CEPC Hadron Calorimeter

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for CEPC Calo Working Group

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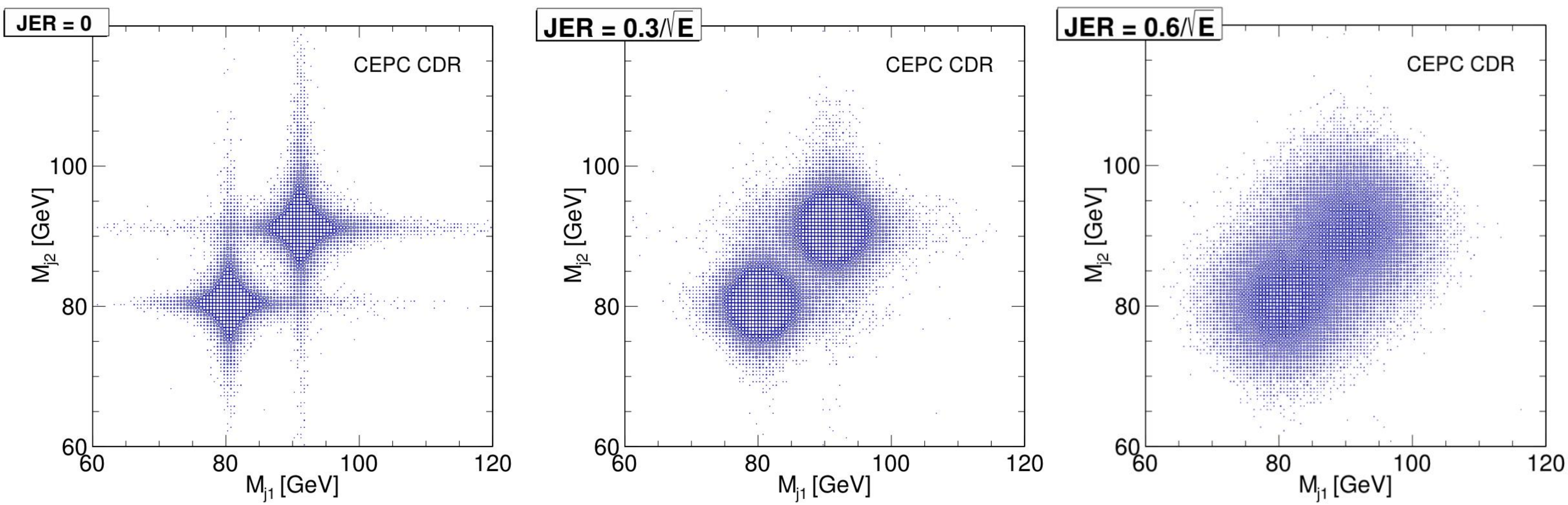
Outline

- **Requirements of CEPC Calorimeters**
- **HCAL Geometry and Optimization**
- **Semi-Digital HCAL based on RPC**
- **Semi-Digital HCAL based on THGEM**
- **Analog HCAL based on Scintillator + SiPM**
- **Summary and Future Plans**

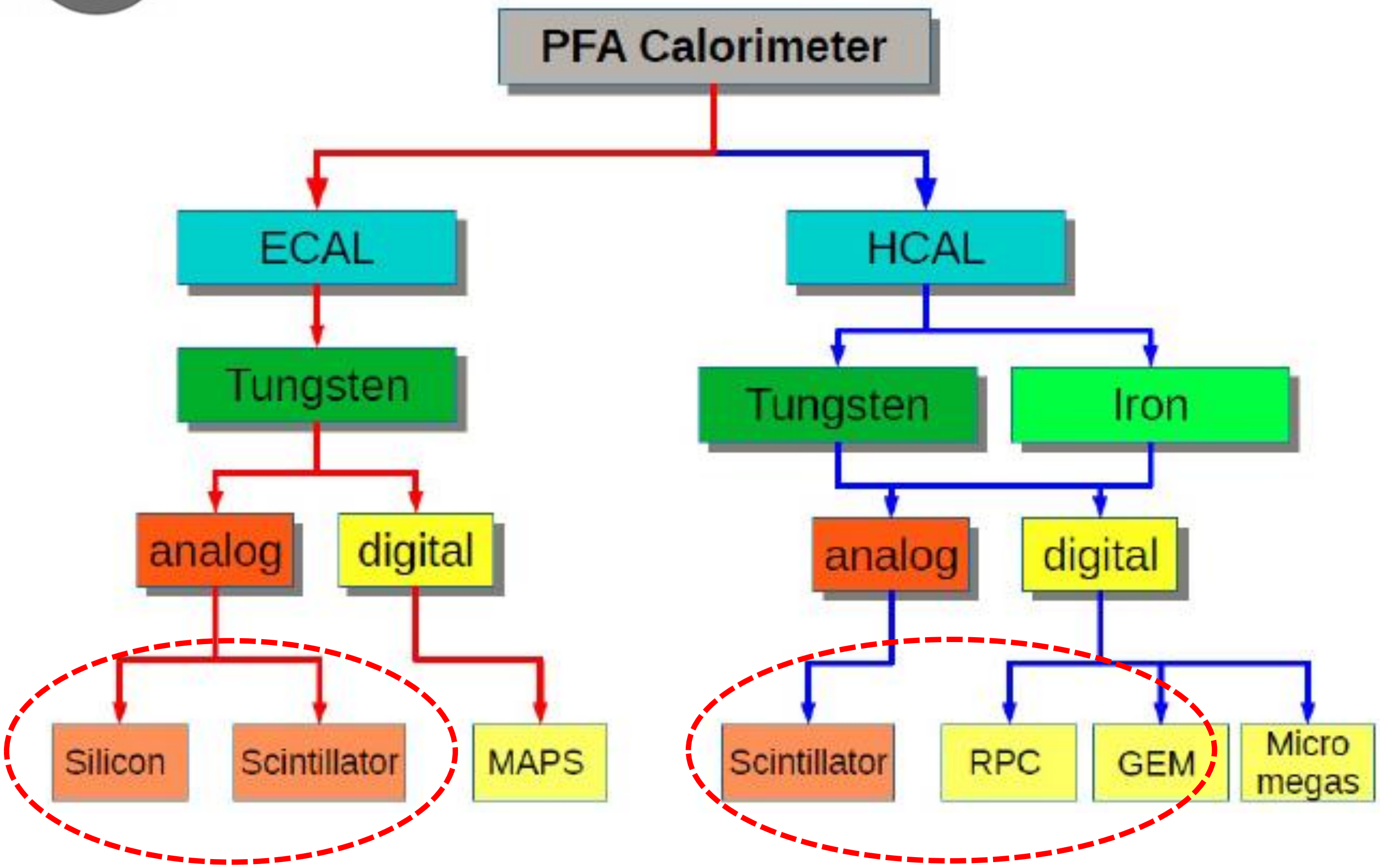
Requirements of CEPC Calorimeters

Physics process	Measurands	Critical detector	Required performance
$ZH \to l^+l^-X$	m_H, σ_{ZH}	Tracker	$\Delta(1/P_T) = 2\times10^{-5} \oplus \frac{0.001}{P(\mathrm{GeV})\sin^{\frac{3}{2}}\theta}$
$H \to \mu^+\mu^-$	$B(H \to \mu^+\mu^-)$		
$H \to b\bar{b}, c\bar{c}, gg$	$B(H \to b\bar{b}, c\bar{c}, gg)$	Vertex	$\sigma_{r\phi} = 5 \oplus \frac{10}{p(\mathrm{GeV})\sin^{3/2}\theta}(\mu\mathrm{m})$
$H \to q\bar{q}, W^+W^-, ZZ$	$B(H \to q\bar{q}, W^+W^-, ZZ)$	ECAL, HCAL	$\sigma_E^{jet} = 3 \sim 4\,\%$ at 100GeV
$H \to \gamma\gamma$	$B(H \to \gamma\gamma)$	ECAL	$\frac{\Delta E}{E} = \frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$



Options of PFA-based HCAL

https://twiki.cern.ch/twiki/bin/view/CALICE/CalicePapers



See Jianbei Liu's talk

AHCAL: Scintillator + SiPM

DHCAL: RPC & MPGD

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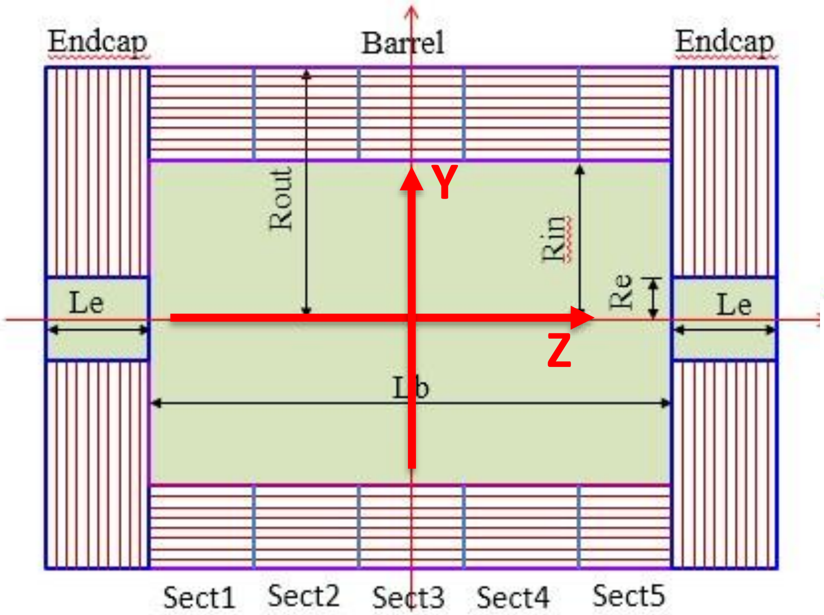
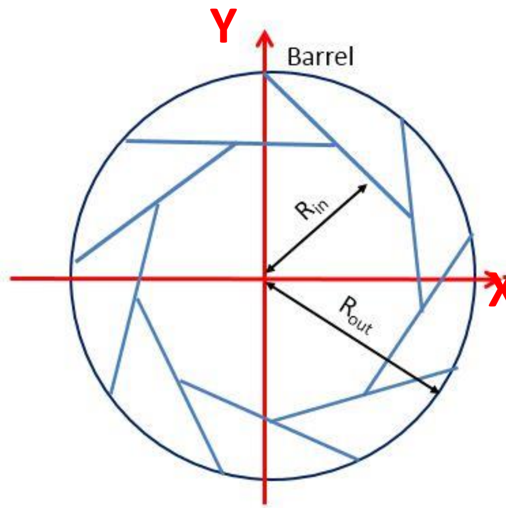
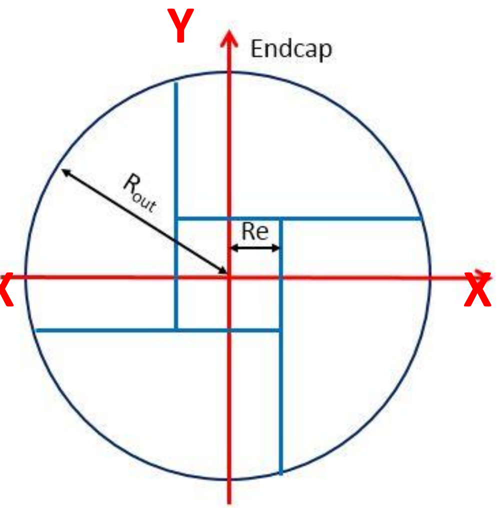
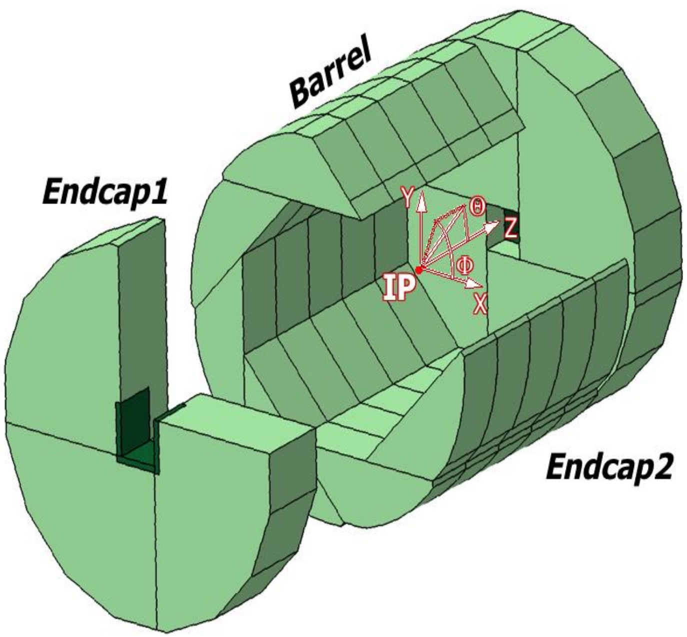
CEPC HCAL Geometry





