Proton Induced Radiation Damage up to 8×10^{15} p/cm^2 in Various Crystal Scintillators

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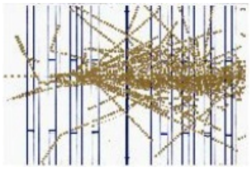
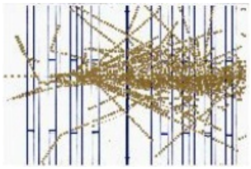


Introduction

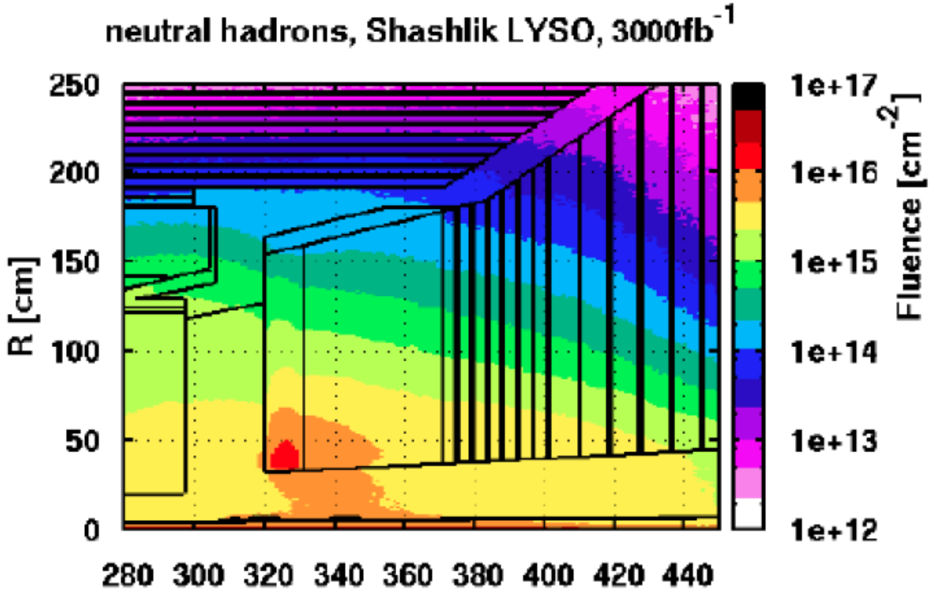
- Future HEP experiments at the energy frontier (HL-LHC) faces a challenge of radiation damage by charged hadrons and neutrons in addition to ionization dose.
- 800 MeV protons at the Weapons Neutron Research facility of Los Alamos Neutron Science Center (WNR of LANSCE) is ideal for the investigation on charged hadron induced radiation damage in crystal scintillators.
- Long crystals of 15 to 22 cm, BGO, CeF_3, LYSO and PWO were irradiated up to 3 x 10^{15} p/cm^2 at Los Alamos in 2014 (6501) and 2015 (6990), with degradation of their longitudinal transmittance measured *in situ*.
- LYSO plates of 14 x 14 x 1.5 mm^3 were also irradiated by 24 GeV/67 MeV protons at CERN/UC Davis up to 8 x 10^{15}/9.5 x 10^{13} p/cm^2.



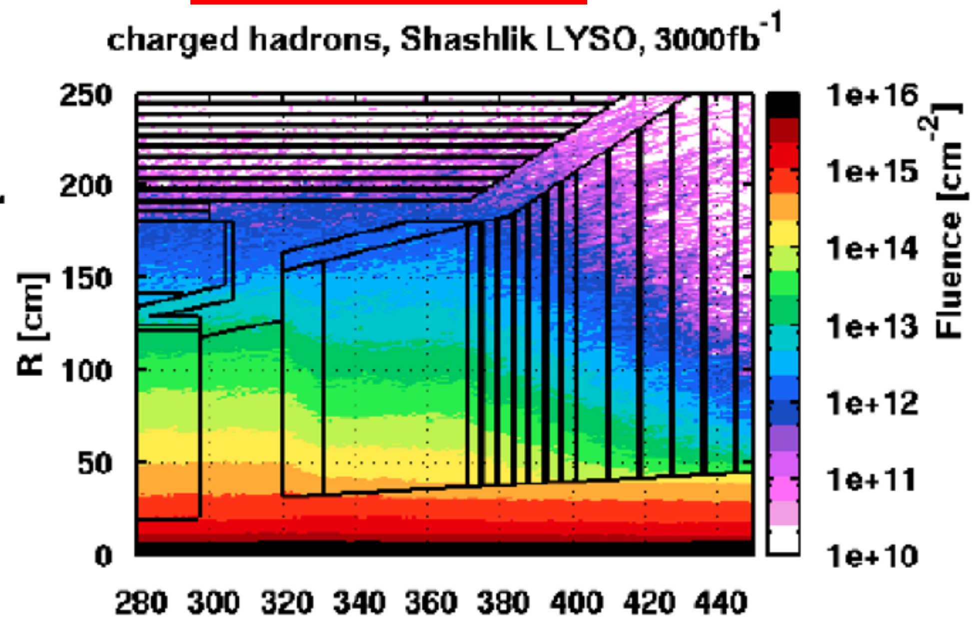
Hadron Fluence @ 3,000 fb^{-1}

FLUKA simulations: the neutron and charged hadron fluence expected by the CMS FCAL at |η| = 3 is 5 x $10^{15}/cm^2$ and 3 x $10^{14}/cm^2$ respectively at the HL-LHC

