Ionization and Proton Induced Radiation Damage in Crystal Scintillators

Ren-Yuan Zhu

California Institute of Technology

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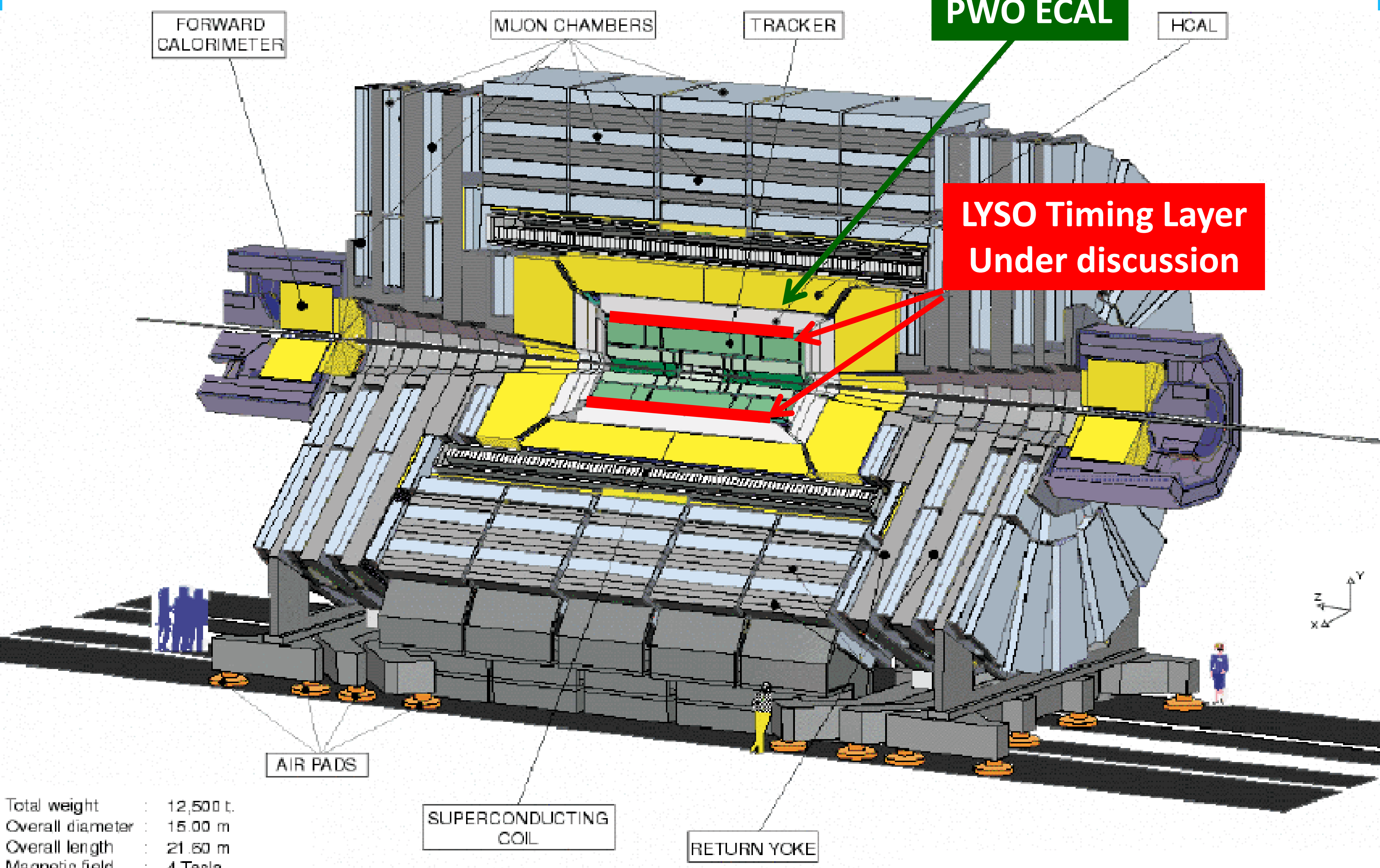
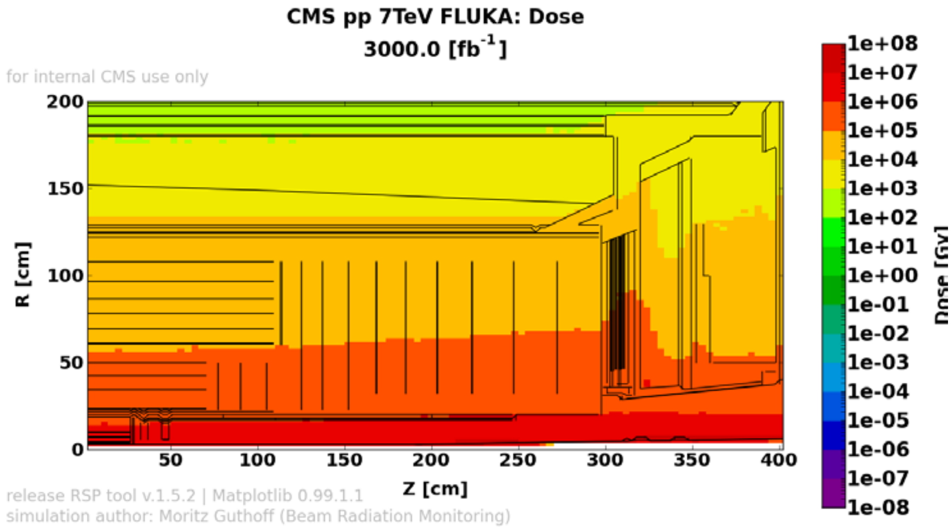
Crystals are widely used in HEP?

- Photons and electrons are fundamental particles. Precision e/γ measurements enhance physics discovery potential for future HEP experiments.
- Performance of crystal calorimeter in e/γ measurements is well understood:
  - The best possible energy resolution;
  - Good position resolution;
  - Good e/ γ identification and reconstruction efficiency.
- Challenges at future HEP Experiments:
  - Radiation damage at the energy frontier (HL-LHC);
  - Ultra-fast rate at the intensity frontier;
  - Good jet mass resolution at the energy frontier (ILC/CLIC).

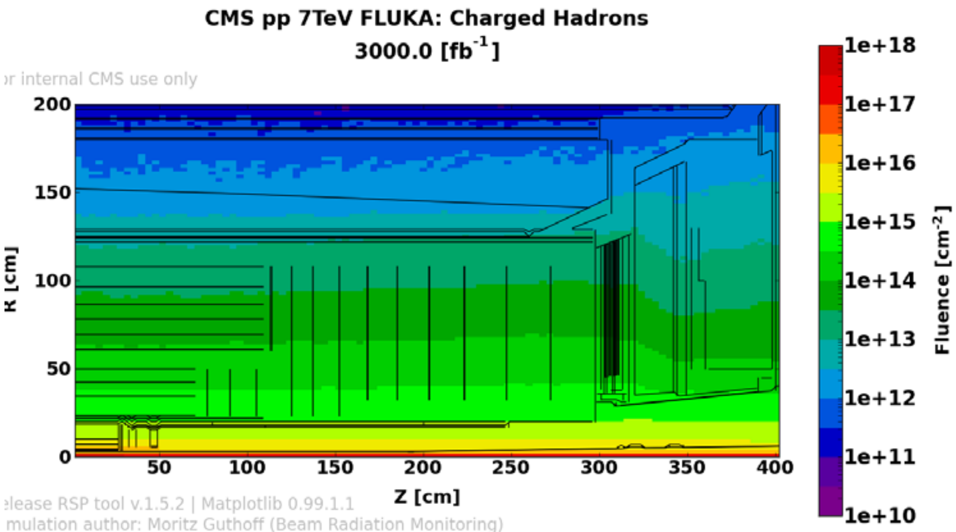
CMS Experiment at LHC

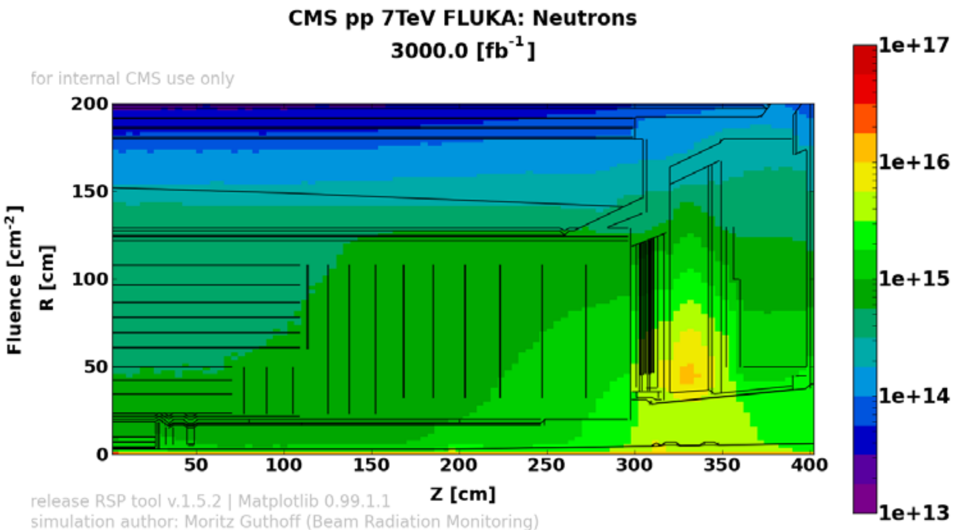


FLUKA Simulation for CMS @ HL-LHC

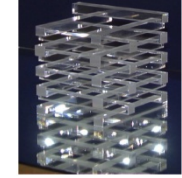


BRIL simulation:
https://cms-project-fluka-flux-map.web.cern.ch/cms-project-fluka-flux-map/,
which are consistent with the CMS note CMS DP-2013/028.





CMS Radiation Environment

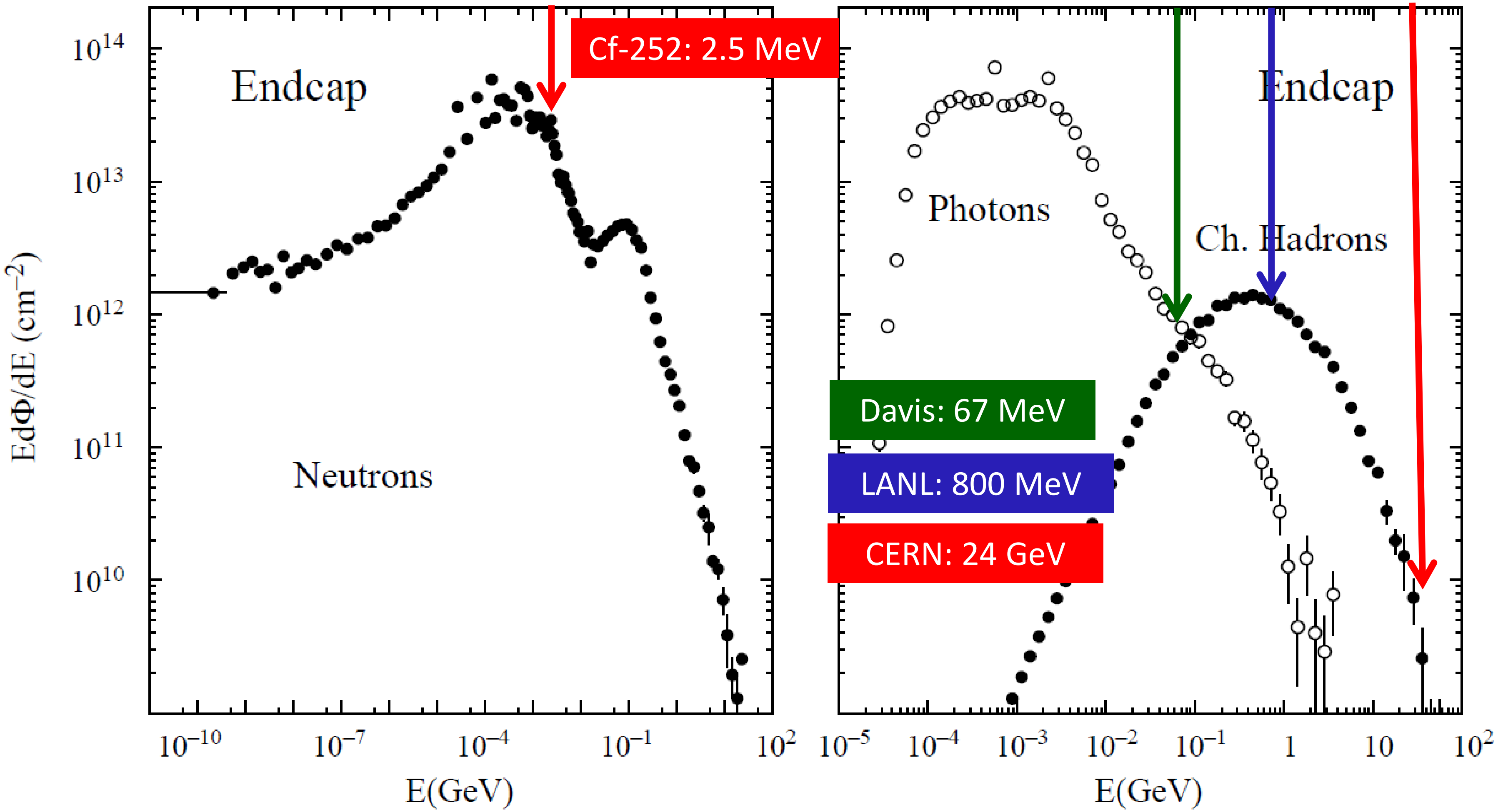


BRIL simulation: https://cms-project-fluka-flux-map.web.cern.ch/cms-project-fluka-flux-map/, which are consistent with the CMS note CMS DP-2013/028.

