中国科学院高能物理研究所
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Progress of the Glass Scintillator Calorimeter

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On behalf of the Glass Scintillators R&D Group

2022.09.21

Outline

1. Motivation and target

2. Standalone simulation of GS-HCAL

--by Dejing Du, Yong Liu

3. PFA performance with GS-HCAL

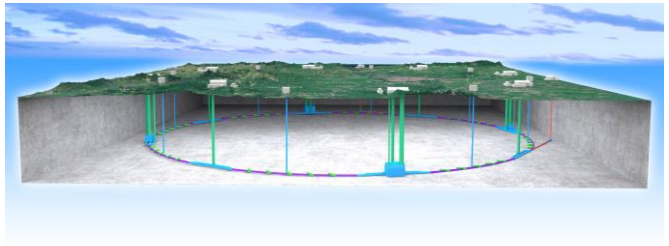
--by Peng Hu, Yuexin Wang, ManQi Ruan

4. Research progress of GS

--by Zhehao Hua, Sen Qian

5. Next Plan

1.1 Motivation

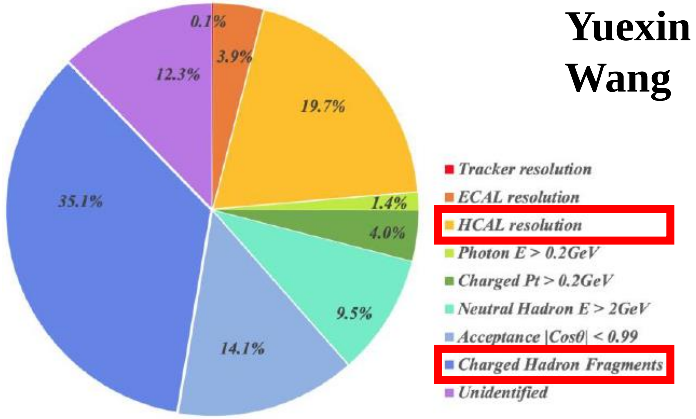


Future electron-position colliders (e.g. CEPC)

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

All Factors in BMR based on PFA

Yuexin Wang

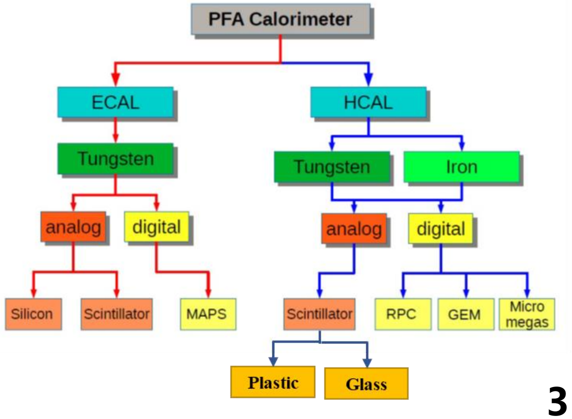


CEPC detector: highly granular calorimeter + tracker

- 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 Target

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	**6-7 g/cm^3**	More compact HCAL structure with higher density
Intrinsic light yield	**1000-2000 ph/MeV**	Higher intrinsic LY can tolerate lower transmittance
Transmittance	~75%	
MIP light yield	~150 p.e./MIP	Needs further optimizations: e.g. SiPM type, 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

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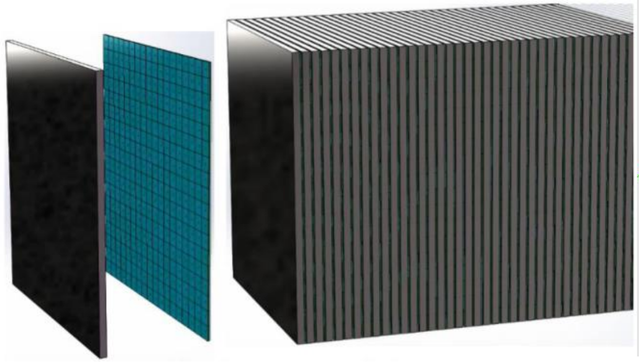
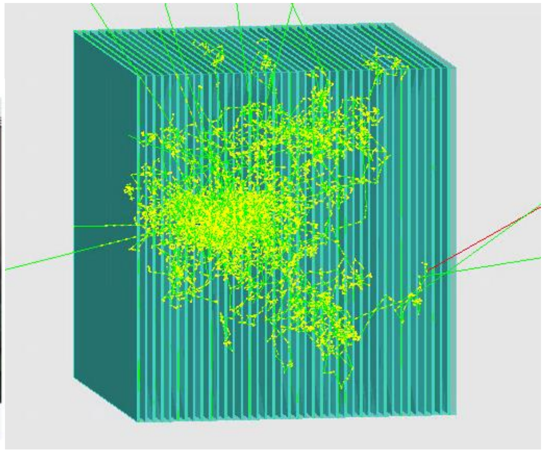
2.1 HCAL setup of standalone simulation

- Geometry: similar to PS AHCAL prototype
  - Transverse plane: $108\times108\ cm^2$
    - Tile size: $3\times3\ cm^2$
  - 60 longitudinal layers, each with
    - Scintillator (sensitive): 3 mm
    - Steel (absorber): 20 mm
    - PCB: 2 mm