Neutron



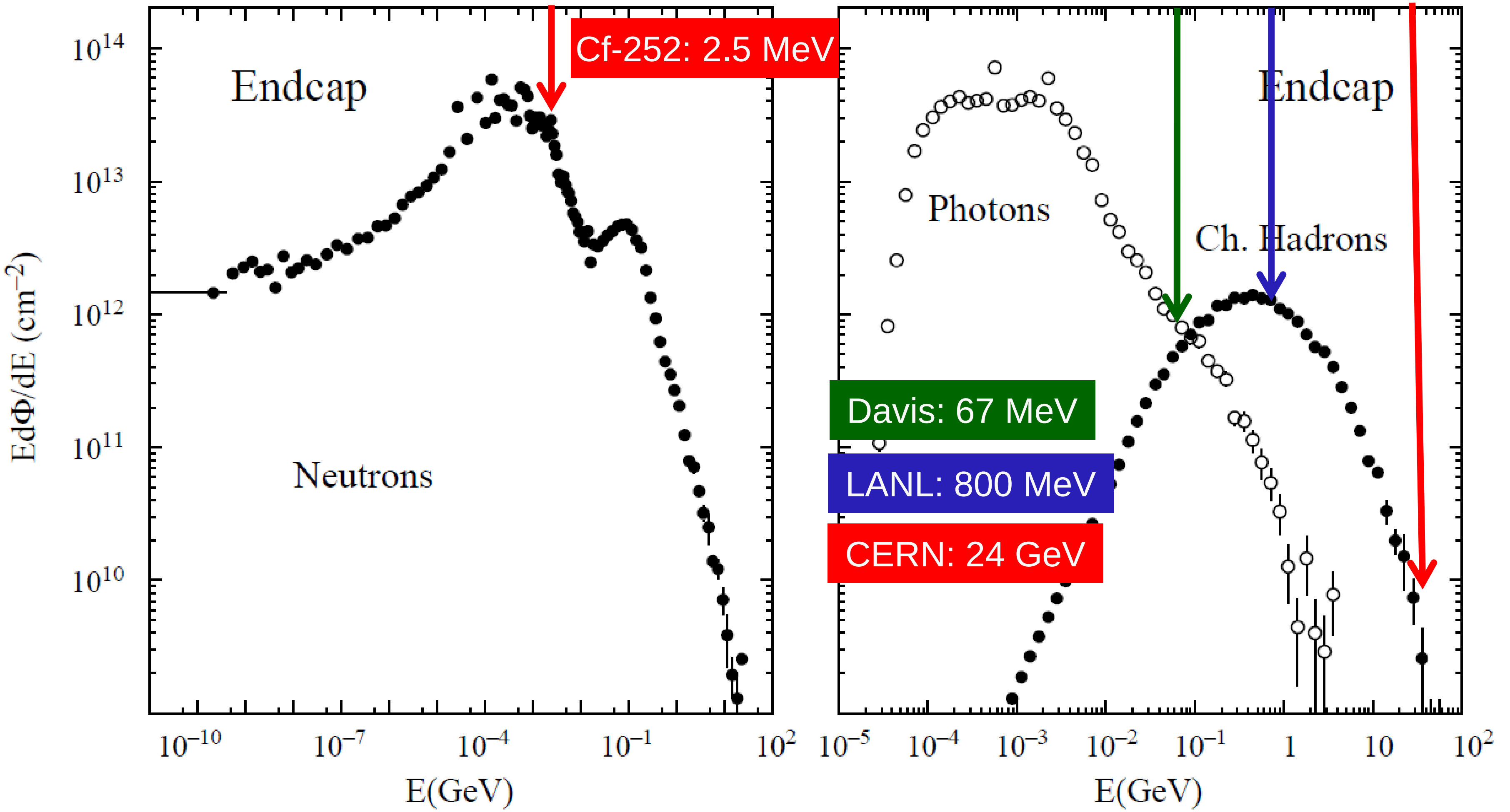
Charged Hadron



No experimental data show that neutrons and charged hadrons would damage crystal scintillators equally, so they should be treated separately

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



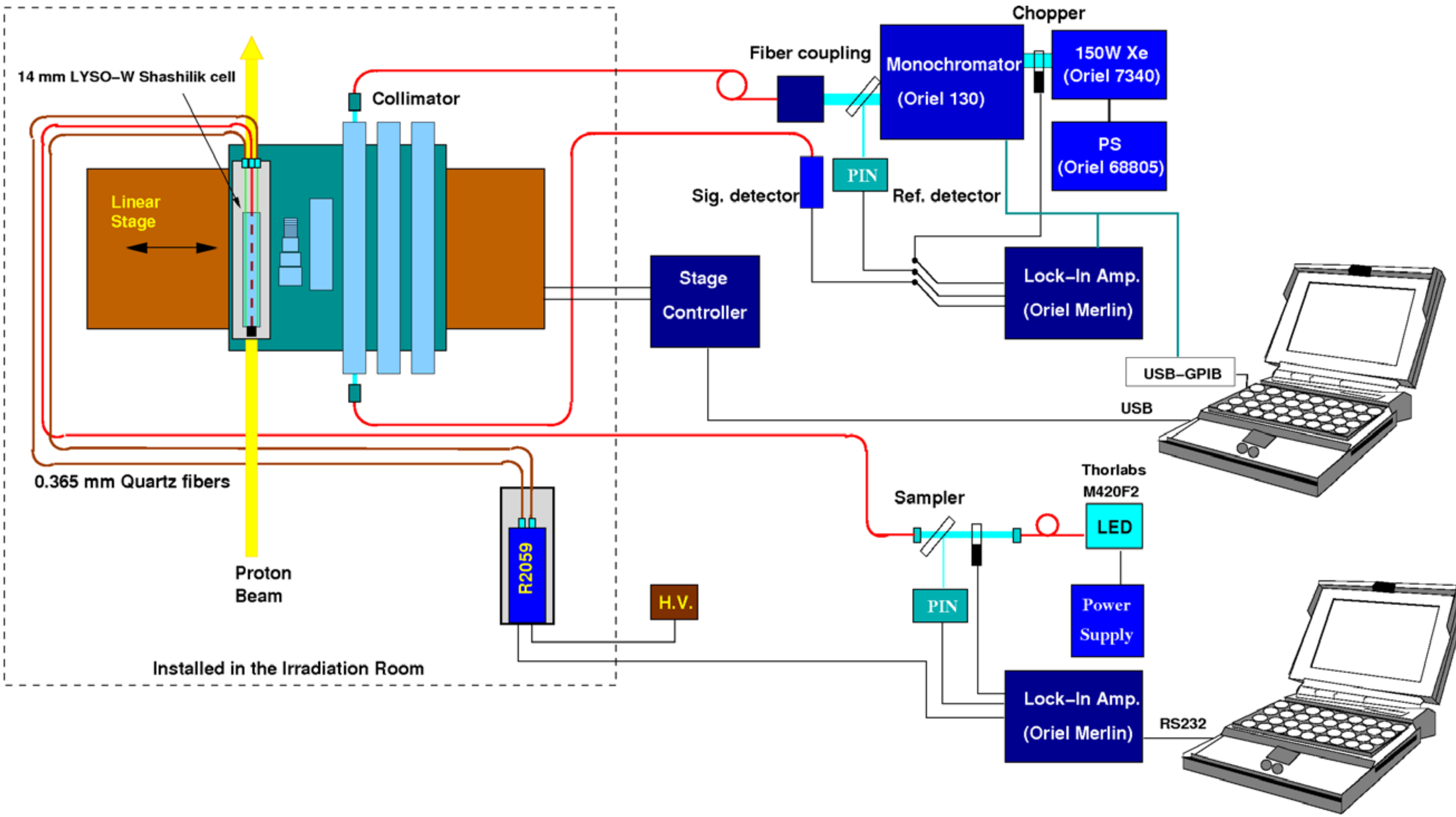
800 MeV Proton Beam at LANL

Environment/Source	Proton Flux ($p\ s^{-1}\ cm^{-2}$)	Fluence on Crystal ($p\ cm^{-2}$)
CMS FCAL (η=1.4) at HL-LHC	4.0×10^4	2.4×10^{12} / 3000 fb^{-1}
CMS FCAL (η=3.0) at HL-LHC	5.0×10^6	3.0×10^{14} / 3000 fb^{-1}
WNR facility of LANSCE	**Up to 2×10^{10}**	**Up to 3×10^{15}**

