Novel Ultrafast Lu_2O_3:Yb Ceramics for Future HEP Applications

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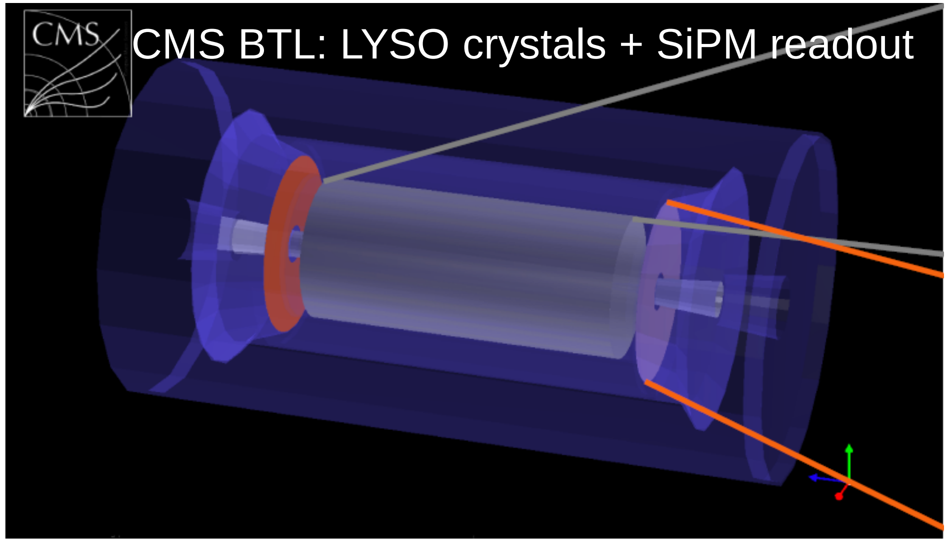
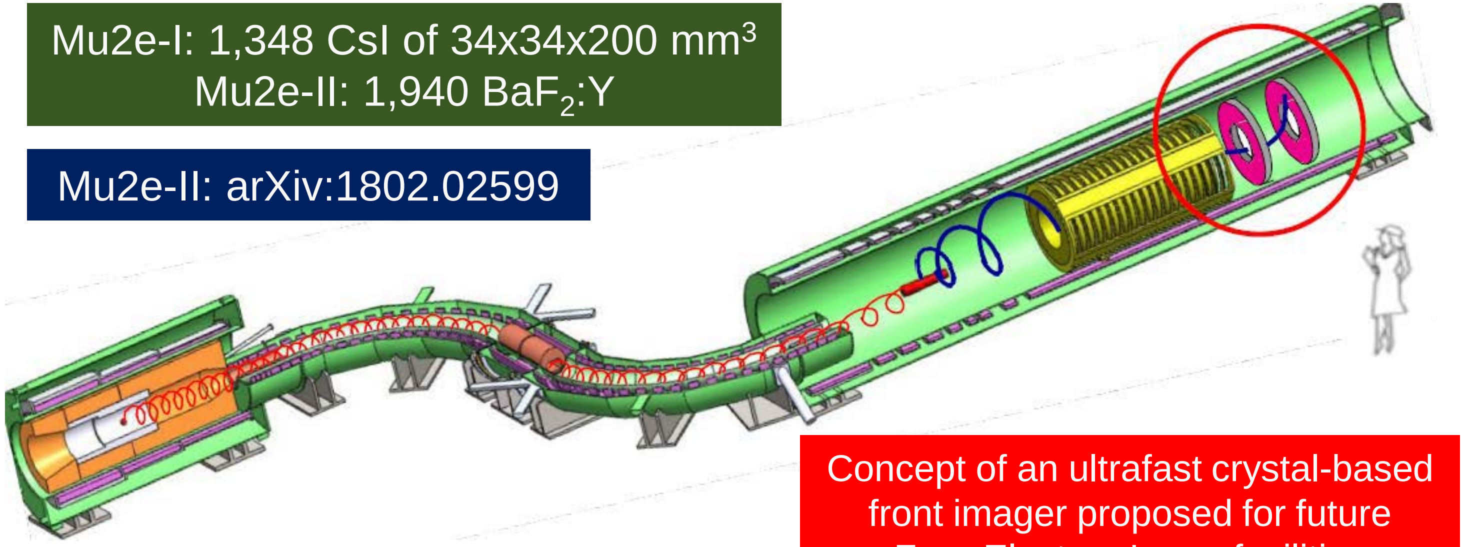
May 17, 2022

Presented in the CALOR 2022 Conference, University of Sussex, UK

Application of Ultrafast Crystals

Figures of merit for TOF: light yield in the 1st ns & the ratio between fast and total


CMS BTL: LYSO crystals + SiPM readout


Mu2e-I: 1,348 CsI of 34x34x200 mm^3
Mu2e-II: 1,940 BaF_2:Y

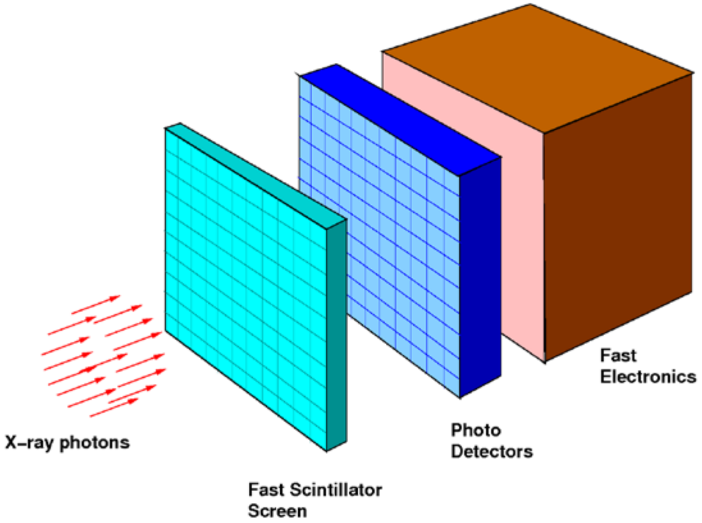
Mu2e-II: arXiv:1802.02599

Concept of an ultrafast crystal-based front imager proposed for future Free-Electron Laser facilities

GHz Hard X-ray Imaging for Free-Electron Lasers

Fast frame rate & hard x-ray require ultrafast crystals

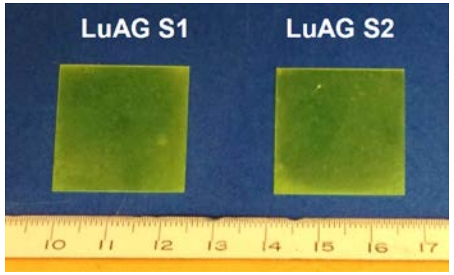
Performance	Type I imager	Type II imager
X-ray energy	**up to 30 keV**	**42-126 keV**
Frame-rate/inter-frame time	**0.5 GHz / 2 ns**	**3 GHz / 300 ps**
Number of frames per burst	≥ 10	10 - 30
X-ray detection efficiency	above 50%	above 80%
Pixel size/pitch	**≤ 300 μm**	**< 300 μm**
Dynamic range	10^3 X-ray Photons/pixel/frame	≥ 10^4 X-ray Photons/pixel/frame
Pixel format	64 × 64[a] (scalable to 1 Mpix)	1 Mpix

