The R&D of the New Glass Scintillator with high density and high light yield

闪烁玻璃合作组
Glass Scintillator Collaboration

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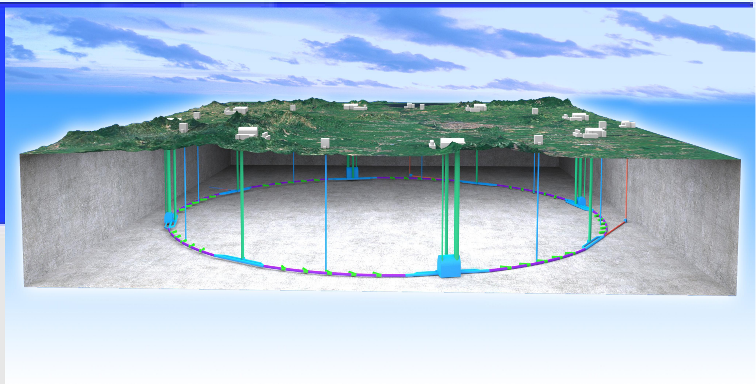
Outline

- 1. The Motivation and the Design
- 2. The Test Facilities for GS
- 3. The Progress of the GS
- 4. Optical Simulation for GS detector
- 5. Summary and Next Plan

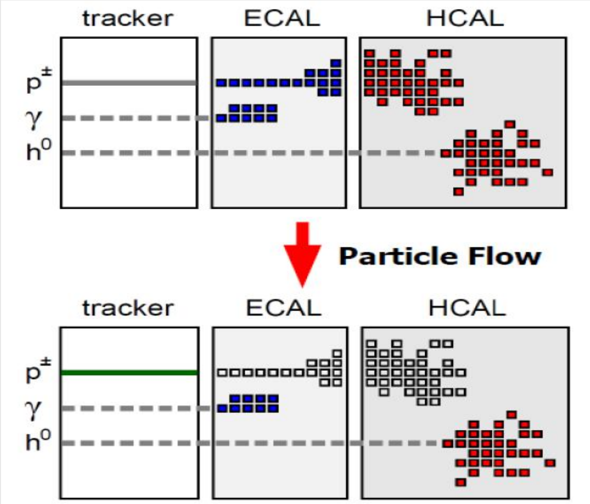
1.1. The GS-HCAL of CEPC



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

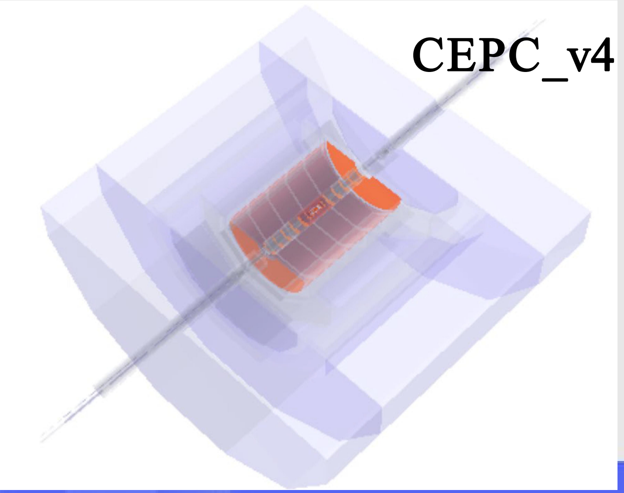
- Main physical goals: precision measurements of the Higgs and Z/W bosons
- Challenge: unprecedented jet energy resolution $\sim 30\%/\sqrt{E(GeV)}$

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)

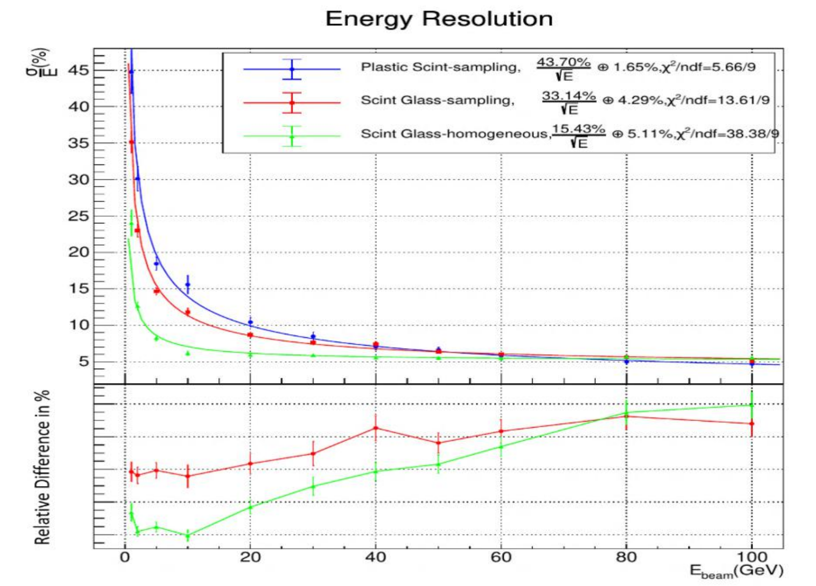


- Higher density provides higher energy sampling fraction
- Doping with neutron-sensitive elements: improve hadronic response (Gd)
- More compact HCAL layout (given 4~5 nuclear interaction lengths in depth)

1.2 The Simulation for GS-HCAL

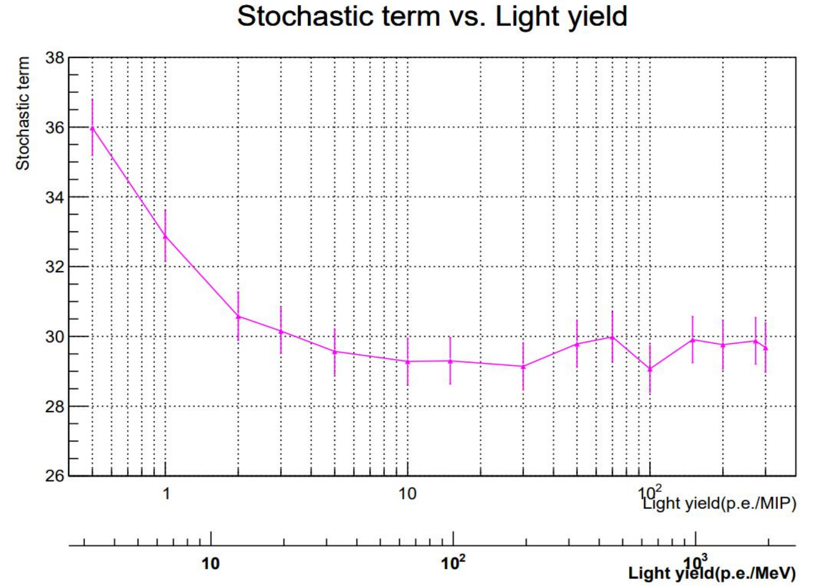
How to achieve the optimized energy resolution (Boson Mass Resolution, BMR)

- **Impact of Scintillator type**



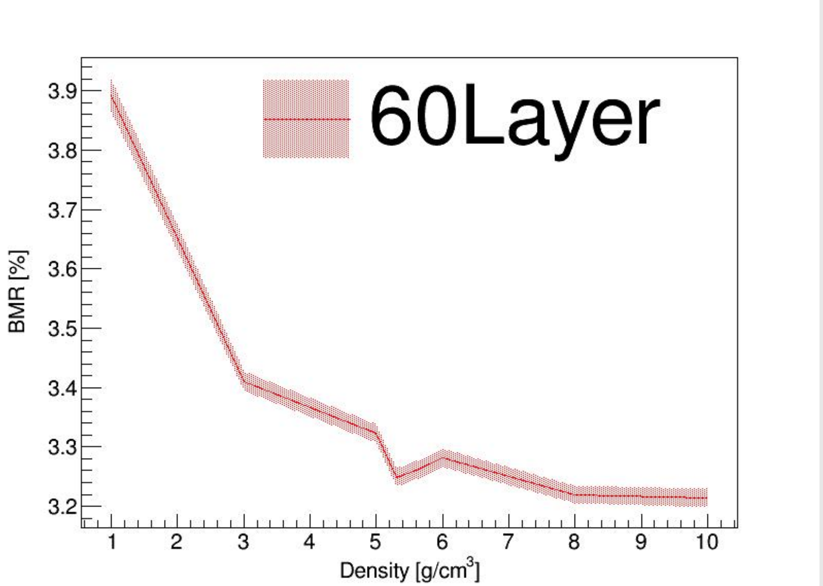
Plastic Scintillator vs Glass Scintillator:
GS has better hadronic energy resolution in low energy region (<30GeV)

- **Impact of Light Yield**



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

- **Impact of Density**

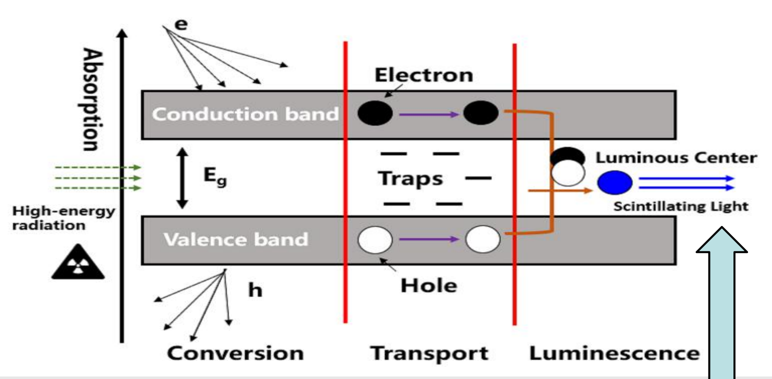


Glass density ~ 6 g/cm3 is a relatively reasonable target, which can guarantee a good BMR (~3.3%) and feasibility in R&D

