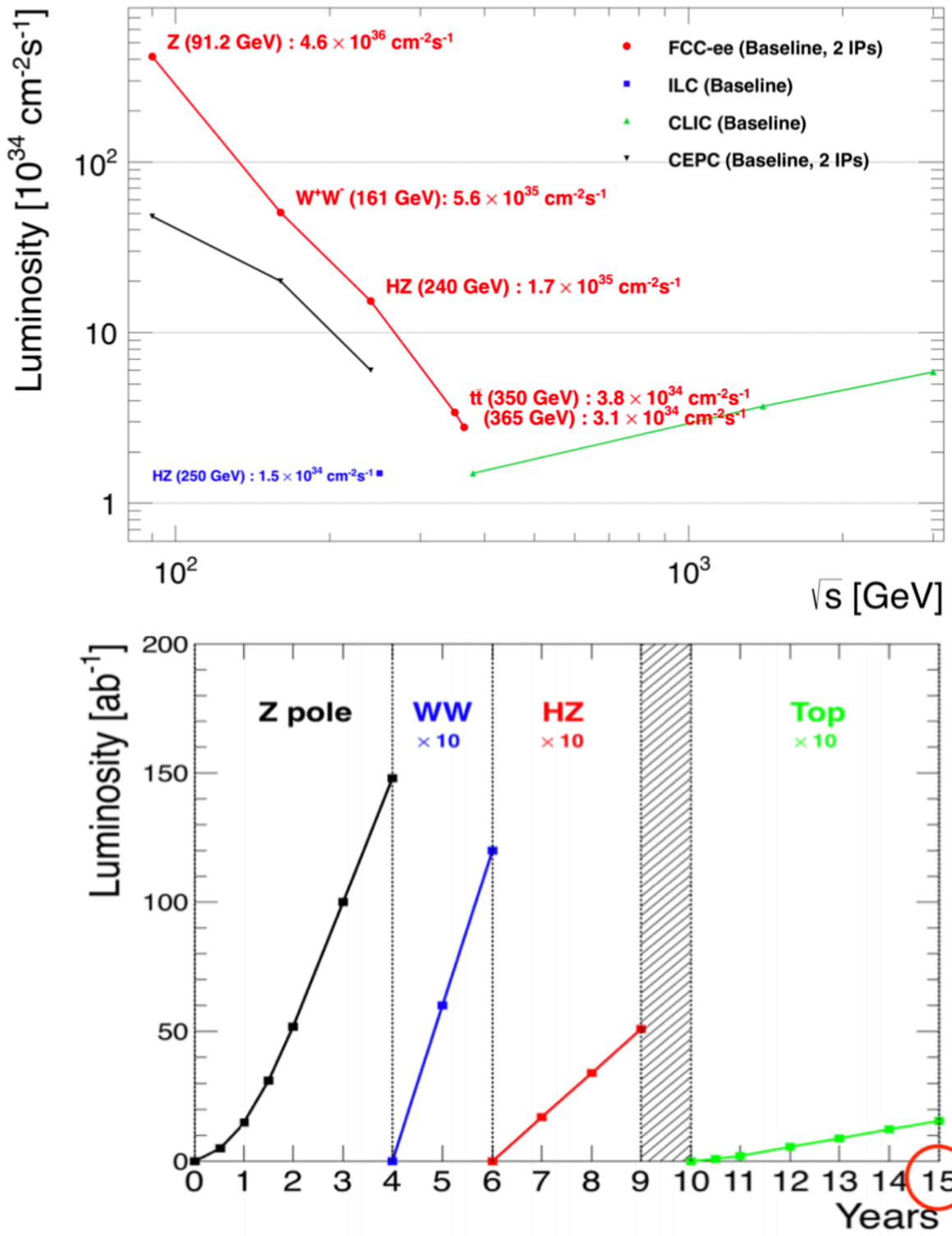






Physics of Future e^+e^- Colliders

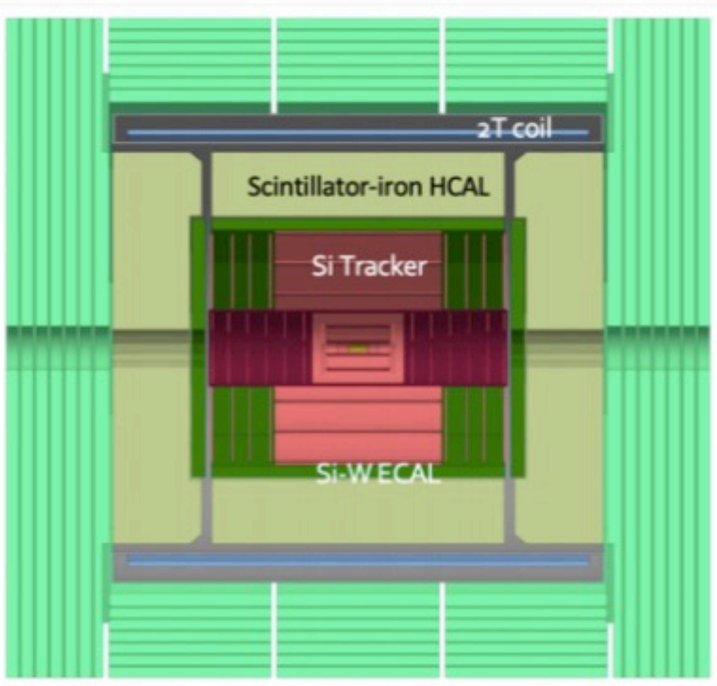
- Precision measurements!
  => Higgs factory!
  - Higgs factory (HZ): 10^6
  - EW & Top factory
    - $5x10^{12}$ (Z), 10^8 (WW), 10^6 (tt)
  - Flavour factory
    - $5x10^{12}$ (Z->bb, cc, $\tau\tau$)
  - QED, QCD, BSM, etc.



FCC-ee Detector Concept

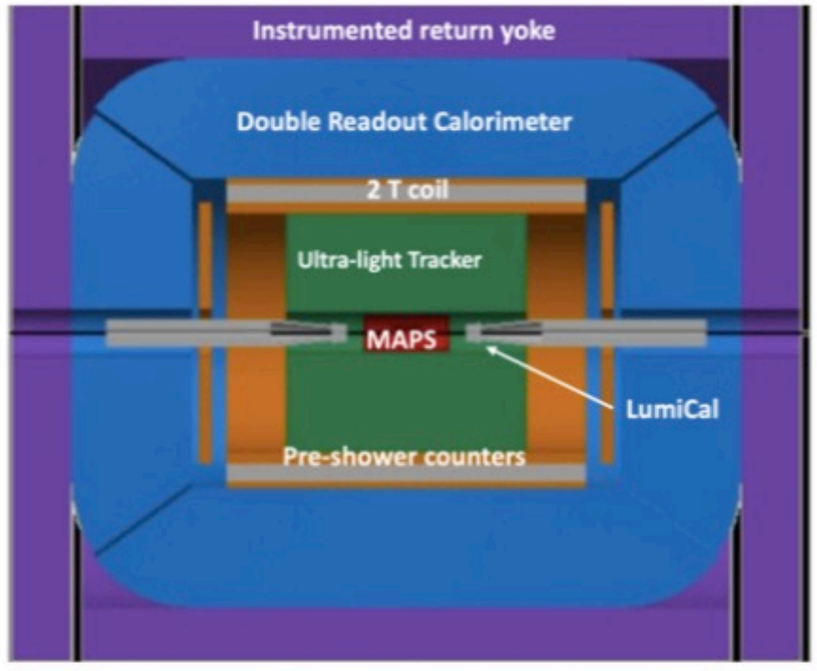
- Korean team led the design of the Dual-Readout Calorimeter (DRC) for IDEA detector

  - Included in the CDRs of both FCC-ee and CEPC, published at the end of 2018



CLD

- Consolidated option based on the detector design developed for CLIC
  - All silicon vertex detector and tracker
  - 3D-imaging highly-granular calorimeter system
  - Coil outside calorimeter system
- Proven concept, understood performance



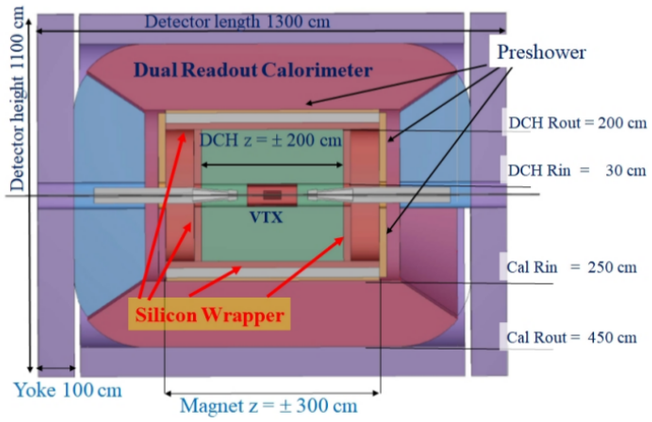
IDEA

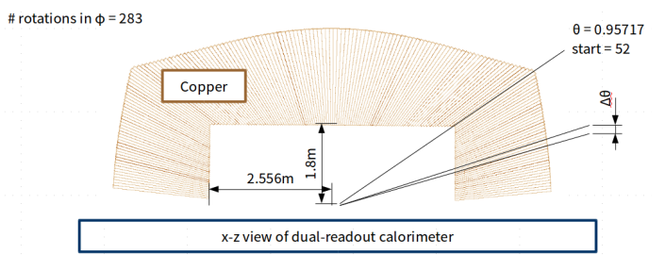
- New, innovative, possibly more cost-effective design
  - Silicon vertex detector
  - Short-drift, ultra-light wire chamber
  - Dual-readout calorimeter
  - Thin and light solenoid coil inside calorimeter system

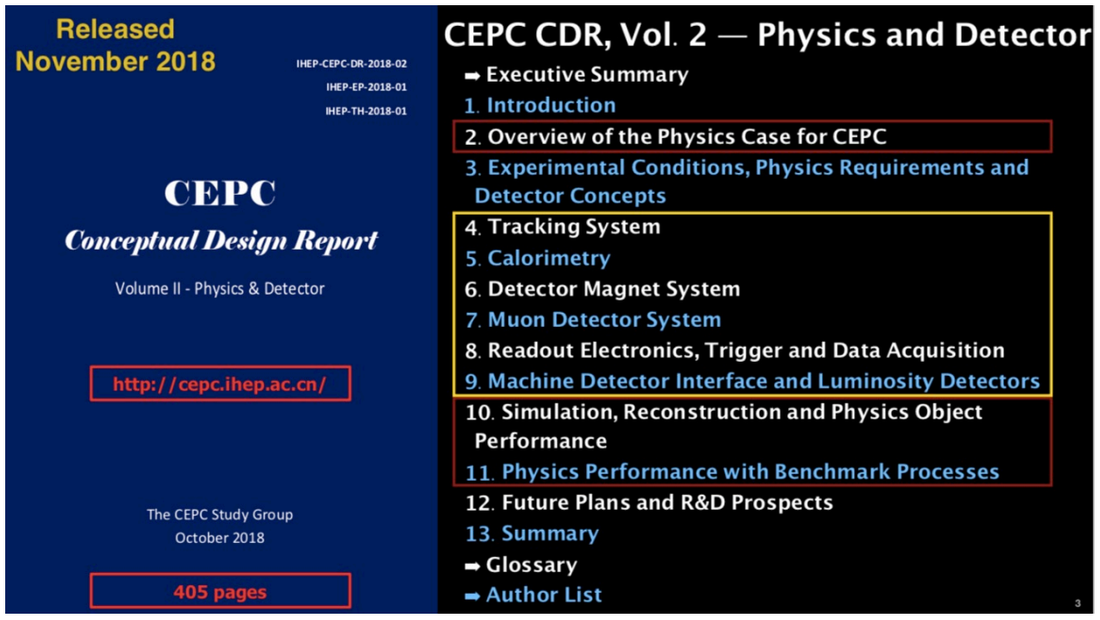
Almost same detector concept for CEPC

Contribution in Korea

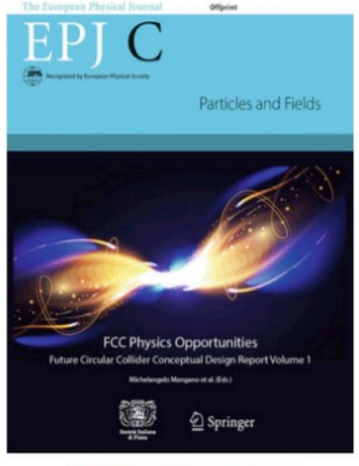
- Dual-readout calorimeter R&D team has contributed major role for CDRs of both CEPC and FCC projects (published in 2018)
  - Prof. Sehwook Lee (KNU), Prof. Jason Lee (UoS), Prof. Hwidong Yoo (Yonsei U.)