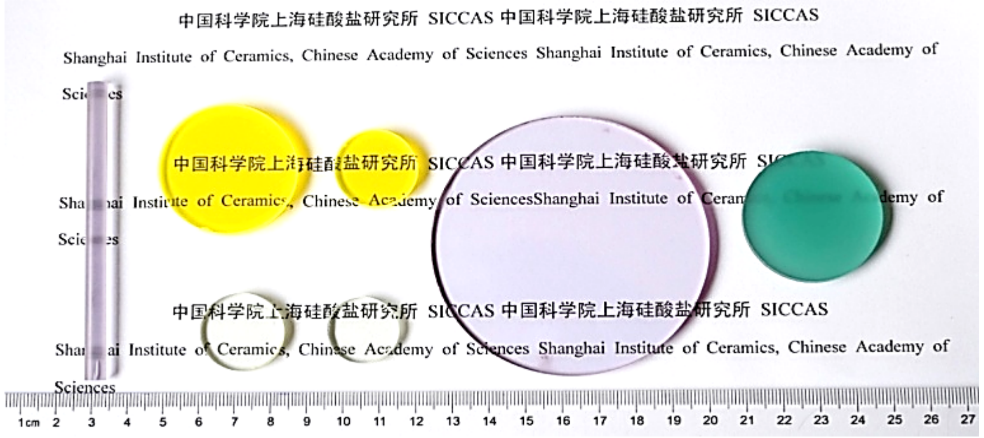


Why Scintillating Ceramics

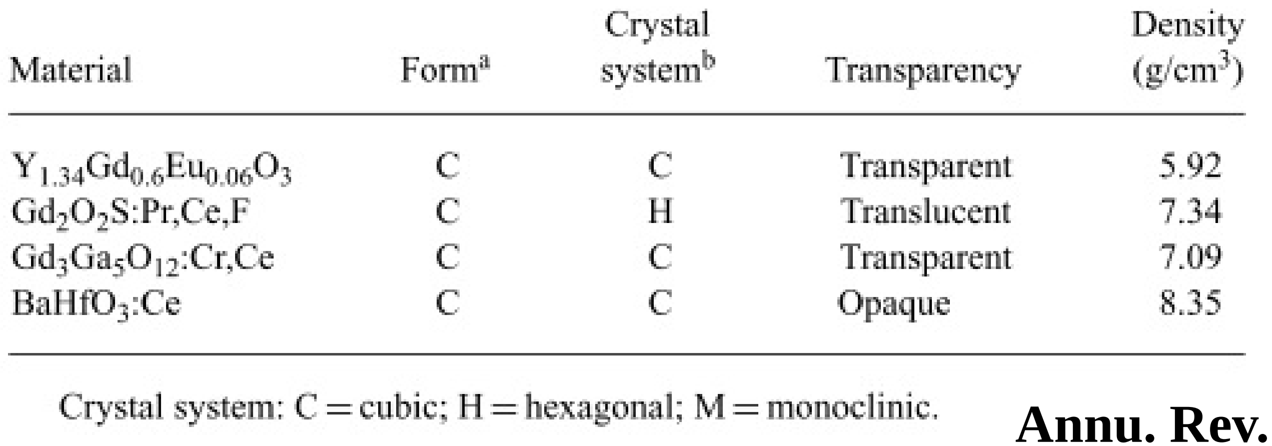
- **Ceramics provide a cost-effective solution for future HEP experiments.**
  - **Simple production technology;**
  - **High raw material usage;**
  - **Minimum after-growth mechanical processing.**

- **Unlike single crystal, ceramic fabrication does not require melting raw material.**
  - **Lower sintering temperature;**
  - **Dopants distribute homogeneously without segregation process;**
  - **Can be made into complex structure.**





Cubic Structure Ceramics can be Transparent

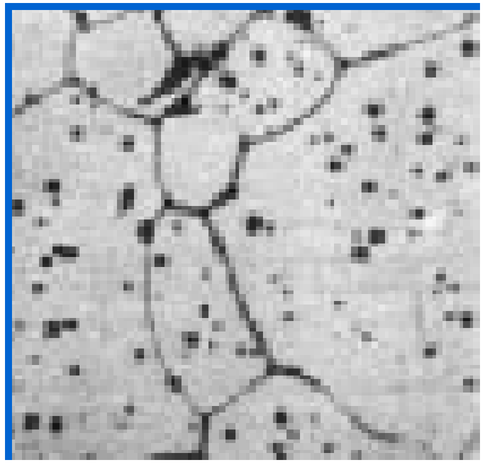


Material	Form[a]	Crystal system[b]	Transparency	Density (g/cm^3)
$Y_{1.34}Gd_{0.6}Eu_{0.06}O_3$	C	C	Transparent	5.92
Gd_2O_2S:Pr,Ce,F	C	H	Translucent	7.34
$Gd_3Ga_5O_{12}$:Cr,Ce	C	C	Transparent	7.09
$BaHfO_3$:Ce	C	C	Opaque	8.35

Crystal system: C = cubic; H = hexagonal; M = monoclinic.

Cost-effective transparent ceramics are pursued by industry

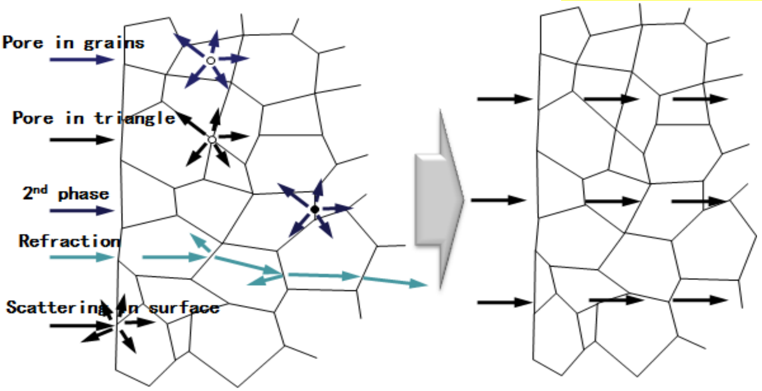
Annu. Rev. Mater. Sci. 1997. 27:69–88

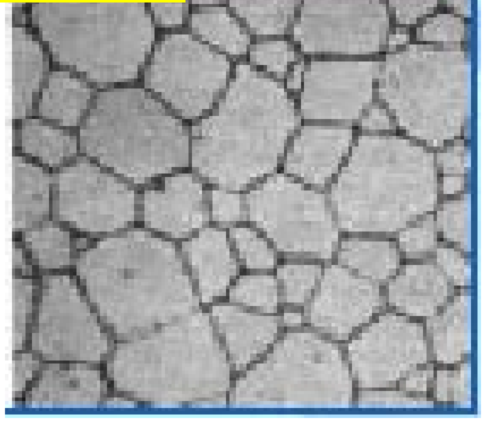


Incident light

Anisotropy

Homogeneity





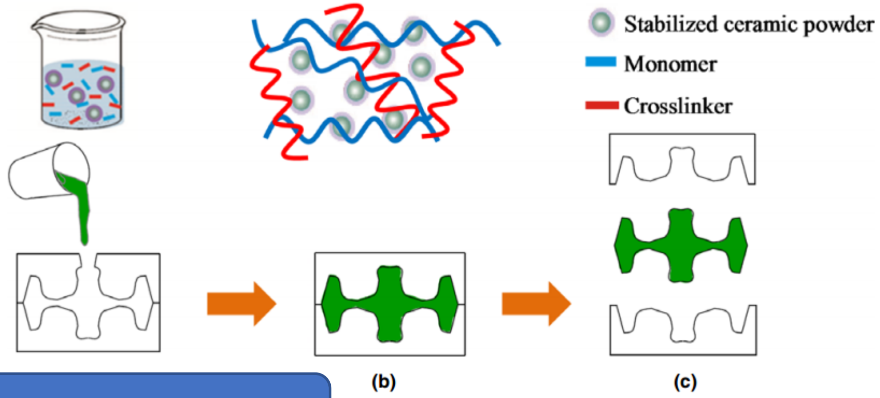
Opaque or translucent

Transparent

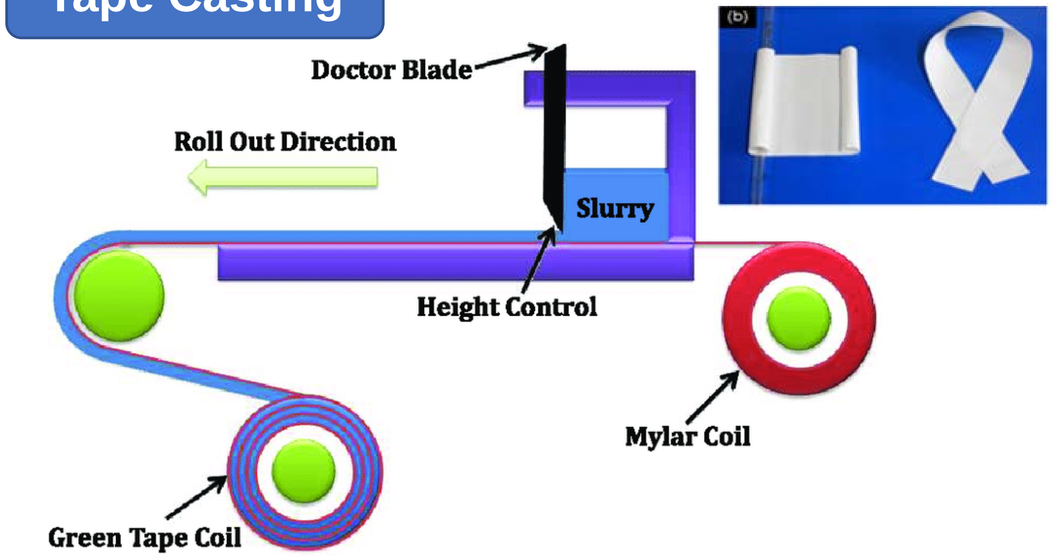
Ceramic Fabrication Process

Ceramic State	**Processing Step**	**Step Objective**
Powder	**Calcination & Ball milling**	Manufacture ceramic powder of required composition and size.
Dry powder or slurry	**Mixing & Milling**	Homogenous mixture of powder, binder, and additives (and suspension medium in the case of wet forming).
Green body	**Forming**	Shape component into desired geometry.
Brown body	**Debinding**	Binder burnout and pre-consolidation.
Dense sintered body	**Furnace sintering**	Densification of the polycrystalline ceramic part with desired microstructure.
Final part	**Machining**	Dimensions and surface finish within tolerances.

