ABS and DSB Glass Samples

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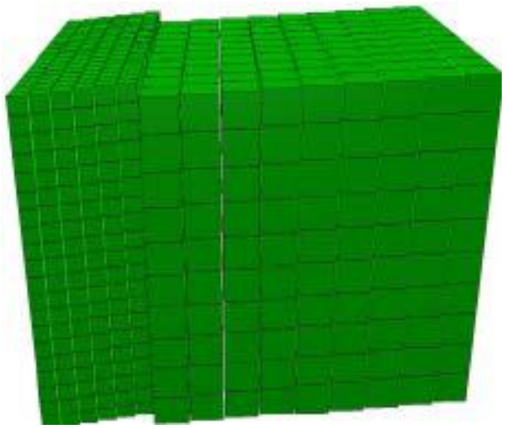
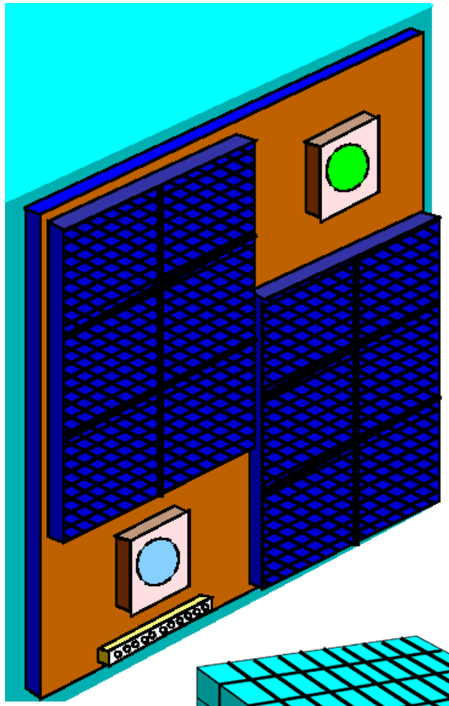
Motivation: Homogeneous Hadron Calorimeter (HHCAL)



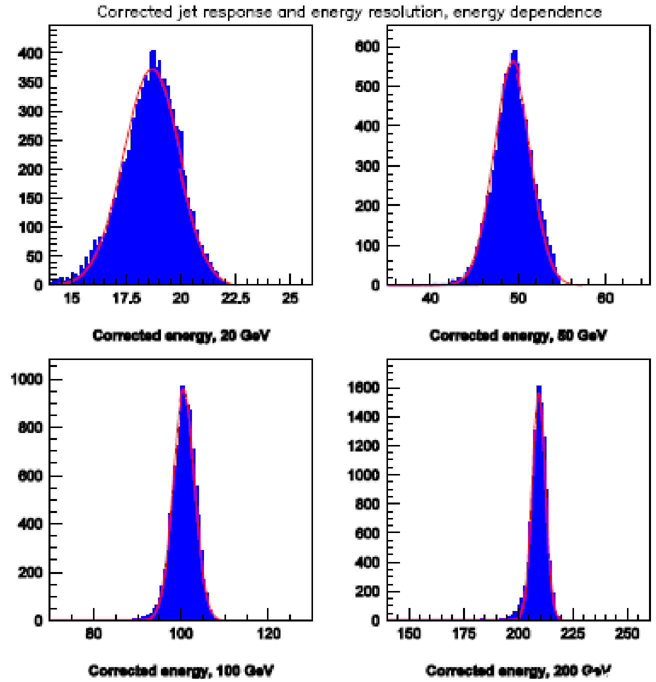
A. Para, H. Wenzel and S. McGill in Callor2012 Proceedings;
A. Benaglia *et al*., IEEE TNS **63** (2016) 574:

Jet energy resolution of <20%/√E is achievable by HHCAL with dual readout of S/C or dual gate

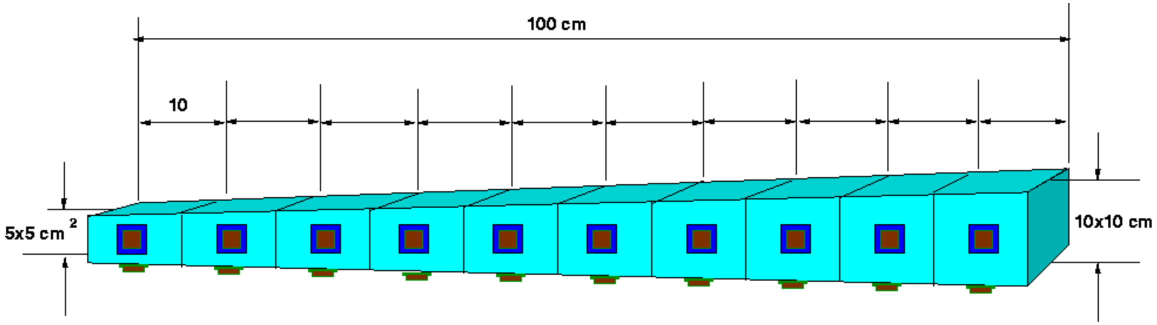
M. Demarteau and H. Wenzel in the CPAD 2021 Workshop

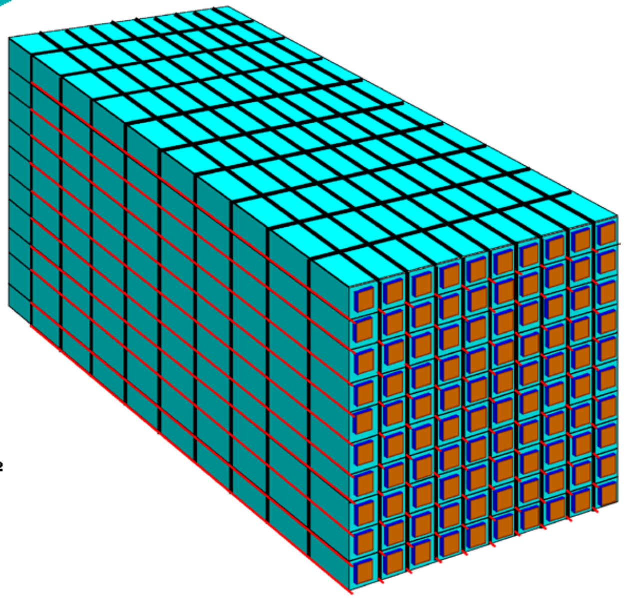


Readout with two SiPMs monitoring with two LEDs



Can we afford?





Inorganic Scintillators for HHCAL

Presented in 10/22/2022 CalVision meeting, also in https://doi.org/10.48550/arXiv.2203.06788

	BGO	BSO	PWO	PbF_2	PbFCl	Sapphire :Ti
Density (g/cm^3)	7.13	6.8	8.3	7.77	7.11	3.98
Melting point (℃)	1050	1030	1123	824	608	2040
X_0 (cm)	1.12	1.15	0.89	0.94	1.05	7.02
R_M (cm)	2.23	2.33	2.00	2.18	2.33	2.88
λ_I (cm)	22.7	23.4	20.7	22.4	24.3	24.2
Z_{eff} value	71.5	73.8	73.6	76.7	74.7	11.1
dE/dX (MeV/cm)	8.99	8.59	10.1	9.42	8.68	6.75
Emission Peak[a] (nm)	480	470	425 420	\	420	300 750
Refractive Index[b]	2.15	2.68	2.20	1.82	2.15	1.76
LY (ph/MeV)[c]	7,500	1,500	130	\	150	7,900
Decay Time[a] (ns)	300	100	30 10	\	3	300 3200
d(LY)/dT (%/°C)[c]	-0.9	?	-2.5	\	?	?
Cost ($/cc)	6.0	7.0	7.5	6.0	?	0.6

	AFO:Ce Glass	DSB:Ce Glass[1]	DSB:Ce Glass[2]	ABS:Ce Glass[3]	DSB:Ce Glass[4,5]	HFG Glass[6]
Density (g/cm^3)	4.6	3.8	4.2	4.53	4.7 - 5.4[d]	5.95
Melting point (℃)	980[7]	1420[8]	1550	?	1420[8]	570
X_0 (cm)	2.96	3.36	2.62	2.41	2.14	1.74
R_M (cm)	2.90	3.52	3.33	3.09	2.56	2.45
λ_I (cm)	26.4	32.8	31.8	28.8	24.2	23.2
Z_{eff} value	41.4	42.9	49.6	51.9	47.2	55.7
dE/dX (MeV/cm)	6.84	5.56	5.90	6.42	7.68	8.24
Emission Peak[a] (nm)	365	440	430	396	440 460	325
Refractive Index[b]	\	\	\	\	\	1.50
LY (ph/MeV)[c]	450	~500	2,500	800	1,300	150
Decay Time[a] (ns)	40	180 30	400 90	1200 260	120, 400 50	25 8
d(LY)/dT (%/°C)[c]	?	-0.04	0.3	?	?	-0.37
Cost ($/cc)	?	2.0	2.0	?	2.0	?

a. Top line: slow component, bottom line: fast component.
b. At the wavelength of the emission maximum.
c. At room temperature (20°C) with PMT QE taken out.
d. Gd loaded.

1. E. Auffray, et al., J. Phys. Conf. Ser. 587, 2015
2. V. Dormenev, et al., NIMA 1015, 2021
3. G. Tang, et al., Opt. Mater. 130, 2022
4. R. W. Novotny, et al., J. Phys. Conf. Ser. 928, 2017
5. V. Dormenev , et al., the ATTRACT Final Conference
6. E. Auffray, et al., CERN-PPE/96-35, 1996
7. R. A. McCauley et al., Trans. Br. Ceram. Soc., 67. 1968
8. I. G. Oehlschlegel, Glastech. Ber. 44, 1971

Progresses

Inorganic scintillator crystals relevant for the CalVision mission characterized at Caltech: BGO, BSO, PbF_2, PWO and LYSO:Ce.