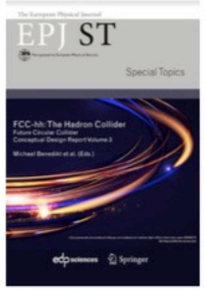


4 CDR volumes submitted to EPJ in December 2018.



FCC Physics Opportunities

FCC-ee: The Lepton Collider

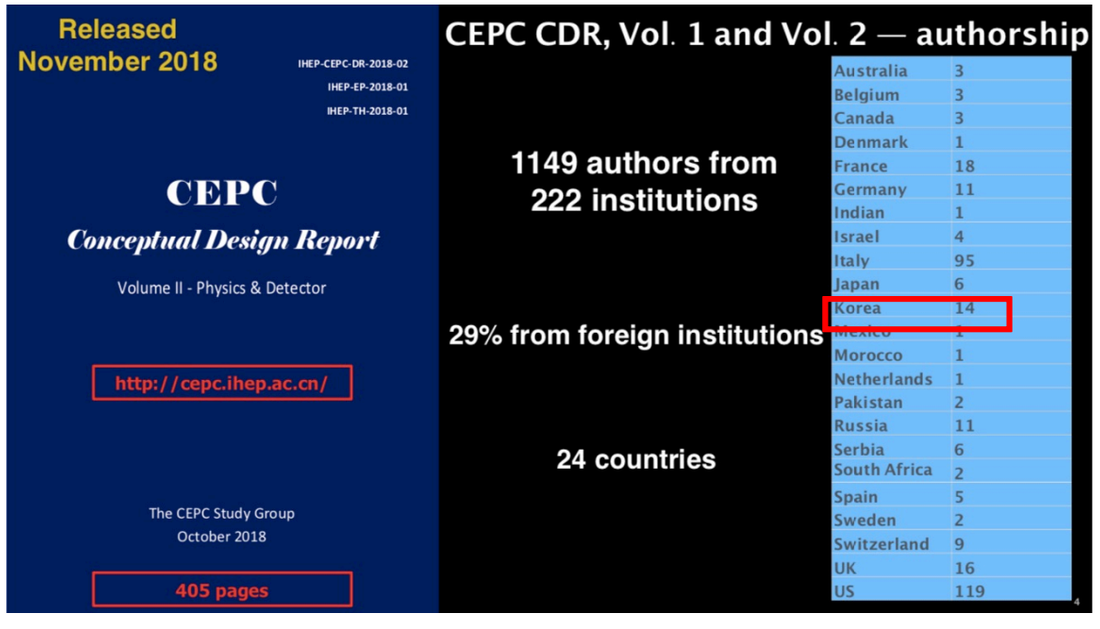


FCC-hh: The Hadron Collider

HE-LHC: The High Energy Large Hadron Collider

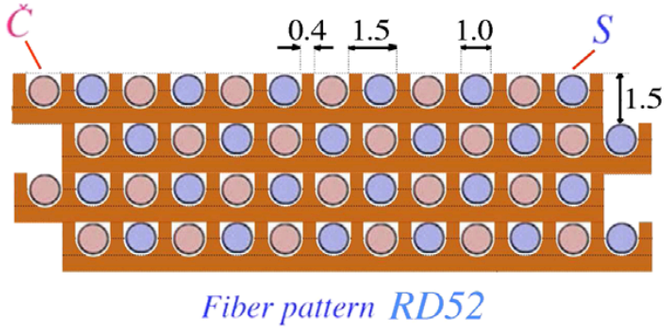
Copies can be requested at
http://get-fcc-cdr.web.cern.ch

5



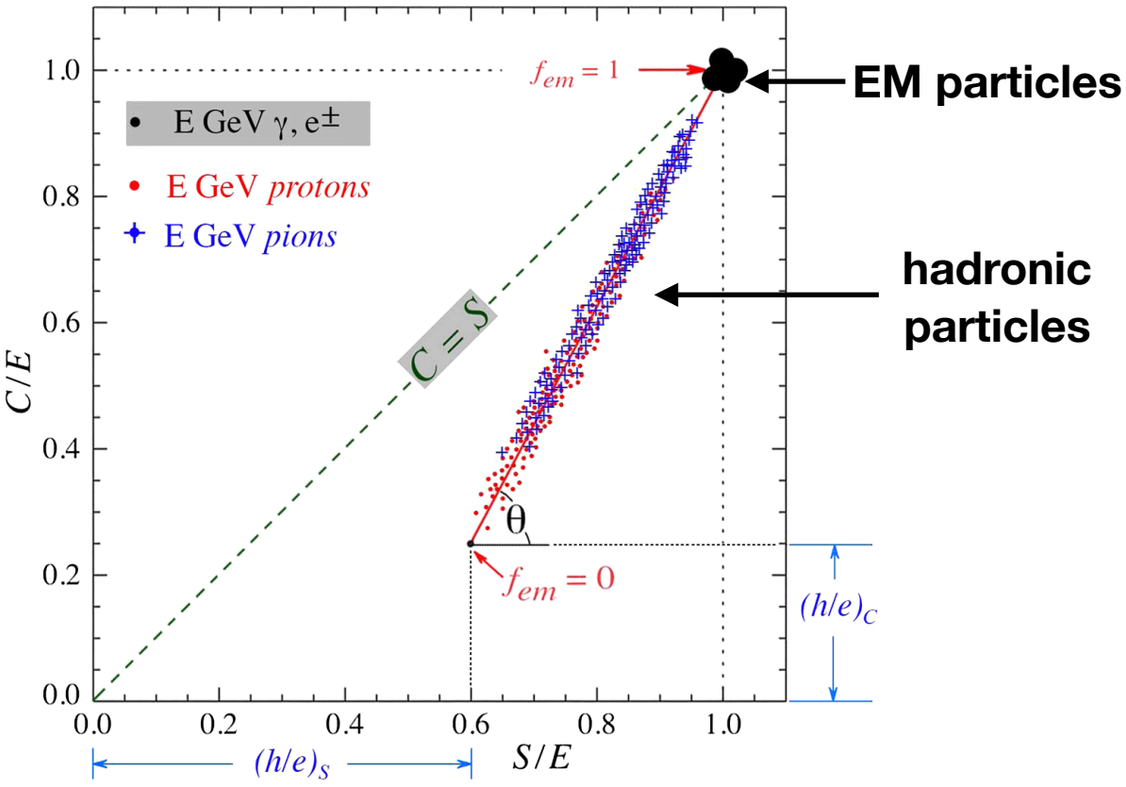
Dual-Readout Calorimeter (DRC)

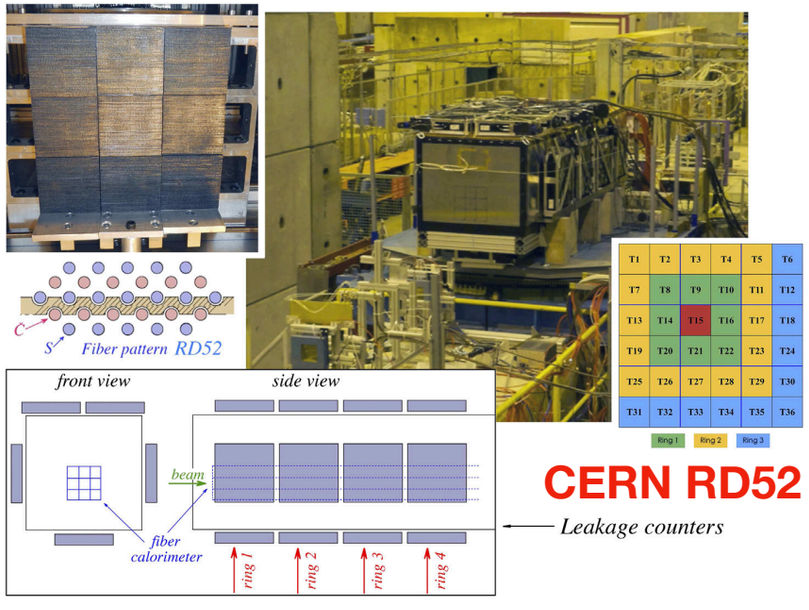
- DRC offers high-quality energy measurement for both EM particles and hadrons
  - DRC consists of two different optical fibers (S, C) in a single component
  - The main culprit of poor hadronic energy resolution is fluctuations of the EM shower components of hadron showers (f_{em})
  - f_{em} can be 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



Fiber pattern RD52

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



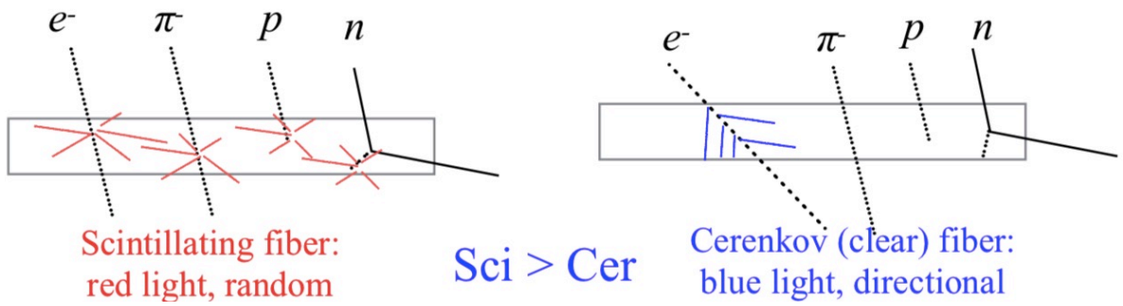


$$E = \frac{S - \chi C}{1 - \chi}.$$

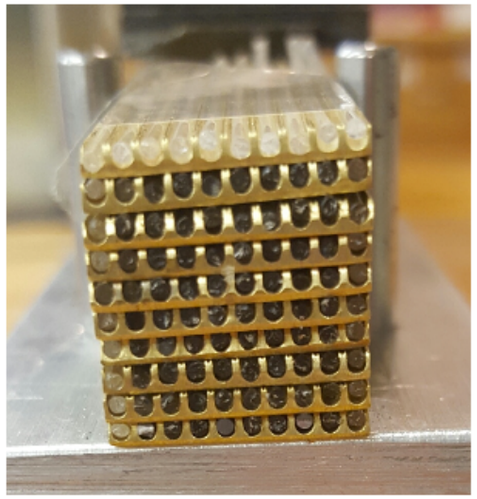
$$\cot\theta = \frac{1 - (h/e)_S}{1 - (h/e)_C} = \chi,$$

