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

闪烁玻璃合作组
Glass Scintillator Collaboration

Sen QIAN, Zhehao HUA,

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

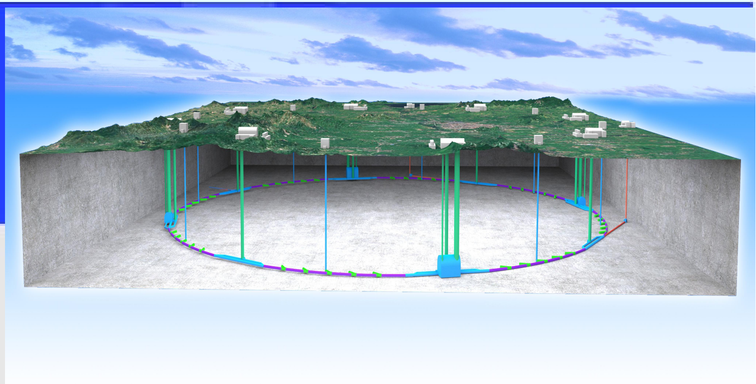
IAS-HEP 2024 - Conference: Experiment / Detector 2024. 01. 23th

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;

闪烁玻璃合作组
Glass Scintillator Collaboration

1.1. The GS-HCAL of CEPC

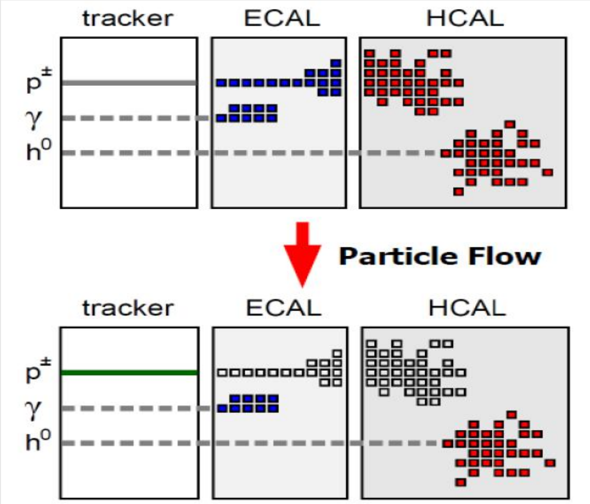


Future electron-position colliders (e.g. CEPC)

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

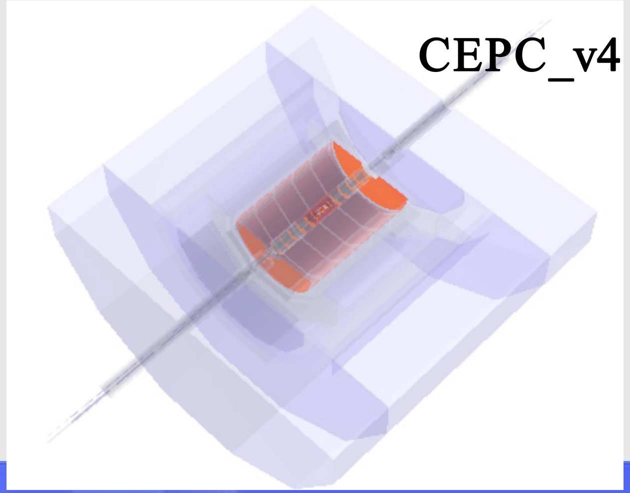
CEPC detector: highly granular calorimeter + tracker

- 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

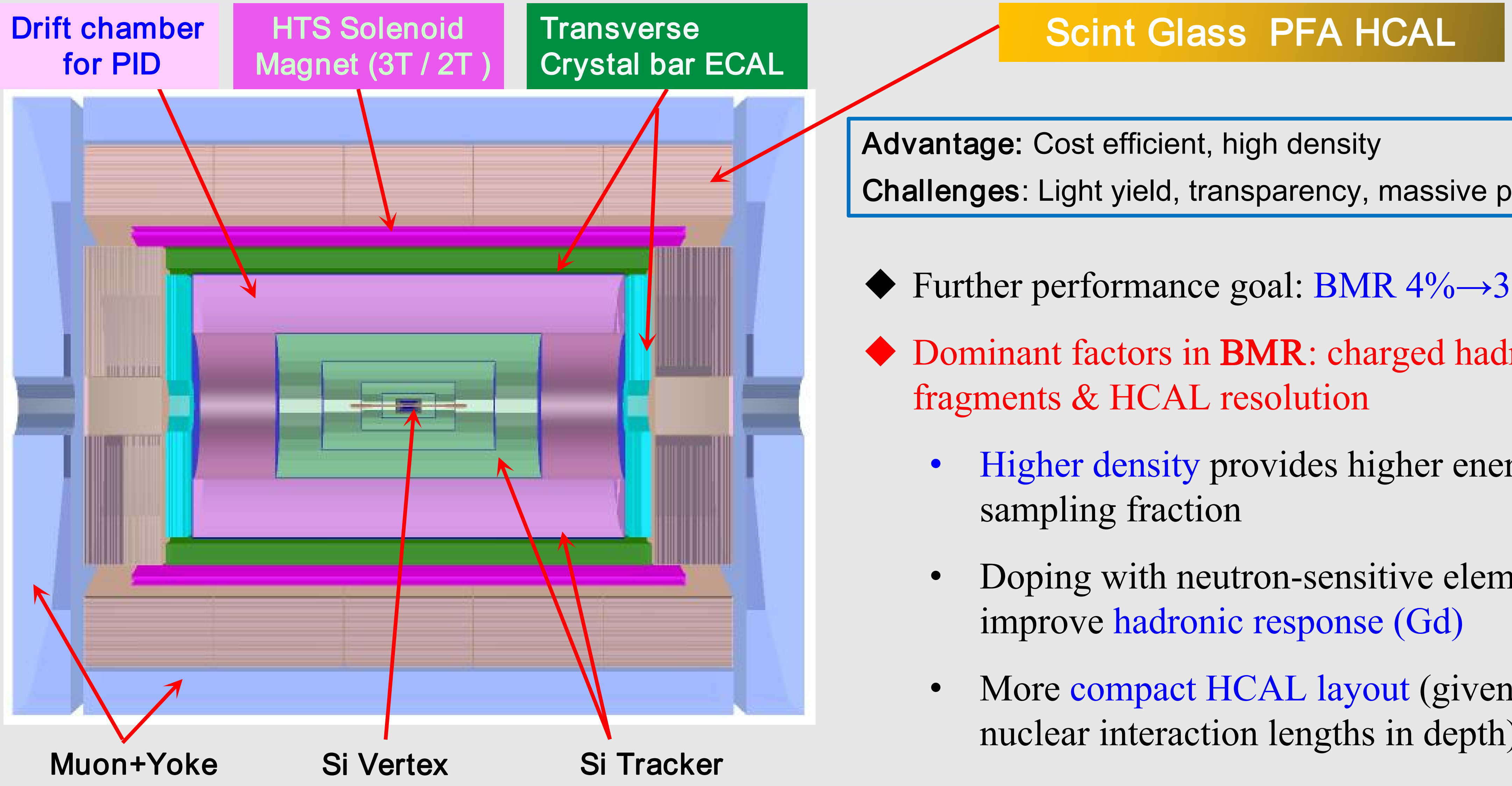


New Option: Glass Scintillator HCAL (GS-HCAL)

