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Irradiation resistance study of dense Gd-Al-B-Si-Ce^{3+} glass scintillator

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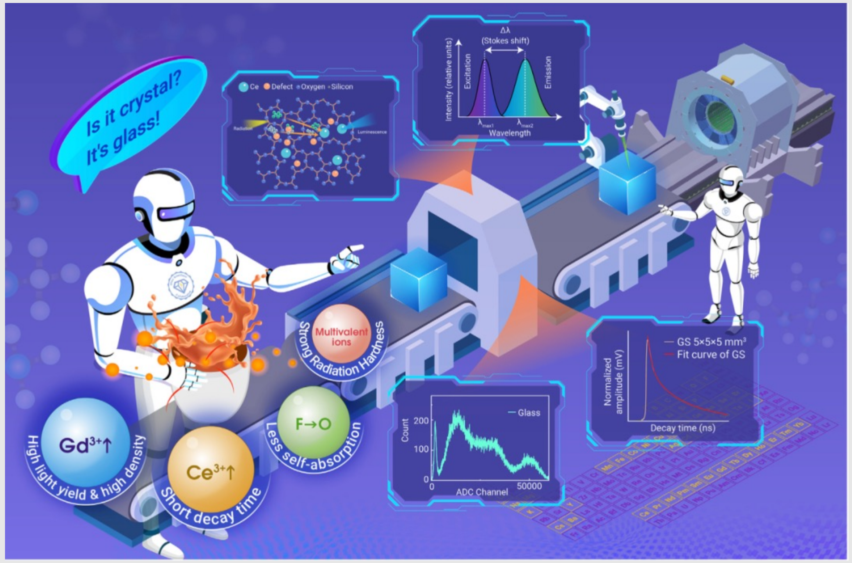
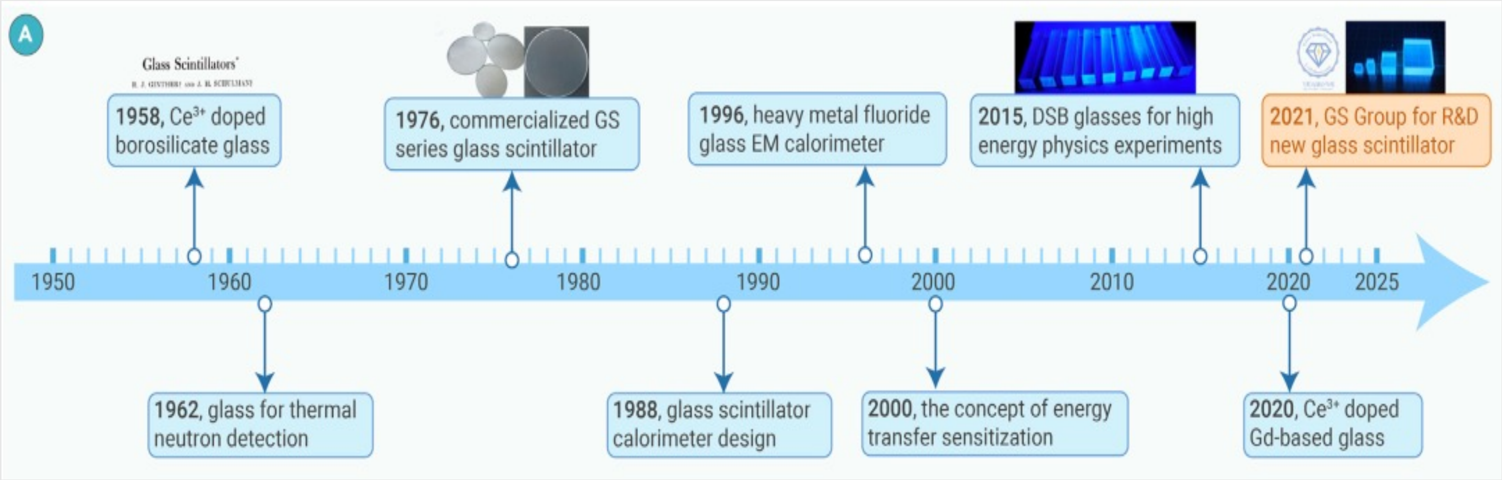
Outline

- **1. Brief introduction to the GS**
- 2. Irradiation resistance requirement on the GS
- 3. Irradiation tests with proton beam
- 4. Irradiation tests with γ-ray
- 5. Summary and Prospect

Glass Scintillator (GS)

◆ **A window to future high-energy radiation detection**

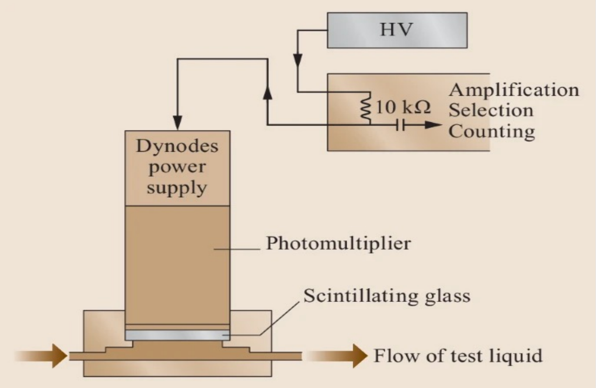


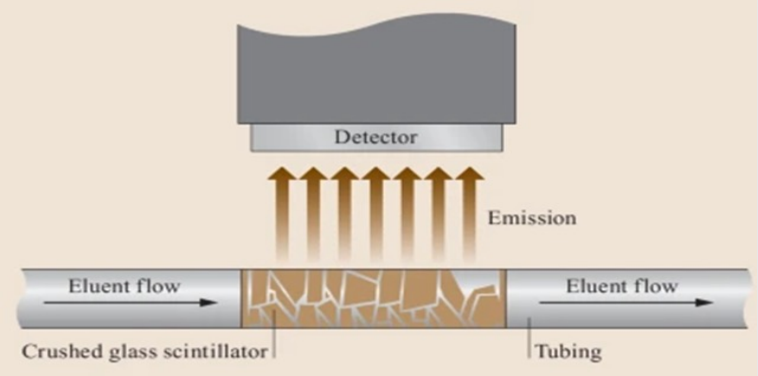


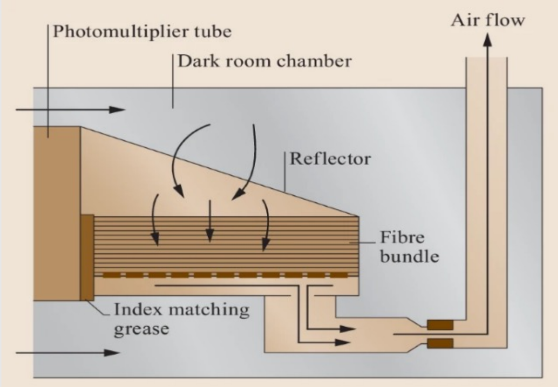
- ☐ Significant progress has been made in high performance scintillation materials due to increasing demand
- ☐ Glass scintillators possess tunable scintillation performance and physicochemical properties by modifying the glass matrix composition and dopants to meet application-specific requirements
- ☐ Simple preparation process, low cost, excellent moldability and scalability for mass production, provide GS with great potential for application in various fields, including nuclear radiation detection and high-energy physics experiments

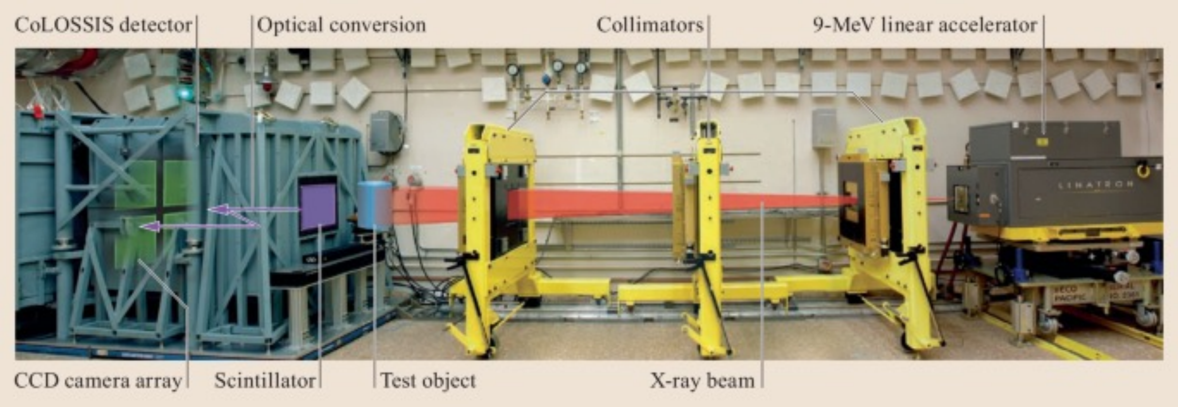
Z. Sui, S. Qian, L. Niu, et al. (2025). Glass scintillator: A window to future high-energy radiation detection. *The Innovation* **6**:100878.