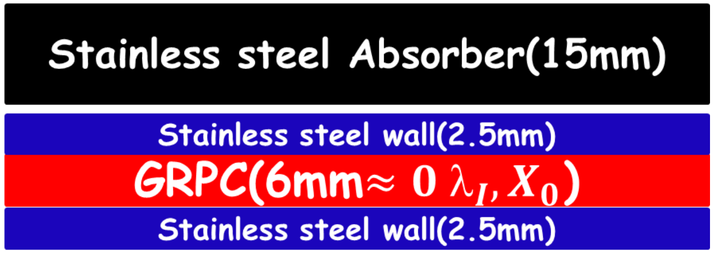




- Inner radius in X-Y plane R_{in} = 2300mm
- Outer radius R_{out} = 3340mm
- Inner & outer of HCAL endcap in Z-axis are 2670mm and 3710mm

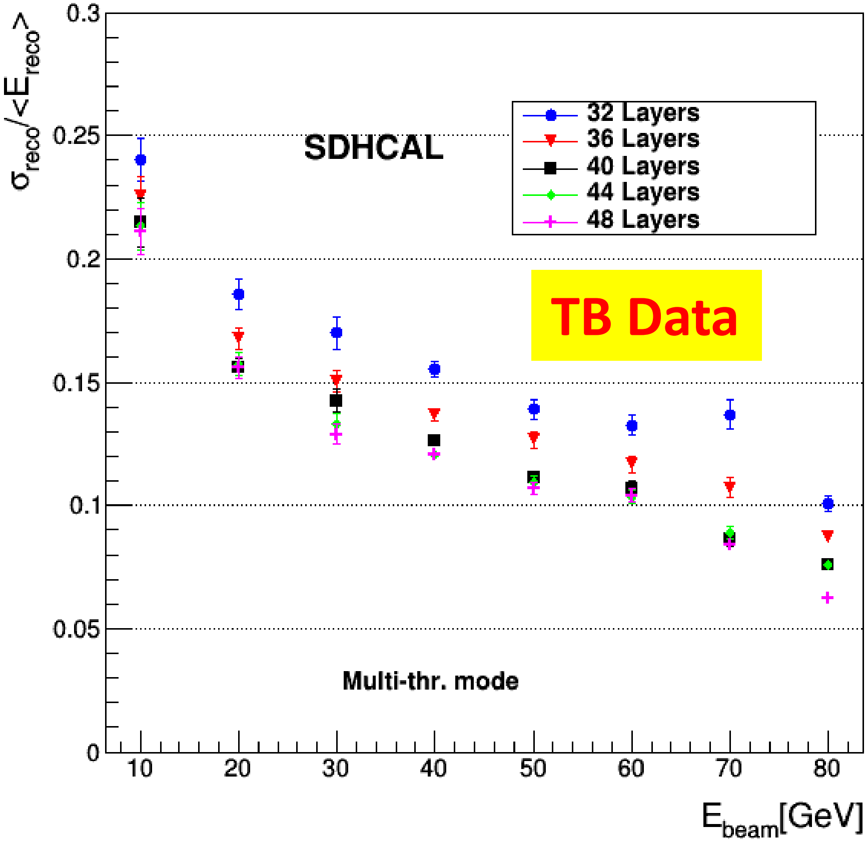
Optimization of SDHCAL Layers

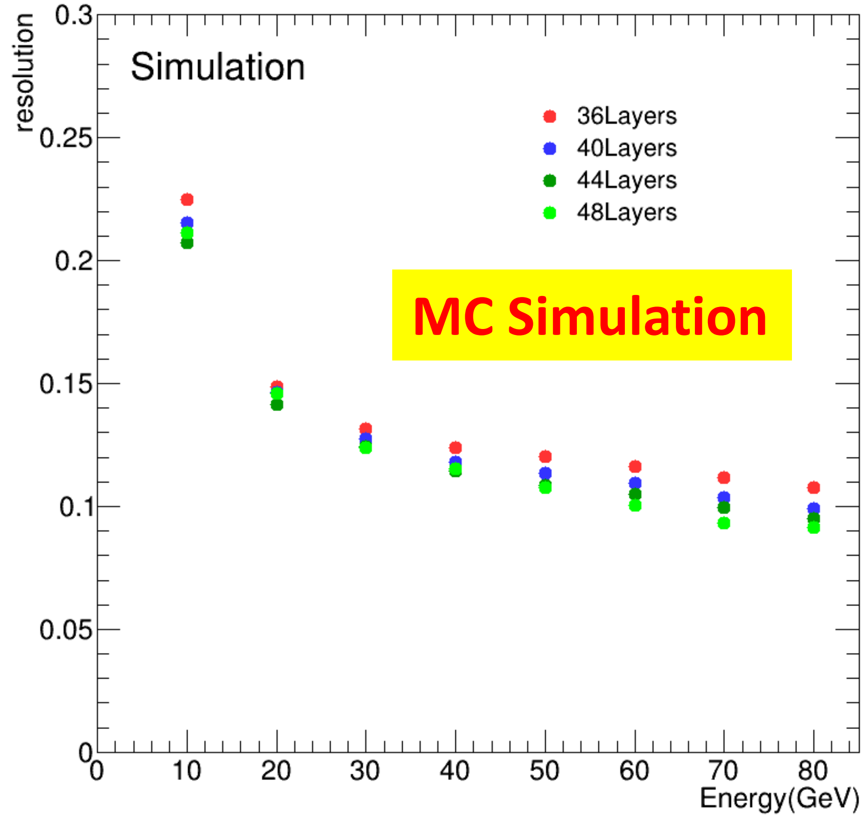
$(0.12\lambda_I, 1.14X_0)$



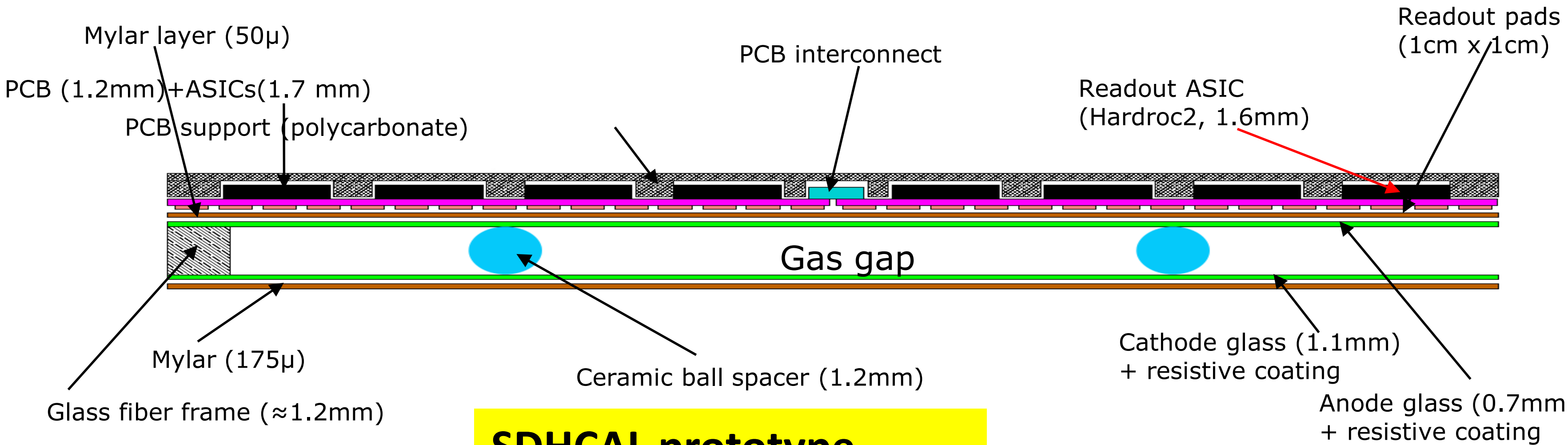
➔SDHCAL has 48 layers:
- 6mm RPC+20mm absorber (steel)

➔40-layer yields decent energy resolution





SDHCAL based on RPC



SDHCAL prototype
Size: 1m x 1m x 1.4m
No. of layers: 48
Cell size: 1cm x 1cm
No. of channels: 440K
Power: 1mW/ch

Large GRPC R&D

- ✓ Negligible dead zone
- ✓ Large size: 1 x 1 m^2

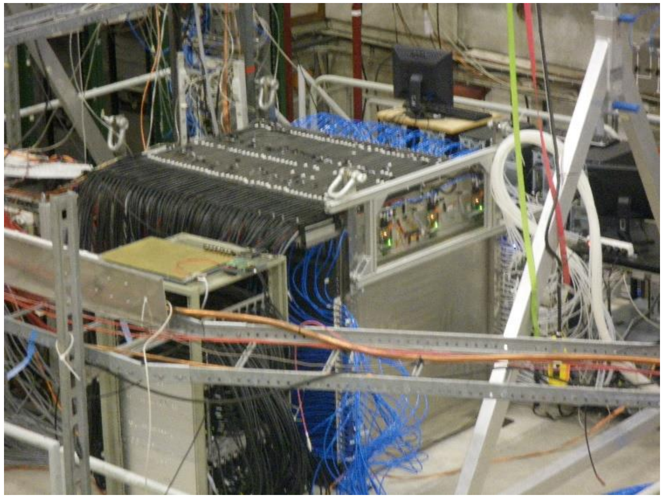
$(0.12\lambda_I, 1.14X_0)$

Stainless steel Absorber(15mm)

Stainless steel wall(2.5mm)

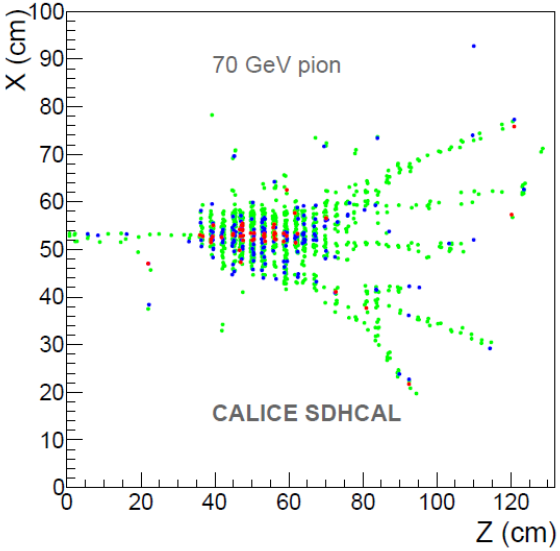
GRPC(6mm $\approx 0\ \lambda_I, X_0$)

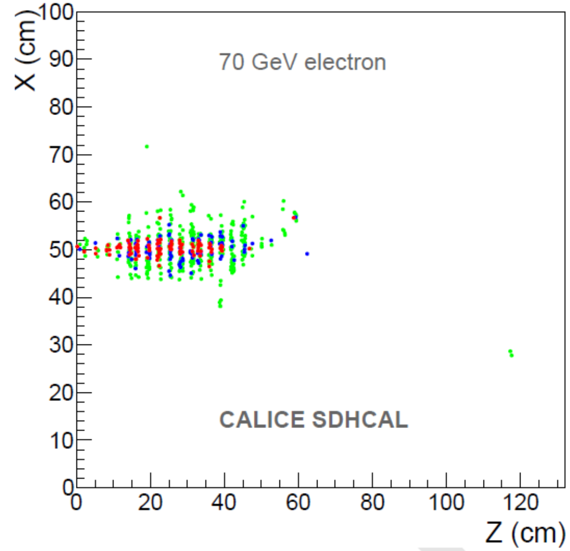
Stainless steel wall(2.5mm)