CMS ECAL Environment	LHC (10^{34} cm^{-2}s^{-1}, 500 fb^{-1})		HL-LHC (7 TeV, 5×10^{34} cm^{-2}s^{-1}, 3000 fb^{-1})			
	Barrel (max)	Endcap (max)	Barrel (η=0)	Barrel (η=1.479)	Endcap (η=1.479)	Endcap (η=3)
Absorbed dose (rad)	3.50E+05	2.10E+07	1.20E+06	2.25E+06	6.03E+05	5.66E+07
Dose rate (rad/h)	21	1260	72	135	36	3394
Fast neutrons fluence (cm^{-2})	3.00E+13	8.00E+14	3.63E+14	5.24E+14	3.35E+14	2.94E+15
Fast neutrons flux (cm^{-2}s^{-1})	5.00E+05	1.33E+07	6.05E+06	8.73E+06	5.58E+06	4.90E+07
Charged hadrons fluence (cm^{-2})	4.00E+11	5.00E+13	6.68E+12	8.65E+12	2.71E+12	5.82E+14
Charged hadrons flux (cm^{-2}s^{-1})	6.67E+03	8.33E+05	1.11E+05	1.44E+05	4.52E+04	9.69E+06

Particle Energy Spectra at LHC

FLUKA simulations: neutrons and charged hadrons are peaked at MeV and several hundreds MeV respectively. Neutron energy of 2.5 MeV from Cf-252 source and proton energy of 800 MeV at LANL are ideal for such investigation.

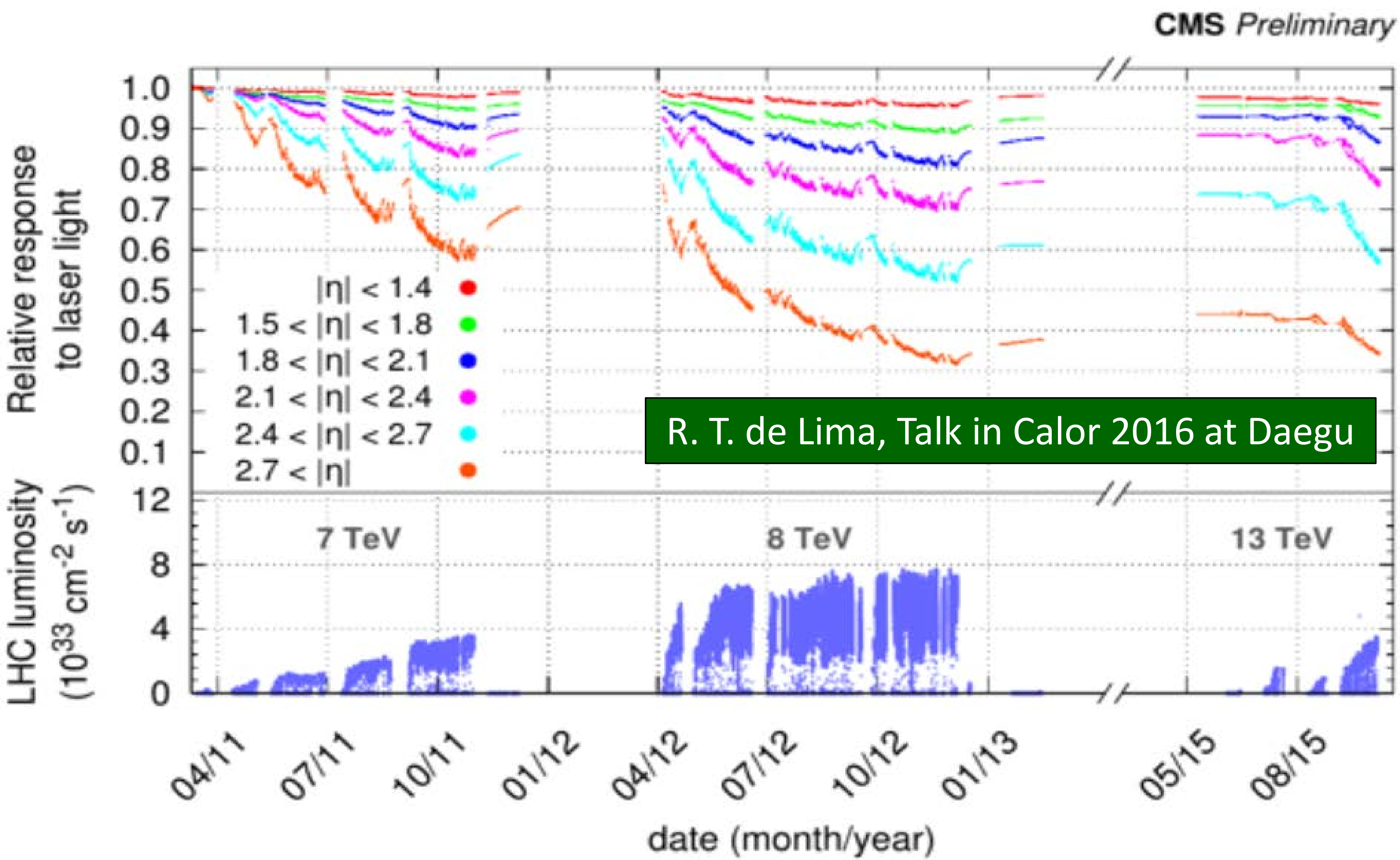


Radiation Damage in Crystals

- Possible damage effects are scintillation mechanism damage, induced absorption and phosphorescence, where induced absorption degrades crystal transparency and light output.
- Gamma-ray induced radiation damage in crystal scintillators was investigated for BaF2, BGO, CeF_3, pure CsI, LSO/LYSO/LFS and PWO by using Co-60 and Cs-137 sources at Caltech, JPL and Sandia.
- Proton induced radiation damage in crystal scintillators was investigated for BGO, CeF_3, LYSO/LFS and PWO by using 800 MeV and 24 GeV protons at Los Alamos and CERN.
- While ionization dose induced damage is well understood, investigation is on-going to understand contribution from the ionization component in charged hadron induced damage and if neutrons cause any damage in scintillators.

Degradation of CMS PWO

Ionization dose induced dose rate dependent damage in PWO is well understood



R. T. de Lima, Talk in Calor 2016 at Daegu

Dose Rate Dependent Damage

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

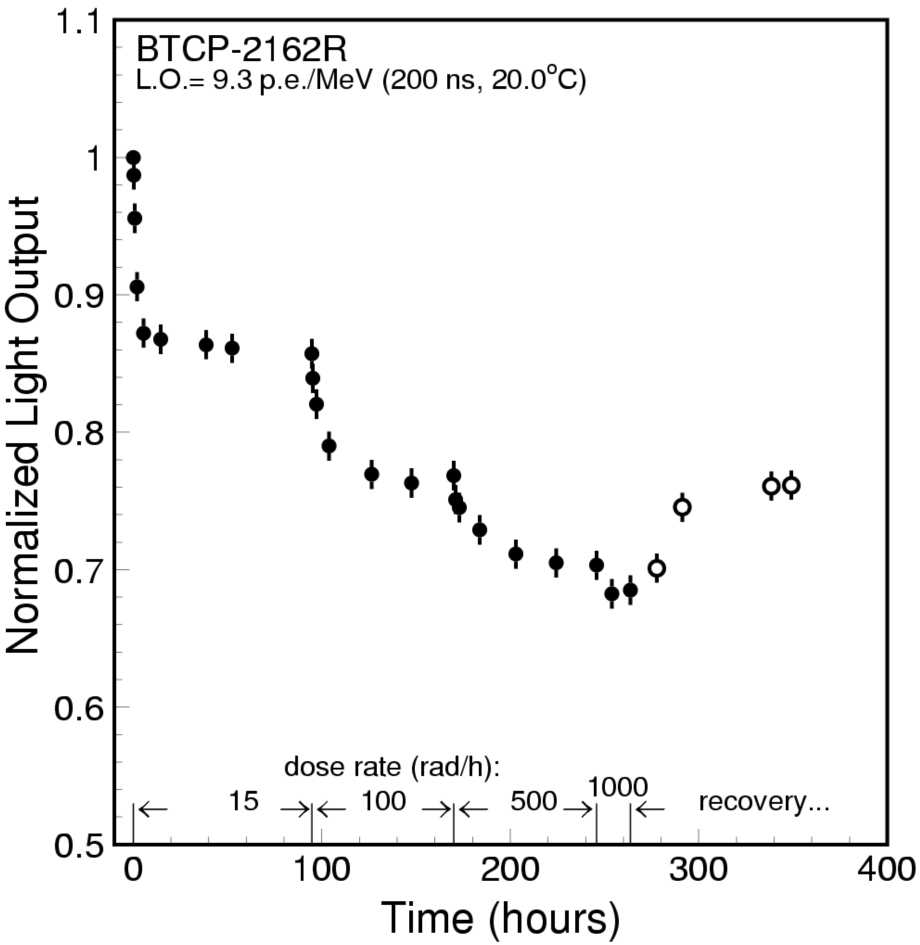
Light output reaches an equilibrium during irradiations under a defined dose rate, showing dose rate dependent radiation damage

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

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

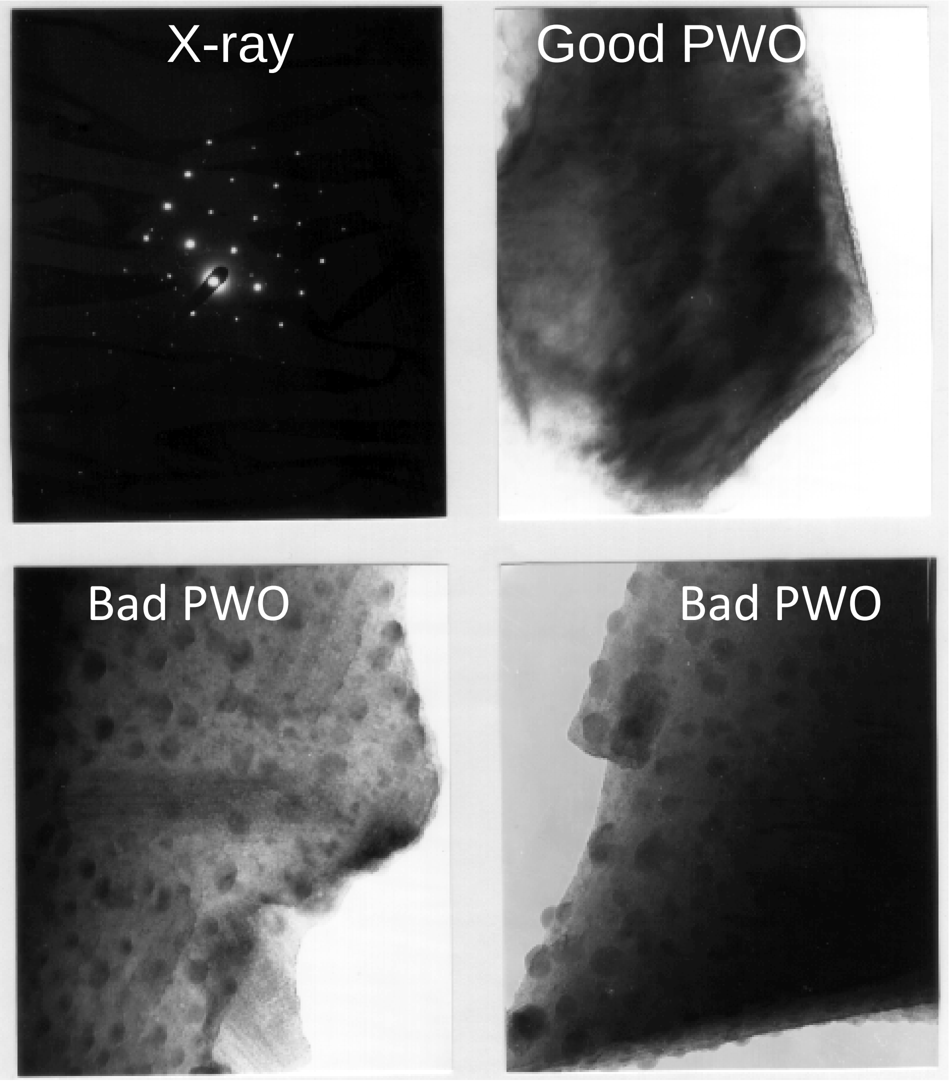
- D_i: color center density in units of m^{-1};
- D_i^0: initial color center density;
- D_i^{all} is the total density of trap related to the color center in the crystal;
- a_i: recovery costant in units of hr^{-1};
- b_i: damage contant in units of kRad^{-1};
- R: the radiation dose rate in units of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

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



Oxygen Vacancies by TEM/EDS

5 to10 nm black spots identified by TOPCON-002B scope, 200 kV, 10 uA
Localized stoichiometry analysis by JEOL JEM-2010 scope and Link ISIS EDS