- 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



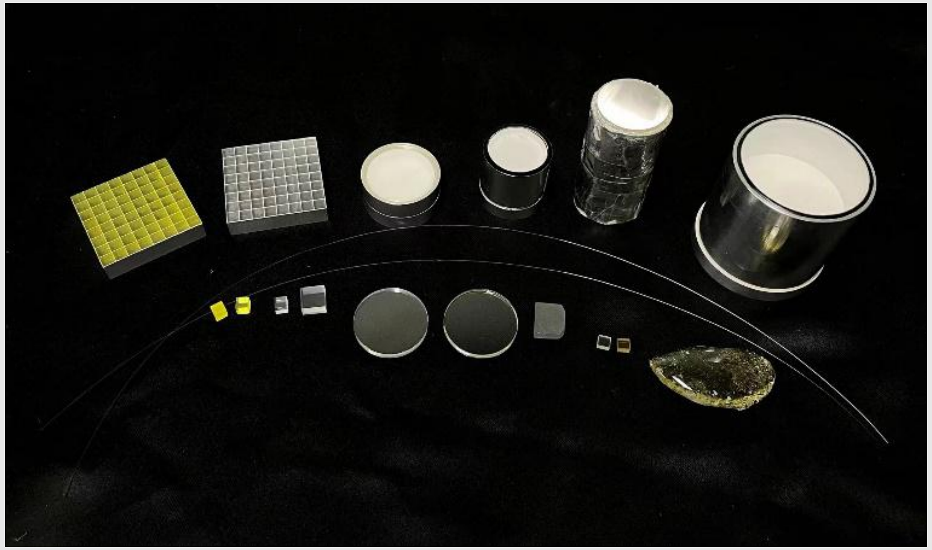
Advantage: Cost efficient, high density

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)

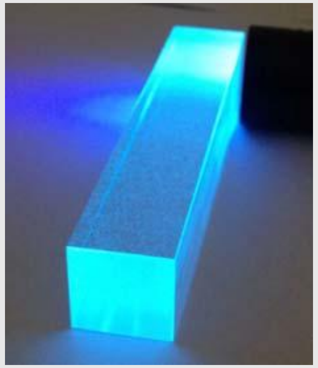
Outline

- 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;



2.0 What is the Glass Scintillator?

Plastic Scintillator



Glass Scintillator

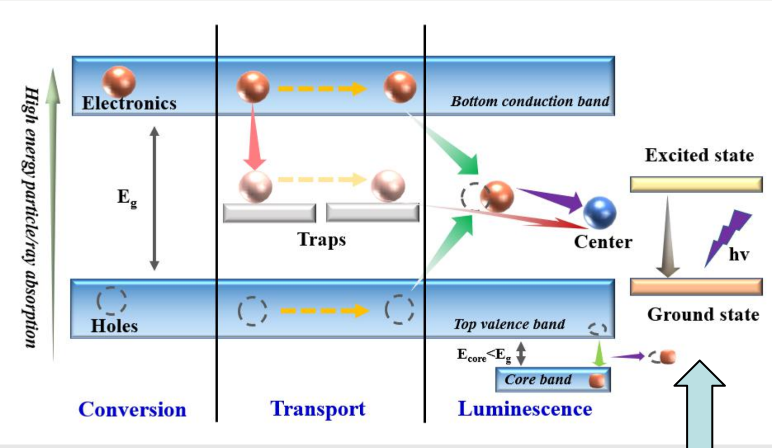
Crystal Scintillator

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

2.1 Target of Glass Scintillator

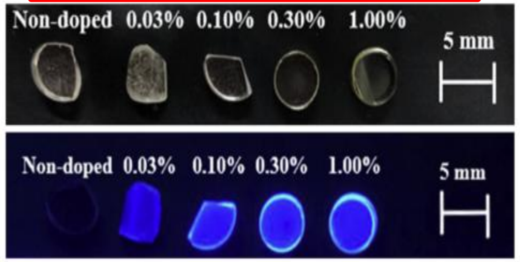
Key parameters	Value	Remarks
➢ Tile size	~30×30 mm^2	Reference CALICE-AHCAL, granularity, number of channels
➢ Tile thickness	~10 mm	Energy resolution, Uniformity and MIP response
➢ **Density**	**5-7 g/cm^3**	More compact HCAL structure with higher density
➢ **Intrinsic light yield**	**1000-2000 ph/MeV**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



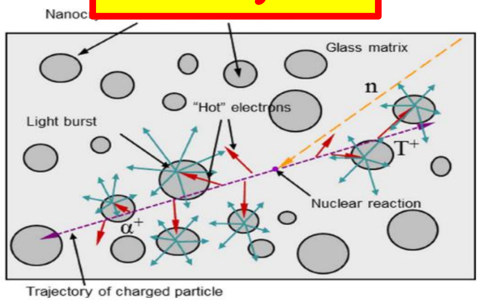
- Scintillation mechanism---- **Luminescence Center**
- **Conversion**—photoelectric effect and Compton scattering effect;
- **Transport**—electrons and holes migrate;
- **Luminescence**—captured by the luminescent center ions

Lanthanide elements



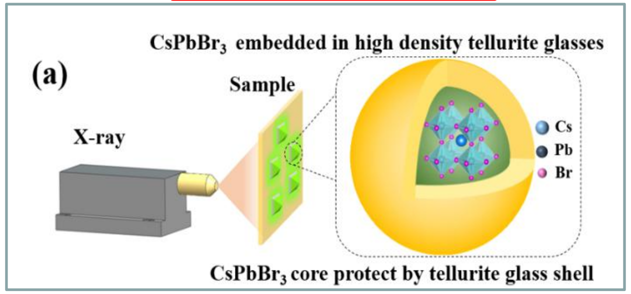
Journal of Alloys and Compounds 782 (2019) 859-864

