Glass Scintillator HCAL at future e+e− Higgs factory

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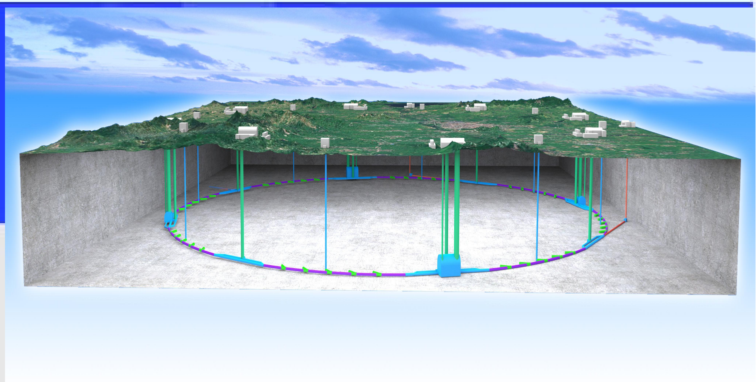
CTICC CAPE TOWN SOUTH AFRICA

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

1.1. The GS-HCAL of CEPC

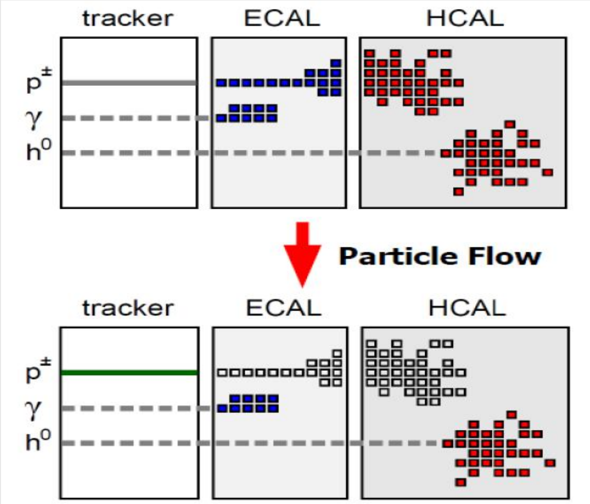


Future electron-position colliders (e.g. CEPC)

- Main physical goals: precision measurements of the Higgs and Z/W bosons
- Challenge: unprecedented jet energy resolution $\sim 30\%/\sqrt{E(GeV)}$

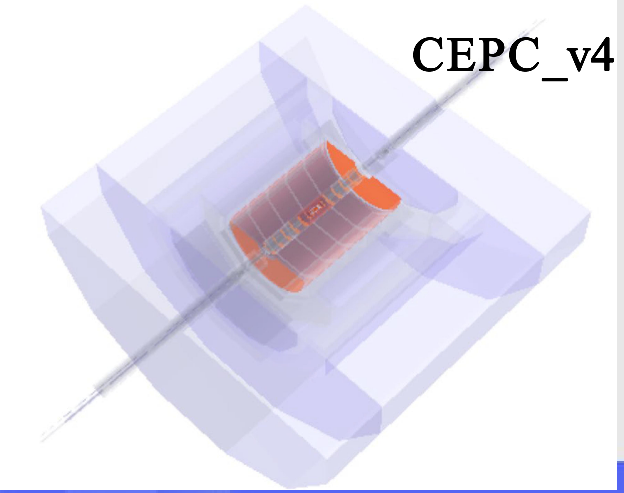
CEPC detector: highly granular calorimeter + tracker

- Boson Mass Resolution (BMR) ~4% has been realized in this baseline design
- Further performance goal: BMR 4%→3%
- Dominant factors in BMR: charged hadron fragments & HCAL resolution

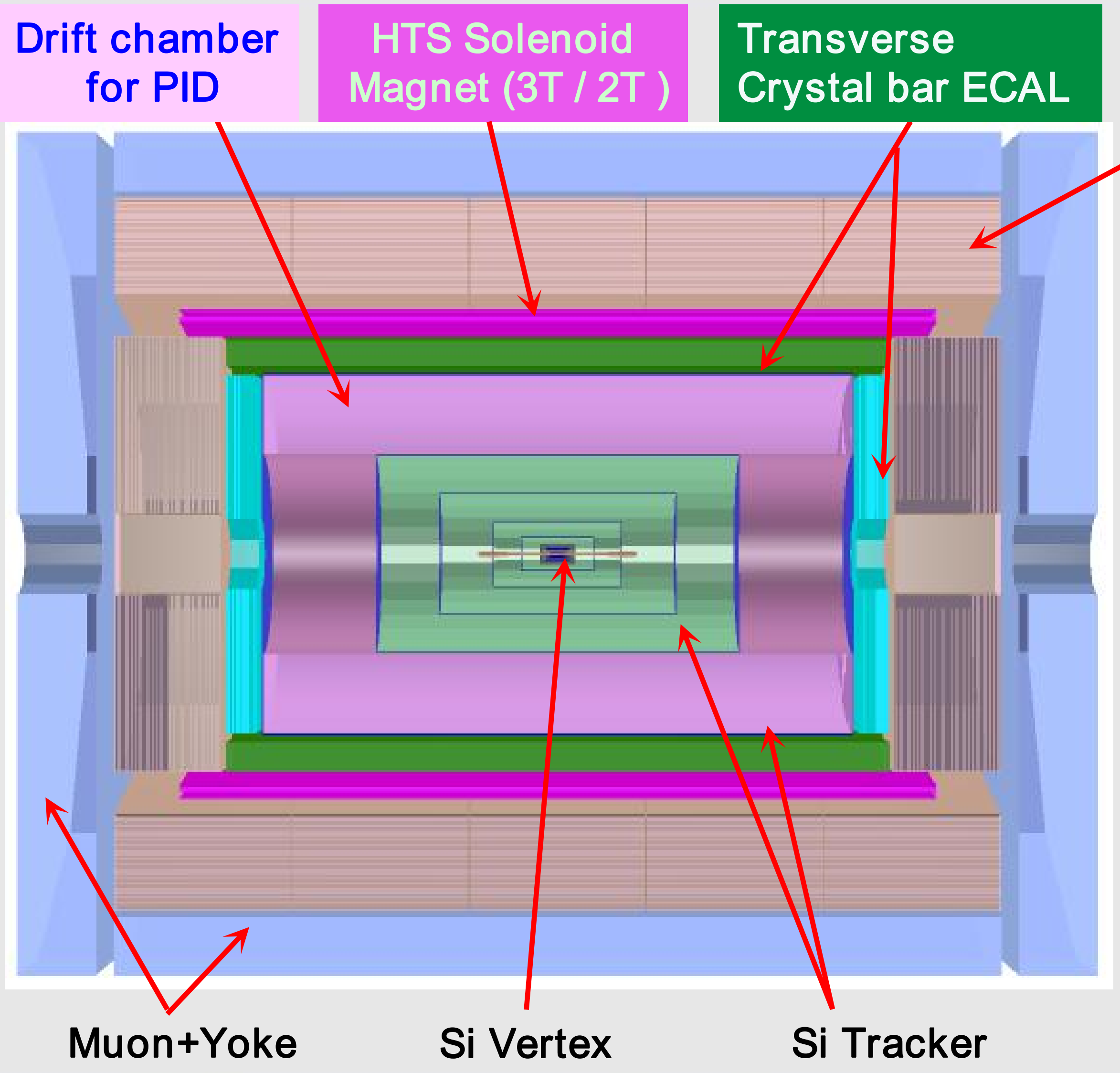


New Option: Glass Scintillator HCAL (GS-HCAL)

