第十届中国LHC物理会议
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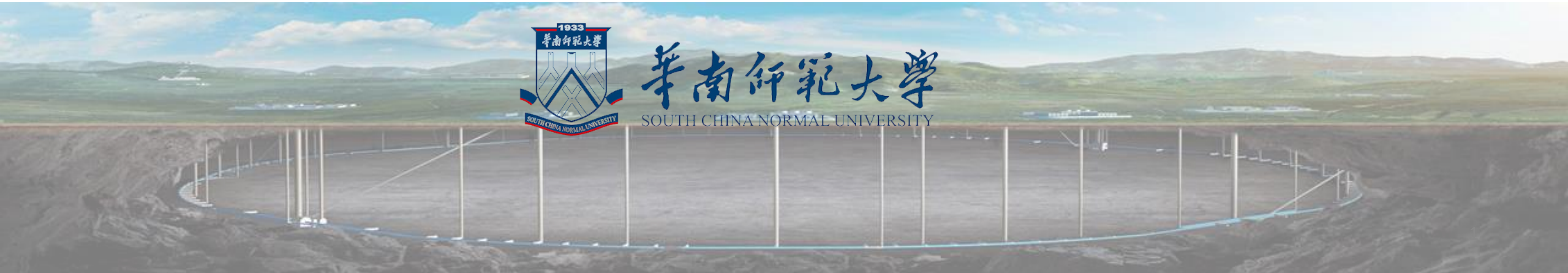
山东省青岛市鳌山湾

Progress of the CEPC GS-HCAL

Hengne Li
on behalf of the CEPC HCAL Group



Content

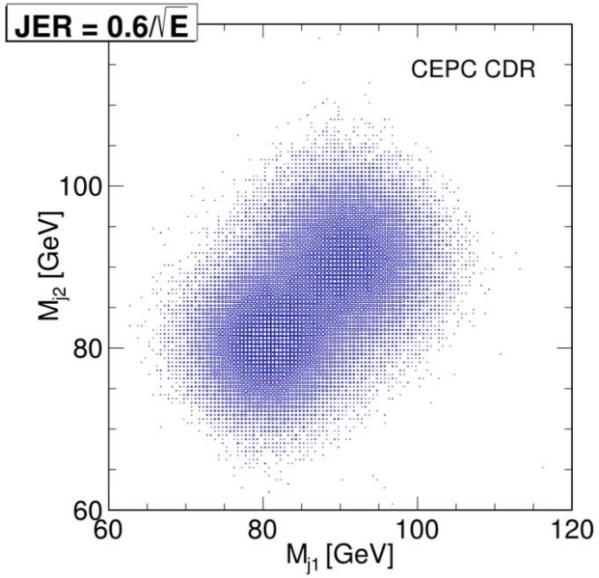
1. Introduction and Requirement

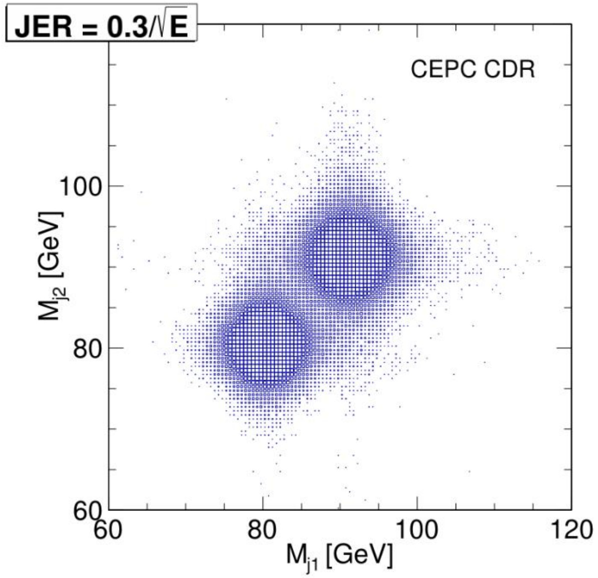
CEPC as Higgs/W/Z boson factories

- ❖ H/W/Z decay into hadronic final states are dominant, it is crucial to design high performance calorimetry system
- ❖ Required Jet Energy Resolution **σ/E ~ 3-4% at 100 GeV**

[CEPC CDR, arXiv:1811.10545]

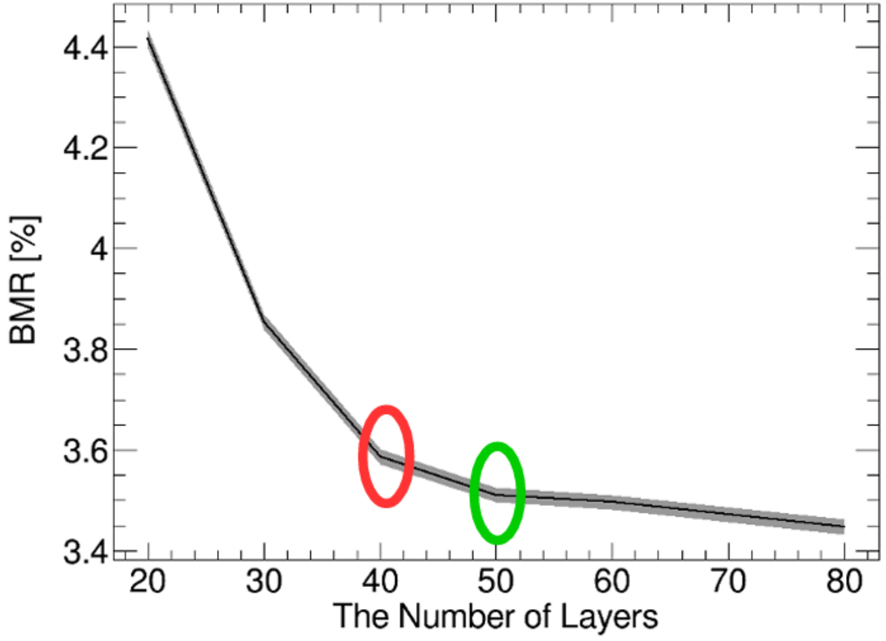
Physics process	Measurands	Detector subsystem	Performance requirement
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\Delta(1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	Vertex	$\sigma_{r\phi} = 5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta} (\mu\mathrm{m})$
$H \to q\bar{q}, WW^*, ZZ^*$	$\mathrm{BR}(H \to q\bar{q}, WW^*, ZZ^*)$	ECAL HCAL	$\sigma_E^{\mathrm{jet}}/E = 3 \sim 4\%$ at 100 GeV
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\Delta E/E = \frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$

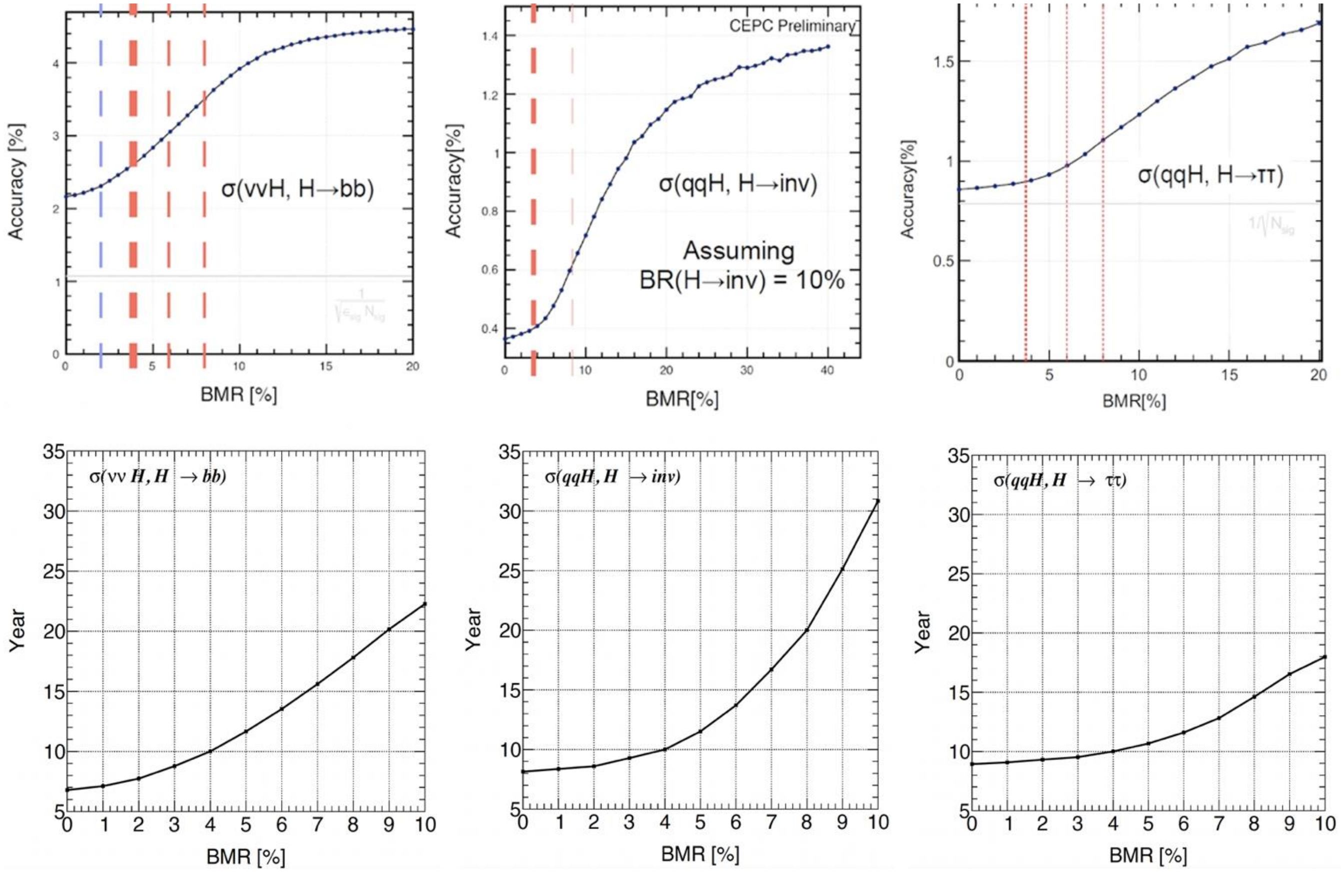




1. Introduction and Requirement

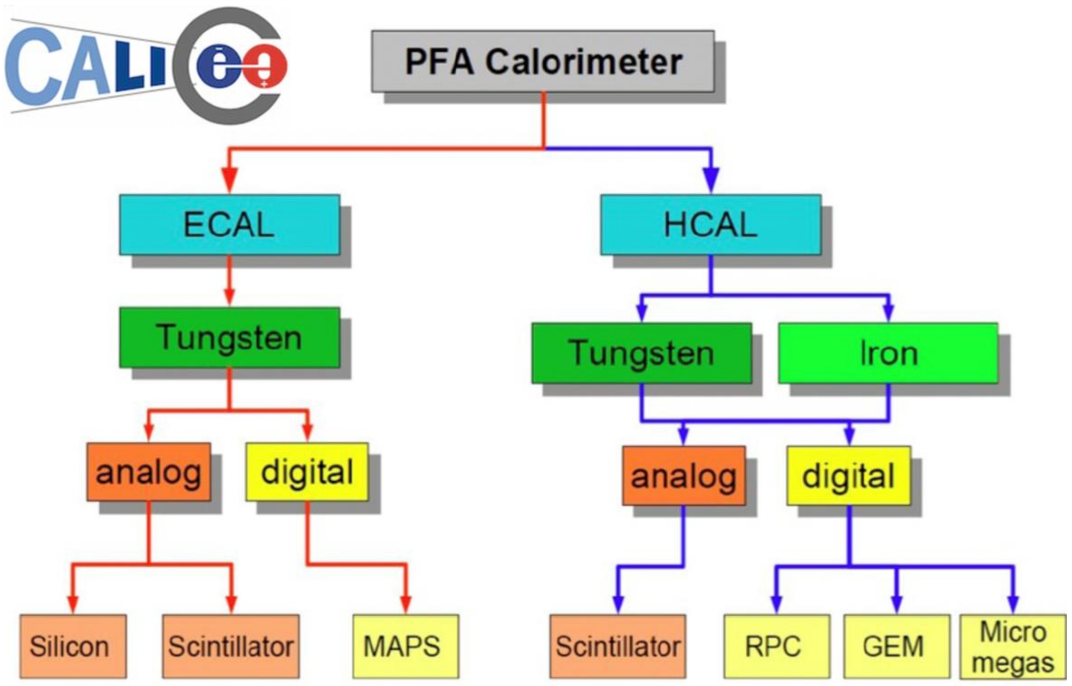
➔The increase of sampling layers (40 → 48 layers) will improve the total nuclear interaction length (~5λ → 6λ) and suppress hadronic shower leakage, which is beneficial to achieve better BMR and accuracy of benchmark physics processes.

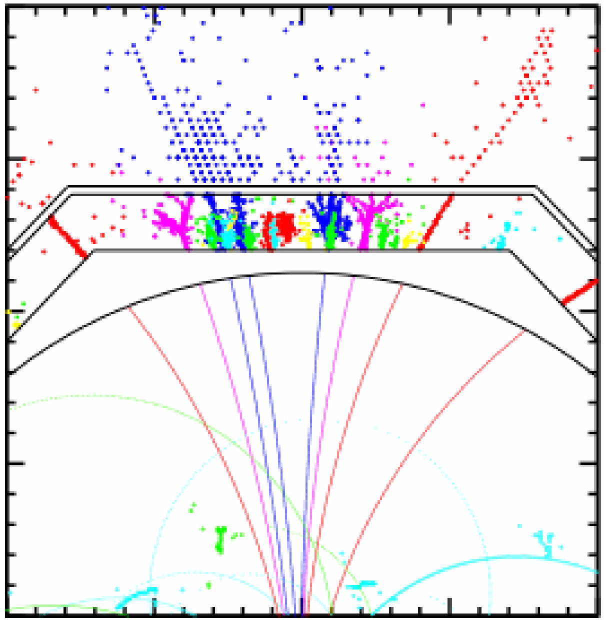


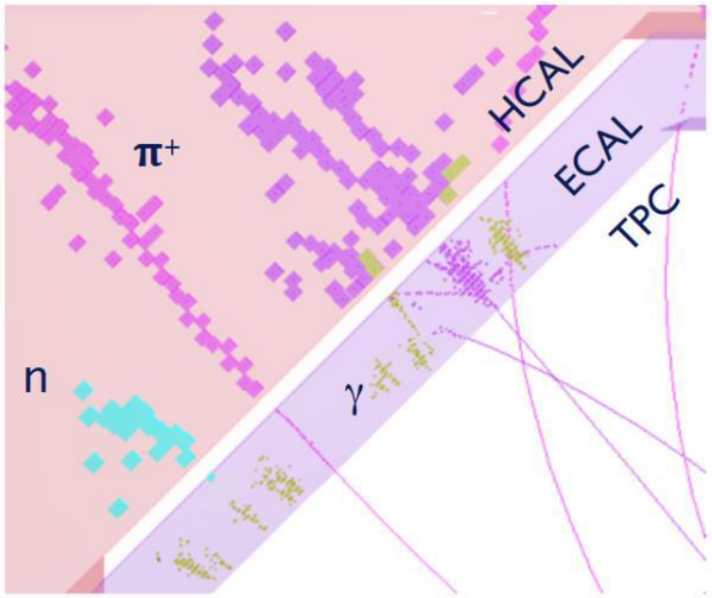


2. Technology Survey and Our Choice

- **Three major options for CEPC Hardronic Calorimeter**
  - ① RPC-DHCAL (SDHCAL, prototype): sampling, 48-layer
  - ② Plastic Scintillator-AHCAL (PS-HCAL, prototype): sampling, 40-layer
  - ③ **Glass Scintillator-AHCAL (GS-HCAL):** (**new design** for CEPC Ref-TDR)





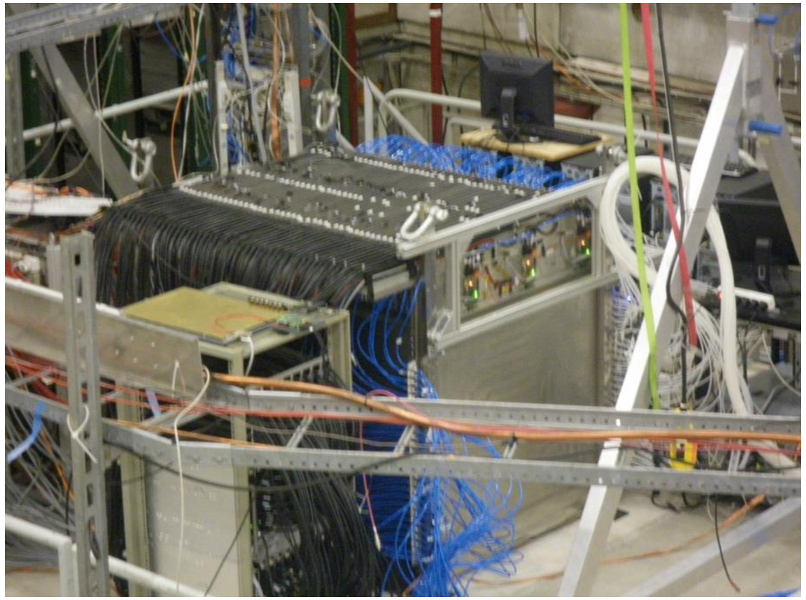


PFA calorimetry: various options explored in the CALICE collaboration in past 20 years

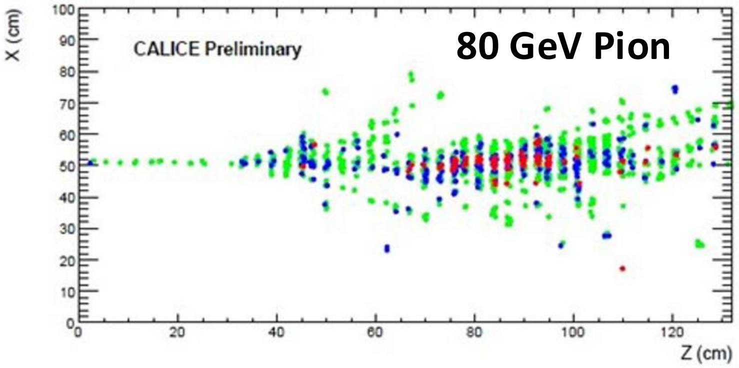
2.1 RPC based SDHCAL (Prototype)

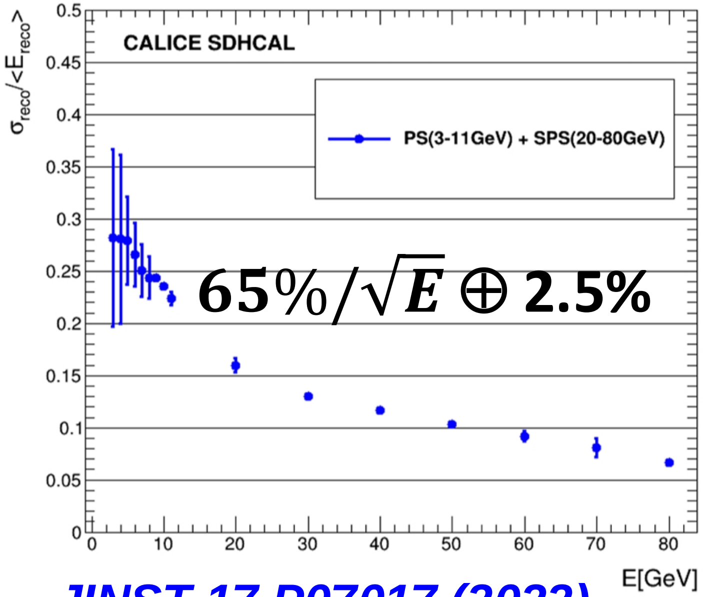
- **Semi-digital HCAL (SDHCAL)**
  - High granularity (1cm x1cm)
  - 48 layers (1m x 1m x 1.3m)
  - Three thresholds readout
  - Stainless-steel absorber with self-supporting mechanical structure

TB at CERN, SDHCAL ($1m^3$), 3 thresholds



JINST 11 (2016) P04001





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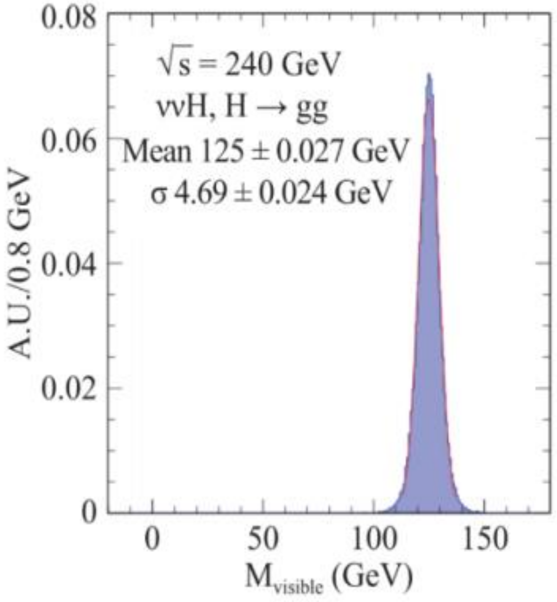


- **DHCAL performance (CDR)**

Boson mass Resolution:

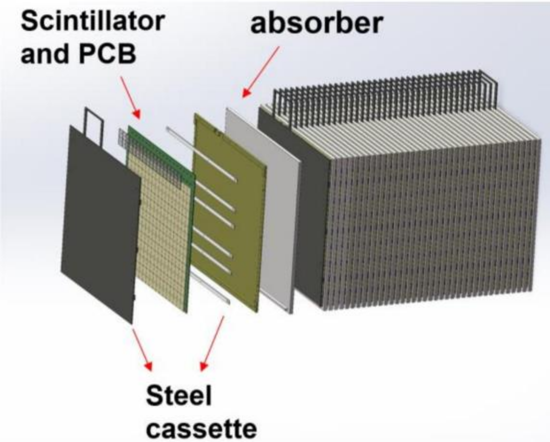
$H \rightarrow gg$: 3.75%

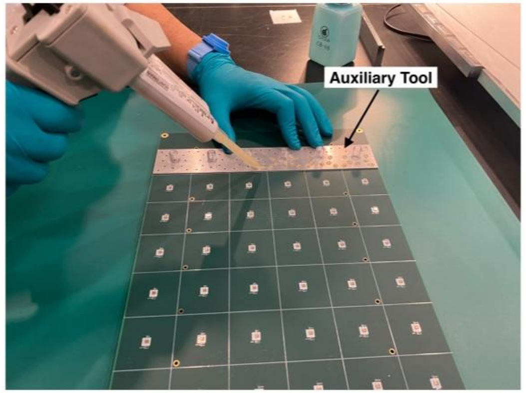
(Full Simu. + Arbor Rec.)

