The Next Generation of Crystal Calorimetry

Ren-Yuan Zhu

California Institute of Technology

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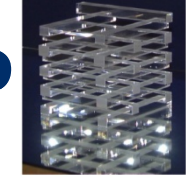
Advances in HEP Calorimetry

- The mission of HEP calorimetry is the measurements of the energy, location and time of electromagnetic and hadronic showers, as well as missing energy.
- An imaging calorimetry has been developed under the leadership of CALICE, and adapted in the CMS FCAL and ILC/CLIC. Particle flow Algorithm (PFA) has been adopted for object reconstruction in a complex system of inter-connected detectors.
- High precision timing detectors are used to distinguish events from one bunch crossing at the HL-LHC, leading to a 4D calorimetry.

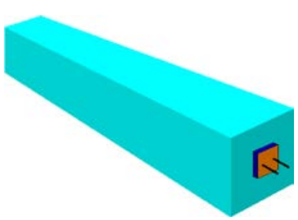
Why Crystal Calorimetry?

- Precision γ/e measurements enhance physics discovery potential in HEP experiments.
- Performance of crystal calorimeter in γ/e measurements is well understood:
  - The best possible energy and position resolutions;
  - Good e/γ identification and reconstruction efficiency.
- Challenges on crystal calorimetry:
  - Ultrafast and radiation hard crystals and γ-ray direction measurement at the energy frontier (HL-LHC);
  - Ultrafast crystals at the intensity frontier (Mu2e-II);
  - Cost-effective crystals for the Homogeneous HCAL;
  - Highly segmented crystal calorimetry, such as HERD LYSO calorimeter, is under development.

Existing Crystal Calorimeters in HEP



Date	75-85	80-00	80-00	80-00	90-10	94-10	94-10	95-30
Experiment	C. Ball	L3	CLEO II	C. Barrel	KTeV	*BaBar*	BELLE	CMS
Accelerator	SPEAR	LEP	CESR	LEAR	FNAL	SLAC	KEK	CERN
Crystal Type	NaI(Tl)	BGO	CsI(Tl)	CsI(Tl)	CsI	CsI(Tl)	CsI(Tl)	$PbWO_4$
B-Field (T)	-	0.5	1.5	1.5	-	1.5	1.0	4.0
r_{inner} (m)	0.254	0.55	1.0	0.27	-	1.0	1.25	1.29
Number of Crystals	672	11,400	7,800	1,400	3,300	6,580	8,800	76,000
Crystal Depth (X_0)	16	22	16	16	27	16 to 17.5	16.2	25
Crystal Volume (m^3)	1	1.5	7	1	2	5.9	9.5	11
Light Output (p.e./MeV)	350	1,400	5,000	2,000	40	5,000	5,000	2
Photosensor	PMT	Si PD	Si PD	WS[a]+Si PD	PMT	Si PD	Si PD	APD[a]
Gain of Photosensor	Large	1	1	1	4,000	1	1	50
σ_N/Channel (MeV)	0.05	0.8	0.5	0.2	small	0.15	0.2	40
Dynamic Range	10^4	10^5	10^4	10^4	10^4	10^4	10^4	10^5

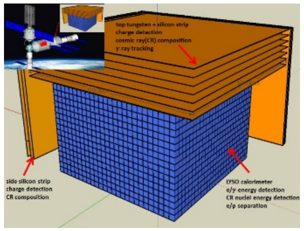


Future crystal calorimeters in HEP:

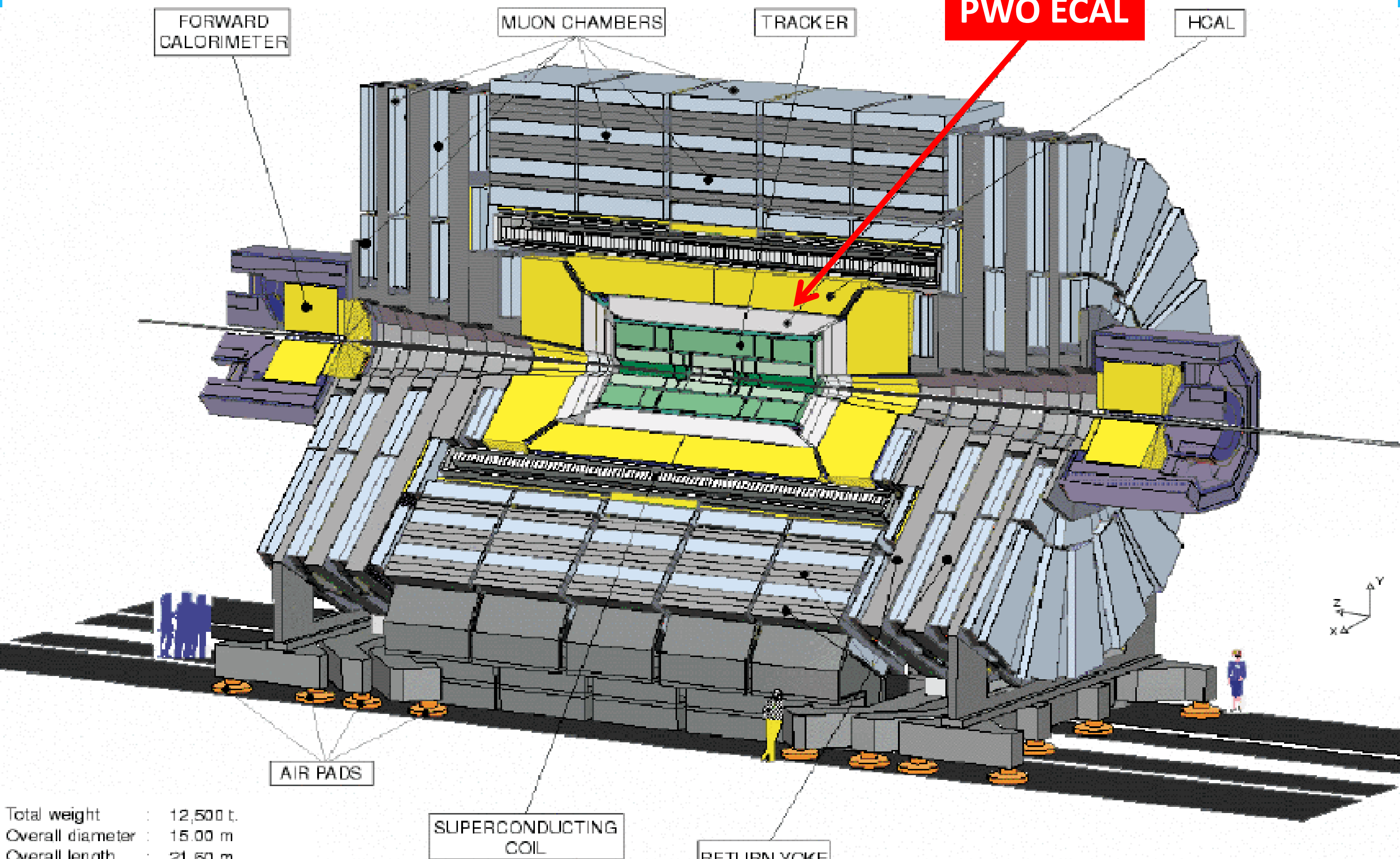
LSO/LYSO for COMET, HERD, and HL-LHC (Sampling)

CsI and BaF_2:Y for Mu2e, PWO for PANDA

BGO, BSO or scintillating glasses for HHCAL



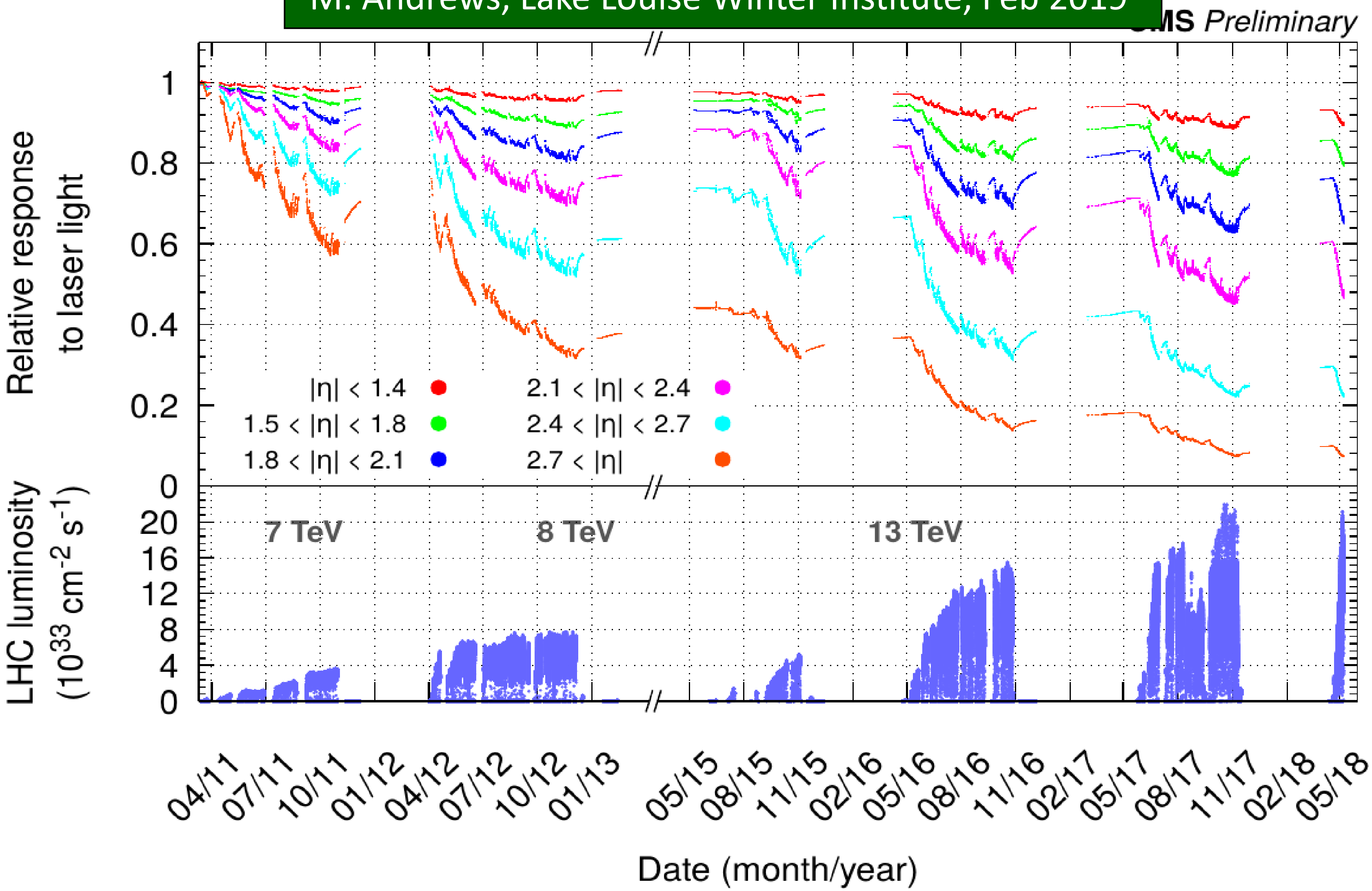
CMS Experiment at LHC



Total weight : 12,500 t.
Overall diameter : 15.00 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

CMS PWO Monitoring Response

M. Andrews, Lake Louise Winter Institute, Feb 2019



http://www.hep.caltech.edu/~zhu/talks/ryz_161028_PWO_mon.pdf

Dose Rate Dependent EM Damage

IEEE Trans. Nucl. Sci., Vol. 44 (1997) 458-476

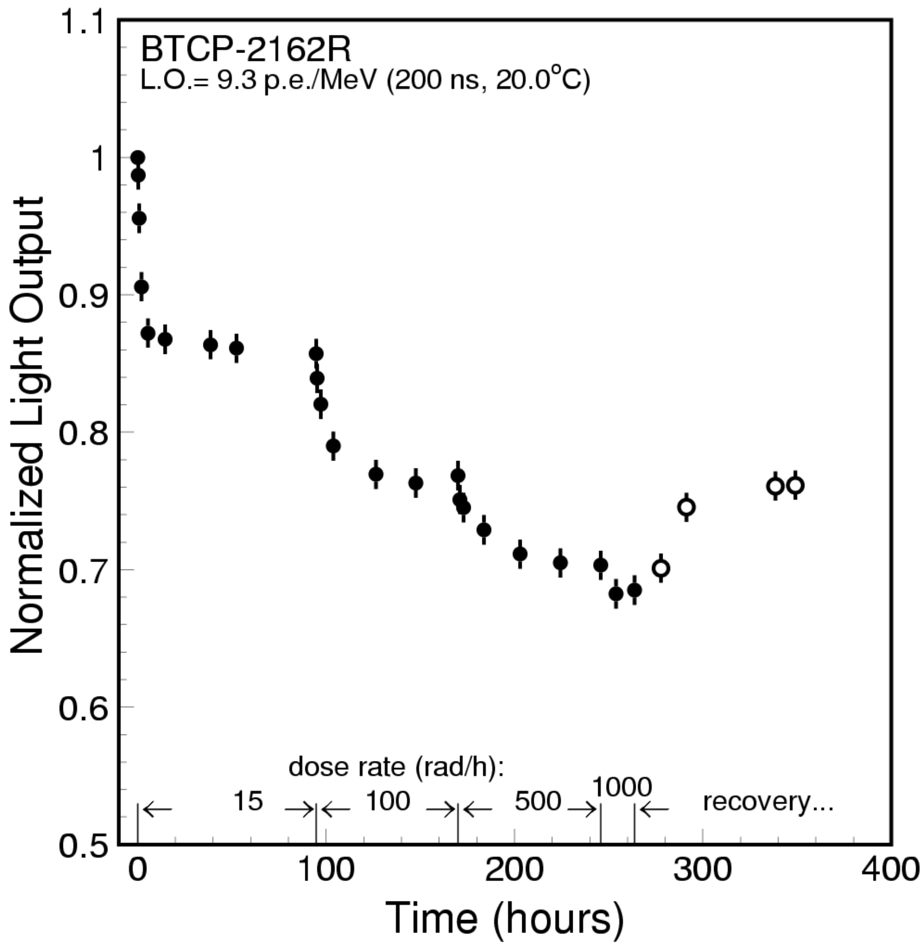
The LO reached equilibrium during irradiations under a defined dose rate, showing dose rate dependent radiation damage

$$dD = \sum_{i=1}^{n} \{ -a_i D_i dt + (D_i^{all} - D_i)\, b_i R dt \}$$

$$D = \sum_{i=1}^{n} \{ \frac{b_i R D_i^{all}}{a_i + b_i R} [1 - e^{-(a_i + b_i R)t}] + D_i^0 e^{-(a_i + b_i R)t} \}$$

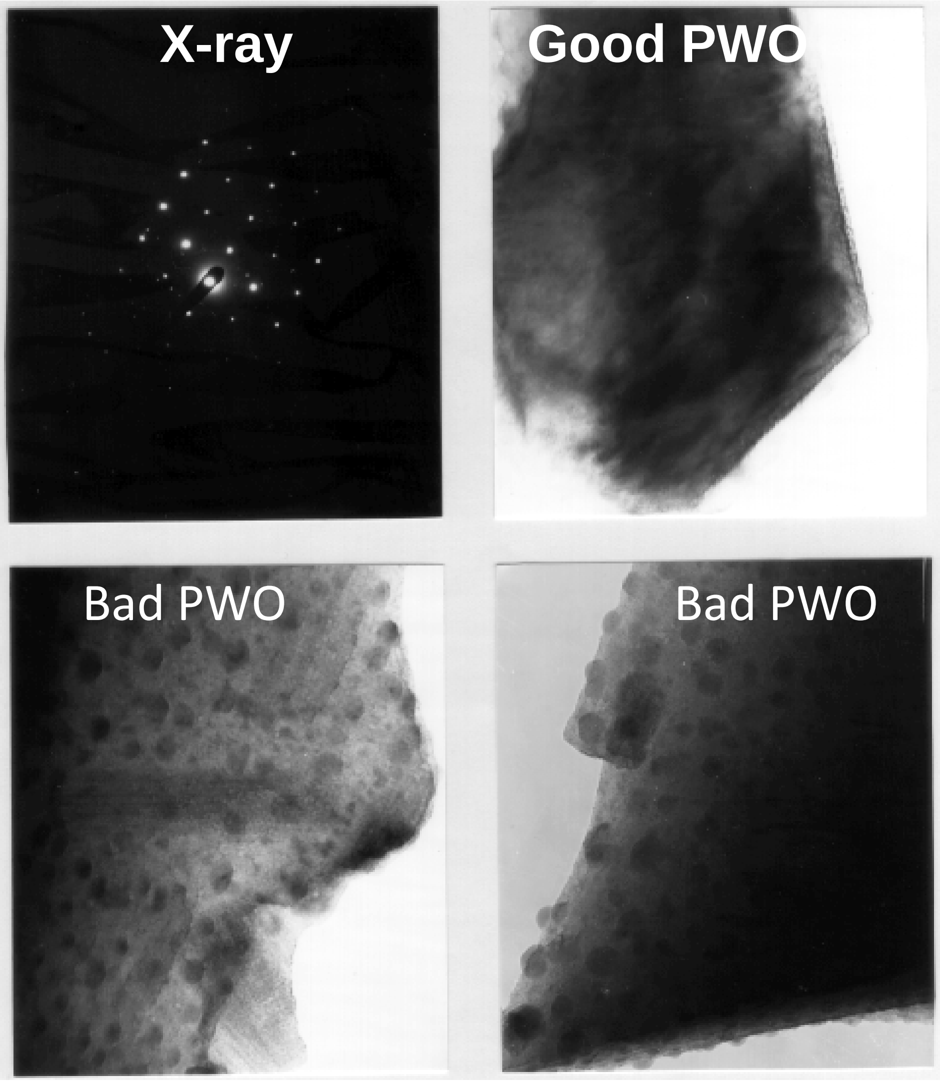
- D_i: color center density in units of m^{-1};
- D_i^0: initial color center density;
- D_i^{all} is the total density of trap related to the color center in the crystal;
- a_i: recovery costant in units of hr^{-1};
- b_i: damage contant in units of kRad^{-1};
- R: the radiation dose rate in units of kRad/hr.