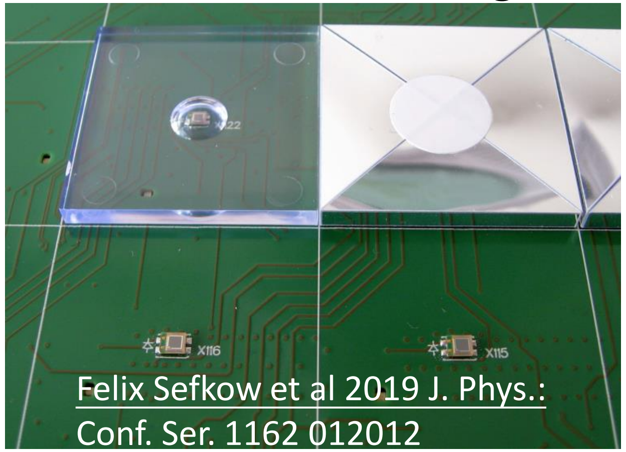
CEPC AHCAL prototype schematics



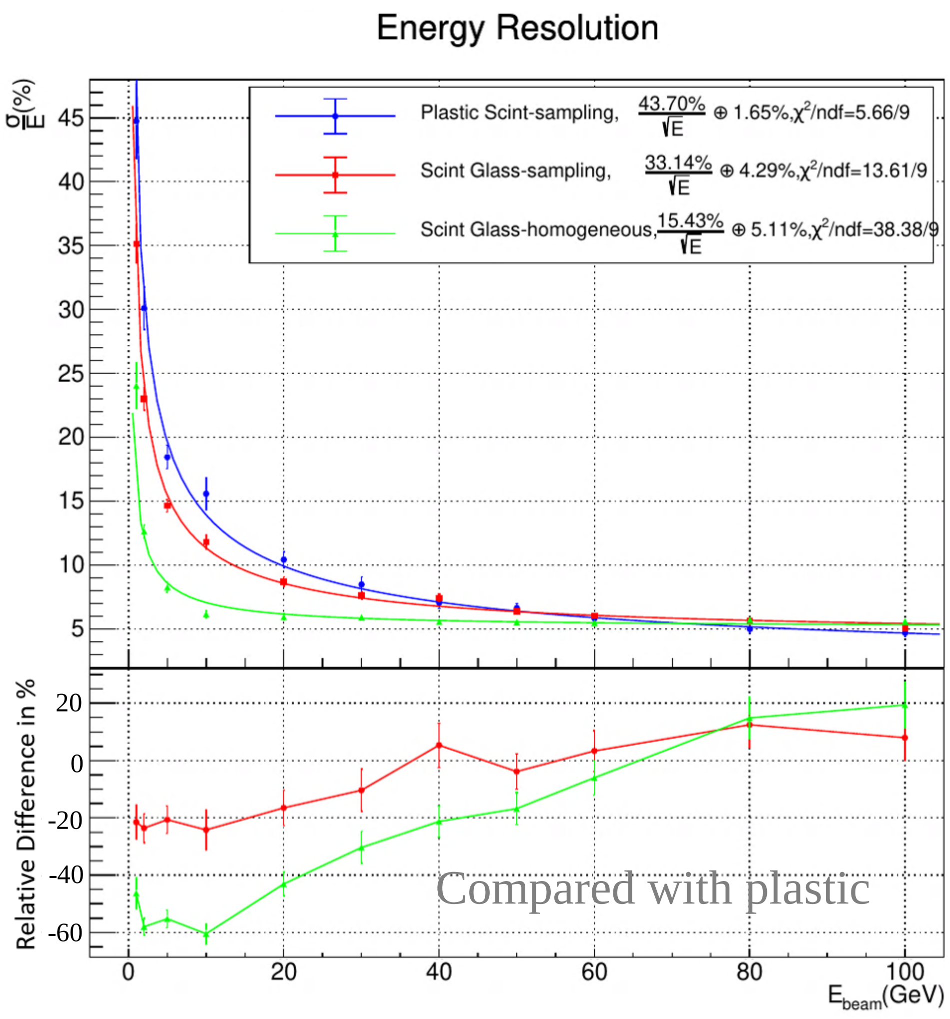


- GS-HCAL
  - Replace plastic scintillator with glass scintillator
    - Component: $B_2O_3 - SiO_2 - Al_2O_3 - Gd_2O_3 - Ce_2O_3$
    - Density = 4.94 g/cm^3 (goal: > 6 g/cm^3)
  - Glass tile design: ongoing optimization

"SiPM-on-Tile" design



2.2 Plastic Scintillator vs Glass Scintillator

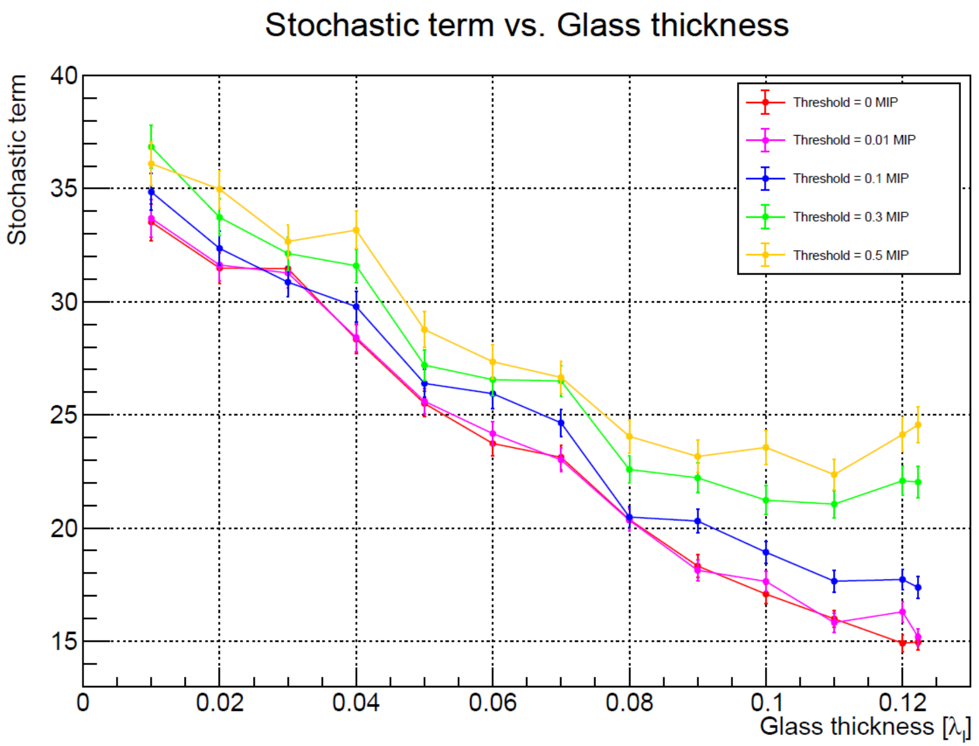


- Incident particle: K_L^0
- Preliminary performance comparison
  - Same thickness of sensitive materials: 3mm
  - No energy threshold applied
- Glass scintillator: better hadronic energy resolution in low energy region (<30GeV)
  - Note that majority of hadrons in jets at CEPC are with low energy
- More details in the next pages

2.3 Impact of thickness to hadronic energy resolution

- Varying thickness: glass scintillator tiles and steel plates
- Extraction of terms in energy resolution

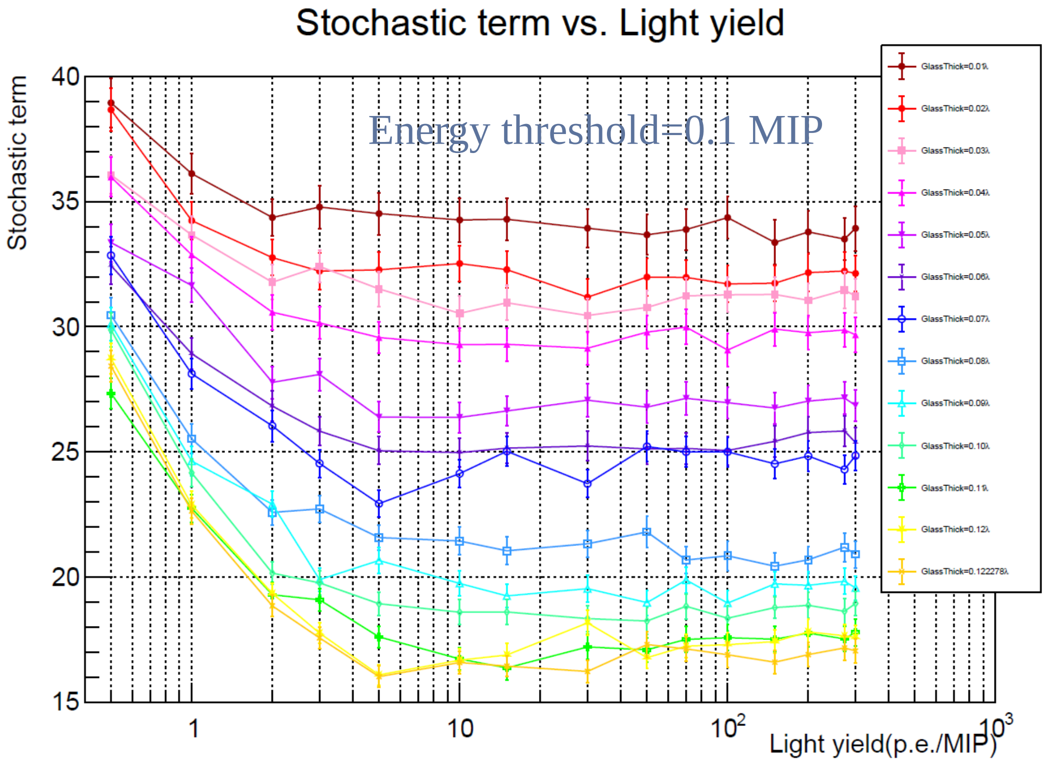
HCAL with 60 layers



- Energy threshold has a significant impact on the energy resolution, lower threshold would always be desirable for better resolution
- The stochastic term will not be improved when glass gets thicker for a given threshold

2.4 Impact of light yield to hadronic energy resolution

- Varying light yield from 0.5 to 300 p.e./MIP
- Extraction of stochastic terms in energy resolution



- A light yield of 10 p.e./MeV seems to be good enough to achieve the optimized energy resolution

2.5 Summary of performance of standalone GS-HCAL

- Better energy resolution below 30 GeV (cover major jet components), and an optimized thickness of glass can be obtained for a given threshold

- A lower threshold is always favorable for the energy resolution

- Preliminary results show light yield of 10 p.e./MIP is good enough to achieve the optimized energy resolution