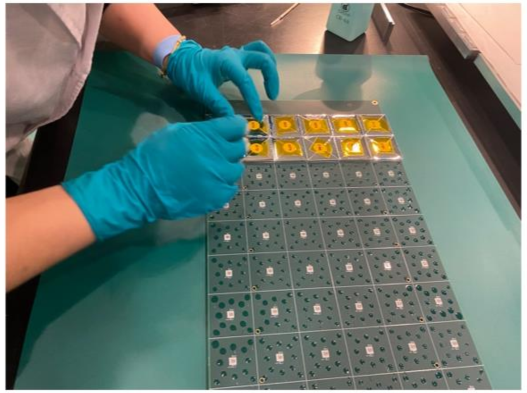
2.2 Plastic Scintillator HCAL (Prototype)

- We have developed a PS-HCAL prototype in 2022 and TB at CERN

Calo	Layers	material	Absorber	Granularity	Electronics	Thickness	Resolution	Weight
PS-HCAL	40	PS+SiPM S14160-1315	Fe	4×4 cm^2	SPIROC-2E 12960-ch	4.6 λ_I	$60\%/\sqrt{E}\oplus 3\%$	5.0 T







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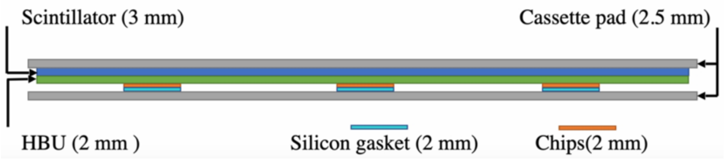
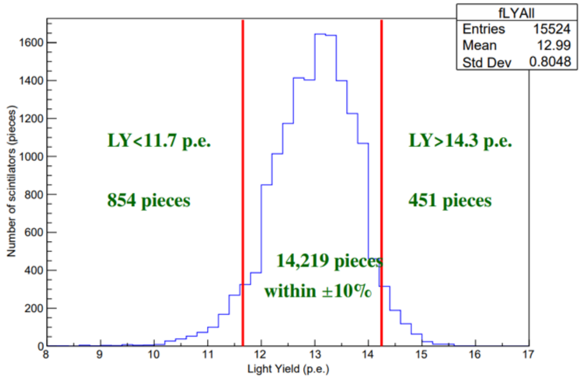
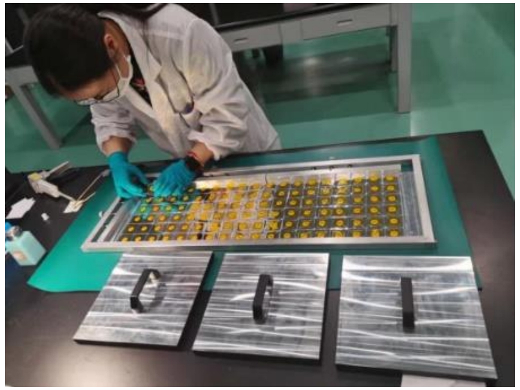
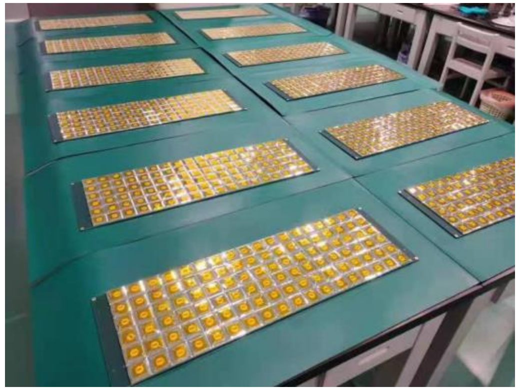
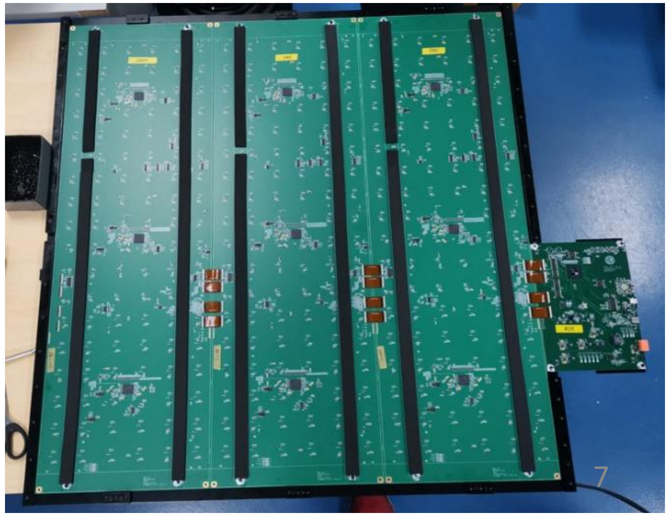




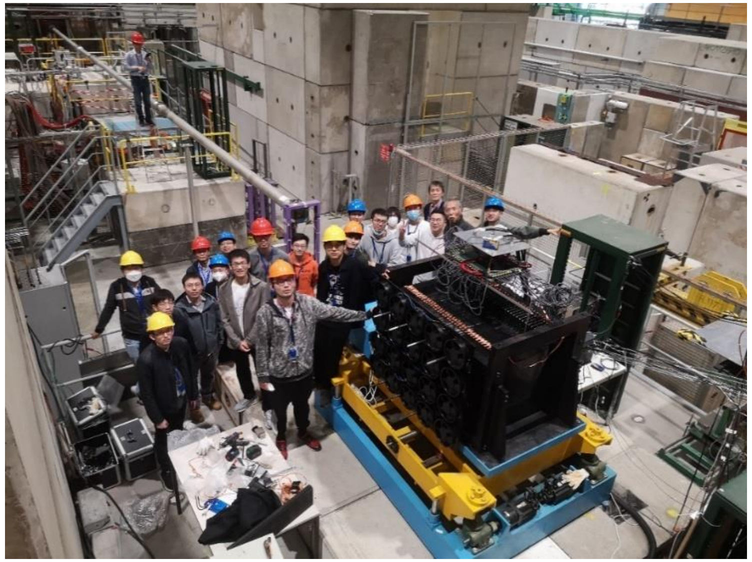






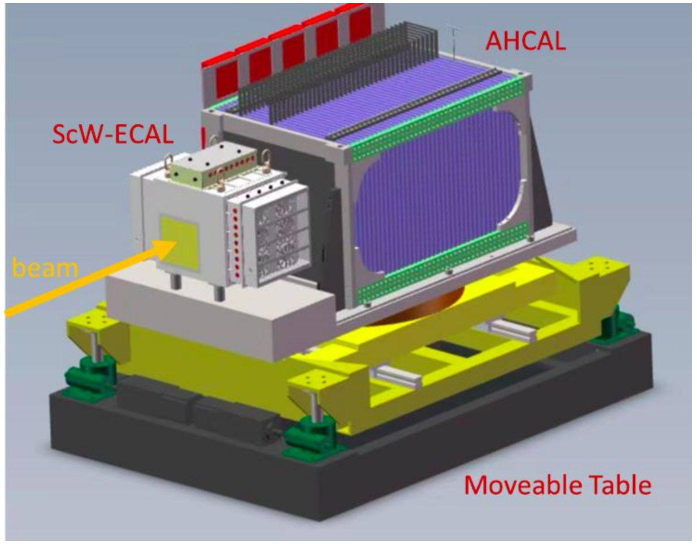
2.2 Plastic Scintillator HCAL (Prototype)

Oct 19 – Nov 2, 2022 — SPS H8 beamline
Apr 26 – May 10, 2023 — SPS H2 beamline
May 17 – 31, 2023 — PS T9 beamline

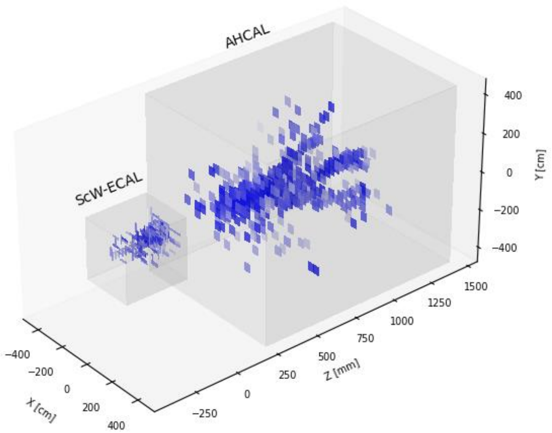


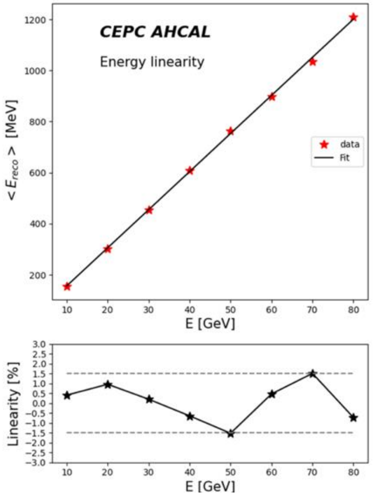
- **Collected large statistics of test beam data samples**
  - Muons: 10 GeV (PS-T9), 108/160 GeV (H8), 120 GeV (H2)
  - Electrons/positrons: 0.5 – 5 GeV at PS; 10 – 120 – 250 GeV at SPS
  - Pions: 1 – 15 GeV at PS, 10 – 120 – 150 – 350 GeV at SPS

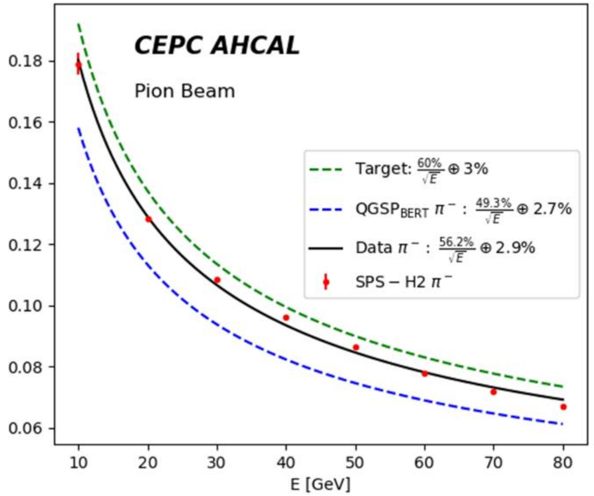
➔ **About 65 M test beam events**



60 GeV negative pion (SPS)



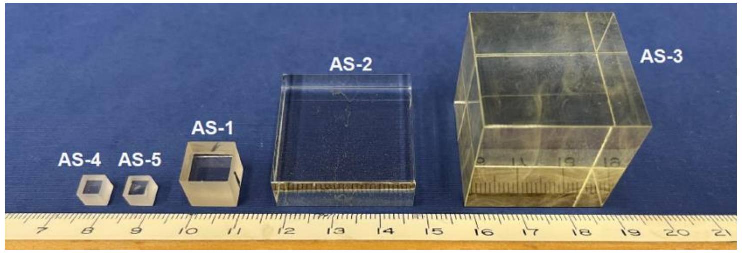


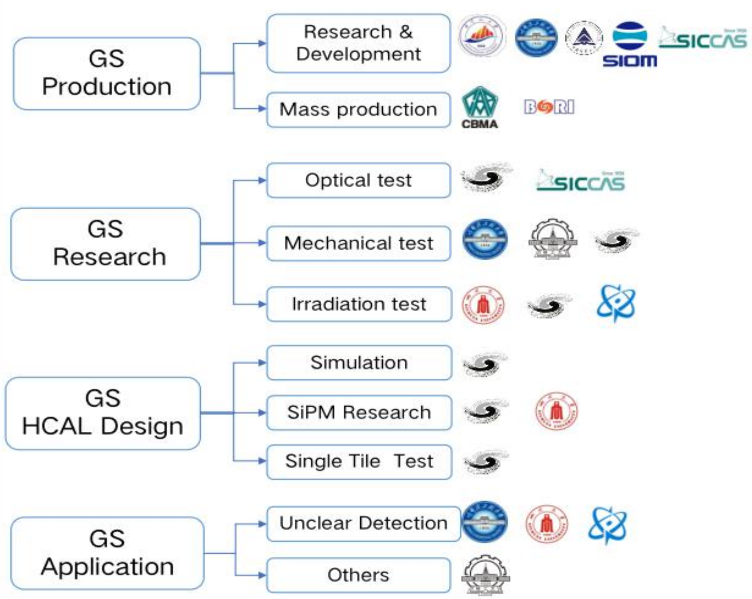


2.3 Glass Scintillator R&D

- The GS collaboration was established in 2021, it focuses on the large-area & high-performance glass scintillator for applications in nuclear and particle physics.
- The GS collaboration is organized by IHEP and the members include 4 Institutes of CAS, 6 Universities, 3 Factories currently.

Glass Scintillator Collaboration
闪烁玻璃合作组
Glass Scintillator Collaboration





Institute of High Energy Physics，CAS
中国科学院高能物理研究所

Jinggangshan University
井冈山大学

Beijing Glass Research Institute
北京玻璃研究院

China Building Materials Academy
中国建筑材料研究院

China Jiliang University
中国计量大学

Harbin Engineering University
哈尔滨工程大学

Harbin Institute of Technology
哈尔滨工业大学

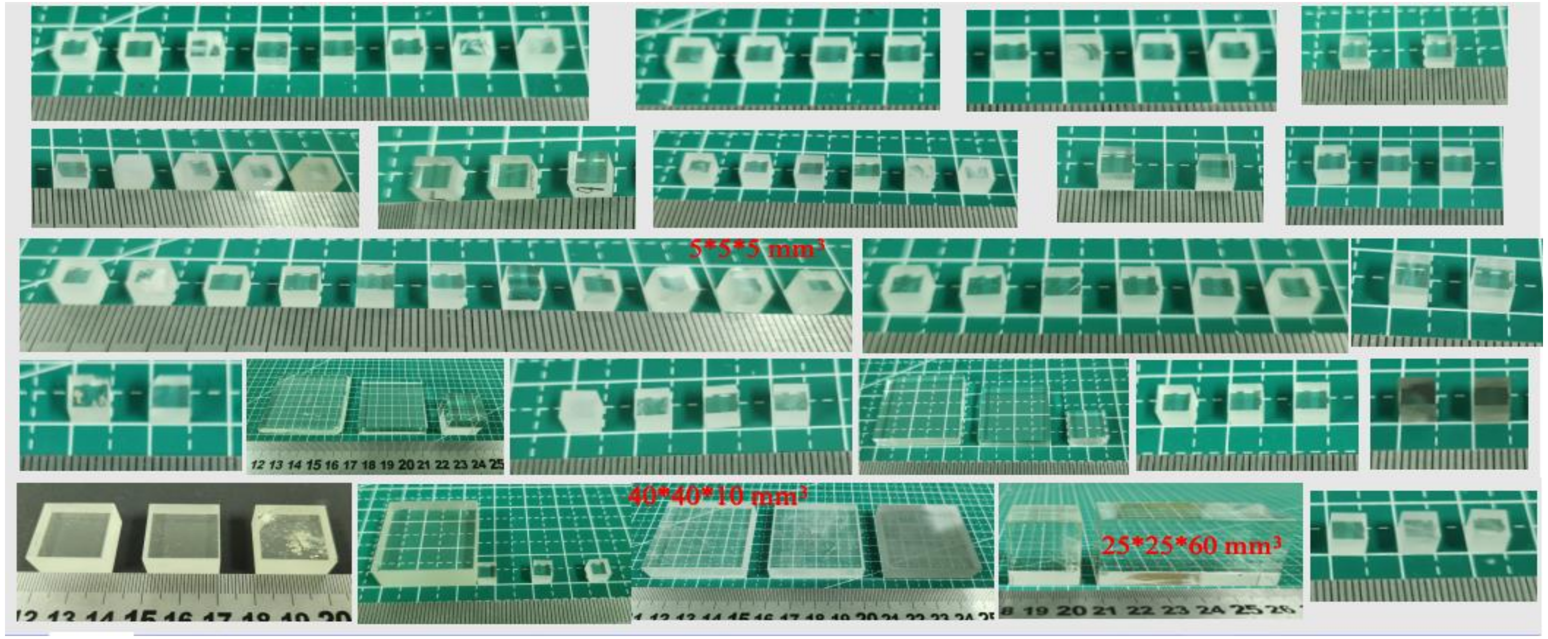
Sichuan University
四川大学

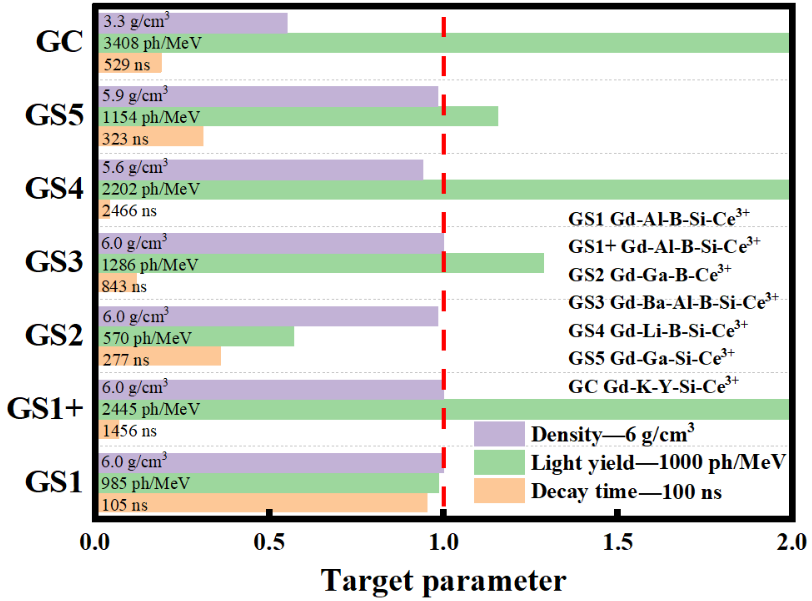
Shanghai Institute of Ceramics，CAS
中国科学院上海硅酸盐研究所