Nanocrystals



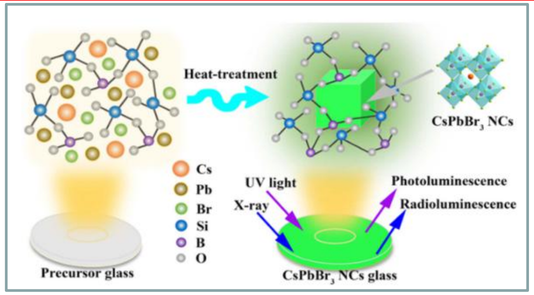
IEEE TNS 60 (2) 2013

Quantum Dots



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

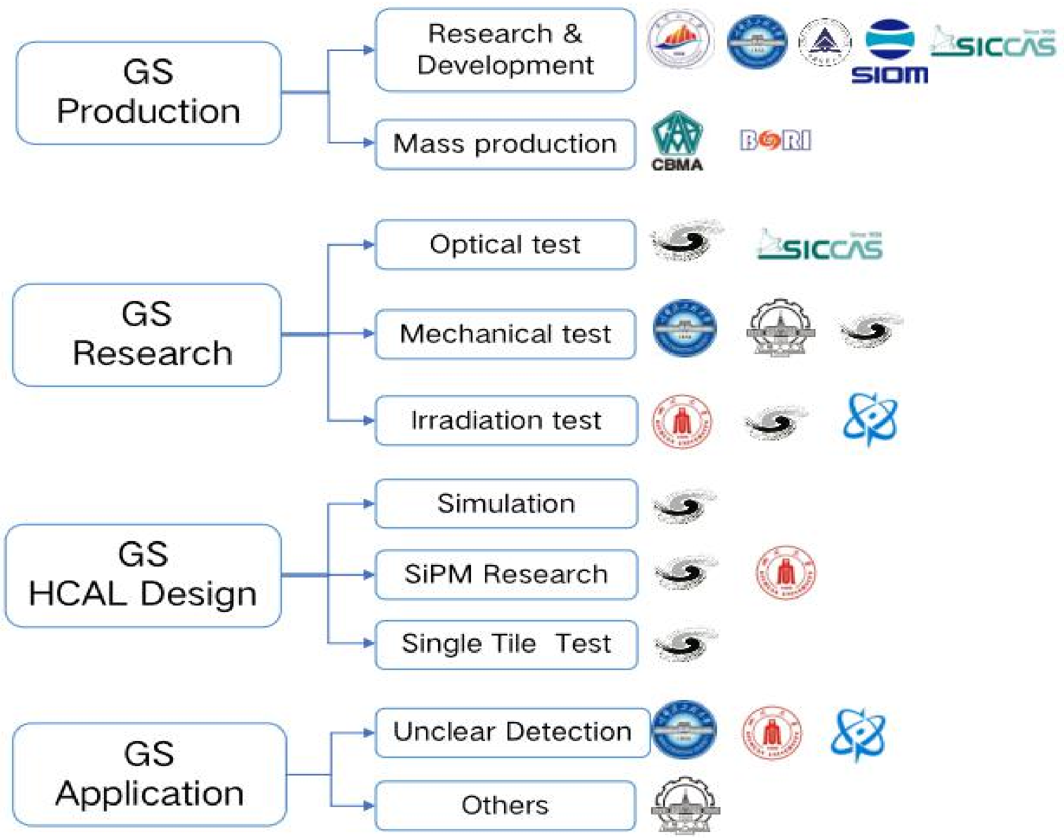
Lanthanide + Quantum Dots



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

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

2.3 Large Area 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

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

Spokesperson：QIAN Sen

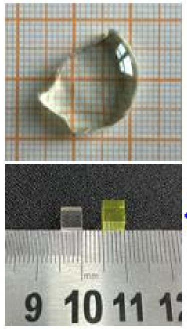
-- The Glass Scintillator Collaboration Group established in Oct.2021, only 5 groups join together；

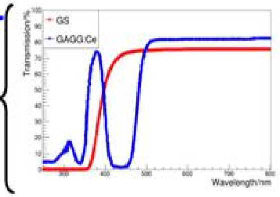
-- There are 3 Institutes of CAS, 5 Universities, 3 Factories join us for the R&D of GS;

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

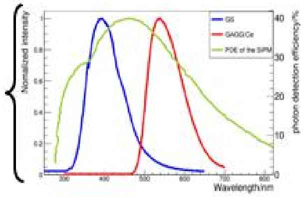
2.4 The Scintillator Test Facilities

➤ **The Scintillator Test System**

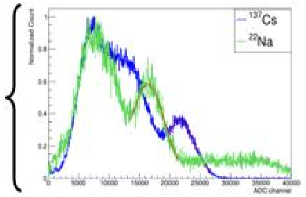




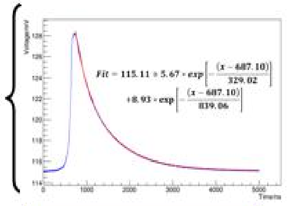
- Density;
- Elastic Modulus;
- Refractive Index;
- Transmission Spectrum



- 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

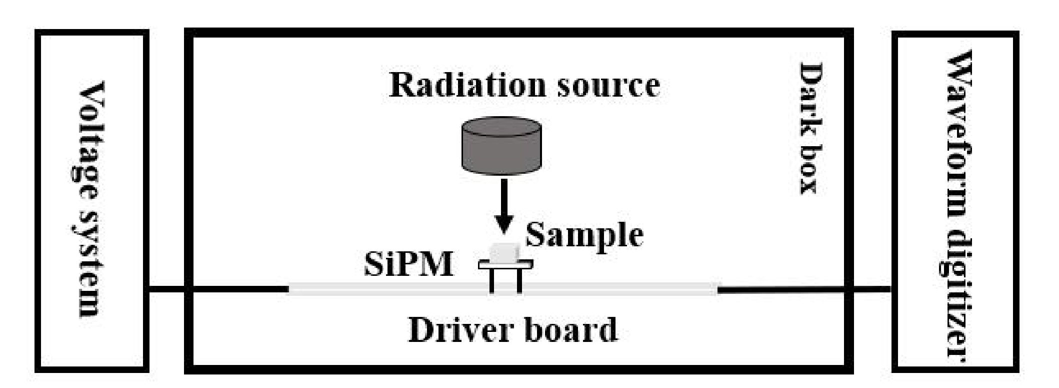
The published papers of different Scintillator samples tested in Lab

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

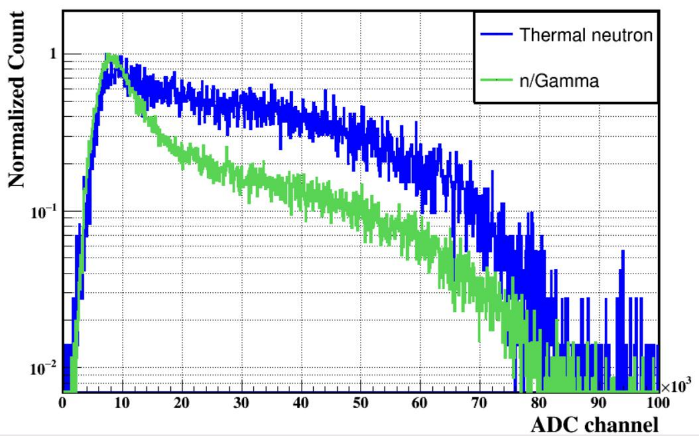
Radioactive Sources Test -- Energy Spectrum --Light Yield

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

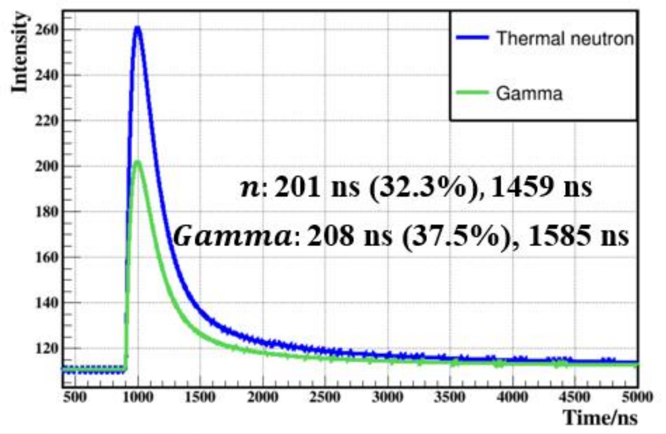
Through the waveform sampling data acquisition system, we can obtain **Light Yield, Energy Resolution and Decay Time** of the scintillator.