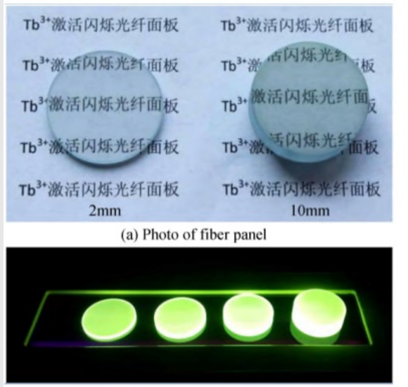
GS for Nuclear Physics





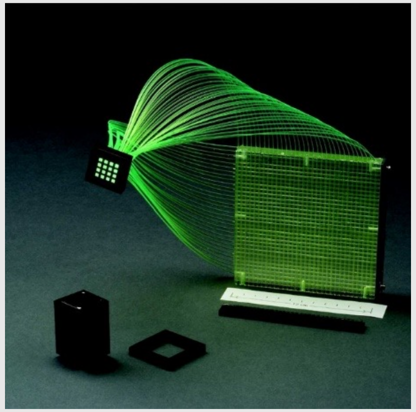






(a) Photo of fiber panel

(b) Luminescence photo of fiber panel



- The glass scintillator (GS) has wide applications in the fields of **radiation detection and imaging**, such as particle discrimination and radiography with glass plate or fiber

Leonard, R.L., Johnson, J.A. (2019). Scintillator Glasses，https://doi.org/10.1007/978-3-319-93728-1_46
吕时超, 周时风, 等. 玻璃闪烁体的研究进展. 光子学报, 2019, 48(11): 1148011.
A. Heller: A CAT scanner for nuclear weapon components. In: Science & Technology Review

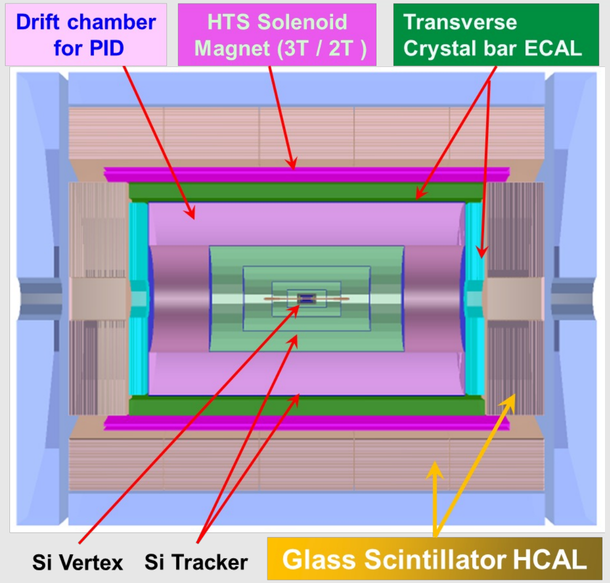
GS for High Energy Physics

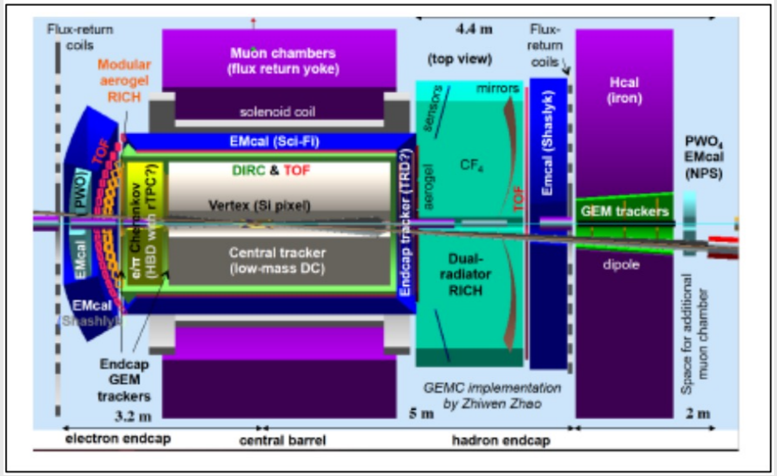
Proposed Calorimeter R&D schedule

带嵌入式电子学的采样型量能器	液化稀有气体量能器	光学量能器
SiW Ecal (ee) ***	LAr Calo (ee/hh/$\mu\mu$) *	HGCCAL (ee) *
Highly compact calo (ee) *		MAXICC (ee) *
DECAL (ee/hh) **		Crilin ($\mu\mu$) *
Sc-Ecal (ee) **		GRAiNITA (ee) *
AHCAL (ee) ***		SpaCal (ee/hh) **
ScintGlassHCAL (ee) *		RADiCAL (ee/hh) *
SDHCAL (ee) ***		DRCal (ee) ***
MPGD-HCAL ($\mu\mu$) *		TileCal (ee/hh) *
ADRIANO3 (ee) **		

量能器类型： 电磁量能器 | 强子量能器 | 电磁+强子量能器

技术成熟度： ***存在大尺寸样机 **存在小尺寸样机 *原理验证阶段

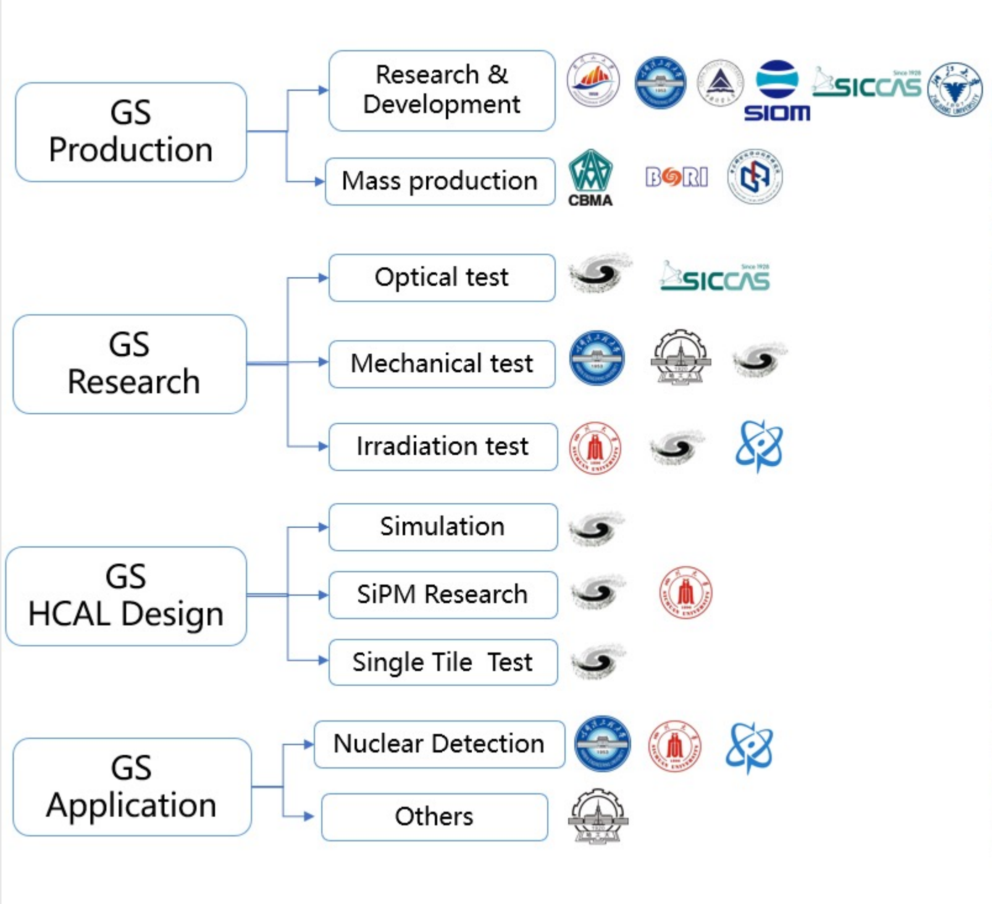




- In 2024 Jan., the hadronic calorimeter (HCAL) based on glass scintillator has been listed in the R&D schedule for the future Higgs factories **in Europe**
- HCAL based on glass scintillator is proposed for the future Higgs factory **in China**, i.e. the Circular Electron Positron Collider (CEPC)
- The electromagnetic calorimeter based on glass scintillator is also an alternative design for the Electron-Ion Collider (EIC) **in U.S.**

EIC Detector R&D Progress Report: Scintillating Glass Development for EIC Calorimeter
Aleksa M, et al. DRD 6: Calorimetry[J]. Governance, 2023, 5: 29. https://cds.cern.ch/record/2886494/files/DRD6-cdscern.pdf.
Peng Hu, et al. GSHCAL at future e+ e- Higgs_factories, NIMA 1059. 168944s