NIM A413 (1998) 297

Atomic Fraction (%) in $PbWO_4$

As Grown Sample

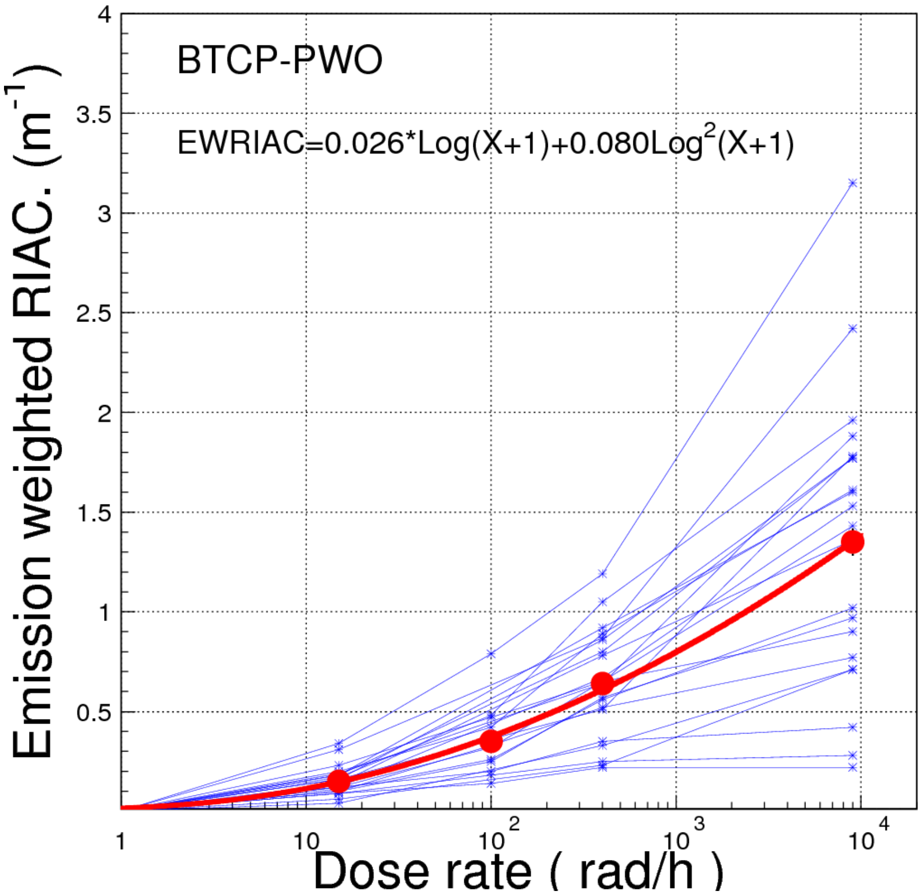
Element	Black Spot	Peripheral	$Matrix_1$	$Matrix_2$
O	1.5	15.8	60.8	63.2
W	50.8	44.3	19.6	18.4
Pb	47.7	39.9	19.6	18.4

The Same Sample after Oxygen Compensation

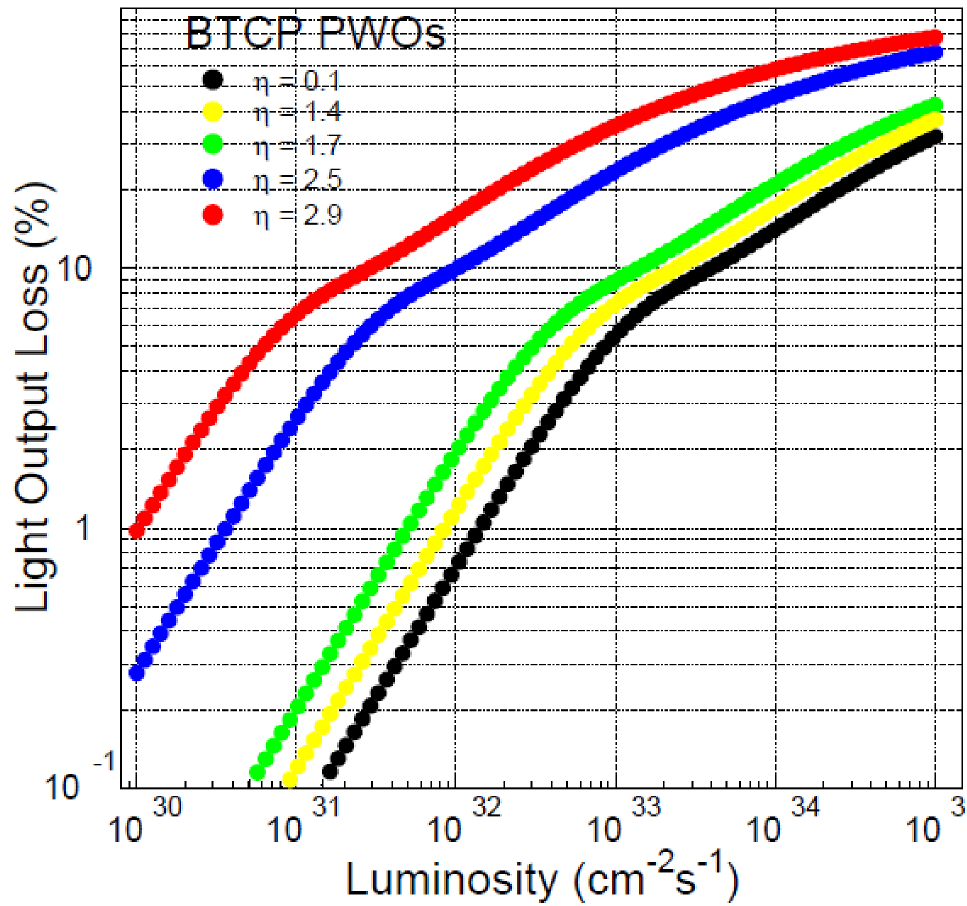
Element	$Point_1$	$Point_2$	$Point_3$	$Point_4$
O	59.0	66.4	57.4	66.7
W	21.0	16.5	21.3	16.8
Pb	20.0	17.1	21.3	16.5

Prediction of PWO Damage

IEEE Trans. Nucl. Sci. NS-51 1777 (2004)

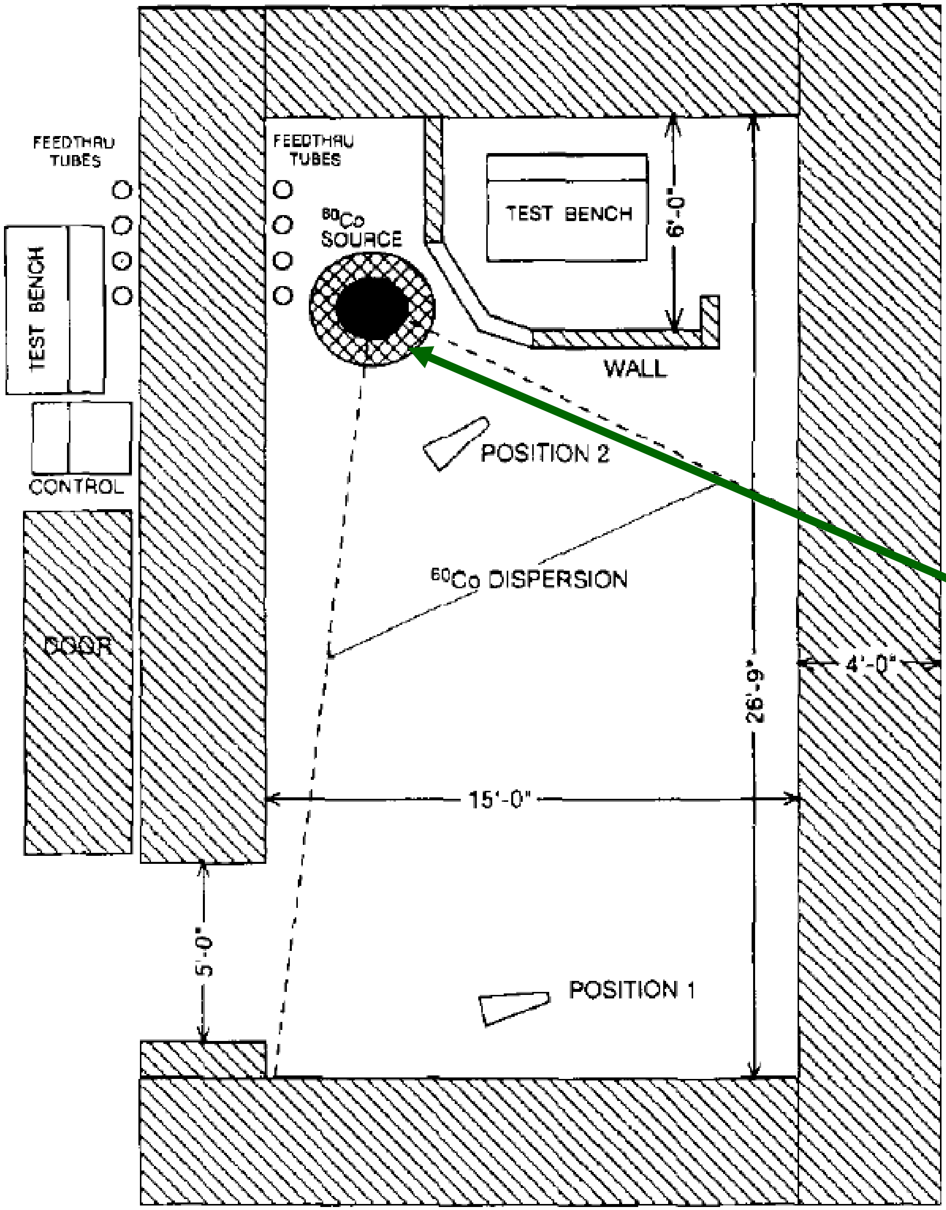


Talk in CMS Forward Calorimeter Taskforce Meeting, CERN, 12/10/2010



Predicted EM dose induced damage agrees well with the LHC data

JPL Total Absorption Dose Facility

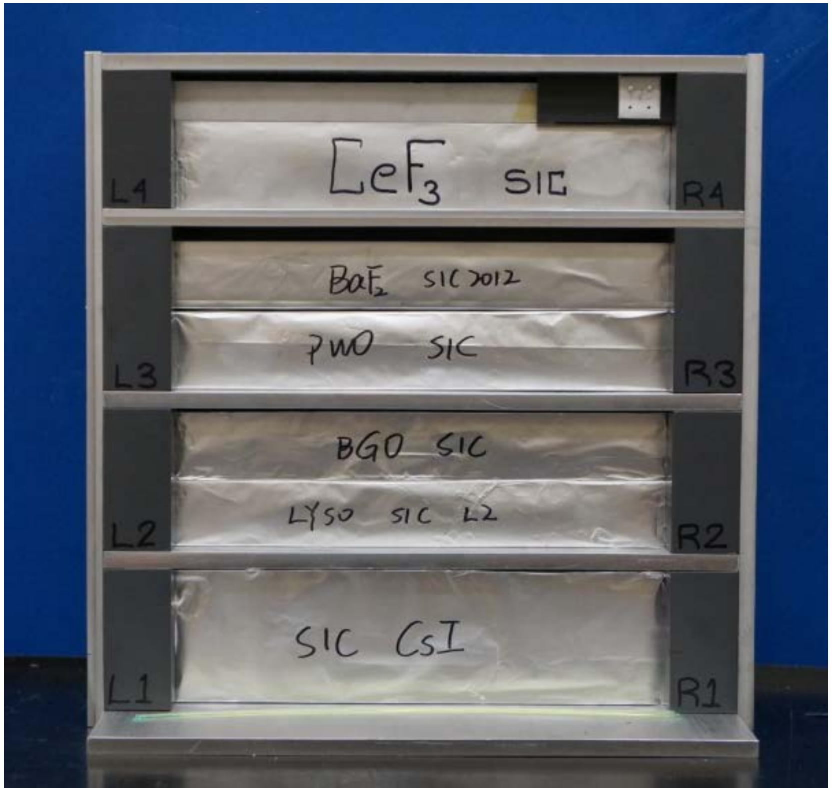


A group of high intensity ^{60}Co sources provides a variable dose rate up to 1 Mrad/h in an opening throat of 10" x 10" x 13.5".

Irradiation was carried out in step: 10 Mrad first, followed by several 100 Mrad steps over weekends.

The time between the end of each irradiation and the measurements at Caltech is less than 30 minutes.

