

R&D of Glass Scintillator-HCAL

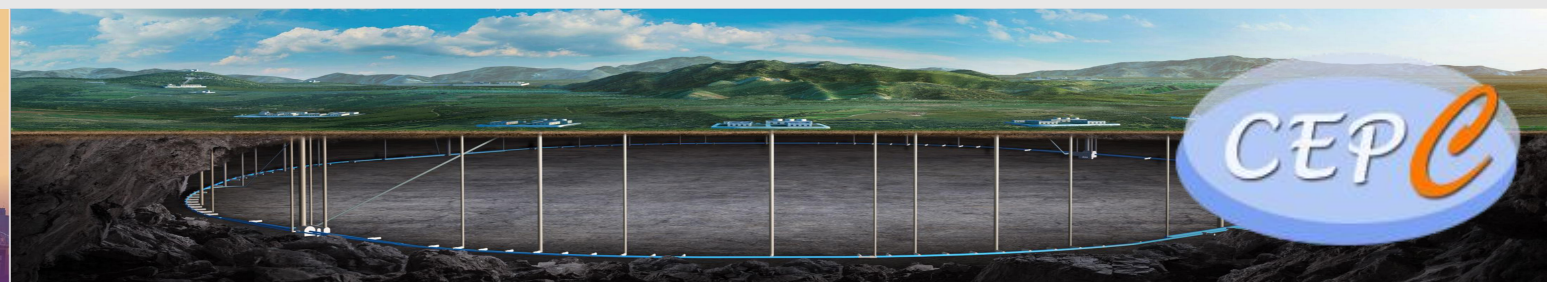
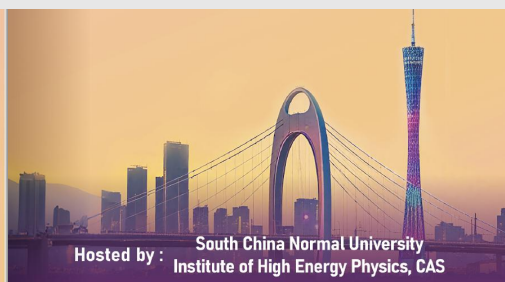
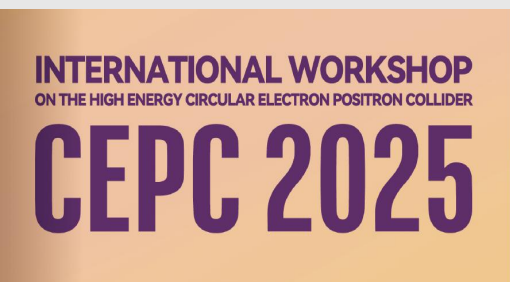


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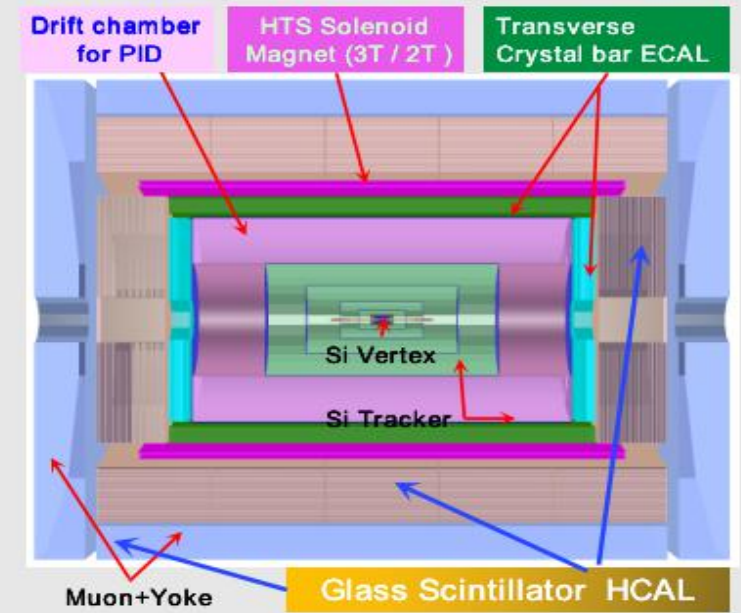
Sen QIAN

qians@ihep.ac.cn; On Behalf of the GS R&D Collaboration Group, The Institute of High Energy Physics, CAS



Outline

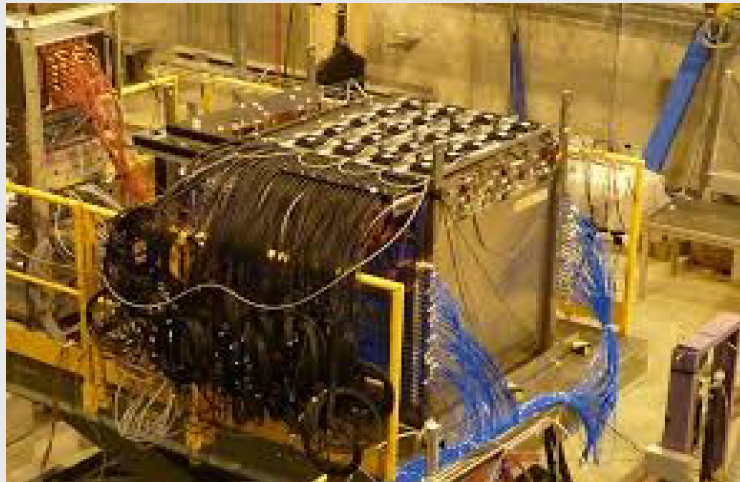
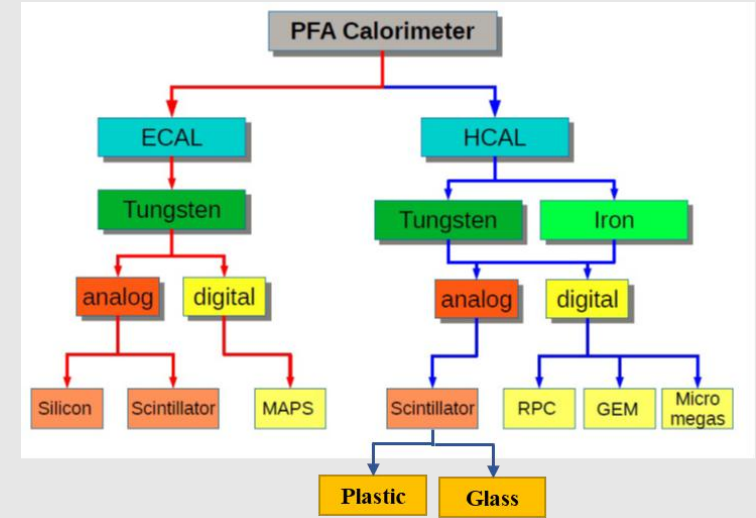
- 1. Motivation for GS-HCAL
- 2. R&D of the GS
- 3. Design of the GS-HCAL in CEPC
- 4. Summary and Next Plan



1.1 HCAL Design Options (The Past)

❑ Several HCAL design options have been proposed

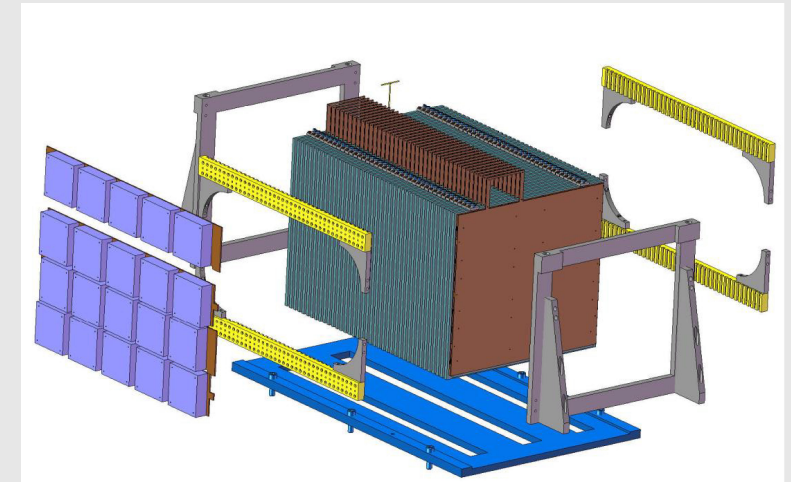
- Based on **Gaseous Detector**
 - e.g. CALICE SDHCAL [doi:10.1088/1748-0221/11/04/P04001](https://doi.org/10.1088/1748-0221/11/04/P04001)
- Based on **Liquid Argon**
 - e.g. ATLAS LAr Endcap HCAL [doi:10.1016/j.nuclphysbps.2011.03.150](https://doi.org/10.1016/j.nuclphysbps.2011.03.150)
- AHCAL: **Plastic Scintillator** & SiPM readout
 - e.g. CEPC AHCAL [doi:10.1088/1748-0221/17/11/P11034](https://doi.org/10.1088/1748-0221/17/11/P11034)



➤ CALICE SDHCAL Prototype

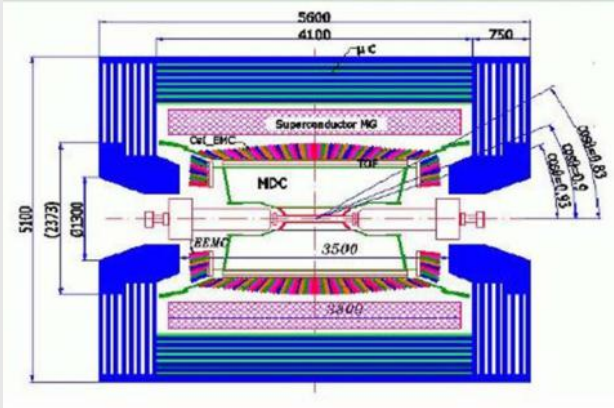


➤ ATLAS LAr Endcap HCAL

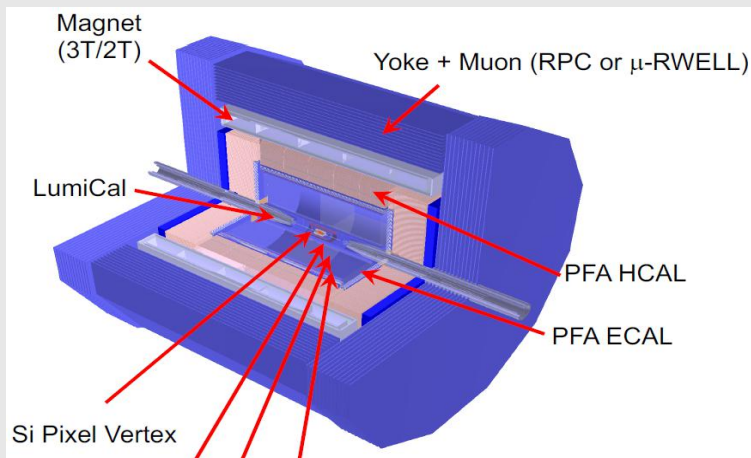


➤ CEPC AHCAL Prototype

Technologies used in Calorimeters

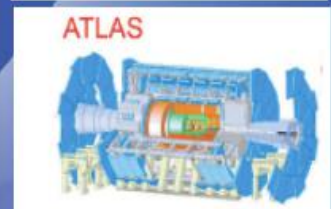
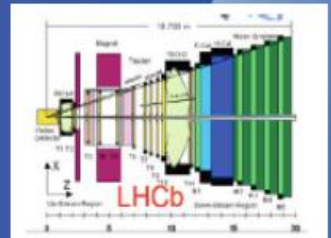


BEPC-BESIII-EMC: CsI + PD



CEPC-CDR-ECAL: Plastic Scintillator tungsten
CEPC-CDR-HCAL: Plastic Scintillator + SiPM

- PbWO_4 homogeneous calorimeter:
 - CMS ECAL, ALICE PHOS
- LAr sampling calorimeter:
 - ATLAS EM Barrel and Endcap, Hadronic Endcap, Forward calorimeters
- Scintillator/WLS fiber sampling calorimeters:
 - CMS HCAL Barrel and Endcap, ATLAS TileCal (barrel HCAL), LHCb HCAL
- Shashlik Pb/Scint sampling calorimeters:
 - ALICE EMCal/DCal, LHCb ECAL
- Quartz Fiber/Steel sampling calorimeter:
 - CMS HCAL Forward

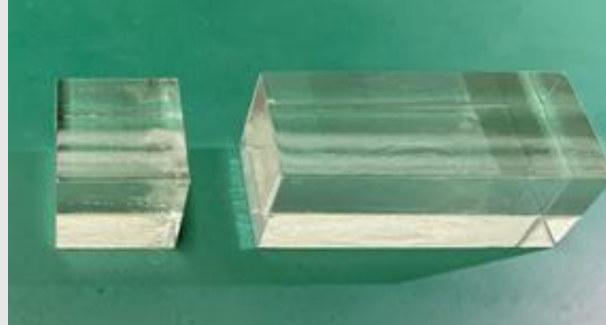


Except PbWO_4 or Plastic Scintillator, Crystal can not be used for the ECAL or HCAL, too expensive!

What is the Scintillator ?



Plastic Scintillator



Glass Scintillator



Crystal Scintillator

Large density ☆

High light yield ☆☆☆

Energy resolution ☆

Low cost ☆☆☆

Fast decay ☆☆☆

Large size ☆☆☆

Large density ☆☆☆

High light yield ☆

Energy resolution ☆☆

Low cost ☆☆

Fast decay ☆☆

Large size ☆☆

Large density ☆☆☆

High light yield ☆☆☆

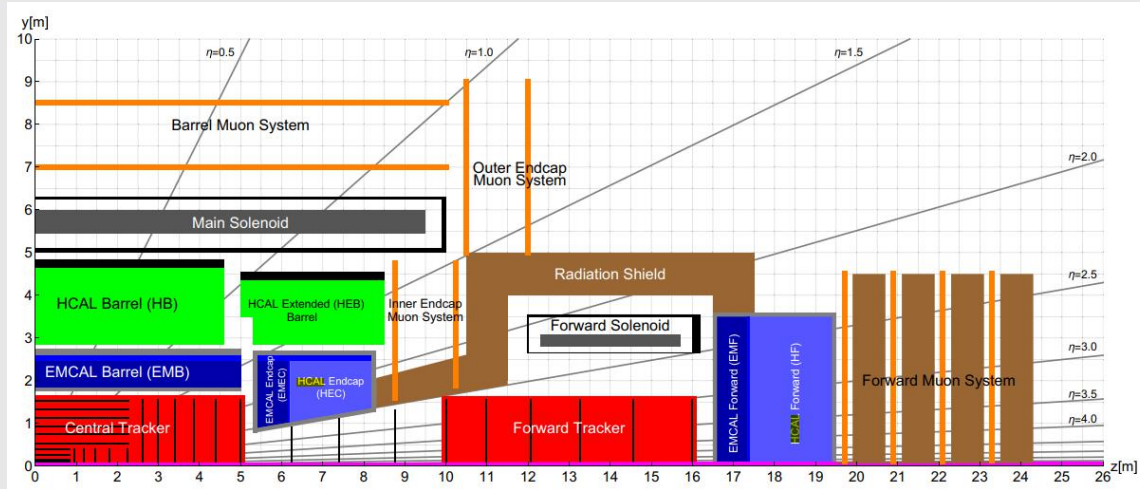
Energy resolution ☆☆☆

Low cost ☆

Fast decay ☆☆

Large size ☆

1.2 HCAL Design Options (The Future)

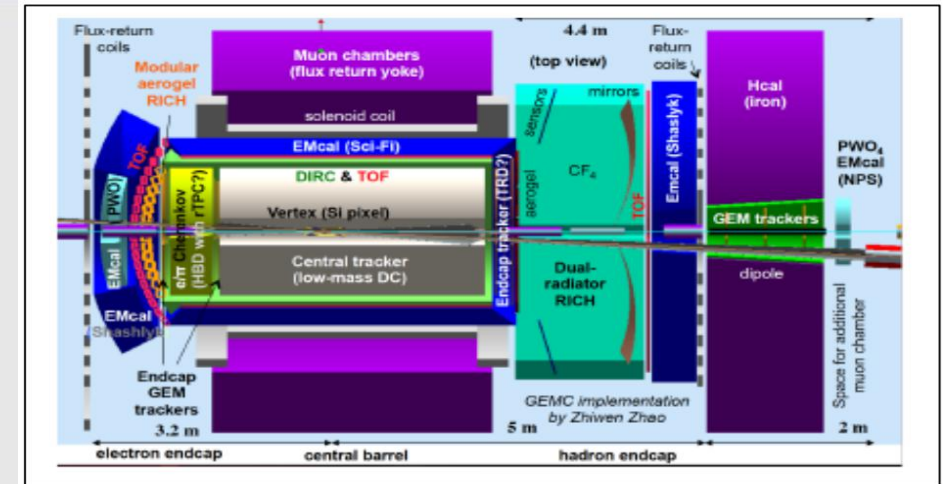


■ Longitudinal cross-section of the FCC-hh reference detector

Task 1.2: Hadronic section with optical tiles	
Subtask 1.2.1: AHCAL	Scintillating plastic tiles/Steel
Subtask 1.2.2: ScintGlassHCAL	Heavy glass tiles/Steel

Task 1.2

- AHCAL: Concept for continuous readout
- ScintGlass HCAL: cm scale tiles



■ Example layout of the EIC detector base design

Glass for EIC:

- Sufficient resolution
- Fast response
- Radiation hardness

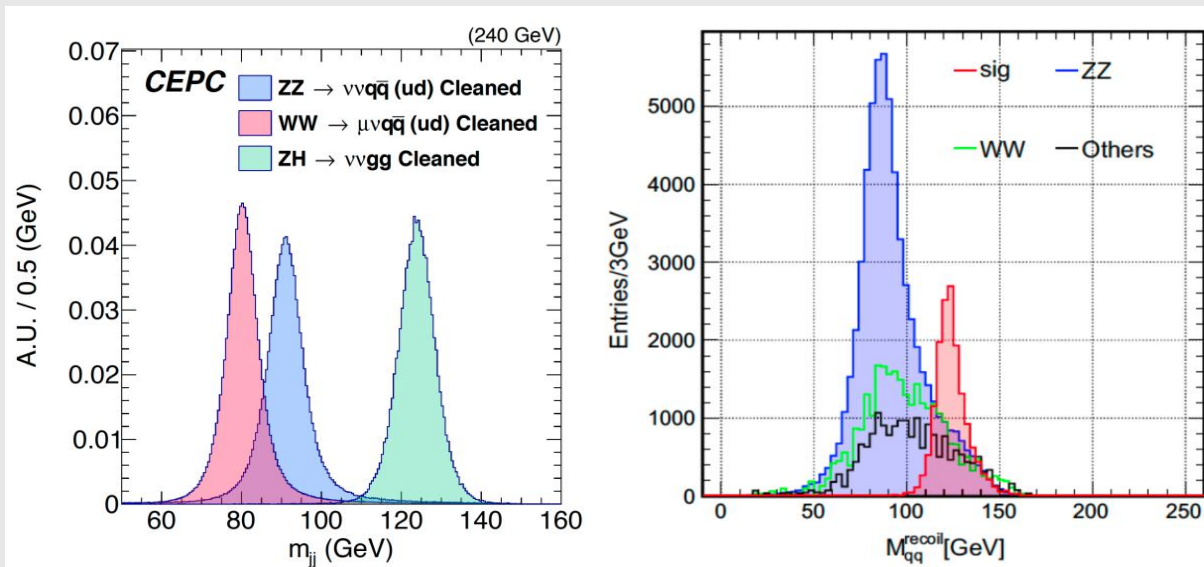
Task 1 : build a cost effective glass-ceramic calorimeter for the outer endcaps and central regions

