The R&D of the New Glass Scintillator for HCAL of CEPC

闪烁玻璃合作组
Glass Scintillator Collaboration

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On Behalf of the GS R&D Group

CEPC Workshop, 2024. 10. 23th

Outline

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

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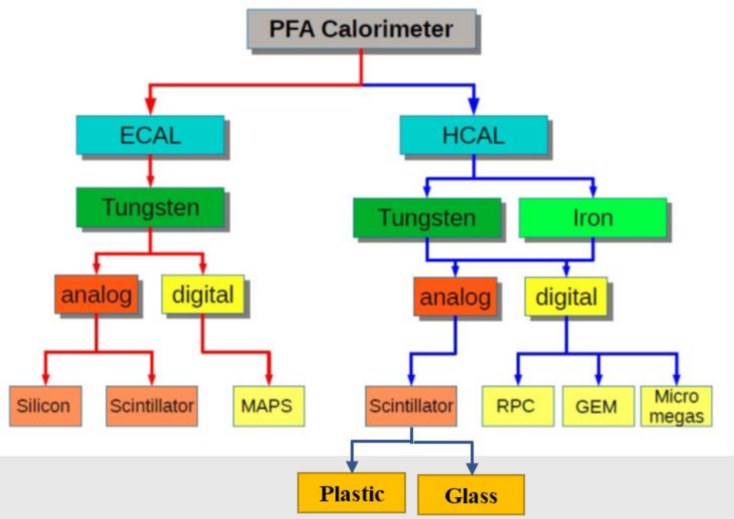
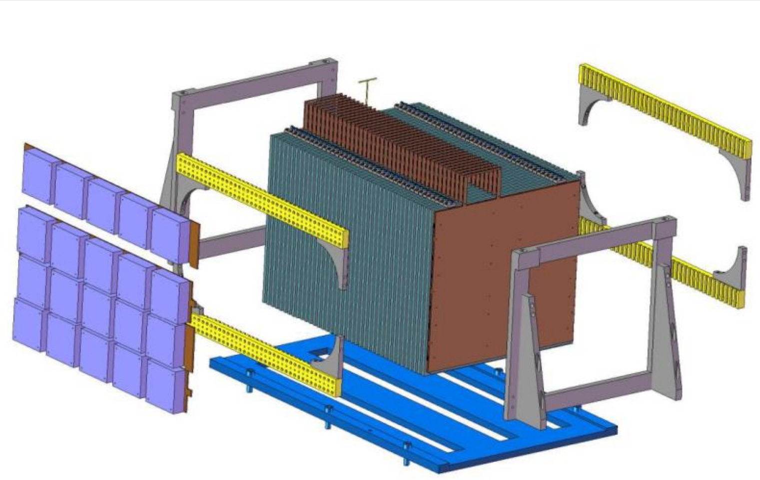
1.1 HCAL Design Options (Before)

- **Several HCAL design options have been proposed**
  - Based on **Gaseous Detector**
    - e.g. CALICE SDHCAL doi: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
  - AHCAL: **Plastic Scintillator** & SiPM readout
    - e.g. CEPC AHCAL doi:10.1088/1748-0221/17/11/P11034