1.3 Target of Glass Scintillator

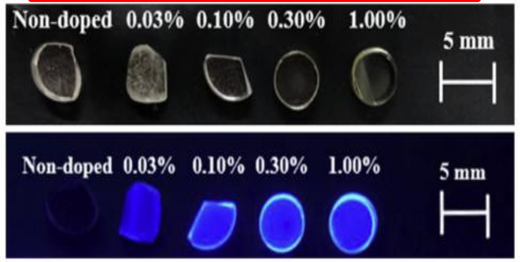
Key parameters	Value	Remarks
➢ Tile size	~30×30 mm^2	Reference CALICE-AHCAL, granularity, number of channels
➢ Tile thickness	~10 mm	Energy resolution, Uniformity and MIP response
➢ **Density**	**5-7 g/cm^3**	More compact HCAL structure with higher density
➢ **Intrinsic light yield**	**1000-2000 ph/MeV**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

1.4. The Design of the Glass Scintillator



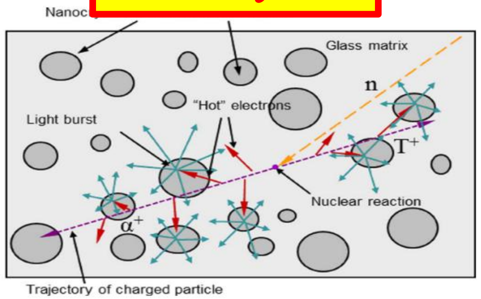
- Scintillation mechanism---- **Luminescence Center**
- **Conversion**—photoelectric effect and Compton scattering effect;
- **Transport**—electrons and holes migrate;
- **Luminescence**—captured by the luminescent center ions

Lanthanide elements



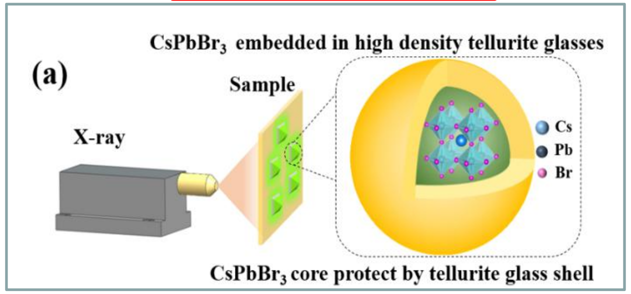
Journal of Alloys and Compounds 782 (2019) 859-864

Nanocrystals



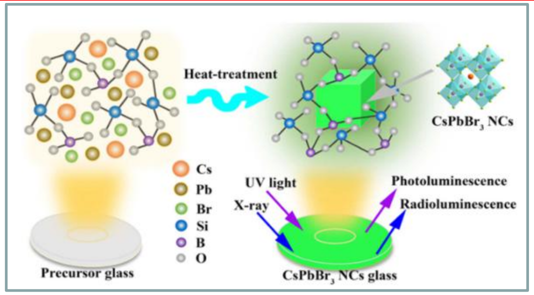
IEEE TNS 60 (2) 2013

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）；

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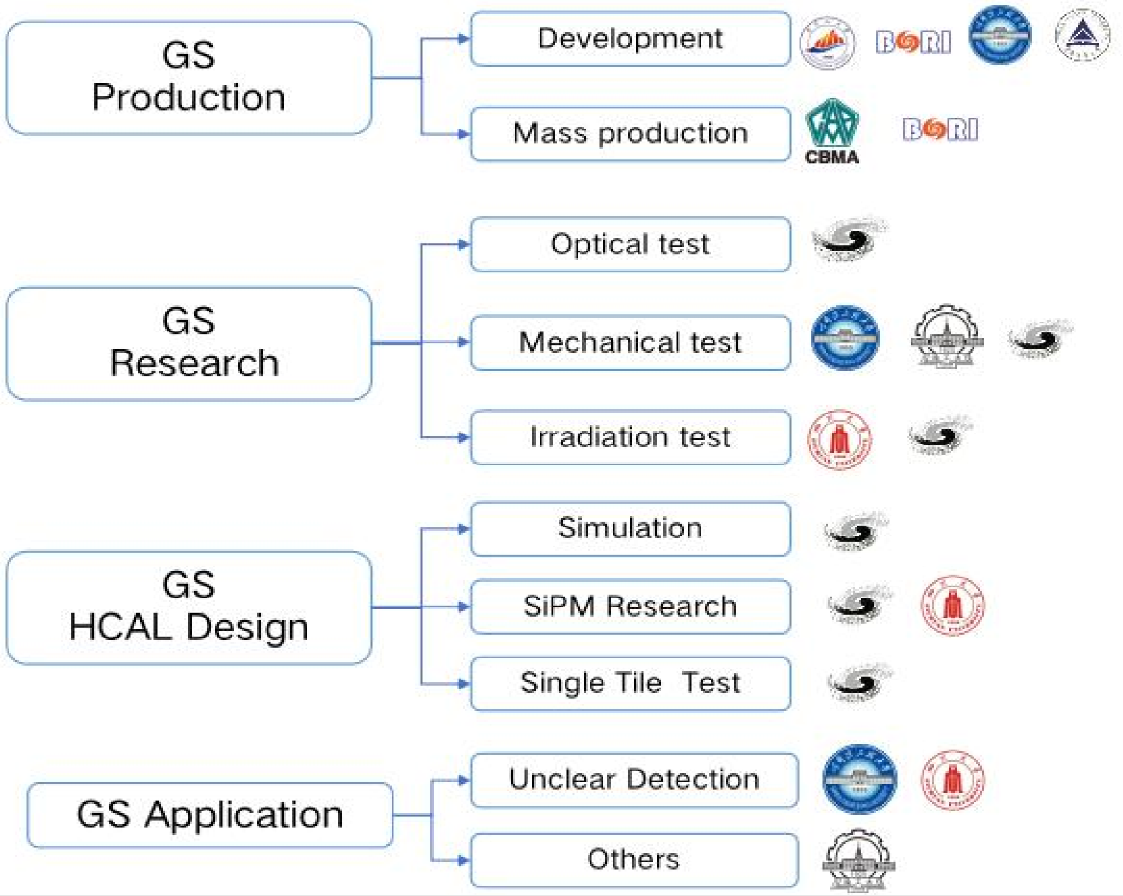
2.1 The GS R&D Collaboration Group



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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

Glass Scintillator Collaboration

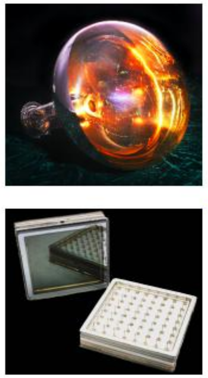
闪烁玻璃合作组
Glass Scintillator Collaboration

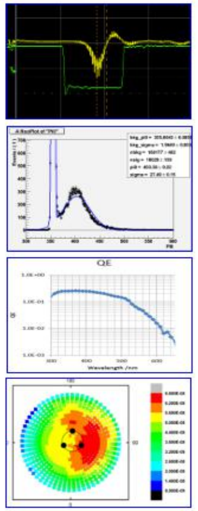
-- The Glass Scintillator Collaboration Group established in Oct.2021；

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

2.2 Test Facilities -- (1) the PMT Lab in IHEP

- **PMT**

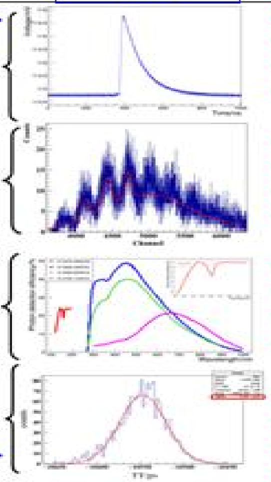




- Anode Pulse Rise Time;
- Pre/Late/After Pulse;
- Dark Count
- The Single Photoelectron Spectrum;
- The voltage distribution (BASE) ;
- The Supply voltage;
- Typical Gain Characteristic;
- Anode Dark Current
- Spectral Response;
- Wavelength of Maximum Response;
- Cathode Sensitivity: Luminous(2856K);
- Quantum efficiency with λ
- Photocathode efficiency Area;
- Photocathode efficiency Uniform;
- The position of the Sb, K, Cs;
- The linearity of the PMT
- Magnetic characteristics;
- Transit Time Spread (FWHM)

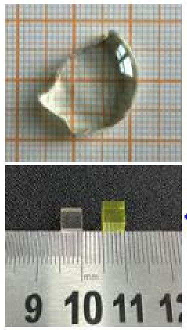
Others
……

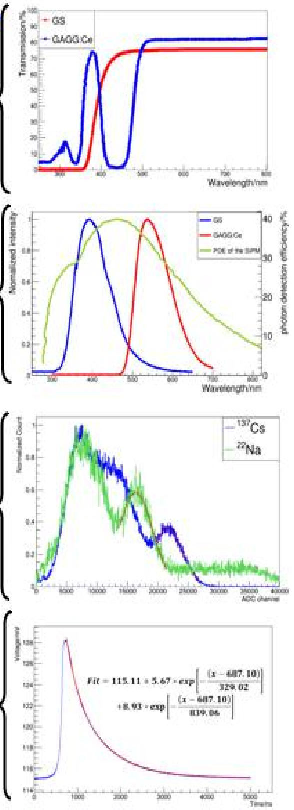
- **SiPM**



- Pixel Number;
- Photosensitive Area;
- Breakdown Voltage;
- Over Bias
- Typical Gain Caracteristic;
- Dark Count;
- Optical Crosstalk;
- Dynamic Range and Linearity
- The Single Photoelectron Spectrum;
- Photon Detection Efficiency;
- Pulse Width;
- Amplitude
- Pulse Rise Time;
- Fall Time;
- Transit Time;
- Transition Time Spread