Crystals Irradiated at JPL



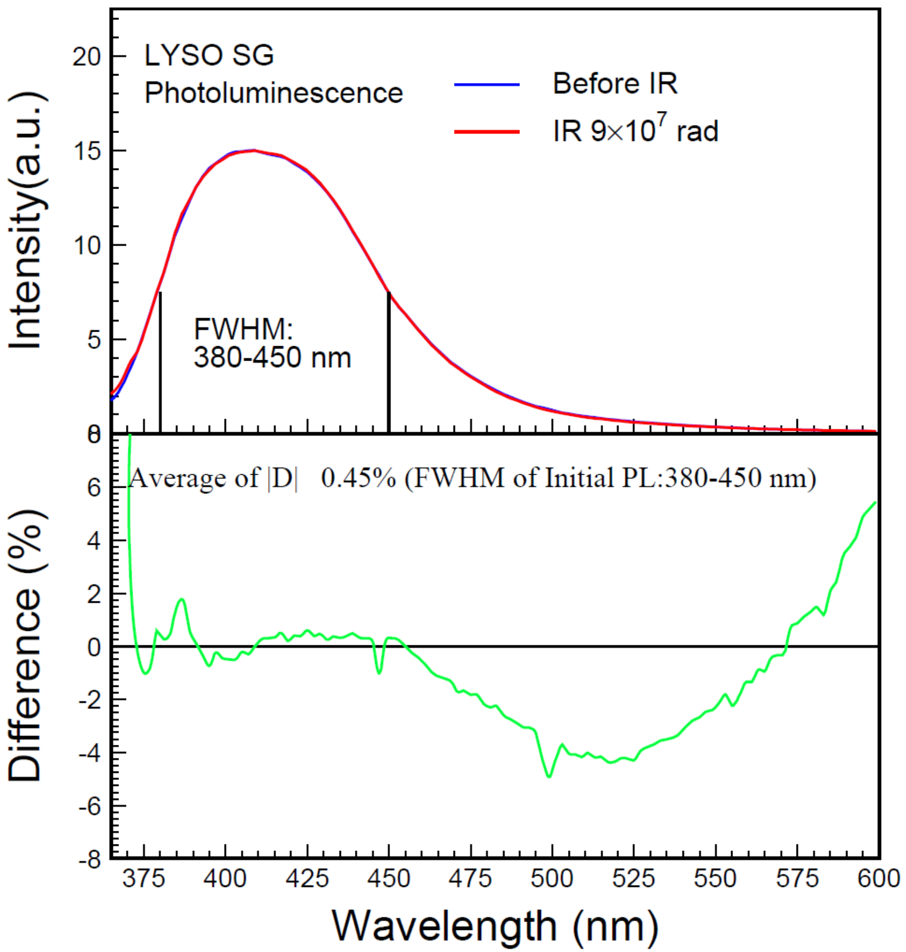
ID	Dimension (mm)
CeF_3	33×32×191
BaF_2	20×20×250
PWO	28.5^2×30^2×220
BGO	25×25×200
LYSO	25×25×200
Pure CsI	50×50×200

Experiments

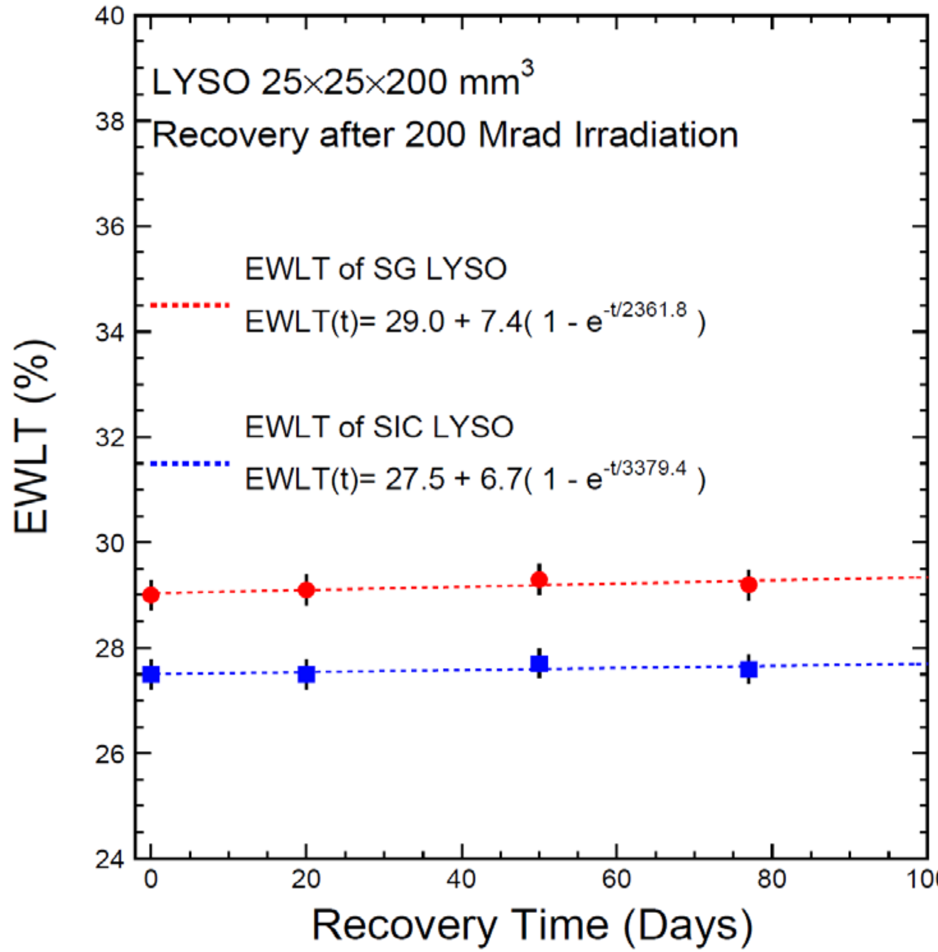
Longitudinal Transmittance (LT) and Light Output (LO) were measured at room temperature before and after each irradiation step.

Gamma-Ray Induced Damage in 20 cm Long LYSO/LSO Crystals

No damage in scintillation mechanism



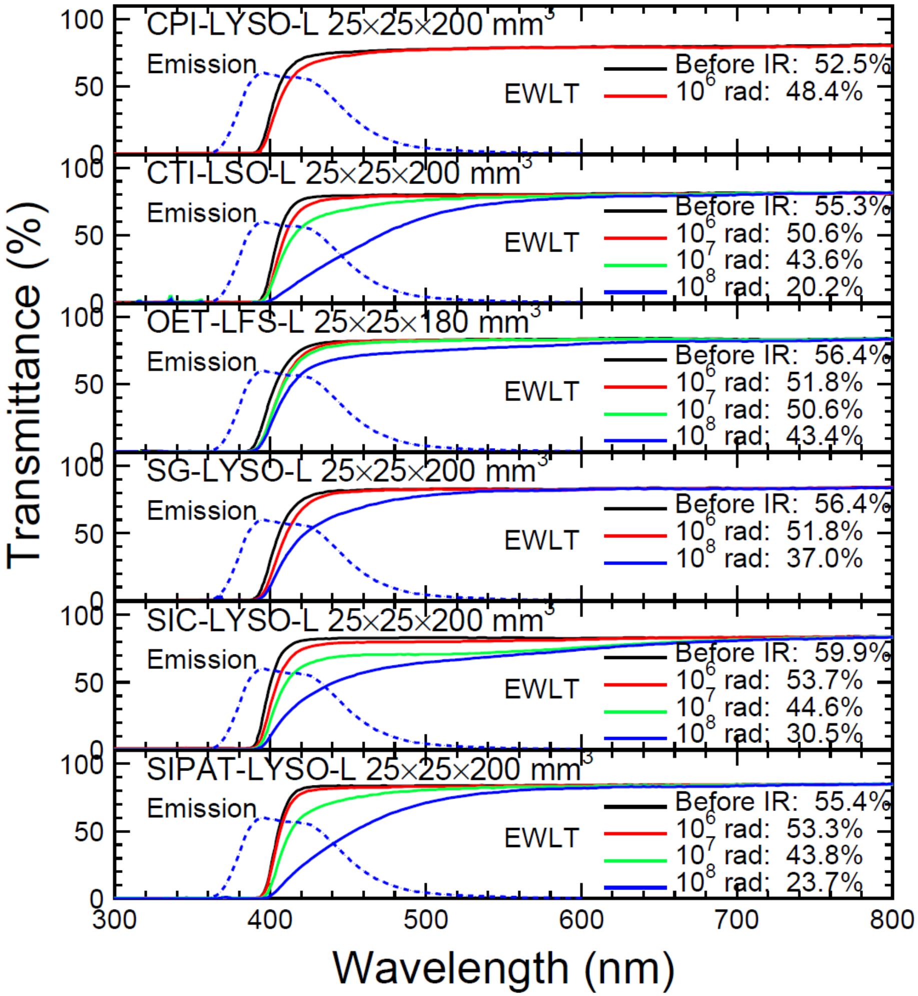
No recovery: dose rate independent



Radiation damage in BaF_2 and pure CsI is dose rate independent

LYSO/LSO/LFS: Radiation Damage in Longitudinal Transmittance (LT)

The best sample: 77% EWLT after 100 Mrad



EWLT or emission weighted longitudinal transmittance is defined as:

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

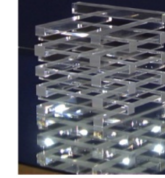
RIAC or radiation induced absorption coefficient is defined as:

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

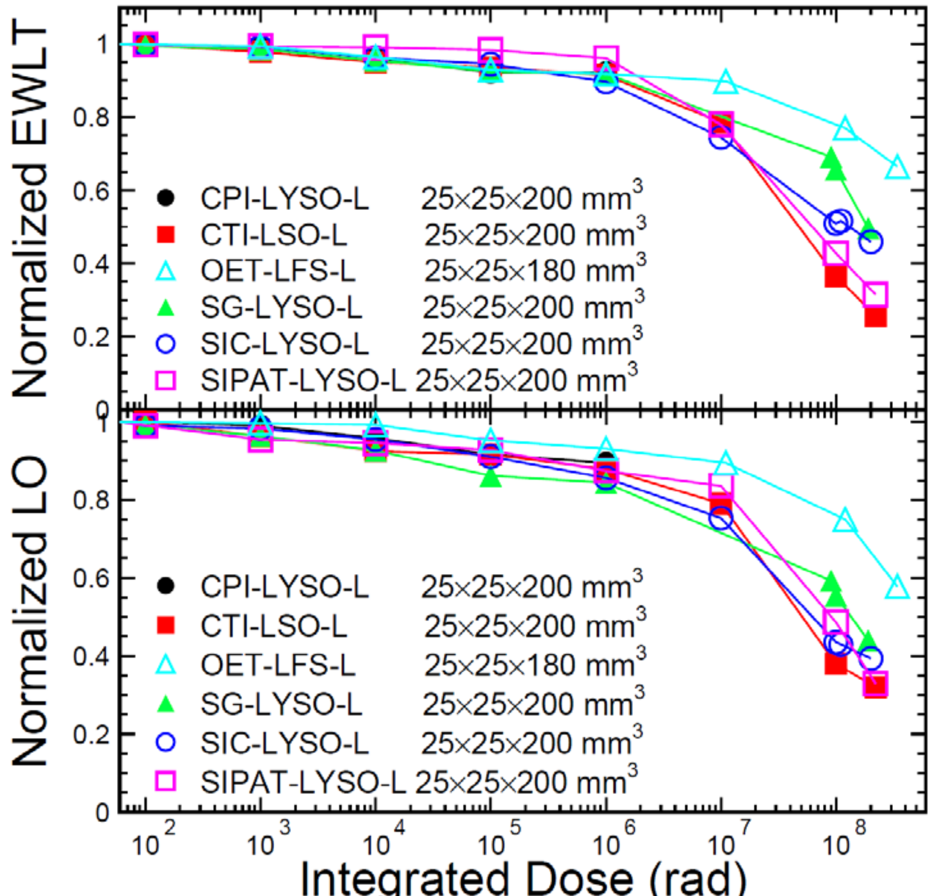
EWRIAC or emission weighted radiation induced absorption coefficient is defined as:

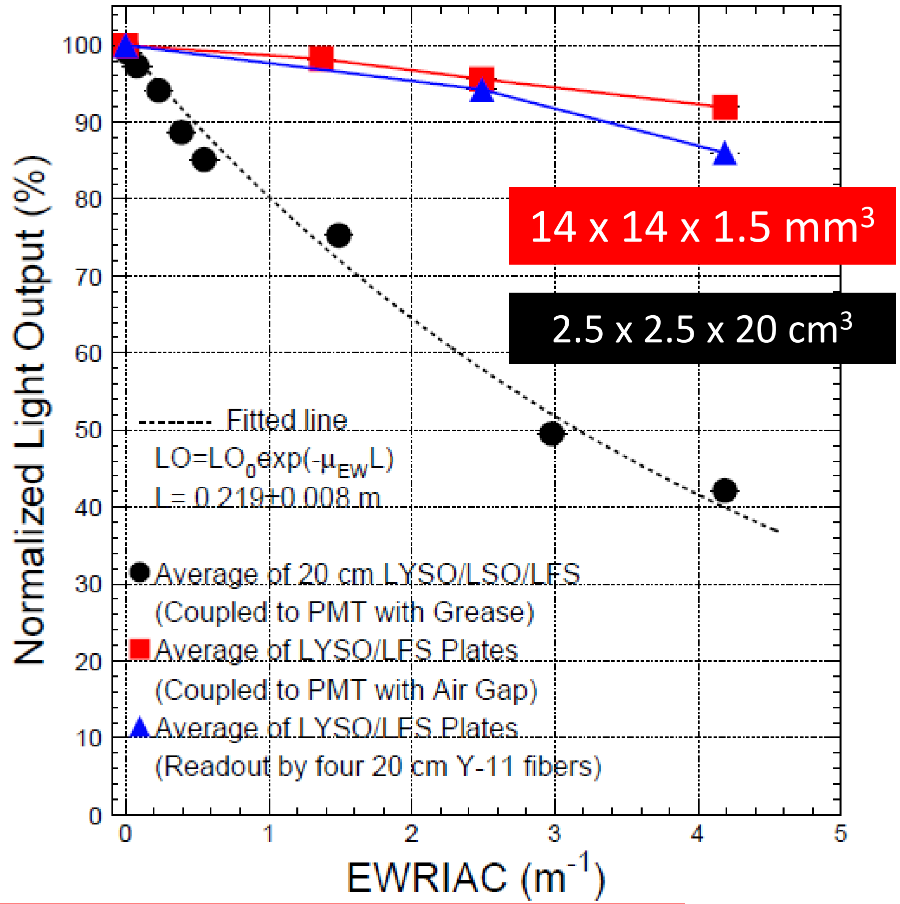
$$\mathrm{EW}RIAC = \frac{\int RIAC(\lambda)\mathrm{Em}(\lambda)d\lambda}{\int \mathrm{Em}(\lambda)d\lambda}$$

