CEPC Hadron Calorimeters

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for CEPC Calo Working Group

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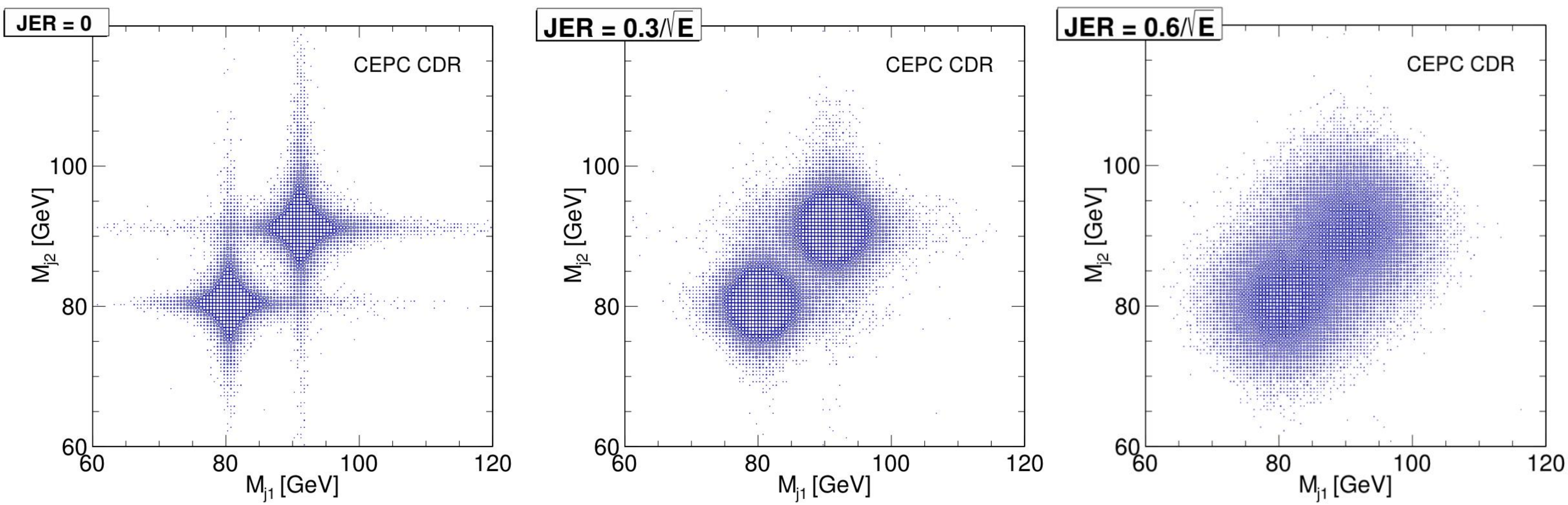
Outline

- **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**

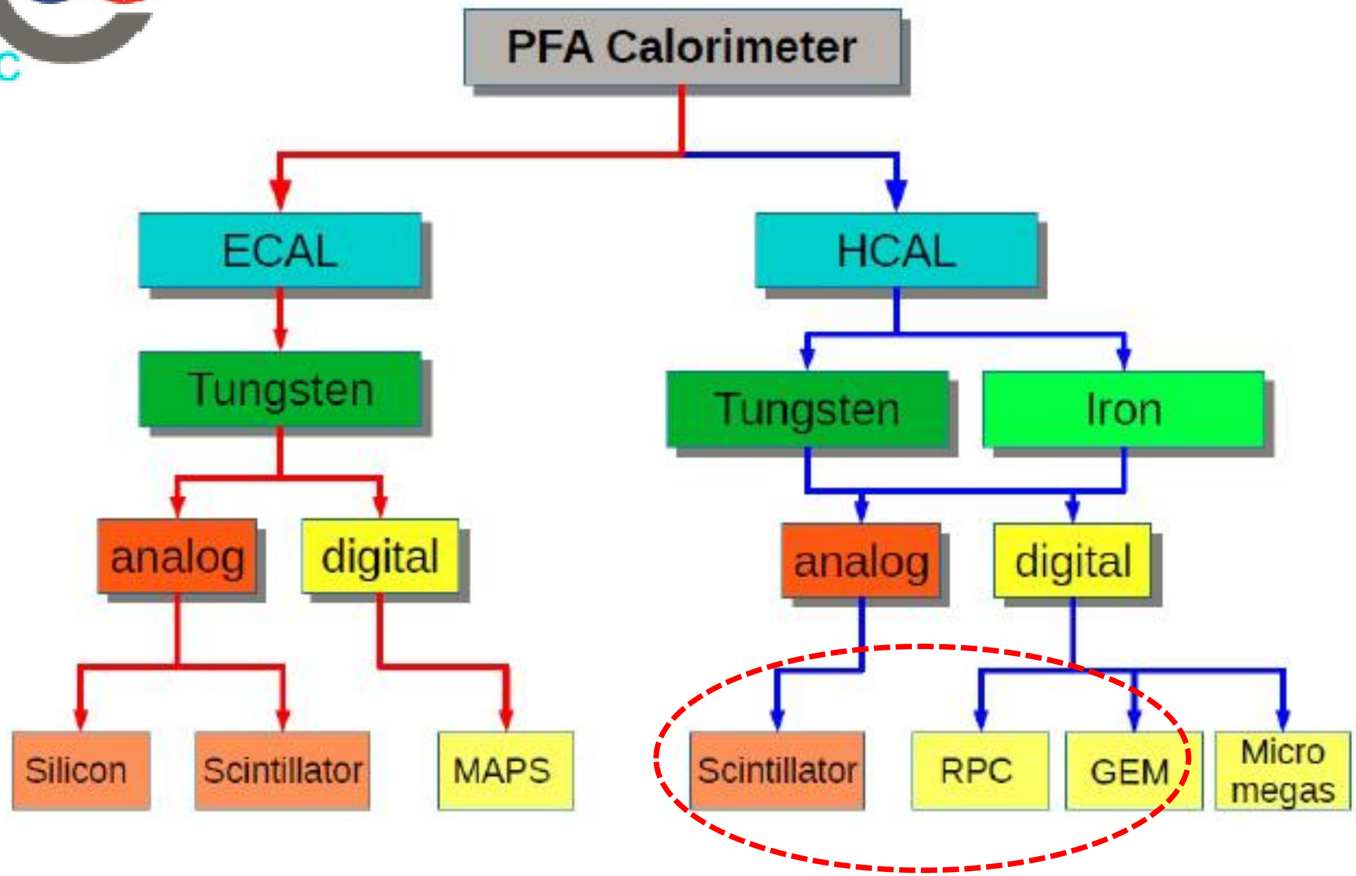
Requirements of CEPC Calorimeters

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



AHCAL: Scintillator + SiPM

DHCAL: RPC & MPGD

Major Contributors for CEPC HCAL

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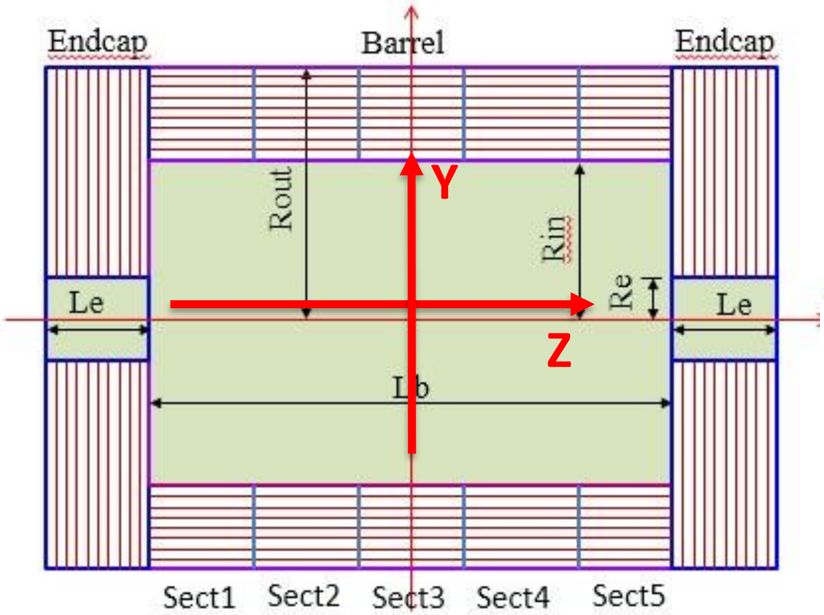
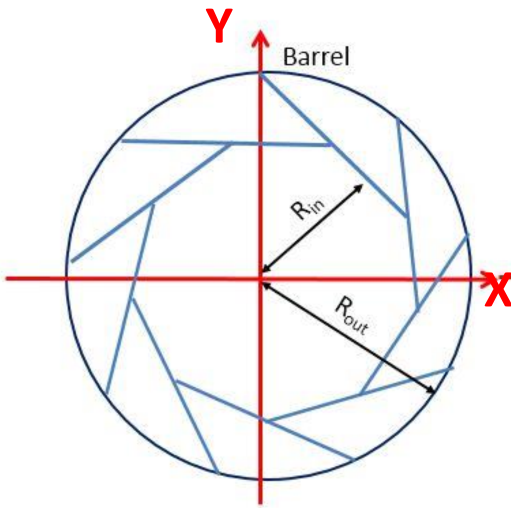
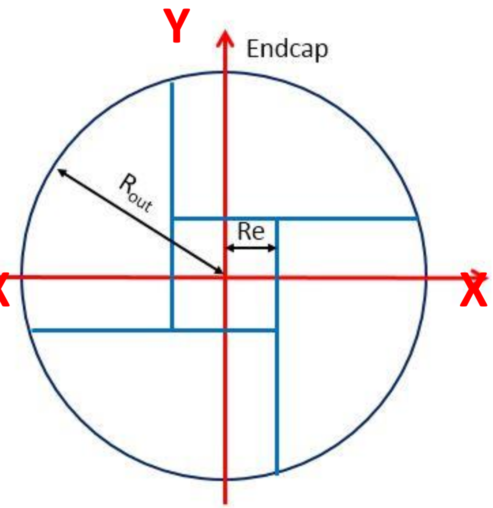
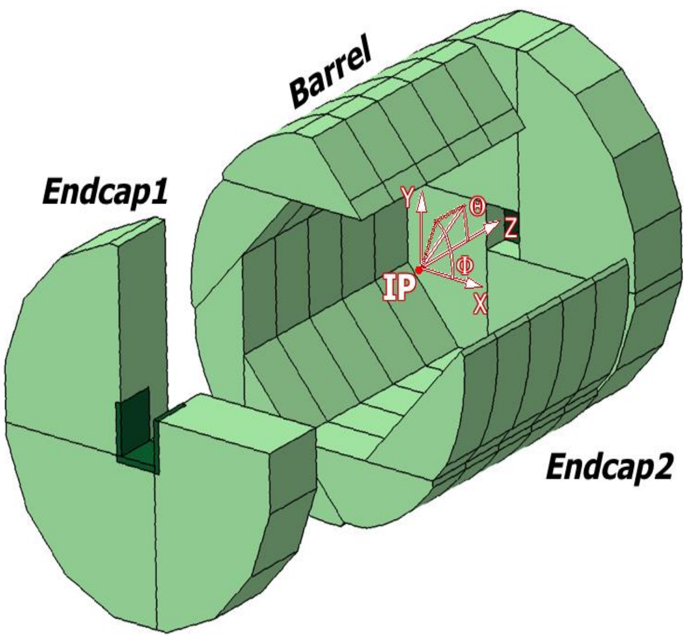
CEPC HCAL Geometry



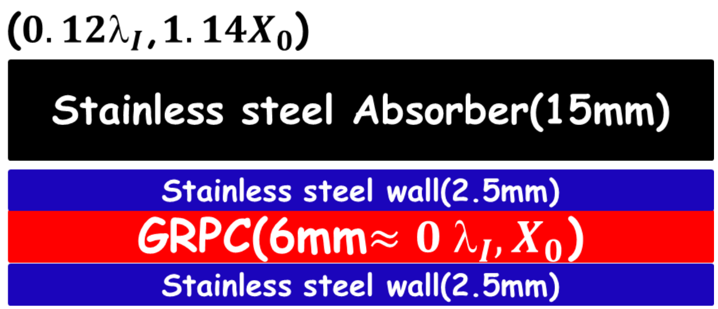




- Inner radius in X-Y plane R_{in} = 2300mm
- Outer radius R_{out} = 3340mm
- Inner & outer of HCAL endcap in Z-axis are 2670mm and 3710mm