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 Nuclear Instrument Co., 中核（北京）核仪器有限责任公司
- Zhejiang University 浙江大学
- Ganjiang Innovation Academy, CAS 中国科学院赣江创新研究院

闪烁玻璃合作组
Glass Scintillator Collaboration

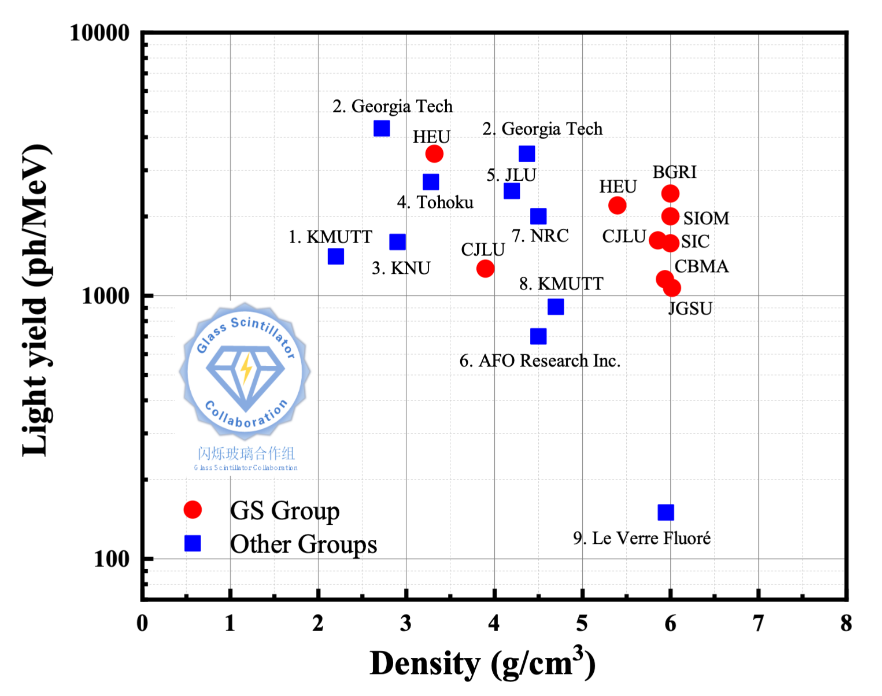
Spokesperson：Sen QIAN

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

-- 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)**.

The Progress of the GS samples



Key parameters	GFO glass	BGO	DSB Glass
Density (g/cm^3)	6.0	7.13	4.2
Melting Point (℃)	1250	1050	1550
Radiation Length (cm)	1.59	1.12	2.62
Molière Radius (cm)	2.49	2.23	3.33
Nuclear Interaction Length (cm)	24.2	22.7	31.8
Z_{eff}	56.6	71.5	49.7
dE/dx (MeV/cm)	8.0	8.99	5.9
Emission Peak (nm)	400	480	430
Refractive Index	1.74	2.15	
Light Yield (ph/MeV)	~ 1500	7500	2500
Energy Resolution (% at 662 keV)	~ 23	9.5	
Scintillation Decay Time (ns)	~ 60, 500	60, 300	90, 400

- Left figure shows the light yields versus density characteristics of the various GS samples invented in the past years by the GS collaboration and other groups
- The Gadolinium Fluoro-Oxide (GFO) glass has been selected ultimately as the baseline material due to its optimal balance between performance characteristics and manufacturability for large-scale production
- Compared with BGO and DSB glass, GFO glass achieves a density of 6.0 g/cm^3, competitive light yield (~1500 ph/MeV) and decay time (~500 ns) in a cost-effective way

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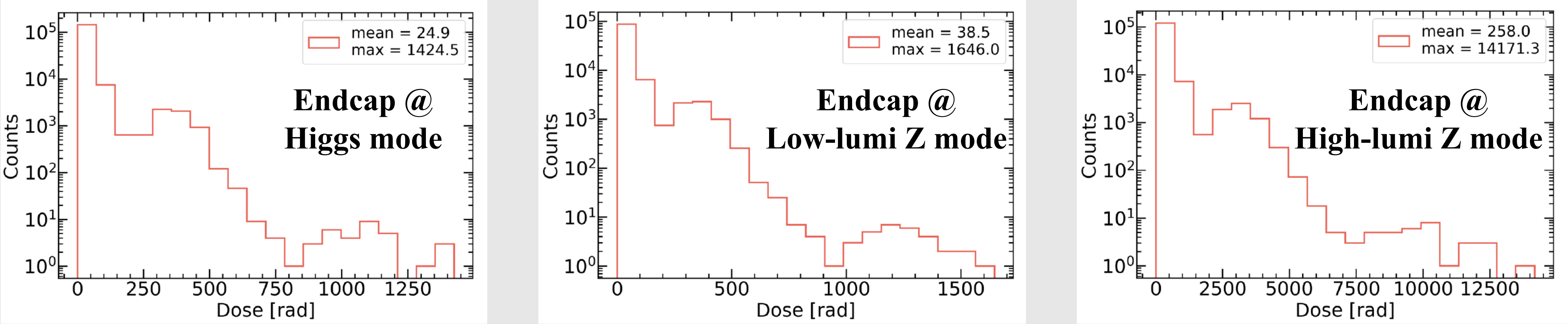
Beam background estimation for GSHCAL



Running Mode	Endcap @ Higgs mode	Endcap @ Low-lumi Z mode	Endcap @ High-lumi Z mode
Dose >99% cells/year	< 5 Gy	< 5 Gy	< 50 Gy
Dose Mean/year	0.25 Gy	0.39 Gy	2.6 Gy
Dose Max/year	14.2 Gy	16.5 Gy	142 Gy

- **Beam background is mainly induced by gamma-rays and electrons**
- **The study is still ongoing and updated background in new MDI is estimated to be less than this result**

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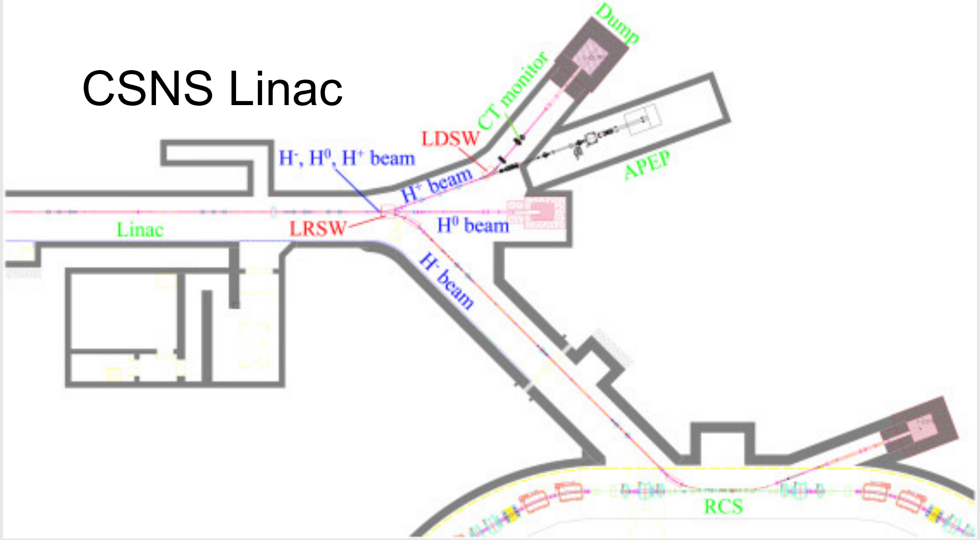
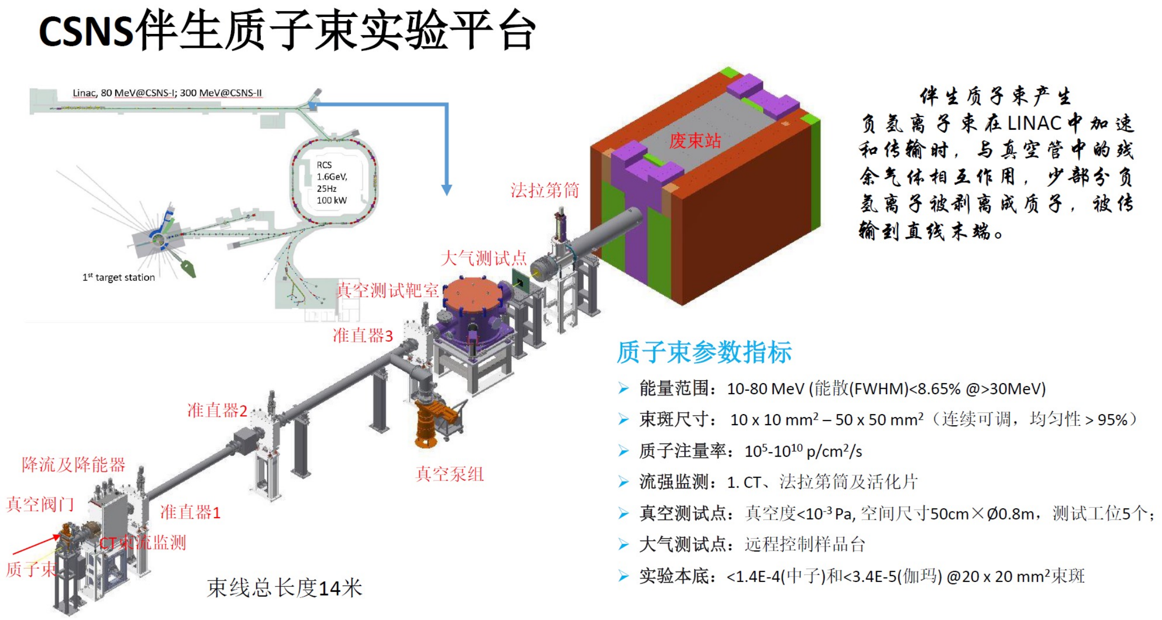
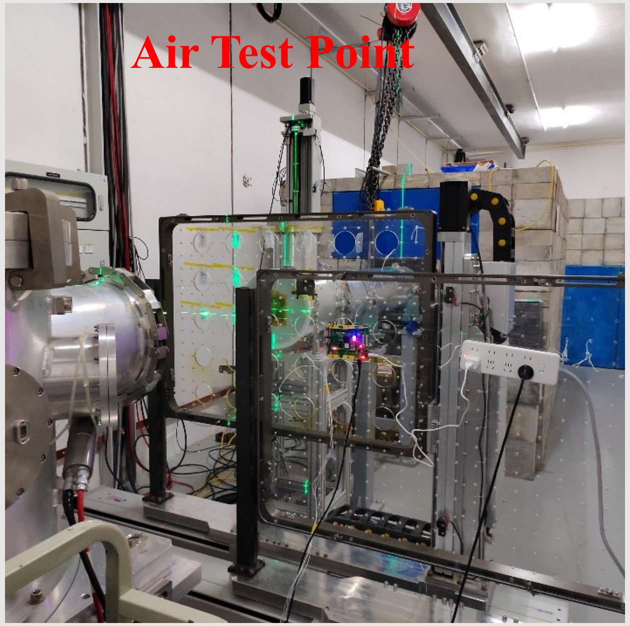
Irradiation test at CSNS APEP Platform