LYSO/LSO/LFS: Normalized EWLT and LO vs. Dose and LO vs. EWLT



The best sample: 58% light output after 340 Mrad

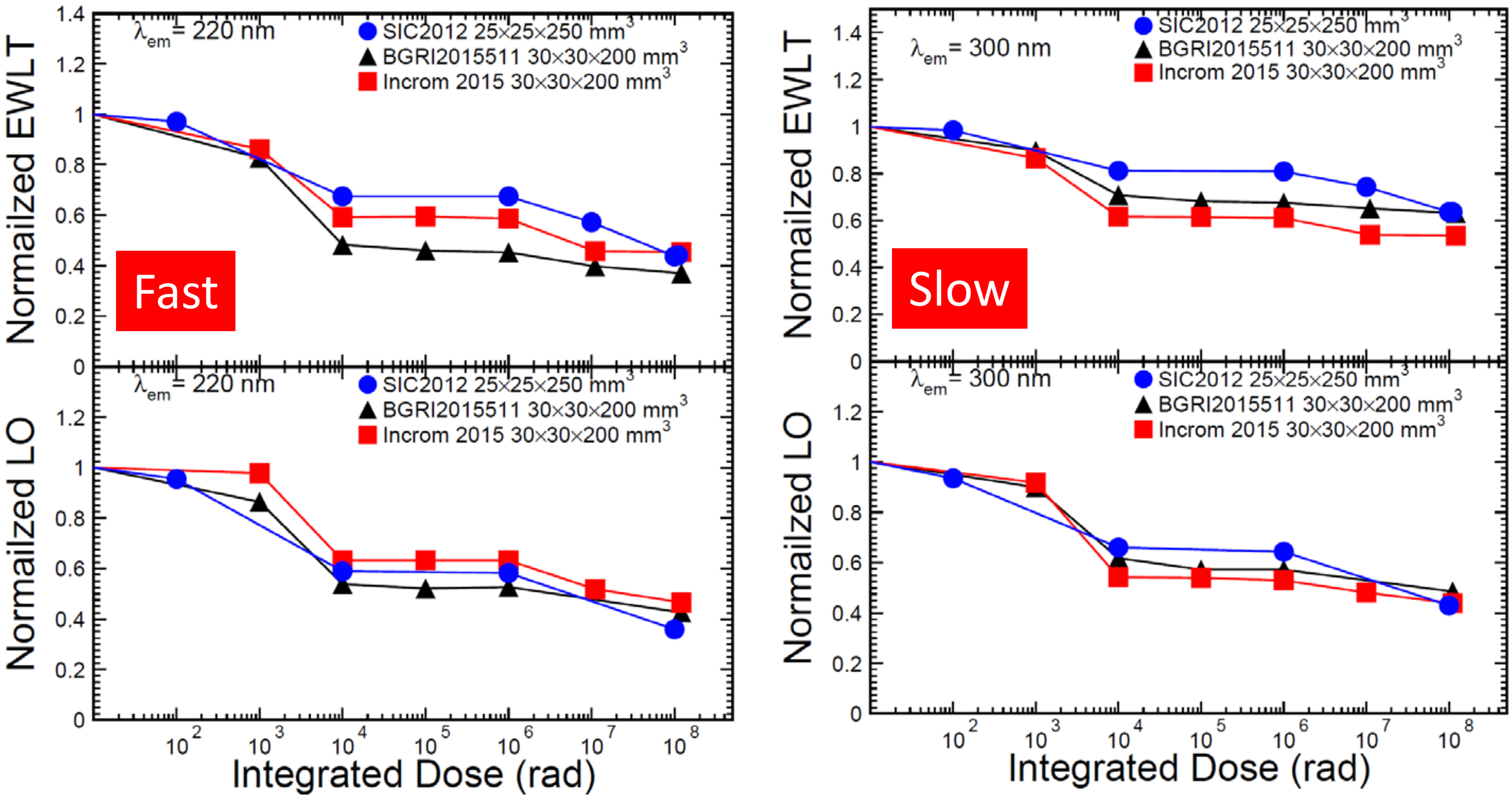




With EWRIAC of 3 m^{-1}, LO losses in 14x14x1.5 mm plates and 20 cm long crystals are 5%/8% for direct/WLS readout and 50%

BaF_2: Normalized EWLT and LO

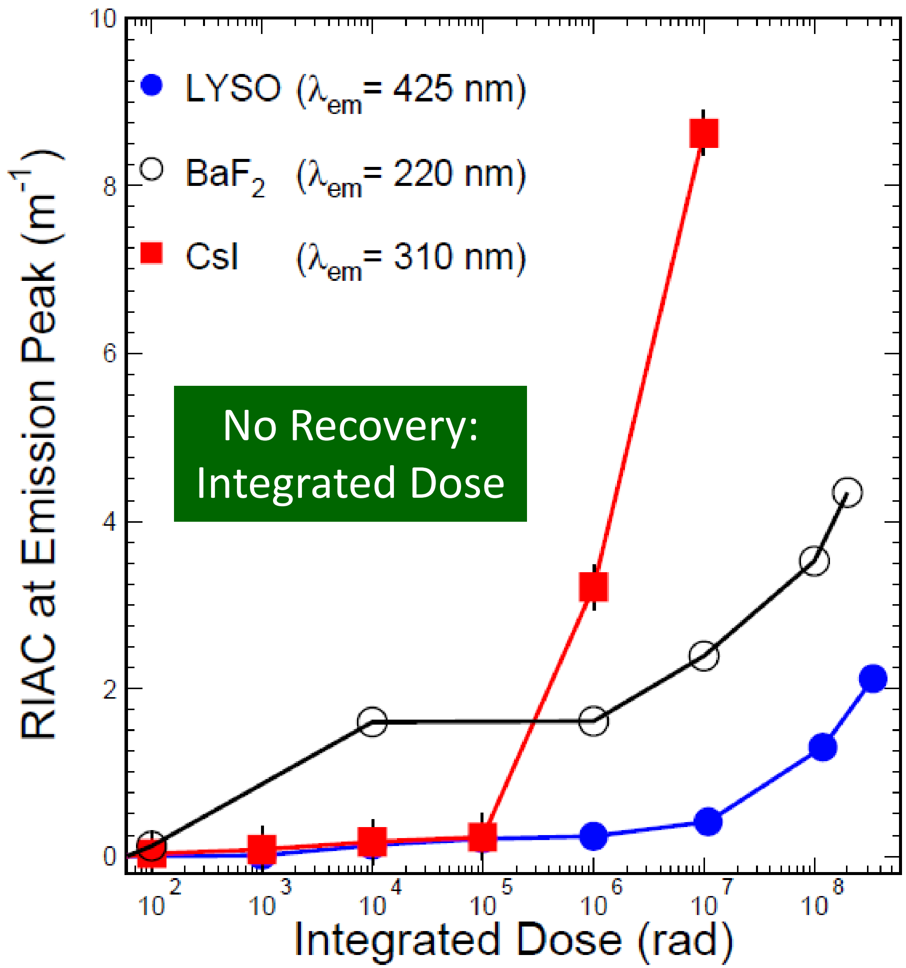
Consistent damage in crystals from three vendors

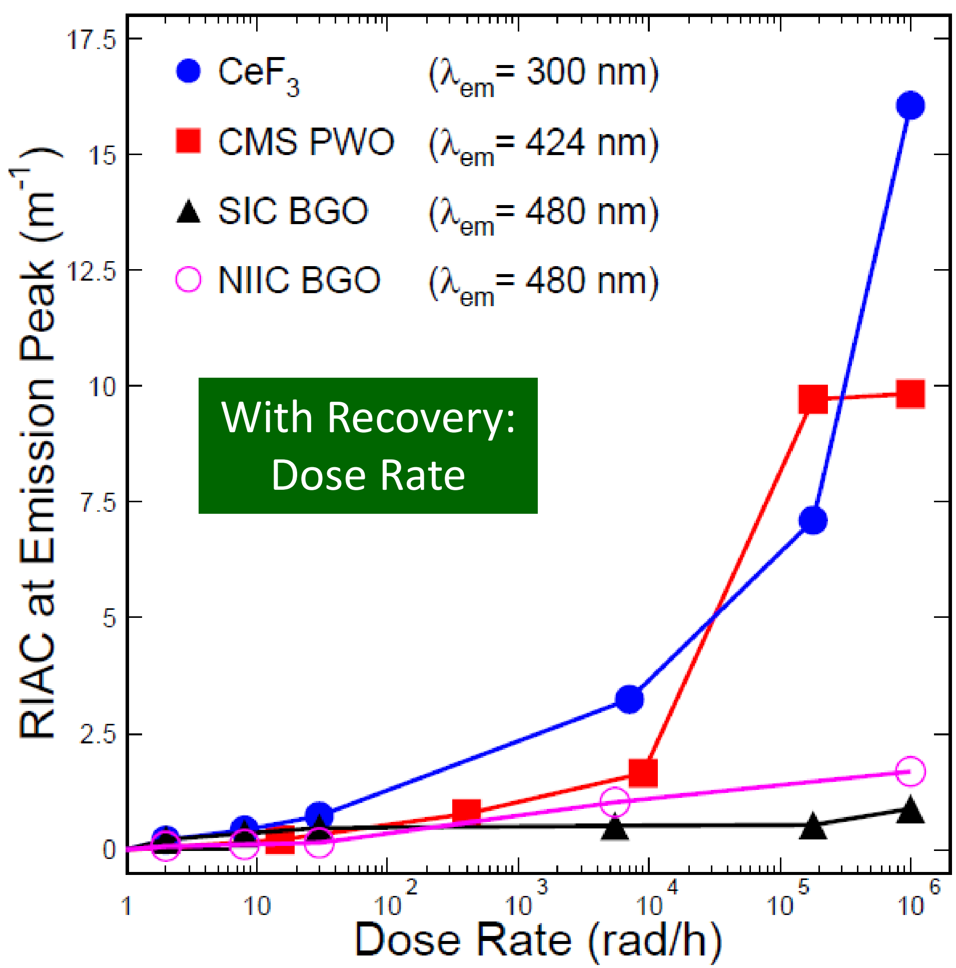


40%/45% LO for the fast/slow component after 120 Mrad

γ-ray Induced RIAC @ λ_{Peak}

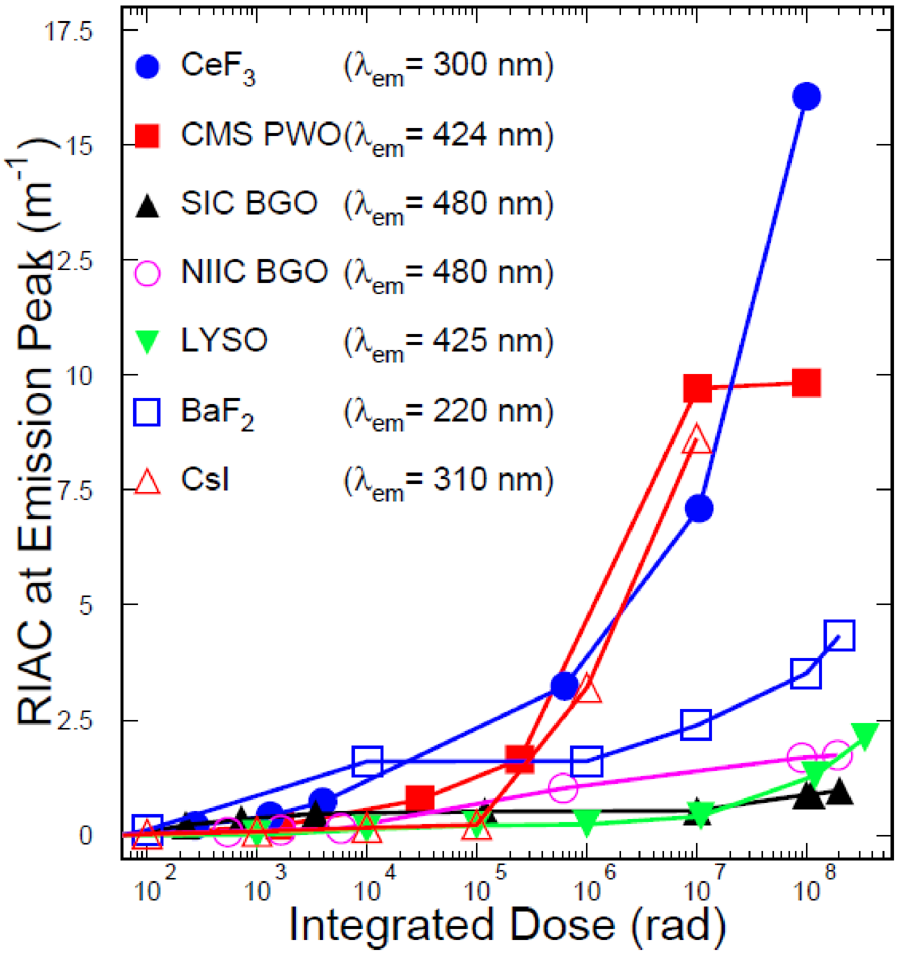
Pure CsI is good below 100 krad; LYSO and BaF_2 are good beyond 1 Mrad
BGO shows small radiation induced absorption up to 1 Mrad/h