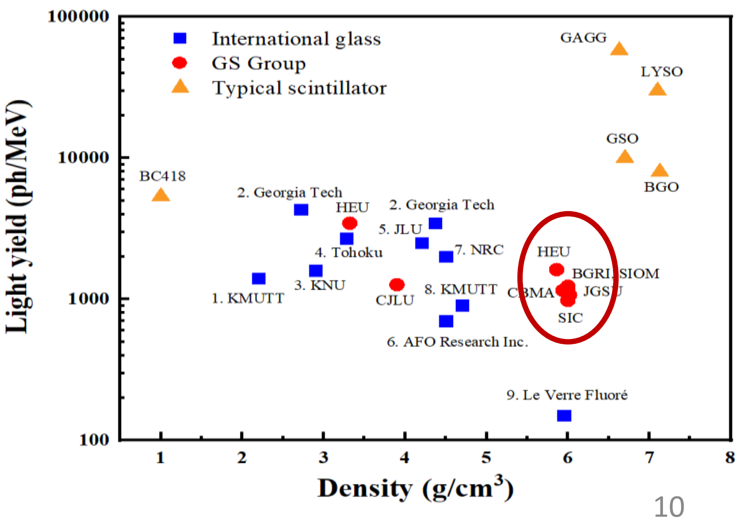
Shanghai Institute of Optics and Fine Mechanics，
中国科学院上海光学精密机械研究所

CNNC Beijing Unclear Instrument Factory
中核（北京）核仪器有限责任公司

2.3 Glass Scintillator R&D





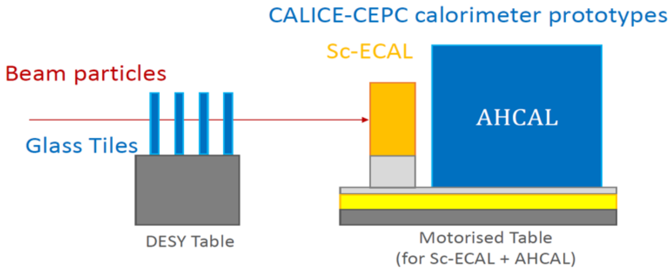


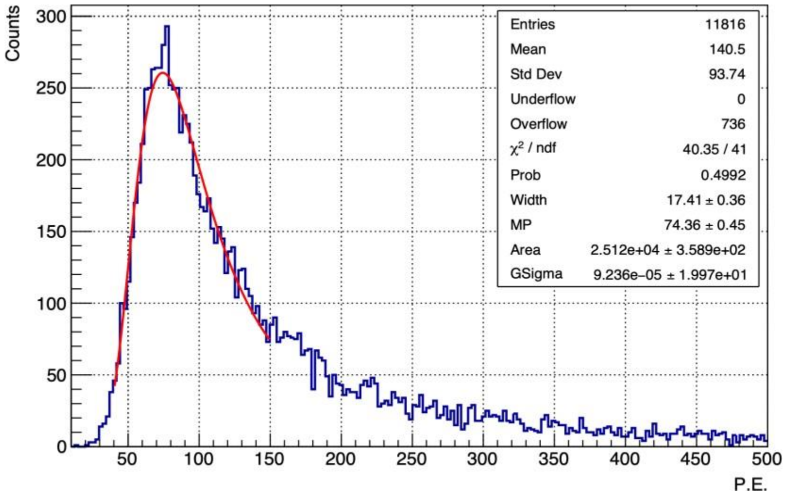
- ✓ The GS group did substantive research based on five glass scintillator types and impressive progress has been achieved
- ✓ The performance of the best glass sample approach the initial goals, i.e. 6 g/cm³ & 1000 ph/MeV & ~100 ns
- ✓ The GS group is leading R&D efforts on high density glass scintillator

2.3 Glass Scintillator (GS1) TB Performance

CERN Muon-beam (10 GeV muon)

11 glass tiles tested at CERN (2023/5)

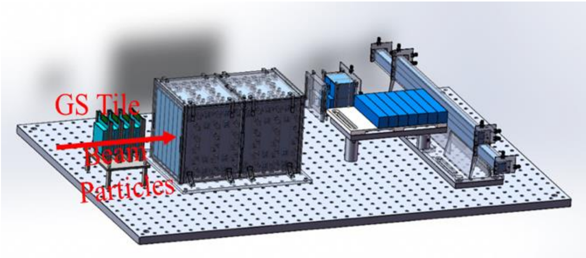


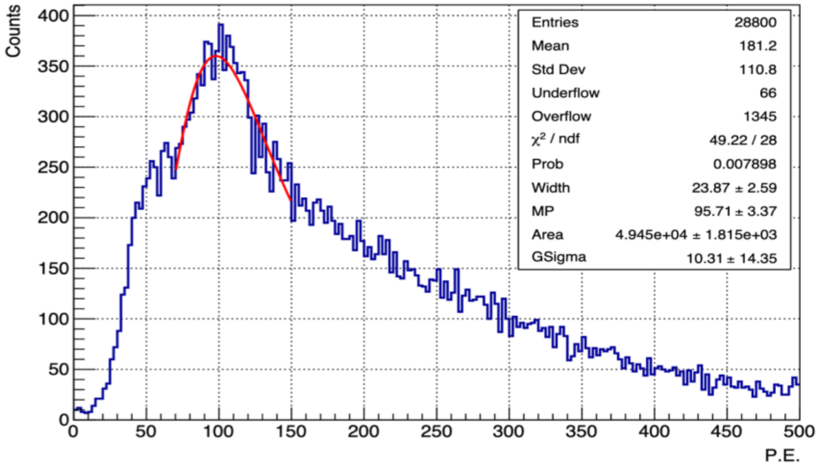


- **Typical Light Yield:**
  500 – 600 ph/MeV
- **Typical MIP response:**
  60 – 70 p.e./MIP

DESY Electron-beam (5 GeV electron)

9 glass tiles tested at DESY (2023/10)

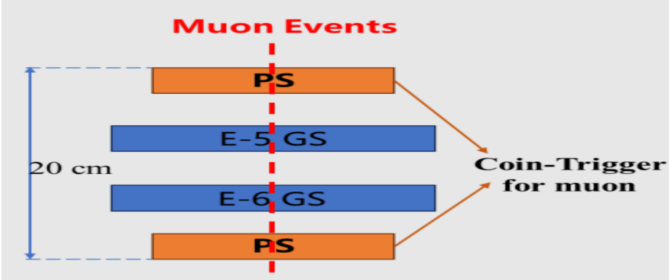


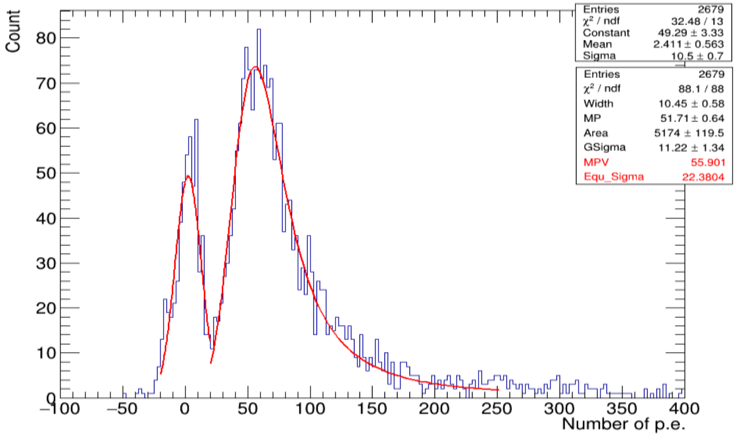


- **Typical Light Yield:**
  600 – 700 ph/MeV
- **Typical MIP response:**
  70 – 80 p.e./MIP

IHEP Cosmic Muon (3 GeV muon)

4 glass tiles tested at IHEP (2024/4)

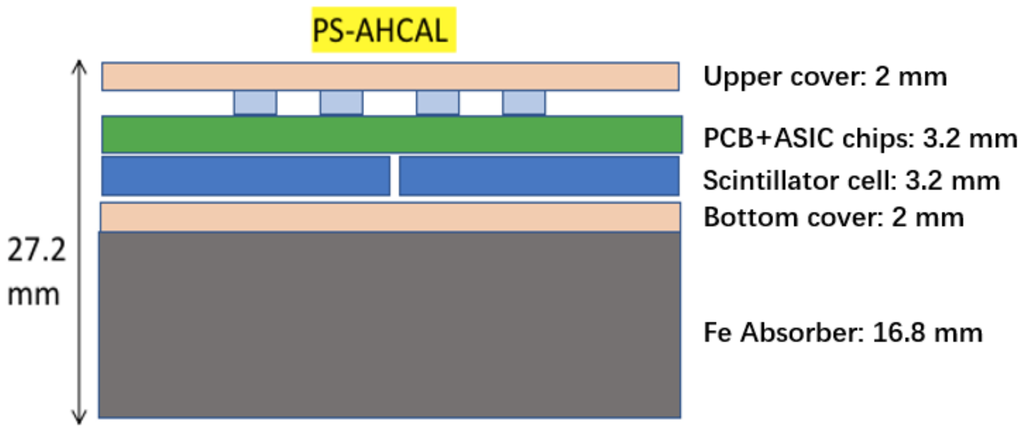




- **Typical Light Yield:**
  500 – 700 ph/MeV
- **Typical MIP response:**
  60 – 80 p.e./MIP

3.1 GS-HCAL vs PS-HCAL

- **Sampling fraction of PS-HCAL and GS-HCAL**



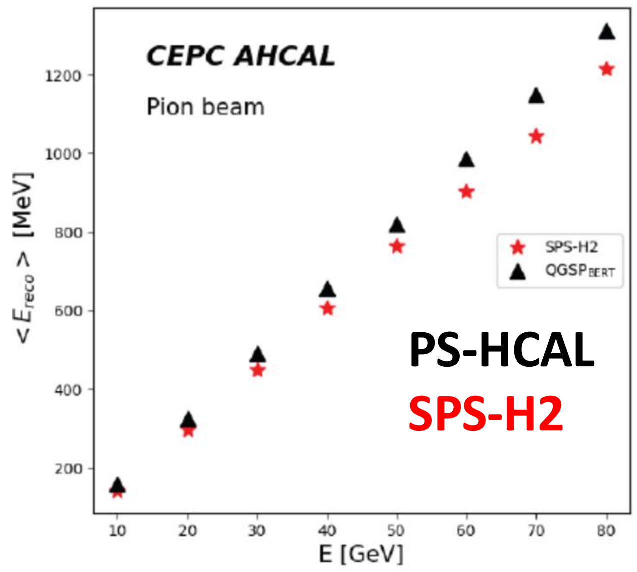
PS-HCAL (6.15 λ_I)

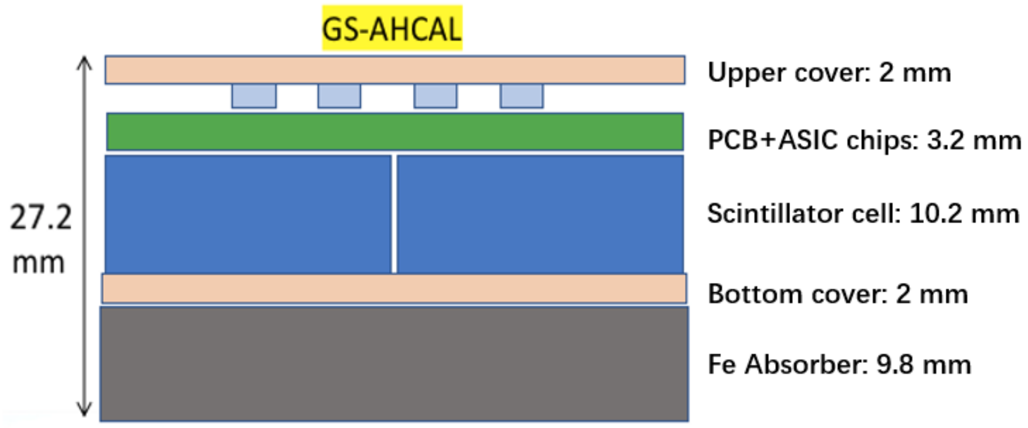
Fe: 20.8mm/171.5mm=0.1213 λ_I

PS: 3mm/688.7mm=0.0044 λ_I

PCB: 1.2mm/492.2mm=0.0024 λ_I

Sampling fraction ~ 1.6% (π^- TB, MC)





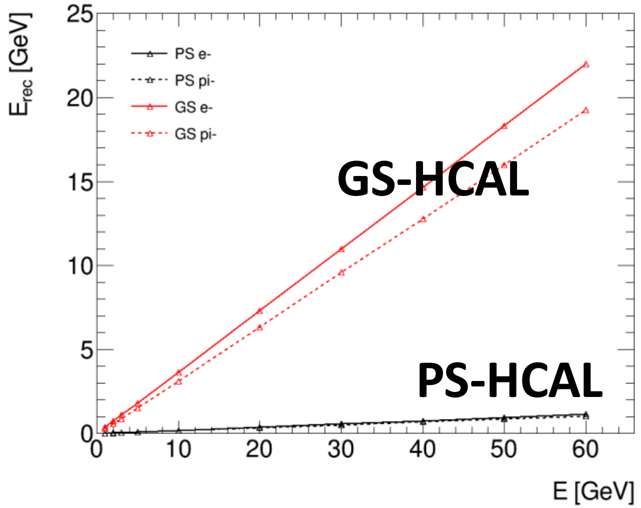
GS-HCAL (6.02λ_I)

Fe: 13.8mm/171.5mm=0.0805 λ_I

GS: 10.2mm/242.8mm=0.0425 λ_I

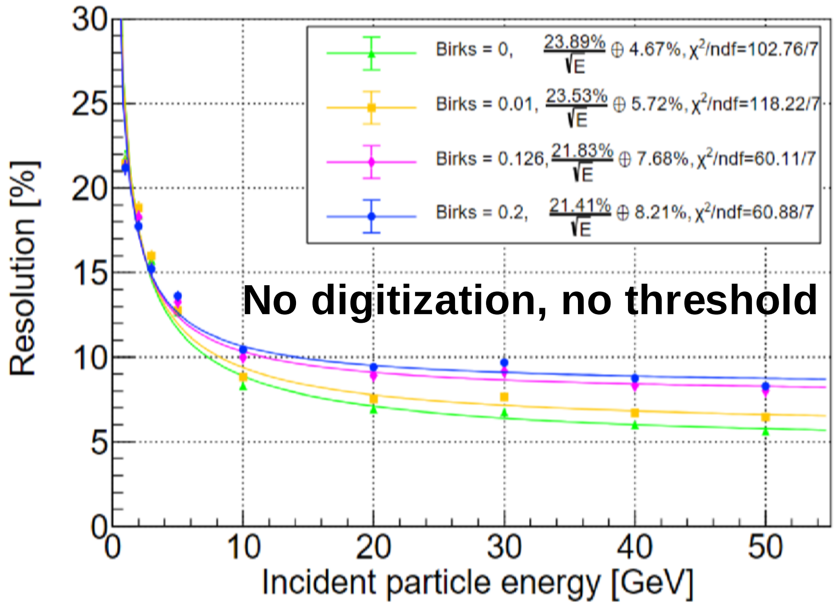
PCB: 1.2mm/492.2mm=0.0024 λ_I

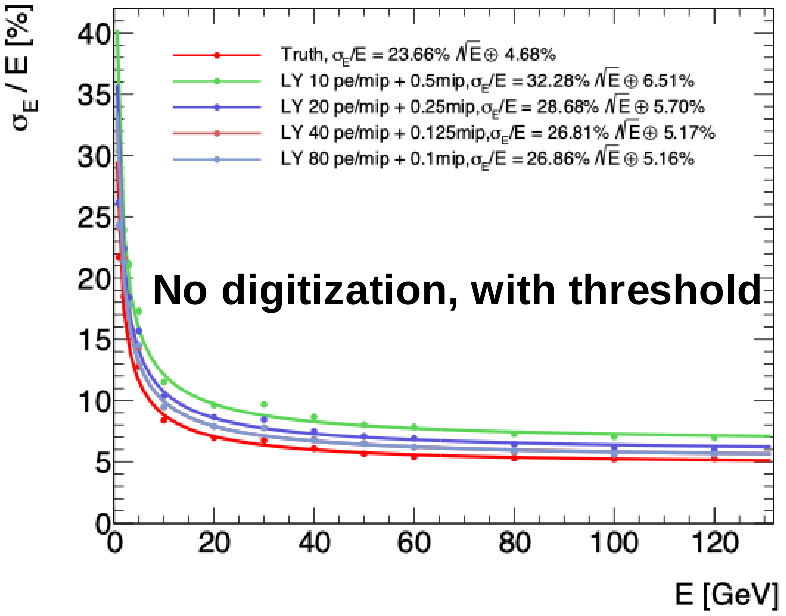
Sampling fraction ~ 31% (MC)

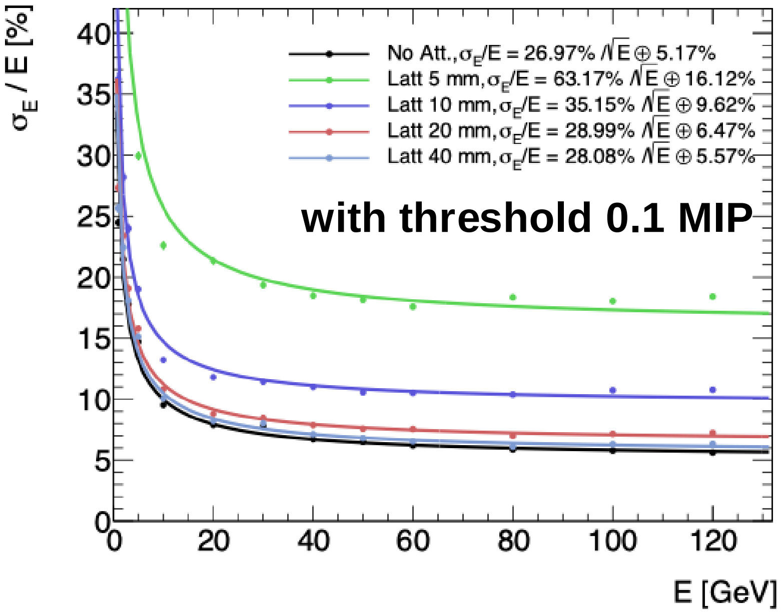


3.2 GS-HCAL Energy Resolution

- **A full detector geometry constructed with DD4hep in CEPCSW**
  - GS1 (Gd-Al-B-Si-Cs): density 6 g/cm^3, $\lambda_I = 242.8$ mm, attenuation length ~ 23mm
  - Geometry: follow the mechanics design, with simplified supporting structures.
  - GS cell size $4 \times 4 \times 1\ \mathrm{cm}^3$, 2.72cm / layer, 48 layers, $6\lambda_I$ in total







