# Inorganic Scintillators for Future HEP and NP Experiments

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# Why Inorganic Scintillators?

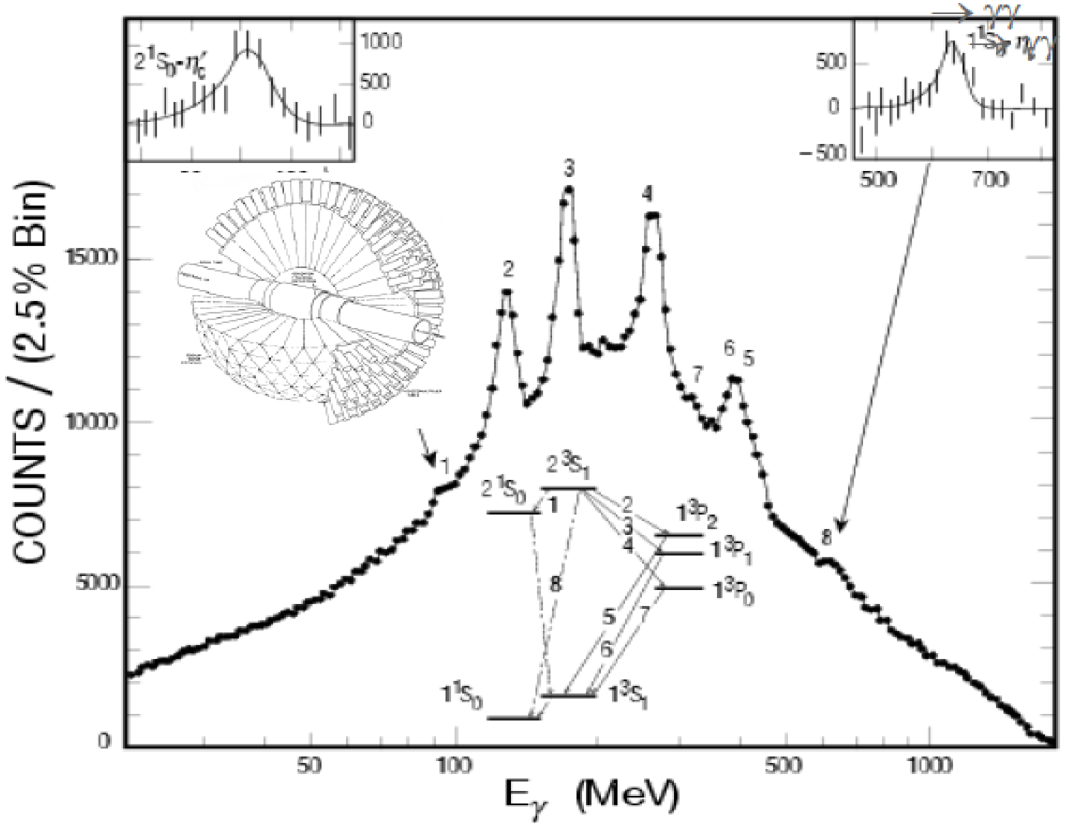
arXiv: 2203.06731 and arXiv: 2203.06788

- Precision e/γ enhance physics discovery potential.
- Performance of total absorption ECAL is well understood for e/γ and jets:
  - Energy resolution achieved: $2\%/\sqrt{E} \oplus 1\%$
  - Position resolution: sub-mm can be achieved;
  - Good identification and reconstruction efficiency;
  - Excellent jet mass resolution with dual readout: C/S light or S/L gate.
- On-going Development in Caltech Crystal Lab:
  - Rad-hard LYSO:Ce crystals and LuAG:Ce ceramics (RADiCAL) for HL-LHC and FCC-hh;
  - Ultrafast $BaF_2$:Y and $Lu_2O_3$:Yb for future ultrafast calorimetry and time of flight;
  - Cost-effective ABS and DSB glasses for Higgs factory (Calvision) and HHCAL.

# Precision e/$\gamma$ Physics in HEP

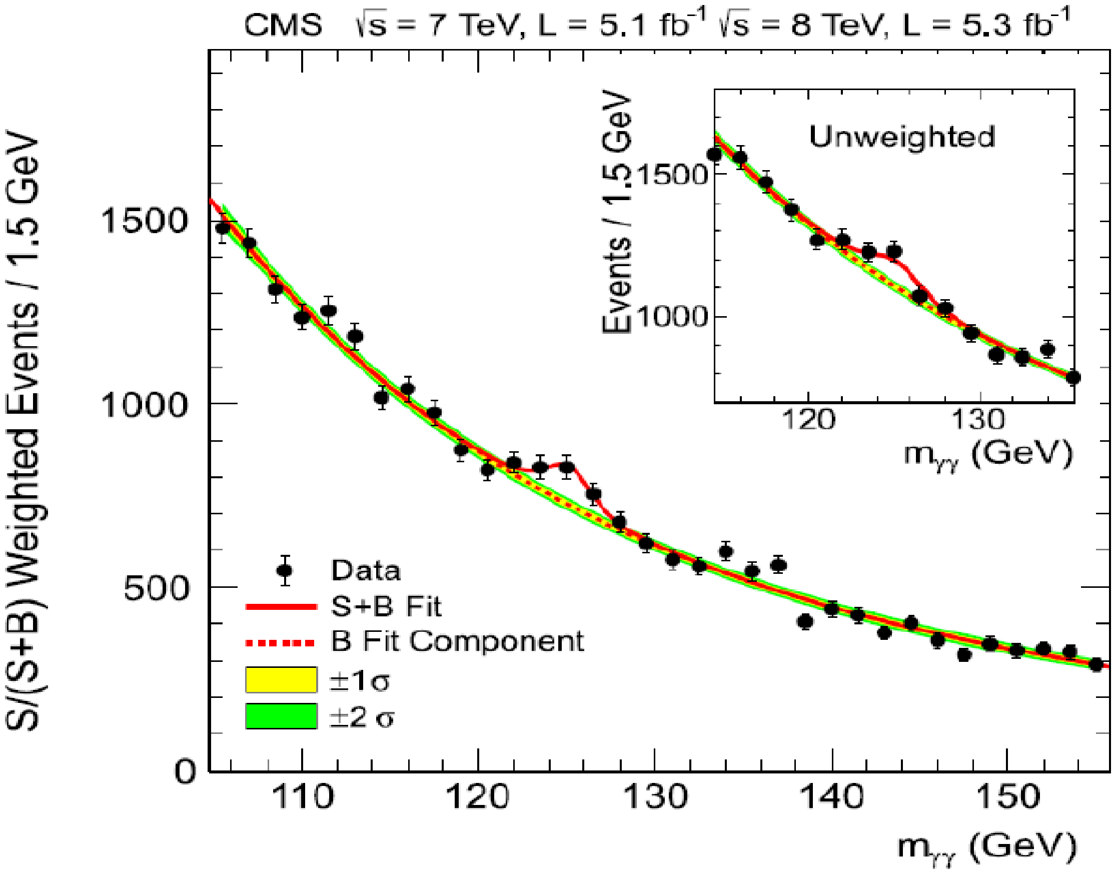
**Charmonium system observed by CB through Inclusive photons**

**CB NaI(Tl)**



**Higgs -> $\gamma\gamma$ by CMS through reconstructing photon pairs**

**CMS PWO**



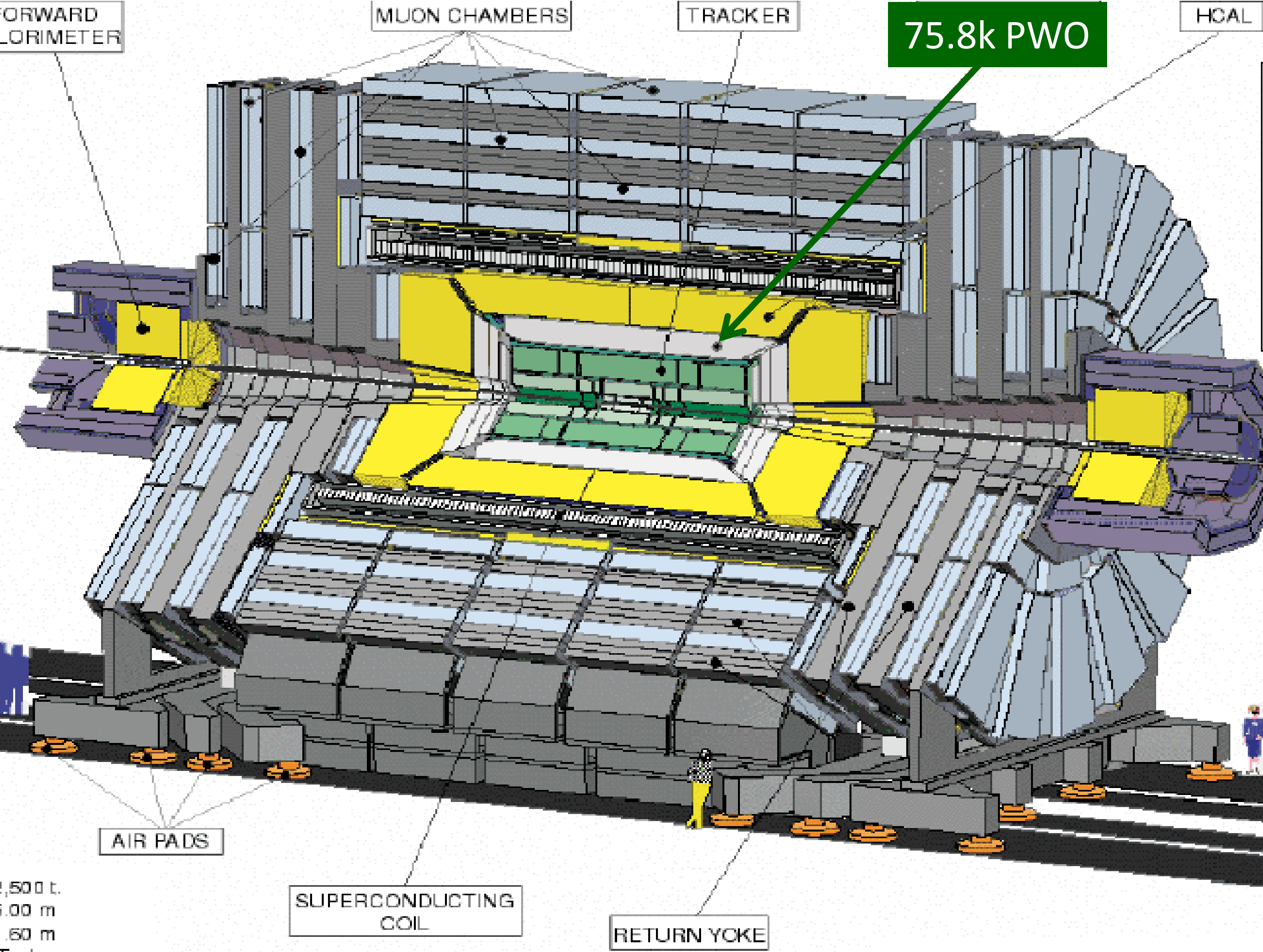
# Crystals Used in HEP Calorimeters

| 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 ($^o$C) | 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 | 420<br>310 | 300<br>220 | 480 | 402 | 425<br>420 | - |
| Decay Time$^b$ (ns) | 245 | 1220 | 30<br>6 | 650<br>0.9 | 300 | 40 | 30<br>10 | - |
| Light Yield$^{b,c}$ (photons/MeV) | 38,000 | 63,000 | 1,400<br>420 | 13,680<br>1,560 | 8,000 | 32,000 | 114<br>40 | - |
| d(LY)/dT$^b$ (%/ $^o$C) | -0.2 | 0.4 | -1.4 | -1.9<br>0.1 | -0.9 | -0.2 | -2.5 | - |
| Experiment | Crystal Ball | BaBar<br>BELLE<br>BES III | KTeV<br>Mu2e<br>S. BELLE | TAPS<br>Mu2e-II? | L3<br>BELLE | COMET<br>CMS BTL<br>PIONEER | CMS<br>ALICE<br>PANDA<br>EIC | A4<br>G-2 |

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

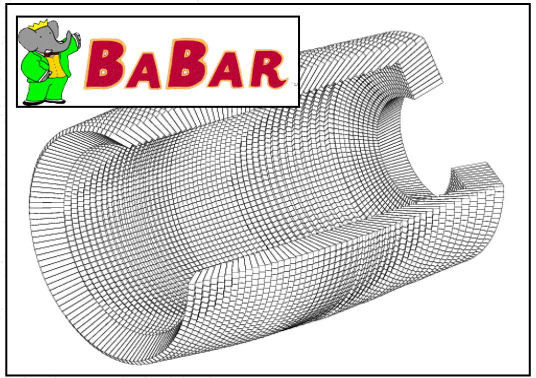
# L3 BGO, BaBar CsI, CMS PWO ECAL

11.4k BGO



75.8k PWO

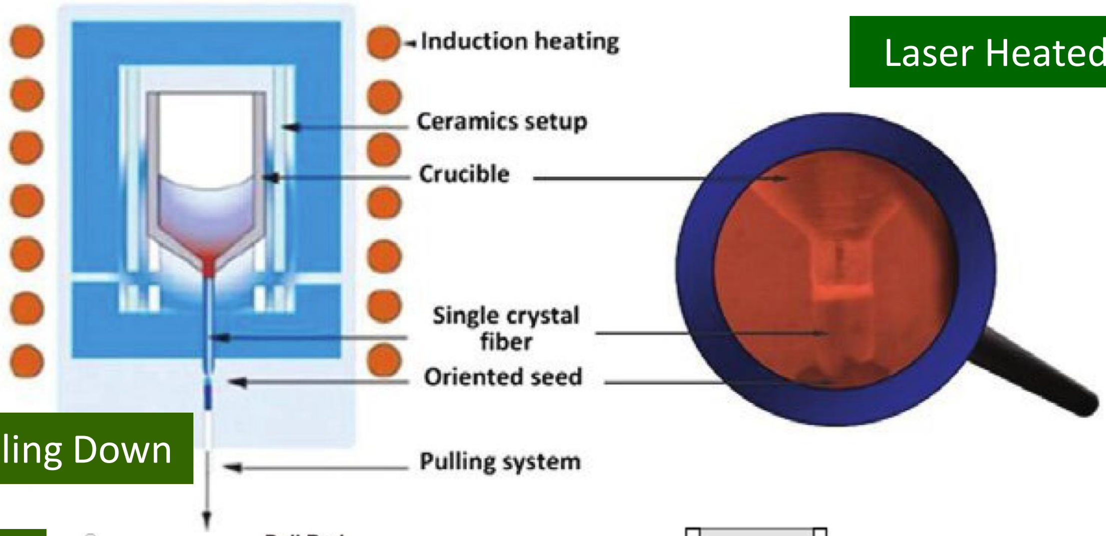
| | | |
|---|---|---|
| Total weight | : | 12,500 t. |
| Overall diameter | : | 15.00 m |
| Overall length | : | 21.60 m |
| Magnetic field | : | 4 Tesla |



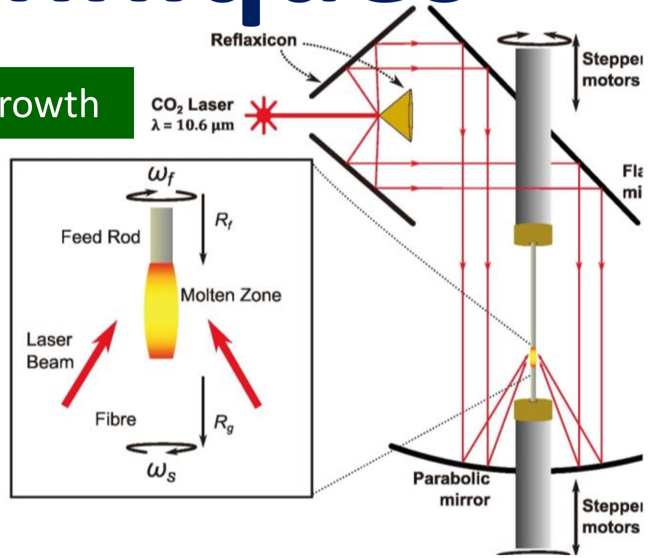
6.6k CsI:Tl

# Crystal Growth Techniques

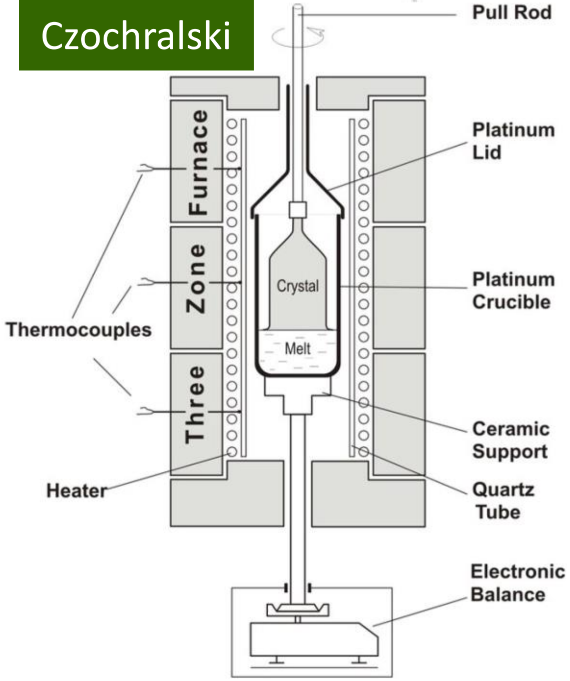
Micro-Pulling Down



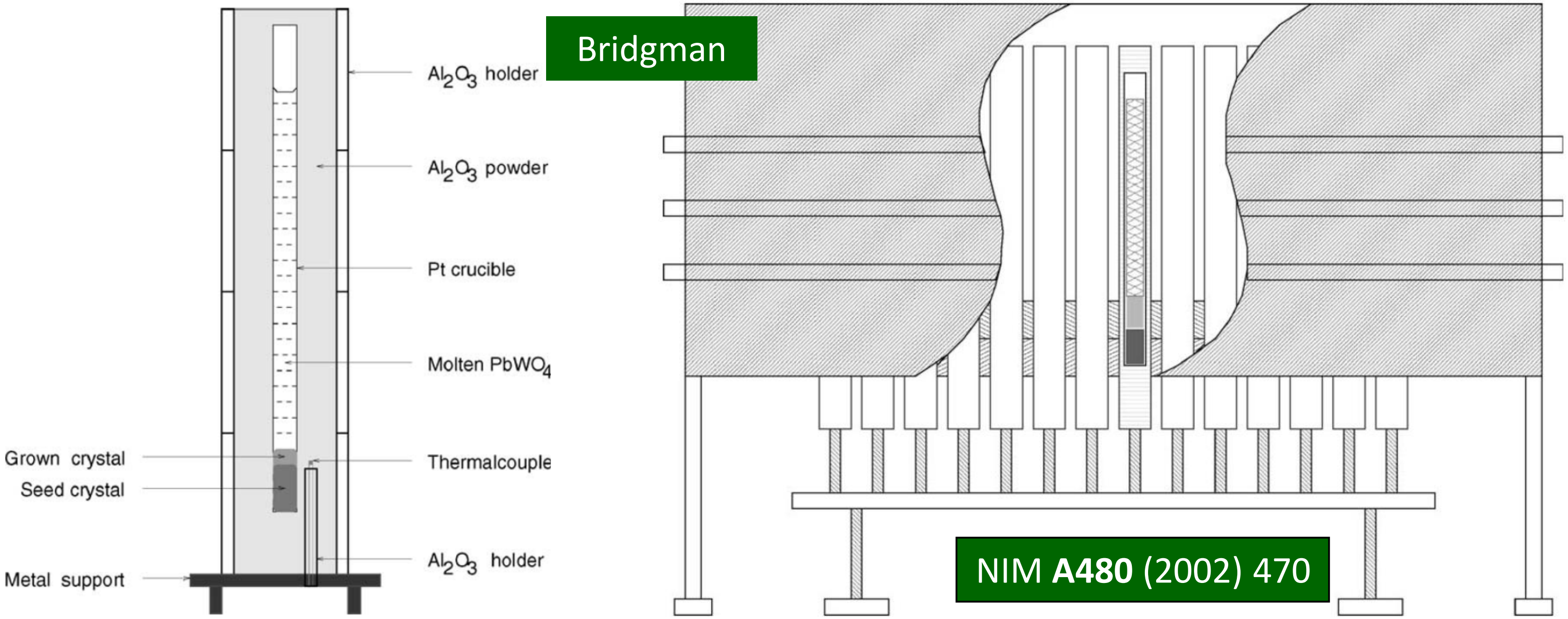
Laser Heated Pedestal Growth



Czochralski

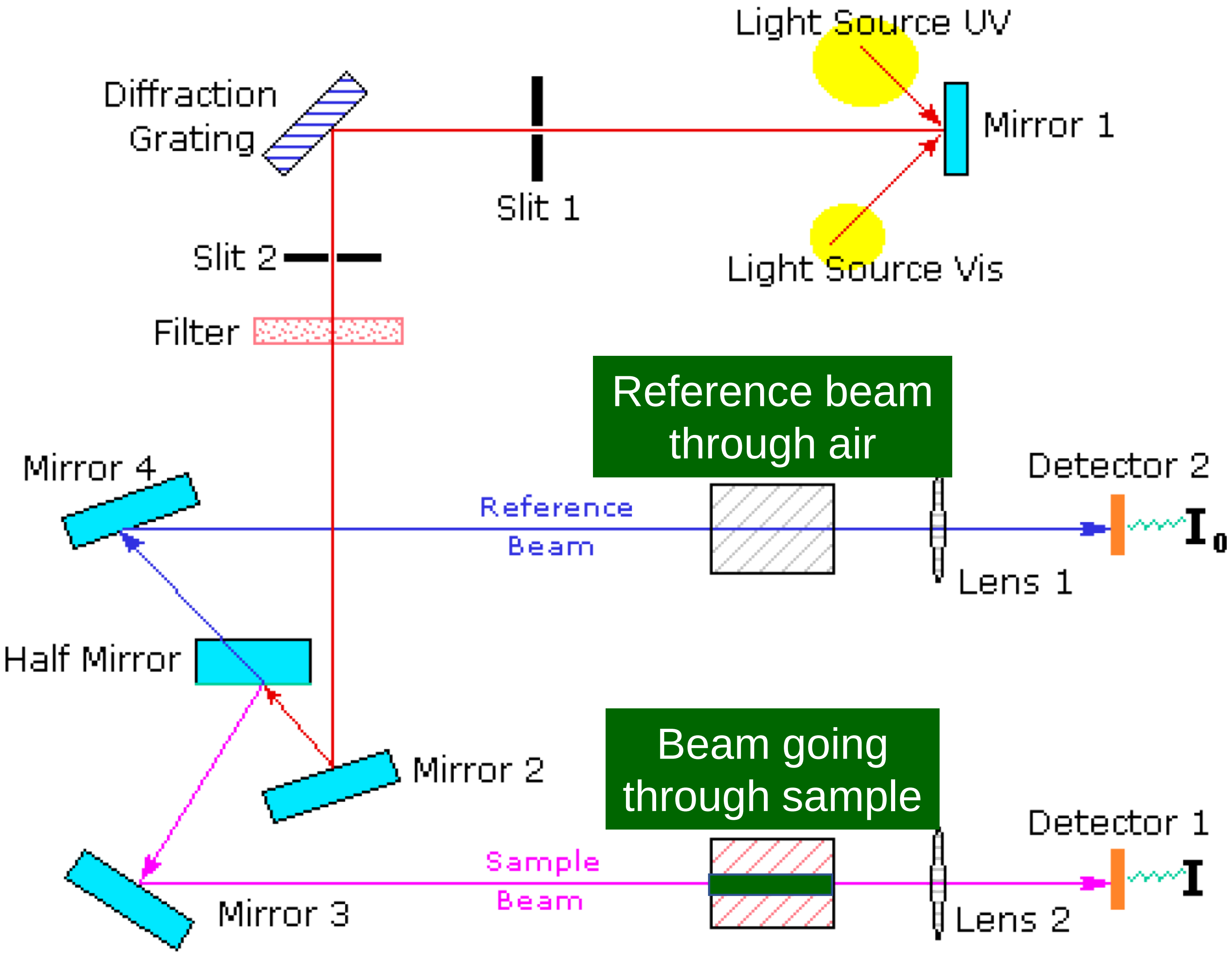


Bridgman



NIM **A480** (2002) 470

# Transmittance and Absorption



Reference beam through air

Beam going through sample

HITACHI U3210 UV/VIS and PerkinElmer Lambda 950 UV/VIS/NIR spectrophotometer with large sample compartment to measure transmittance and absorption