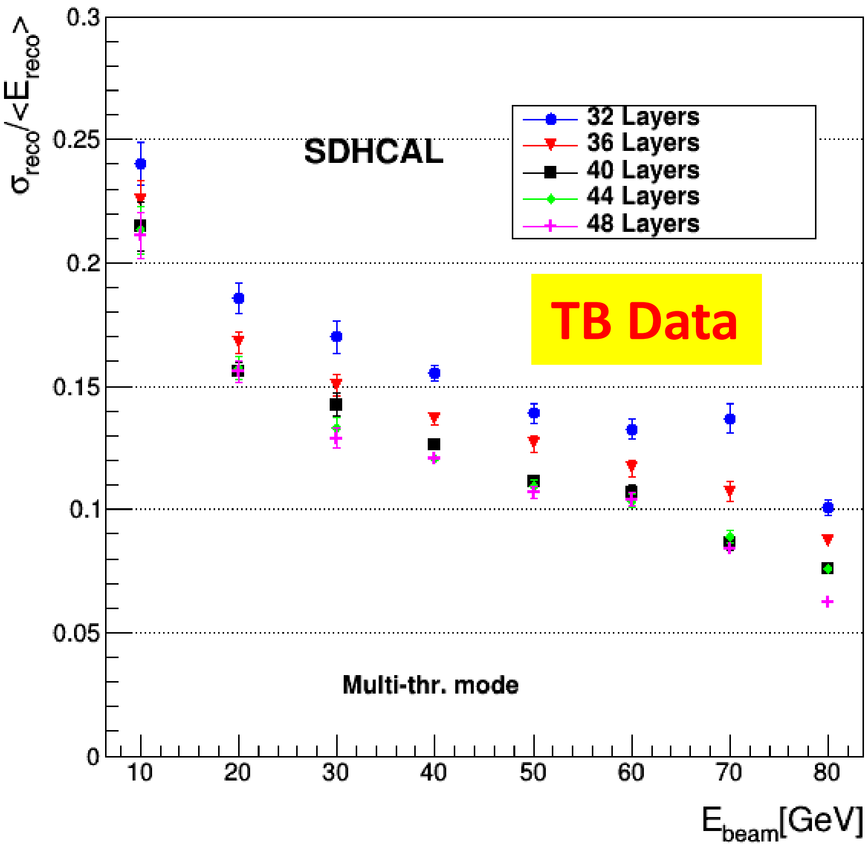


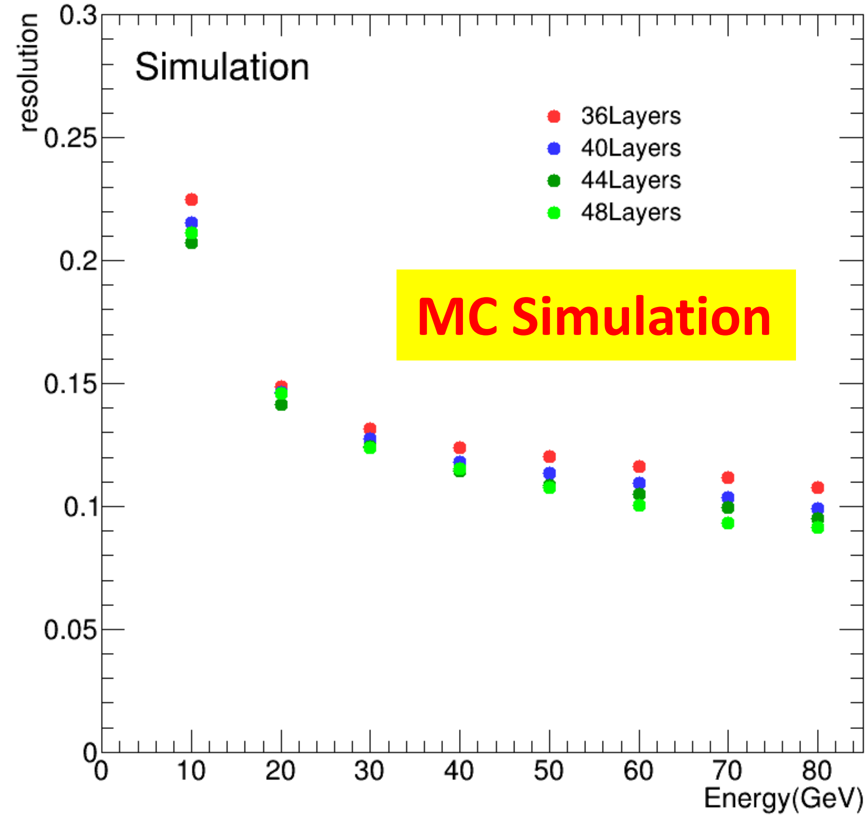
Optimization of SDHCAL Layers



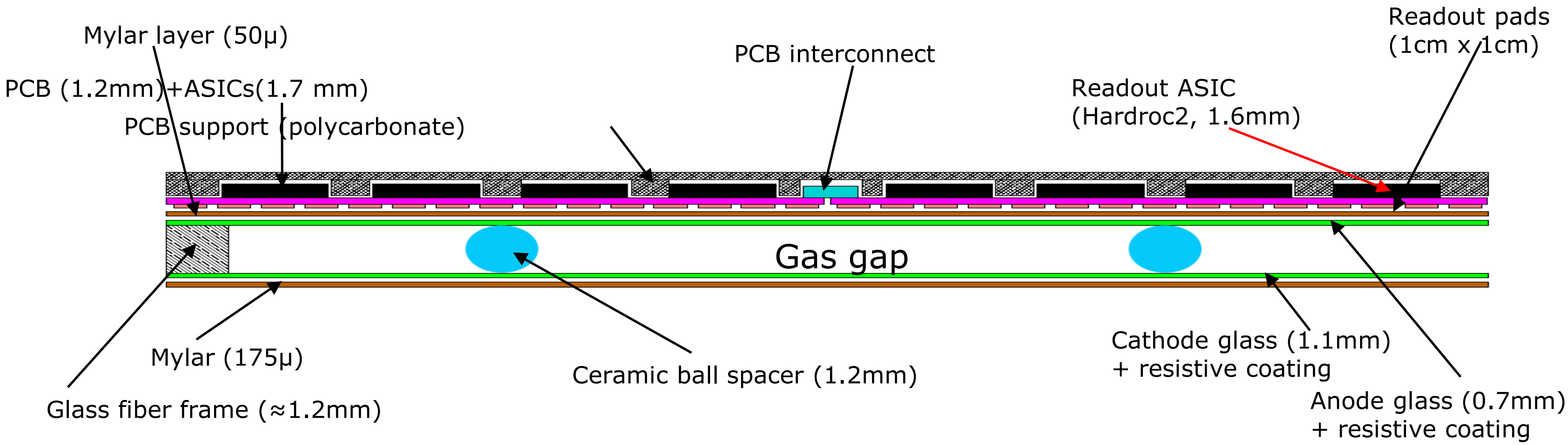
➔SDHCAL has 48 layers:
- 6mm RPC+20mm absorber

➔40-layer SDHCAL yields decent energy resolution.





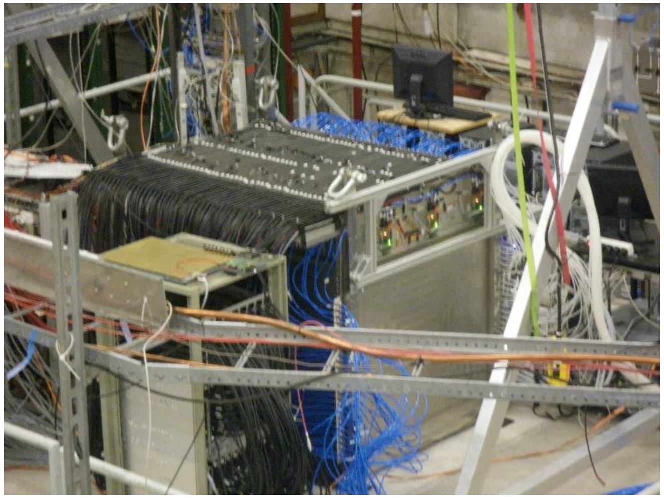
SDHCAL based on RPC



Large GRPC R&D

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

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



$(0.12\lambda_I, 1.14X_0)$

Stainless steel Absorber(15mm)

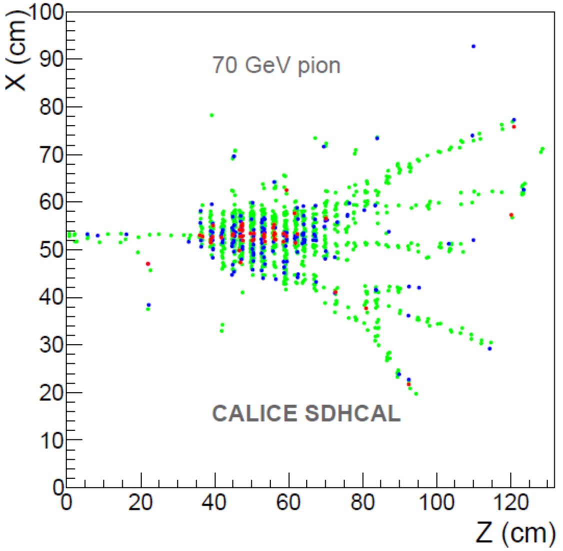
Stainless steel wall(2.5mm)

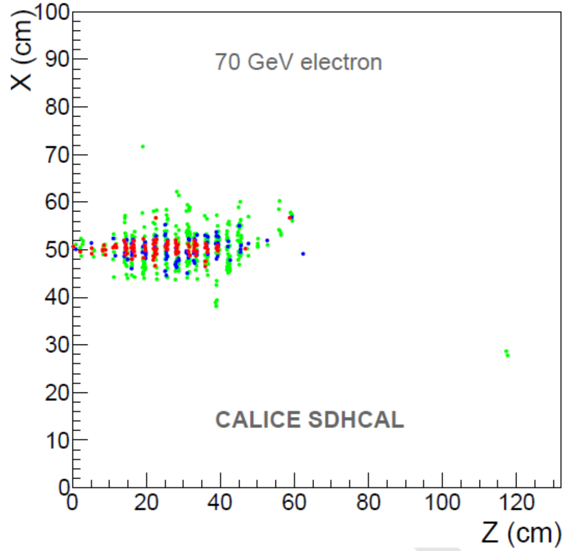
GRPC(6mm$\approx 0\ \lambda_I, X_0$)

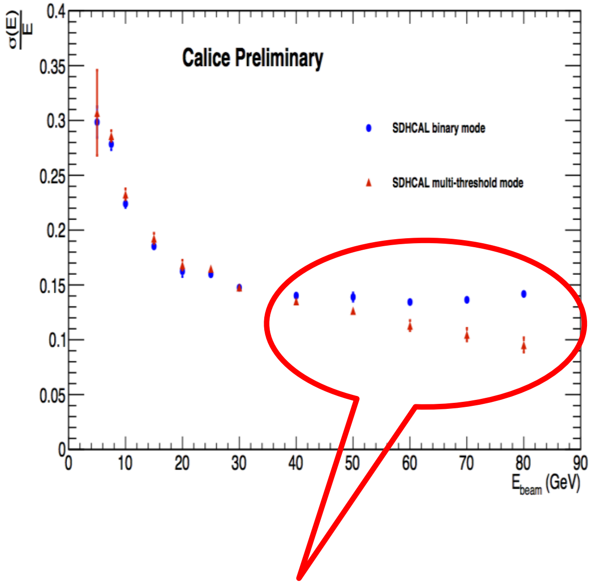
Stainless steel wall(2.5mm)

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

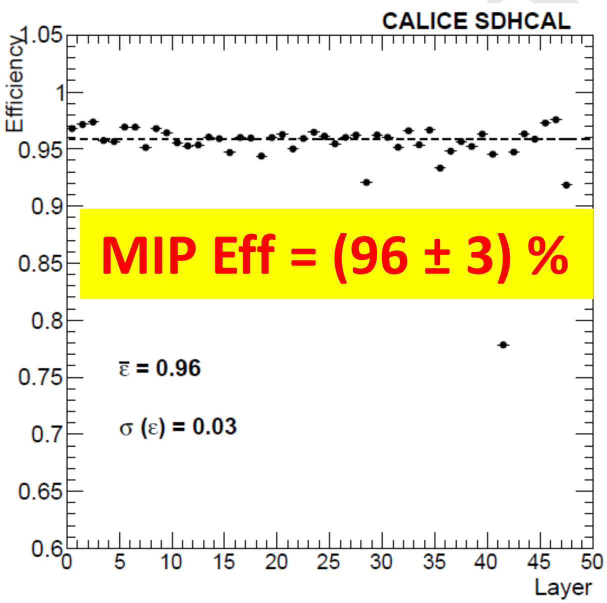
SDHCAL based on RPC



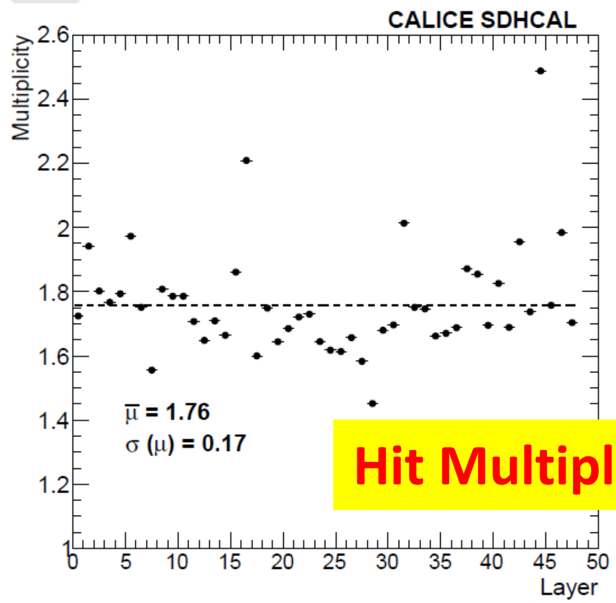




SDHCAL with 3-threshold results in better energy resolution than binary mode for E_{beam} > 40 GeV