One end of a long crystal is bombarded by 800 MeV protons of a Gaussian shape with FWHM of one inch

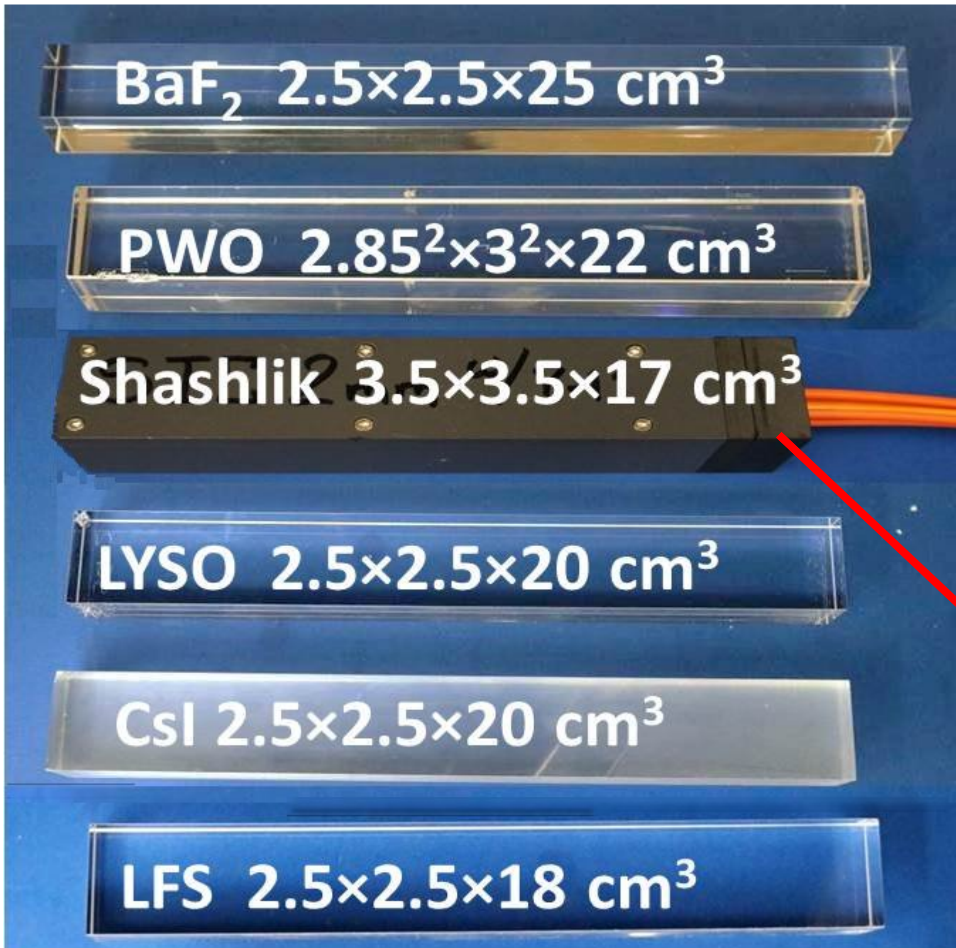
6990: On-line Monitoring

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

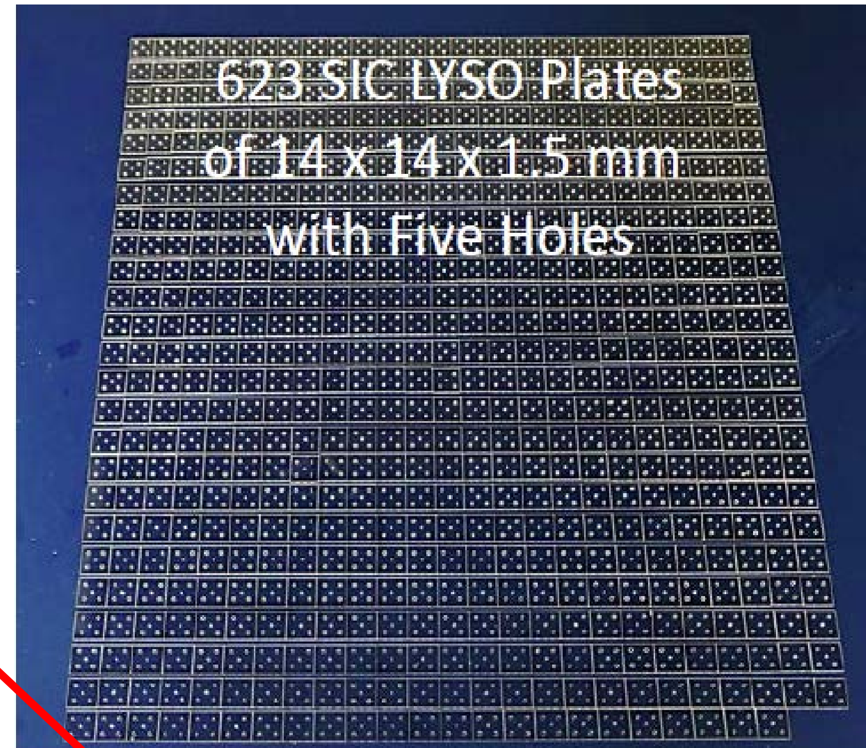


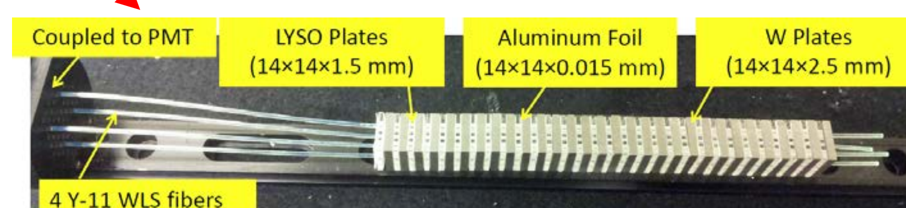