Typical Precision:
0.2 to 0.3%

Watch out:
Birefringence, sample surface and scattering centers

# LAL and Birefringence

Light attenuation length (LAL), or inverse of its light absorption coefficient, extracted from transmittance

$$LAL(\lambda) = \frac{l}{\ln\left\{\left[T(\lambda)(1-T_s(\lambda))^2\right] / \left[\sqrt{4T_s^4(\lambda)+T^2(\lambda)\left(1-T_s^2(\lambda)\right)^2}-2T_s^2(\lambda)\right]\right\}} \tag{2}$$

where T(λ) is the longitudinal transmittance measured along crystal length $l$, and $T_s(\lambda)$ is the theoretical transmittance assuming multiple bouncings between two crystal ends and without internal absorption:

$$T_s(\lambda) = (1-R(\lambda))^2 + R^2(\lambda)(1-R(\lambda))^2 + \cdots = (1-R(\lambda))/(1+R(\lambda)) \tag{3}$$

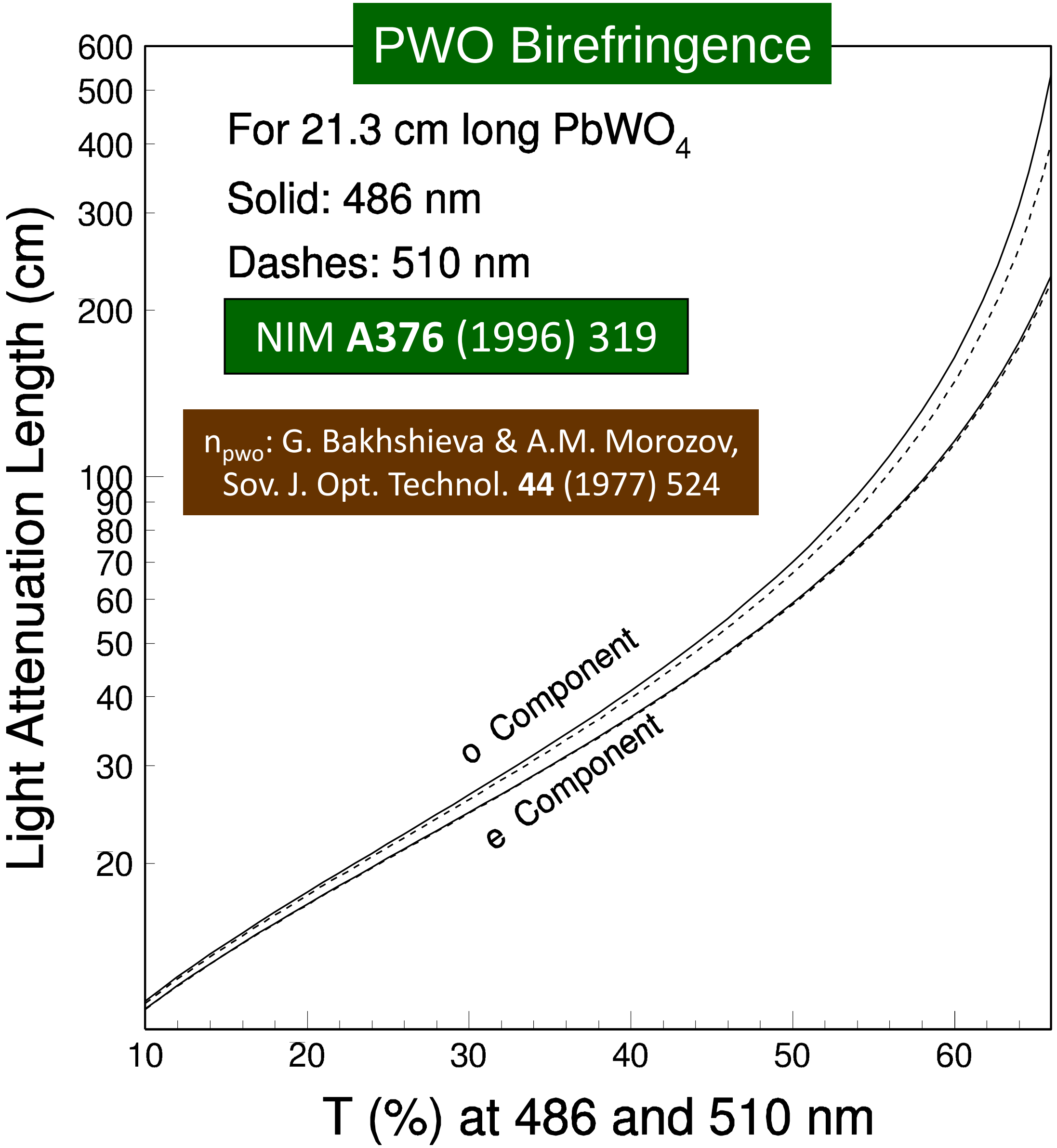
and

NIM **A333** (1993) 422

$$R(\lambda) = \frac{(n_{\text{crystal}}(\lambda) - n_{\text{air}}(\lambda))^2}{(n_{\text{crystal}}(\lambda) + n_{\text{air}}(\lambda))^2} \tag{4}$$

where $n_{\text{crystal}}(\lambda)$ and $n_{\text{air}}(\lambda)$ are the refractive indices for crystal and air, respectively.

## PWO Birefringence



For 21.3 cm long $PbWO_4$

Solid: 486 nm

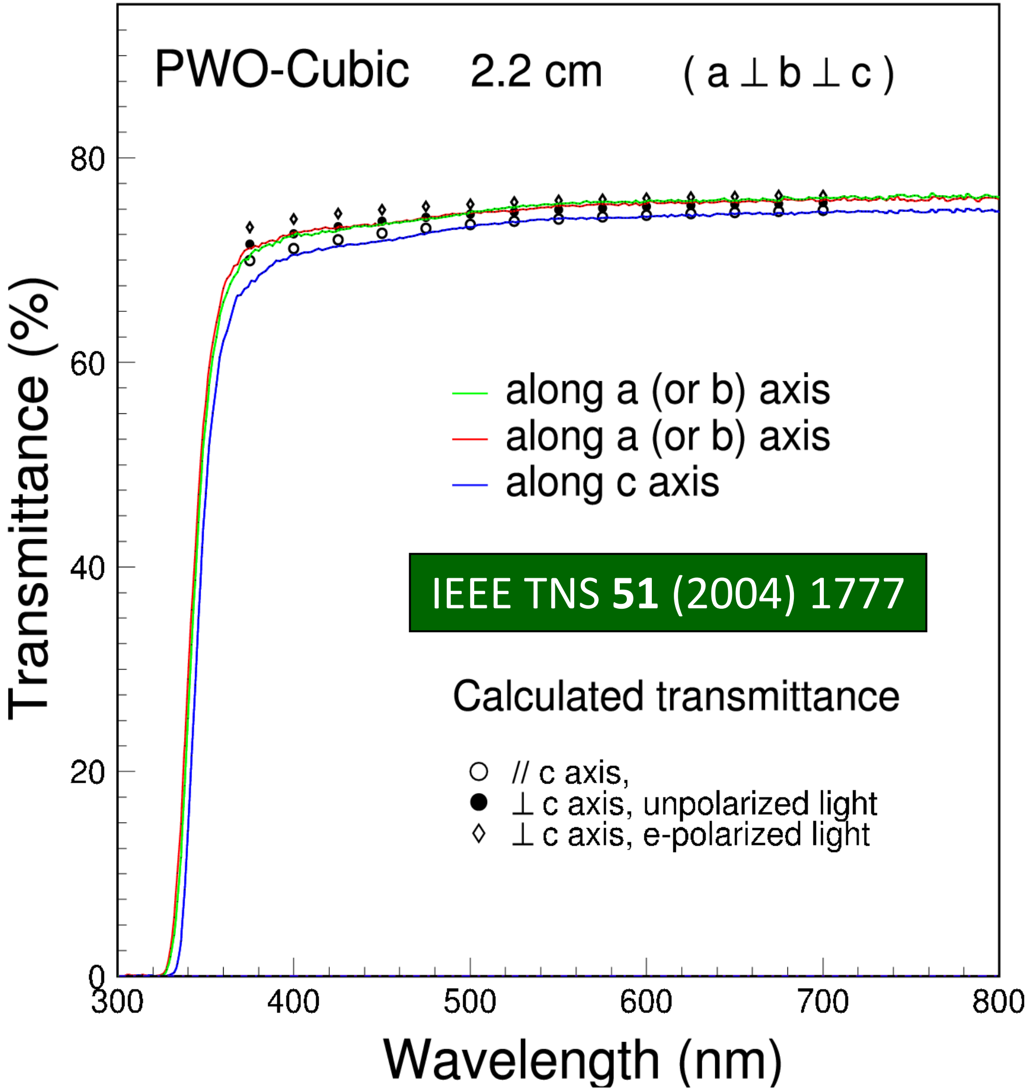
Dashes: 510 nm

NIM **A376** (1996) 319

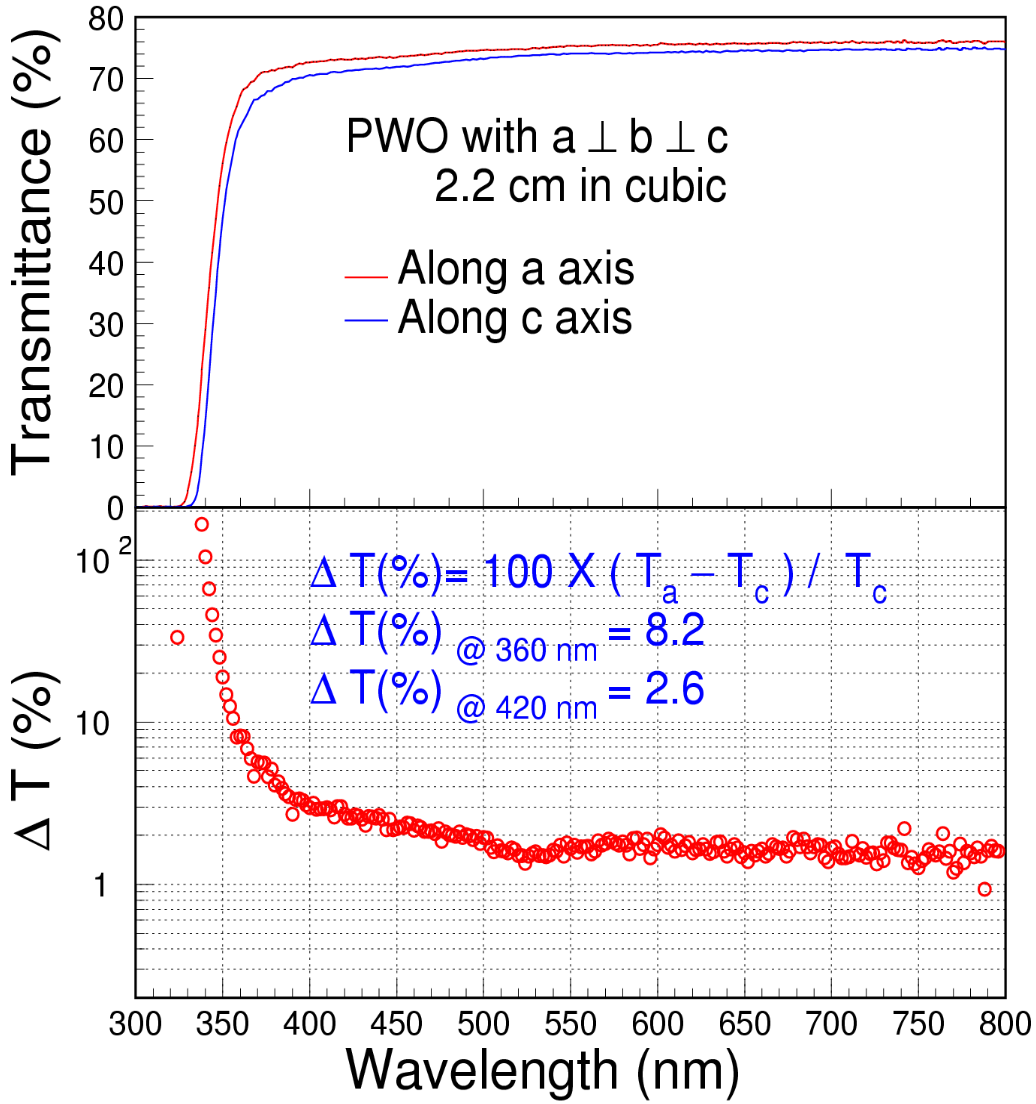
$n_{pwo}$: G. Bakhshieva & A.M. Morozov, Sov. J. Opt. Technol. **44** (1977) 524

# PWO Birefringence

Attention to be paid to the crystal orientation vs. optical axis



IEEE TNS **51** (2004) 1777



# LY, LO, LCE and LRU

Crystal light yield (LY) in photons/MeV energy deposition: $\beta E_g$ is the energy required for an e-h pair, S is energy transferred to the luminescence center and Q is its quantum efficiency.

Measured light output (LO) in photoelectrons/MeV depends on crystal LY, light collection efficiency (LCE) and the quantum efficiency of the photodetector used for the measurement.

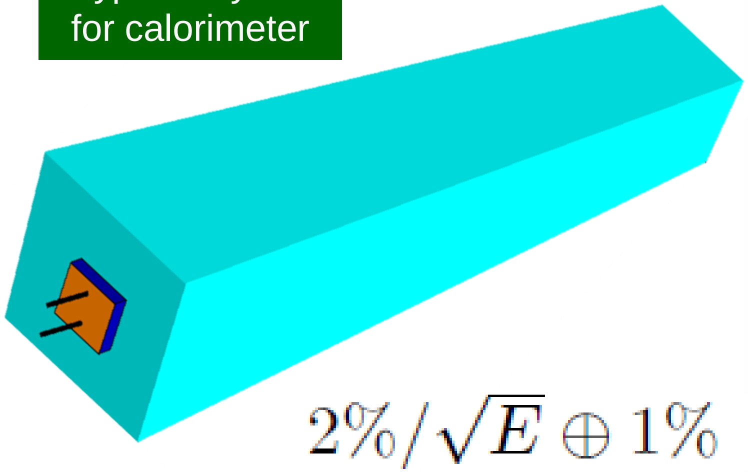
LCE is sample dependent

$$LY = 10^6 \ S \cdot Q / (\beta \cdot E_g)$$

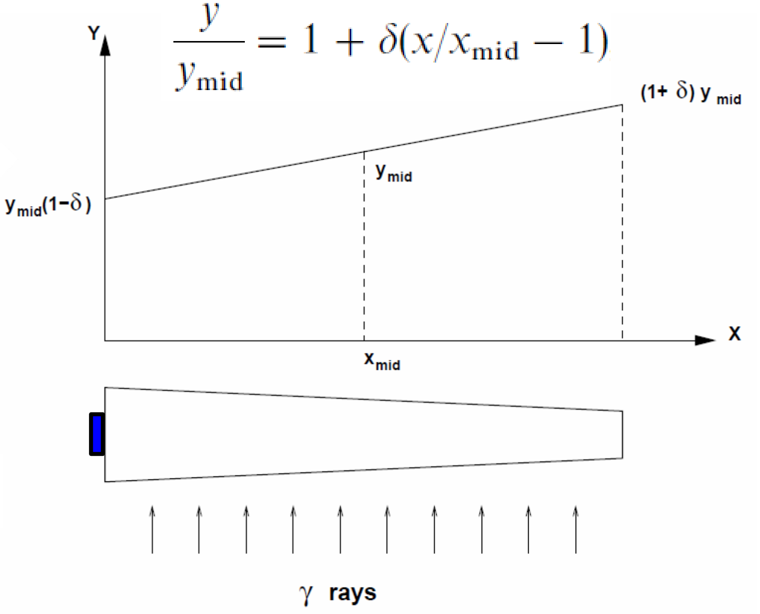
$$LO = LY \cdot LCE \cdot QE$$

Light Response Uniformity (LRU)
CMS Specification

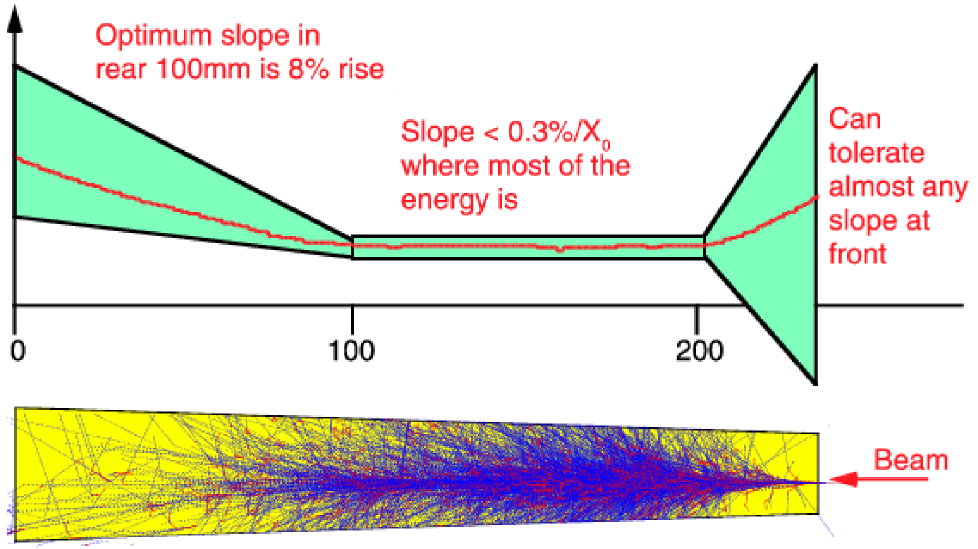
Typical crystal for calorimeter



$$2\% / \sqrt{E} \oplus 1\%$$



$$\frac{y}{y_{\mathrm{mid}}} = 1 + \delta(x/x_{\mathrm{mid}} - 1)$$



Optimum slope in rear 100mm is 8% rise

Slope < 0.3%/$X_0$ where most of the energy is

Can tolerate almost any slope at front

# Radiation Damage Effects

NIM A413 (1998) 297, https://doi.org/10.1007/978-3-319-47999-6_22-2

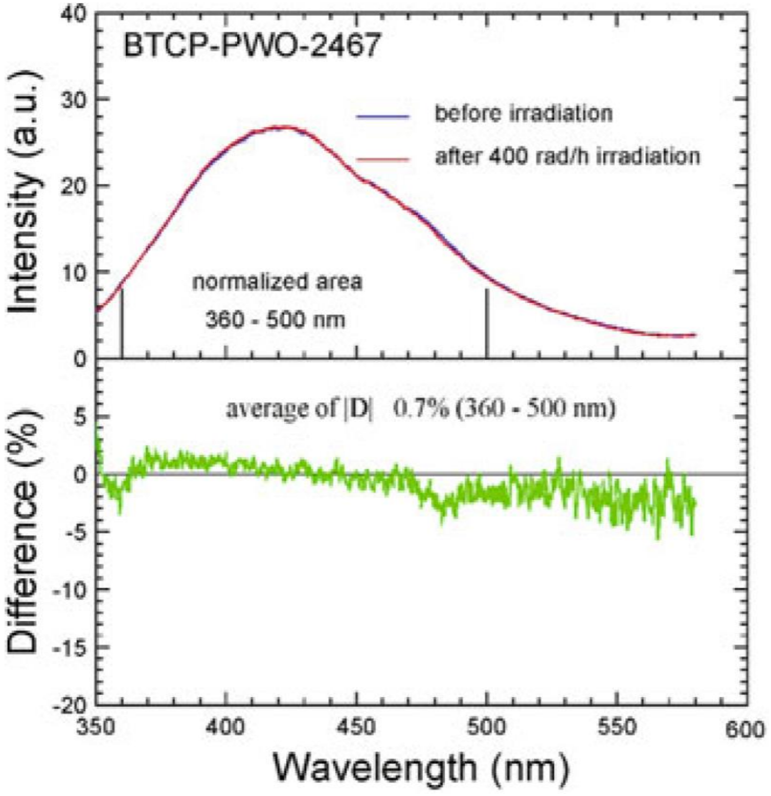
- **Scintillation mechanism damage: reduced LY and LO and maybe also LRU;**
- **Radiation-induced phosphorescence (afterglow): increase dark current, dark counting rate and readout noise;**
- **Radiation-induced absorption (color centers): reduced light attenuation length, LO and maybe also LRU.**

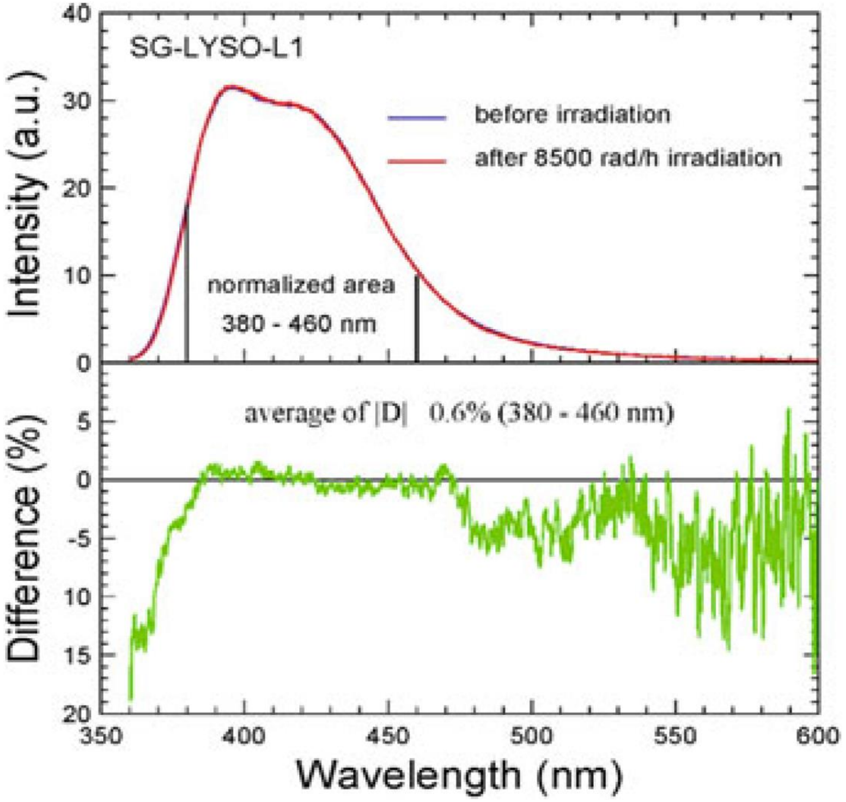
| | CsI:Tl | CsI | $BaF_2$ | BGO | PWO | LSO/LYSO |
|---|---|---|---|---|---|---|
| Scintillation mechanism | No | No | No | No | No | No |
| Phosphorescence (afterglow) | Yes | Yes | Yes | Yes | Yes | Yes |
| Absorption (color centers) | Yes | Yes | Yes | Yes | Yes | Yes |
| Recovery | slow | No | No | Yes | Yes | No |
| Dose rate dependence | No | No | No | Yes | Yes | No |
| Thermal Annealing | No | No | Yes | Yes | Yes | Yes |
| Optical Bleaching | No | No | Yes | Yes | Yes | Yes |

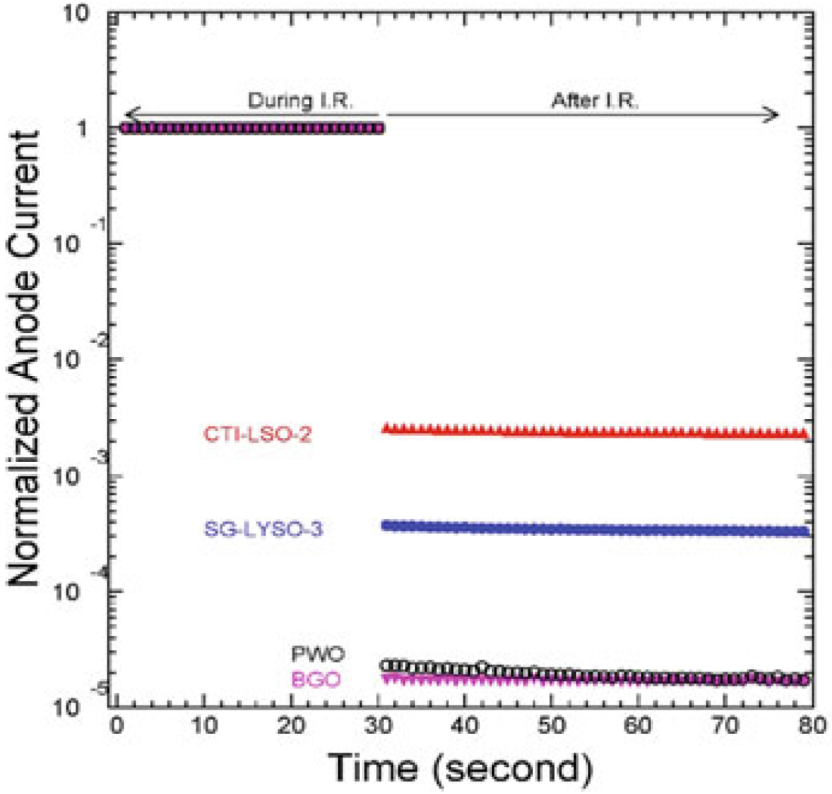
# Scintillation Mechanism and Afterglow

https://doi.org/10.1007/978-3-319-47999-6_22-2

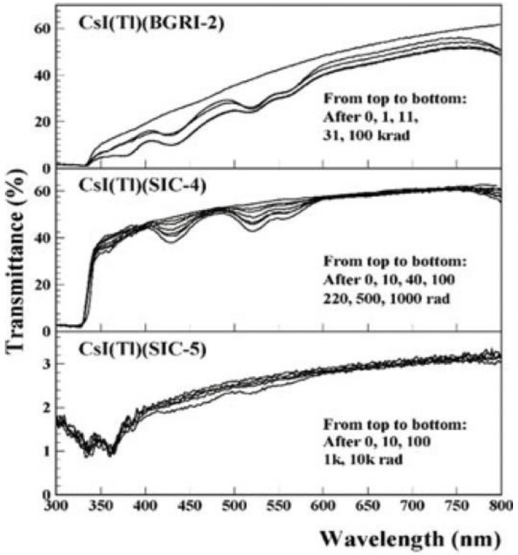
Crystal's scintillation mechanism is not damaged by γ -rays, neutrons and charged hadrons, as shown in no variation in the emission spectra measured before and after irradiations. Radiation-induced phosphorescence is measured as the photo-current after radiation, which is at a level of $10^{-5}$ for BGO and PWO and $3 \times 10^{-4}$ for LYSO, and $2 \times 10^{-3}$ for LSO.