➢ γ/n Energy Spectra



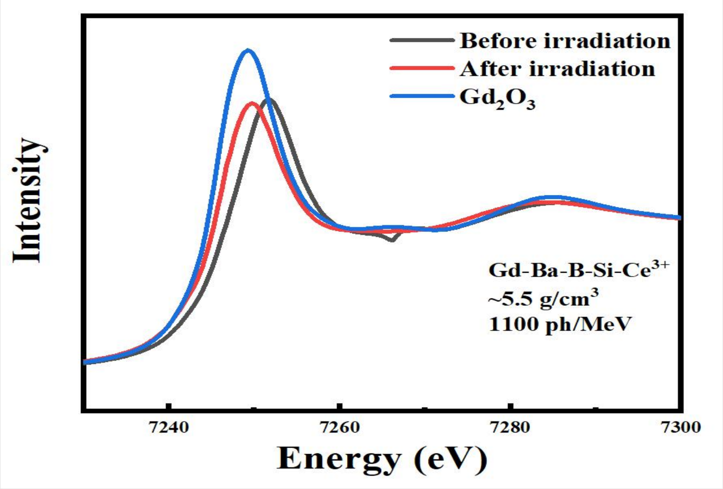
➢ γ/n Decay Time



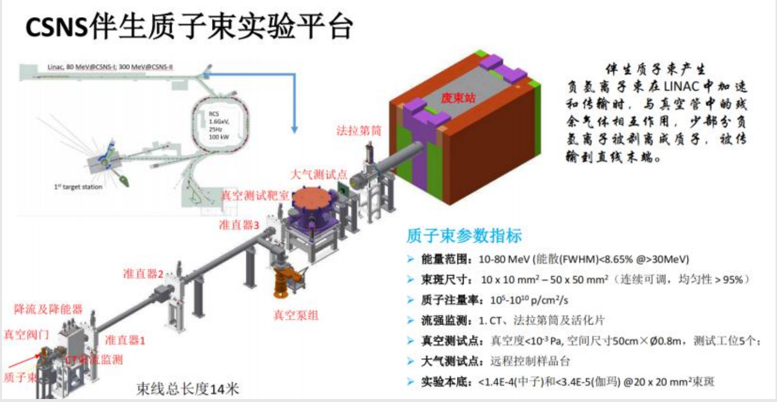
Special Condition TEST Platform

- IHEP--XAFS

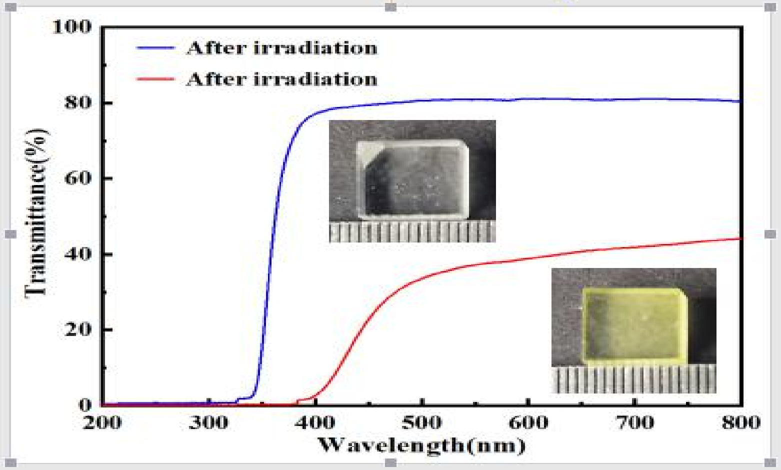
Study the elements influence of GS sample



- IHEP-CSN-- P Beam

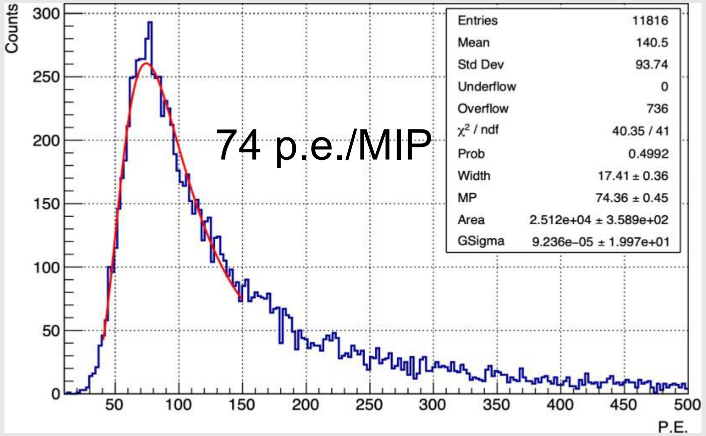


Study the anti-irradiation characteristics of samples;



- CERN-MUON beam

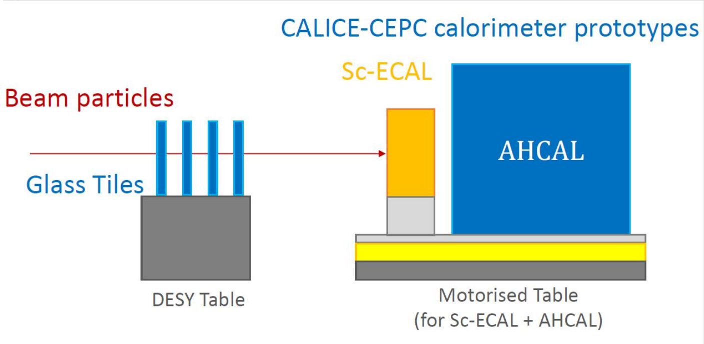
Study the particle interaction in GS sample with MUON

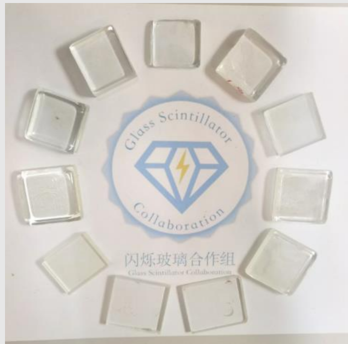


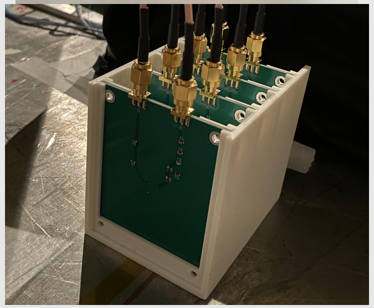
2.5 Beam Test Experiments

CERN Muon-beam

- 11 glass tiles tested at CERN (2023, May 16)
- CERN Proton Synchrotron (10 GeV muon beam)
- Measure the MIP response of glass samples