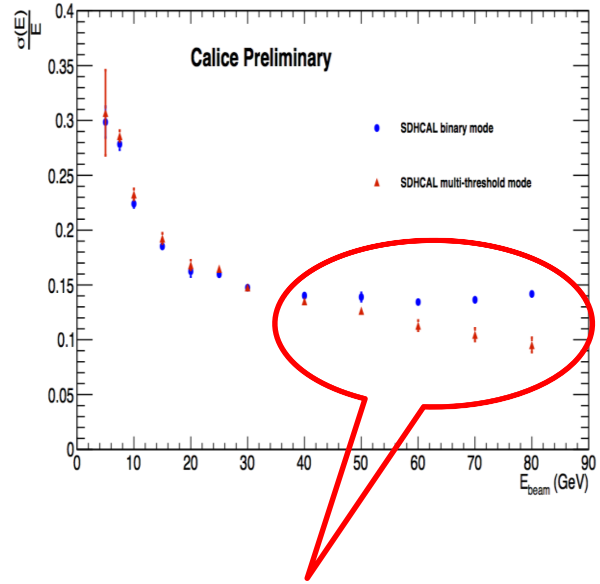


ASIC HARDROC (64 ch)
3-threshold: 110fC, 5pC, 15pC

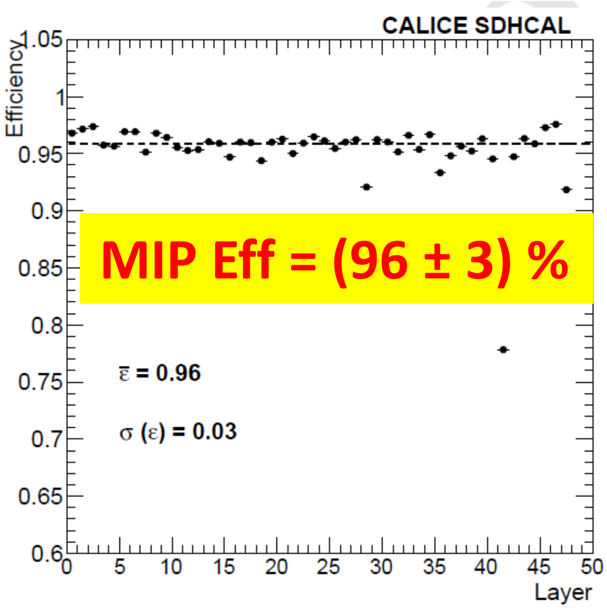
Performance of SDHCAL



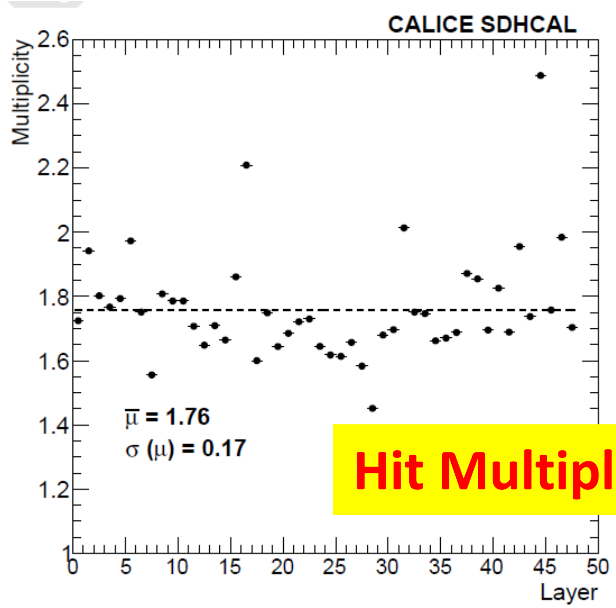




SDHCAL with 3-threshold results in better energy resolution than binary mode for E_{beam} > 40 GeV