- Higher density provides higher energy sampling fraction
- Doping with neutron-sensitive elements: improve hadronic response (Gd)
- More compact HCAL layout (given 4~5 nuclear interaction lengths in depth)



The 4th Conceptual Detector Design



Scint Glass PFA HCAL

Advantage: Cost efficient, high density

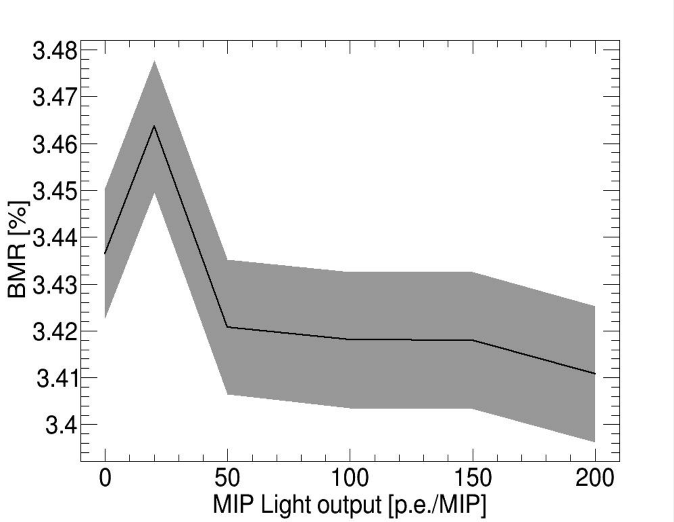
Challenges: Light yield, transparency, massive production.

- 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)

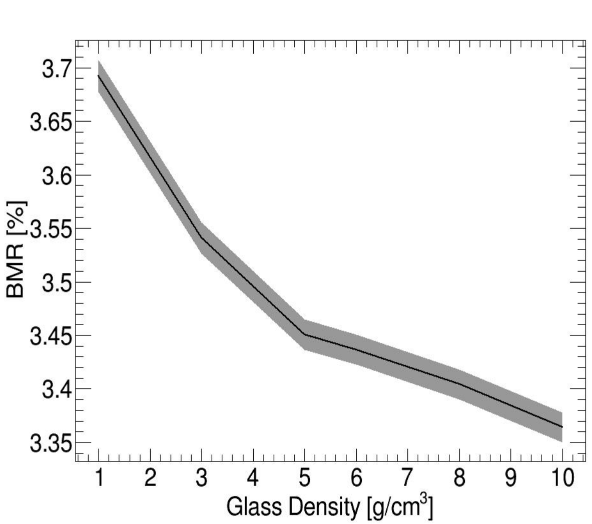
1.2 The Simulation for GS-HCAL

How to achieve the optimized energy resolution (Boson Mass Resolution, BMR)

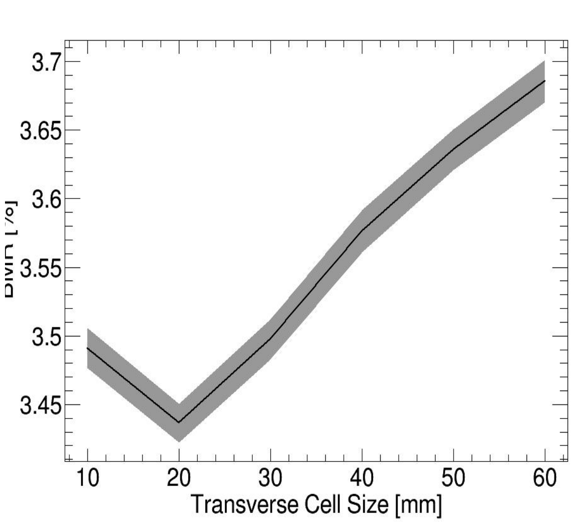
➢ Impact of Light Yield



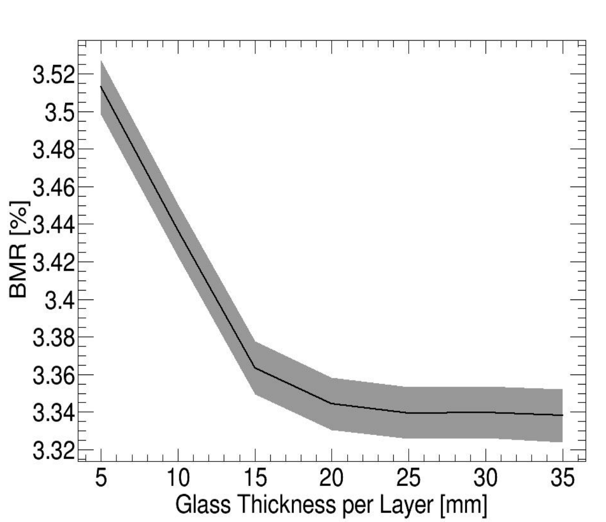
➢ Impact of Density



➢ Impact of Size



➢ Impact of Thickness



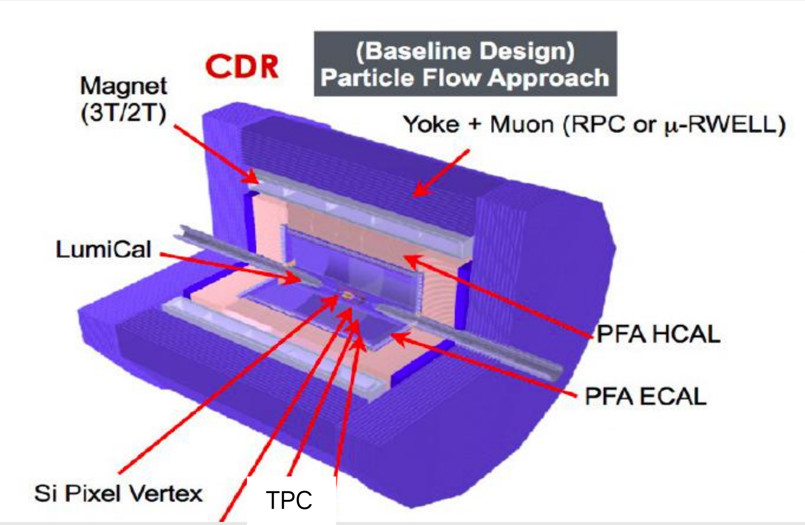
Light Yield： A light yield of 100 p.e./MIP or 1000p.e./MeV seems to be good enough for better BMR;