$$D_{eq} = \sum_{i=1}^{n} \frac{b_i R D_i^{all}}{a_i + b_i R}$$



Oxygen Vacancies Identified by TEM/EDS

TOPCON-002B scope, 200 kV, 10 uA, 5 to10 nm black spots identified
JEOL JEM-2010 scope and Link ISIS EDS localized Stoichiometry Analysis



NIM A413 (1998) 297

Atomic Fraction (%) in $PbWO_4$

As Grown Sample

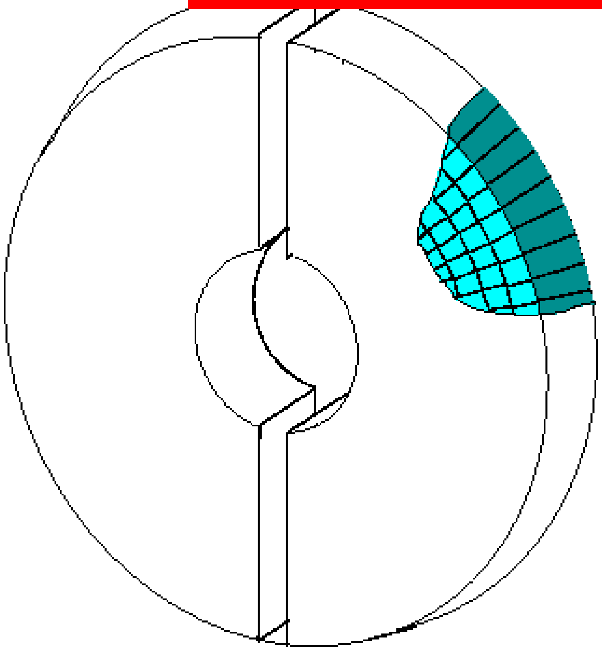
Element	Black Spot	Peripheral	$Matrix_1$	$Matrix_2$
O	1.5	15.8	60.8	63.2
W	50.8	44.3	19.6	18.4
Pb	47.7	39.9	19.6	18.4

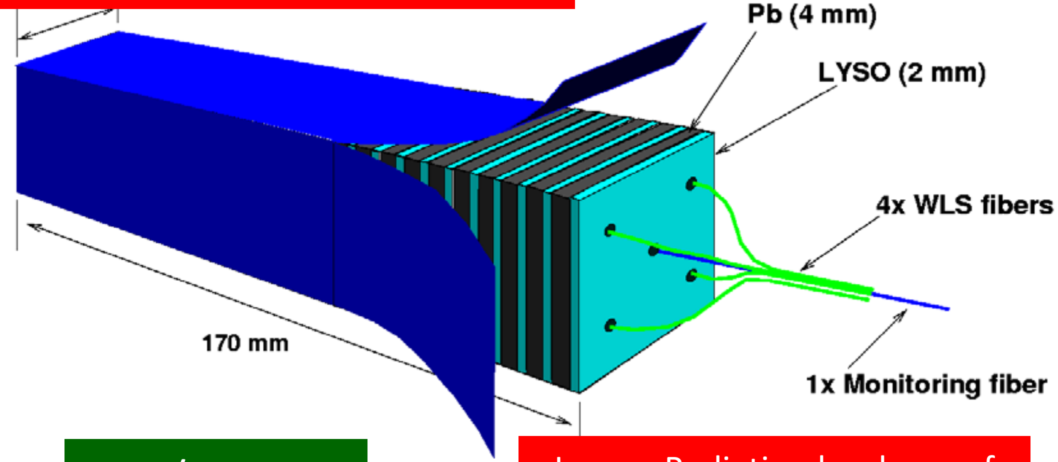
The Same Sample after Oxygen Compensation

Element	$Point_1$	$Point_2$	$Point_3$	$Point_4$
O	59.0	66.4	57.4	66.7
W	21.0	16.5	21.3	16.8
Pb	20.0	17.1	21.3	16.5

CMS Forward Calorimeter Upgrade

Talk in CMS FCAL Taskforce Meeting at CERN, 6/30/2011

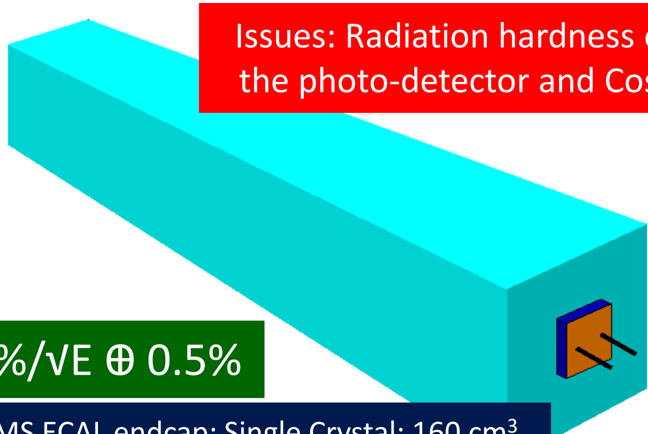




10%/√E ⊕ 1%

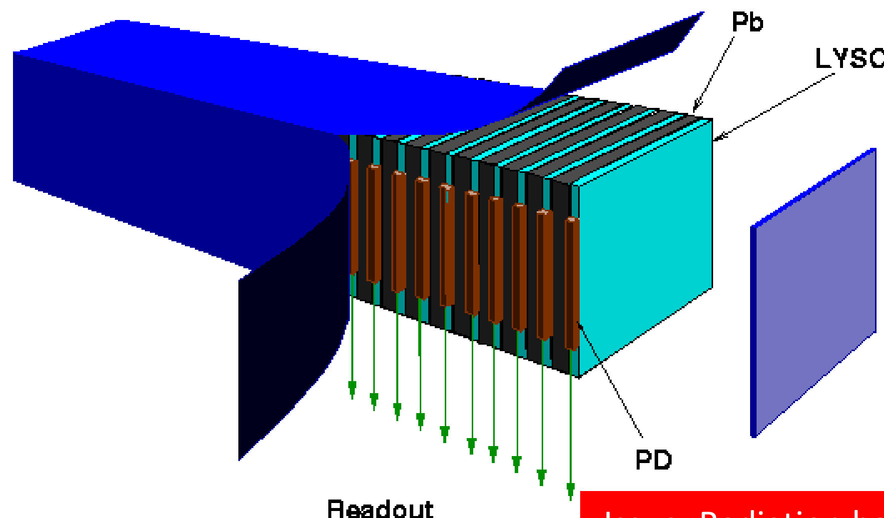
Issues: Radiation hardness of photo-detector and WLS fiber

Issues: Radiation hardness of the photo-detector and Cost



2%/√E ⊕ 0.5%

CMS ECAL endcap: Single Crystal: 160 cm^3
Total number: 16,000 Total Volume: 3 m^3
Expected Crystal Cost: ~$90M@$30/cc

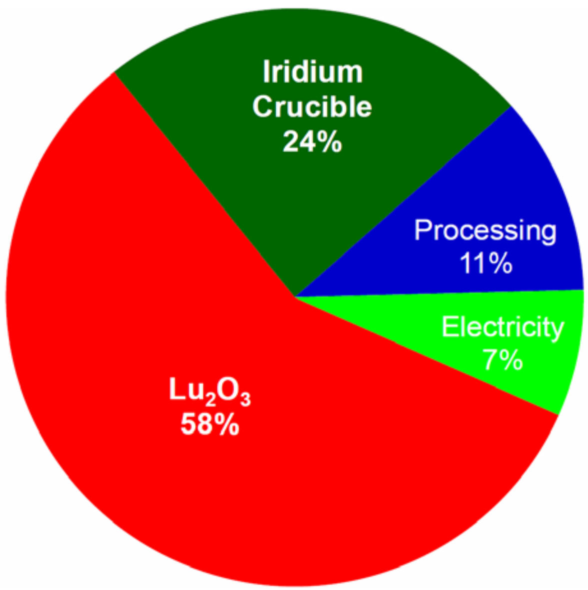


With longitudinal segmentation

Issue: Radiation hardness of the photo-detector

LSO/LYSO/LFS Crystal Cost

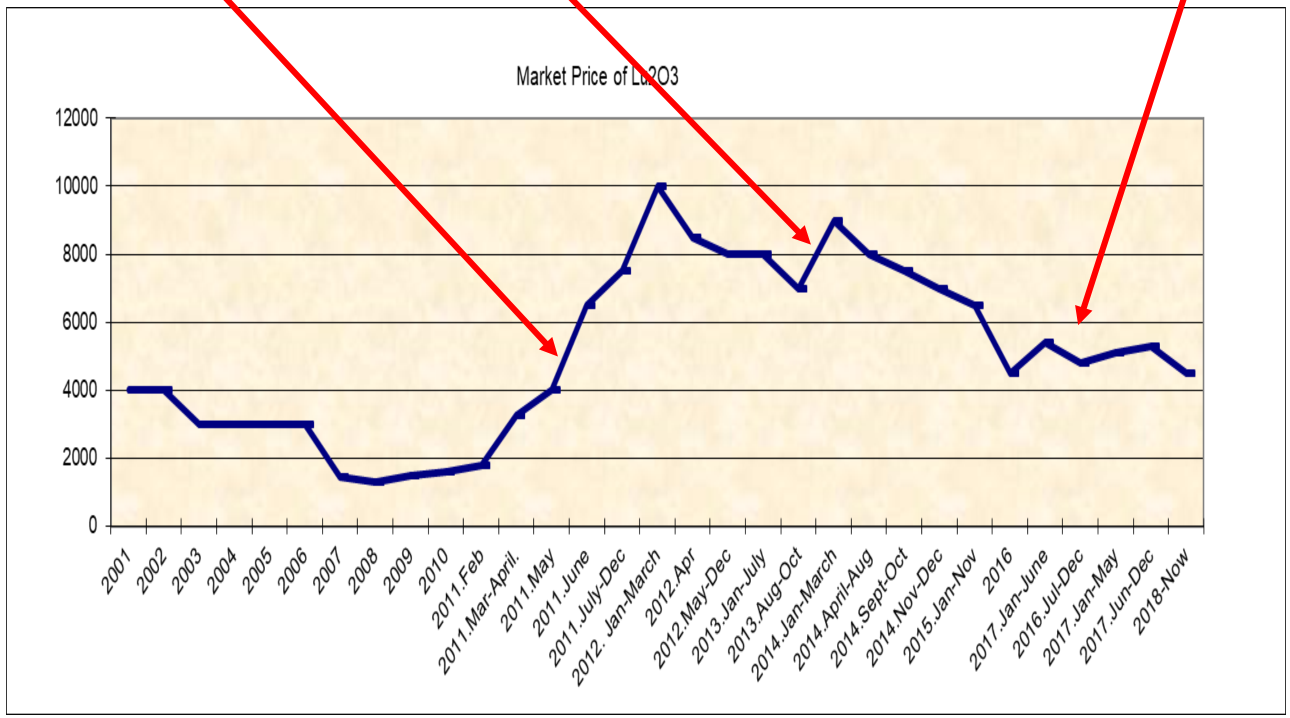
Crystal Cost Breakdown



Rare earth export control in China

Rare earth strategic reserve in China

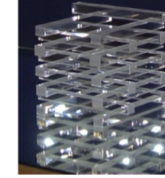
Rare earth market going to normal



Assuming Lu_2O_3 at $400/kg and 33% yield the cost is about $18/cc. Quotations received at $22-25/cc.

Current Lu_2O_3 price indicates that LYSO price is at a level of $30/cc

The CMS MIP Timing Detector

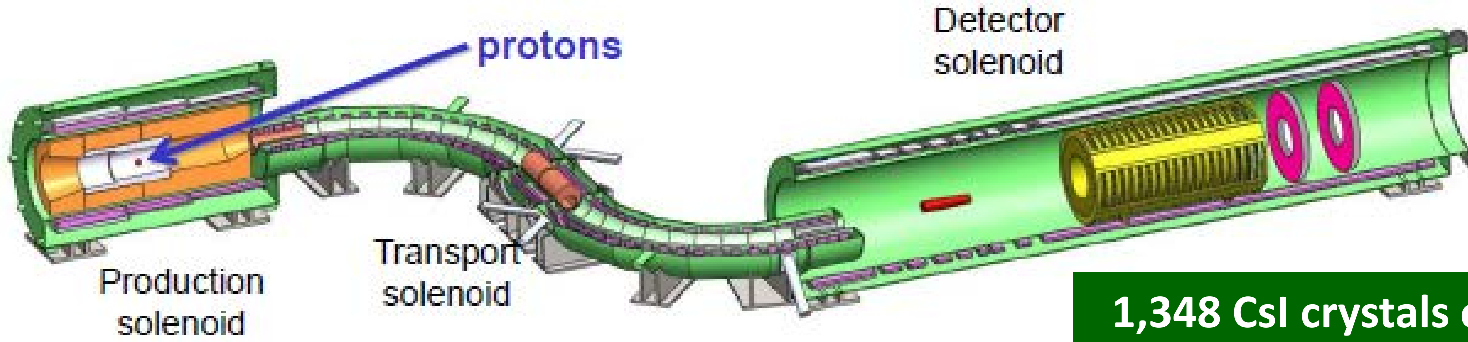


CMS Hermetic Timing Concept

BTL technology choice – SiPM/LYSO :

- **Timing performance <20 ps with MIPs in PET crystals.**
- **Radiation hardness established at the required level.**
- **Extensive experience with this technology.**
- **Cost effective mass market components**

Mu2e CsI Calorimeter in Construction



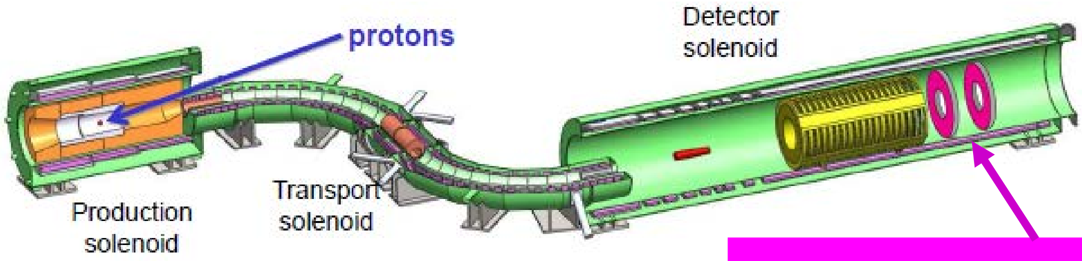
1,348 CsI crystals of 34 x 34 x 200 mm under production

- Crystal lateral dimension: ±100 μ, length: ±100 μ.
- Scintillation properties at seven points along the crystal wrapped by two layers of Tyvek paper of 150 μm for alternative end coupled to a bi-alkali PMT with an air gap. Light output and FWHM resolution are the average of seven points with 200 ns integration time. The light response uniformity is the rms of seven points. F/T is measured at the point of 2.5 cm to the PMT.
  - Light output (LO): > **100 p.e./MeV** with 200 ns gate, will be compared to reference for cross-calibration;
  - FWHM Energy resolution: **< 45%** for Na-22 peak;
  - Light response uniformity (LRU, rms of seven points): **< 5%**;
  - Fast (200 ns)/Total (3000 ns) Ratio: **> 75%**.
- Radiation related spec::
  - Normalized LO **after 10/100 krad: > 85/60%;**
  - Radiation Induced noise **@ 1.8 rad/h: < 0.6 MeV**.

