Progress of the Glass Scintillator Calorimeter

闪烁玻璃合作组
Glass Scintillator Collaboration

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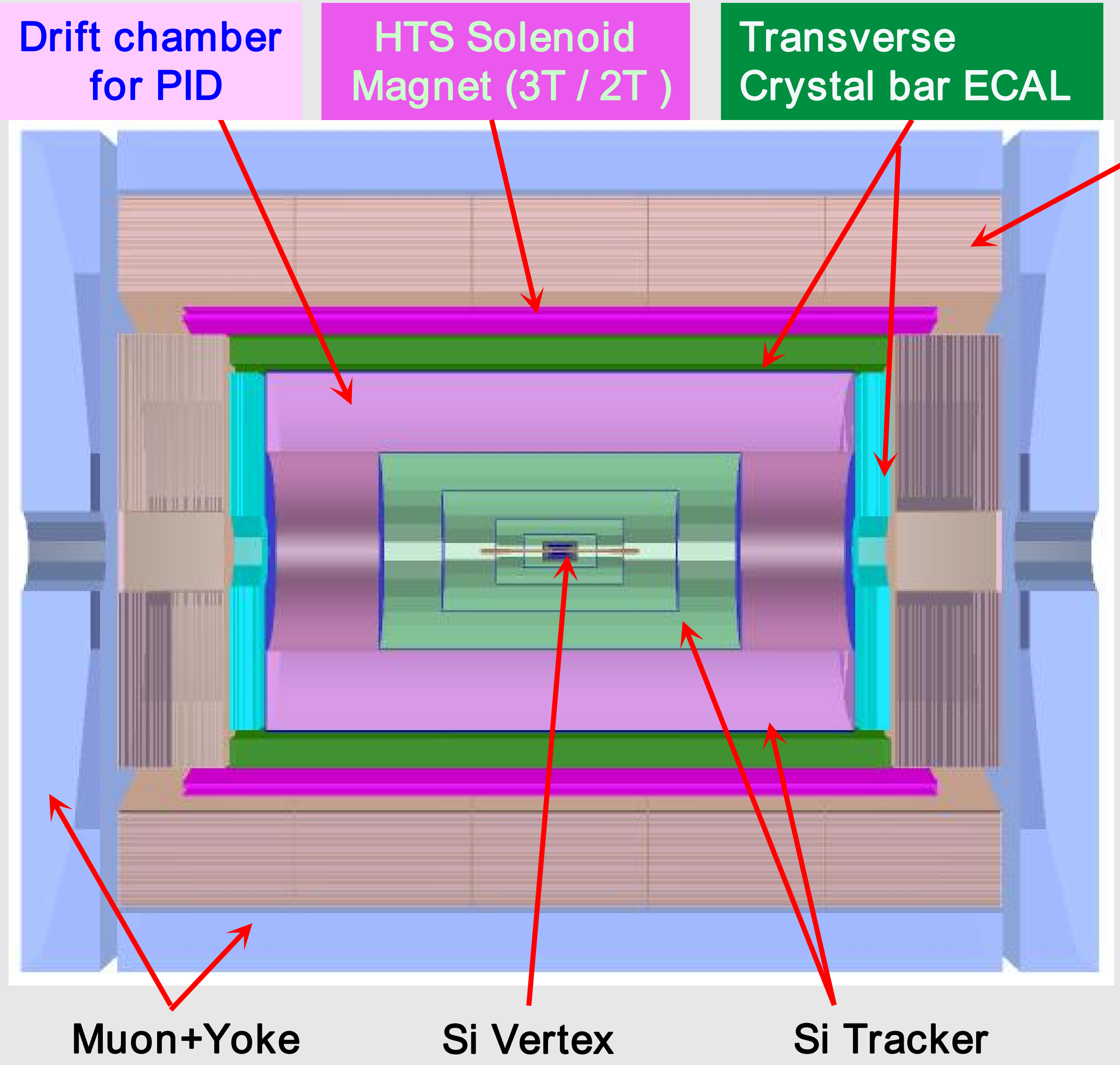
The Institute of High Energy Physics, CAS

2023. July. 3rd-7th, The **2023 International Workshop on Circular Electron PositronCollider (European Edition)**

The 4th Conceptual Detector Design



Scint Glass PFA HCAL

Advantage: Cost efficient, high density

Challenges: Light yield, transparency, massive production.

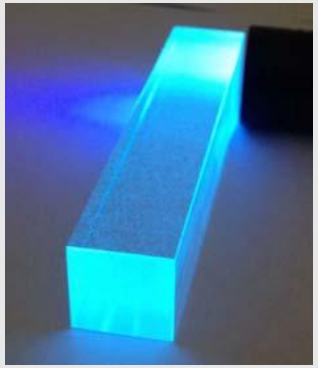
- Further performance goal: BMR 4%→3%
- Dominant factors in **BMR**: charged hadron fragments & HCAL resolution
  - Higher density provides higher energy sampling fraction
  - Doping with neutron-sensitive elements: improve hadronic response (Gd)
  - More compact HCAL layout (given 4~7 nuclear interaction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

Outline

- 1. The Status of the GS Group;
- 2. The Simulation for GS Detector
- 3. The Progress of the GS Production;
- 4. Summary and Next Plan

1.0 What is the Glass Scintillator？

Plastic Scintillator

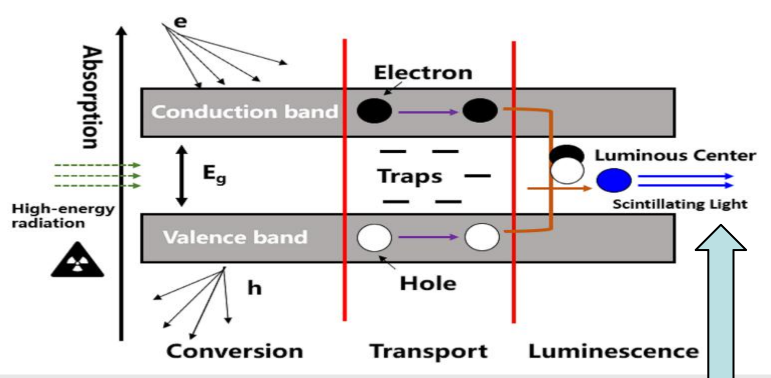


Glass Scintillator

Crystal Scintillator

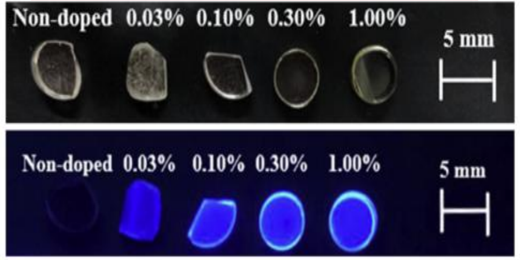
High light yield	★★	High light yield	★	High light yield	★★★
Fast decay	★★★	Fast decay	★★	Fast decay	★★
Low cost	★★★	Low cost	★★★	Low cost	★
Large Density	★	Large Density	★★	Large Density	★★★
Energy resolution	★	Energy resolution	★★	Energy resolution	★★★
Large size	★★★	Large size	★★★	Large size	★

1.1. The Design of the Glass Scintillator



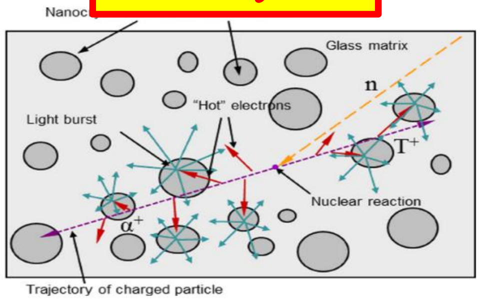
- Scintillation mechanism---- **Luminescence Center**
- **Conversion**—photoelectric effect and Compton scattering effect;
- **Transport**—electrons and holes migrate;
- **Luminescence**—captured by the luminescent center ions

Lanthanide elements



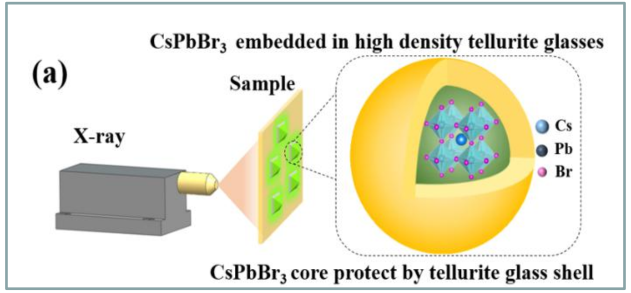
Journal of Alloys and Compounds 782 (2019) 859-864