- The Associated Proton beam Experiment Platform (APEP) at the China Spallation Neutron Source (CSNS) can provide high-flux proton beam at low energy
- About 5000 h / year can be provided for users
- Users can apply for the beam test via https://apep.csns.ihep.ac.cn/ and fill in some detail info about your test schedule

CSNS APEP Platform



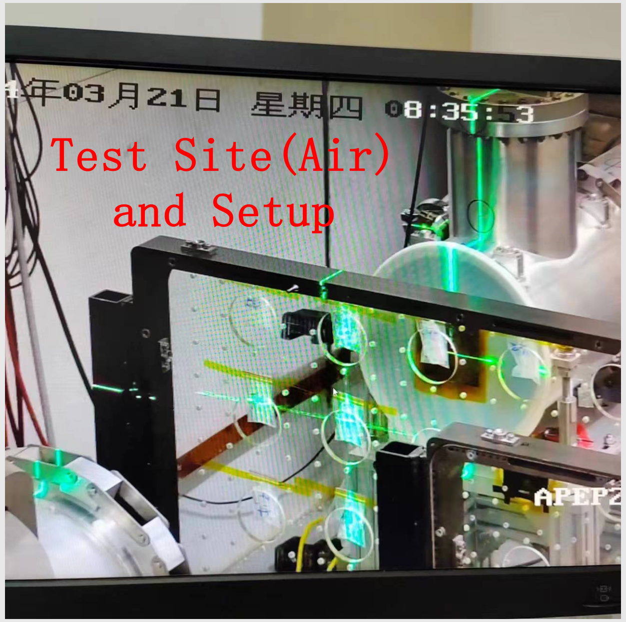


- APEP can provide proton beam from 10 to 80 MeV
- Two test points are provided, i,e., a vaccum test point and an air test point; A frame installed on a two-dimensional displacement platform was placed in the air test point to fix samples
- The beam spot size can be tuned from 10×10 mm^2 to 50×50 mm^2, with a homogeneity > 95%
- Currently, the intensity of proton beam can be tuned from ~10^6 to ~10^9 p/cm2/s, which also depends on the beam spot size and energy

Setup of proton irradiation test

Samples	GS1	GS2
Size	4×4×1 cm^3	
Density	6 g/cm^3	
Light yield	507 ph/MeV	788 ph/MeV
Decay time	94, 992 ns	76, 1014 ns
Max. emi	386 nm	395 nm
T@400 nm	78.9%	76.6%

Proton Energy	80 MeV
Beam spot size	50x50 mm^2
Intensity	~4.86×10^9 $p/cm^2/s$
Energy deposition in samples (1 cm)	~ 40.7 MeV
Absorbed dose rate	~315 Gy/min



- Two large glass samples (GS1 and GS2) produced by the GS collaboration were processed into 7 small glass samples (1×1×1 cm^3, labled as GS1-1 to GS1-7 and GS2-1 to GS2-7) to evaluate irradiation-induced performance degradation across a wide dose range
- Samples were fixed at the two-dimensional displacement platform in advance
- The main experimental parameters used in this test are listed in the table above

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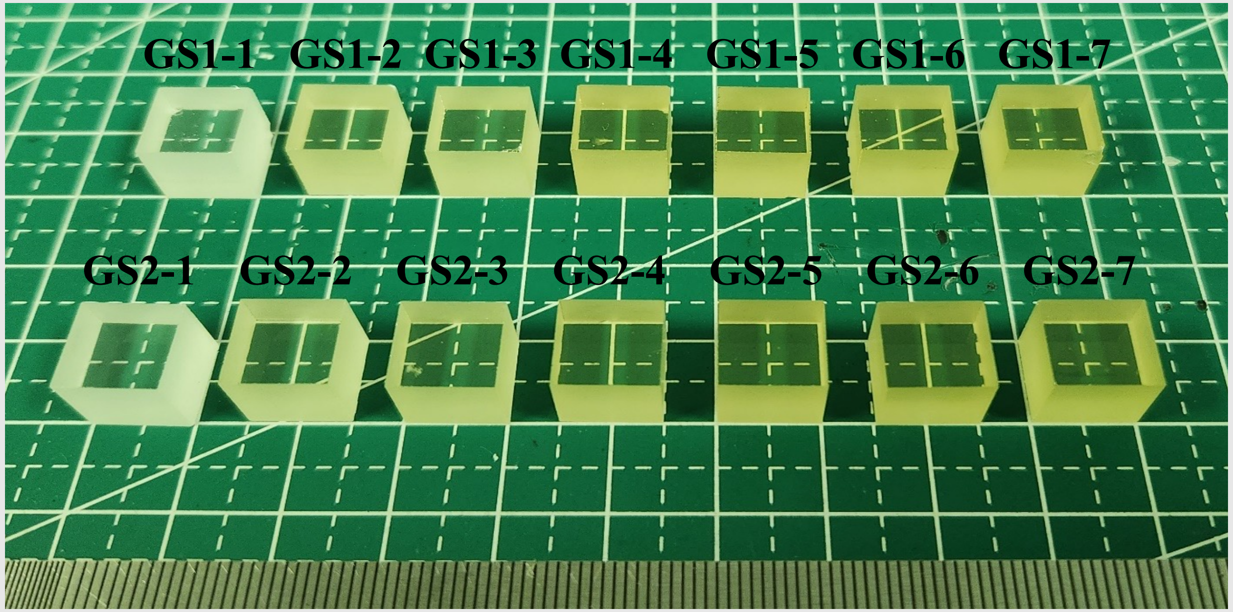
The Samples after irradiation

Group ID	Samples	proton flux (p/cm^2/s)	Irradiated time	Absorbed dose (Gy)	Integral flux (proton/cm^2)
1	GS1-1 GS2-1	0	0	0	0
2	GS1-2 GS2-2	4.86×10^9	1 m 16 s	$\sim 4.0 \times 10^2$	3.69×10^{11}
3	GS1-3 GS2-3	4.86×10^9	2 m 33 s	$\sim 8.0 \times 10^2$	7.44×10^{11}
4	GS1-4 GS2-4	4.86×10^9	6 m 24 s	$\sim 2.0 \times 10^3$	1.87×10^{12}
5	GS1-5 GS2-5	4.86×10^9	12 m 49 s	$\sim 4.1 \times 10^3$	3.74×10^{12}
6	GS1-6 GS2-6	4.86×10^9	25 m 38 s	$\sim 8.1 \times 10^3$	7.47×10^{12}
7	GS1-7 GS2-7	4.86×10^9	2 h 8 m 12 s	$\sim 4.1 \times 10^4$	3.74×10^{13}