Ultrafast BaF_2:Y Crystal Calorimeter

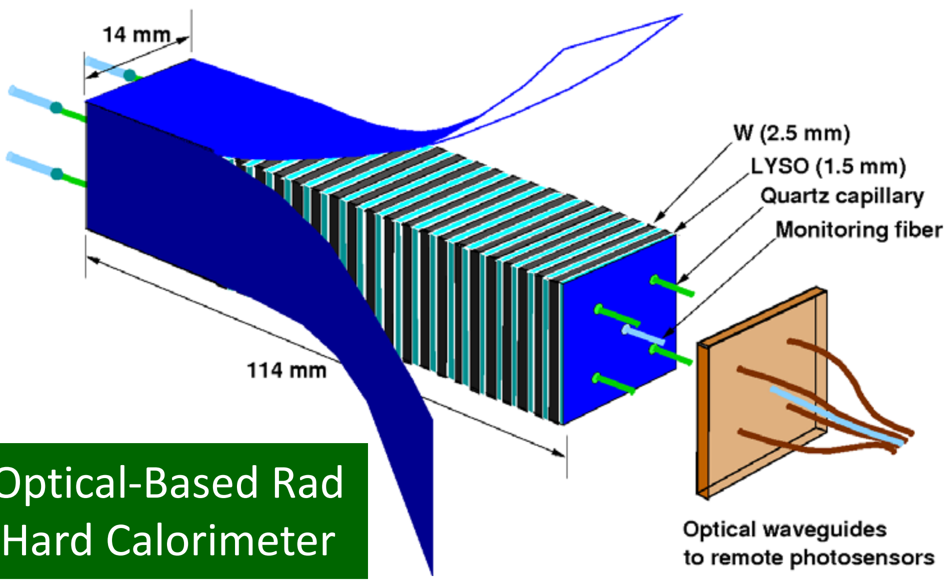
Ultrafast and radiation hard inorganic scintillators have broad applications

Mu2e-II: arXiv:1802.02599

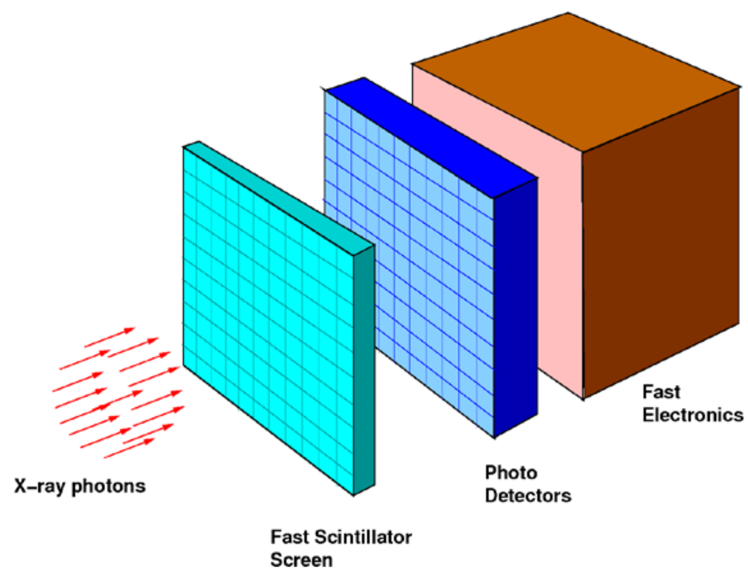


1,940 BaF_2:Y crystals
30 x 30 x 218 mm

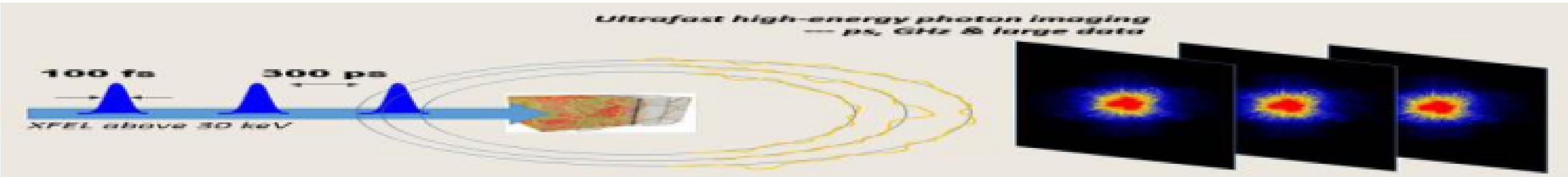
BaF_2:Y, ZnO:Ga and $CsPbX_3$ QD attractive for an ultrafast front imager for the FEL based **GHz Hard** X-ray imaging



Optical-Based Rad Hard Calorimeter



GHz Hard X-Ray Imaging



High-Energy and Ultrafast X-Ray Imaging Technologies and Applications

Organizers: Peter Denes, Sol Gruner, Michael Stevens & Zhehui (Jeff) Wang[1]

(***Location/Time****: Santa Fe, NM, USA /Aug 2-3, 2016)*

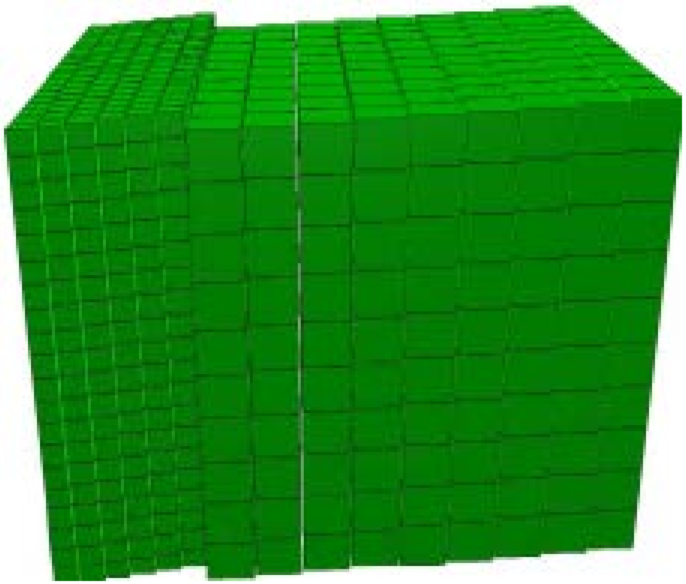
The goals of this workshop are to gather the leading experts in the related fields, to prioritize tasks for ultrafast hard X-ray imaging detector technology development and applications in the next 5 to 10 years, see Table 1, and to establish the foundations for near-term R&D collaborations.

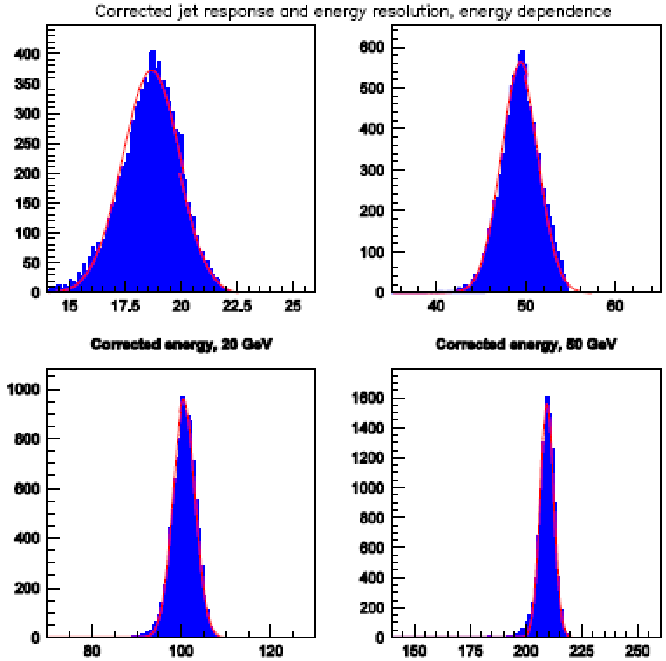
Table I. High-energy photon imagers for MaRIE XFEL

Performance	Type I imager	Type II imager
X-ray energy	30 keV	42-126 keV
Frame-rate/inter-frame time	0.5 GHz/2 ns	3 GHz / 300 ps
Number of frames	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	≥ 10^4 X-ray photons
Pixel format	64 x 64 (scalable to 1 Mpix)	1 Mpix

2 ns and 300 ps inter-frame time requires very fast sensor

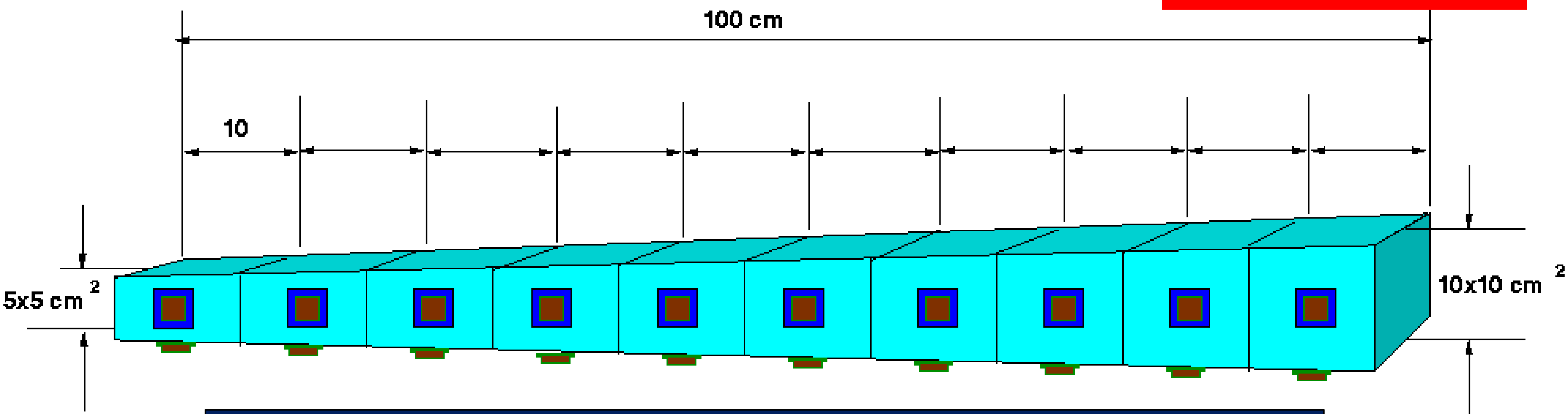
The HHCAL Detector Concept





A. Para, H. Wenzel, and S. McGill, Callor2012: GEANT simulations show a jet energy resolution at a level of 20%/√E. Also dual gate.

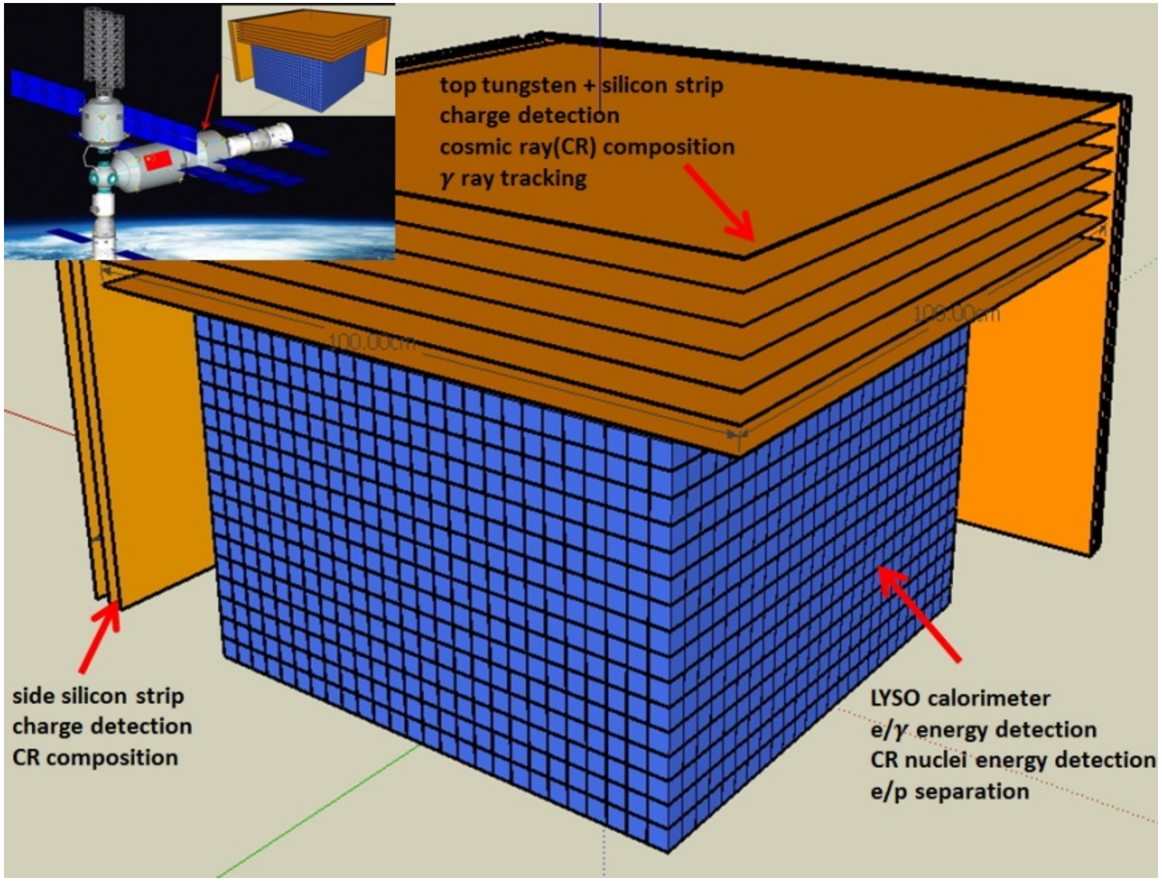
Can we afford?



R.-Y. Zhu, ILCWS-8, Chicago: a HHCAL cell with pointing geometry

The HERD LYSO Calorimeter

9261 LYSO crystals of 3 cm cube with WLF readout: 55 X_0 and 3 λ



See presentations by Profs. Chris Tully, Yong Liu and Zhigang Wang , on novel designs of Crystal EM Calorimeters for CEPC.

Good resolutions for γ/e energy, position and direction

Fast & Rad Hard Inorganic Scintillators

- **Supported by the DOE ADR program we are developing fast and radiation hard inorganic scintillators to face the challenge for future HEP applications.**
- **LYSO:Ce, BaF_2:Y and LuAG:Ce will survive the radiation environment expected at HL-LHC with 3000 fb^{-1}:**
  - **Absorbed dose: up to 100 Mrad,**
  - **Charged hadron fluence: up to 6×10^{14} p/cm^2,**
  - **Fast neutron fluence: up to 3×10^{15} n/cm^2.**
- **Ultra-fast scintillators with excellent radiation hardness is also needed to face the challenge of unprecedented event rate expected at future HEP experiments at the intensity frontier, such as Mu2e-II and the proposed Marie project at Los Alamos. BaF_2:Y with sub-ns decay time and suppressed slow scintillation component is a leading candidate for all applications.**

Inorganic Scintillators for HEP Calorimetry

Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	LYSO(Ce)	PWO	PbF_2
Density (g/cm^3)	3.67	4.51	4.51	4.89	7.13	7.40	8.3	7.77
Melting Point (ºC)	651	621	621	1280	1050	2050	1123	824
Radiation Length (cm)	2.59	1.86	1.86	2.03	1.12	1.14	0.89	0.93
Molière Radius (cm)	4.13	3.57	3.57	3.10	2.23	2.07	2.00	2.21
Interaction Length (cm)	42.9	39.3	39.3	30.7	22.8	20.9	20.7	21.0
Refractive Index [a]	1.85	1.79	1.95	1.50	2.15	1.82	2.20	1.82
Hygroscopicity	Yes	Slight	Slight	No	No	No	No	No
Luminescence [b] (nm) (at peak)	410	550	310	300 220	480	402	425 420	?
Decay Time [b] (ns)	245	1220	26	650 <0.6	300	40	30 10	?
Light Yield [b,c] (%)	100	165	4.7	36 4.1	21	85	0.3 0.1	?
d(LY)/dT [b] (%/ ºC)	-0.2	0.4	-1.4	-1.9 0.1	-0.9	-0.2	-2.5	?
Experiment	Crystal Ball	BaBar BELLE BES-III	KTeV S.BELLE Mu2e-I	(GEM) TAPS Mu2e-II?	L3 BELLE HHCAL?	COMET & CMS (Mu2e & SuperB)	CMS ALICE PANDA	A4 g-2 HHCAL?

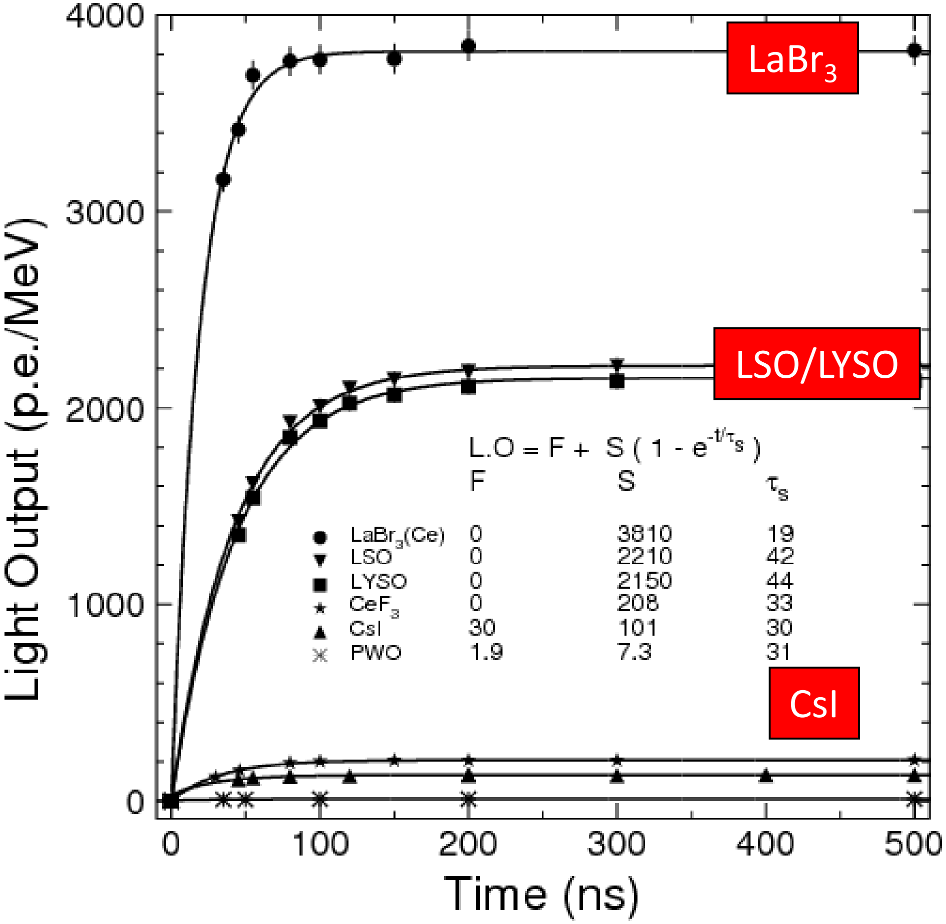
a. at peak of emission; b. up/low row: slow/fast component; c. QE of readout device taken out.