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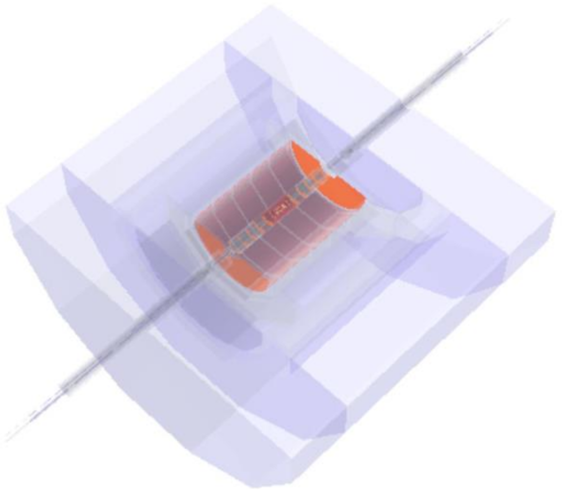
3.1 PFA performance simulation for Glass Scintillator

☐ Setup

- CEPCSoft Framework: CEPC_v4, glass scintillator/steel HCAL + Si/W ECAL
- Primaries input: 240 GeV e+e- → ZH (Z → υυ, H → gg)
- Glass composition: Simu1-GS1, Simu1-GS2, Simu1-GS4, Simu1-GS6, Simu1-GS9, Simu1-GS10
- Glass cell size: 3x3x1 cm^3 (fixed)
- Steel thickness: ~1.5 cm, vary correspondingly with different glass options, here the thickness of glass and nuclear interaction length of each sampling layer are fixed (0.124 λ, 3mm PS+ 2cm steel)
- Total Layers: 40
- Simulated event number: ~16k



theoretical value

	Composition	Density (g/cm^3)	MIP Edep (MeV/mm)	NIL (mm)
Simu1-GS1	Gd-Al-Si-Ce^{3+}	5.10	0.596	274.8
Simu1-GS2	Gd-B-Si-Ce^{3+}	5.35	0.617	267.8
Simu1-GS3	Gd-B-Si-Ce^{3+}	5.49		261.9
Simu1-GS4	Gd-B-Si-Ge-Ce^{3+}	5.51	0.636	259.5
Simu1-GS5	Gd-Ga-Si-B-Ce^{3+}	5.64		254.1
Simu1-GS6	Gd-Ge-B-Ce^{3+}	5.68	0.656	251.3
Simu1-GS7	Gd-Ga-B-Ce^{3+}	5.77		247.3
Simu1-GS8	Gd-Ga-Ba-B-Ce^{3+}	5.78		249.6
Simu1-**GS9**	**Gd-Ga-Ba-B-Si-Ce^{3+}**	**5.81**	**0.670**	**250.5**
Simu1-GS10	Gd-Ga-Ge-B-Si-Ce^{3+}	6.03	0.699	241.0

3.2 BMR Analysis with Marlin

Setup

- Edep threshold in glass cell was set to 0.01 MIP, 0.1 MIP and 0.3 MIP
- Edep in each sampling layer of HCAL was based on sampling fraction ***f*** and calibration coefficient ***k*** (i.e. $Edep_{layer}=\boldsymbol{k}\times Edep_{GS}/\boldsymbol{f}$)
- BMR Cut： Pt_ISR<1 GeV && Pt_neutrino<1 GeV && |Cos(Theta_Jet)|<0.8 (~10k events after selection)

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        <processor name="MySimpleMuonDigi"/>

        <processor name="MyMarlinArbor"/>
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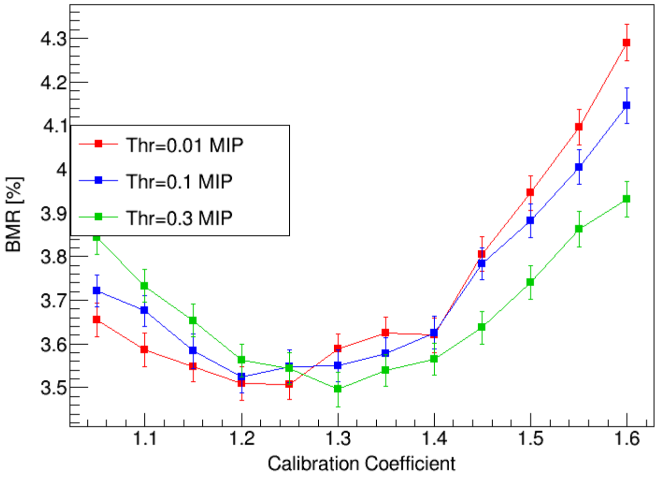
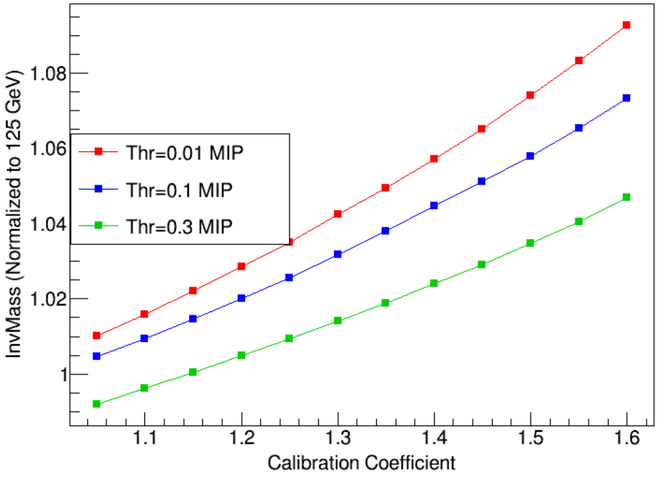
- Track digitization and reconstruction
- CaloHit digitization (only Edep threshold is applied, while the scintillation process and readout digitization were not considered yet)
- CaloHit clustering, cluster and track linking, PID

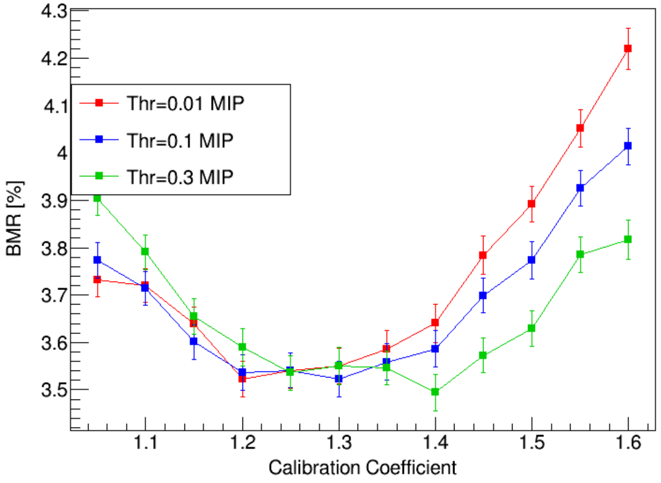
3.3 Calibration coefficient & threshold scanning