Nanocrystals



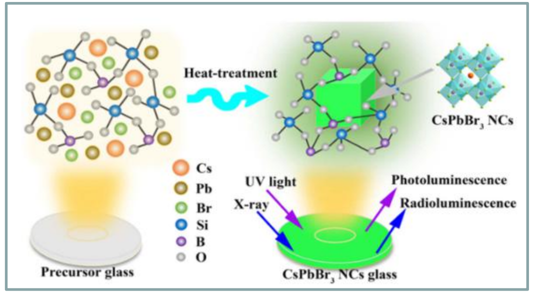
IEEE TNS 60 (2) 2013

Quantum Dots



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

Lanthanide + Quantum Dots



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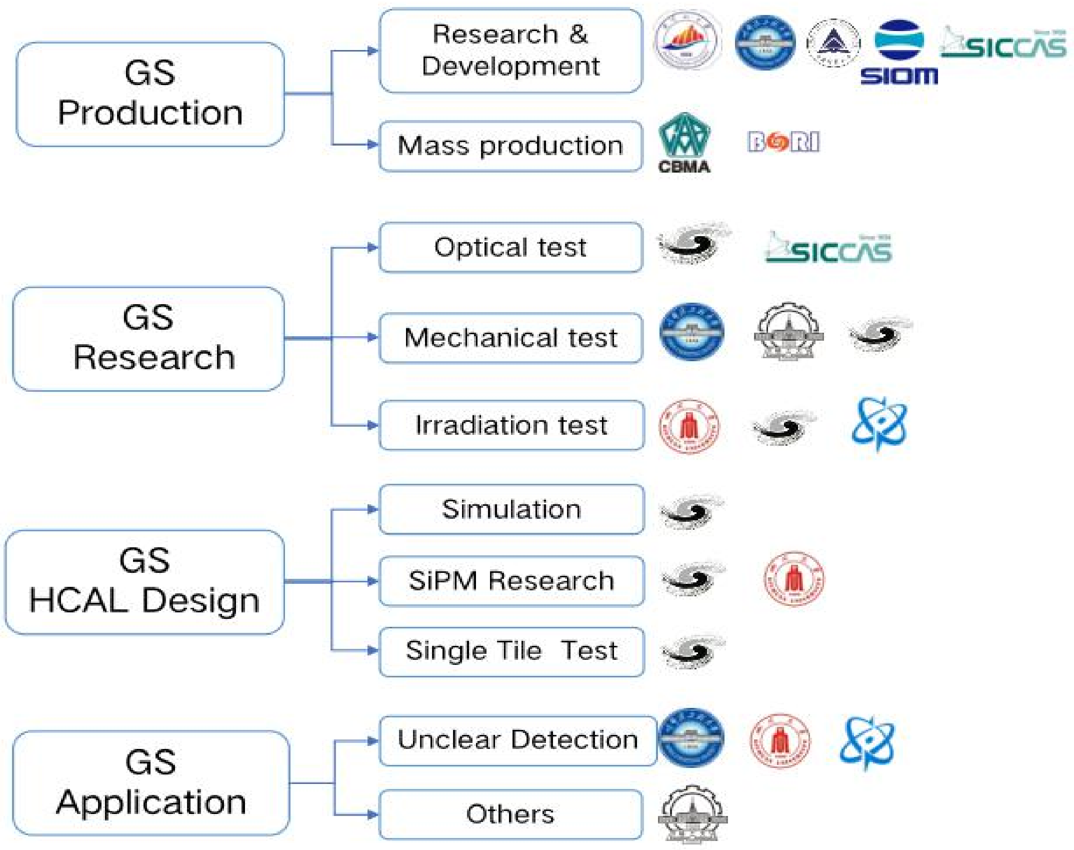
- High Light Yield： Lanthanide for the Luminescence Center：Cerium（Ce）；
- High Density and Low radioactivity background：Gadolinium（Gd）；

1.2 Large Area Glass Scintillator Collaboration



- GS Production
  - Research & Development
  - Mass production
- GS Research
  - Optical test
  - Mechanical test
  - Irradiation test
- GS HCAL Design
  - Simulation
  - SiPM Research
  - Single Tile Test
- GS Application
  - Unclear Detection
  - Others

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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
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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

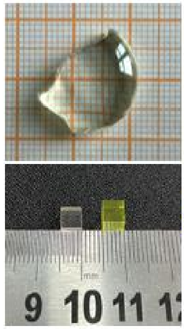
-- The Glass Scintillator Collaboration Group established in Oct.2021, only 5 groups join together；

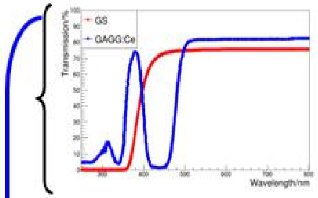
-- There are 3 Institutes of CAS, 5 Universitys, 3 Factorys join us for the R&D of GS;

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

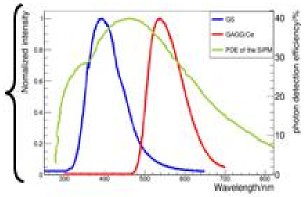
1.3 The Scintillator Test Facilities

➢ The Scintillator Test System

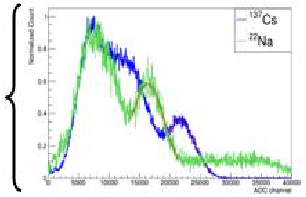




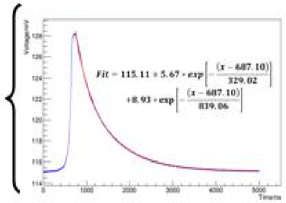
- ➢ Density;
- ➢ Elastic Modulus;
- ➢ Refractive Index;
- ➢ Transmission Spectrum



- ➢ 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

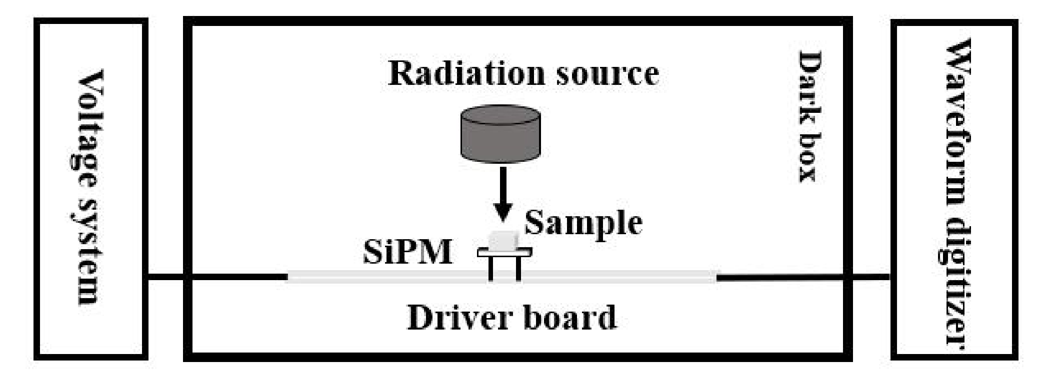
- ■ Spectroscopy: Transmission/Absorption、PL-PLE、XEL
- ■ Nuclear radiation detection: Light yield、Energy resolution、MIP response、n/γ Discrimination
- ■ Time characteristics: Rise time、Decay time、Afterglow、Coincidence time resolution
- ■ Reliability: Aging test、Radiation resistance characteristics

The published papers of different Scintillator 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

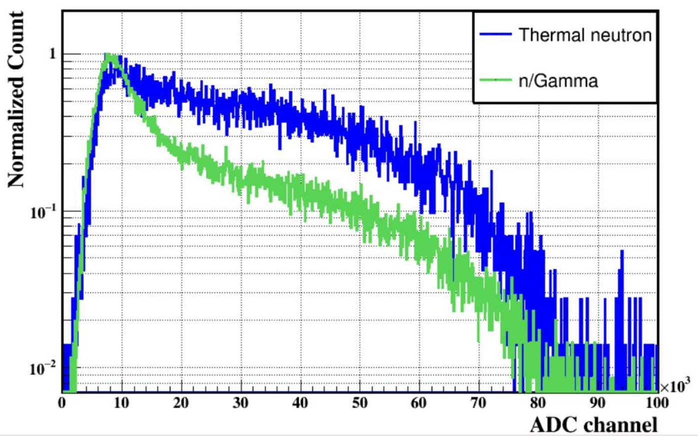
Radioactive Sources Test -- Energy Spectrum

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

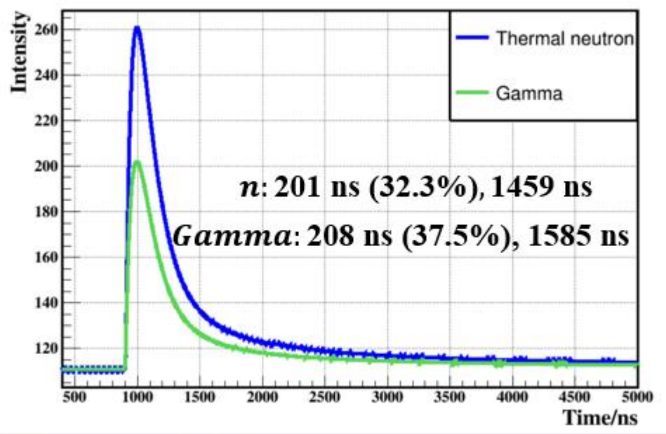


Through the waveform sampling data acquisition system, we can obtain **Light Yield, Energy Resolution and Decay Time** of the scintillator.