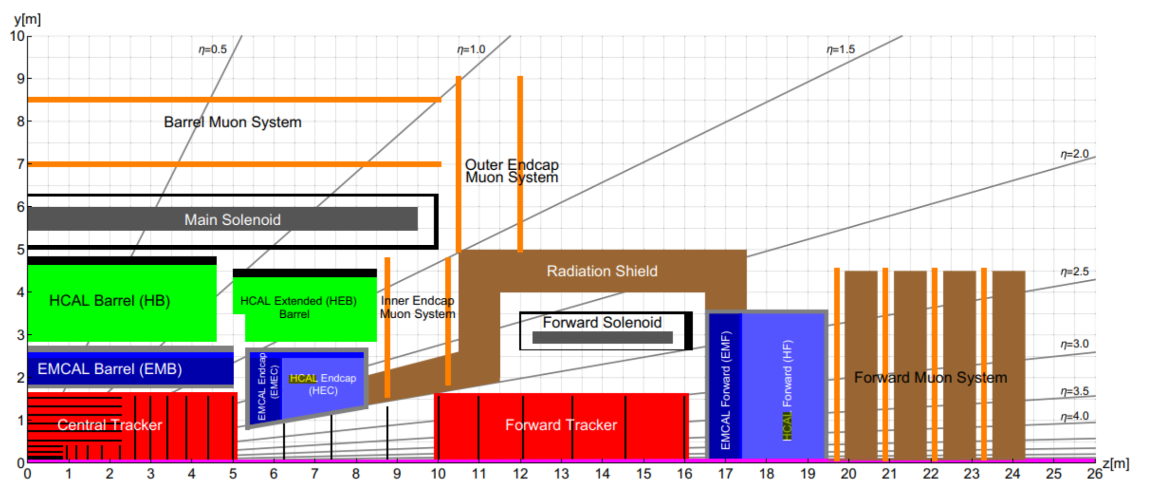
➢ CALICE SDHCAL Prototype

➢ ATLAS LAr Endcap HCAL

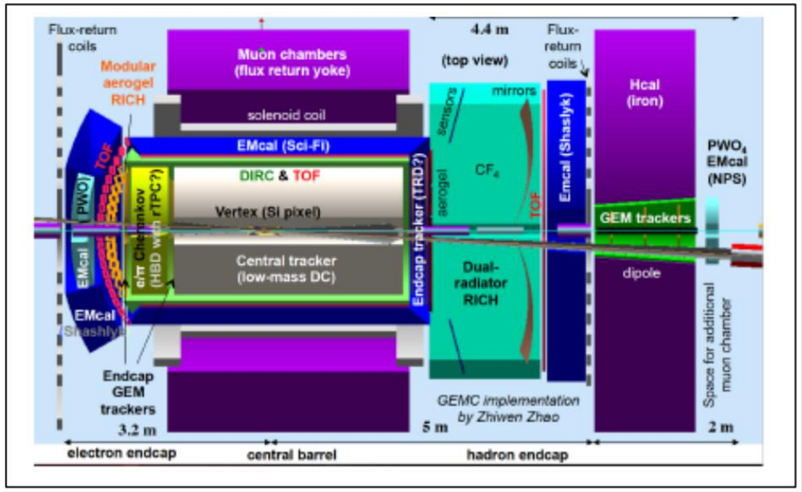


➢ CEPC AHCAL Prototype

1.2 HCAL Design Options (After)



Longitudinal cross-section of the FCC-hh reference detector



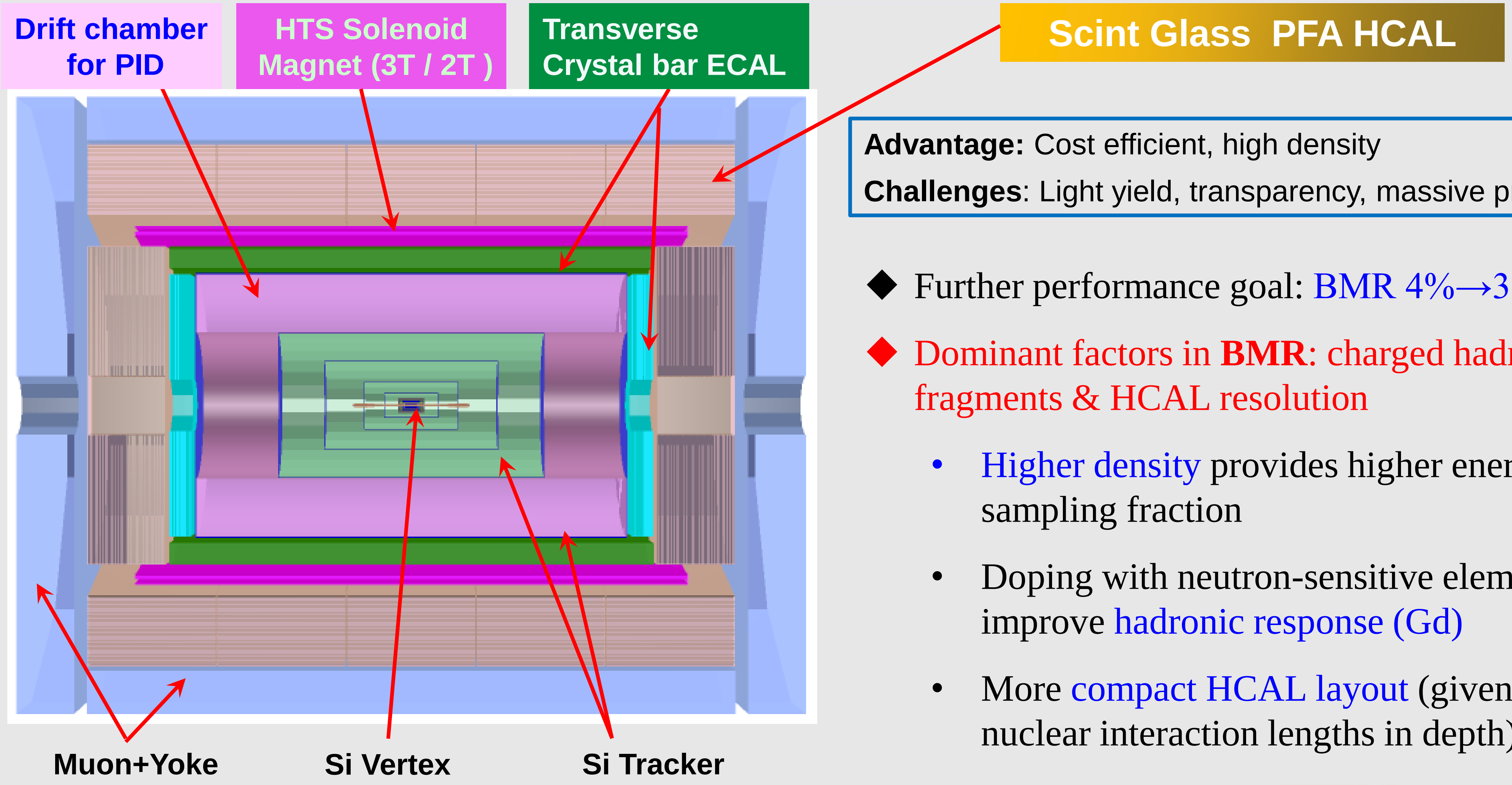
Example layout of the EIC detector base design

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 1.3: Hadronic section with gaseous readout	
Subtask 1.3.1: T-SDHCAL	Resistive Plate Chambers/Steel
Subtask 1.3.2: MPGD-HCAL	Multipattern Gas Detectors/Steel
Subtask 1.3.3: ADRIANO3	Resistive Plate Chambers+Scintillating plastic tiles/ Heavy Glass

Task 1.2
- AHCAL: Concept for continous readout
- ScintGlass HCAL: cm scale tiles

Task 1.3
- T-SDHCAL: Study of the impact of timing on the PFA performance
- MPDG-HCAL: Completion of 6 layer 20x20 cm^2 proto
- ADRIANO3: Small scale test layers

The 4th Conceptual Detector Design



Advantage: Cost efficient, high density

Challenges: Light yield, transparency, massive production.

- Further performance goal: BMR 4%→3%
- Dominant factors in **BMR**: charged hadron fragments & HCAL resolution
  - Higher density provides higher energy sampling fraction
  - Doping with neutron-sensitive elements: improve hadronic response (Gd)
  - More compact HCAL layout (given 4~7 nuclear interaction lengths in depth)

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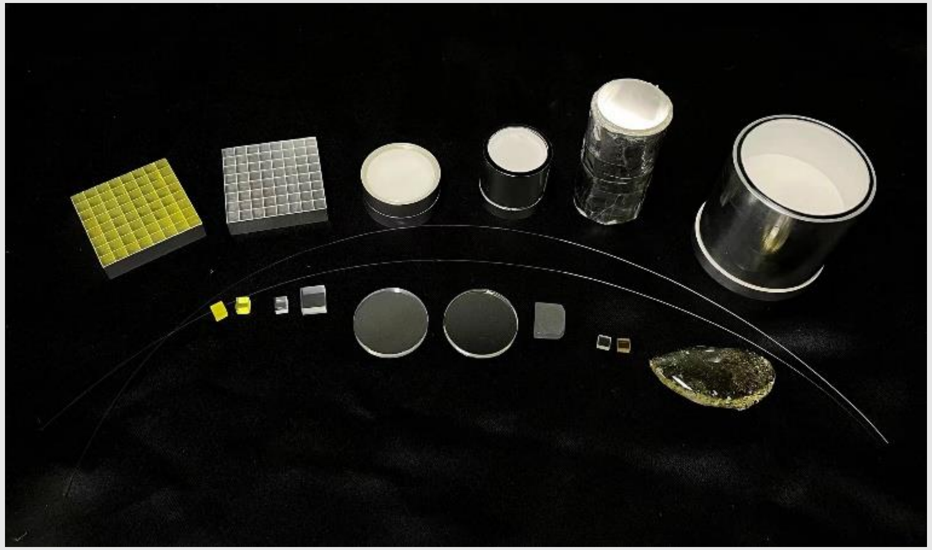
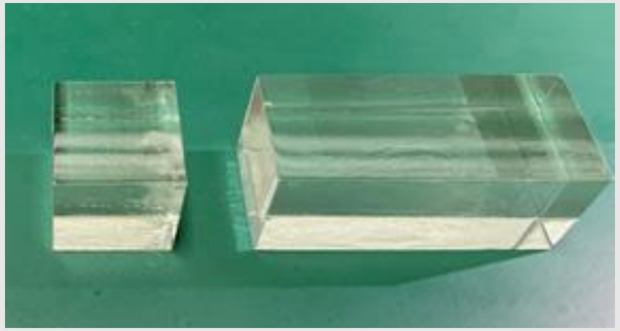


2.0 What is the Glass Scintillator?

Plastic Scintillator



Glass Scintillator

Crystal Scintillator

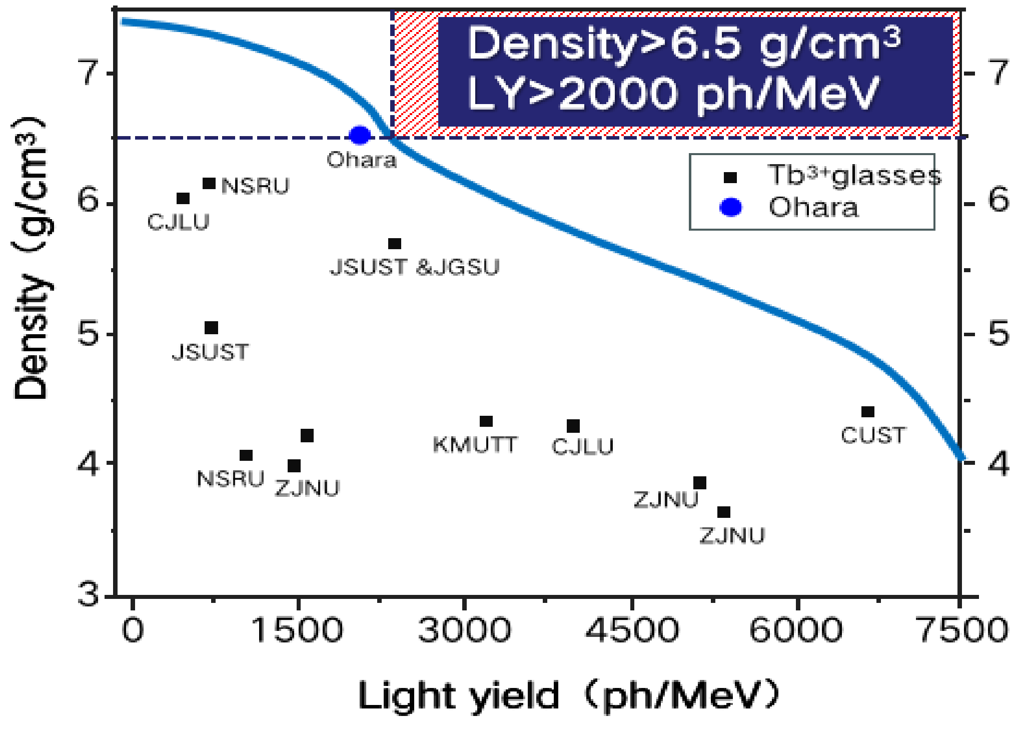
Plastic		Glass		Crystal	
High light yield	★★	**High light yield**	★	**High light yield**	★★★
Fast decay	★★★	**Fast decay**	★★	**Fast decay**	★★
Low cost	★★★	**Low cost**	★★★	**Low cost**	★
Large Density	★	**Large Density**	★★	**Large Density**	★★★
Energy resolution	★	**Energy resolution**	★★	**Energy resolution**	★★★
Large size	★★★	**Large size**	★★★	**Large size**	★