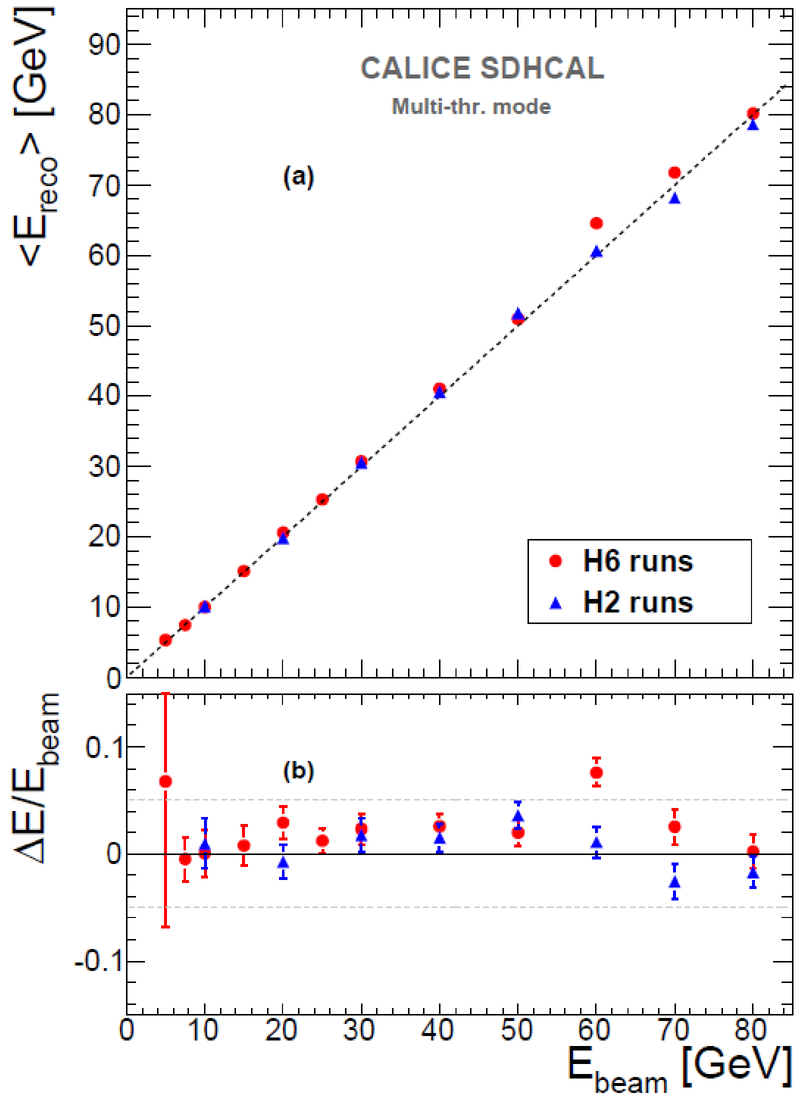


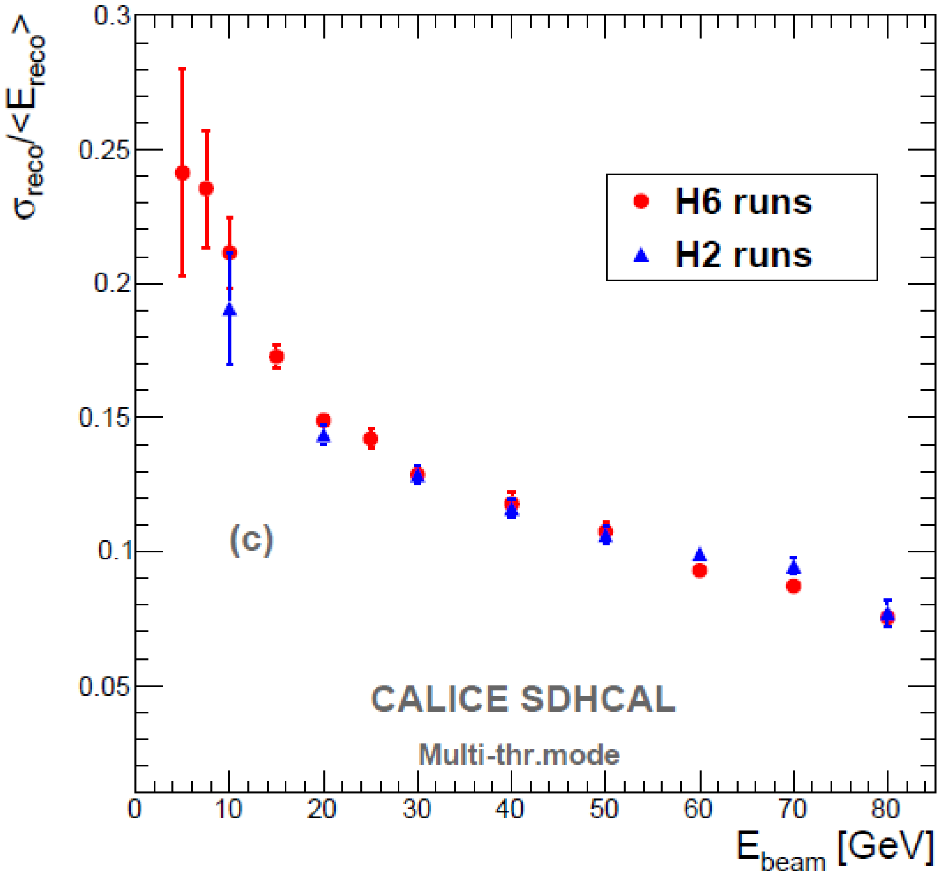
MIP Eff = (96 ± 3) %



Hit Multiplicity = 1.76 ± 0.17

SDHCAL based on RPC

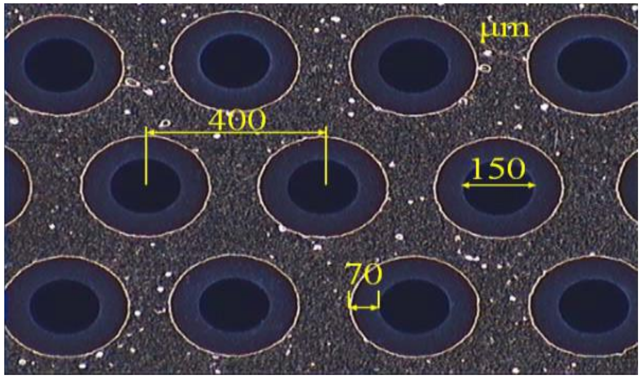


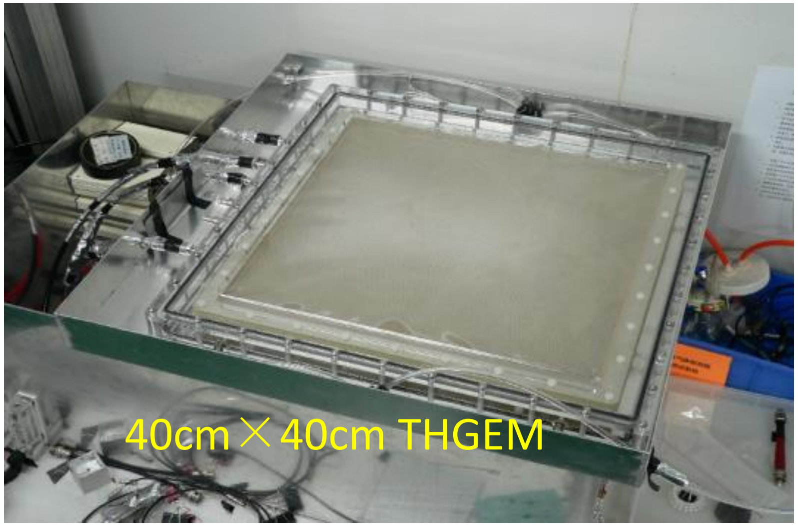


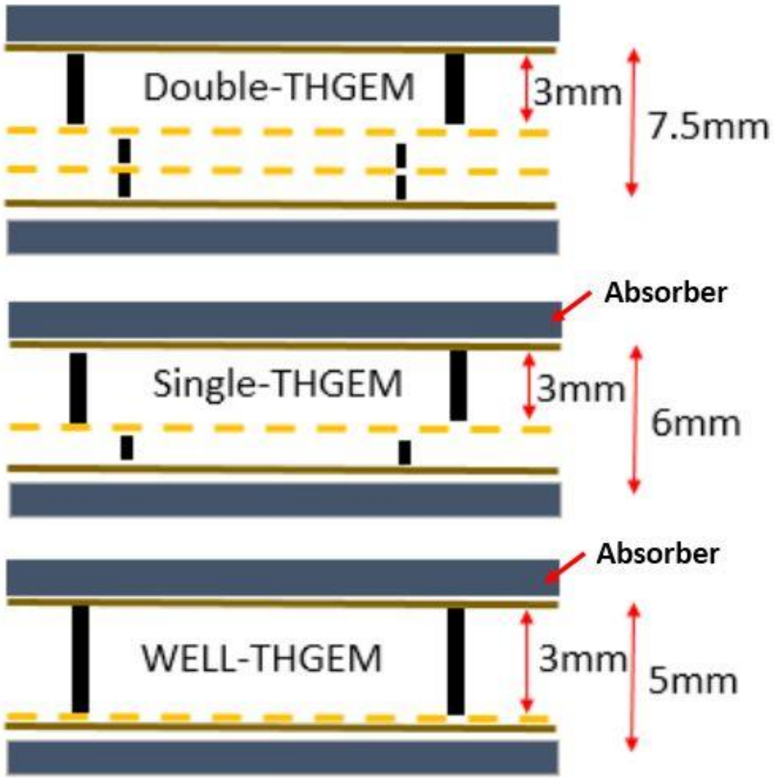
Relative Energy resolution vs E_{beam}

DHCAL based on THGEM

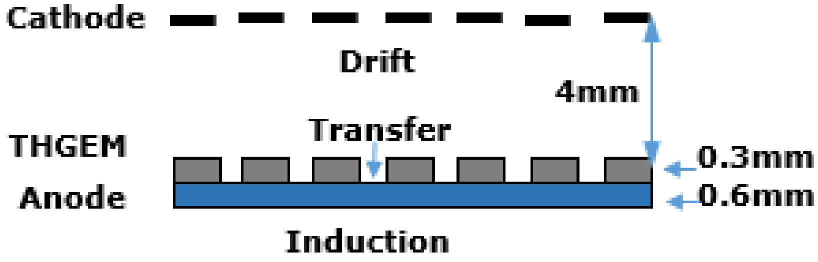
- Three THGEM options are explored:
  - Double - THGEM
  - Single - THGEM
  - WELL - THGEM
- WELL-THGEM is optimal choice
  Thinner, lower discharge
- 40×40 cm^2 of THGEM (below) was produced in China