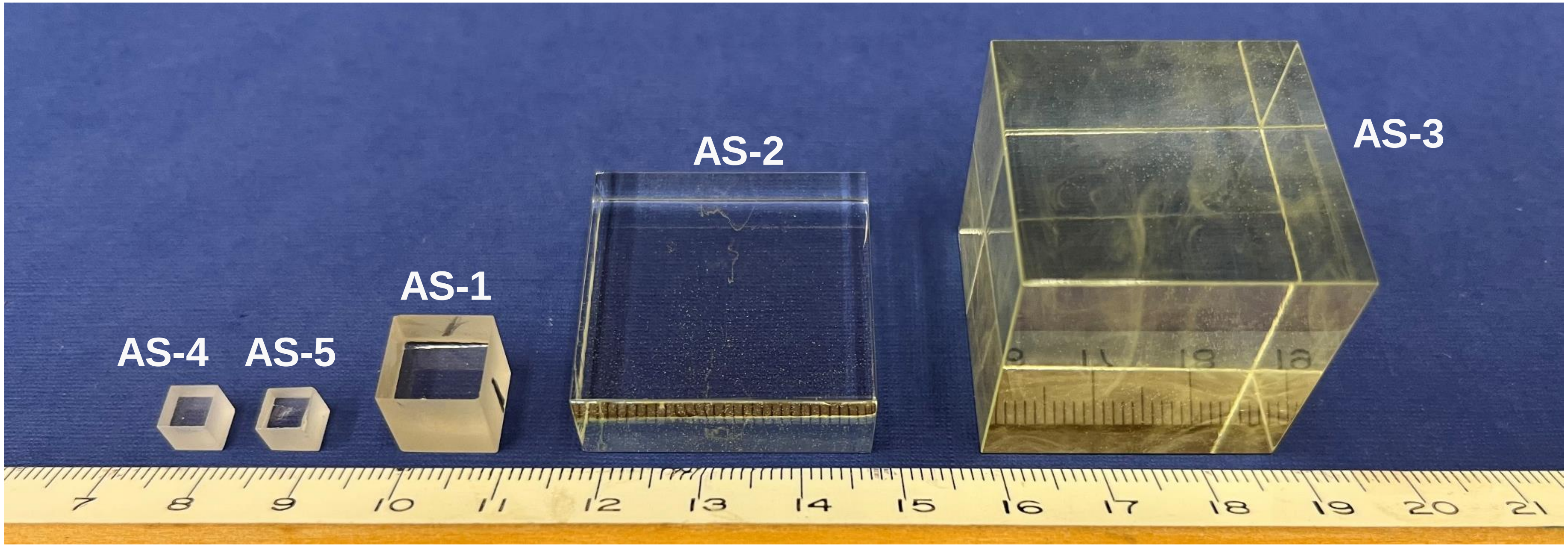
Five aluminoborosilicate glass (B_2O_3–SiO_2–Al_2O_3–Gd_2O_3–Ce_2O_3, ABS) samples from IHEP characterized in June.

An X-ray tube from Amptek received and commissioned in July.

Two barium di-silicate (BaO-$2SiO_2$, DSB) glass samples from Giessen characterized in August.

RMD Inc. received a DOE Phase-I SBIR award to develop scintillating glass for CalVision. Samples expected in 2024.

Five ABS Glass Samples



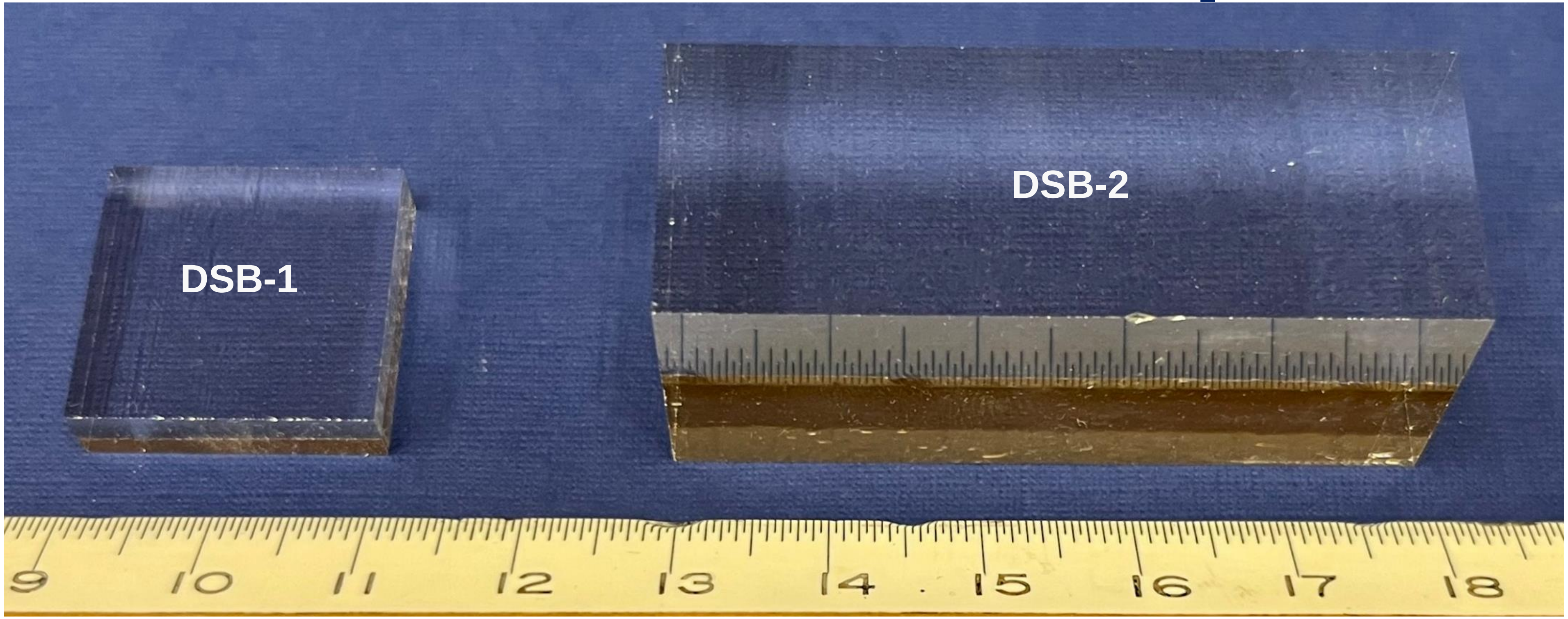
Samples were received on June 15, 2023.

No.	ID	Doping	Dimensions (mm^3)	Lot info.
1	AS-1		10×10×10	new batch, low LO
2	AS-2		30×30×10	new batch, low LO
3	AS-3		30×30×30	new batch, low LO
4	AS-4	$1Ce^{3+}$	5×5×5	old batch, high LO.
5	AS-5	$1.5Ce^{3+}$	5×5×5	old batch, high LO

Result at room temperature:

- Density, X_0 and λ_I
- Transmittance
- X-ray excited emission
- EWLT, EWQE
- Pulse Height Spectra (PHS)
- Light Output (LO) vs. Integration Time and Decay Time (τ)

Two DSB Glass Samples



Samples were received on Aug. 2, 2023.

No.	ID	Doping	Dimensions (mm^3)	Lot info.
1	DSB-1	Ce	20×20×5	new batch, low LO
2	DSB-2	Ce	20×20×50	new batch, low LO

Measurements at room temperature:

- Density, X_0 and λ_I
- Transmittance
- X-ray excited emission
- EWQE, EWLT
- Pulse Height Spectra (PHS)
- Light Output (LO) vs. Integration Time and Decay Time (τ)

Density Measurement

ABS reaches 6 g/cm^3, DSB shows consistent 4.3 g/cm^3

Glass Crystal	Dimensions (mm^3)	Measurement			Volume (cm^3)	Weight (g)	ρ (g/cm^3)
		L (mm)	W (mm)	H (mm)			
DSB-1	**20×20×5**	**20.015**	**19.964**	**5.029**	**2.010**	**8.6**	**4.3**
DSB-2	**20×20×50**	**20.015**	**19.939**	**50.013**	**19.959**	**85.9**	**4.3**
AS-1	**10×10×10**	**9.982**	**10.084**	**10.109**	**1.018**	**5.1**	**5.0**
AS-2	**30×30×10**	**29.997**	**29.972**	**10.008**	**8.998**	**48.0**	**5.3**
AS-3	**30×30×30**	**29.997**	**30.023**	**28.499**	**25.666**	**137.5**	**5.4**
AS-4	**5×5×5**	**4.953**	**4.953**	**4.801**	**0.118**	**0.705**	**6.0**
AS-5	**5×5×5**	**4.953**	**4.953**	**4.648**	**0.114**	**0.675**	**5.9**
BGO	17×17×17	17.018	17.023	17.023	4.932	34.9	7.1
BSO	17×17×17	17.069	17.069	17.069	4.973	33.6	6.8
PbF	14×14×14	14.097	14.072	13.995	2.776	21.3	7.7
PWO	13×13×13	13.005	12.954	12.929	2.178	18.1	8.3