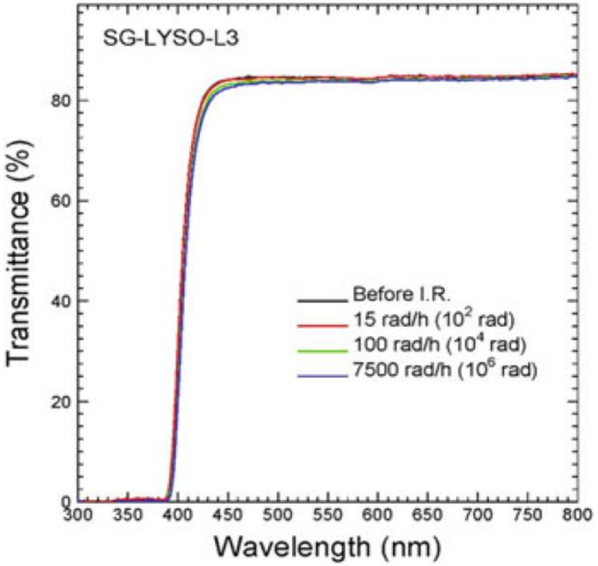






# Radiation-Induced Color Centers





https://doi.org/10.1007/978-3-319-47999-6_22-2

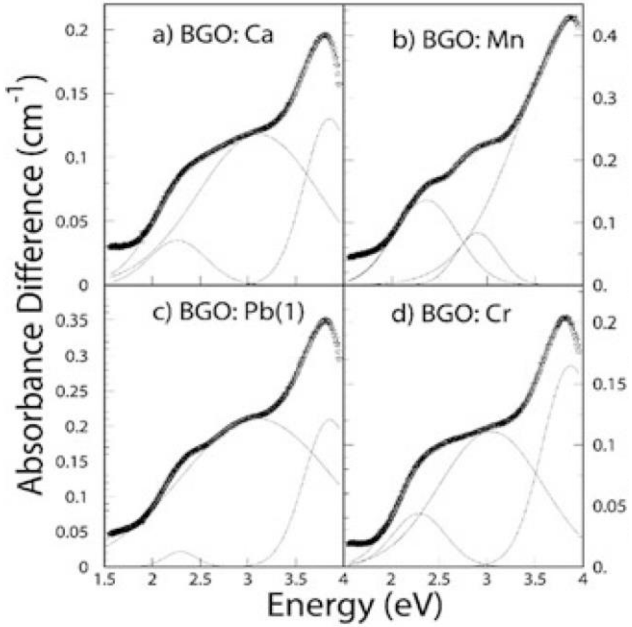
$$EWLT = \frac{\int LT(\lambda)\, Em(\lambda)\, d\lambda}{\int Em(\lambda)\, d\lambda}$$

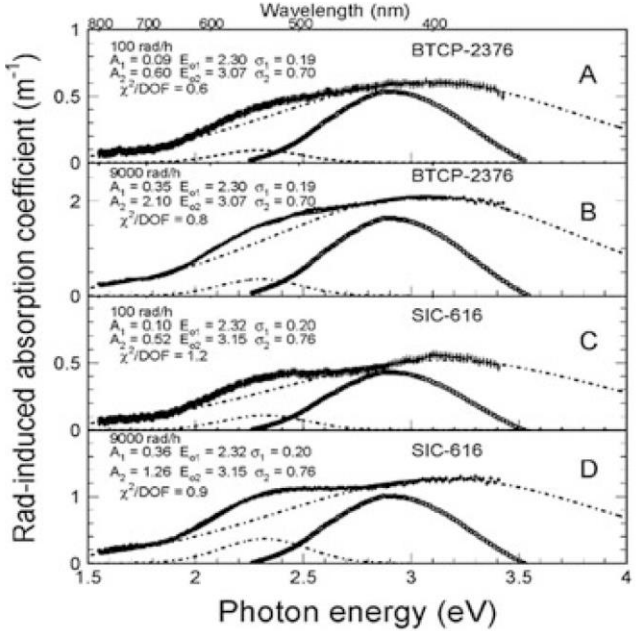
$$RIAC(\lambda)\ \ or\ \ D(\lambda) = 1/LAL_{\text{after}}(\lambda) - 1/LAL_{\text{before}}(\lambda)$$

$$RIAC(\lambda) = \frac{1}{l}\ln\frac{T_0(\lambda)}{T(\lambda)}$$

$$EWRIAC = \frac{\int RIAC(\lambda)\, Em(\lambda)\, d\lambda}{\int Em(\lambda)\, d\lambda}$$

$$RIAC(\lambda) = \sum_{i=1}^{n} A_i e^{-\frac{(E(\lambda)-E_i)^2}{2\sigma_i^2}}$$





NIM A**302** (1991) 69, NIM A**376** (1996) 319

# Dose Rate Dependent Damage in PWO

PWO light reached an equilibrium under a dose rate, showing a dose rate dependent damage
Damage/recovery requires continuous light monitoring to maintain PWO energy resolution

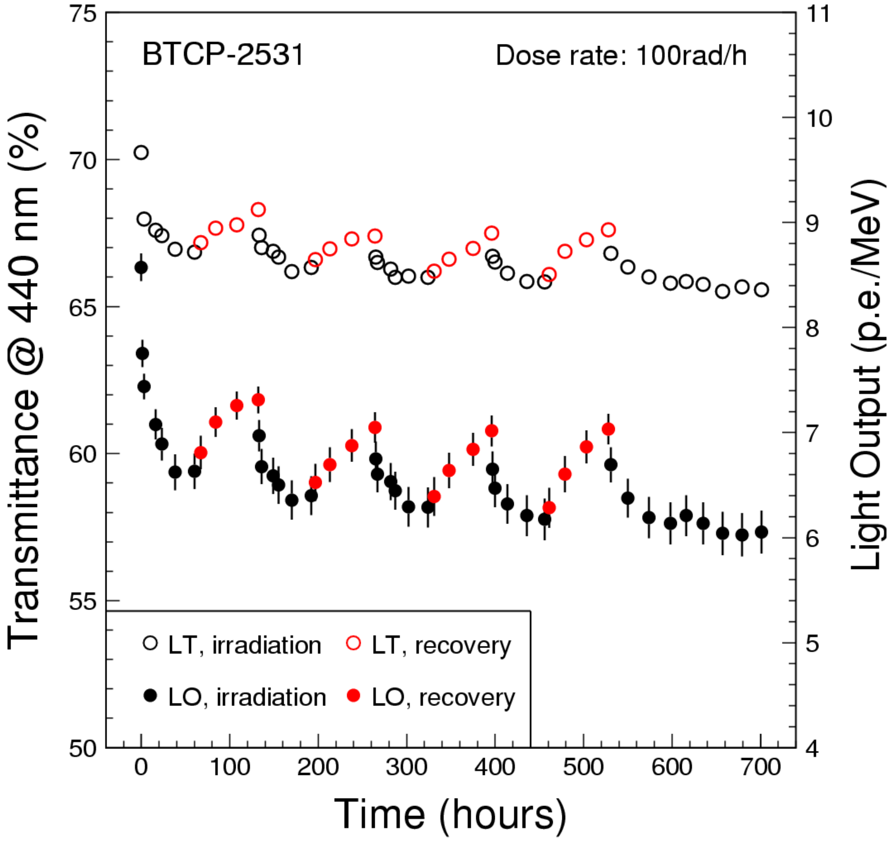
Damage/recovery observed in early lab investigation:
IEEE Trans. Nucl. Sci., Vol. 44 (1997) 458-476

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

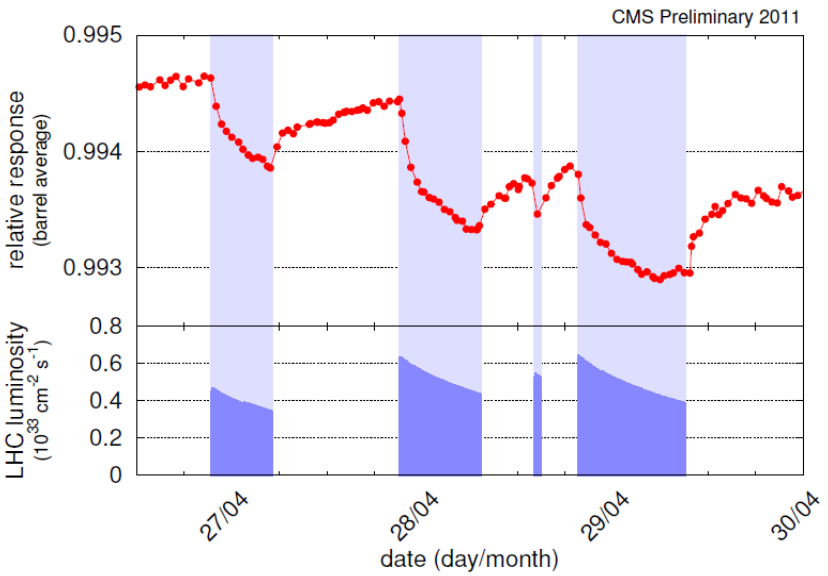
$$D = \sum_{i=1}^{n} \{\frac{b_i R D_i^{all}}{a_i + b_i R}\, [1 - e^{-(a_i+b_i R)t}] + D_i^0 e^{-(a_i+b_i R)t}\}$$

- $D_i$: 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.

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



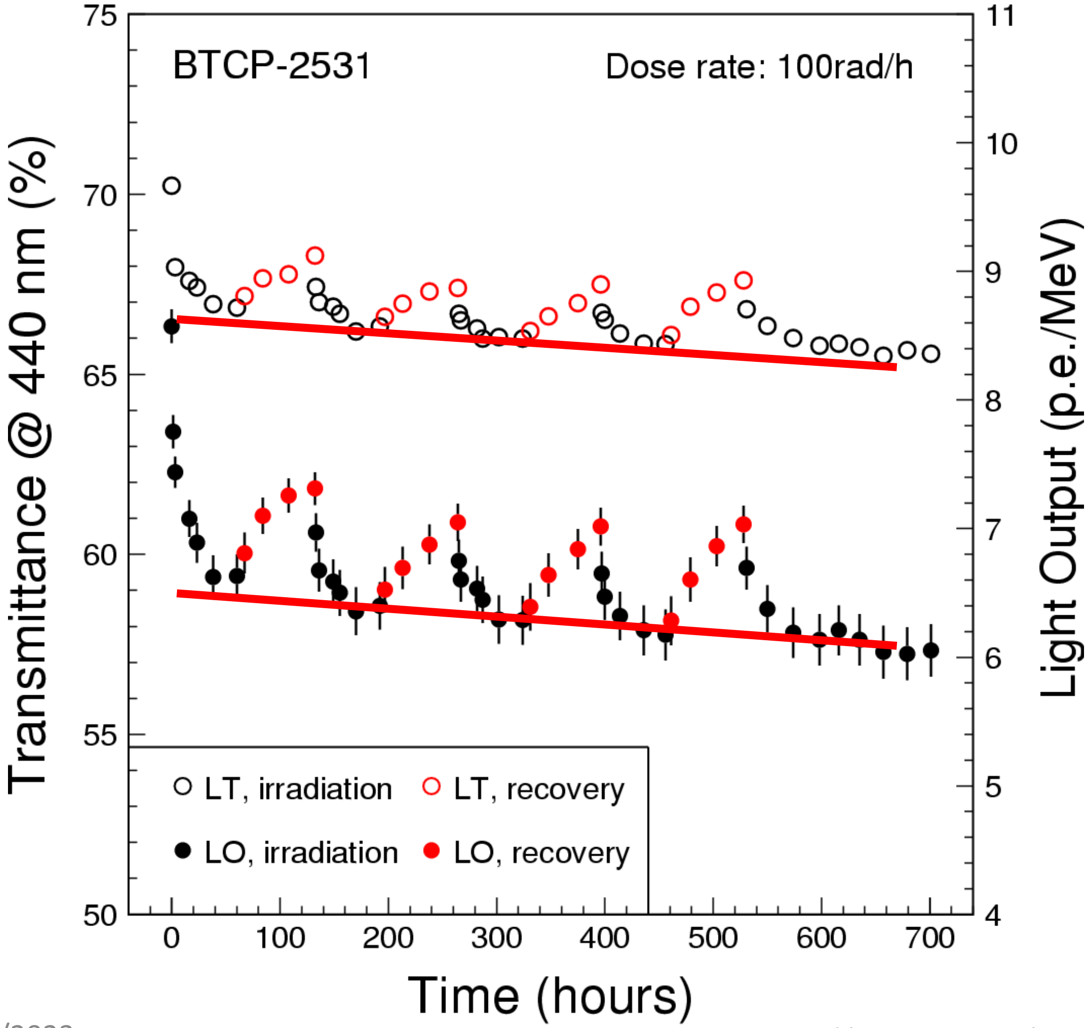
Damage and recovery observed *in situ* at the LHC by the CMS light monitoring system

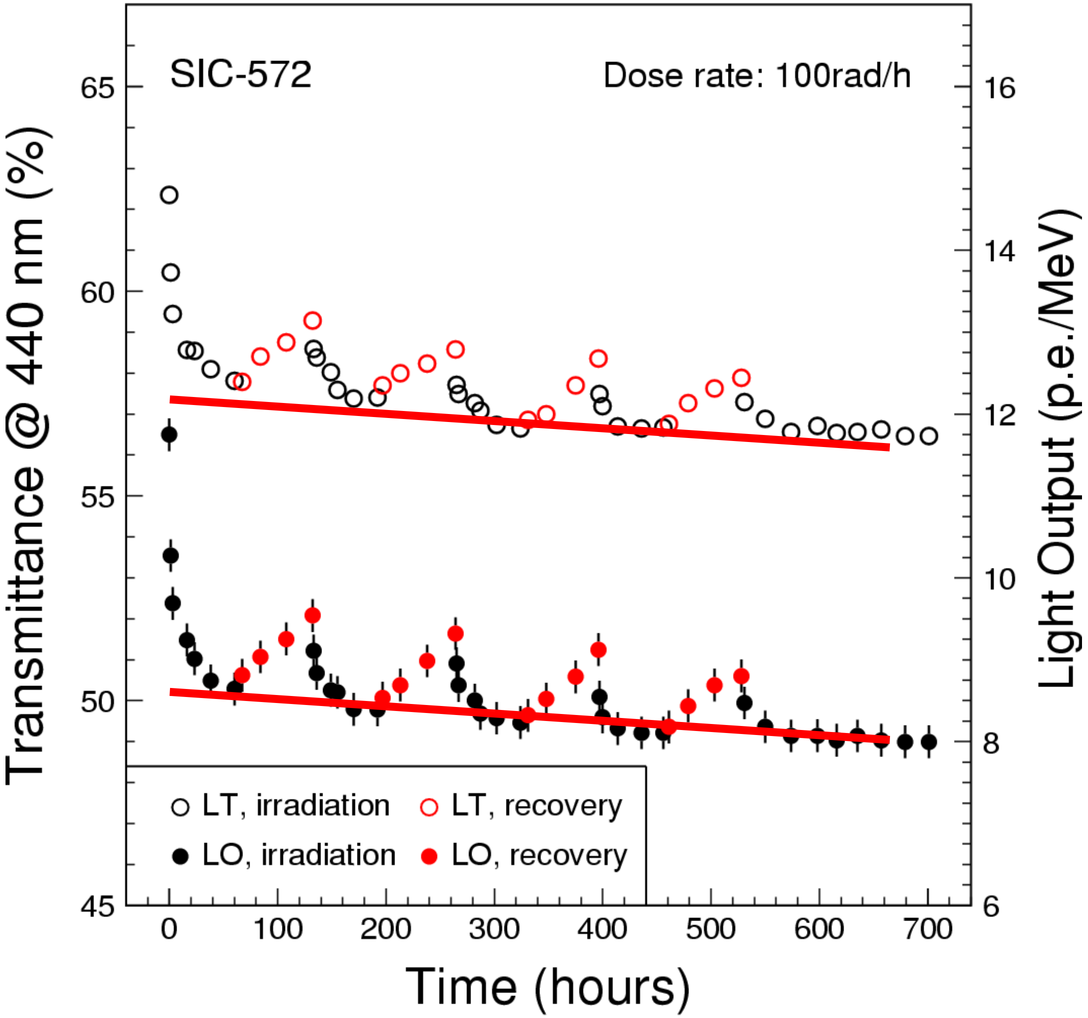


# Effect of Multiple Color Centers

BTCP & SIC PWO @ 100 rad/h and recovery

AIP Conference Proceedings 867 (2006) 252





# Radiation Damage Mechanism

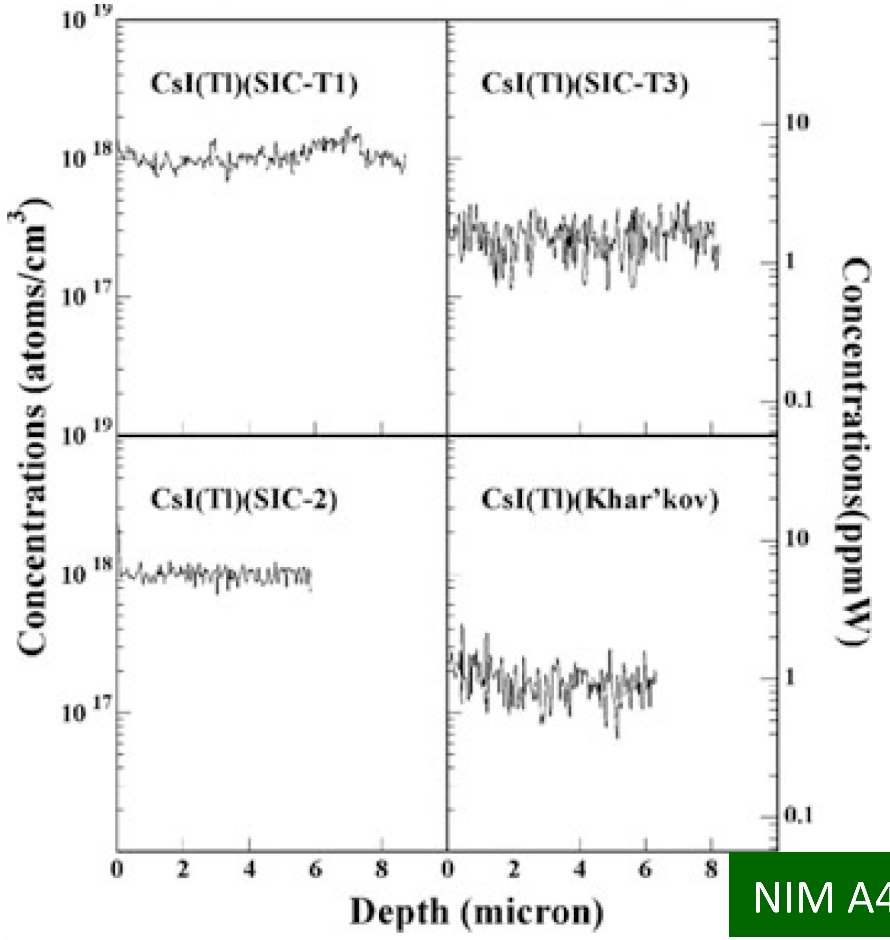
SIMS analysis revealed that damage in alkali halides was caused by the oxygen and/or hydroxyl contamination. Localized stoichiometry analysis by TEM/EDS revealed that damage in oxides was caused by stoichiometry-related defects, e.g. oxygen vacancies.