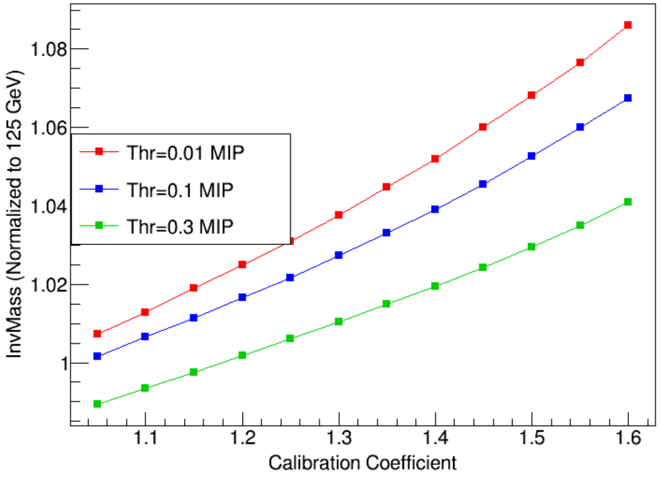
- Simu1-GS1 5.10 g/cm^3



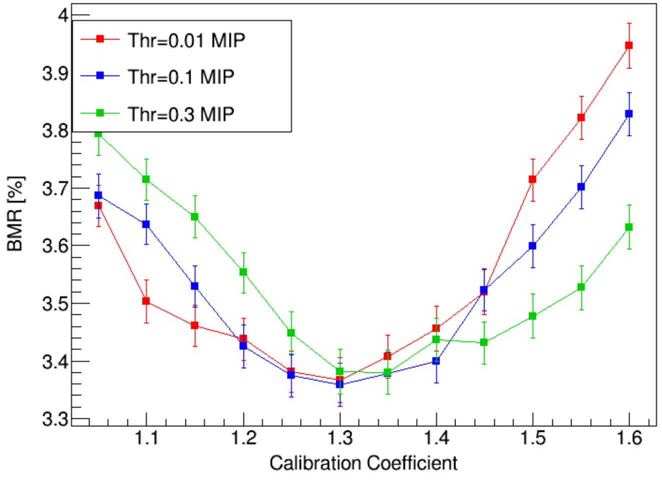


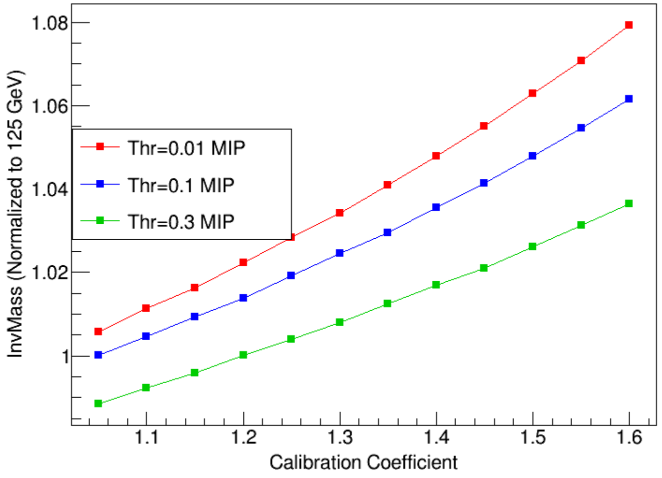
- Simu1-GS2 5.35 g/cm^3





- Simu1-GS4 5.51 g/cm^3

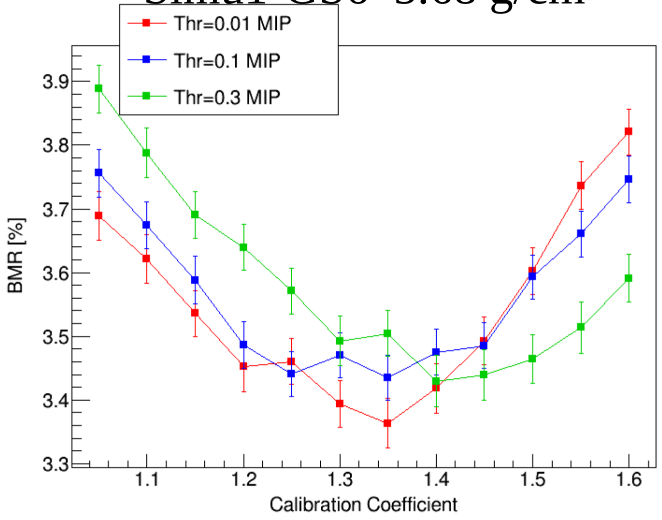


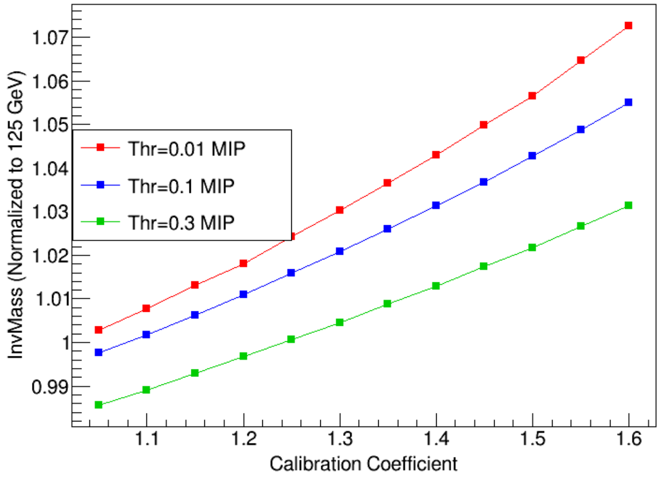


- A optimized BMR can be obtained by the parameter scanning for each glass sample

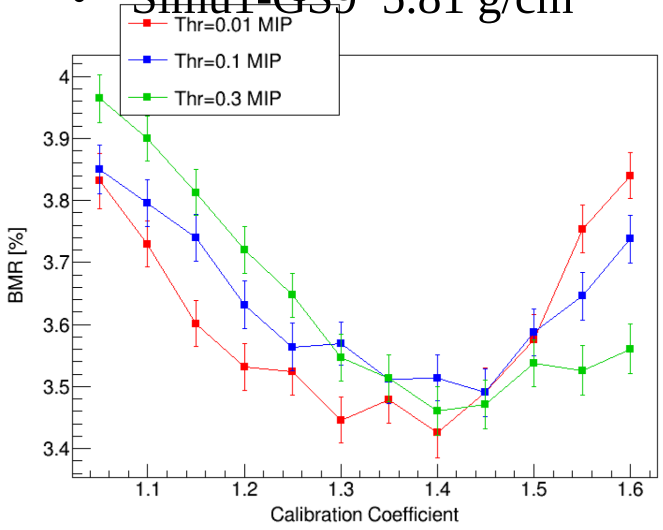
3.3 Calibration coefficient & threshold scanning