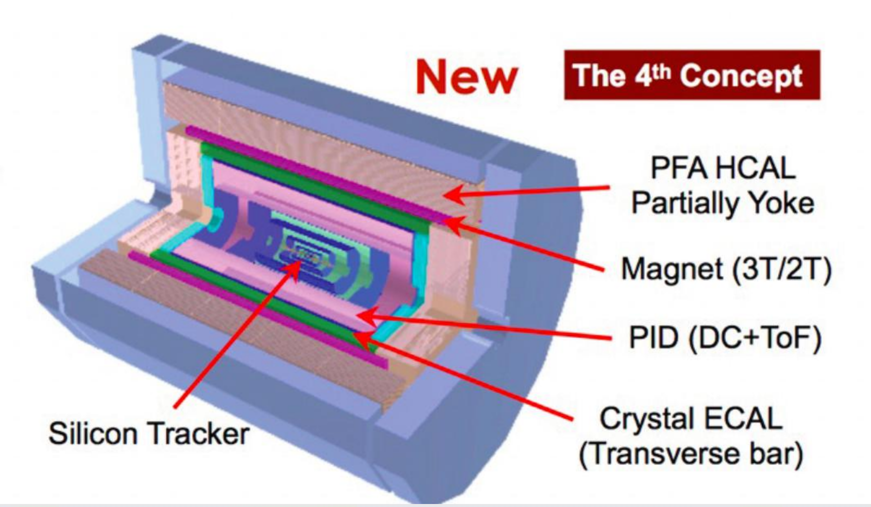
Density： The optimized BRM is almost same (~3% variation) for glass density from 5-6 g/cm^3,

Size： The size of the glass cell is a very important factor for the granularity and total number of readout channels of the GSHCAL；

Thinkness： A thicker glass cell is conducive to a higher sampling fraction and a better BMR, but worse position response;

Comparing nominal GSHCAL with AHCAL

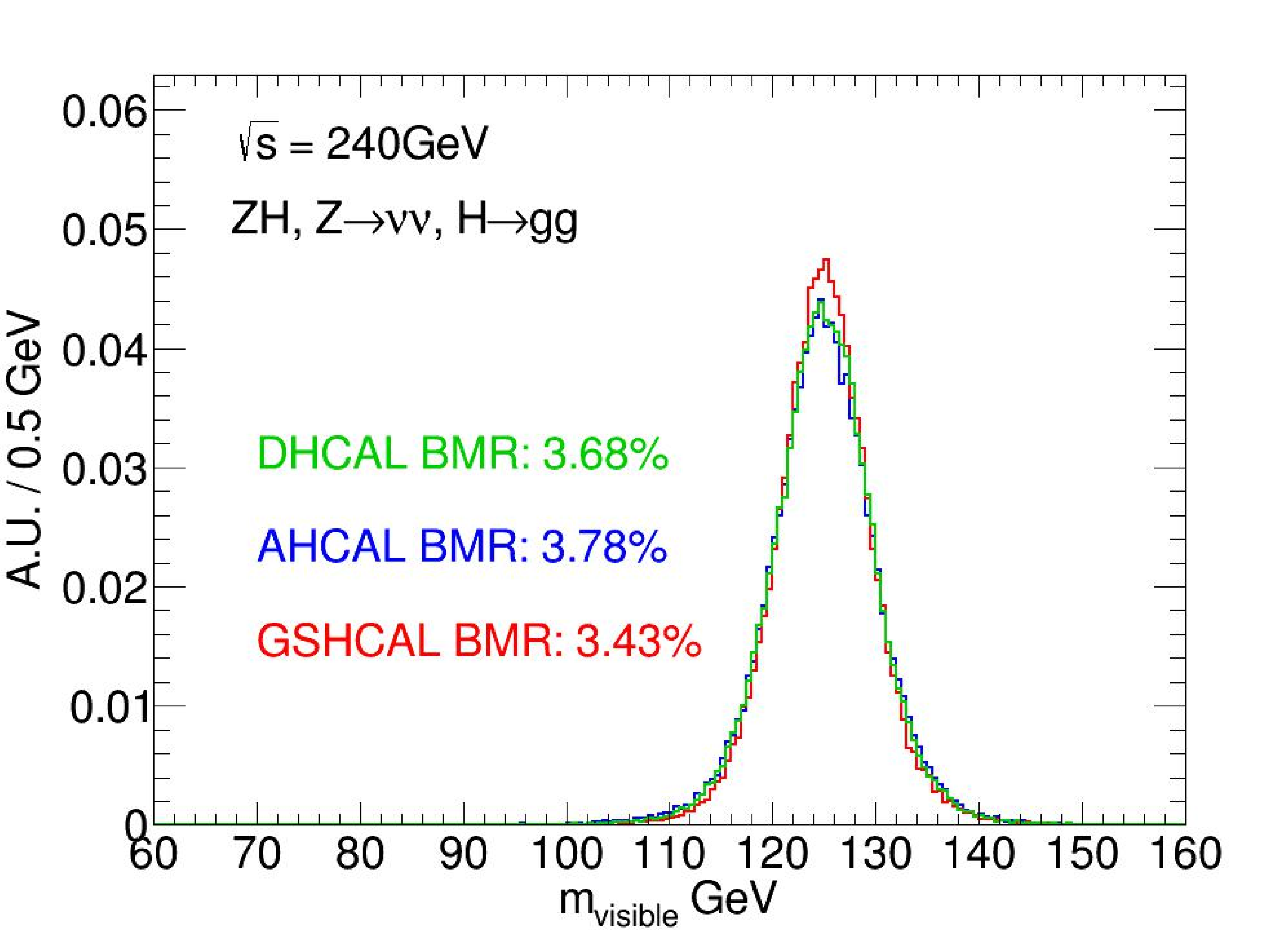




Parameter (nominal)	AHCAL	GSHCAL
Number of layers	40	40
Scintillator	Plastic Scintillator	Glass Scintillator
Layer thickness	0.124 lambda (3 mm PS+20 mm Steel)	0.15 lambda (10mm GS+Steel)
Total Nuclear Interaction Length	~5 lambda	6 lambda
Transverse Cell Size	30x30 mm^2	20x20 mm^2
Sensitive Material Density	~1 g/cm^3	~6 g/cm^3
Sensitive Material Light Yield	~1e4 ph/MeV	~1e3 ph/MeV
Sensitive Material Decay Time	~ 2 ns	~100 ns
Readout Threshold	0.1 MIP	0.1 MIP

Comparing nominal GSHCAL with DHCAL and AHCAL

- Gaussian Fitting Range: Mean +/- 2 RMS;
- In CEPC_v4 baseline HCAL, the BMR of DHCAL ~3.7%, and of AHCAL ~3.8%;
- By replacing the CEPC_v4 baseline HCAL with the GSHCAL , the BMR can reach **~3.4%** in the nominal setup and show ~10% improvement with. the AHCAL baseline design (~3.8%).