- 7 groups of glass samples were irradiated by the 80 MeV proton beam for a minimum of 1 m 23 s and a maximum of around 2 h 8 m 12s, corresponding to an absorbed dose from ~4.0x10^2 Gy to ~4.1x10^4 Gy
- All glass samples have experienced varying degrees of color change after proton irradiation, depending on the absorbed dose

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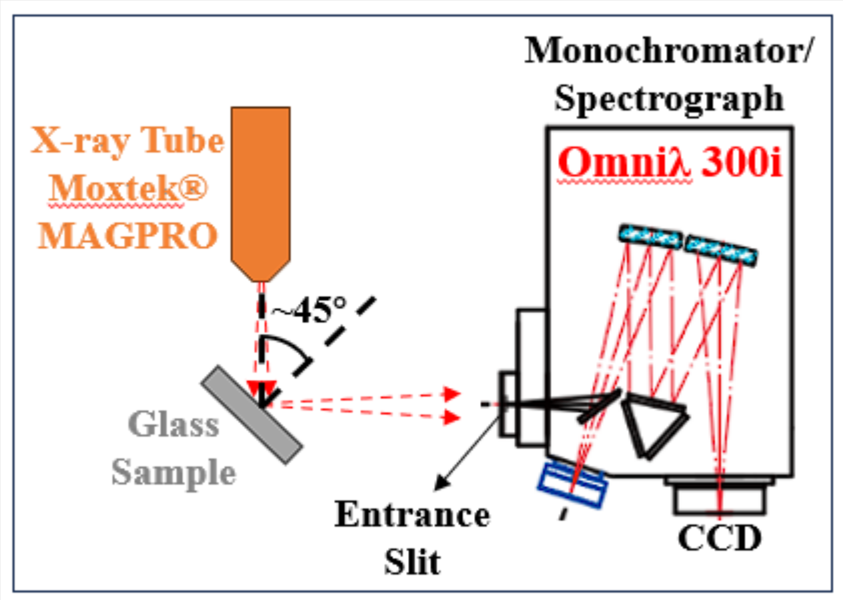
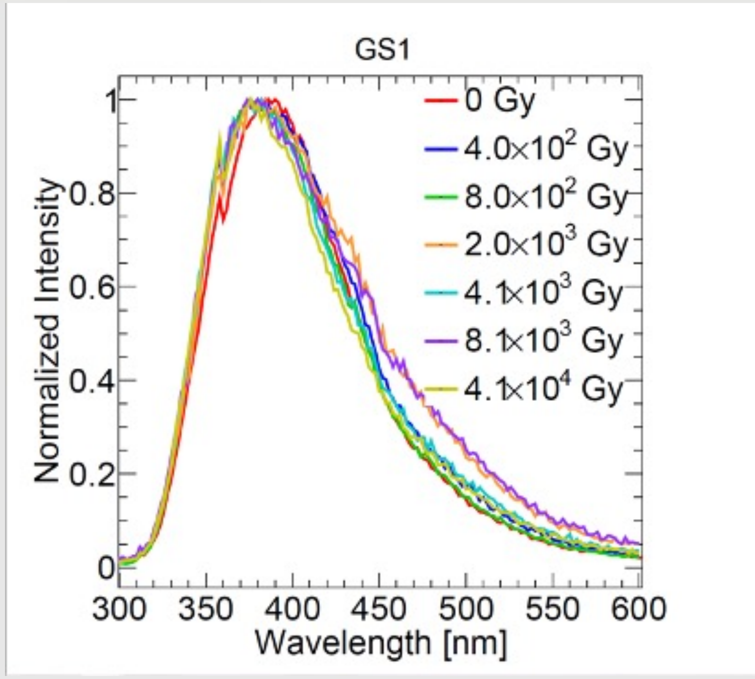
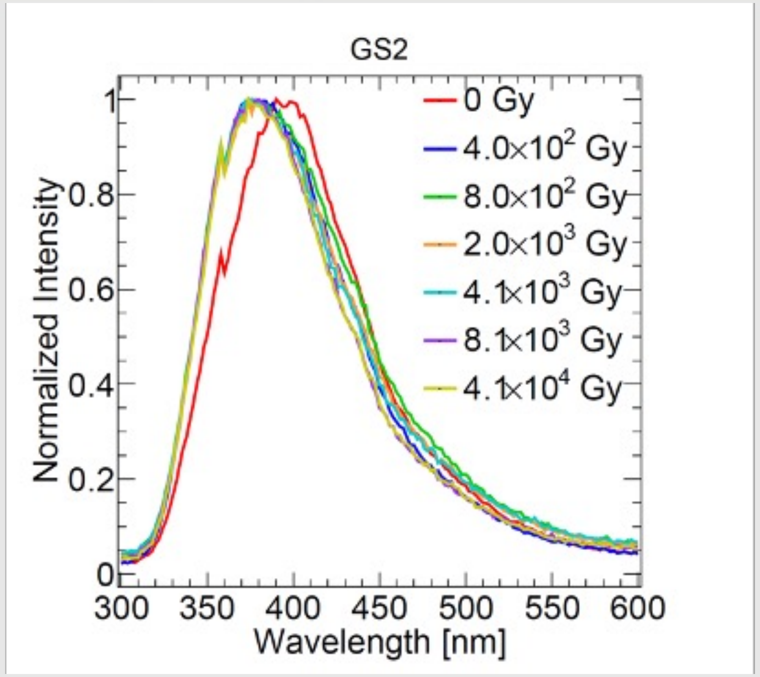
X-ray Excited Luminescence



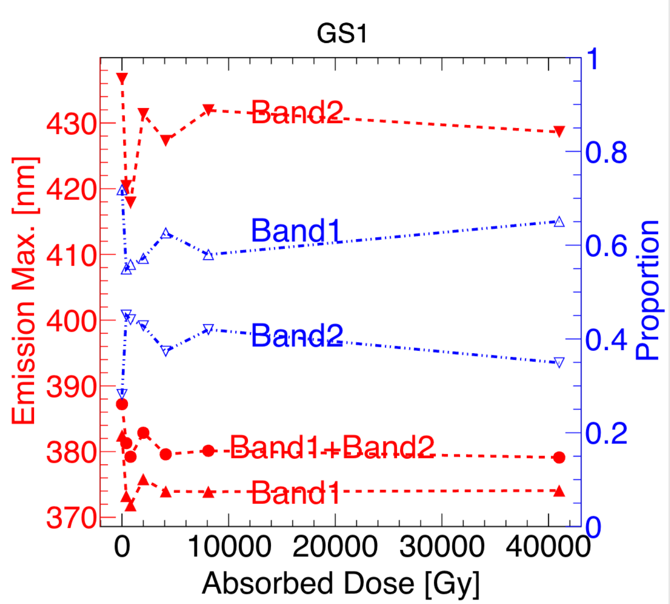


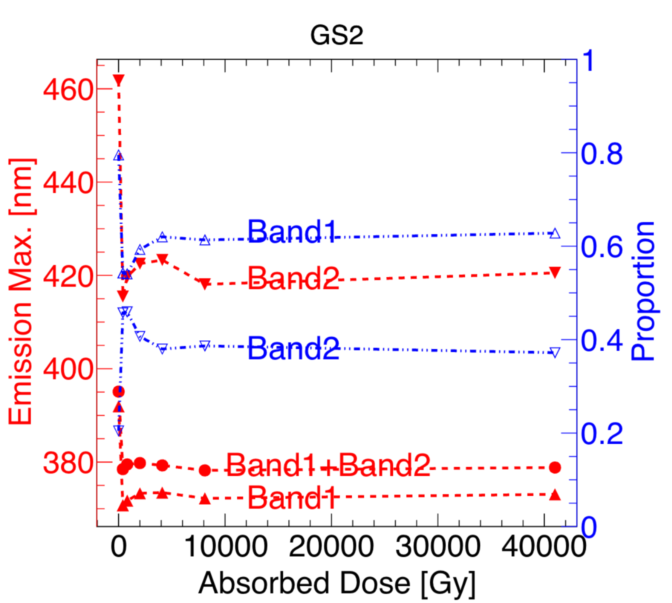


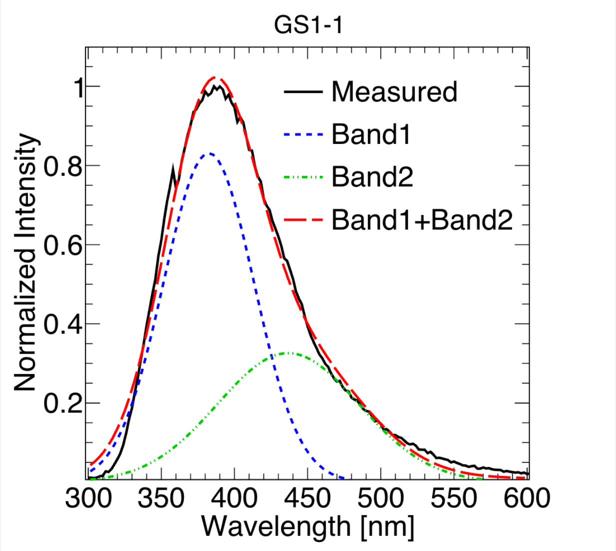
- The X-ray excited luminescence (XEL) spectra of glass samples were and **a blue shift (7~16 nm) of the emission peak was found for all glass samples after irradiation**
- A comparable blue shift (10 nm) was also reported in Li-B-Ce^{3+} (LBPO) glasses after proton irradiation
- A possible reason is that the structure of the glass and [CeO_n] polyhedra became more flexible and larger after proton irradiation.