2.1 Target of Glass Scintillator

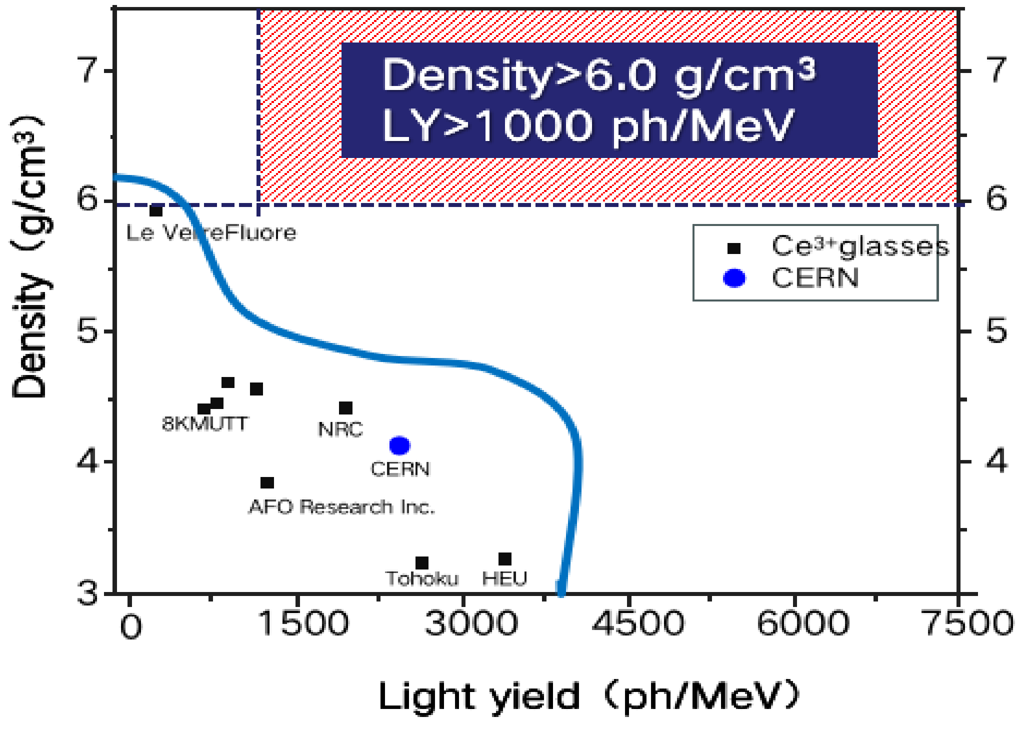
Key parameters	Value	Remarks
➢ Tile size	~40×40 mm^2	Reference CALICE-AHCAL, granularity, number of channels
➢ Tile thickness	~10 mm	Energy resolution, Uniformity and MIP response
➢ **Density**	**6-7 g/cm^3**	More compact HCAL structure with higher density
➢ **Intrinsic light yield**	**1000-2000 ph/MeV**	Higher intrinsic LY can tolerate lower transmittance
➢ Transmittance	~75%	
➢ MIP light yield	~100 p.e./MIP	Needs further optimizations: e.g. SiPM-glass coupling
➢ Energy threshold	~0.1 MIP	Higher light yield would help to achieve a lower threshold
➢ Scintillation decay time	<300 ns	Mitigation pile-up effects at CEPC Z-pole (91 GeV)
➢ Emission spectrum	Typically 350-600 nm	To match SiPM PDE and transmittance spectra

2.2 Current Research Status of the GS

- Before 2000, the high-density GS is mainly based on Pb (plumbum) or Bi (bismuth), with poor scintillation light;
- After 2000, GS with rare-earth elements （Tb,Terbium; Ce,**Cerium**） attract more attention for improved LY
- However, **it's a great challenge to realize a high density and high light yield at the same time**

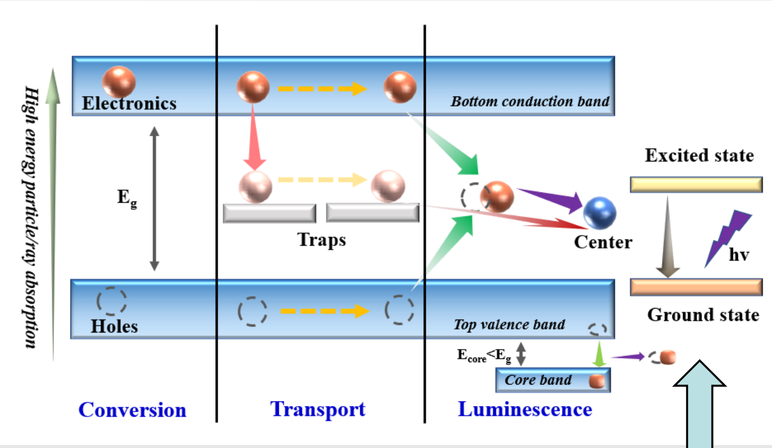


Tb^{3+} doped glass with high light yield



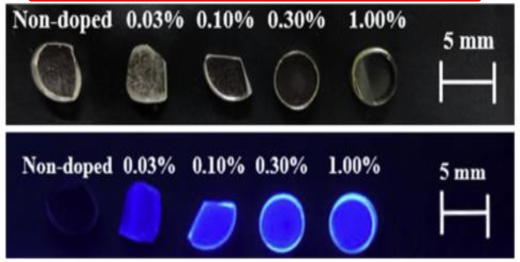
Ce^{3+} doped glass with short decay time

2.3 The Design of the Glass Scintillator



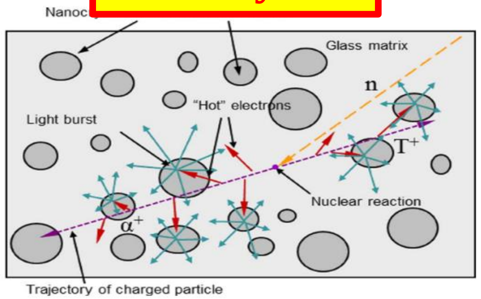
- **Scintillation mechanism---- Luminescence Center**
- **Conversion**—photoelectric effect and Compton scattering effect;
- **Transport**—electrons and holes migrate;
- **Luminescence**—captured by the luminescent center ions

Lanthanide elements



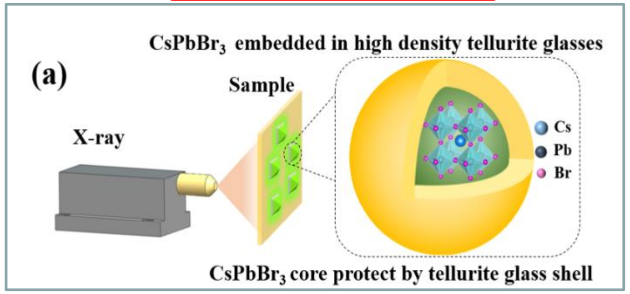
Journal of Alloys and Compounds 782 (2019) 859-864