Slip Casting



Tape Casting



Complex structure (rod, dome, sandwich etc.) can be fabricated with minimum after-growth processing

Background: Lu_2O_3:Yb Ceramics

2005—1st report on Lu_2O_3:Yb ceramics

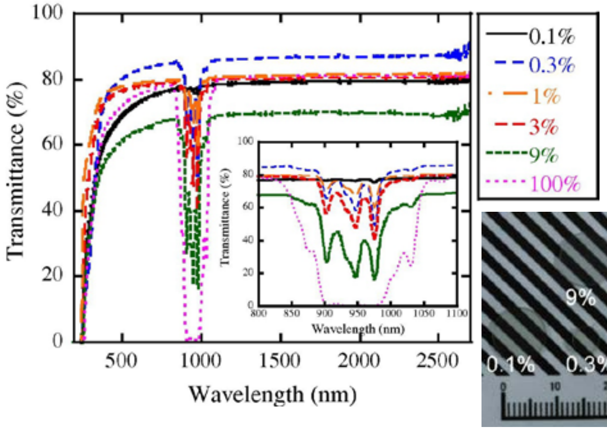
- Takaichi K et al., *phys. stat. sol.* (a) 202, R1-R3 (2005)

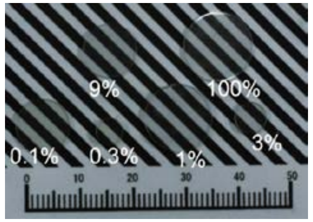
2011—Lu_2O_3:Yb ceramics fabricated by hot-pressing method

- Sanghera J et al., *Opt. Mater.* 33, 670-674 (2011)

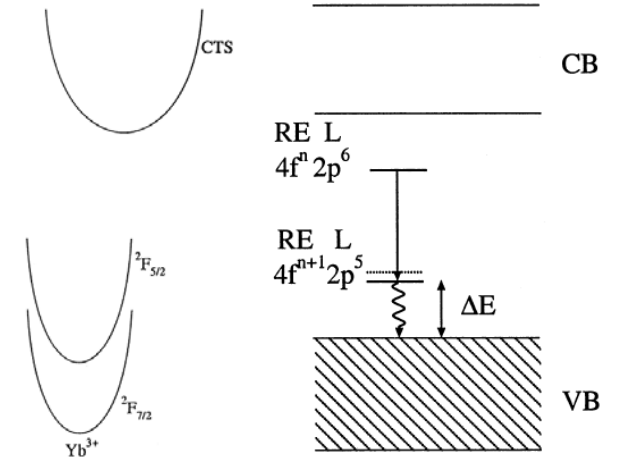
2014—Lu_2O_3:Yb ceramics as a heavy and ultrafast scintillator

- Yanagida T et al., *Opt. Mater.* 36, 1044-1048 (2014)



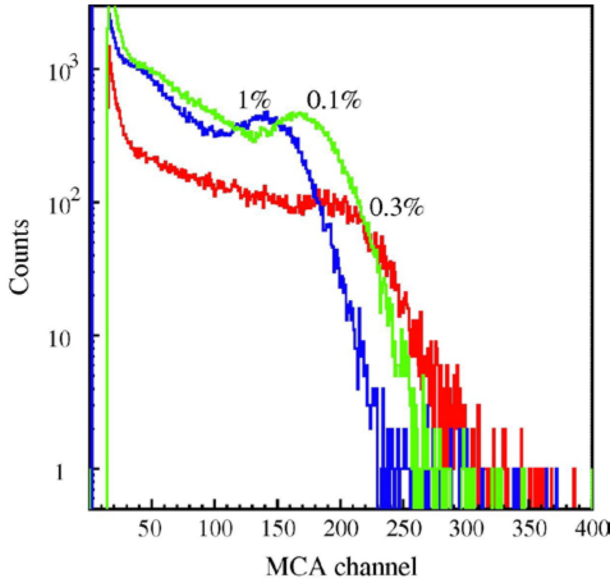


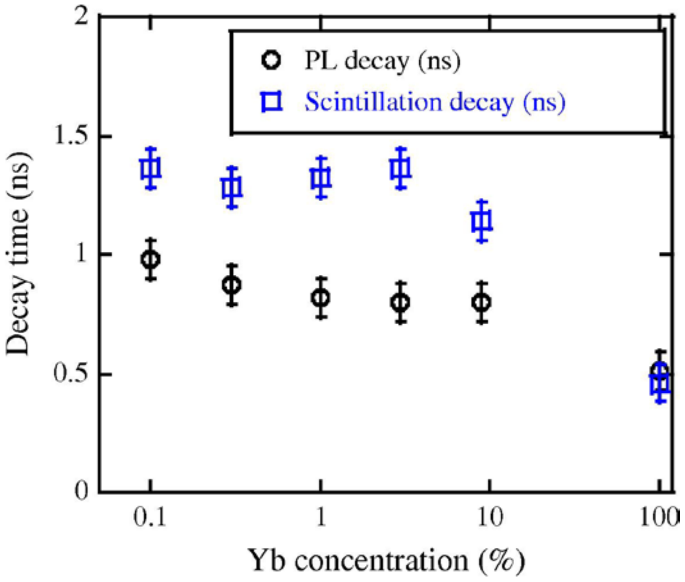
Excellent optical quality approaches theoretical transmittance observed in Lu_2O_3:Yb ceramic samples



Yb^{3+} charge transfer luminescence and thermal quenching mechanism

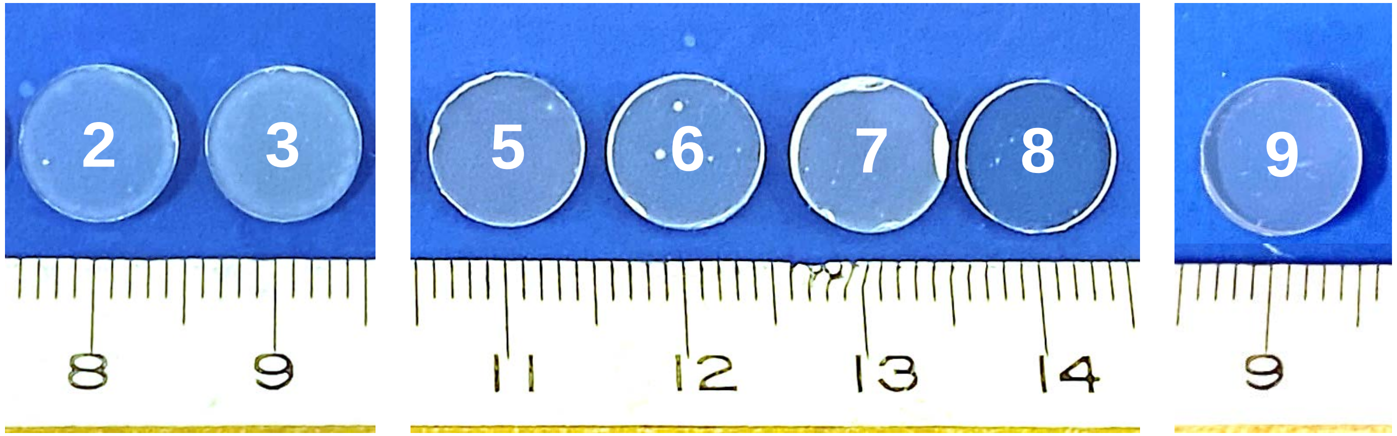
van Pietersen L et al., J. Lumin. 91, 177-193 (2000)





Because of the thermal quenching nature of Yb^{3+} and CT luminescence light yield of 500 ph/MeV and decay time of ~1 ns were observed