Nuclear Properties

ABS reaches 1.56 cm X_0 and 24.2 cm λ_I, DSB show 2.58 cm X_0 and 30.9 cm λ_I

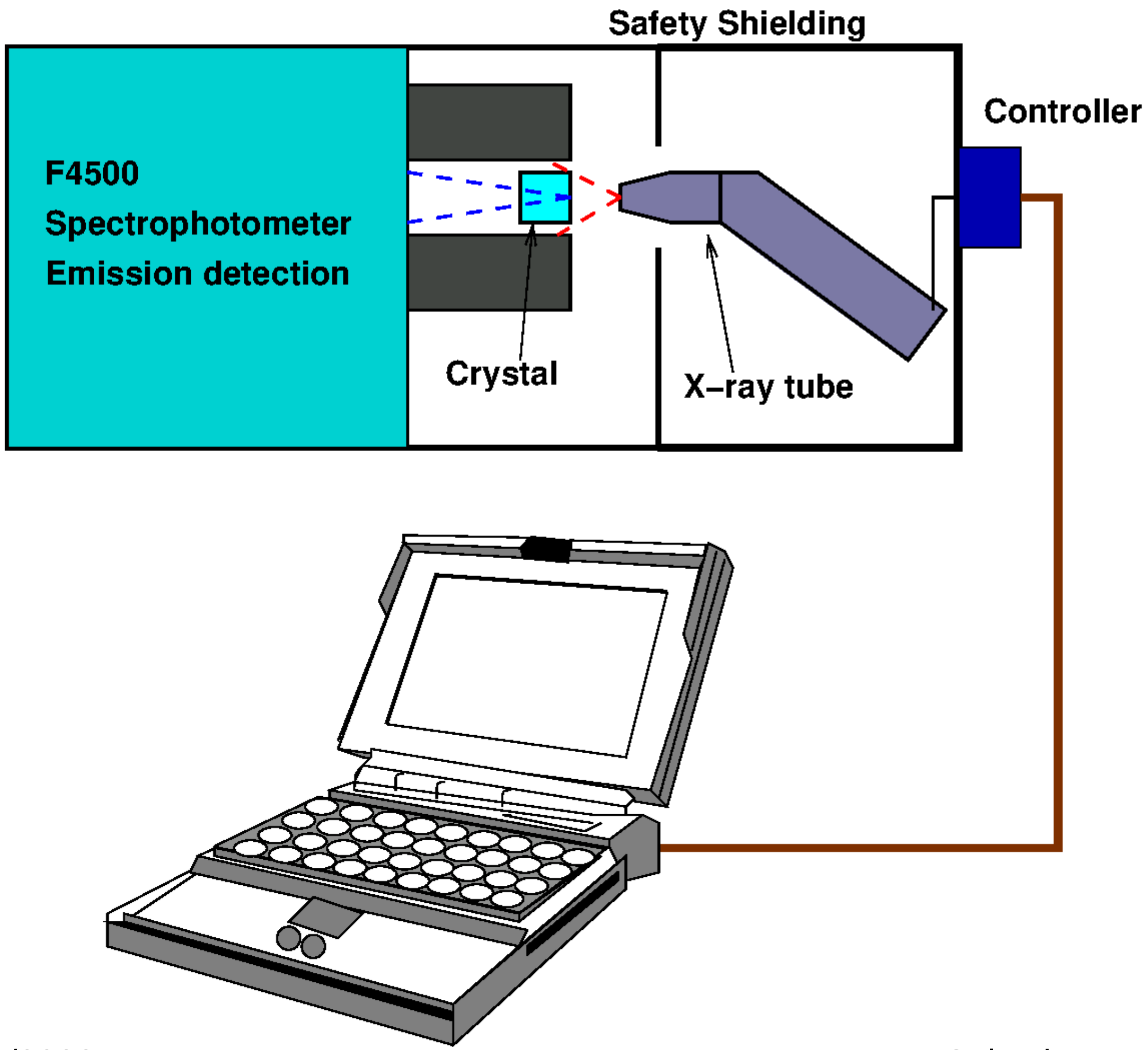
Crystal and Glass	BGO	BSO	PWO	Gd-ABS					Gd-DSB	
				ABS*	AS-1	AS-2	AS-3	AS-4,5	BGS**	DSB-1,2
Density (g/cm^3)	7.1	6.8	8.3	**4.5**	**5.0**	**5.3**	**5.4**	**6.0**	**4.2**	**4.3**
X_0 (cm)	1.12	1.15	0.89	**2.41**	**1.89**	**1.88**	**1.79**	**1.56**	**2.62**	**2.58**
R_M (cm)	2.23	2.33	2.00	**3.09**	**2.97**	**2.74**	**2.73**	**2.49**	**3.33**	**3.24**
λ_I (cm)	22.7	23.4	20.7	**28.8**	**29.3**	**26.5**	**26.6**	**24.2**	**31.8**	**30.9**
Z_{eff}	71.5	73.8	73.6	**51.9**	**56.0**	**54.3**	**55.3**	**56.6**	**49.7**	**49.5**
dE/dX (MeV/cm)	9.0	8.6	10.1	**6.4**	**6.7**	**7.2**	**7.3**	**8.0**	**5.9**	**6.1**