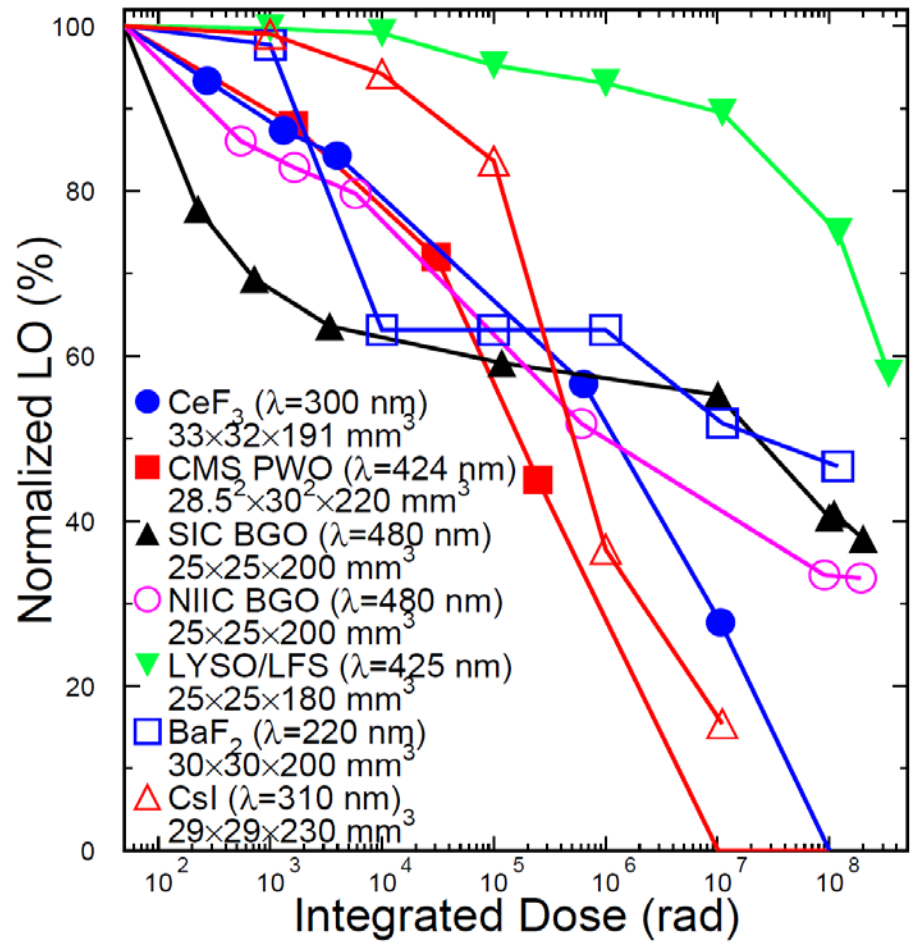




All Crystals: RIAC and LO

Ignoring dose rate dependence, the values of RIAC at the emission peak and normalized LO shown as a function of the integrated dose

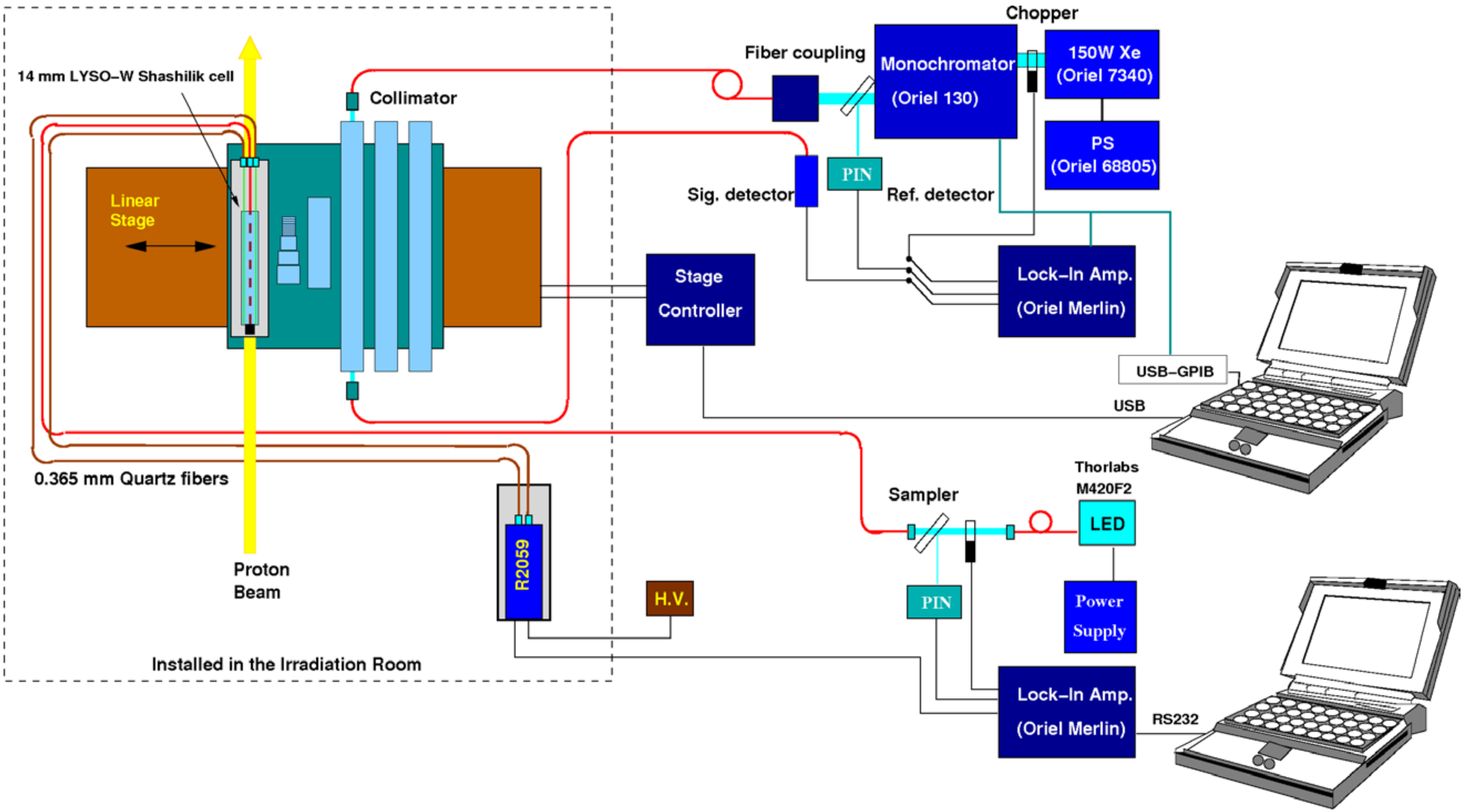




LYSO crystals show the best radiation hardness up to 340 Mrad

LANL 6990: On-line Monitoring

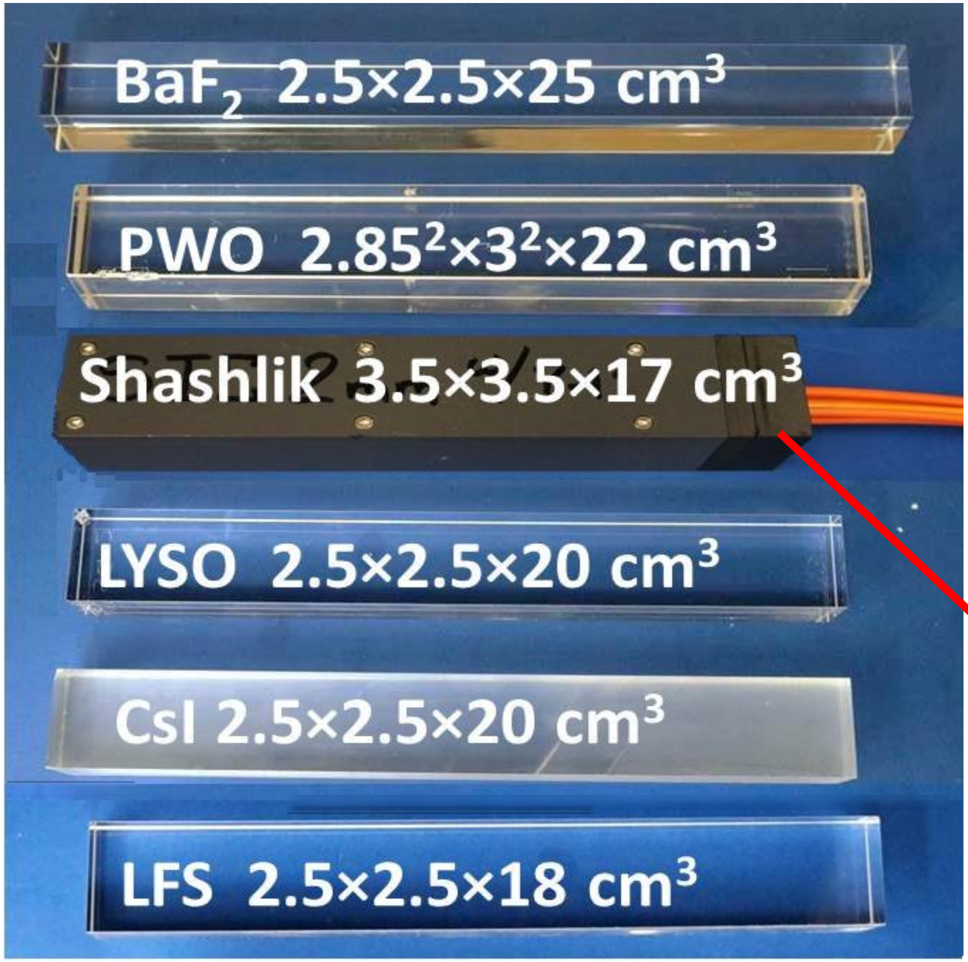
A LYSO-W-Capillary Shashlik cell and three long crystals were monitored by a 420 nm LED and a fiber based spectrophotometer (300 – 800 nm) respectively before, during and after irradiation

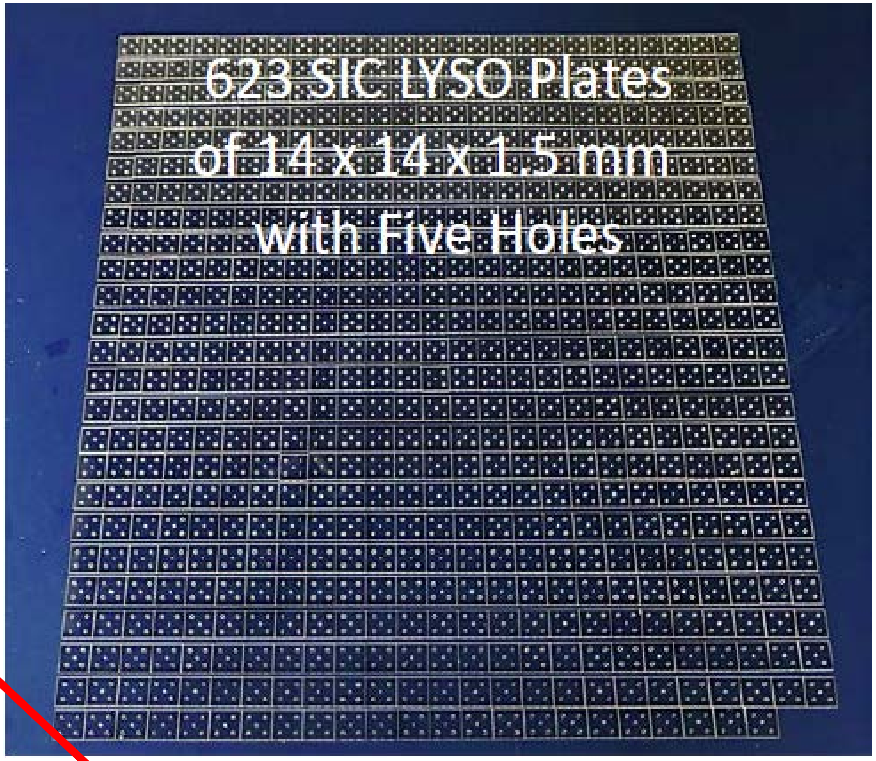


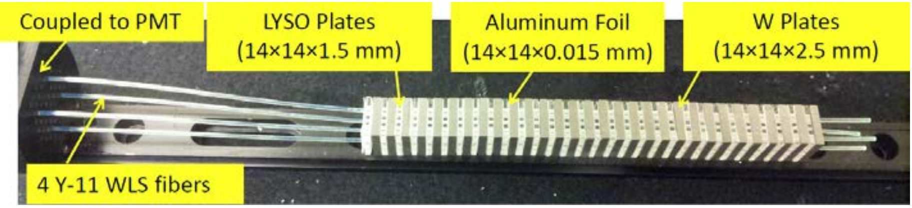
Irradiated Samples

20 cm crystals and a LYSO/W Shashlik tower in the Target 2

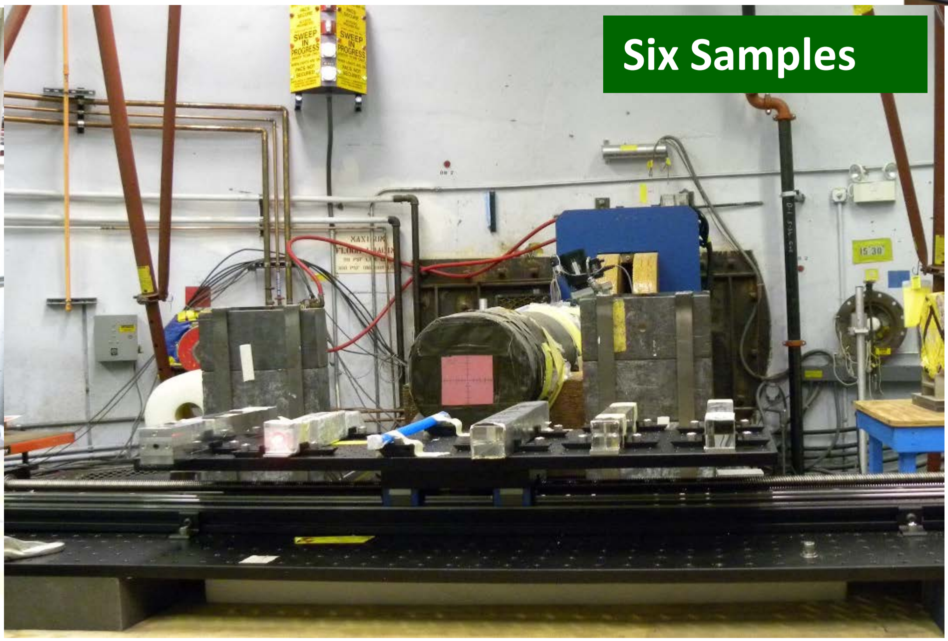
14 x 14 x 1.5 mm LYSO plates in the Target 4 East Port