RMD Lu_2O_3:Yb Ceramic Samples



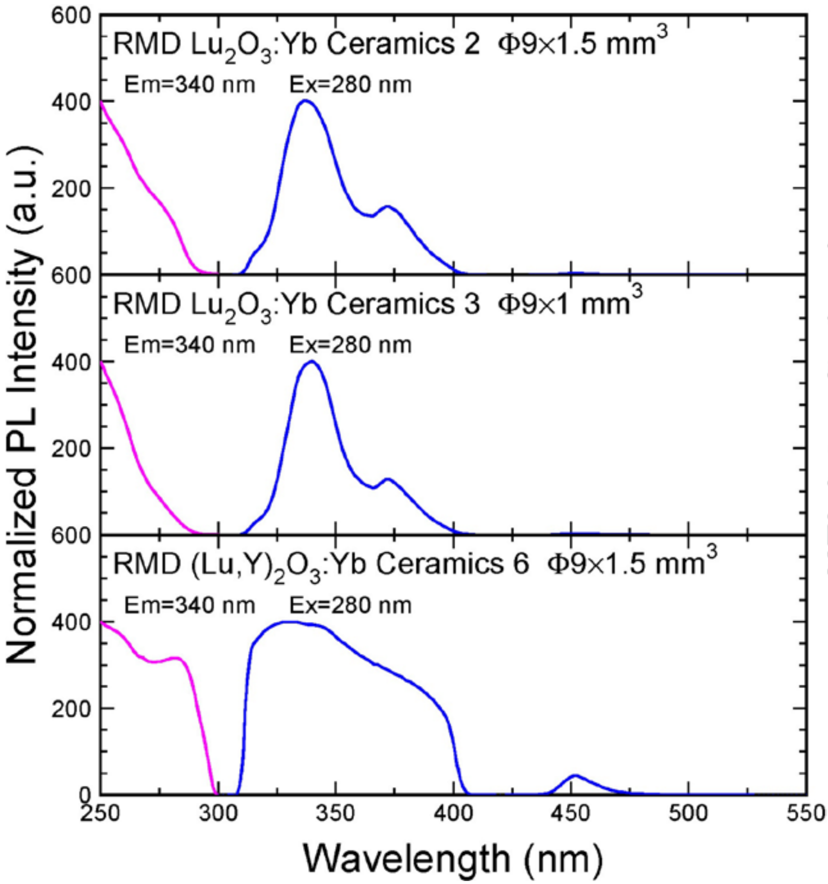
ID	Dimension (mm^3)	Composition
RMD-2	Φ9×1.5	Lu_2O_3
RMD-3	Φ9×1	Lu_2O_3
RMD-5	Φ9×1.5	$(Lu,Y)_2O_3$
RMD-6	Φ9×1.5	$(Lu,Y)_2O_3$
RMD-7	Φ9×2	Lu_2O_3
RMD-8	Φ9×1	$(Lu,Y)_2O_3$
RMD-9	Φ9×2	$(Lu,Y)_2O_3$

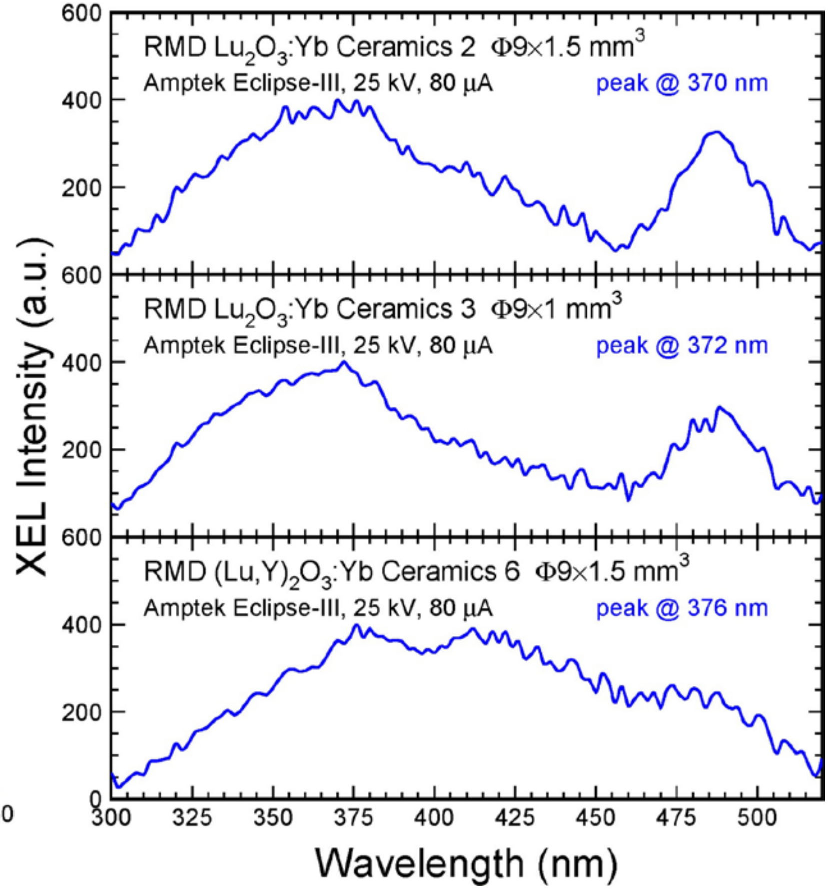
	Lu_2O_3	LYSO	BaF_2	LuAG
Density (g/cm^3)	9.42	7.4	4.89	6.76
Melting points (°C)	2490	2050	1280	2060
X_0 (cm)	0.81	1.14	2.03	1.45
R_M (cm)	1.72	2.07	3.1	2.15
λ_I (cm)	18.1	20.9	30.7	20.6
Z_{eff}	68.0	64.8	51.6	60.3
dE/dX (MeV/cm)	11.6	9.55	6.52	9.22

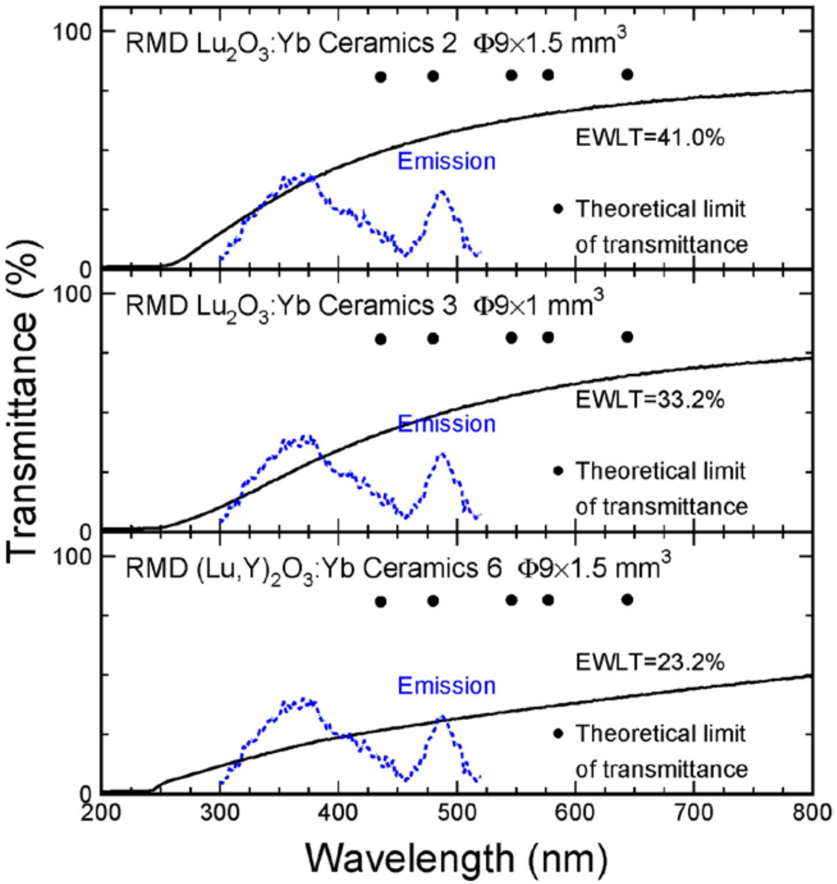
Lu_2O_3:Yb is attractive to the HEP community: high density, ultrafast decay and large dE/dX. Single crystal growth is an expensive process due to its very high melting point. Ceramics are a promising approach.