Task 2: Push the performance of **glass ceramics** towards crystals

1.3 Physics Requirements of CEPC-HCAL

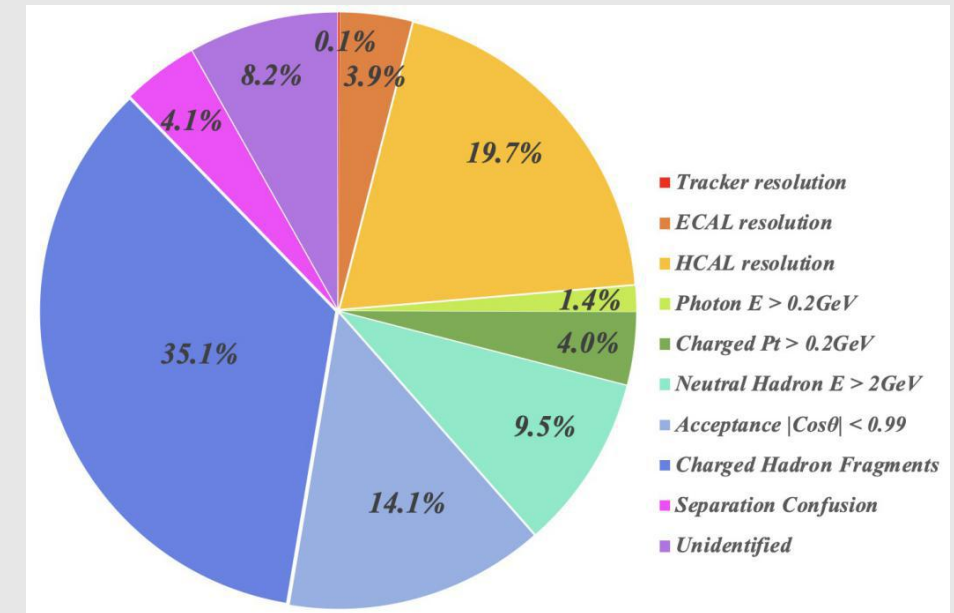
■ CEPC as Higgs/W/Z factories:

- Jet Energy Resolution $s/E \sim 5\%$
- Boson Mass Resolution (BMR) $< 4\%$:
it is strongly motivated by H/W/Z hadronic final states, BSM & Flavor Physics



■ Leading contributions to BMR:

- HCAL resolution dominant the uncertainties from intrinsic detector resolution: $\sim 19.7\%$
- Further improvement of HCAL is needed

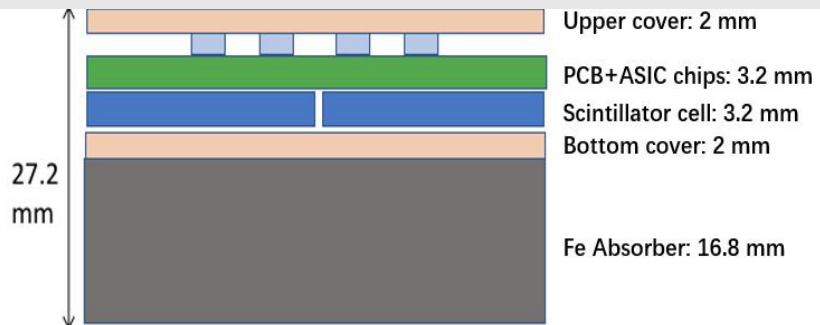


CDR baseline ([arXiv:1811.10545](https://arxiv.org/abs/1811.10545)): BMR = 3.75%, lots reports were discussed by Manqi Ruan.

Glass Scintillator CEPC-HCAL

- **Basic idea:** to increase sampling fraction for better energy resolution
- With high density and thick GS cell design, the sampling fraction of GS-HCAL can be increased by **a factor of ~20** compared to that of PS-HCAL.

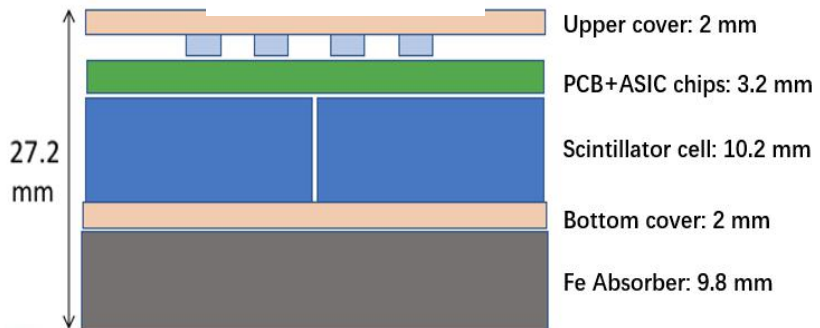
PS-HCAL



PS-HCAL

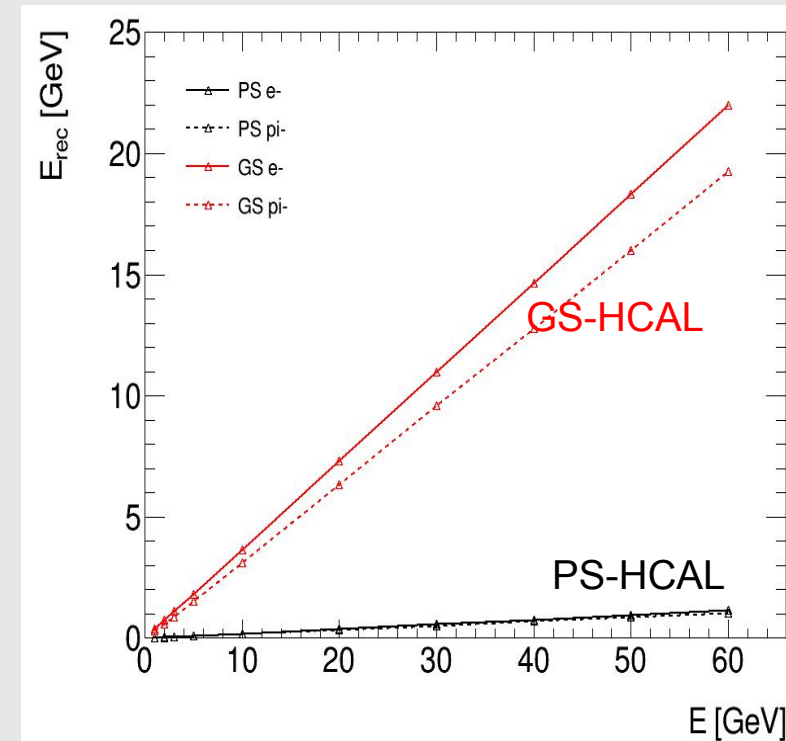
- Fe: $20.8\text{mm}/171.5\text{mm}=0.1213 \lambda_I$
- PS: $3\text{mm}/688.7\text{mm}=0.0044 \lambda_I$
- PCB: $1.2\text{mm}/492.2\text{mm}=0.0024 \lambda_I$
- Sampling fraction ~ 1.6% (π TB, MC)

GS-HCAL



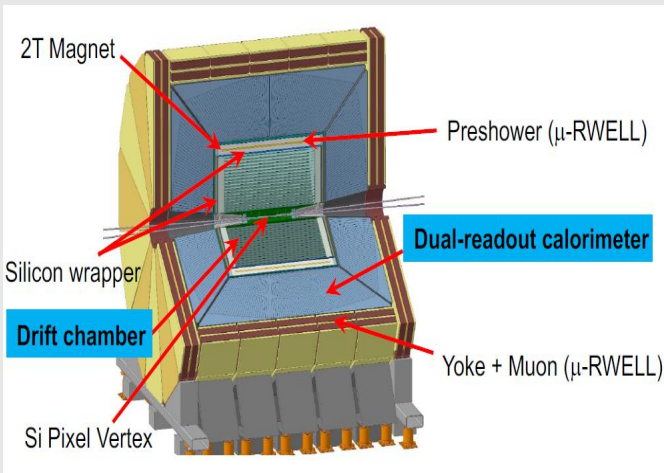
GS-HCAL

- Fe: $13.8\text{mm}/171.5\text{mm}=0.0805 \lambda_I$
- GS: $10.2\text{mm}/242.8\text{mm}=0.0425 \lambda_I$
- PCB: $1.2\text{mm}/492.2\text{mm}=0.0024 \lambda_I$
- Sampling fraction ~ 31% (MC)



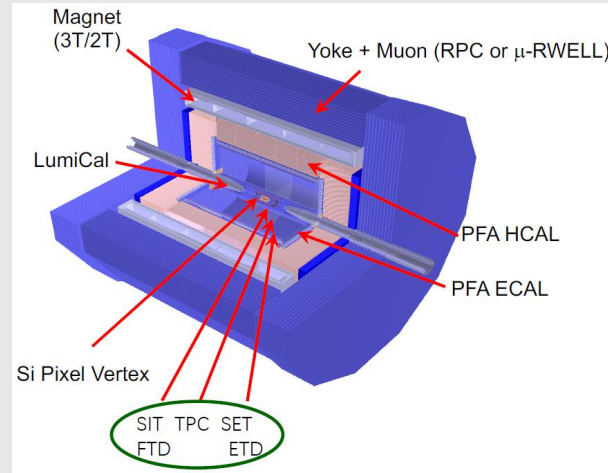
CEPC Conceptual Detector Design (The Future)

1st IDEA Concept (also proposed for FCC-ee)



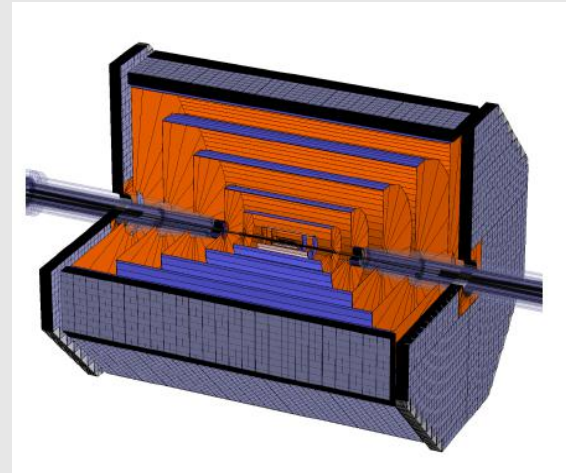
- Dual-readout calorimeter (Cerenkov-Fiber & Scint-Fiber)
- both for EM and Hadronic Shower

2nd CDR Baseline Design (Particle Flow Approach)



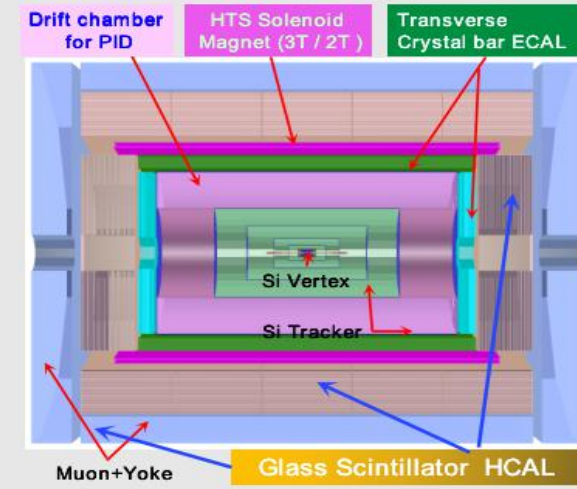
- AHCAL (PS/Steel) or SDHCAL (Gas/Steel)
- Si/W ECAL or PS/W ECAL

3rd FST concept (Full Silicon Tracker)



- AHCAL (PS/Steel) or SDHCAL (Gas/Steel)
- Si/W ECAL or PS/W ECAL

4th Conceptual Detector



- GSHCAL (GS/Steel)
- BGO Crystal ECAL

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2.0 Development of Glass Scintillator

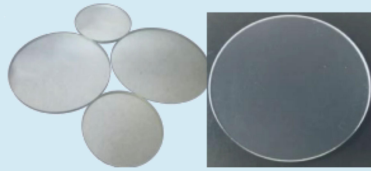
1. Commercialization of glass scintillator

Glass Scintillators*

R. J. GINTHER† AND J. H. SCHULMAN†

1958, Ce-doped high-silicon glass.

Under γ -ray excitation, the pulse height is 10% of NaI(Tl).



1976, commercialized GS series glass scintillator (GS20 $\rho=2.5 \text{ g/cm}^3$, LY=6000 ph/neutron)

1950 1960 1970 1980 1990 2000 2010 2020 2025

1962, glass for thermal neutron detection

1988, glass scintillator calorimeter design

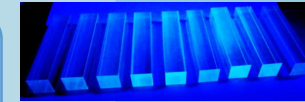
2000, the concept of energy transfer sensitization

2020, Ce^{3+} doped Gd-based glass

2. High density

2015, DSB glasses for high energy physics experiments,
 $\rho=3.8 \text{ g/cm}^3$,
LY=1360 ph/MeV

1996, heavy metal fluoride glass EM calorimeter



3. High LY

4. High density & LY



2021, GS Group for R&D new glass scintillator
 $\rho=6 \text{ g/cm}^3$ LY=1000 ph/MeV

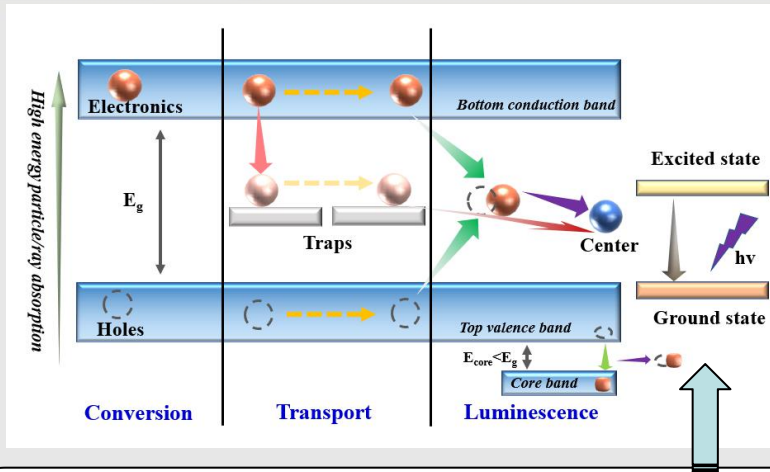
2.1 Large Area Glass Scintillator Collaboration



Spokesperson: Sen QIAN

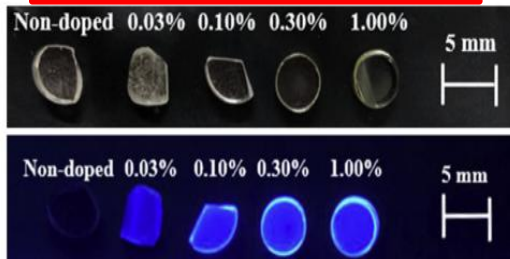
- The Glass Scintillator Collaboration Group established in Oct.2021;
- There are 4 Institutes from CAS, 6 Universitys, 3 Companies join us for the R&D of GS;

2.2 Design of the GS



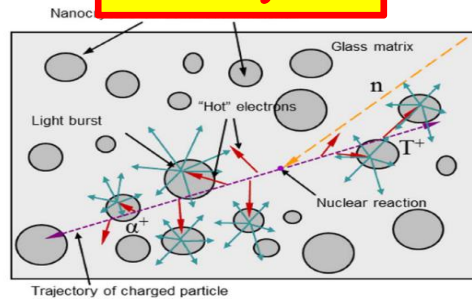
- **Scintillation mechanism----** **Luminescence Center**
- **Conversion**—photoelectric effect and Compton scattering effect;
- **Transport**—electrons and holes migrate;
- **Luminescence**—captured by the luminescent center ions

Lanthanide elements



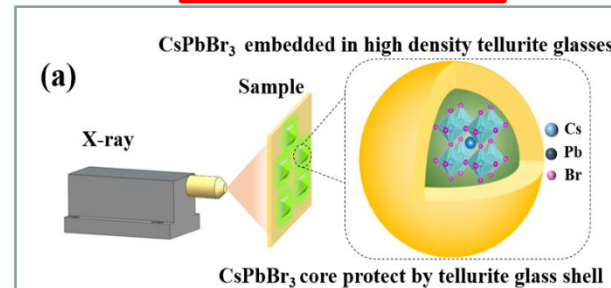
Journal of Alloys and Compounds
782 (2019) 859-864

Nanocrystals



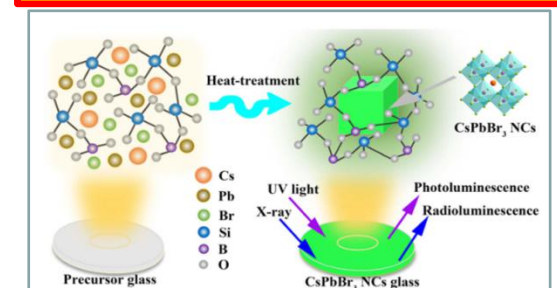
IEEE TNS 60 (2) 2013

Quantum Dots



Optics Letters 46(14) 3448-3451 (2021)