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
……

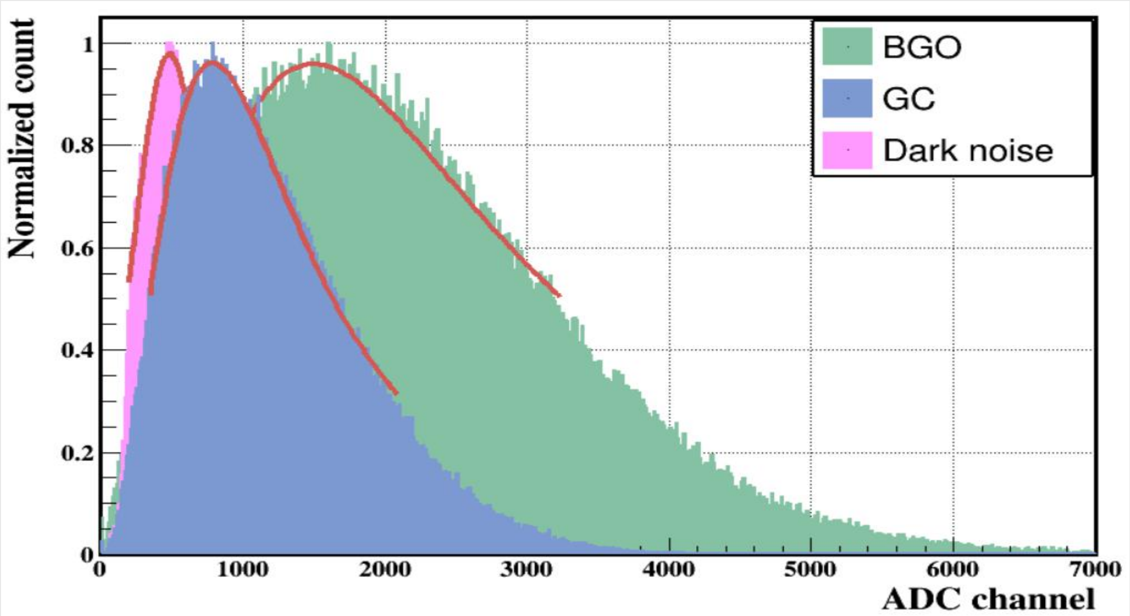
- XPS
- XRD

The PMTs information could be see the talk in WG7 <The R&D of the MCP based PMTs for High Energy Physics Detectors>

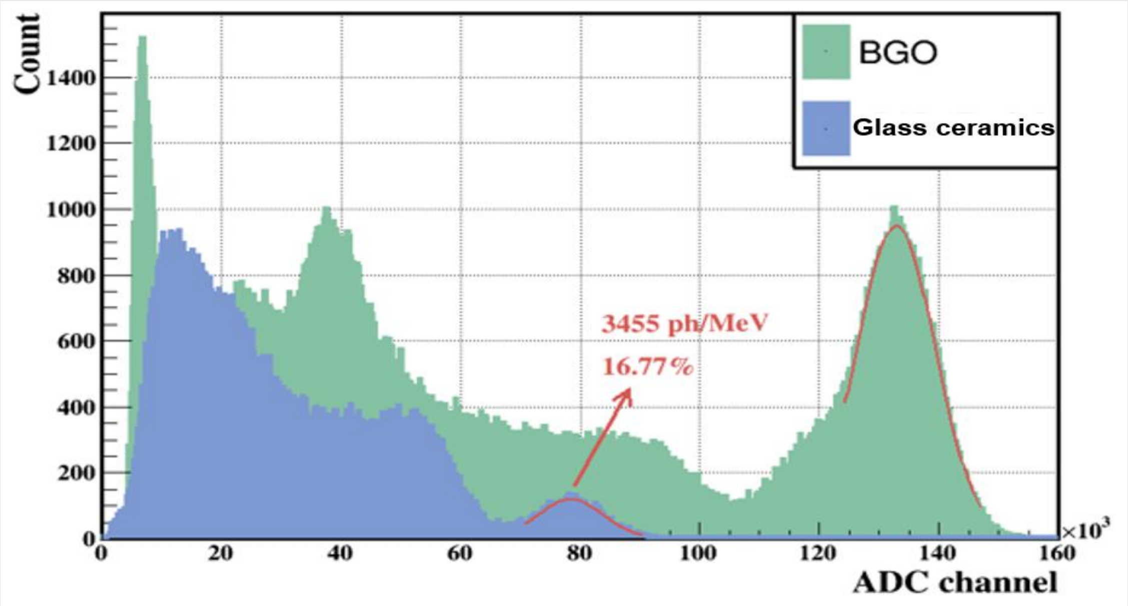
2.3 Energy Spectra--Light Yield

Light Yield @gamma-ray VS @ X-ray

- X-Ray Energy Spectra

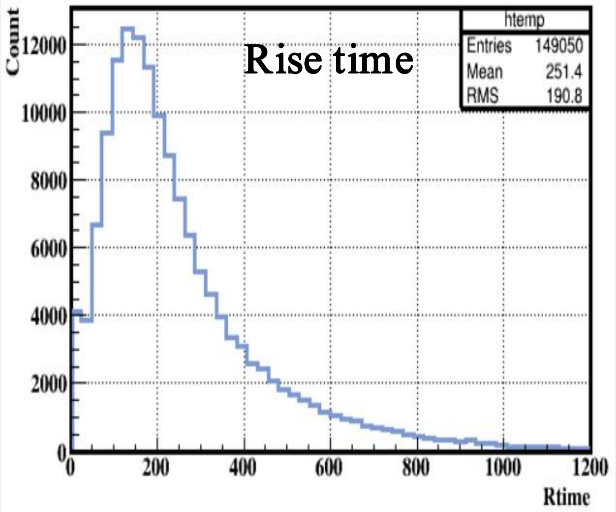


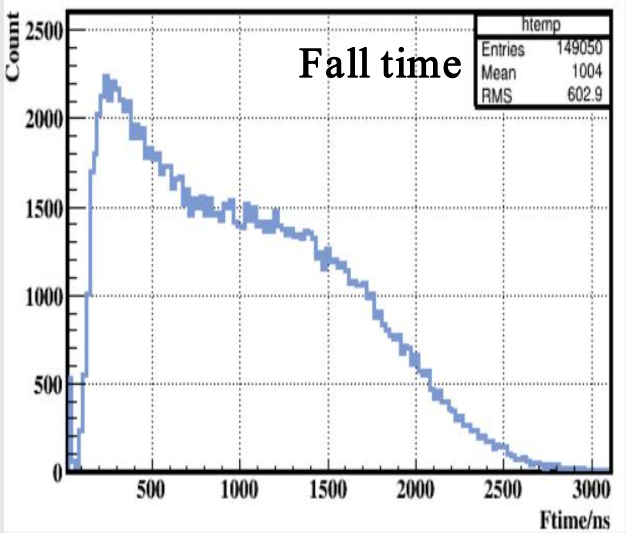
- ^{137}Cs γ-Ray Energy Spectra

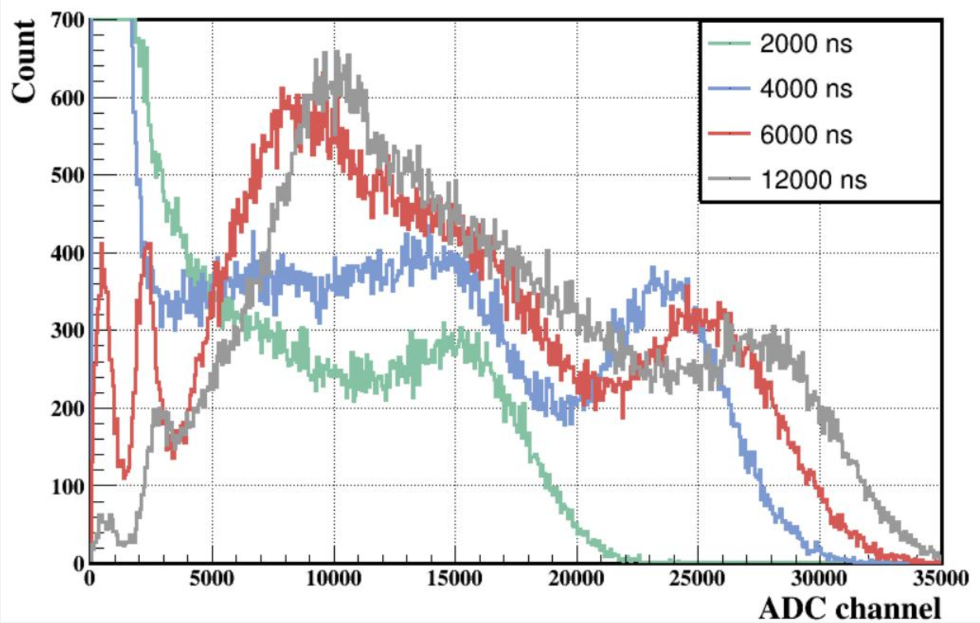


- Under X-ray, the photon number of the GC detected by SiPM is about **32%** of BGO crystal;
- Under ^{137}Cs, the photon number of the GC detected is about **59%** of BGO crystal;
- Therefore, the relative light yield of glass scintillator under X rays is not equal to γ rays.