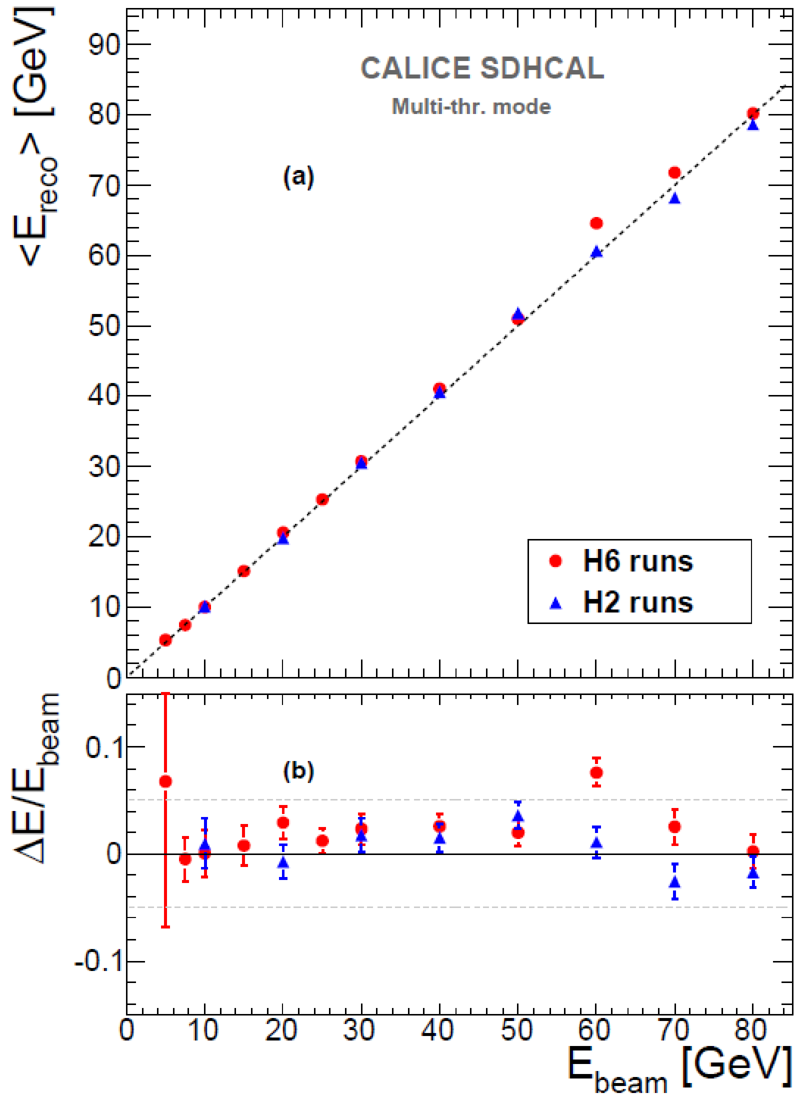


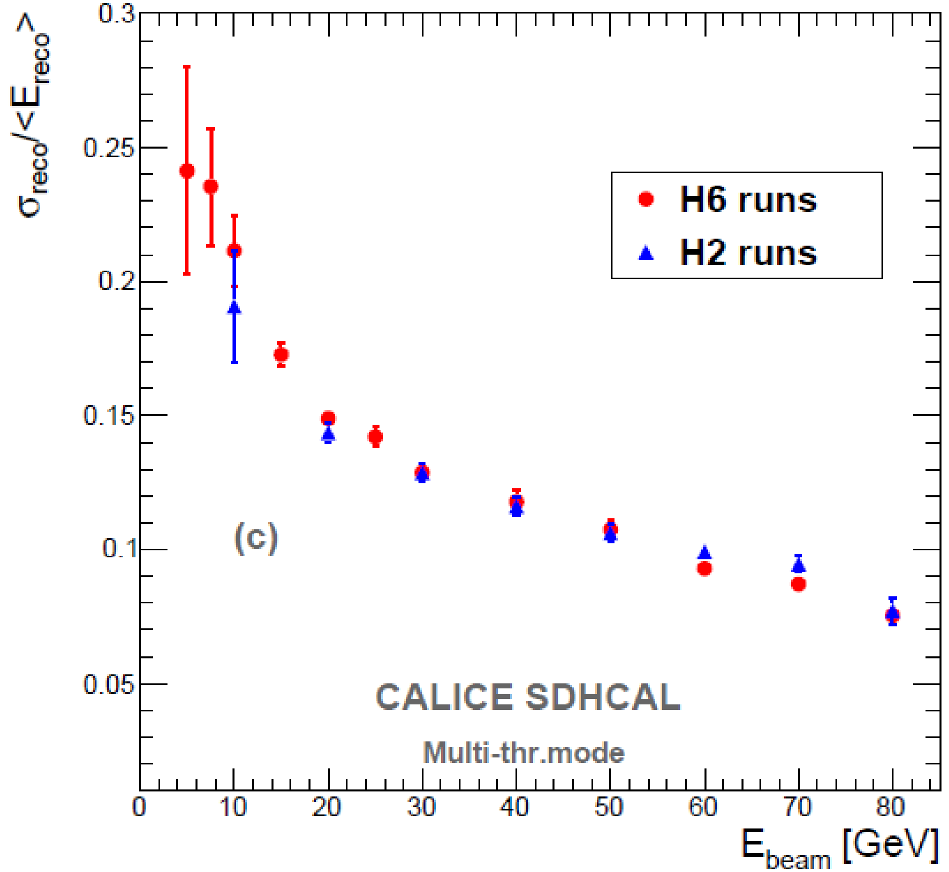
MIP Eff = (96 ± 3) %



Hit Multiplicity = 1.76 ± 0.17

Performance of SDHCAL

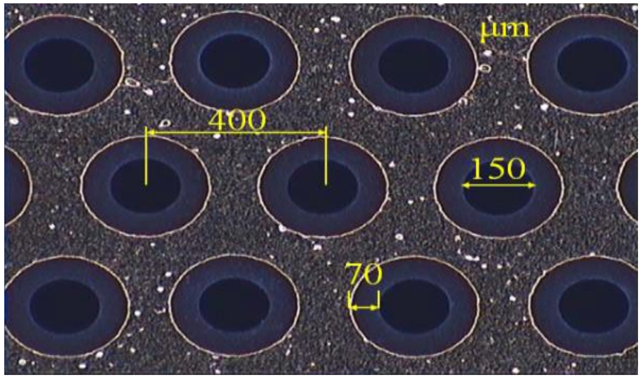


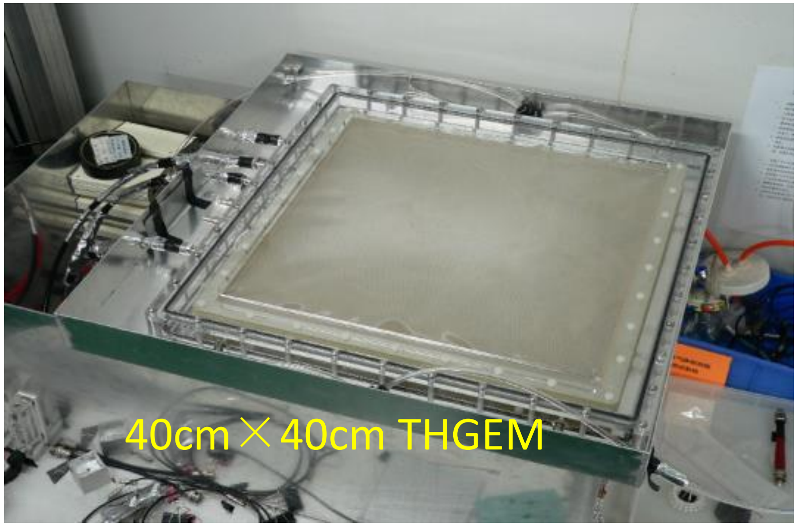


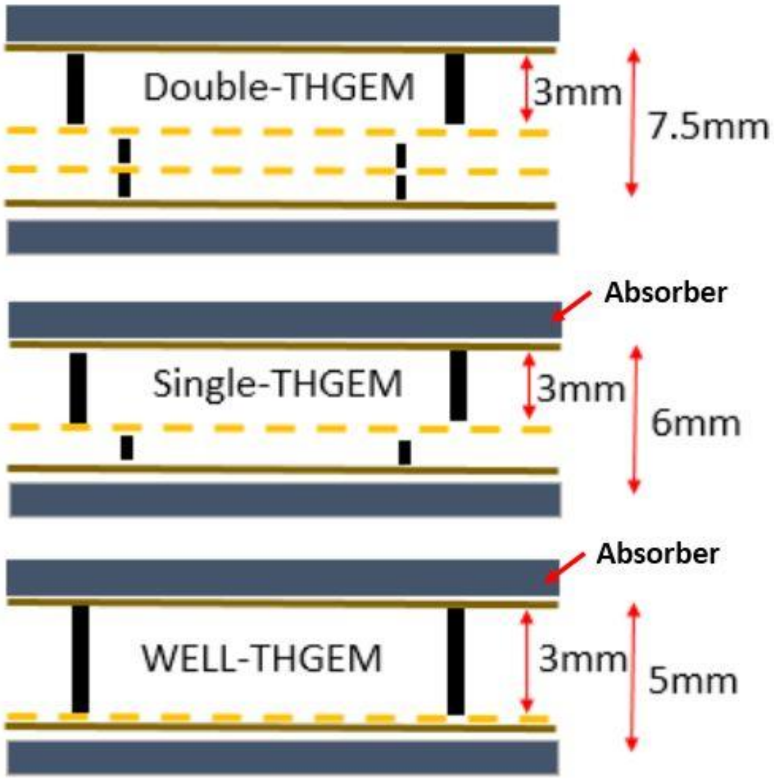
Relative Energy resolution vs E_{beam}

DHCAL based on THGEM

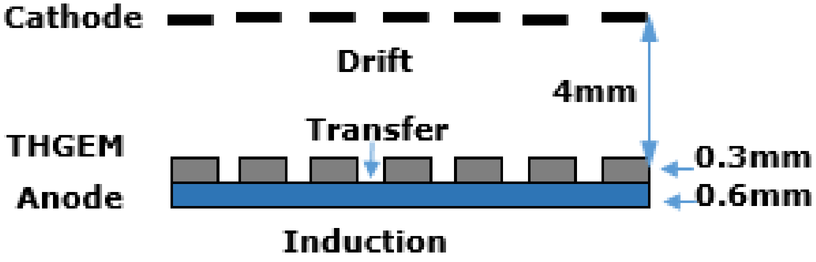
- Three THGEM options are explored:
  - Double - THGEM
  - Single - THGEM
  - WELL - THGEM
- WELL-THGEM is optimal choice
  Thinner, lower discharge
- $40 \times 40\ cm^2$ of THGEM (below) was produced in China



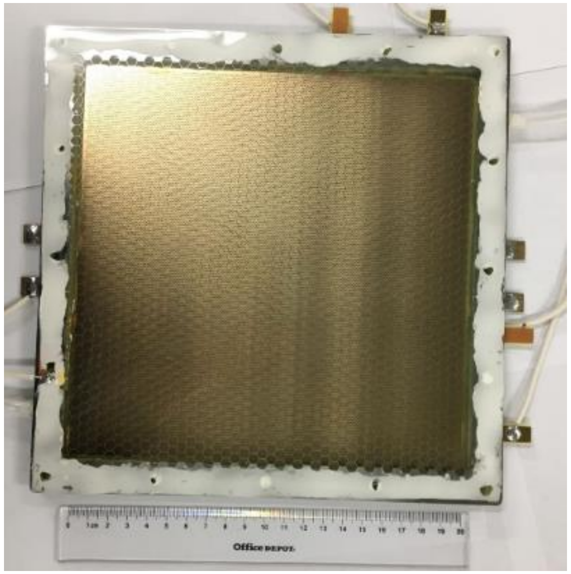


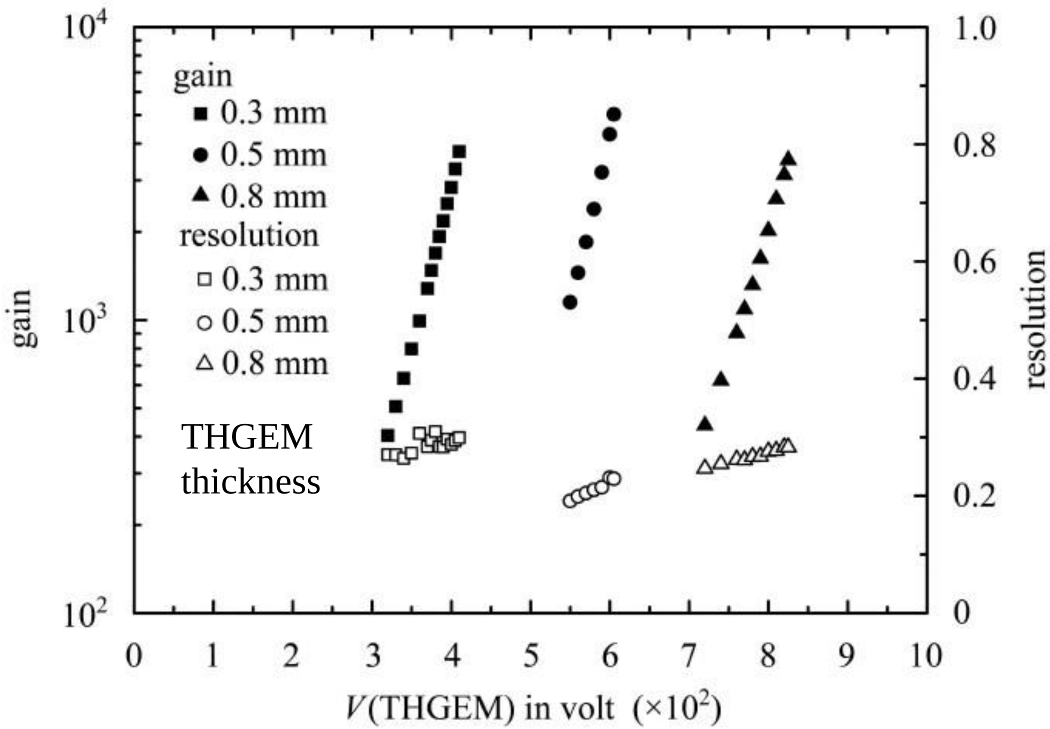


DHCAL based on THGEM



20cm × 20cm WELL-THGEM



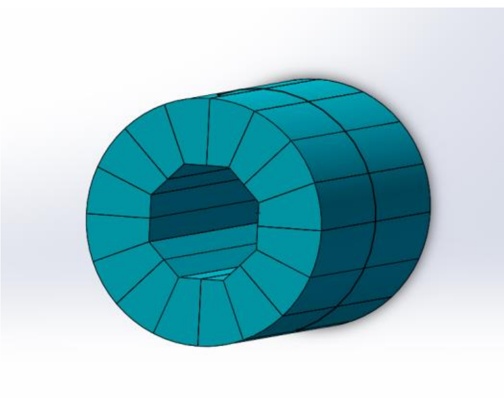


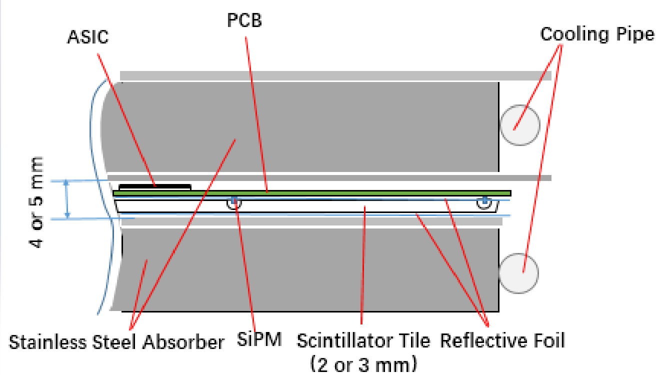
WELL-THGEM: ^{55}Fe (Xray ~ KeV), gain ~ 5000, energy resolution is 20%-25%
high rate ~ 1 MHz/cm^2, MIP eff > 95%

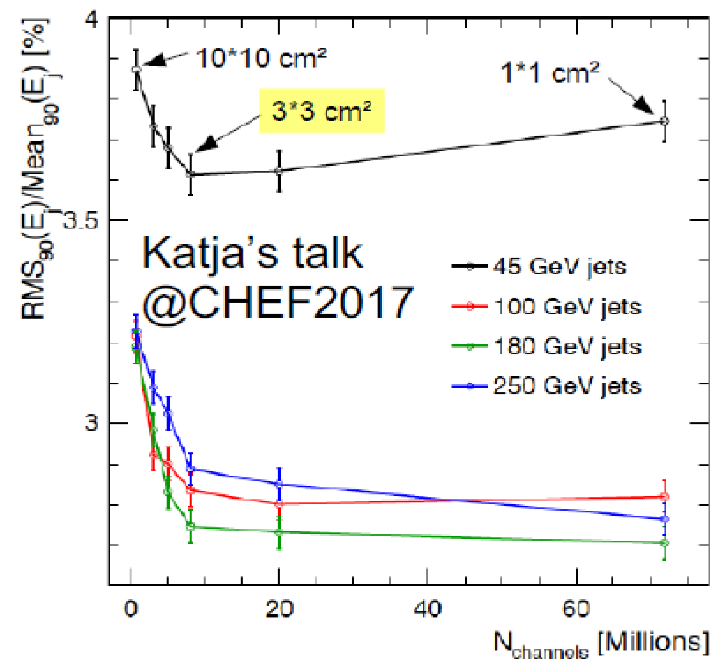
AHCAL based on Scintillator + SiPM

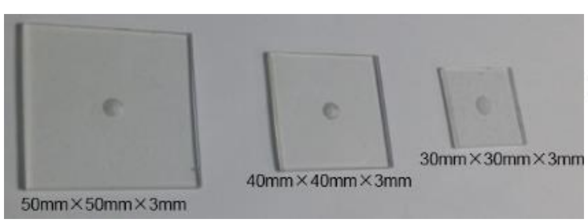
AHCAL (Scintillator + SiPM) for CEPC

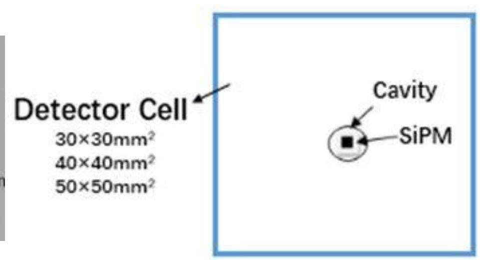
- Scintillator cell size: **3x3cm^2**, 4x4cm^2, 5x5cm^2
- 32 super modules (16+16) in barrel region
- Number of layers: 40
- Each active layer + readout ~ 5mm
- Each absorber (stainless steel) ~ 20mm