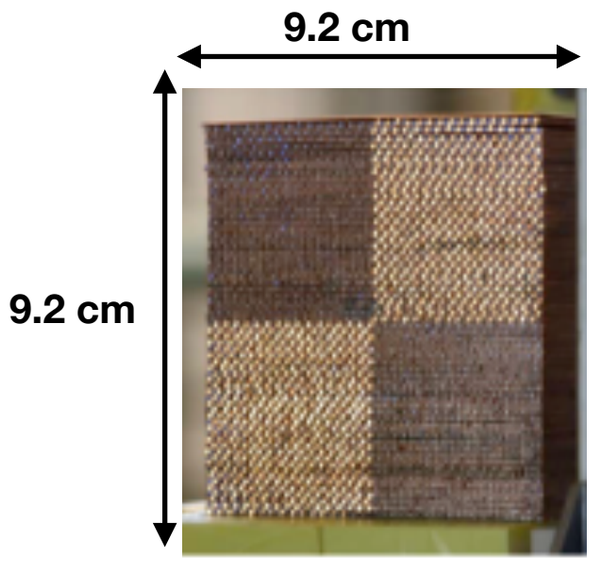
CERN RD52 experiment

Signal generation: Scintillating & Cerenkov fibers

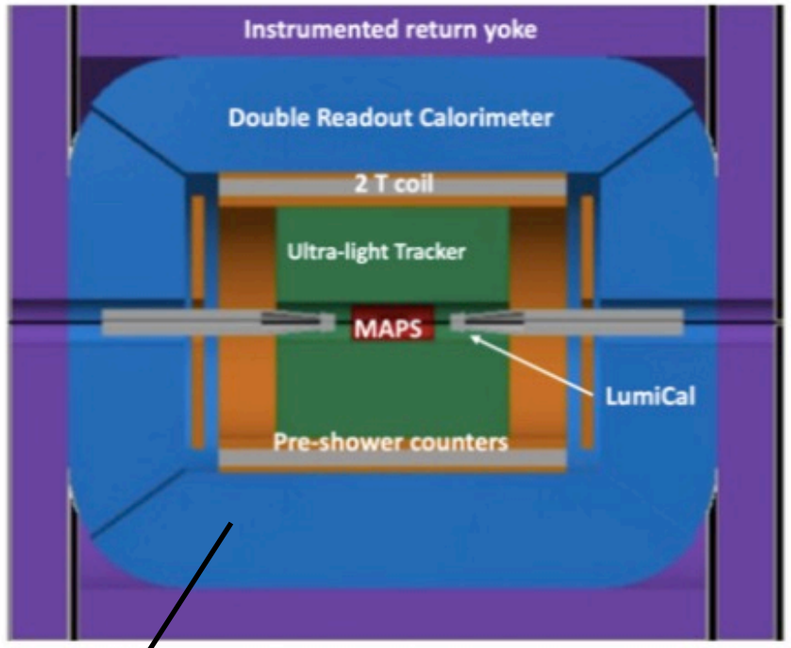


DRC Geometry and Module

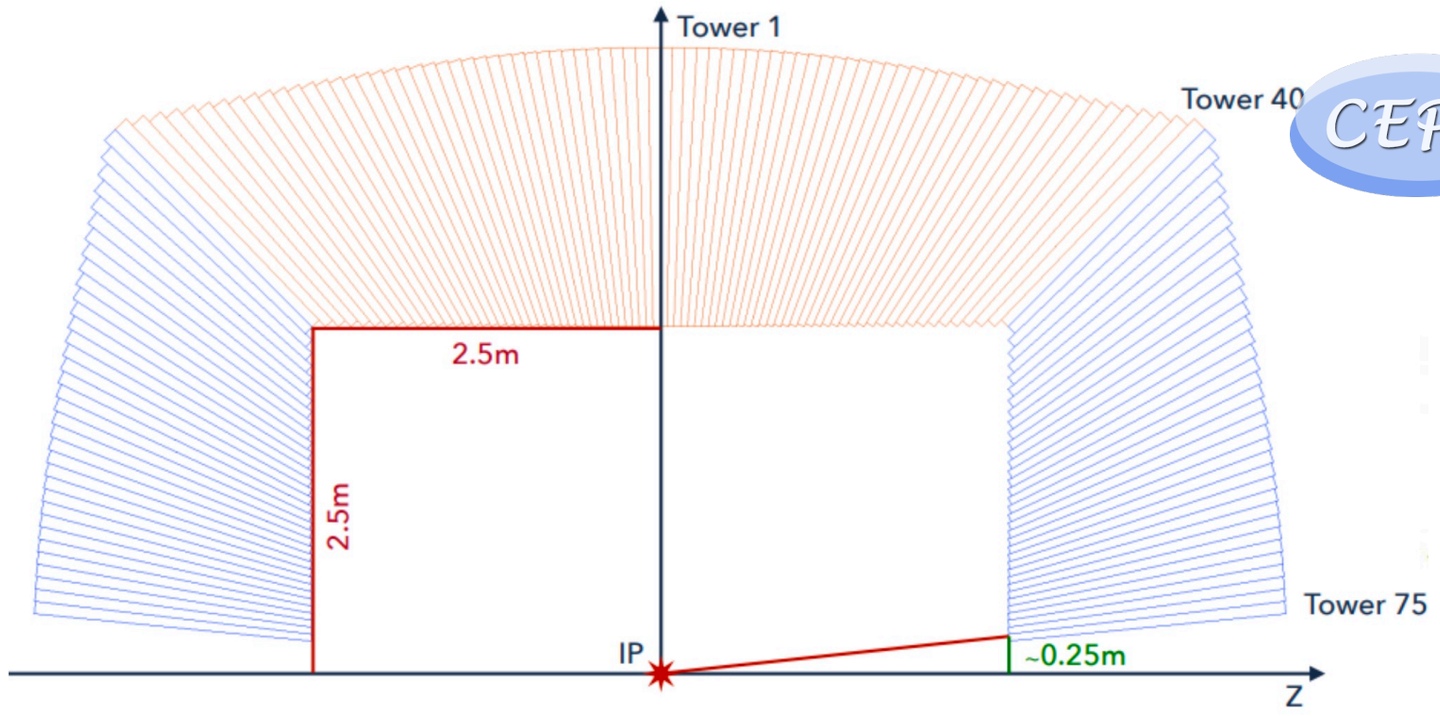




Size of unit module



IDEA



DRC International Collaboration

Prof. Hyonsuk Jo (KNU)
Prof. Yongsun Kim (Sejong U.)
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)

Prof. Rong-Shyang Lu

Prof. Chia Ming Kuo

Taiwan

Korea

Japan

Prof. Yuji Enari

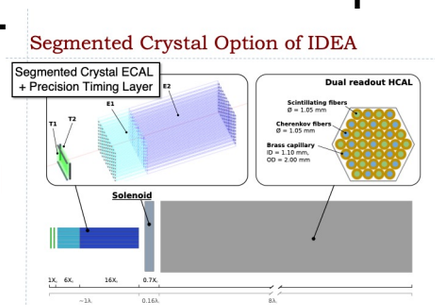
USA

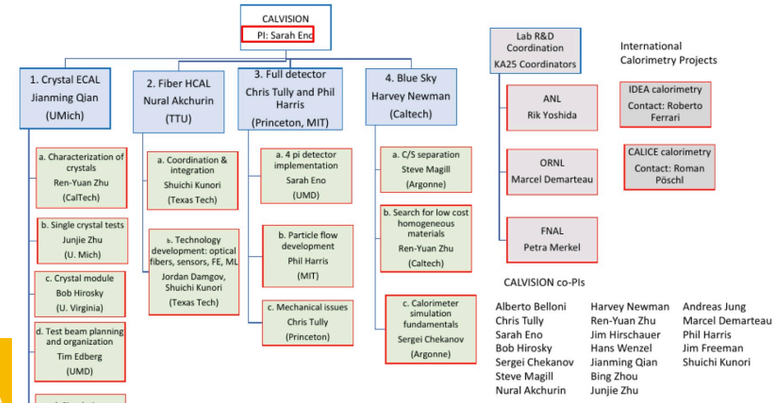
Europe

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

Prof. Iacopo Vivarelli

DRC with crystal





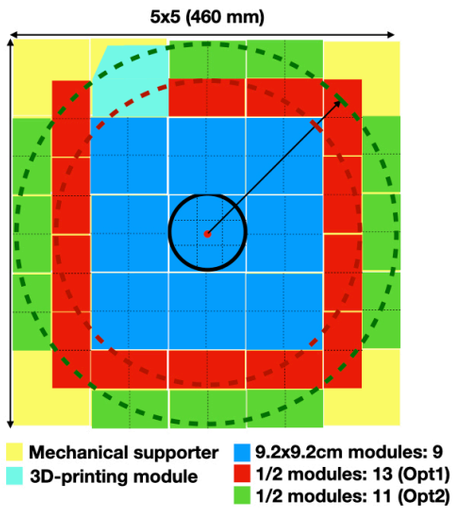
A very high-level overview of planned activities follows

Prof. Sarah Eno

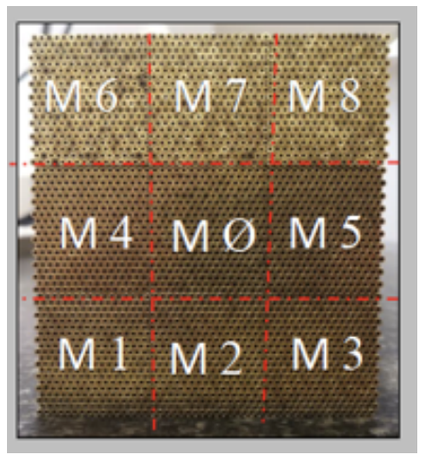
Prof. Richard Wigmans

Prof. John Hauptman

Full-size prototype detector

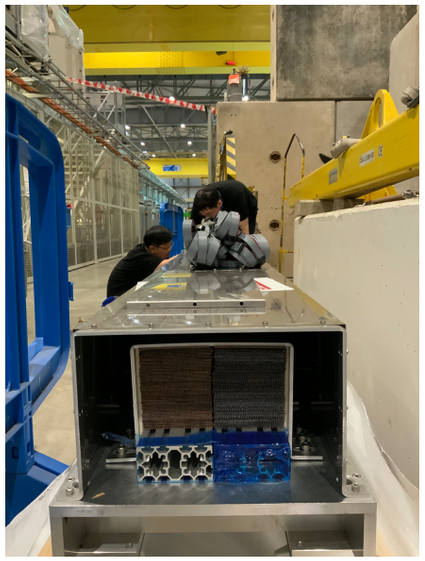


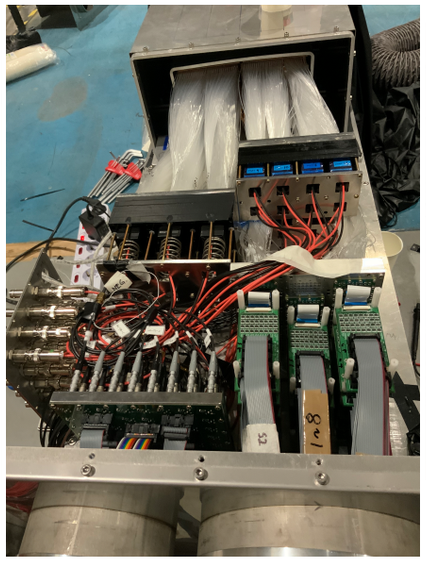
Bucatini prototype

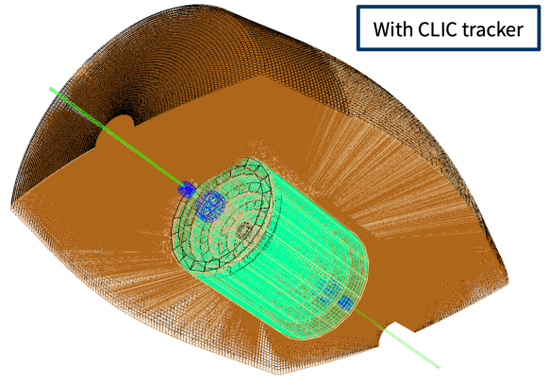


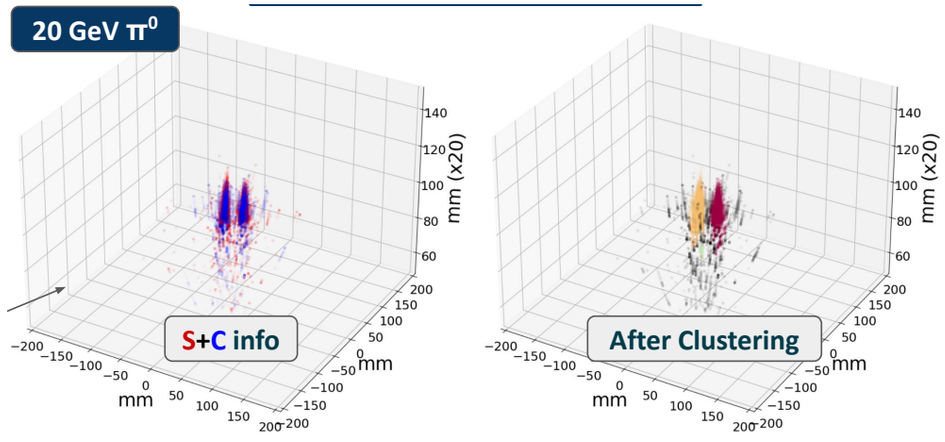
Status of DRC R&D in Korea

- 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







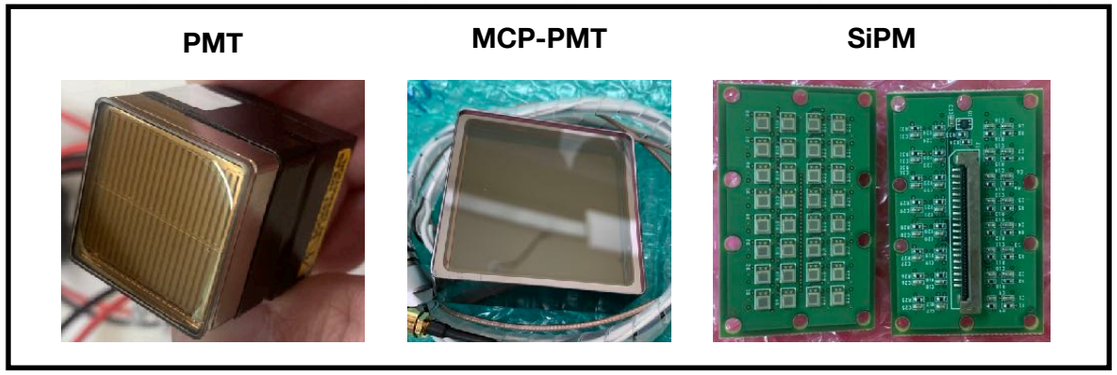


Test-beam (TB) 2022 Preparation

- **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

- **Location : CERN North area (H8)**
- **R&D Goal**
  - Readout system test (MCP-PMT & SiPM)
  - Study of various type of optical fibers (scintillation)