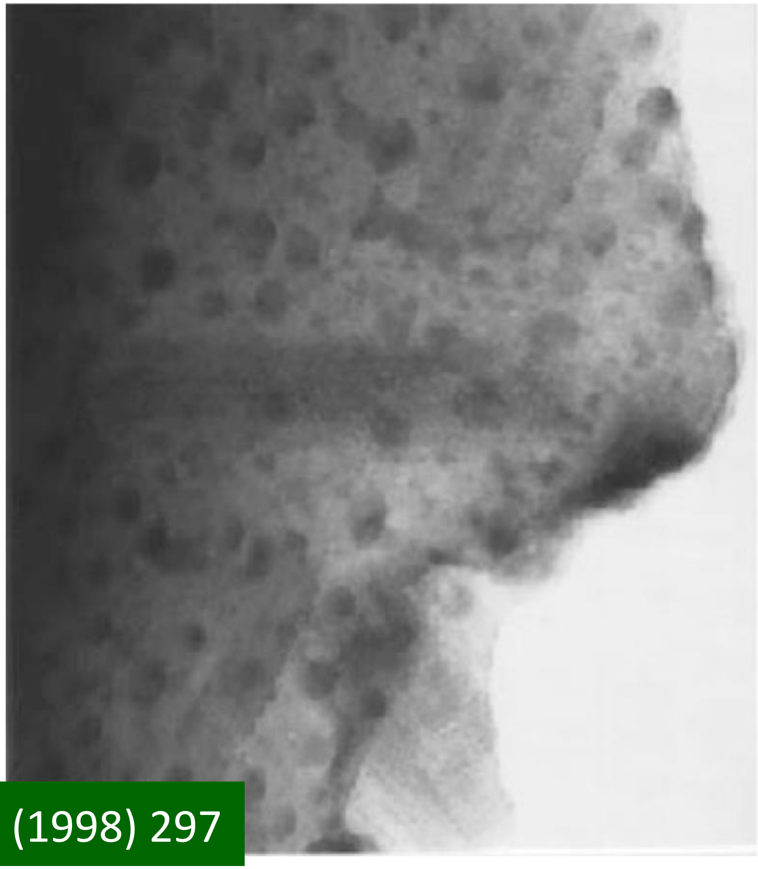
*As grown sample*

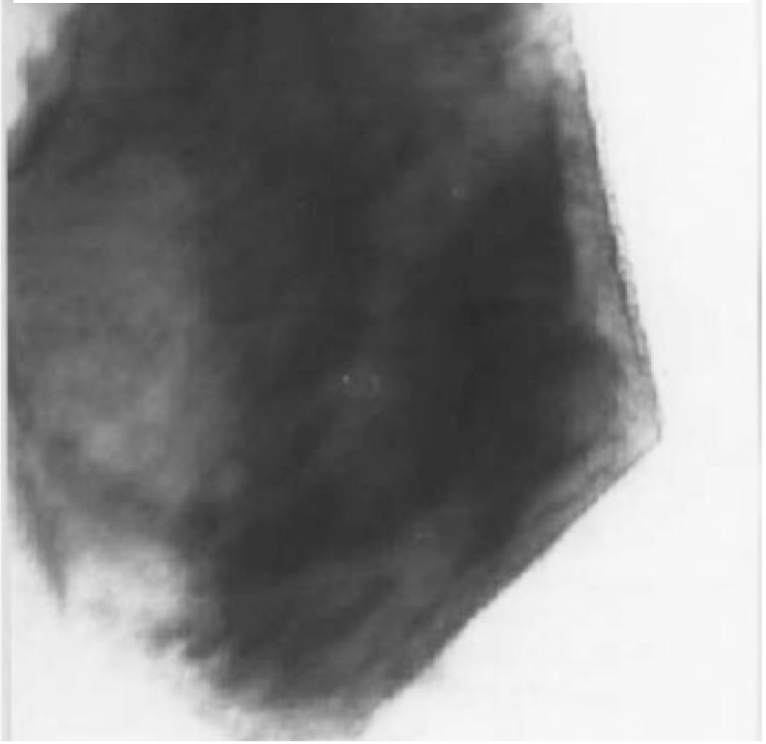
| Element | Black spot | Peripheral | $\text{Matrix}_1$ | $\text{Matrix}_2$ |
|---|---|---|---|---|
| O | 1.5 | 15.8 | 60.8 | 63.2 |
| W | 50.8 | 44.3 | 19.6 | 18.4 |
| Pb | 47.7 | 39.9 | 19.6 | 18.4 |

*The same sample after oxygen compensation*

| Element | $\text{Point}_1$ | $\text{Point}_2$ | $\text{Point}_3$ | $\text{Point}_4$ |
|---|---|---|---|---|
| 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 |



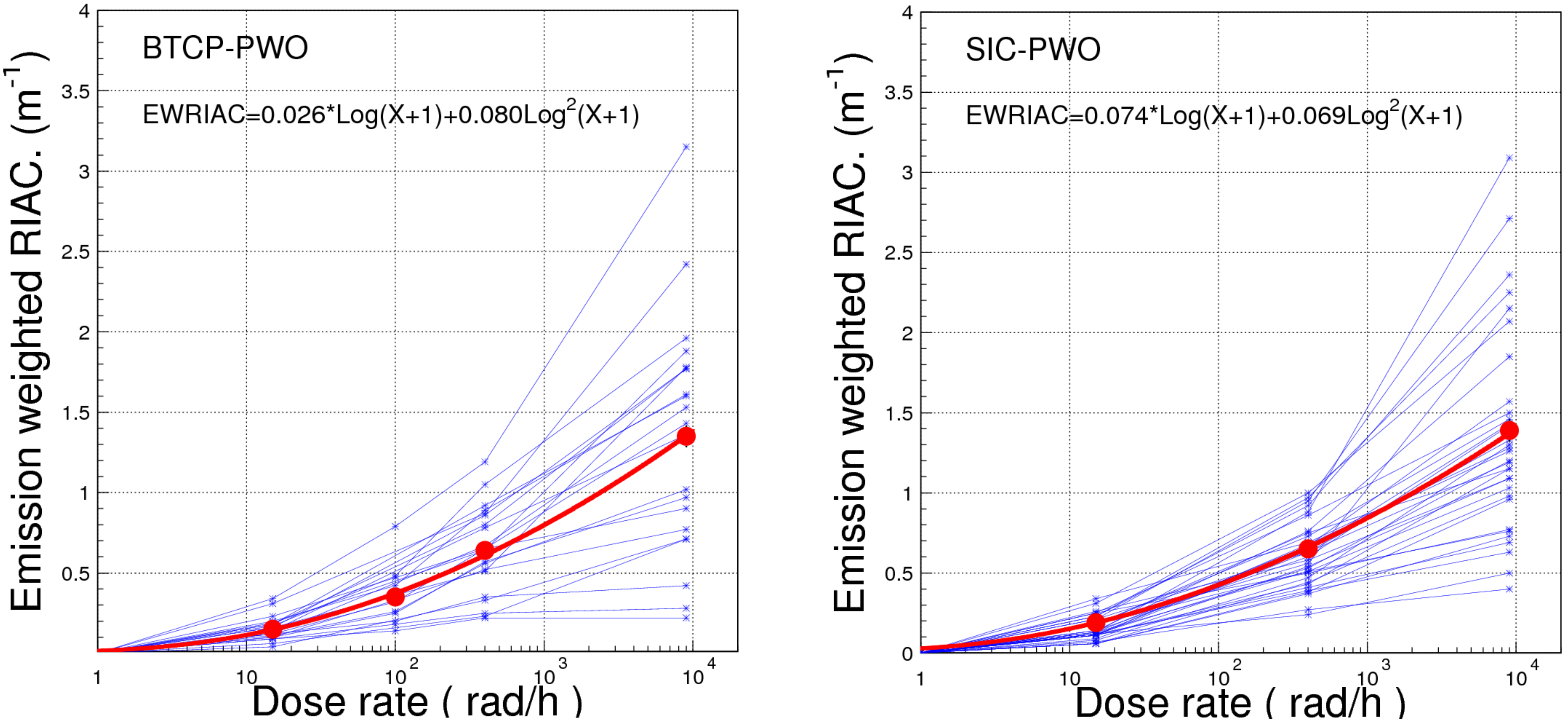




NIM A413 (1998) 297

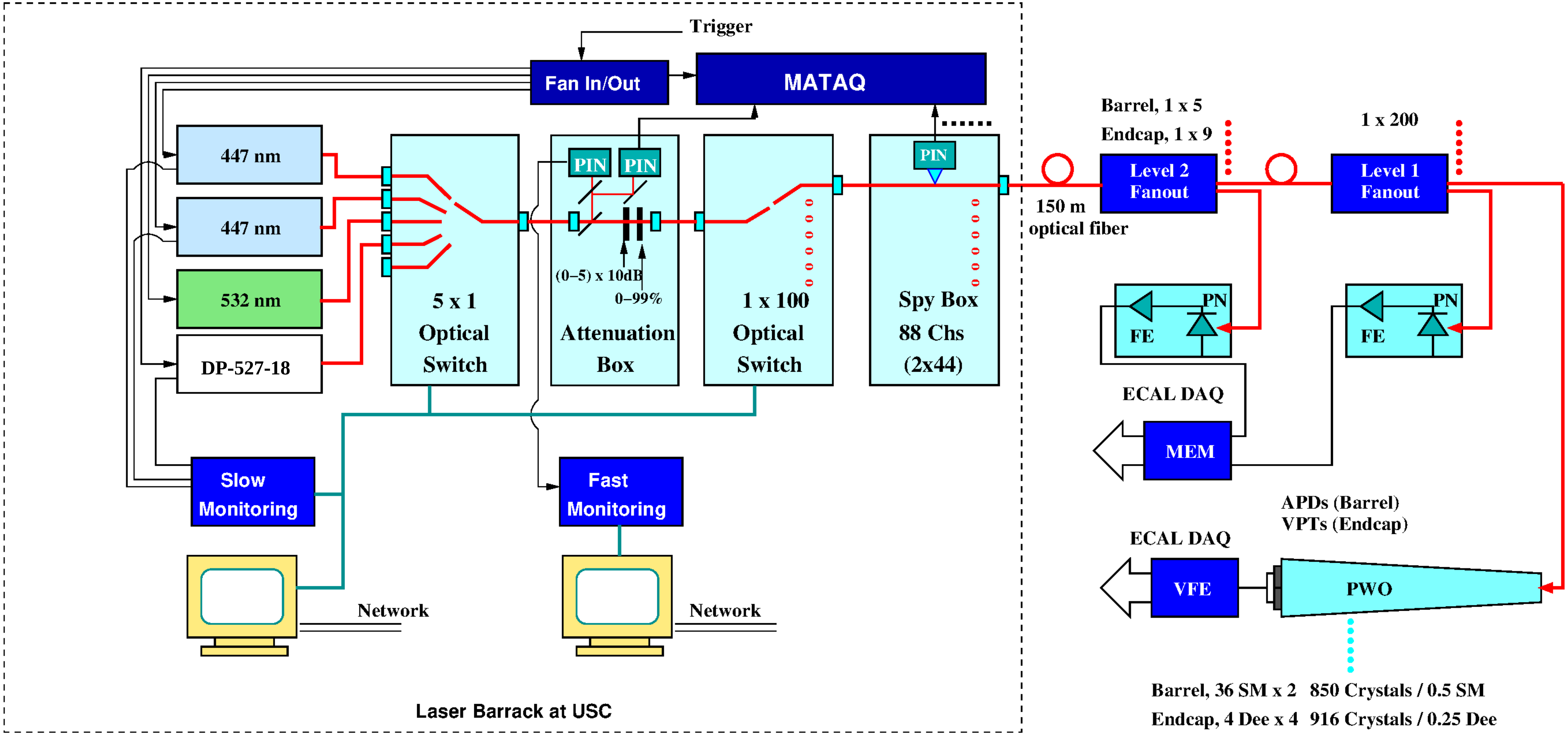
# EWRIAC vs. Ionization Dose Rate

Large spread observed for both BTCP and SIC PWO with EWRIAC fit to 2nd order polynomials of dose rate. IEEE Trans. Nucl. Sci. NS-51 (2004) 1777



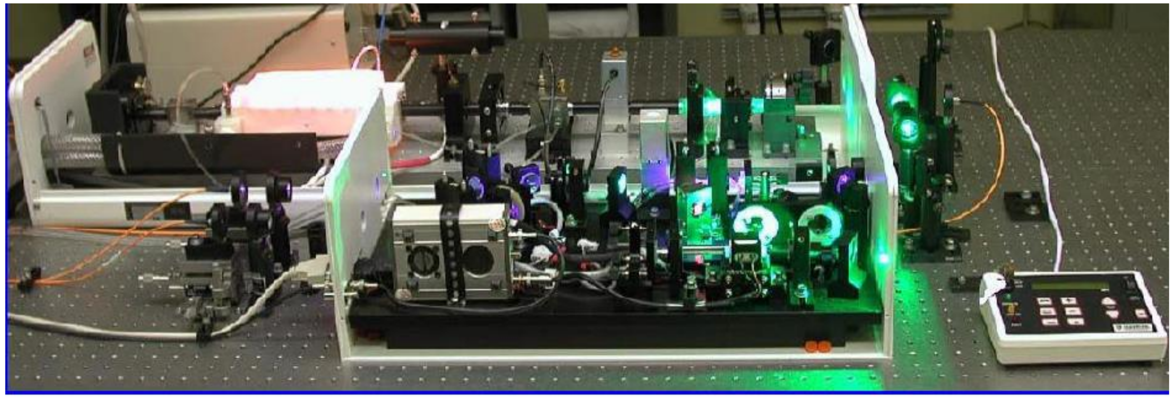
# CMS PWO ECAL Laser Monitoring

Runs 24/7 providing 600 laser pulses/crystal at 100 Hz every 30 min

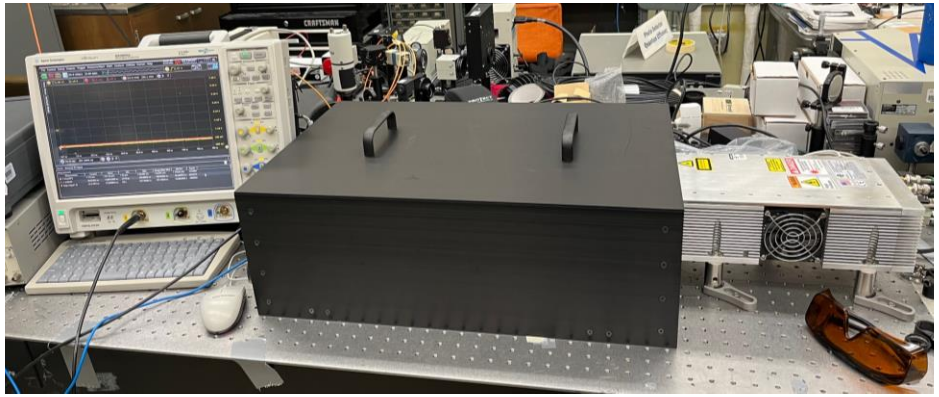


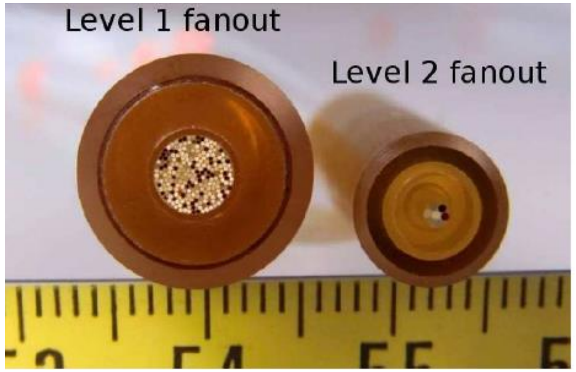
# CMS Laser Monitoring Hardware

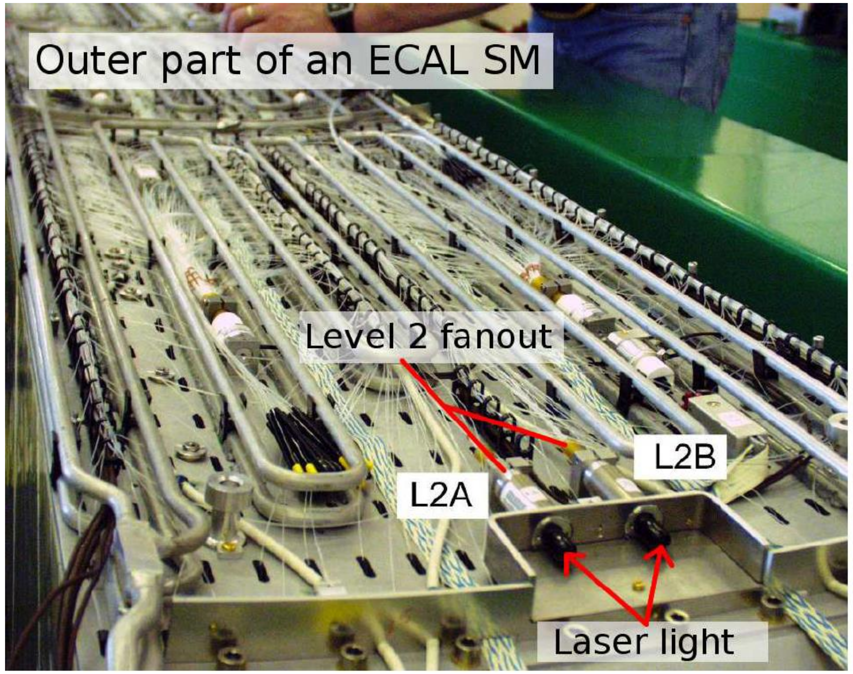
Lamp Pumped Lases: 2002 to 2012

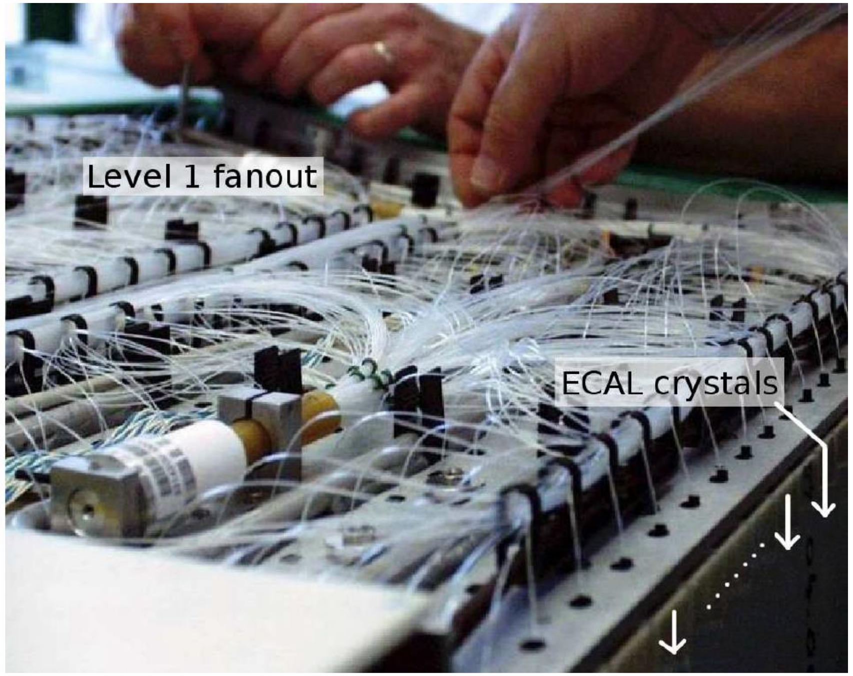


Diode Pumped Lases: since 2012



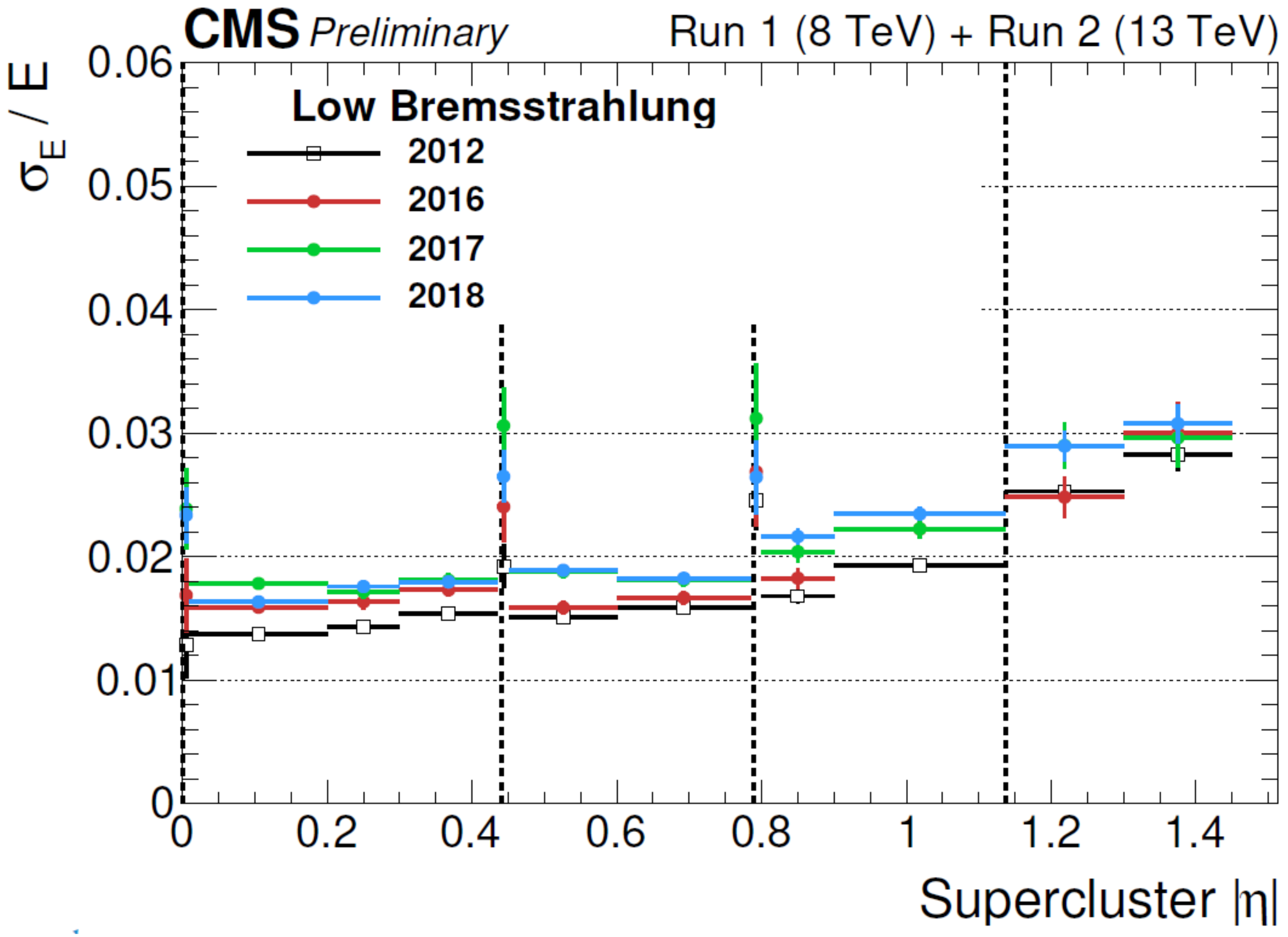


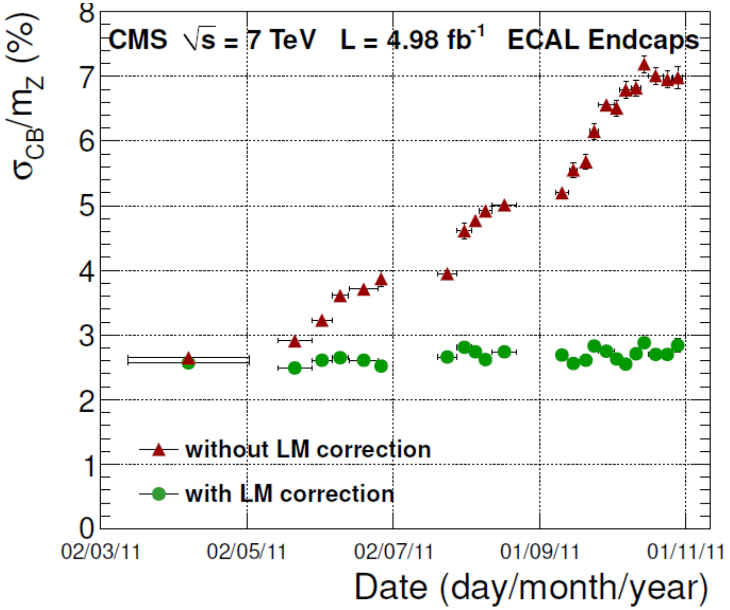


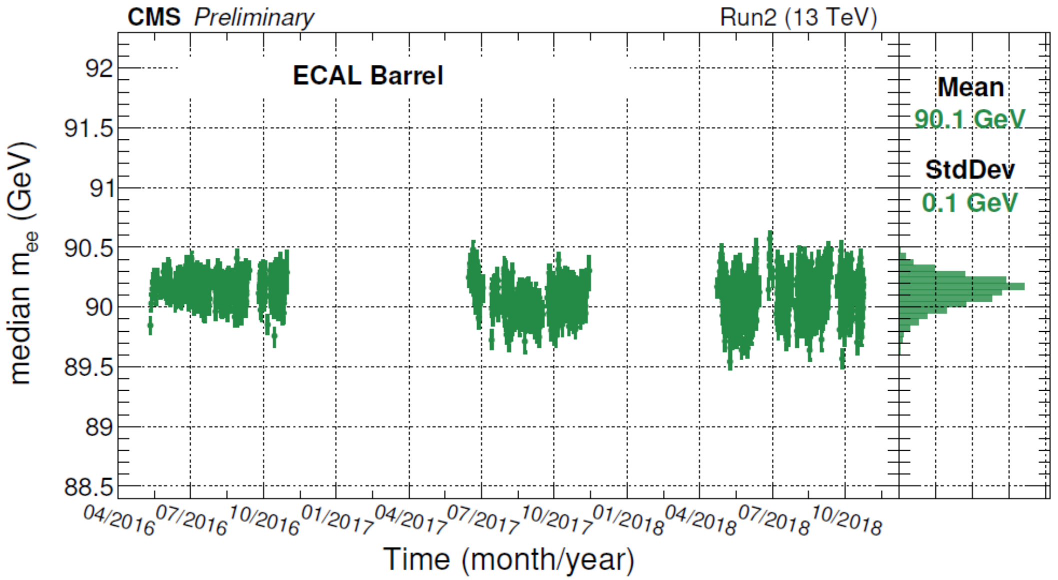


# CMS ECAL Performance at LHC

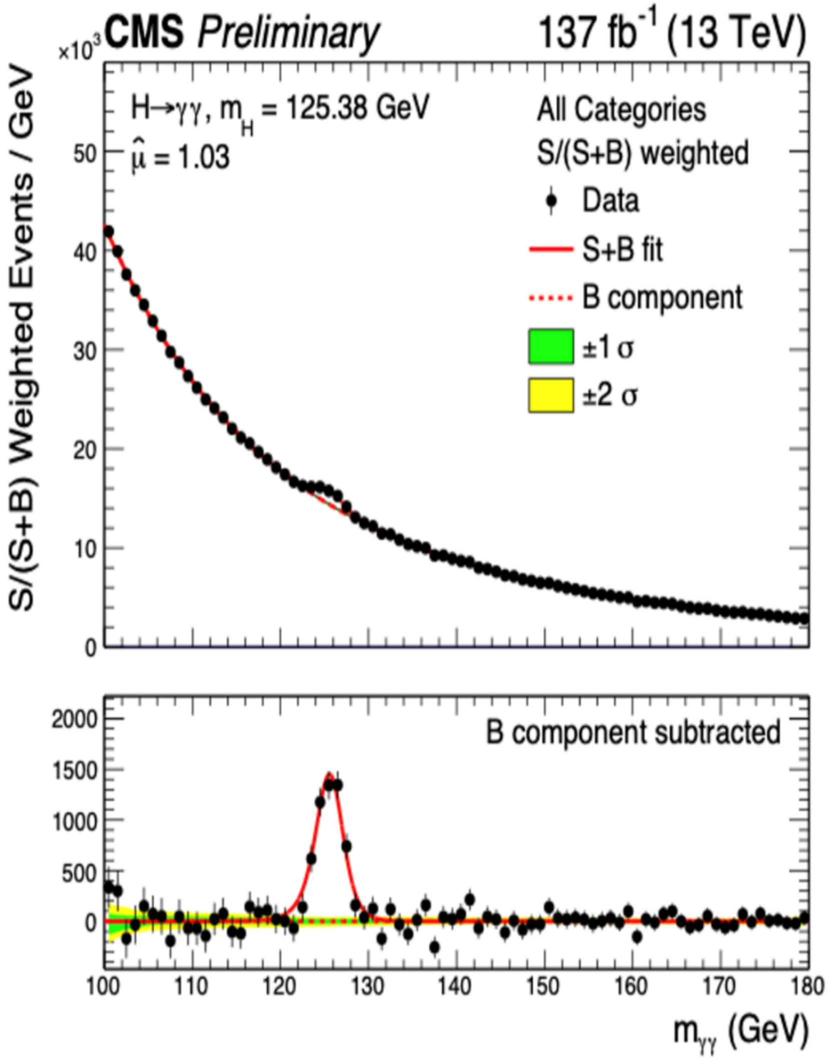
Degradation of energy resolution due to radiation damage
F. Ferri, presented in Calor 2022, Brighton