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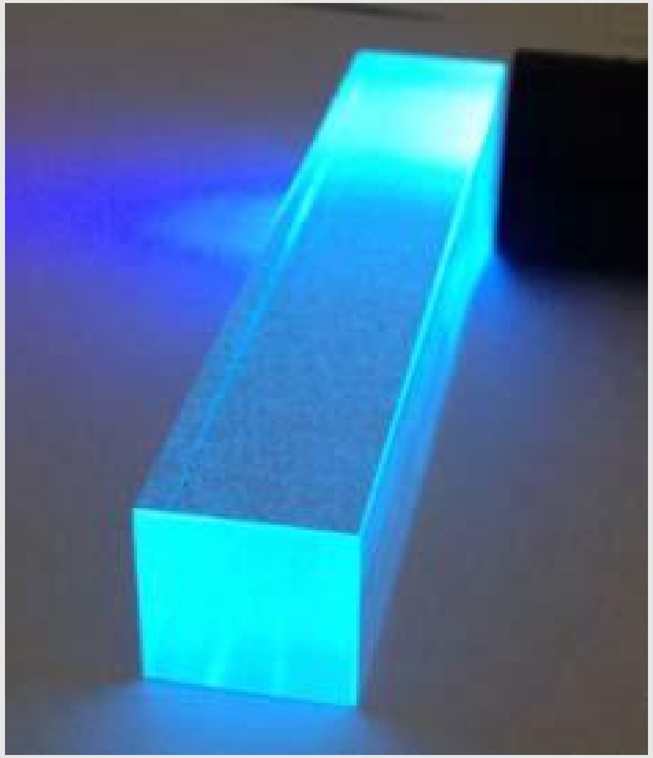
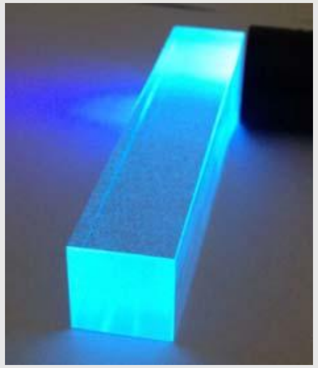


2.0 What is the Glass Scintillator？

Plastic Scintillator



Glass Scintillator

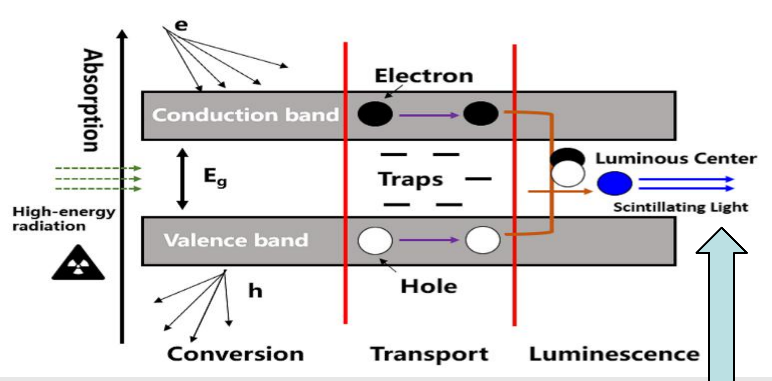
Crystal Scintillator

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

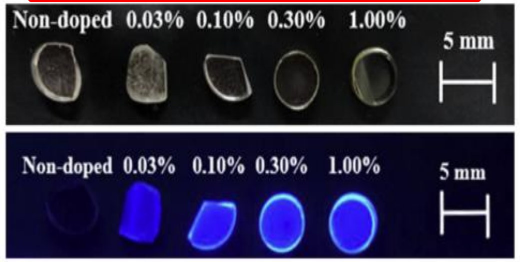
Key parameters	Value	Remarks
➢ Tile size	~30×30 mm^2	Reference CALICE-AHCAL, granularity, number of channels
➢ Tile thickness	~10 mm	Energy resolution, Uniformity and MIP response
➢ **Density**	**5-7 g/cm^3**	More compact HCAL structure with higher density
➢ **Intrinsic light yield**	**1000-2000 ph/MeV**	Higher intrinsic LY can tolerate lower transmittance
➢ Transmittance	~75%	
➢ MIP light yield	~150 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	~100 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 The Design of the Glass Scintillator



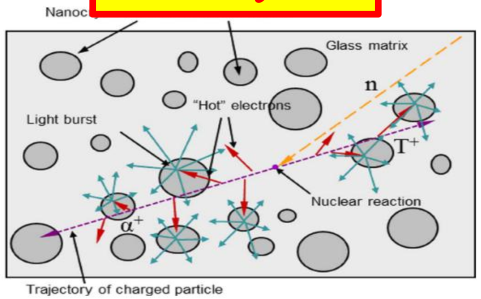
- Scintillation mechanism---- **Luminescence Center**
- **Conversion**—photoelectric effect and Compton scattering effect;
- **Transport**—electrons and holes migrate;
- **Luminescence**—captured by the luminescent center ions

Lanthanide elements



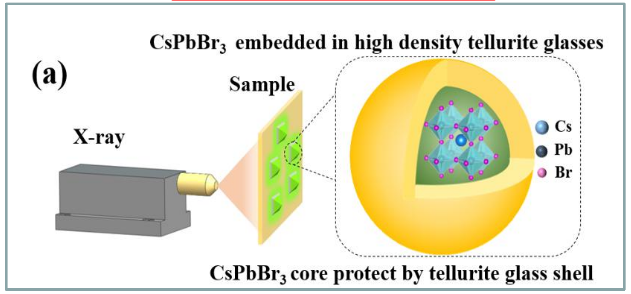
Journal of Alloys and Compounds 782 (2019) 859-864

Nanocrystals



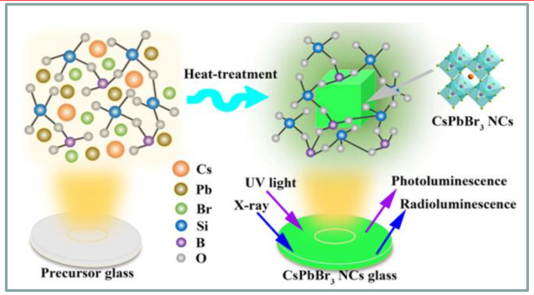
IEEE TNS 60 (2) 2013

Quantum Dots



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

Lanthanide + Quantum Dots



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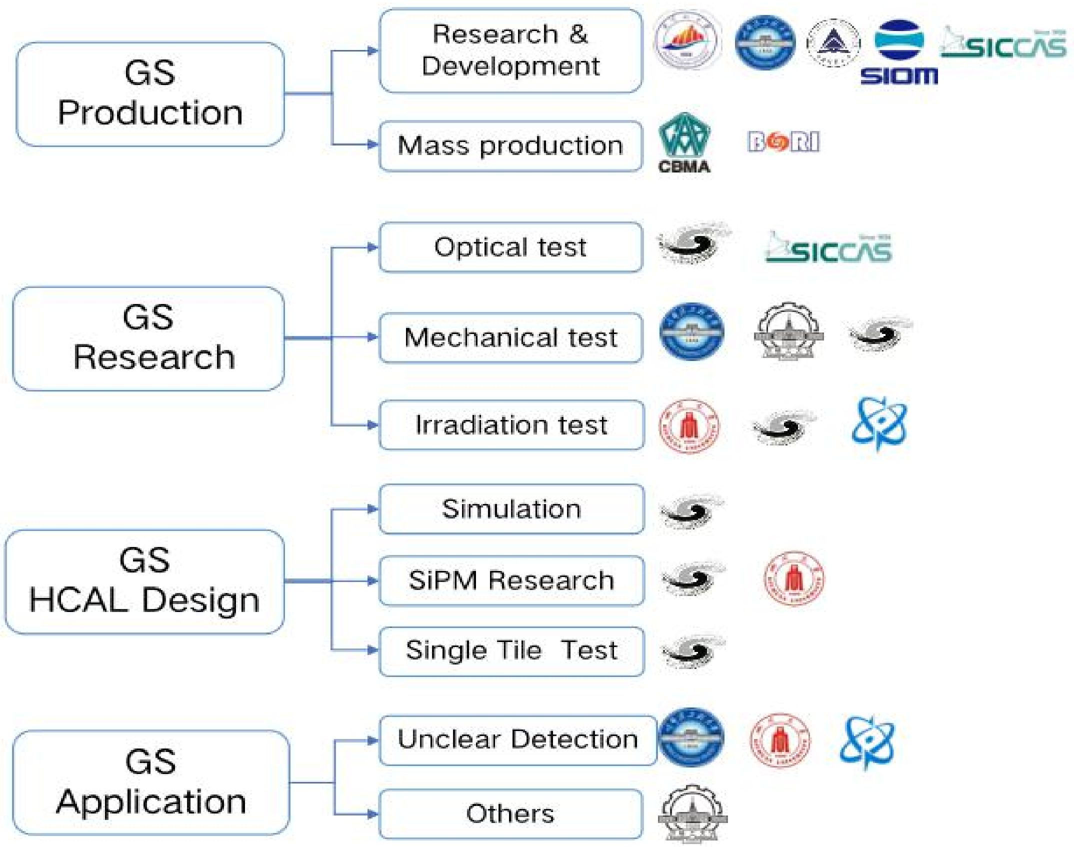
- High Light Yield： Lanthanide for the Luminescence Center：Cerium（Ce）；
- High Density and Low radioactivity background：Gadolinium（Gd）；