Light Output & Decay Kinetics

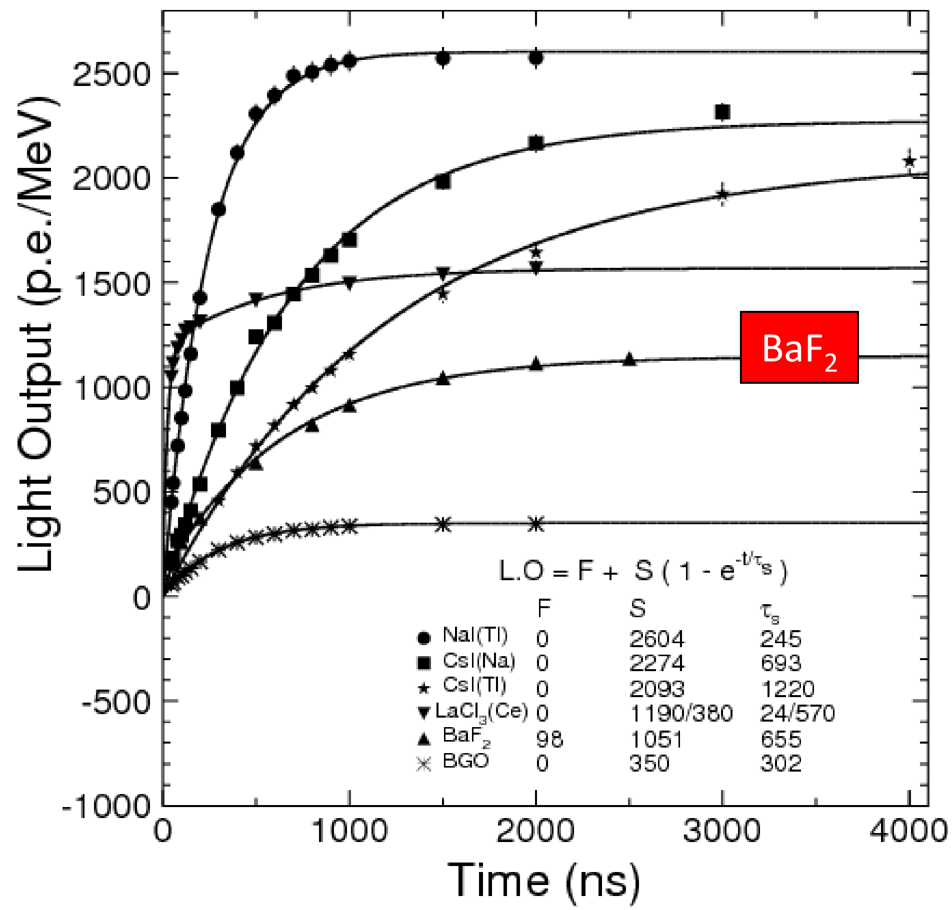
Measured with Philips XP2254B PMT (multi-alkali cathode)

p.e./MeV: LSO/LYSO is 6 & 230 times of BGO & PWO respectively

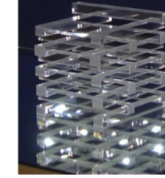
Fast Crystal Scintillators



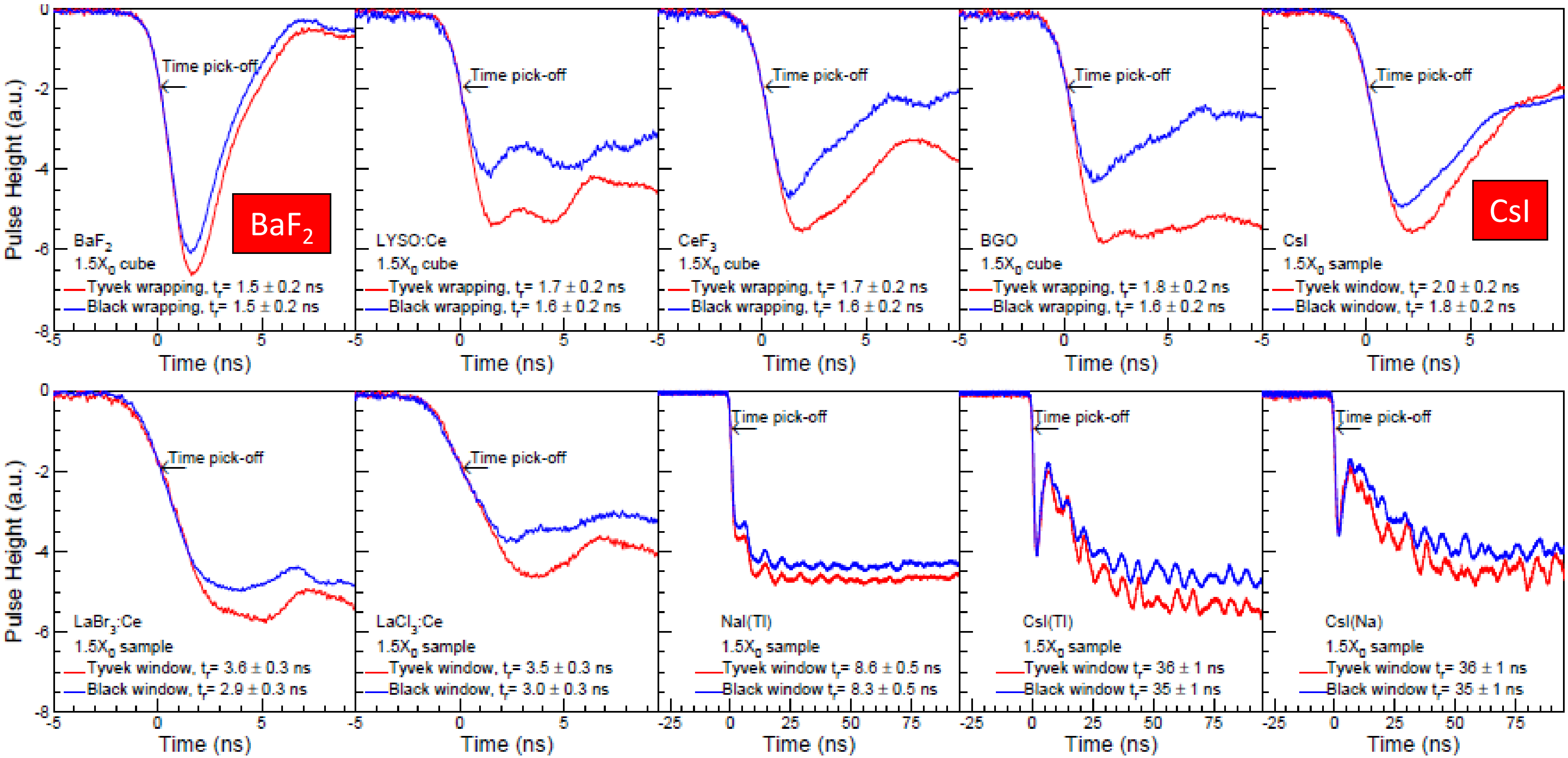
Slow Crystal Scintillators



Fast Signals with 1.5 X_0 Samples

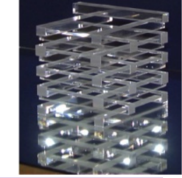


Hamamatsu R2059 PMT (2500 V)/Agilent MSO9254A (2.5 GHz) DSO with 1.3/0.14 ns rise time



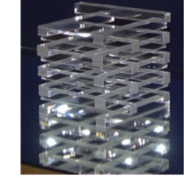
The 3 ns width of BaF_2 pulse is further reduced by faster photodetector
LYSO, $LaBr_3$ & $CeBr_3$ have tail, which would cause pile-up for GHz readout

Fast Inorganic Scintillators for HEP



	LYSO:Ce	LSO:Ce, Ca[1]	LuAG:Ce[2]	LuAG:Pr[3]	GGAG:Ce[4,5]	CsI	BaF_2[6]	BaF_2:Y	$CeBr_3$	$LaBr_3$:Ce[7]
Density (g/cm^3)	7.4	7.4	6.76	6.76	6.5	4.51	4.89	4.89	5.23	5.29
Melting points (°C)	2050	2050	2060	2060	1850[d]	621	1280	1280	722	783
X_0 (cm)	1.14	1.14	1.45	1.45	1.63	1.86	2.03	2.03	1.96	1.88
R_M (cm)	2.07	2.07	2.15	2.15	2.20	3.57	3.1	3.1	2.97	2.85
λ_I (cm)	20.9	20.9	20.6	20.6	21.5	39.3	30.7	30.7	31.5	30.4
Z_{eff}	64.8	64.8	60.3	60.3	51.8	54.0	51.6	51.6	45.6	45.6
dE/dX (MeV/cm)	9.55	9.55	9.22	9.22	8.96	5.56	6.52	6.52	6.65	6.90
λ_{peak}[a] (nm)	420	420	520	310	540	310	300 220	300 220	371	360
PL Emission Peak (nm)	402	402	500	308	540	310	300 220	300 220	350	360
PL Excitation Peak (nm)	358	358	450	275	445	256	<200	<200	330	295
Absorption Edge (nm)	170	170	160	160	190	200	140	140	n.r.	220
Refractive Index[b]	1.82	1.82	1.84	1.84	1.92	1.95	1.50	1.50	1.9	1.9
Normalized Light Yield[a,c]	100	116[e]	35[f] 48[f]	44 41	40 75	4.2 1.3	42 5.0	1.7 5.0	99	153
Total Light yield (ph/MeV)	30,000	34,800[e]	25,000[f]	25,800	34,700	1,700	13,000	2,100	30,000	46,000
Decay time[a] (ns)	40	31[e]	981[f] 64[f]	1208 26	319 101	30 6	600 <0.6	600 <0.6	17	20
Light Yield in 1st ns (photons/MeV)	740	950	240	520	260	100	1200	1200	1,700	2,200
Issues					neutron x-section	Slightly hygroscopic	Slow component	DUV PD	hygroscopic	

Fast Inorganic Scintillators (II)



a. Top line: slow component, bottom line: fast component;

b. At the wavelength of the emission maximum;

c. Excited by Gamma rays;

d. For $Gd_3Ga_3Al_2O_{12}$:Ce

e. For 0.4 at% Ca co-doping

f. Ceramic with 0.3 Mg at% co-doping

[1] Spurrier, et al., *IEEE T. Nucl. Sci.* 2008,55 (3): 1178-1182

[2] Liu, et al., *Adv. Opt. Mater.* 2016, 4(5): 731–739

[3] Hu, et al., *Phys. Rev. Applied* 2016, 6: 064026

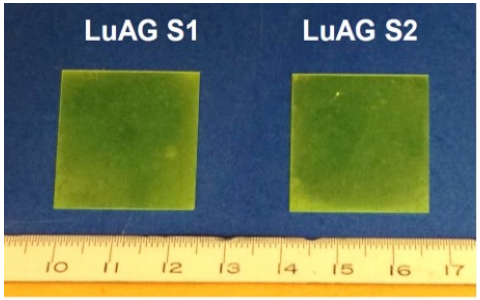
[4] Lucchini, et al., *NIM A* 2016, 816: 176-183

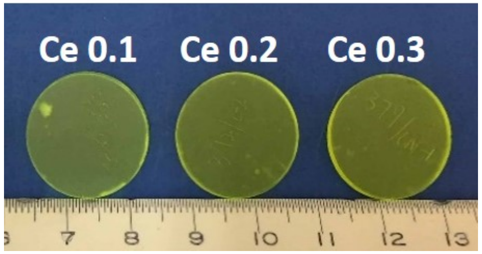
[5] Meng, et al., *Mat. Sci. Eng. B-Solid* 2015, 193: 20-26

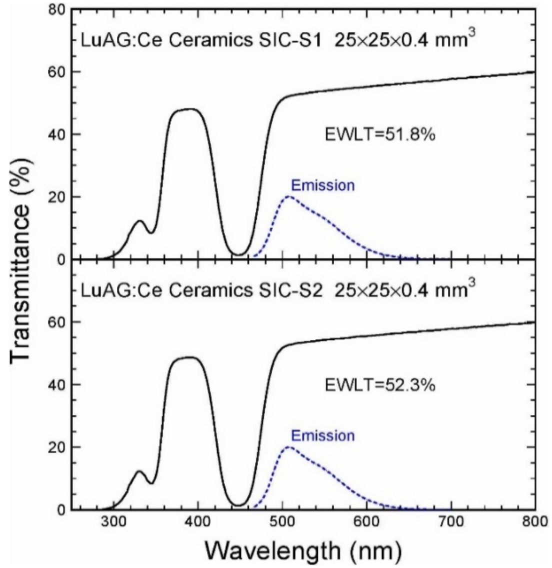
[6] Diehl, et al., *J. Phys. Conf. Ser* 2015, 587: 012044

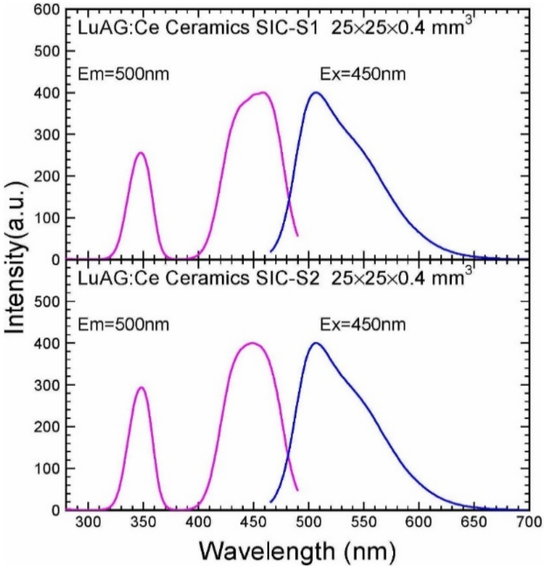
[7] Pustovarov, et al., Tech. Phys. Lett. 2012, 784-788

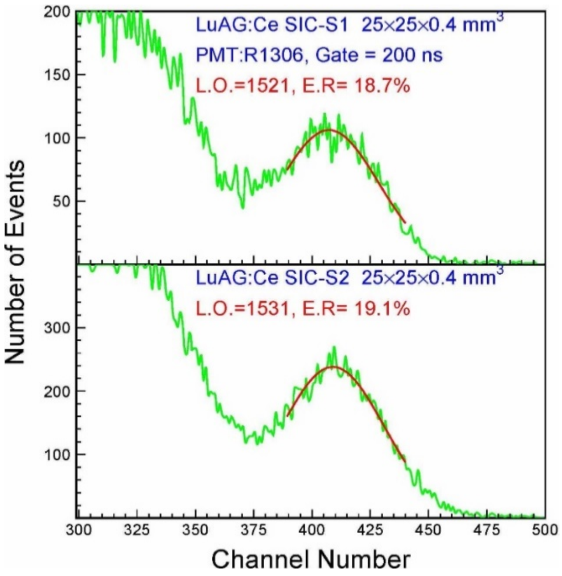
LuAG:Ce Ceramic Samples

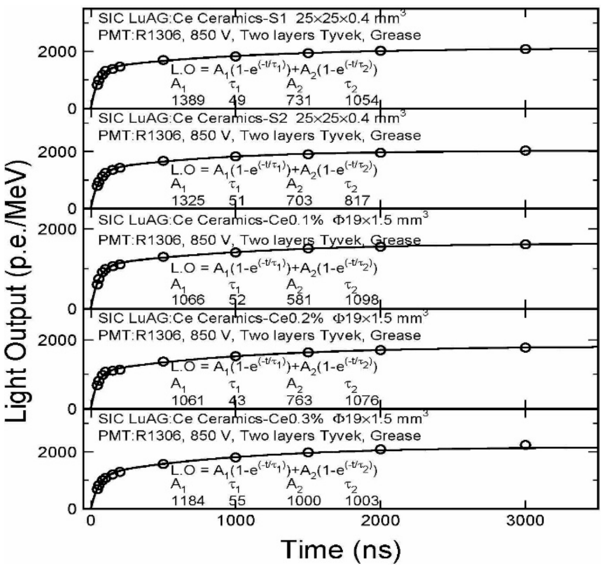


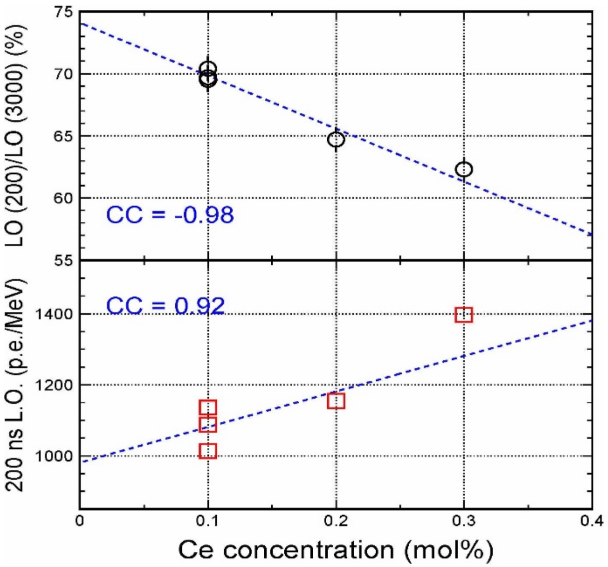








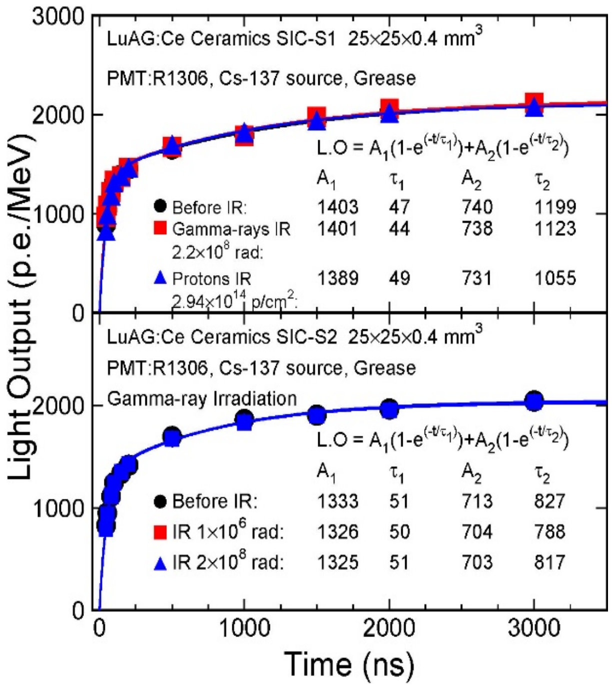


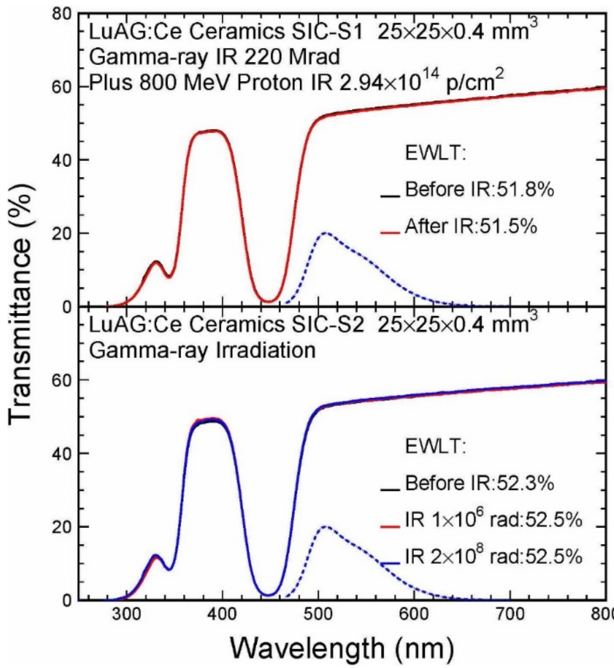


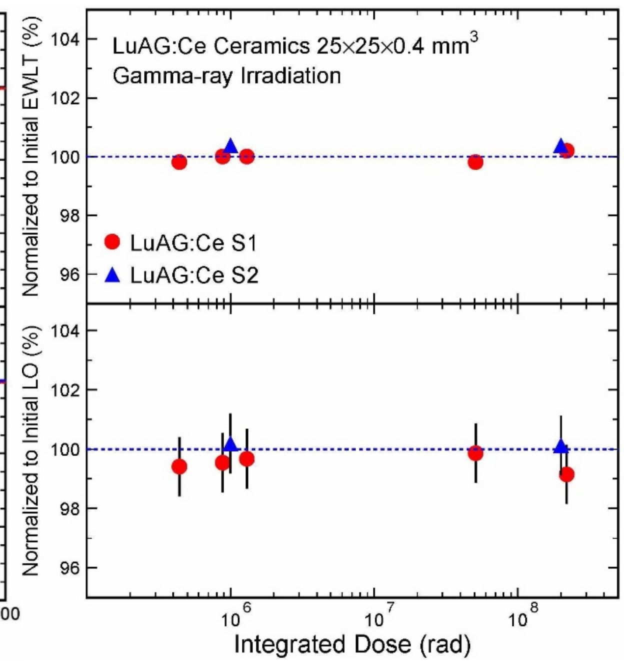
Excellent Radiation Hardness

No damage observed in both transmittance and light output after 220 Mrad ionization dose and 3 × 10^{14} p/cm^2 of 800 MeV