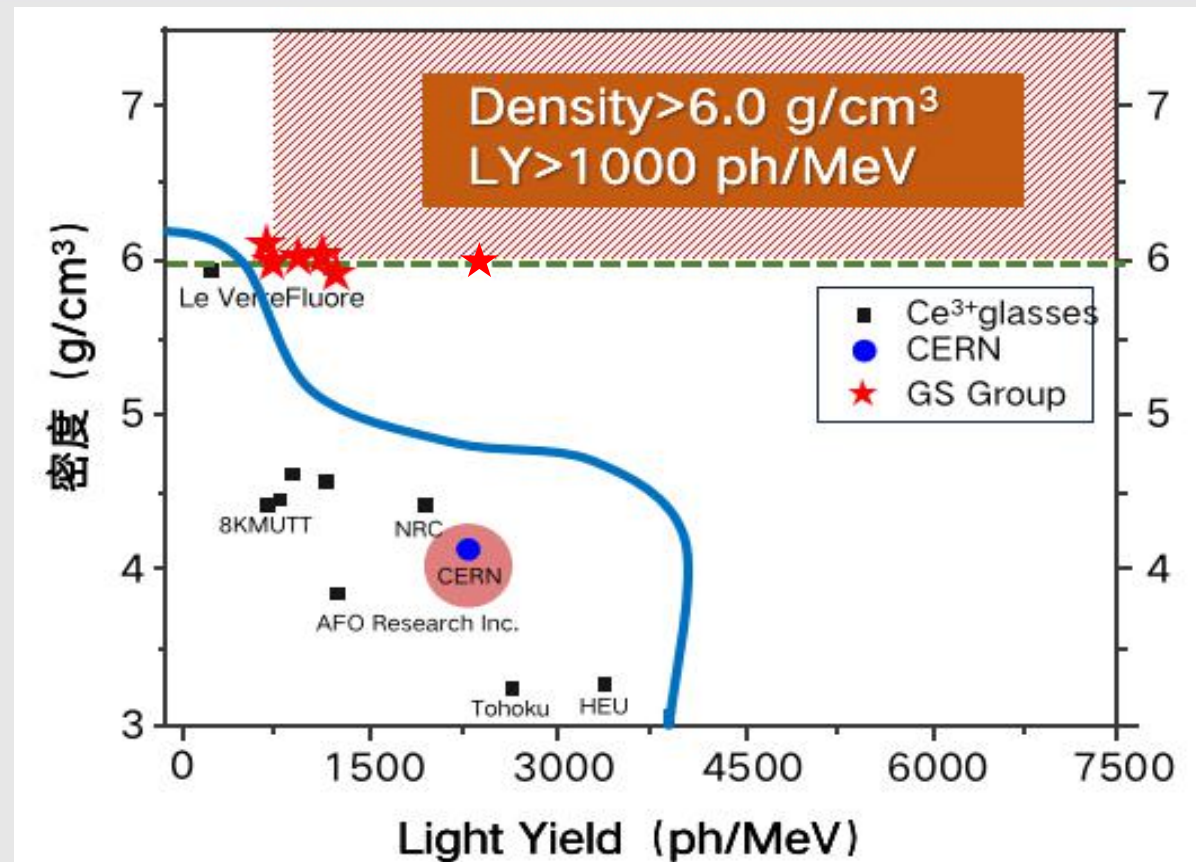
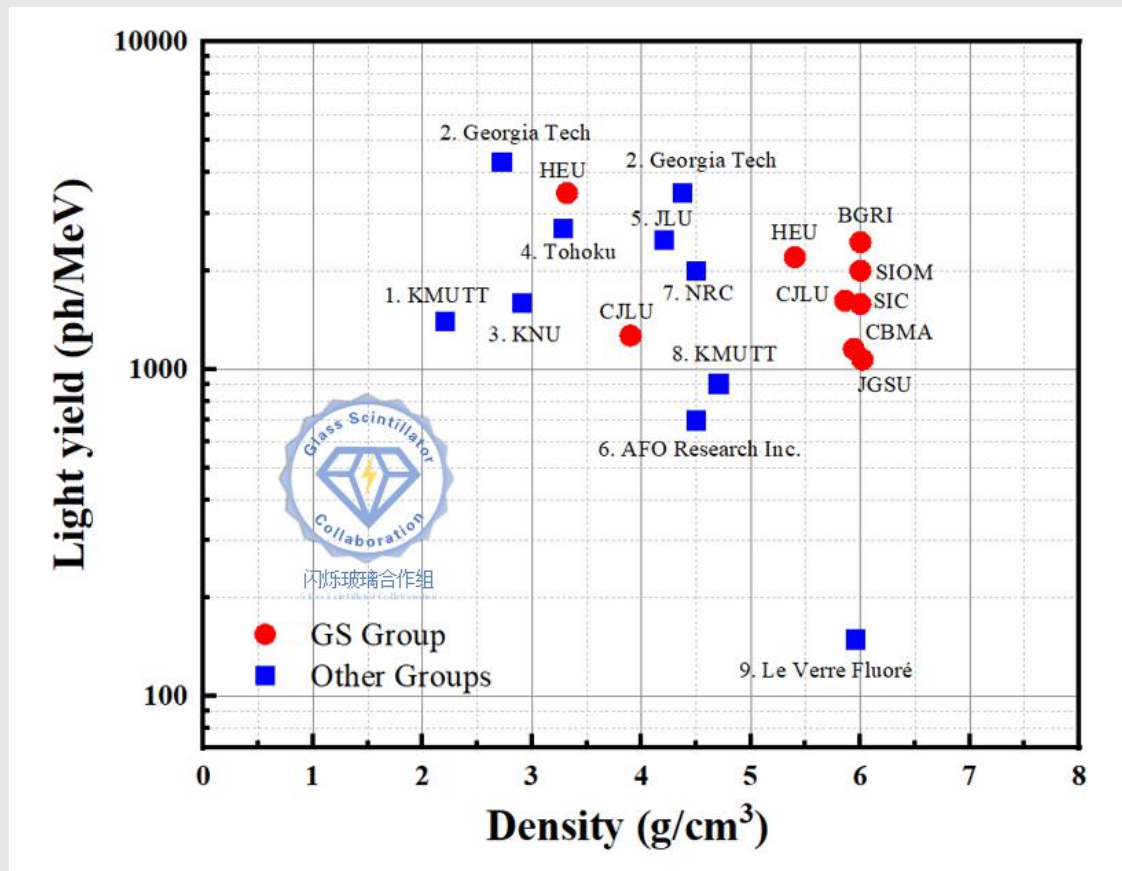
Lanthanide + Quantum Dots



Vol. 9, No. 12 / 2021 / Photonics Research

- High Light Yield (> 2000 ph/MeV): Lanthanide for the Luminescence Center: **Cerium (Ce)**;
- High Density (> 6 g/cm³) and Low radioactivity background: **Gadolinium (Gd)**; ~~lutetium (Lu)~~

2.3 GS Group Samples

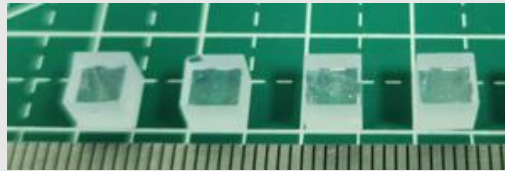


- The GS group has carried out a comprehensive and complete study;
- For high density glass scintillator, the light yield of GS group samples is in the absolute lead.

Small Size Sample

GFO & GFO+ (5mm × 5mm × 5mm)

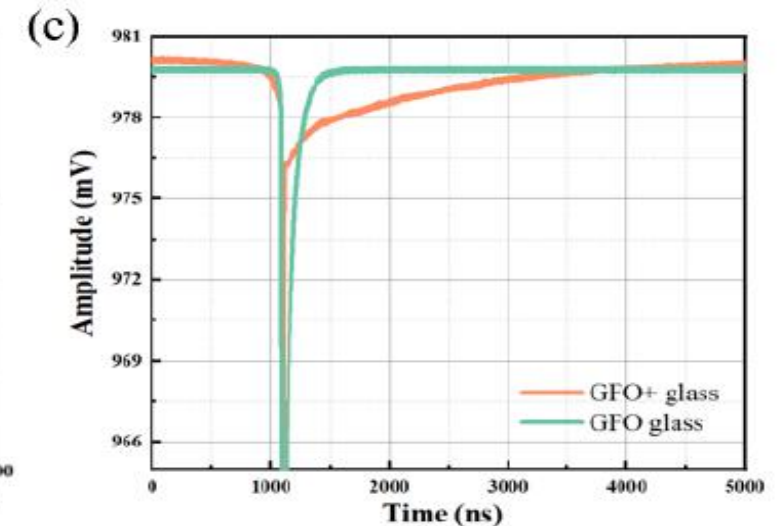
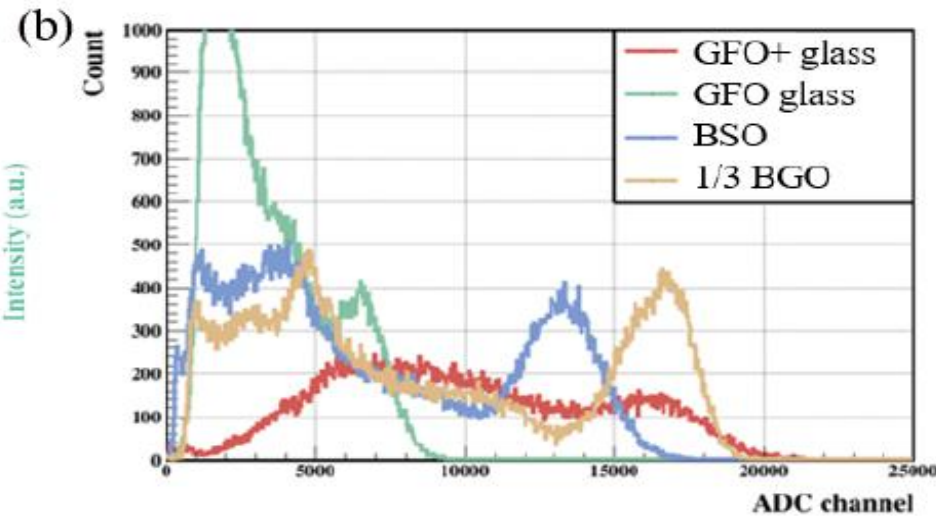
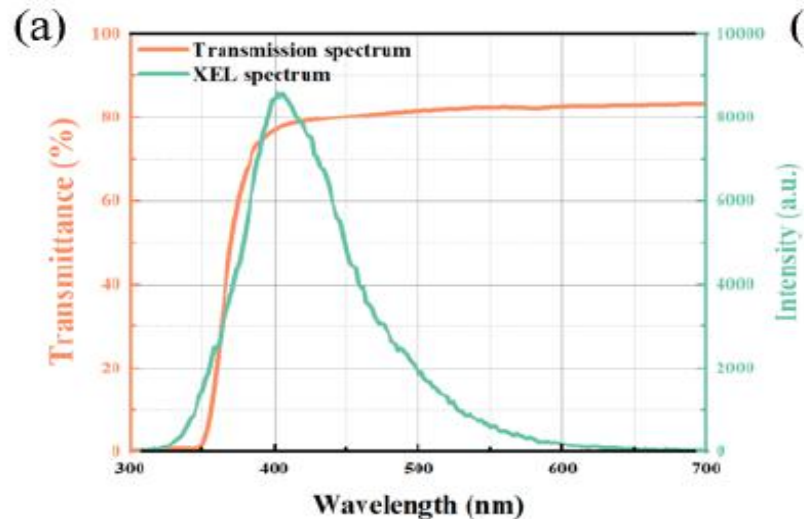
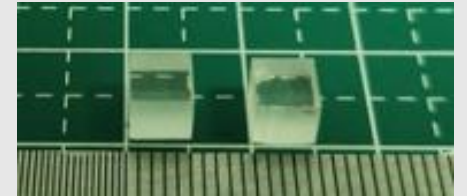
GFO



- Density~6.0 g/cm³
- LY=985 ph/MeV
- ER=30.3%
- LO in 1μs=982 (99%)
- Decay=36 (8%), 105 ns

- Density~6.0 g/cm³
- LY=2445 ph/MeV
- ER=25.8%
- LO in 1μs=1074 (44%)
- Decay=101 (2%), 1456 ns

GFO+



➤ (a) Transmission and XEL spectra

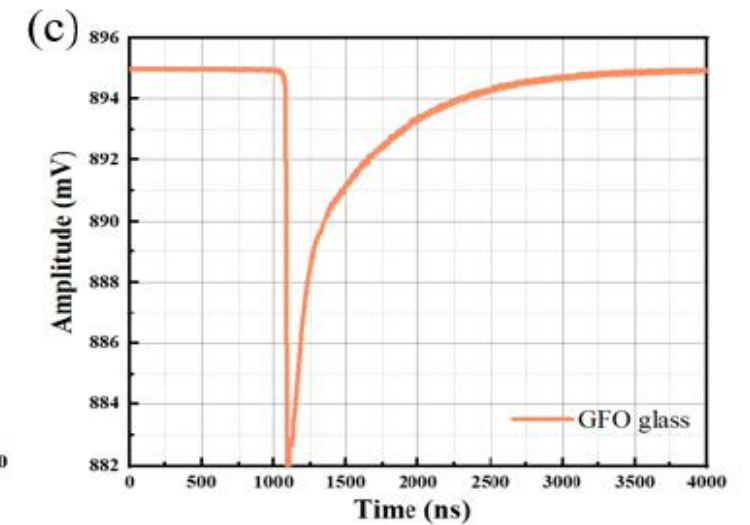
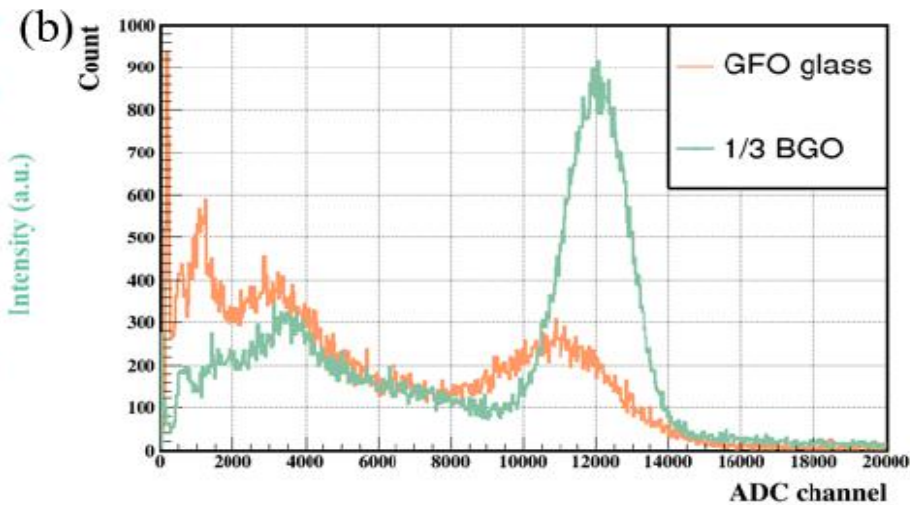
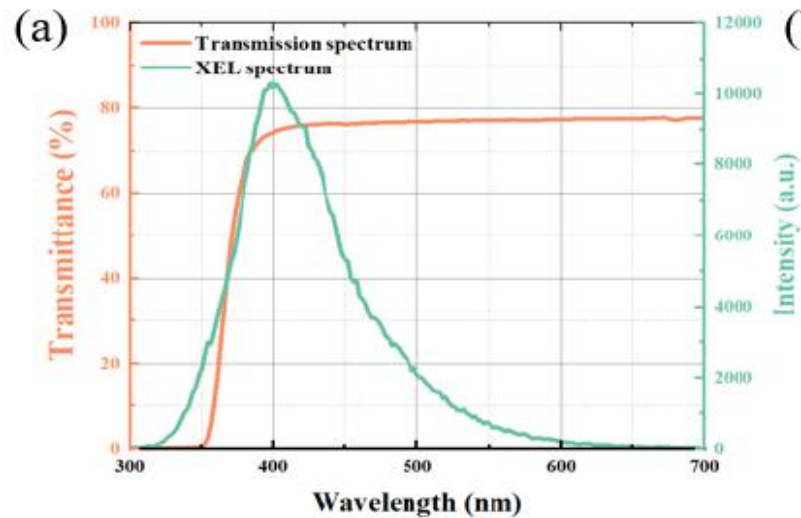
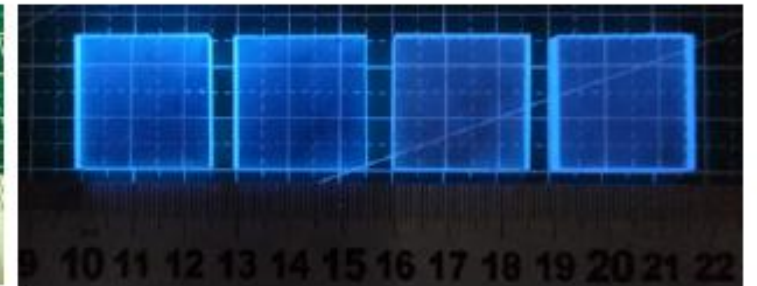
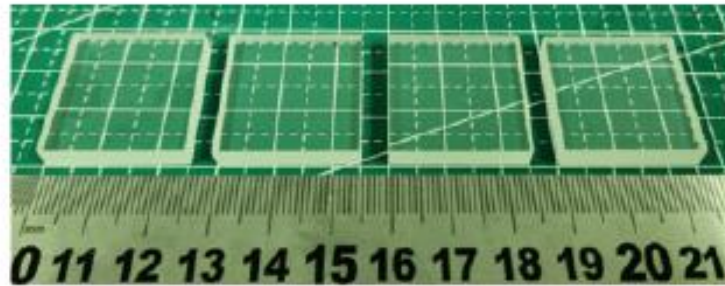
➤ (b) Energy spectra

➤ (c) Scintillation decay curves

Large Size Sample

GFO (40mm × 40mm × 10mm)

- Density=6.0 g/cm³
- LY=1506 ph/MeV
- ER=41.2%
- LO in 1μs=1129 (75%)
- Decay=53 (3%), 655 ns

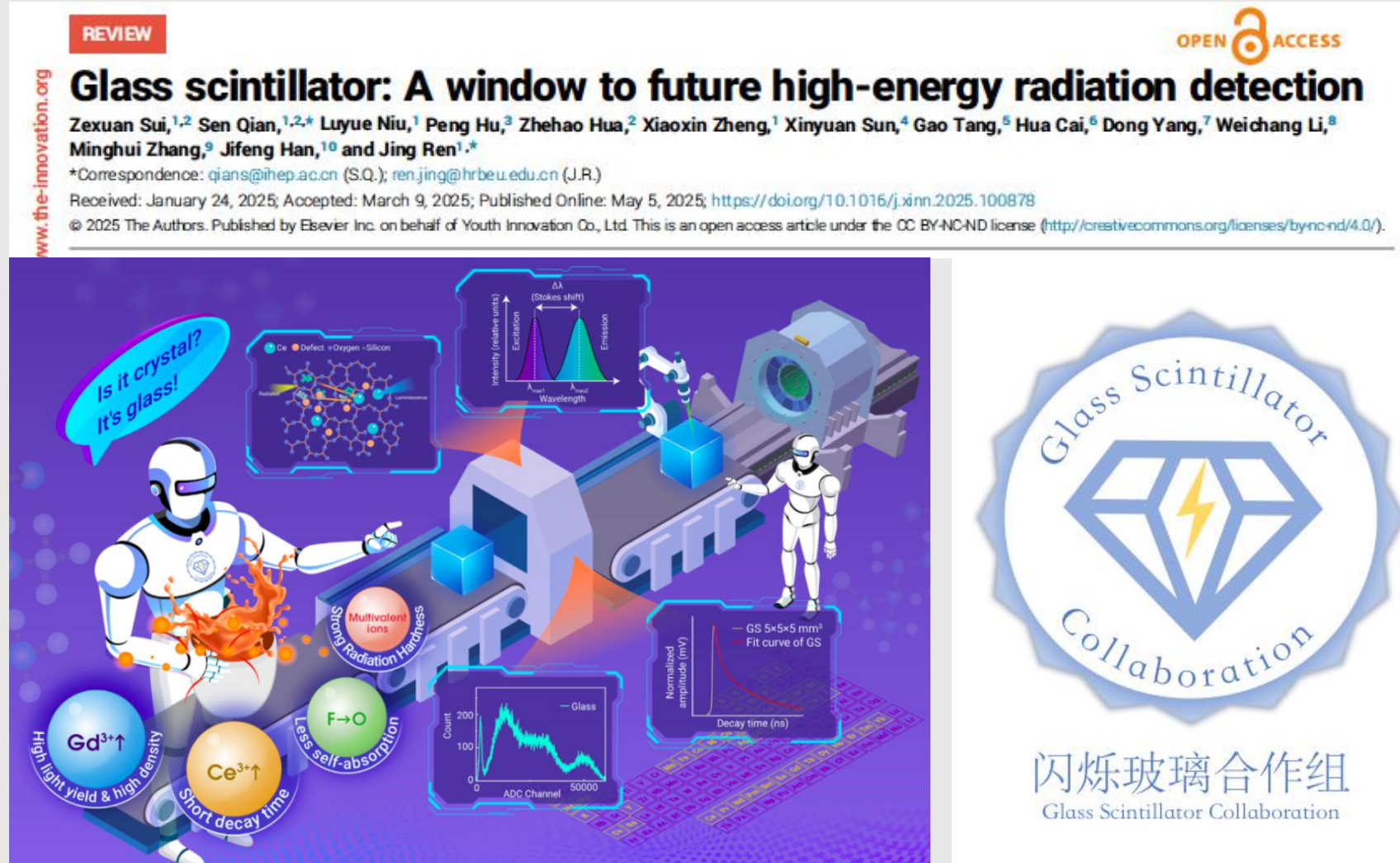


➤ (a) Transmission and XEL spectra

➤ (b) Energy spectra

➤ (c) Scintillation decay curves

The Innovation Review Paper

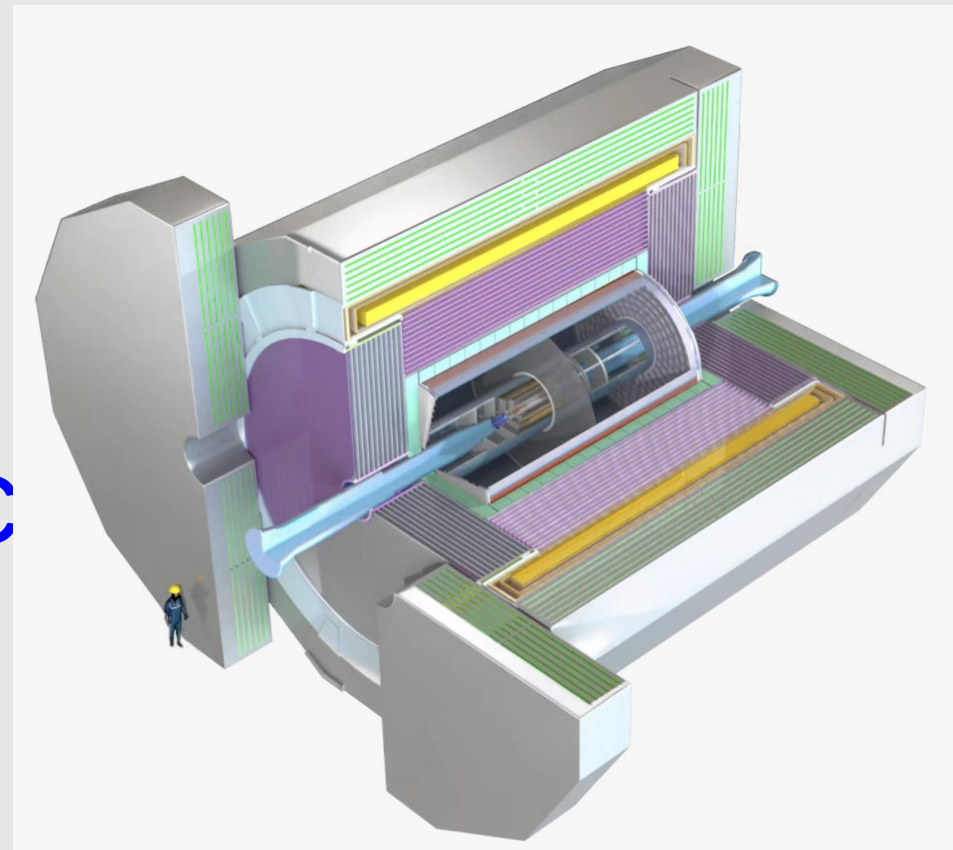


DOI:10.1016/j.xinn.2025.100878;