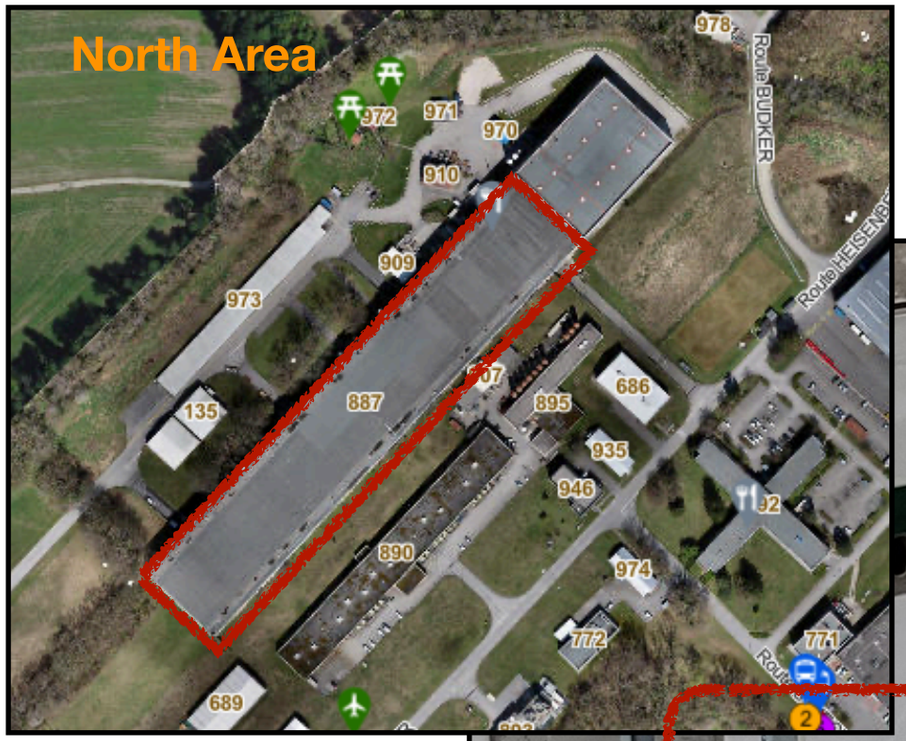
- **Training Goal**
  - Training next generation experts for DRC HW

- **Schedule of test beam preparation**

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

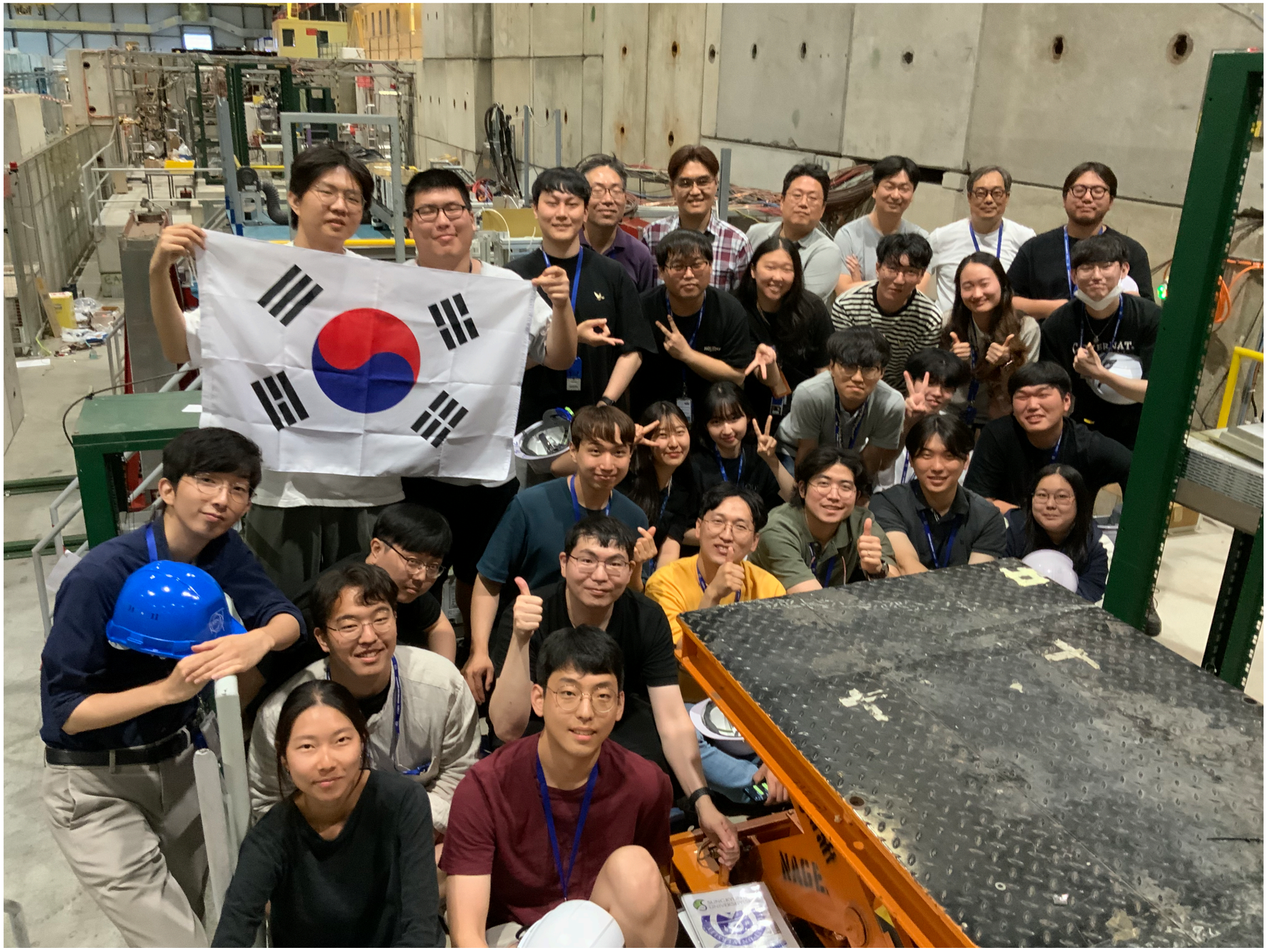


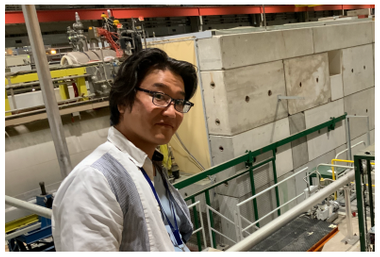
Modules

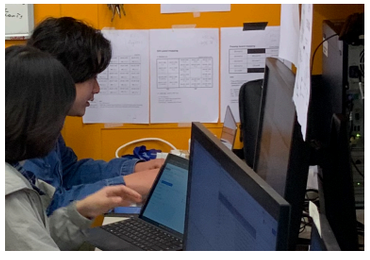
Auxiliary detectors

TB 2022: Participants

- 13 institutes 34 participants (including 23 students)