*Optical Materials 130 (2022) 112585

**Nuclear Inst. and Methods in Physics Research, A 1015 (2021) 165762

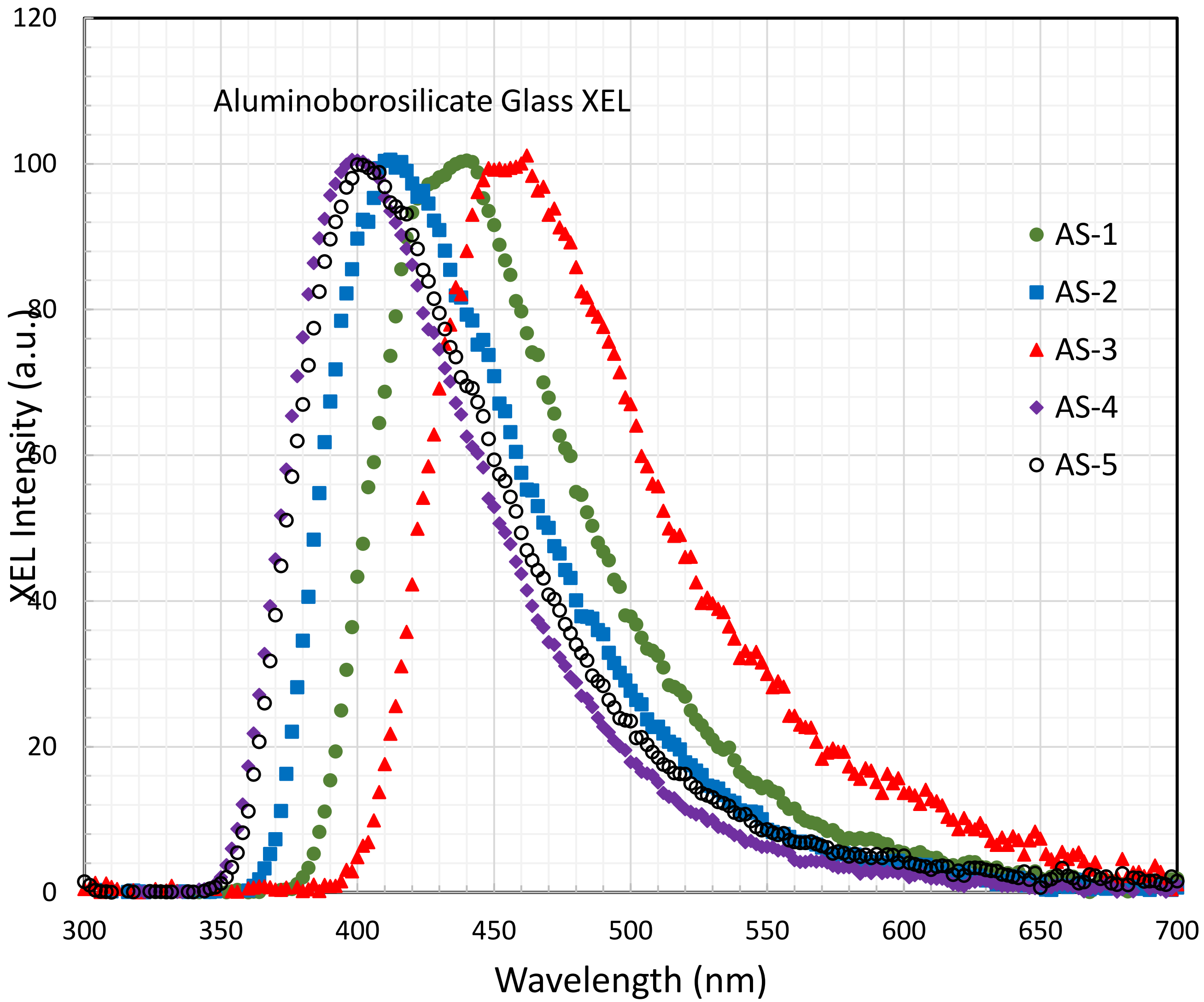
Amptek X-Ray Tube-based XEL Bench

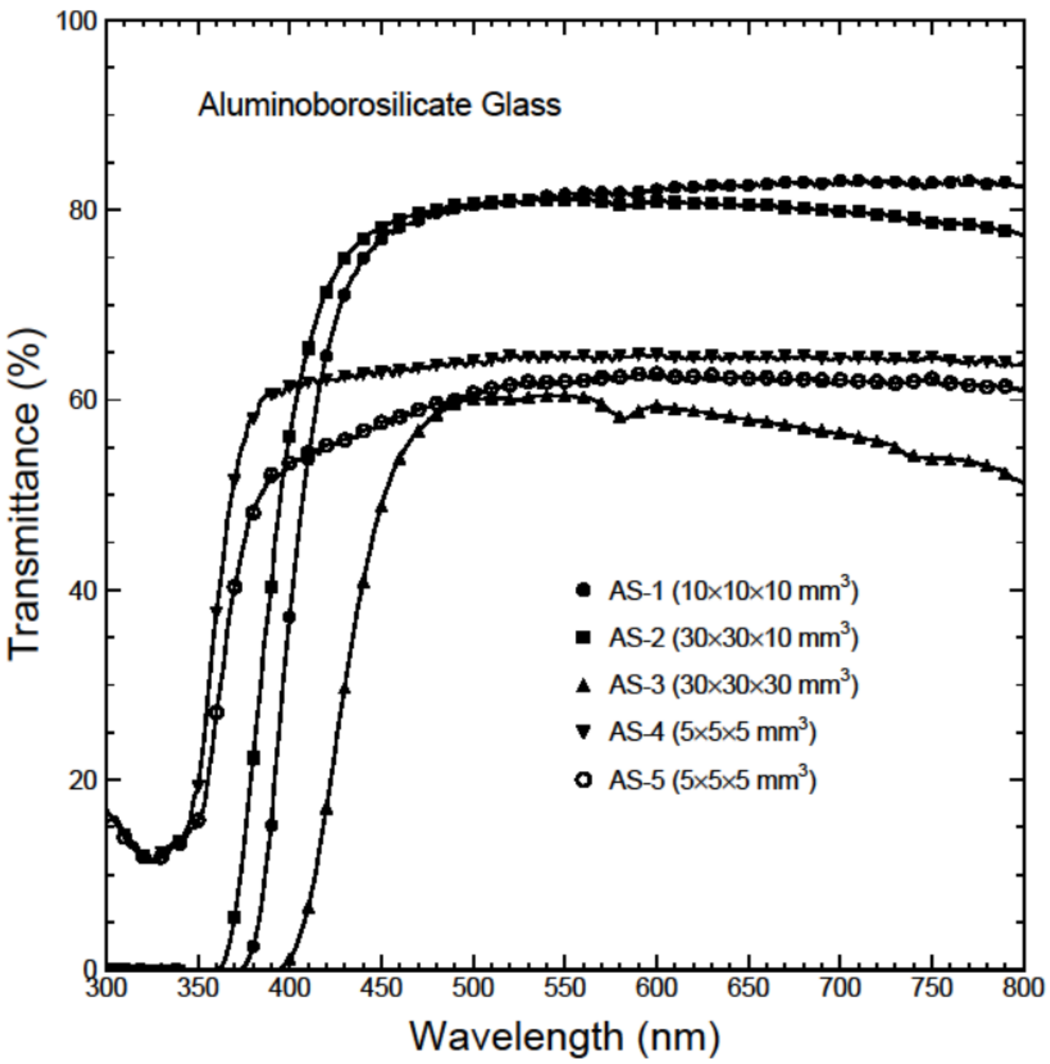
XEL affected by light path and glass sample chemical composition



ABS XEL and Transmittance

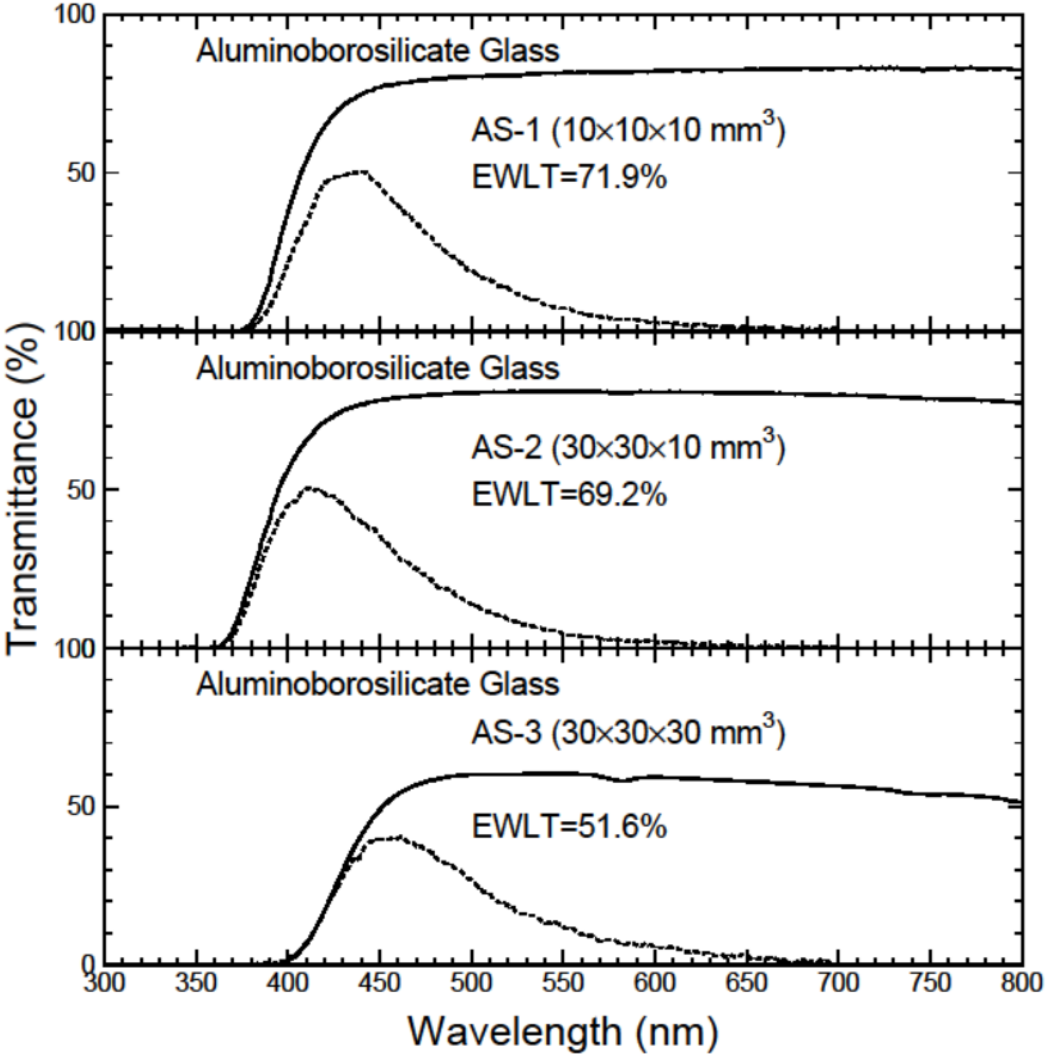
Both XEL and transmittance affected by light path and chemical composition