- γ/n Energy Spectra



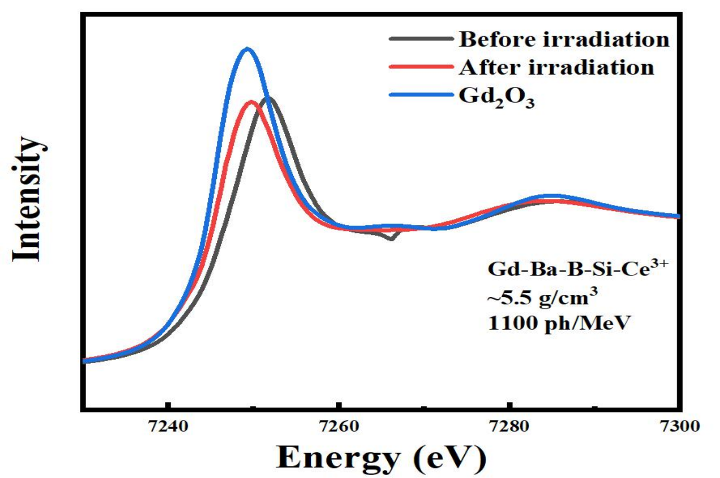
- γ/n Decay Time



Special Condition TEST Platform

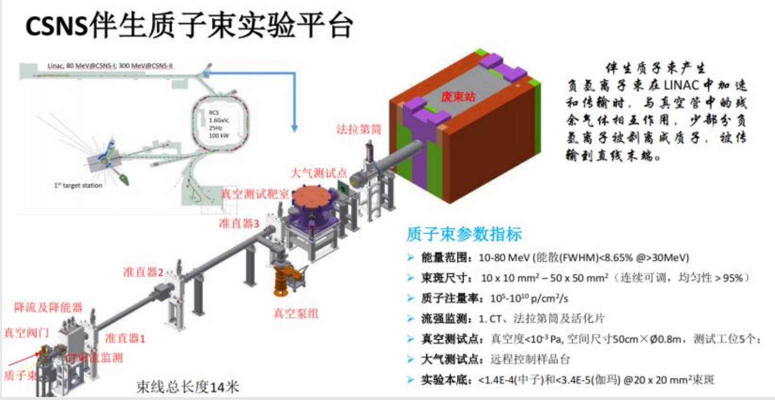
- IHEP--XAFS

Study the elements influence of GS sample



Gd-Ba-B-Si-Ce^{3+}
~5.5 g/cm^3
1100 ph/MeV

- IHEP-CSN-- P Beam



CSNS伴生质子束实验平台

束线总长度14米

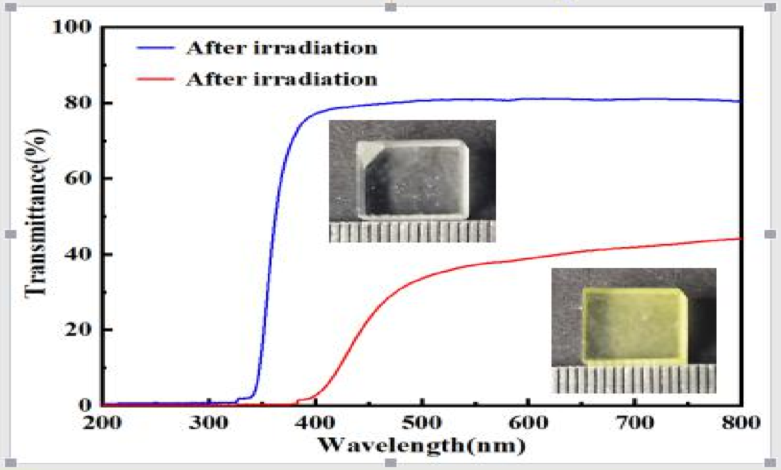
伴生质子束产生

负氢离子束在LINAC中加速和传输时，与真空管中的残余气体相互作用，少部分负氢离子被剥离成质子，被传输到直线末端。

质子束参数指标

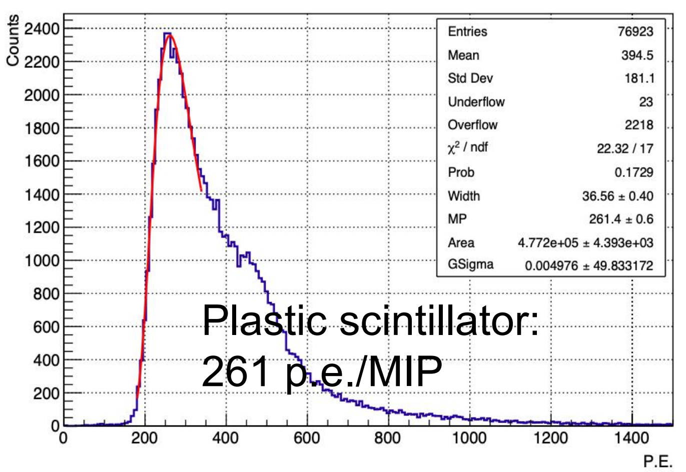
- **能量范围：** 10-80 MeV (能散(FWHM)<8.65% @>30MeV)
- **束斑尺寸：** 10 x 10 mm^2 – 50 x 50 mm^2（连续可调，均匀性 > 95%）
- **质子注量率：** 10^5-10^{10} p/cm^2/s
- **流强监测：** 1. CT、法拉第筒及活化片
- **真空测试点：** 真空度<10^{-3} Pa, 空间尺寸50cm×Ø0.8m，测试工位5个；
- **大气测试点：** 远程控制样品台
- **实验本底：** <1.4E-4(中子)和<3.4E-5(伽玛) @20 x 20 mm^2束斑

Study the anti-irradiation characteristics of samples;



- CERN-MUON beam

Study the particle interaction in GS sample with MUON



Plastic scintillator:
261 p.e./MIP

Outline

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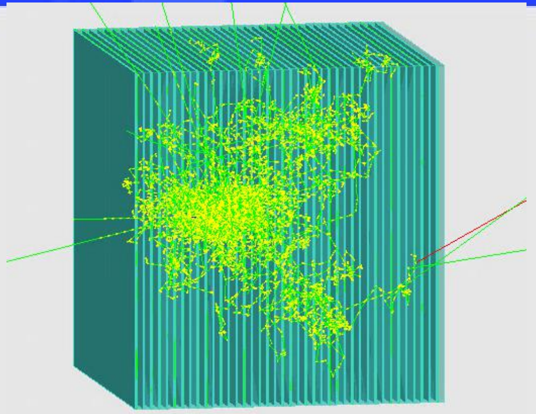
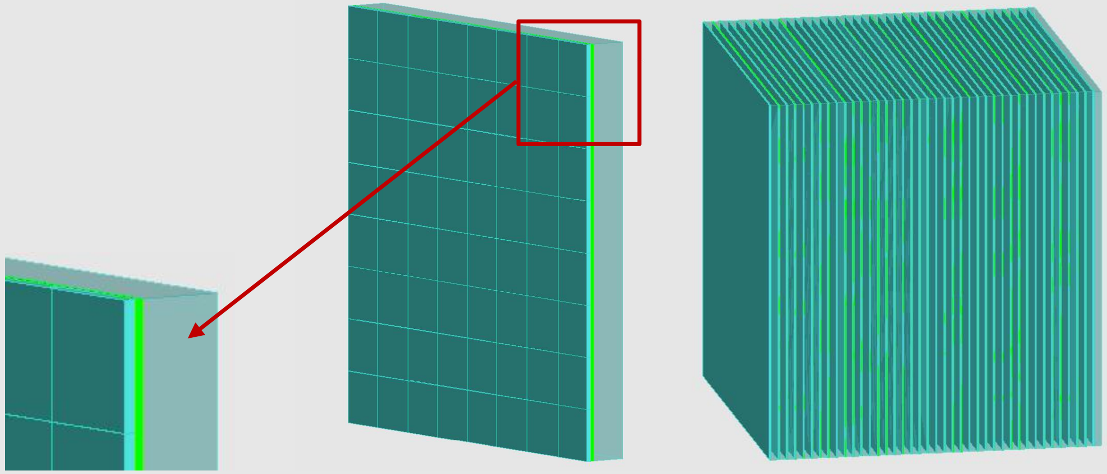
2.1 The Simulation for the Standalone

- Geometry: refer to Scintillator-Steel AHCAL (CEPC CDR baseline)
  - Replace plastic scintillator with glass scintillator
  - Nuclear interaction length (NIL) of glass and steel: 0.124 lambda for each layer (same as 3 mm PS + 20 mm Steel)
  - Glass tile transverse size: 30mm × 30mm
  - Glass tile thickness: 10 mm (target)
- Scintillator glass
  - Composition: Gd-Al-B-Si-Ce^{3+}
  - density: 6 g/cm^3 (nominal)
  - NIL: 22.4 cm
  - MIP Edep: 6.85 MeV/cm
- Energy threshold: 0.1 MIP



Event display

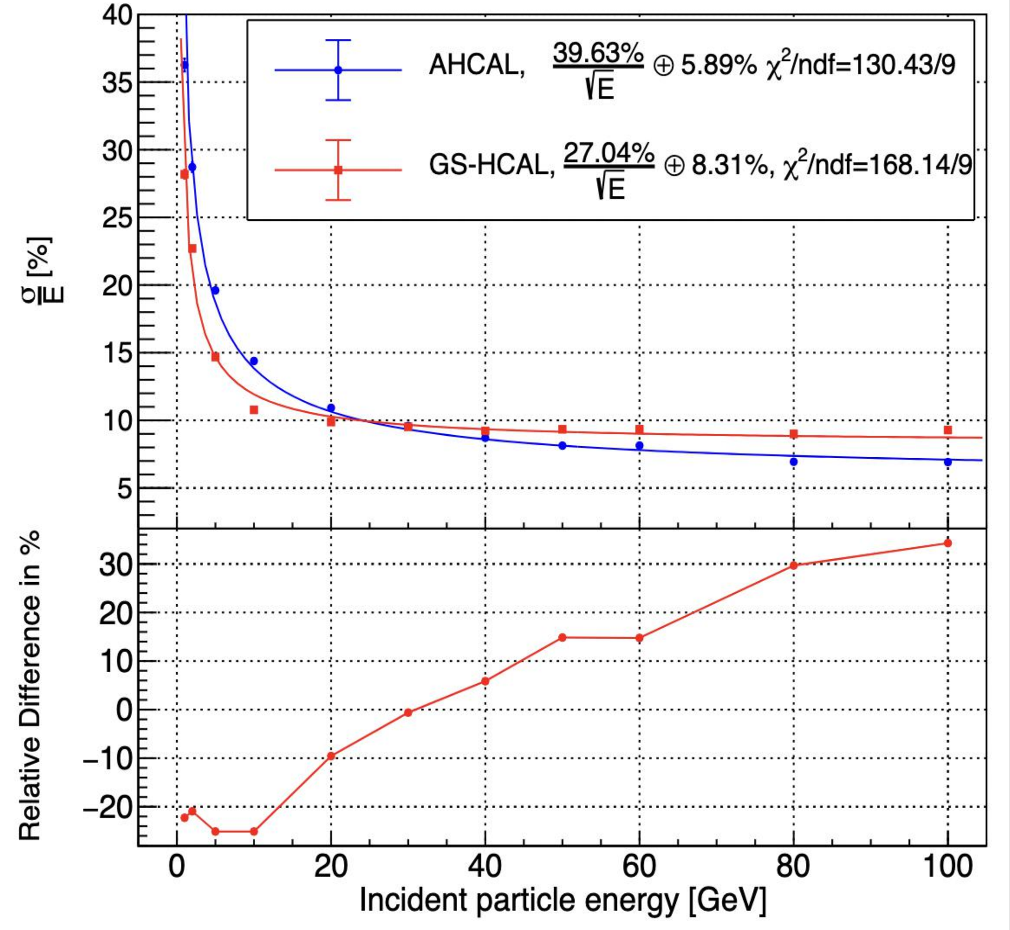


HCAL module and layer structure

CEPC AHCAL prototype schematics

MC sample: 1-100 GeV K_L^0

ENR: AHCAL vs. GSHCAL



- By varying **#layers/transverse size** of GSHCAL, to study the impact of **energy leakage** to energy resolution;
- By varying **#thickness**(glass scintillator tiles and steel plates), to study the impact of **sampling fraction** to energy resolution;
- By varying **#glass scintillator density:** 3 to 7 g/cm^3, to study the impact of **glass density** to energy resolution;
- By varying **#transverse size** of glass scintillator tile: 1X1 cm^2 to 5X5 cm^2, to study the impact of **tile transverse size** to energy resolution;

Preliminary performance comparison:

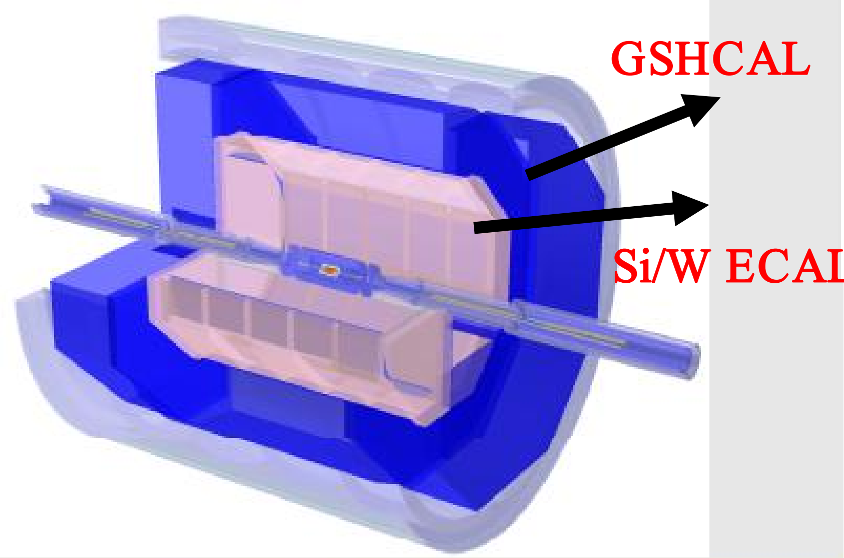
- Same tile transverse size: 30×30 mm^3
- The number of layers: 40
- Glass thickness: 10 mm
- Glass density: 6 g/cm^3
- Energy threshold: 0.1 MIP

- **GS-HCAL has a better hadronic energy resolution for jet components, since most particles in jets are below 10 GeV**

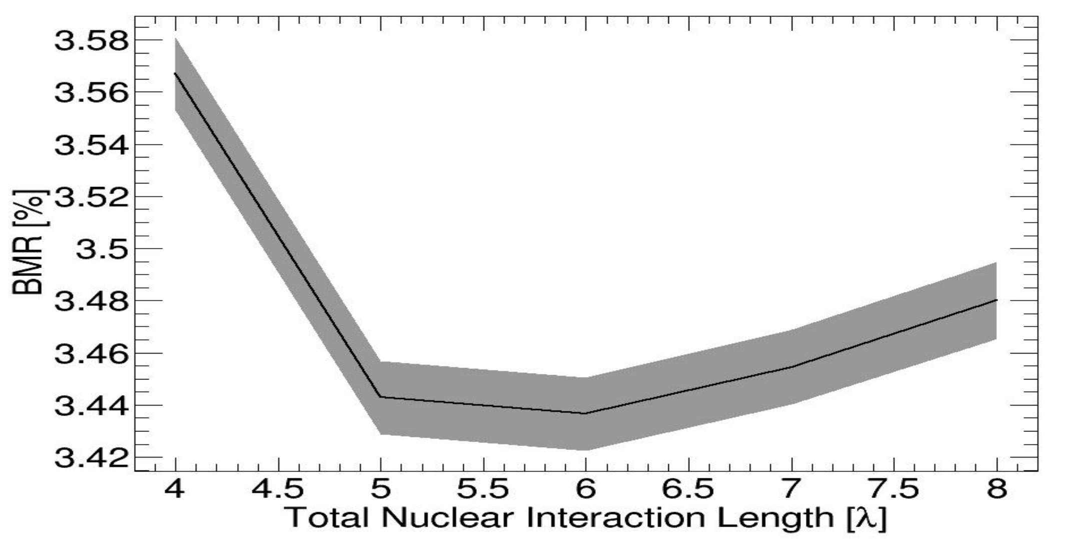
2.2 PFA performance simulation for Glass Scintillator

- Based on CEPCSoft framework and CEPC_v4 design, but replacing the SDHCAL with glass scintillator/steel HCAL
- Primaries input: 240 GeV e+e- → nu+nu_bar+H (H → gg)
- GS material parameters: as shown in right figure
- Edep threshold in glass cell was set to 0.1 MIP
- Edep in each sampling layer of HCAL was based on sampling fraction ***f*** and calibration coefficient ***k*** (i.e. $Edep_{layer}=\boldsymbol{k}\times Edep_{GS}/\boldsymbol{f}$)
- Selection Cut： Pt_ISR<1 GeV && Pt_neutrino<1 GeV && |Cos(Theta_Jet)|<0.8

	Composition	**Density (g/cm^3)**	**MIP Edep (MeV/mm)**	**NIL (mm/λ)**
Simu-GS1	Gd-B-Si-Ge-Ce^{3+}	1	0.115	1226.5
Simu-GS2	Gd-B-Si-Ge-Ce^{3+}	3	0.331	476.6
Simu-GS3	Gd-B-Si-Ge-Ce^{3+}	5	0.573	286.0
Simu-GS4	Gd-B-Si-Ge-Ce^{3+}	6	0.695	238.3
Simu-GS5	Gd-B-Si-Ge-Ce^{3+}	8	0.94	178.7
Simu-GS6	Gd-B-Si-Ge-Ce^{3+}	10	1.188	143.0

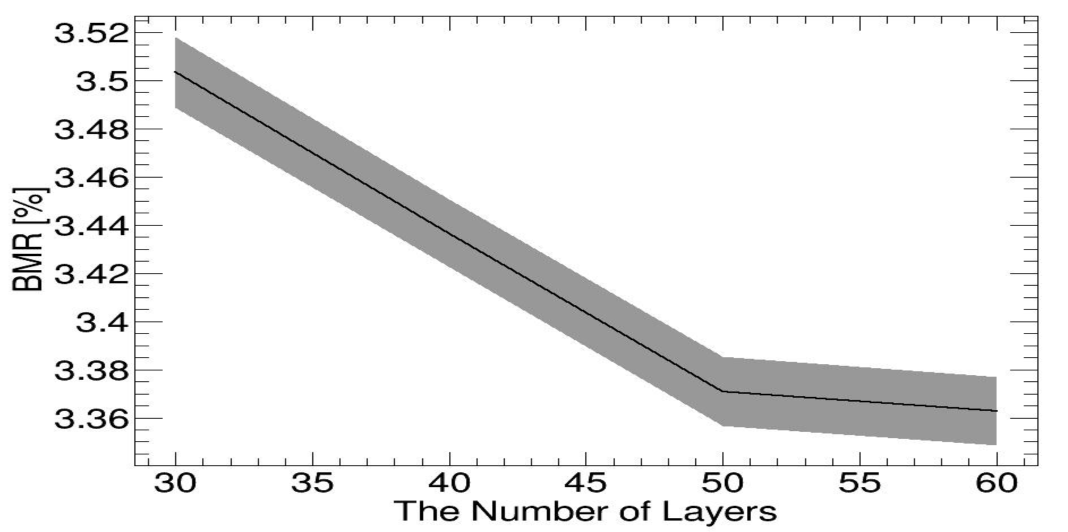


☐ BMR vs Nuclear Interaction Length



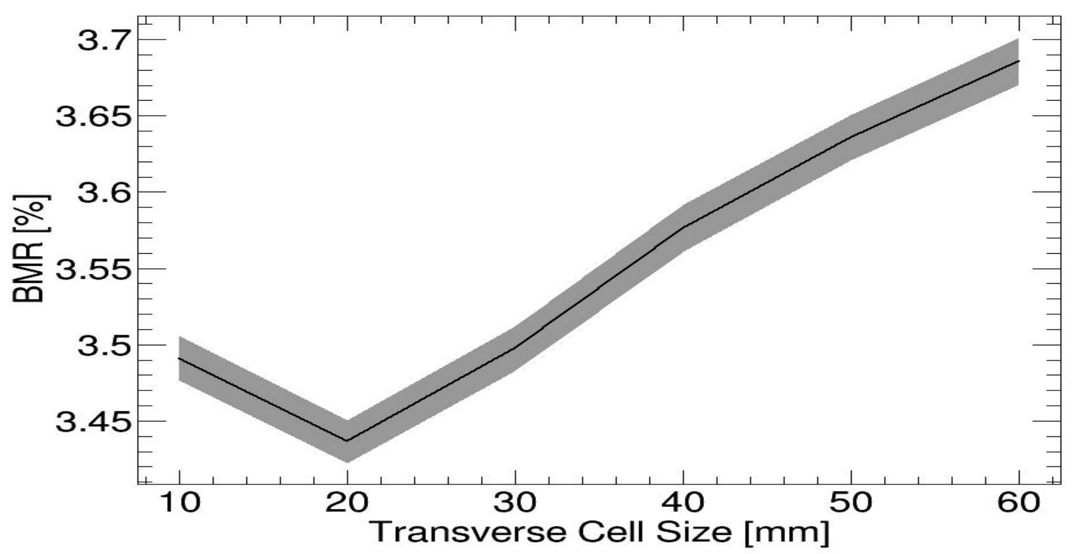
- The BMR is subjected to shower leakage and sampling fraction when varying the total nuclear interaction length of the GSHCAL.
- The BMR is dominated separately by shower leakage (<6 λ) and sampling fraction (>6 λ);
- A total NIL of 6 λ will be chosen for current design to obtain a optimal BMR.

☐ BMR vs Number of Layers



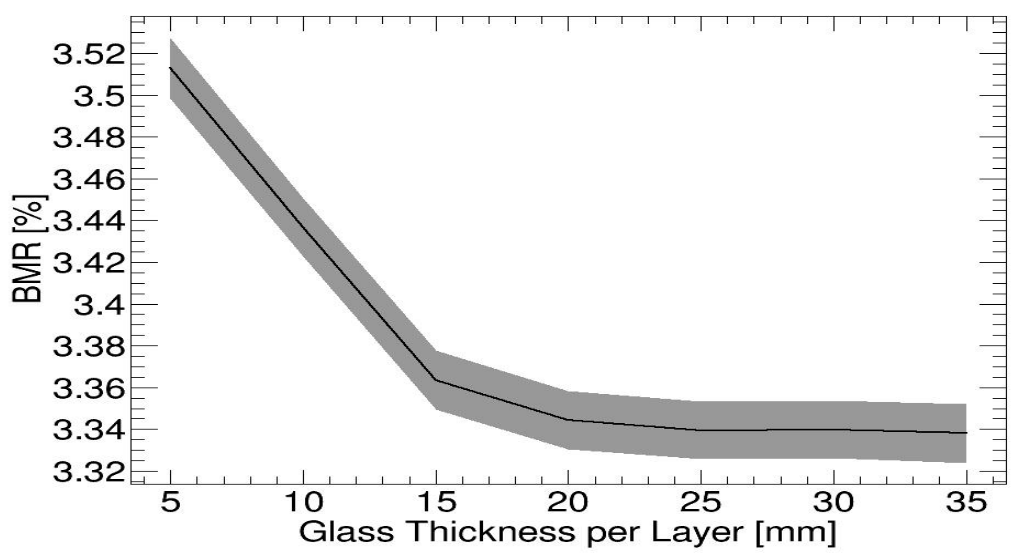
- The increase of sampling layers will improve the sampling frequency and sampling fraction, which is beneficial to achieve a better BMR.
- 40 sampling layers will be chosen for current design, considering the BMR improvement provided by more sampling layers is not significant and the number of readout channels is in a reasonable level.