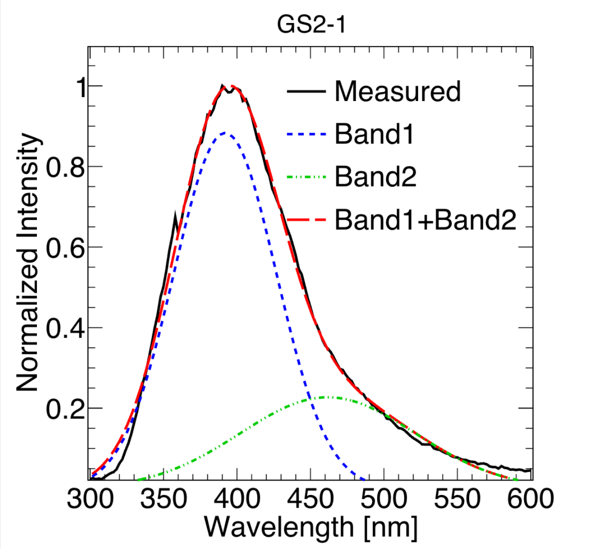
NIMA ***1081 (2026),*** 170869
Z.J. Zhang, et al., OME, 11 (2017), 3979

X-ray Excited Luminescence









- The measured XEL spectrum comprise of two emission band, which can be fitted with a bi-Gaussian function;
- The blue-shift of Accumulated peak for GS1 and GS2 are ~7 nm and ~16 nm, respectively; the peak and proportion of band1 and band2 after irradiation are more or less the same for GS1 and GS2, which are ~373 nm (~60%) and ~420 nm (~40%)

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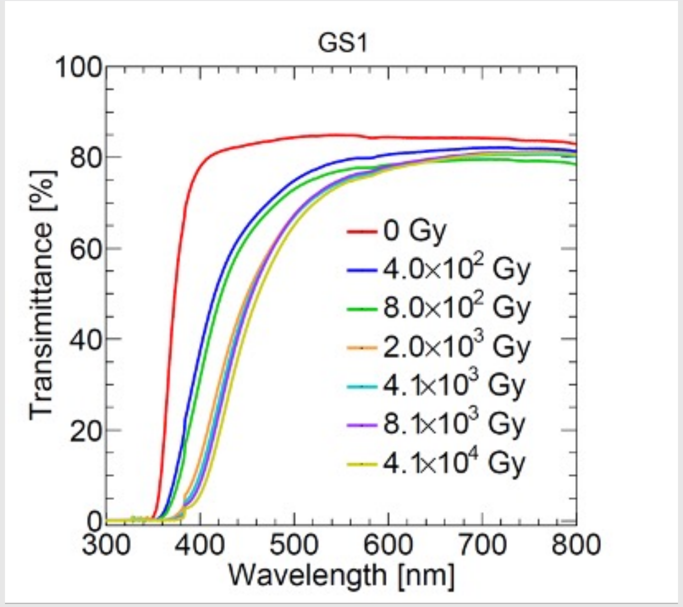
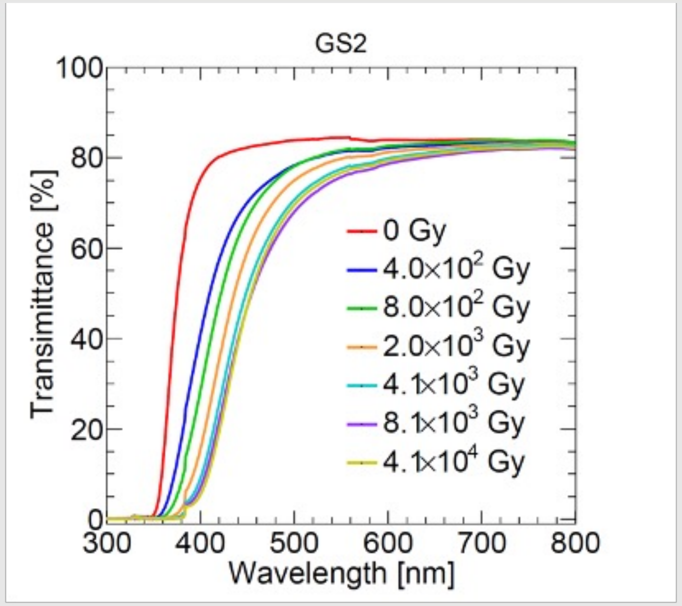
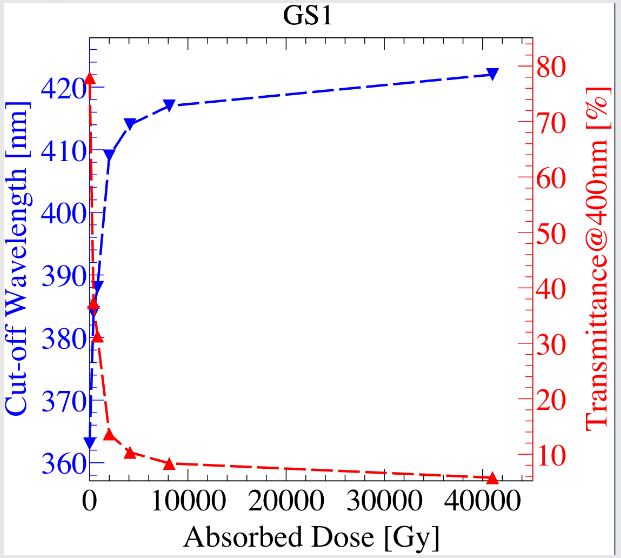
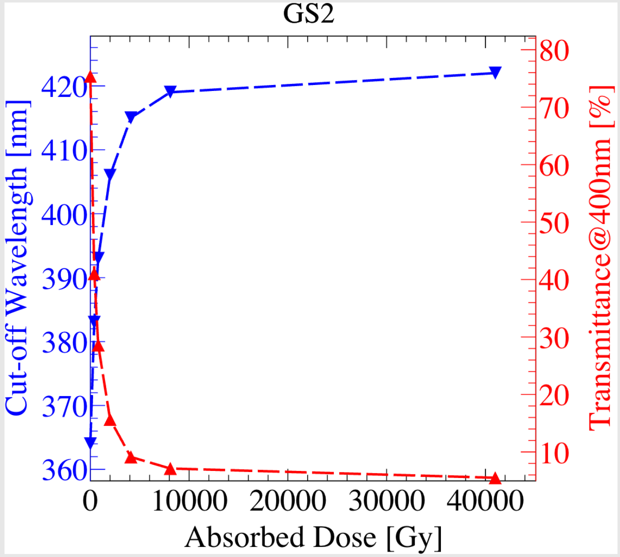
Transmittance







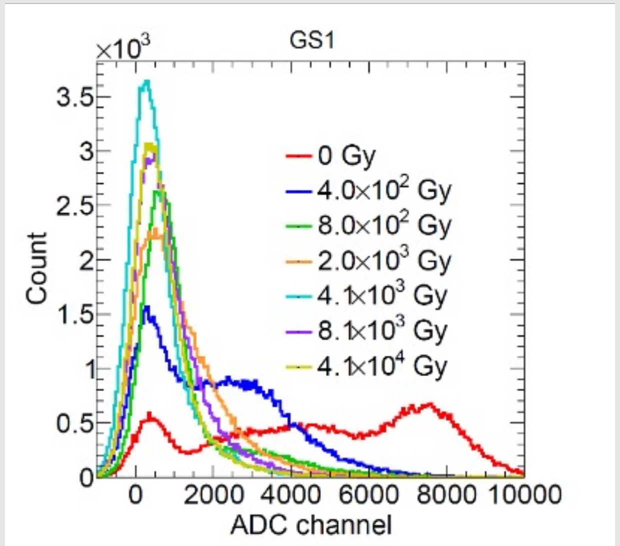


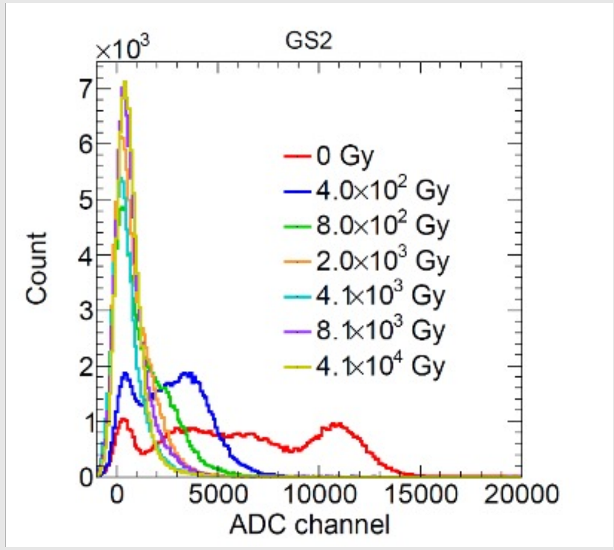
- The transmittance spectra of glass samples were measured and a significant degradation in transmittance was observed
- The cut-off wavelength shifts rapidly from ~360 nm to ~410 nm as the absorbed dose increases from 0 Gy to ~2×10^3 Gy. The transmittance at 400 nm decreases by about 50% after irradiation of 400 Gy.