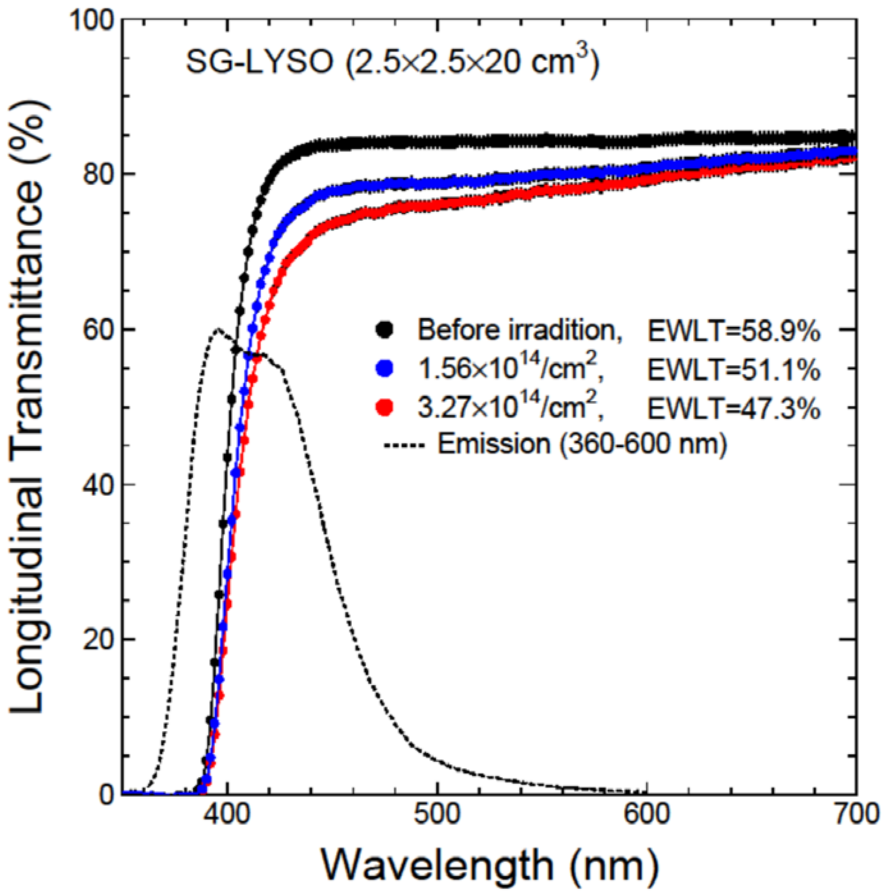


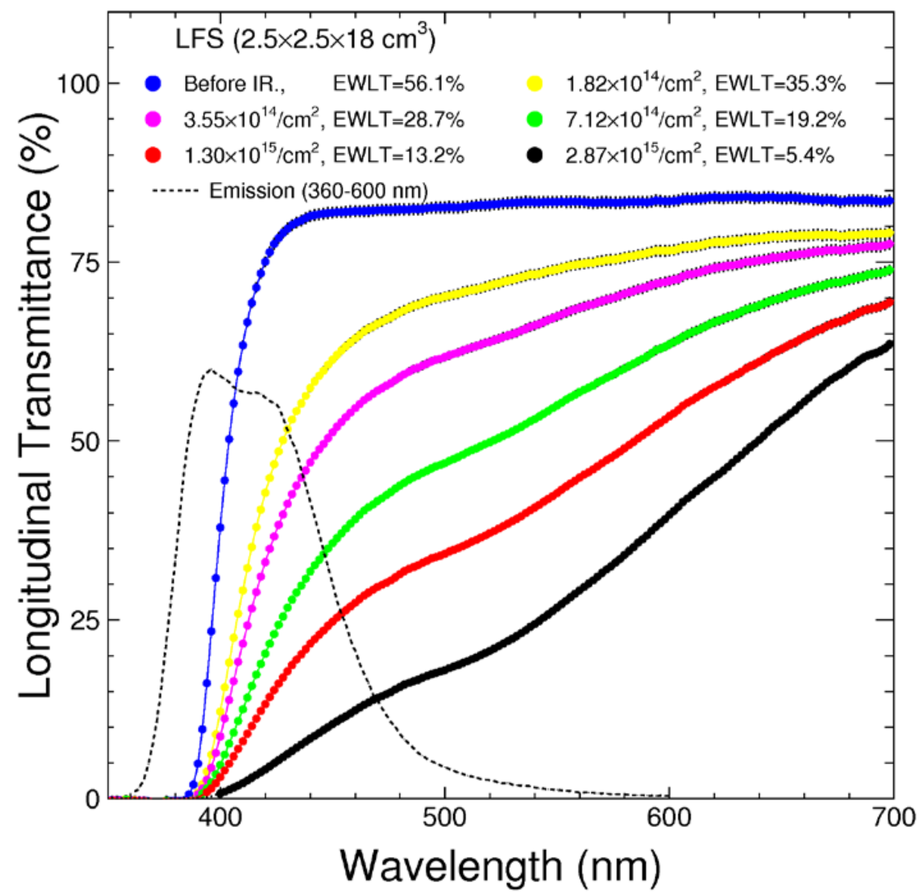
6990: Photos at Los Alamos



LYSO: LT Damage and RIAC

LYSO and LFS crystals irradiated to 3.3 and 3.6 $\times 10^{14}$ p/cm^2 with EWRIAC of 1 and 3.7 m^{-1}, indicating excellent radiation hardness of LYSO





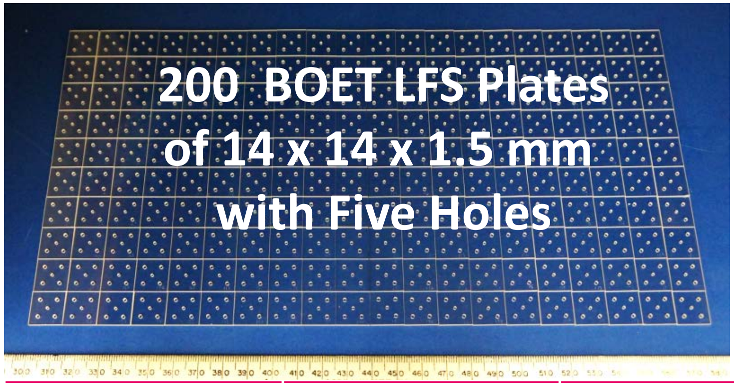
RIAC at the Emission Peak by 800 MeV Protons

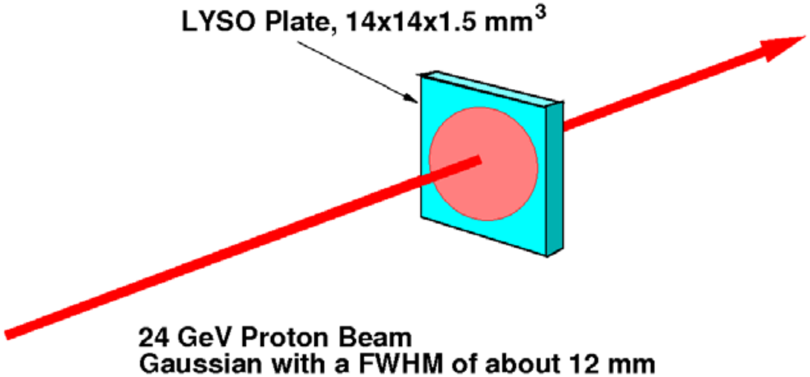
Measured Values at about E14, and extracted to 3E14 p/cm^2

Crystal	Dimensions (mm^3)	ID	Emission Peak (nm)	Fluence (p/cm^2)	RIAC at EP (1/m)	@ 3E+14
BGO	25×25×200	SIC-BGO	480	1.77E+14	14.7	24.9
CeF_3	$22^2\times26^2\times150$	SIC-CeF	340	1.40E+14	17.4	37.3
LYSO	**25×25×200**	**SG-LYSO**	**430**	**3.27E+14**	**0.86**	**0.8**
LFS	**25×25×180**	**OET-LFS**	**430**	**3.55E+14**	**3.7**	**3.1**
PWO*	$28.5^2\times30^2\times220$	SIC-PWO	420	1.80E+14	> 36	> 60