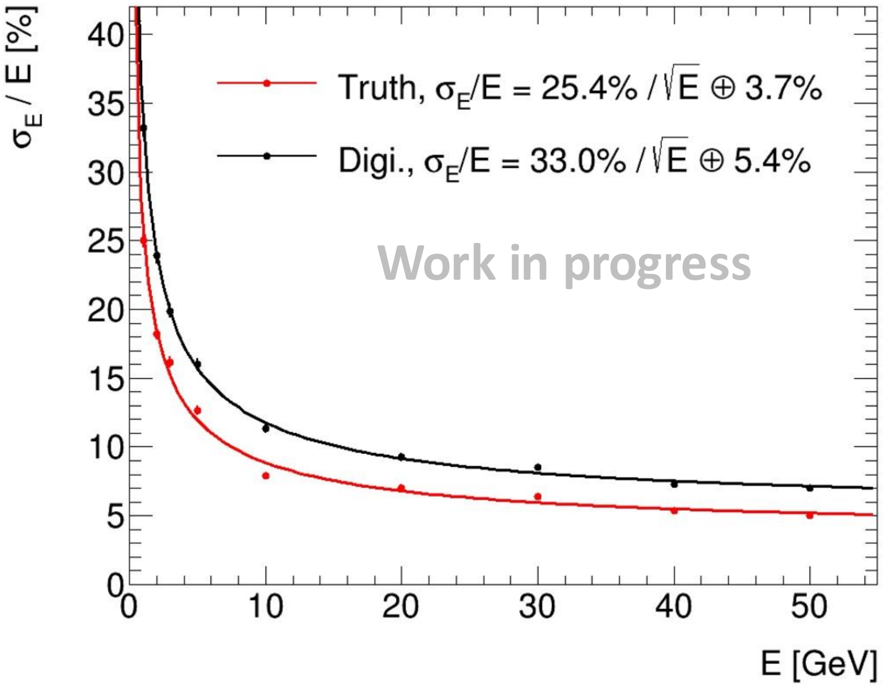
- Scintillator non-linearity in light output caused by quenching, Birks constant : C_{birks} $\sim 0.01\ (GS)$ vs $\sim 0.008\ (BGO)$

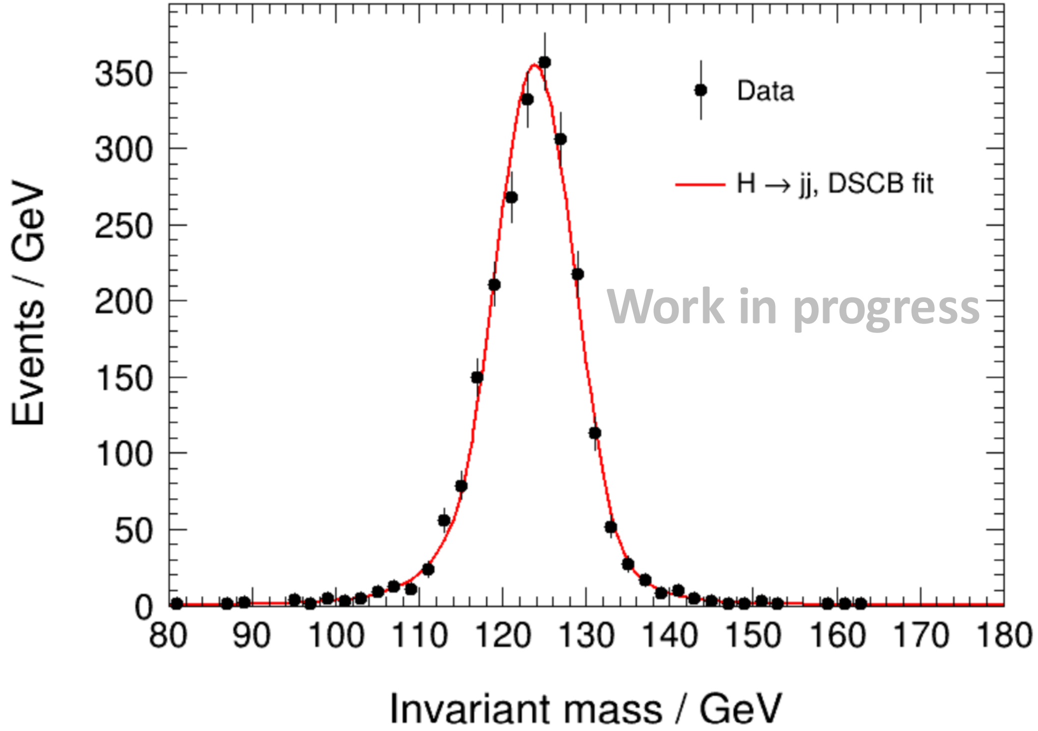
- GS light yield: > 50 p.e/MIP
- Threshold: 0.1 MIP (> 5 p.e)

- GS attenuation length: ~23mm

3.3 GS-HCAL Physics Performance

- **Hadron Energy Resolution (full sim + digi) :** $\boldsymbol{\sigma_E/E = \frac{33.0\%}{\sqrt{E}} \oplus 5.4\%}$
- **PFA Reconstruction for $ee \to ZH \to \nu\nu gg$ events:**
  - Tracker + Crystal ECAL + GS-HCAL (barrel only)
  - Improvements are expected with further optimizations (e.g. tracking, clustering, calibrations)
  - **BMR = 3.95$\pm$0.10% ($m_{jj} = 123.81 \pm 4.89$ GeV).**

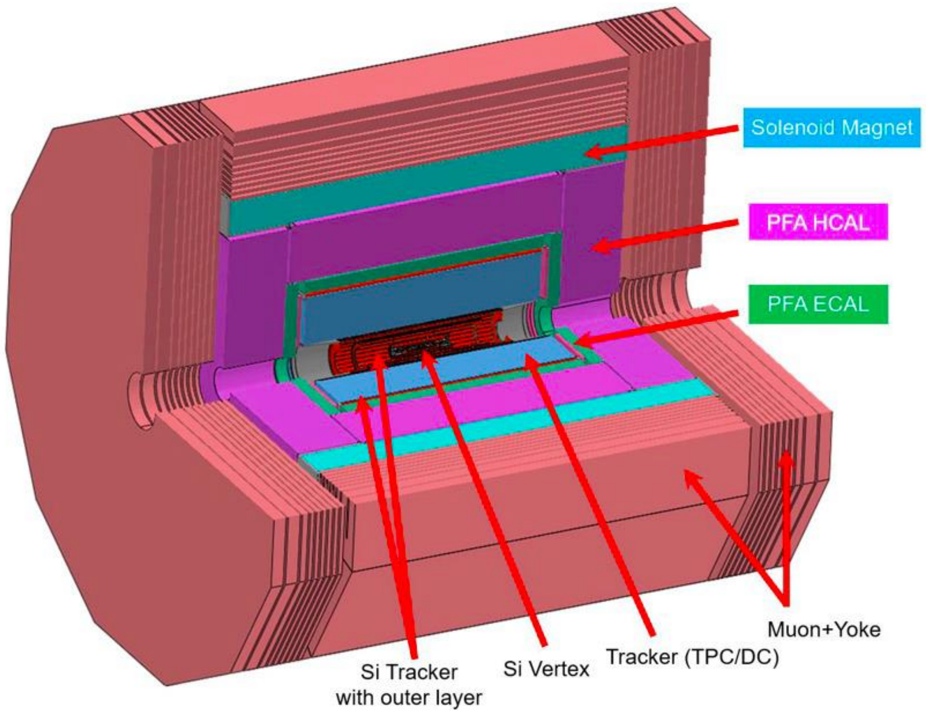


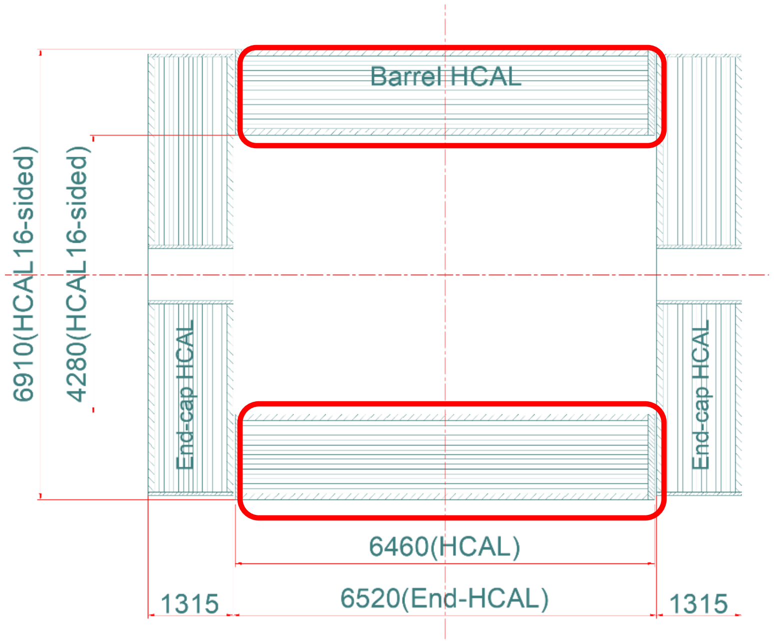


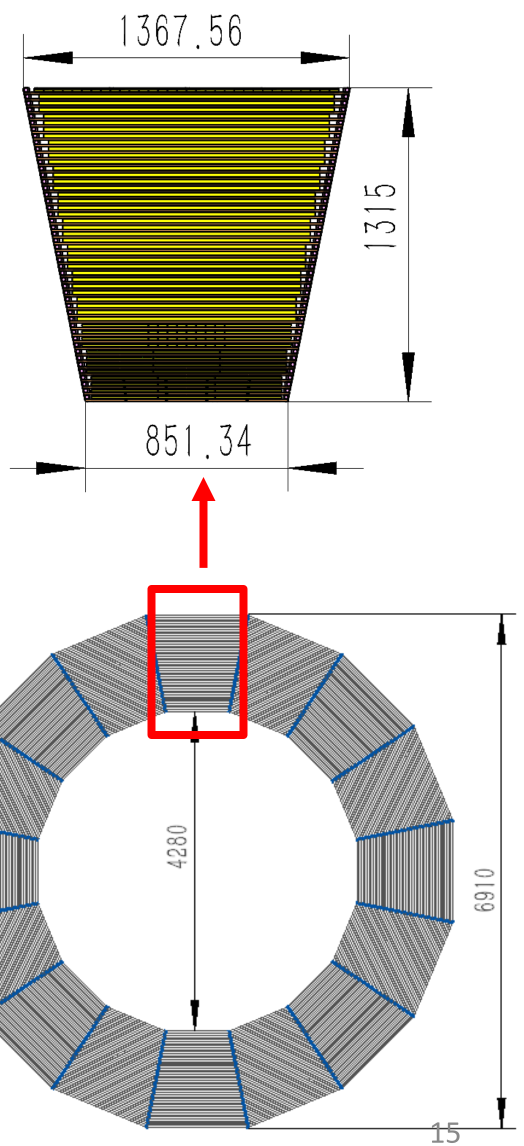
4. GS-HCAL Design

Total channels: 3.38 M, GS buget: 378 M RMB

- **GS-HCAL: Barrel (16 sectors) and two Endcaps**
  - Thickness of the Barrel : 1315 mm
  - Inner radius of the Barrel : 2140mm (D_{in}=4280 mm)
  - Barrel Length along beam direction : 6460 mm
  - Number of Layers : 48 (~ 6 λ_I)

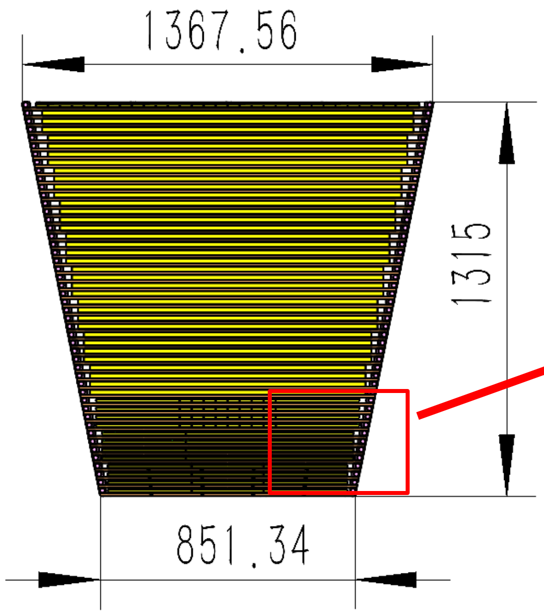




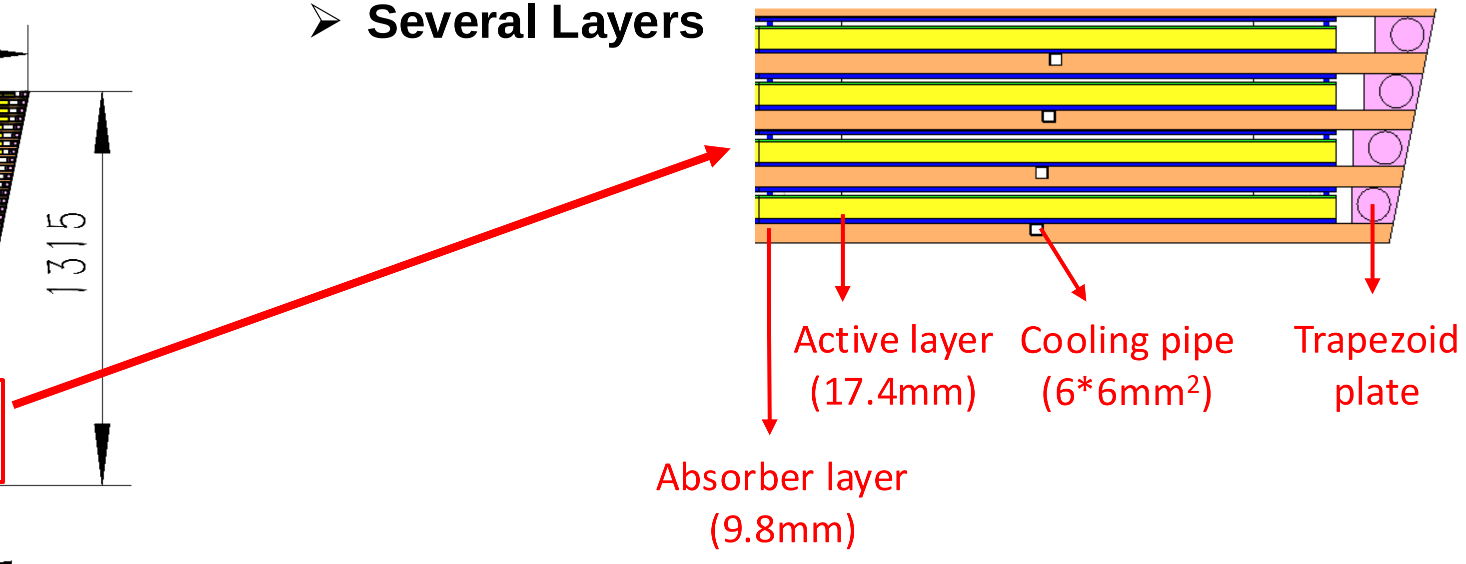


4.1 GS-HCAL Mechanical Design (Barrel)

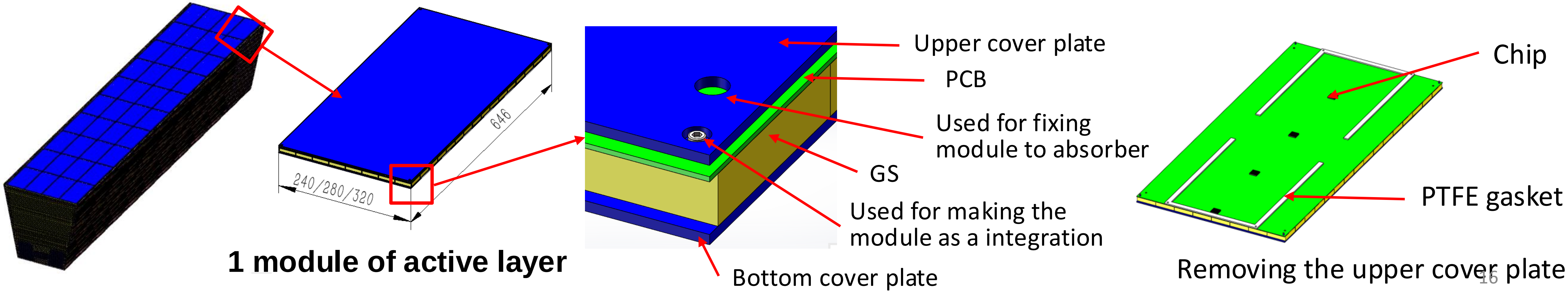
- **One Sector**



- **Several Layers**

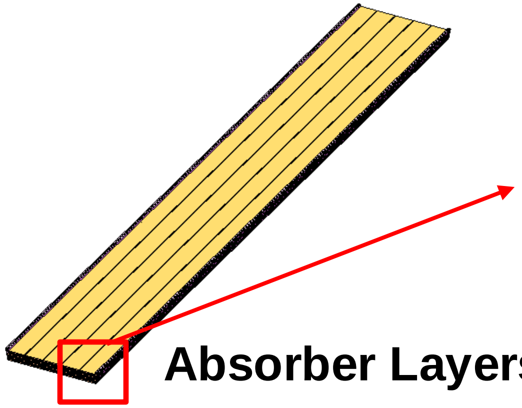


- **Active layer structure**

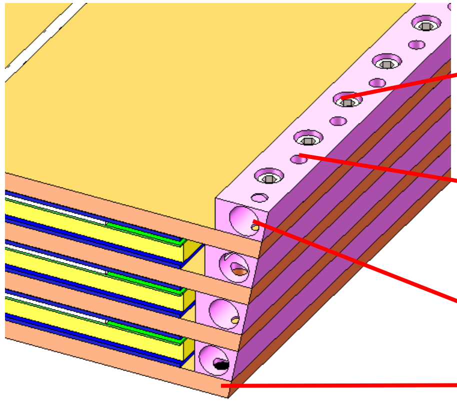


4.1 GS-HCAL Mechanical Design (Barrel)

- **Absorber layer structure**



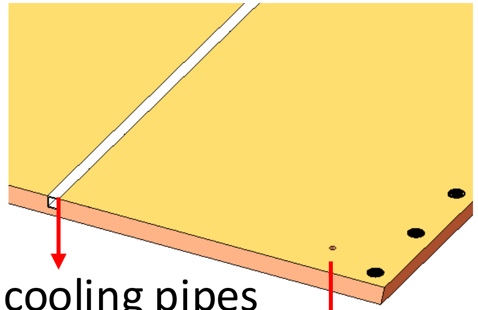
Absorber Layers



The bolts go through the upper trapezoid plate, the lower absorber layer and fix it with the lower trapezoid plate

Screws used for fix the upper absorber plate and upper trapezoid plate

Screws used for fix the edge sealing

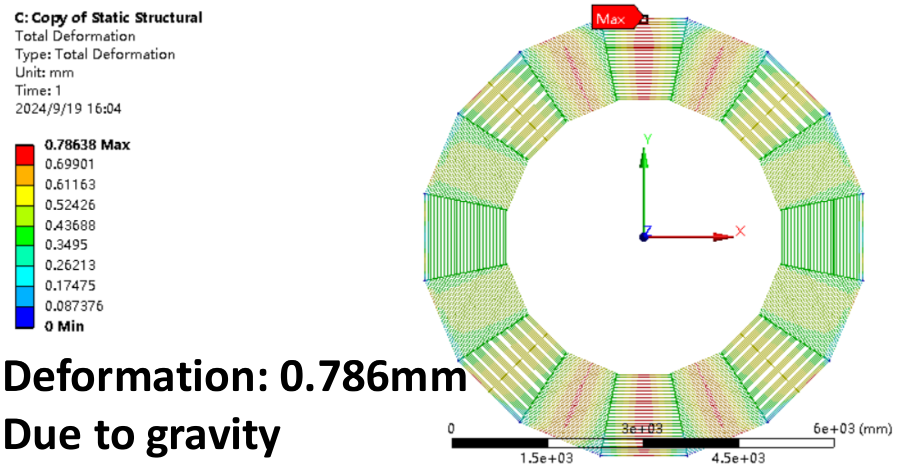


4 cooling pipes for each layer

Screw for fixing active layer module

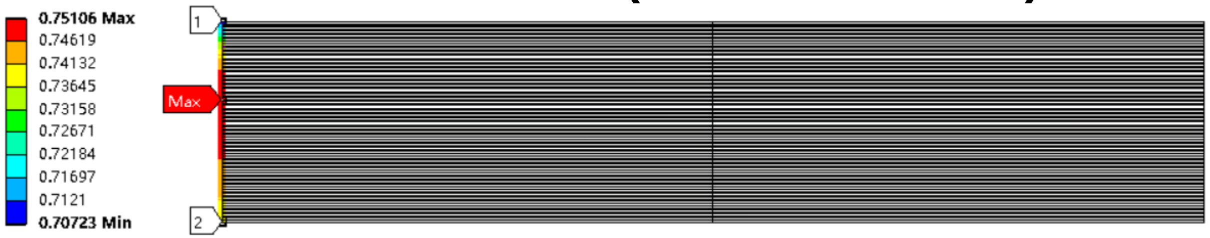
module (320mm × 646mm)