Very promising for optical-based radiation hard calorimeter







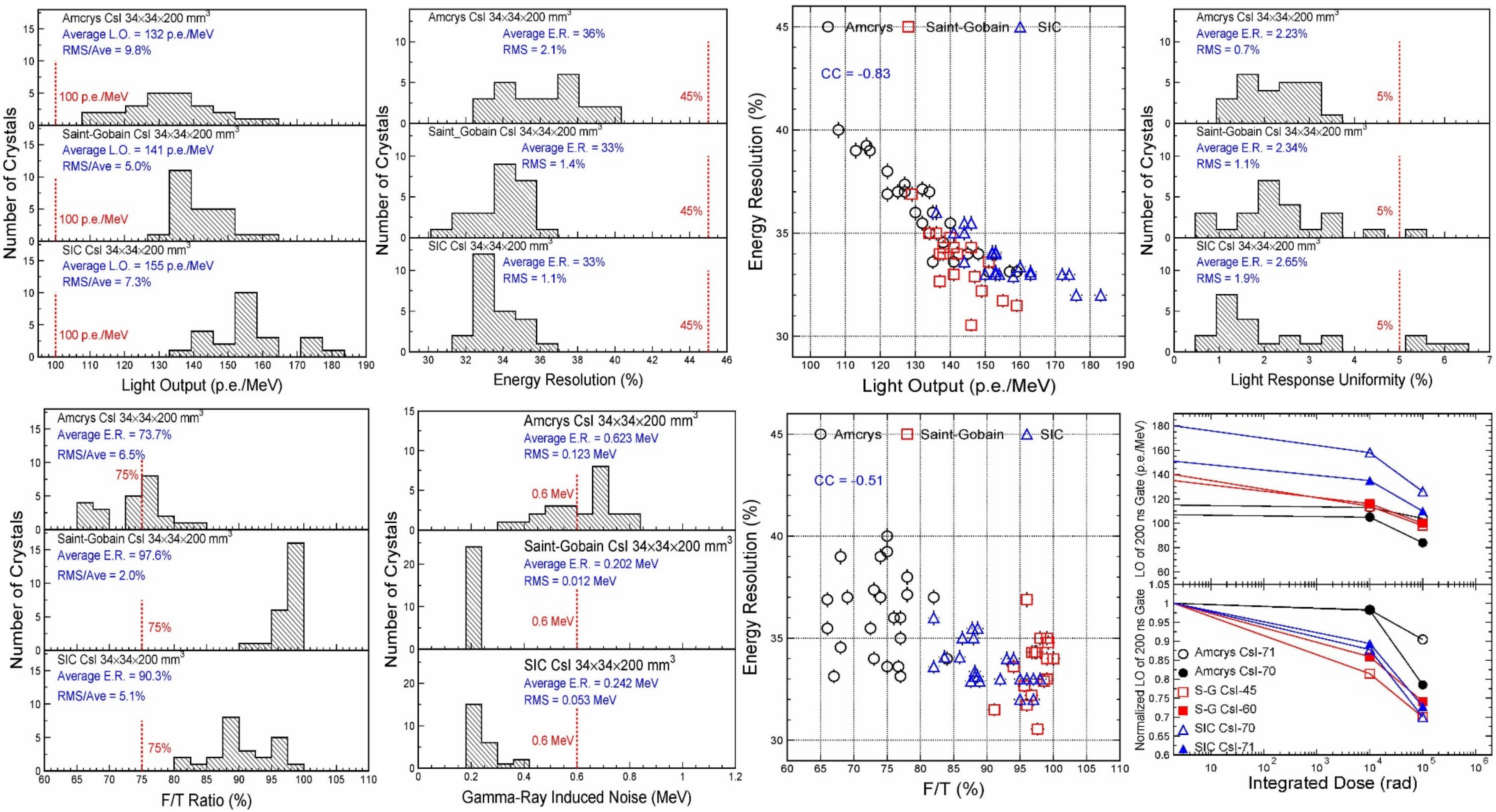
Key issue: slow scintillation component

Mu2e Preproduction CsI

A total of 72 crystals from Amcrys, Saint-Gobain and SICCAS has been measured at Caltech and LNF

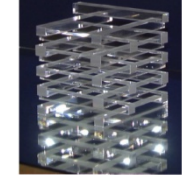
Quality of Pre-Production CsI

IEEE TNS Vol. 65, No. 2, February 2018, 752-757



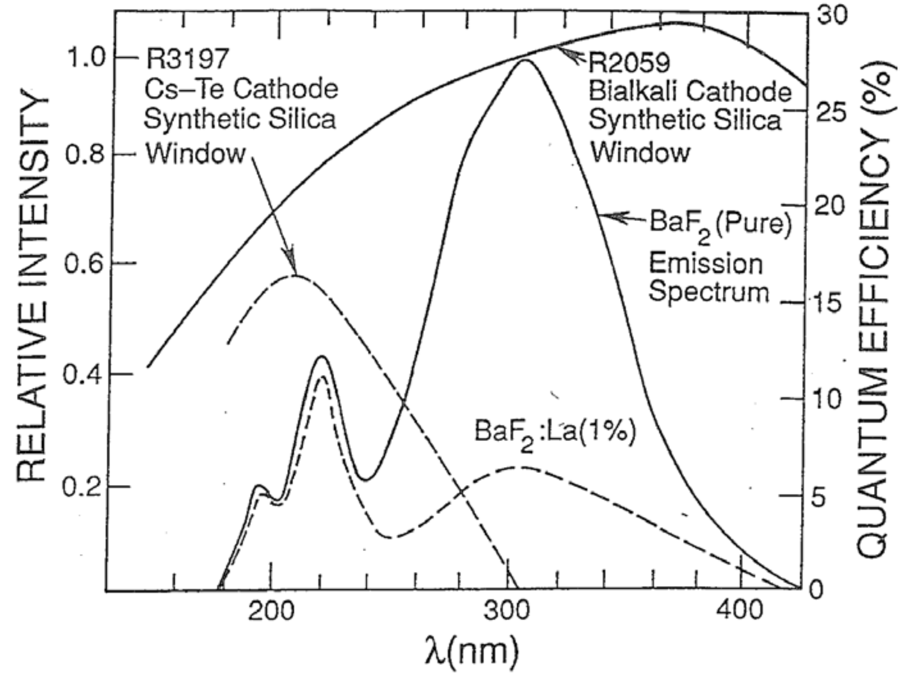
Most preproduction crystals satisfy specifications

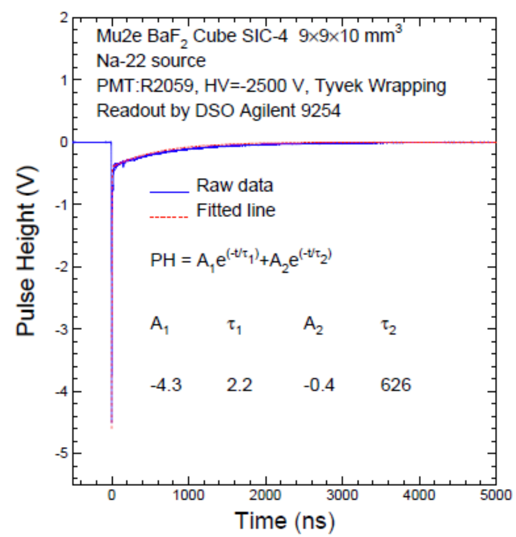
Fast and Slow Light from BaF_2

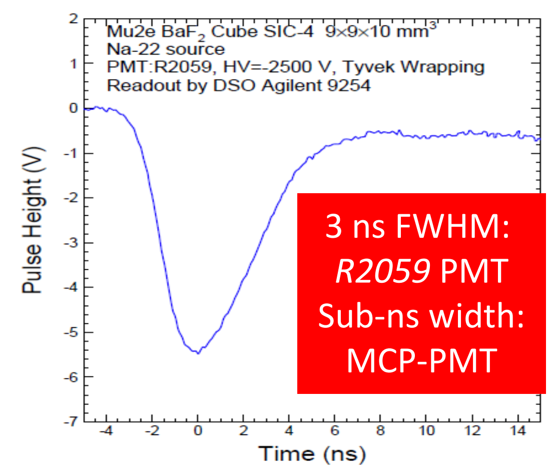


The fast component at 220 nm with 0.6 ns decay time has a similar LO as undoped CsI.

Spectroscopic selection of fast component may be realized by solar blind photocathode and/or selective doping.

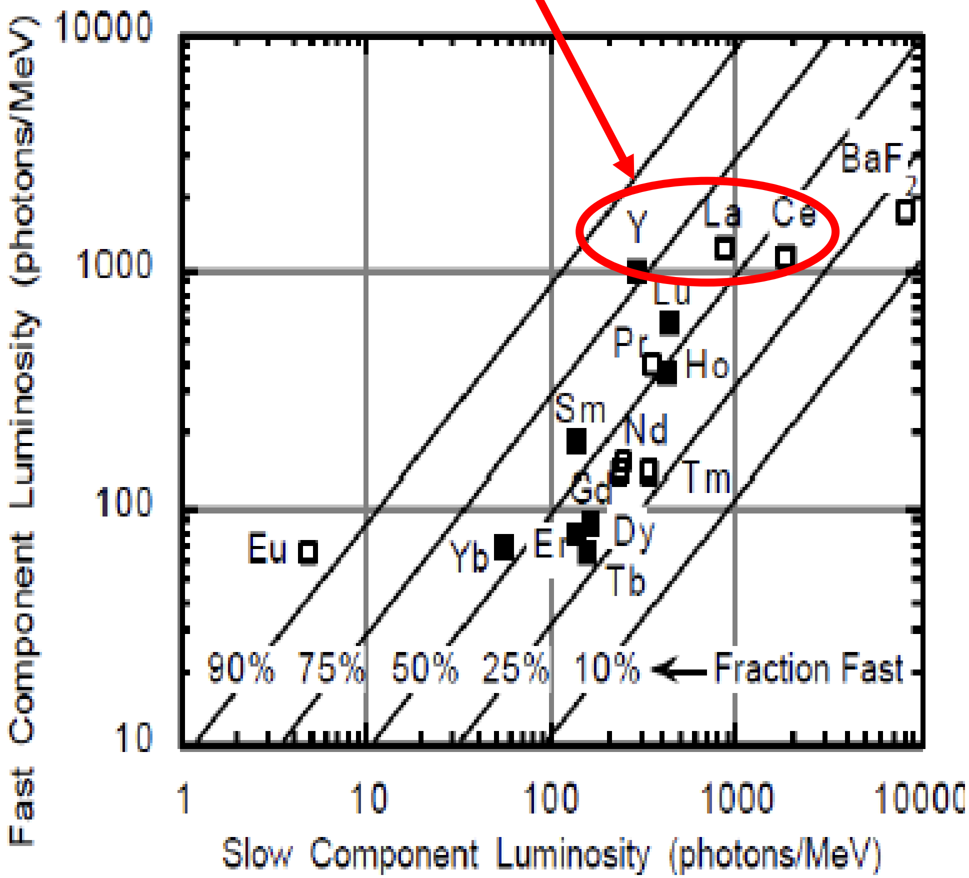


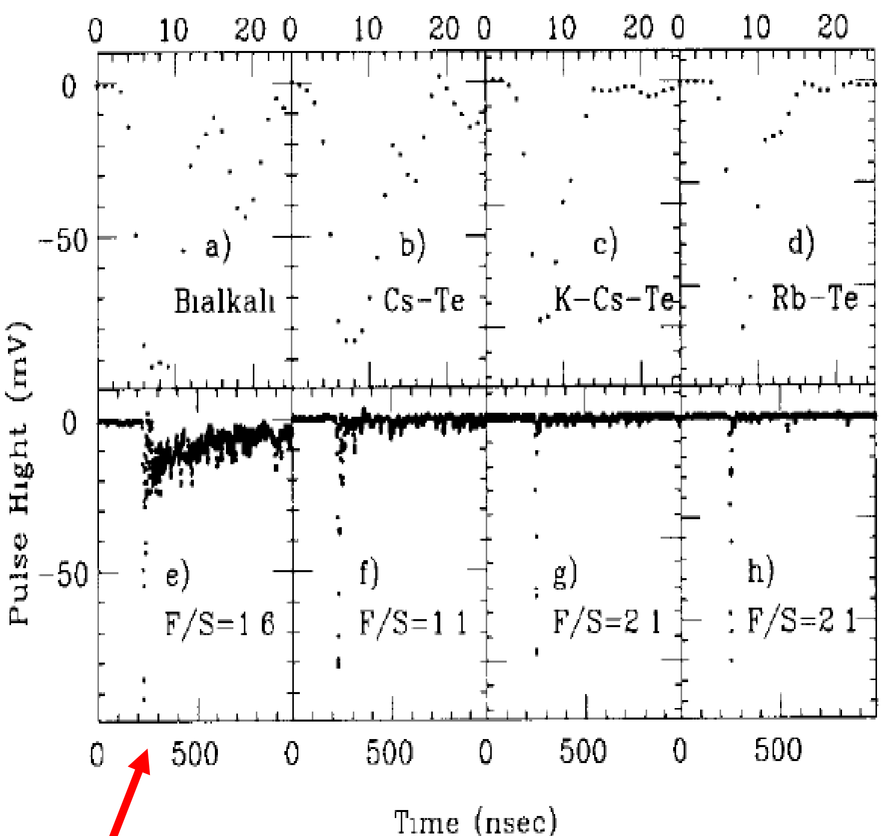




Slow Suppression: Doping & Readout

MRS Proceedings (1994) 277: Slow suppressed by RE doping

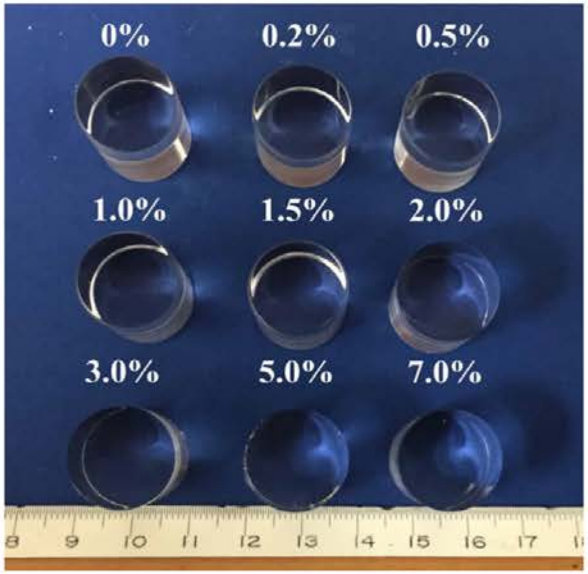


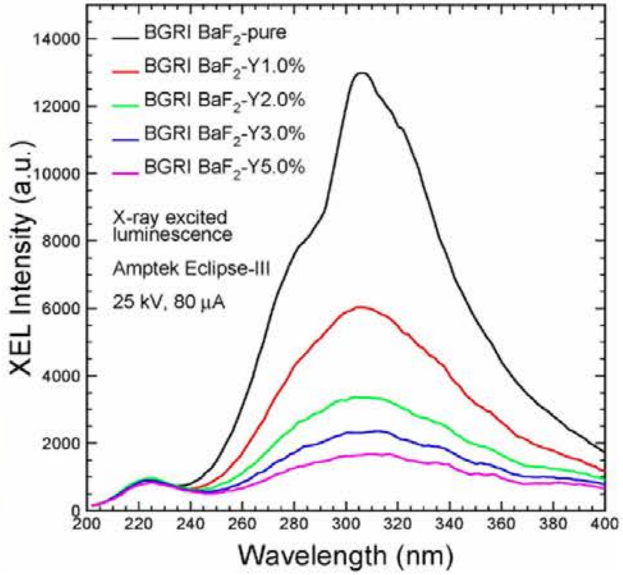


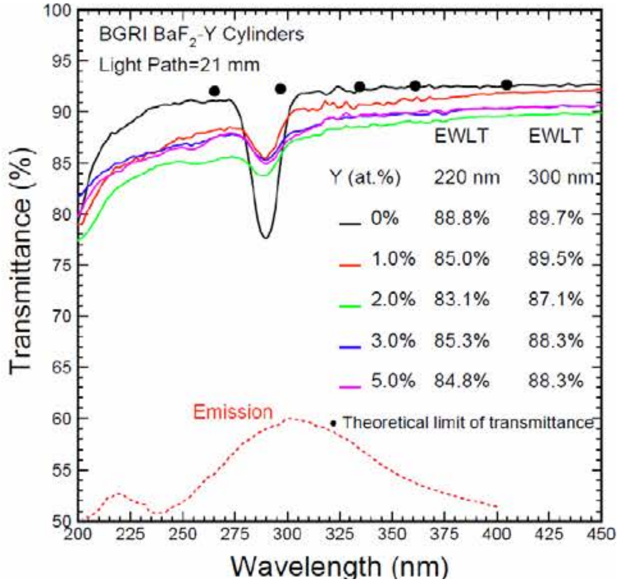
NIM 240 (1994) 442: Cs-Te, K-Cs-Te and Rb-Te cathode achieved F/S = 2/1