☐ BMR vs Transverse Cell Size



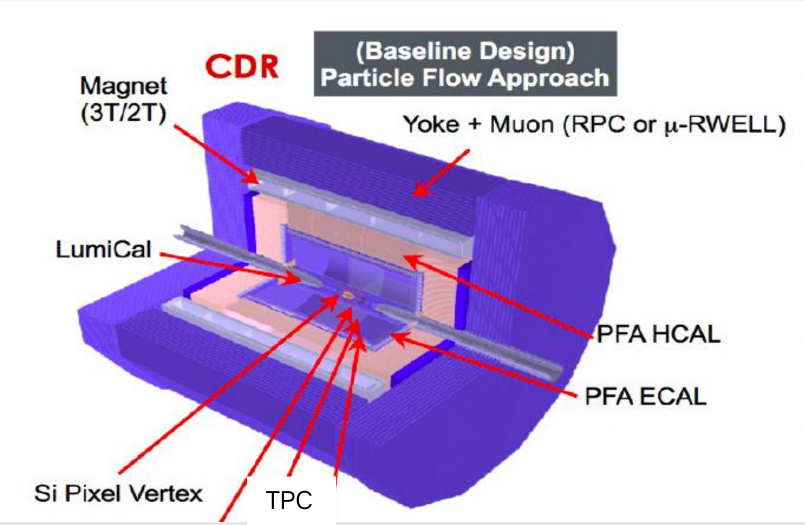
- The transverse size of the glass cell is a very important factor for the granularity and total number of readout channels of the GSHCAL
- Considering the PFA performance and total number of readout channels, a transverse size of 20 mm will be chosen for current design (though the behavior with cell size lower than 20 mm needs a further study)

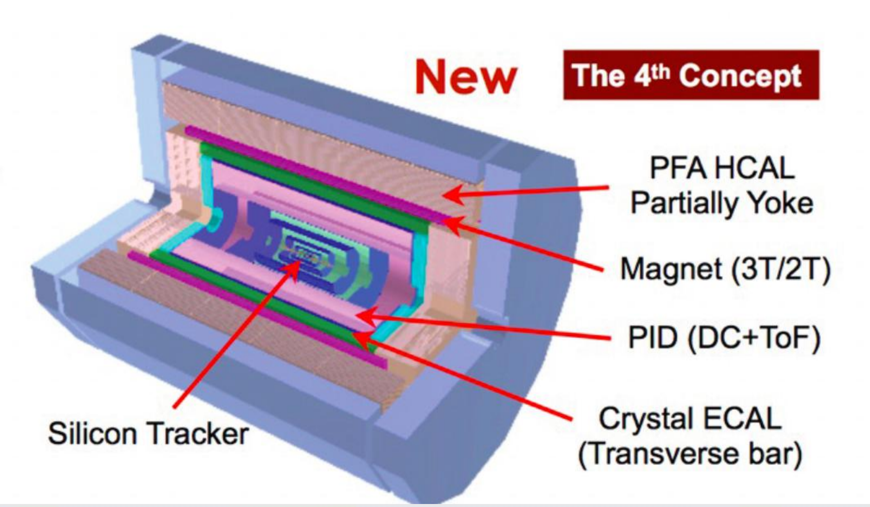
☐ BMR vs Number of Layers



- A thicker glass cell is conducive to a higher sampling fraction and a better BMR;
- The transmittance and the position response non-uniformity will become worse; besides, the glass thickness will be also limited by the total thickness of the GSHCAL
- A thickness of 10 mm will be chosen for current design

Comparing nominal GSHCAL with AHCAL

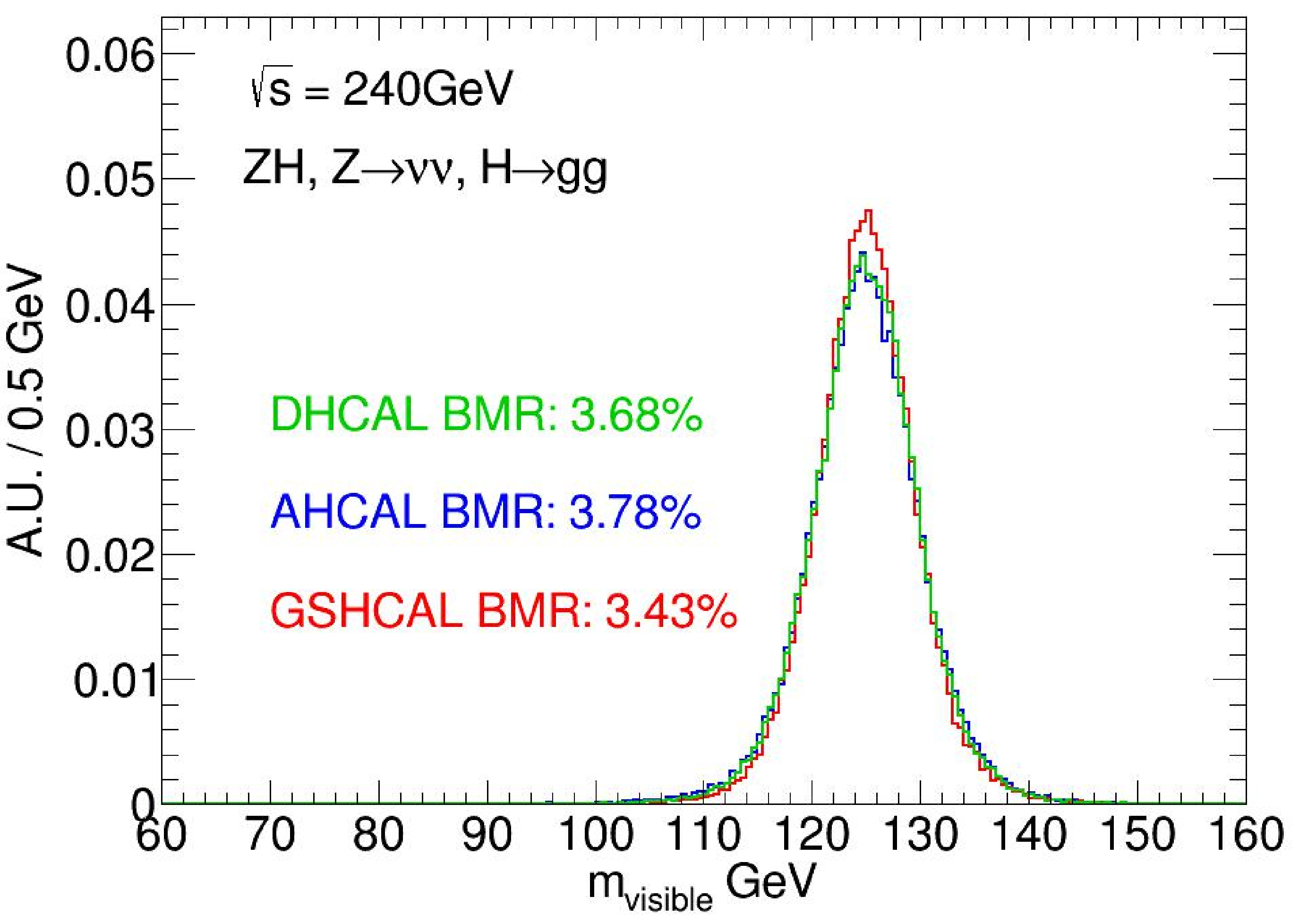




Parameter (nominal)	AHCAL	GSHCAL
Number of layers	40	40
Layer thickness	0.124 lambda (3 mm PS+20 mm Steel)	0.15 lambda (10mm GS+Steel)
Total Nuclear Interaction Length	~5 lambda	6 lambda
Transverse Cell Size	30x30 mm^2	20x20 mm^2
Sensitive Material Density	~1 g/cm^3	~6 g/cm^3
Sensitive Material Light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

- 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%).

Comparing nominal GSHCAL with DHCAL and AHCAL



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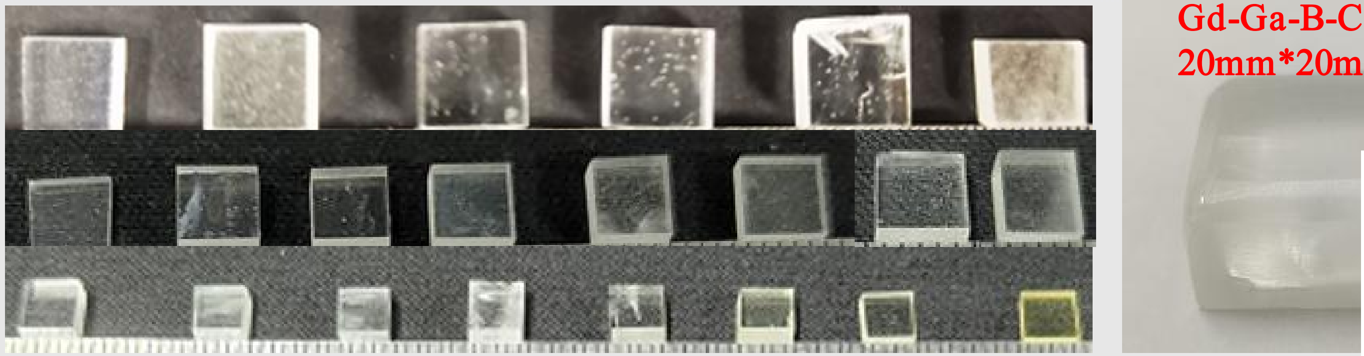
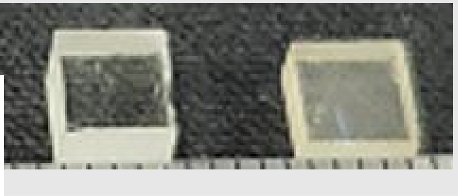
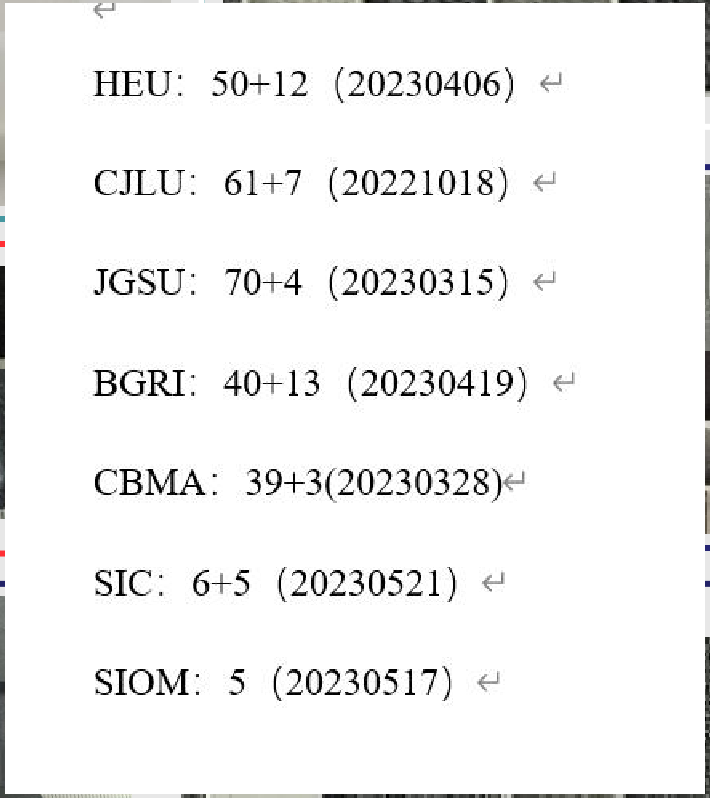
3.0 The GS Samples produced （>315）