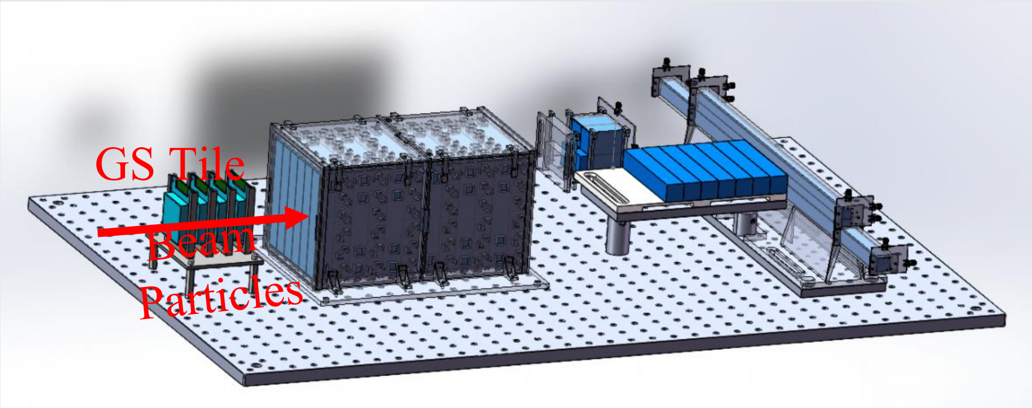


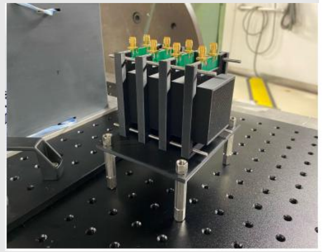




DESY Electron-beam

- 4+9 glass scintillator (CERN8-11 + DESY1-9) (2023, Oct 2)
- DESY II Electron Synchrotron (5 GeV electron beam)
- Measure the MIP response of new glass samples

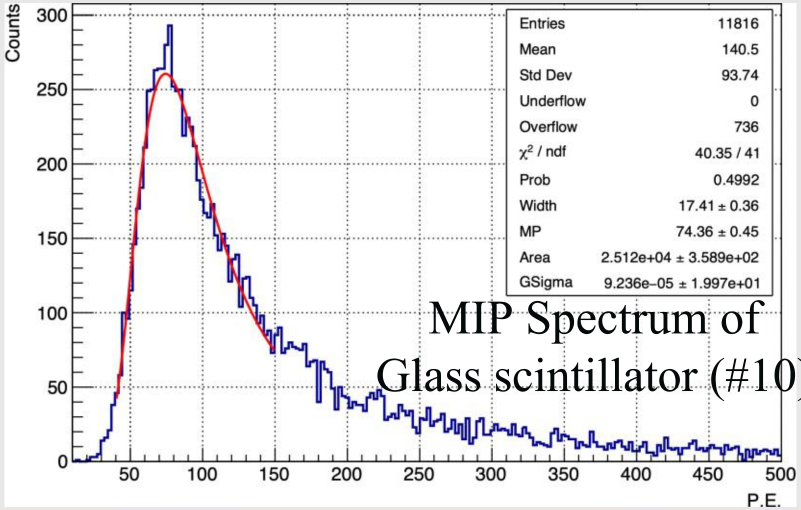




(1) MUON Beam Test of GS Samples

☐ Beam test results at CERN

- ➢ Each glass sample was covered by the Teflon tape and readout by an individual SiPM ($6*6\ mm^2$)
- ➢ The density and composition of these glass samples are the same: ~$5.1\ g/cm^3$ & Gd-Al-Ba-B-Si-Ce
- ➢ Preliminary results look promising: typical MIP response (in 10 mm) is 60 – 100 p.e./MIP



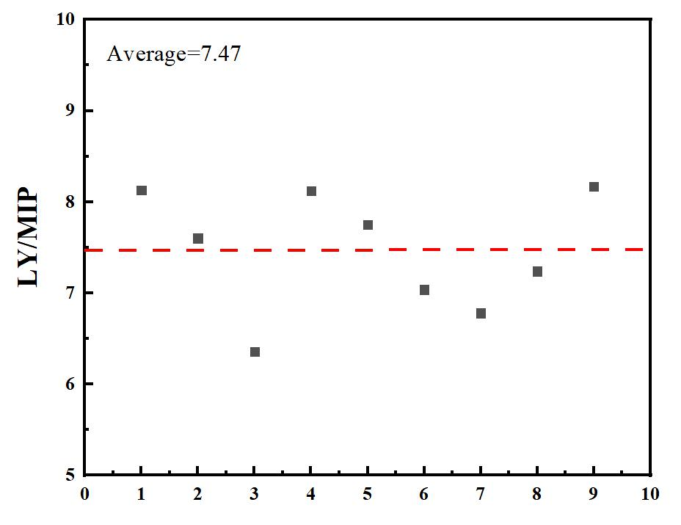
MIP Spectrum of Glass scintillator (#10)

CERN	Size (mm^3)	T@420 nm (%)	LY (ph/MeV)	MIP_LO (p.e./MIP)	Normalized MIP_LO (10 mm)
#1	33.5*27.6*5.1	69	551	15	29
#2	30.2*29.5*6.6	61	645	35	53
#3	29.9*28.1*10.2	70	617	66	65
#4	37.2*35.1*5.3	80	571	31	59
#5	40.0*35.1*4.2	78	571	38	91
#6	30.3*29.8*9.4	55	484	67	71
#7	34.8*34.8*7.5	65	505	60	80
#8	27.8*25.6*5.0	81	840	41	82
#9	34.6*34.7*7.5	49	352	69	92
#10	34.7*35.2*7.4	64	524	74	100
#11	30.5*30.0*8.7	81	767	73	84

(2) Electron Beam Test of GS Samples

◻ Beam test results at DESY

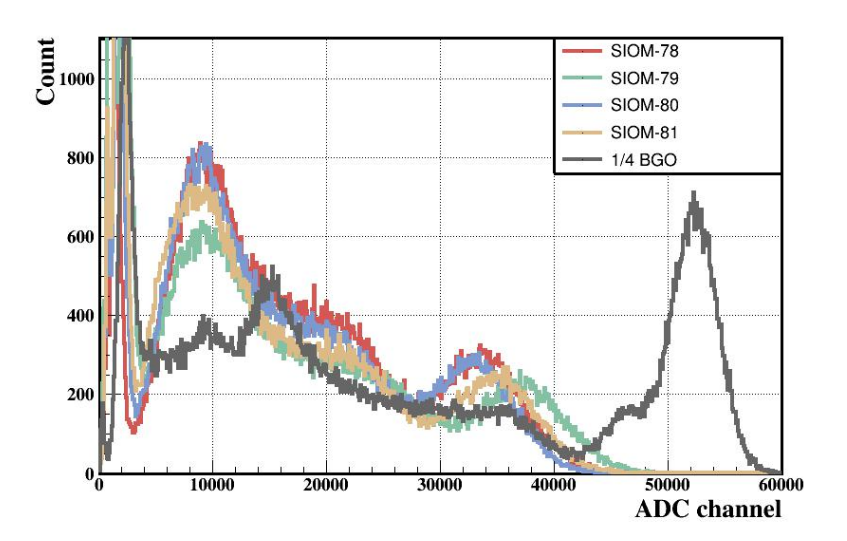
- Each glass sample was covered by the Teflon tape and readout by an individual SiPM ($6*6\ mm^2$)
- The density, cell size and composition of these glass samples are the same: ~6 g/cm^3 & $40*40*10\ mm^3$ & Gd-Al-B-Si-Ce
- Typical MIP response is 80 – 90 p.e./MIP, the average ratio between the LY and MIP light output is ~ 7.5