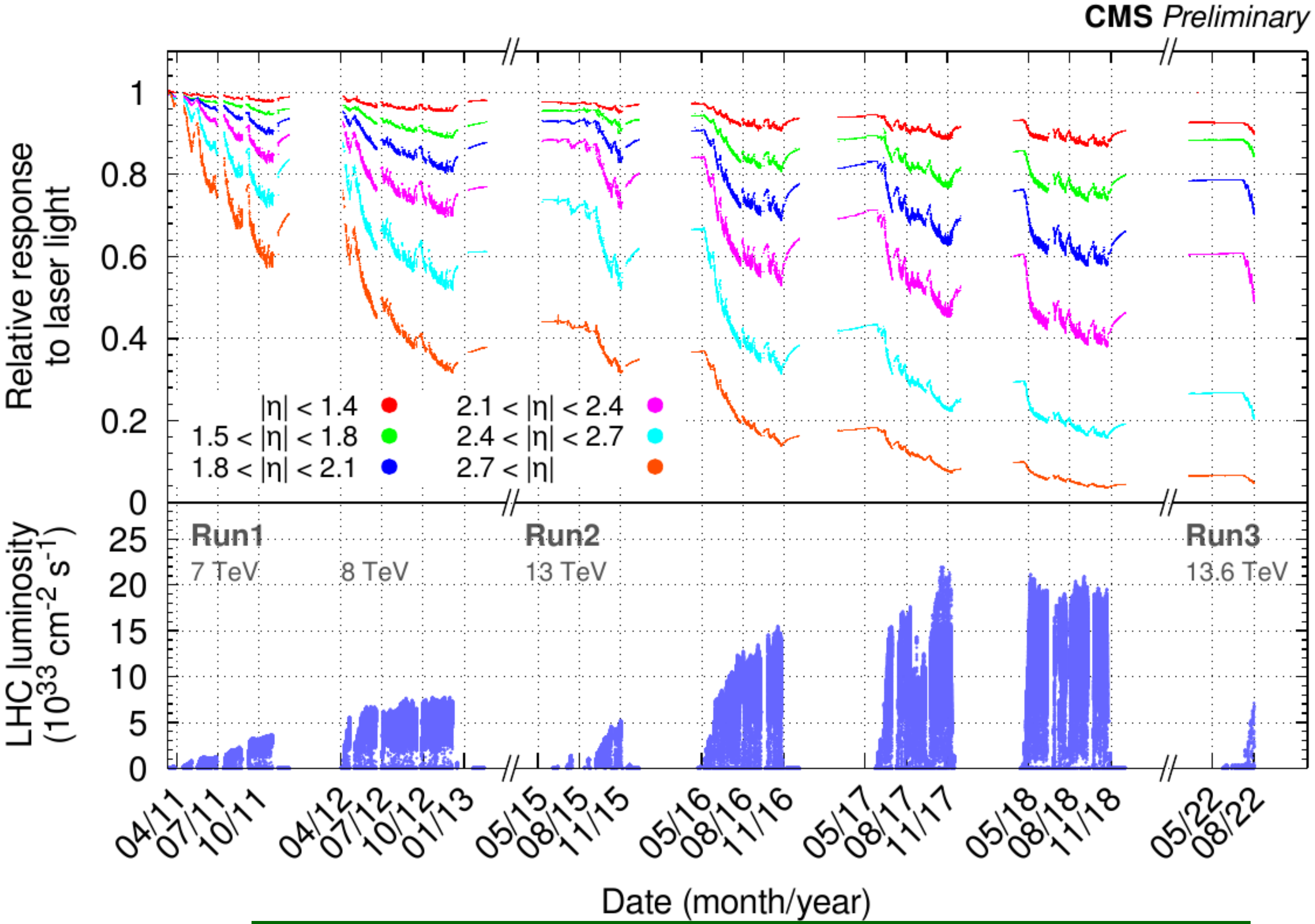




# CMS H -> $\gamma\gamma$ and PWO Damage



T. Dimova, TIPP2023, light monitoring data

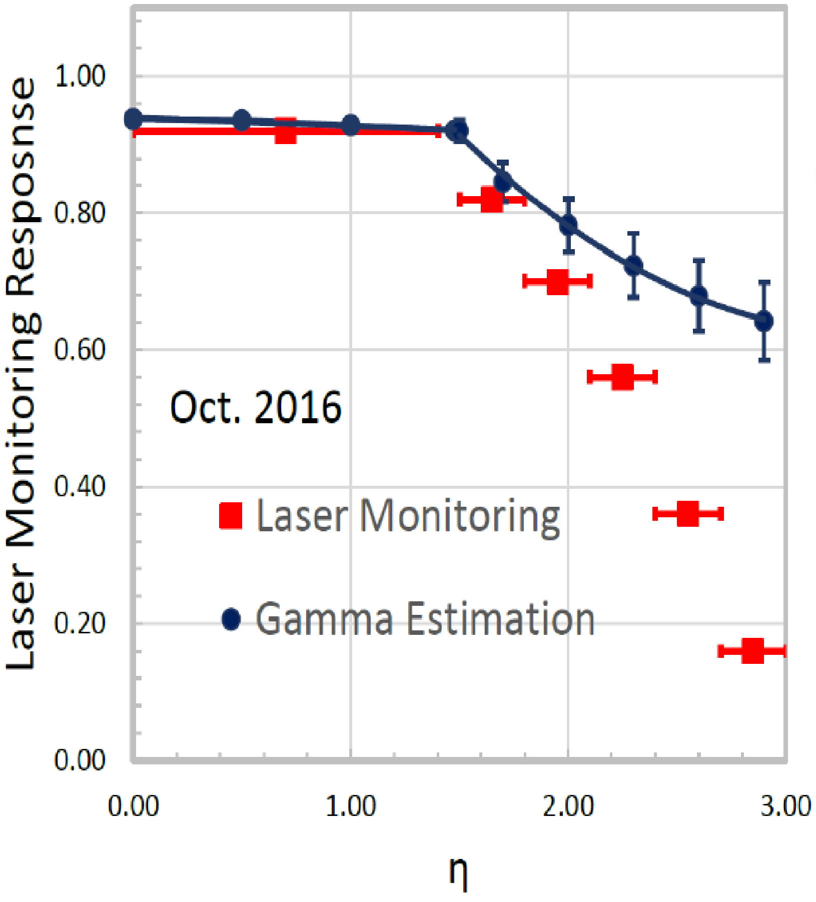


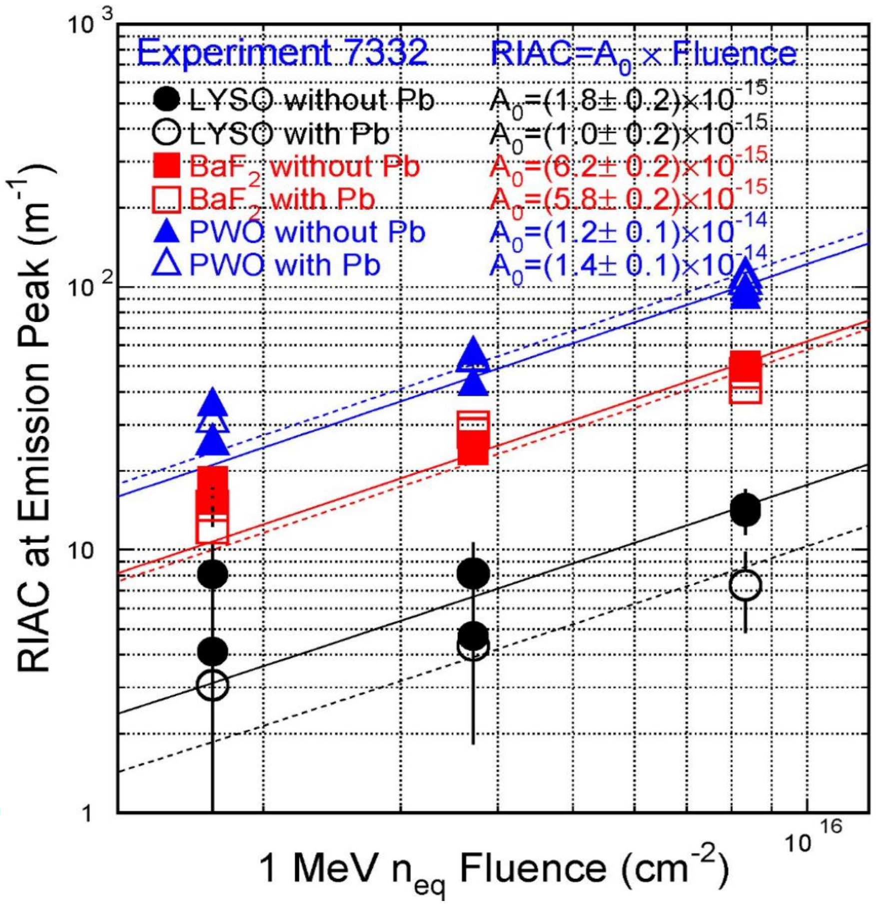
PWO damage due to ionization dose and hadrons

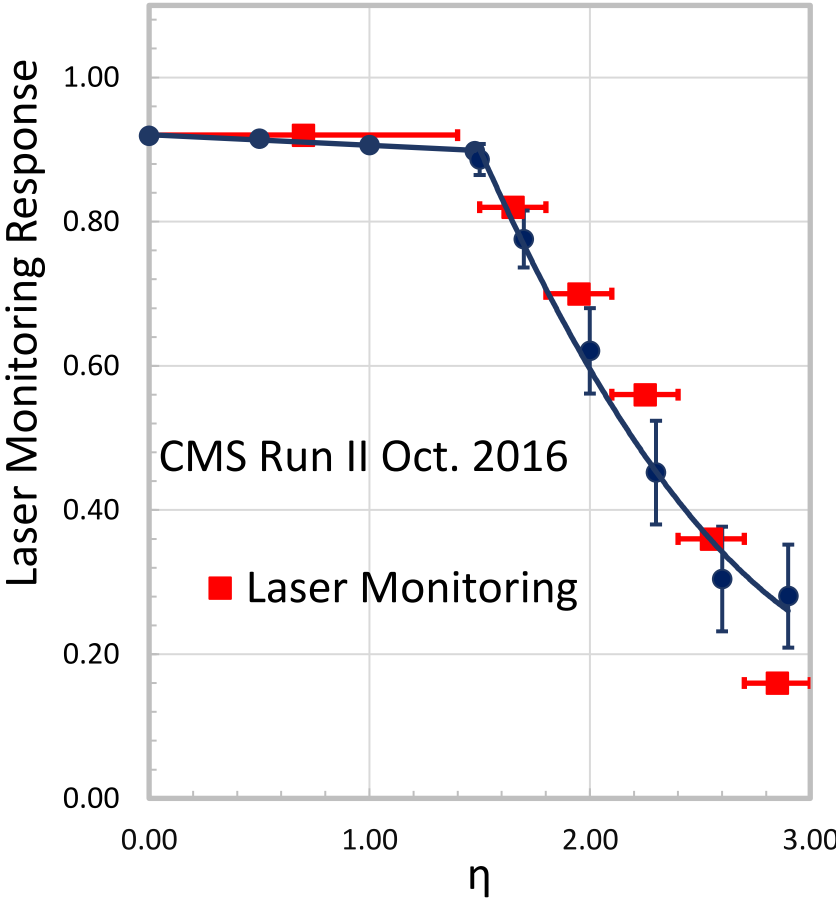
# PWO Damage by Ionization & Neutrons

RIAC in PWO = 1.4 × $10^{-14}$ × 1 MeV $n_{eq}$ Fluence

γ-ray and hadron induced absorption explains CMS PWO monitoring data
http://www.its.caltech.edu/~rzhu/talks/ryz_161028_PWO_mon.pdf & Trans. NS. 67 (2020) 1086-1092







# Comparison: ePIC and BTL at HL-LHC

The ionization dose rate and neutron flux of the ePIC PWO ECAL are two to three orders of magnitude lower than that of the CMS BTL (LYSO:Ce+SiPM) at the HL-LHC
The expected RIAC values are small. QC is needed for mass-produced PWO crystals

| Radiation | EIC / Year | EIC* | CMS BTL** / 4000 fb-1 (η= 0-1.45) | CMS BTL** (η= 0-1.45) |
|---|---|---|---|---|
| Ionization Dose | 3 Krad | 1.3 rad/h | 2.7-4.8 Mrad | 110-190 rad/h |
| 1 MeV eq. Neutrons | $10^{10}$ /cm$^2$ | 1.2×$10^3$ /cm$^2$/s | (2.5~2.9)×$10^{14}$ /cm$^2$ | (2.8~3.2)×$10^6$ /cm$^2$/s |
| Charged Hadrons | | | (2.2~2.5)×$10^{13}$ /cm$^2$ | (2.4~2.8)×$10^5$ /cm$^2$/s |

*Estimated by assuming 100 days operation per year.

** IEEE Trans. Nucl. Sci. NS-68 (2021) 1244-1250

# 2019 DOE Basic Research Needs Study
# Priority Research Directions for Calorimetry

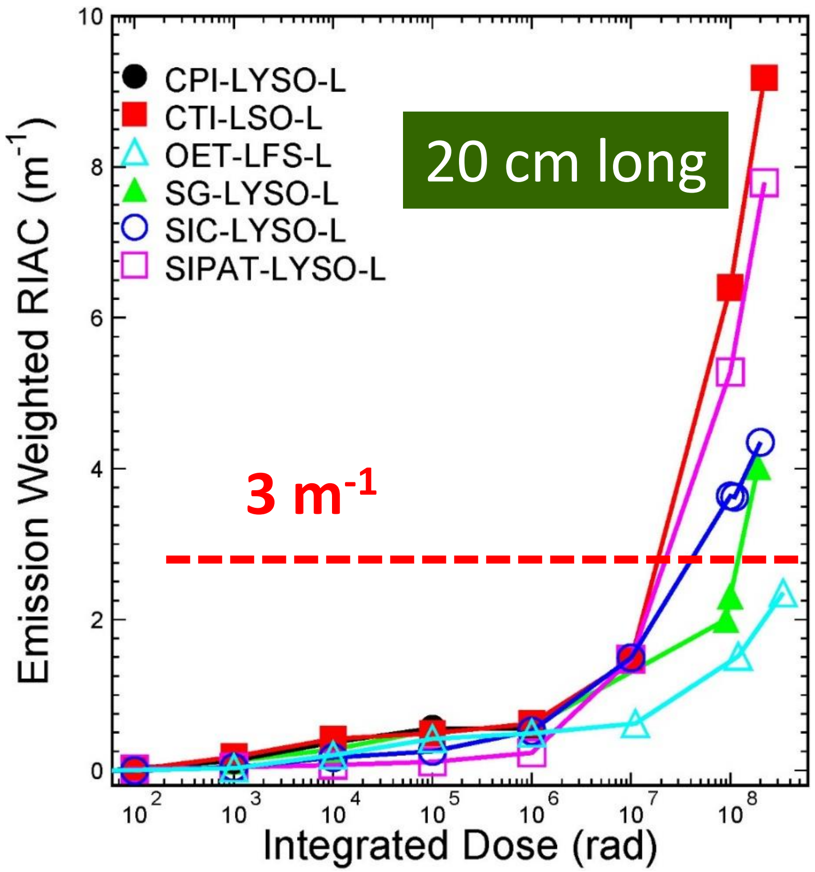
- Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements;
- Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments;
- Develop ultrafast media to improve background rejection in calorimeters and particle identication detectors.

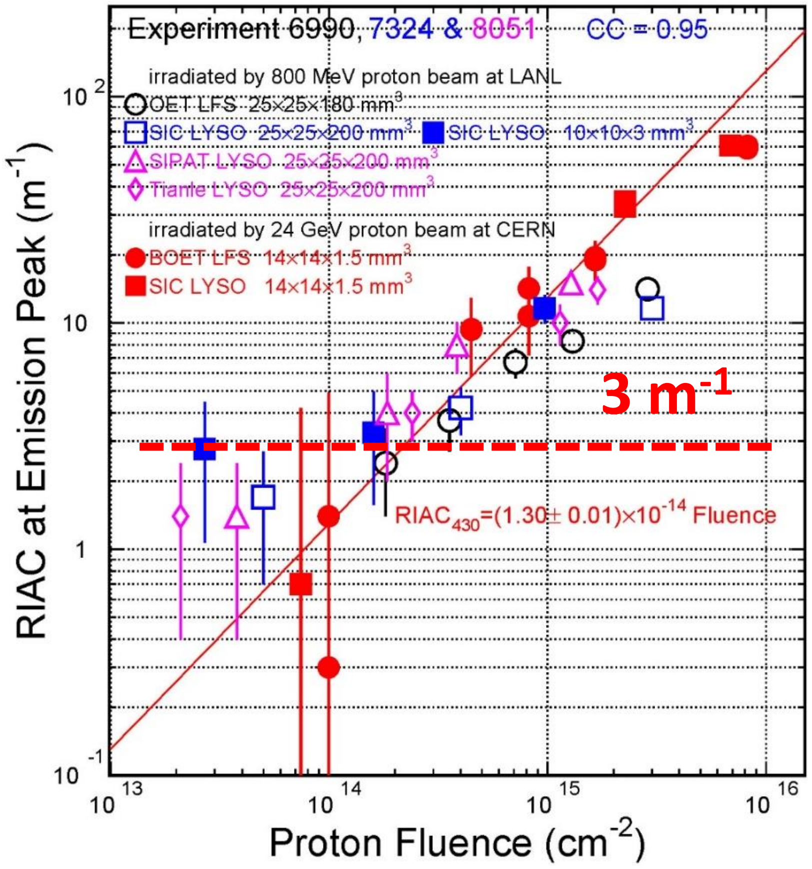
DOE 2019: https://www.osti.gov/servlets/purl/1659761
ECFA 2021: https://cds.cern.ch/record/2784893
Snowmass 2021: https://arxiv.org/abs/2209.14111
Fast/ultrafast, radiation hard and cost-effective inorganic scintillators

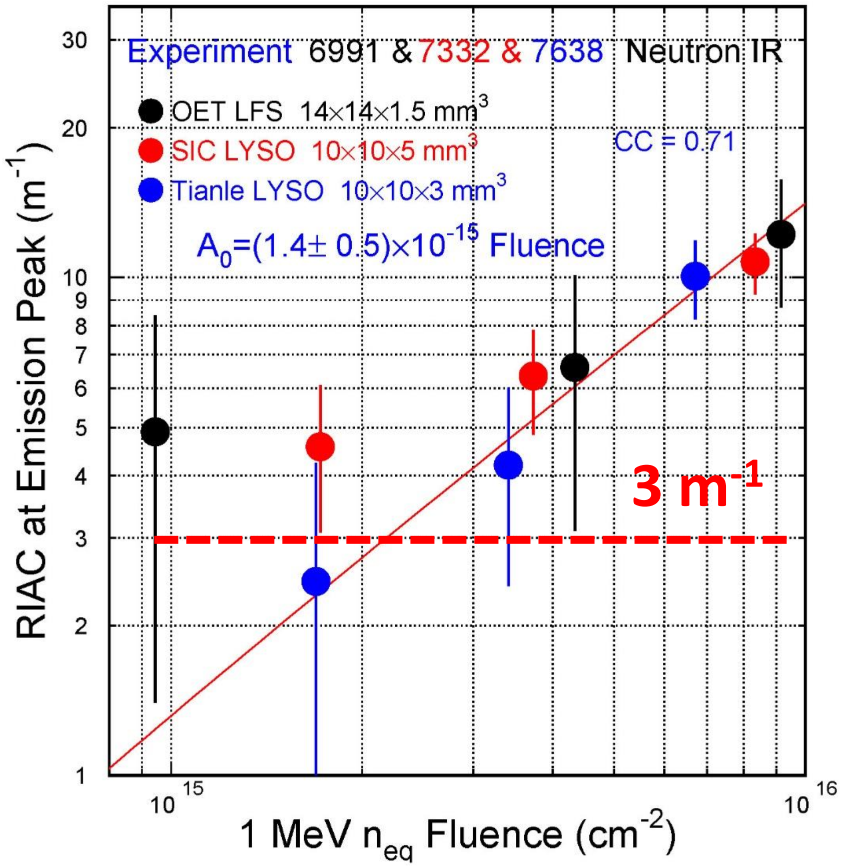
# LYSO:Ce Radiation Hardness

IEEE TNS 63 (2016) 612-619

CMS BTL LYSO spec: RIAC < 3 $m^{-1}$ after 4.8 Mrad, 2.5 x $10^{13}$ p/$cm^2$ and 3.2 x $10^{14}$ $n_{eq}$/$cm^2$







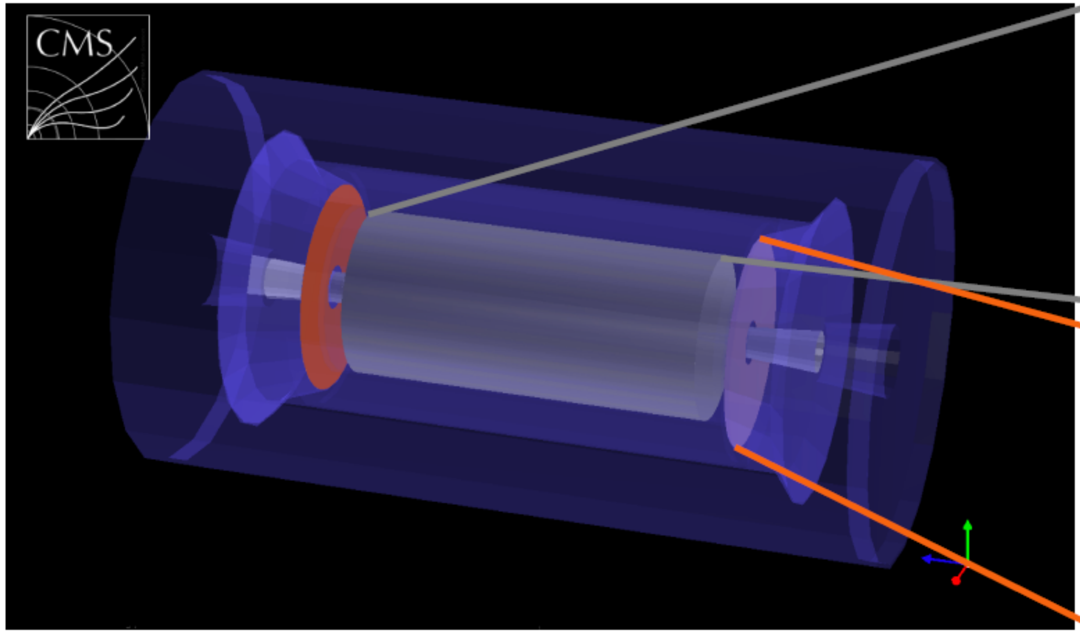
Damage induced by protons is larger than that from neutrons
Due to ionization energy loss in addition to displacement and nuclear breakup

# LYSO:Ce for CMS MIP Timing Detector

MTD performance goal: 30-40 ps at the start degrading to < 60 ps at 3000 $fb^{-1}$