2.4 Effect of integral time on glass scintillator



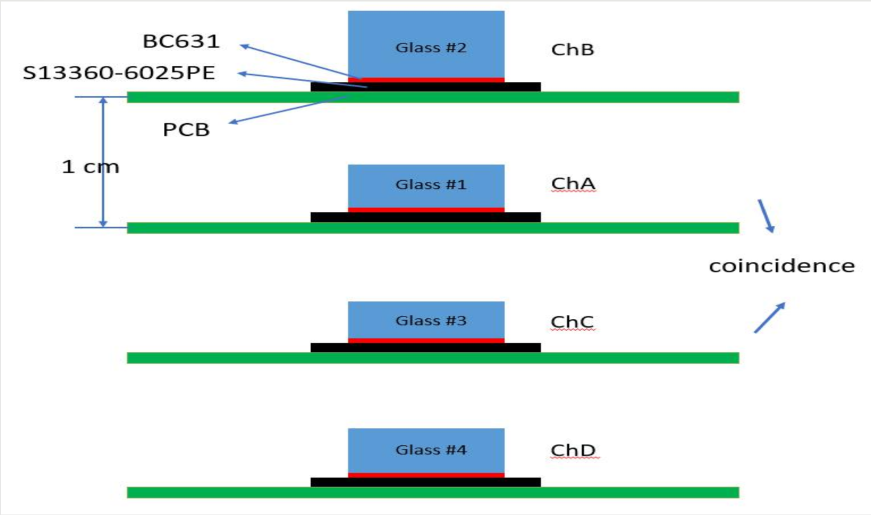


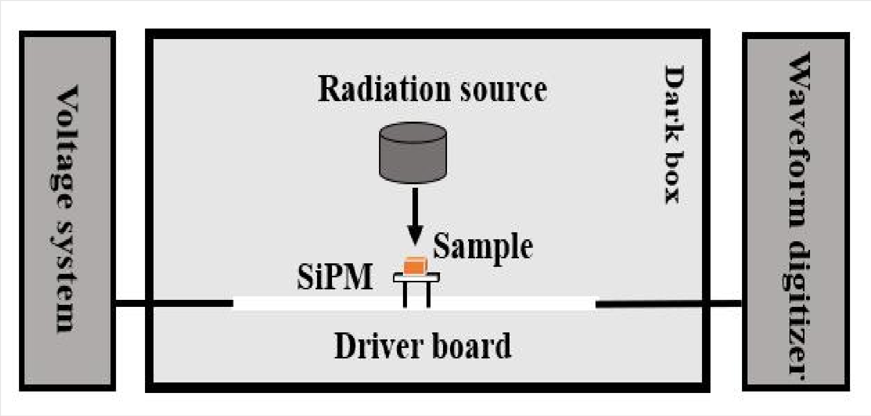


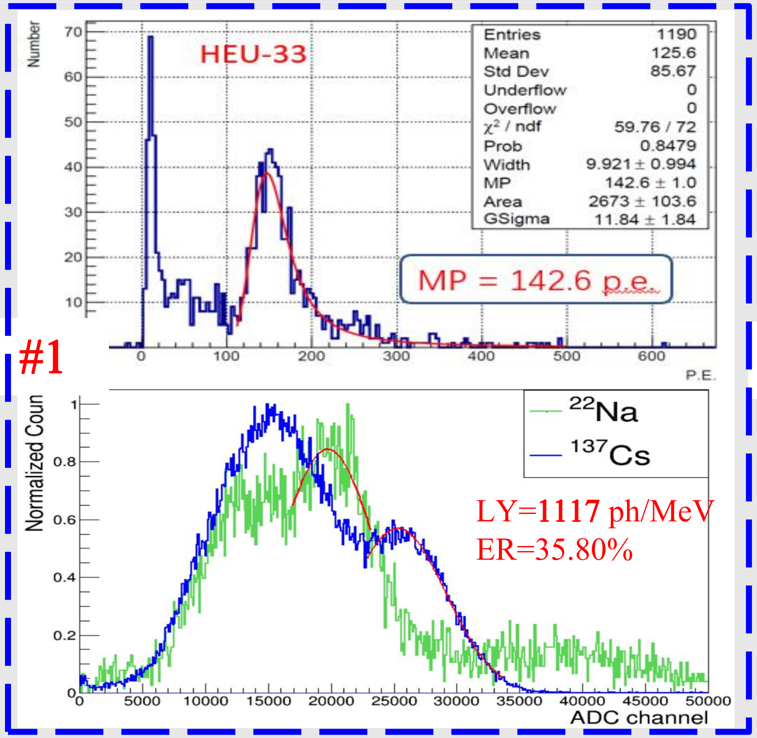
Integral time (ns)	LY (ph/MeV)	ER (%)	Decay time (ns)
1000	/	/	619.9
2000	708	44.2	279.4 (0.3%), 3594.7
4000	1126	26.4	198.7 (0.9%), 1708.0
6000	1204	28.6	165.8 (0.6%), 1652.2
8000	1247	28.8	152.2 (0.5%), 1653.5
10000	1278	28.6	167.5 (0.6%), 1649.0
12000	1296	30.0	166.0 (1.0%), 1642.4

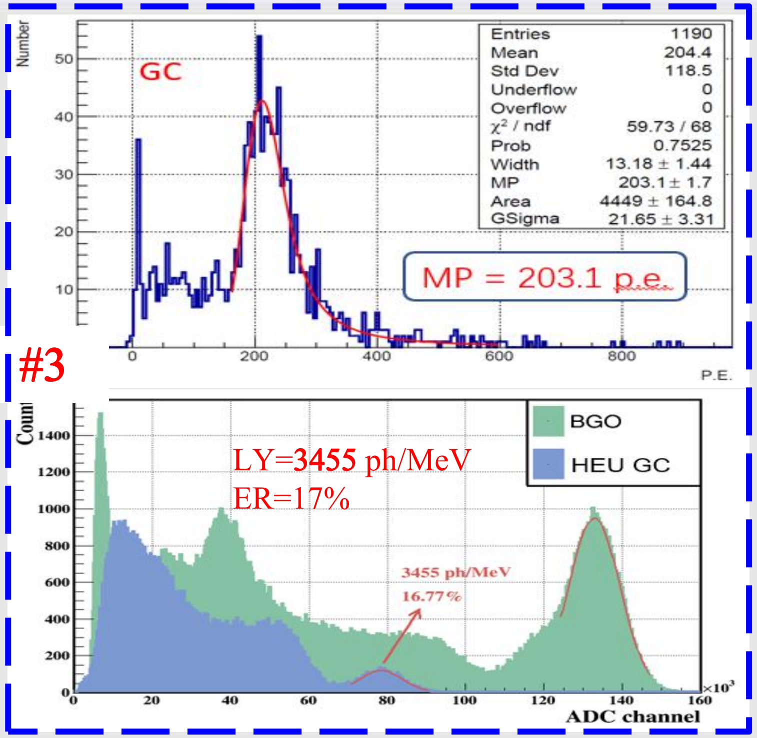
- According to RT+FT, the integral time should be set to more than 4000 ns.
- Taking **0.5 mol% Ce^{3+}-doped glass** as an example, the calculated light yield increases with the increase of the integral time due to large slow component decay time, and the longer the integral time, the worse the energy resolution.
- Therefore, the appropriate integral time should be set up according to different decay of the glasses.

2.5 The Light Yield--Cosmic Ray VS Gamma Ray









- Considering the density and thickness of the glasses, the MIP response by the cosmic ray is consistent with the light yield of the glass scintillator by gamma ray.

	MIP（p.e.）	LY（ph/MeV）	Thicknes（mm）	Density（g/cm³）	mip/(Thi*Den)	LY/MIP
#1	143	1117	2.6	5.4	10.2	**110**
#3（GC）	203	3455	2	3.3	30.6	**113**

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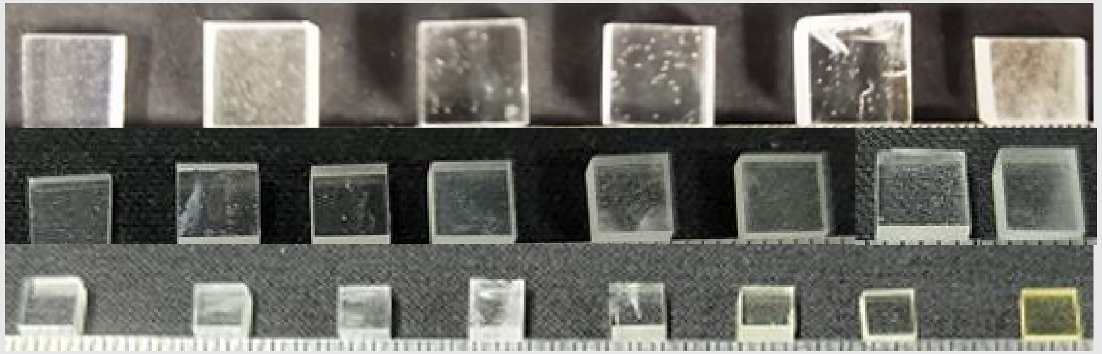
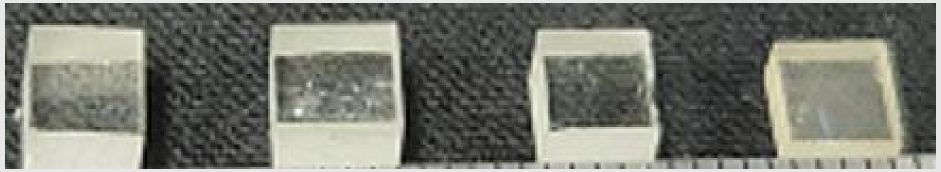
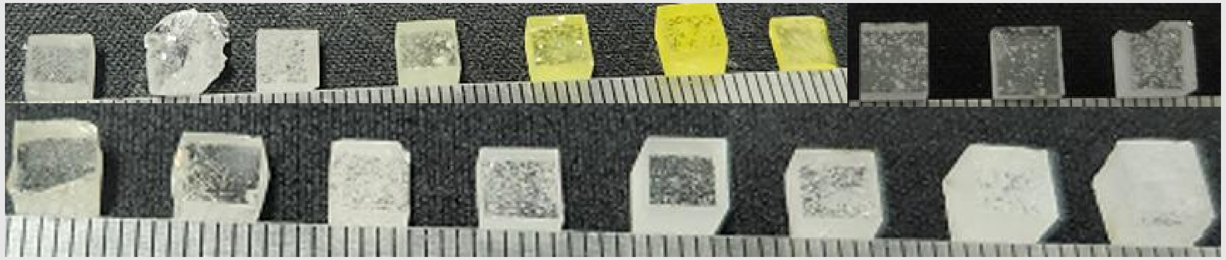
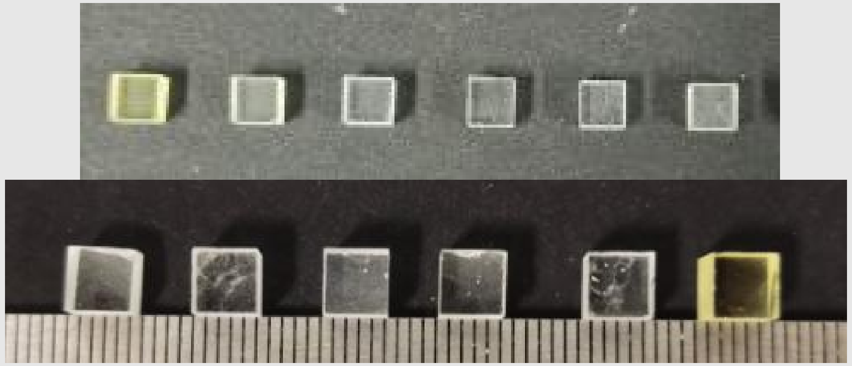
3.0 The GS Samples produced in one year（>200）