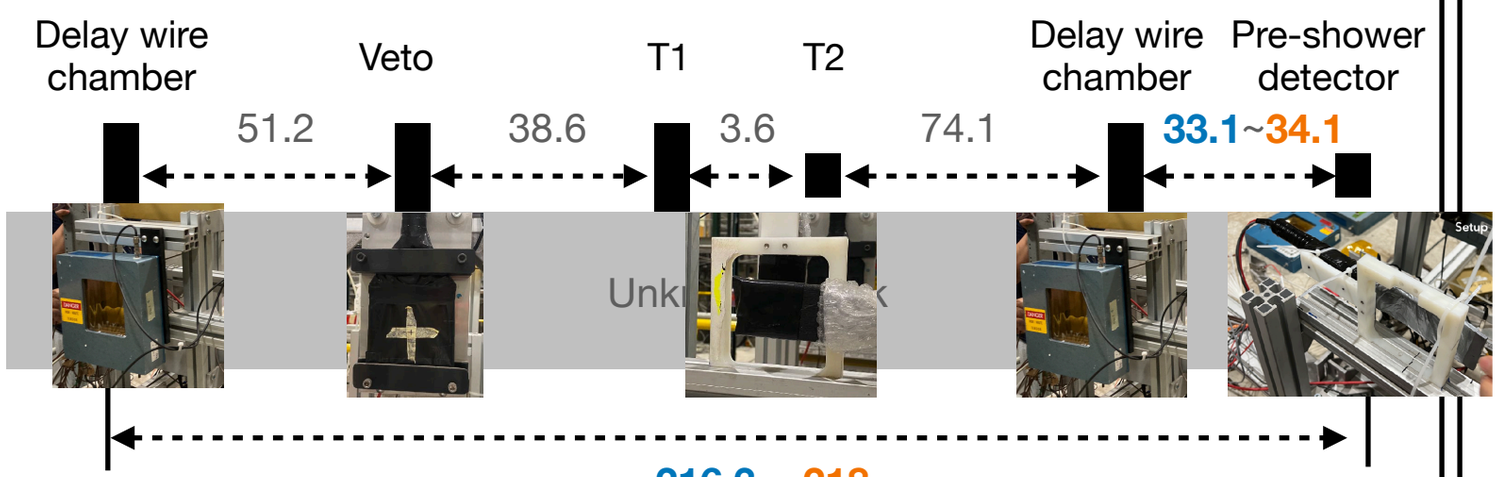




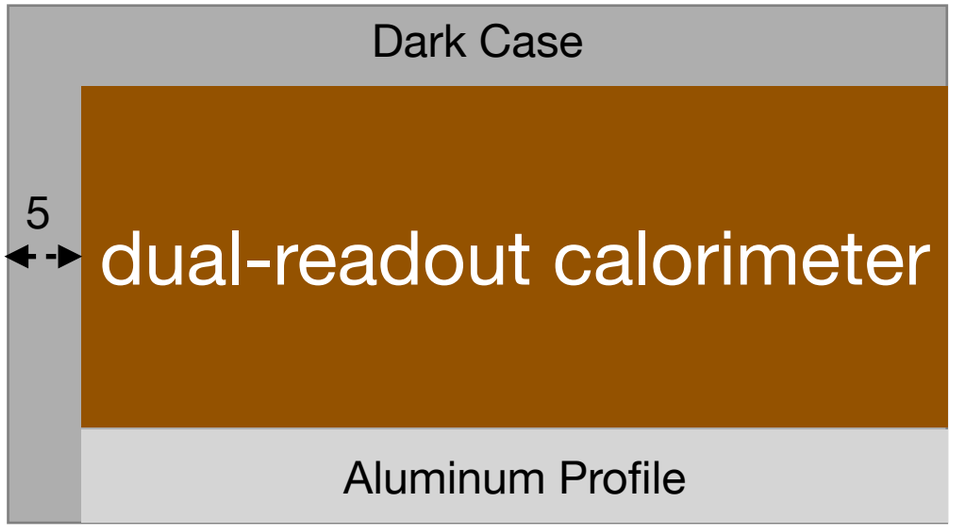
TB 2022: Apparatus Setup

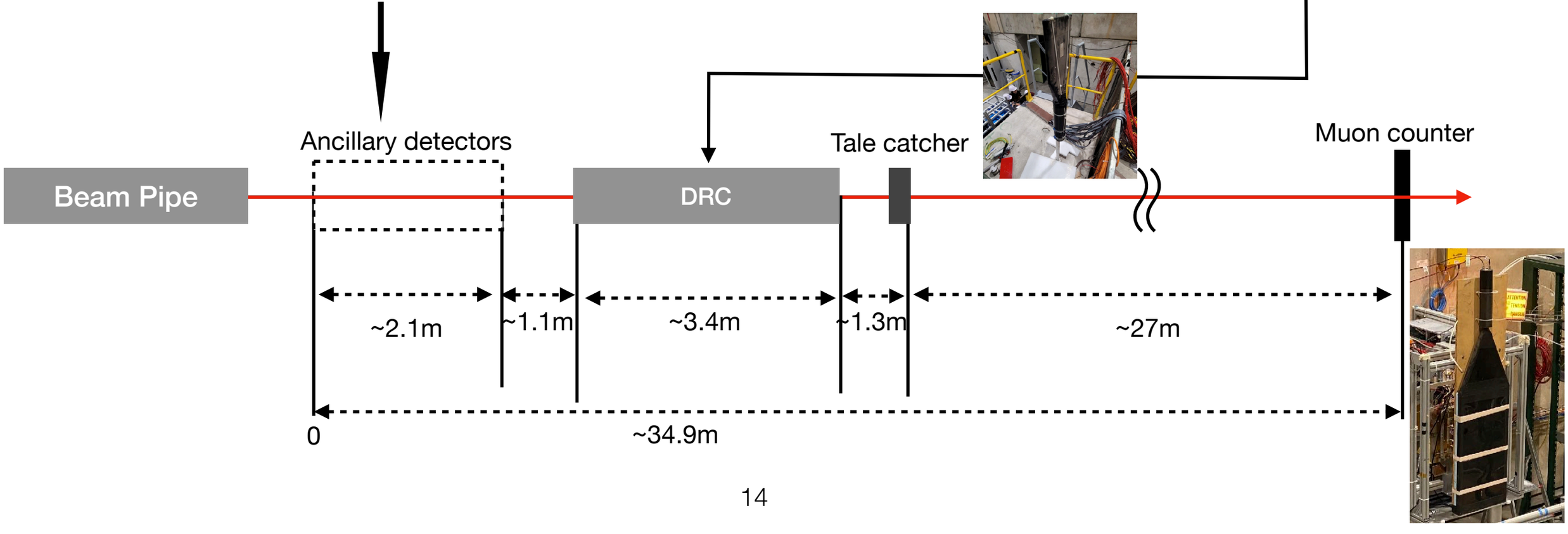
Ancillary detectors

Unit: cm



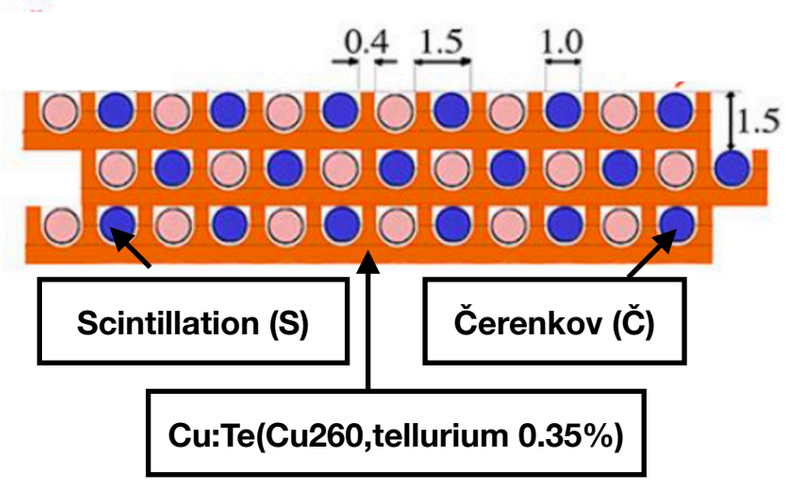
Unit: cm





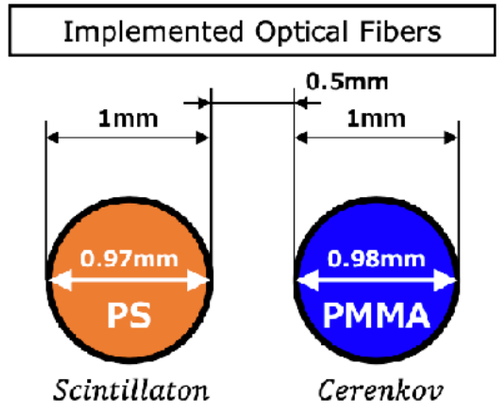
TB 2022: Module Building

- **Copper Plate & Fibers**



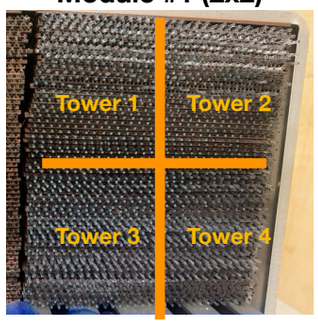
- Copper plate (60)
- Width : 10 cm
- Length : 2.5 m
- Thickness : ~1.6 mm
- Hole : 1 mm (diameter)
- Distance between hole : ~ 0.63 mm

- Optical fibers
- Scintillation fibers & Cerenkov fibers

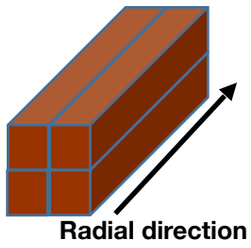


- **Configuration of Fibers & Readout detector for Test Beam**

Module #1 (2x2)



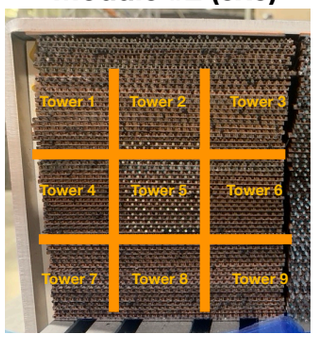
Module#1



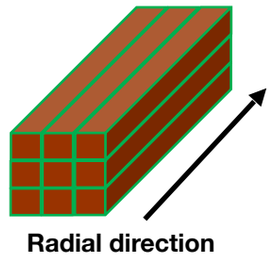
Module#1

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

Module #2 (3x3)



Module#2



Module#2

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

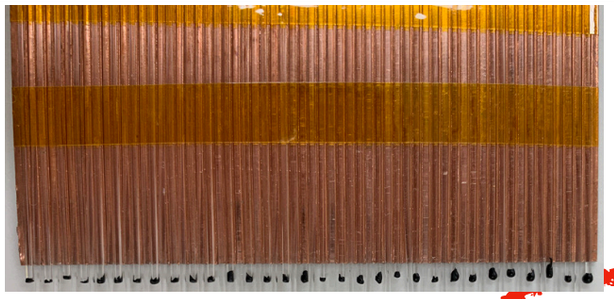
Combination of fibers for Module#1

	Tower #1	Tower #2	Tower #3	Tower #4
Scintillation fibers	Round / Single cladding	Round / Double cladding	Round / Single cladding	Square / Single cladding
Cherenkov 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

Combination of fibers for Module#2

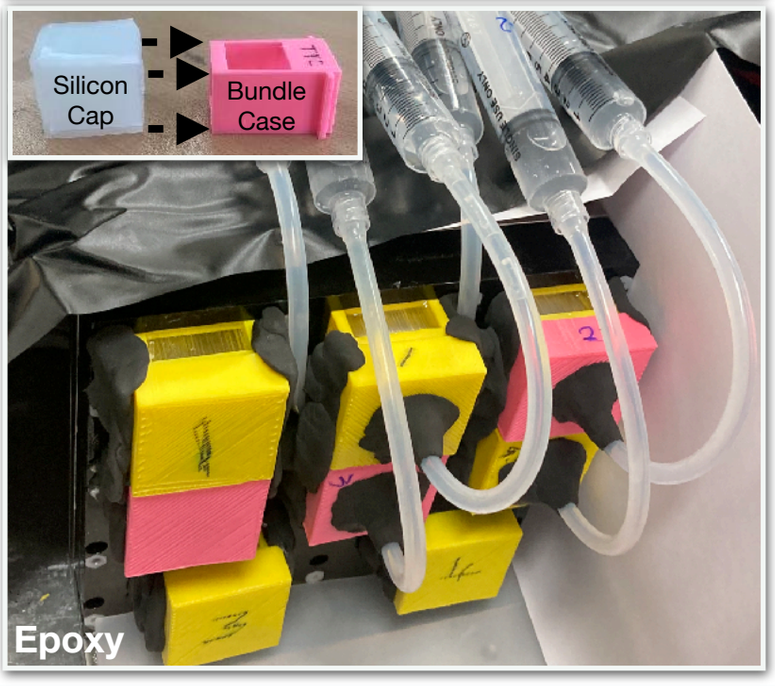
	Tower #1~4 and #6~9	Tower #5
Scintillation fibers	Round / Single cladding	Round / Single cladding
Cherenkov fibers	Round / Single cladding	Round / Single cladding
Readout detector (400+16 ch)	16 PMTs	400 SiPMs

TB 2022: Module Building

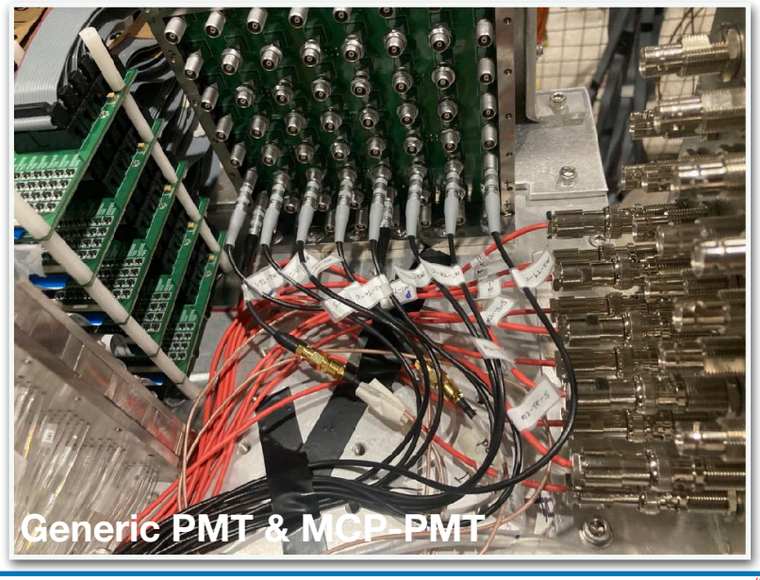


Assembly

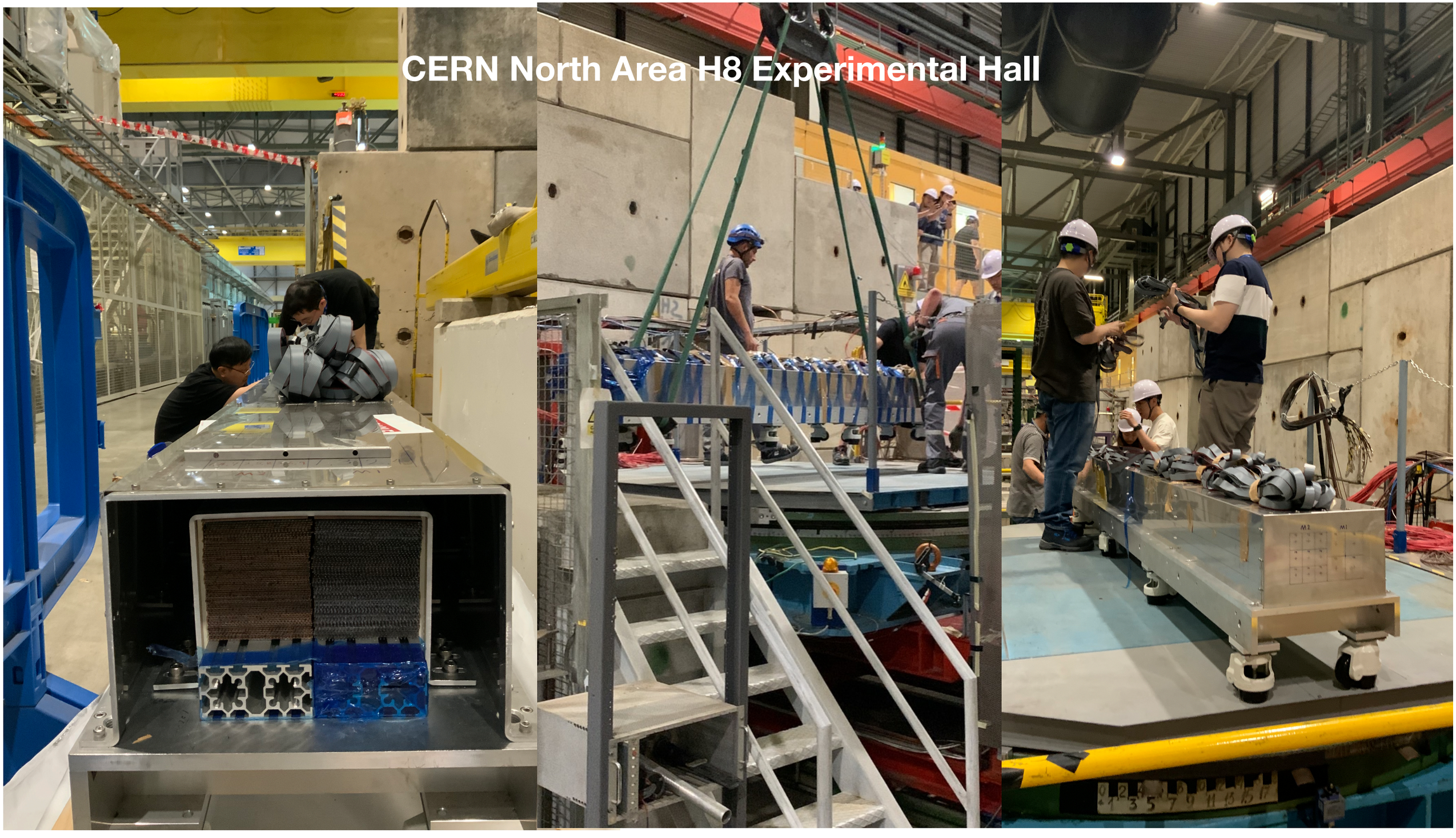
Bundling & Epoxy



PMT Installation & Reflector

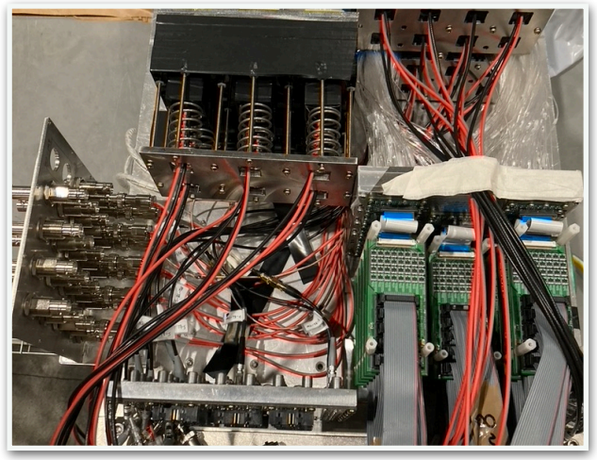


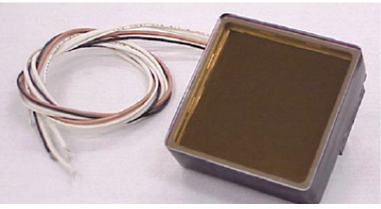
TB 2022: Installation



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 Efficinecy (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