- **Simulation of absorber structure**

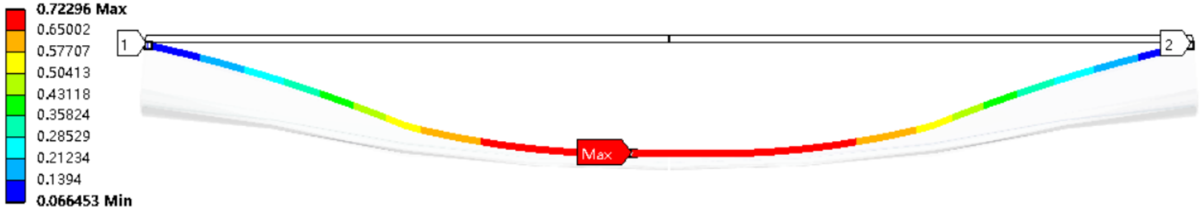


Deformation: 0.786mm

Due to gravity

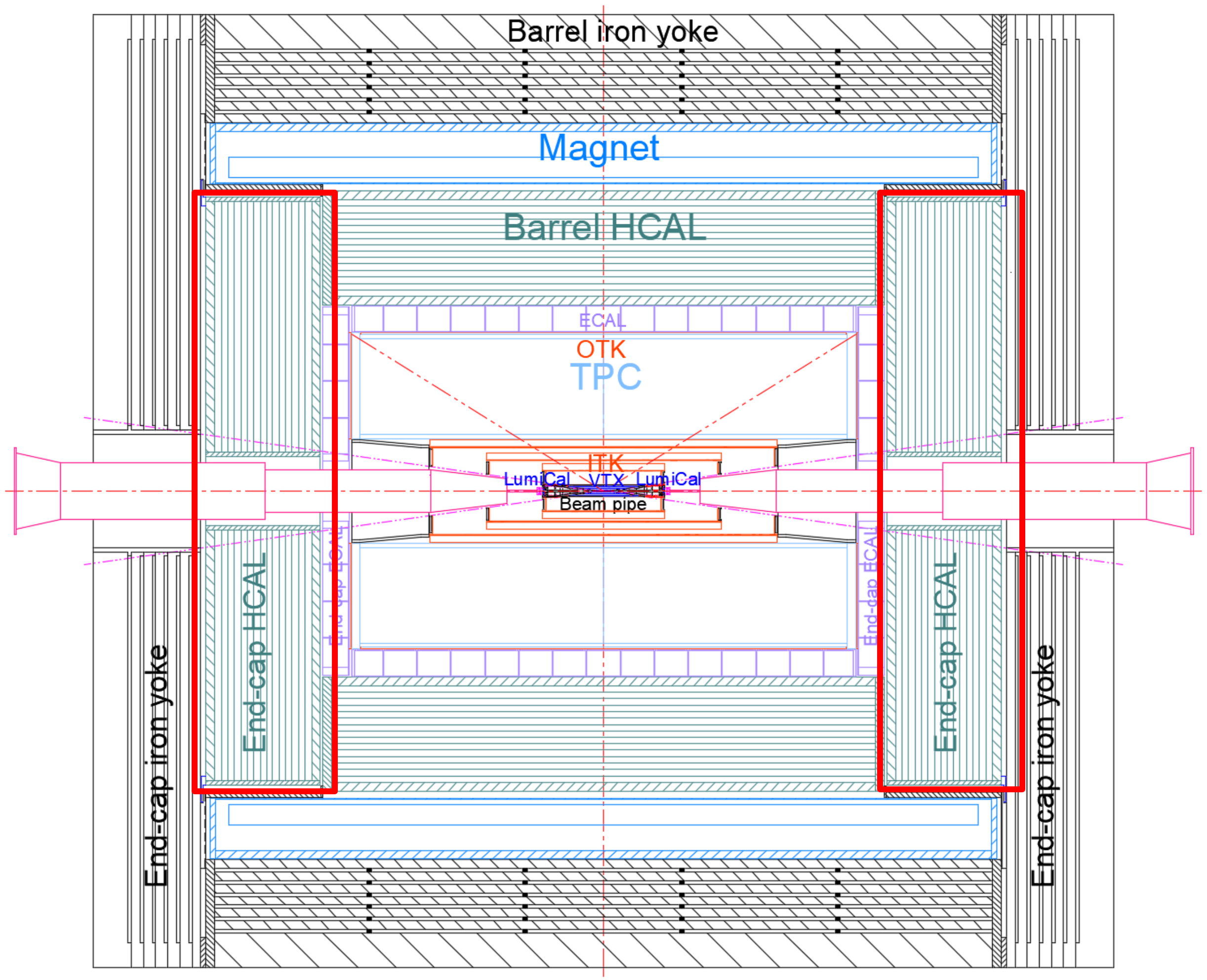


Deformation difference between 48 layers is lower than 0.05mm

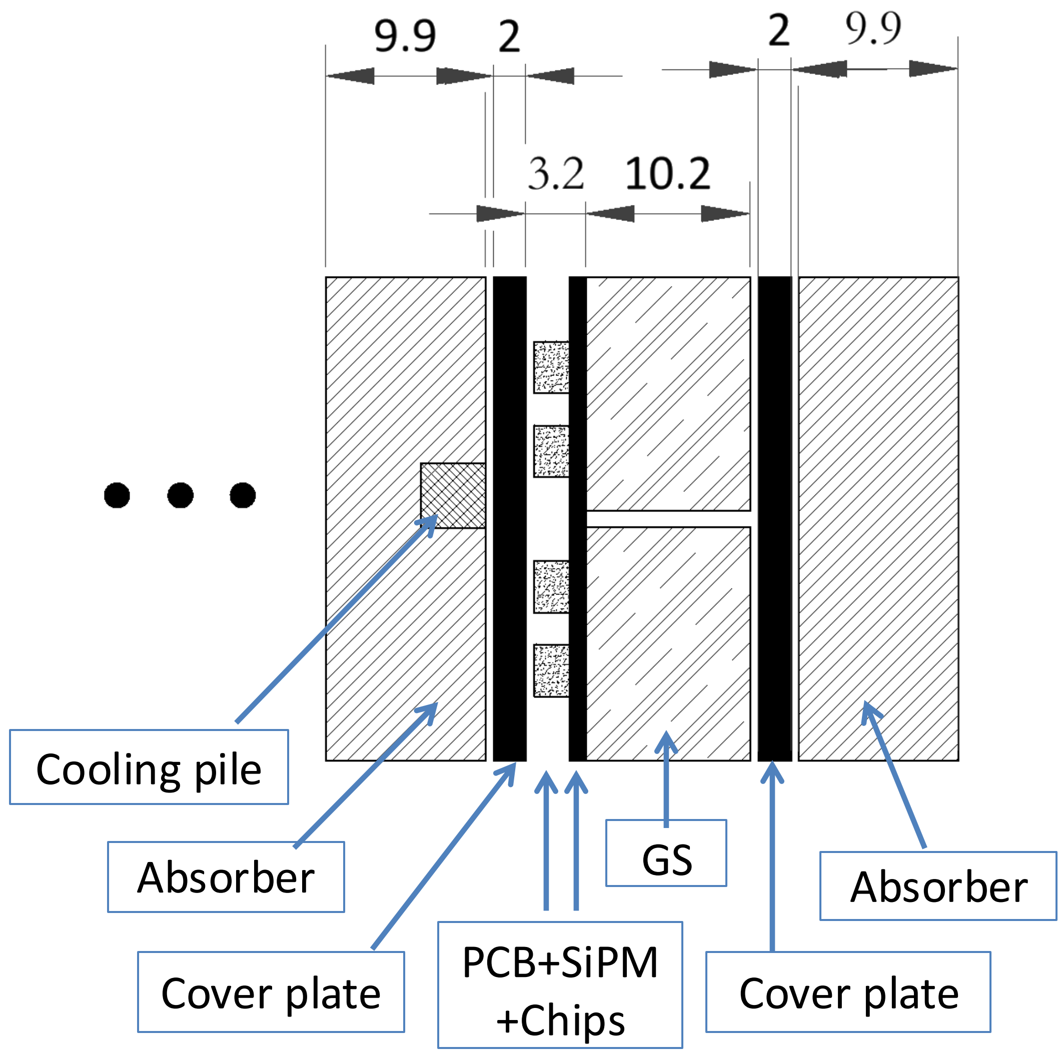


Deformation difference within 1 layer is lower than 0.7mm

4.2 GS-HCAL Mechanical Design (Endcap)

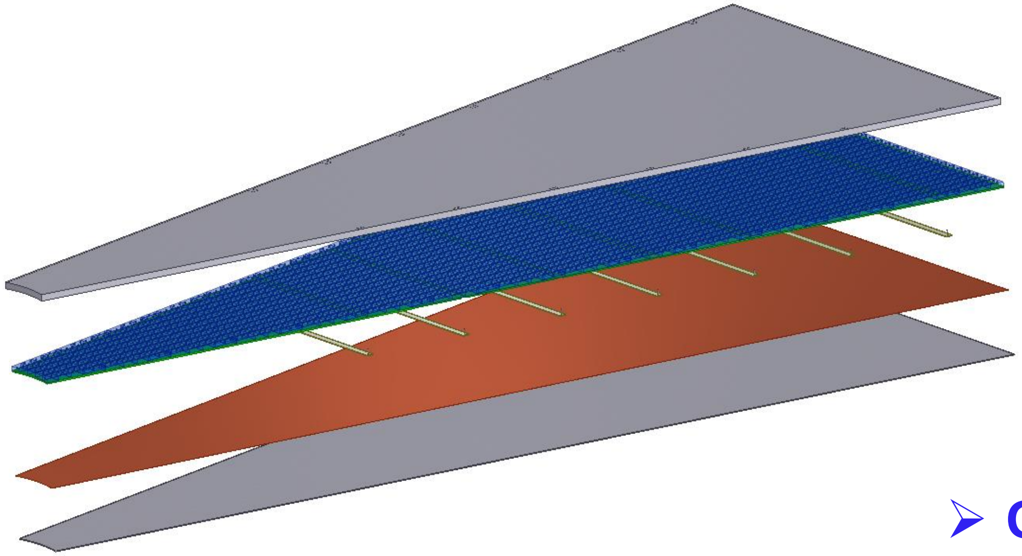


Two GS-HCAL endcap, 360 tons / each

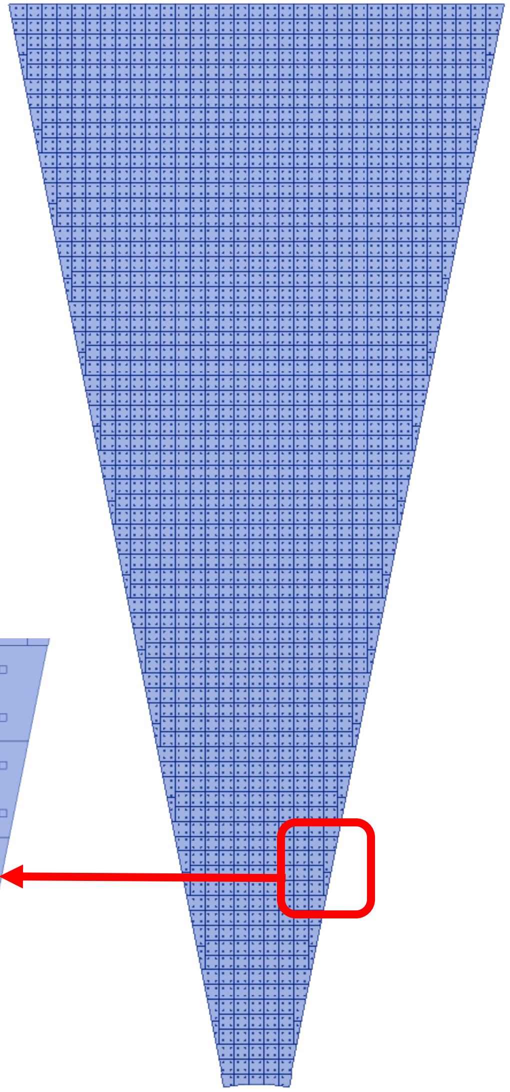


Schematic of one layer

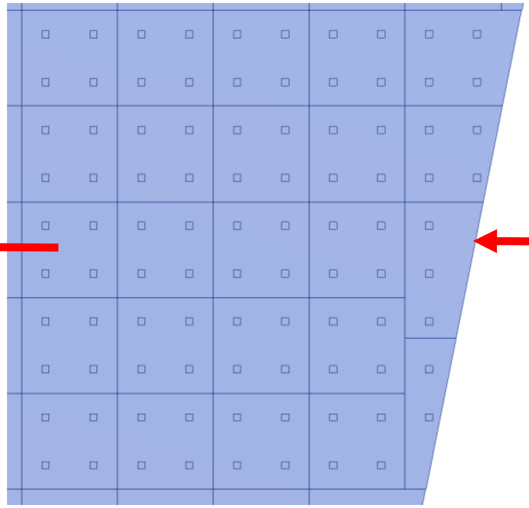
4.2 GS-HCAL Mechanical Design (Endcap)

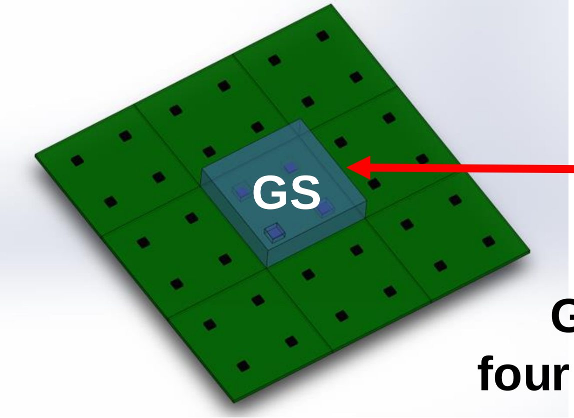


- Cover plate
- GS + PCB
- Tighten Strips
- Thermal Conductor
- Cover plate



- GS cell size: 40 × 40 × 10 mm^3
- Four special-shaped at edge



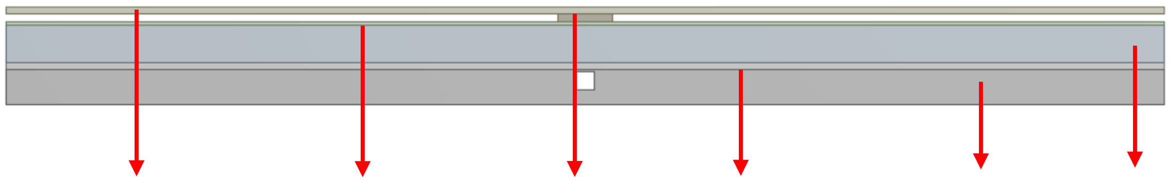


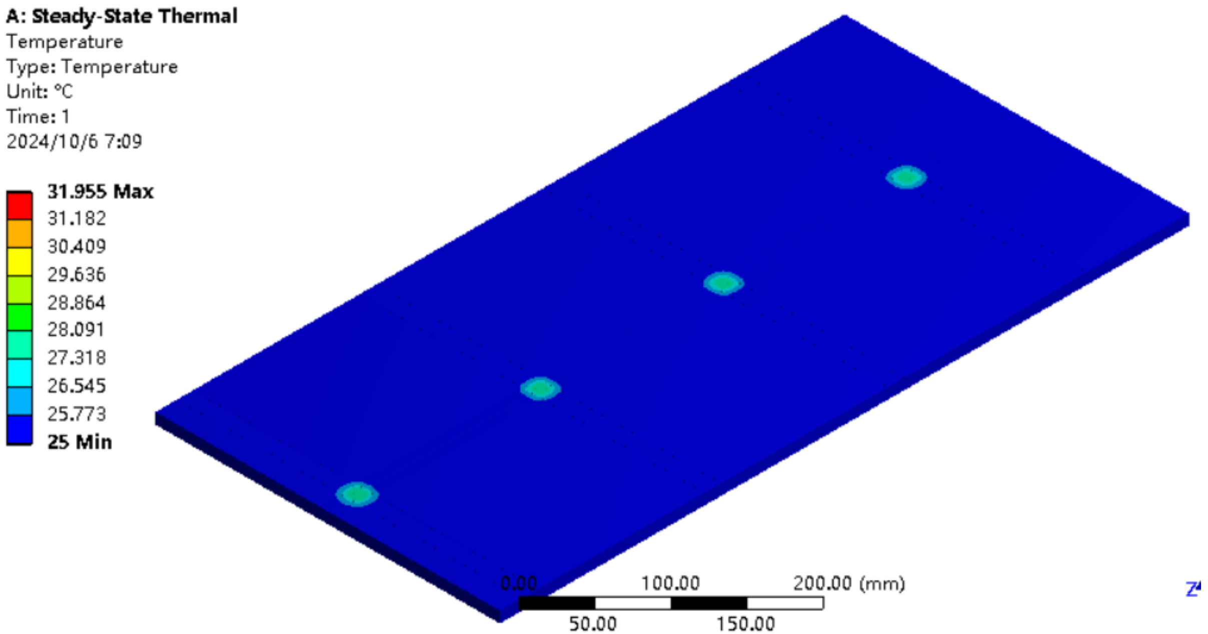
GS-SiPM-PCB
four SiPM (3x3 mm^2)

4.3 GS-HCAL Cooling Simulation

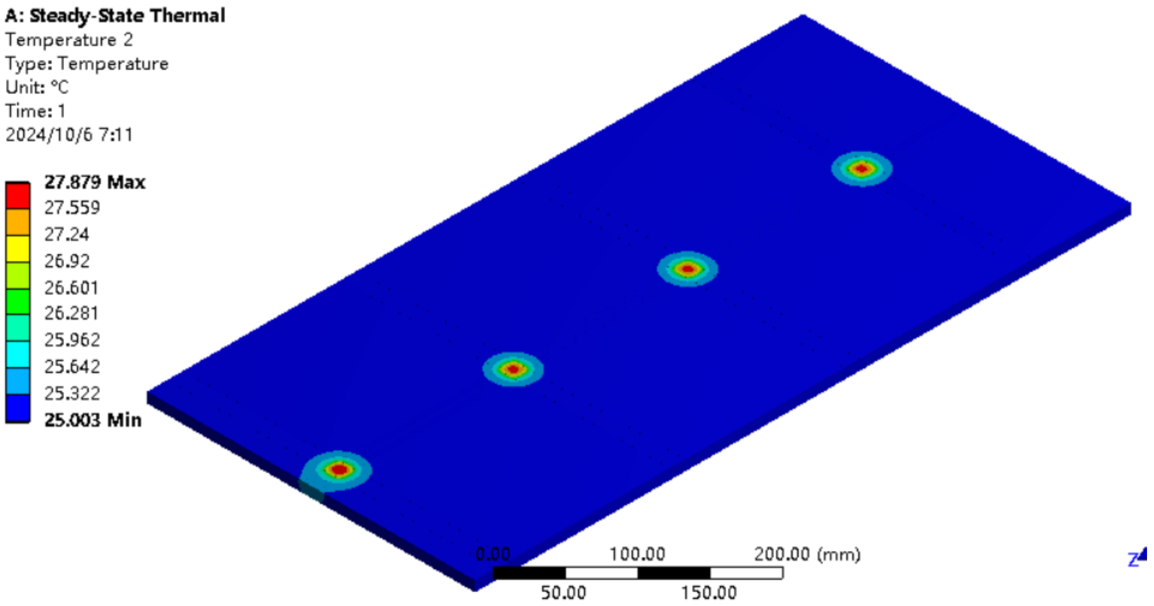
➢ Cooling simulation of 1 active layer module (320mm × 646mm)