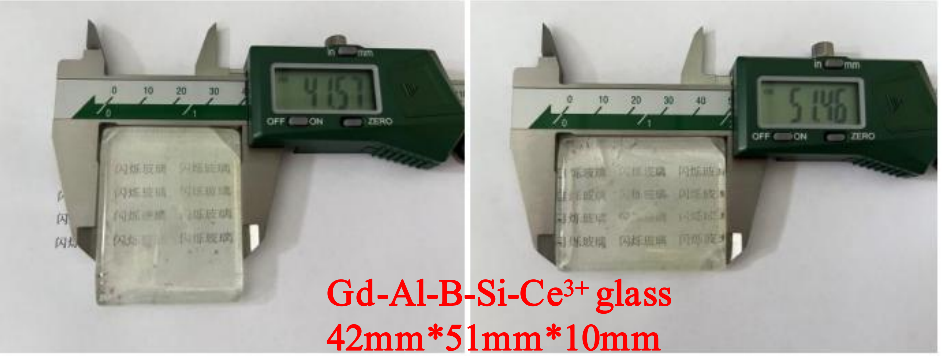


Gd-Ga-B-Ce^{3+} glass
20mm*20mm*12mm



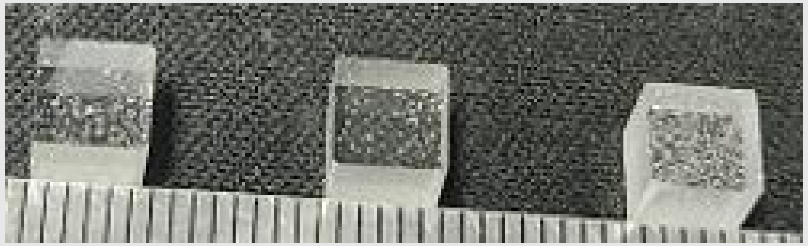






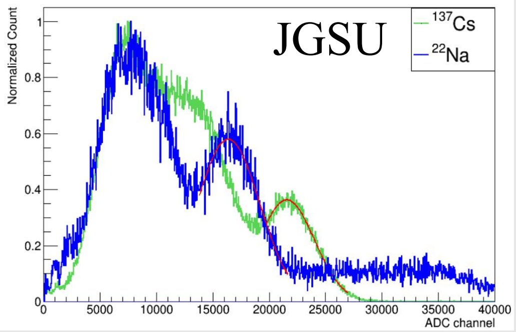
Gd-Al-B-Si-Ce^{3+} glass
42mm*51mm*10mm

Gd-Al-B-Si-Ce^{3+} glass
37mm*30mm*9mm



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 ns (18%), 1235 ns



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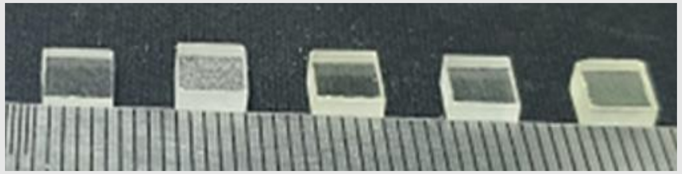
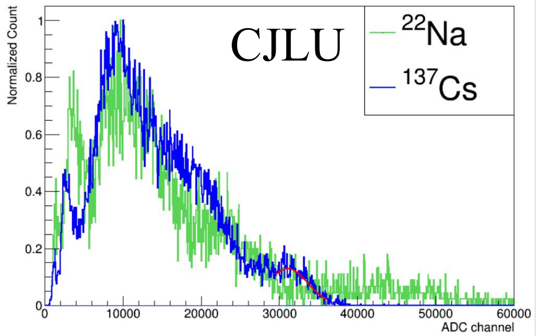
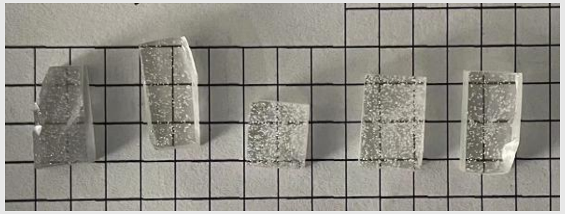


(2022.05)Opt. Mater. 2022(130): 112585

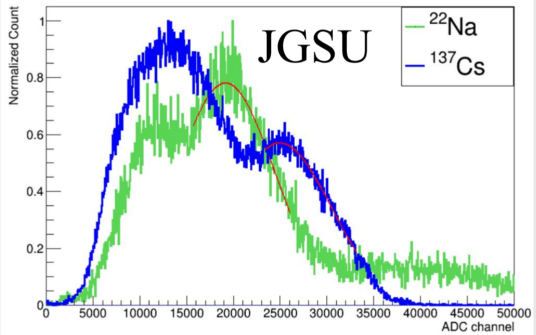
- Density~4.0 g/cm^3
- LY>1200 ph/MeV
- ER=23.2%
- Decay=231 ns (10%), 1897 ns



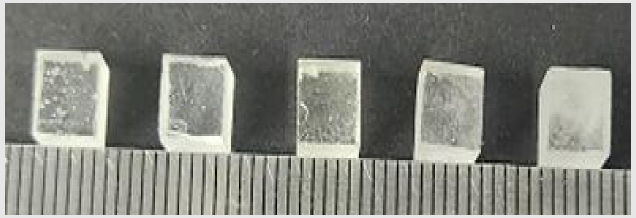
2022.06



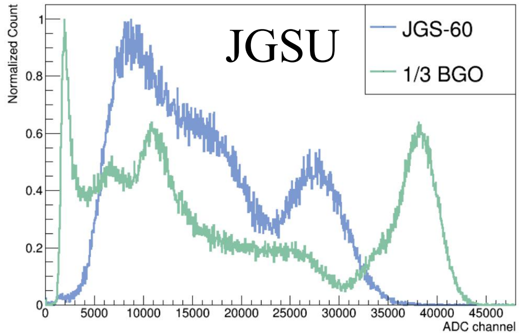
- Density~6.0 g/cm^3
- LY>1000 ph/MeV
- ER=49.6%
- Decay=847 ns



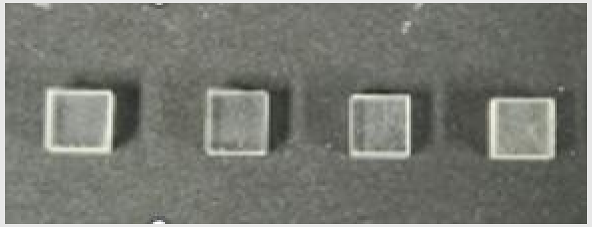
2022.11



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

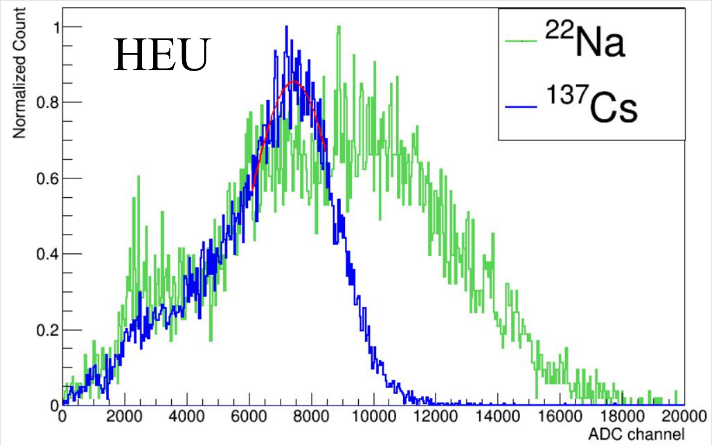


2023.02



3.2 Borate glass (Gd-Ga-B-Ce^{3+}) --GS2

- Density=5.9 g/cm^3
- LY=550 ph/MeV
- ER=None
- Decay=148 ns (16%), 1076 ns



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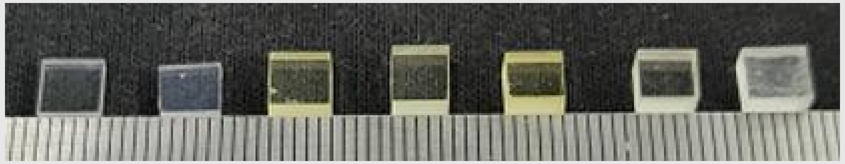
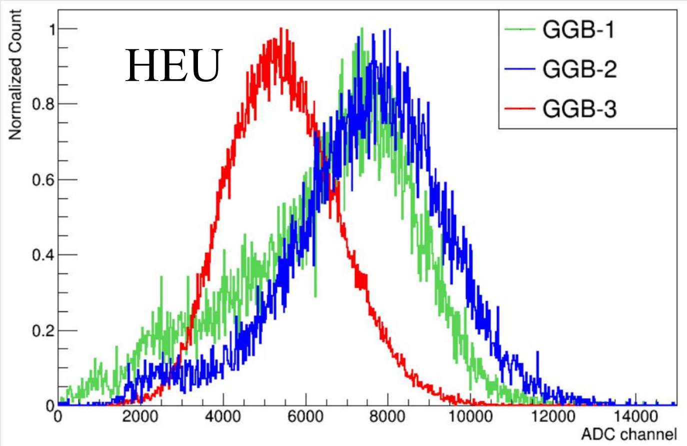
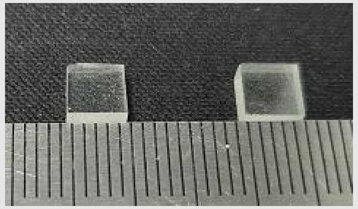