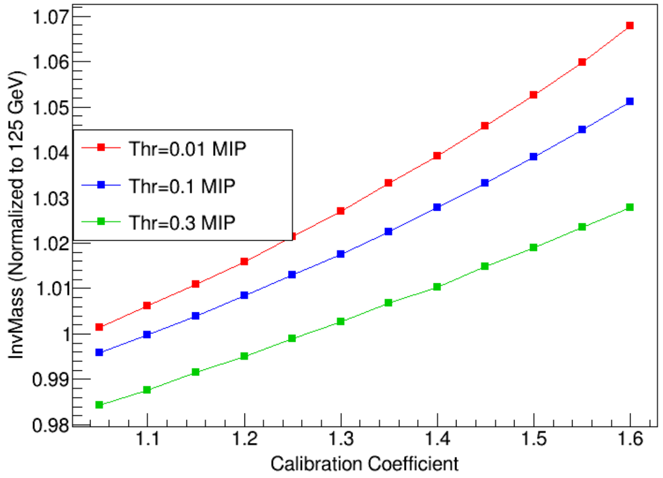
- Simu1-GS6 5.68 g/cm^3



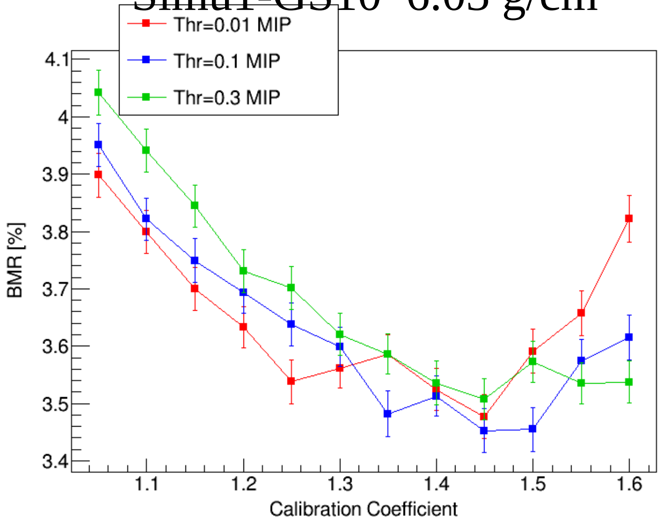


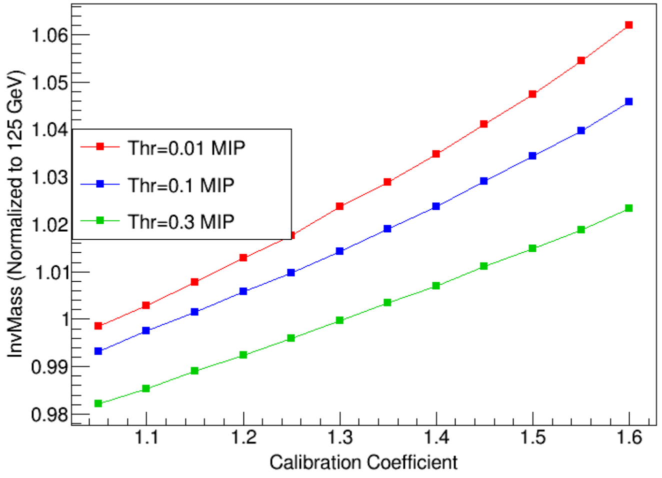
- Simu1-GS9 5.81 g/cm^3





- Simu1-GS10 6.03 g/cm^3





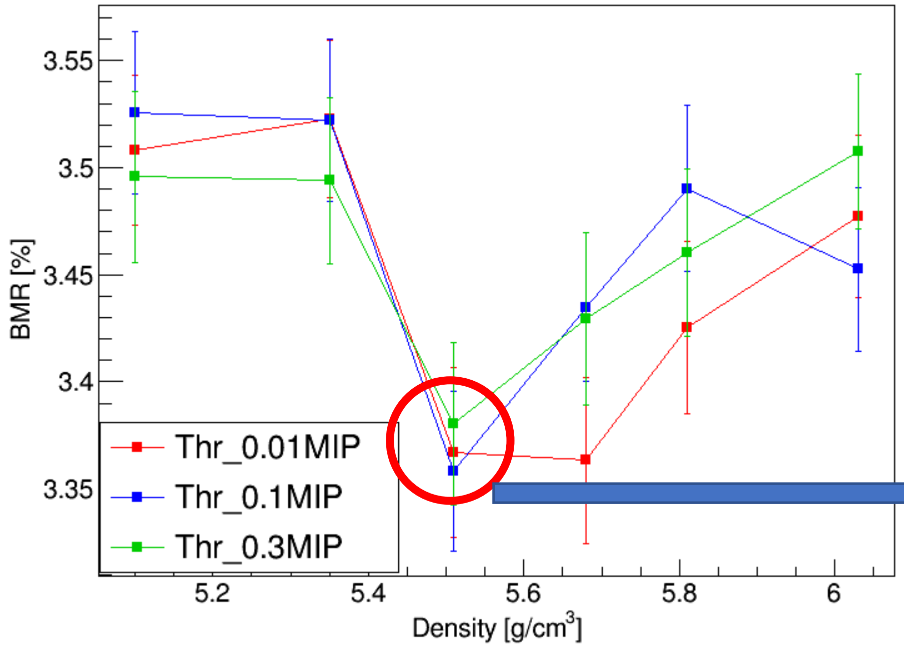
- A optimized BMR can be obtained by the parameter scanning for each glass sample

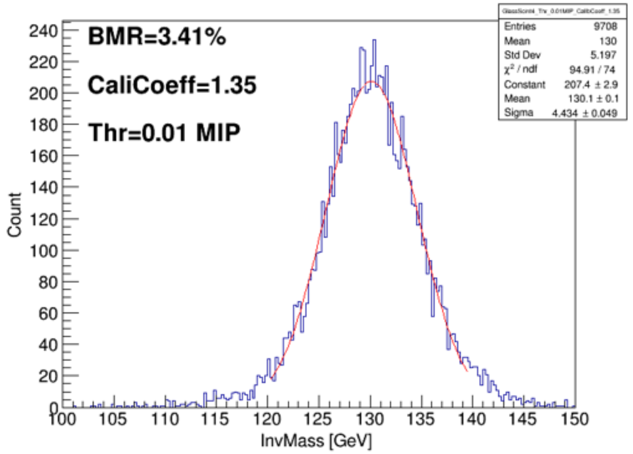
3.4 Optimized BMR

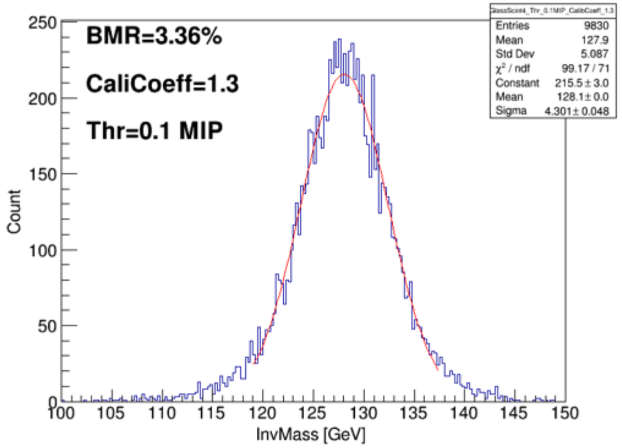
Preliminary

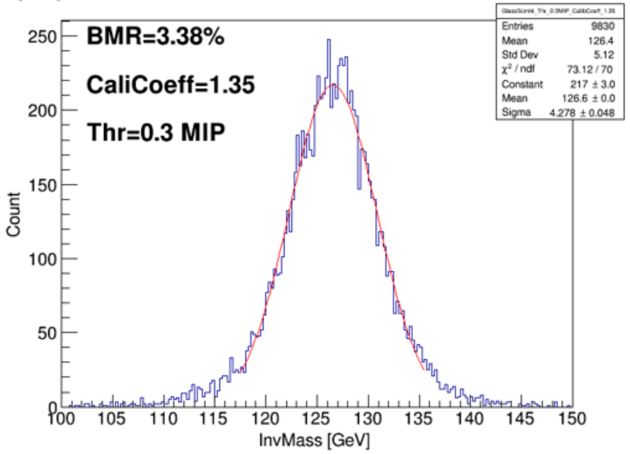
- In the case of different density and threshold

Optimized BMR for each glass sample









- The optimized BRM is almost same (~3% variation) for glass density from 5-6 g/cm^3, with a deviation of lower than ~4% for the mean value of higgs mass. Though a insignificant optimized density seems to be around 5.5 g/cm^3

3.5 Summary of PFA performance with GS-HCAL

- Under the CEPC_v4 and Arbor PFA framework, the BMR with GS-HCAL can reach ~3.35% and show ~10% improvement w.r.t. the baseline design (3.8%), which is also the best result we can obtain at present.