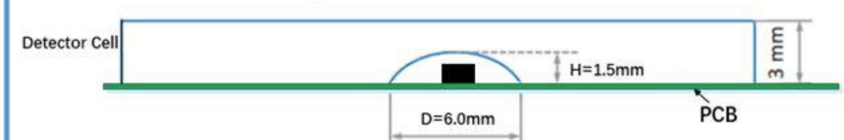




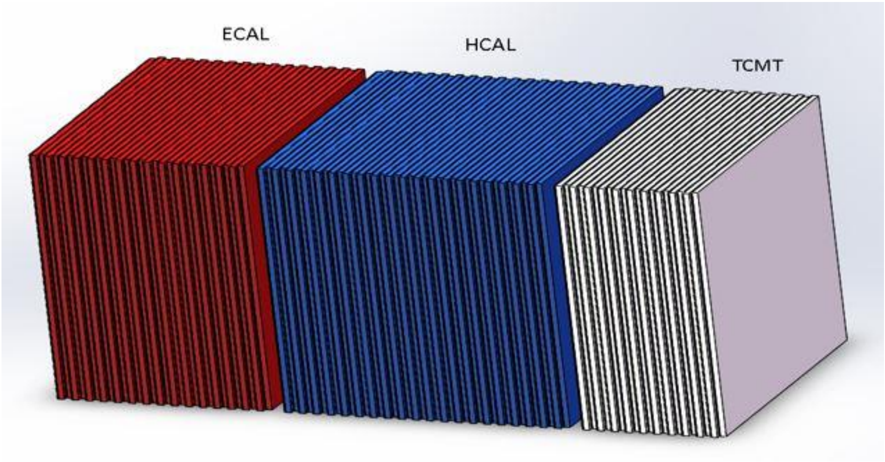


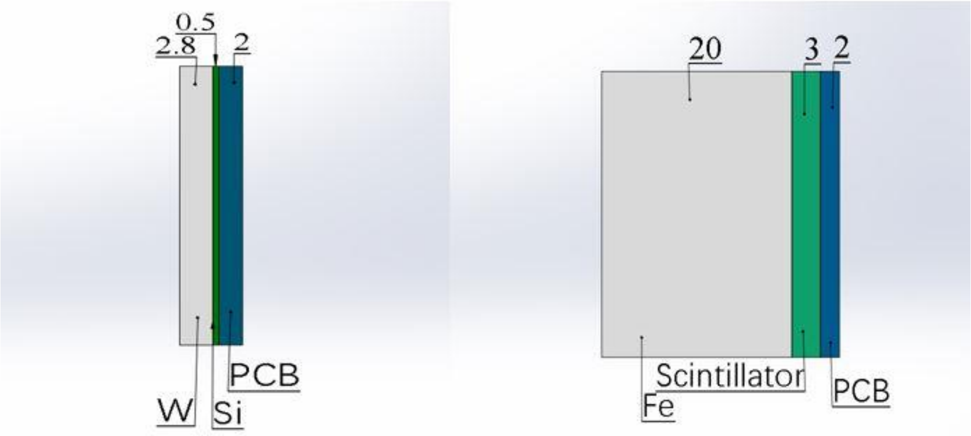


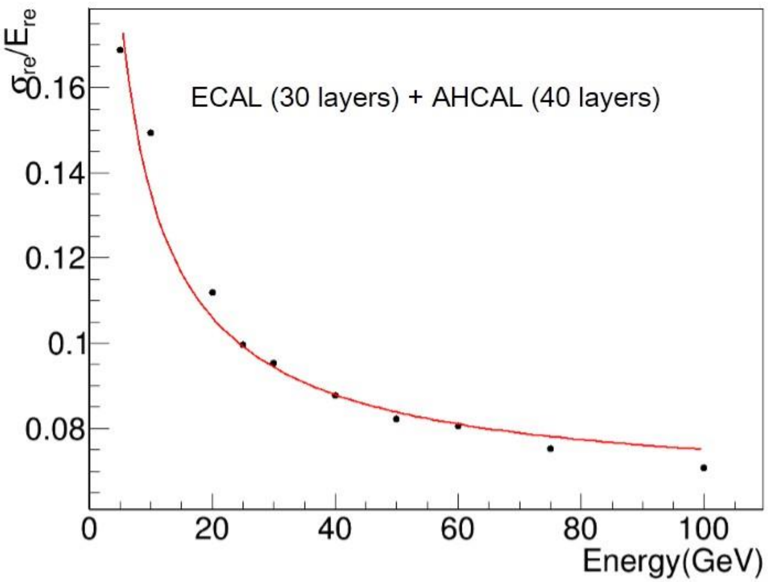




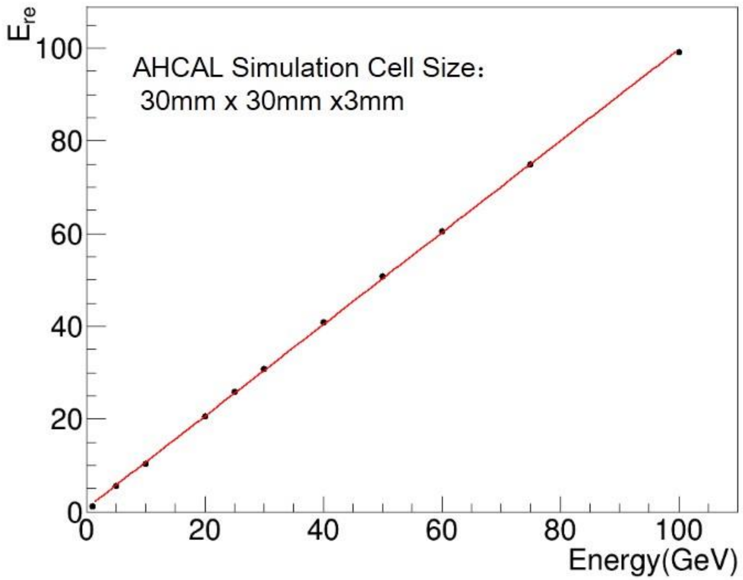
AHCAL based on Scintillator + SiPM





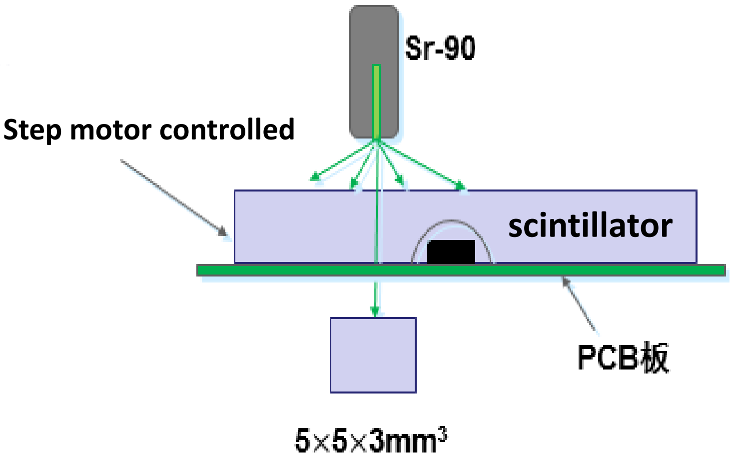


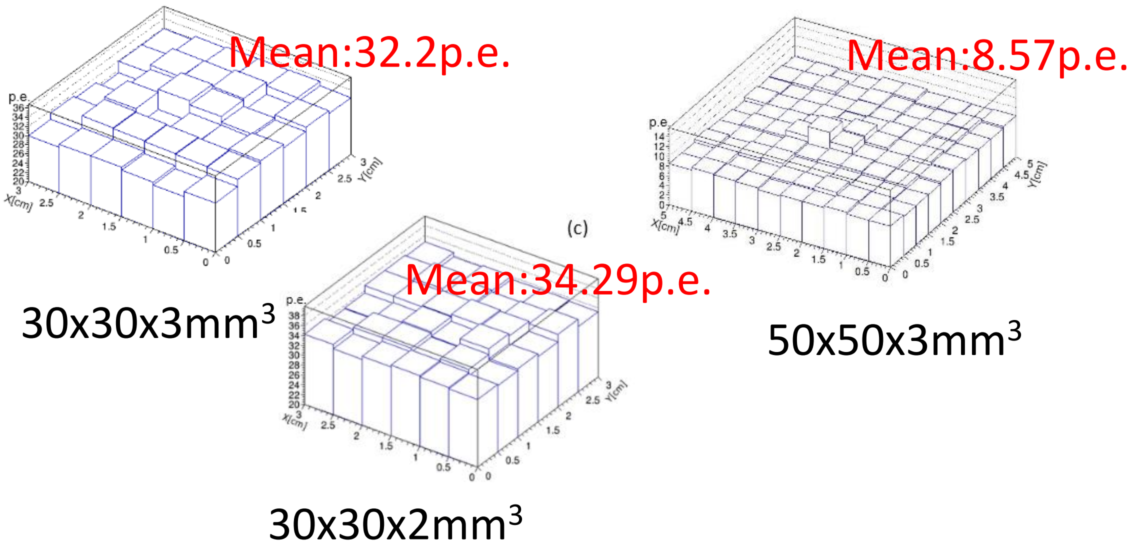
Relative energy resolution vs E_{beam}



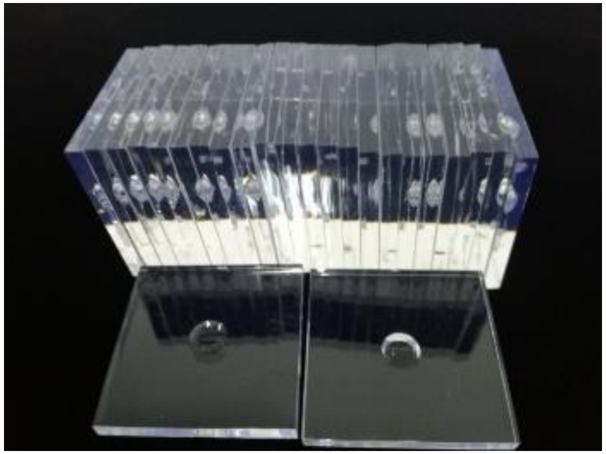
Energy linearity vs E_{beam}

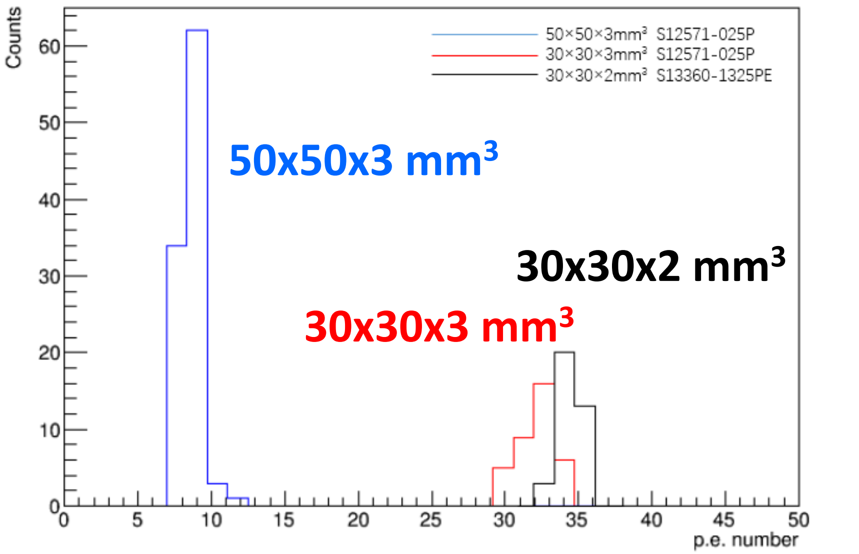
Test: Scintillator + SiPM





- Test of Uniformity
- MIP detection eff. > 95%

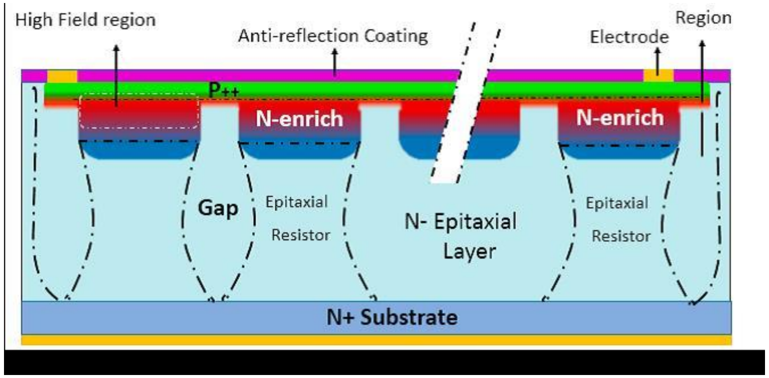




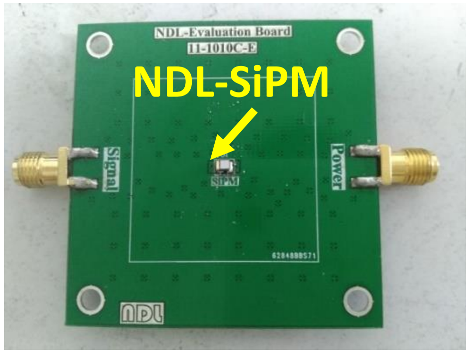
Development of SiPM

Hamamatsu MPPC vs NDL EQR SiPM (epitaxial quenching resistors)