- New glass system

- Density=6.0 g/cm^3
- LY=570 ph/MeV
- ER=None
- Decay=277 ns



2022.09



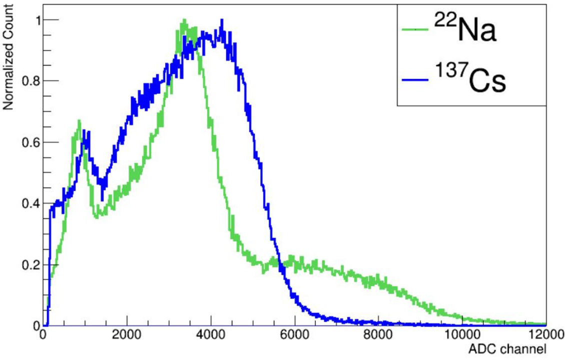
Large size
20mm*20mm*12mm

2022.10

- Large size
- Fast decay

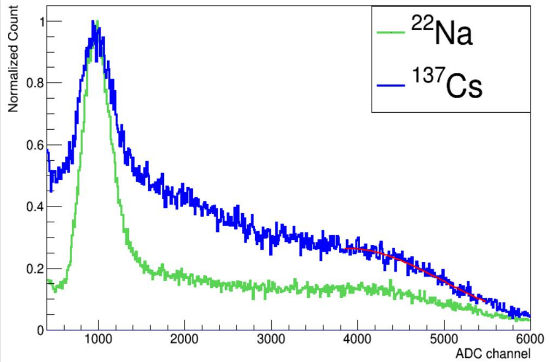
3.3 The Large size glass

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



2022.10

- Size=30*30*10 mm^3
- Density=5.2 g/cm^3
- LY~600 ph/MeV
- ER=None



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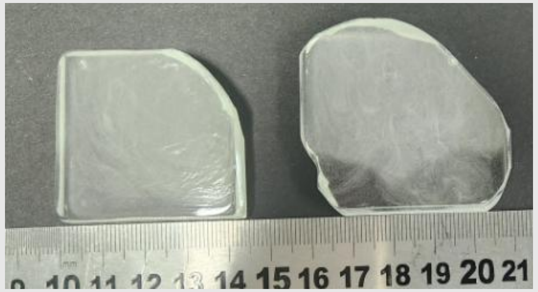
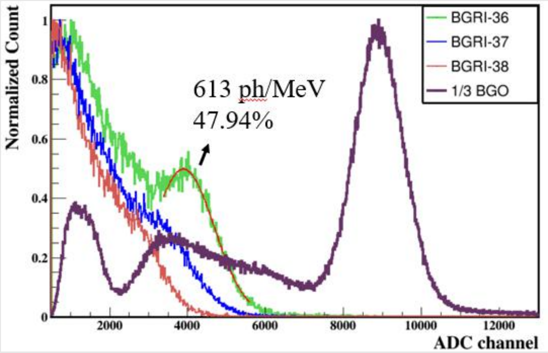


- Size=28*28*10 mm^3
- Density=5.2 g/cm^3
- LY=613 ph/MeV
- ER=47.9%



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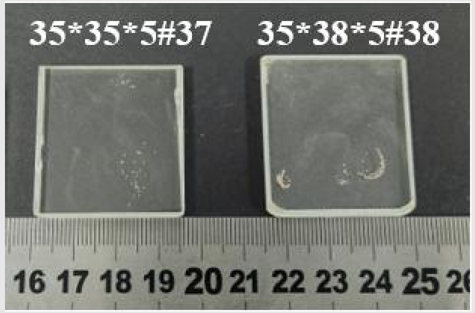
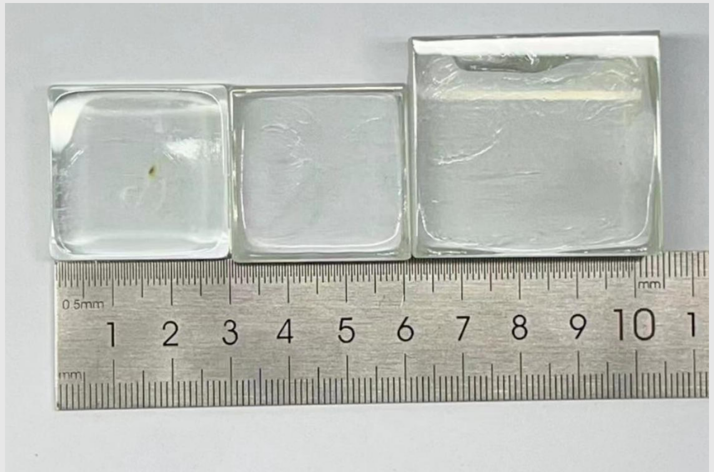


Under Test

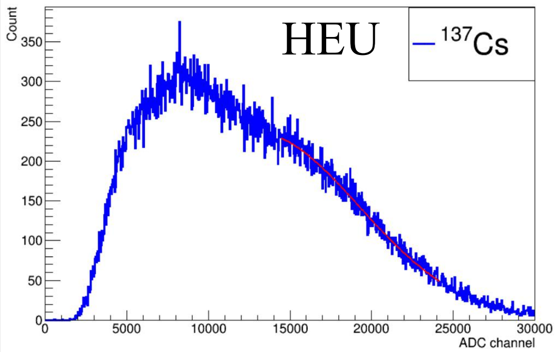
2023.03



3.4 Glass Ceramic（Gd-Y-K-Si-Ce^{3+}）--GC

About Glass Ceramic could be seen in these Ref.
(2021.07) Opt. Lett. (2021), 46(14), 3448;
(2021.11) J. Mater. Chem. C, 2021, 9, 17504;
(2022.11) J. Eur. Ceram. Soc., 2022;

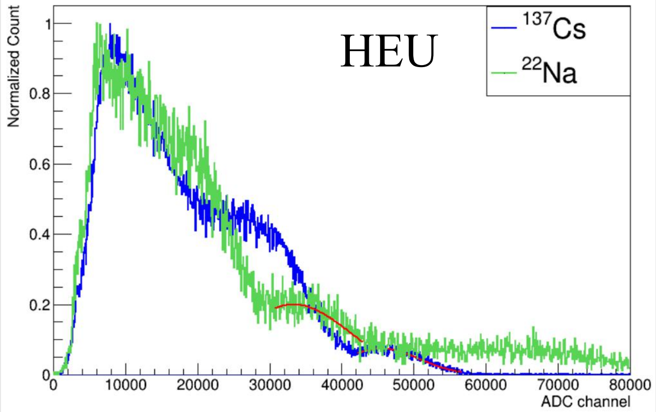
- Density~ 3.3 g/cm³
- LY=519 ph/MeV
- ER=None
- Decay=240 ns (47%)， 1752 ns



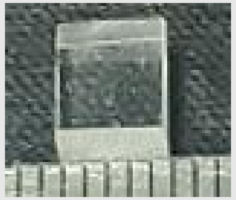
2022.04

(2022.10) J. Mater. Chem. C, 2021, 9, 17504

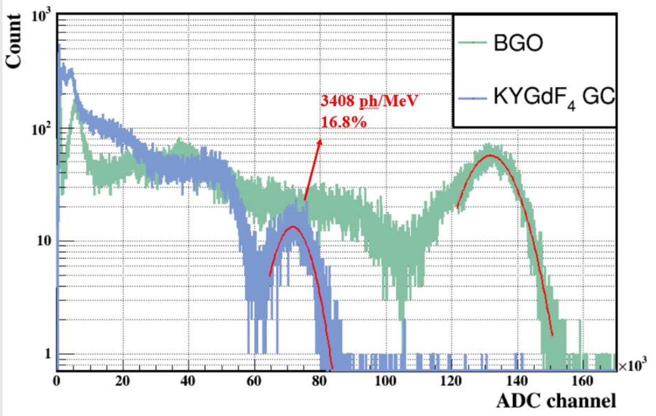
- Density~ 3.3 g/cm³
- LY>1600 ph/MeV
- ER=27.3%
- Decay=210 ns (53%)， 1622 ns



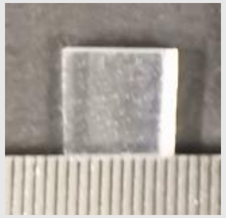
2022.10



- Density~3.3 g/cm³
- LY>3400 ph/MeV
- ER=16.8%
- Decay= 321 ns (33%), 1606 ns



2022.11



Outline

- 1. The Motivation and the Design
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4.0 Simulation setting （--> next to G4）

TracePro

- The Monte Carlo method
- To solve various statistical calculation problems
- Accurately simulate the randomness of diffuse reflection
- Trace and record each photon from its creation to its disappearance