- Preliminary results show the optimized BRM is almost same (~3% variation) for glass density from 5-6 g/cm3, with a deviation of lower than ~4% for the mean value of higgs mass. Though a insignificant optimized density seems to be around 5.5 g/cm3

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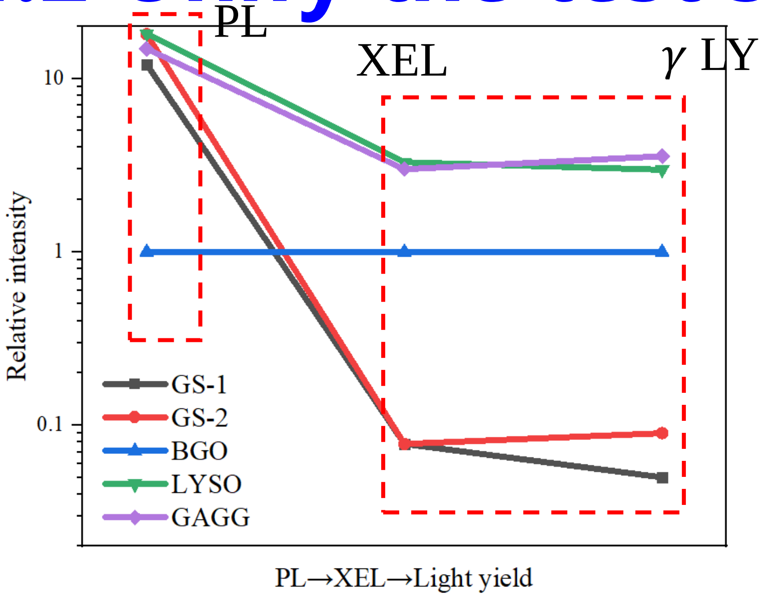
4.1 previous status of glass scintillators

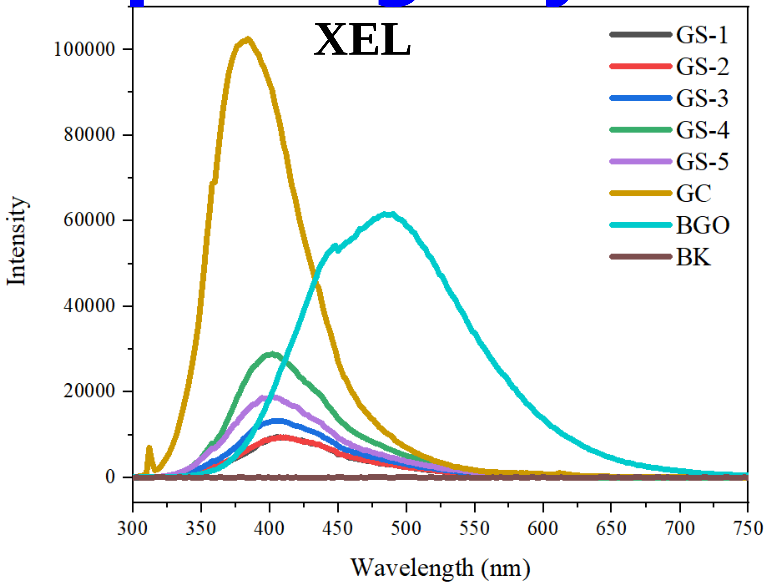
Number	Composition	Density (g/cm³)	Transmittance (%)	Light yield (ph/MeV)	Energy Resolution (%)	Decay time (ns)	Emission peak (nm)	Size (mm)	Price/1 cm³ (RMB)
EU-GS1	HfF_4-YbF_3-PbF_2-ZnF_2-BaF_2-CeF_3 (HFG: Ce)	6.0	85	150	/	8, 25	325	150*30*30	150
EU-GS2	SiO_2-BaO-Al_2O_3-Gd_2O_3-Ce_2O_3 (DSB:Ce)	4.2	86	2500	/	90 (45%), 400	430	17*20*5	5
JPN-GS3	25BaF_2-20Al_2O_3-50B_2O_3-5Ce^{3+} (Ba-B glass)	3.4	90	1800	/	40, 271	360	10*10*1	6
US-GS4	SiO_2–LiF–$GdBr_3$–$CeBr_3$ (high Gd-glass)	4.4	/	3460	14	522	430	/	65
RUS-GS5	Gd_2O_3-Al_2O_3-SiO_2-Ce^{3+} (Gd-Si glass)	4.5	/	2000	/	93 (62%), 317	430	/	6
JGSU	Gd-Al-B-Si-Ce^{3+}	4.5	67	802	26.77	318,1380	393	10*10*5	6
CJLU	Gd-Al-Si-Ce^{3+}	4.2	65	1206	22.98	346,1740	430	10*10*5	4.5
HEU	Gd-K-Y-Si-Ce^{3+}	3.3	80	1601	27.27	210,1622	380	10*10*5	5
CBMA	Gd-Ba-Al-Si-Ce^{3+}	4.2	80	460	/	197, 1235	420	10*10*5	5
	?	~6	>75	~2000	<20	<100	350-500	30*30*10	< 0.1$/c.c

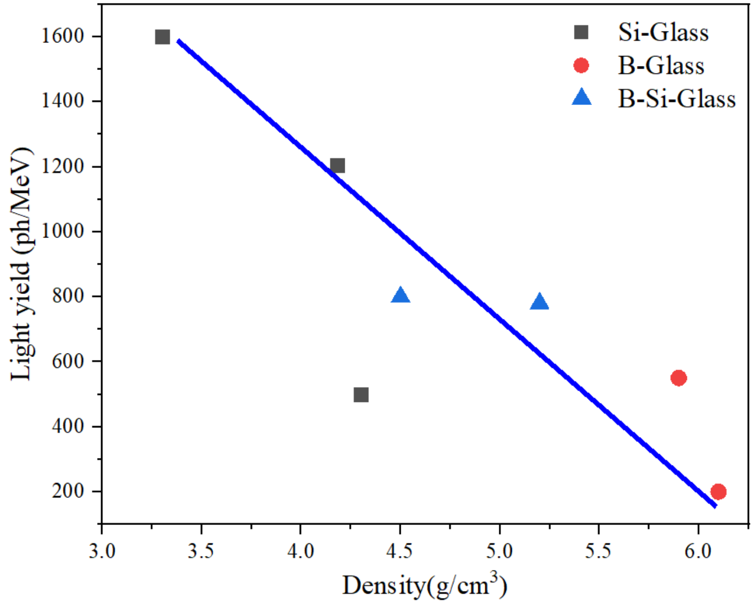
performance bottleneck

high density + high light yield

4.2 Unify the test setup of light yield







	Density (g/cm^3)	XEL	Light yield
GS-1	4.67	0.103	0.050
GS-2	4.50	0.105	0.091
GS-3	4.53	0.144	0.077
GS-4	4.20	0.289	0.091
GS-5	4.18	0.203	0.136
GC	3.30	0.949	0.181
BGO	7.13	1	1

- Photoluminescence is not related to its scintillation properties；
- X-rays and gamma rays interact with scintillation materials in different processes;
- When the composition of glass scintillator is similar, the lower the glass density, the higher the light yield;

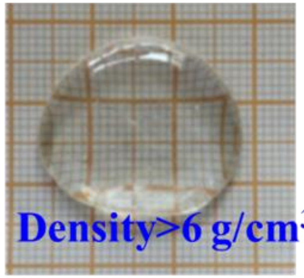
4.3 Joint research (2022.7.26-2022.7.28)

- Unify the supply channels of raw materials and crucibles for scintillating glass of each unit;
- Refine and distinguish the different points in the preparation process of each unit, and explore the influence of different processes on the performance of scintillating glass;
- Establish standardized scintillation performance testing schemes and devices;