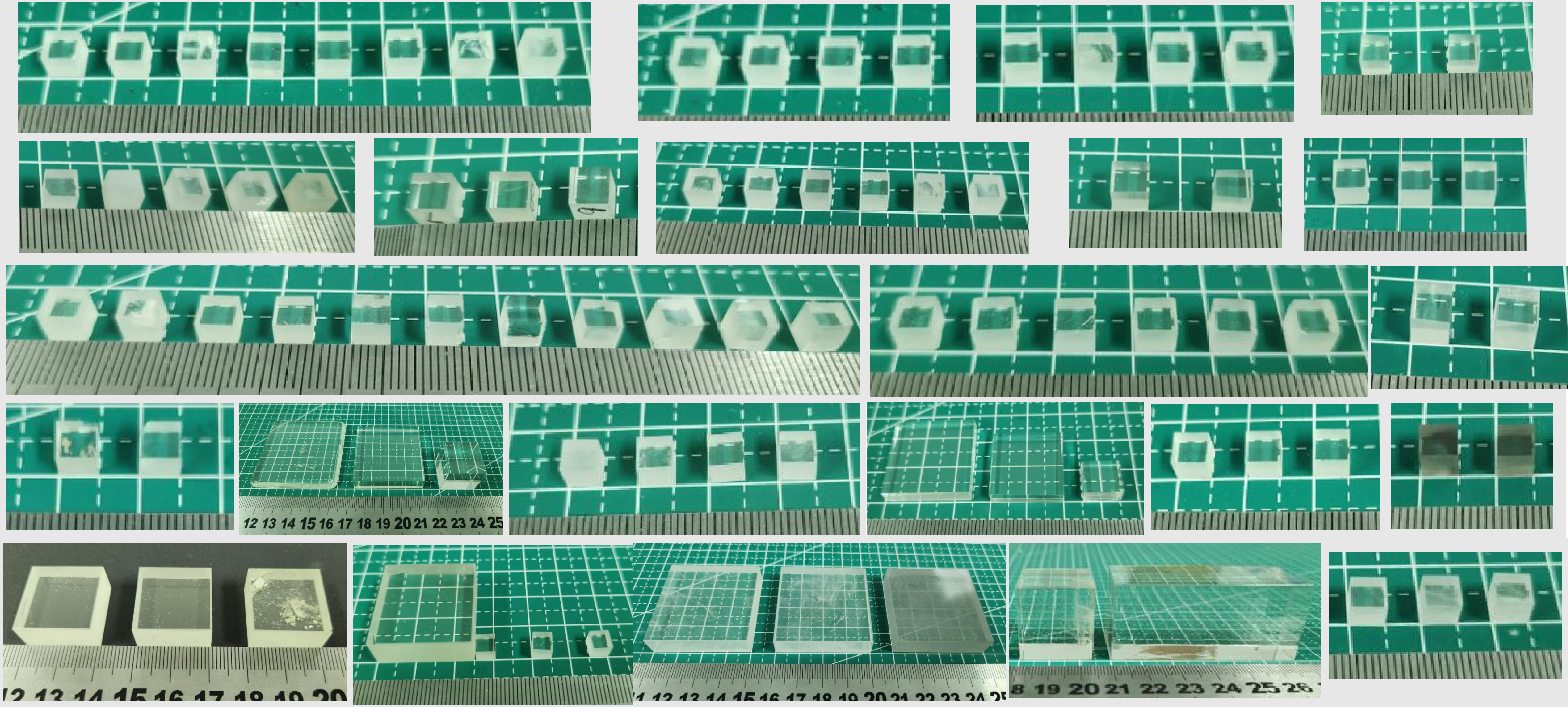
DESY	T @ 420 nm (%)	LY (ph/MeV)	MIP_LO (p.e./MIP)	LY/MIP_LO
#1	16.8	626	77	8.13
#2	77	684	90	7.6
#3	75	572	90	6.38
#4	84	788	97	8.12
#5	78	674	87	7.75
#6	64	507	72	7.04
#7	73	576	85	6.78
#8	81	673	93	7.24
#9	80	768	94	8.17

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;



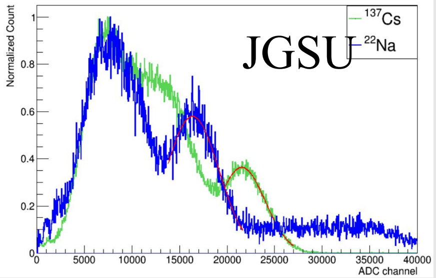
3.0 The GS Samples produced （>600）

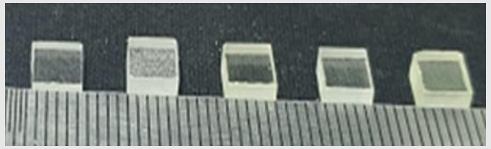


3.1 Borosilicate Glass（Gd-Al-B-Si-Ce^{3+}）--GS1

2021.11

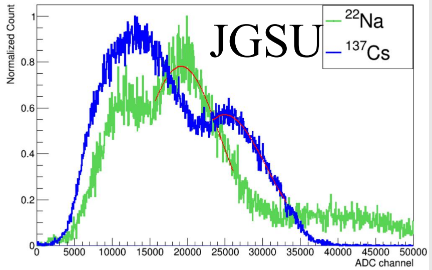
- Density~4.5 g/cm^3
- LY=802 ph/MeV
- ER=26.8%
- Decay=262 (18%)
  1235 ns

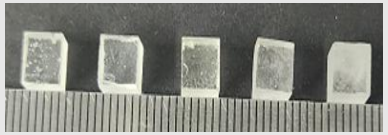




2022.11

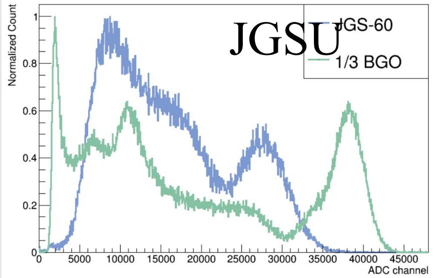
- Density~6.0 g/cm^3
- LY>1000 ph/MeV
- ER=49.6%
- Decay=847 ns

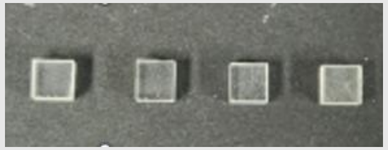




2023.02

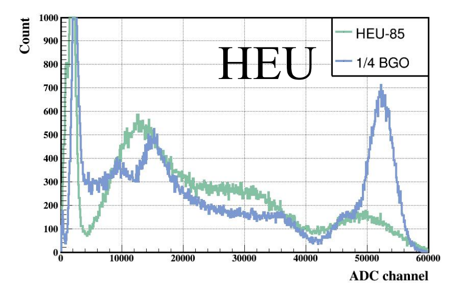
- **Density~6.0 g/cm^3**
- **LY~1100 ph/MeV**
- **ER=24.4%**
- **LO in 1μs=899 ph/MeV**
- **Decay=92 (8%), 473 ns**