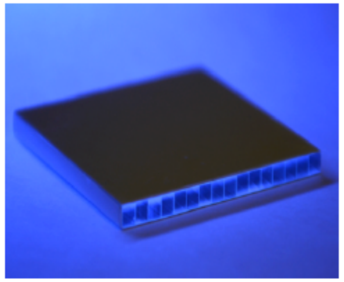
Barrel Timing Layer: arrays of LYSO crystal bars connected to SiPMs at both ends and readout by TOFHIR

Ultrafast inorganic scintillators would help to break the pico-second time barrier



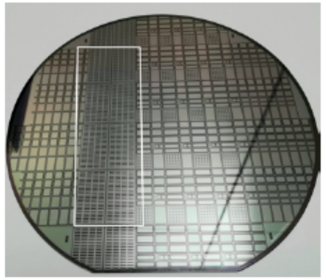
**BTL: LYSO bars + SiPM read-out**

- TK / ECAL interface ~ 45 mm thick
- $|\eta| < 1.45$ and $p_T > 0.7$ GeV
- Active area ~ 38 $m^2$ ; 332k channels
- Fluence at 3 $ab^{-1}$: $2\times10^{14}$ $n_{eq}/cm^2$

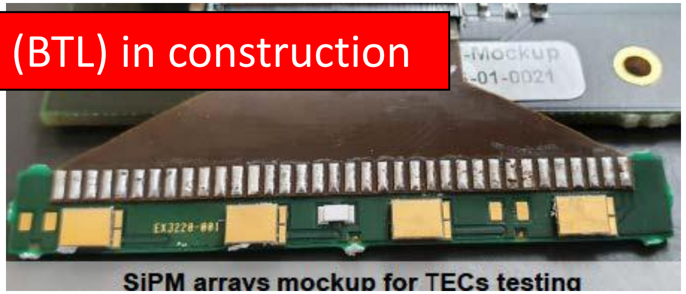


**ETL: Si with internal gain (LGAD)**

- On the HGC nose ~ 65 mm thick
- $1.6 < |\eta| < 3.0$
- Active area ~ 14 $m^2$; ~ 8.5M channels
- Fluence at 3 $ab^{-1}$: up to $2\times10^{15}$ $n_{eq}/cm^2$



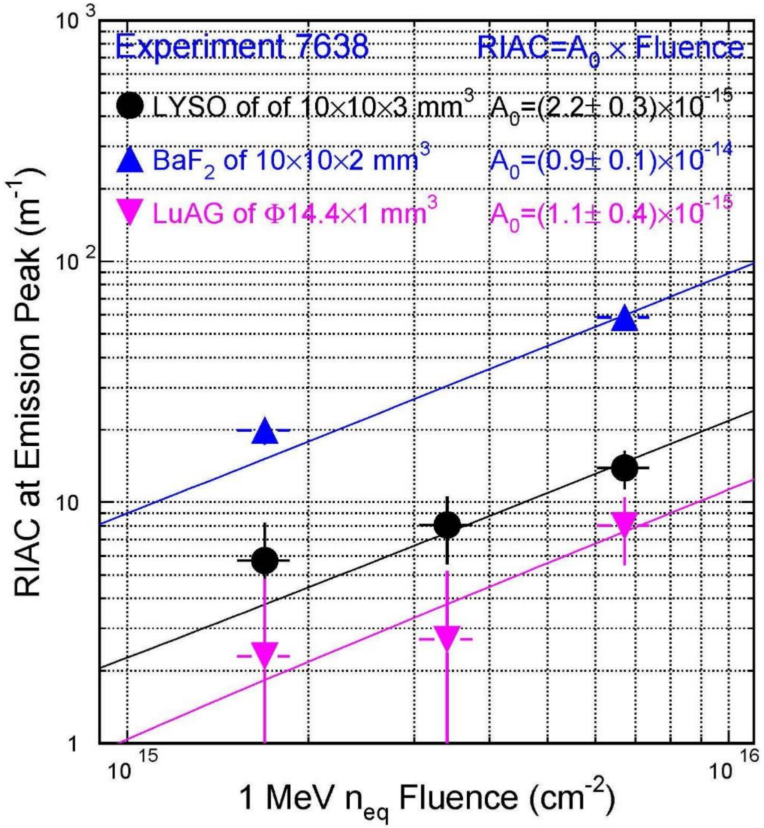
LYSO + SiPM with Thermal Electric Cooler (TEC) for CMS Barrel Timing Layer (BTL) in construction

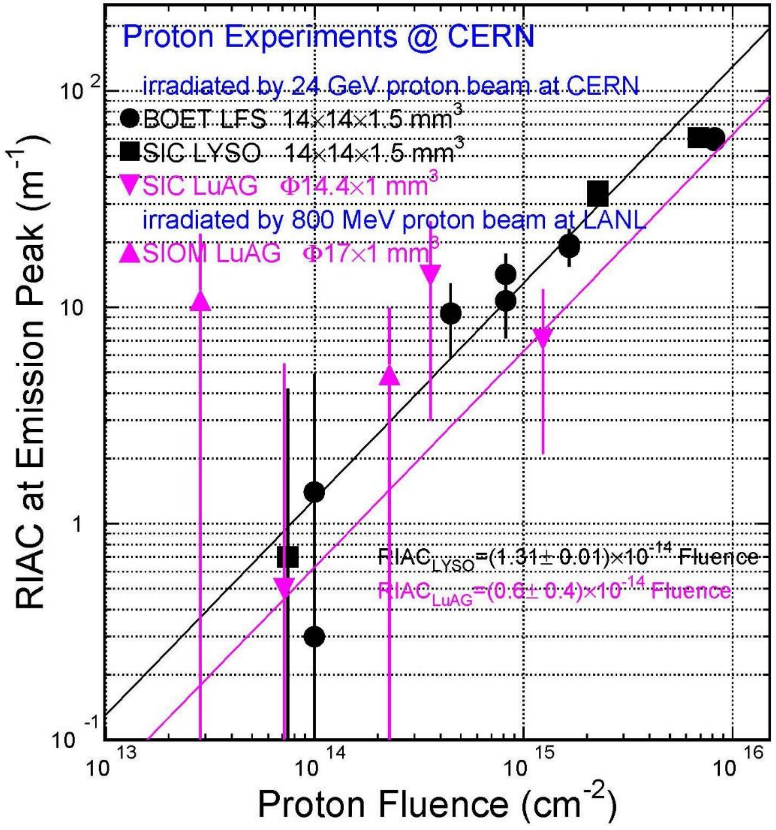


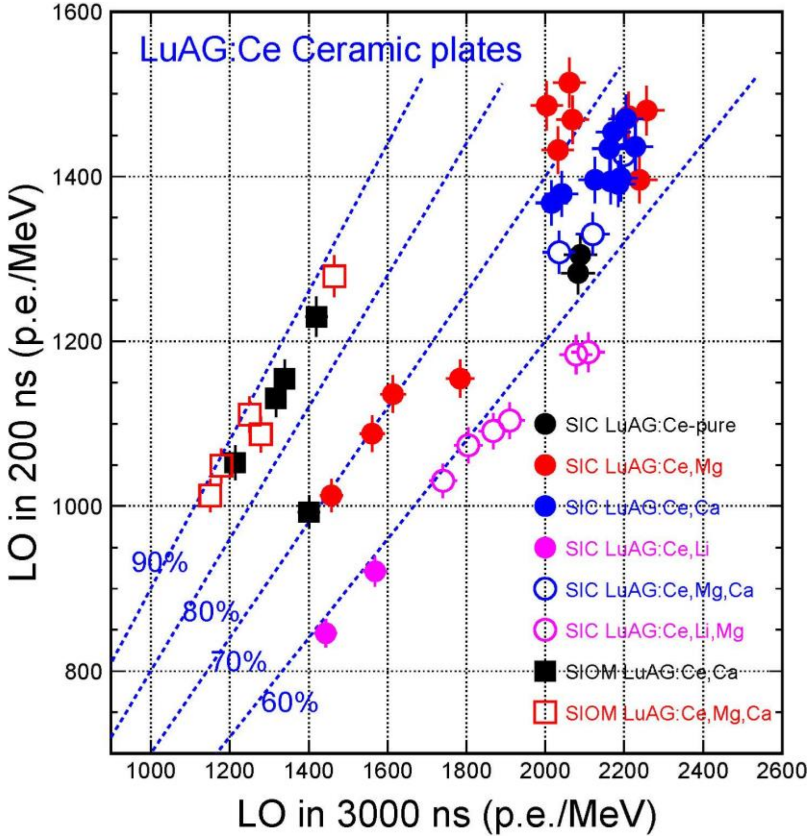
# LuAG:Ce Ceramics Radiation Hardness

IEEE TNS 69 (2022) 181-186

LuAG:Ce ceramics show a factor of two smaller RIAC values than LYSO:Ce up to $6.7\times10^{15}$ $n_{eq}/cm^2$ and $1.2\times10^{15}$ $p/cm^2$, promising for FCC-hh





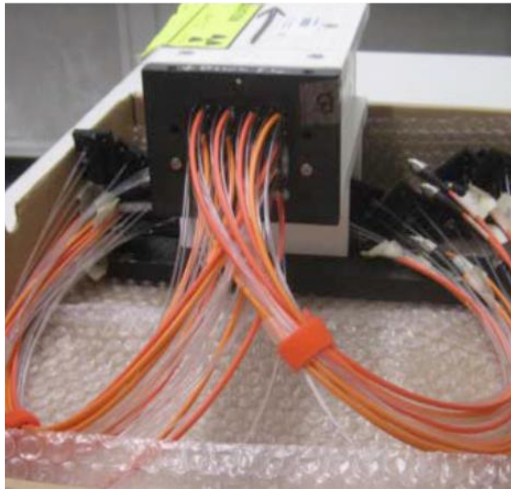


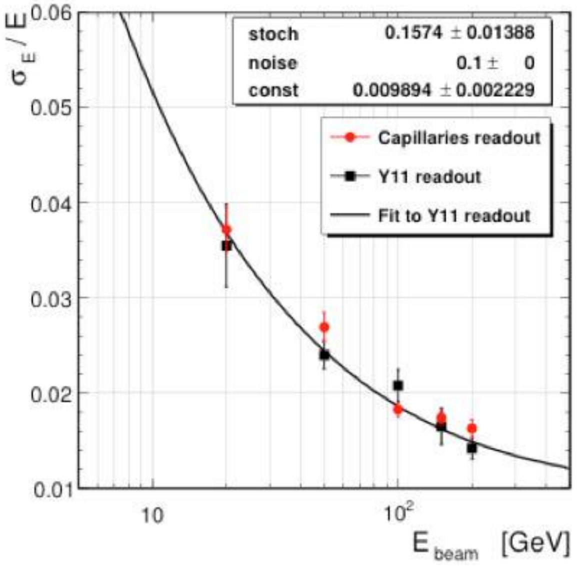
R&D on slow component suppression by Ca co-doping, and radiation hardness by ɣ/p/n

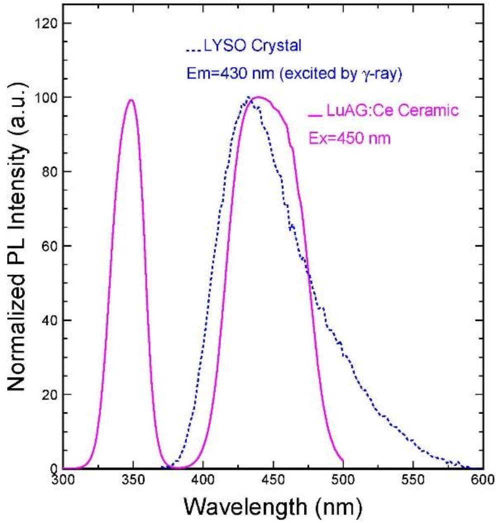
# RADiCAL: LYSO/LuAG Shashlik ECAL

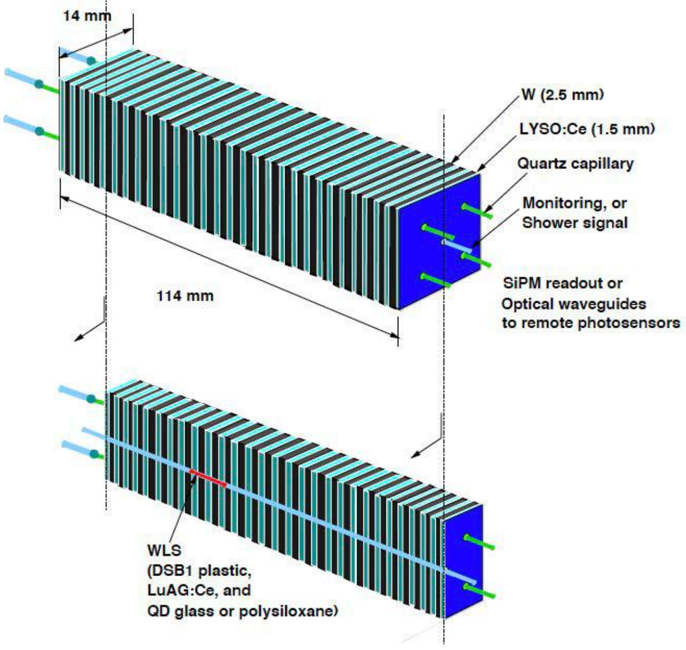
arXiv: 2203.12806

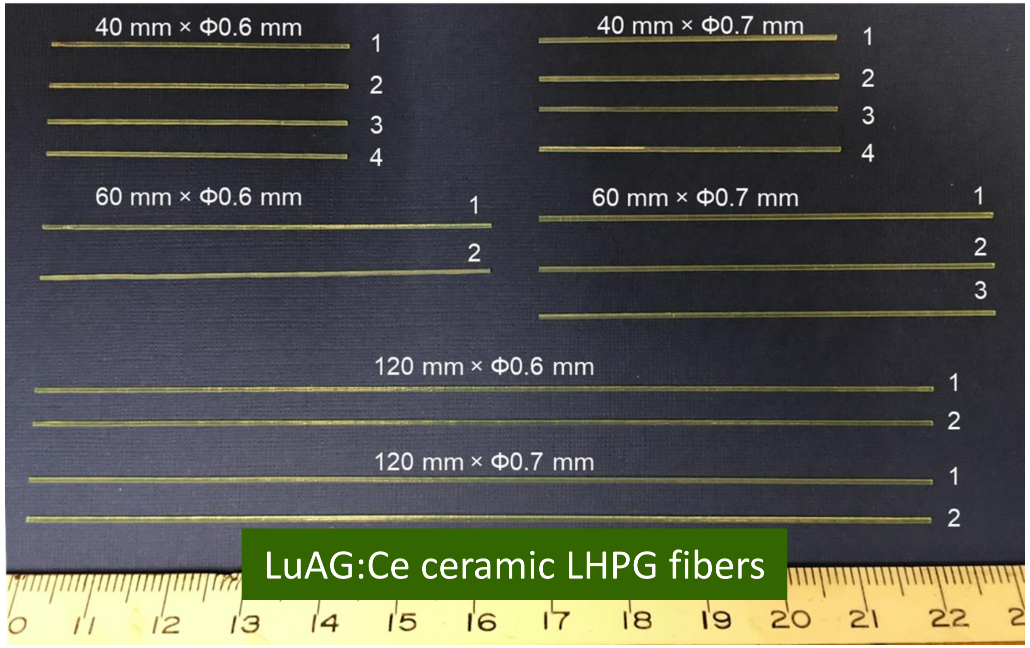
**RAD**iation hard **CAL**orimetry
Reducing light path length to mitigate radiation damage effect
Using radiation hard materials: LuAG:Ce ceramics excitation matches LYSO:Ce emission



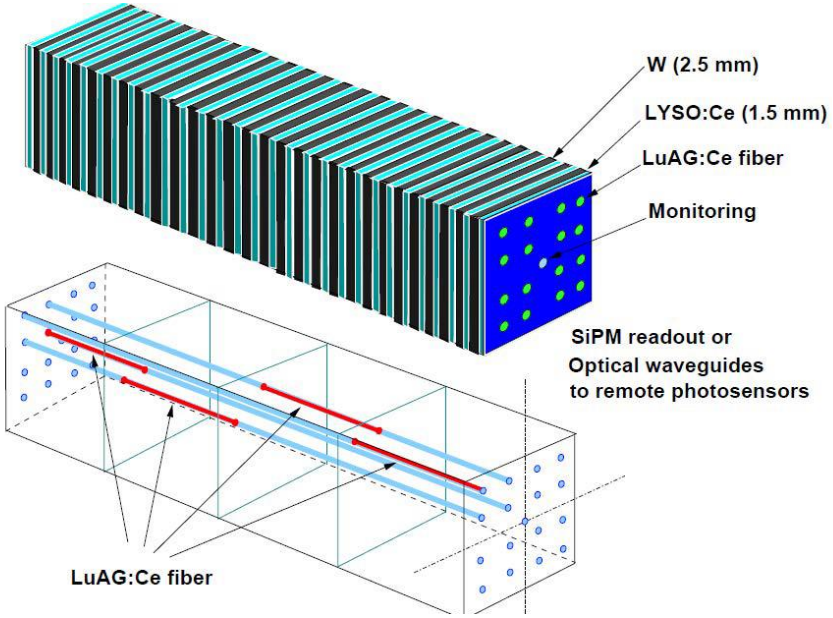








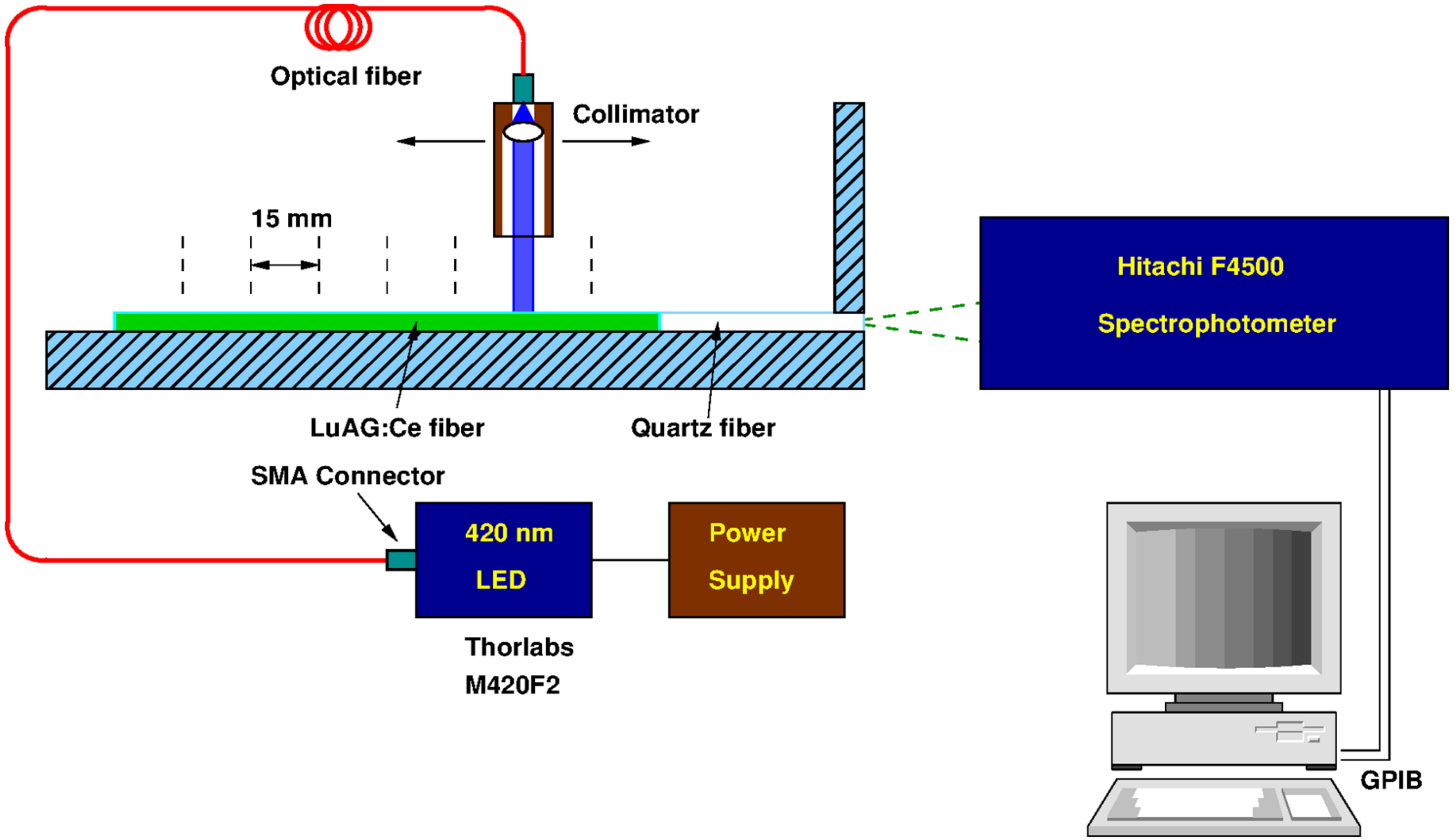
LuAG:Ce ceramic LHPG fibers

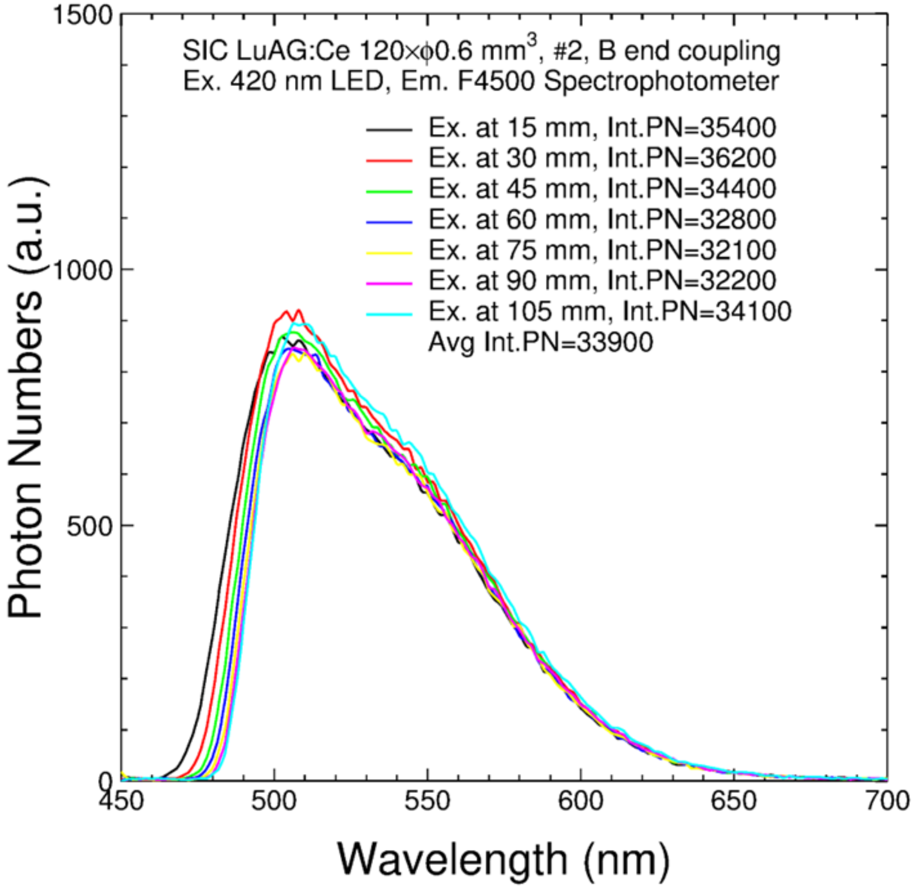


# Light Output and Response Uniformity

10.1109/NSS/MIC44867.2021.9875908

Excellent longitudinal uniformity observed for a Φ0.6 ×120 mm$^3$ LuAG:Ce ceramic excited by a 420 nm LED at different location, with a solid coupling to a quartz fiber, mimicking its application in RADiCAL