2.3 Large Area Glass Scintillator Collaboration



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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

闪烁玻璃合作组
Glass Scintillator Collaboration

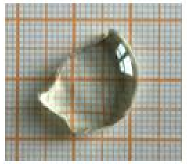
-- The Glass Scintillator Collaboration Group established in Oct.2021, only 5 groups join together;

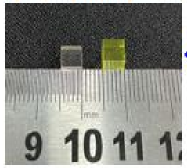
-- There are 3 Institutes of CAS, 5 Universitys, 3 Factorys join us for the R&D of GS;

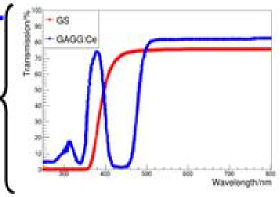
-- The Experts of the GS in the University, Institute and Industry are still welcomed to join us (qians@ihep.ac.cn).

2.4 The Scintillator Test Facilities（1）

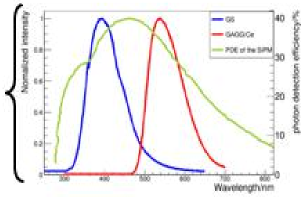
➢ The Scintillator Test System



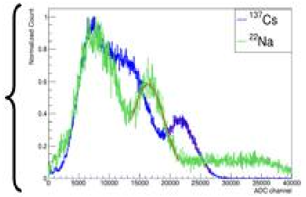




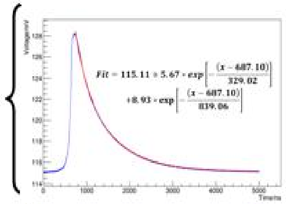
- Density;
- Elastic Modulus;
- Refractive Index;
- Transmission Spectrum



- Absorbance;
- Excitation Spectrum;
- Emission Spectrum;
- PL QY



- Light Yield;
- Energy Resolution;
- Decay time;
- Afterglow



- Coincidence Time Resolution;
- Neutron/Gamma Discrimination;
- Irradiation Damage

Others

……

- XPS
- XRD

- Spectroscopy: Transmission/Absorption、PL-PLE、XEL
- Nuclear radiation detection: Light yield、Energy resolution、MIP response、n/γ Discrimination
- Time characteristics: Rise time、Decay time、Afterglow、Coincidence time resolution
- Reliability: Aging test、Radiation resistance characteristics

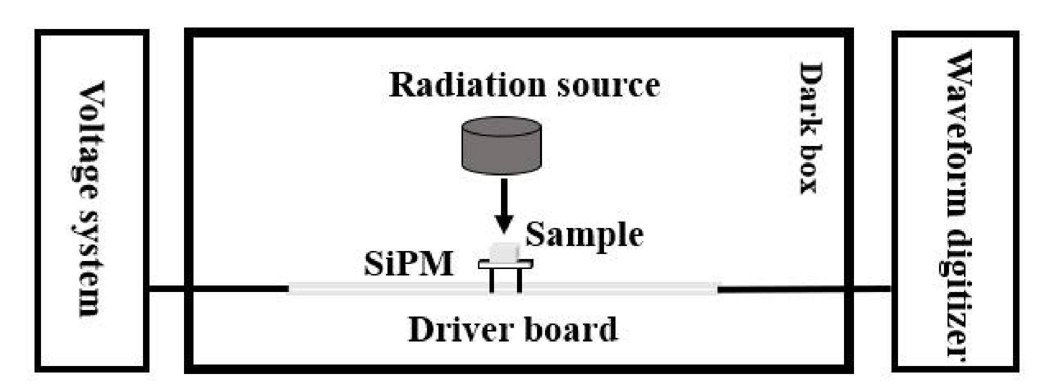
The published papers of different Scintillator sampls tested in Lab

1.Optical Materials; 105 109964; 2020; GAGG
2.Optical Materials; 125 112102; 2022; Sn-doped glass
3.Optical Materials; 130 112585; 2022; Aluminoborosilicate glass
4.Journal of Instrumentation; 17 T08001; 2022; CLLB
5.Journal of Instrumentation; 17 T09010; 2022; LYSO

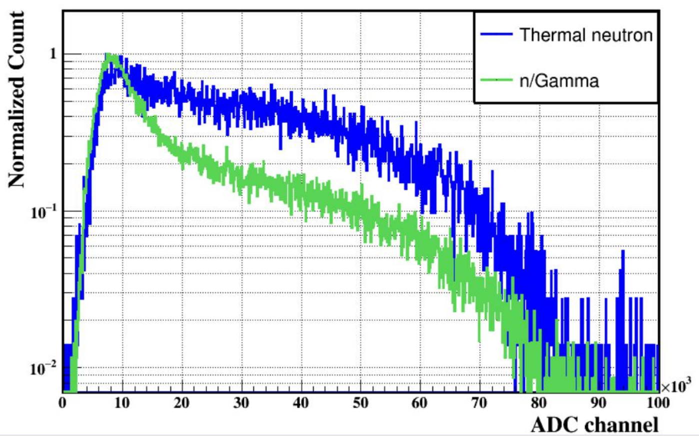
Radioactive Sources Test -- Energy Spectrum --Light Yield

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

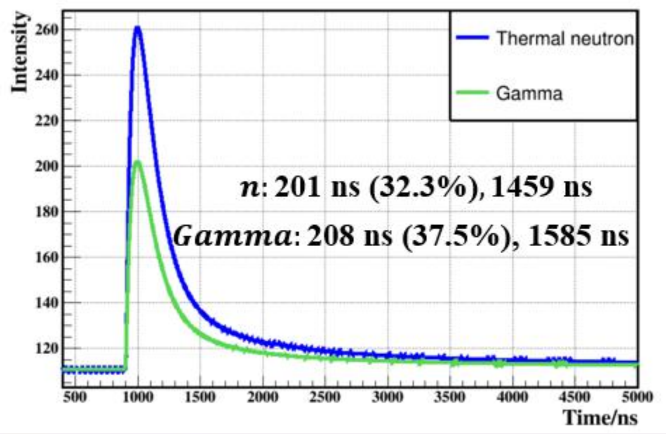
Through the waveform sampling data acquisition system, we can obtain **Light Yield, Energy Resolution and Decay Time** of the scintillator.