- Heat source (chip): 15 mW/ch
- coefficient of heat conduction： 5000W/m^2 K;
- Inlet water 25°C, environment temperature is 25°C
- Thermal contact resistance： 500W/m^2





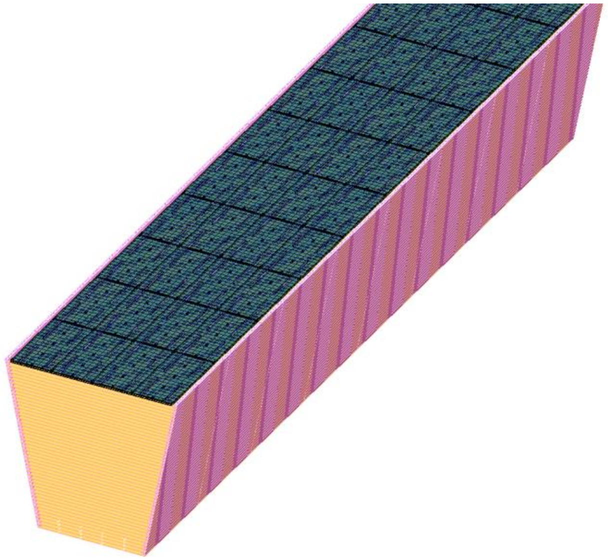
Temperature distribution: 25 ℃ ~ 32 ℃

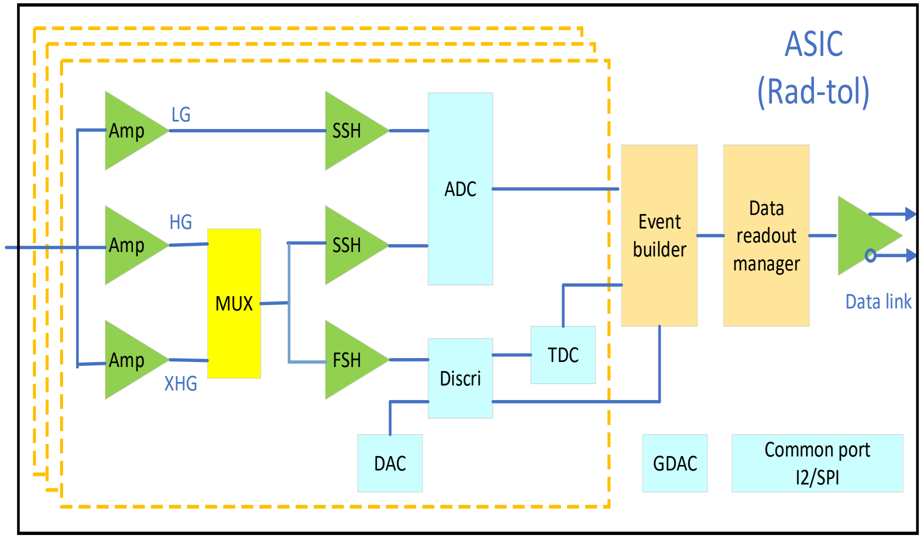


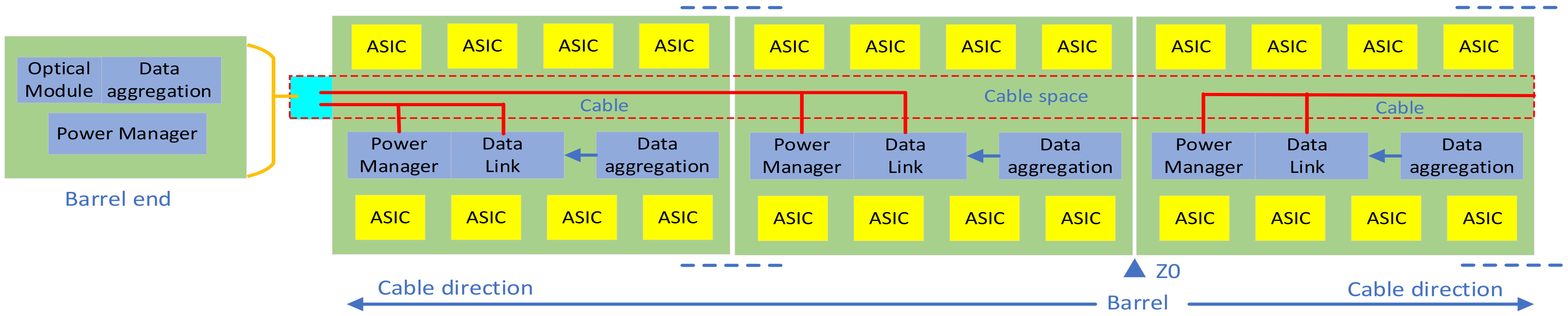
Temperature difference (GS vs SiPM): 2.8 ℃

5. GS-HCAL Readout Electronics

- **Thickness: 3.2mm**
  - PCB 1.2mm
  - ASIC Chip 2mm
- **Power: 15 mW/ch**
- **Aggregation board at the end of barrel**





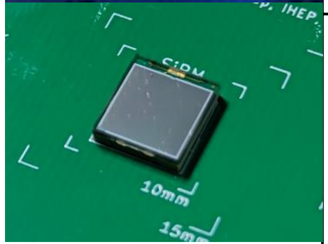


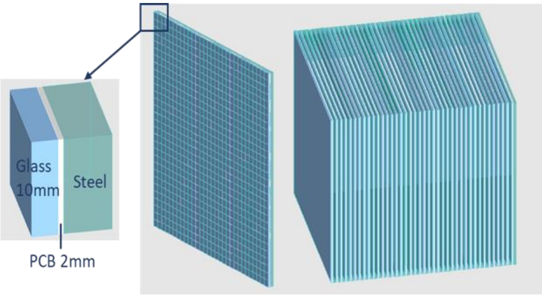
Aggregation board at the end of barrel, cable connection

6. HCAL Research Group

- **CEPC-HCAL team：**
  - **IHEP, USTC, SJTU, XJTU, SCNU, SCU, HEU, ZZU**
  - **Detector for PS/GS-AHCAL：** Staff(**9**) + Student(~**6**)
  - **Electronics:** Staff(**5**)
  - **Mechanics:** Staff(**3**)
- **The Glass Scintillator Collaboration**
  - Institute (13) + Staff (26)+ Student (10)

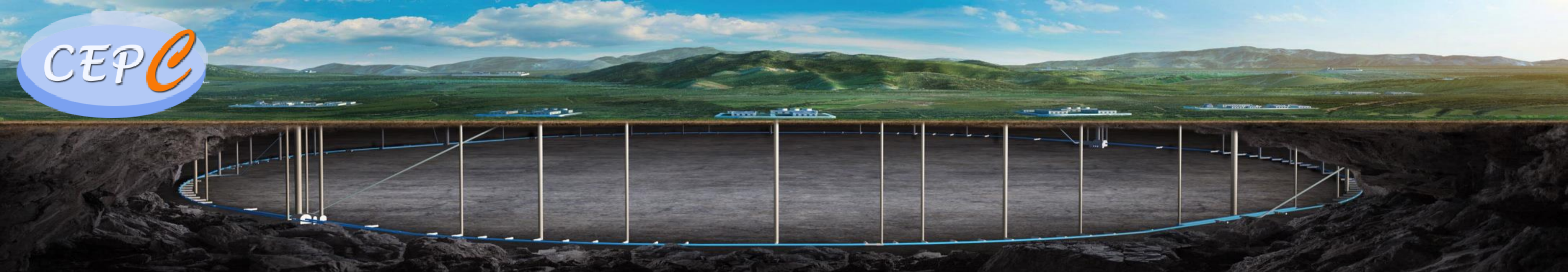
7. Working Plan and Schedule



	2021-2023	2024-2025	2026	2027
Physics+ Software+ Design+ Mechanics	Design TDR	Optimization calibration	New Design; calibration; beam test	 Assembly the cell; Finish the Module for performance test; The cosmic ray test; the beam test;
Glass Scintillator	R&D 5X5X5 mm^3	R&D 40X40X10 mm^3	10K pieces mass production batch test	
SiPM	Test samples	Performance test, choice	40K pieces batch test	
Electronics	The design of ASIC and FEE, power supply	V1, V2 performance test	V2 mass production batch test	

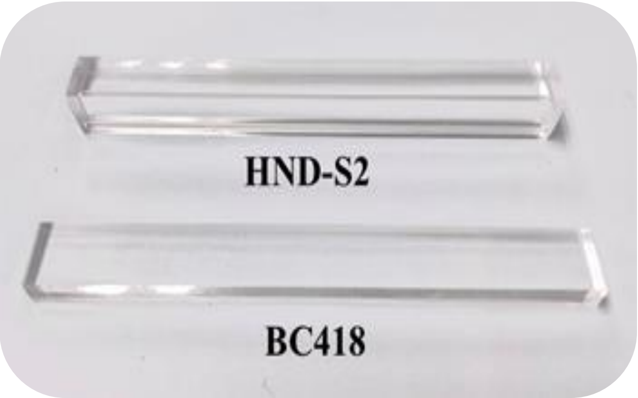
8. Summary

- **Overview of three HCAL options and R&D activities in the past decade**
- **GS-HCAL is selected as a baseline option for CEPC reference detector**
  - First design of GS-HCAL: mechanics, cooling and readout electronics
  - Intensive R&D on high quality GS
  - Preliminary performance study with CEPCSW
- **More efforts needed to address critical issues for reference detector TDR**
  - Optimization of granularity, GS-SiPM coupling, mechanics, cooling, electronics etc.
  - GS-HCAL full simulation and reconstruction for benchmark physics
- **Further R&D efforts beyond TDR**
  - Developing technique for mass production of high quality GS cost-wise
  - Developing full-scale GS-HCAL prototype with integrated electronics for beam test

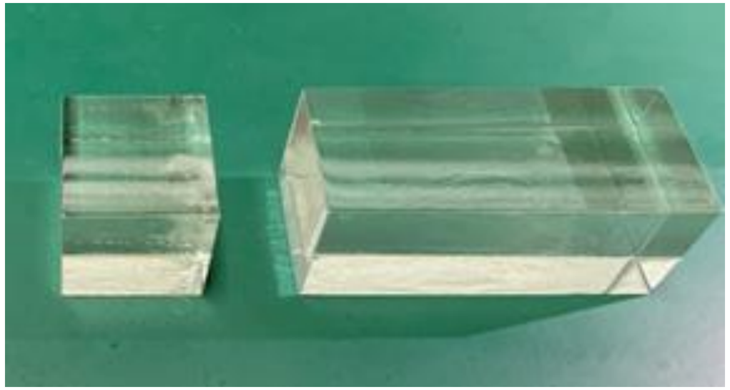


Thanks for your attention！

3.3 Comparison of Scintillators



Plastic Scintillator



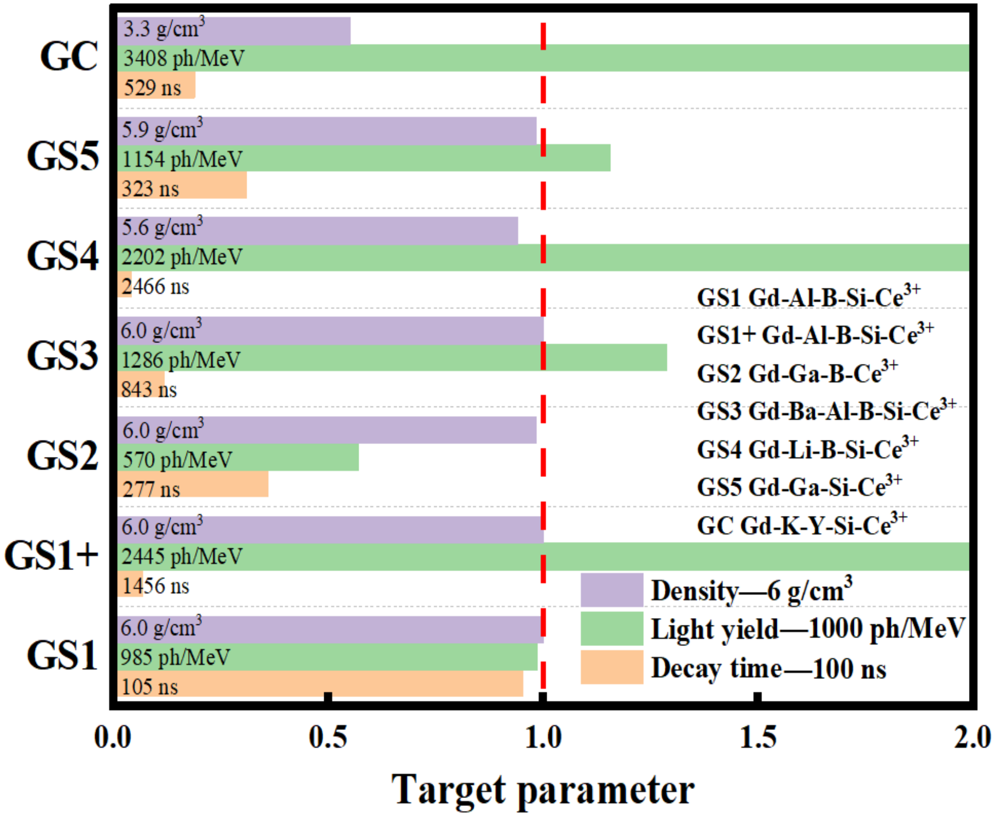
Glass Scintillator

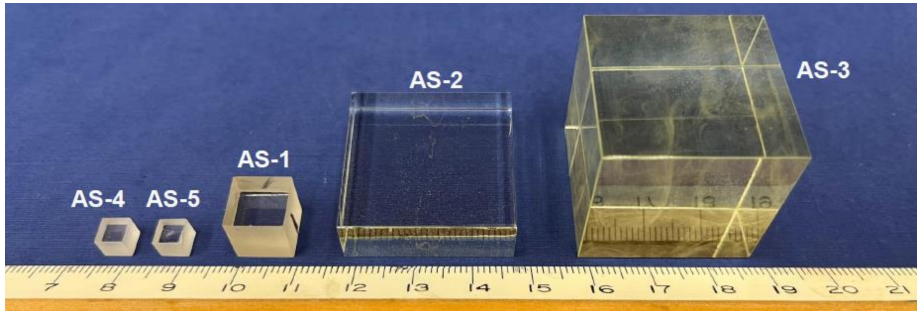
Crystal Scintillator

	Plastic Scintillator		Glass Scintillator		Crystal Scintillator
Large density	★	Large density	★★	Large density	★★★
High light yield	★★	High light yield	★★	High light yield	★★★
Energy resolution	★	Energy resolution	★★	Energy resolution	★★★
Low cost	★★★	Low cost	★★	Low cost	★
Fast decay	★★★	Fast decay	★★	Fast decay	★★
Large size	★★★	Large size	★★	Large size	★★

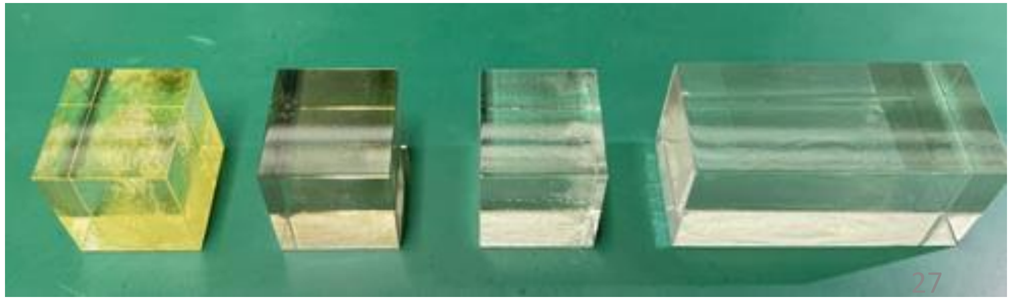
1. GS-HCAL: Sample test

Parameters	Unit	BGO	GS1	GS1+	GS5
Cost		1	0.1 ?		
Density	g/cm^3	7.13	6.0	6.0	5.9
Transmittance	%	82	70	80	80
Refractive Index	--	2.1	1.74	1.71	1.75
Emission peak	nm	480	400	390	390
Light yield, LY	ph/MeV	8000	985	2445	1154
Energy resolution, ER	%	9.5	30.3	25.8	25.4
Decay time	ns	60, 300	36, 105	101,1456	90, 300





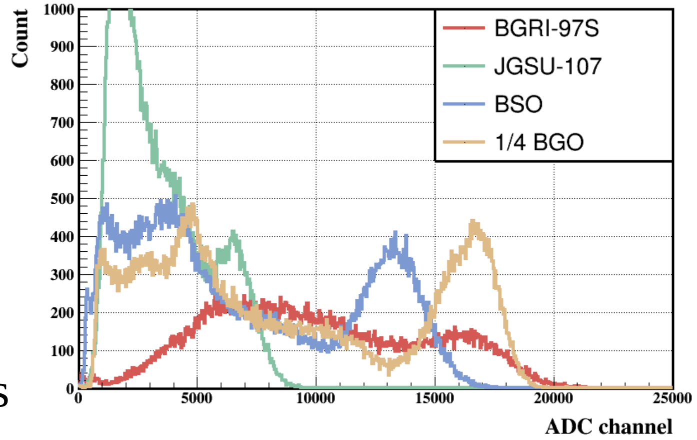
The samples (called AS glass) post to EIC for the test.