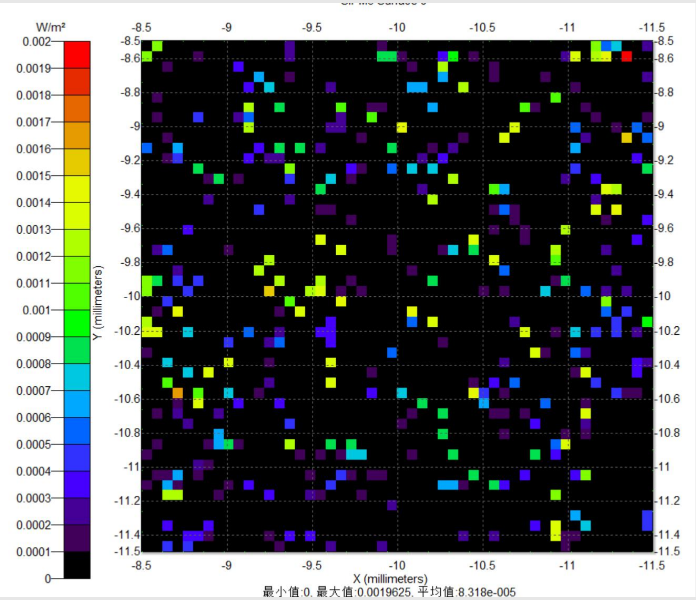
01 Set up the geometrical mode

02 Set optical material

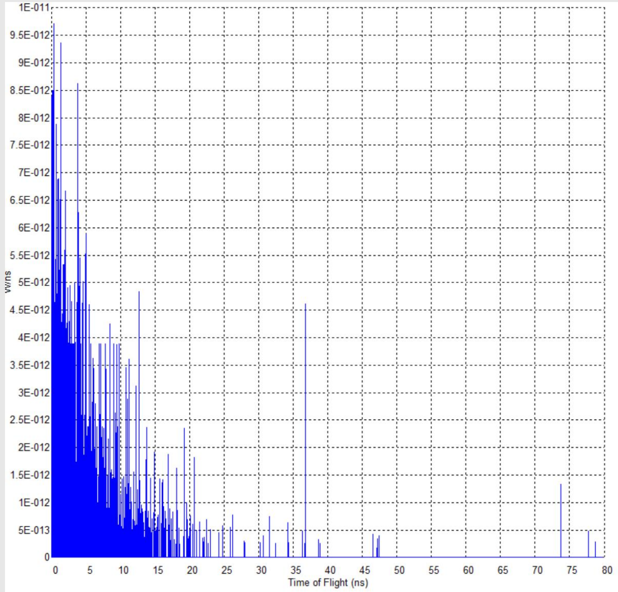
03 Define light source parameters

04 Perform ray tracing

05 Analyze simulation results

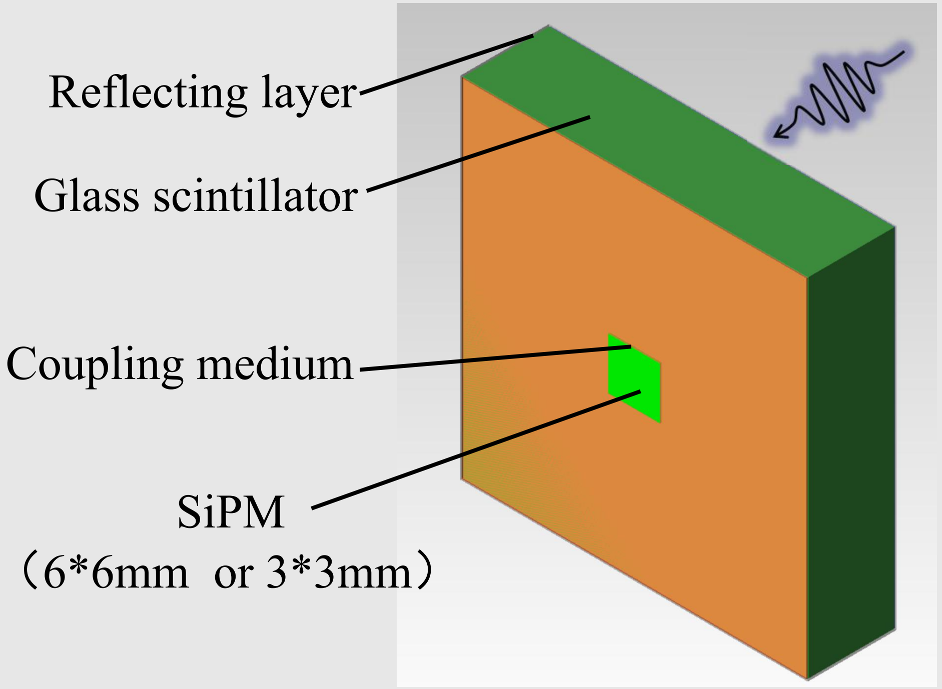


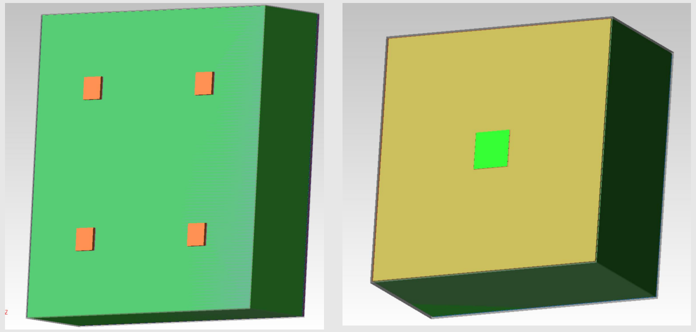
➢ the Uniformity of light yield



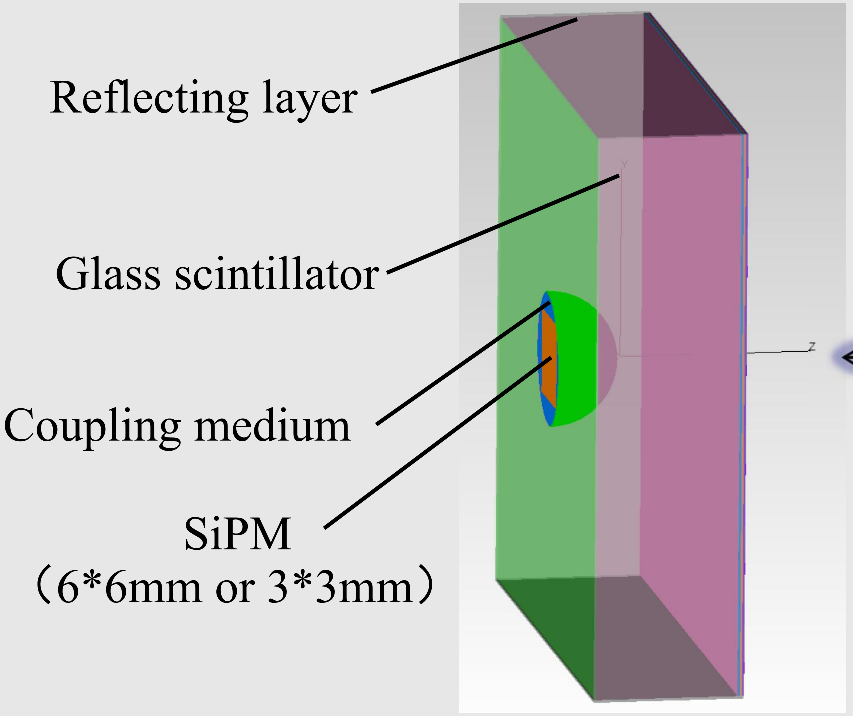
➢ the output light with time

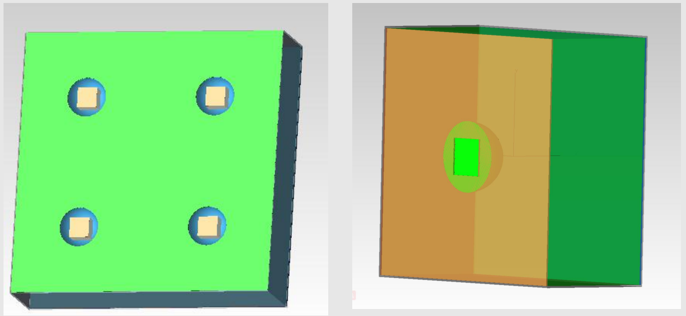
4.1 Module (1) Coupling mode of GS and SiPM





- Direct detection





- Hemisphere detection

4.1 Module (2) The Reflection Film

Aluminum / ESR film

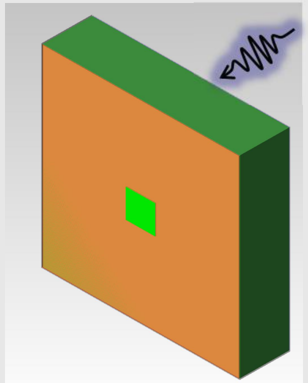
(specular reflection)

ref.ratio = 80% / 99%

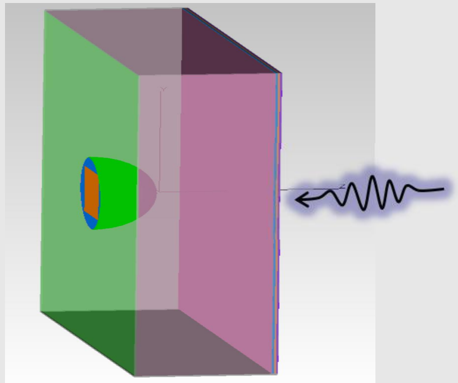
Teflon/

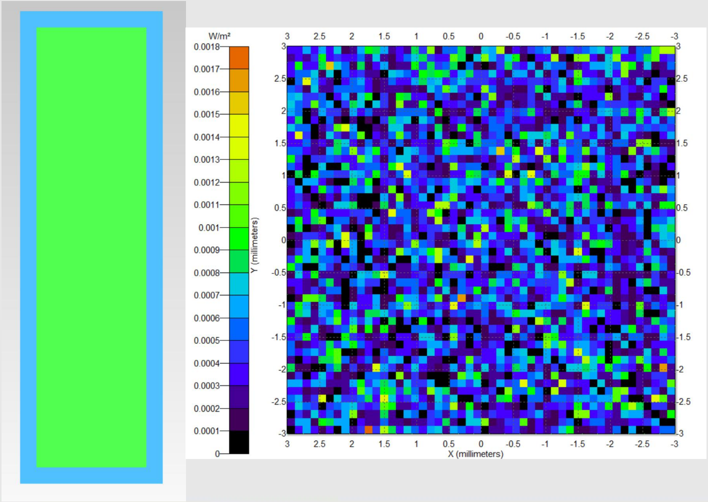
(diffuse reflection)