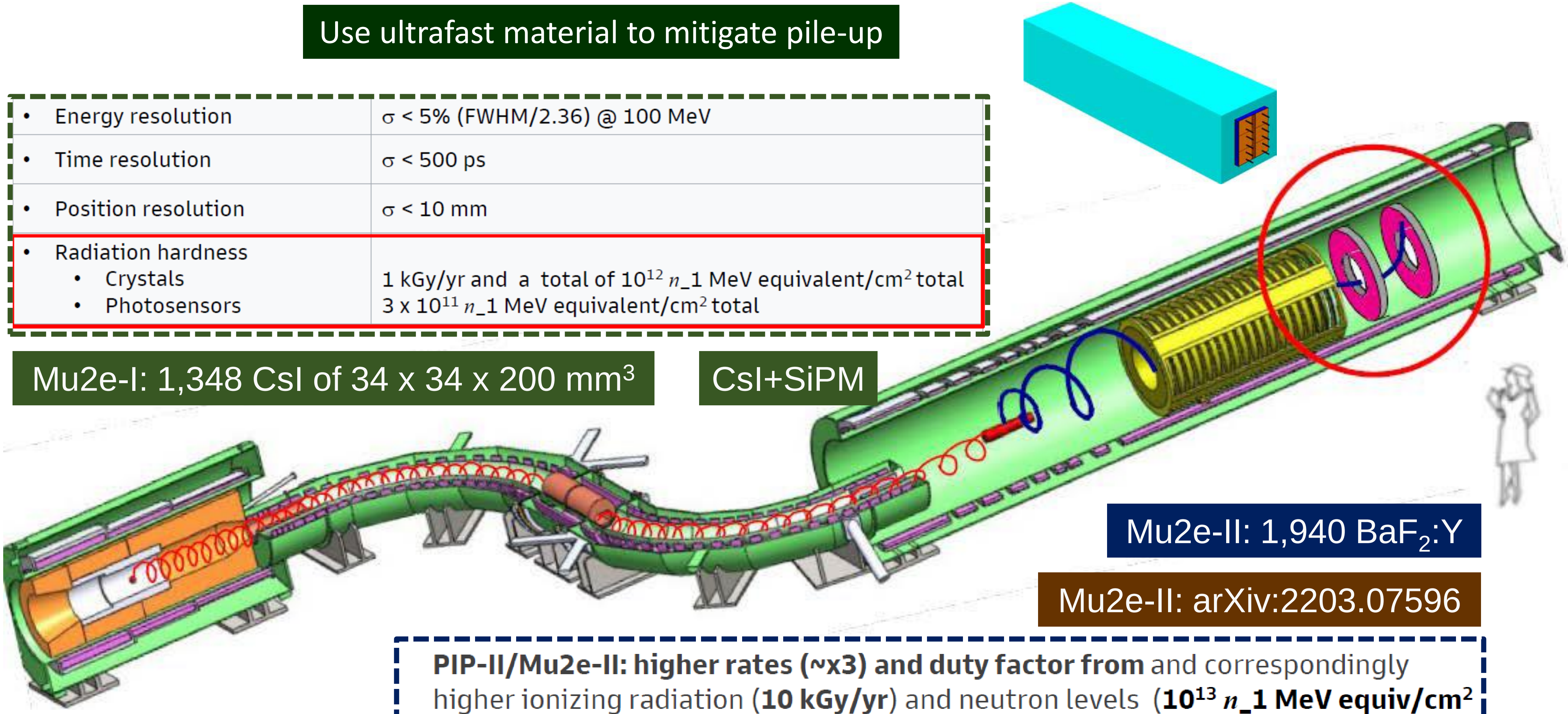




# Ultrafast BaF$_2$:Y Calorimeter for Mu2e-II

Use ultrafast material to mitigate pile-up

| | |
|---|---|
| • Energy resolution | $\sigma < 5\%$ (FWHM/2.36) @ 100 MeV |
| • Time resolution | $\sigma < 500$ ps |
| • Position resolution | $\sigma < 10$ mm |
| • Radiation hardness<br>• Crystals<br>• Photosensors | <br>1 kGy/yr and a total of $10^{12}$ $n$_1 MeV equivalent/cm$^2$ total<br>3 x $10^{11}$ $n$_1 MeV equivalent/cm$^2$ total |



Mu2e-I: 1,348 CsI of 34 x 34 x 200 mm$^3$

CsI+SiPM

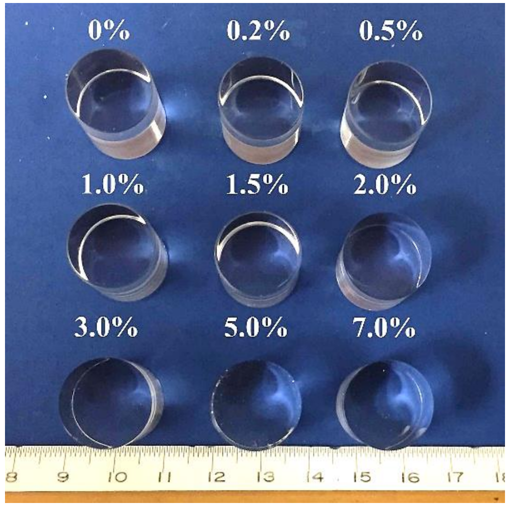
Mu2e-II: 1,940 BaF$_2$:Y

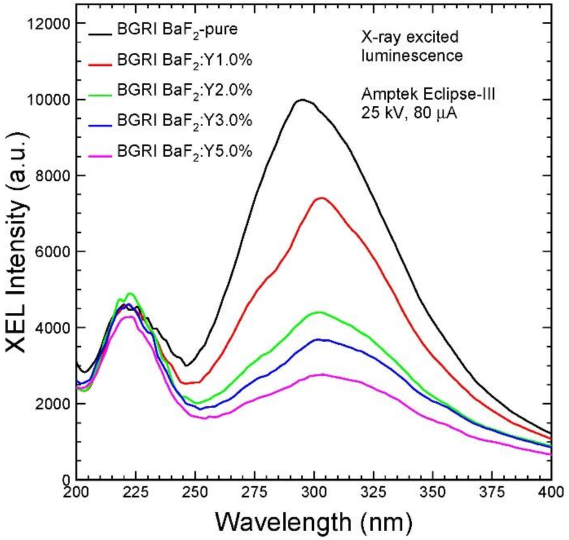
Mu2e-II: arXiv:2203.07596

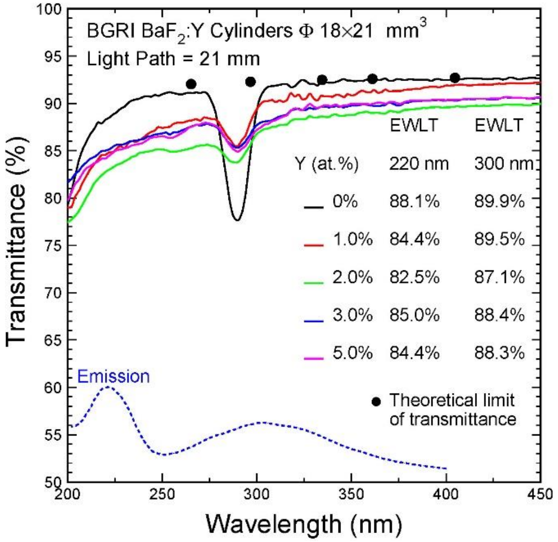
**PIP-II/Mu2e-II: higher rates (~x3) and duty factor from** and correspondingly higher ionizing radiation (**10 kGy/yr**) and neutron levels (**$10^{13}$ $n$_1 MeV equiv/cm$^2$ total**), which are particularly important at the inner radius of disk 1

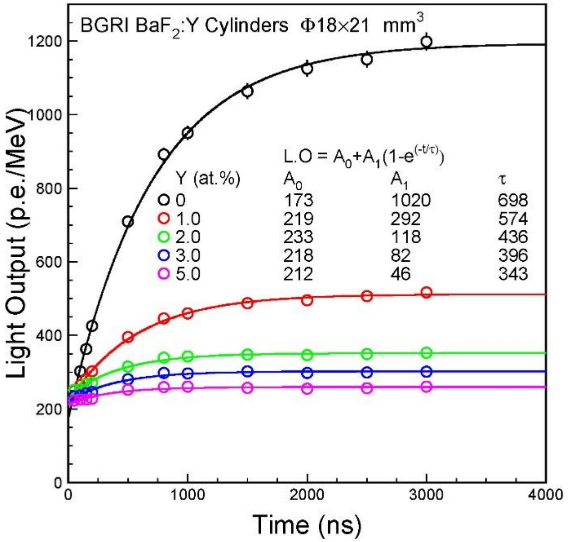
# $BaF_2$:Y for Calorimetry & Imaging

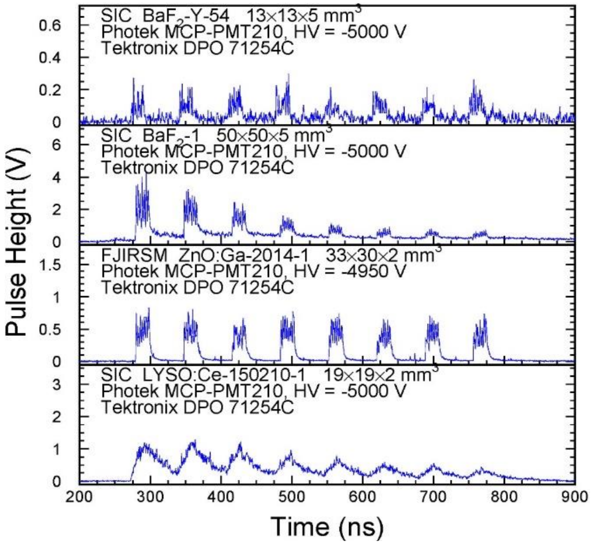
Increased F/S ratio observed in BGRI $BaF_2$:Y crystals: Proc. SPIE 10392 (2017)

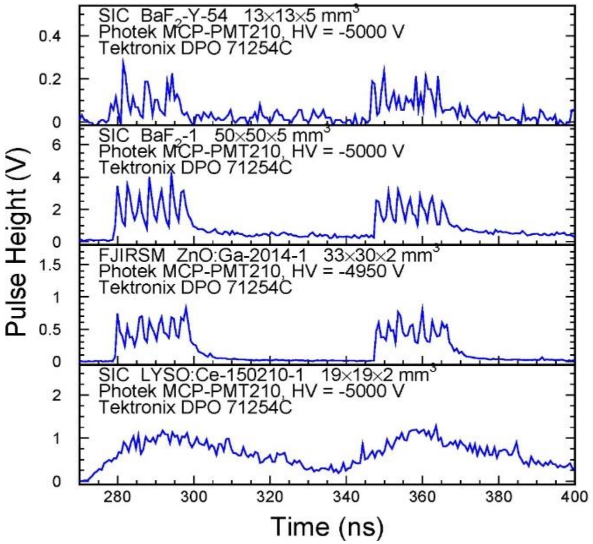


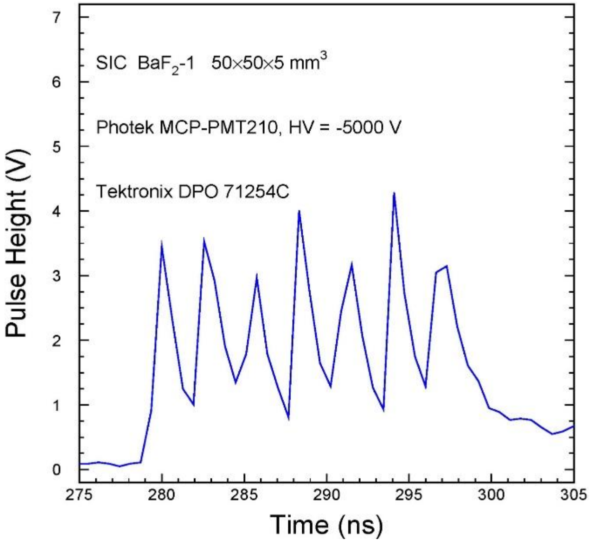












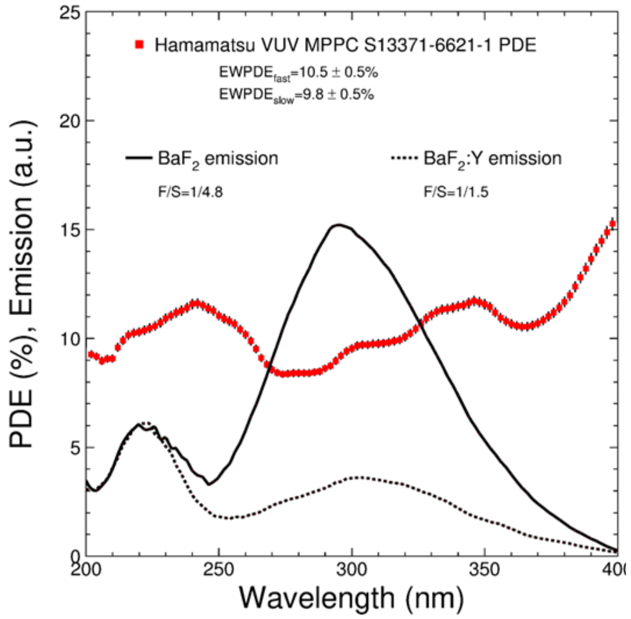
X-ray bunches with 2.83 ns spacing in septuplet are clearly resolved by ultrafast $BaF_2$:Y and $BaF_2$ crystals: for GHz Hard X-ray Imaging NIMA 240 (2019) 223-239

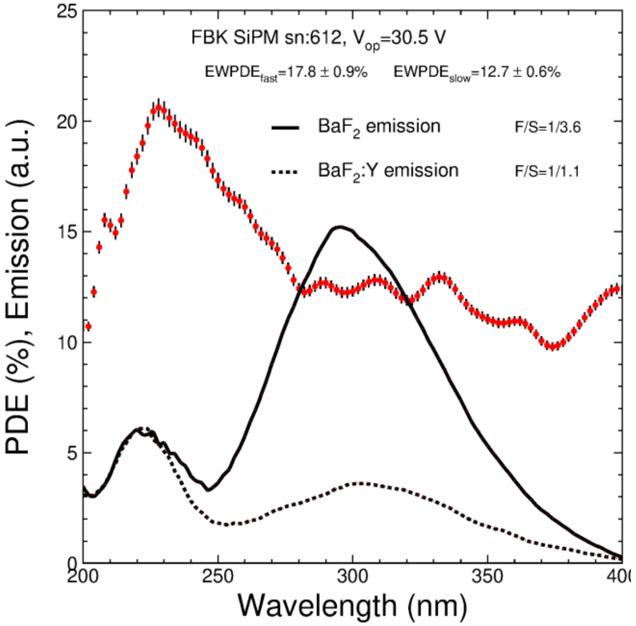
# PDE of UV SiPM for $BaF_2$ and $BaF_2$:Y

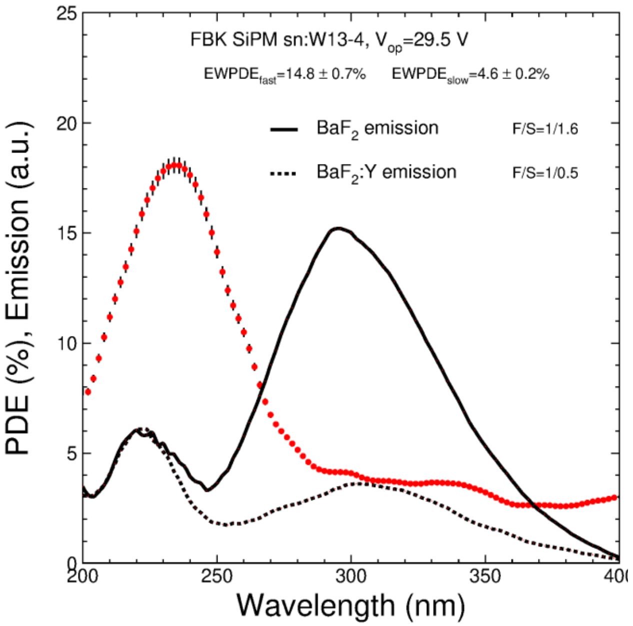
IEEE TNS **69** (2022) 958-964

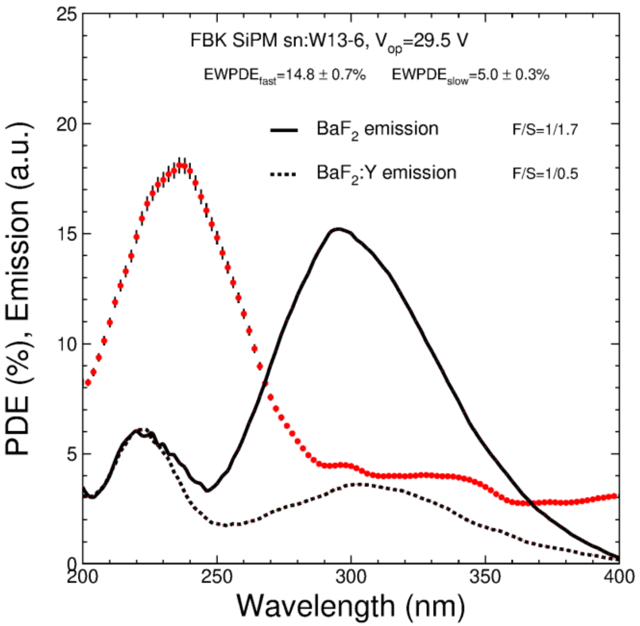
| Photodetector | $EWPDE_{fast}$ (%) | $EWPDE_{slow}$ (%) | Relative $F/S_{BaF}$ | Relative $F/S_{BaF:Y}$ |
|---|---|---|---|---|
| Hamamatsu MPPC | 10.5 | 9.8 | 1/4.8 | 1/1.5 |
| FBK SiPM 2021 | 17.8 | 12.7 | 1/3.6 | 1/1.1 |
| FBK SiPM 2023-1 | 14.8 | 4.6 | 1/1.6 | 1/0.5 |
| FBK SiPM 2023-2 | 14.8 | 5.0 | 1/1.7 | 1/0.5 |

γ-ray induced readout noise is reduced by $BaF_2$:Y slow suppression & solar-blind PDE



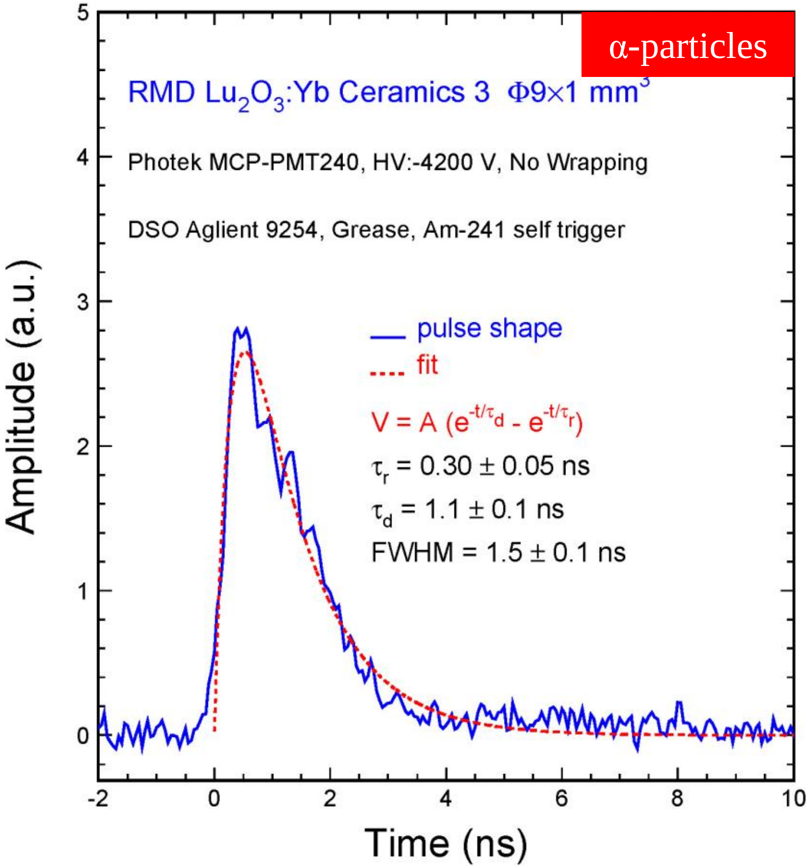


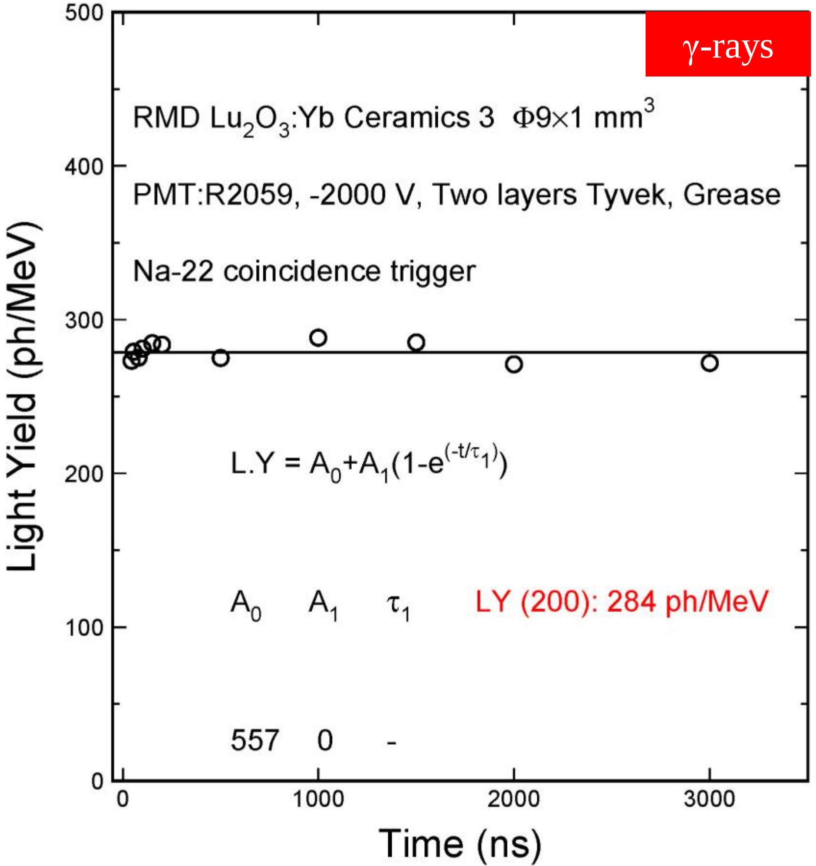


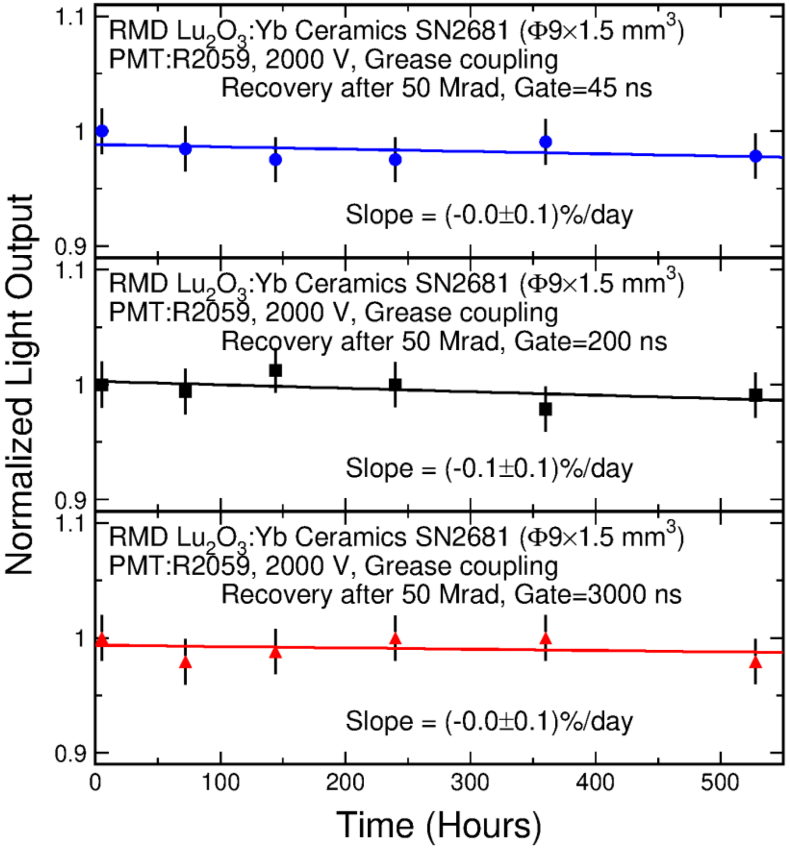


# Novel $Lu_2O_3$:Yb Ceramics

Presented in the NSS2022 conference https://www.its.caltech.edu/~rzhu/talks/NSS22_N21-03.pdf