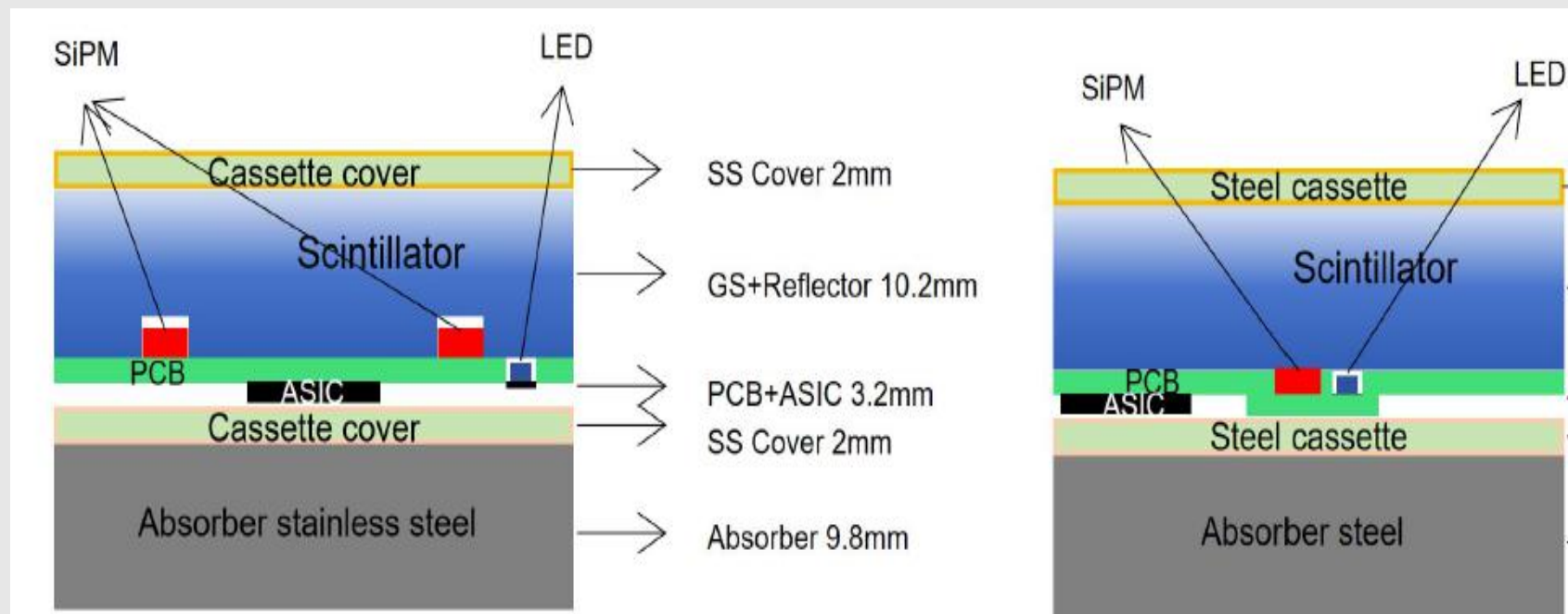
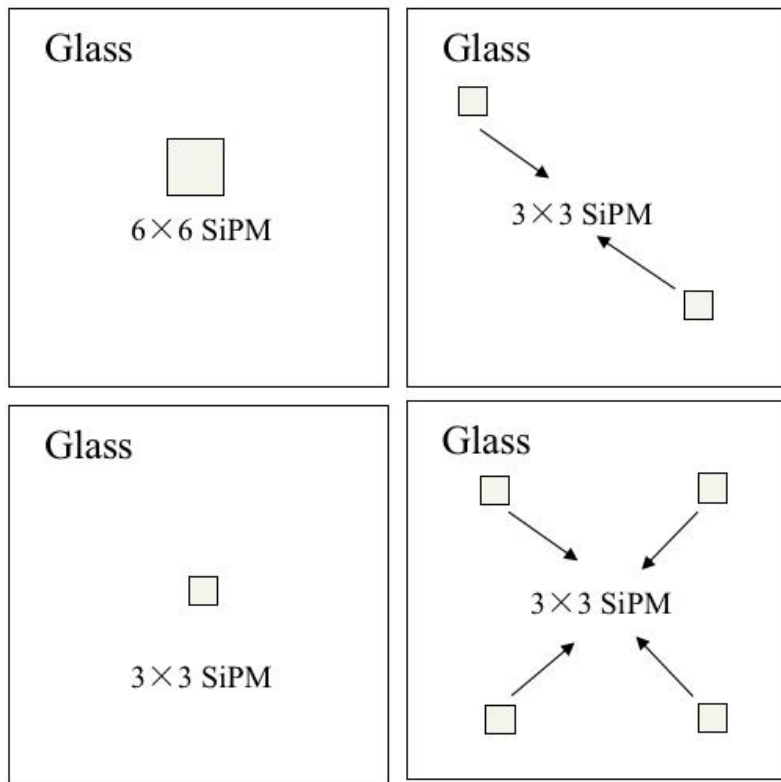
Sui Z., Qian S., Niu L., et al. (2025). Glass scintillator: A window to future high-energy radiation detection. The Innovation 6:100878.

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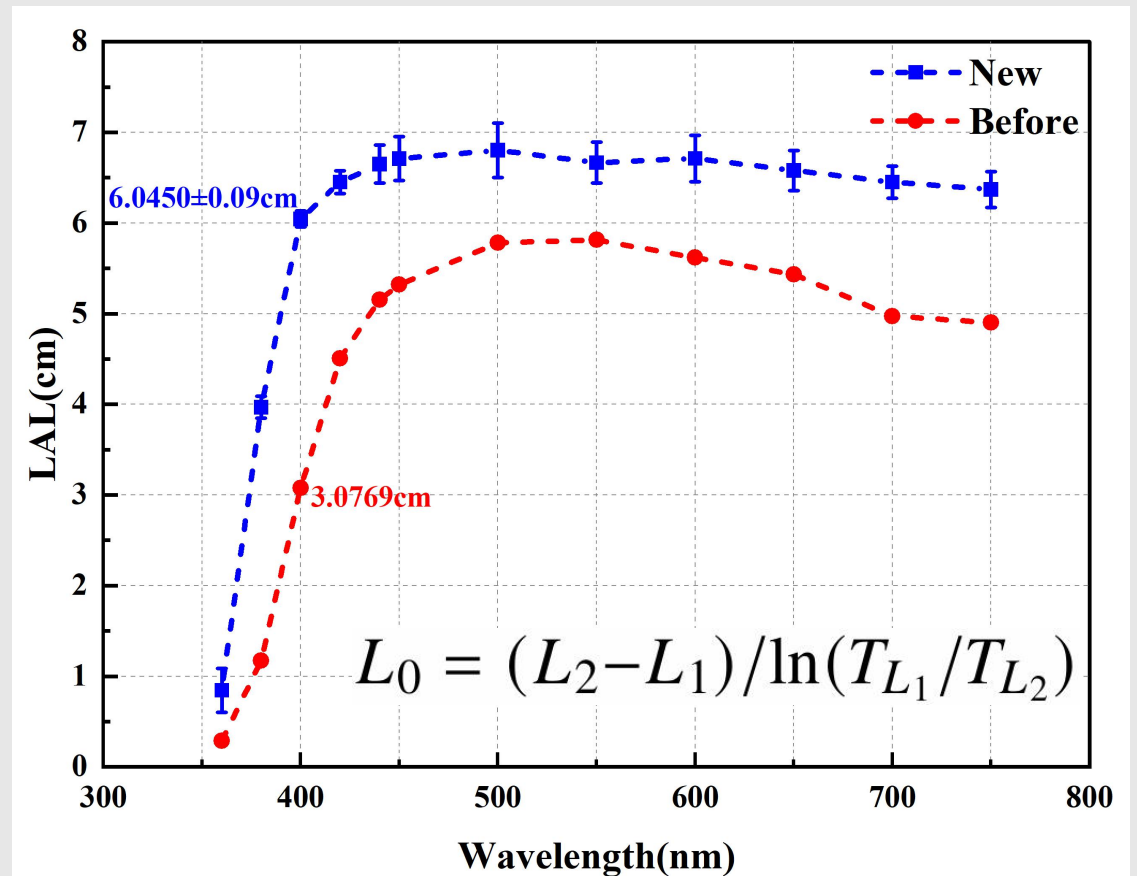
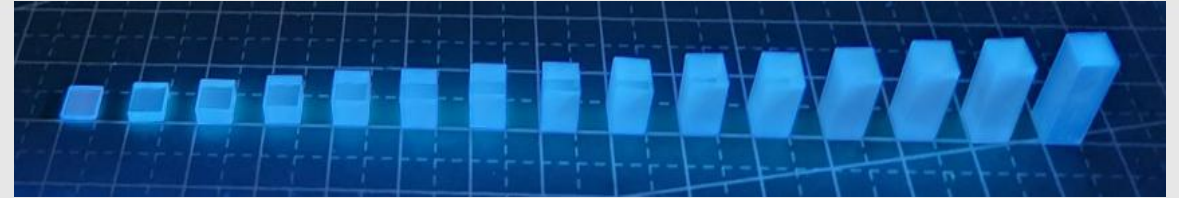
3.1 Detector Cell = GS + SiPM



- at the beginning, light attenuation length is only ~ 23 mm, more SiPMs are needed to collect sufficient light.
- One scintillator is coupled with either 1, 2, or 4 SiPMs ($3 \text{ mm} \times 3 \text{ mm}$ SiPMs).
- There is a gap to hold the SiPM either in the GS or in the PCB. More tests are needed to determine the optimal position of this gap (in the glass or PCB) and to identify a low-cost and practical method for implementation.

Attenuation Length of new GS

- GS samples before IDRC review
 - attenuation length: 3.1 cm @ 400nm
- NEW GS samples after IDRC review
 - attenuation length: 6.1 cm @ 400nm
- Feasible to use one SiPM per GS tile



Progress of SiPM for Detector

A significant breakthrough achieved in the production of high-performance SiPMs with epitaxial quenching resistors

Sen Qian,^{1,2,3,*} Peng Hu,⁴ Zheng Liu,⁵ JieFeng Han,⁶ and XiaoLong Wang^{1,2}

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⁴China Nuclear (Beijing) Nuclear Instrument Co., Ltd, Beijing 100176, China

⁵Paul C. Lauterbur Research Center for Biomedical Imaging, Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen 518055, China

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Received: July 10, 2025; Accepted: August 26, 2025; <https://doi.org/10.1016/j.xinn.2025.101090>

Custom: Qian S., Hu P., Liu Z., et al., (2025). A significant breakthrough achieved in the production of high-performance SiPMs with epitaxial quenching resistors. The Innovation 6(12), 101090.

Recently, a significant breakthrough has been achieved in the production of high-performance silicon photomultipliers (SiPMs) with epitaxial quenching resistors (EQRs).¹ The EQR SiPM packaging production line, developed by CGN Capital Photonics Technology (Tianjin), has been successfully launched with a product yield exceeding 90%. This breakthrough has sparked new growth in China's semiconductor optoelectronic device industry.

The SiPM is a solid-state photon detector known for its high sensitivity and compact structure. It is a silicon chip that is composed of a series of miniature avalanche photodiodes (APDs), each operating in Geiger mode by being reverse biased above the breakdown voltage to realize the avalanche multiplication of photoelectrons. A special resistor is connected with each APD to quench the avalanche multiplication after detection. These micro APDs are operating independently, and their summed outputs are sensitive to injected light intensity, enabling single-photon detection and high gain comparable with traditional photomultiplier tubes (PMTs).

SiPMs are progressively replacing traditional PMTs across diverse fields, including high energy physics (where radiation hardness is a significant constraint), astrophysics, nuclear medical imaging, and autonomous driving, owing to their superior performance characteristics. In addition to their inherent advantages—excellent single-photon resolution, magnetic fields immunity, low operating voltage, compact size, and ease of integration—SiPMs are continually

optimized for critical performance parameters such as enhanced photon detection efficiency (PDE), higher photon count rate, broader linear dynamic range, and cost-effectiveness to meet the increasing requirements in these fields and other advanced applications. Due to the compactness, good timing performance and insensitive to magnetic field, SiPMs are currently used for the most commercial clinical TOF-PET scanners, especially in the PET/MRI, PET/CT. Time-of-flight measurement in a PET system can improve the signal/noise ratio of the reconstructed images, reduce the radiation dose, and shorten the scan time. The latest EQR SiPMs (EQR20 series) demonstrate a short pulse width and a sharp rising edge, which could enhance its application in TOF-PET scanners. Besides, EQR SiPMs achieved a high fill factor (more than 40%) and a high microcell density (up to 2,500/mm²), which could achieve high energy resolution and broad dynamic range.

The quenching resistor is a critical component in SiPMs, enabling their operation in Geiger mode while ensuring stable and reproducible photon detection. Currently, polysilicon quenching resistors are widely used in commercially available SiPMs due to their tunable resistivity and compatibility with standard CMOS fabrication processes. However, the utilization of polysilicon resistors along with connected metal lines leads to the occupation of active area within the devices, diminishing the geometric fill factor and consequently decreasing the PDE, particularly in cases where there is a large number of pixels. To

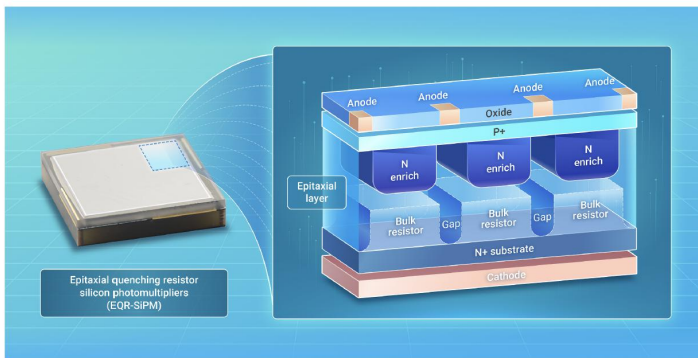


Figure 1. Schematic structure of the SiPM with epitaxial quenching resistor Modified from Zhao et al.¹

CellPress Partner Journal

The Innovation 6(12): 101090, December 1, 2025

The Innovation

Company	Onsemi	Broadcom	HPK	ZJ (NDL)
Product Mode	J-series 40035 ^[1]	AFBR-S4N44P014M ^[2]	S14160-4050HS ^[3]	EQR20-11-4040-NS ^[4]
Microcell Size	35 μm	40 μm	50 μm	20 μm
Microcell density	816/mm ²	625/mm ²	400/mm ²	2500/mm ²
Gain	6.3×10^6	7.3×10^6	2.5×10^6	8.0×10^5
Dark count	150 kHz/mm ²	125 kHz/mm ²	—	150 kHz/mm ²
Detection Efficiency	50% @420 nm	63% @420 nm	50% @450 nm	47.8% @420 nm
EfficiencyActive area	$3.93 \times 3.93 \text{ mm}^2$	$3.72 \times 3.62 \text{ mm}^2$	$4.00 \times 4.00 \text{ mm}^2$	$3.76 \times 3.76 \text{ mm}^2$
Package Area	$4.00 \times 4.00 \text{ mm}^2$	$4.31 \times 4.18 \text{ mm}^2$	$4.40 \times 4.40 \text{ mm}^2$	$4.12 \times 4.12 \text{ mm}^2$
Packaging Method	TSV	COB	TSV	CGB
Quenching Resistor	Polycrystalline silicon Resistor	Polycrystalline silicon Resistor	Polycrystalline silicon Resistor	Epitaxial Resistor

[1]<https://www.onsemi.cn/download/data-sheet/pdf/microj-series-d.pdf>

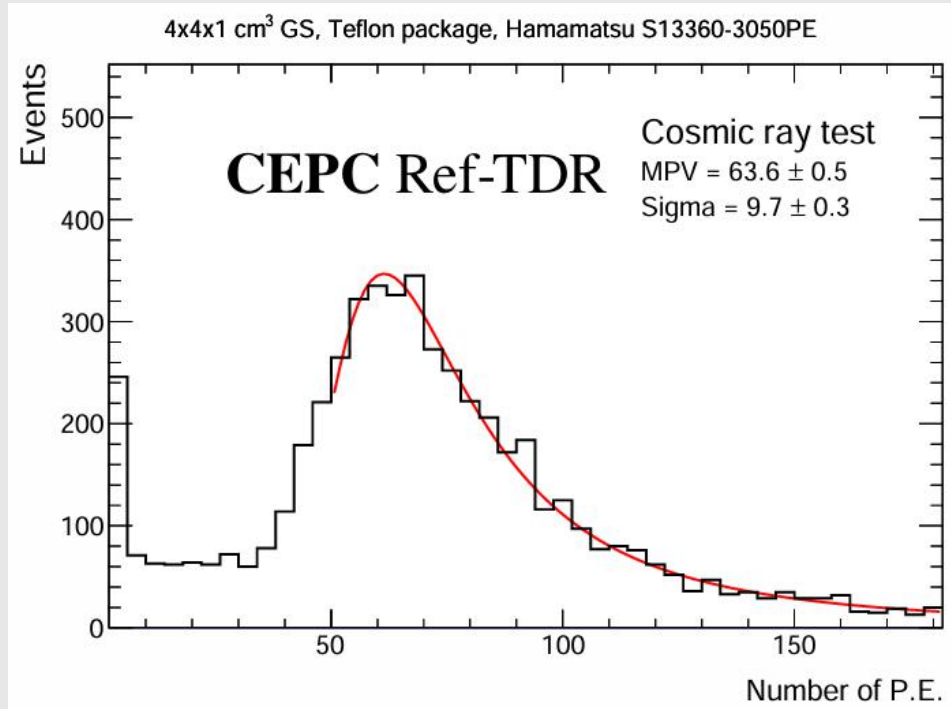
[2]<https://docs.broadcom.com/doc/AFBR-S4N44P014M-NUV-MT-Silicon-Photomultiplier>

[3]https://www.hamamatsu.com/content/dam/hamamatsuphotonics/sites/documents/99_SALES_LIBRARY/ssd/s14160_s14161_series_kapd1064e.pdf

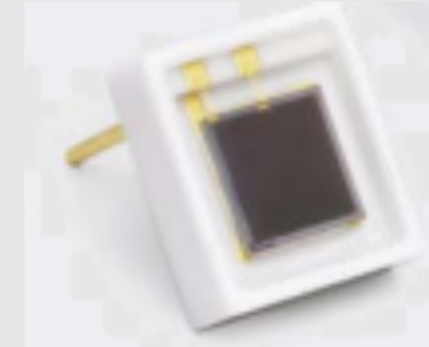
[4] Zhao, T., Preston, R., Jiang, J. et al. (2018). NIMA. 912:252–254. DOI:<https://doi.org/10.1016/j.nima.2017.11.069>.