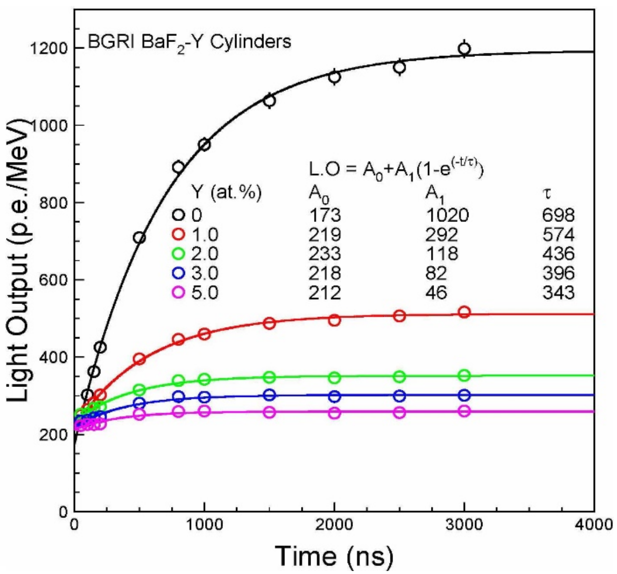
Yttrium Doping in BaF_2

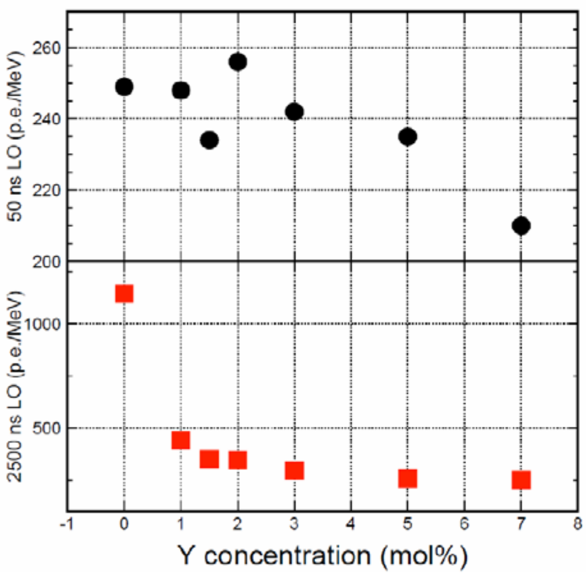
Significant increase in F/S ratio observed

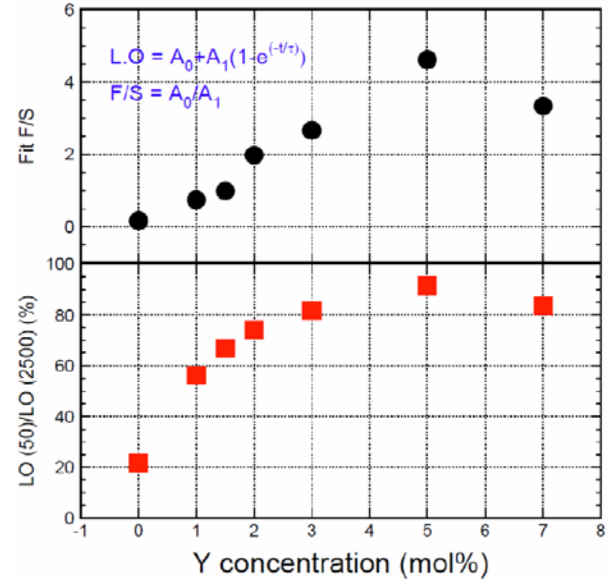




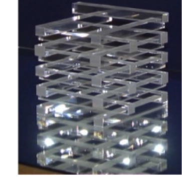






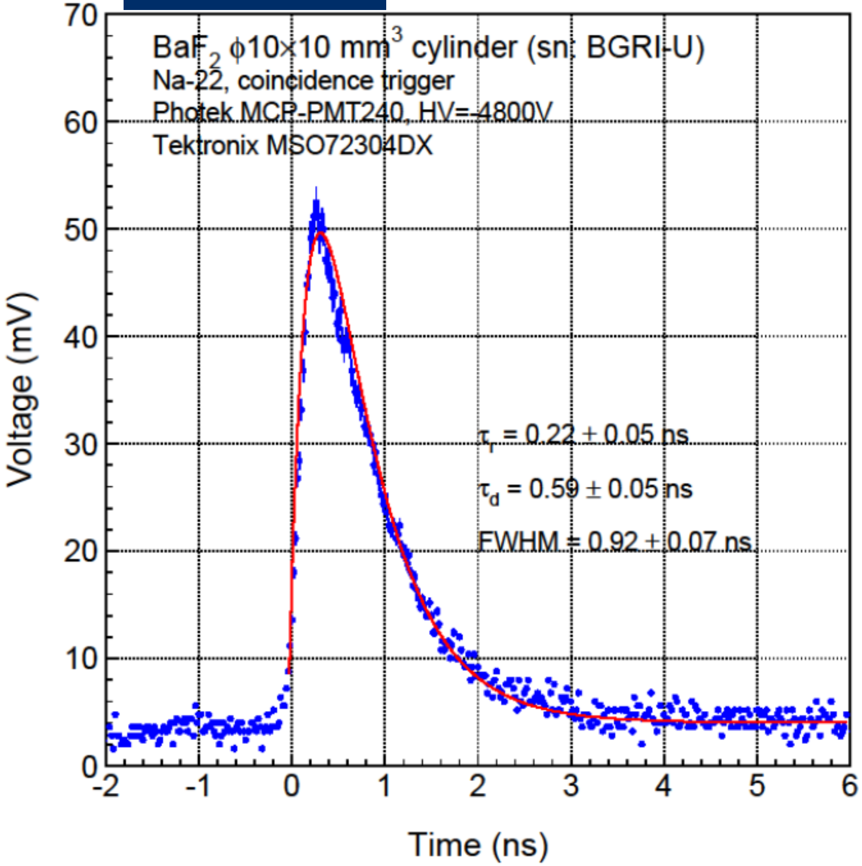


Pulse Shape: BaF_2 Cylinders

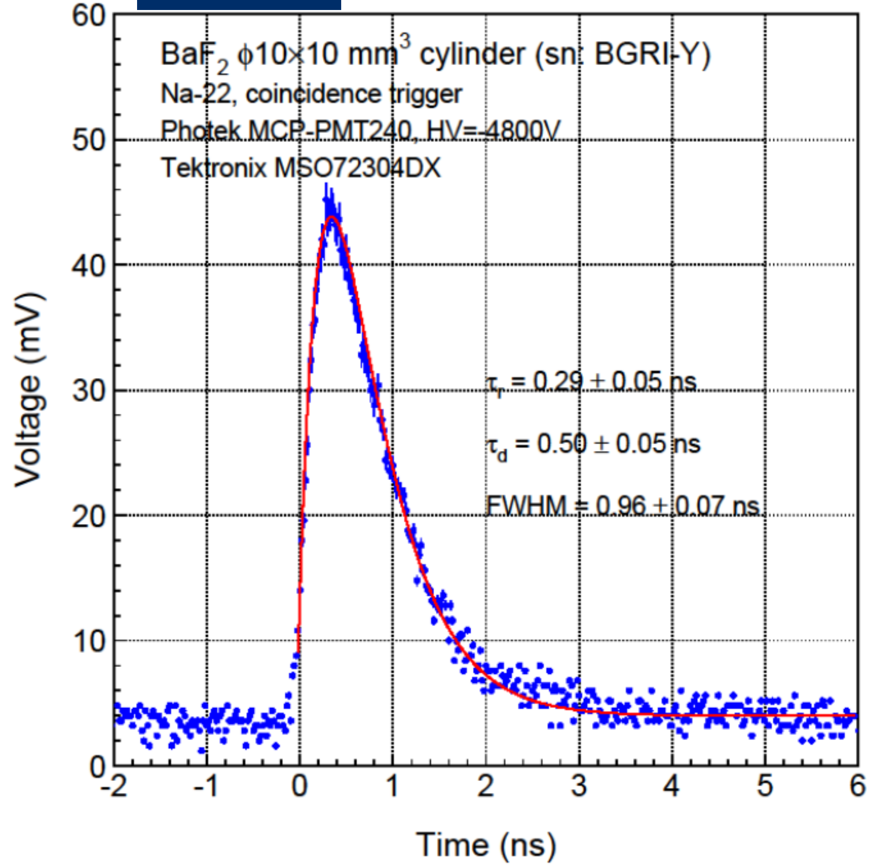


BaF_2 cylinders of $\Phi 10 \times 10$ cm^3 shows ɣ-ray response: 0.26/0.55/0.94 ns of rising/decay/FWHM width