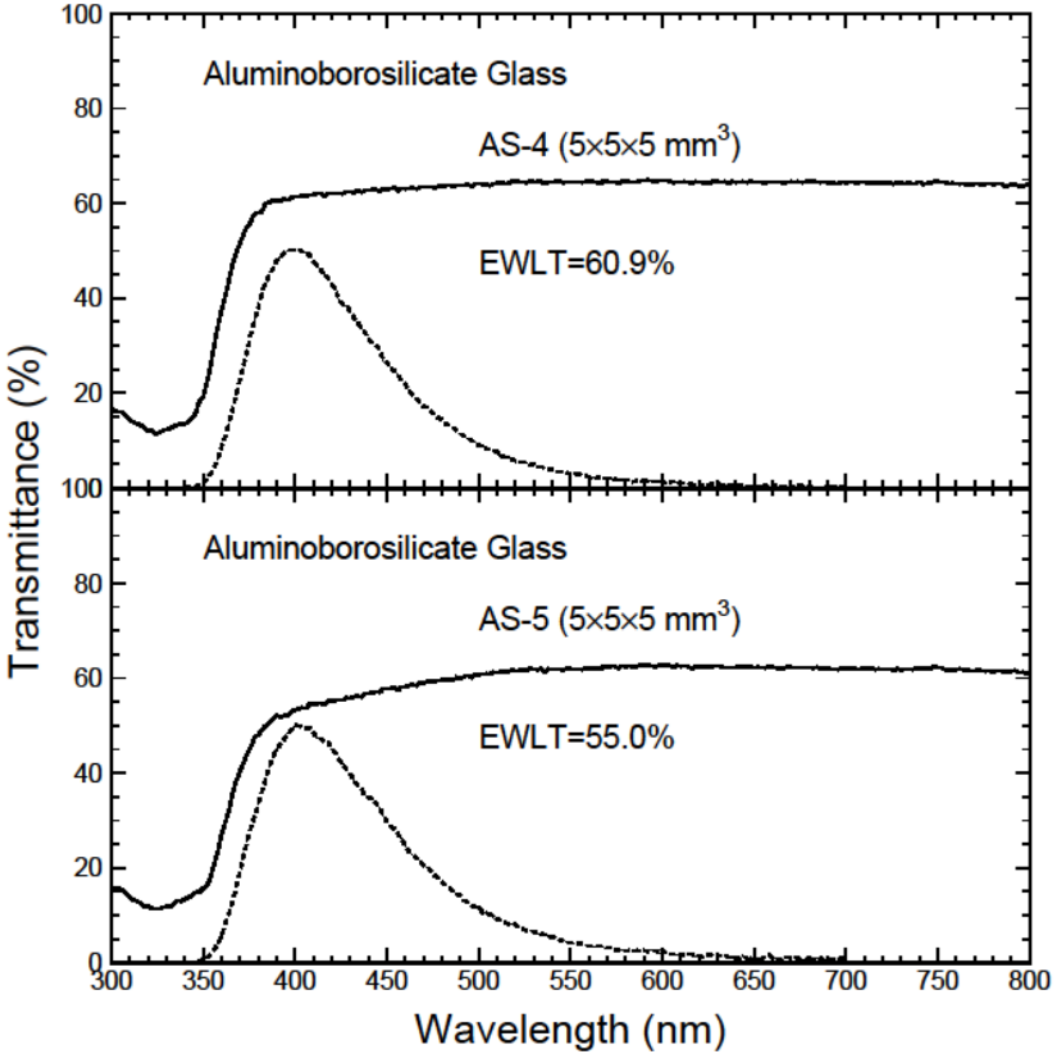




ABS EWLT

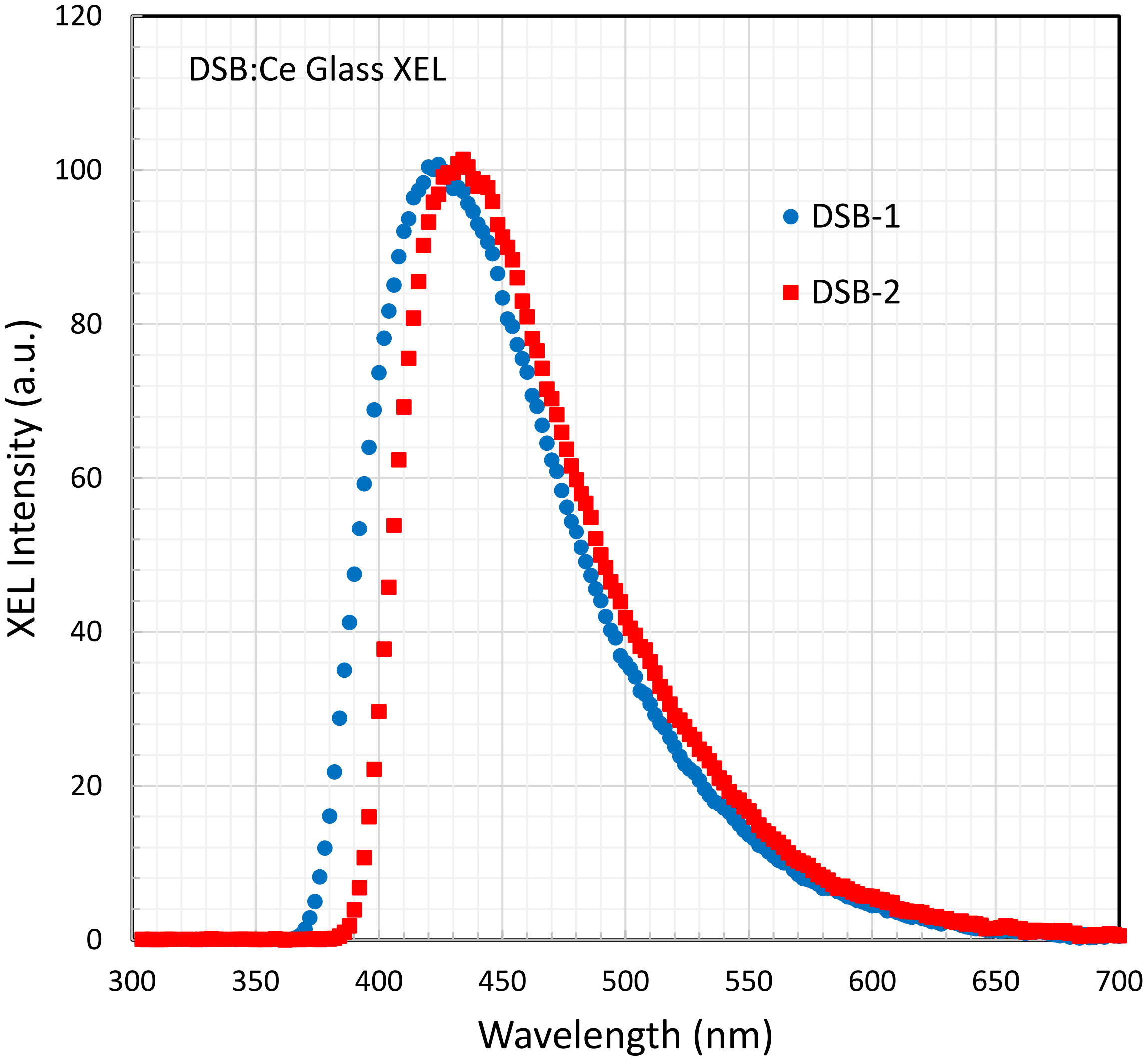
EWLT affected by refractive index, light path, scattering, surface and absorption