3.2 Performance of GS-SiPM coupling

- Cosmic ray test of GS-SiPM coupling
- Light output is ~ 64 pe/MIP



NDL EQR20

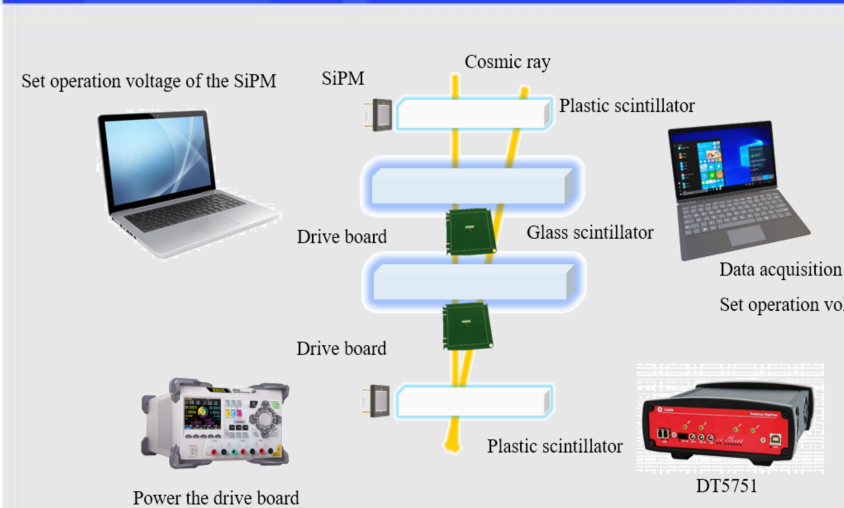


HPK S13360

- Mass production of high quality SiPM;
 - HPK S13360 $\sim 22\%$ PDE $\rightarrow$ HPK S14160 $\sim 43\%$
 - NDL EQR20 $\sim 42\%$ PDE $\rightarrow$ NDL $\sim 50\%$
- Cost of mass production (~ 5.3 M)
 - GS: ~ 0.5 CHF/cc, SiPM: ~ 1.25 CHF/pcs

- Further Optimization of GS size, thickness, GS-SiPM couplings (air vs optical glue).

3.3 Cosmic Ray test result



1.BGRI-146L $40 \times 40 \times 10 \text{ mm}^3$

2.BGRI-4# $40 \times 40 \times 20 \text{ mm}^3$

•Detector:

1. NDL EQR20 11-3030 $3 \times 3 \text{ mm}^2$,

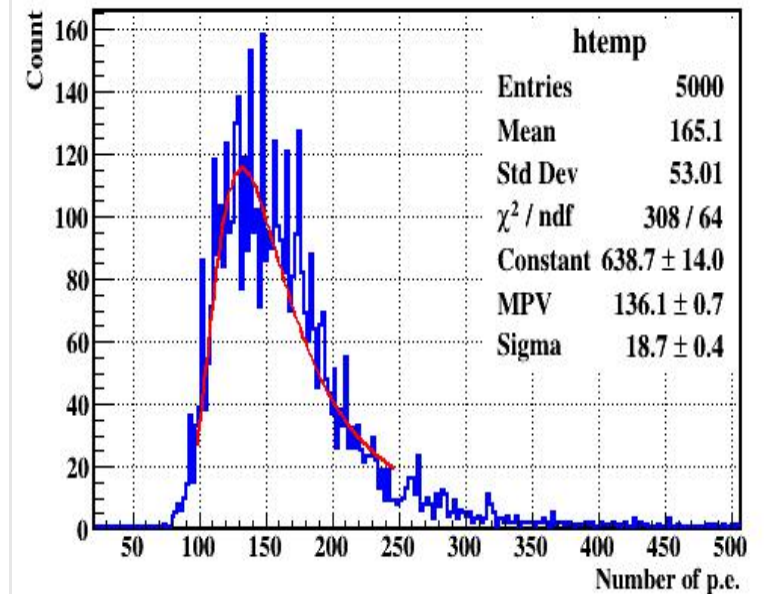
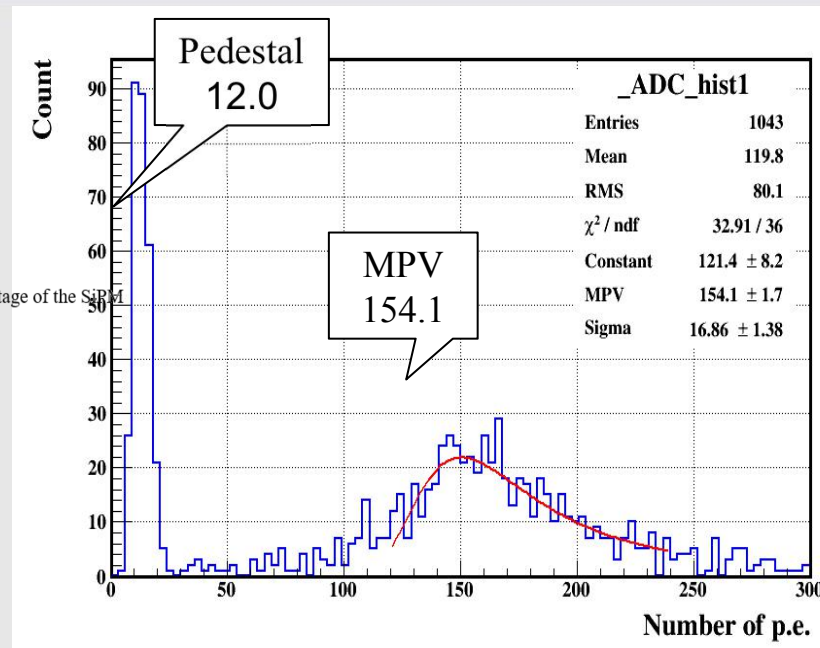
Weighted PDE=42.5%

•Reflector: Teflon

•DAQ: DT5751 Integral time=1000 ns

•Trigger: PS $30 \times 30 \times 10 \text{ mm}^3 \times 2$

•Distance: 5 cm



Cosmic ray test (ADC pedestal deducted) MIP response simulation for Muon

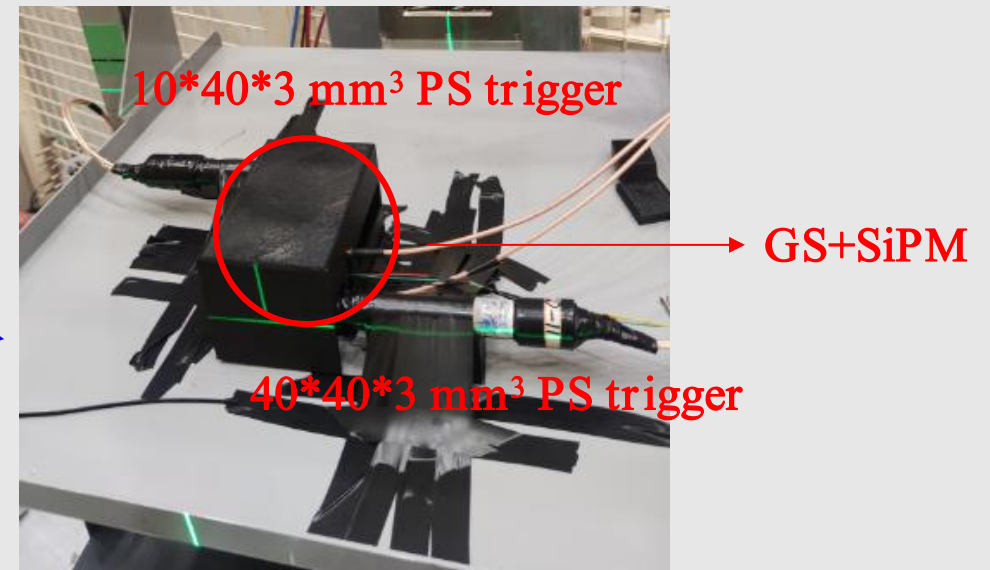
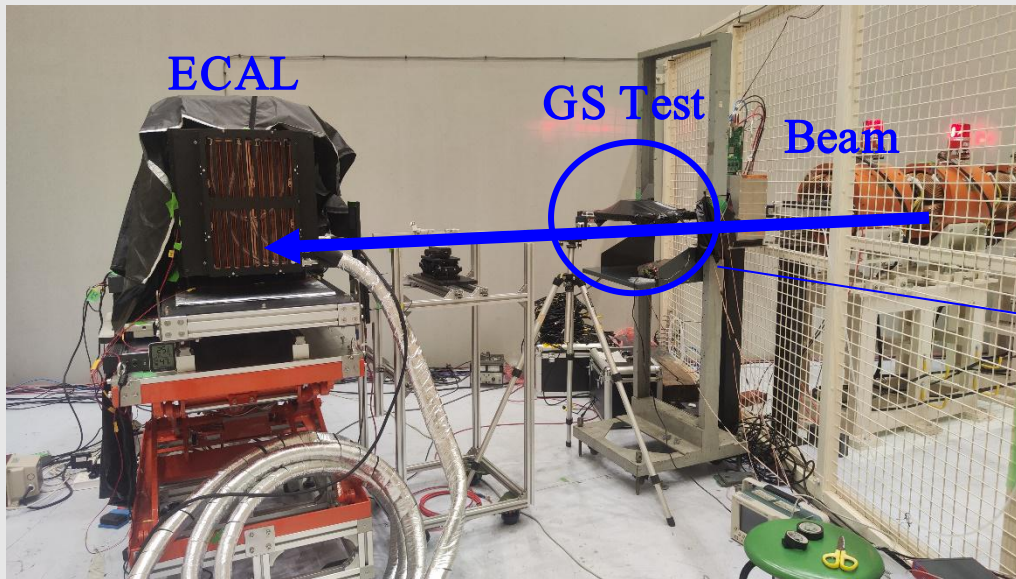
MIP Response (p.e./MIP)	
Cosmic ray experiment	G4 Muon simulation
142.1 ± 1.7	136.1 ± 0.7

3.4 GS Beam Test at KEK

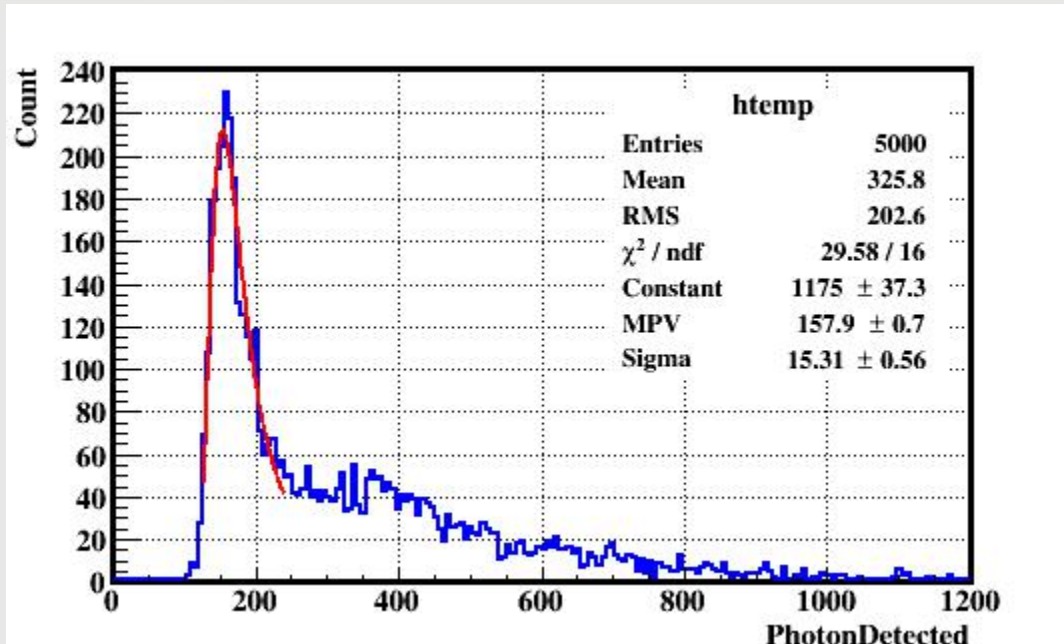
- GS tile size: $4 \times 4 \times 1 \text{ cm}^3$ & 1 SiPM ($3 \times 3 \text{ mm}^2$) for each GS tile

KEK test beam in 2025.6 Experimental goals for GS-HCAL

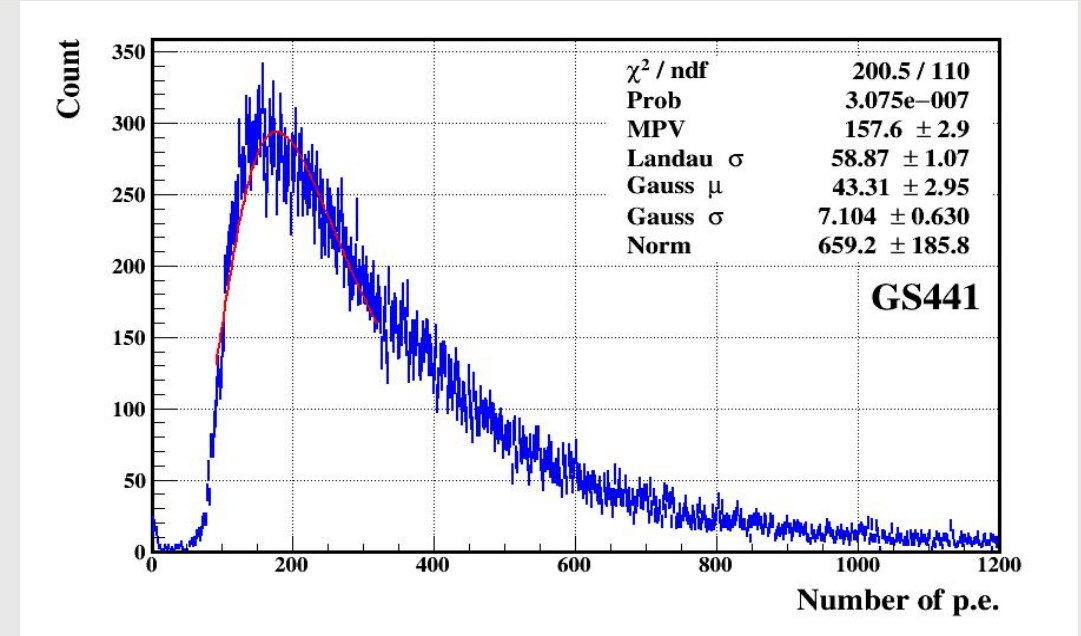
- 5 GeV electron
- 1.6 kHz (from beam line)
- MIP response calibration with low-energy electron for GFO glass
- Compare light output with previous samples measured by DESY
- Compare wrapping effects of different reflectors (Teflon, Tyvek, TiO₂)
- Compare performance of various SiPMs from different manufacturers



Electron beam test result



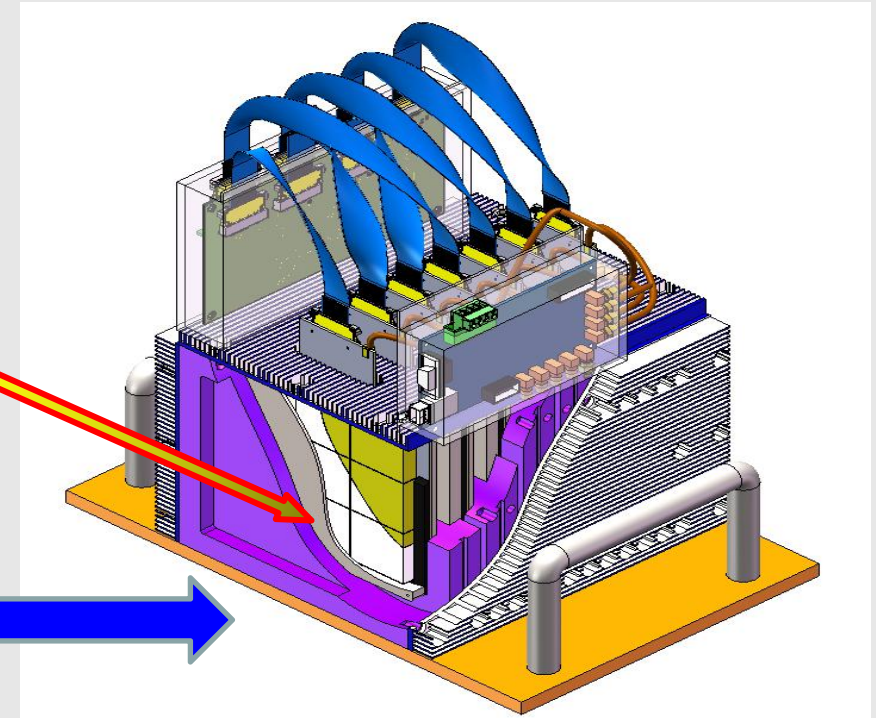
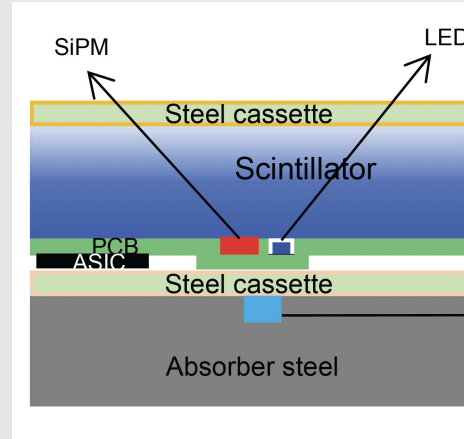
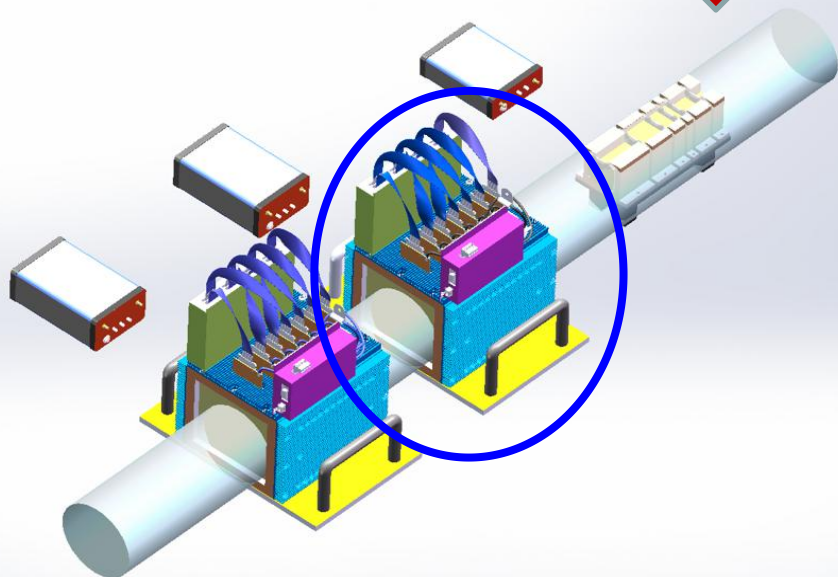
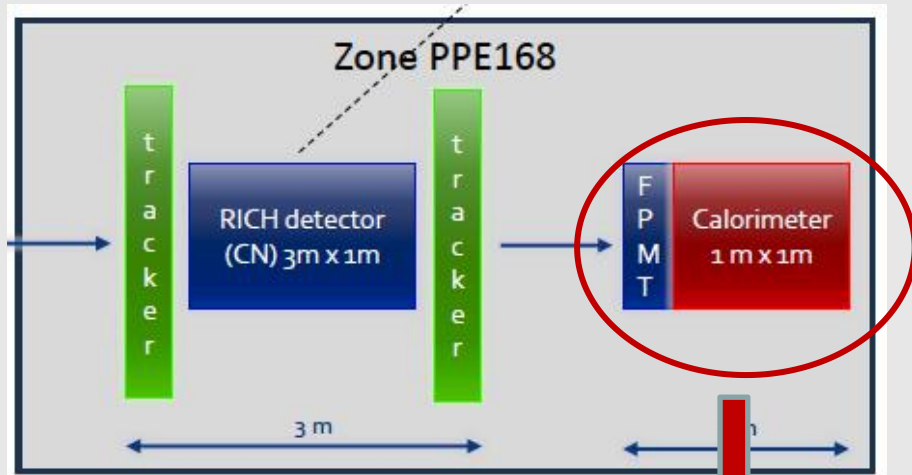
MIP response simulation for electron beam