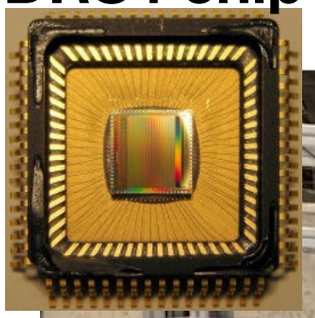
- **DAQ System**
  - 15 DAQ Board + 1 TCB Board

  - 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

DRS4 chip



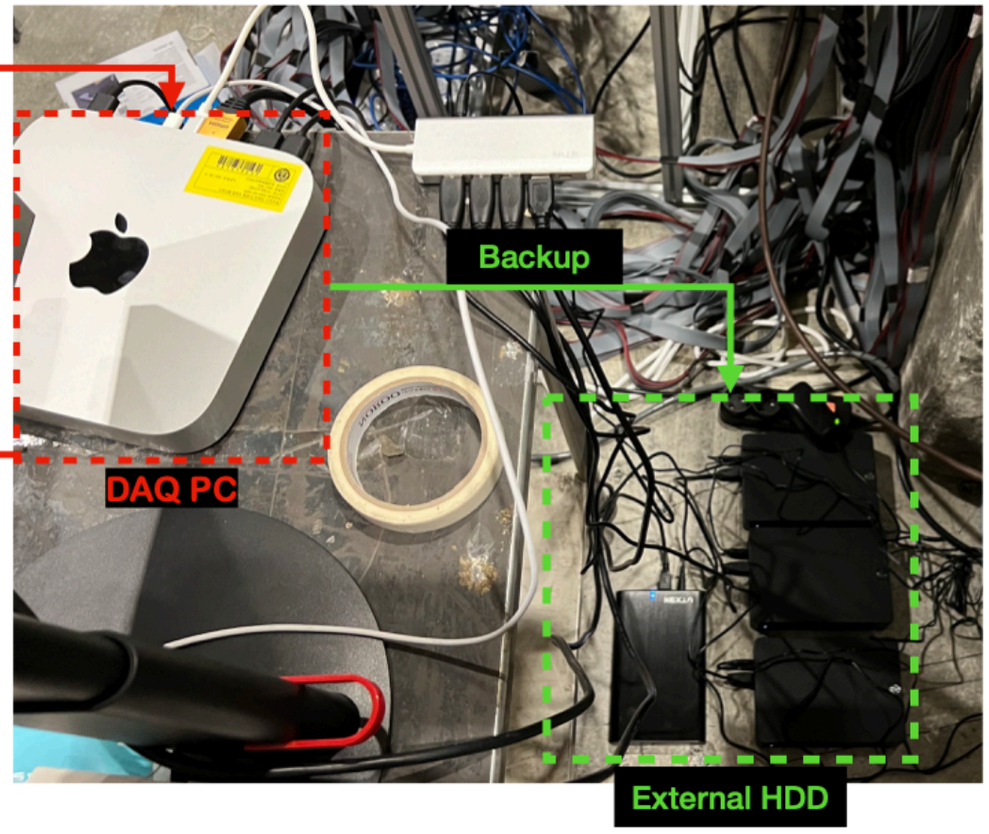
	PMT	MCP-PMT	Auxilary detector	SiPM
channels	22	4	11	400
DAQ	2			13

TB 2022: Storage System

Beam → Aux. & DRC detectors → Signal

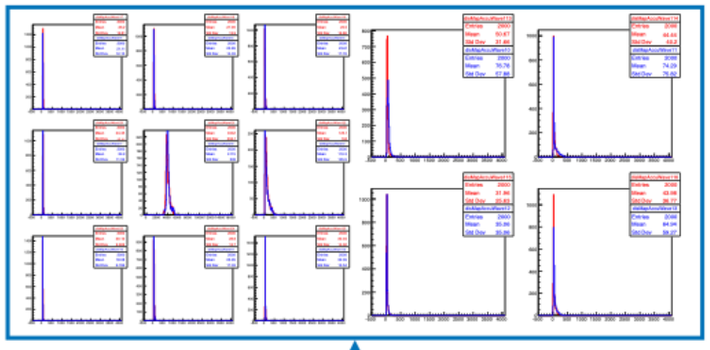
DAQ

Data

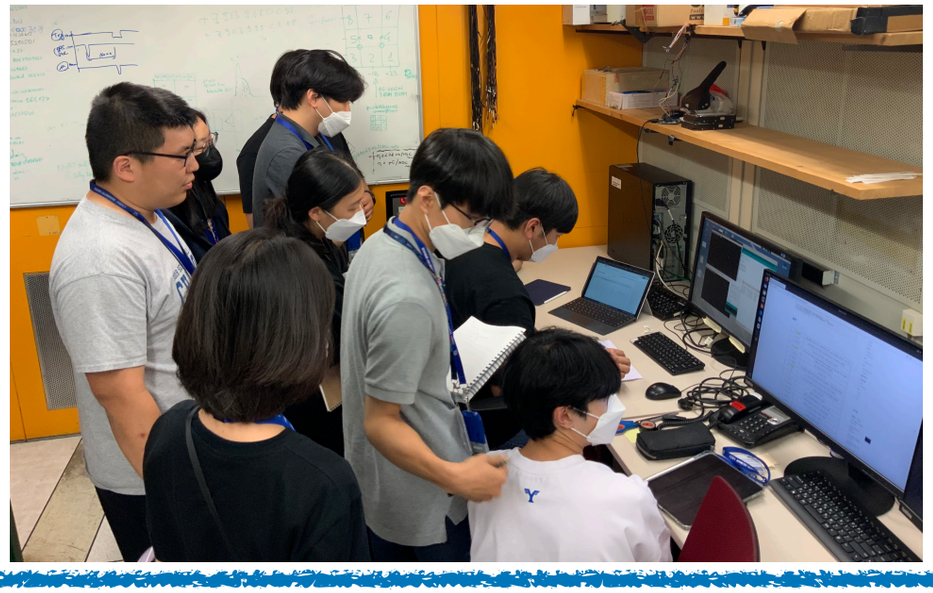


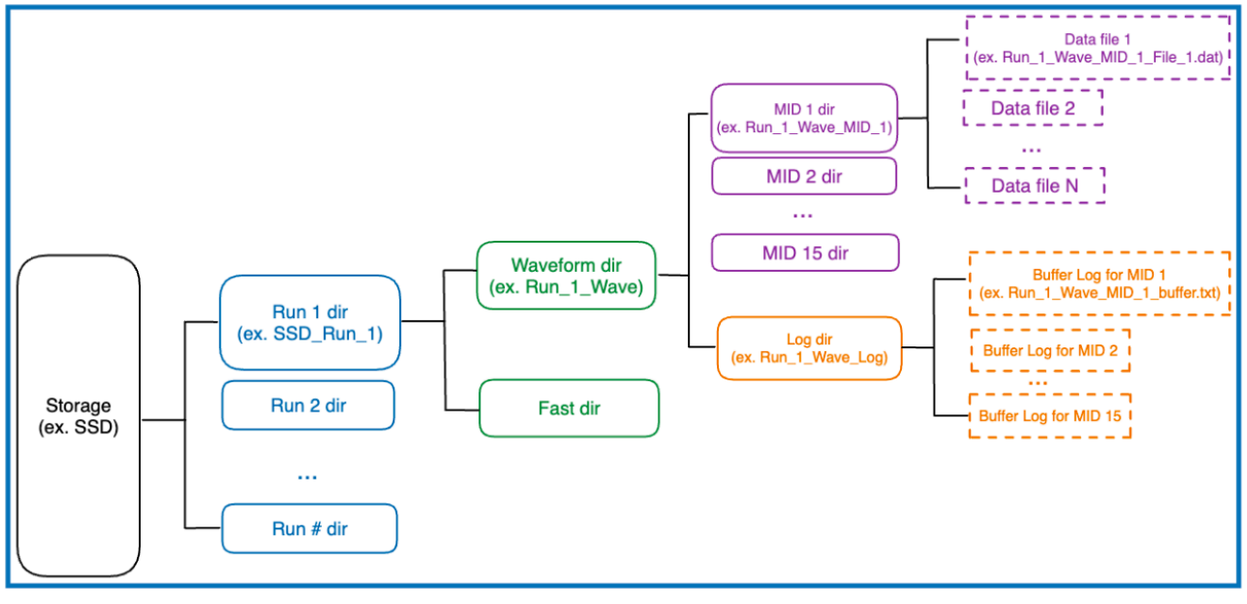
DQM data

In control Room



Draw DQM plots



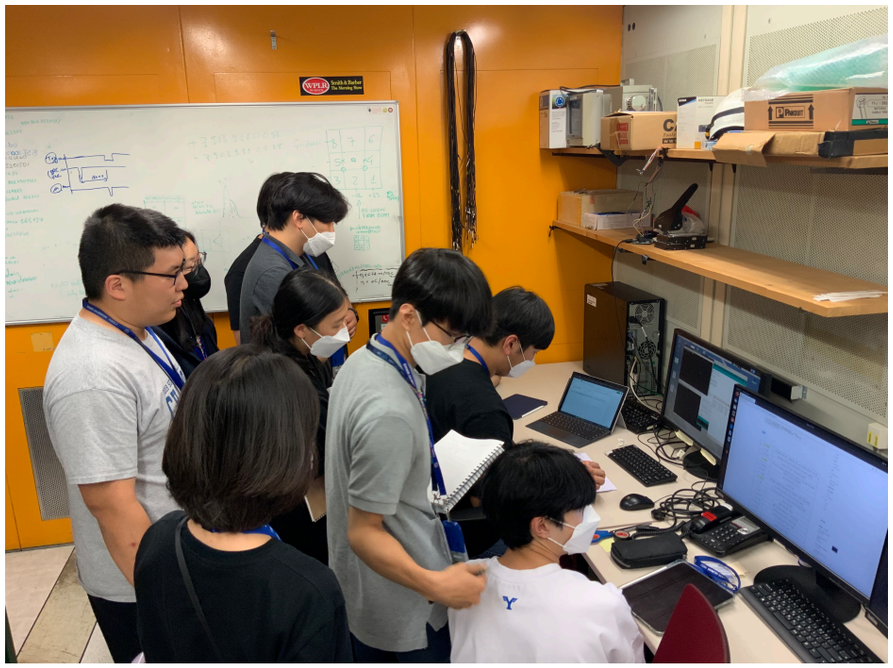


TB 2022: Program

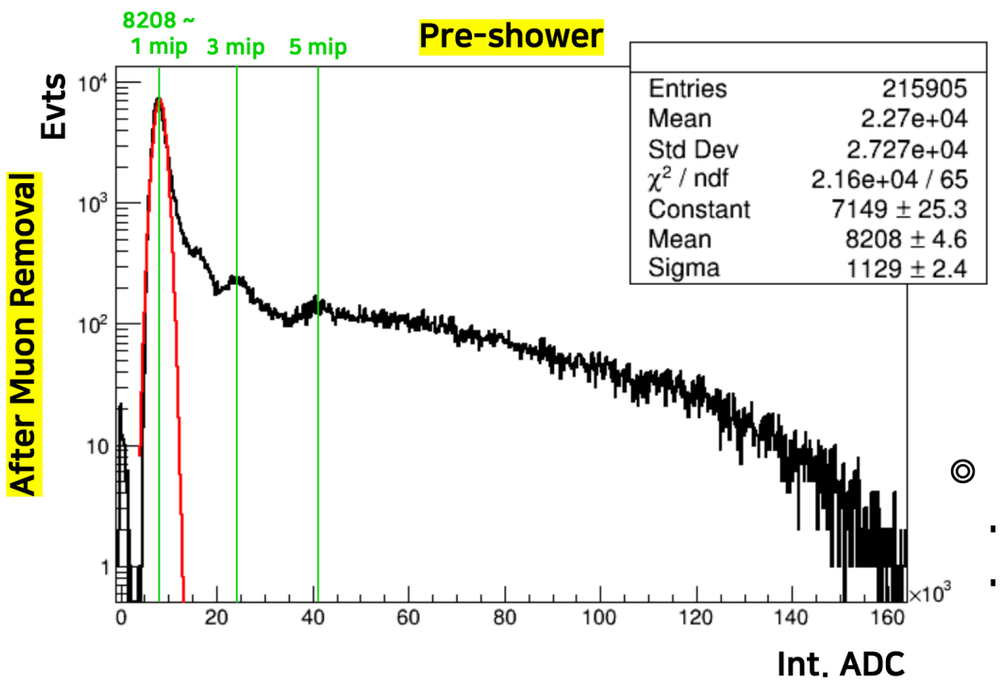
Aim	Module	Description
Finding towers (scanning tower position)	M1, M2	- Using positron beam (20 GeV) - 1cm vertical & horizontal scan - Find boundary of tower!
Gain tests	M1, M2	- Check signal level w.r.t. HV
Calibration	M1, M2	- Using positron 20 GeV, finding optimized HV (similar response ADC S and 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, variated 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!**