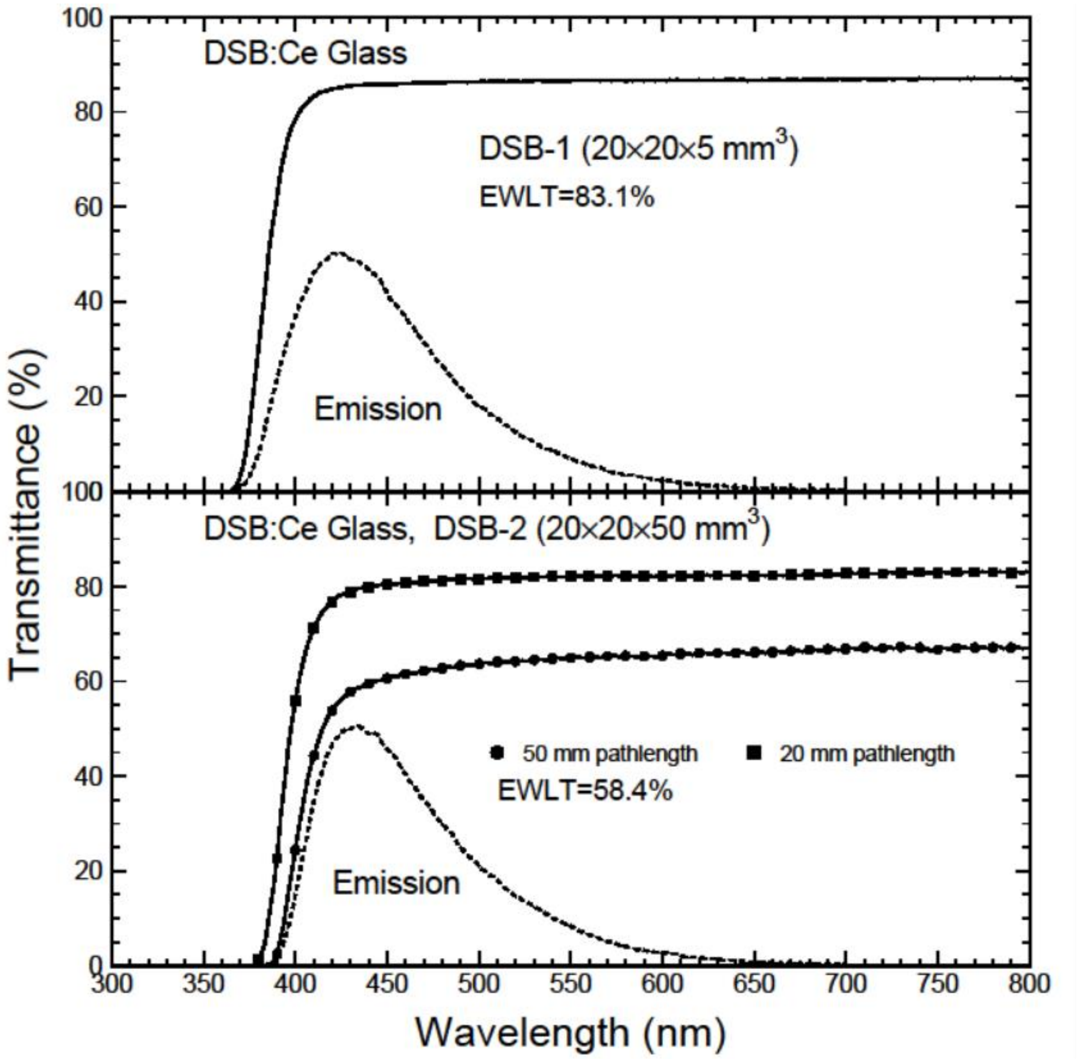




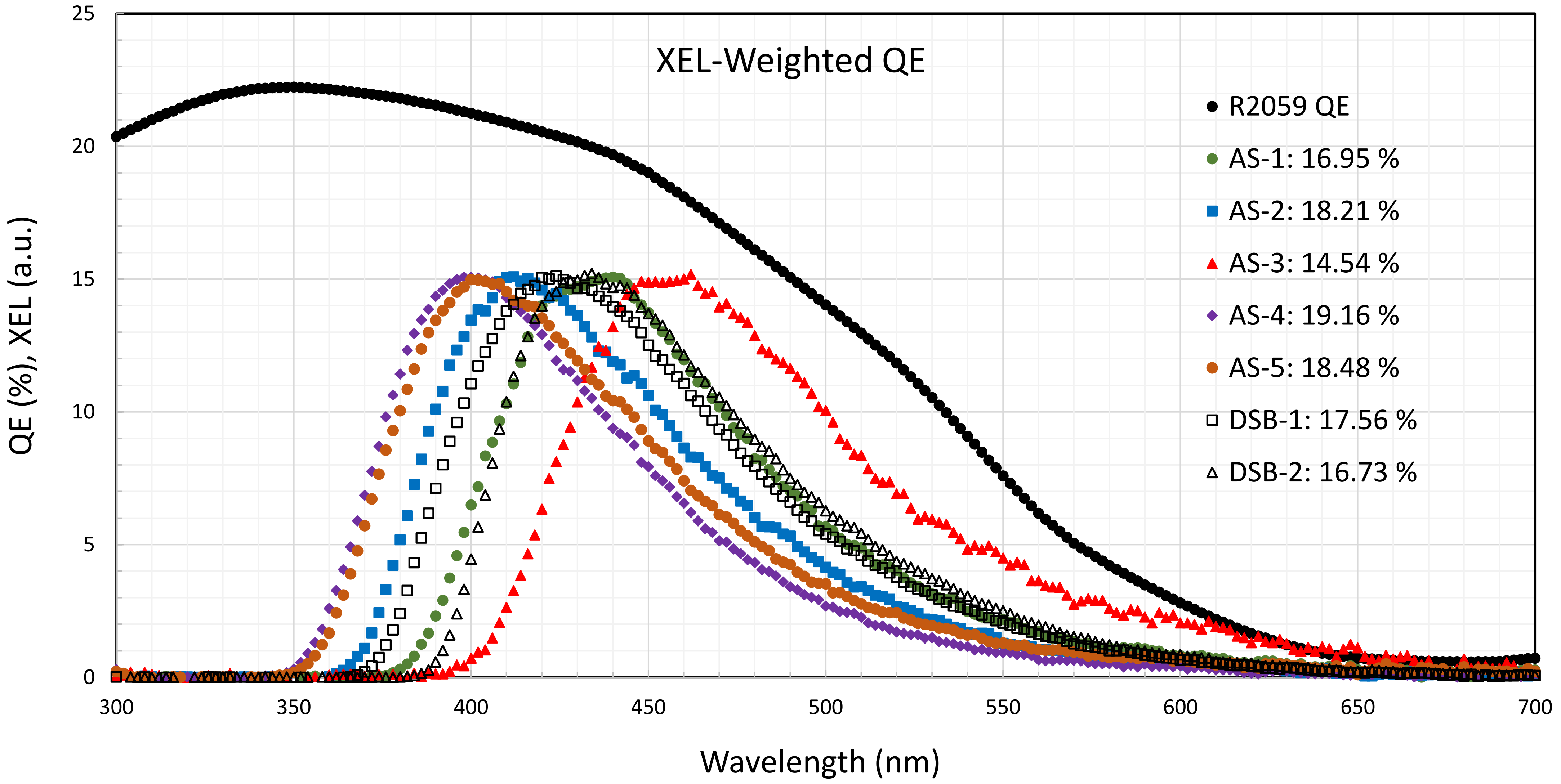
DSB XEL, Transmittance and EWLT

EWLT affected by refractive index, light path, scattering, surface and absorption