KEK electron beam test

GS	Reflector	MIP Response (p.e./MIP)	
		NDL 3030 (Weighted PDE=42.5%)	
		Simulation for Electron	Electron Beam Test
		157.9 ± 0.7	157.6 ± 2.9
BGRI-146	Teflon		

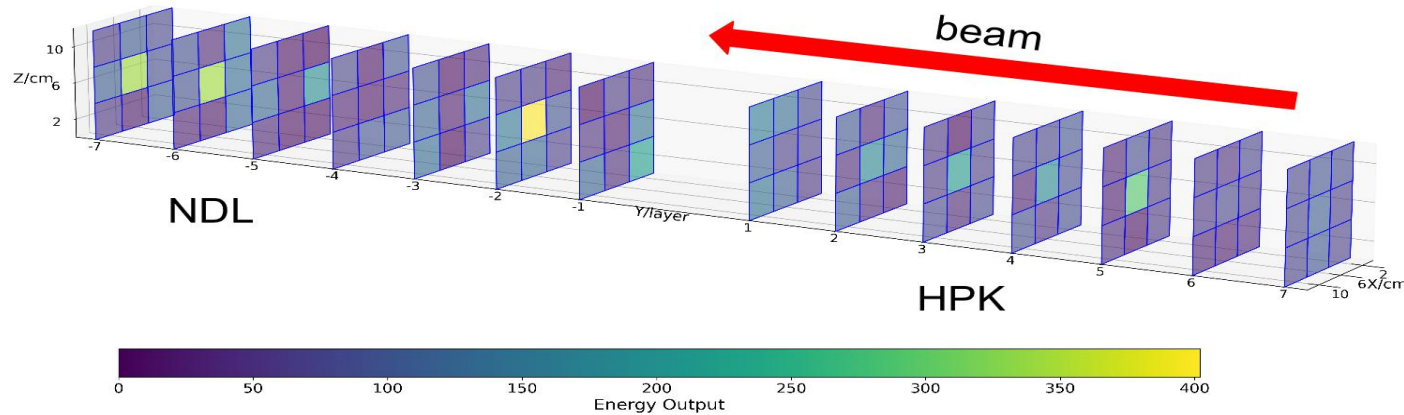
3.5 GS-HCAL Mini-prototype in CERN



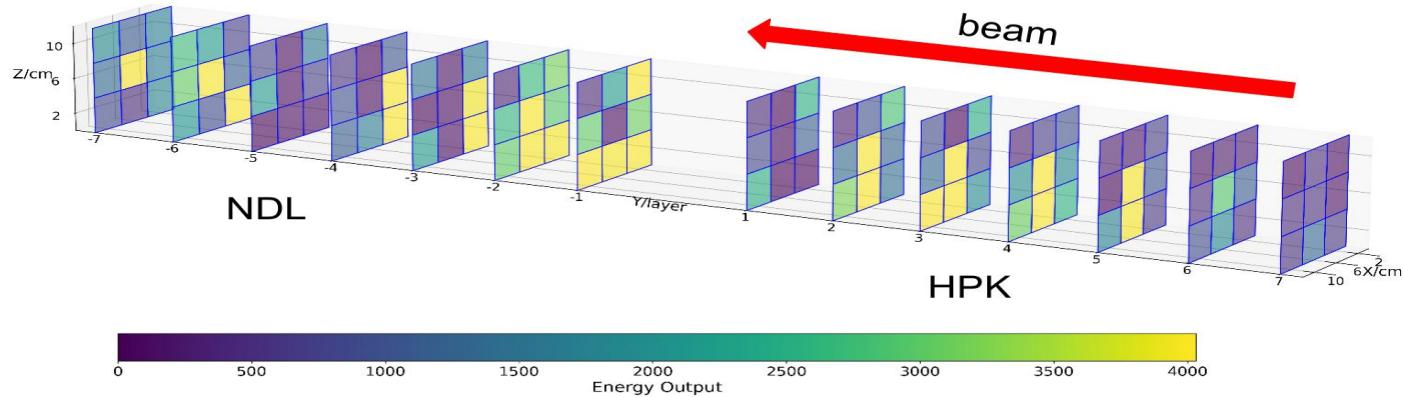
- **Mini-Prototype:** 7 layers, each layer has $3 \times 3 = 9$ GS tiles, 63 GS tiles in total, each GS size of $4 \times 4 \times 1 \text{ cm}^3$
- **Two mini-prototypes** using HPK & NDL, respectively
- **CERN beam tests** (Pion / Muon) in October 2025

Pion/Muon beam test result-event shown

Detector Energy Distribution for Event 45

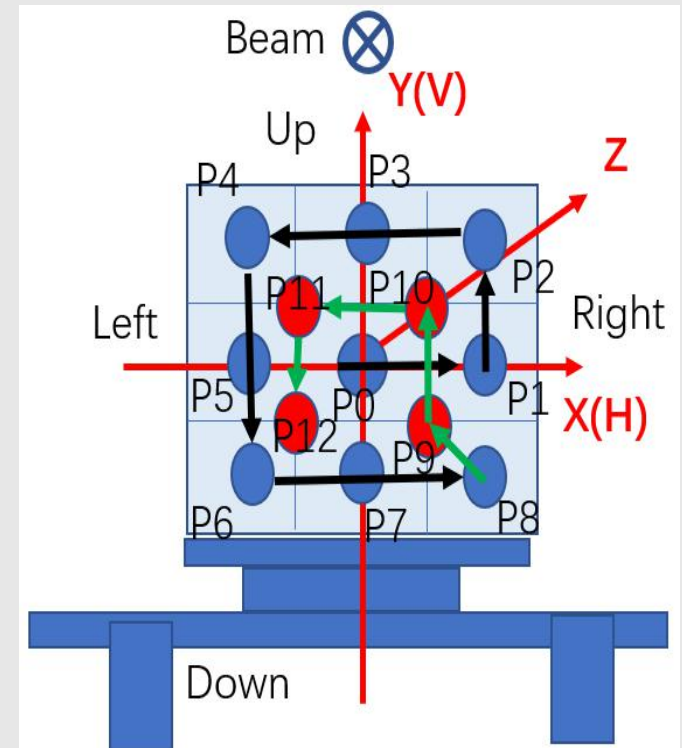


Detector Energy Distribution for Event 36



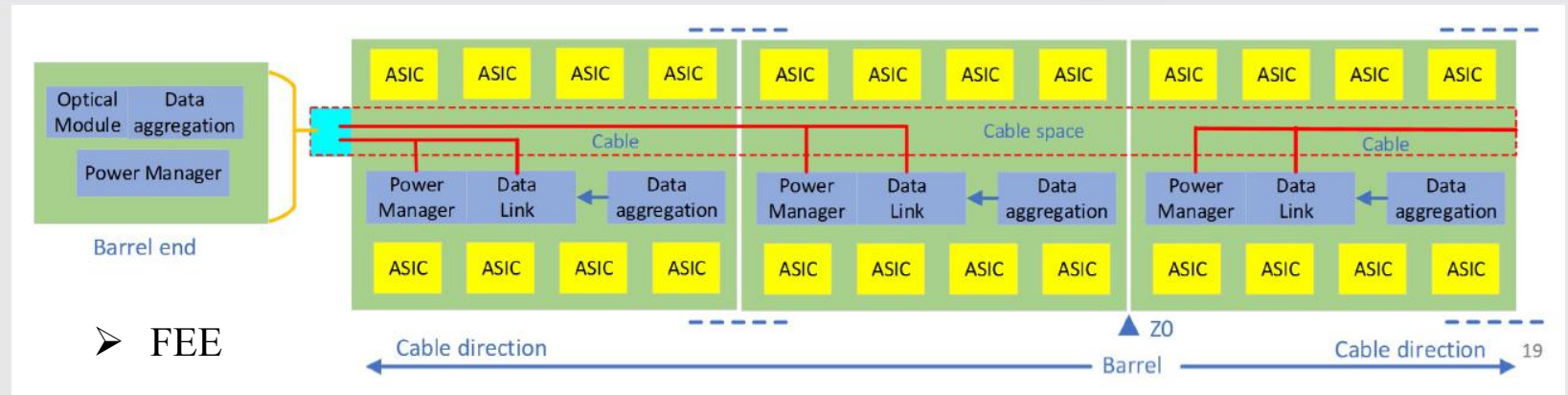
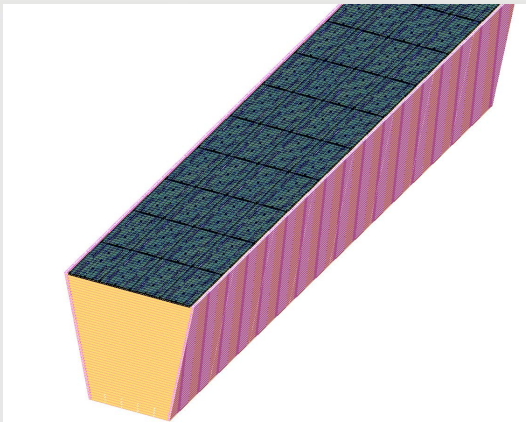
CERN SPS H8 Beamline

- Particle: Pion and Moun
- Energy: 0-180 GeV
- Beam spot: SigmaX and $\text{SigmaY} \approx 1 \text{ cm}$



- waiting for the come back of the module from CERN for futther test for the data callaboration.

3.6 Readout Electronics



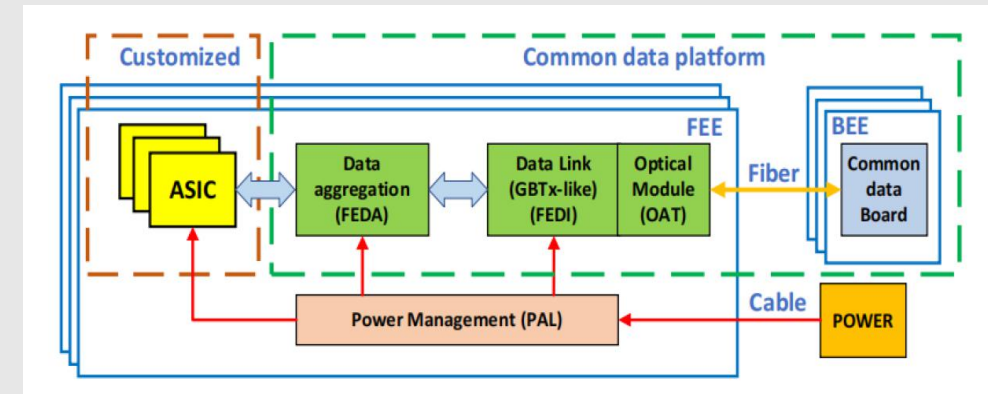
■ Front-End Electronics (FEE) readout boards in HCAL cell Box

- Thickness: 3.2mm = PCB 1.2mm + ASIC Chip 2mm
- SiPMs, ASICs and Data Aggregation
- PCB dimensions: flexible in different positions

■ SiPM-readout ASIC: under development

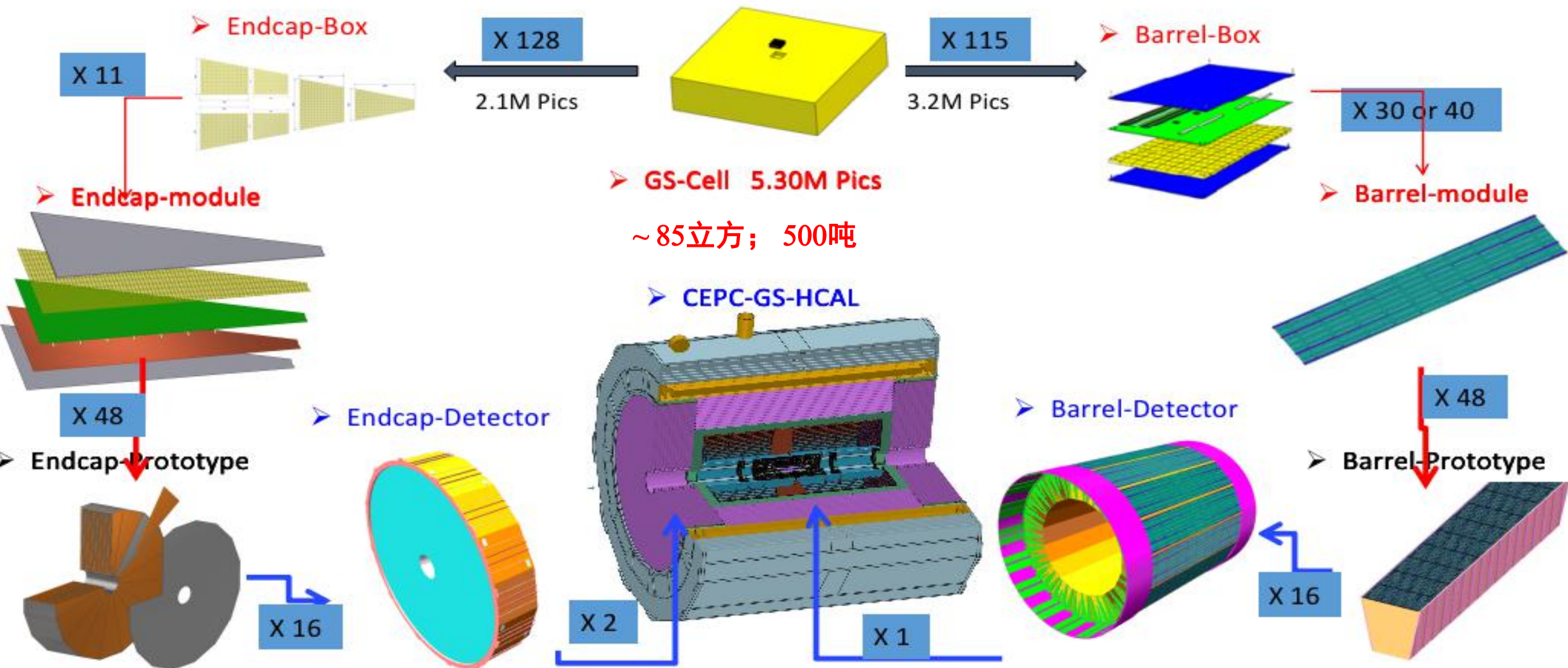
- Self-developed for CEPC calorimeter system
- Functionality: energy and time measurements
- Power consumption: target at 15mW/ch

■ Aggregation board at the end of barrel, cable connection



- **Energy Measurement:** ASIC for ECAL & HCAL
- **Data transmission:** common data platform
- **Trigger mode:** FEE triggerless readout

3.7 Overview of the Mechanics

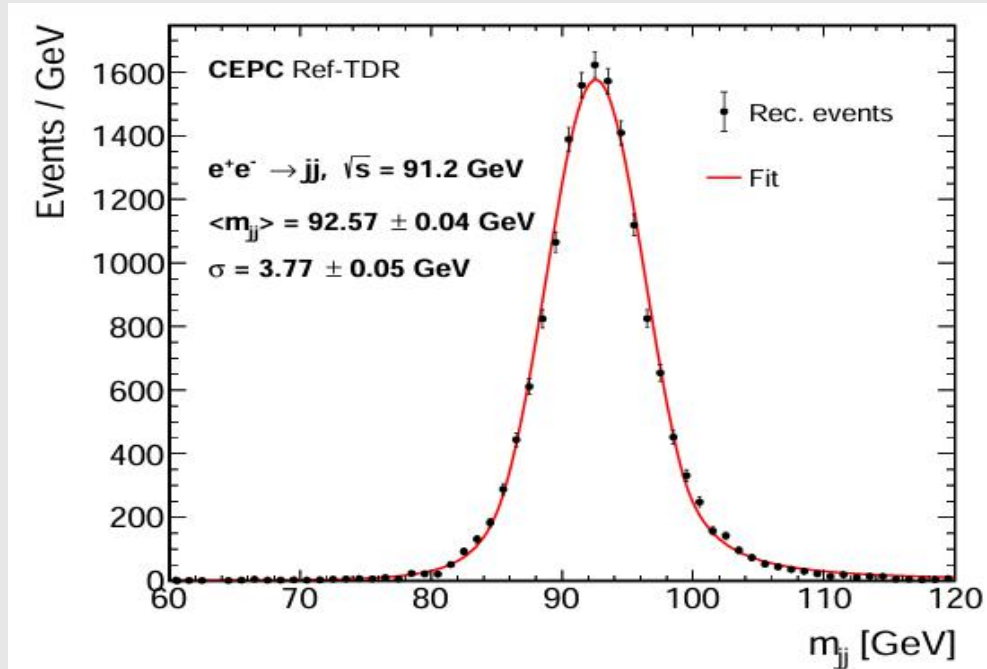


3.8 GS-HCAL Physics Performance simulation

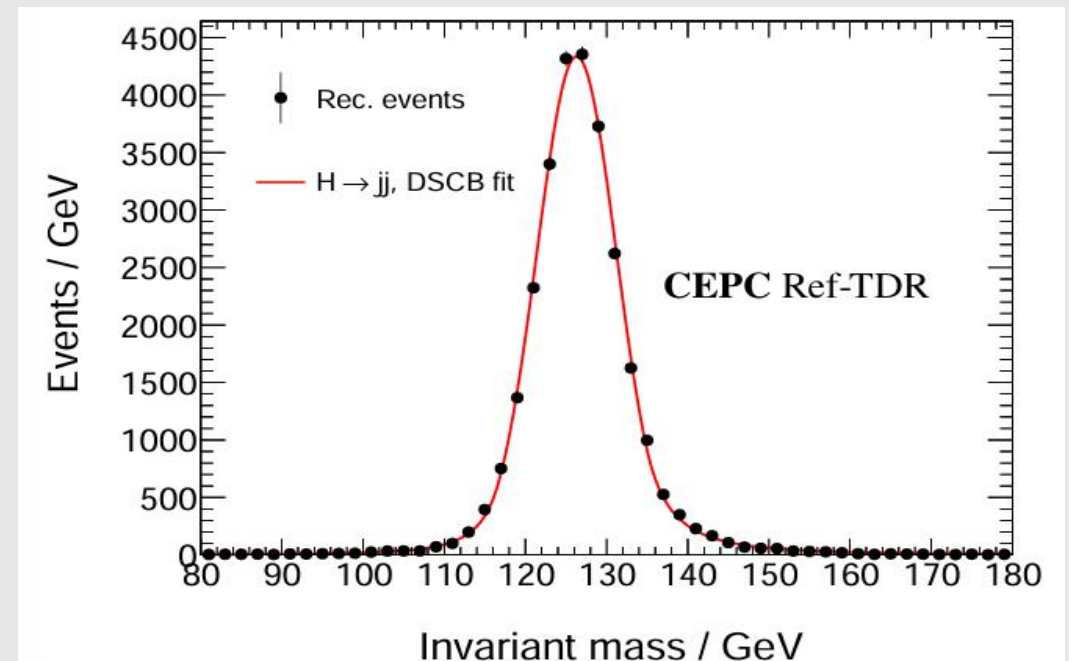
◆ Hadron Energy Resolution (full simu. + digitization):

- MC Sample: $ee \rightarrow Z \rightarrow jj$ @ 91.2 GeV, $ee \rightarrow ZH \rightarrow nngg$ @ 240 GeV
- Tracker (Si + TPC) + Crystal ECAL + GS-HCAL, Cyber PFA Reconstruction

BMR ($Z \rightarrow jj$) = 4.0%



BMR ($H \rightarrow gg$) = 3.88%



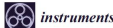
Outline

- 1. Motivation for GS-HCAL
- 2. R&D of the GS
- 3. Design of the GS-HCAL in CEPC
- 4. Summary and Next Plan

4.1 Finished the GS-HCAL design for Ref-TDR

CEPC Reference Detector Technical Design Report

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Article

Development of a Novel Highly Granular Hadronic Calorimeter with Scintillating Glass Tiles

Dajing Du^{1,2,3,*} on behalf of the CEPC Calorimeter Working Group and Yong Liu^{1,2,3,4,5} on behalf of the Scintillating Glass R&D Collaboration

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Abstract: Based on the particle-flow paradigm, a new hadronic calorimeter (HCAL) with scintillating glass tiles is proposed to address major challenges from precision measurements of jets at the future lepton colliders, such as the Circular Electron Positron Collider (CEPC). Tiles of high-density scintillating glass, with a high-energy sampling fraction, can significantly improve the hadronic energy resolution in the low-energy region (typically below 10 GeV for major jet components at Higgs factories). The hadronic energy resolution of single hadrons and the effects of jet parameters of scintillating glass have been evaluated in the Geant4 full simulation, followed by the physics benchmark studies on the Higgs boson with jets in the final state. R&D efforts of scintillating glass materials are ongoing within a dedicated collaboration since 2021 with the aim to achieve a high light yield, a high density, and a low cost. Measurements have been performed for the first batches of scintillating glass samples including the light yield, emission and scintillation spectra, scintillation decay times, and cosmic response. An optical simulation model of a single-scintillating glass tile has been established to provide guidance in the development of scintillating glass. Highlights of the expected detector performance and the latest scintillating glass developments are presented in this contribution.