Samples

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

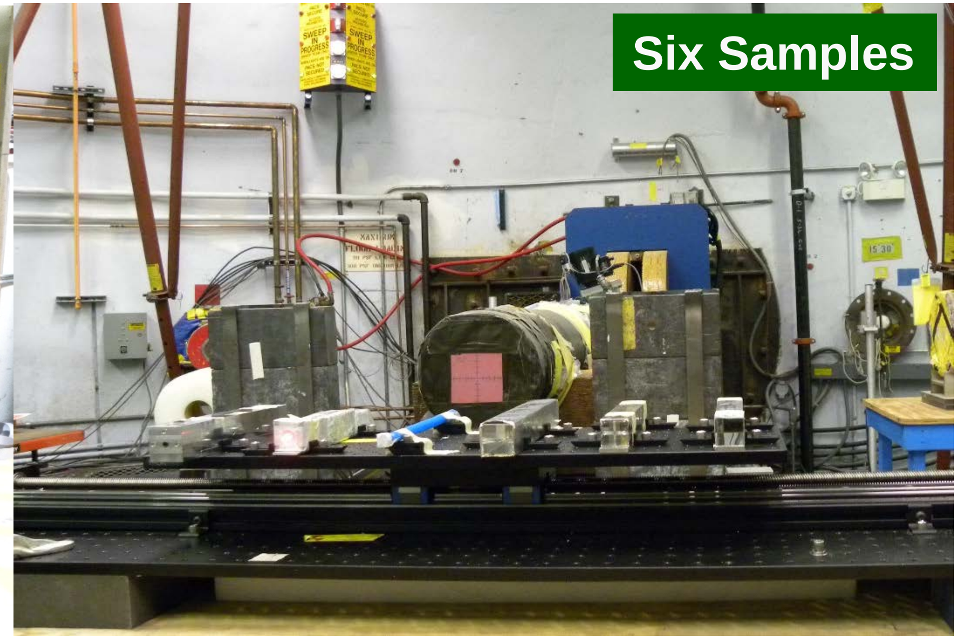


14 x 14 x 1.5 mm LYSO plates in the Target 4 East Port

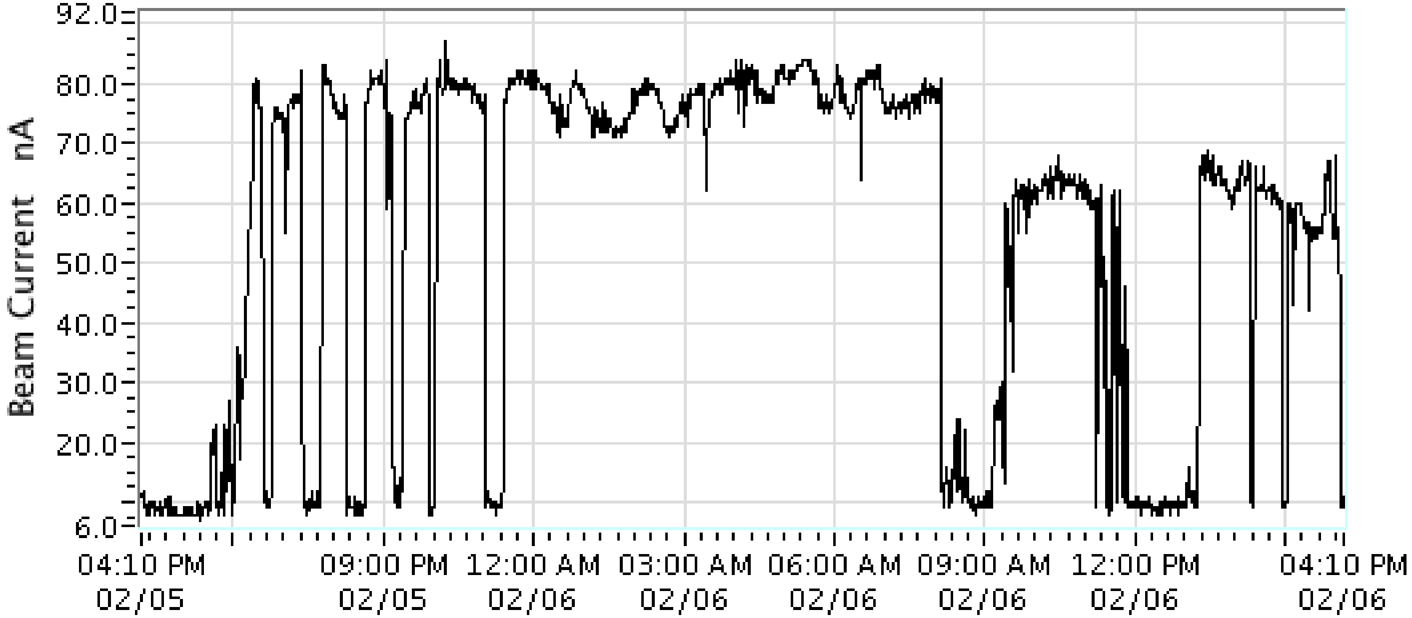


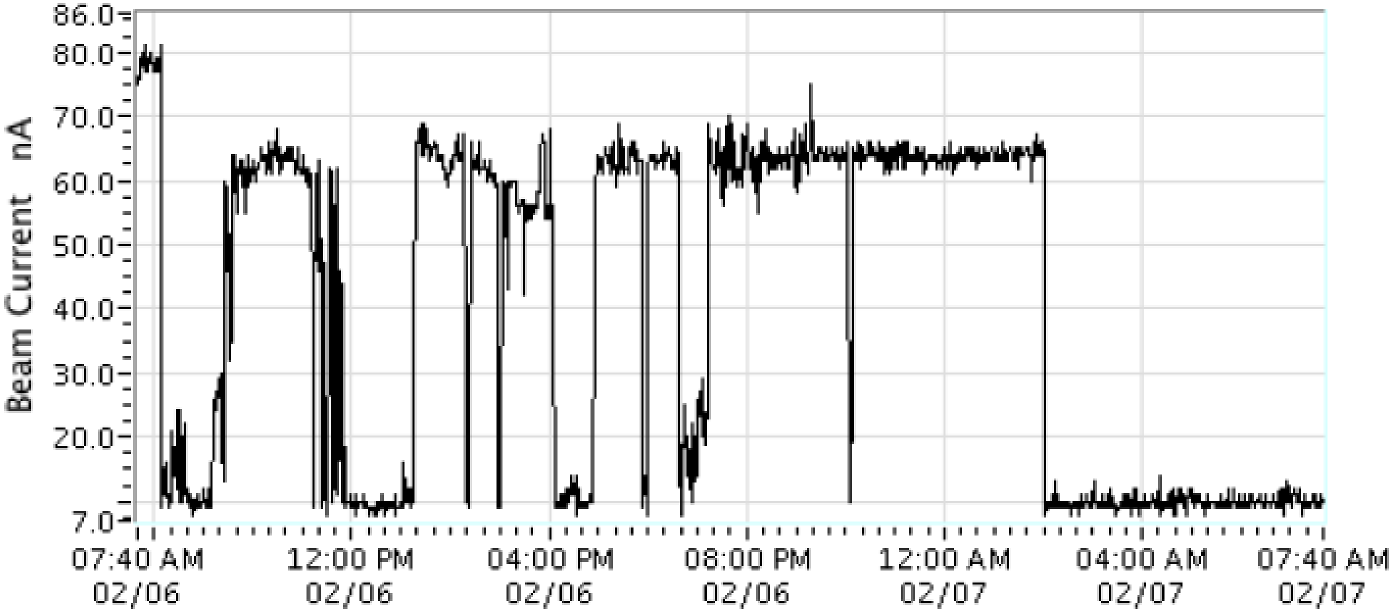


6990: Photos at Los Alamos