➢ γ/n Energy Spectra



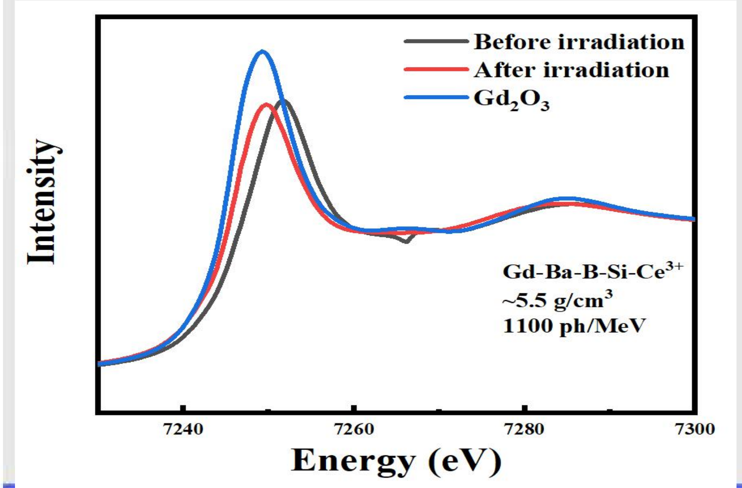
➢ γ/n Decay Time



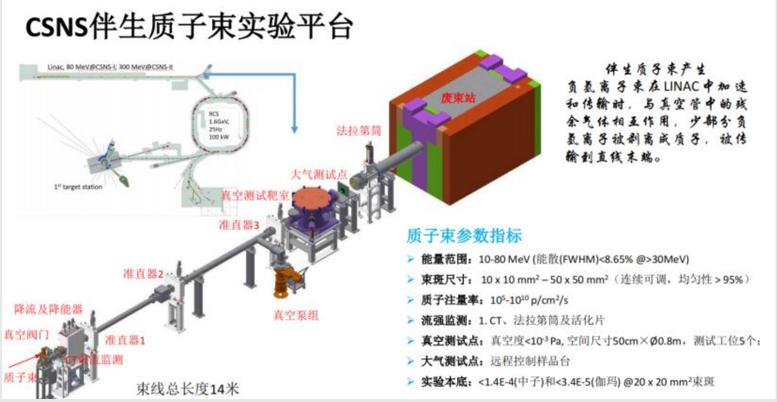
Special Condition TEST Platform

- IHEP--XAFS

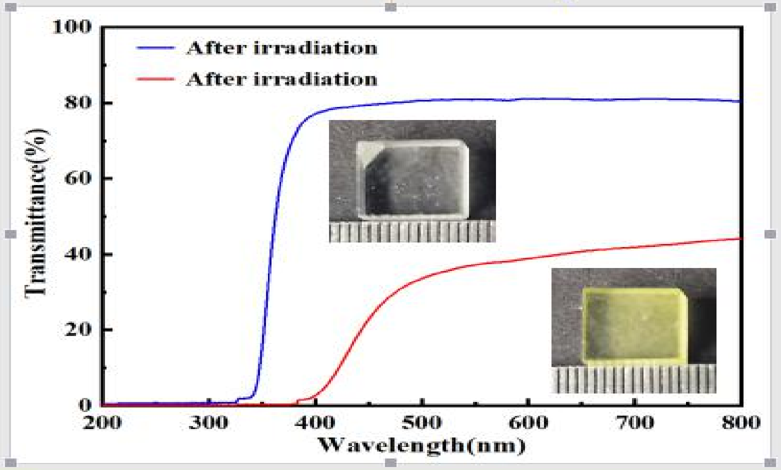
Study the elements influence of GS sample



- IHEP-CSN-- P Beam

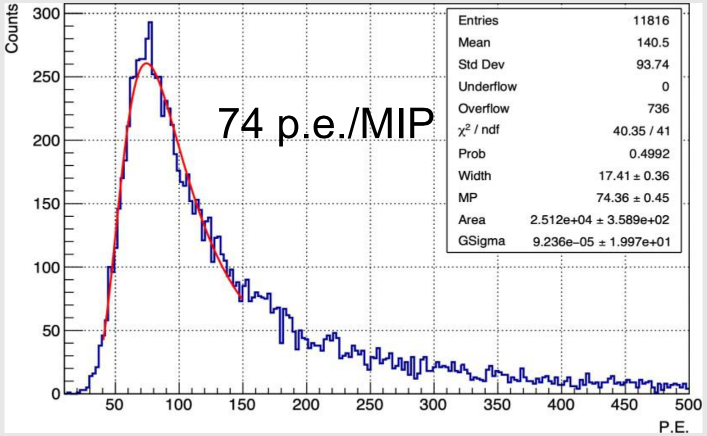


Study the anti-irradiation characteristics of samples;



- CERN-MUON beam

Study the particle interaction in GS sample with MUON



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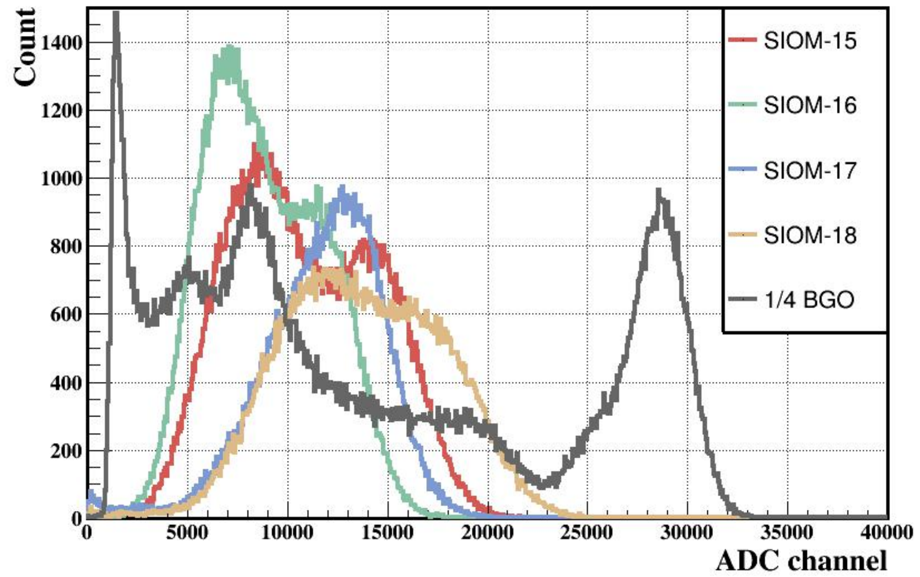
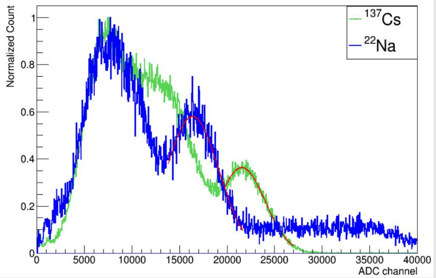