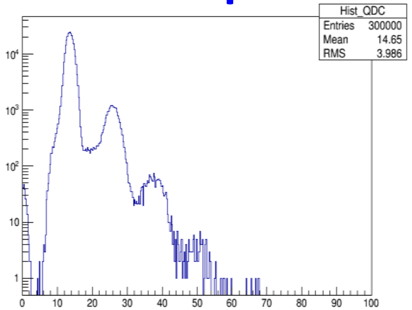
- Short recovery time
- High counting rate capability



NDL-SiPM 11-1010C (domestic)



Photon Spectrum



NDL EQR-SiPM VS Hamamatsu MPPC

	NDL SiPM		Hamamatsu MPPC	
Effective Active Area	11-3030 B-S	22-1414 B-S	S13360-3025PE	S13360-1325PE
	3.0×3.0 mm²	1.4×1.4 mm² (2×2 Array)	3.0×3.0 mm²	1.3×1.3 mm²
Effective Pitch	10 μm	10 μm	25 μm	25μm
Micro-cell Number	90000	19600	14400	2668
Fill Factor	40%	40%	47%	47%
Breakdown Voltage (V_b)	23.7±0.1V	23.7±0.1V	53±5V	53±5V
Measurement Overvoltage (V)	3.3	3.3	5	5
Peak PDE	27%@420nm	35%@420nm	25%@450nm	25%@450nm
Max. Dark Count (kcps)	< 7000	<1500	1200	210
Gain	2×10^5	2×10^5	7.0×10^5	7.0×10^5
Temp. Coef. For V_b	17mV/° C	17mV/° C	54mV/° C	54mV/° C

Estimated HCAL Channels

- HCAL Barrel, R_{in} = 2.3m, R_{out} = 3.34m, length = 2.67*2=5.34m, N_{layer}=40

  Area of HCAL barrel = $2*PI*[(R_{in}+R_{out})/2]*L*N_{layer}$ = 3782 m^2

- HCAL Endcap (2), R_{in} = 0.35m, R_{out} = 3.34m, N_{layer}=40

  Area of HCAL endcap = $2*PI*(R_{out}*R_{out} - R_{in}*R_{in})*N_{layer}$ = 2772 m^2

Cell Size \ channels	HCAL Barrel	HCAL Endcap	Channels (N_{ch})	Power AHCAL	Power SDHCAL
1cm x 1cm	37.82M	27.72M	65.5M		110 kW
2cm x 2cm	9.455M	6.93M	16.4M		52 kW
3cm x 3cm	4.2M	3.08M	7.3M	110 kW	43 kW
4cm x 4cm	2.36M	1.73M	4.1M	88 kW	
5cm x 5cm	1.51M	1.11M	2.6M	77 kW	

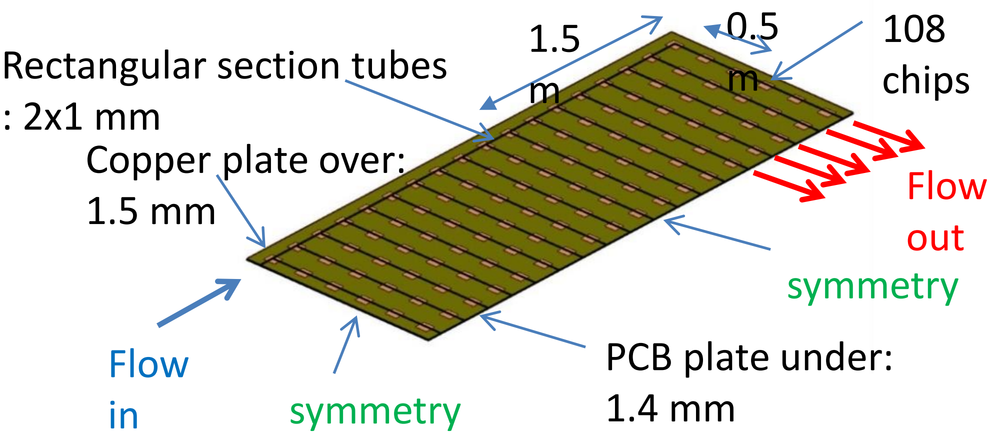
Power Consumption (rough estimation):

AHCAL: 7mW/ch * N_{ch3} + 9W/DIF/m^2 * 6554 (59kW)

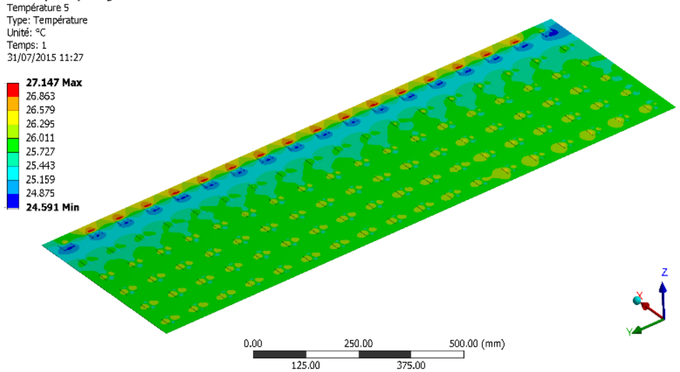
SDHCAL: 1mW/ch * N_{ch1} + 5.4W/DIF/m^2 * 6554 (35.4kW)

Active Cooling

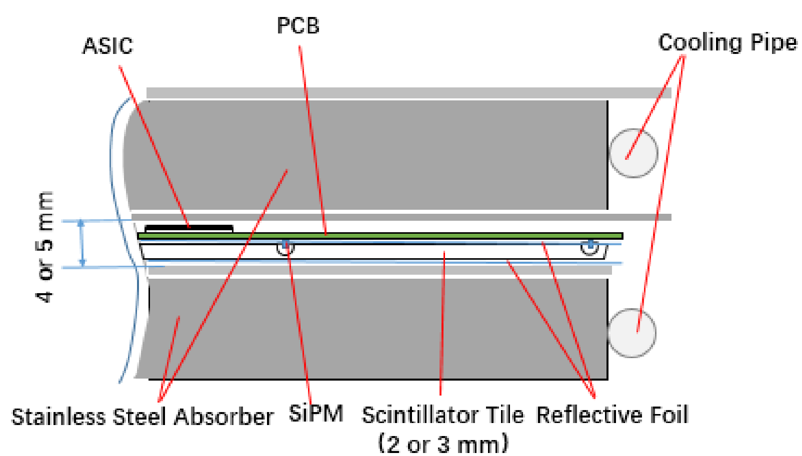
Cooling may become necessary if it is operating at continuous mode (CEPC)



27.147 (max) – 24.591 (min) =2.556 °C



- A water-based cooling system inside copper tubes in contact with the ASICs to absorb excess heat.
- Temperature distribution in an active layer of the SDHCAL.



Water cooling : h = 10000 W/m²/k
Thermal load : 80 mW/chip

- For AHCAL, a water-based copper cooling system embedded in the stainless steel absorber.

Summary and Future Plans

- **Semi-Digital HCAL (RPC, THGEM) and Analog HCAL (Scintillator+SiPM) are considered as options of CEPC hadron calorimeter, both conceptual designs with 40 layers can reach required energy resolution.**
- **Baseline cell size for SDHCAL and AHCAL are 1cm ×1cm and 3cm×3cm, respectively.**

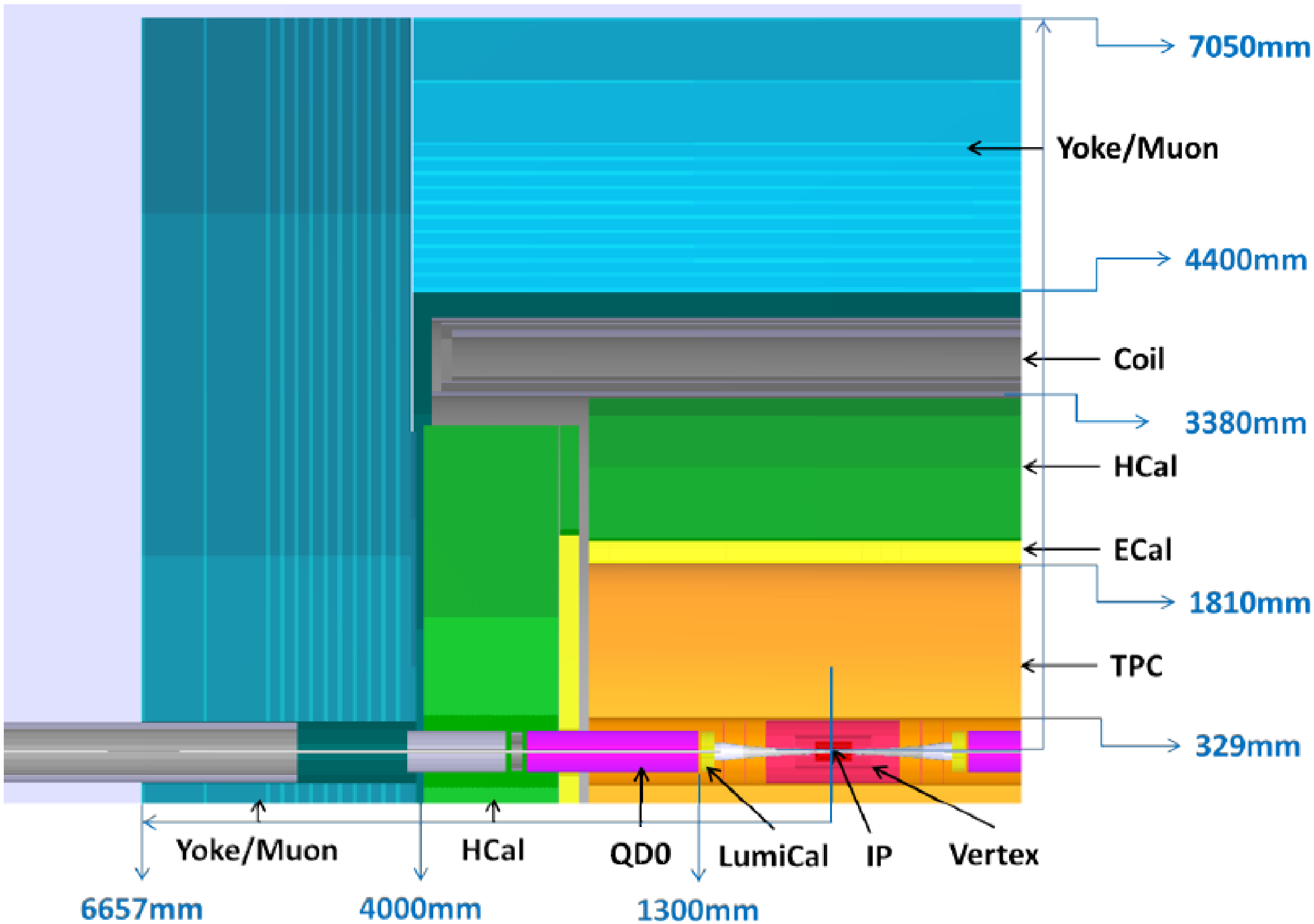
Future plans:

- Optimization of cell size and number of channels
- Design of low power ASIC chip
- Design of active cooling system
- …

Thanks for your attention !

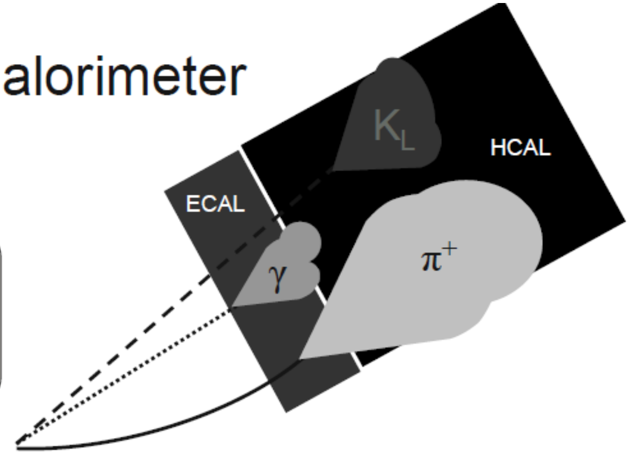
Backup!