Nanocrystals



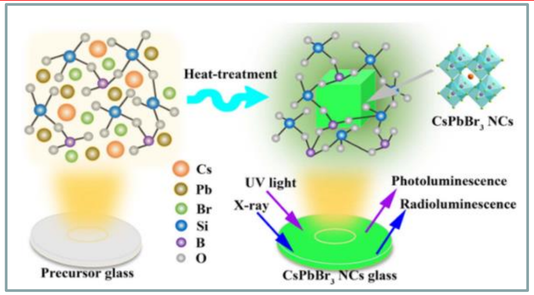
IEEE TNS 60 (2) 2013

Quantum Dots



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

Lanthanide + Quantum Dots



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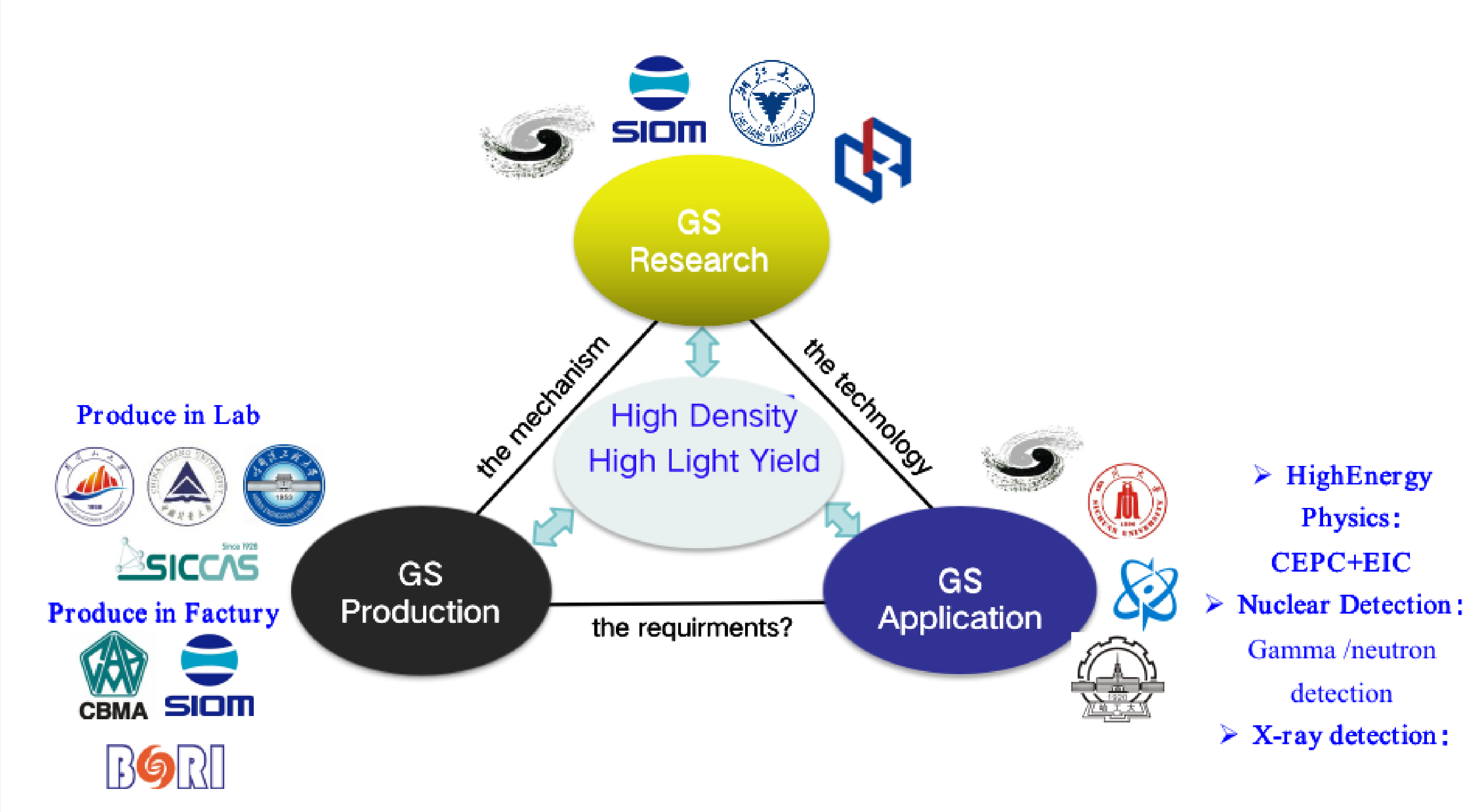
- **High Light Yield: Lanthanide for the Luminescence Center: Cerium (Ce);**
- **High Density and Low radioactivity background： Gadolinium (Gd);**

2.4 Large Area Glass Scintillator Collaboration



Glass Scintillator Collaboration
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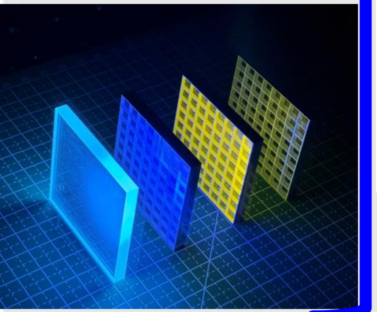
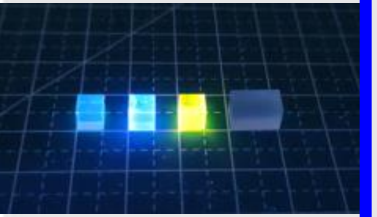
Glass Scintillator Collaboration

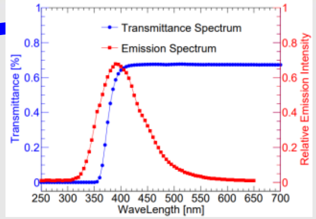
Spokesperson：Sen QIAN

- 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.

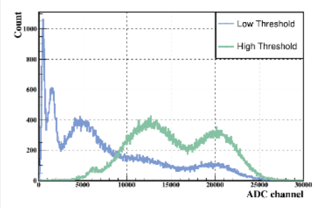
2.5 The Scintillator Test Facilities for GS



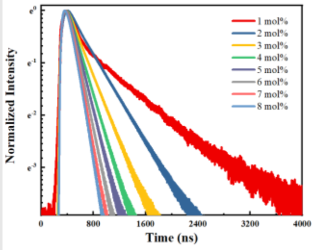




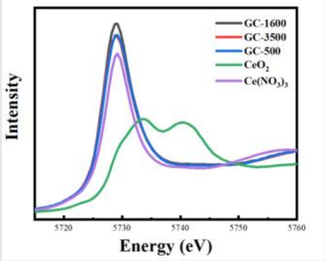
- Transmittance
- Absorbance
- Refractive index
- Emission peak



- Light yield
- Energy resolution
- MIP response
- Neutron discrimination



- Rise time
- Fall time
- Decay time
- Afterglow
- Coincidence time



- Valence state
- Coordination
- Elemental analysis
- Structural analysis

Others

......

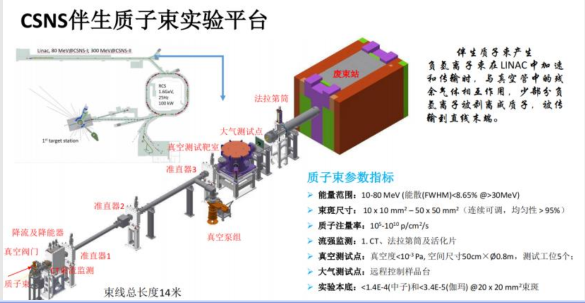
- Faraday effect
- Radiation resistance
- Homogeneity

- IHEP--PMT Lab for Scintillator Test

- IHEP--Radioactive Test

- IHEP--XAFS

- IHEP-CSN-- P Beam

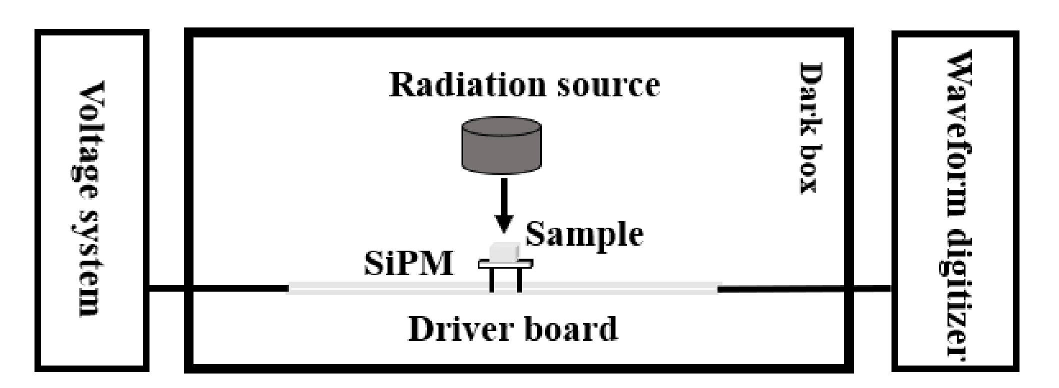


- CERN-MUON Beam

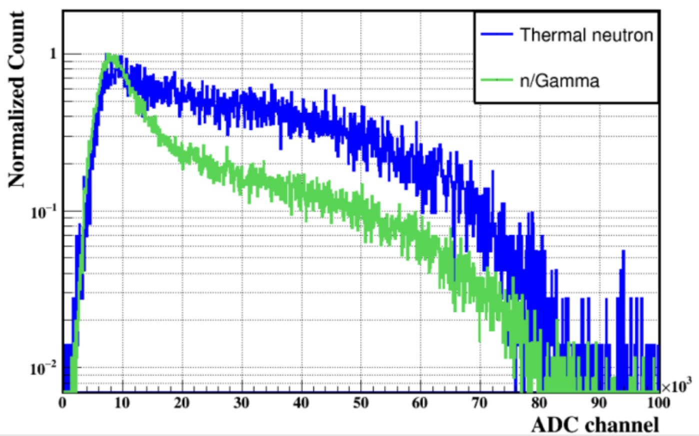
Radioactive Sources Test -- Energy Spectrum --Light Yield