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





↵

HEU：50+12（20230406）↵

CJLU：61+7（20221018）↵

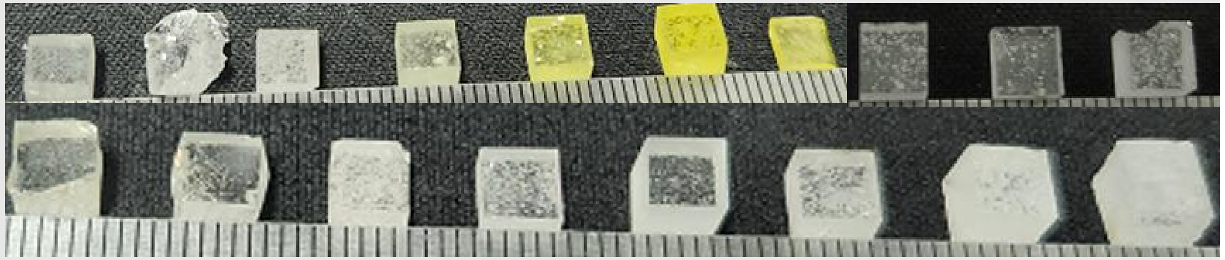
JGSU：70+4（20230315）↵

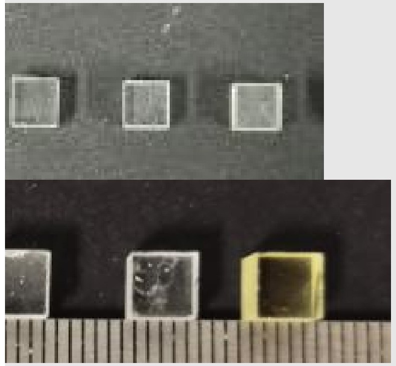
BGRI：40+13（20230419）↵

CBMA：39+3(20230328)↵

SIC：6+5（20230521）↵

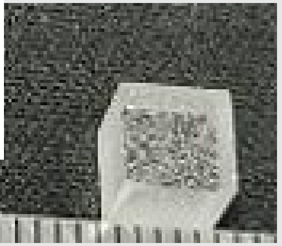
SIOM：5（20230517）↵





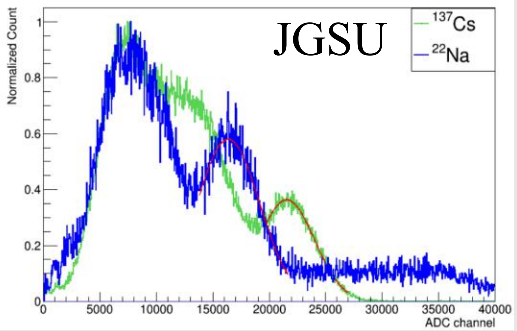
Gd-Al-B-Si-Ce^{3+} glass
42mm*51mm*10mm

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

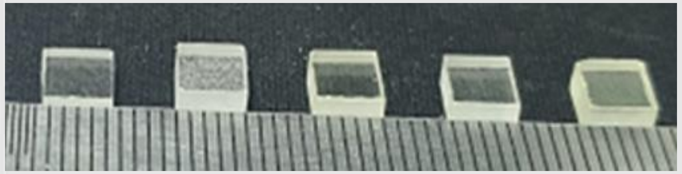


3.1 Borosilicate Glass（Gd-Al-B-Si-Ce^{3+}）--GS1

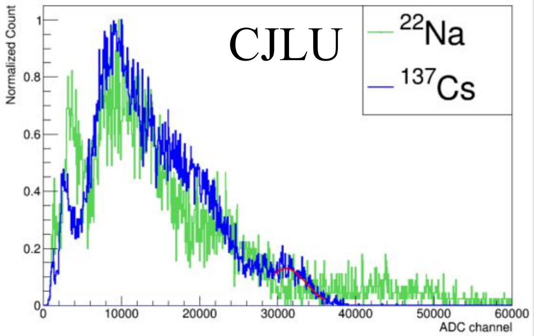
- Density~4.5 g/cm^3
- LY=802 ph/MeV
- ER=26.8%
- Decay=262 ns (18%), 1235 ns



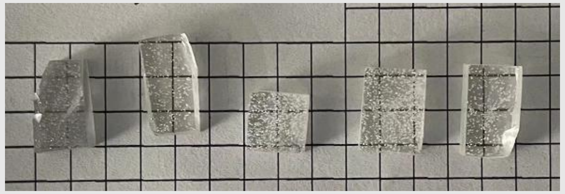
2021.11



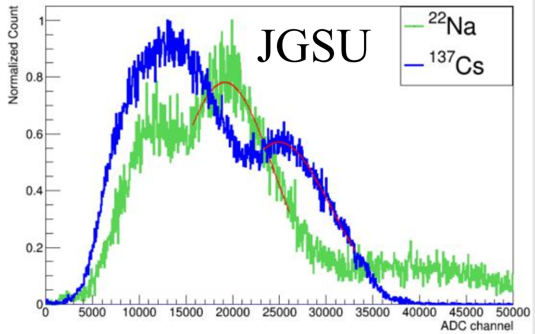
- Density~4.0 g/cm^3
- **LY>1200 ph/MeV**
- ER=23.2%
- Decay=231 ns (10%), 1897 ns



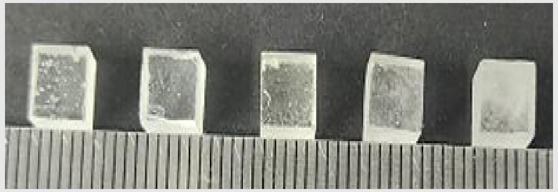
2022.06



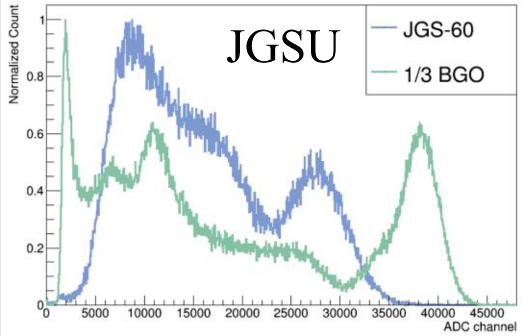
- **Density~6.0 g/cm^3**
- **LY>1000 ph/MeV**
- ER=49.6%
- Decay=847 ns



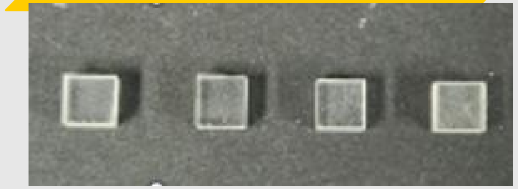
2022.11



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



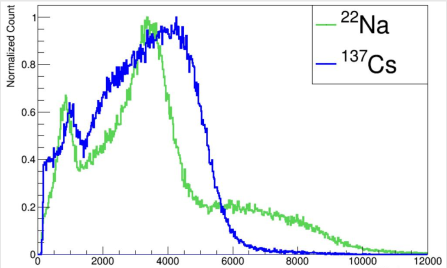
2023.02



- There are 4 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.

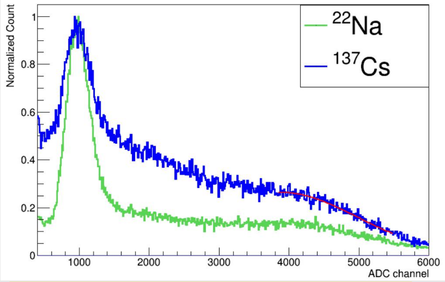
3.2 Large Size Glass（Gd-Ba-Al-B-Si-Ce^{3+}） --GS1

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



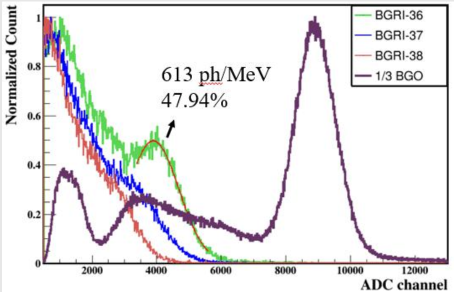
2022.10

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

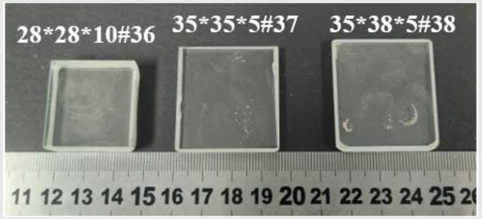


2022.12

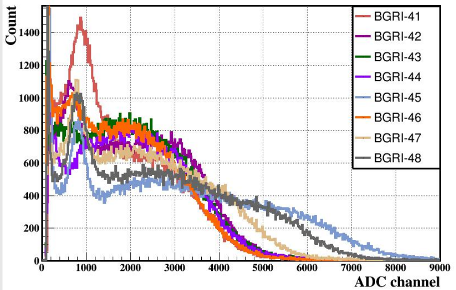
- ■ Size=28*28*10 mm^3
- ■ Density=5.2 g/cm^3
- ■ LY=613 ph/MeV
- 🟦 ER=47.9%