Schematic of CEPC Detector



Particle Flow Algorithm

Particle Flow Algorithms and Imaging Calorimeter



The idea…

Charged particles	measured with the	**Tracker**
Neutral particles		**Calorimeter**

Particles in jets	Fraction of energy	Measured with	Resolution [σ^2]
Charged	65 %	Tracker	Negligible
Photons	25 %	ECAL with 15%/$\sqrt{E}$	$0.07^2\ E_{jet}$
Neutral Hadrons	10 %	ECAL + HCAL with 50%/$\sqrt{E}$	$0.16^2\ E_{jet}$
Confusion	Required for 30%/$\sqrt{E}$		$\leq 0.24^2\ E_{jet}$

(Charged + Photons + Neutral Hadrons: 18%/$\sqrt{E}$)

Requirements for detector system

→ Need excellent tracker and high B – field
→ Large R_I of calorimeter
→ Calorimeter inside coil
→ Calorimeter as dense as possible (short X_0, λ_I)
(Calorimeter inside coil; Calorimeter as dense as possible) } **thin active medium**
→ Calorimeter with **extremely fine segmentation**

Particle Flow Algorithm (Arbor)

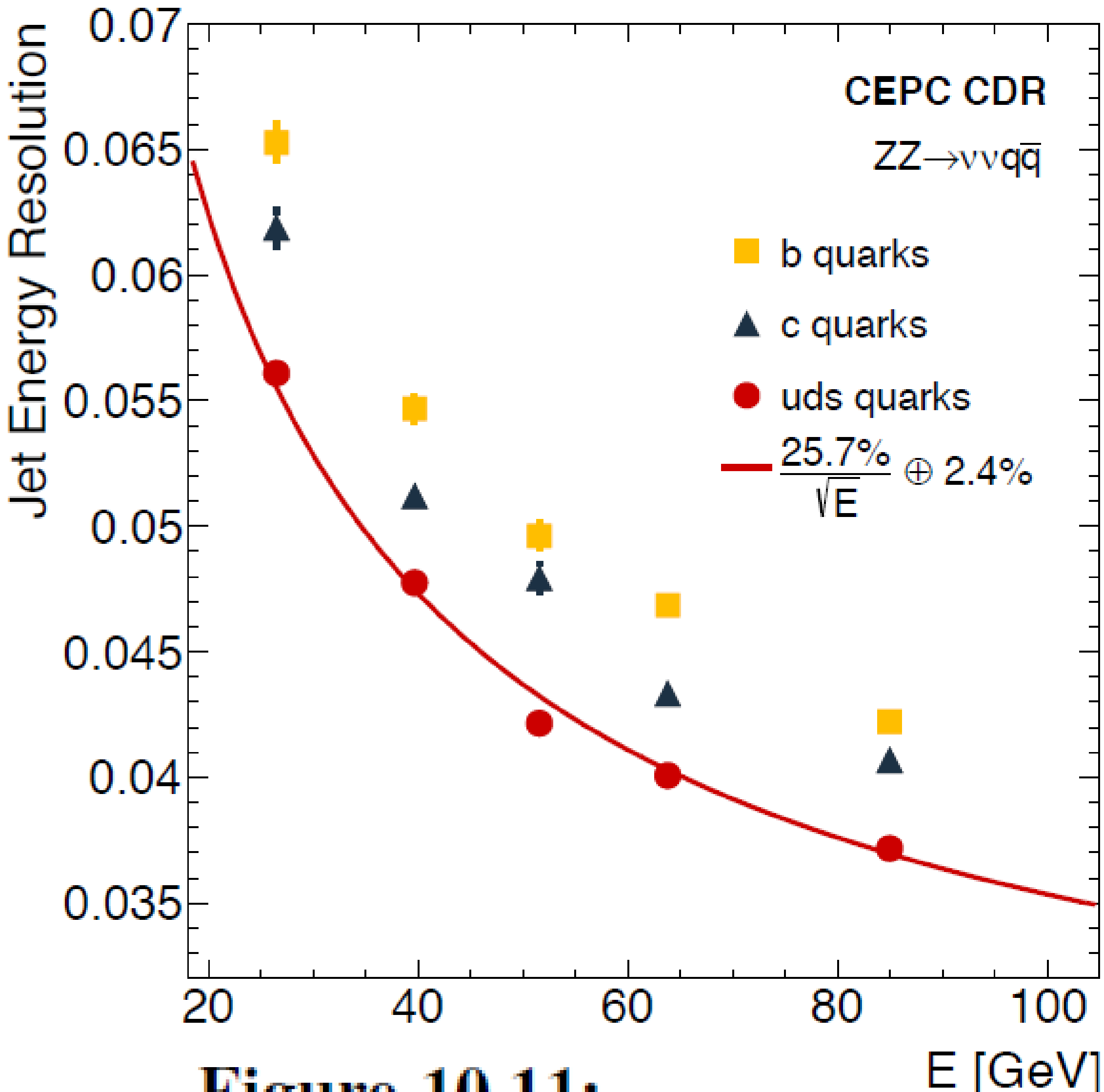


Figure 10.11:

Particle Flow Algorithm (Arbor)

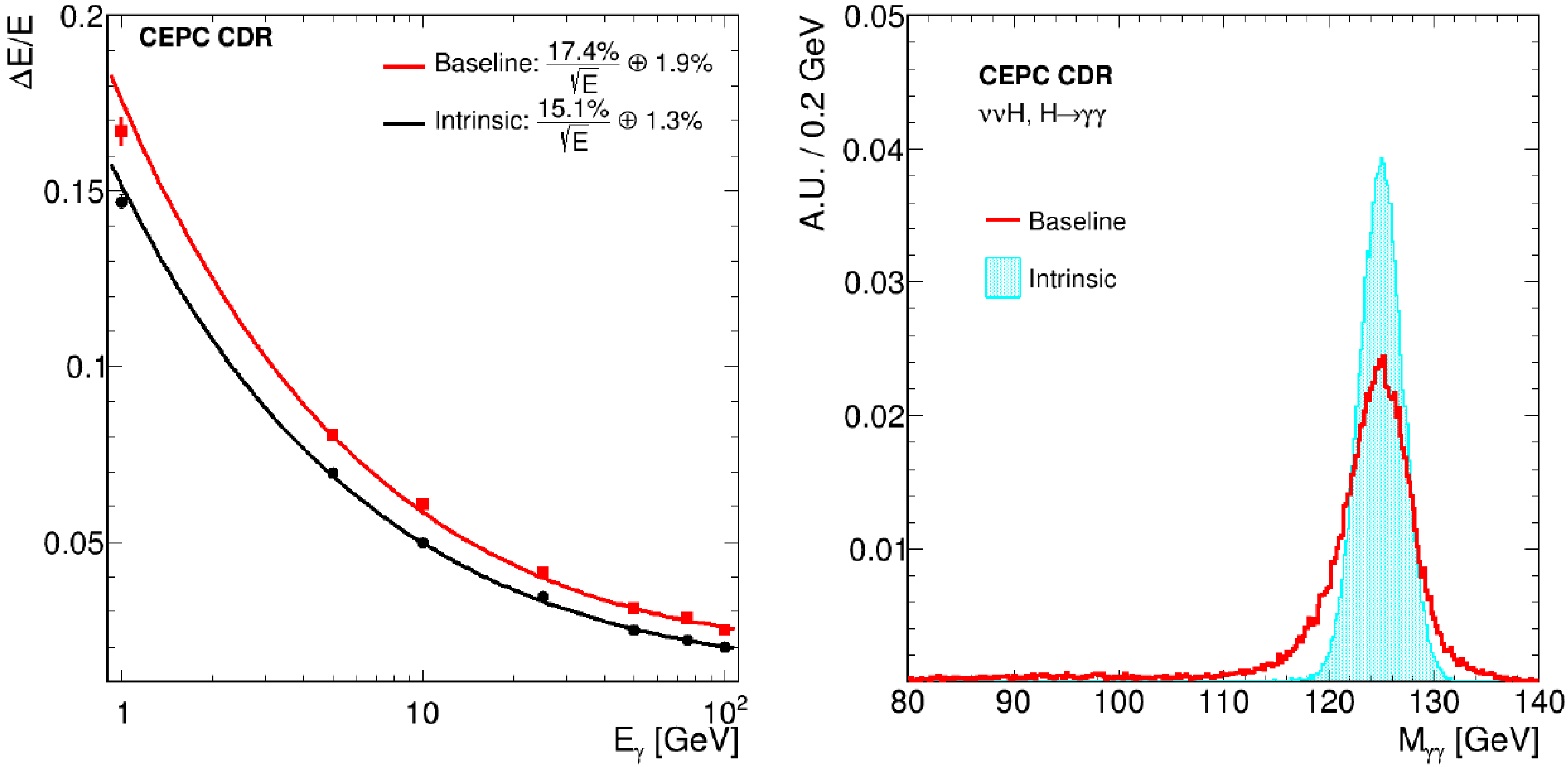


Figure 10.9: (a) The energy resolution of unconverted photons

Data Rate Estimation

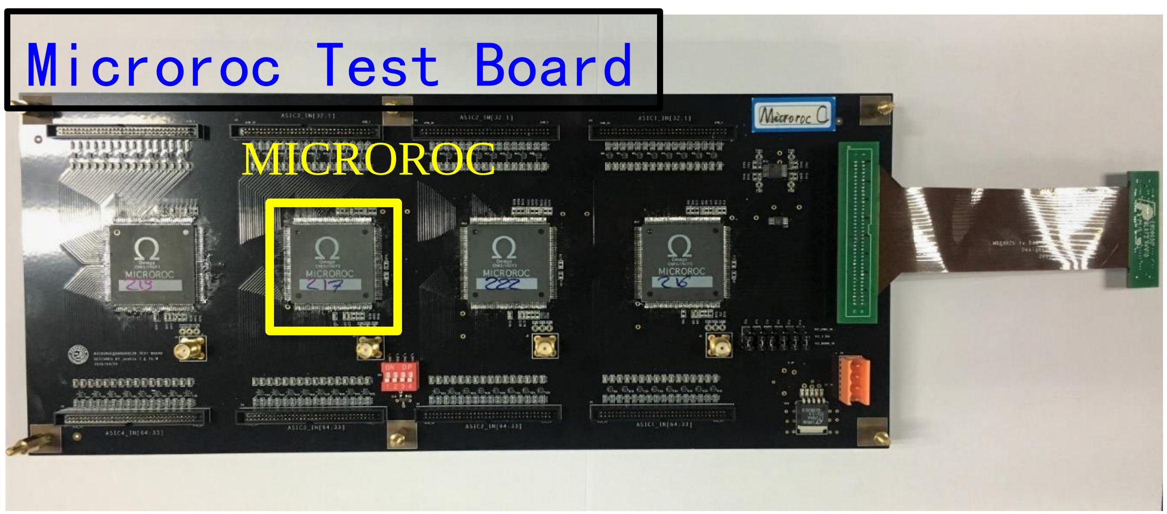
	Total # channels $M(10^6)$	Occupancy %	Nbit /channel	# Channels readout/evt $k(10^3)$	Volume /evt MBytes	Data rate @100 kHz GBytes/s
Vertex	690	0.3	32	2070	8.3	830
Silicon Tracker						
Barrel	3238	$0.01 \sim 1.6$	32	1508	3.15	315
Endcap	1238	$0.01 \sim 0.8$	32	232	0.4	40
TPC	2	0.1-8	30	1375	5	500
Drift Chamber	0.056	5-10	480	?	3	300
ECAL						
Barrel	17/7.7	0.17	32	28.8/13.1	0.117/0.053	11.7/5.3
Endcap	7.3/3.3	0.31	32	22.4/10.2	0.090/0.041	9.0/4.1
AHCAL						
Barrel	3.6	0.02	32	0.72	0.0029	0.3
Endcap	3.1	0.12	32	3.72	0.015	1.5
DHCAL						
Barrel	32	0.004	2	1.28	0.00032	0.03
Endcap	32	0.01	2	3.2	0.0008	0.08
Dual Readout Calorimeter	22	0.4-1.6	64	88-352	0.704-2.8	70-280
Muon						
Barrel	4.9	0.0002	24	0.01	< 0.0001	< 0.01
Endcap	4.6	0.0002	24	0.01	< 0.0001	< 0.01

Table 8.1: CEPC DAQ Data Rate Estimation. TPC and drift chamber are options of outer side tracker. With the level-1 trigger operating at 100 kHz, the total raw data rate is 2 TBytes/s.