Emission and Transmittance

Photo-luminescence and X-ray excited luminescence peaked at ~340 nm and ~370 nm
$(Lu,Y)_2O_3$:Yb sample 6 show poor transmittance, probably due to increased scattering



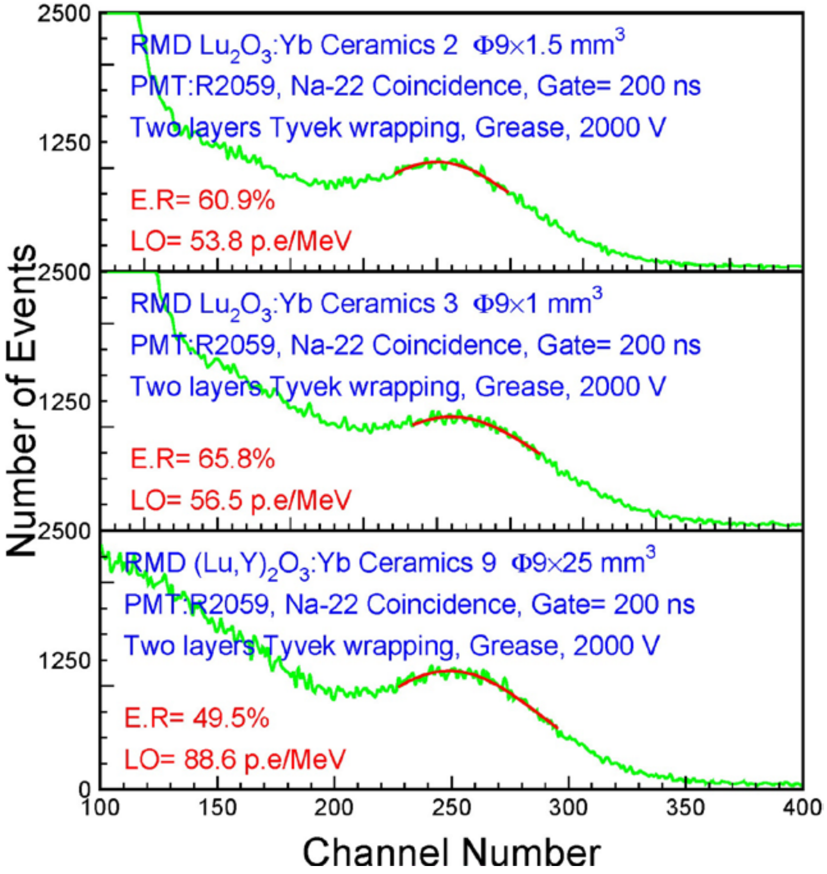


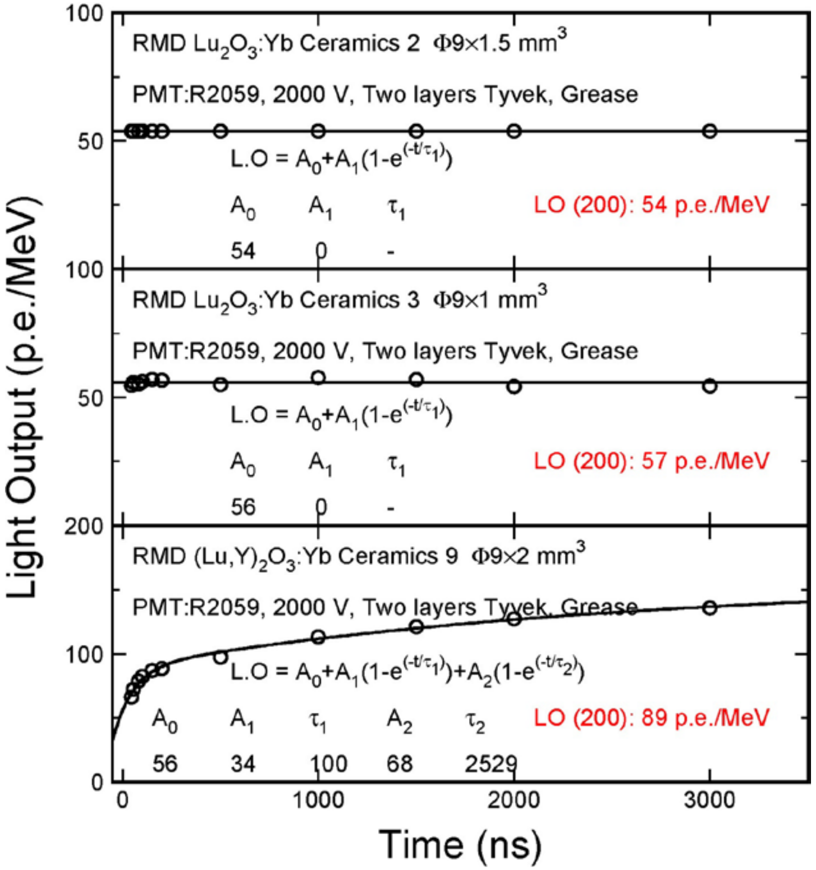


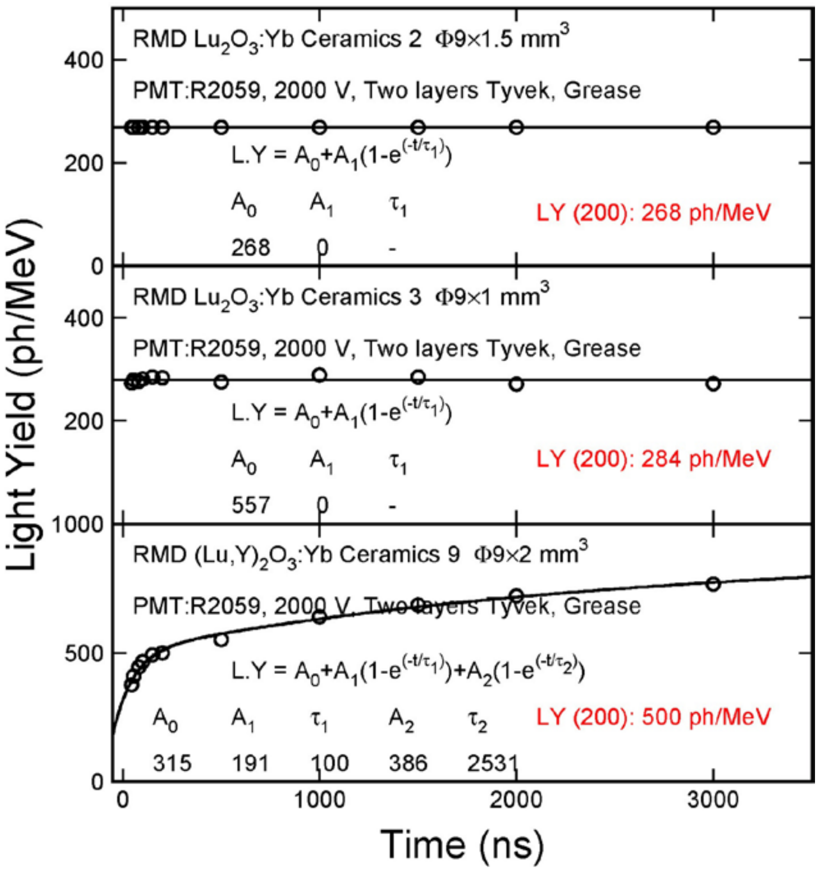
Light Output/Yield: Lu_2O_3:Yb Ceramics

RMD
A Dynasil Company

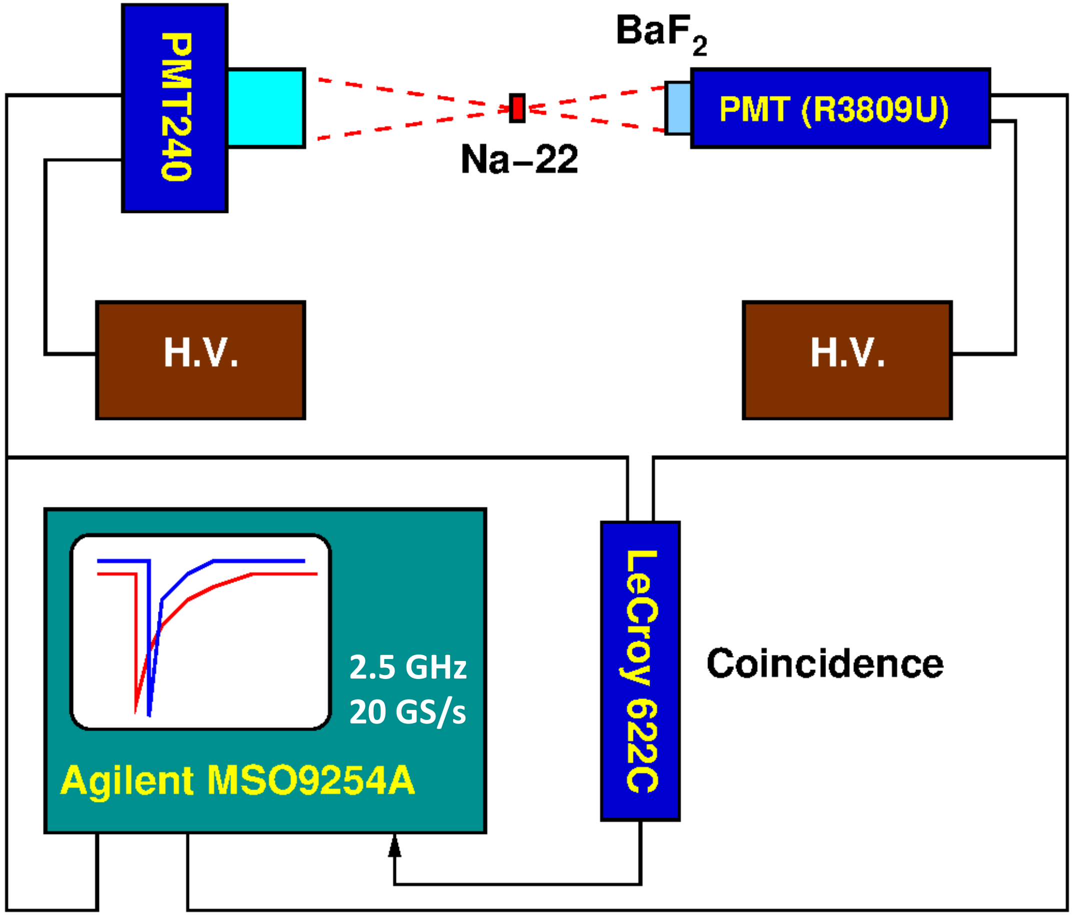
Light yield calculated by taking QE/PDE out of the measured light output