- In IHEP Radioactive Sources Station；
- gamma： 137Cs，60Co，133Ba,
- neutron： 252Cf， Am-Be
- electron：90Sr-90Y， 22Na

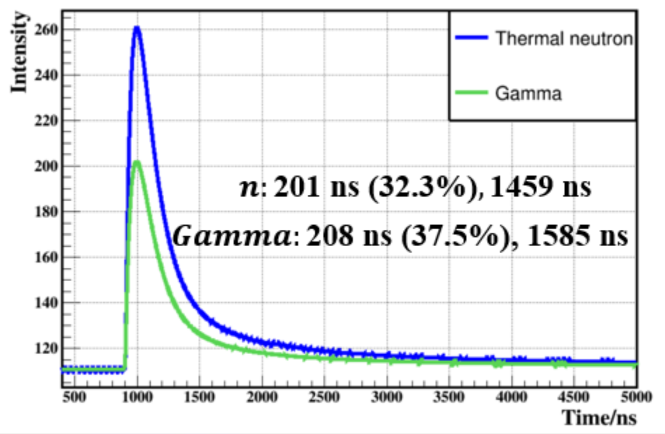
Through the waveform sampling data acquisition system, we can obtain **Light Yield, Energy Resolution and Decay Time** of the scintillator.



➢ γ/n Energy Spectra



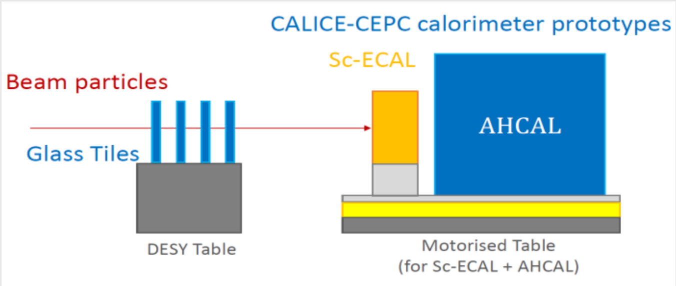
➢ γ/n Decay Time

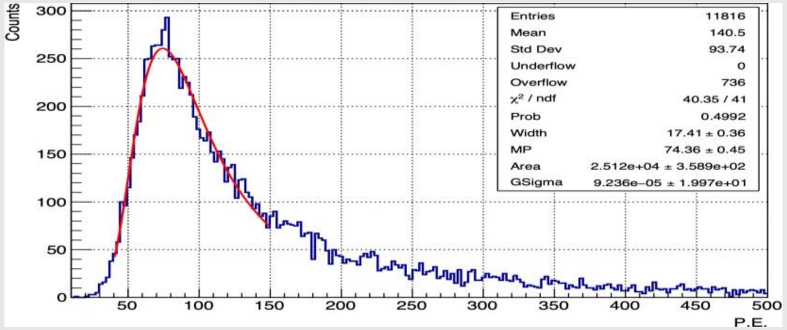


Special Condition TEST Platform

CERN Muon-beam (10 GeV muon)

11 glass tiles tested at CERN (2023/5)

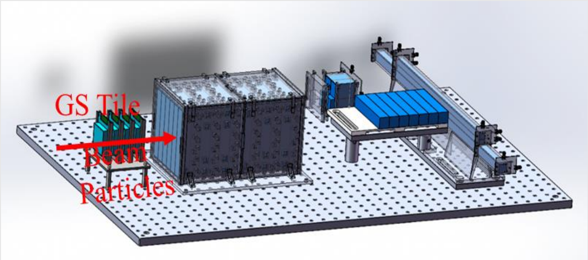


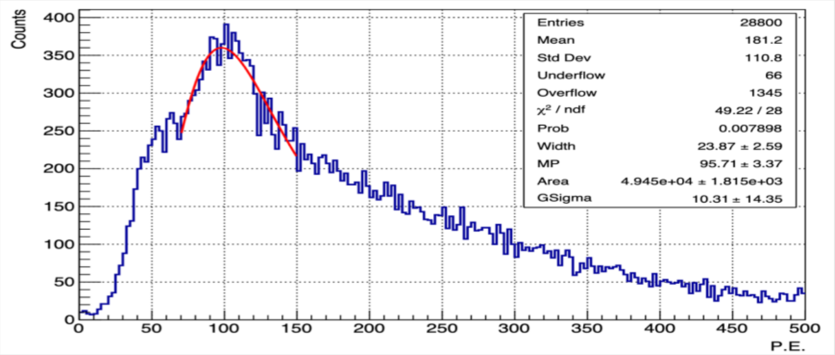


- Typical light yield: 500 – 600 ph/MeV
- Typical MIP response: 60 – 100 p.e./MIP

DESY Electron-beam (5 GeV electron)

9 glass tiles tested at DESY (2023/10)

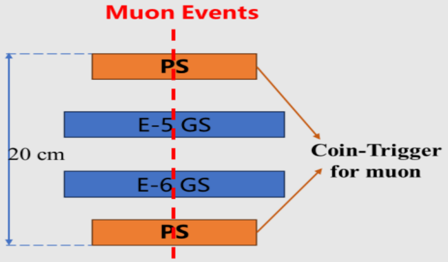


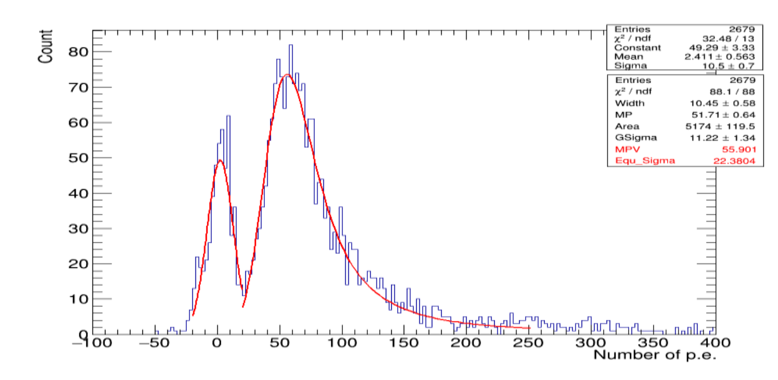


- Typical light yield: 600 – 700 ph/MeV
- Typical MIP response: 80 – 90 p.e./MIP

IHEP Cosmic-Muon- (3GeV muon)

4 glass tiles tested at IHEP (2024/4)