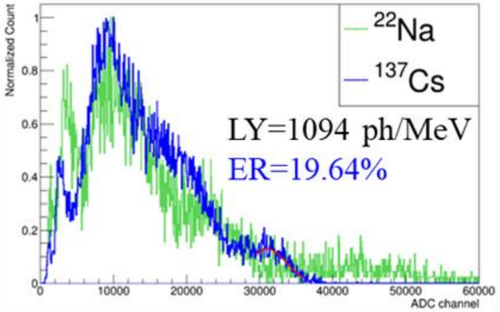
4.4 Overview of Research progress

Three glass systems are being investigated simultaneously

2022.09

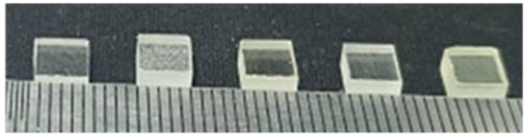


2022.06



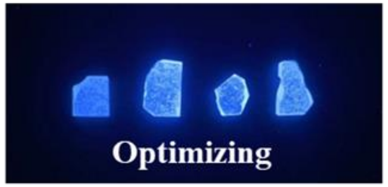
2021.11

Density=4.5 g/cm^3
LY>800 ph/MeV

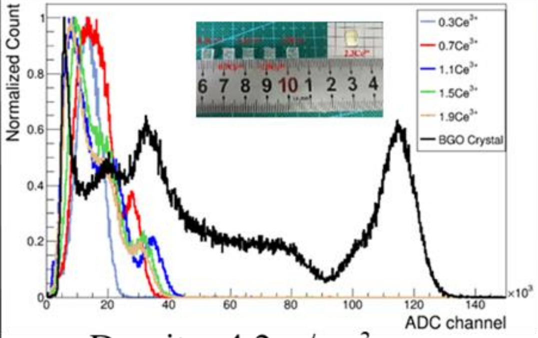


Gd-Al-B-Si-Ce^{3+}

2022.09

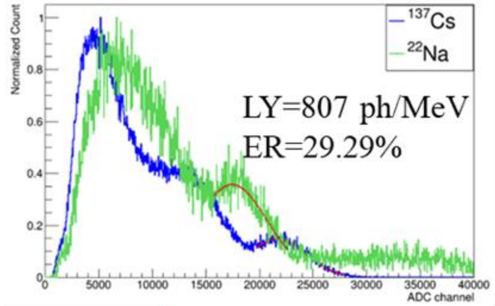


2022.05



Density=4.2 g/cm^3
LY>1200 ph/MeV

2022.03



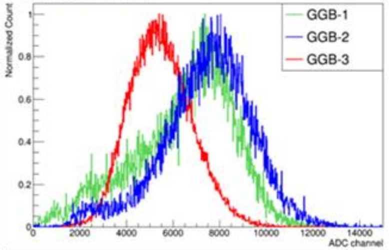
Gd-Al-Si-Ce^{3+}

2022.09

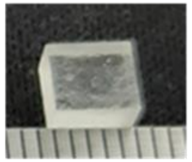
Add BaO
Density>6 g/cm^3

2022.08

LY=570 ph/MeV



2022.07



Density=5.9 g/cm^3
LY=550 ph/MeV

Gd-Ga-B-Ce^{3+}

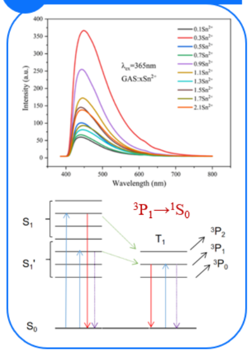
4.5 Articles published (submission time order)

1. (2021.12)Opt. Mater. 2022(125): 112012

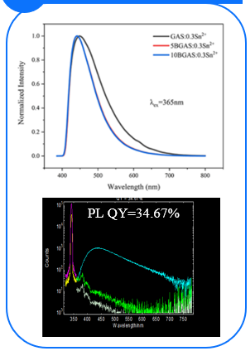
R&D on Sn^{2+}-doped Gadolinium Aluminum-Silicate Glasses

Research on photoluminescence and scintillation properties of Sn^{2+}-doped Gd_2O_3-Al_2O_3-SiO_2 glasses.

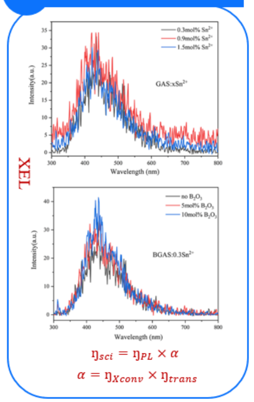
1 Energy level transition



2 Optical basicity



3 Scintillation

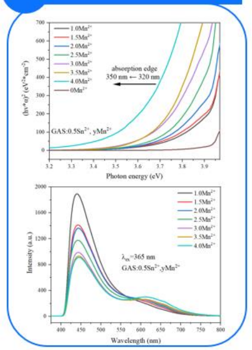


2. (2022.02)发光学报 2022(43): 691-701

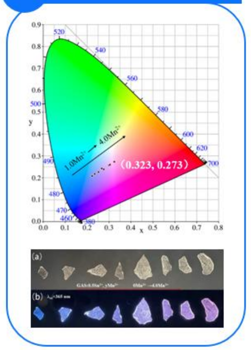
R&D on Sn^{2+}-Mn^{2+} co-doped Gadolinium Aluminum-Silicate Glasses

Research on white light emission and energy transfer of Sn^{2+}-Mn^{2+} co-doped Gd_2O_3-Al_2O_3-SiO_2 glasses.

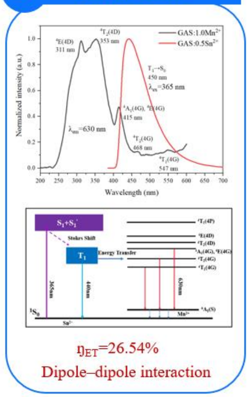
1 Optical properties



2 Color coordinates



3 Energy transfer

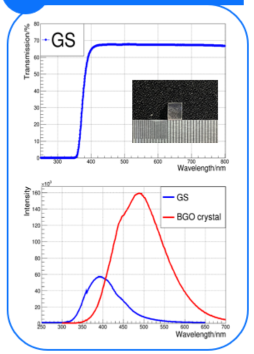


3. (2022.05)Opt. Mater. 2022(130): 112585

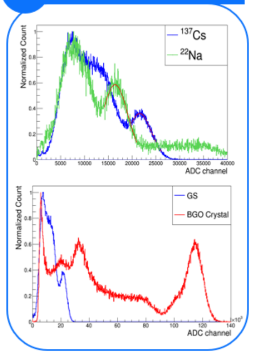
Optical and scintillation properties of aluminoborosilicate glass

The B_2O_3–SiO_2–Al_2O_3–Gd_2O_3–$1Ce_2O_3$ glass shows high light yield of 802 ph/MeV with an energy resolution of 26.77%.

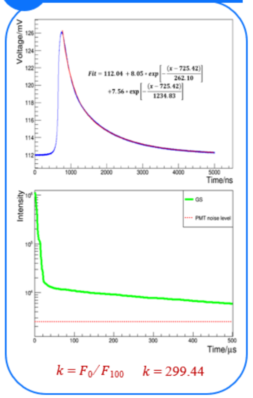
1 Optical properties



2 Energy spectra



3 Time properties

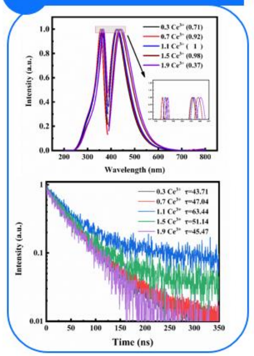


4. (2022.05)J. Am. Ceram. Soc. 2022: 1-12

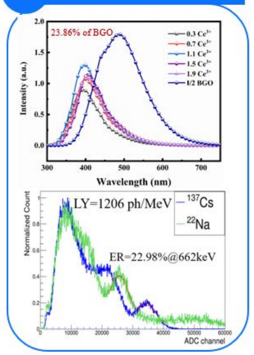
R&D on Ce^{3+}-doped Gadolinium Aluminum-Silicate Glasses

Research on photoluminescence and scintillation properties and mechanism of Ce^{3+}-doped Gd_2O_3-Al_2O_3-SiO_2 glasses.

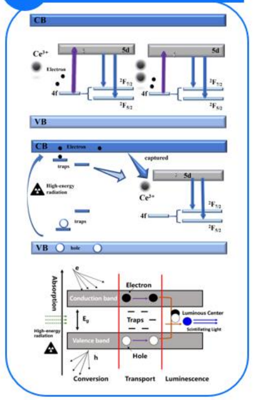
1 Photoluminescence



2 Scintillation



3 Luminescent mechanism

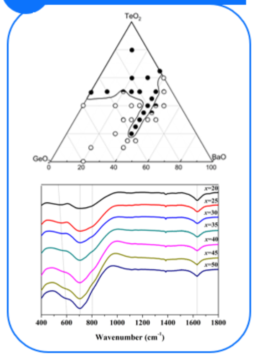


5. (2022.06)Opt. Mater. Accepted

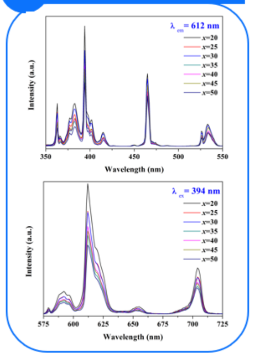
Luminescent properties on Eu^{3+} doped TeO_2-GeO_2-BaO scintillation glasses

Research on photoluminescence and scintillation properties of Eu^{3+}-doped TeO_2-GeO_2-BaO scintillation glasses.