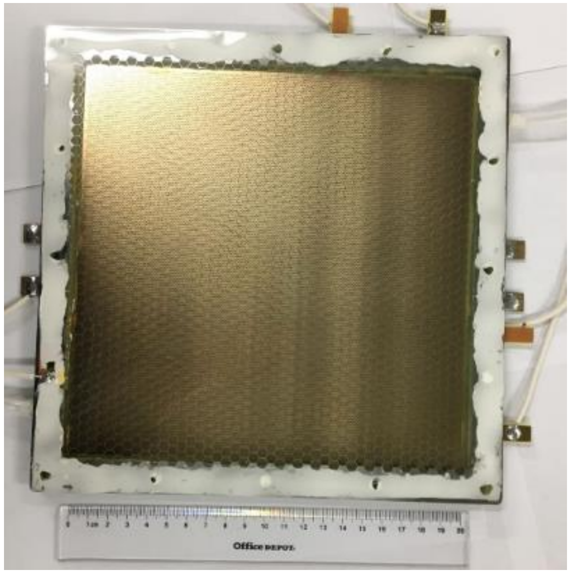


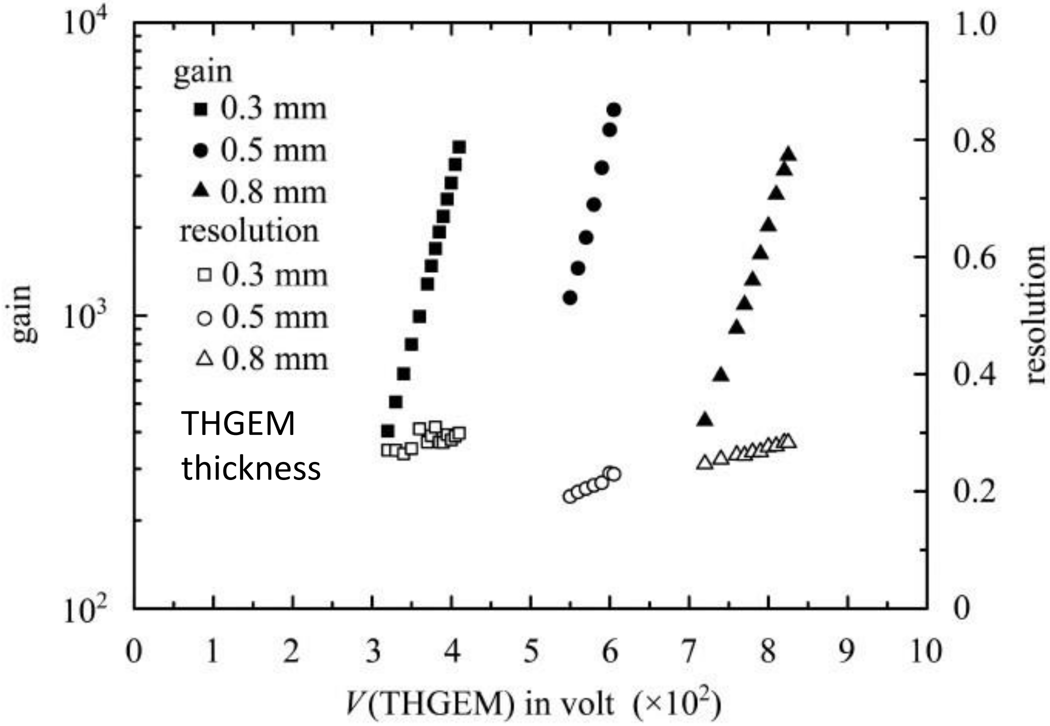


DHCAL based on THGEM



20cm×20cm WELL-THGEM



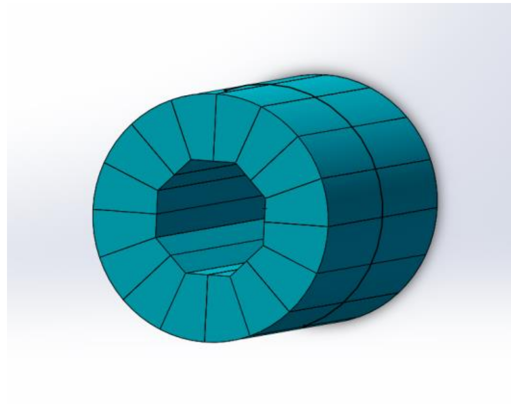


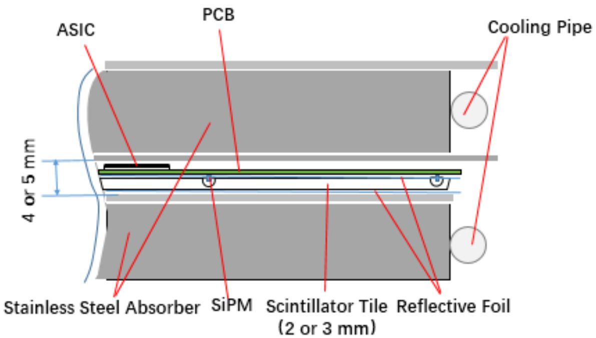
WELL-THGEM: gain ~ 5000, high rate ~ 1 MHz, MIP eff > 95%

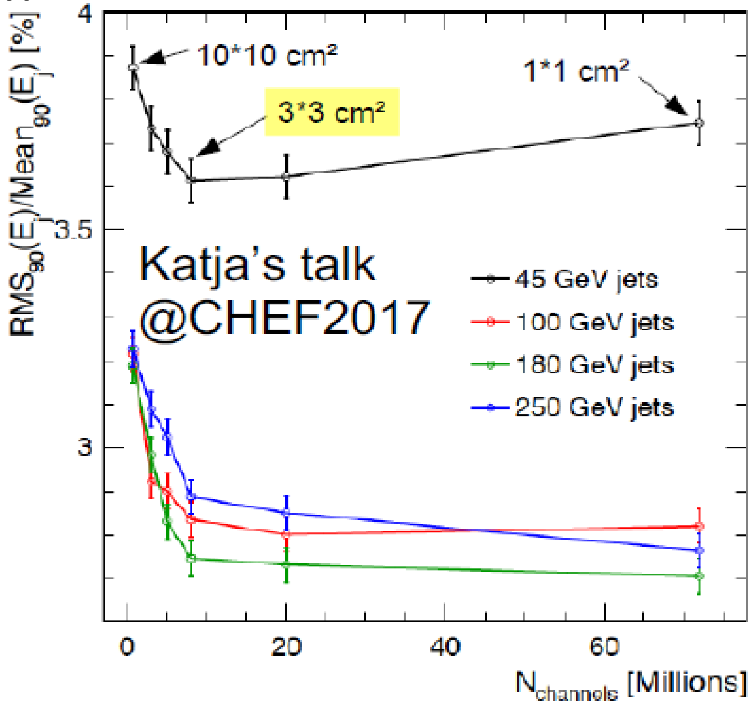
AHCAL based on Scintillator + SiPM

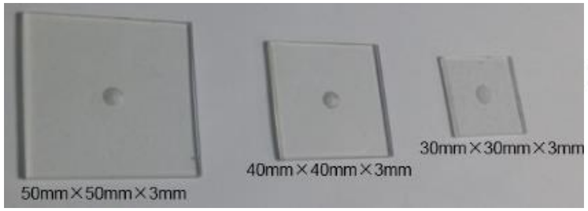
AHCAL (Scintillator + SiPM) for CEPC

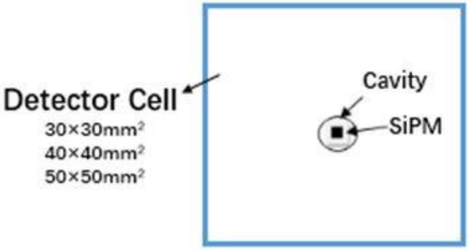
- Scintillator cell size: **3cm x 3cm**, 4cm x 4cm, 5cm x 5cm
- 32 super modules (16+16) in barrel region
- Number of layers: 40
- Each active layer + readout ~ 5mm
- Each absorber (stainless steel) ~ 20mm