1. GS-HCAL: Sample test

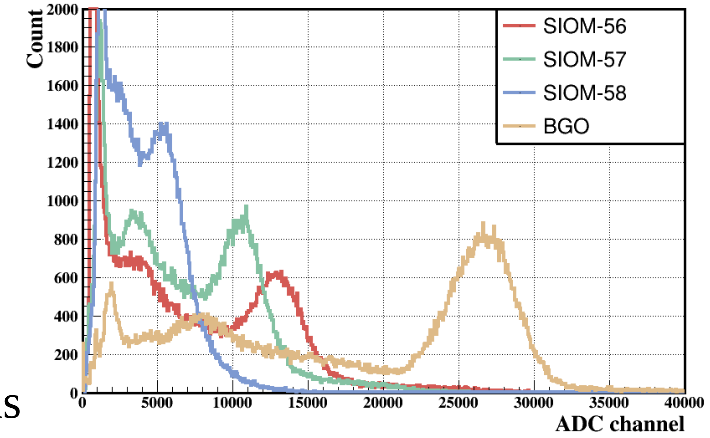
Small-Size Sample

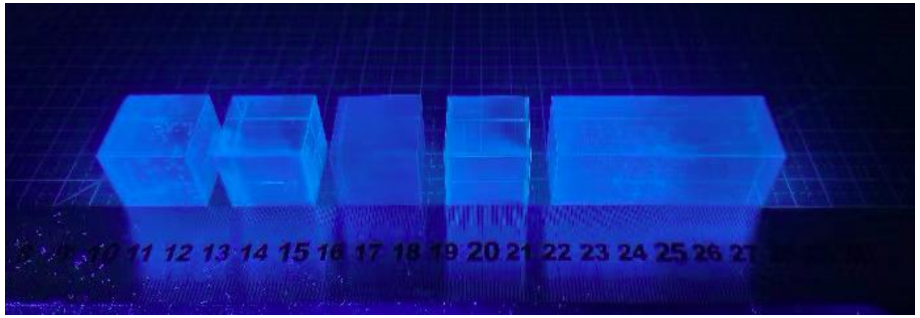
- **Size=5*5*5 mm³**
- Density~6.0 g/cm³
- **LY~2445 ph/MeV**
- ER=25.8%
- LO in 1μs=1074 ph/MeV
- Decay=**101** (2%), 1456 ns

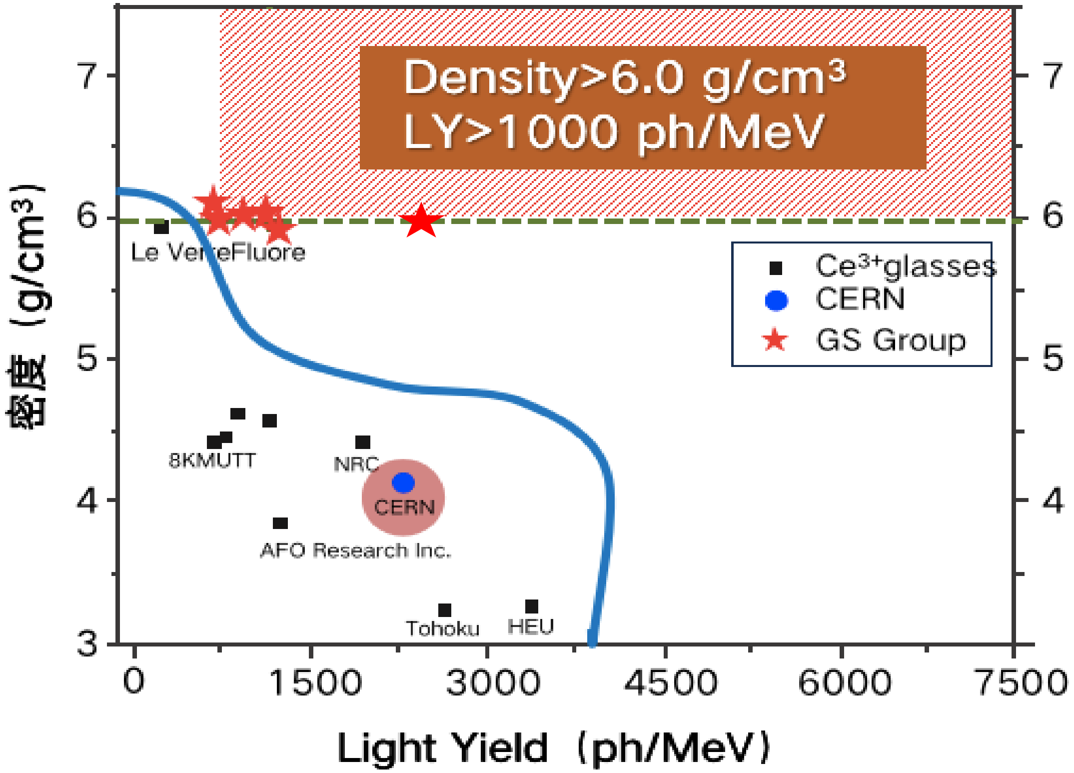


Large-Size Sample

- **Size=40*40*10 mm³**
- Density=6.0 g/cm³
- **LY ~1200 ph/MeV**
- ER=33.0%
- LO in 1μs=607 (51%)
- Decay=117 (3%), 1368 ns





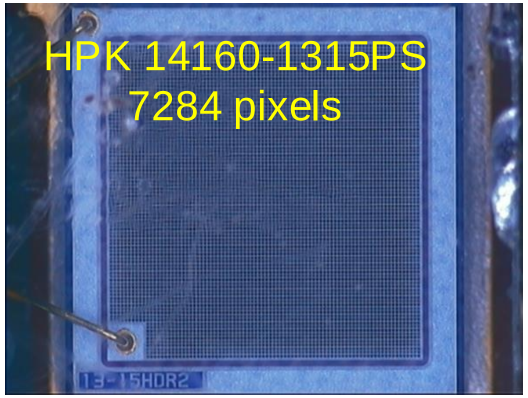


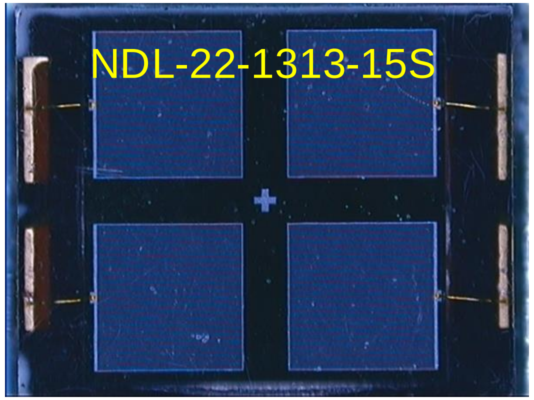
SiPM

NIMA 980 (2020) 164481

- **HPK-SiPM**
  - Low PDE, dark rate and crosstalk
  - High breakdown voltage
  - Better quality control

- **NDL-SiPM**
  - High PDE, dark rate and crosstalk
  - Low breakdown voltage
  - Low price

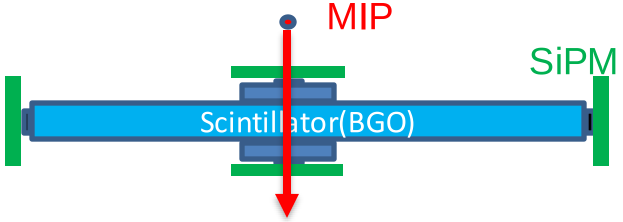


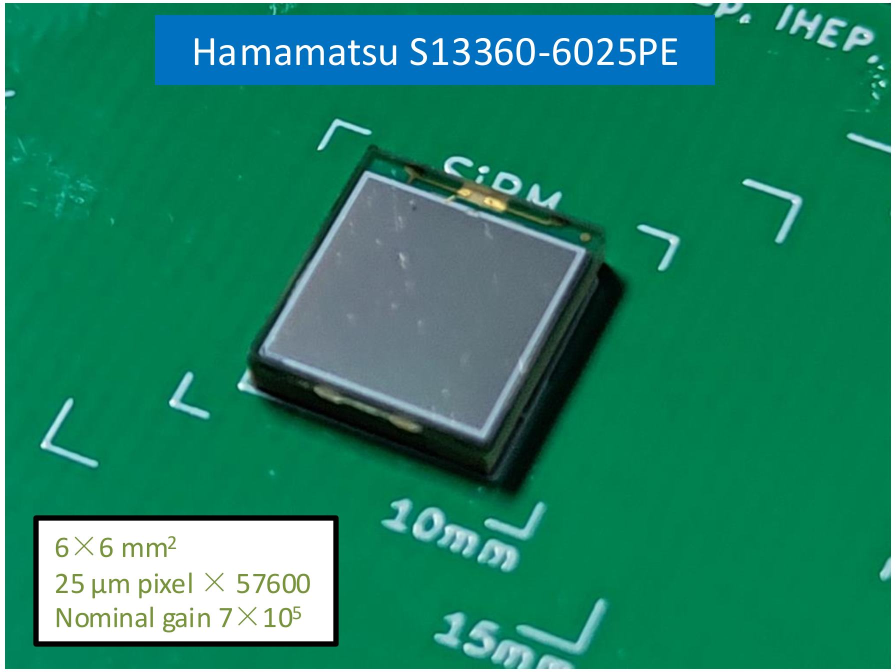


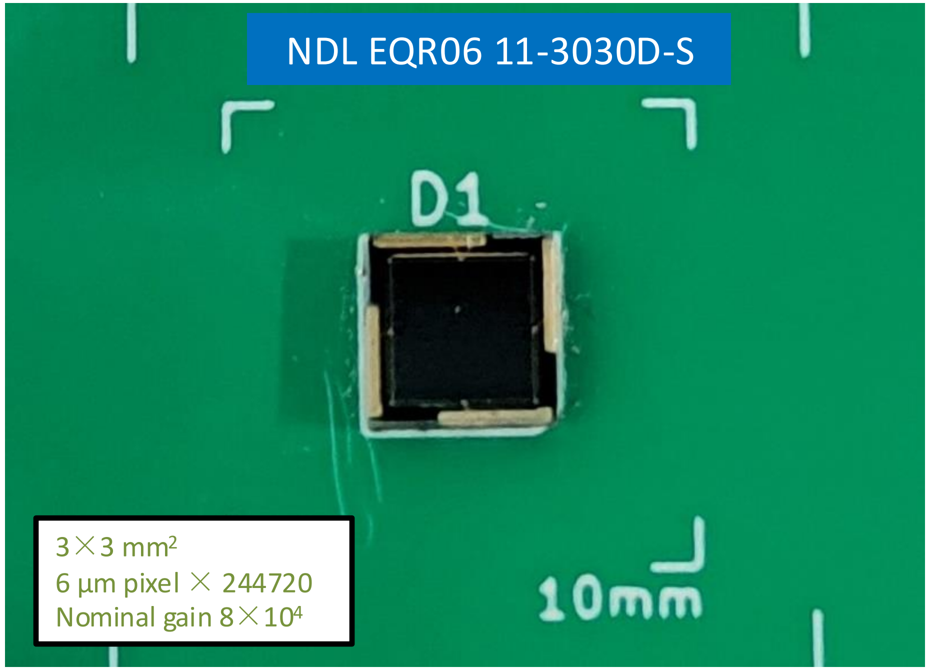
Company	HPK			NDL
Type	13360-1325PE	14160-1315PS	14160-3015PS	22-1313-15S
Light output [p.e.]	13	17		20
Crosstalk[%]	1.59	1.17		4.4
Dark Counts [kHz]	120	290	700	550
Breakdown[V]	53	38	38	27.5

SiPM

- **SiPM Options：**
  - **HPK S13360-6025PE，57600 pixels**
  - **NDL EQR06 11-3030D-S，244760 pixels**
  - **HPK S14160-3015PS，39984 pixels**
  - **HPK S14160-3025PS, 14440 pixels**

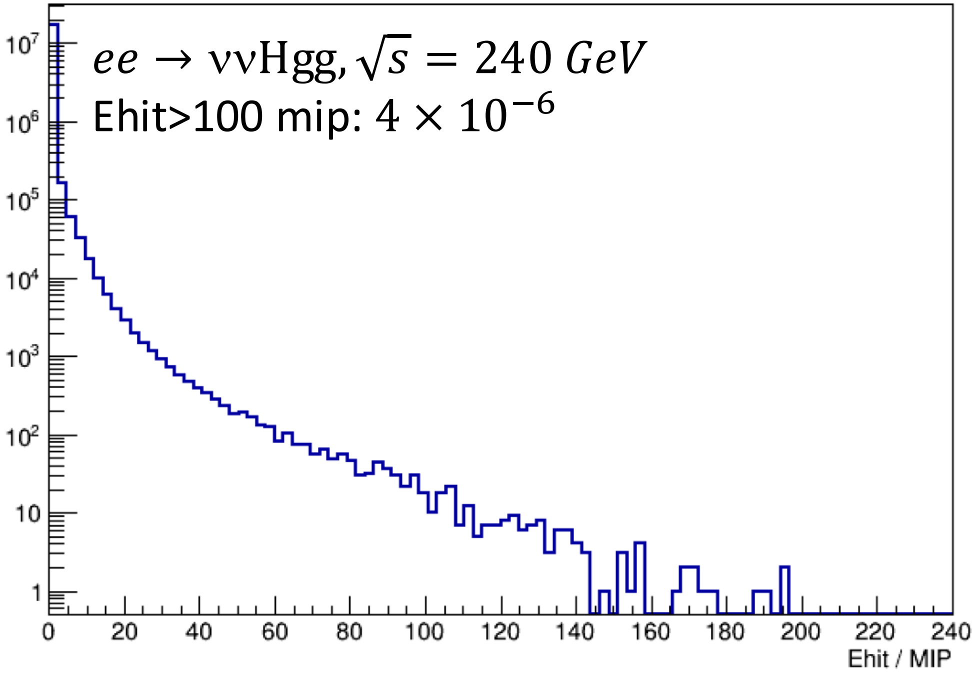


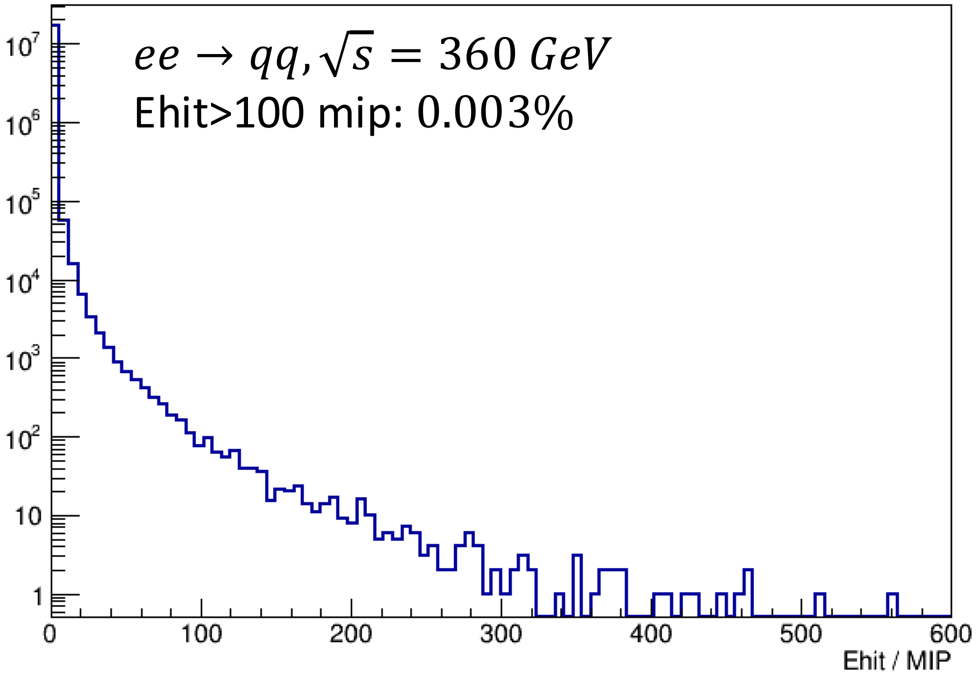




Key parameters to energy resolution

- **Dynamic range: 0 ~ 100 MIP can cover >99.99% cases**
  - For SiPM: 8000 p.e. can be controlled in linear range (suppose LY ~ 80 p.e./MIP).
  - For electronics: 1~1k can be achieved.
  - Considering the common electronics design for ECAL, HCAL and Muon, HCAL's demands can be covered by ECAL.



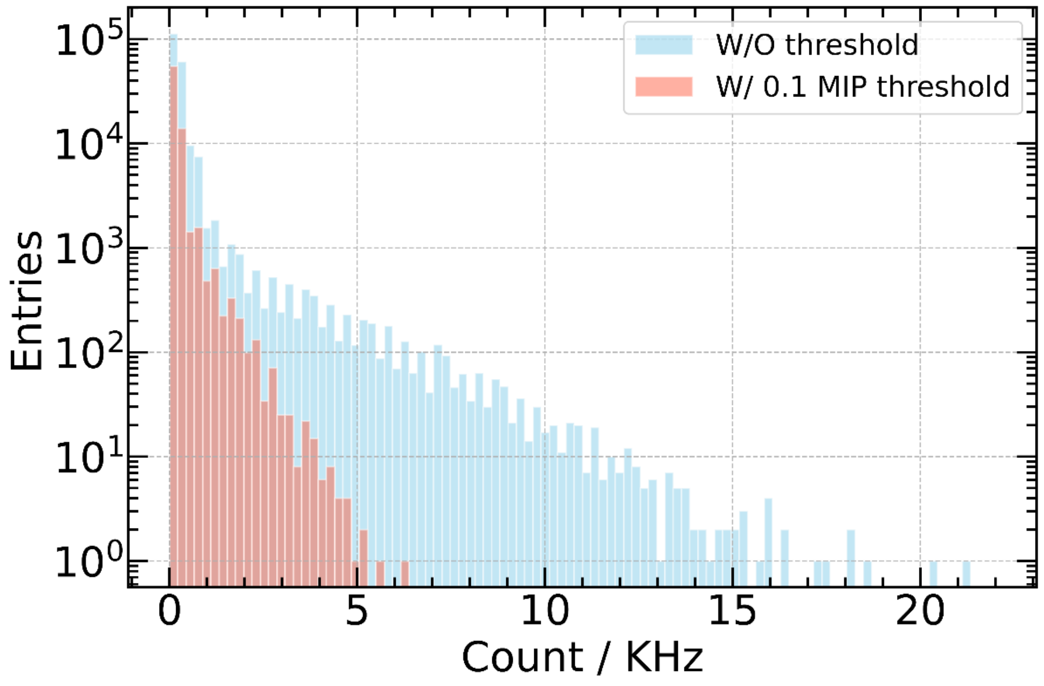


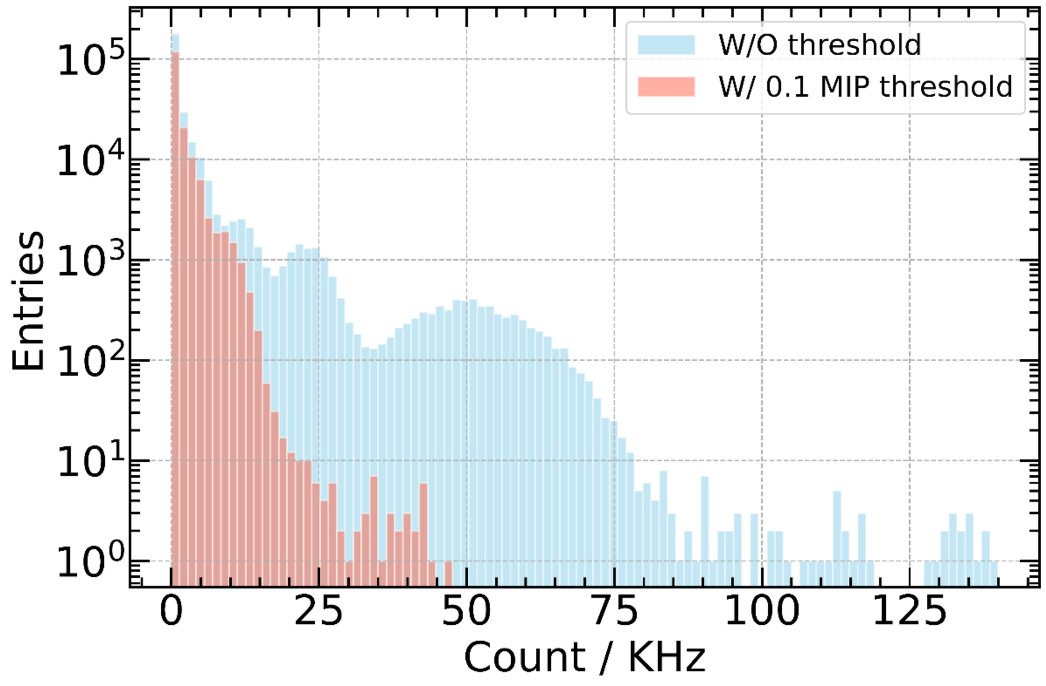
2. Requirement

Parameter	Conservative	Ambitious	Remarks
Hadron Energy Resolution	$60\%/\sqrt{E} \oplus 3\%$	$40\%/\sqrt{E} \oplus 5\%$	Jet performance flavor physics
Longitudinal Depth	48 layers, total depth of 6 λ_I		Containment most of jets
Transverse Granularity	40mm × 40 mm		H → gg (gluon jets)
Signal Dynamic Range	1 – 100 MIPs		0.1 MIP as trigger threshold
Time Resolution (1-MIP signal)	1 ns		Bunch crossing ID timing hadron performance
Power Consumption	15 mW/ch		O(5.6M) channels