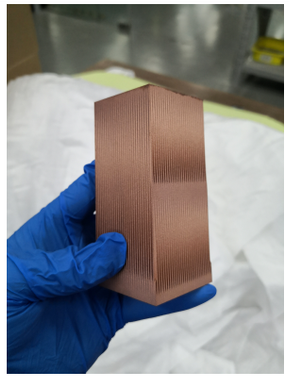
Total wave	Total Fast	Total Time (min)	Total Time (hour)
4,657,849	23,248,704	5,046	84

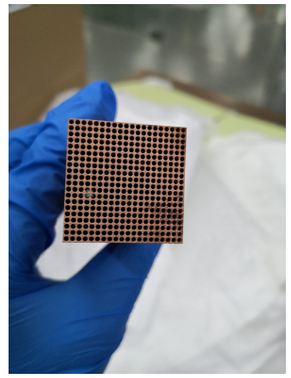


Prompt data analysis on-going

Module Building R&D

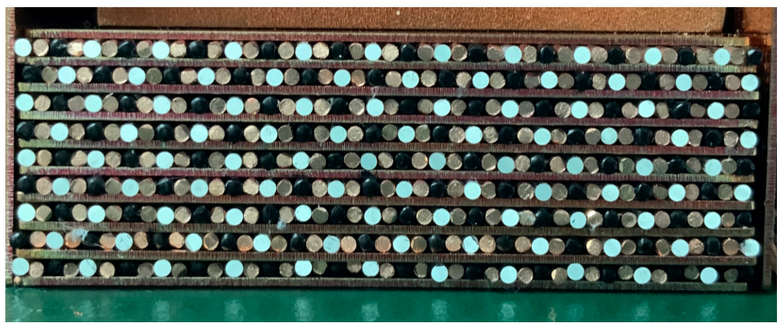
- **3D printing**





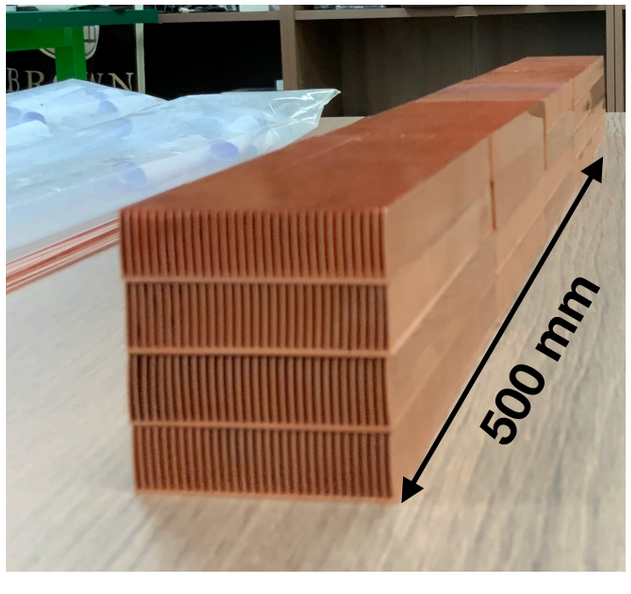
It has very perfect accuracy, but the cost is very high

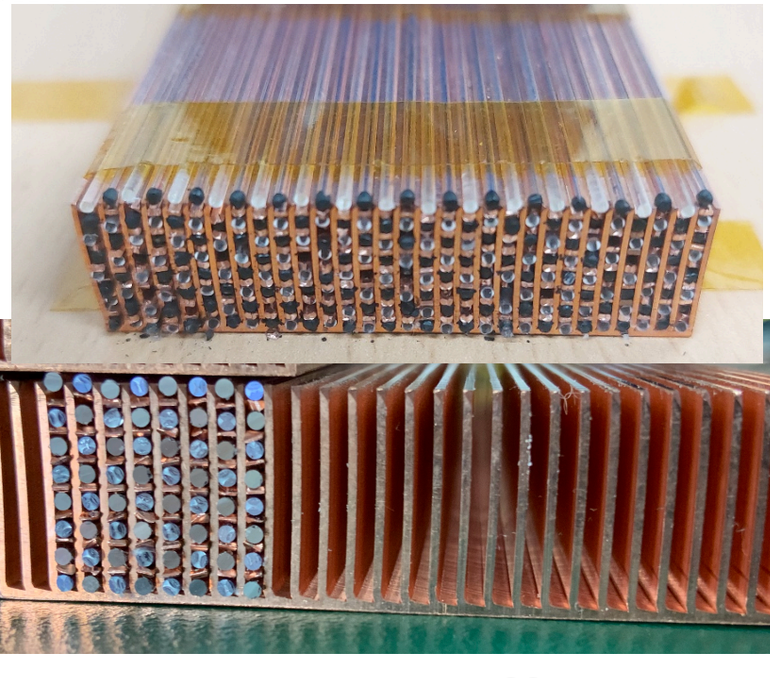
- **LEGO-like (Copper pipe)**

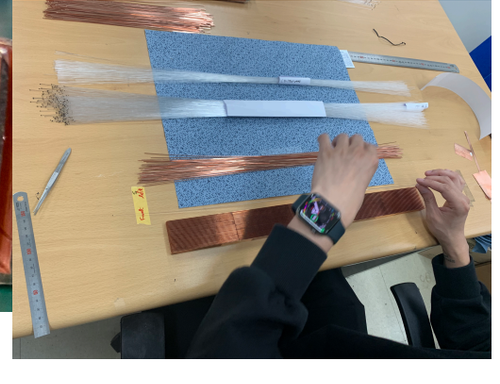


It has very good accuracy, and pretty low cost

- **Skiving Fin Heatsink**



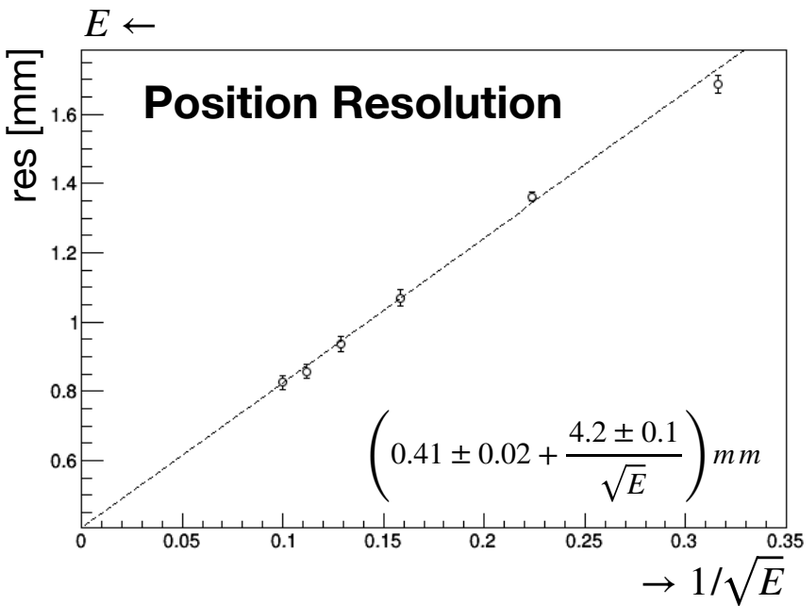


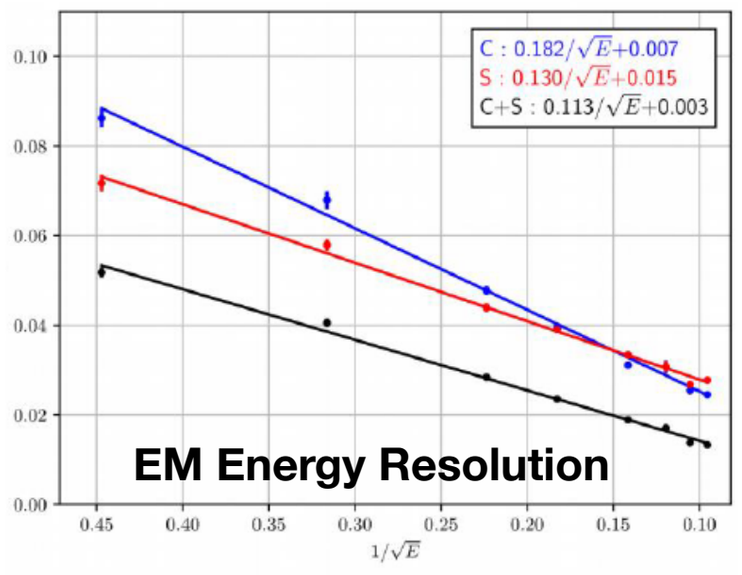


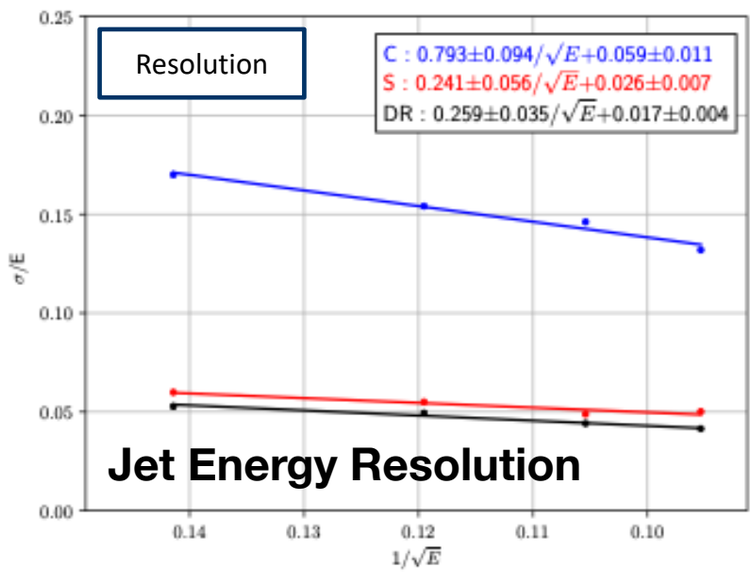
It has very excellent accuracy, and cost is low

Possibility for mass production!