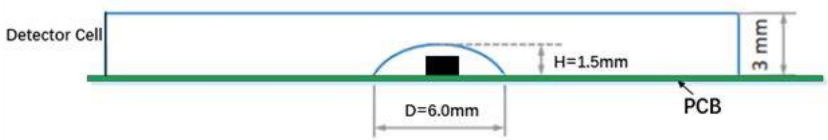




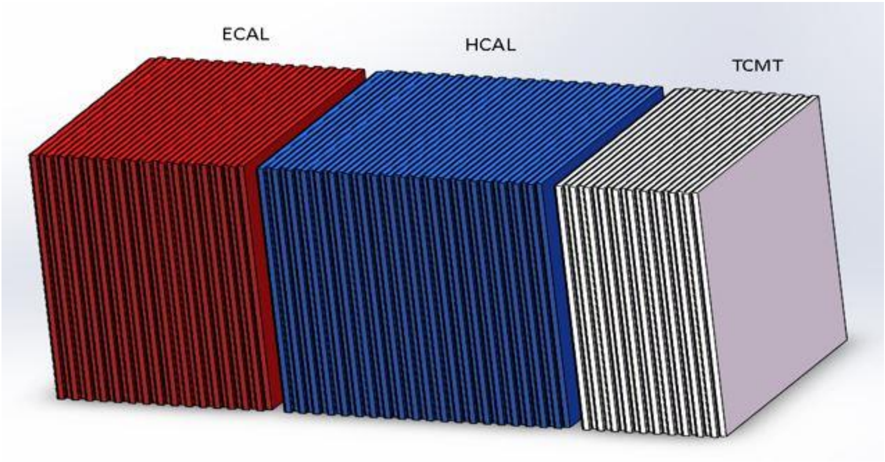


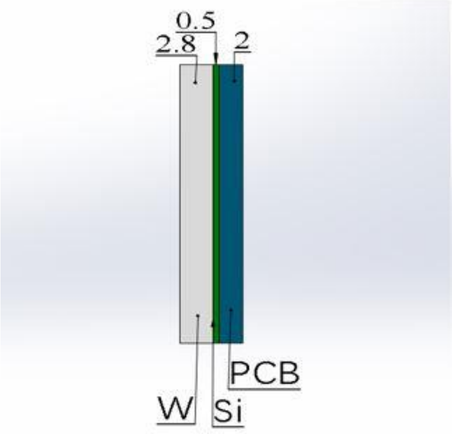


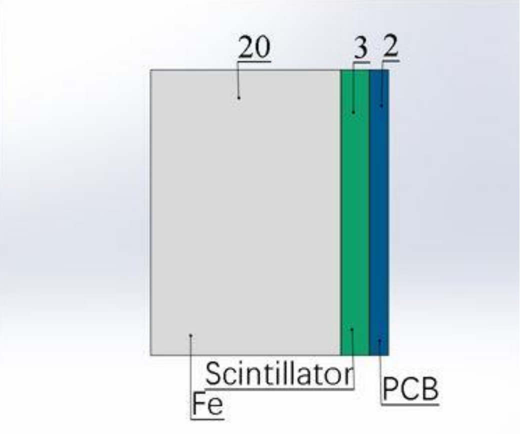


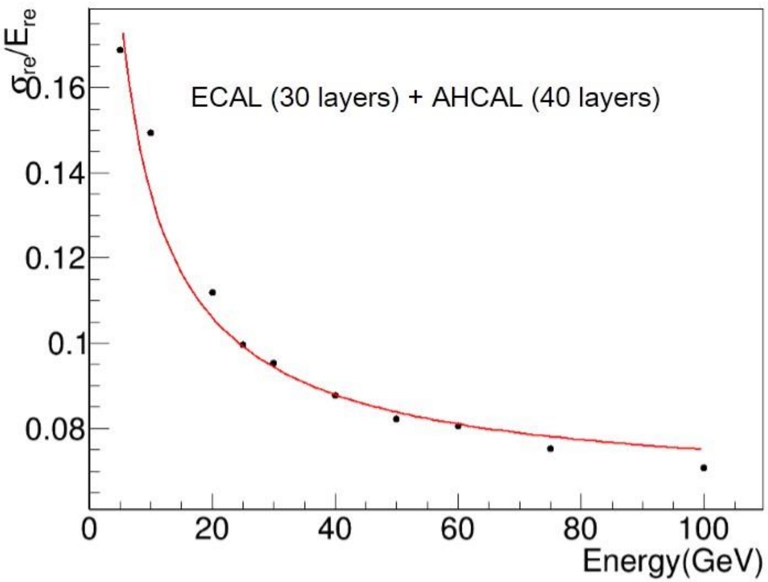


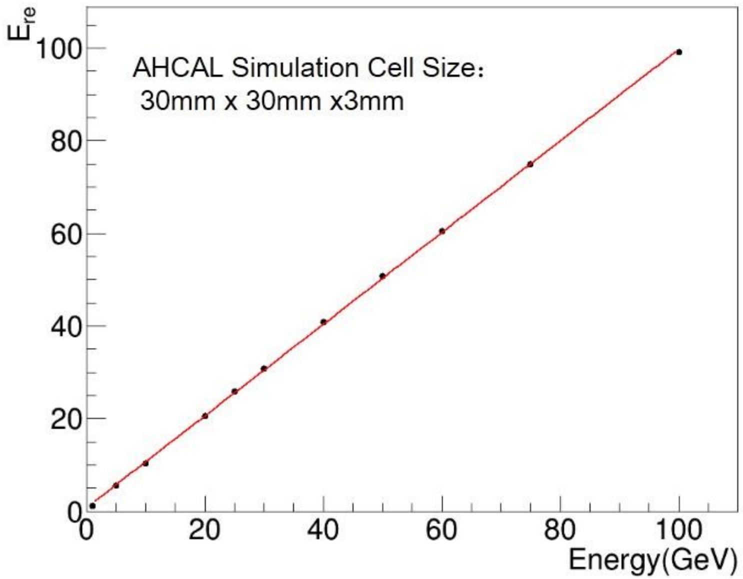
AHCAL based on Scintillator + SiPM







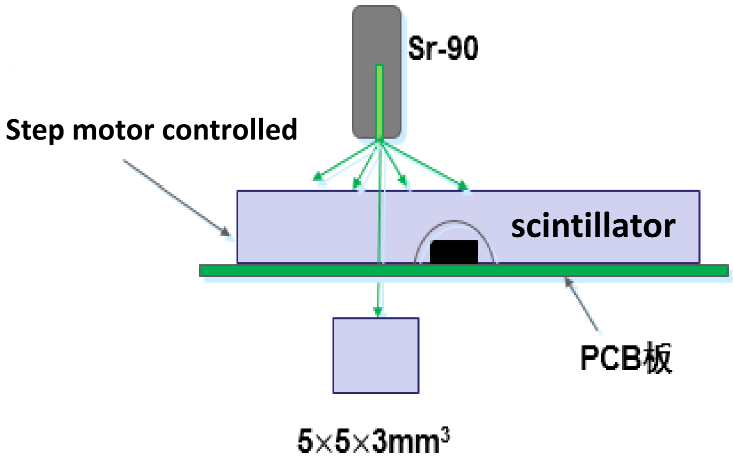


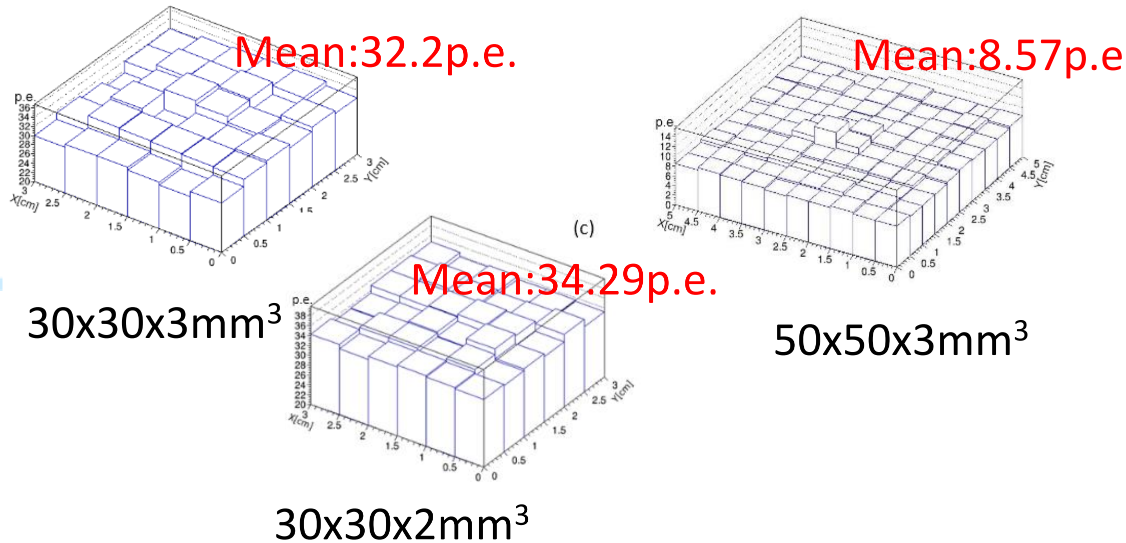


Relative energy resolution vs E_{beam}

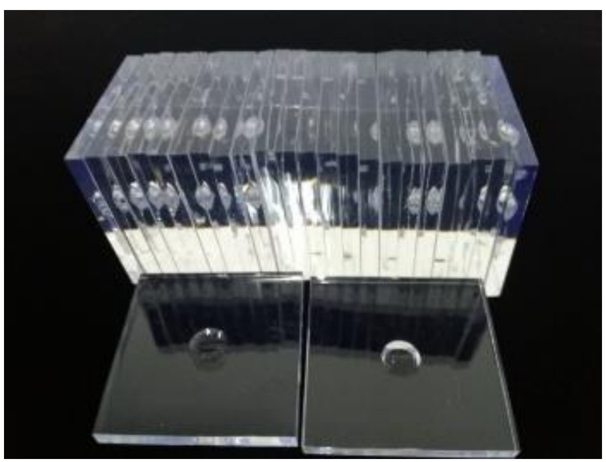
Energy linearity vs E_{beam}

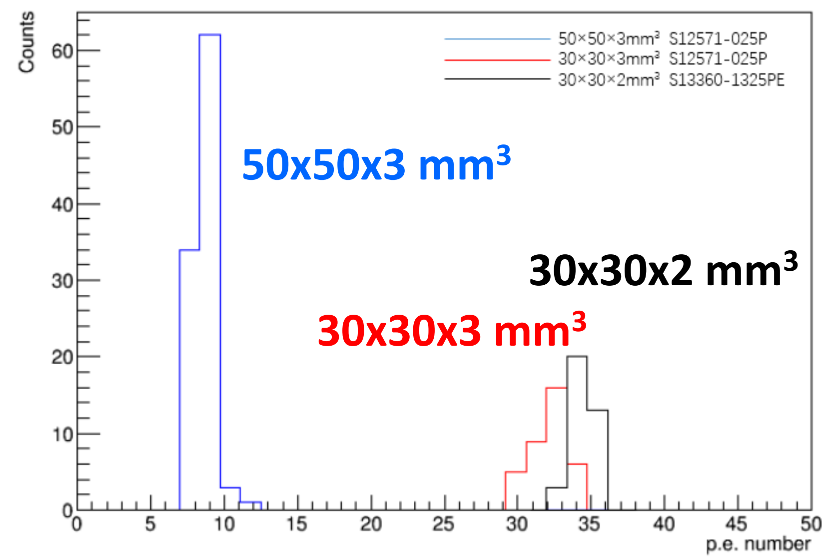
Test: Scintillator + SiPM





- **Test of Uniformity**
- **MIP detection eff. ~ 98%**

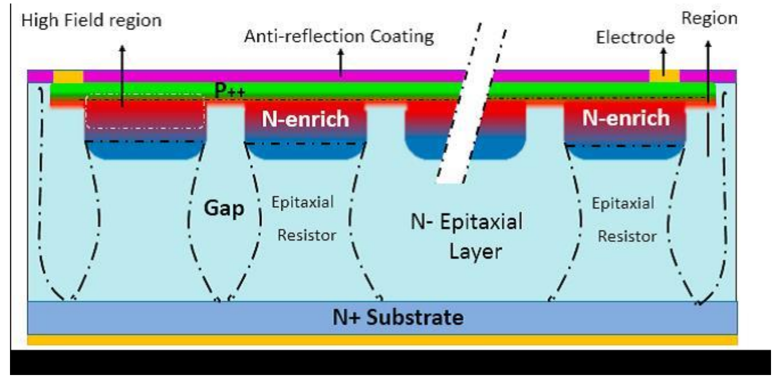




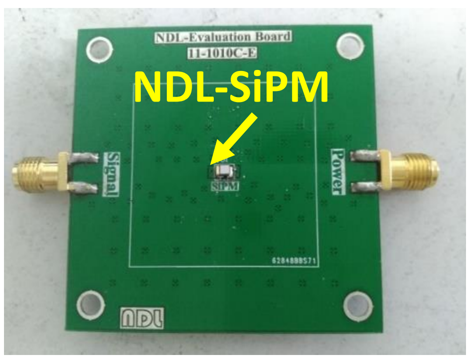
Development of SiPM

Hamamatsu MPPC vs NDL EQR SiPM (epitaxial quenching resistors)

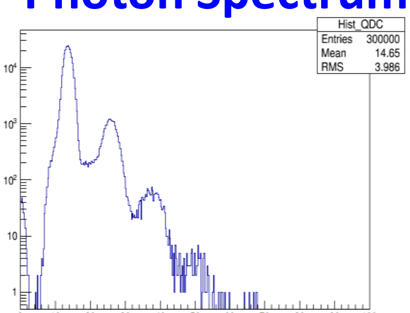
- Short recovery time
- High counting rate capability



NDL-SiPM 11-1010C



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	

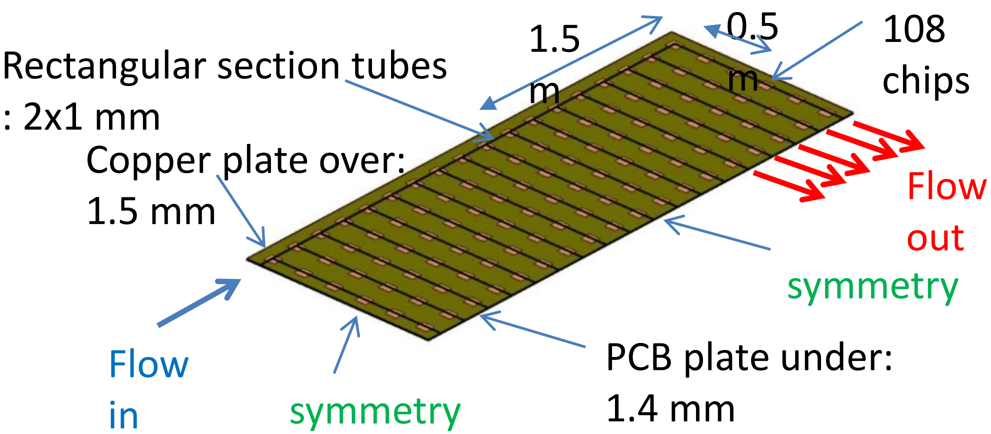
Power Consumption (rough estimation):

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

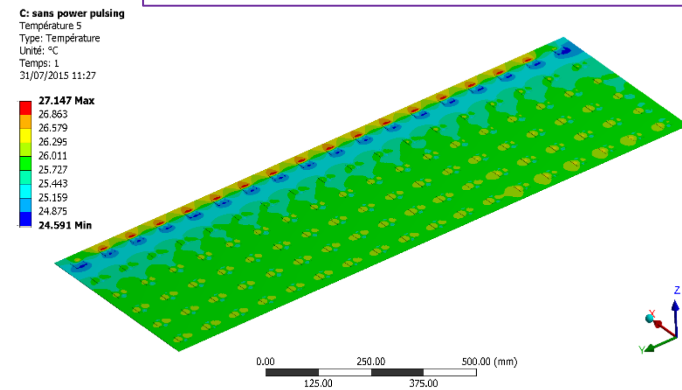
SDHCAL: 1mW/ch * N_{ch1} + 5.4W/DIF/m^2 * 6554 (35.4kW)

Active Cooling

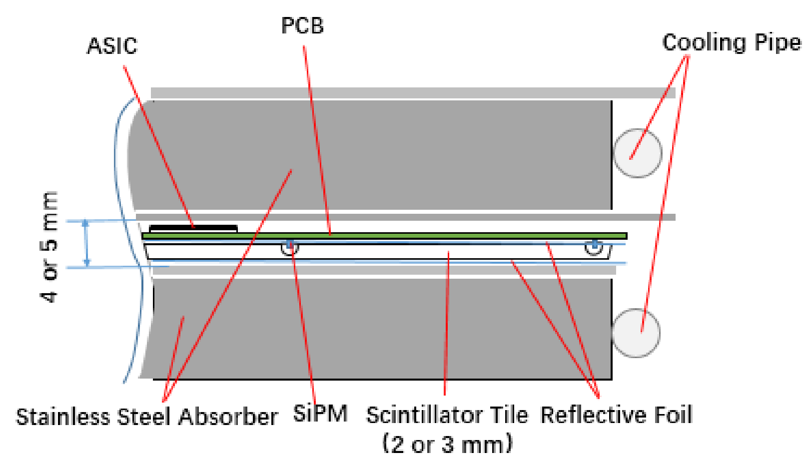
Cooling may become necessary if it is operating at continuous mode (CEPC)



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 and Analog HCAL are considered as options of CEPC hadron calorimeter, both conceptual designs with 40 layers can reach comparable energy resolution.**
- **Baseline cell size for SDHCAL and AHCAL are 1cm ×1cm and 3cm×3cm, respectively.**