Lu_2O_3:Yb shows light yield up to 280 ph/MeV with negligible slow component
Y admixture increases light output, but introduces slow light of ~100 and ~2,500 ns







Temporal Response: An MCP-Based Test Bench



Fitting:

$$V = A\left(e^{-\frac{t}{\tau_d}} - e^{-\frac{t}{\tau_r}}\right)+B$$

A: amplitude,

B: background noise
or slow component,

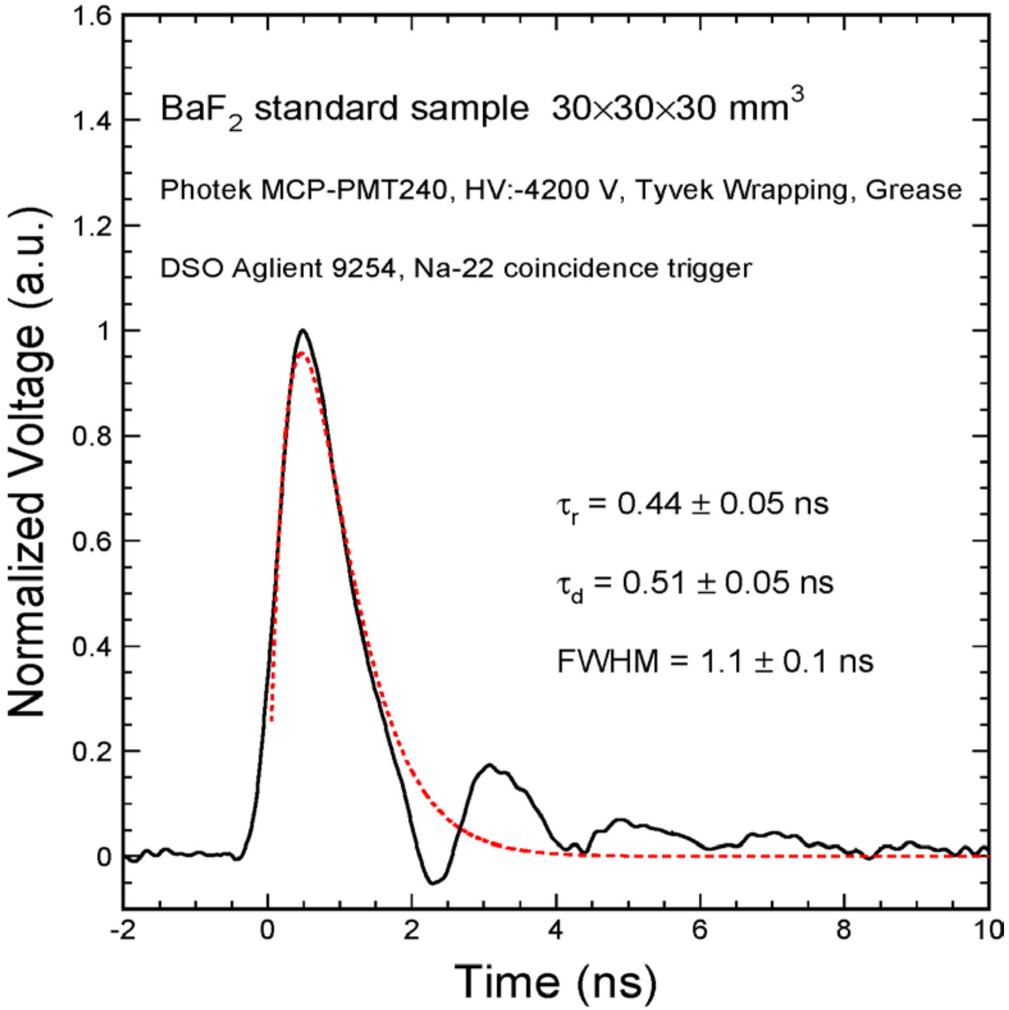
τ_r: rise time,

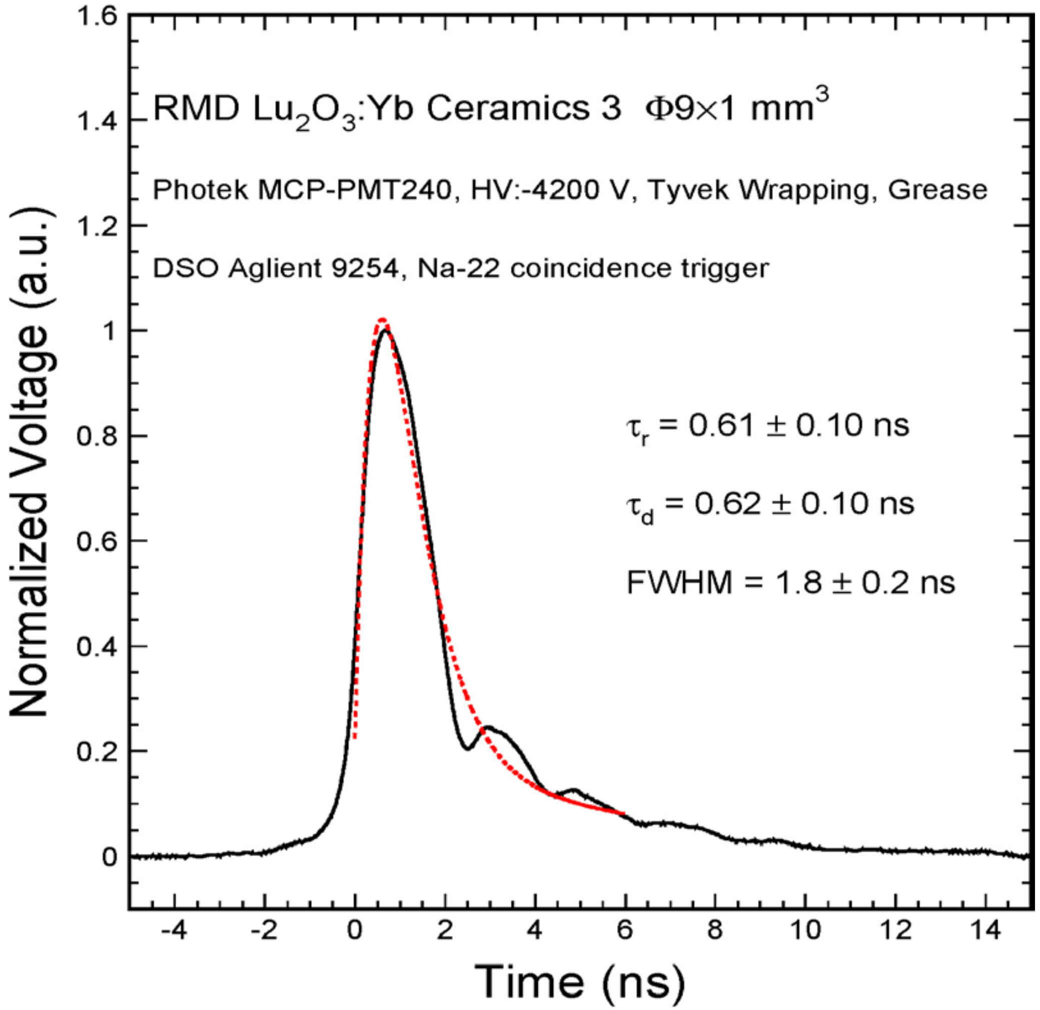
τ_d: decay time.