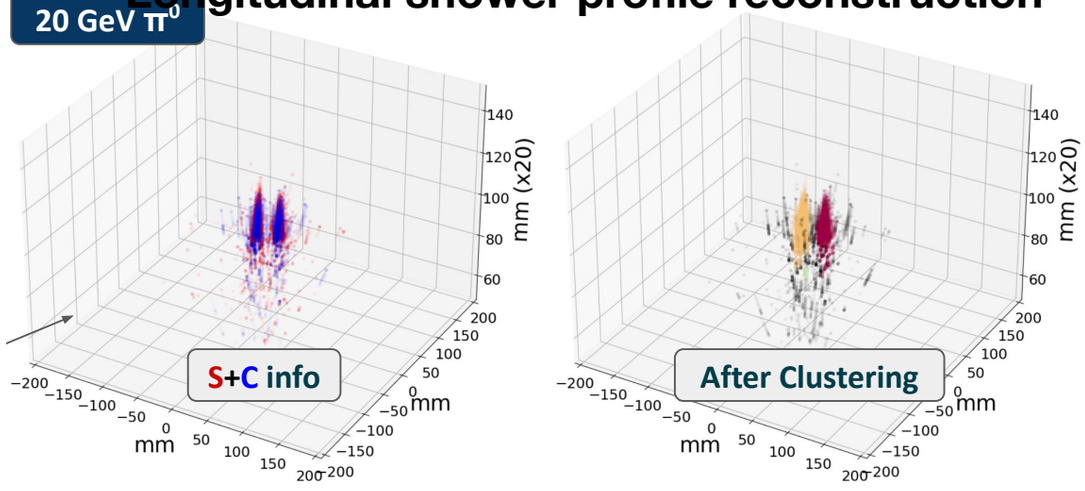
Simulation R&D

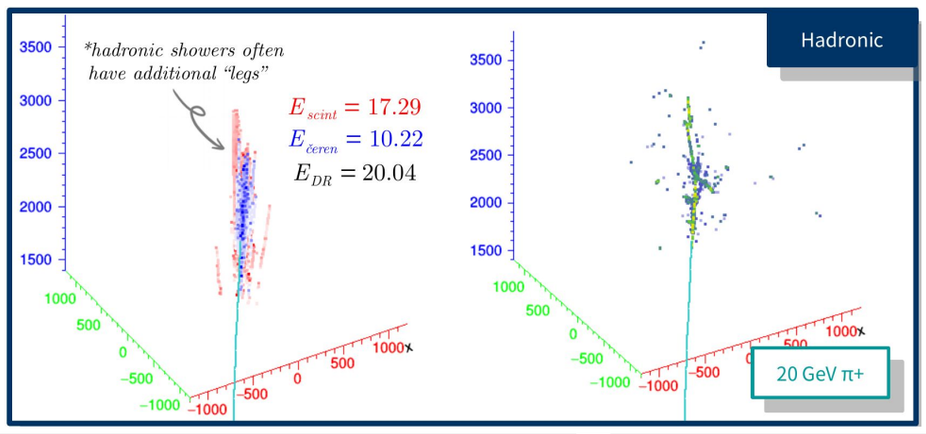




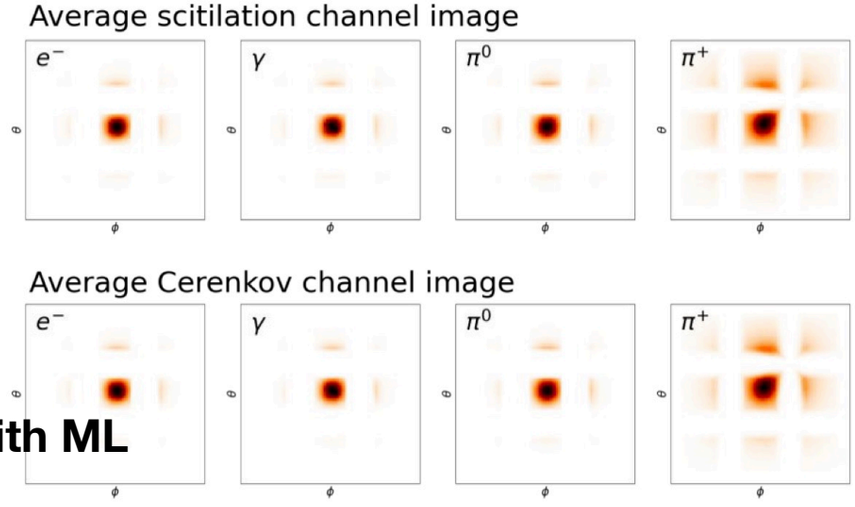


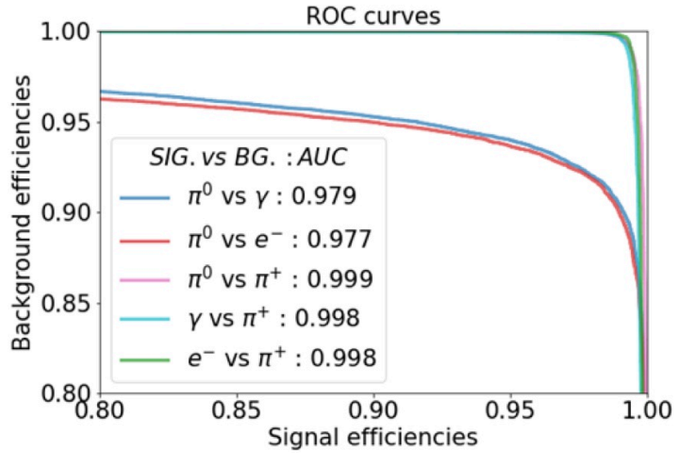
Longitudinal shower profile reconstruction

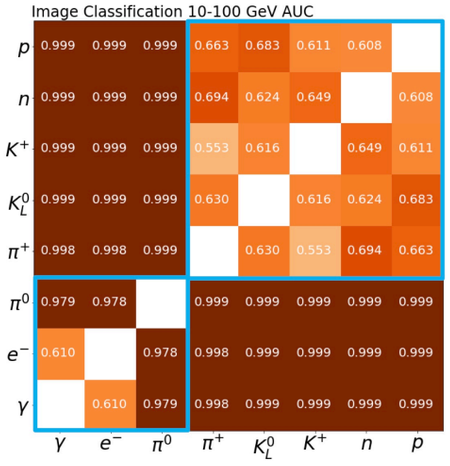




Particle IDs with ML

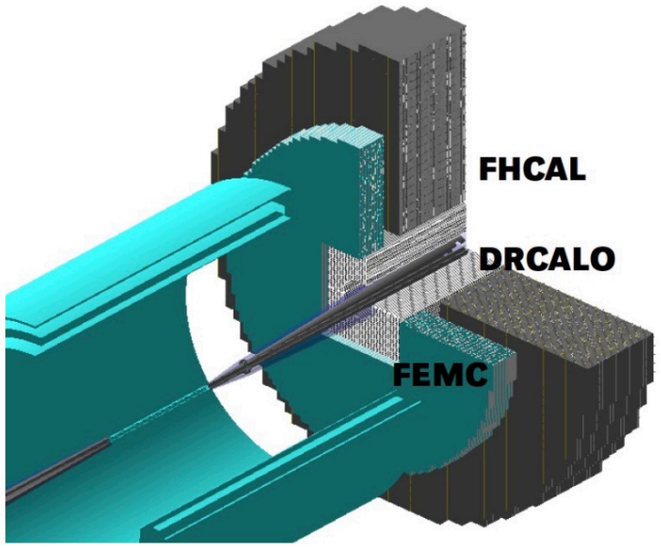




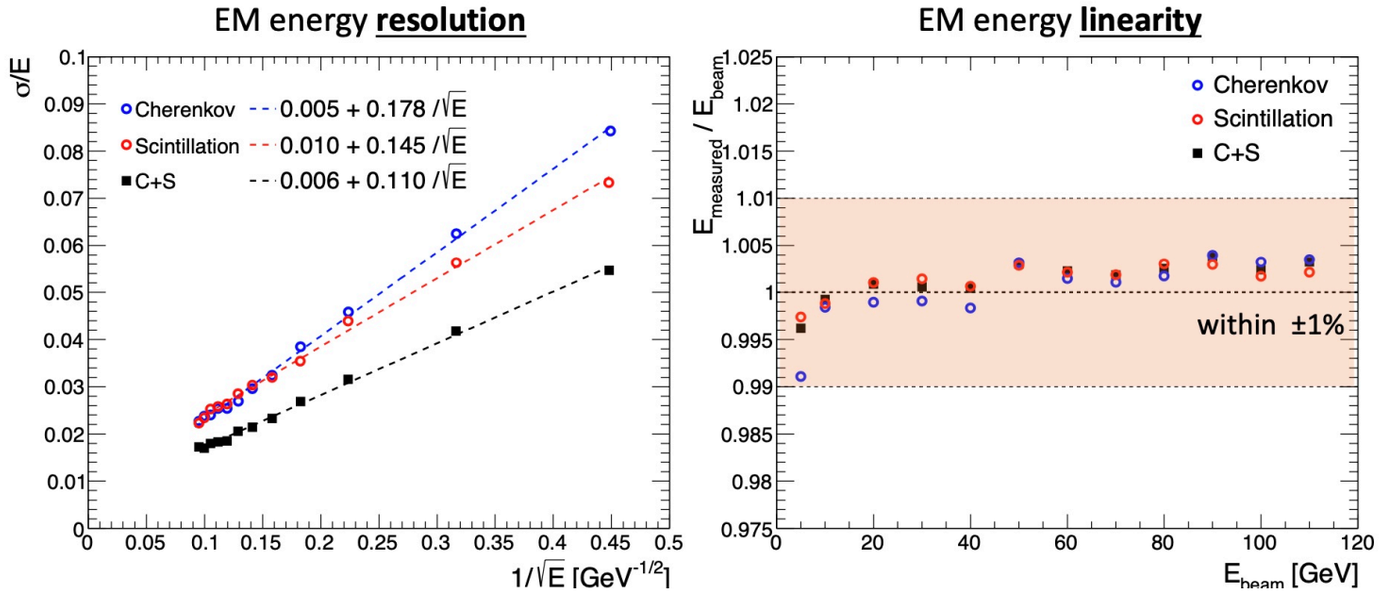


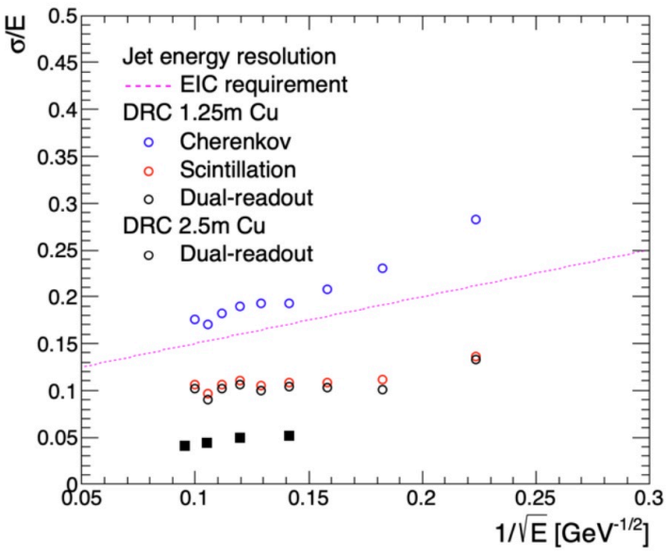
Simulation Study for EIC

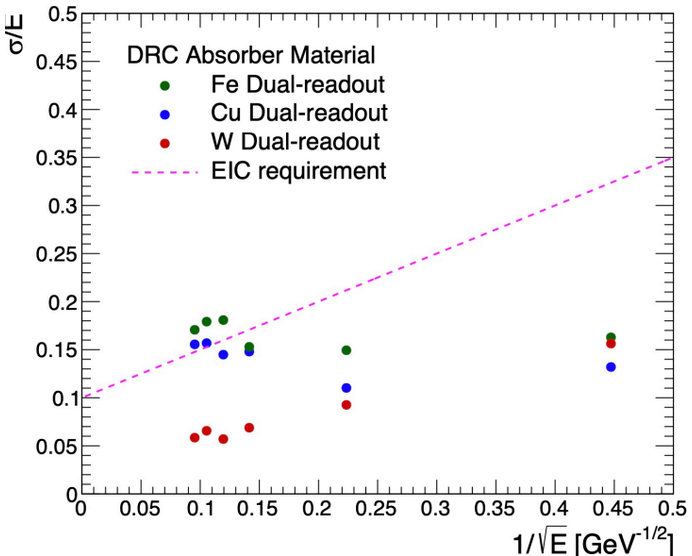
- Initial design and feasibility study for ECCE
  - DRC pre-design is implemented in Fun4All framework
  - Various absorbers (Cu, W, Fe) tested with shorter length design

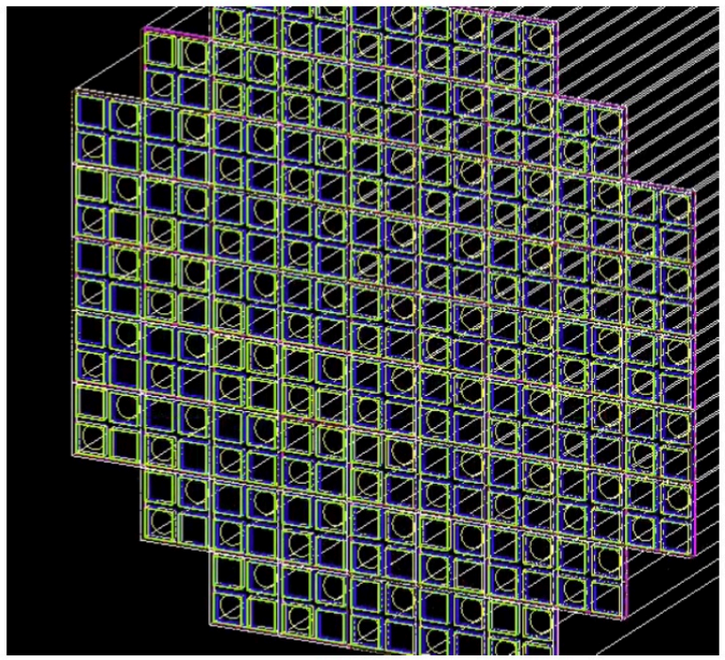


GEANT4 display with inlay DRC in EIC-ECCE









End of towers in EIC framework

Summary & Prospects

- 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
- Calorimeter design and study for EIC project have been performed
  - Hope to continue fruitful collaboration