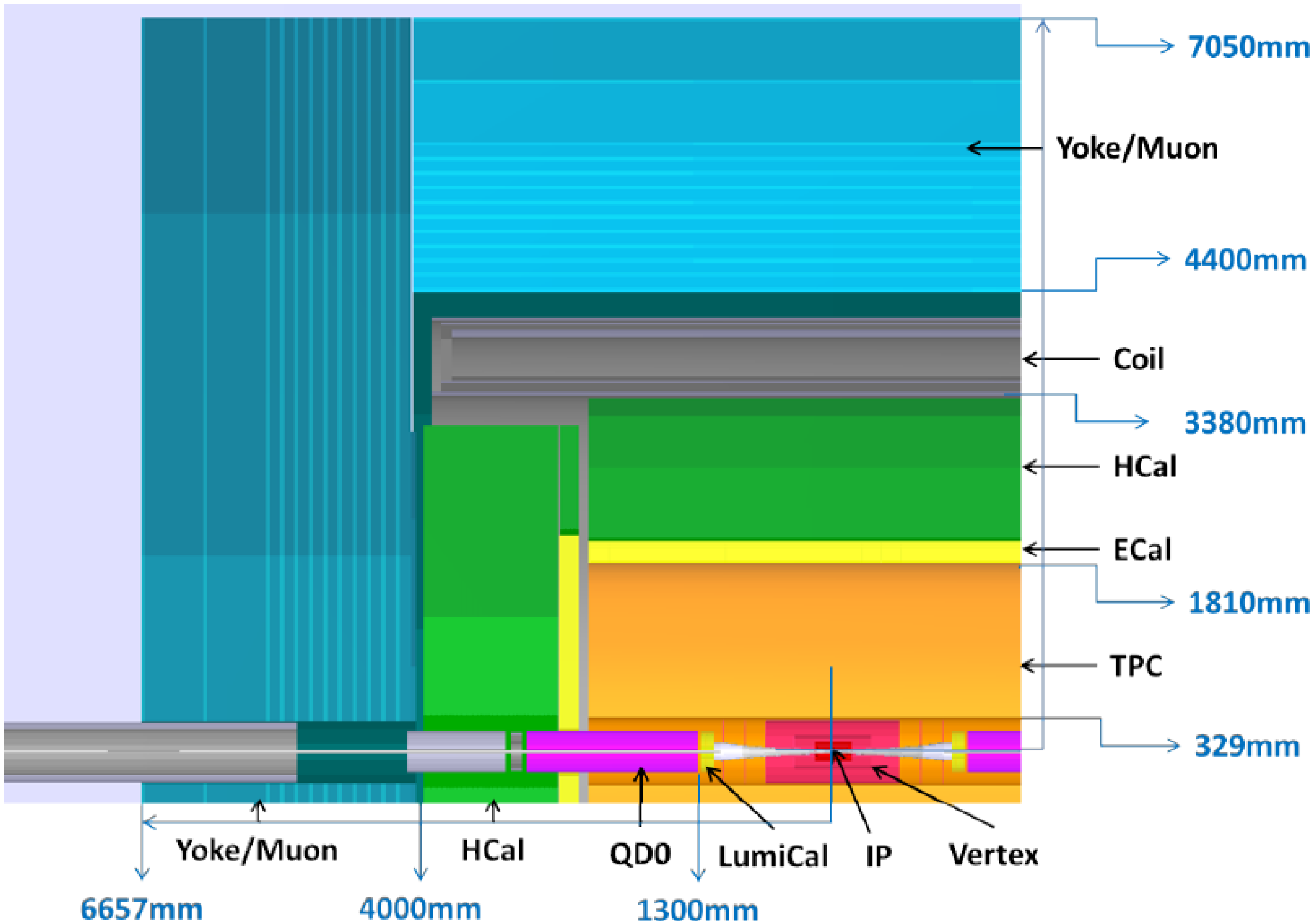
Future plans:

- Optimization of HCAL geometry
- Optimization of cell size
- Low power ASIC chip design
- Design of active cooling system
- …

Thanks for your attention !

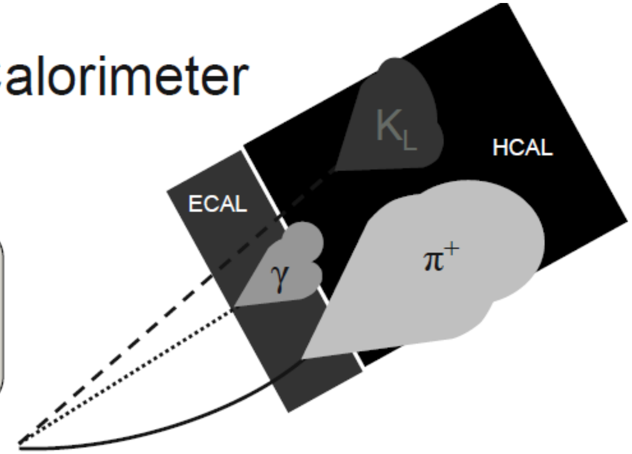
Backup!

Schematic of CEPC Detector



Particle Flow Algorithm

Particle Flow Algorithms and Imaging Calorimeter



The idea…

Charged particles } measured with the { **Tracker**

Neutral particles } measured with the { **Calorimeter**

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

(Charged, Photons, Neutral Hadrons) } 18%/√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)

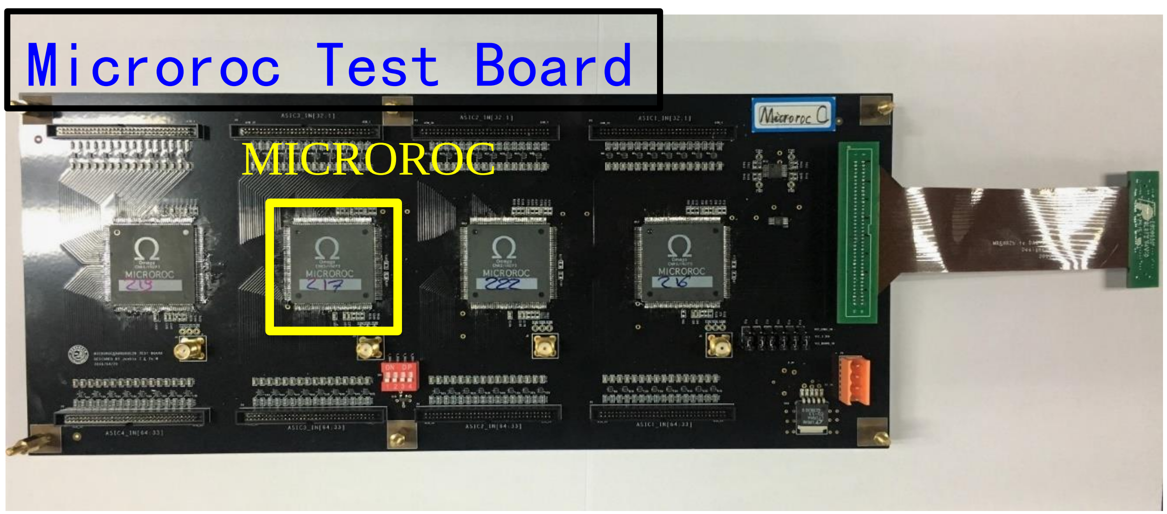
} **thin active medium**

→ Calorimeter with **extremely fine segmentation**

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(ILC)
DCAL	64	20fC~200fC	Single	——
HARDROC2	64	10fC~10pC	Multiple	1.42mW/ch,10μW/ch(ILC)
MICROROC	64	1fC~500fC	Multiple	335μW/ch, 10μW/ch (ILC)

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



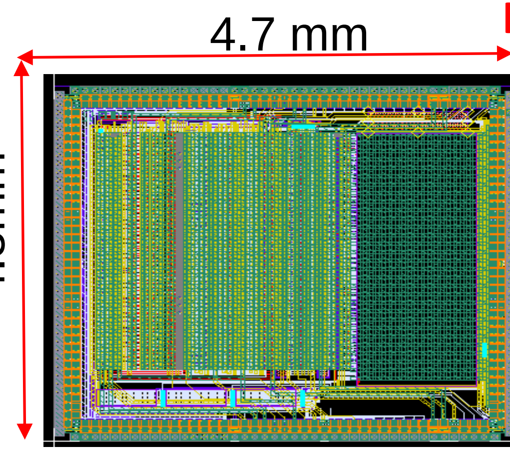
MICROROC Parameters

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

Electronics Readout

Imad Laktineh (IPNL)

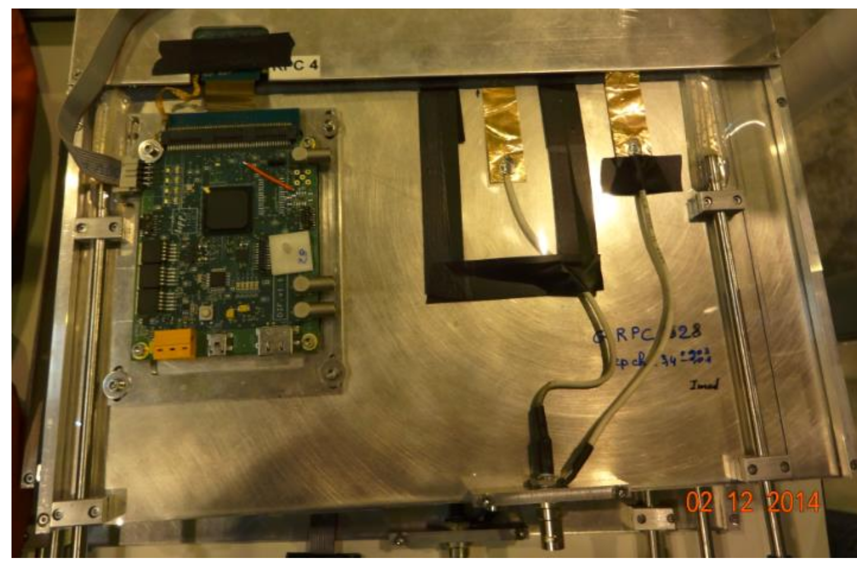
ASICs : HARDROC2
64 channels
Trigger less mode
Memory depth : 127 events
3 thresholds
Range: 10 fC-15 pC
Gain correction → uniformity



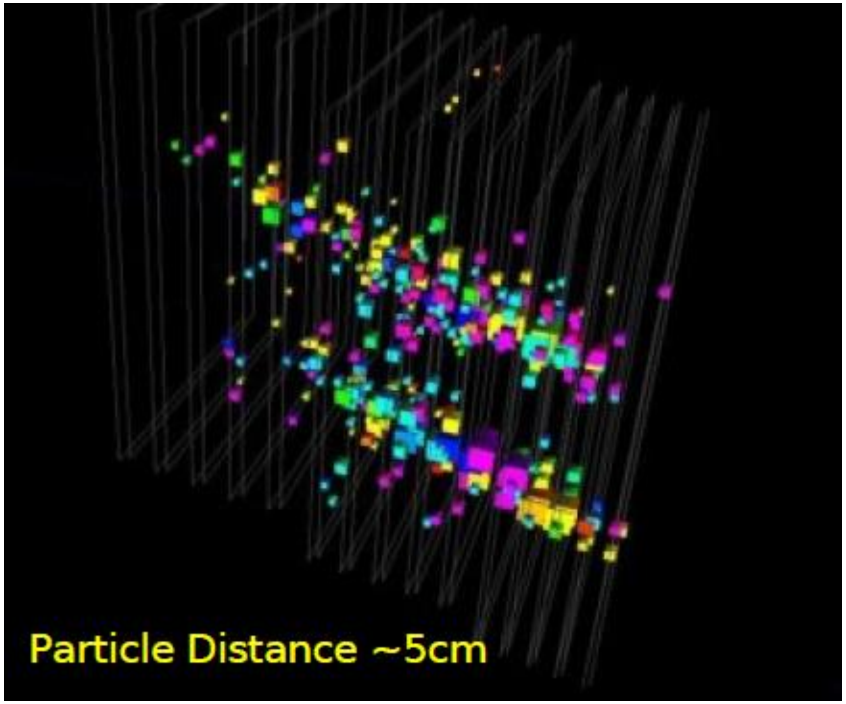
Printed Circuit Boards (PCB) were designed to reduce the cross-talk with 8-layer structure and buried vias.

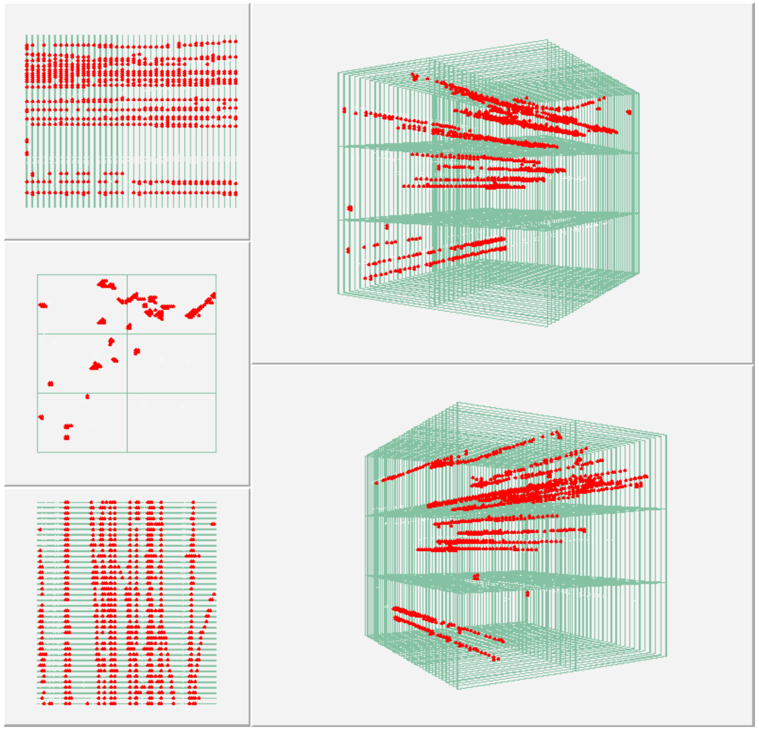
Tiny connectors were used to connect the PCB two by two so the 24X2 ASICs are daisy-chained. $1\times1m^2$ has 6 PCBs and 9216 pads.