Rise, decay and FWHM obtained by fitting pulse shape responding to ^{22}Na

Decay Time: BaF_2 and Lu_2O_3:Yb

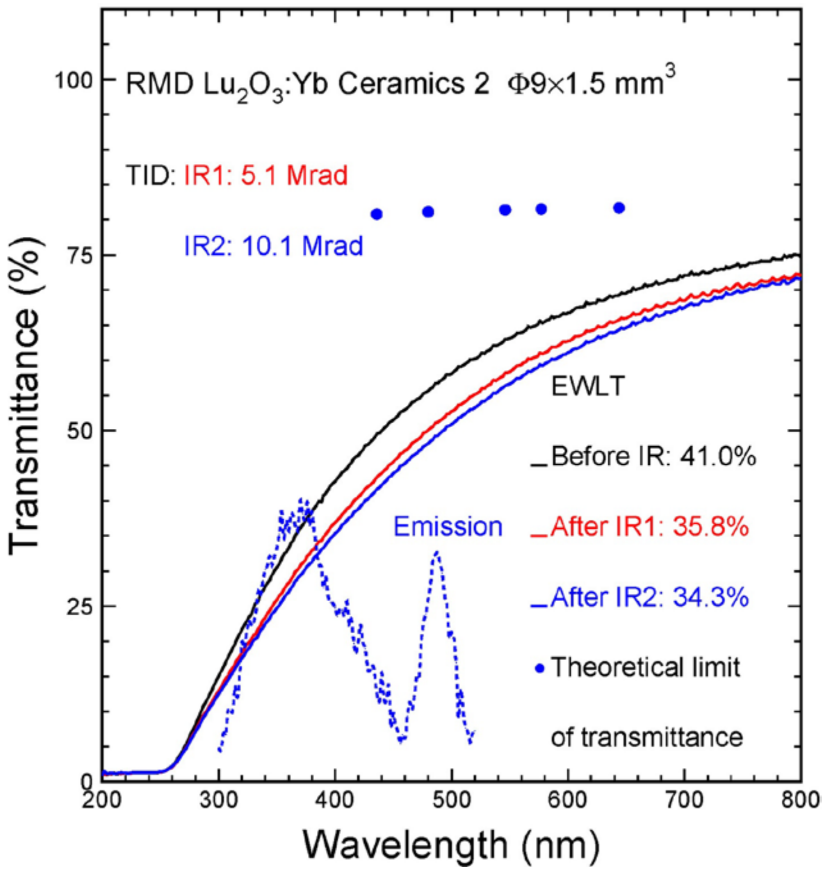
Decay time of 0.5 and 0.6 ns observed for a BaF_2 crystal and RMD Lu_2O_3:Yb-3

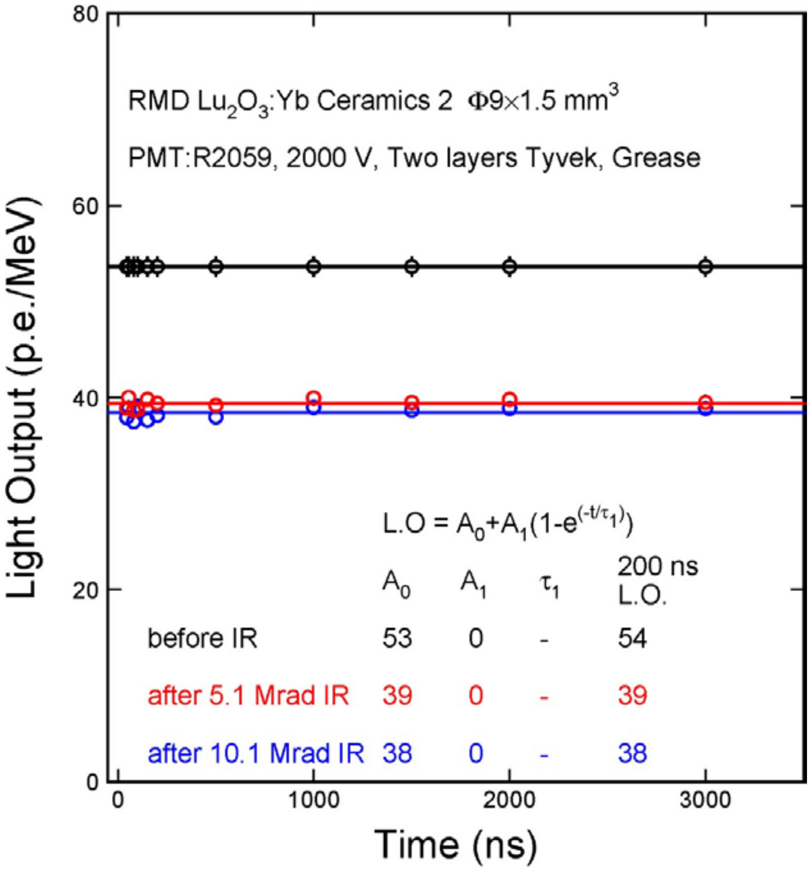




Radiation Hardness: Lu_2O_3:Yb Ceramics

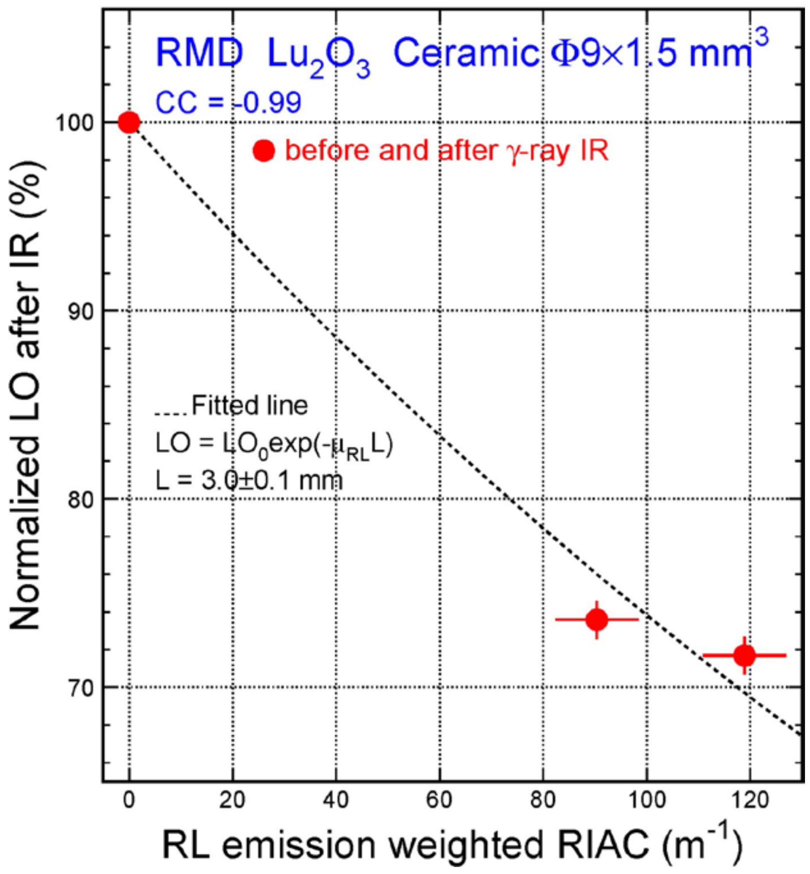
Damage appears saturated after 5.1 Mrad. Dose rate dependence under study
Light output loss is due to induced absorption with a mean light path of 3 mm