NIMA ***1081 (2026)***:170869.

Light output (Using ^{137}Cs)

	GS1-1	GS1-2	GS1-3	GS1-4	GS1-5	GS1-6	GS1-7
Light yield (ph/MeV)	552	187	/	/	/	/	/
Absorbed dose (Gy)	0	400	800	2000	4000	8000	$4x10^4$
	GS2-1	**GS2-2**	**GS2-3**	**GS2-4**	**GS2-5**	**GS2-6**	**GS2-7**
Light yield (ph/MeV)	807	255	/	/	/	/	/
Absorbed dose (Gy)	0	400	800	2000	4000	8000	$4x10^4$





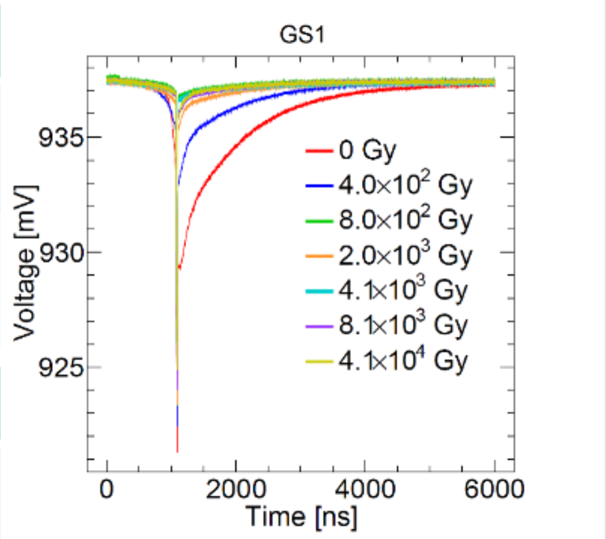
- The light output of glass sample was measured by the XP2020 PMT
- The light output of the glass sample will decrease to 1/3 of its original level after receiving a dose of 400 Gy.
- The light output is too weak to be detected when the absorbed dose is larger than 400 Gy

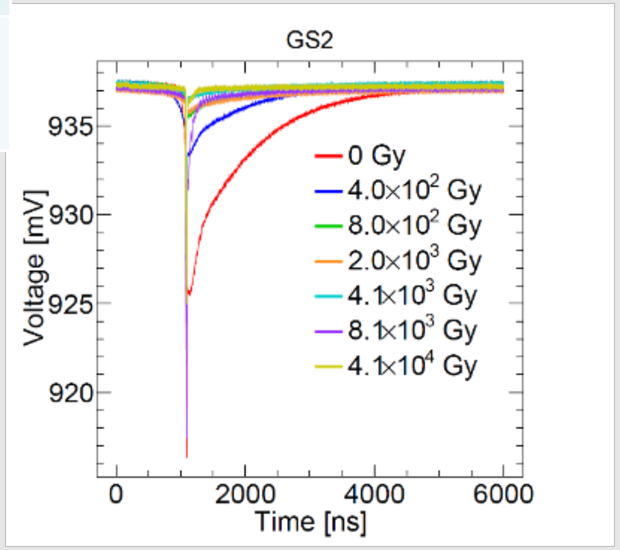
NIMA ***1081 (2026)***:170869.

Decay time

	GS1-1	GS1-2	GS1-3	GS1-4	GS1-5	GS1-6	GS1-7
Decay time (ns)	87, 985	89, 980					
Absorbed dose (Gy)	0	400	800	2000	4000	8000	$4x10^4$

	GS2-1	GS2-2	GS2-3	GS2-4	GS2-5	GS2-6	GS2-7
Decay time (ns)	70, 1028	67, 1017					
Absorbed dose (Gy)	0	400	800	2000	4000	8000	$4x10^4$





- The decay time is obtained by fitting the falling edge of average waveform of all events with a di-exponential function
- There appears to be no significant change as the absorbed dose increases. Similar results were also reported in Li-B-Ce^{3+} (LBPO) glasses after proton irradiation

NIMA ***1081 (2026),*** 170869
Z.J. Zhang, et al., OME, 11 (2017), 3979

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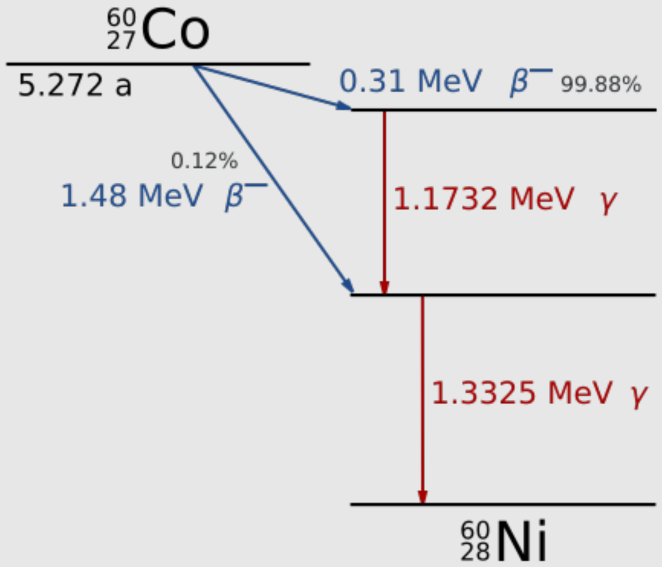
Gamma irradiation in CNNC 261



Decay Mode: β⁻		Half-Life: (1925.3 ± 0.4) d			[2]
Radiation Type		Energy (keV)	Intensity (%)		Ref.
Auger-L		0.7 - 0.9	0.0392	12	[1]
Auger-K		6.26 - 8.32	0.0154	5	[1]
β⁻max		157.8	« 0.001	--	[1]
β⁻max		318.22	99.88	3	[1]
β⁻av		95.77			[1]
β⁻max		665.3	« 0.001	--	[1]
β⁻max		1491.4	0.12	3	[1]
β⁻av		625.87			[1]
β⁻max		2823.9	« 0.001	--	[1]
X-ray L	Σ	0.74 - 0.94	< 0.001	--	[1]
X-ray Kα	Σ	7.46 - 7.48	0.0098	4	[1]
X-ray Kβ	Σ	8.26 - 8.27	0.00136	5	[1]
γ		347.14	0.0075	4	[2]
γ		826.10	0.0076	8	[2]
γ		1173.2	99.85	3	[2]
γ		1332.5	99.9826	6	[2]
γ		2158.8	0.0012	2	[2]
γ		2505.7	« 0.001	--	[2]

- A ^{60}Co source (type II) with an activity of 3.656×10^{11} Bq can be used for the gamma irradiation test of samples
- Two gamma-rays (1.1732 MeV and 1.3325 MeV) will be emitted per decay of ^{60}Co atom

Absorbed dose rate estimation

- For a point source, the absorbed dose rate of monoenergetic gamma-rays at a certain point P under Charged-Particle Equilibrium is

$$\frac{dD}{dt} = \varphi \cdot \left(\frac{\mu_{en}}{\rho}\right) \cdot E_{\gamma}$$

$\frac{dD}{dt}$ — the absorbed dose at point P, Gy/s

φ — the fluence rate at point P, photons/(m^2·s)

$\frac{\mu_{en}}{\rho}$ — mass energy-absorption coefficient, m^2/kg

E_{γ} — energy of gamma-rays, J

- The φ of ^{60}Co at 10 cm is ~ 2.94×10^{12} photons/(m^2·s)
- The $\frac{\mu_{en}}{\rho}$ of 1.1732 MeV and 1.3325 MeV gamma-rays for latest glass samples is ~ 0.0264 and ~ 0.0249 cm^2/g
- Then the total absorbed dose rate at 10 cm is ~ 3×10^{-3} Gy/s or ~10 Gy/h