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

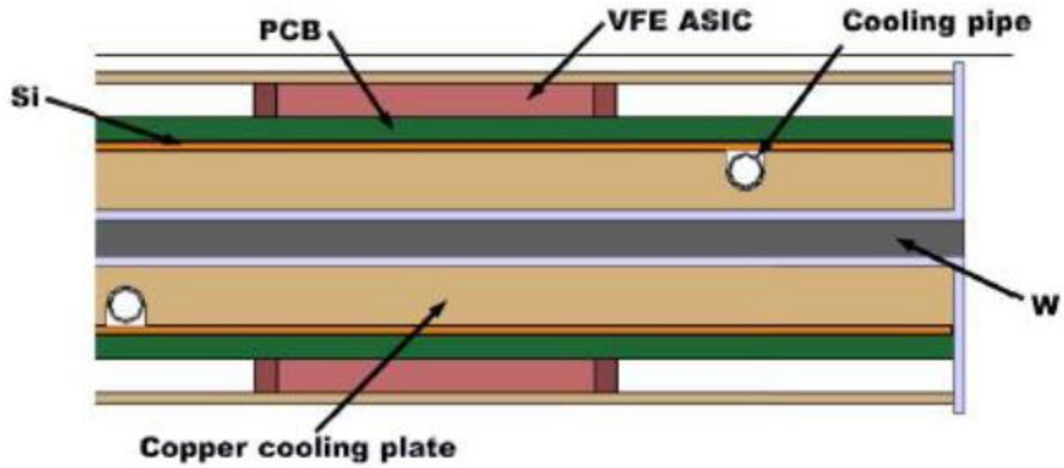
This is exactly what PFA needs: distinguishing individual showers within jet environment, in order to get excellent jet energy/mass resolution

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.

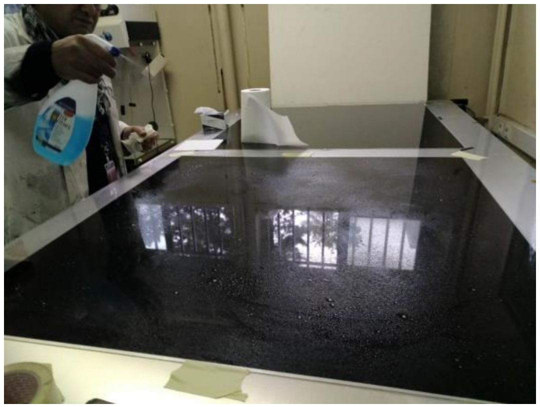
→ The silicon sensors are glued to PCB with VFE chips, cooled by the copper plates with CO_2 cooling pipes.

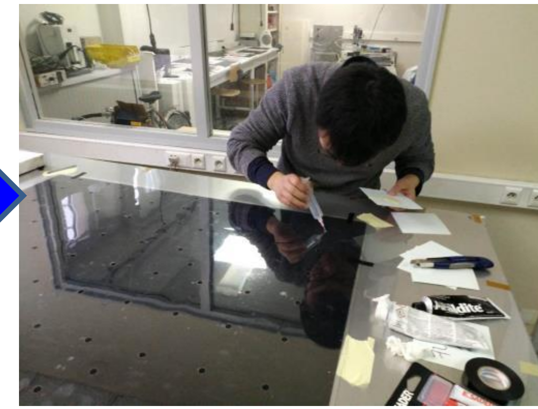


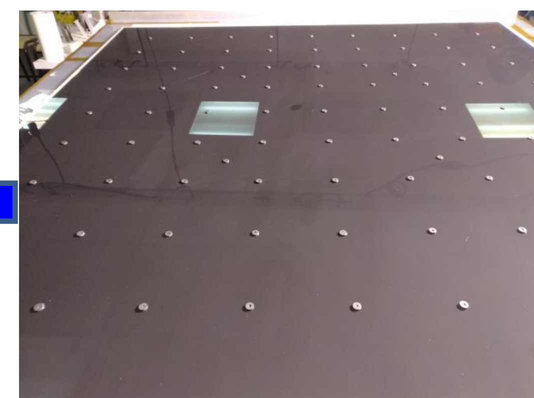
RPC Construction at IPNL

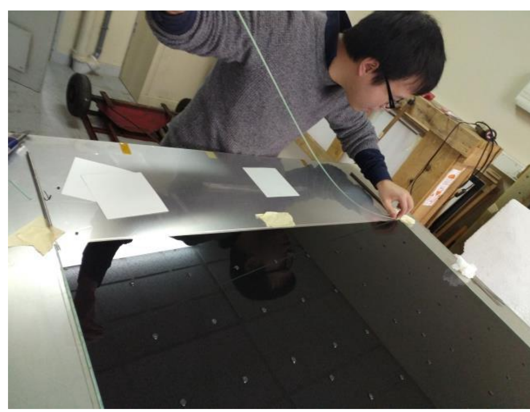
Cleaning of glass

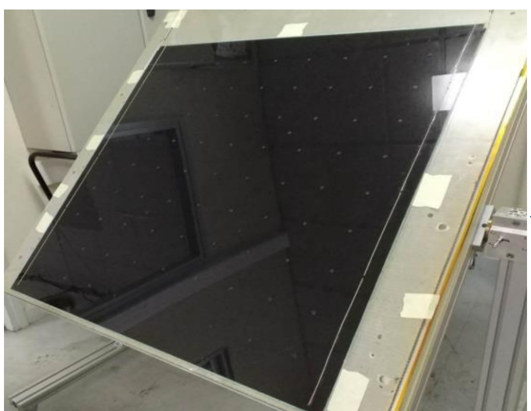
Place spacers









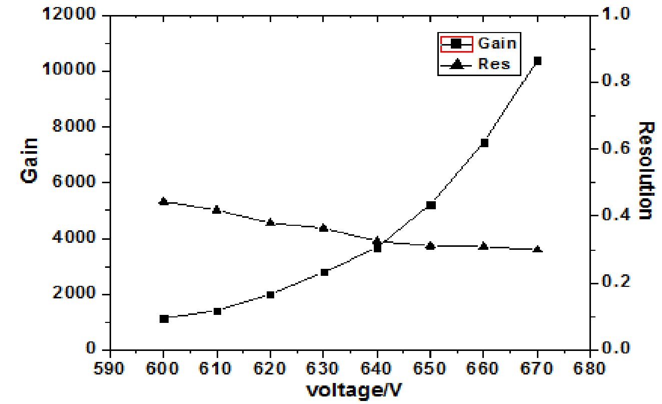


RPC chamber

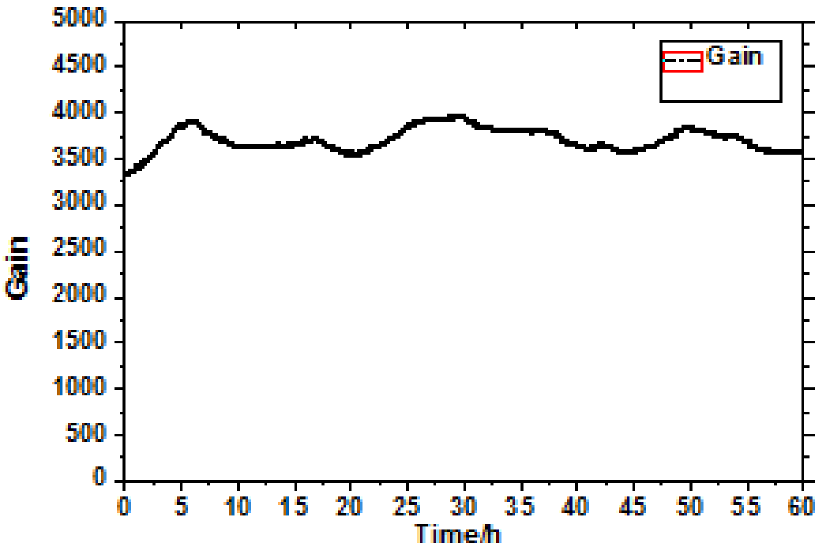
Sealing RPC chamber

Performance of 20cm×20cm 8mm THGEM

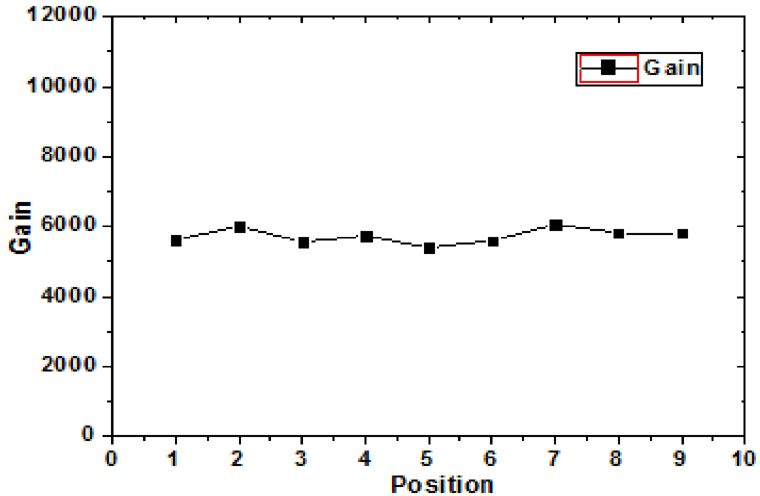
- The gas gain can reach to 10^4
- Long time stability is good
- The gain uniformity meet the requirement



Gain and energy resolution vs voltage



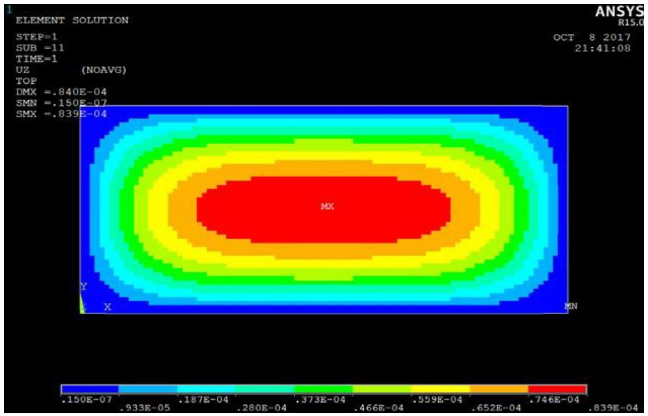
Stability measurement of THGEM detector



Gain uniformity measurement of THGEM detector

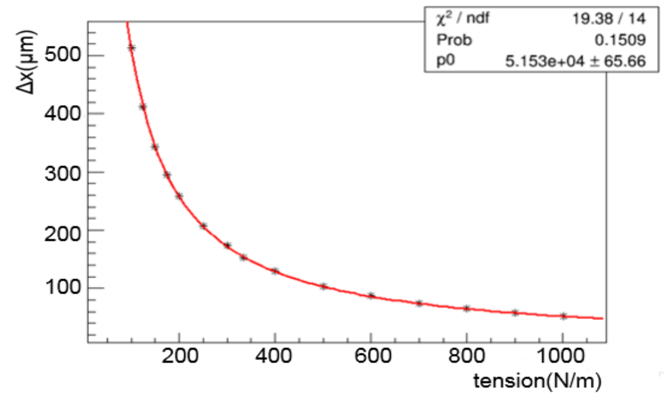
Deformation simulation of GEM foil

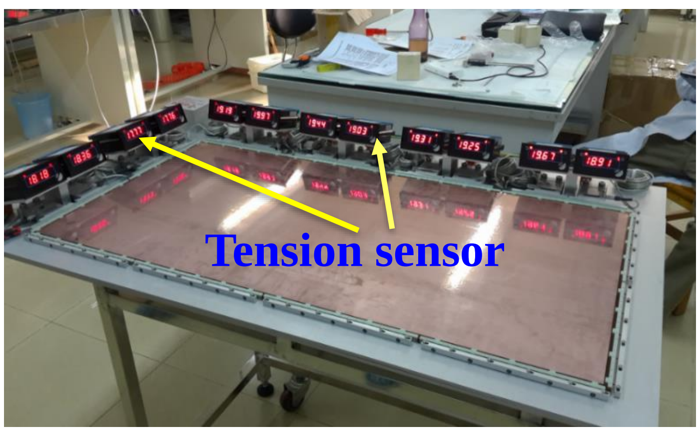
Vertical displacements simulation of GEM foil