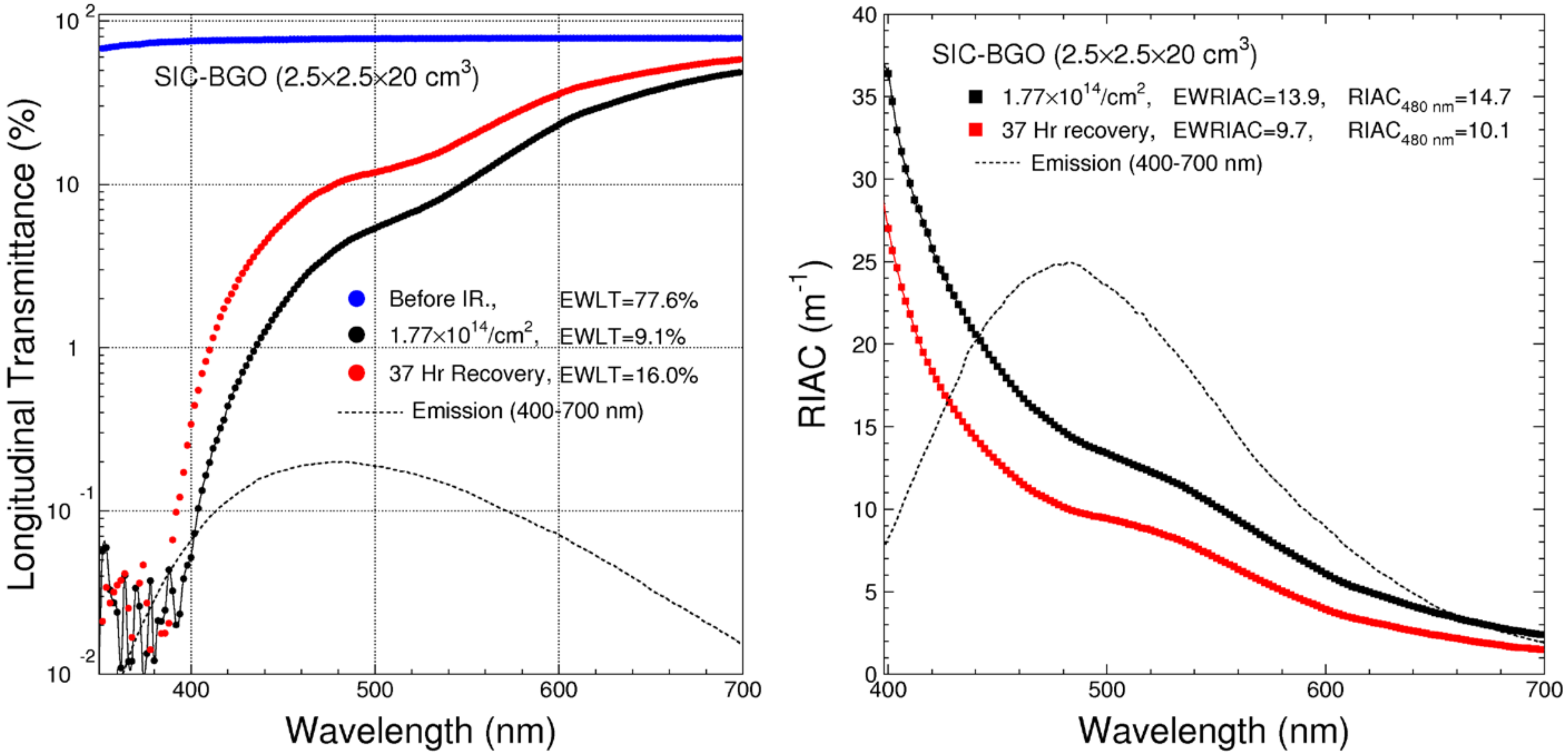
6990: Proton Beam History





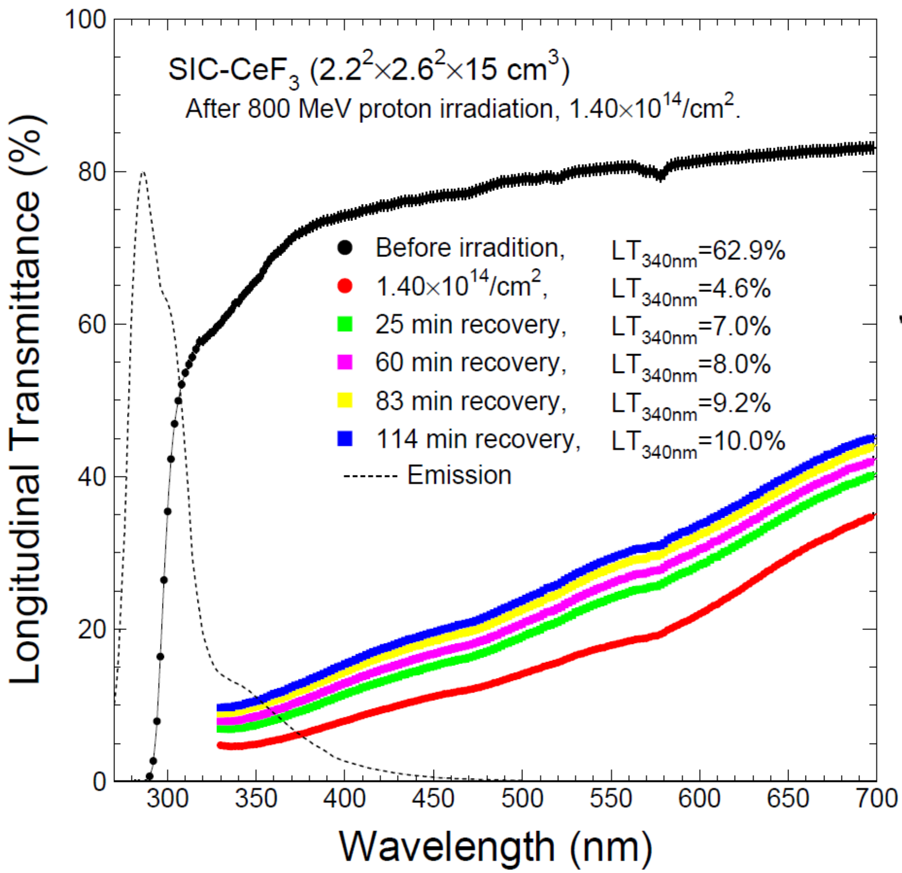
BGO: LT Damage and RIAC

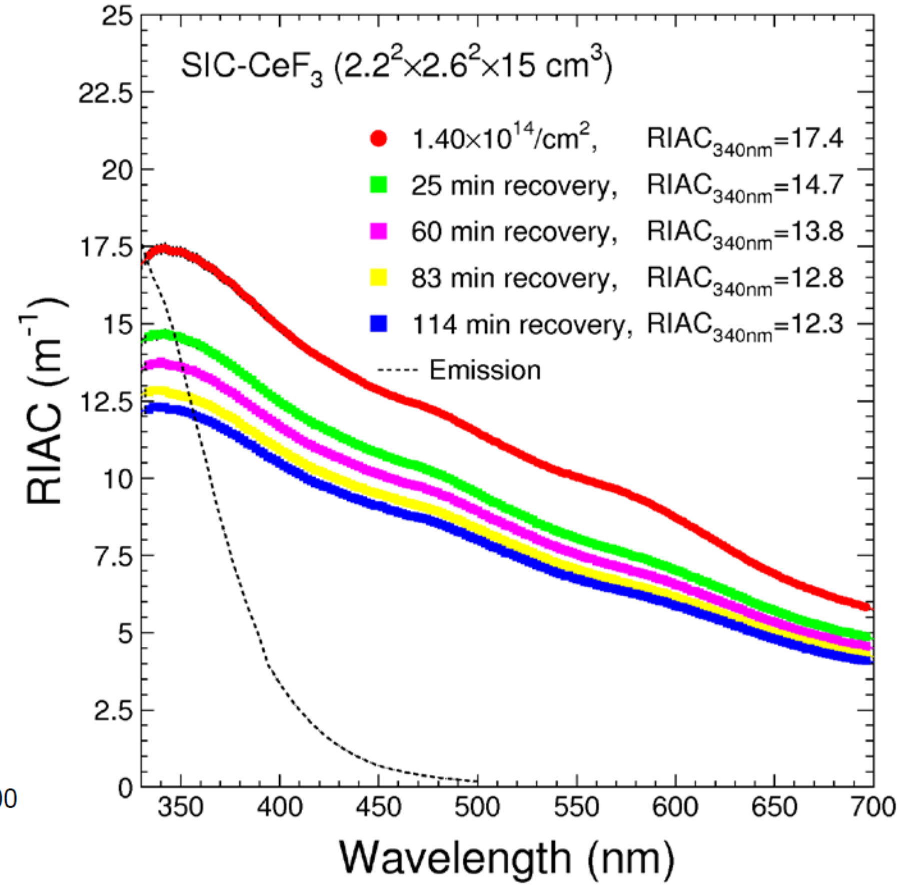
A 20 cm BGO sample irradiated to 1.8×10^{14} p/cm^2 with a flux of 3.1×10^{14} p/cm^2/hr. is completely