- Typical light yield: 600 – 700 ph/MeV
- Typical MIP response: 50 – 60 p.e./MIP

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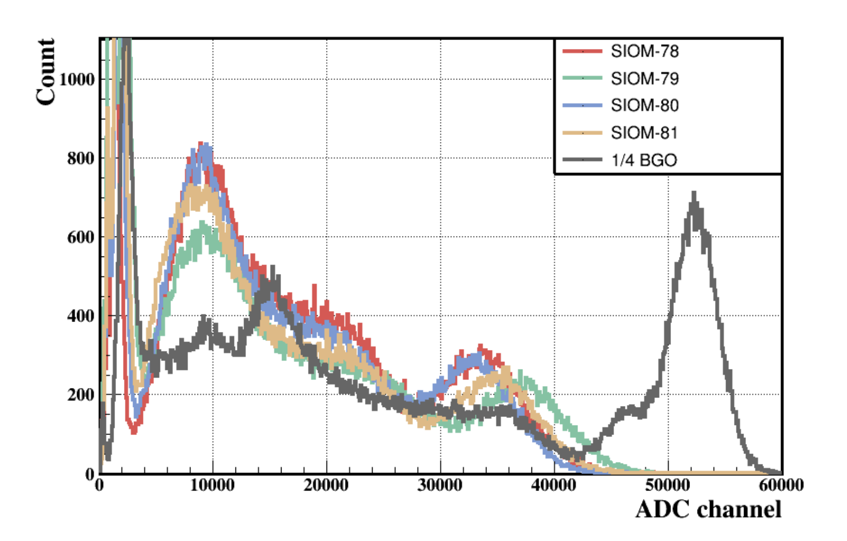
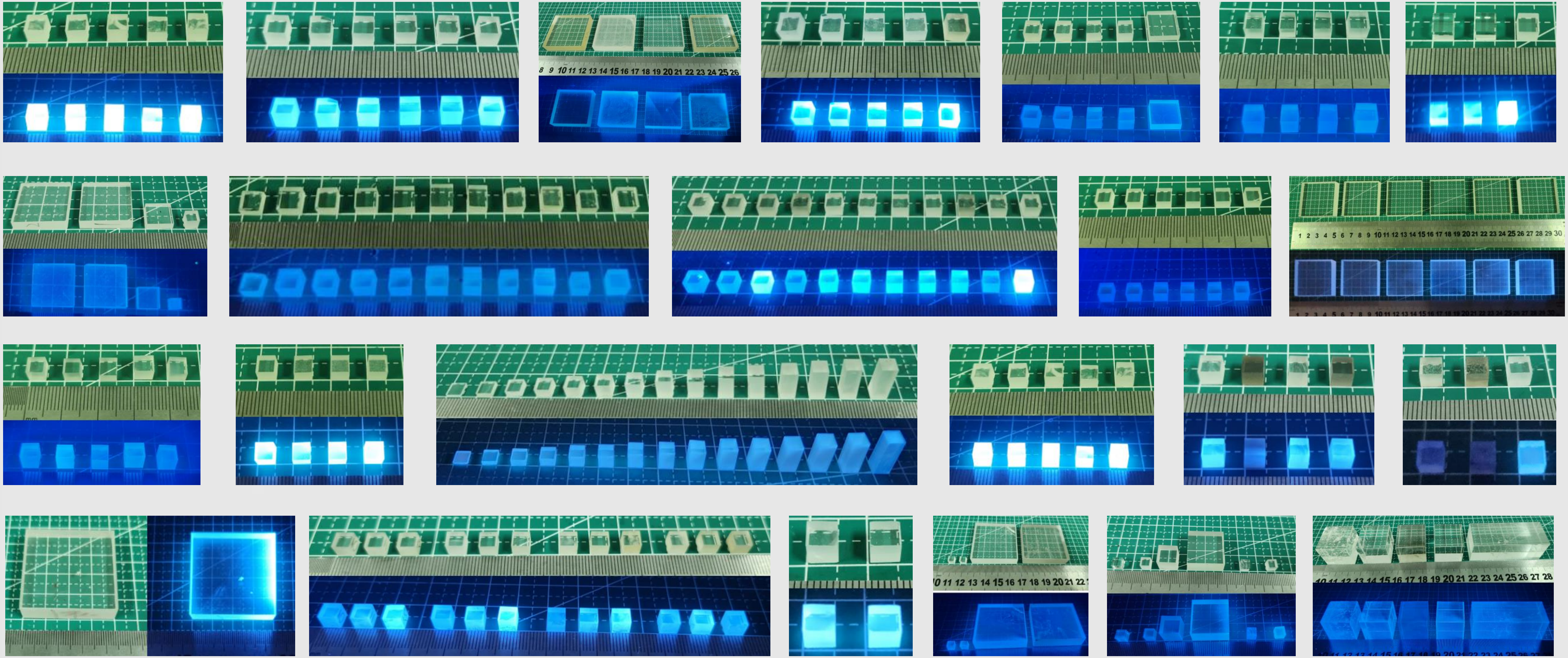


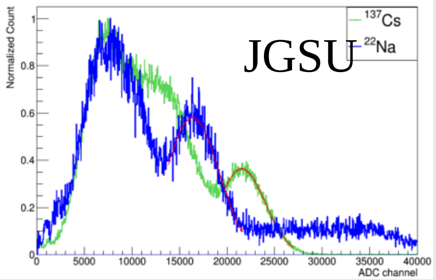
3.0 The GS Samples produced （>1000)

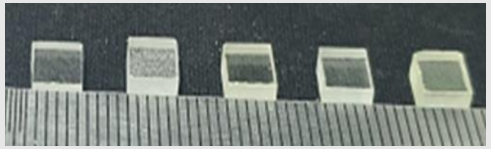


3.1 Borosilicate Glass（Gd-Al-B-Si-Ce^{3+}）--GS1

2021.11

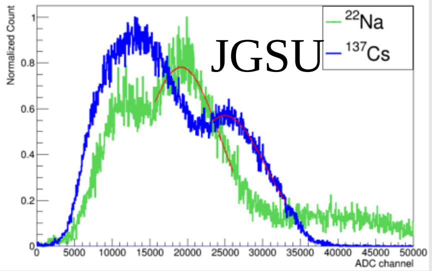
- Density~4.5 g/cm^3
- LY=802 ph/MeV
- ER=26.8%
- Decay=262 (18%)
  1235 ns

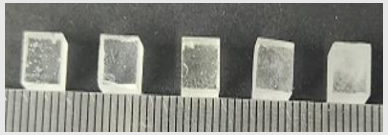




2022.11

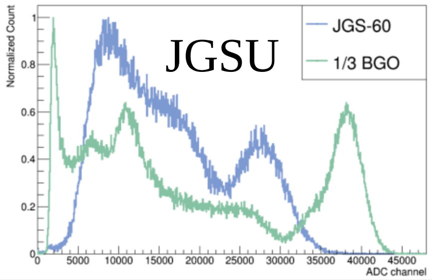
- Density~6.0 g/cm^3
- LY>1000 ph/MeV
- ER=49.6%
- Decay=847 ns

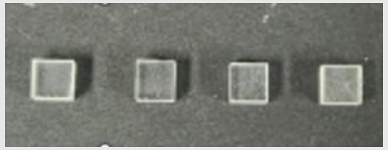




2023.02

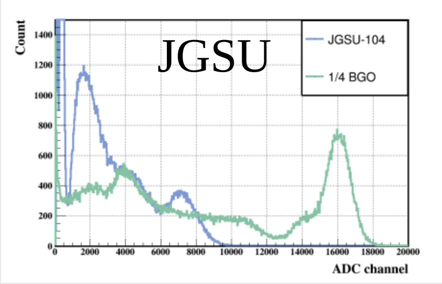
- Density~6.0 g/cm^3
- LY~1100 ph/MeV
- ER=24.4%
- LO in 1μs=899 (84%)
- Decay=92 (8%)
  473 ns

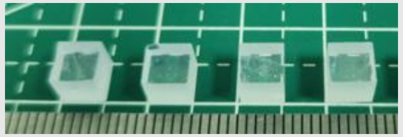




2024.04

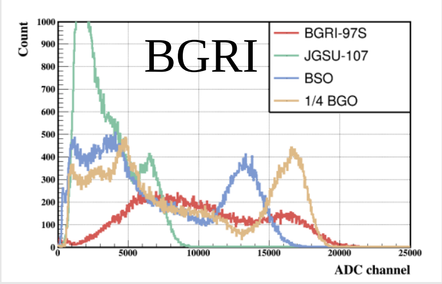
- **Density~6.0 g/cm^3**
- **LY=985 ph/MeV**
- **ER=30.3%**
- **LO in 1μs=982 (99%)**
- **Decay=36 (8%)
  105 ns**

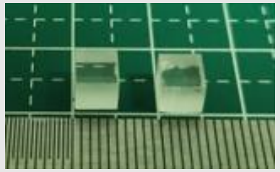




2024.06

- **Density~6.0 g/cm^3**
- **LY=2455 ph/MeV**
- **ER=25.8%**
- **LO in 1μs=1074 (44%)**
- **Decay=101 (2%)
  1456 ns**

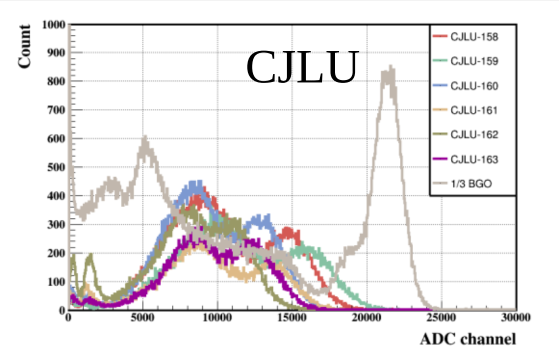




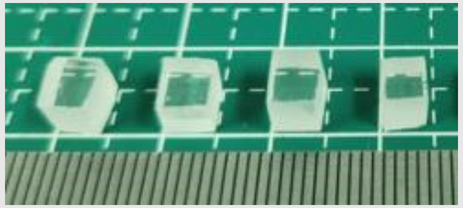
- There are 5 types of GS for the study, and focous on the GS1, **Borosilicate Glass** for better performance;
- Now, the **Density~6.0 g/cm^3，LY>2400 ph/MeV, ER=25.8%, could be accept to be the candidate for GS-HCAL;**