Readout ASIC

Readout ASIC	Channels	Dynamic Range	Threshold	Consumption
GASTONE	64	200fC	Single	2.4mW/ch
VFAT2	128	18.5fC	Single	1.5mW/ch
DIRAC	64	200fC for MPGD	Multiple	1mW/ch, 10μW/ch
DCAL	64	20fC~200fC	Single	——
HARDROC2	64	10fC~10pC	Multiple	1.42mW/ch,10μW/ch
MICROROC	64	1fC~500fC	Multiple	335μW/ch, 10μW/ch

Considered the multi-thresholds readout, dynamic range and power consumption, MICROROC is an appropriate readout ASIC



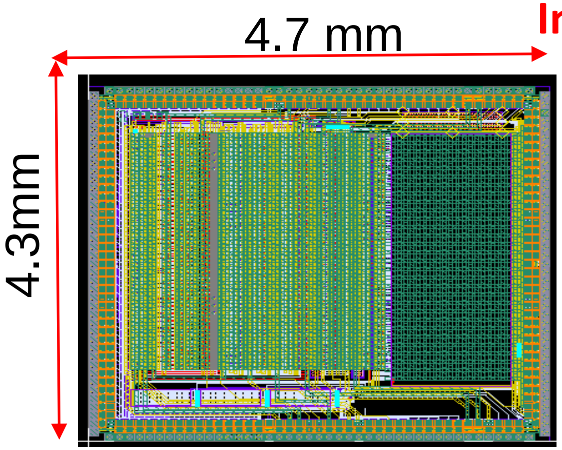
MICROROC Parameters

- Thickness: 1.4mm
- 64 Channels
- 3 threshold per channel
- 128 hit storage depth
- Minimum distinguishable charge:2fC

Electronics Readout

Imad Laktineh (IPNL)

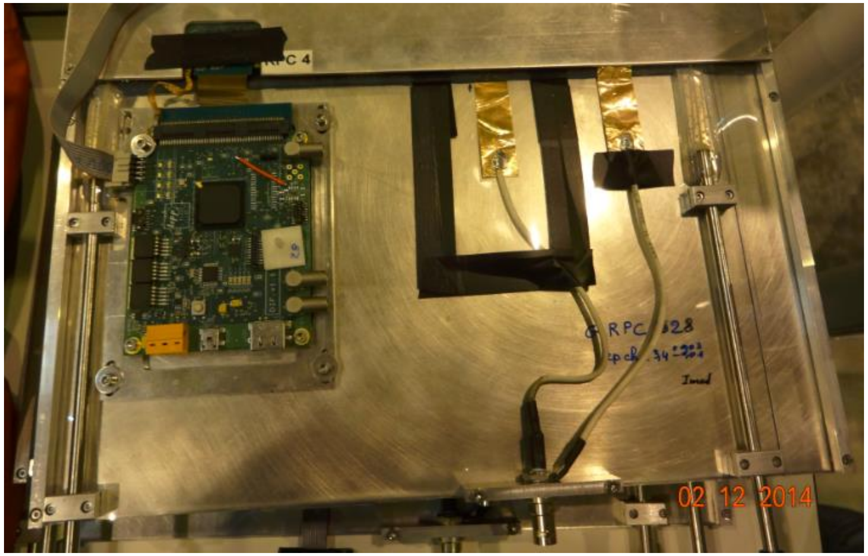
ASICs : HARDROC2
64 channels
Trigger less mode
Memory depth : 127 events
3 thresholds
Range: 10 fC-15 pC
Gain correction → uniformity



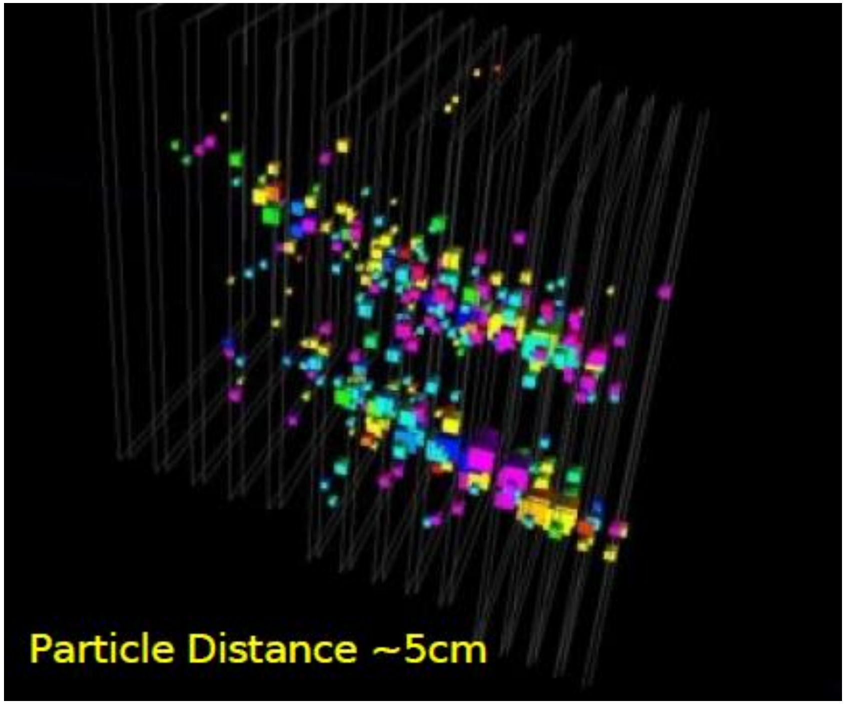
Printed Circuit Boards (PCB) were designed to reduce the cross-talk with 8-layer structure and buried vias.

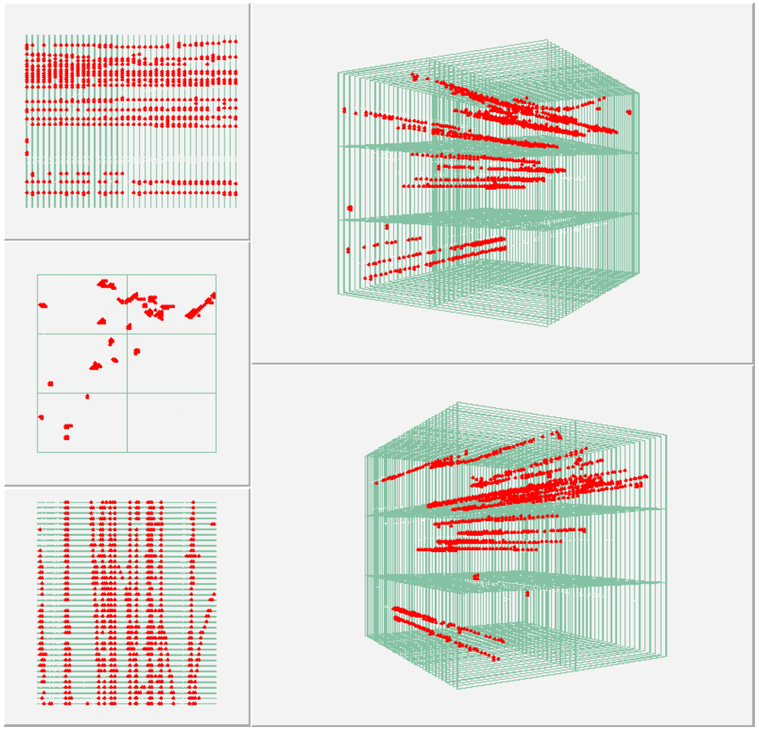
Tiny connectors were used to connect the PCB two by two so the 24X2 ASICs are daisy-chained. 1×1m^2 has 6 PCBs and 9216 pads.

DAQ board (DIF) was developed to transmit fast commands and data to/from ASICs.



Imaging Calorimeters





Two electrons ~ 5cm apart
CALICE SiW ECAL

~20 muons in 1m^2 area
CALICE RPC DHCAL

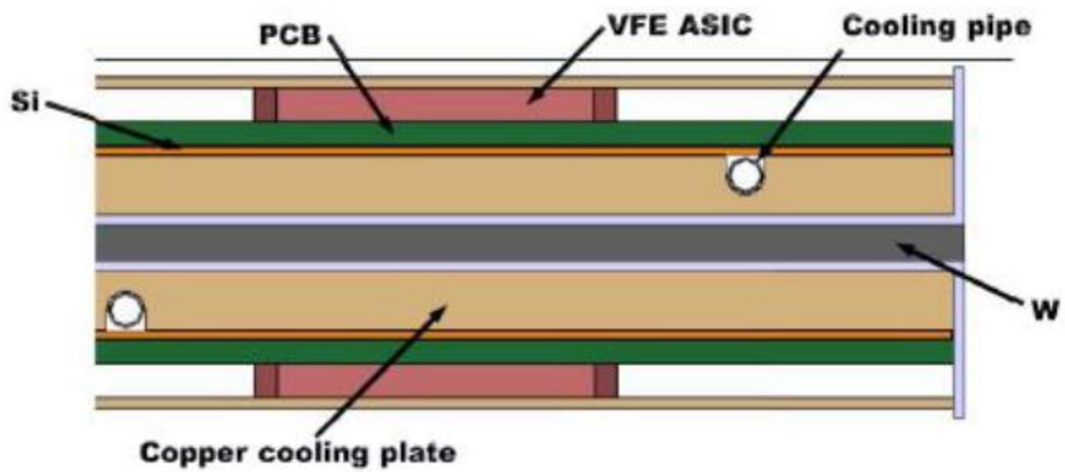
This is exactly what PFA needs: distinguishing individual showers within jet environment, in order to get excellent jet energy/mass resolution

Active Cooling

- CEPC is designed to operate at continuous mode with beam crossing rate: 2.8×10^5 Hz. Power pulsing will not work at CEPC.
- Compare to ILD, the power consumption of VFE readout electronics at CEPC is about two orders of magnitude higher, hence it requires an active cooling
    - Evaporative CO_2 cooling in thin pipes embedded in Copper exchange plate.
    - For CMS-HGCAL design: heat extraction of 33 mW/cm^2, allows operation with 6×6 mm^2 pixels with a safety margin of 2
- To be modelled for Mokka simulation

→ Transverse view of the slab with one absorber and two active layers.

→ The silicon sensors are glued to PCB with VFE chips, cooled by the copper plates with CO_2 cooling pipes.



Extra Info

No.	Detector Cell	MPPC Type	Reflective Foil Type	Mean $N_{p.e.}$	Polishing Methods
1	30×30×3mm^3	S12571-025P	ESR	31.39±0.65	Ultra Precise Polishing
2	30×30×3mm^3	S12571-025P	ESR	22.55±0.7	Precise Polishing
3	30×30×3mm^3	S12571-025P	ESR	18.92±0.39	Rough Polishing
4	30×30×3mm^3	S12571-025P	TYVEK	13.63±0.33	Precise Polishing
5	40×40×3mm^3	S12571-025P	ESR	14.89±0.73	Precise Polishing
6	50×50×3mm^3	S12571-025P	ESR	9.87±0.43	Precise Polishing
7	30×30×2mm^3	S13360-1325PE	ESR	33.89±0.49	Precise Polishing

Material	λ_I(cm)	X_0(cm)	λ_I/X_0
Fe	16.77	1.76	9.5
Pb	17.09	0.56	30.52
W	9.95	0.35	28.4

Calorimeter: key of PFA concept

- Ecal baseline
  - 30 layers
  - Cell size: $1 \times 1\text{cm}^2$
  - 24 X_0
- Hcal baseline
  - 40 layers
  - $\lambda_I = 4.9$