1m×0.5m GEM foils

Maximum deformation as a function of tension



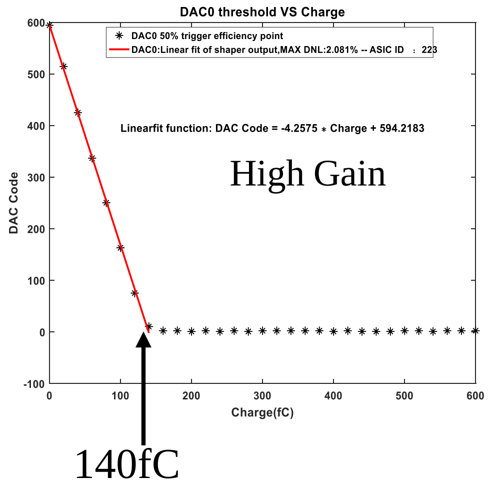


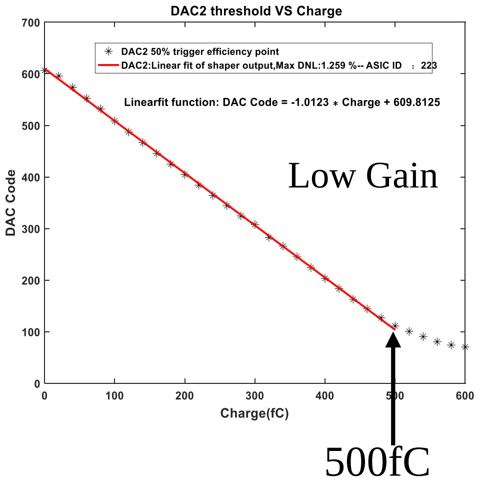
When tension is 500N/m,

- the maxiumum displacement is about **100μm**,
- extension of GEM foil is about **2.5mm**。

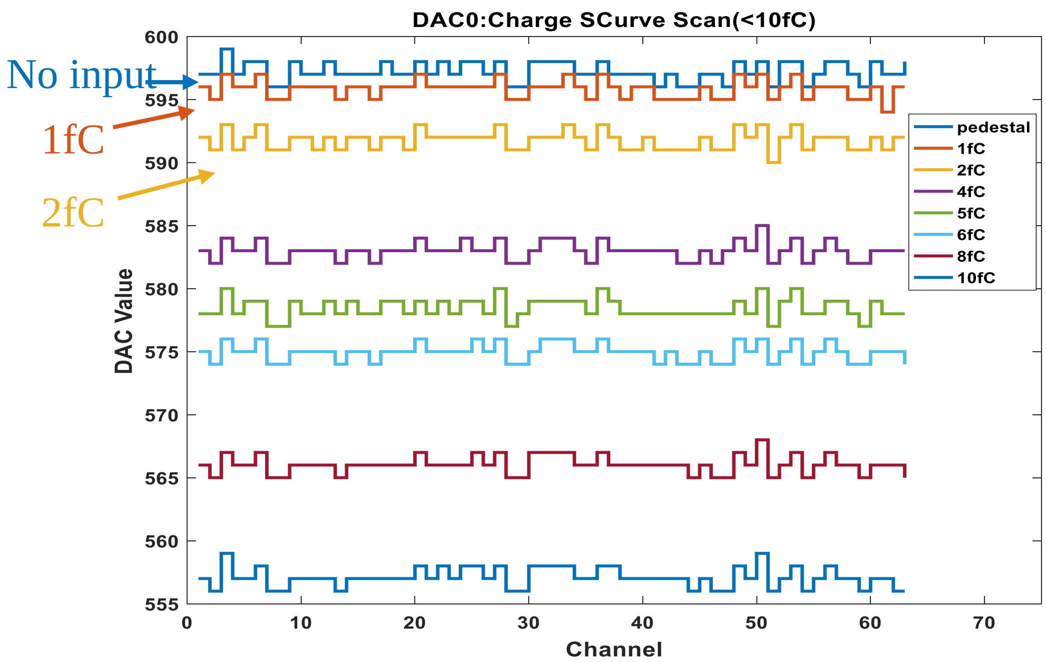
Test of MICROROC

- Calibration curve





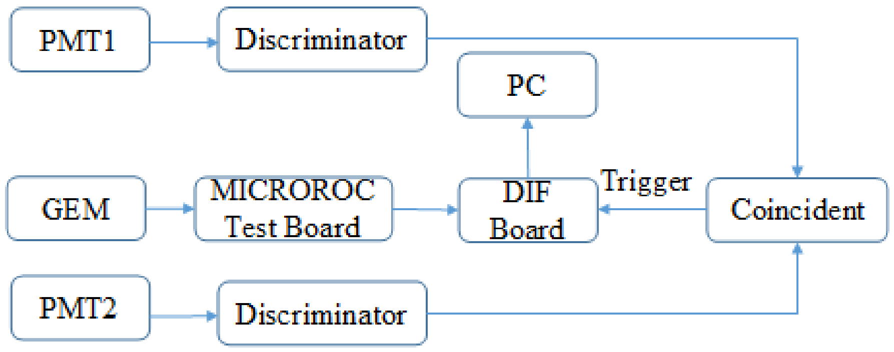
- Uniform between 64 channels

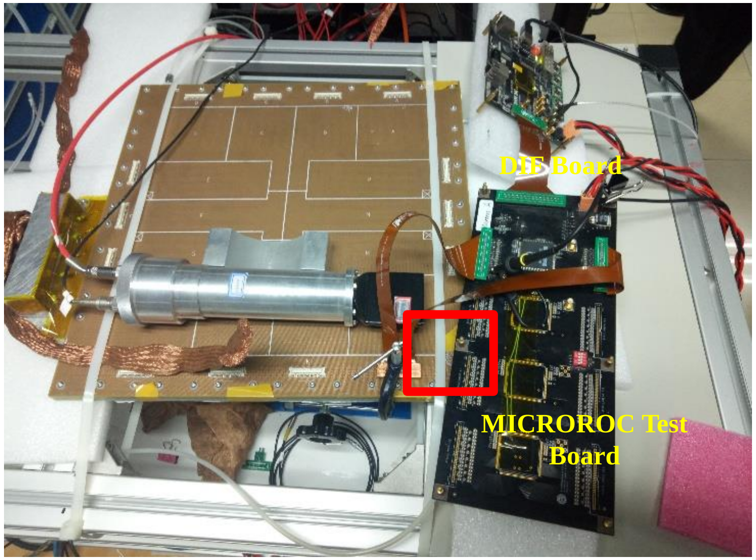


Minimum distinguishable charge: 2fC

Detection Efficiency and Multiplicity test_1

Electronics system based on MICROROC chip



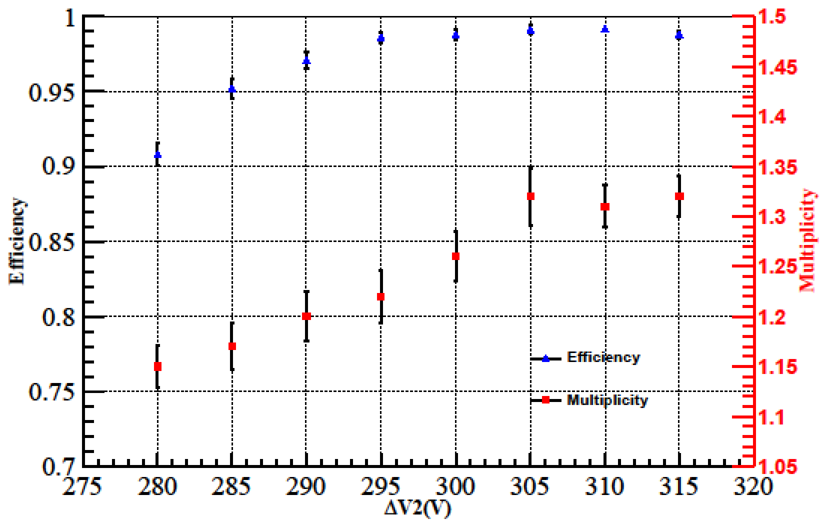


Ar-5%iC_4H_{10}

Working condition:

- △V1: 285 V;
- △V2: 295 V
- Step: 5V
- E_{drift}: 1.45 kV/cm;
- E_{trans}: 2.95 kV/cm ;
- E_{ind}: 3 kV/cm

Detection efficiency and multiplicity vs voltage

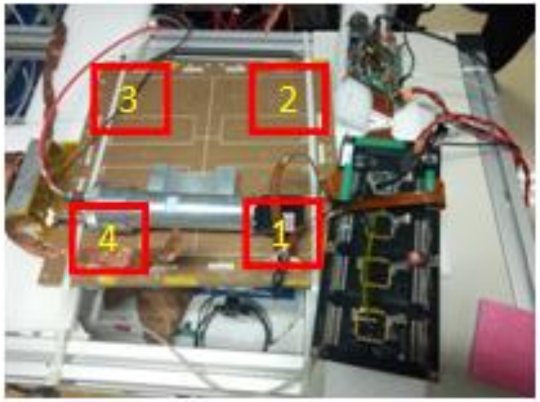


Detection Efficiency and Multiplicity test_2

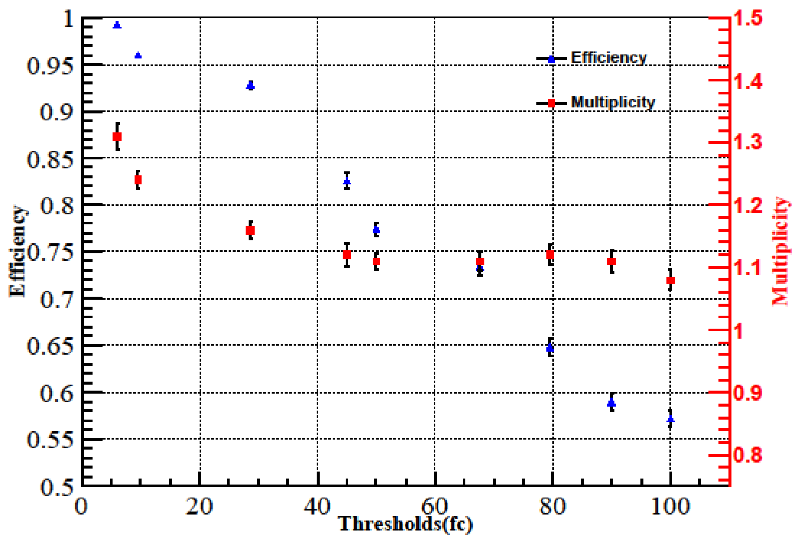
Ar-5%iC_4H_{10}

Working condition:

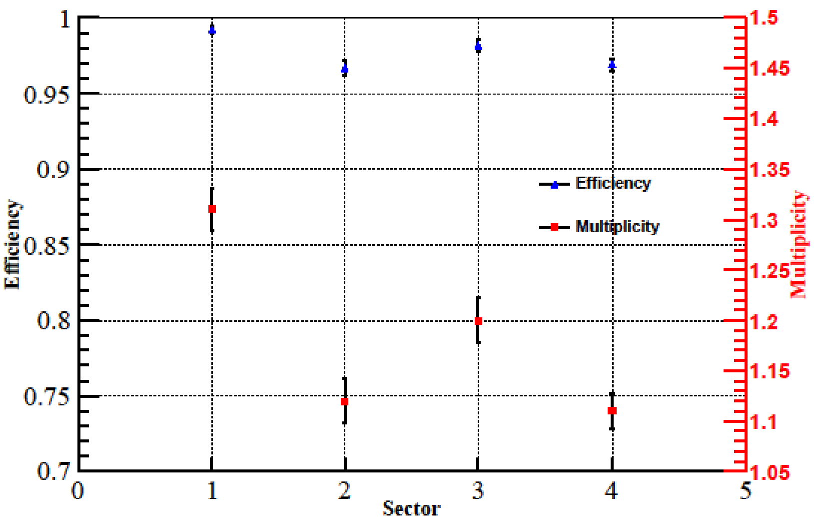
- △V1: 285 V;
- △V2: 295 V
- E_{drift}: 1.45 kV/cm;
- E_{trans}: 2.95 kV/cm ;
- E_{ind}: 3 kV/cm



Detection efficiency and multiplicity vary with thresholds



Detection efficiency and multiplicity in different areas



Test: Scintillator + SiPM

No.	Detector Cell	MPPC Type	Reflective Foil Type	Mean $N_{p.e.}$	Polishing Methods
1	$30\times30\times3mm^3$	S12571-025P	ESR	31.39±0.65	Ultra Precise Polishing
2	$30\times30\times3mm^3$	S12571-025P	ESR	22.55±0.7	Precise Polishing
3	$30\times30\times3mm^3$	S12571-025P	ESR	18.92±0.39	Rough Polishing
4	$30\times30\times3mm^3$	S12571-025P	TYVEK	13.63±0.33	Precise Polishing
5	$40\times40\times3mm^3$	S12571-025P	ESR	14.89±0.73	Precise Polishing
6	$50\times50\times3mm^3$	S12571-025P	ESR	9.87±0.43	Precise Polishing
7	$30\times30\times2mm^3$	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