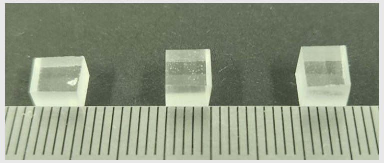




2023.12

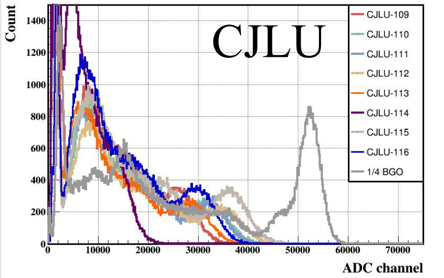
- Density~5.9 g/cm^3
- LY~1620 ph/MeV
- ER=25.6%
- LO in 1μs=543 (34%)
- Decay=131 (5%),
  2073 ns

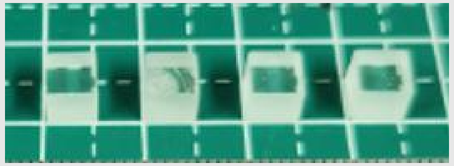




2024.01

- **Density~6.0 g/cm^3**
- **LY=1241 ph/MeV**
- **ER=23.8%**
- **LO in 1μs=859 (70%)**
- **Decay=87 (4%), 554 ns**

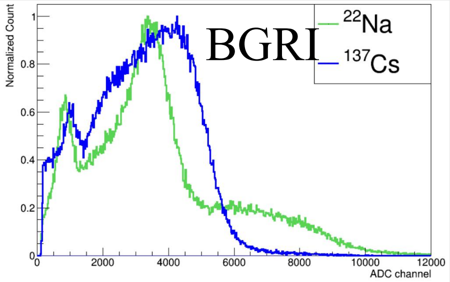




- There are 5 types of GS for the study, and focous on the GS1, **Borosilicate Glass** for better performance;
- Now, the **Density~6.0 g/cm^3, LY>1200 ph/MeV, ER=23.8%, could be accept to be the candidate for GS-HCAL;**
- But the Decay time ~ 500 ns, still need to improve.

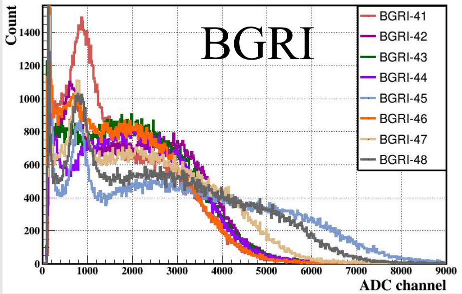
3.2 Large size glass（Gd-Al-B-Si-Ce^{3+}）--GS1

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

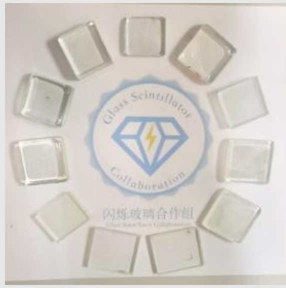


2022.10

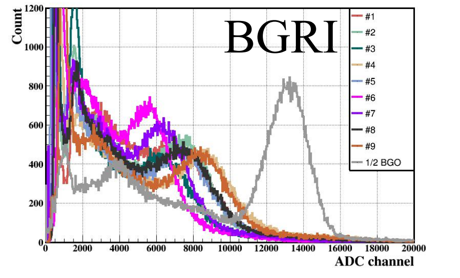
- Size=30*30*9 mm^3
- Density=5.1 g/cm^3
- LY=767 ph/MeV
- ER=None



2023.04

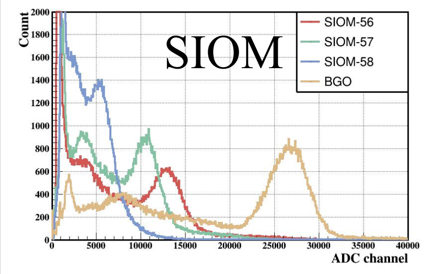


- Size=40*40*10 mm^3
- Density=6.0 g/cm^3
- LY=788 ph/MeV
- ER=48.4%
- Decay=87 (2%), 1024 ns

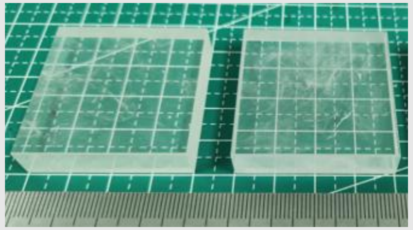


2023.10

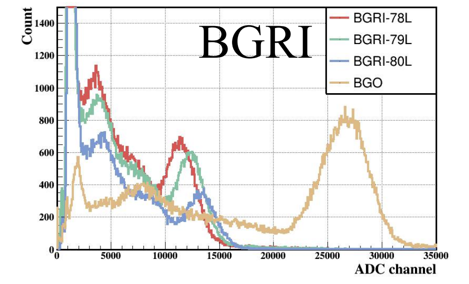
- **Size=40*40*10 mm^3**
- **Density=6.0 g/cm^3**
- **LY=1198 ph/MeV**
- **ER=33.0%**
- **LO in 1μs=607 (51%)**
- **Decay=117 (3%), 1368 ns**



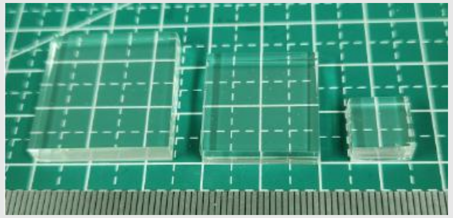
2023.11



- 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

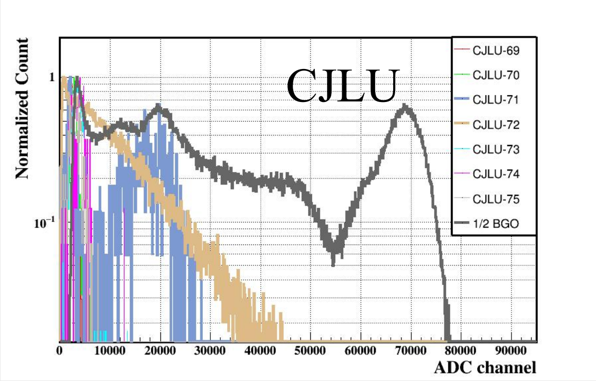


The Bottleneck：

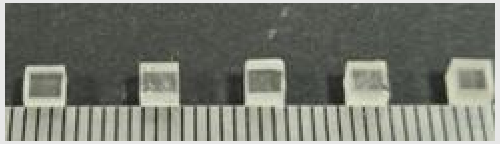
1. How to ensure the performance stability of large size glass sample?
2. How to improve the light collection efficiency when coupling large size glass and SiPM?