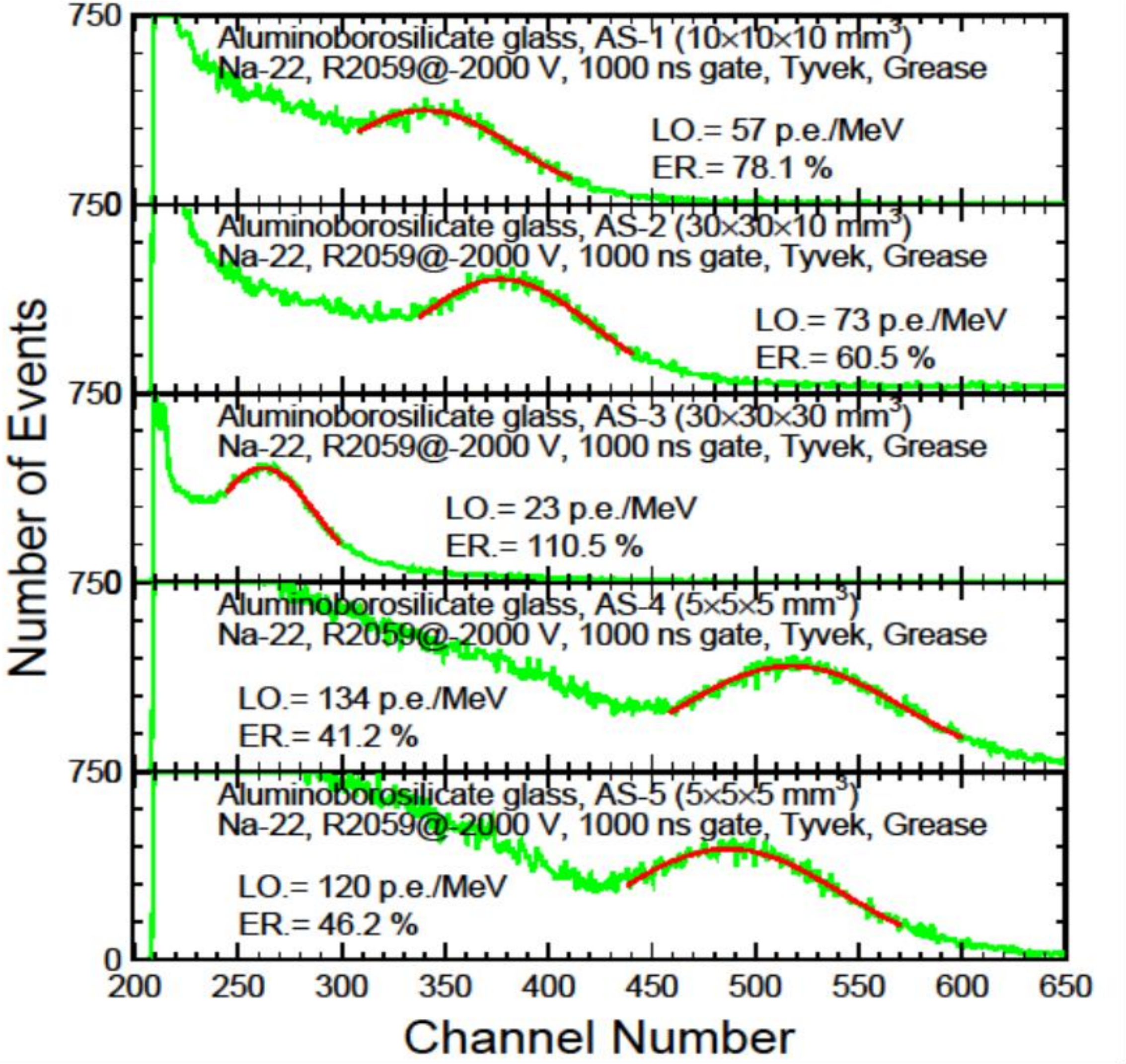


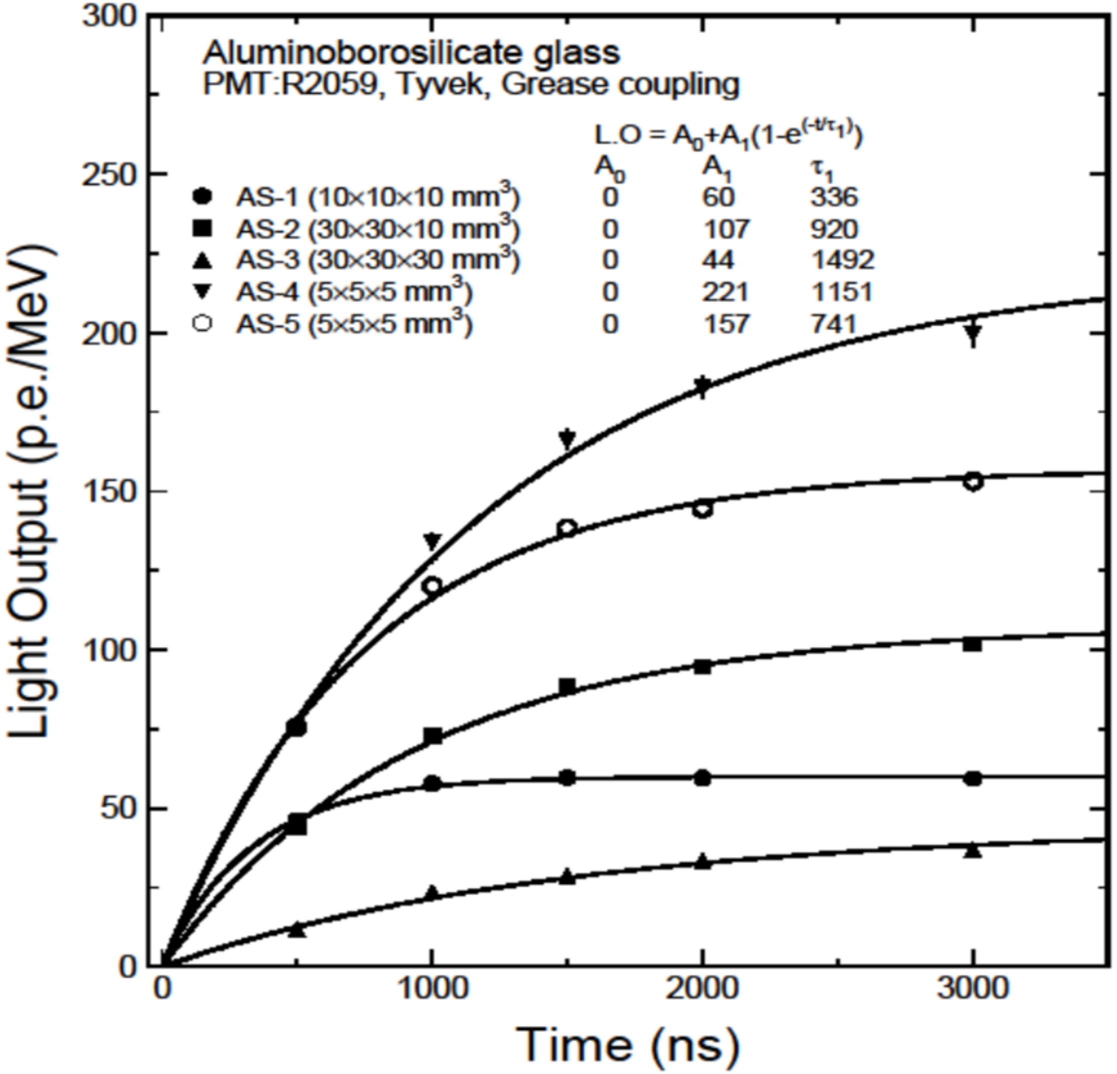
EWQE of Hamamatsu R2059 PMT



ABS PHS, LO and Decay

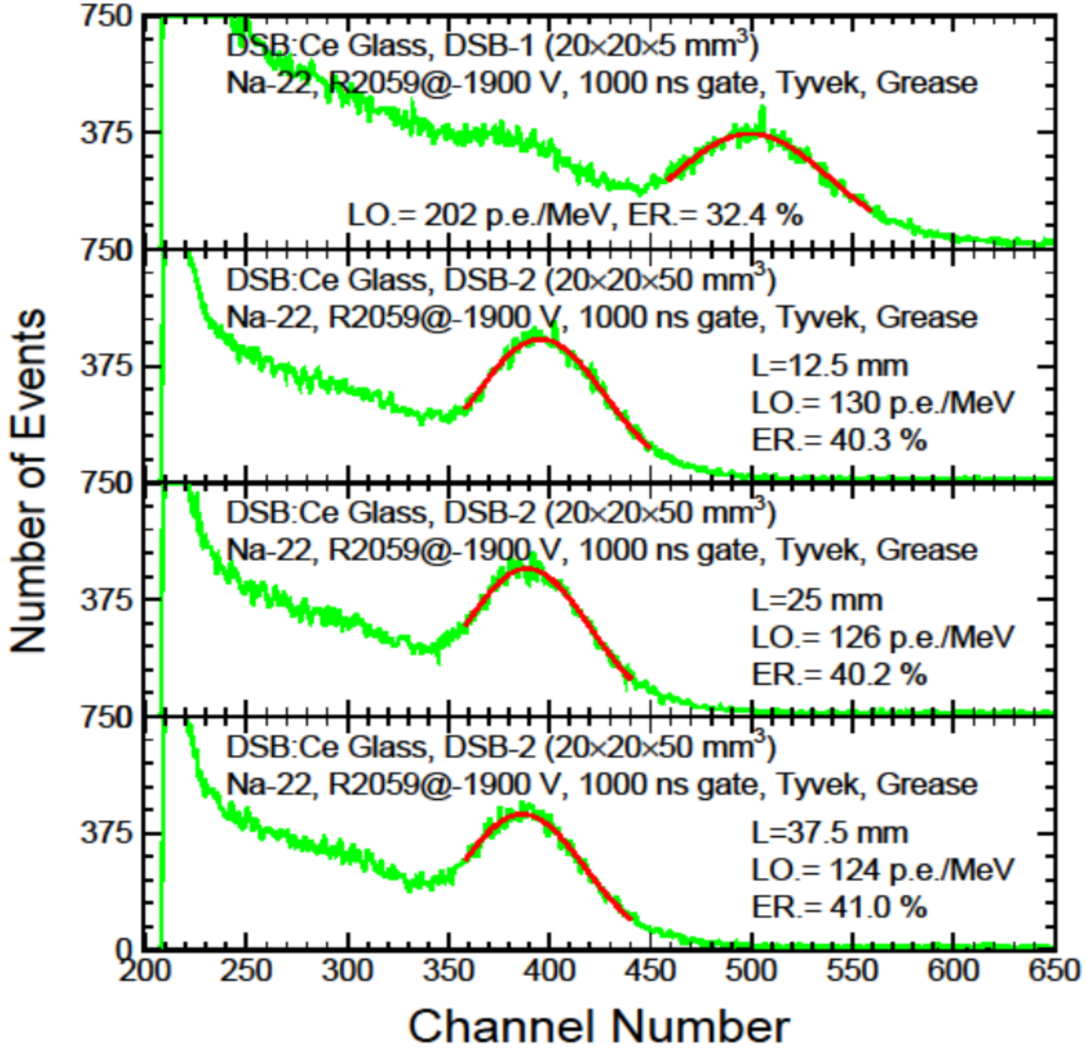
LO = LY × LCE (light path, wrapping and coupling) × QE (photodetector)

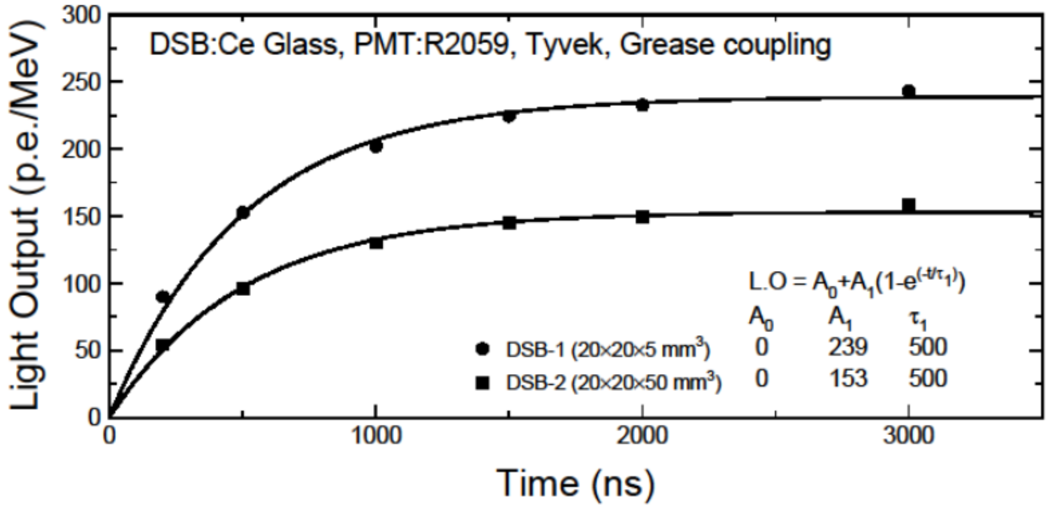


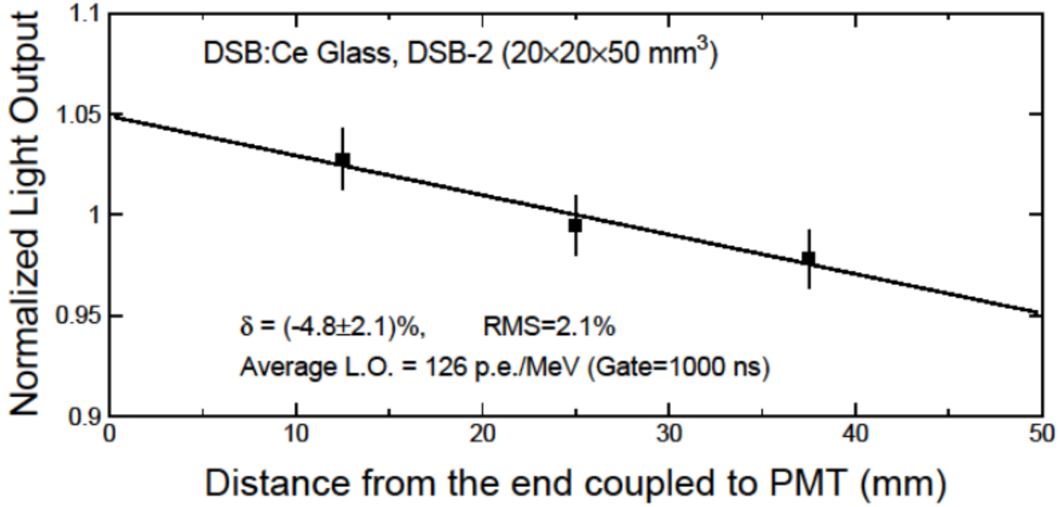


DSB PHS, LO, Decay and LRU

LO = LY × LCE (light path, wrapping and coupling) × QE (photodetector)







Summary: EWLT, EWQE, LO, Decay and LY

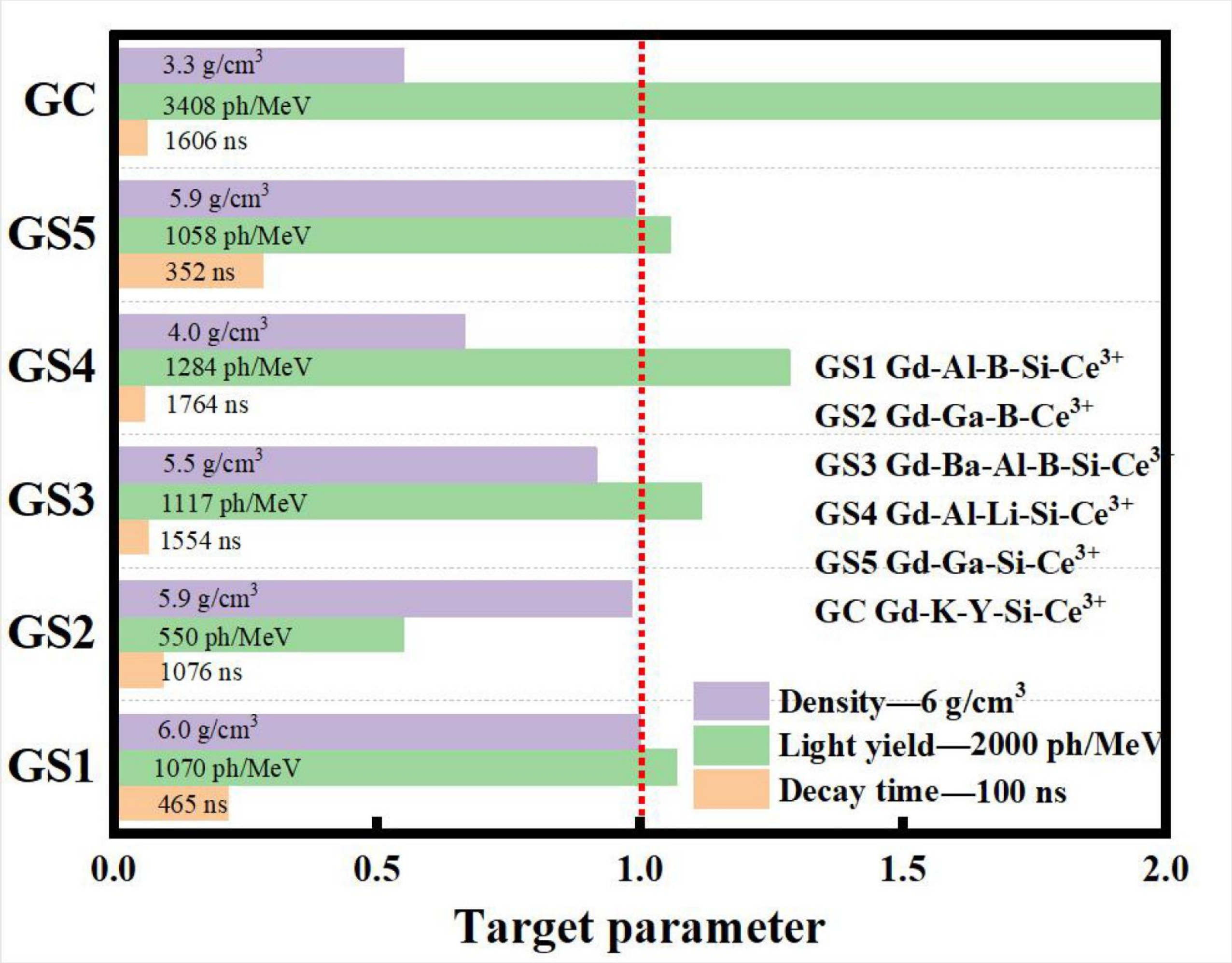
LY values include LCE, so are the lower limit