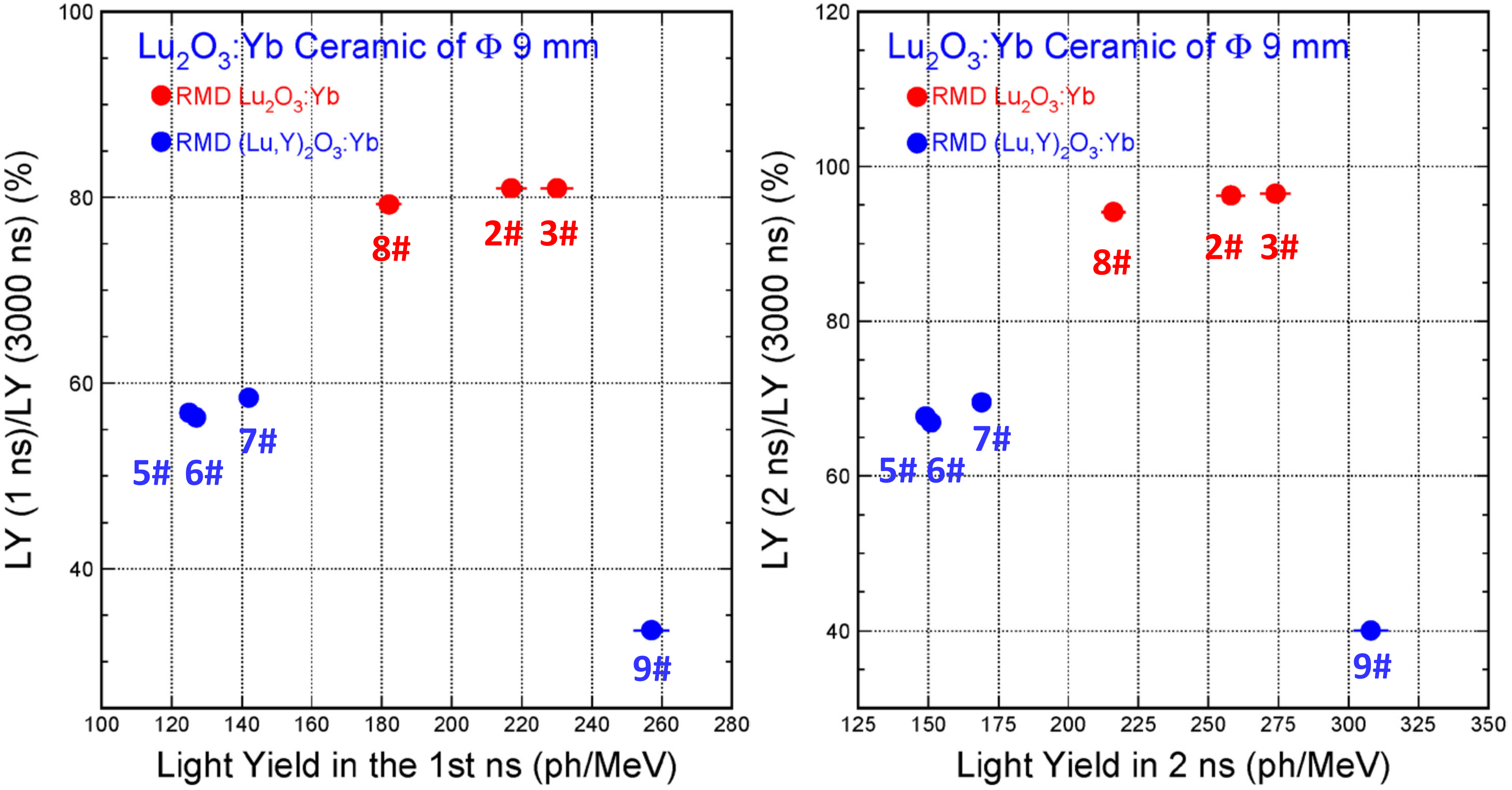


$L.O = A_0+A_1(1-e^{(-t/\tau_1)})$

	A_0	A_1	τ_1	200 ns L.O.
before IR	53	0	-	54
after 5.1 Mrad IR	39	0	-	39
after 10.1 Mrad IR	38	0	-	38



Comparison: Lu_2O_3:Yb vs. $(Lu,Y)_2O_3$:Yb



Lu_2O_3:Yb shows higher ultrafast and lower slow light with the ratio between the light yield in the 1st and 2 ns to the light yield in 3,000 ns (U/T) exceeds 80% and 95% respectively

One $(Lu,Y)_2O_3$:Yb sample shows the highest LY in the 1st ns, but also the lowest U/T ratio

Fast and Ultrafast Inorganic Scintillators

	BaF$_2$	BaF$_2$:Y	ZnO:Ga	Lu$_2$O$_3$:Yb	YAP:Yb	YAG:Yb	β-Ga$_2$O$_3$	PWO	LYSO:Ce	LuAG:Ce	YAP:Ce	GAGG:Ce	LuYAP:Ce	YSO:Ce
Density (g/cm^3)	4.89	4.89	5.67	9.42	5.35	4.56	5.94[1]	8.28	7.4	6.76	5.35	6.5	7.2[f]	4.44
Melting points (°C)	1280	1280	1975	2490	1870	1940	1725	1123	2050	2060	1870	1850	1930	2070
X_0 (cm)	2.03	2.03	2.51	0.81	2.77	3.53	2.51	0.89	1.14	1.45	2.77	1.63	1.37	3.10
R_M (cm)	3.1	3.1	2.28	1.72	2.4	2.76	2.20	2.00	2.07	2.15	2.4	2.20	2.01	2.93
λ_I (cm)	30.7	30.7	22.2	18.1	22.4	25.2	20.9	20.7	20.9	20.6	22.4	21.5	19.5	27.8
Z_{eff}	51.6	51.6	27.7	68.0	31.9	30.0	28.1	74.5	64.8	60.3	31.9	51.8	58.6	33.3
dE/dX (MeV/cm)	6.52	6.52	8.42	11.6	8.05	7.01	8.82	10.1	9.55	9.22	8.05	8.96	9.82	6.57
λ_{peak} [a] (nm)	300 220	300 220	380	370	350	350	380	425 420	420	520	370	540	385	420
Refractive Index[b]	1.50	1.50	2.1	2.0	1.96	1.87	1.97	2.20	1.82	1.84	1.96	1.92	1.94	1.78
Normalized Light Yield[a,c]	42 4.8	1.7 4.8	6.6[d]	0.95	0.19[d]	0.36[d]	6.5 0.5	1.6 0.4	100	35[e] 48[e]	9 32	115	16 15	80
Total Light yield (ph/MeV)	13,000	2,000	2,000[d]	280	57[d]	110[d]	2,100	130	30,000	25,000[e]	12,000	34,400	10,000	24,000
Decay time[a] (ns)	600 0.5	600 0.5	<1	0.6	1.5	4	148 6	30 10	40	820 50	191 25	53	1485 36	75
LY in 1st ns (photons/MeV)	1200	1200	610[d]	230	28[d]	24[d]	43	5.3	740	240	391	640	125	318
LY in 1st ns /Total LY (%)	9.2	60	31	82	49	22	2.0	4.3	2.5	1.0	3.3	1.9	1.3	1.3
40 keV Att. Leng. (1/e, mm)	0.106	0.106	0.407	0.127	0.314	0.439	0.394	0.111	0.185	0.251	0.314	0.319	0.214	0.334

Summary

- Development of ultrafast heavy crystals with sub-nanosecond decay time is important to break the ps timing barrier for future HEP TOF system and ultrafast calorimetry, and for GHz hard X-ray imaging.
- All Lu_2O_3:Yb samples show PL and XEL emission peaked at ~340 and ~370 nm.
- Lu_2O_3:Yb ceramics show light yield up to 280 ph/MeV with negligible slow component. Mixing Lu_2O_3 with Y_2O_3 appears increase light yield in 200 ns to 500 ph/MeV with significant slow component of 100 and 2,500 ns decay time.
- Sub-nanosecond decay time of 0.6 ns was observed by using MCP-PMT.
- With high density, ultrafast decay time and high U/T ratio Lu_2O_3:Yb ceramics is promising for future HEP TOF and calorimetry applications. RMD is continuing to optimize its composition to increase the ultrafast light with slow component under control.

Acknowledgements: DOE HEP Award DE-SC0011925 and SBIR Award DE-SC0021686