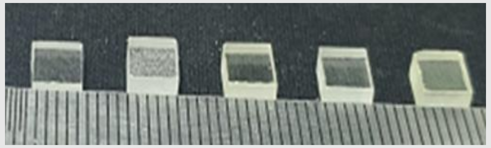
3.0 The GS Samples produced （>400）

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

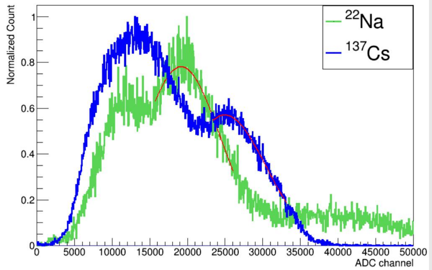
- Density~4.5 g/cm^3
- LY=802 ph/MeV
- ER=26.8%
- Decay=262 (18%)
  1235 ns



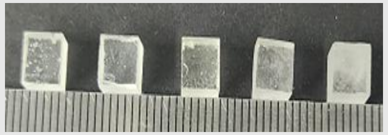
2021.11



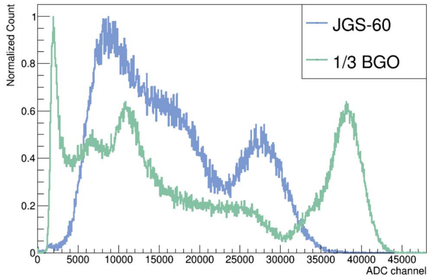
- Density~6.0 g/cm^3
- LY>1000 ph/MeV
- ER=49.6%
- Decay=847 ns



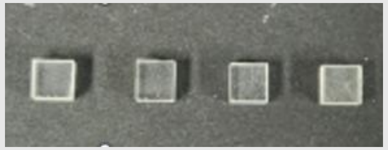
2022.11



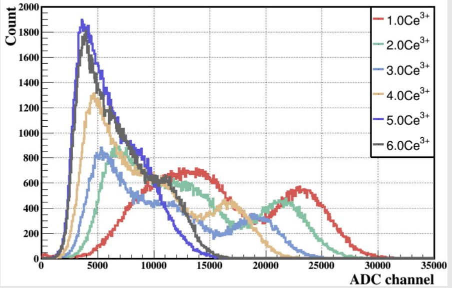
- **Density~6.0 g/cm^3**
- **LY~1100 ph/MeV**
- **ER=24.4%**
- **Decay=460 ns**



2023.02

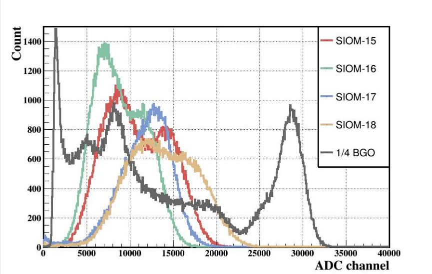


- Density~5.8 g/cm^3
- LY~1000 ph/MeV
- ER=26.8%
- Decay=1091 ns

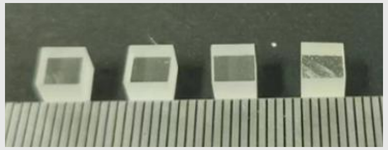


2023.04

- Density~6.0 g/cm^3
- LY~700 ph/MeV
- ER=32.3%
- Decay=382 ns



2023.07

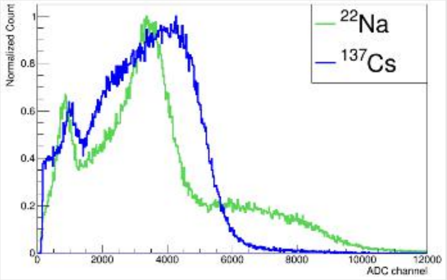


- There are 5 types of SG for the study, and focous on the GS1, the Borosilicate Glass for better performance;
- Finally, the **Density~6.0 g/cm^3，LY>1100 ph/MeV, ER=24.4%, could be accept to be the candidate for GS-HCAL**
- But the Decay time =460 ns, still need to improve.

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

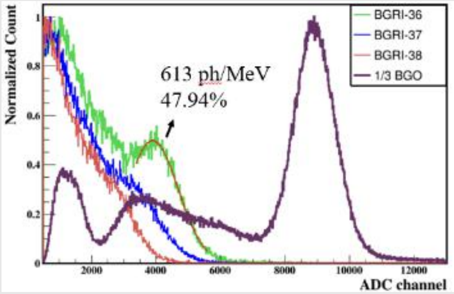
2022.10

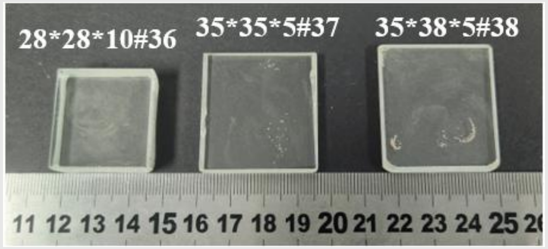
- Size=30*27.5*9 mm^3
- Density=5.1 g/cm^3
- LY=466 ph/MeV
- ER=None



2023.01

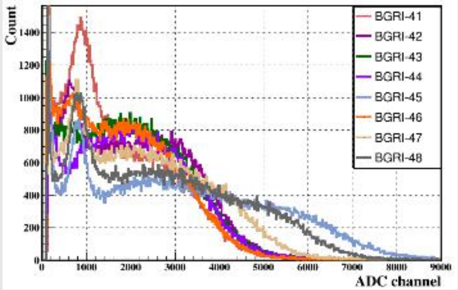
- Size=28*28*10 mm^3
- Density=5.2 g/cm^3
- LY=613 ph/MeV
- ER=47.9%

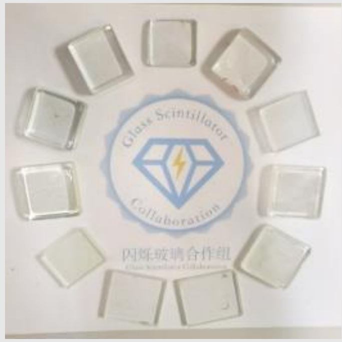




2023.04

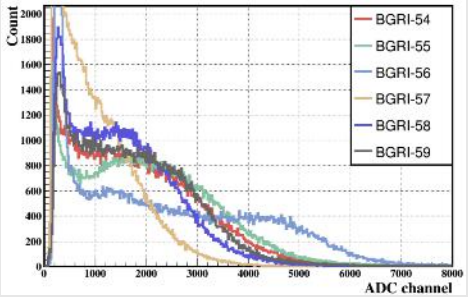
- Size=30*30*9 mm^3
- Density=5.1 g/cm^3
- LY=767 ph/MeV
- ER=None

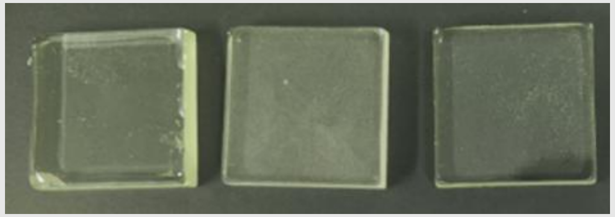




2023.05

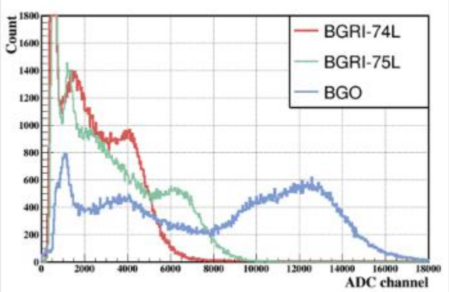
- Size=50*50*10 mm^3
- Density=5.8 g/cm^3
- LY=172 ph/MeV
- ER=None