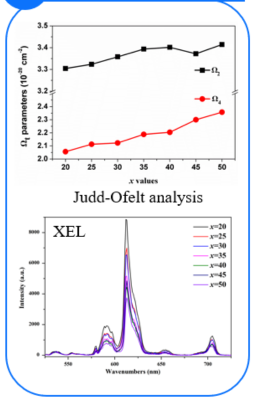
1 Structural Analysis



2 Photoluminescence



3 Scintillation

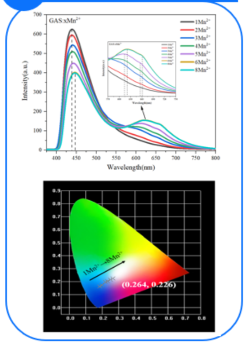


6. (2022.09) Chem. Eng. J. Under review

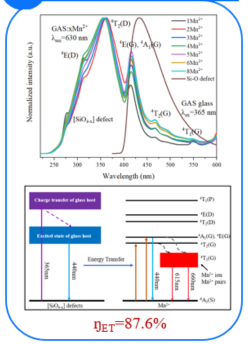
R&D on Mn^{2+} single-doped Gadolinium Aluminum-Silicate Glasses

Research on white light emission and red scintillation of Mn^{2+} single-doped Gd_2O_3-Al_2O_3-SiO_2 glasses.

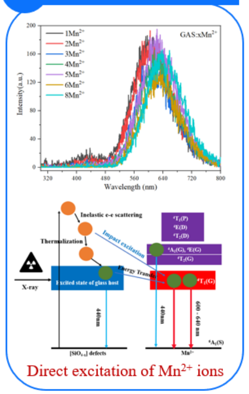
1 White light emission



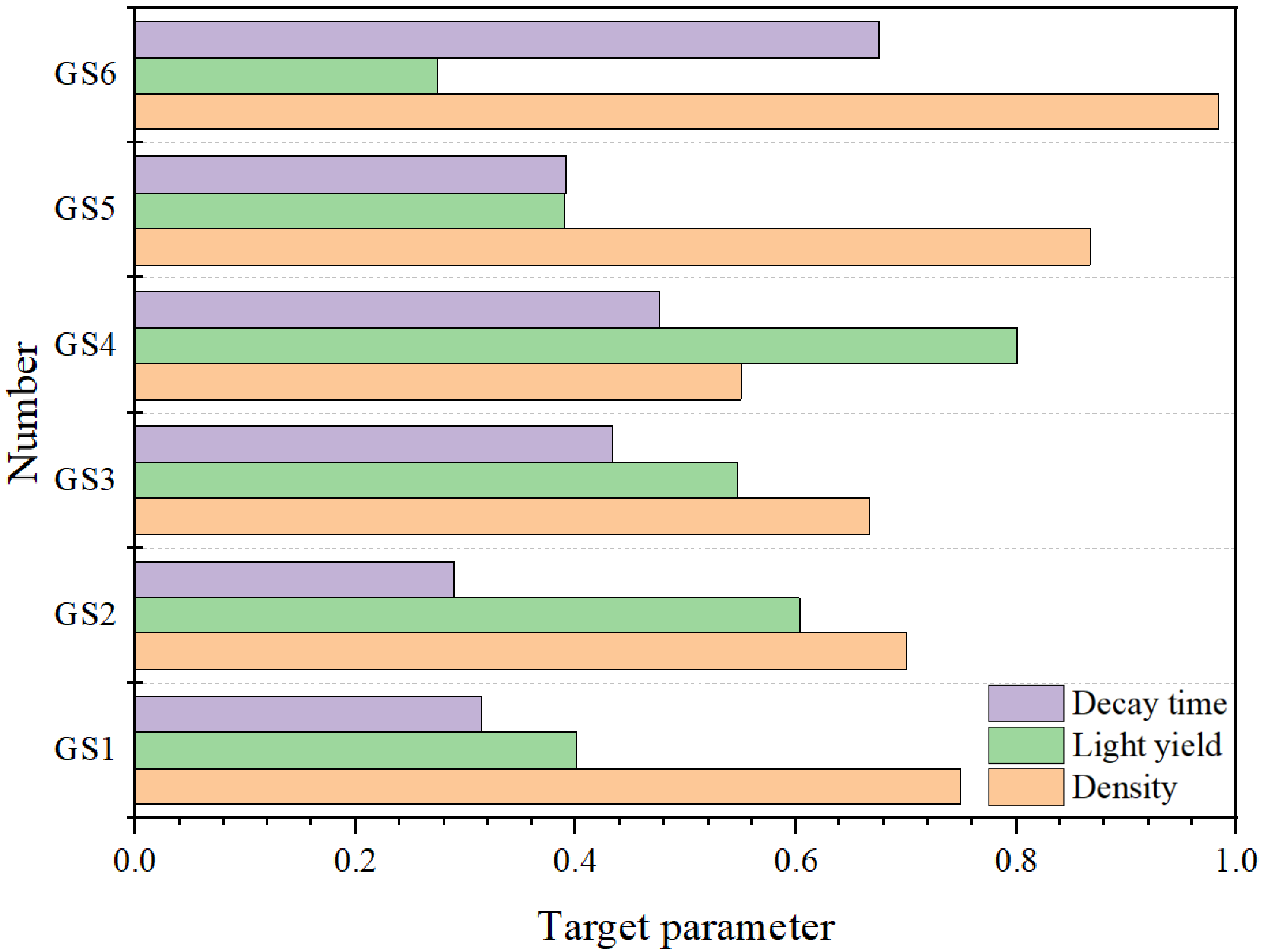
2 Energy transfer



3 Scintillation



4.6 Summary of R&D progress of GS



- Ultra-high density tellurite glass—6.6 g/cm^3
- High light yield glass ceramic—1600 ph/MeV
- Fast scintillating decay time— 100 ns
- Large size glass—42mm*51mm*10mm

Glass scintillator of high density and light yield

- **5.2 g/cm^3 & 800 ph/MeV—Gd-B-Si-Ce^{3+} glass**
- **5.9 g/cm^3 & 550 ph/MeV—Gd-Ga-B-Ce^{3+} glass**

Outline

1. Motivation and target

2. Standalone simulation of GS-HCAL

--by Dejing Du, Yong Liu

3. PFA performance with GS-HCAL

--by Peng Hu, Yuexin Wang, ManQi Ruan

4. Research progress of GS

--by Zhehao Hua, Sen Qian

5. Next Plan

5.1 Next Plan

□ Standalone simulation

- Update the simulation results with the latest glass scintillator samples
- Change the geometry setup to be consistent with the baseline design (i.e. 40 layers)
- Study the Shower Start Algorithm to exclude the shower leakage in the simulation of 40-layer HCAL

□ PFA performance simulation

- More simulation needed to confirm the density effect observed in this preliminary result
  - BMR scanning in a fixed glass composition with different densities
  - Some parameters used in Arbor PFA should be tuned for the glass scintillator HCAL
  - Combination with the homogenous crystal ECAL
- Increase the thickness of HCAL to exclude the influence of shower leakage
- Scintillation process and readout digitization will be added to obtain the optimized performance parameters for glass scintillator and SiPM

5.2 Next Plan

☐ SiPM

- Study the light collection uniformity with a multi-SiPM coupling scheme (e.g. 4 in the corner and 1 in the center)
- Cooperate with BNU for a customized NDL SiPM, which can improve the specific performance according to our requirements.

☐ GS R&D

- **Gd-Ga-B-Si glass** will be the focus of future research.
- This glass can balance the targets of high density and high light yield.
- Next, the properties of the glass will be further improved through raw material purification and vacuum preparation.

Thank you!