LSO/LYSO/LFS is radiation hard against protons

24 GeV Proton Irradiation

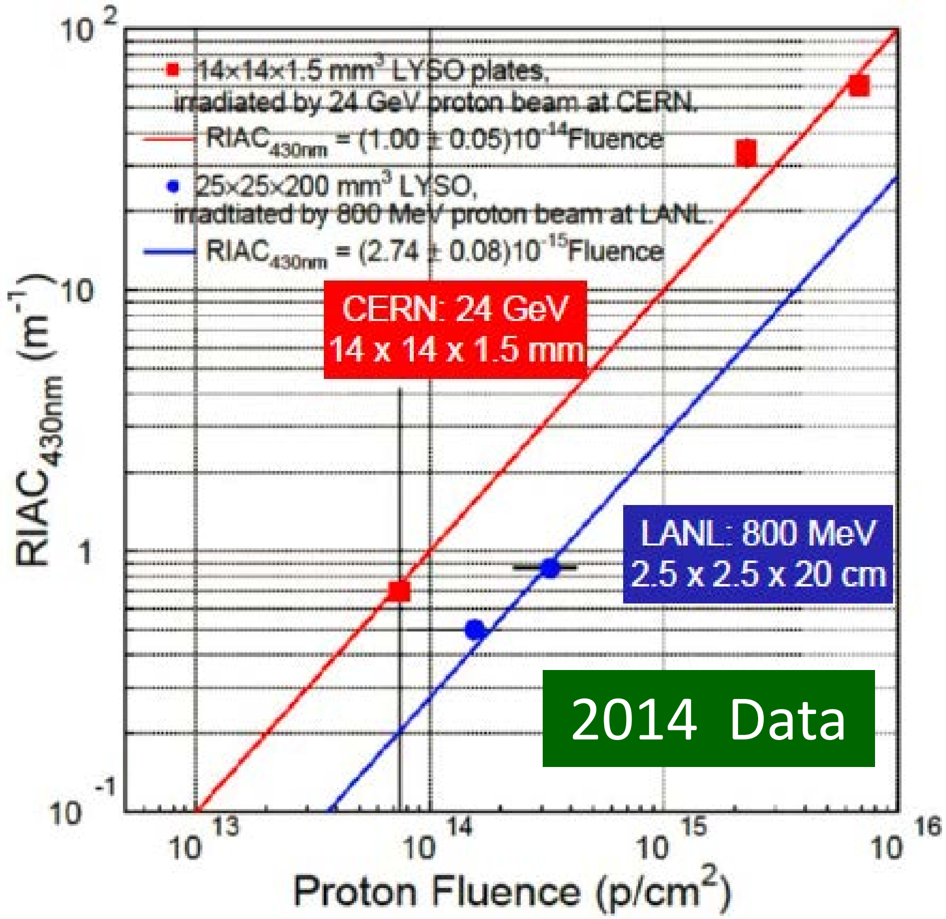


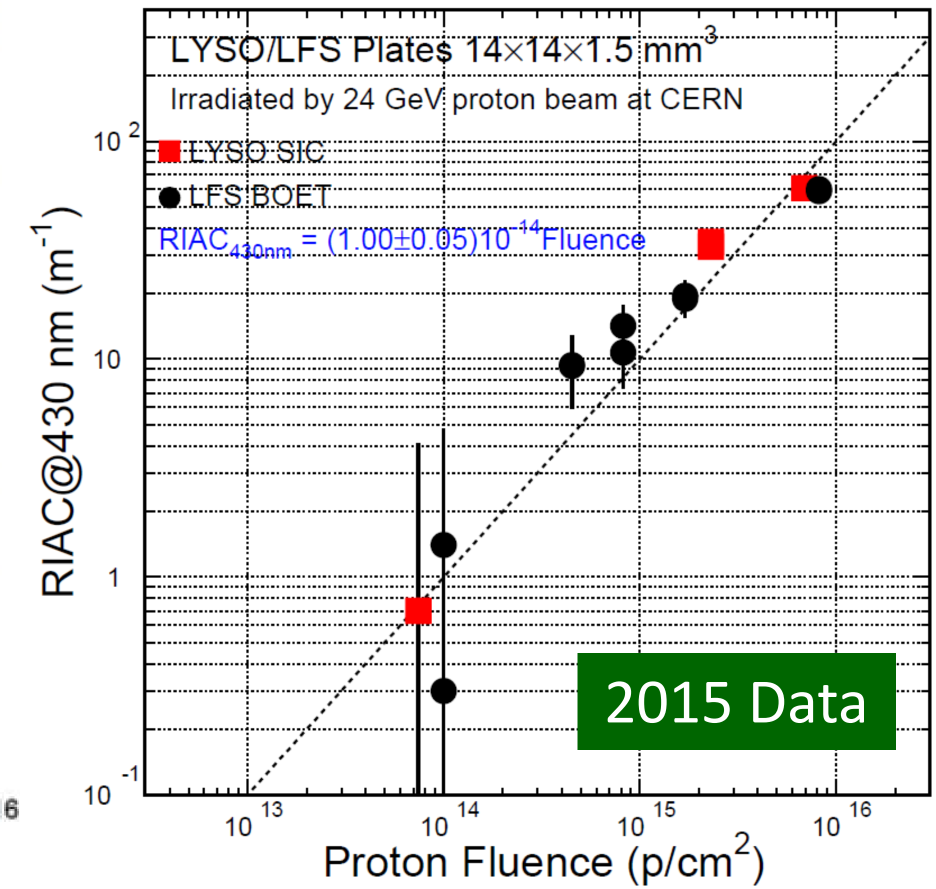


ID	Dimension (mm^3)	Facility	Protons (GeV)	Irradiation Set	Fluence (p/cm^2)	Error (+/- %)
LFS BOET-6	14×14×1.5	CERN	24	2045	9.97×10^{13}	7.0
LFS BOET-7	14×14×1.5	CERN	24	2045	9.97×10^{13}	7.0
LFS BOET-8	14×14×1.5	CERN	24	2046	4.48×10^{14}	8.4
LFS BOET-9	14×14×1.5	CERN	24	2046	4.48×10^{14}	8.4
LFS BOET-10	14×14×1.5	CERN	24	2047	8.21×10^{14}	7.6
LFS BOET-11	14×14×1.5	CERN	24	2047	8.21×10^{14}	7.6
LFS BOET-12	14×14×1.5	CERN	24	2048	1.65×10^{15}	7.5
LFS BOET-13	14×14×1.5	CERN	24	2048	1.65×10^{15}	7.5
LFS BOET-14	14×14×1.5	CERN	24	2049	8.19×10^{15}	7.3
LFS BOET-15	14×14×1.5	CERN	24	2049	8.19×10^{15}	7.3

24 GeV Protons: RIAC@ 430 nm

Consistent damage in LFS and LYSO Plates

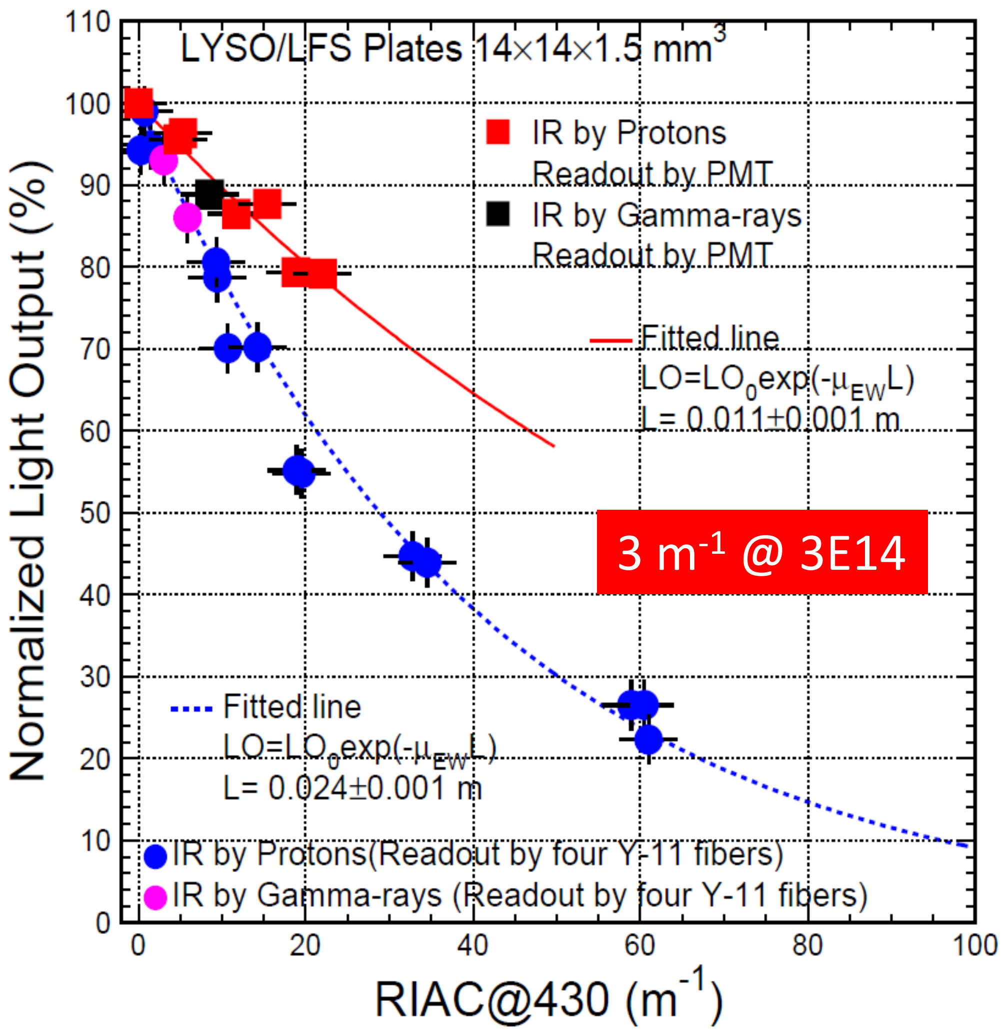




RIAC at 430 nm of 3 m^{-1} after 3×10^{14} p/cm²

LO by ɣ-Rays & Protons

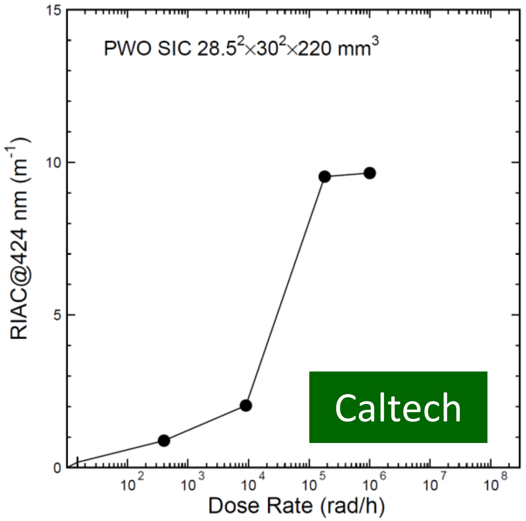
Consist damage by ɣ-rays and protons in LYSO and LFS plates with average light path length of 1.1 and 2.4 cm at 430 nm for direct and Y-11 readout respectively.

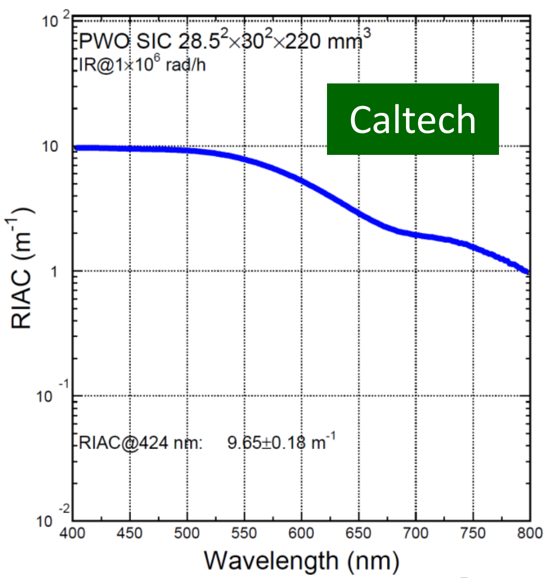


LO losses of 5% in 14x14x1.5 mm plates after 3×10^{14} p/cm^2

A Comparison of damages in PWO caused by γ-rays and Neutrons up to 10^{19} n/cm^2

Gamma Irradiation at JPL





$7.8 \times 10^{18}/1.2 \times 10^{19}/4.0 \times 10^{19}$ n/cm^2 for fast/epithermal/thermal
Corresponding dose received: 33 Grad @ 300 Mrad/h

Saclay neutron test:
30 cm^{-1}@ 420 nm
under 300 Mrad/h

Caltech gamma test:
0.1 cm^{-1}@ 420 nm
Under 1 Mrad/h

Neutron induced damage seems negligible

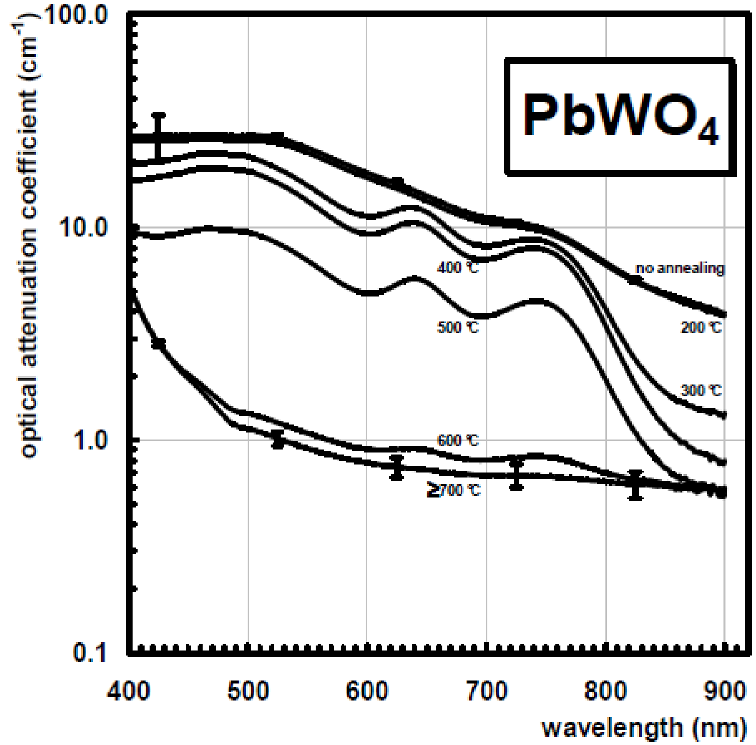


Fig. 2. Optical attenuation coefficient of the irradiated sample before annealing and after successive annealing temperatures.

[50] R. Chipaux et al., ***Behaviour of PWO scintillators after high fluence neutron irradiation,*** in Proc. 8th Int. Conference on Inorganic Scintillators,SCINT2005, A. Getkin and B. Grinyov eds, Alushta, Crimea, Ukraine, September 19–23 (2005), pp. 369–371

Summary

- γ-ray and proton induced radiation damage was investigated up to 340 Mrad and 8 x 10^{15} p/cm^2 respectively, showing that LYSO/LSO/LFS crystals have the best radiation hardness among all crystals tested. It has about 5% light output loss in 14 x 14 x 1.5 mm plates after 200 Mrad or 3 x 10^{14} p/cm^2.
- BaF_2 is another promising fast crystal: 40%/45% light output is observed after 120 Mrad for the fast/slow component.
- CsI crystals are good below 100 krad, working well for Mu2e.
- Damage in CeF_3, BGO and PWO recovers at room temperature, so is dose rate dependent, requiring frequent monitoring.
- While ionization dose induced damage is well understood, it is important to understand if there is proton specific damage since existing data indicate no damage caused by neutrons up to 10^{19} n/cm^2. Experiments 7332 at Los Alamos is designed for clarify this point.

No Neutron Damage in PWO

5.2 Radiation damage effects under neutron irradiation

In view of the intense neutron flux expected in CMS (see section 2) the effects on lead tungstate of neutron exposure were studied in nuclear reactors [47, 48]. The neutron fluxes and energies in these exposures were comparable to those expected in CMS. However, in reactors there is a strong associated gamma dose. The effect arising from neutrons was estimated by comparing the reactor results with results obtained from pure gamma irradiations. This indicated that there was no specific effect due to neutrons on the optical and scintillating properties of lead tungstate, at least up to fluences of 10^{14} cm^{-2}. This was confirmed by later independent studies [49]. It is also to be mentioned that recent tests performed at a very high fluence, of the order of 10^{19} to 10^{20} n$\cdot$cm^{-2} and 330 MGy (i.e. well above the level that will be ever achieved in any physics experiment) revealed the robustness of lead tungstate crystals which were not destroyed nor locally vitrified, and remained scintillating after such heavy irradiation [50].

The CMS Electromagnetic Calorimeter Group, ***Radiation hardness qualification of $PbWO_4$ scintillation crystals for the CMS Electromagnetic Calorimeter,*** 2010 JINST 5 P03010