black below 400 nm with recovery recorded from 15 to 10 m^{-1} at its emission peak after 37 hr



CeF_3: LT Damage and RIAC

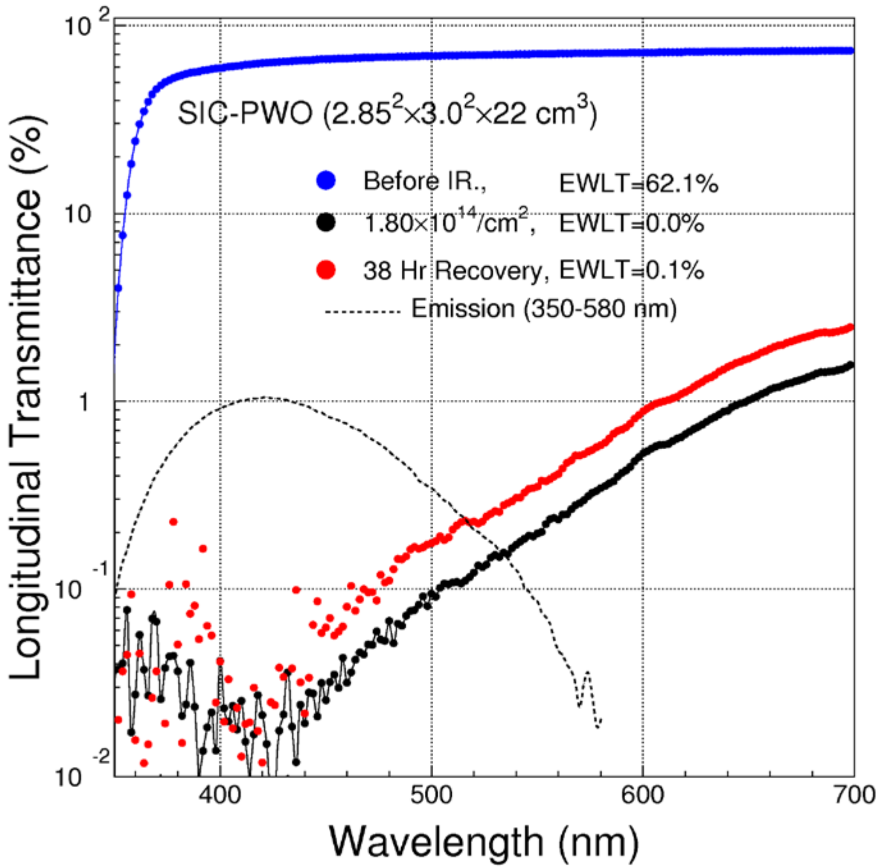
A CeF_3 of $2.2^2 \times 15 \times 2.6^2$ cm^3 was irradiated to 1.4×10^{14} p/cm^2 with RIAC @ 340 nm of 17 m^{-1}