Parameters	1.5 X_0 Crystal Cubes			Gd-ABS					Gd-DSB	
	BGO	BSO	PWO	AS-1	AS-2	AS-3	AS-4	AS-5	DSB-1	DSB-2
Dimensions (mm^3)	17×17×17	17×17×17	13×13×13	10×10×10	30×30×10	30×30×30	5×5×5	5×5×5	20×20×5	20×20×50
EWLT (%)	72.7	72.9	66.7	71.9	69.2	51.6	60.9	55.0	83.1	58.4
EWQE (R2059, %)	13.02	13.05	18.53	16.95	18.21	14.54	19.16	18.48	17.56	16.73
LO w/ 1 µs gate (p.e./MeV)	743	152	23	57	73	23	134	120	202	126
LY* w/ 1 µs gate (ph/MeV)	5708	1165	124	336	401	158	699	649	1151	753
E.R w/ 1 µs gate 511 keV (%)	16.6	34.9	86.5	78.1	60.5	110.5	41.2	46.2	32.4	40.2
Decay time (ns)	312	94	29	336	920	1492	1151	741	500	500
Fitted LO (p.e./MeV)	760	152	23	60	107	44	221	157	239	153
Fitted LY* (ph/MeV)	5839	1165	124	354	588	303	1153	850	1361	915

* LY with photodetector QE taken out

IHEP Glass Scintillator Summary by Sen Qian at TIPP

AS 1, 2 and 3 are GS3, AS 4 and 5 are GS1
Expecting large GS1 and GS5 samples in Fall



Glass scintillator of high density and light yield

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

6.0 g/cm³ & 1070 ph/MeV with 24.4% @662keV & 460 ns

- ◆ GS5: Gd-Ga-Si-Ce^{3+} glasses: (Silicate glass)

5.9 g/cm³ & 1060 ph/MeV with 23.7% @662keV & 352 ns

- Ultra-high density **Tellurite Glass**—6.6 g/cm³
- High light yield **Glass Ceramic**—3500 ph/MeV
- Fast scintillating Decay Time—100 ns
- Large size Glass—42mm*51mm*10mm

Inorganic Scintillators for HHCAL

All samples measured at Caltech HEP Crystal Lab

	BGO	BSO	PWO	PbF_2	PbFCl	Sapphire:Ti	AFO Glass	DSB:Ce Glass	ABS:Ce Glass
Density (g/cm^3)	7.13	6.8	8.3	7.77	7.11	3.98	4.6	4.3	6.0
Melting point (℃)	1050	1030	1123	824	608	2040	980[7]	1550	?
X_0 (cm)	1.12	1.15	0.89	0.94	1.05	7.02	2.96	2.58	1.56
R_M (cm)	2.23	2.33	2.00	2.18	2.33	2.88	2.90	3.24	2.49
λ_I (cm)	22.7	23.4	20.7	22.4	24.3	24.2	26.4	30.9	24.2
Z_{eff} value	71.5	73.8	73.6	76.7	74.7	11.1	41.4	49.5	56.6
dE/dX (MeV/cm)	8.99	8.59	10.1	9.42	8.68	6.75	6.84	6.1	8.0
Emission Peak[a] (nm)	480	470	425 420	\	420	300 750	365	420	400
Refractive Index[b]	2.15	2.68	2.20	1.82	2.15	1.76	?	?	?
LY (ph/MeV)[c]	7,500	1,500	130	\	150	7,900	450	1,360	1,150
Decay Time[a] (ns)	300	100	30 10	\	3	300 3200	40	500	740
d(LY)/dT (%/°C)[c]	-0.9	?	-2.5	\	?	?	?	0.3	?
Cost ($/cc)	6.0	7.0	7.5	6.0	?	0.6	2.0	2.0	<1

a. Top line: slow component, bottom line: fast component. b. At the wavelength of the emission maximum. c. At room temperature (20°C) with PMT QE taken out.

Summary

The **HHCAL concept** promises the best jet mass resolution via total absorption. Because of its large volume development of cost-effective heavy inorganic scintillator is crucial, so scintillating glasses.

Novel ABS and DSB glass samples characterized at Caltech in 2023 with result fed back to IHEP and Giessen respectively. ABS reaches 6 g/cc density, 1.56 cm X_0 and 24.2 cm λ_I. Combined with its low cost it appears promising for the HHCAL concept.

Will look glass samples developed under DOE SBIR program from Scintilex and RMD. Plan to reach a conclusion in 2024.

Acknowledgements: DOE HEP Award DE-SC0011925

Raw Material Cost for Glasses

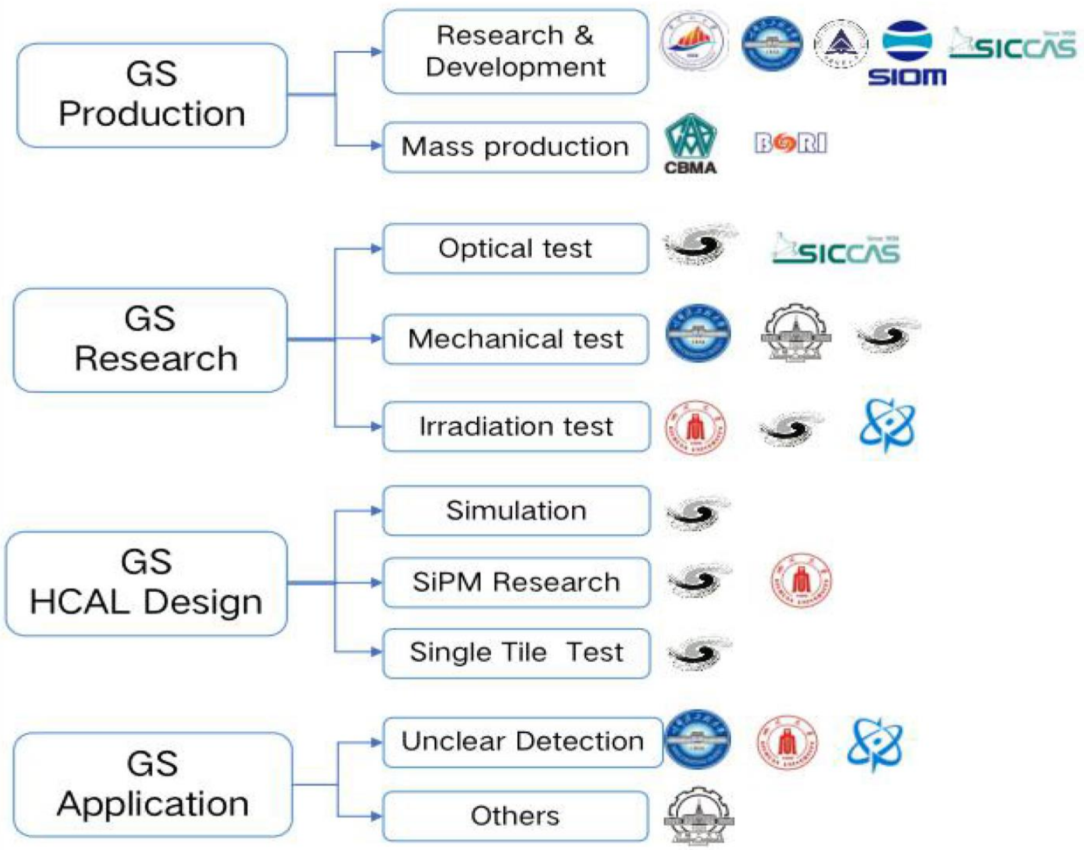
Weight ratio (%)	DSB Glass	DSB:Gd Glass	HFG Glass	Price/kg*
BaO	56.1	44.9	\	5
B_2O_3	\	\	\	3.4
SiO_2	43.9	35.1	\	0.57
Al_2O_3	\	\	\	1.5
Lu_2O_3	\	\	\	500
Gd_2O_3	\	20	\	10
BaF_2	\	\	28	0.95
AlF_3	\	\	2	0.8
YF_3	\	\	2	3
NaF	\	\	12	1
HfF_4	\	\	56	160
CeF_3	Unknown	Unknown	Unknown	10
Price/CC	0.01	0.02	0.54	

Use low-cost raw materials, such as Gd_2O_3 and BaF_2, would help

* https://www.alibaba.com/

Large Area Glass Scintillator Collaboration Led by IHEP

A large collaboration led by IHEP to develop glass scintillators for HCAL at Higgs Factory



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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,
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CNNC Beijing Unclear Instrument Factory
中核（北京）核仪器有限责任公司

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).