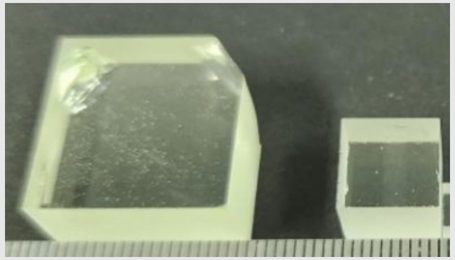




2023.08

- Size=20*20*10 mm^3
- Density=5.8 g/cm^3
- LY=506 ph/MeV
- ER=50%





The Bottleneck：

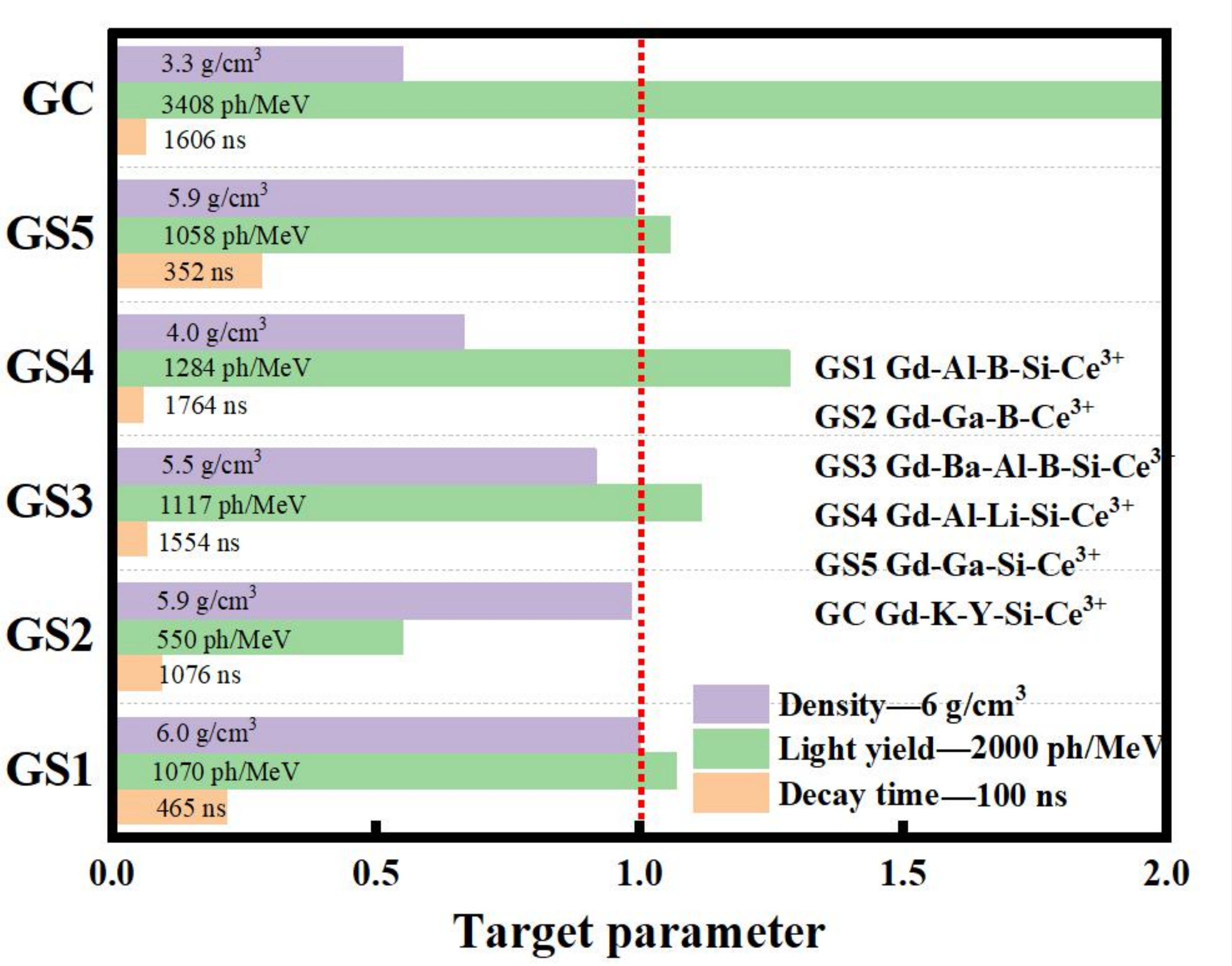
1. How to produce the large size sample in factory, with the same performance of small size in the university Lab.
2. How to increase the denisty and light yield in large siza sample?

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 & 1070 ph/MeV with 24.4% @662keV & 460 ns

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

5.9 g/cm³ & 1060 ph/MeV with 23.7% @662keV & 352 ns

- Ultra-high density **Tellurite Glass**—6.6 g/cm³
- High light yield **Glass Ceramic**—3500 ph/MeV
- Fast scintillating Decay Time—100 ns
- Large size Glass—42mm*51mm*10mm

4.2 Next Plan for GS-HCAL

- By replacing the CEPC_v4 baseline HCAL with the GSHCAL , **the BMR can reach ~3.4%** in the nominal setup and show ~10% improvement with. the AHCAL baseline design (~3.8%);
- The R&D of large-size glass tiles featuring **high density, high light yield and short decay time** is the main focus of next stage for the Glass Scintillator R&D collaboration;
- More detailed studies like **SiPM performances**, coupling designs with the glass cell and the photon collection efficiency will be done to give advice for glass tile design;
- The mechanical and **modular design** of the GSHCAL will be studied later;

See the unseen
change the unchanged

The Innovation

THANKS

The Scintillator data

Typy	Composition	Density (g/cm³)	Light yield (ph/MeV)	Decay time (ns)	Emission peak(nm)	Price/1 c.c (RMB)
Glass Scintillator in Paper	Ce-doped high Gadolinium glass[1]	4.37	3460	522	431	~10
	Ce-doped fluoride hafnium glass[2]	6.0	2400	23.4	348	150
Plastic Scintillator	BC408[3]	~1.0	5120	2.1	425	60
	BC418[3]	~1.0	5360	1.4	391	80
Crystal	GAGG:Ce[4]	6.6	50000	50	560	2400
	LYSO:Ce[5]	7.1	30000	40	420	1200
	BGO[6]	7.3	8000	300	480	800
Glass Scintillator for CEPC (preliminaryl target)	?	>7	>1000	< 100	350-500	~1
Stuaus of Glass Scintillator	?	>6	>1000	< 200	350-500	~?

[1] Struebing, C . Journal of the American Ceramic Society, 101(3). [2] Zou, W. Journal of Non-Crystalline Solids, 184(1), 84-92 . [3] Plastic Scintillators | Saint-Gobain Crystals. [4] Zhu, Y. Qian, S. Optical Materials, 105, 109964. [5] Ioannis, G. Nuclear Instruments & Methods in Physics Research. [6]Akapong Phunpueok, et al. Applied Mechanics and Materials, 2020,901:89-94.