Non-doped

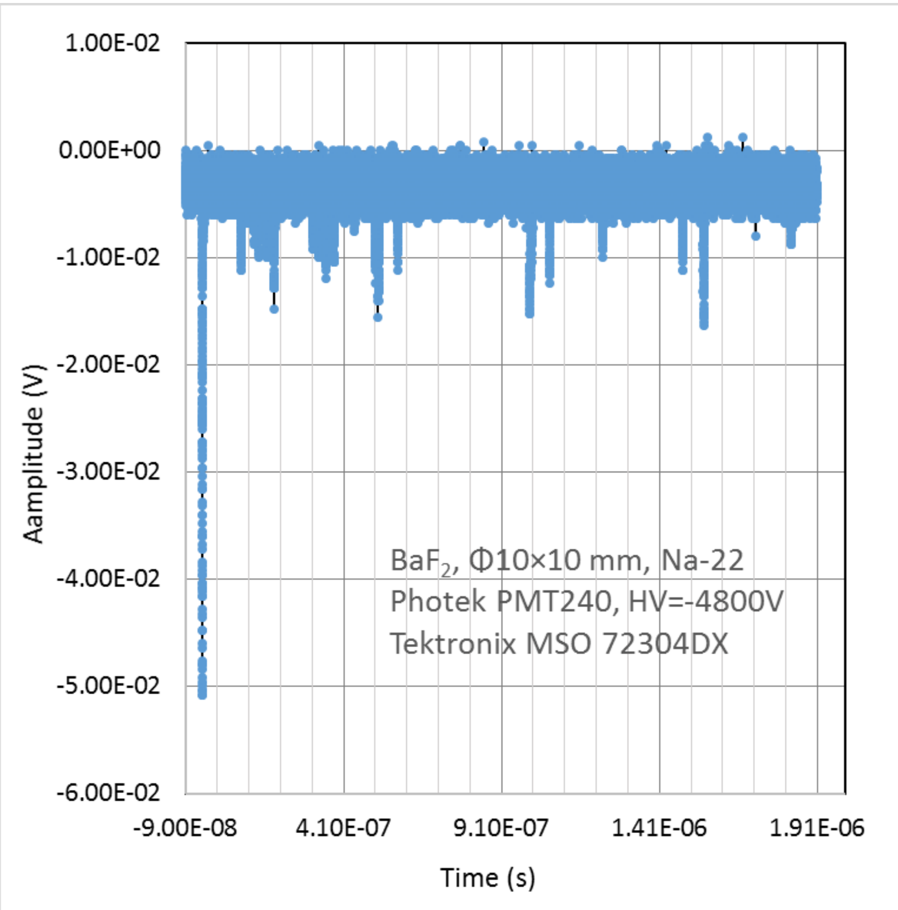


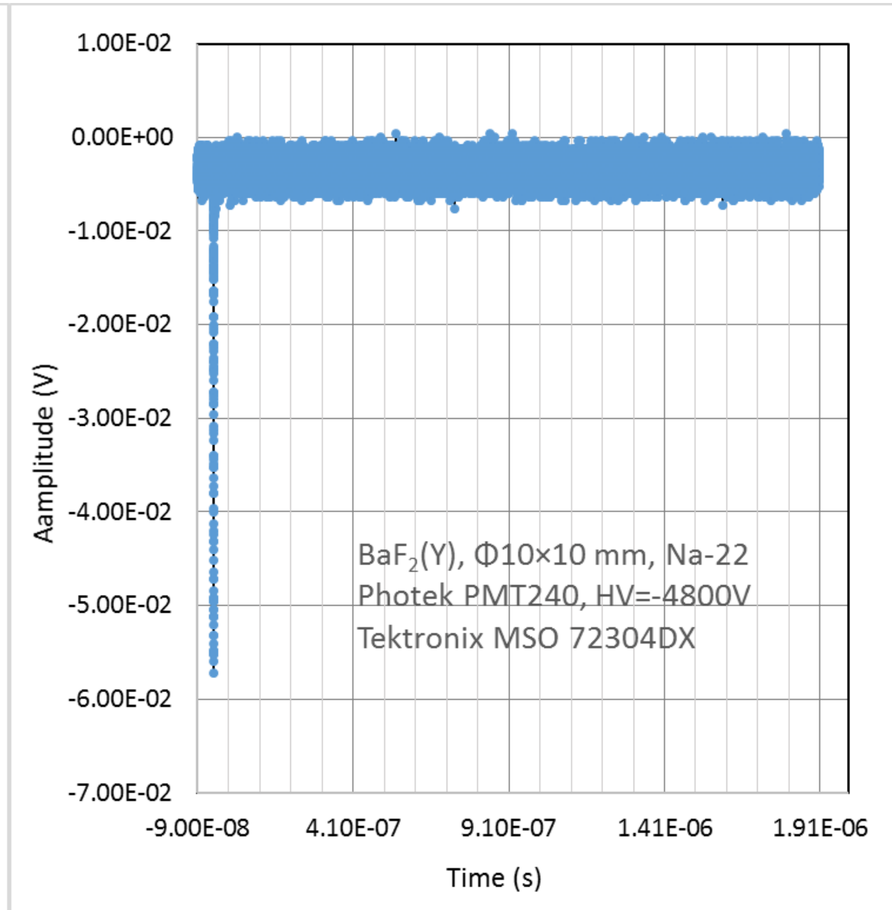
Y-doped



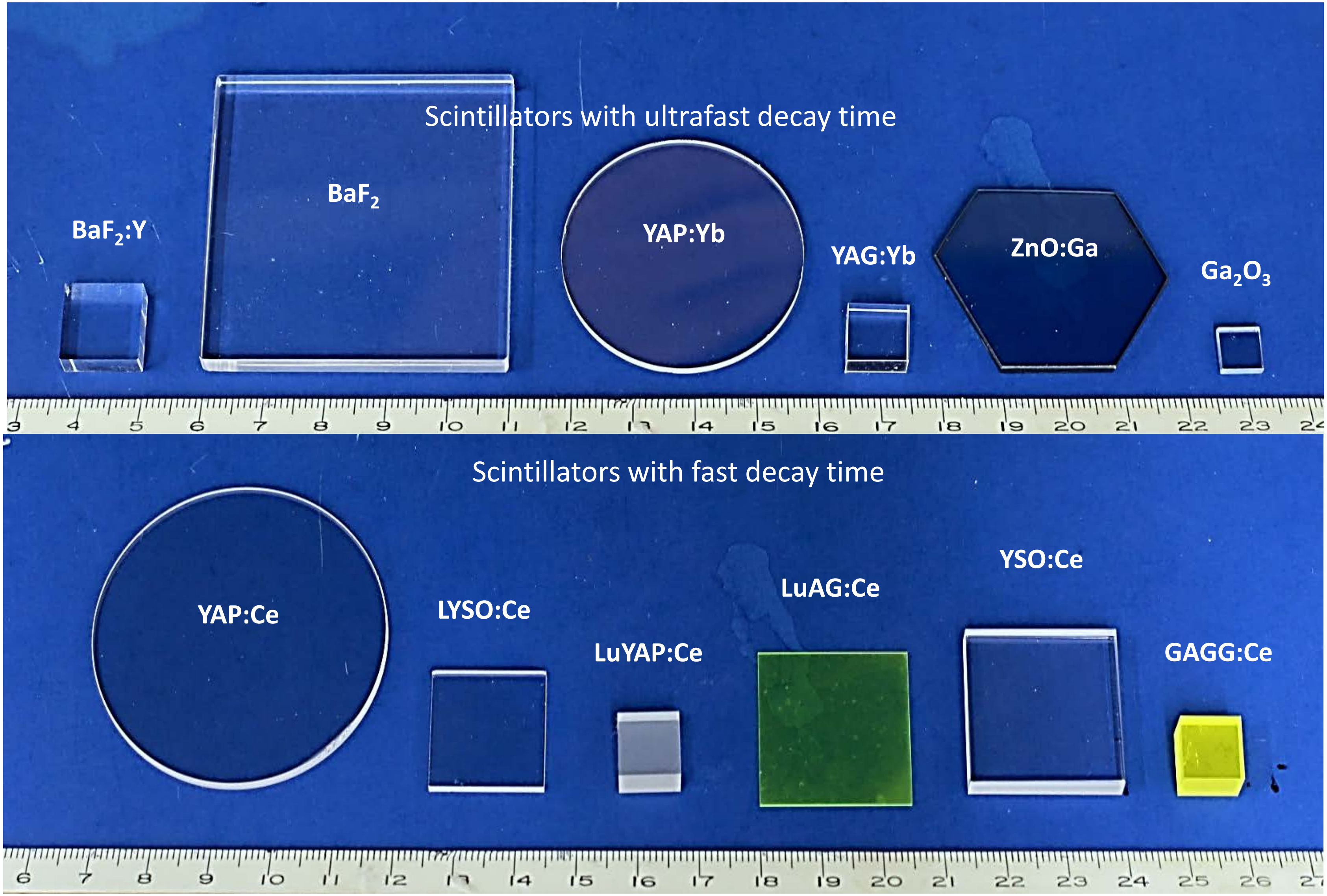
Tail Reduced in BaF_2:Y

Slow tail observed in 2 μs in BaF_2, much reduced in BaF_2:Y





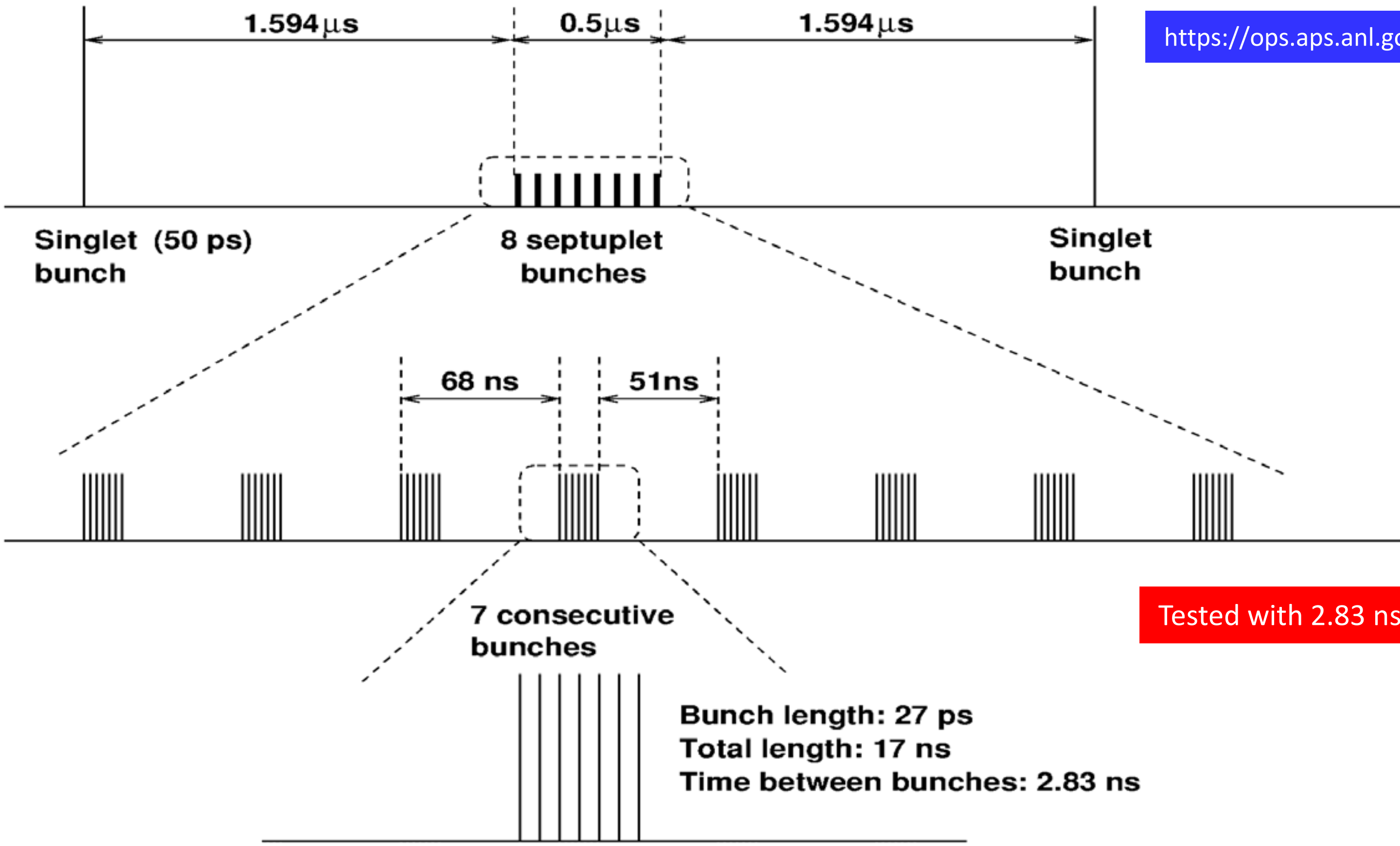
Temporal Response Measured at APS



APS 30 keV X-Ray Hybrid Beam

Singlet (16 mA, 50 ps) isolated from 8 septuplets (88 mA) with 1.594 μs gap; 8 septuplets (88 mA) with a 68 ns period and a 51 ns gap; Each septuplet of 17 ns consists of 7 bunches (27 ps) and 2.83 ns apart; Total beam current: 102 mA, rate: 270 kHz, period: 3.7 μs.

https://ops.aps.anl.gov/SRparameters/node5.html

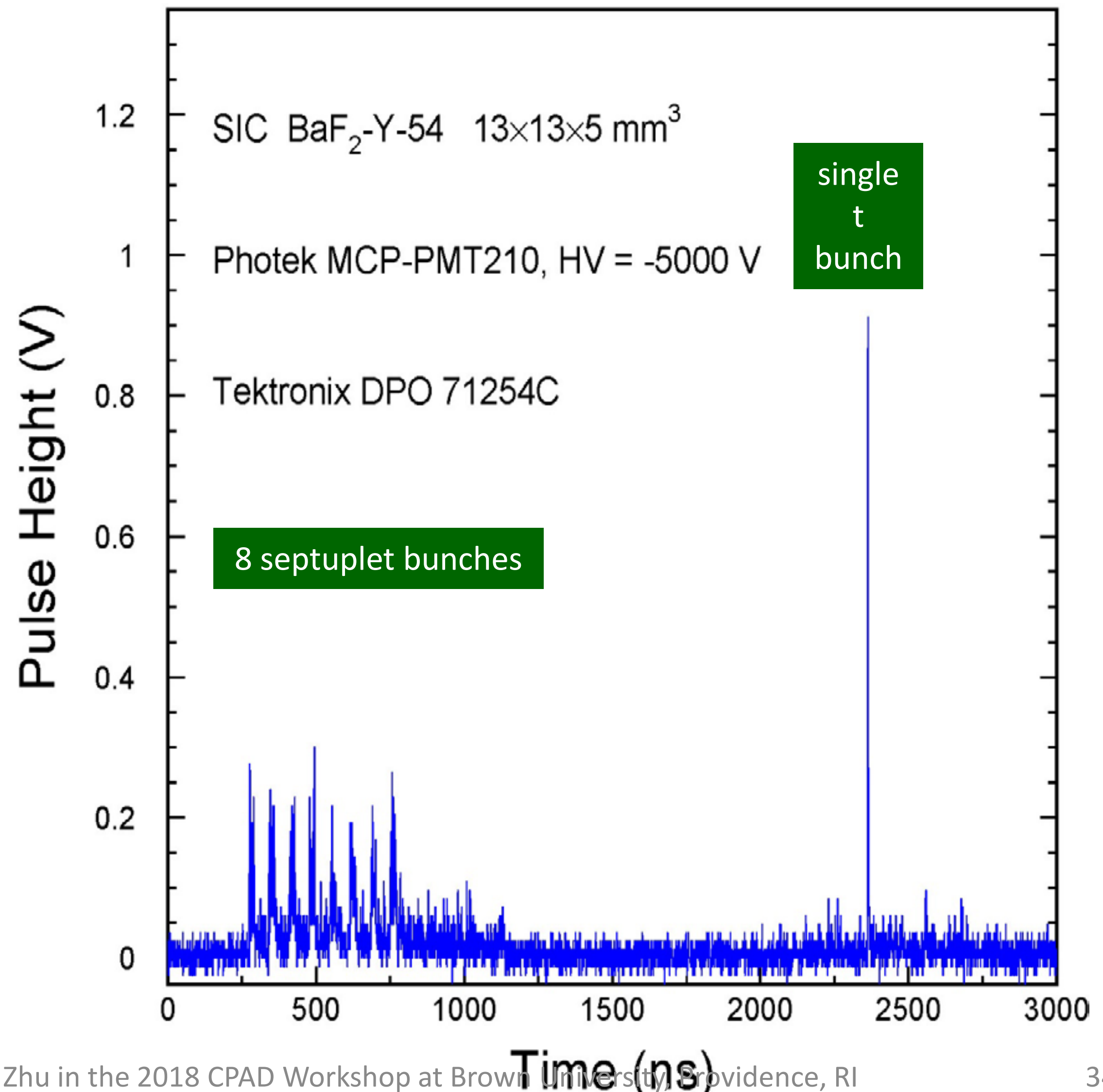


Tested with 2.83 ns x-ray bunches at APS of ANL

BaF_2:Y Response to Hybrid Beam

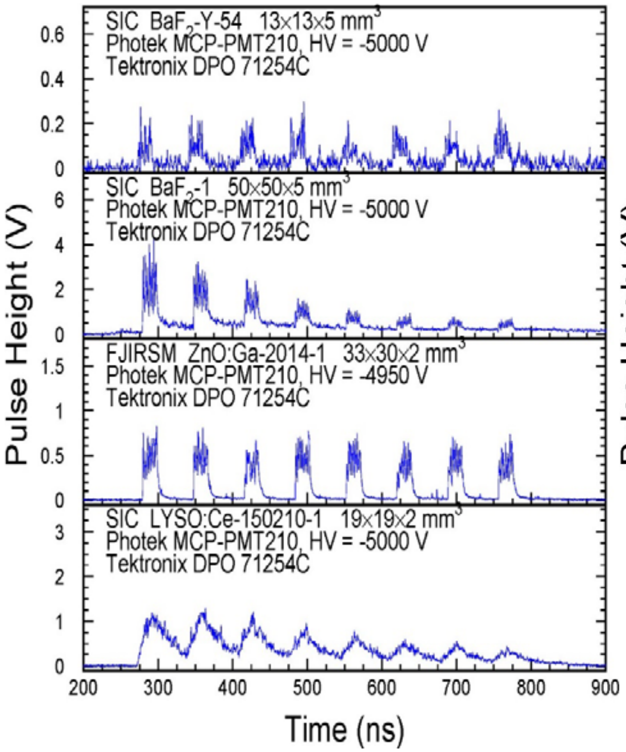
Data taken with ultrafast Photek PMT & gate unit for septuplet bunches show BaF_2:Y's capability for 30 keV X-ray imaging with 2.83 ns bunch spacing. No pile-up for 8 septuplets

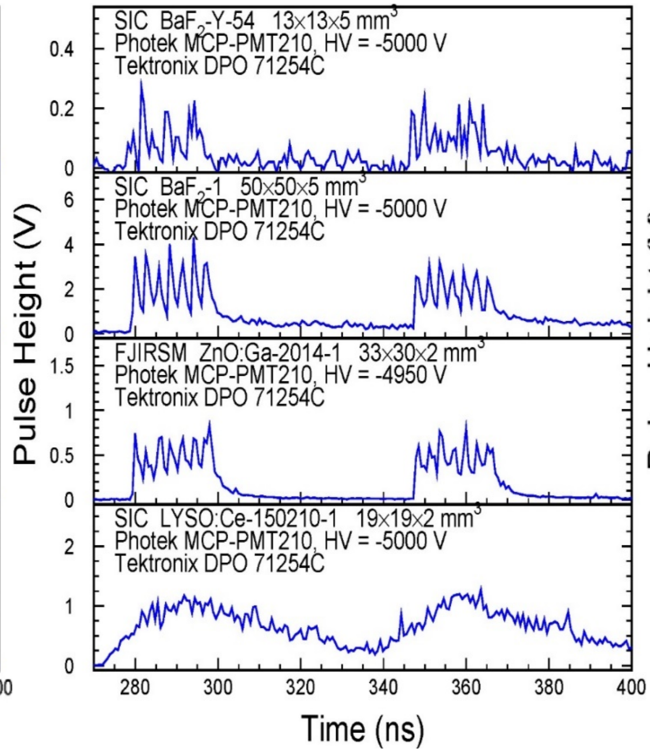
Data were also taken for singlet bunches to show various crystal's temporal response.

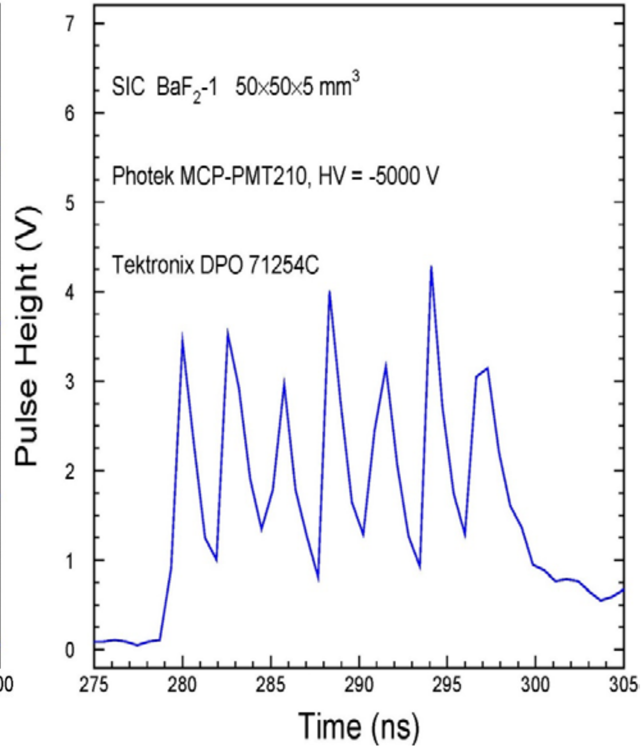


Response to Septuplets

X-ray bunches with 2.83 ns spacing in septuplet are clearly resolved by ultrafast BaF_2:Y and BaF_2 crystals, showing a proof-of-principle for the type –I imager







Amplitude reduction in BaF_2 and LYSO from slow scintillation, but not in BaF_2:Y
Reducing the 15 m cable length will reduce BaF_2 pulse width to sub-ns

Summary: Temporal Response

http://www.hep.caltech.edu/~zhu/papers/18_nss_CR_ultrafast.pdf

Crystal	Vendor	ID	Dimension (mm^3)	Emission Peak (nm)	EWLT (%)	LO (p.e./MeV)	Light Yield in 1^{st} ns (ph/MeV)	Rising Time (ns)	Decay Time (ns)	FWHM (ns)
BaF_2:Y	SIC	4	10×10×5	220	89.1	258	1200	**0.2**	**1.2**	**1.4**
BaF_2	SIC	1	50×50×5	220	85.1	209	1200	**0.2**	**1.2**	**1.6**
YAP:Yb	Dongjun	2-2	Φ40×2	350	77.7	9.1*	28	**0.4**	**1.1**	**1.7**
ZnO:Ga	FJIRSM	2014-1	33×30×2	380	7	76*	157	**0.4**	**1.8**	**2.3**
YAG:Yb	Dongjun	4	10×10×5	350	83.1	28.4*	24	**0.3**	**2.5**	**2.7**
Ga_2O_3	Tongji	2	7x7x2	380	73.8	259	43	**0.2**	**5.3**	**7.8**
YAP:Ce	Dongjun	2102	Φ50×2	370	54.7	1605	391	**0.8**	**34**	**27**
LYSO:Ce	SIC	150210-1	19x19×2	420	80.1	4841	740	**0.7**	**36**	**28**
LuYAP:Ce	SIPAT	1	10×10×7	385	\	1178	125	**1.1**	**36**	**29**
LuAG:Ce Ceramic	SIC	S2	25×25×0.4	520	52.3	1531	240	**0.6**	**50**	**40**
YSO:Ce	SIC	51	25×25×5	420	72.6	3906	318	**2.0**	**84**	**67**
GAGG:Ce	SIPAT	5	10×10×7	540	\	3212	239	**0.9**	**125**	**91**

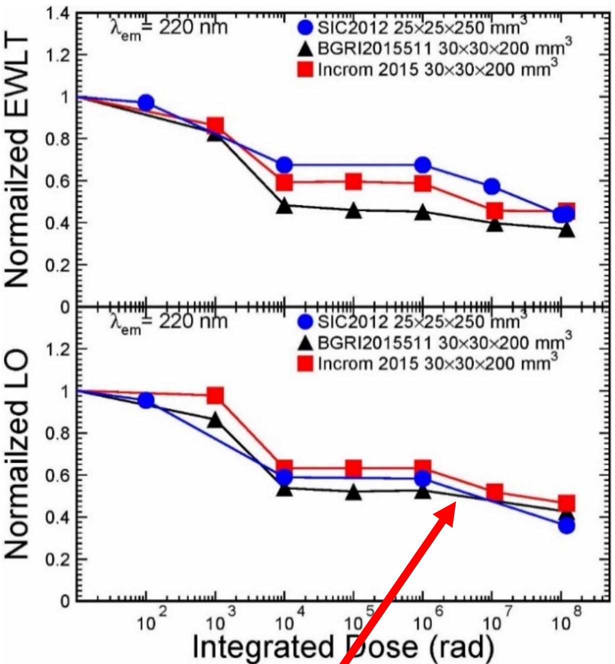
Samples are ordered based on its FWHM to singlet bunches