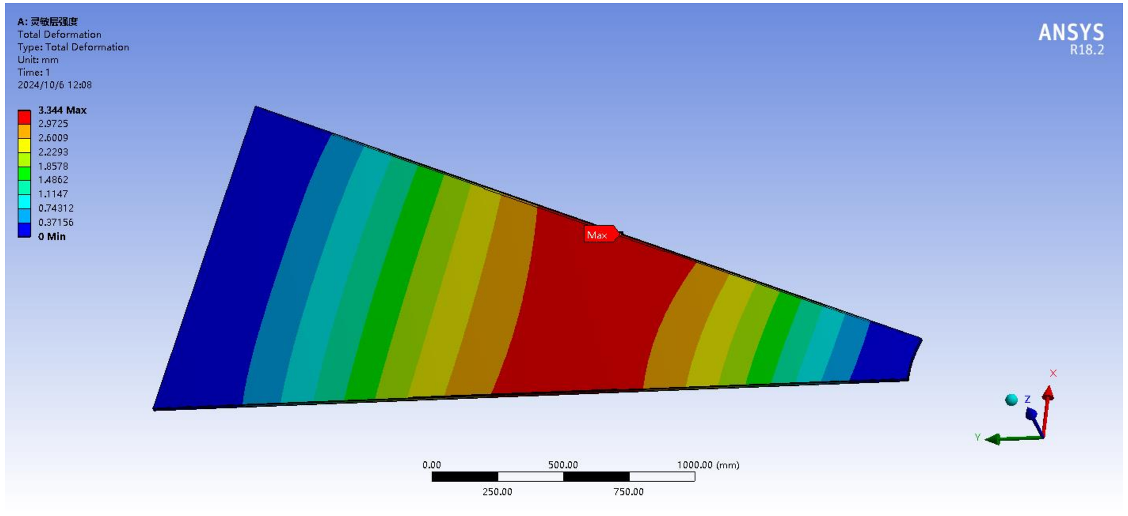
4.4 GS-HCAL Background Estimation

- **Simulation of beam background processes:**
  - 50 MW(H), bunch spacing 355 ns, with pair production, single beam processes
  - Event rate with 0.1 MIP threshold: barrel < 5 kHz, endcap < 50 kHz

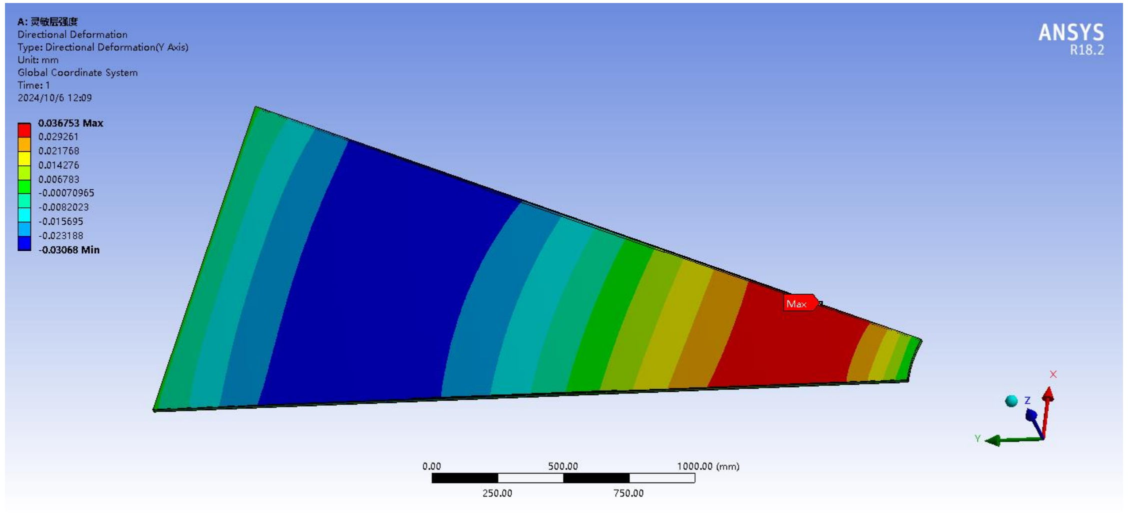


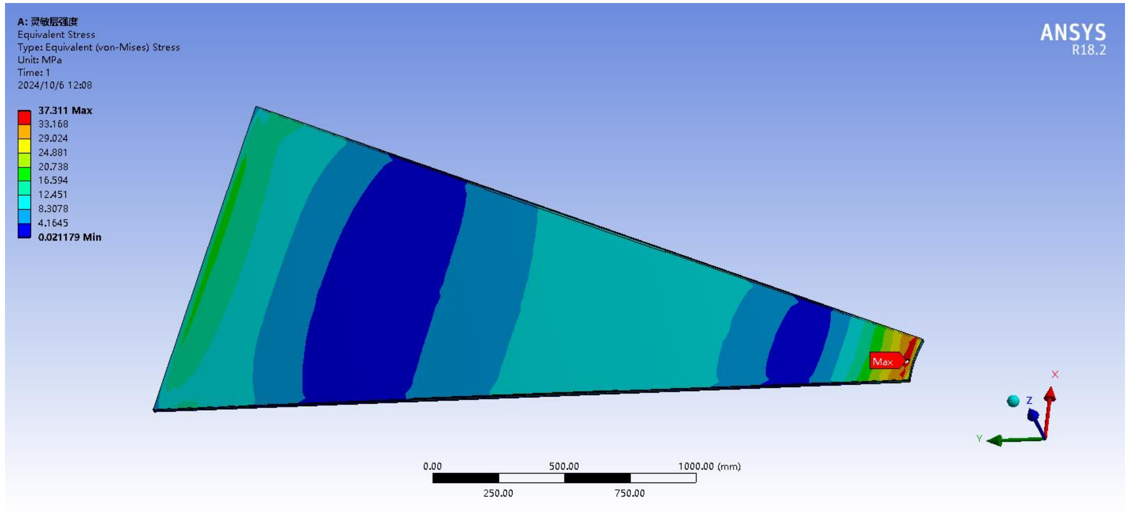


5.2 GS-HCAL Mechanical Design (Endcap)

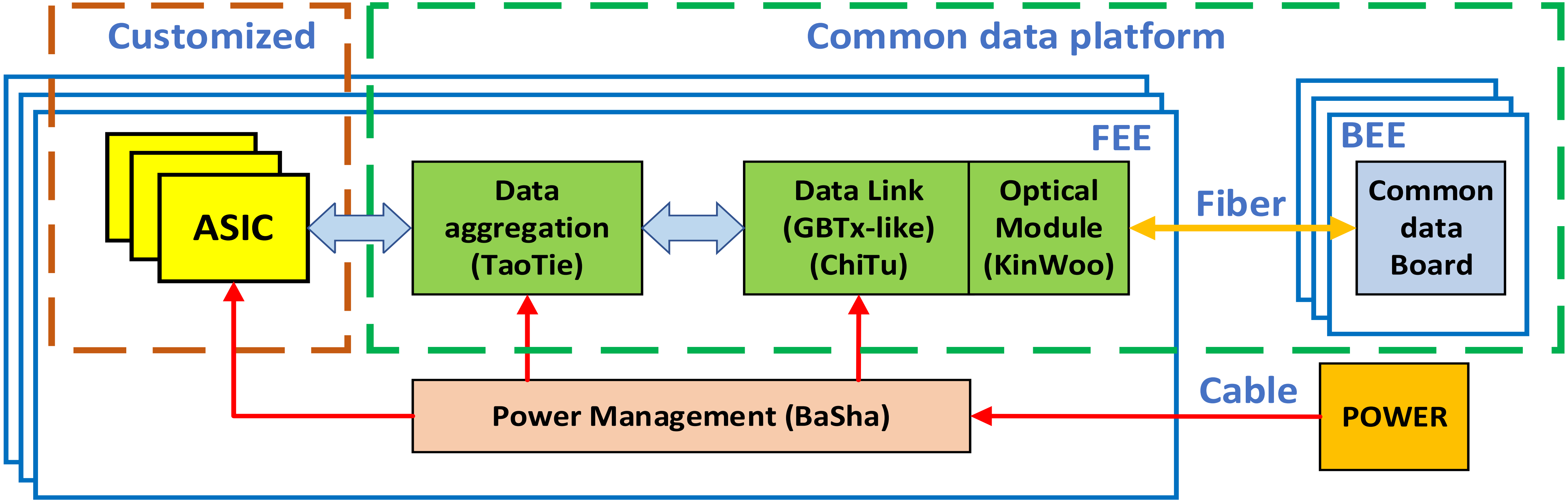


- Max. deformation in one active layer: 3mm (due to gravity)
- Horizontal extrusion deformation: 0.037mm
- Max. principal stress at narrow end: 37MPa





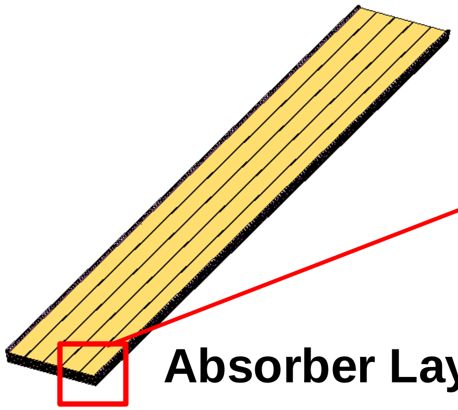
6. GS-HCAL Readout Electronics



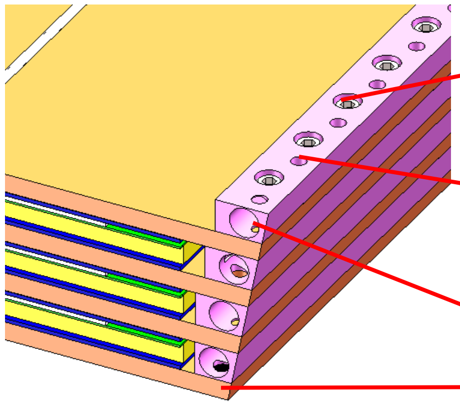
- **Energy Measurement:** ASIC for ECAL & HCAL
- **Data transmission:** common data platform (see electronics report)
- **Trigger mode:** FEE trigger-less readout

5.1 GS-HCAL Mechanical Design (Barrel)

- **Absorber layer structure**



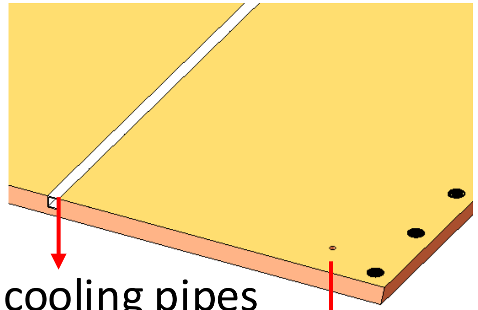
Absorber Layers



The bolts go through the upper trapezoid plate, the lower absorber layer and fix it with the lower trapezoid plate

Screws used for fix the upper absorber plate and upper trapezoid plate

Screws used for fix the edge sealing

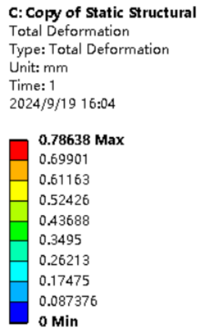


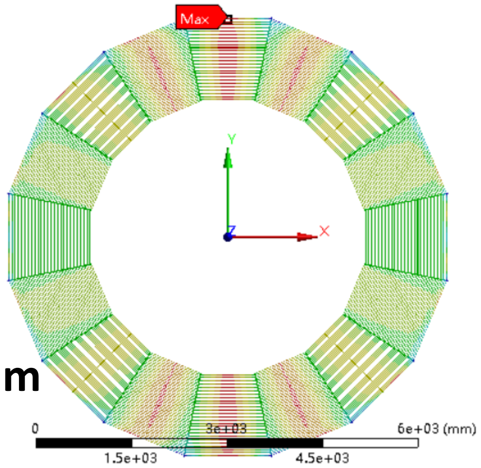
4 cooling pipes for each layer

Screw for fixing active layer module

module (320mm × 646mm)

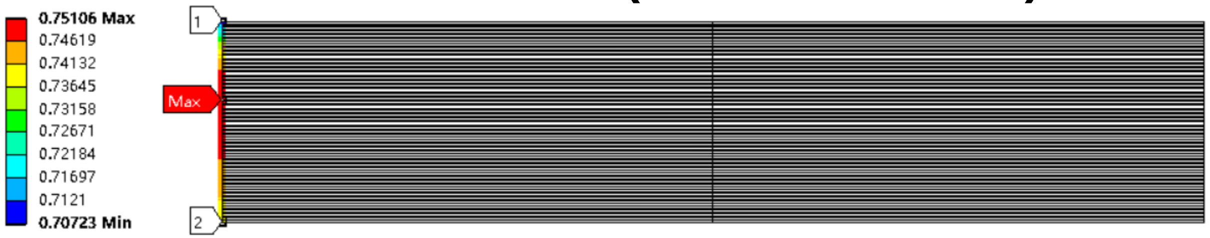
- **Simulation of absorber structure**



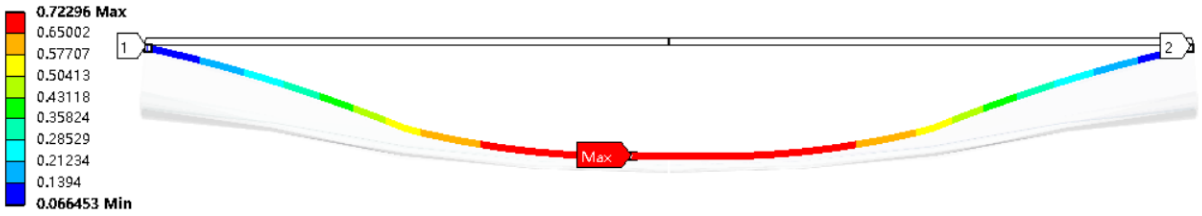


Deformation:0.786mm

Due to gravity



Deformation difference between 48 layers is lower than 0.05mm



Deformation difference within 1 layer is lower than 0.7mm

3. GS-HCAL Mechanical Design

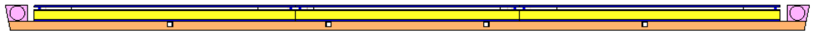
- Assembling of one division

① 

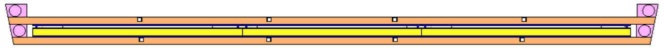
First absorber

② 

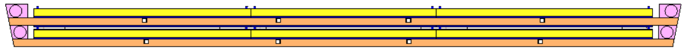
First trapezoid plate

③ 

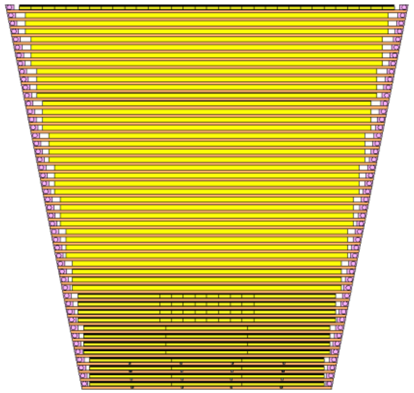
First active layer

④ 

Second absorber and trapezoid plate

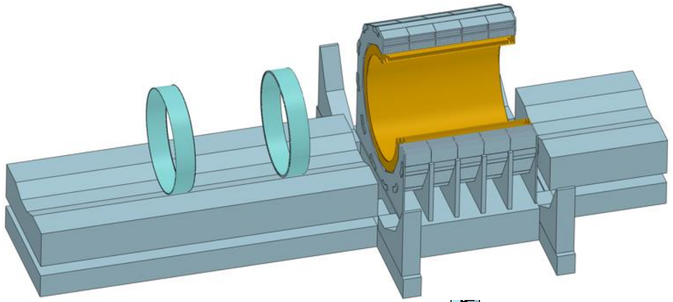
⑤ 

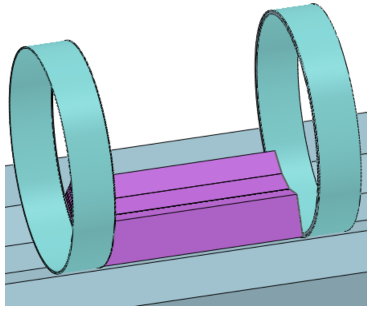
Second active layer

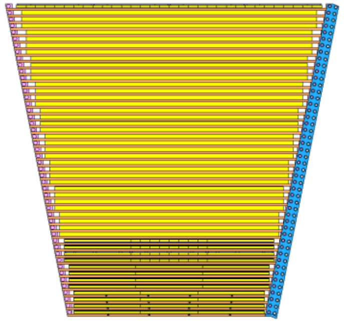
⑥ 

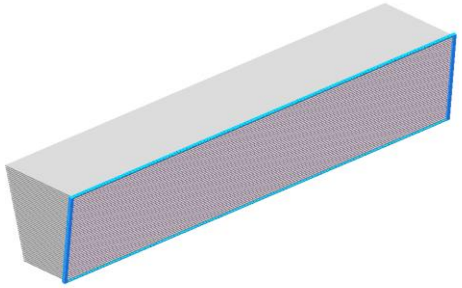
One division

- Installation

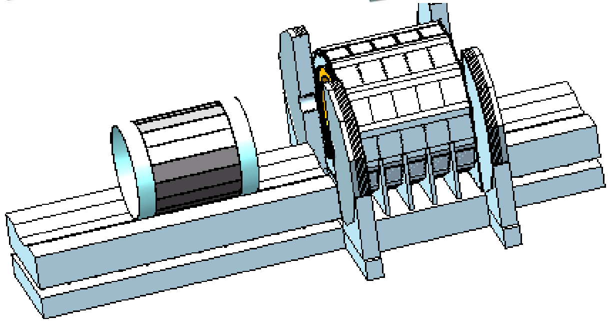


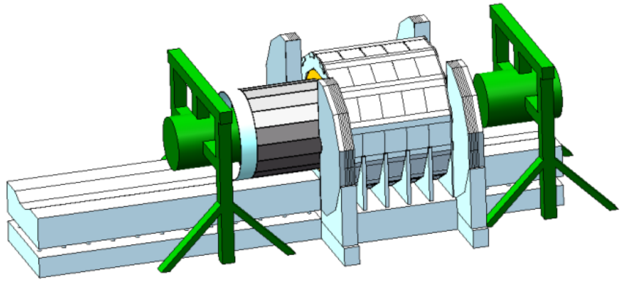


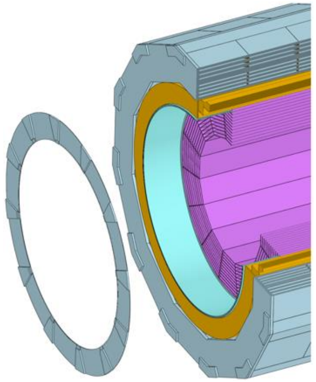




Using edge sealing to connect two division







7. Cost Estimation: GS-HCAL vs PS-HCAL

Parameter Name	Barrel	Endcaps (x2)	GS-HCAL	PS-HCAL
Inner Radius for HCAL	2140 mm	400 mm	-	-
Length for barrel or Radius	6460 mm	3455 mm (R_{out})	-	-
Longitudinal Depth	$1315\ mm\ (6\lambda_I)$		-	-
Glass Scintillator ($1/cc) Granularity 4cm x 4cm	54.6 m^3	35.6 m^3	GS (90.2 m^3) **$1/cc, $90.2M**	Plastic Scintillator **$1.5/ch, $8.4M**
Material Volume (m^3) Fe (tons, $8/kg)	75.3 m^3	49.2 m^3	124.5 983.6 t ($7.9M)	188.3 m^3 1488 t ($11.9M)
Readout channels	3.4M (5450m^2)	2.2M (3552m^2)	5.6M	5.6M
Power (15mW/ch)	51 kW	33 kW	84 kW	84 kW
SiPM ($1.5/ch)	$5.1M	$3.3M	$33.6M	$8.4M
Electronics: $2.5/ch	$8.5M	$5.5M	$14M	$14M
Total			**$145.7M (x7) ~1020M RMB**	**$42.7M (x7) ~ 299M RMB**

7. Cost Estimation: RPC-SDHCAL

Parameter Name	Barrel	Endcaps (x2)	Sum
Inner Radius for HCAL	2140 mm	400 mm	NA
Length for barrel; Outer radius for endcap*	6460 mm	3455 mm	NA
Longitudinal Depth	$6\lambda_I$ (Thickness depends on each option)		NA
RPC + Casette ($1425/m^2) Granularity 2cm x 2cm	5450 m^2	3552 m^2	9002 m^2 ($12.9M)
Material Volume (m^3) Fe (tons, $8/kg)	86 m^3	56 m^3	142 m^3 1122 t ($9M)
Readout channels	13.6M (5450m^2)	8.9M (3552m^2)	22.5M
Power (kW) 1.4mW/ch, 5.4W/DIF/m^2	48.5 kW	31.6 kW	80.1 kW
Electronics: $1/ch	$13.6M	$8.9M	$22.5M
Total	**$44.4M (x 7) ~ 311M (RMB)**		