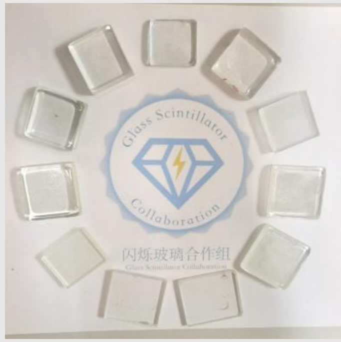
2023.01



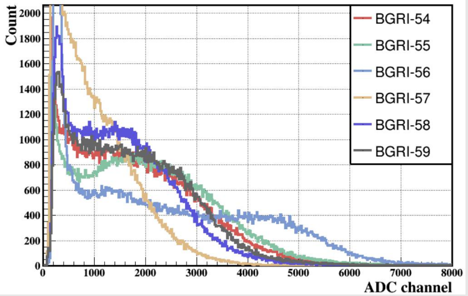
- 🟦 Size=30*30*9 mm^3
- ■ Density=5.1 g/cm^3
- 🟦 LY=767 ph/MeV
- ■ ER=None



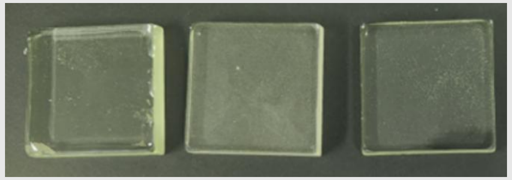
2023.04



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



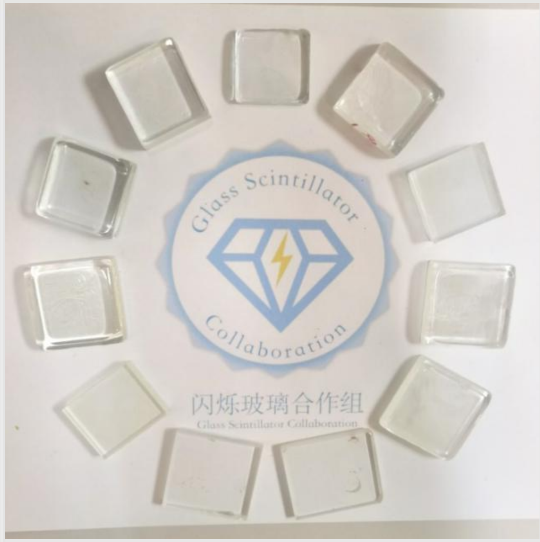
2023.05

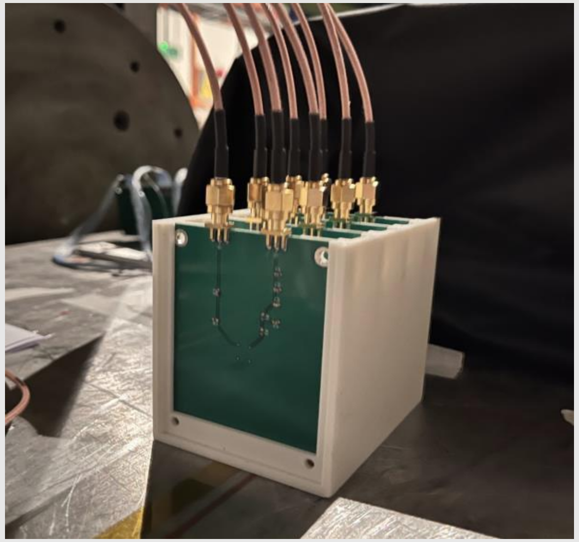


The Bottleneck：

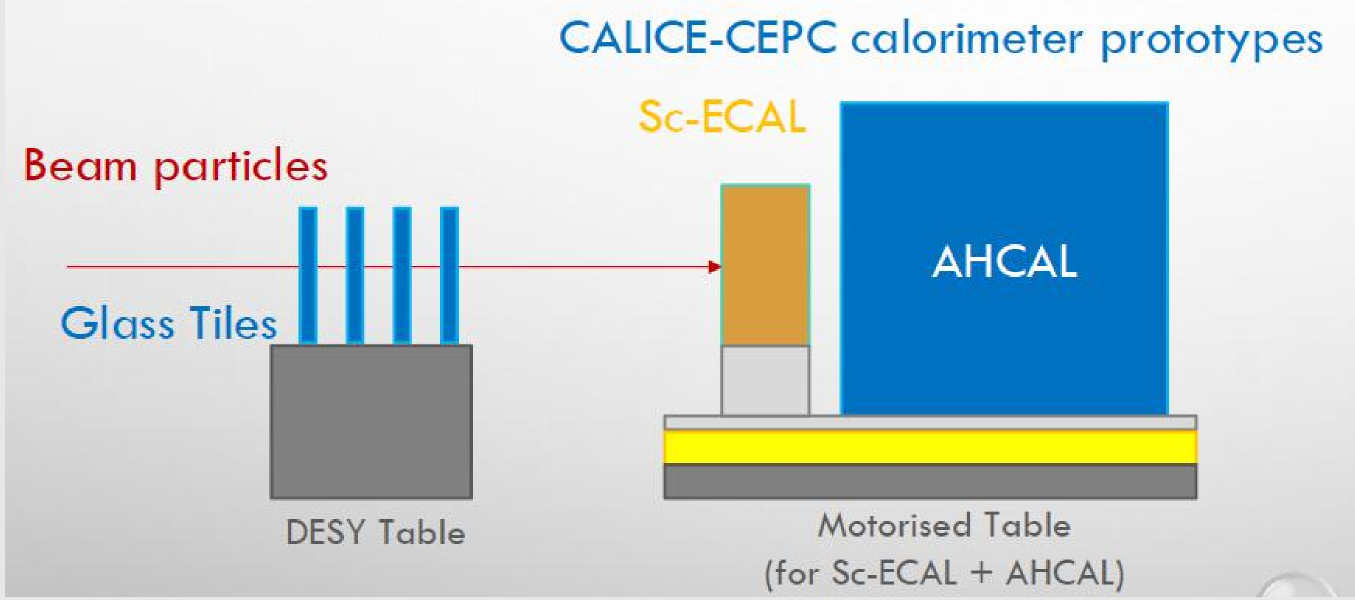
1. How to produce the large size sample in factory, with the same performance of small size in the university Lab.
2. How to increase the denisty and light yield in large siza sample?

3.3 CERN Muon beam test





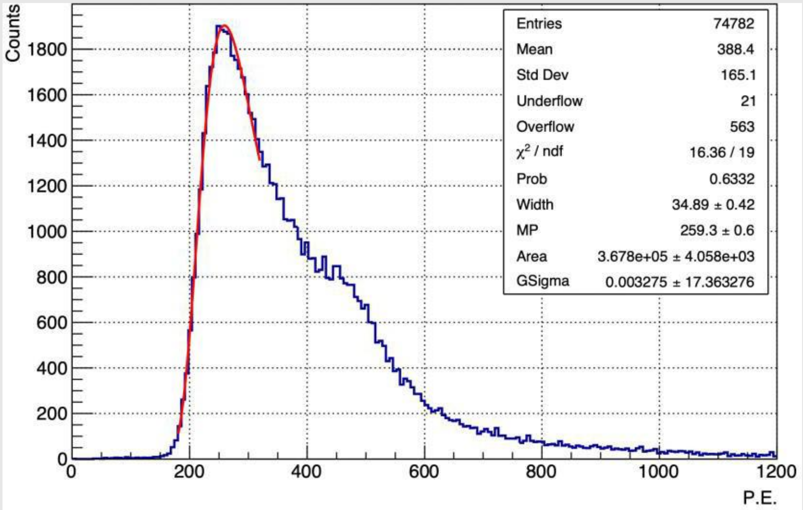
- Beam test setup
  - 4 tiles with individual SiPM readout
  - 3 glass scintillator tiles and 1 plastic scintillator tile (as reference);
  - Data acquisition using a 4-ch fast oscilloscope (5GS/s)



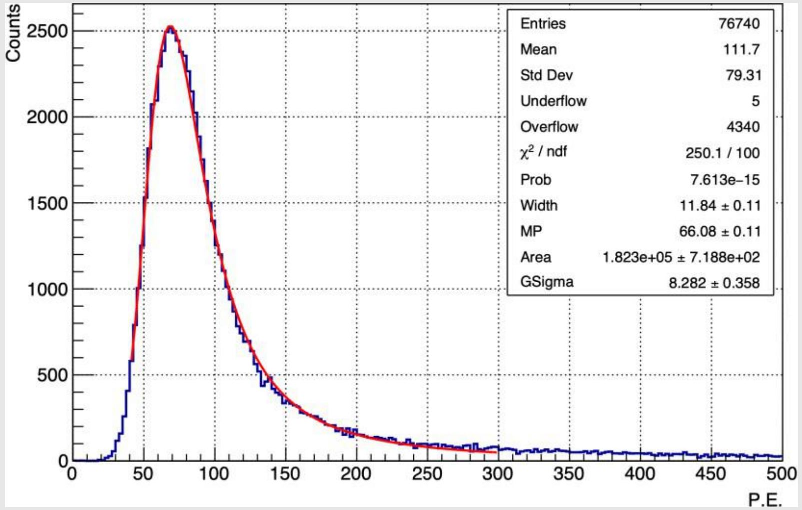
- First batch of large-scale glass samples from the Glass Scintillator Collaboration.
- 11 large-scale scintillator glass tiles successfully delivered from IHEP to CERN for the beam test;
- Major motivation: use muon beam to measure MIP response of each glass tile