3.3 Silicate glass（Gd-Ga-Si-Ce^{3+} glass）—GS5

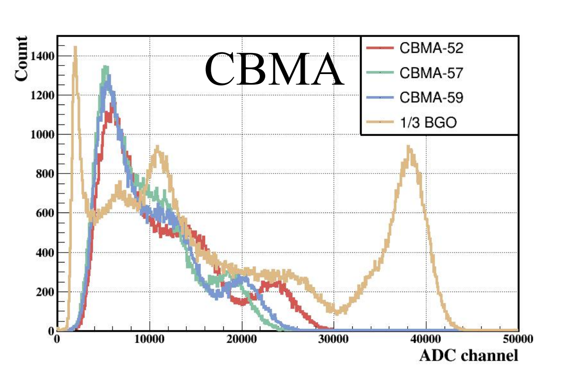
- Density~5.0 g/cm^3
- LY>2000 ph/MeV?
- ER=None
- Decay=287 ns



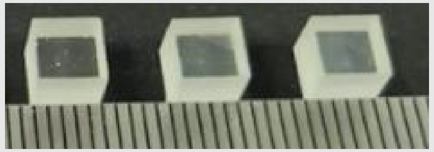
2023.07



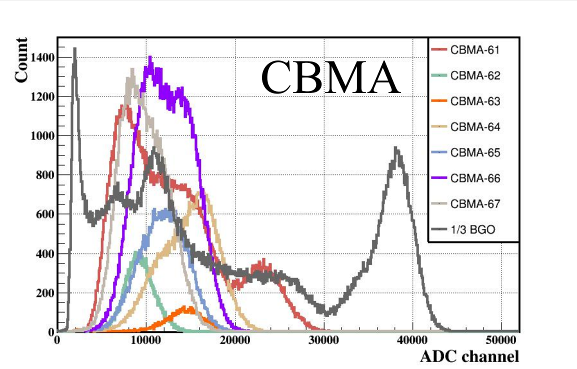
- Density~5.9 g/cm^3
- LY=1058 ph/MeV
- ER=23.7%
- Decay=97 ns (44%), 352 ns



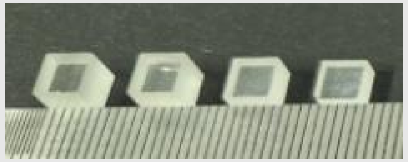
2023.08



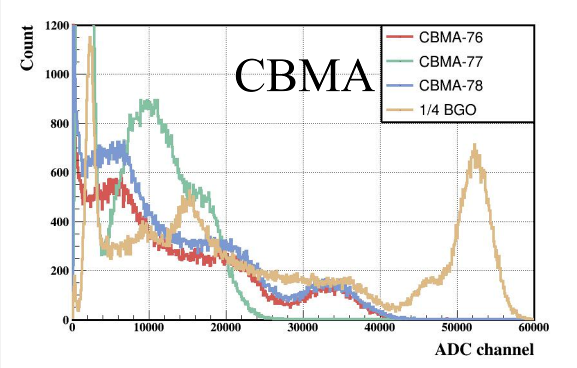
- Density~5.9 g/cm^3
- LY=1040 ph/MeV
- ER=25.8%
- Decay=107 (43%), 450 ns



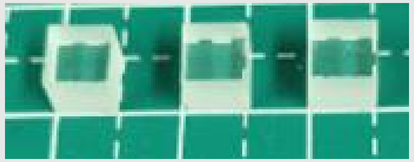
2023.08



- Density~5.9 g/cm^3
- LY~1154 ph/MeV
- ER=25.4%
- LO in 1μs=1137 (98%)
- Decay=92 (39%), 323 ns



2023.12



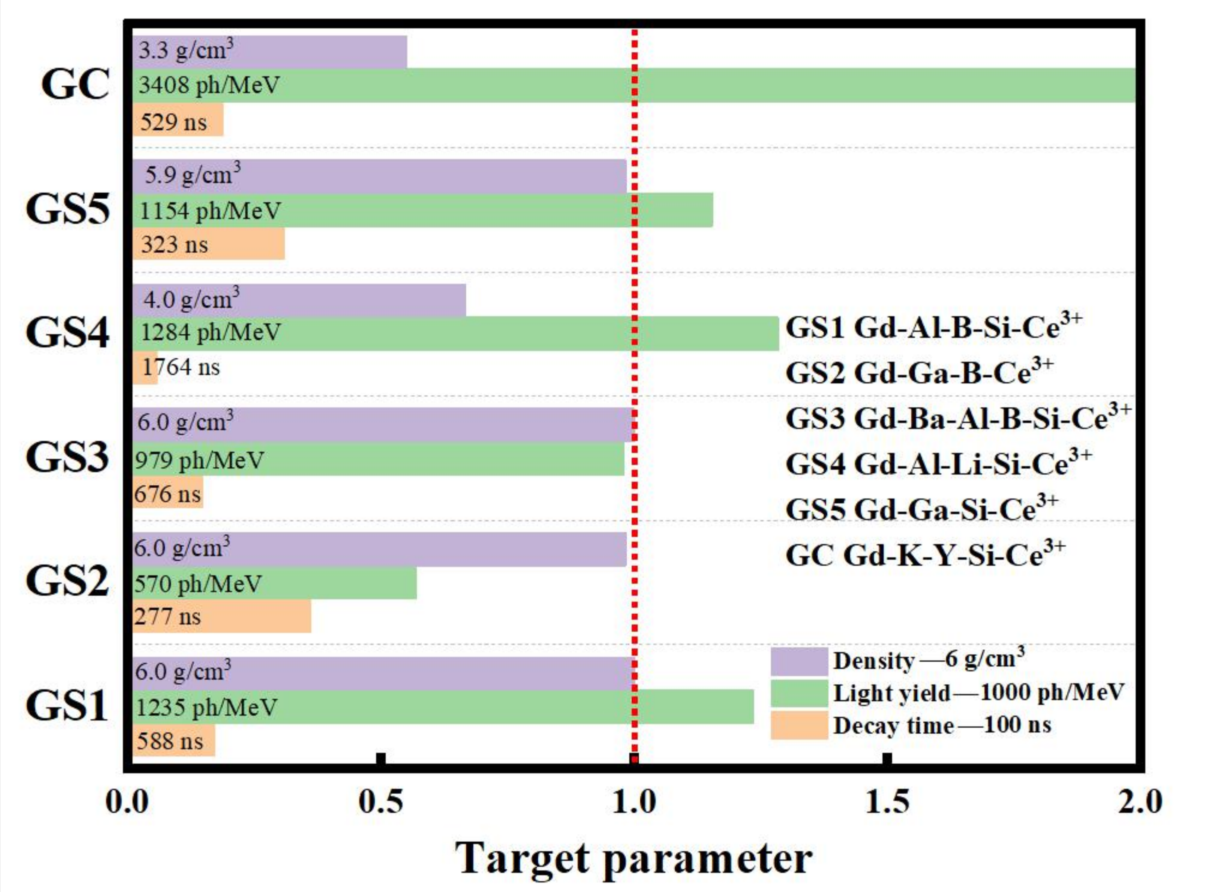
- There are 5 types of GS for the study, and the GS5, **Silicate Glass** is to be the other option for us;
- Now, the **Density~6.0 g/cm^3, LY>1100 ph/MeV, ER=25.4%, could be accept to be the candidate for GS-HCAL;**
- But the preparation and performance stability of glass still need to be further investigated.

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 & 1235 ph/MeV with 24.0% @662keV & 588 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 Next Plan for GS R&D

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

- The performance of glass is further improved from energy band/composition engineering;
- Shorten the scintillation decay time of the glasses (<300 ns);
- Repeated preparation and performance optimization of large size glass;
- Improve raw material purity → improve scintillation performance;
- Explore the structure, radiation resistance and mechanical properties of the glasses.

Promote Applied Research of GS in CEPC， FCC， ……

Glass Scintillator Collaboration

See the unseen
change the unchanged

The Innovation

THANKS