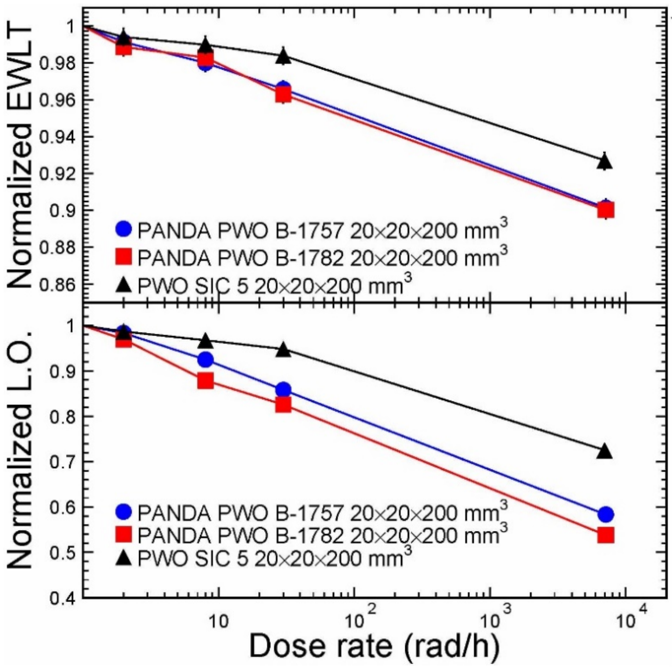
BGRI/Incrom/SIC BaF_2 Samples

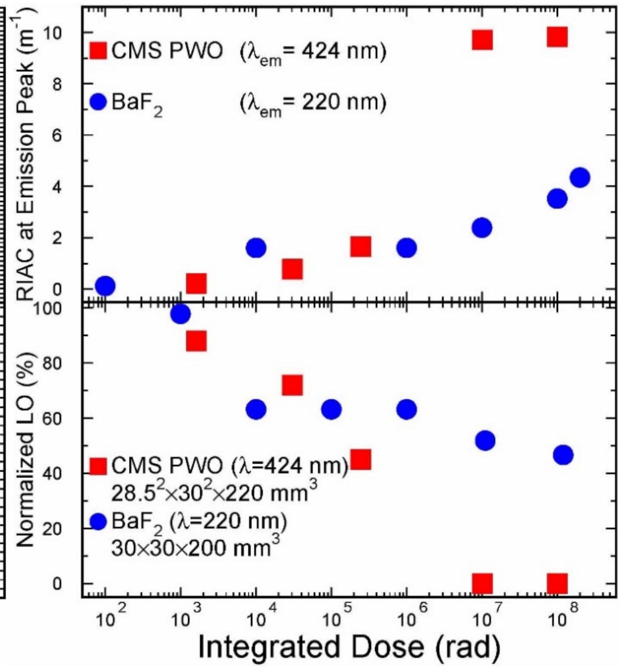
ID	Vendor	Dimension (mm^3)	Polishing
SIC 1-20	SICCAS	30x30x250	Six faces
BGRI-2015 D, E, 511	BGRI	30x30x200	Six faces
Russo 2, 3	Incrom	30x30x200	Six faces

Ionization Dose: BaF_2 and PWO

Dose rate dependent damage in PWO
Good radiation hardness in BaF_2 up to 130 Mrad



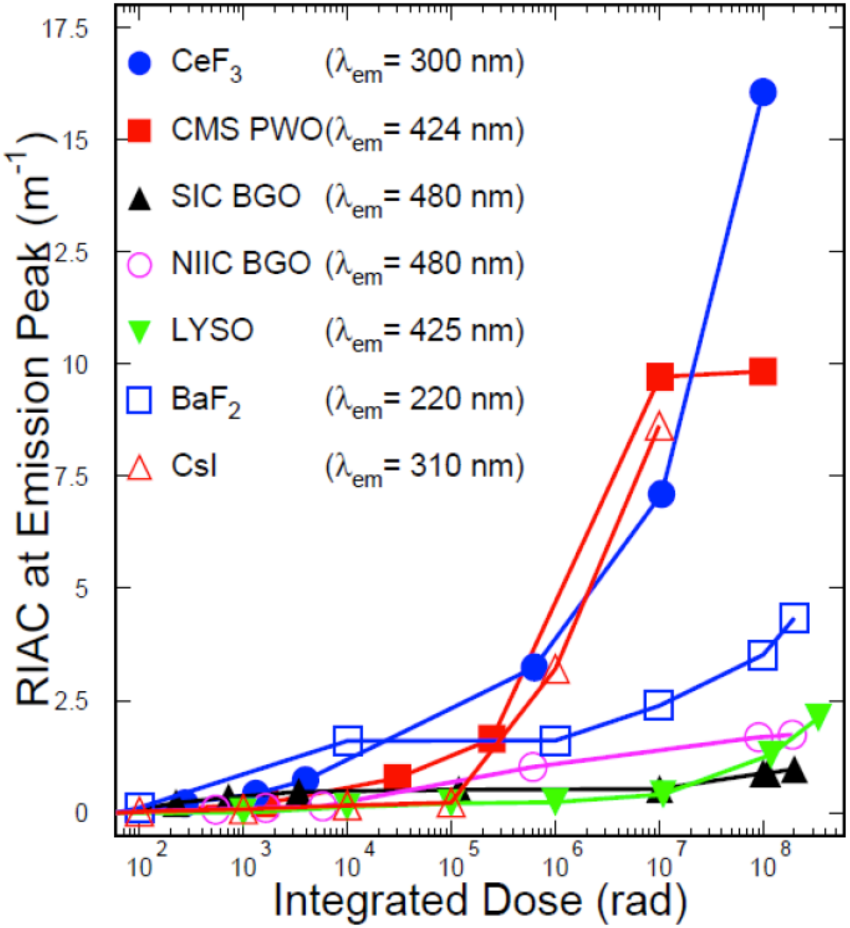


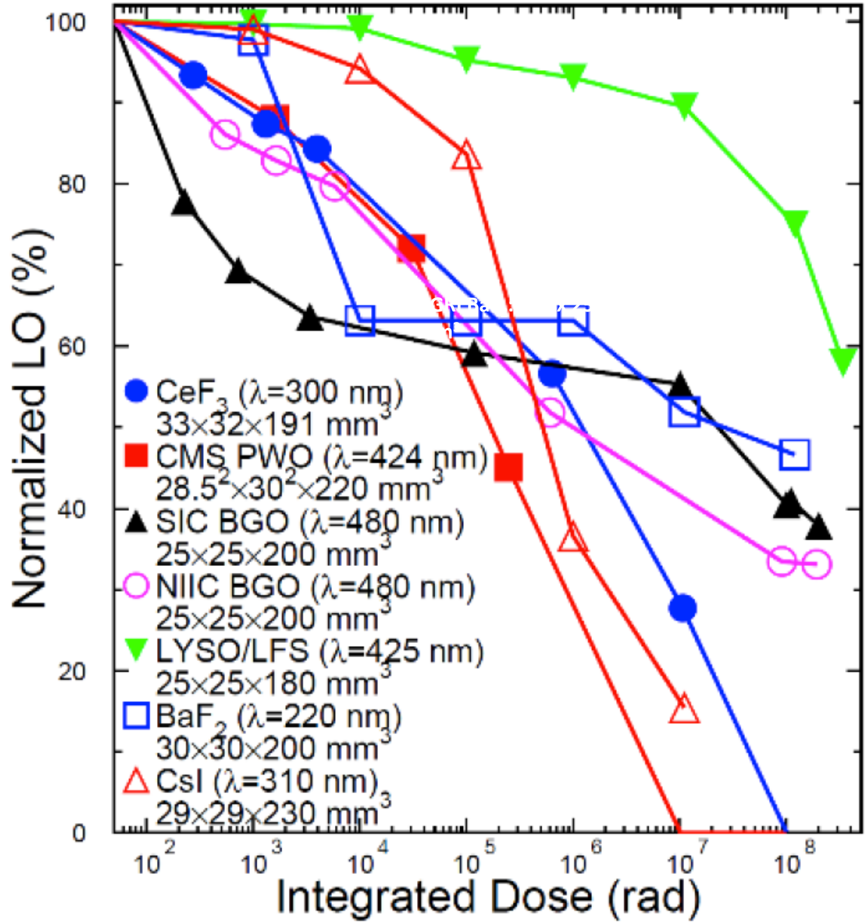


40% fast scintillation light remains after 120 Mrad ionization dose

Fan Yang *et al.*, IEEE TNS 63 (2016) 612-619

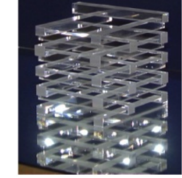
γ-Ray Induced Radiation Damage in Crystals of Large Size



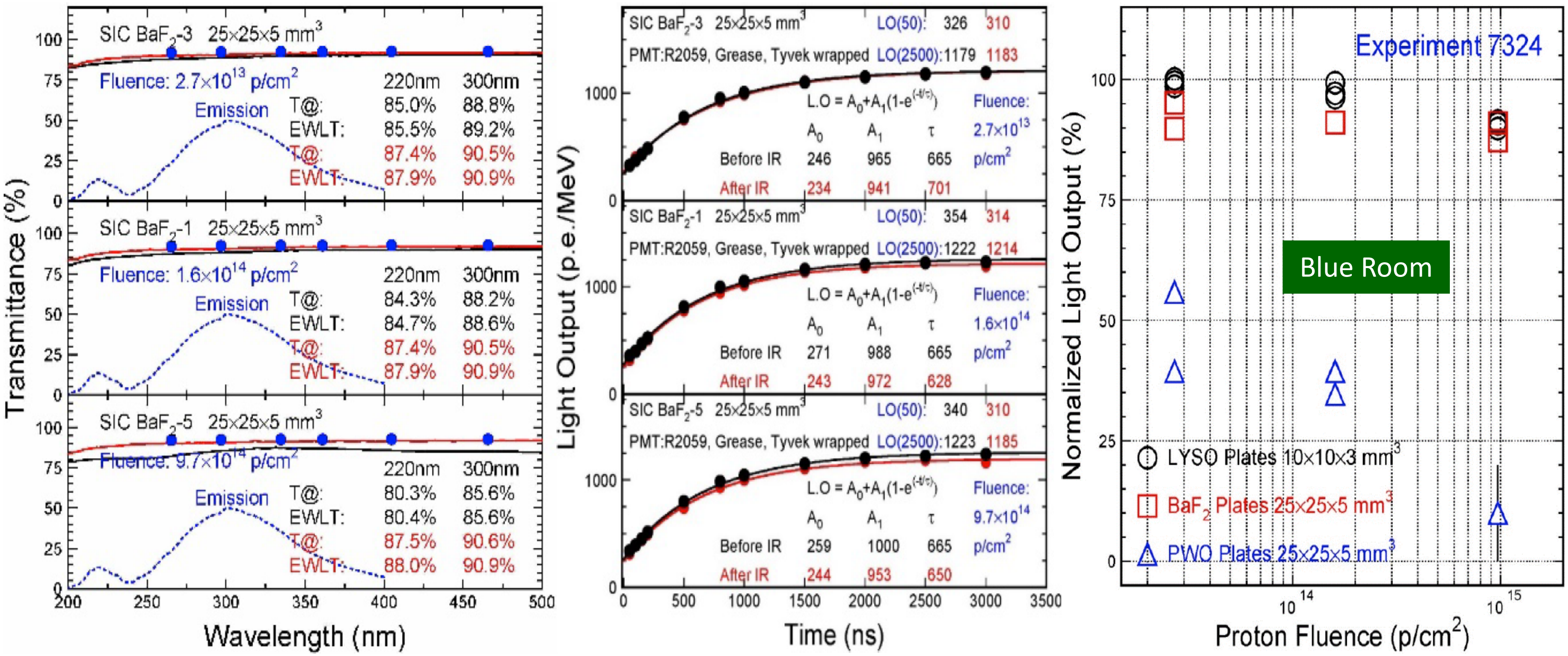


Fan Yang *et al.*, IEEE TNS 63 (2016) 612-619

Protons: LYSO/BaF_2/PWO at LANSCE



LYSO, BaF_2 and PWO plates of 5 mm were irradiated up to 1×10^{15} p/cm^2 in three steps at the Blue Room of LANSCE

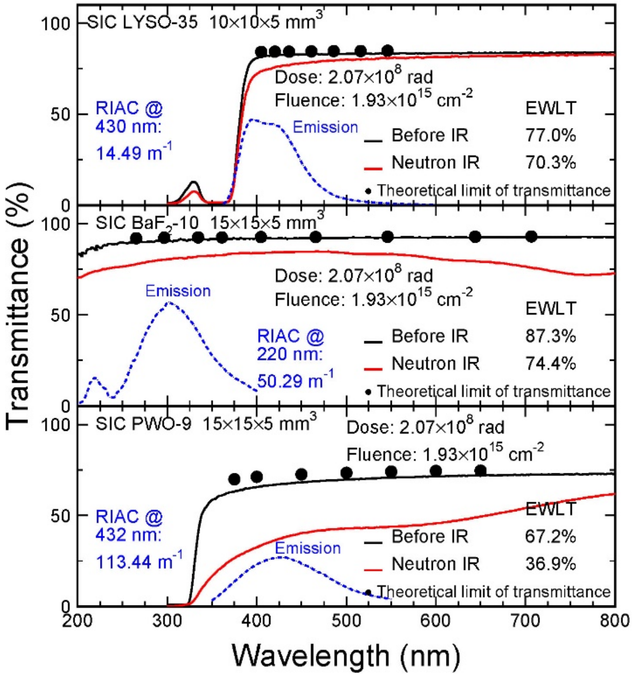


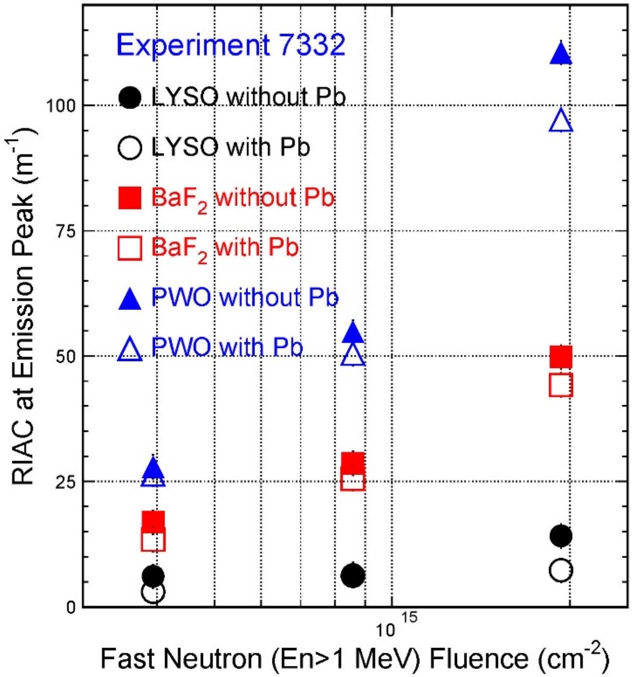
Excellent radiation hardness observed in LYSO and BaF_2, but not PWO

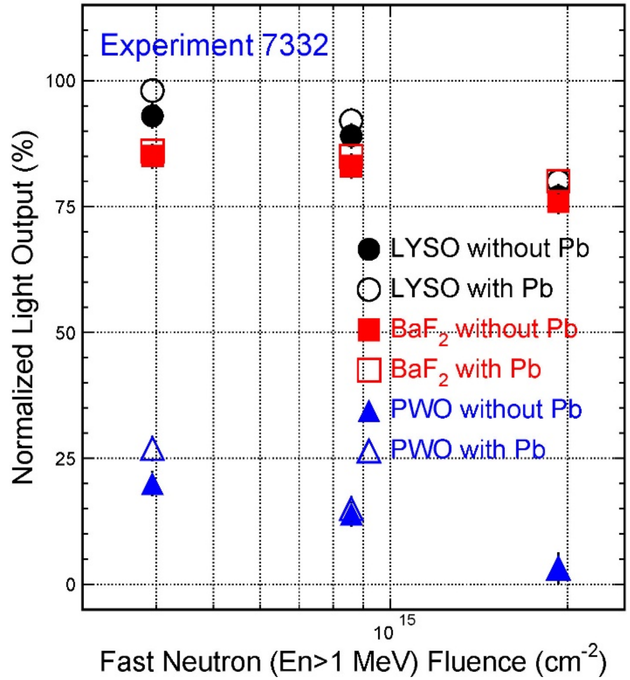
Fan Yang et al., IEEE TNS 65 (2018) 1018-1024

Neutrons: LYSO/BaF_2/PWO at LANSCE

LYSO, BaF_2 and PWO plates of 5 mm were irradiated up to 2×10^{15} n/cm^2 in three steps at the East Port of LANSCE







Excellent radiation hardness observed in LYSO and BaF_2, but not PWO

Chen Hu *et al., i*n Calor2018 Proceedings
http://www.hep.caltech.edu/~zhu/papers/Calor18_ultrafast_R.pdf

Summary

- LYSO, BaF_2 crystals and LuAG ceramics show excellent radiation hardness beyond 100 Mrad, 1 x 10^{15} p/cm^2 and 2 x 10^{15} n/cm^2, promising a fast and robust detector at the HL-LHC.
- Undoped BaF_2 crystals provide sufficient fast light with sub-ns decay time. Yttrium doping increases its F/S ratio significantly while maintaining the intensity of the sub-ns fast component, promising an ultrafast calorimetry and GHz X-ray imaging.
- The CEPC requirements on response time & radiation hardness are not as stringent as the HL-LHC. The game thus is wide open for innovative detector concepts.

SIC Crystal Cost for CEPC

Item	Size	1 m^3	10 m^3	100 m^3
BGO	2.23×2.23×28 cm	$8/cc	$7/cc	$6/cc
BaF_2:Y	3.10×3.10×50.75 cm	$12/cc	$11/cc	$10/cc
LYSO	20.7x20.7x285 mm	$36/cc	$34/cc	$32/cc
PWO	20x20x223 mm	$9/cc	$8/cc	$7.5/cc
BSO	22x22x274 mm	$8/cc	$7.5/cc	$7.0/cc
CsI	3.57x3.57x46.5 cm	$4.6/cc	$4.3/cc	$4.0/cc