GS1—LY＞2000 ph/MeV

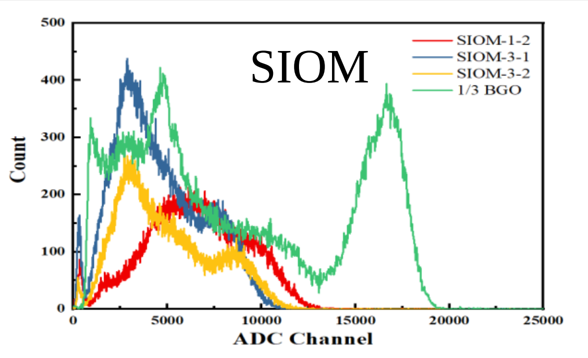
- Density~5.6 g/cm^3
- LY=2202 ph/MeV
- ER=27.7%
- Decay=129 (6%), 2466 ns



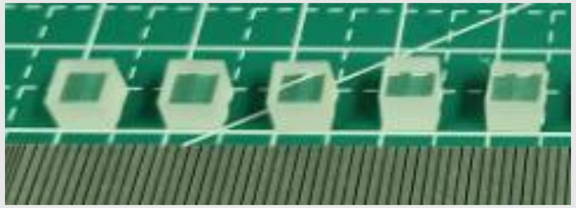
2024.04



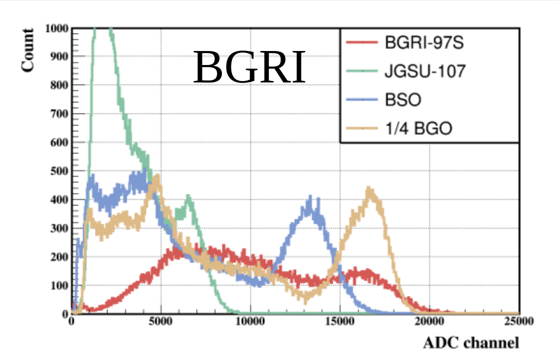
- Density~6.0 g/cm^3
- LY=2005 ph/MeV
- ER=37.6%
- Decay=111 (5%), 1063 ns



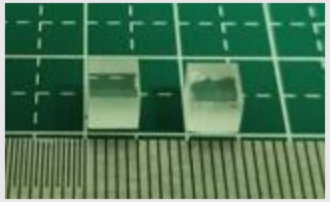
2024.06



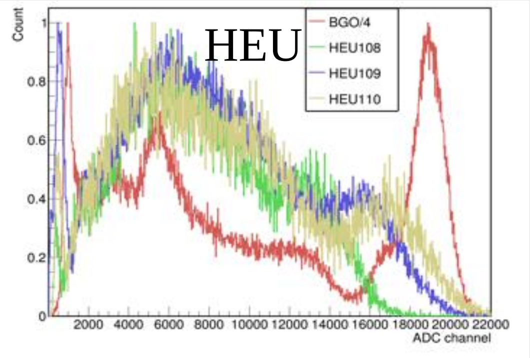
- **Density~6.0 g/cm^3**
- **LY=2455 ph/MeV**
- **ER=25.8%**
- **Decay=101 (2%), 1456 ns**



2024.06



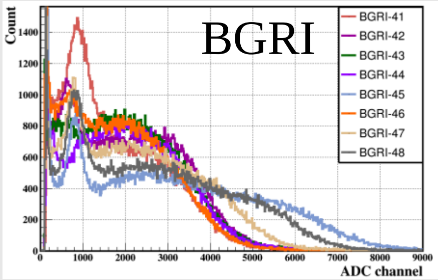
- Density~5.1 g/cm^3
- LY=2066 ph/MeV
- ER=30.2%
- Decay=125 (4%), 1782 ns



2024.08

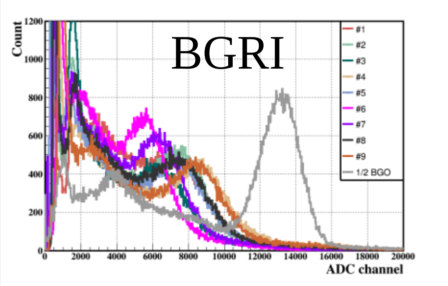
3.2 Large size glass (Gd-Al-B-Si-Ce^{3+}) --GS1

- Size=30*30*9 mm^3
- Density=5.1 g/cm^3
- LY=767 ph/MeV
- ER=None



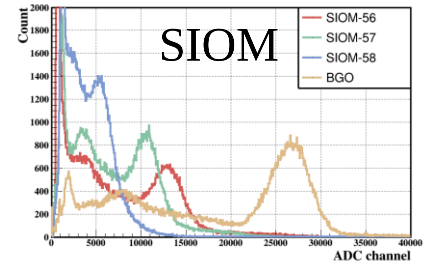
2023.04

- Size=40*40*10 mm^3
- Density=6.0 g/cm^3
- LY=788 ph/MeV
- ER=48.4%
- Decay=87 (2%), 1024 ns

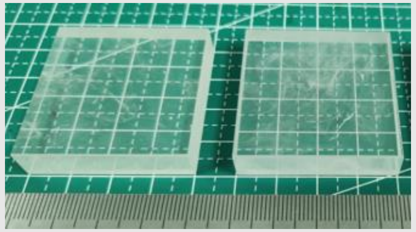


2023.10

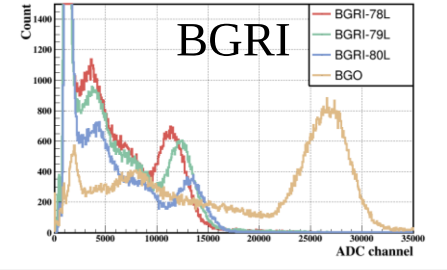
- **Size=40*40*10 mm^3**
- **Density=6.0 g/cm^3**
- **LY=1198 ph/MeV**
- **ER=33.0%**
- **LO in 1μs=607 (51%)**
- **Decay=117 (3%), 1368 ns**



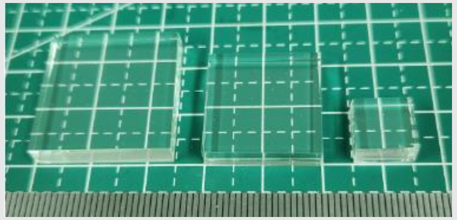
2023.11



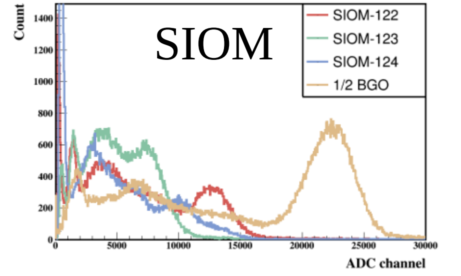
- **Size=10*10*5 mm^3**
- **Density=6.0 g/cm^3**
- **LY=1235 ph/MeV**
- **ER=24.0%**
- **LO in 1μs=897 (73%)**
- **Decay=89 (6%), 588 ns**



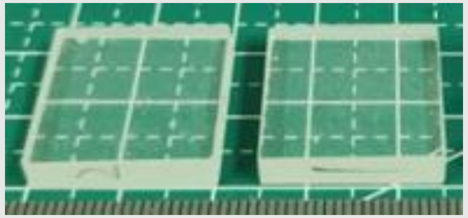
2023.12



- Size=20*20*10 mm^3
- Density=6.0 g/cm^3
- LY=961 ph/MeV
- ER=30.0%
- LO in 1μs=749 (78%)
- Decay=103 (9%), 621 ns



2024.05



The Bottleneck:

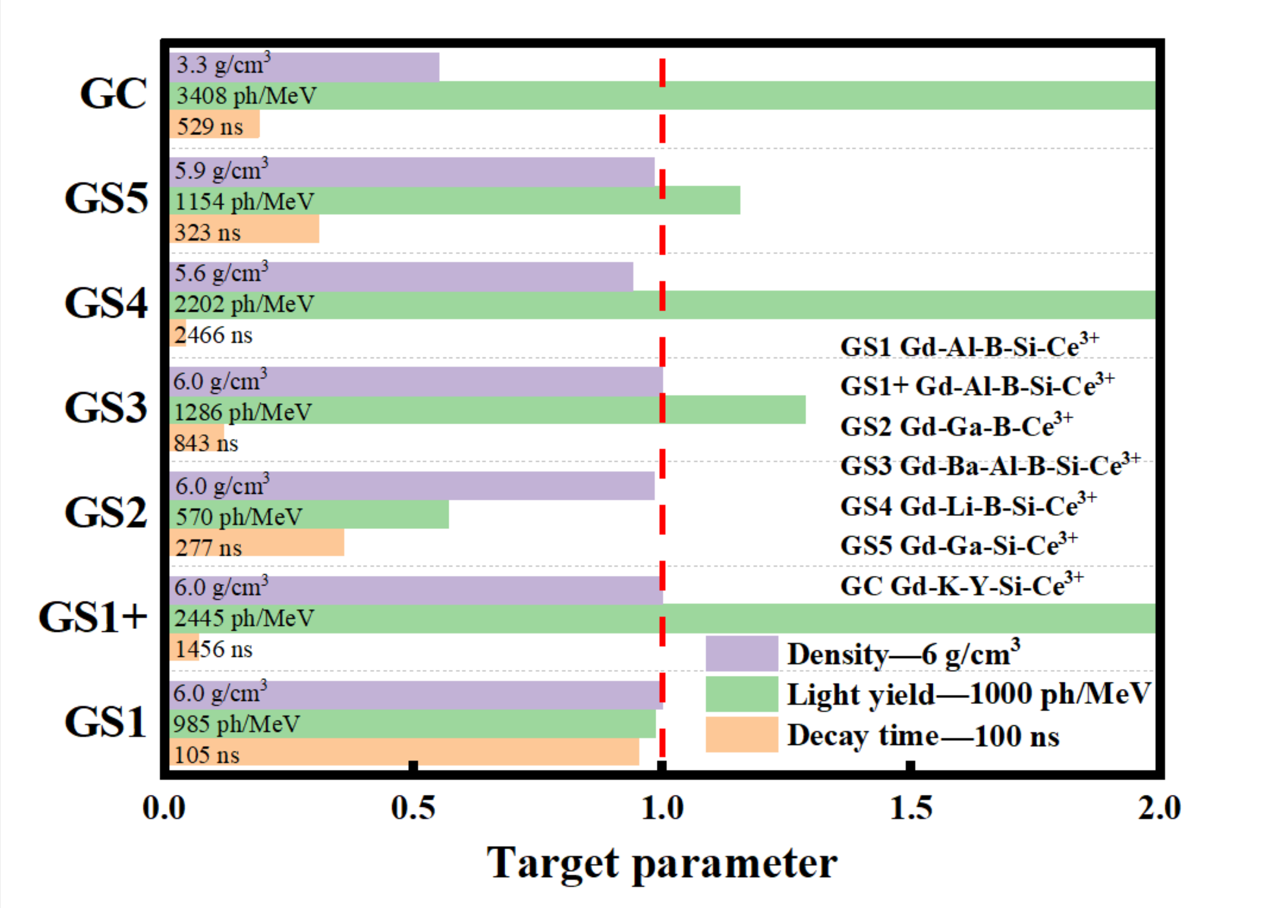
1. How to ensure the performance stability of large size glass sample?
2. How to improve the light collection efficiency when coupling large size glass and SiPM?

Outline

- 1. The GS-HCAL of CEPC;
- 2. The Motivation and Design of GS ;
- 3. The progress of the R&D of GS;
- **4. Summary and Next Plan;**

闪烁玻璃合作组
Glass Scintillator Collaboration

4.1 Summary of GS



Glass scintillator of high density and light yield

◆ **GS1: Gd-Al-B-Si-Ce^{3+} glasses: (Borosilicate Glass)**

6.0 g/cm³ & 985 ph/MeV with 30.3%@662keV & 105 ns

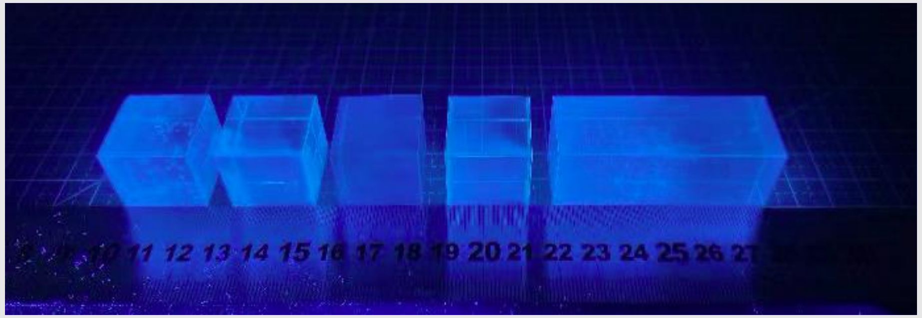
◆ **GS5: Gd-Ga-Si-Ce^{3+} glasses: (Silicate glass)**

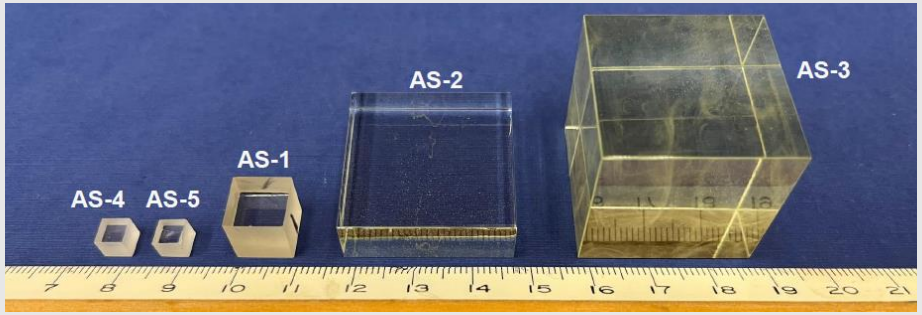
5.9 g/cm³ & 1154 ph/MeV with 25.4%@662keV & 323 ns

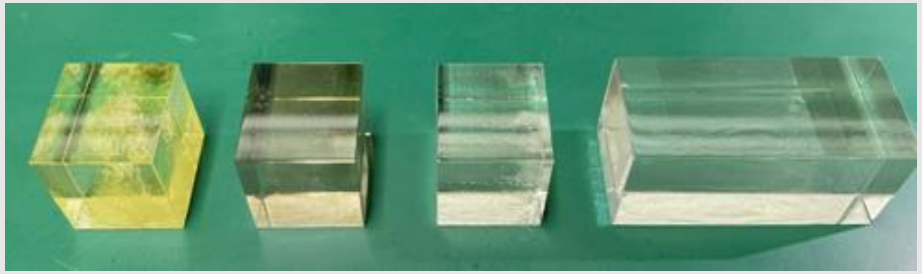
- Ultra-high density **Tellurite Glass**—6.6 g/cm³
- High light yield **Glass Ceramic**—3500 ph/MeV
- Fast Decay Time **Pr^{3+}-doped Glass**—100 ns
- Large size Glass—51mm*51mm*10mm

4.2 Summary of GS R&D

Parameters	Unit	BGO	GS1	GS1+	GS5
Cost		1	0.1 ?		
Density	g/cm^3	7.13	6.0	6.0	5.9
Hygroscopicity	--	No	No	No	No
Radiation Length, X_0	cm	1.12	1.59	1.60	1.61
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 data of the GS1 and GS5 come from the small size of 5mm*5mm*5mm, we need to produce the large size smaple of 40mm*40mm*10mm for the CEPC-GSHCAL module.

4.3 Next Plan for GS-HCAL

Gd-R-B-Si-Ce^{3+} (R=Al, Ga) oxyfluoride is still the focus of future research

- Stable preparation of large size glass scintillator with light yield of 1000 ph/MeV
- Try to prepare large size glass scintillator with light yield of more than 2000 ph/MeV
- Design different glass system for different requirements
- Control the cost of glass scintillator

See the unseen
change the unchanged

The Innovation

THANKS