Preliminary results with muon beam

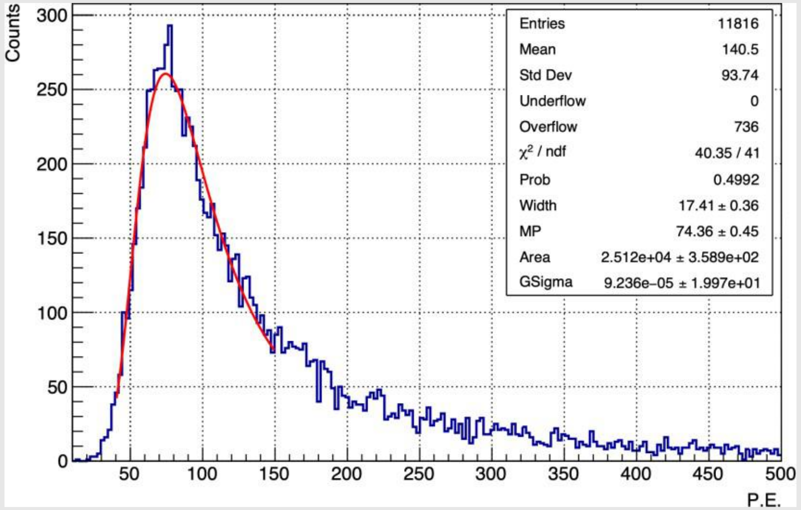
- Observed clear MIP signals in all 11 glass samples
  - Various glass tile dimensions: 25-40 mm in length, 5-10mm in thickness
- Preliminary results look promising
  - **Typical glass MIP response: 40 – 70 p.e./MIP**
- Also observed other structures in energy spectrum: due to 2-muon incidence



Plastic scintillator: 259 p.e./MIP
(40 × 40 × 10 mm^3)



Glass scintillator (#3): 66 p.e./MIP
(29.8 × 28.1 × 10.2 mm^3)

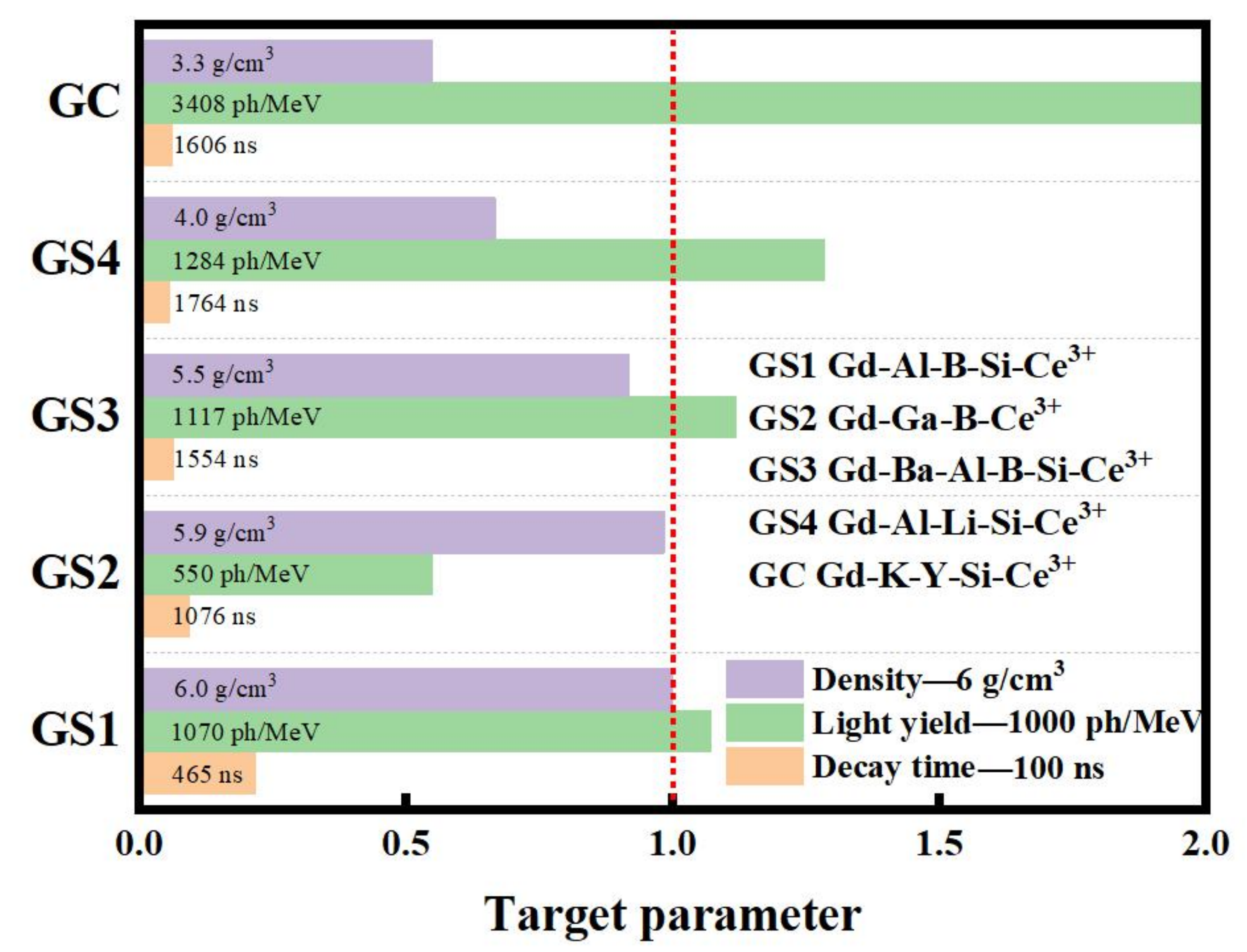


Glass scintillator (#10): 74 p.e./MIP
(34.7 × 35.2 × 7.4 mm^3)

Outline

- 1. The Status of the GS Group;
- 2. The Simulation for GS Detector;
- 3. The Progress of the GS Production;
- 4. Summary and Next Plan

4.1 Summary of GS



- Ultra-high density **Tellurite Glass**—6.6 g/cm^3
- High light yield **Glass Ceramic**—3400 ph/MeV
- Fast scintillating Decay Time—100 ns
- Large size Glass—42mm*51mm*10mm

◆ **6.0 g/cm^3 & 1070 ph/MeV with 23.8% @662keV & 465 ns —Gd-Al-B-Si-Ce^{3+} glass;**

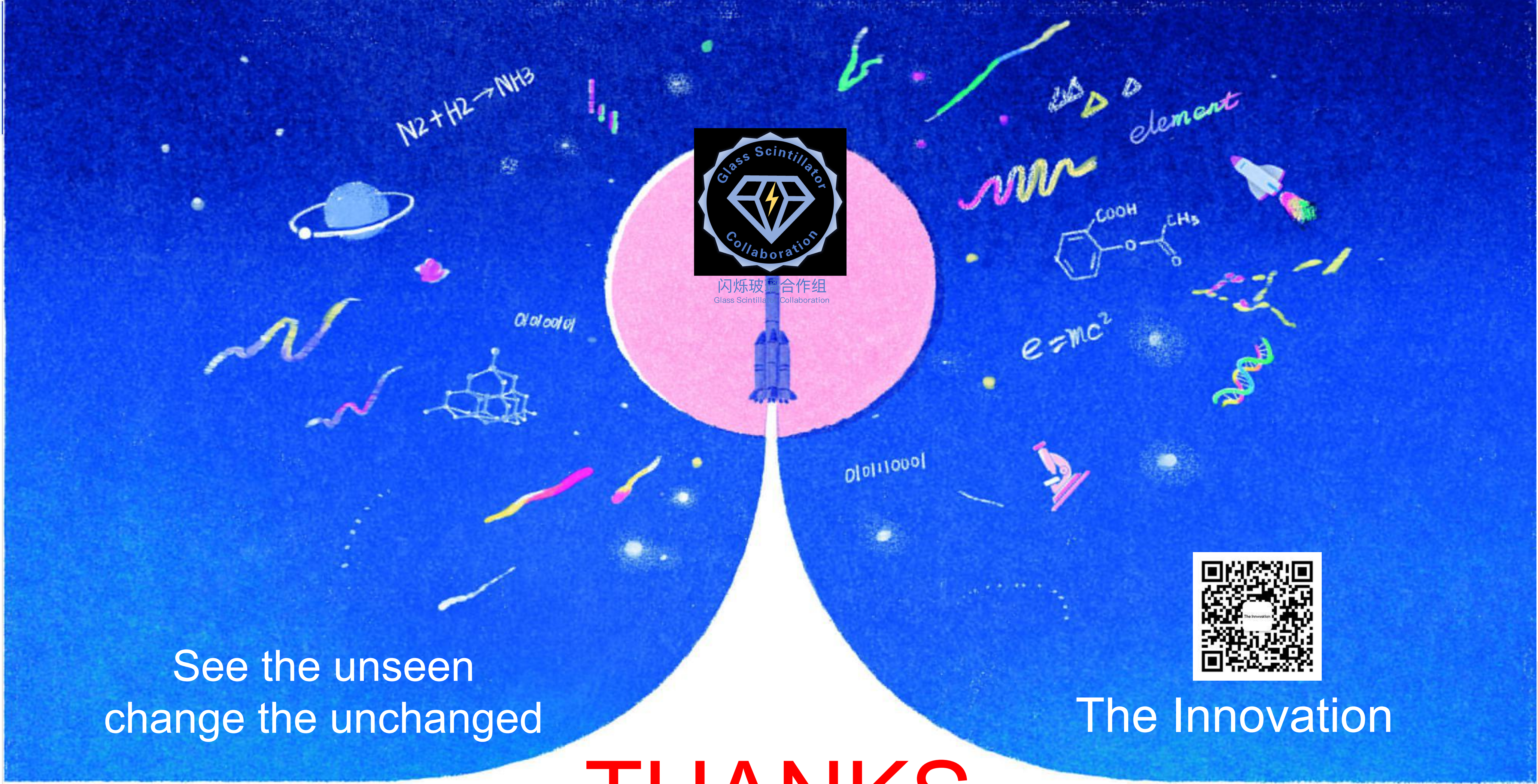
- The properties of the glasses will be further improved through **raw material purification;**
- to Reduce the scintillation decay time (<100 ns);
- to produce the Large size and mass preparation samples;
- Test the radiation resistance and mechanical properties of the glasses;

4.2. 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 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
➢ **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

4.3 Summary and Plan of 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%);
- 11 glass samples (~ 3x3x0.8 cm^3) have been tested with the muon beam in CERN SPS to obtain their MIP responses and most of them can reach **above 60 p.e./(MIP*cm);**
- 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;
- Apply for the **financial support** for better R&D;



闪烁玻璃合作组
Glass Scintillator Collaboration

See the unseen
change the unchanged

The Innovation

THANKS

The Scintillator data

Typy	Composition	Density (g/cm^3)	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.