Keywords: scintillating glass; hadronic calorimeter; high granularity calorimetry; silicon photomultiplier

1. Introduction

High-energy electron-positron collider experiments have been proposed for precision measurements of the Higgs boson, which was discovered at the Large Hadron Collider (LHC) in 2012 [1,2], and to explore new physics beyond the Standard Model. The Circular Electron Positron Collider (CEPC), as one option among next-generation colliders as Higgs factories, requires accurate identification and reconstruction of all final states from Higgs, W , and Z bosons. Therefore, the jet energy resolution of the CEPC detector needs to achieve $\sim 30\%/\sqrt{E_{\text{jet}}(\text{GeV})}$ [3], which poses challenges for the calorimetry system. A feasible paradigm to achieve this goal is the high granularity calorimetry based on the particle flow algorithm (PFA) [4], which makes use of the optimal sub-detector according to determine the energy-momentum of each particle within a jet. An essential prerequisite for calorimeters is to distinguish clusters of nearby individual particles in order to match the tracking system for charged particles and identify clusters originating from neutral particles, which can only be measured in calorimeters. TFA-oriented calorimeters with various technical options featuring high granularity to achieve an excellent three-dimensional spatial resolution are being developed and extensively studied within the CALICE collaboration [5].

As the majority of jet components at Higgs factories with a center-of-mass energy of 240 GeV are relatively low energy (mostly below 10 GeV, as shown in Figure 1), a better hadronic energy resolution would be useful for better PFA performance and jet

check for updates

Citation: Du, D., on behalf of the CEPC Calorimeter Working Group; Liu, Y., on behalf of the Scintillating Glass R&D Collaboration. Development of a Novel Highly Granular Hadronic Calorimeter with Scintillating Glass Tiles. *Instruments* 2022, 6, 32. <https://doi.org/10.3390/instruments6030032>

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journal homepage: www.elsevier.com/locate/nima

Full Length Article

GS-HCAL at future e^+e^- Higgs factories

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ARTICLE INFO

Keywords: High-energy
CEPC
HCAL
Glass scintillator

ABSTRACT

The excellent jet energy resolution is crucial for the precise measurement of the Higgs properties at future e^+e^- Higgs factories, such as the Circular Electron Positron Collider (CEPC). For this purpose, a novel design of the particle flow oriented hadronic calorimeter based on glass scintillators (GS-HCAL) is proposed. Compared with the design based on gas or plastic scintillators, the GS-HCAL can achieve a higher sampling fraction and more compact structure in a cost-effective way, benefiting from the high density and low cost of glass scintillators. In order to explore the physics potential of the GS-HCAL, its intrinsic energy resolution and the contribution to the measurement of the hadronic system was investigated by Monte Carlo simulations. Preliminary results show that the stochastic term of hadronic energy resolution can reach around 24% and the Beam Mass Resolution (BMR) can reach around 3.58% when the GS-HCAL is applied. Besides, the key technical R&D of high-performance glass scintillator tile is also introduced.

1. Introduction

Since the discovery of the Higgs boson [1,2] at the Large Hadron Collider (LHC), the precise measurement of Higgs boson properties has become one of the primary goals of particle physics experiments. However, the precision of Higgs boson couplings at the high-luminosity LHC (HL-LHC) is typically limited to 5%–10% level [3,4] due to the huge QCD background. It requires Higgs coupling measurements with precision at least at present level to probe new physics significantly beyond the LHC [5]. A future Higgs factory based on the e^+e^- colliders, which can provide much cleaner collision environment and measurable and adjustable initial states, is therefore a better choice. The Circular Electron Positron Collider (CEPC) [6,7], the Future Circular Collider with its e^+e^- mode (FCC-ee) [8,9], the International Linear Collider (ILC) [10–12], and the Compact Linear Collider (CLIC) [14] are the four currently proposed linear e^+e^- Higgs factories worldwide. A large number of Higgs, W and Z bosons, as well as the top quarks produced at these future e^+e^- colliders will provide a excellent opportunity to precisely examine the Standard Model (SM) and also to search for new physics (NP).

The precise measurement of the hadronic system is crucial to achieve the major scientific goals of these future colliders, since the majority of Higgs, W and Z bosons decay into quarks or gluons which further fragment into hadronic final states. To avoid the complexity

induced by the jet clustering algorithms, a quantity called the Beam Mass Resolution (BMR) [7] is defined to characterize the performance of the hadronic system, which emphasizes on the detector and particle flow reconstruction performance. The BMR is usually applied to physics events with two final state jets that decay from one intermediate boson, such as $e^+e^- \rightarrow \nu\bar{\nu}H \rightarrow b\bar{b}(\nu\bar{\nu}Z), e^+e^- \rightarrow Z\nu\bar{\nu}(\nu\bar{\nu}Z) \rightarrow q\bar{q}, e^+e^- \rightarrow W^+W^-\nu\bar{\nu}(W^+W^-\nu\bar{\nu})$, etc., in which the remaining particles (except the jet final states) are either invisible or can be easily identified (i.e., isolated leptons). The invariant mass of the hadronic system is the crucial variable to discriminate these events and the BMR is the mass resolution of these hadronic systems. A BMR of 4% or better is needed to achieve a separation larger than 2 σ between W and Z bosons in their hadronic decays [7]. In addition, BMR < 4% is generally required in the Higgs width measurement via $e^+e^- \rightarrow \nu\bar{\nu}H \rightarrow b\bar{b}$ [15], the measurement of $H \rightarrow e^+e^-$ via $e^+e^- \rightarrow Z\nu\bar{\nu}q\bar{q}(H \rightarrow e^+e^-)$ [16], and the study of the Higgs invisible decay via $e^+e^- \rightarrow Z\nu\bar{\nu}q\bar{q}(H \rightarrow \text{invisible})$ [17]. Fig. 1 shows their measurement accuracies as a function of BMR. More details can be found in [15–18].

Oriented by the Particle Flow Algorithm (PFA) [19,20], the baseline CEPC detector design, which has a high-resolution tracking system, a high-granularity calorimeter system, and a high magnetic field of 3T, already reaches a BMR of 3.8% [15,21]. Even though this performance has fulfilled most requirements of Higgs measurements, it is still

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Preliminary optimization study on the PFA-based GS-HCAL for the CEPC

P. Hu,^a S. Qian,^{a,b,*} H. Cai,^a D.P. Chen,^a D.J. Du,^a C.D. Fu,^a J.F. Han,^a D.B. He,^a C. Hu,^a Z.H. Hua,^a S.Q. Li,^a W.C. Li,^a S. Liu,^a Y. Liu,^b L.S. Qin,^a J. Ren,^a M.Q. Ruan,^a Z.X. Sui,^{a,c} X.Y. Sun,^a G. Tang,^a Y.X. Wang,^a Z.L. Wang,^a Y.F. Wen,^a D. Yang,^a S.H. Yin,^a M.H. Zhang^a and Y. Zhu^a

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2024 JINST 19 T06008

ABSTRACT: Precision measurements of properties of the Higgs, W and Z bosons are the key scientific goals at future e^+e^- Higgs factories. A main challenge for these goals is to fulfill an unprecedented jet energy resolution, and the design of the hadronic calorimeter (HCAL) is found to be one of the most

* Corresponding author.

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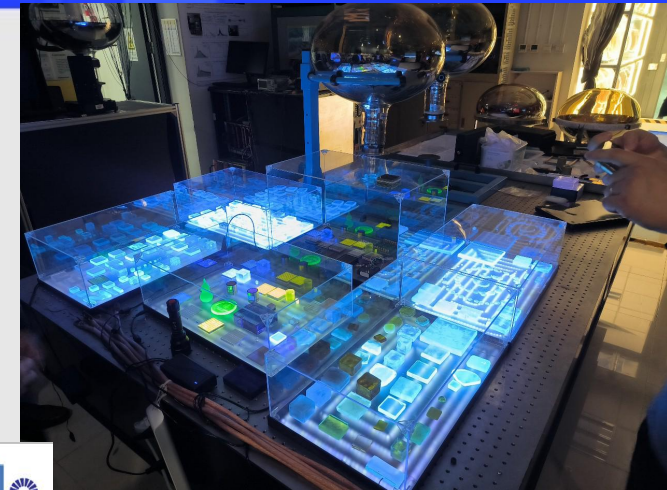
➤ 2024 JINST 19 T06008

4.2 Contribute to the DRD6 and DRD review

 **Work Package 3 – Comparison of optical materials** 

➤ Scintillator Materials

➤ Performance of Scintillator Glass



Scintillating Materials – Glasses around the world

Development in Caltech/Calvision

Main R&D Topic Light Yield

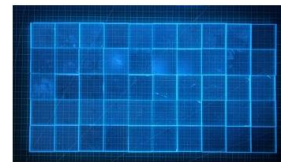
Laboratory-fabricated sample produced in 2015

WP1 – Subtask 1.2.2 – ScintGlassHCAL

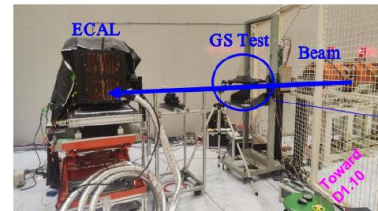
Glass scintillator R&D: Light yield

WP1 – Subtask 1.2.2 – ScintGlassHCAL

Glass scintillators – Alternative to Xtals?



Combined setup with HGCCAL at KEK



DRD Jamboree – Octobre

DRD Calo – Introduction and Status

Roman Pöschl
On behalf of the DRD Calo Collaboration



DRD Jamboree – CERN October 2025

For a full overview please consult the [DRD Calo Webpage](#)

➤ Simulation Design of GS-HCAL

➤ Beam test of GS

GS-HCAL Full-size Prototype

■ Plan towards a full-scale prototype

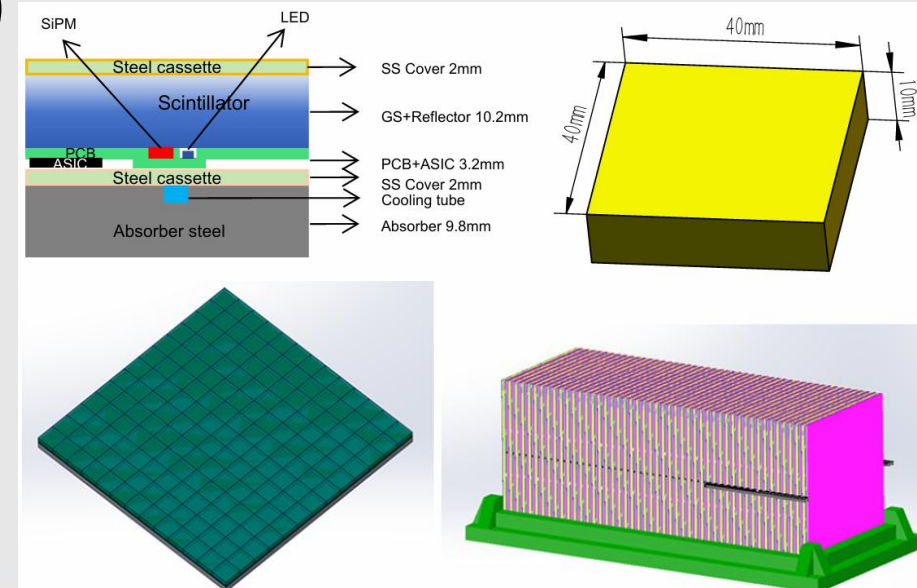
- Step 1: test beam of new GS tiles at KEK (2025.6)
- Step 2: test beam of mini-prototype at CERN (2025.10)
- Step 3: batch production & test of ~10k GS (2025-2026)
- Step 4: build full-scale prototype with ~8k GS tiles (2026)
- Step 5: test beam of full-scale prototype (2027)

■ Full-scale GS-HCAL prototype (2025-2026)

- Total: 48 layers, Total GS tiles: $13 \times 13 \times 48 = 8112$
- Each layer: 13×13 GS tiles (52×52 cm²)
- GS tile size: $4 \times 4 \times 1$ cm³
- 1 SiPMs (3×3 mm²) for each GS tile
- ASIC Chip with power consumption of 15mW/ch
- Stainless steel as absorber and covers: 13.8mm

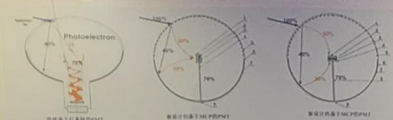
■ Test beam plan (2027)

- CERN: PS or SPS
- KEK (Japan): 5 GeV electron
- HEPS (China): 6 GeV electron



新型MCP-PMT研制

根据在材料科学中大面积光电倍增管的研制，研制下一代大型中微子探测计划，结合国际上最新光电倍增管技术，研制一种新型光电倍增管，为大型中微子探测计划提供关键技术支撑。



Thanks for your attention!



Backup slides

Summary and Future Plans

■ Physics requirement for the design:

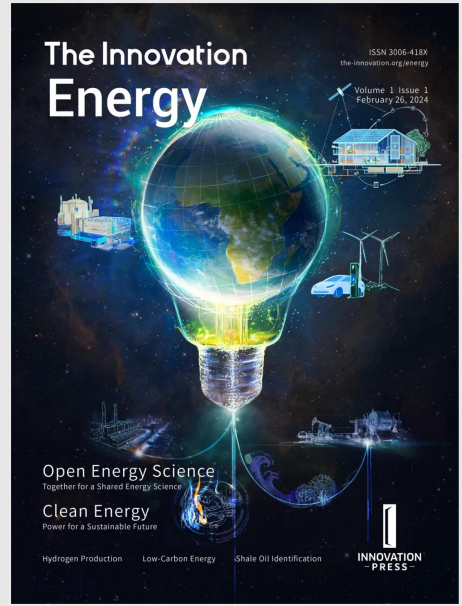
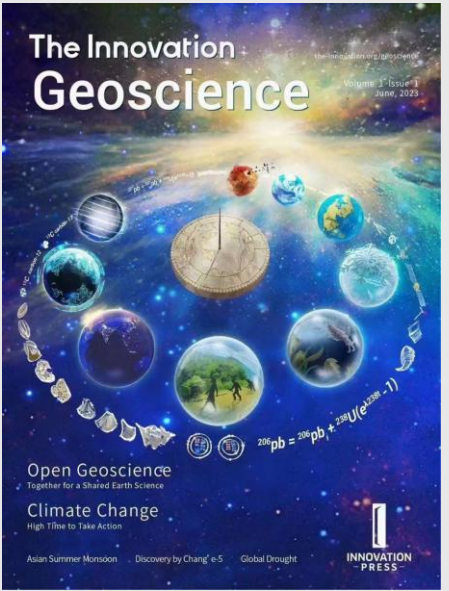
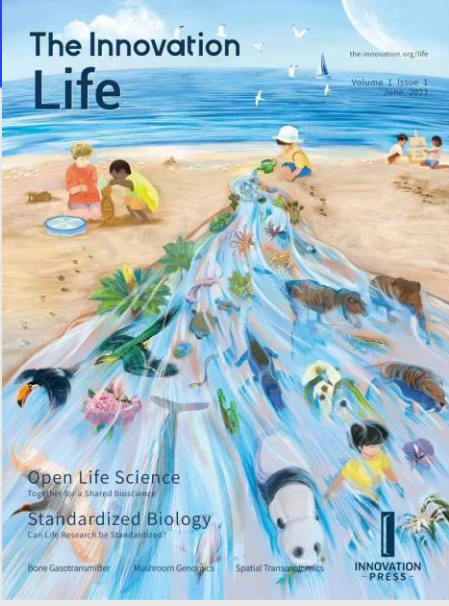
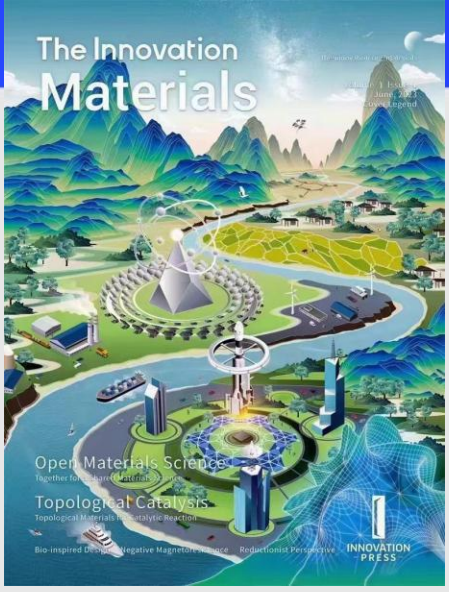
- Hadron energy resolution $< 5\%$
- Boson mass resolution (BMR) $< 4\%$

■ GS-HCAL is selected as baseline based on its promising performance

- Intensive R&D on high quality GS (e.g. light yield, decay time, attenuation length)
- Update design of GS-HCAL mechanics, cooling and readout electronics
- Preliminary study with CEPCSW shows promising result which is feasible for Ref-TDR