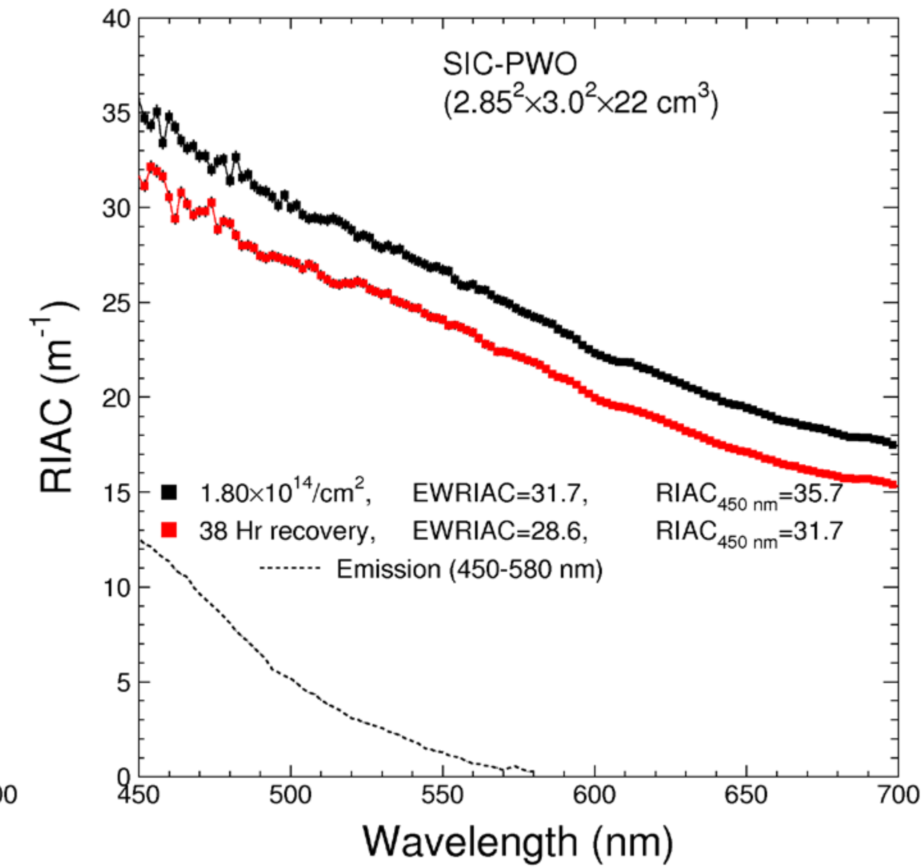




PWO: LT Damage and RIAC

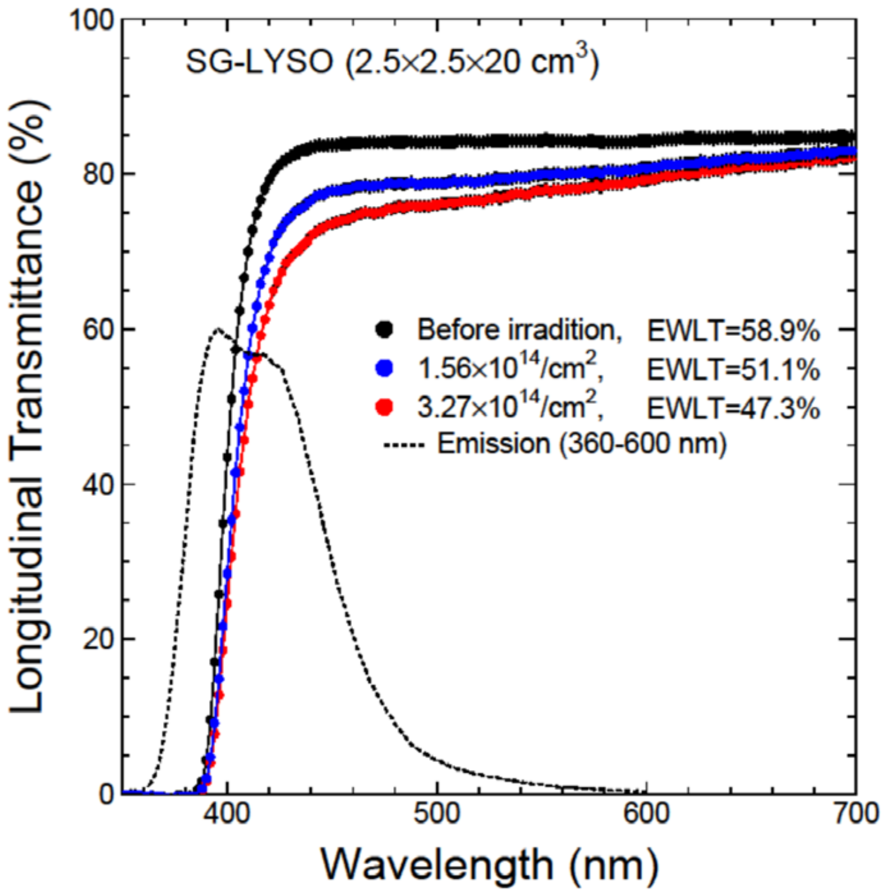
The 22 cm PWO sample irradiated to 1.8×10^{14} p/cm^2 with a flux of 3.1×10^{14} p/cm^2/hr is completely black below 450 nm with recovery observed after 38 hr.