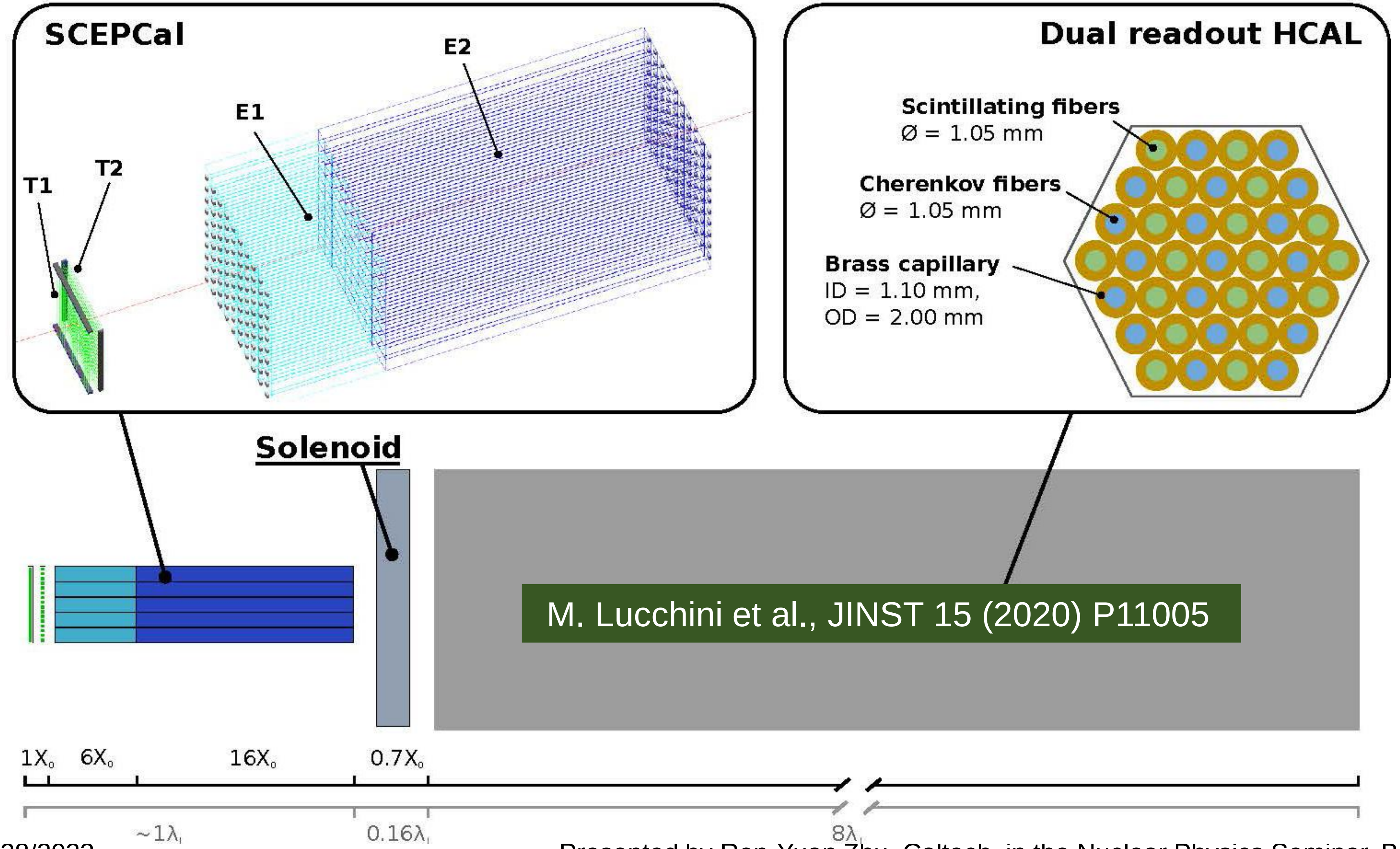


$Lu_2O_3$:Yb ceramic of 9.4 g/cc shows an ultrafast decay time of **1.1 ns** by Am-241 with negligible slow component observed in integrated light output measurement

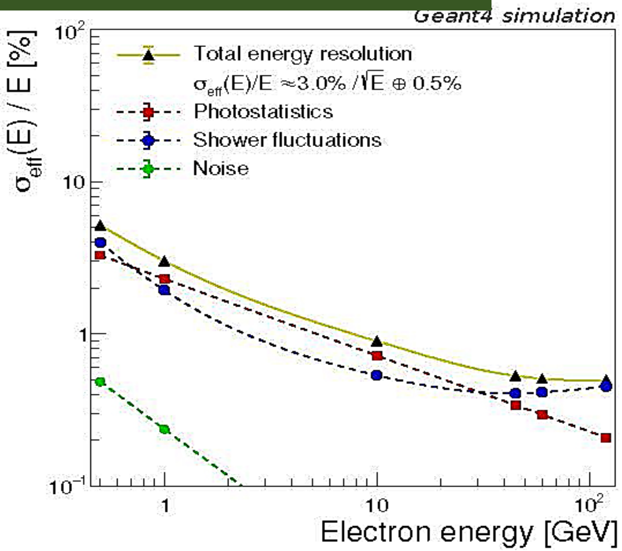
# CalVision: Segmented Crystal ECAL

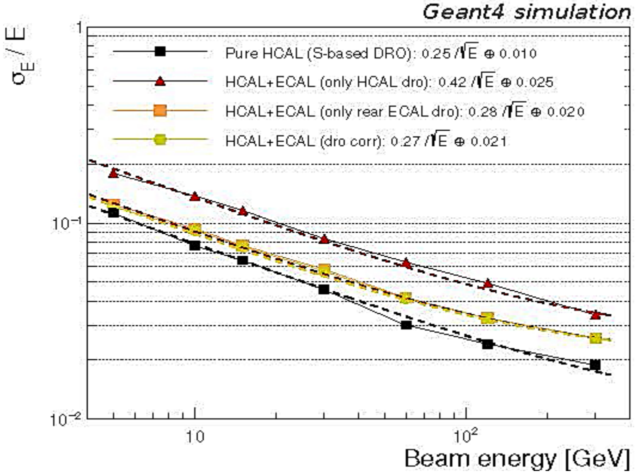
arXiv: 2203.04312

Followed by the IDEA DR HCAL, aiming at both EM and jet resolution

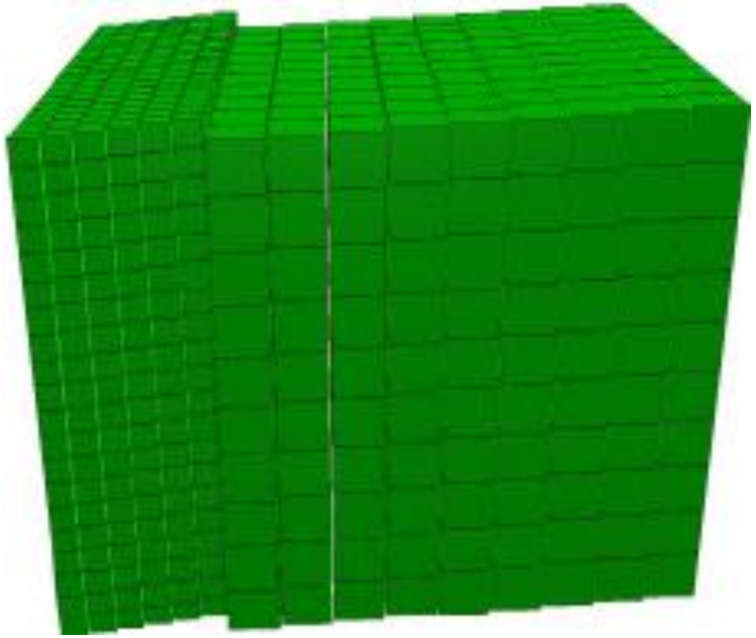


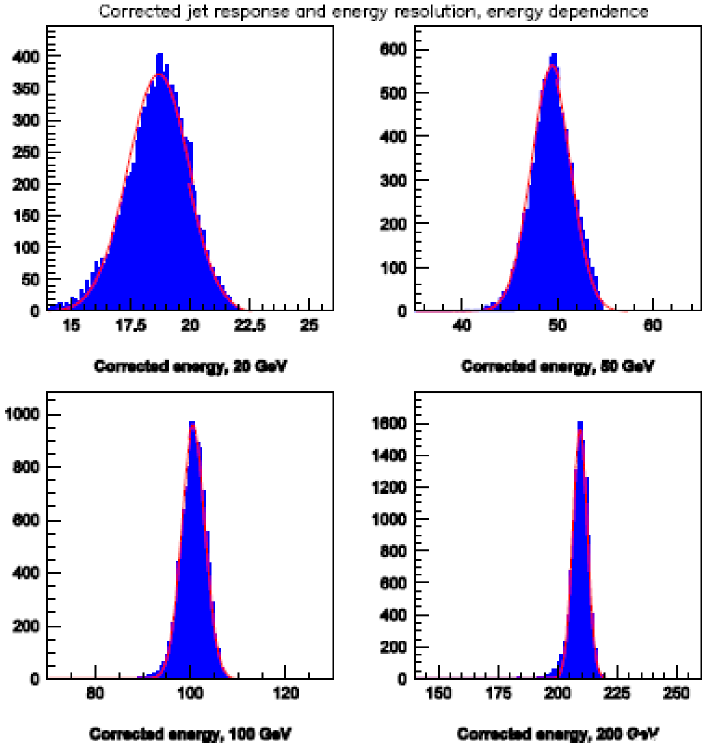
M. Lucchini et al., JINST 15 (2020) P11005



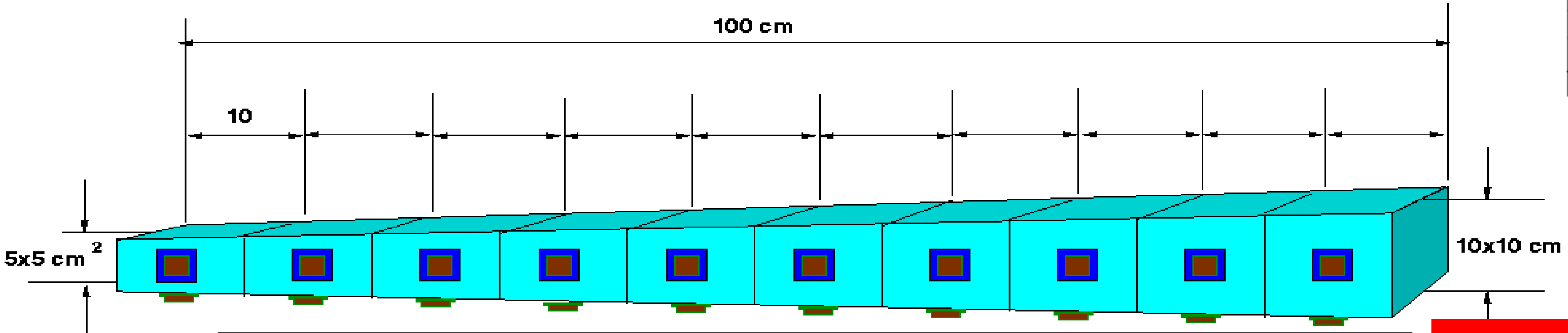


# The HHCAL Concept



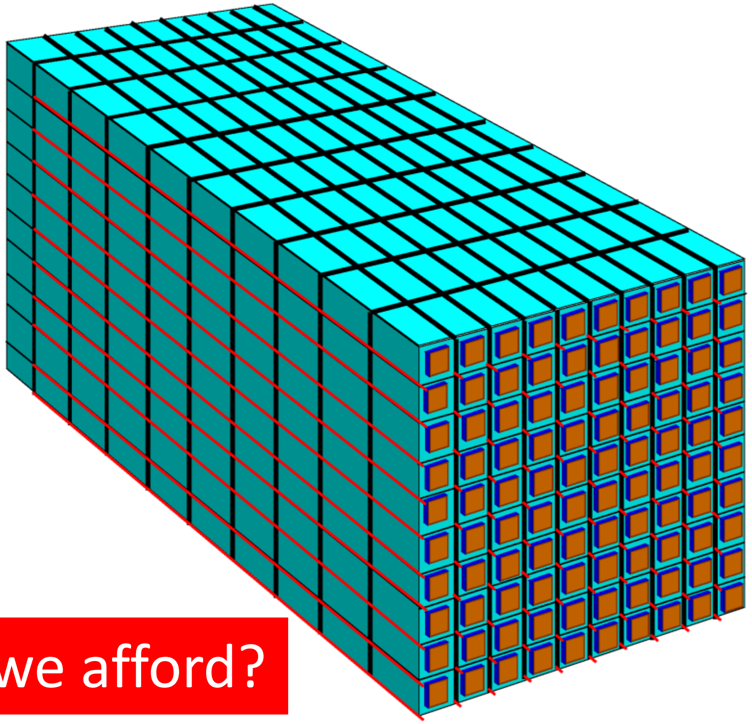


A. Para, H. Wenzel and S. McGill in Callor2012 Proceedings and A. Benaglia *et al.*, IEEE TNS **63** (2016) 574-579: a jet energy resolution at a level of 20%/√E by HHCAL with dual readout of S/C or dual gate.
M. Demarteau, 2021 CPAD Workshop



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

Can we afford?

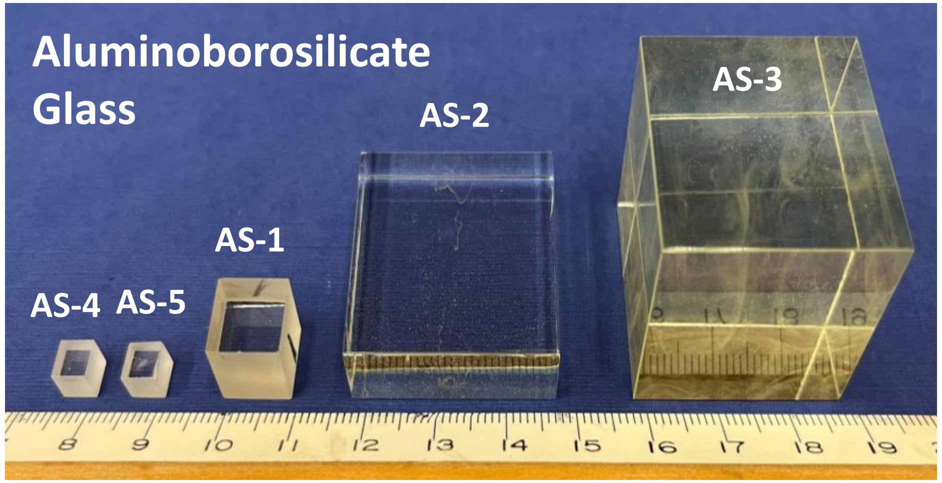


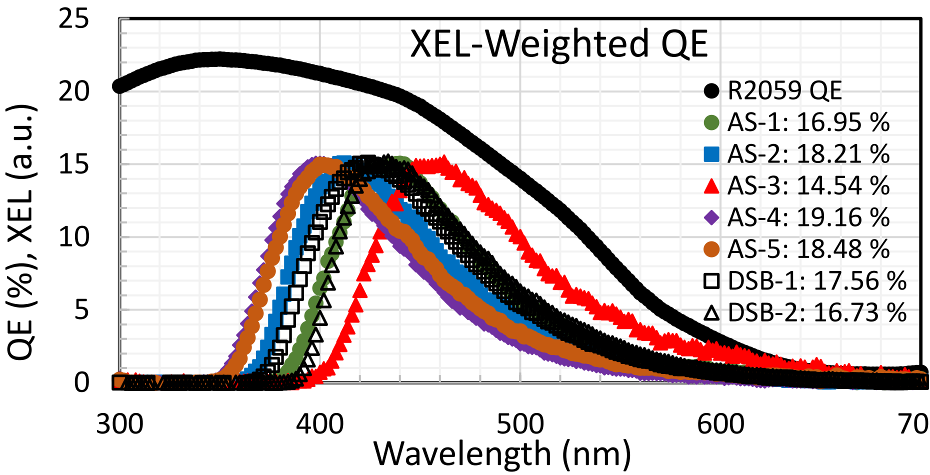
# Crystal Cost for CEPC (Mar 2019)

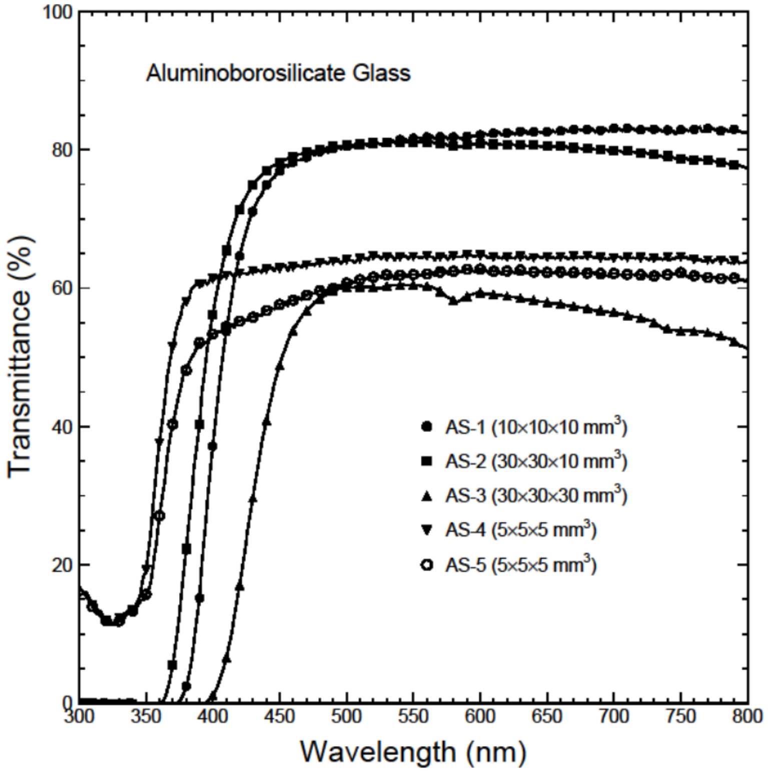
Cost-effectiveness scaled with $X_0$: PWO, BGO, CsI, BSO, $BaF_2$:Y, LYSO

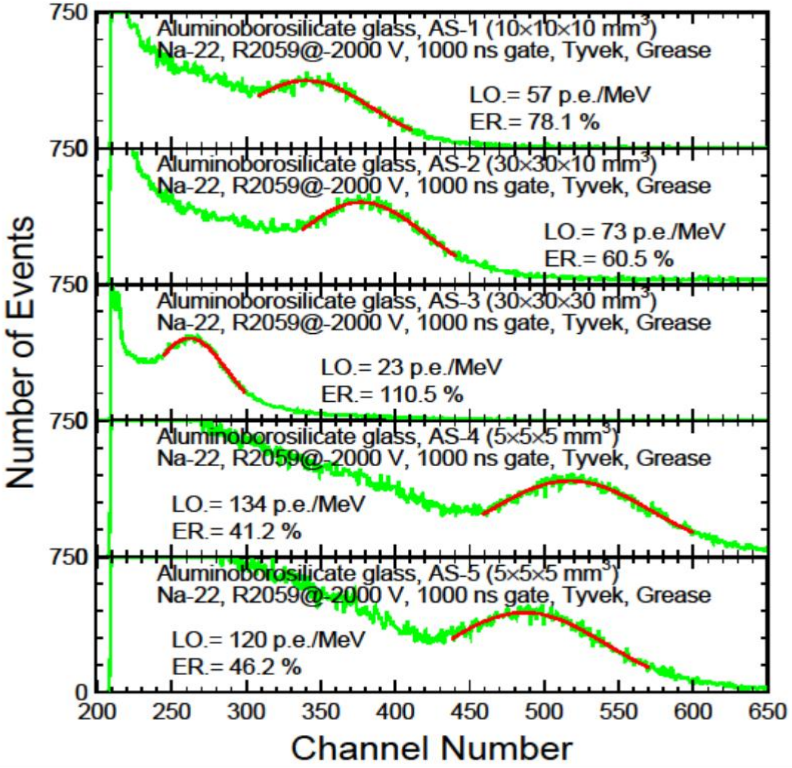
| Item | Size ($R_M$x$R_M$x25 $X_0$) | 1 $m^3$ | 10 $m^3$ | 100 $m^3$ | Scaled to $X_0$ |
|---|---|---|---|---|---|
| BGO | 22.3×22.3×280 mm | $8/cc | $7/cc | $6/cc | 1.23 |
| $BaF_2$:Y | 31.0×31.0×507.5 cm | $12/cc | $11/cc | $10/cc | 2.28 |
| LYSO:Ce | 20.7x20.7x285 mm | $36/cc | $34/cc | $32/cc | 1.28 |
| PWO | 20x20x223 mm | $9/cc | $8/cc | $7.5/cc | 1.00 |
| BSO | 22x22x274 mm | $8.5/cc | $7.5/cc | $7.0/cc | 1.29 |
| CsI | 35.7x35.7x465 mm | $4.6/cc | $4.3/cc | $4.0/cc | 2.09 |

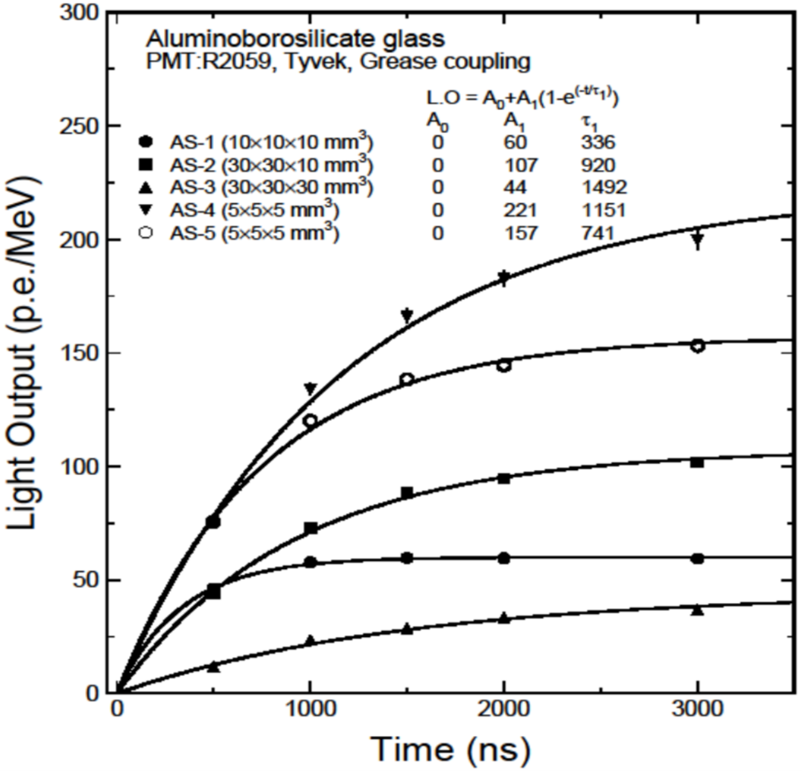
# ABS ($B_2O_3$–$SiO_2$–$Al_2O_3$–$Gd_2O_3$–$Ce_2O_3$) Glass











# Inorganic Scintillators for HHCAL

Presented in the 9/14/2023 CalVision meeting all samples measured at Caltech

| | BGO | BSO | PWO | $PbF_2$ | PbFCl | Sapphire:Ti | AFO:Ce 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 |
| **$\lambda_I$ (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<br>420 | \ | 420 | 300<br>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<br>10 | \ | 3 | 300<br>3200 | 40 | 500 | 740 |
| **d(LY)/dT (%/$^o$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 |

# Summary

The HL-LHC and FCC-hh require fast and radiation hard inorganic scintillator.

**RADiCAL** proposes an ultra-compact, fast timing and longitudinally segmented shashlik calorimeter with LuAG:Ce ceramics as wavelength shifter for LYSO:Ce crystals. R&D is on-going to suppress slow components in LuAG:Ce.

**Mu2e-II** considers ultrafast $BaF_2$:Y calorimeter. R&D is on radiation hardness of $BaF_2$:Y and solar-blind SiPM. Industry is developing ultrafast $Lu_2O_3$:Yb ceramics.

**CalVision** proposes a dual readout longitudinally segmented crystal ECAL combined with the IDEA HCAL promising excellent EM and Hadronic resolutions for the proposed lepton Higgs factory.

Homogeneous HCAL (**HHCAL**) promises the best jet mass resolution by total absorption. Novel cost-effective heavy scintillating glass is under development.

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# R&D On-going at Caltech

## Fast/ultrafast, radiation hard and cost-effective heavy scintillators

Bright, fast and radiation hard inorganic scintillators for the severe radiation environment expected by the proposed $FCC_{hh}$. YAG, LuAG, GGAG, GYAG and GLuAG suffer from slow scintillation component.

Ultrafast inorganic scintillators: Cross-luminescence. Wide gap semiconductor-based scintillators with sub-ns decay time and quantum confinement-based inorganic $CsPbX_3$ (X = Cl, Br, I, mixed Cl/Br and Br/I), halide perovskite quantum dots may help to break the ps timing barrier for future HEP TOF.

Dense, UV-transparent, cost-effective heavy inorganic scintillators for the homogeneous hadron calorimeter (HHCAL) concept for the Higgs factory.

Compact UV sensitive photodetectors with sufficient dynamic range for ultrafast calorimeters.

Presented in the DRC9 round table discussion in 2023 CPAD Workshop, SLAC