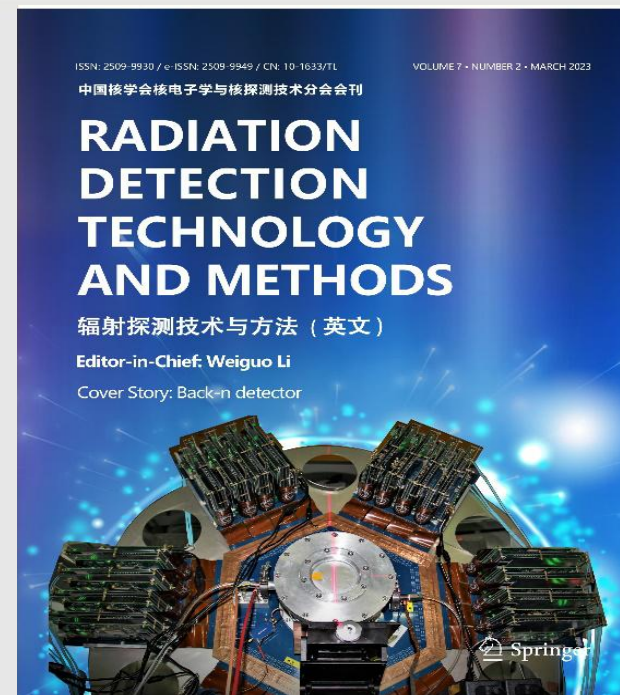
■ Future R&D plans

- To further optimize GS size, GS-SiPM coupling, cooling and readout electronics
- To optimize simulation, digitization, reconstruction and analysis chain
- To develop techniques for mass production of GS, SiPM with low cost
- To prepare full-size GS-HCAL prototype with integrated electronics for beam test

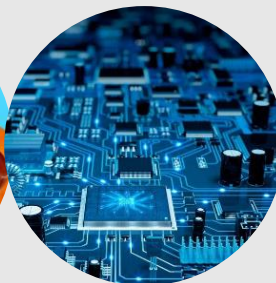


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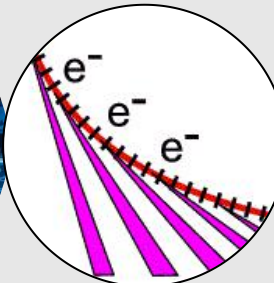
核电子学与核探测技术 & Radiation Detection Technology and Methods



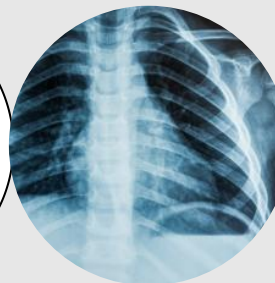
核探测
技术



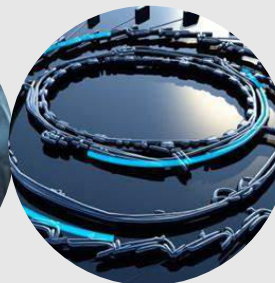
核电子学
技术



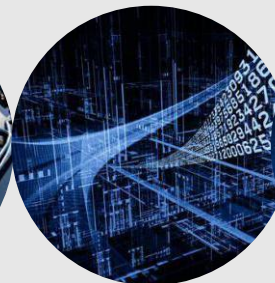
加速器
技术



核医学
技术



同步辐射
技术



计算机
技术



天体粒子
技术

HCAL Research Group

- Actively involve in DRD-Calo Collaboration
- CEPC-HCAL team: IHEP, USTC, SJTU, XJTU, SCNU, SCU, HEU, ZZU
 - Detector for PS/GS-HCAL: Staff(9) + Student(10)
 - Electronics: Staff(5), Mechanics: Staff(3)
 - GS Collaboration: 13 institutes, Staffs (26) + Students (10)

Convener: Sen Qian (IHEP), Jianbei Liu (USTC)

Physics: Manqi Ruan(IHEP), Haijun Yang (SJTU)

Software: Sengsen Sun(IHEP)

Design: Fangyi Guo(IHEP), Hengne Li(SCNU), Qingming Zhang(XJTU), Weizheng Song(IHEP), Peng Hu(261)

Dejing Du(IHEP), Hongbing Diao(USTC), Jiyuan Chen(SJTU), to design the GS-HCAL based on CEPCSW;

Glass Scintillator: Sen Qian(IHEP), Jing Ren(HEU), the GS collaboration (13 institutes, 26 staffs +10 students);

SiPM: Yuguang Xie(IHEP), Jifeng Han(SCU), Guang Luo(SYSU), SiPM and electronics for the GS performance test;

Electronics: Jingfan Chang(IHEP), to design the ASIC and FEE, power supply, cables etc.;

DAQ: Chen Boping(IHEP)

Mechanics and cooling system: Yatian Pei(IHEP), Junsong Zhang(IHEP), Shang Bofeng(ZZU)

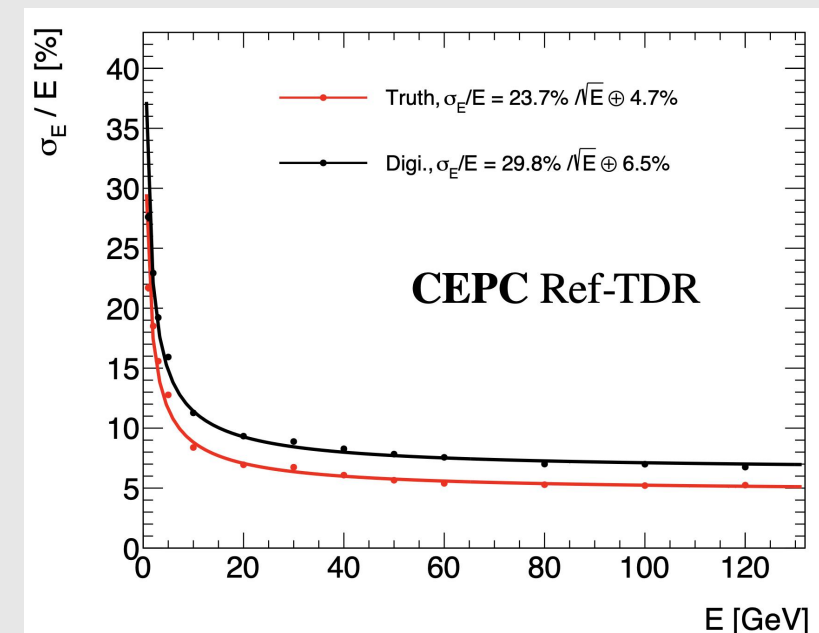
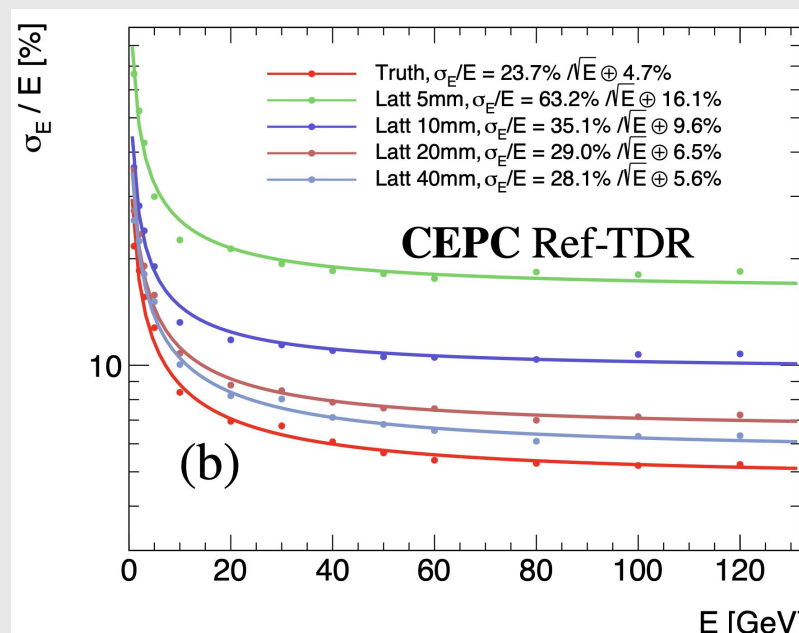
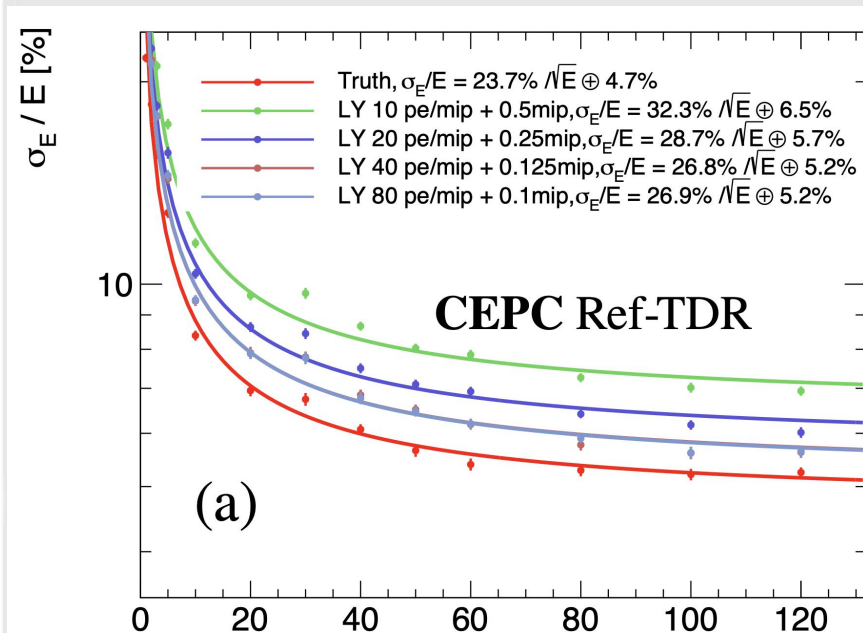
Detector: Boxiang Yu(IHEP), Yunlong Zhang (USTC), Yong Liu (IHEP), GS-HCAL module, TB and cosmic test;

GS-HCAL Energy Resolution

■ A full detector geometry constructed with DD4hep in CEPCSW

- GS density 6 g/cm^3 , $\lambda_I = 242.8 \text{ mm}$, attenuation length $\sim 60 \text{ mm}$
- GS cell size $4 \times 4 \times 1 \text{ cm}^3$, 48 layers, $6\lambda_I$ in total
- Geometry: follow the mechanics design with supporting structures.

$$\sigma_E/E = 29.8\%/\sqrt{E} \oplus 6.5\%$$



- GS light output: $> 50 \text{ p.e./MIP}$
- Threshold: $0.1 \text{ MIP} (> 5 \text{ p.e})$

- GS attenuation length

- GS attenuation length: $\sim 60 \text{ mm}$

GS-HCAL Constant Term

■ **GS-HCAL in full simu+digi:** $6\lambda, \frac{\sigma_E}{E} = \frac{29.8\%}{\sqrt{E}} \oplus 6.5\%$ (**all events**)

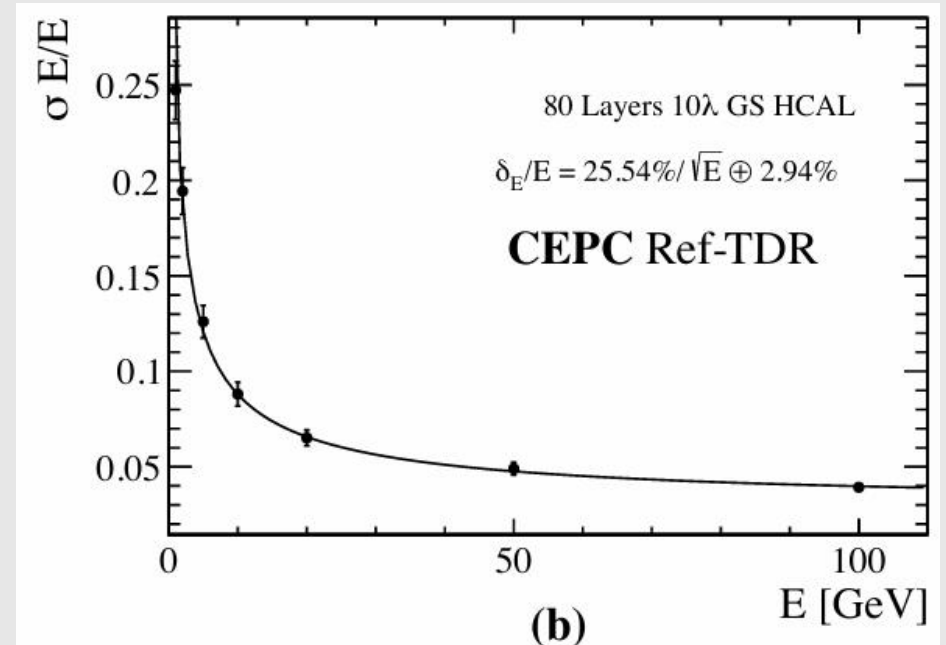
■ Large HCAL (80 layers, 10λ): $\frac{\sigma_E}{E} = \frac{24.7\%}{\sqrt{E}} \oplus 2.9\%$

■ Shower starts at the first 2 layers: $\frac{\sigma_E}{E} = \frac{25.9\%}{\sqrt{E}} \oplus 3.5\%$

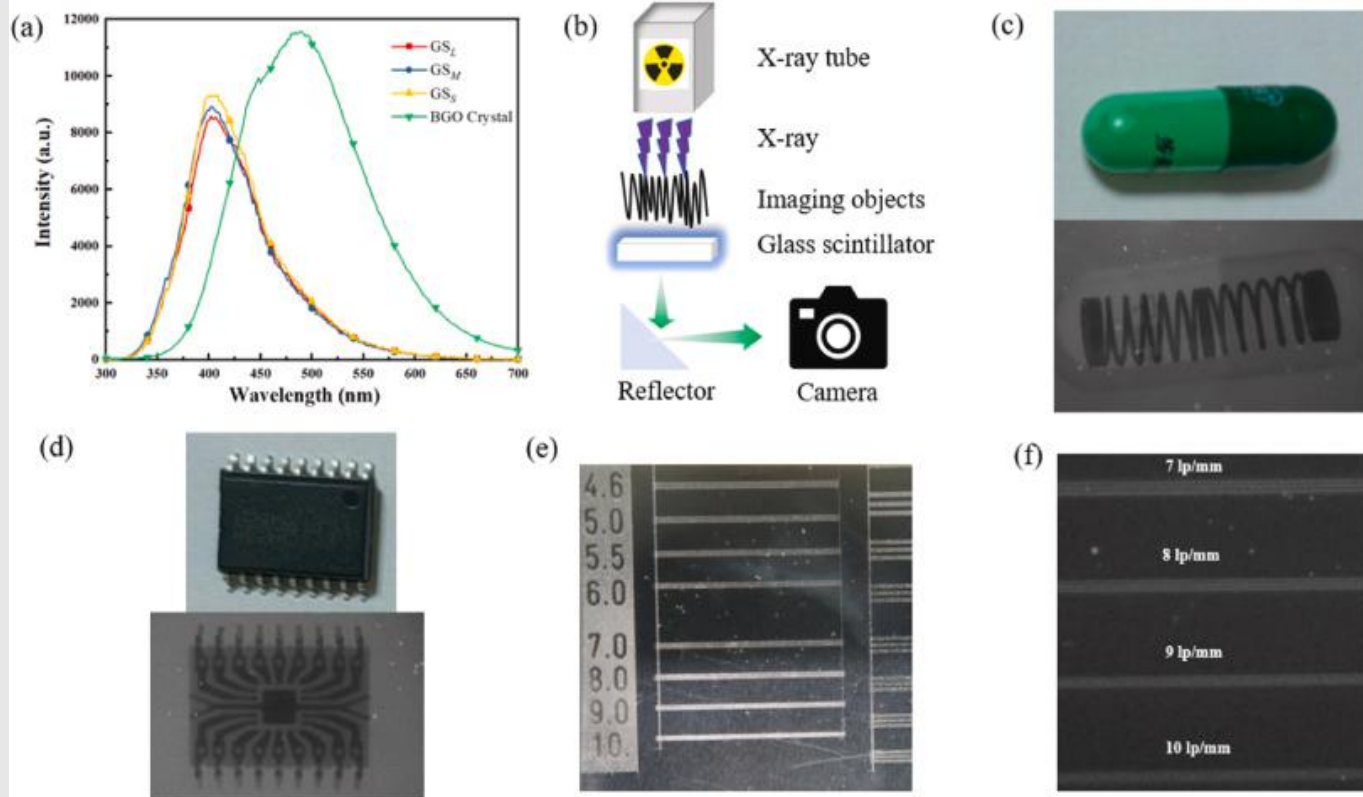
■ Large constant term in GS-HCAL is mainly due to longitudinal shower leakage, combining ECAL($1.2 \lambda_1$) and HCAL($6 \lambda_1$) helps to reduce leakage

■ Software compensation is expected to reduce constant term

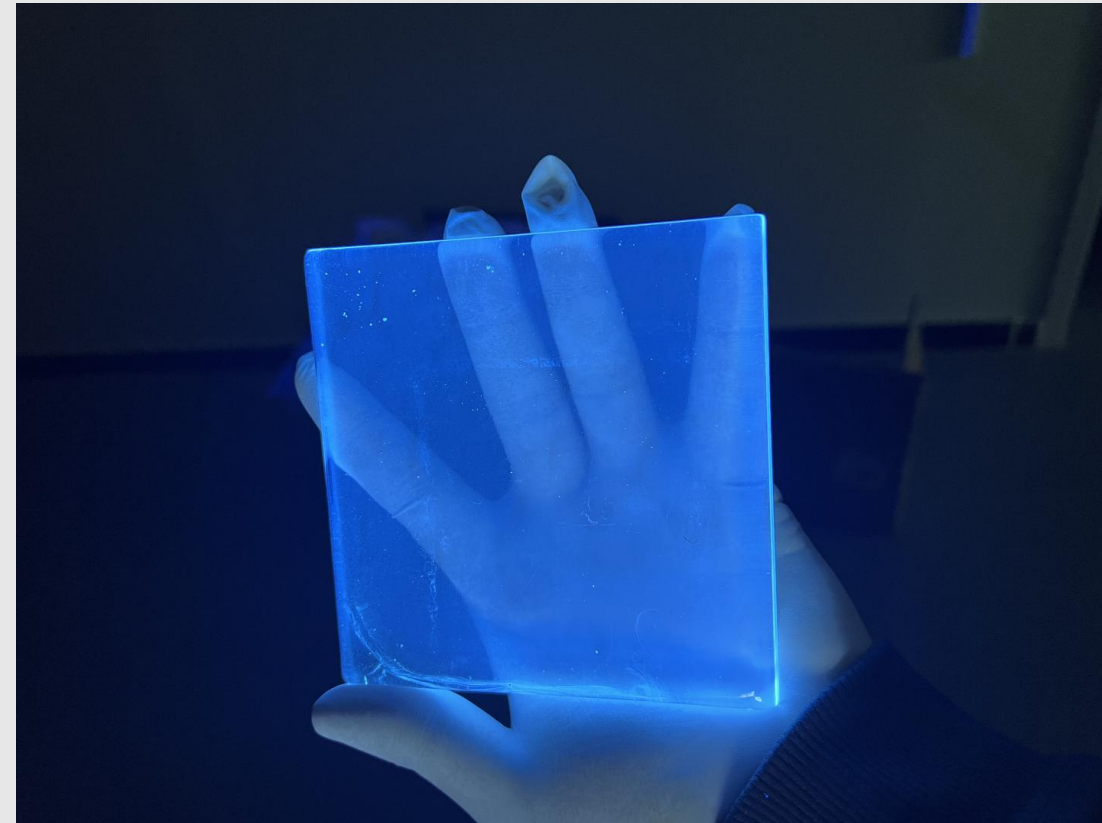
80 layers (10λ)



The Application of the Glass Scintillator



Ultra-Large size glass (12.5cm X 122cm)



From: [Adv. Opt. Mater.](#) 2025, 2403243

From: [Ceram. Int.](#), 50 (2024) 47253–47258

From: [Ceram. Int.](#), 2025.02.151