ref.ratio =98%

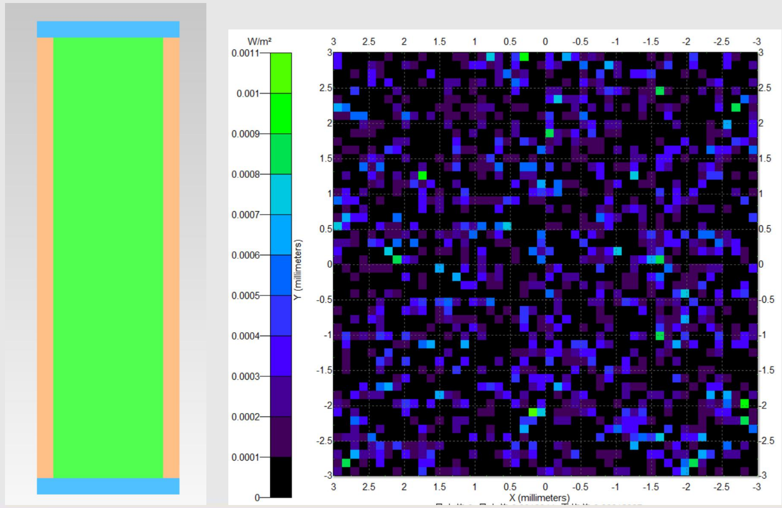


VS

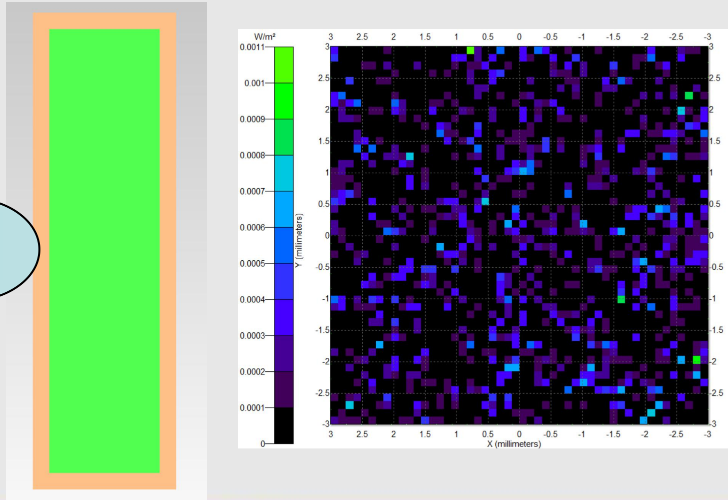




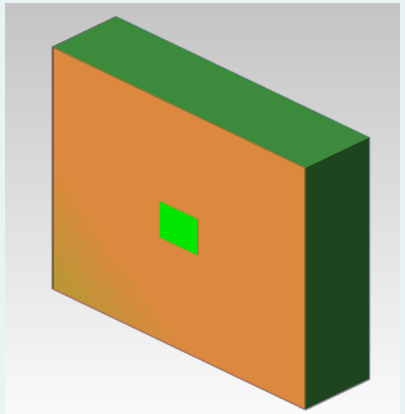
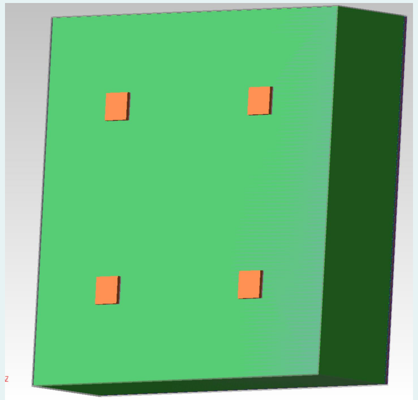
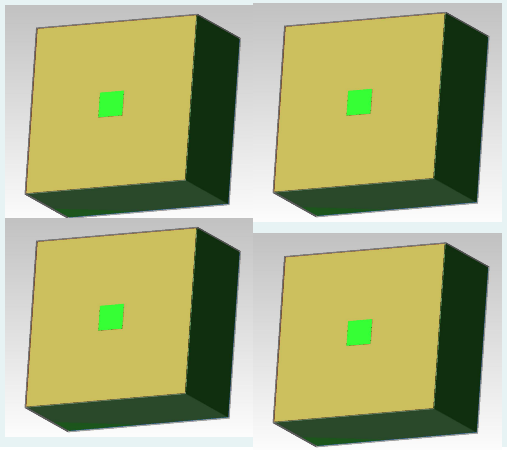
VS



VS



4.2 The Results

	GS=40mm*40mm SIPM= 6mm*6mm	GS=40mm*40mm SIPM= 3mm*3mm X 4	GS=20mm*20mm X 4 SIPM= 3mm*3mm X 4
Direct detection			
Al	32777ph 3.63ns	33310ph 3.65ns	30764ph 3.69ns
Teflon	6634ph 0.55[illegible]	[illegible]	7036ph 0.64ns
Teflon+Al	9364p[illegible] [illegible].87ns	9637ph 0.78ns	8740ph 0.66ns

Preliminary Results!

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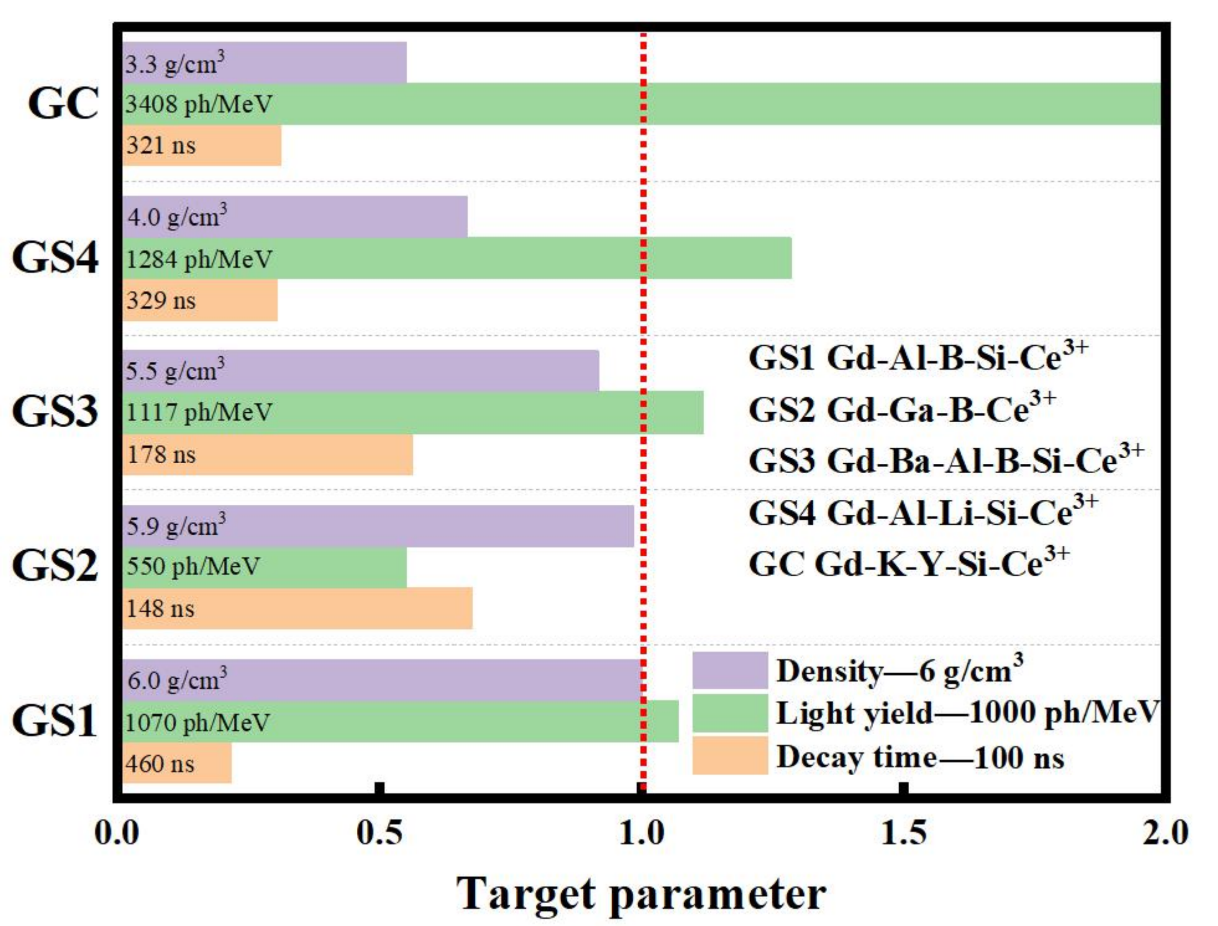
5.1 Summary



Glass scintillator of good energy resolution, fast decay, high density and light yield

- **6.0 g/cm³ & 1072 ph/MeV with 24.4% @662keV & 460 ns —Gd-Al-B-Si-Ce^{3+} glass**

- Ultra-high density **Tellurite Glass**—6.6 g/cm³
- High light yield **Glass Ceramic**—3400 ph/MeV
- Fast scintillating Decay Time—100 ns
- Large size Glass—42mm*51mm*10mm

5.2 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.

5.3 Next plan

Gd-(Ba/Al)-B-Si -Ce^{3+} glass will be the focus of future research.

- The glass scintillators were prepared repeatedly to ensure its performance stability;
- The properties of the glasses will be further improved through **raw material purification;**
- To reduce the scintillation decay time of the glasses (<100 ns);
- To produce the large size and mass preparation samples(4cm*4cm);
- Test the **radiation resistance** and **mechanical properties** of the glasses (MDI);
- Explore the structural properties of the glasses.

闪烁玻璃合作组
Glass Scintillator Collaboration

See the unseen
change the unchanged

The Innovation

THANKS