X-Ray Mass Attenuation Coefficients

NIST Standard Reference Database 126

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Tables of X-Ray Mass Attenuation Coefficients and Mass Energy-Absorption Coefficients from 1 keV to 20 MeV for Elements Z = 1 to 92 and 48 Additional Substances of Dosimetric Interest*

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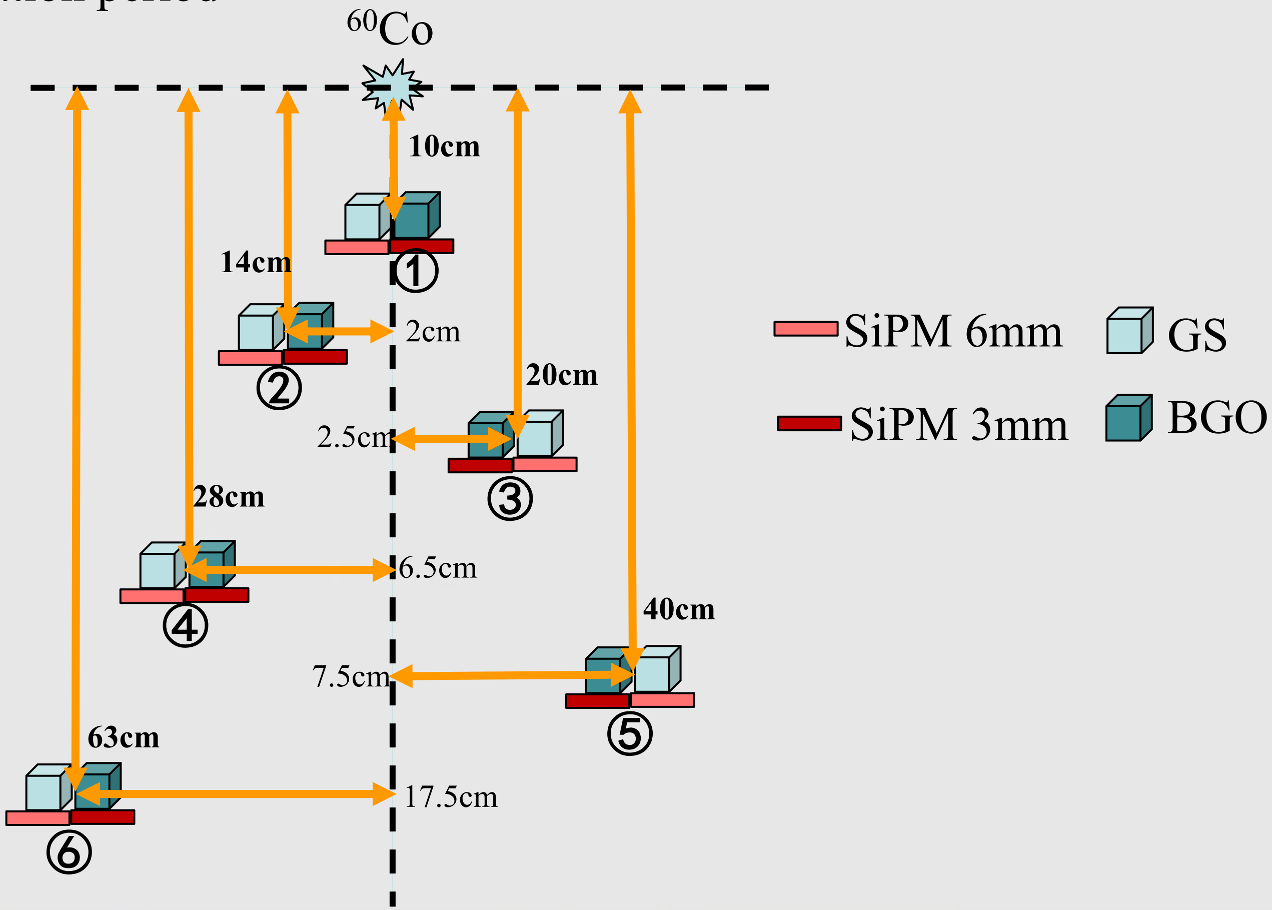
Abstract

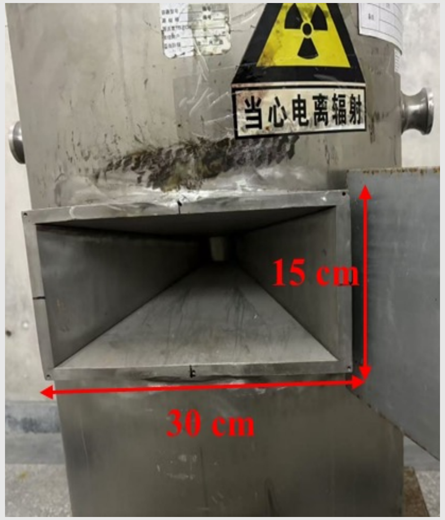
Tables and graphs of the photon mass attenuation coefficient μ/ρ and the mass energy-absorption coefficient μ_{en}/ρ are presented for all of the elements Z = 1 to 92, and for 48 compounds and mixtures of radiological interest. The tables cover energies of the photon (x-ray, gamma ray, bremsstrahlung) from 1 keV to 20 MeV. The μ/ρ values are taken from the current photon interaction database at the National Institute of Standards and Technology, and the μ_{en}/ρ values are based on the new calculations by Seltzer described in Radiation Research **136,** 147 (1993). These tables of μ/ρ and μ_{en}/ρ replace and extend the tables given by Hubbell in the International Journal of Applied Radiation and Isotopes **33,** 1269 (1982).

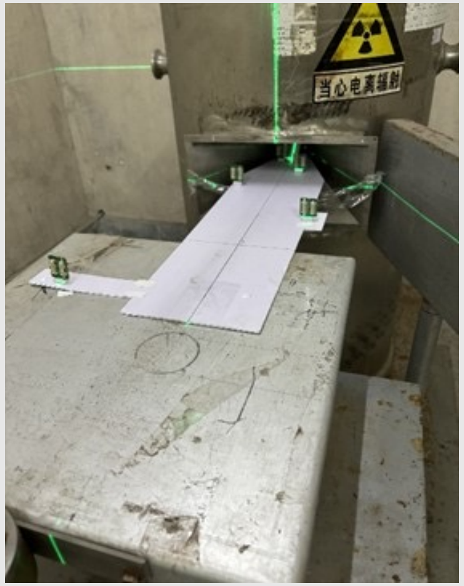
- $\frac{\mu_{en}}{\rho}$ is obtained from the NIST database (XAAMDI)

Experiment Setup

- As illustrated below, 6 glass samples, 6 BGO samples (both 5×5×5 mm^3) and SiPM samples were positioned at varying distances to acquire different dose rates, thereby achieving different absorbed doses within the same irradiation period







Absorbed dose calculation

- 6 groups of glass samples were irradiated by a ^{60}Co source for around 42 h, corresponding to an absorbed dose of ~10 Gy to ~400 Gy
- SiPMs from Hama/NDL/JB were also irradiated by a ^{60}Co source for around 42 h, corresponding to an absorbed dose of ~5 Gy to ~100 Gy
- Data analysis is still ongoing

Scintillator	Total dose(Gy@42h)					
	Pos1	Pos2	Pos3	Pos4	Pos5	Pos6
GS	~431.8	~215.5	~106.4	~52.3	~26.2	~10.1
BGO	~502.8	~253.6	~124.6	~61.4	~30.6	~11.9

SiPM	Total dose(Gy@42h)					
	Pos1	Pos2	Pos3	Pos4	Pos5	Pos6
EQR20 6060	~111.3	~64.0	~33.4	~17.6	~10.0	~4.3
S13360-6050CS	~68.6	~42.2	~22.9			
JSP TP6050	~159.5	~90.1	~47.1			
EQR20 3030	~111.3	~64.0	~33.4	~17.6	~10.0	~4.3
S13360-3050CS	~68.6	~42.2	~22.9			

Outline

- 1. Brief introduction to the GS
- 2. Irradiation resistance requirement on the GS
- 3. Irradiation tests with proton beam
- 4. Irradiation tests with γ-ray
- **5. Summary and Prospect**

Summary and Prospect

- The irradiation test of early glass samples (performance is relatively poor) was performed by using **80 MeV proton beam** at APEP with a dose rate of **315 Gy/min.**
- The light output will **decrease to 1/3 of its original level after receiving a dose of 400 Gy**, along with blue shift of emission, decrease of transmittance and unchanged decay time.
- The radiation tolerance of a GSHCAL Endcap cell is estimated to be ~500 Gy (10 years) and is probably lower in updated MDI design.
- The gamma-ray irradiation test of glass samples and SiPMs was also performed and analysis is ongoing; preliminary results show irradiation resistance of GS samples is not a main constraint.
- Damage mechanism studies and optimization of glass composition and manufacture process is still ongoing to realize better radiation tolerance.

Glass Scintillator Collaboration

See the unseen
change the unchanged

The Innovation

THANKS