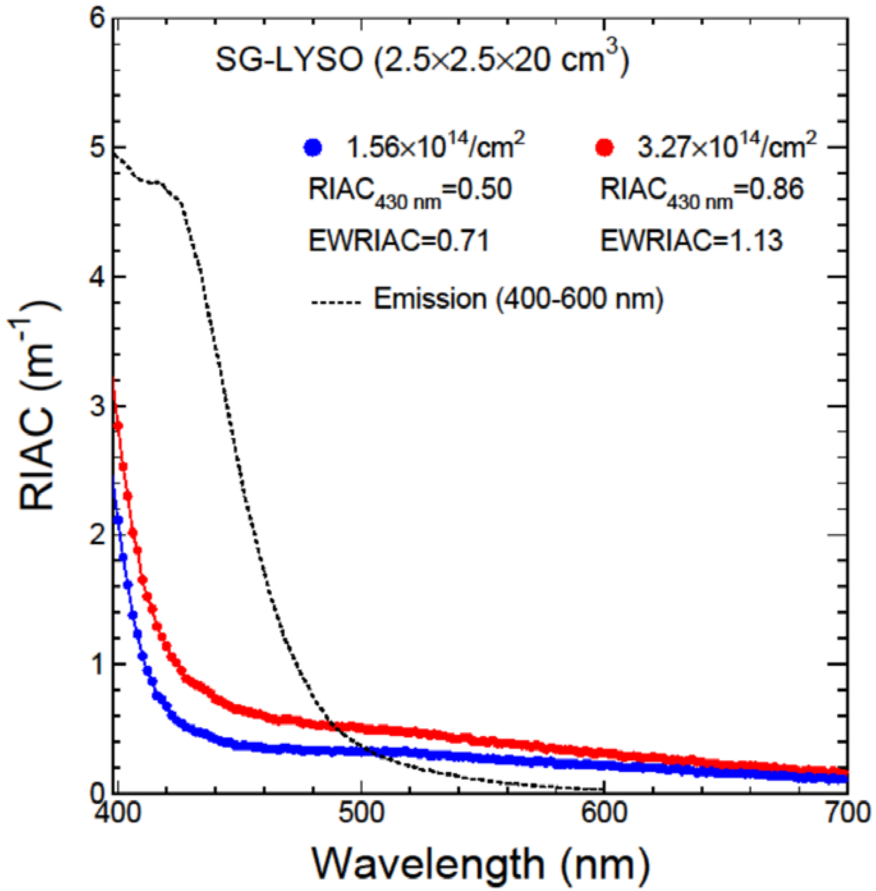




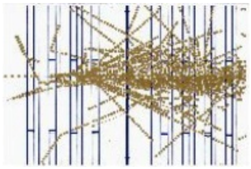
LYSO: LT Damage and RIAC

A LYSO of 2.5×2.5×20 cm^3 irradiated to 3.3×10^{14} p/cm^2 with EWRIAC of 1 m^{-1}, indicating excellent radiation hardness of LYSO against protons

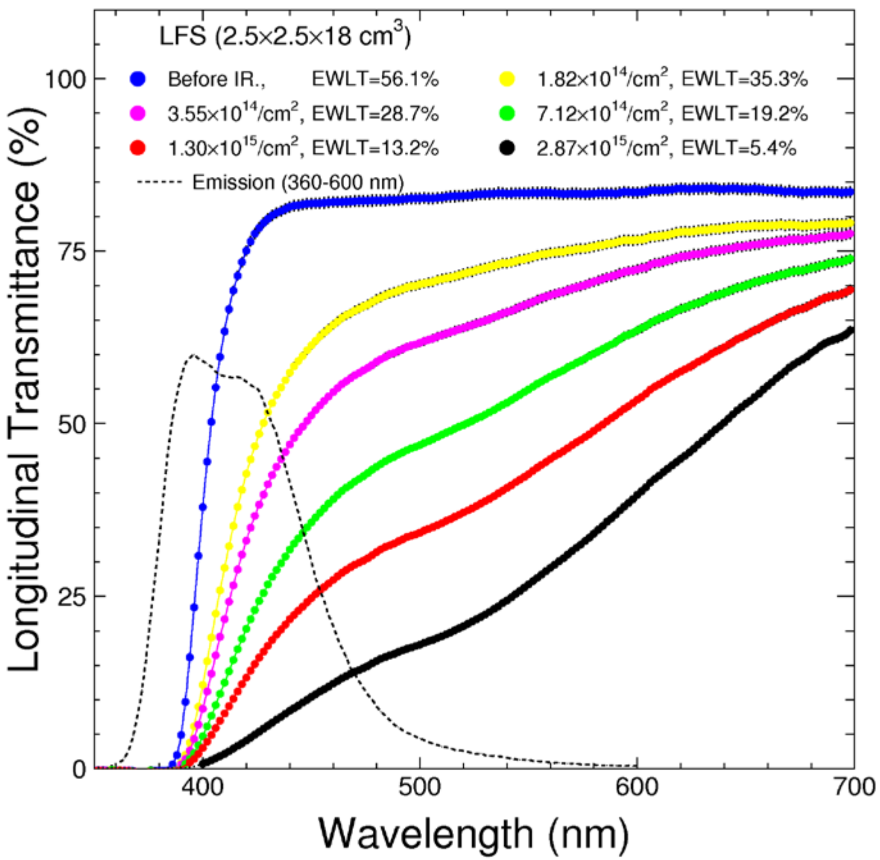


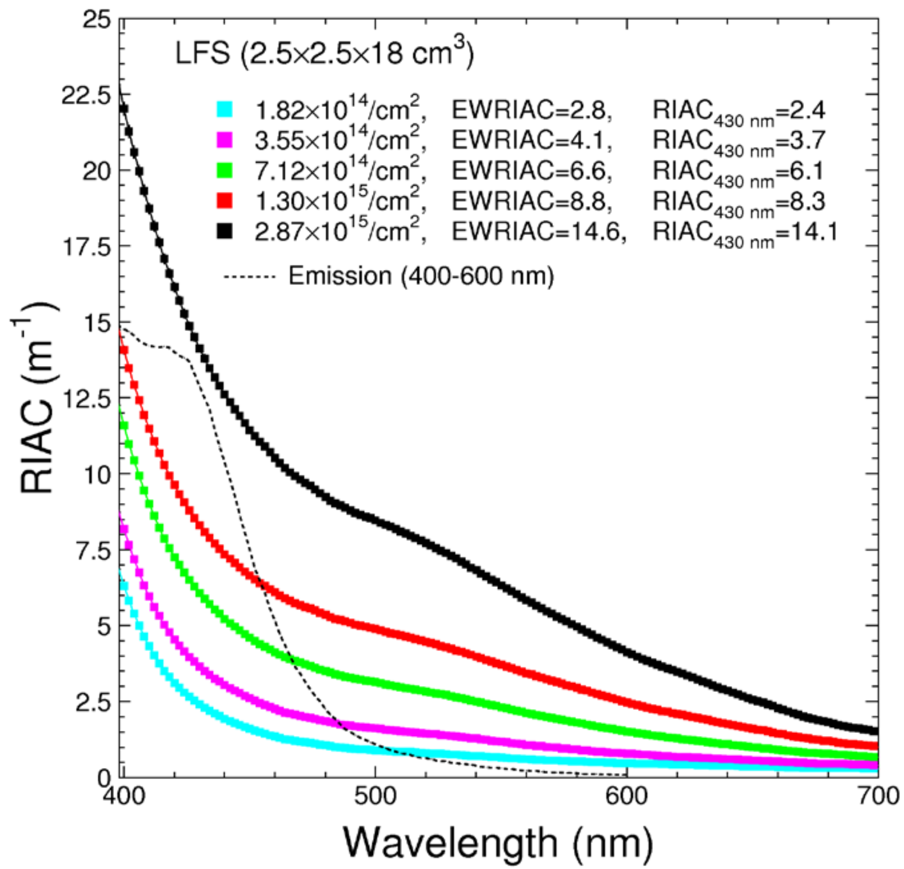


LFS: LT Damage and RIAC

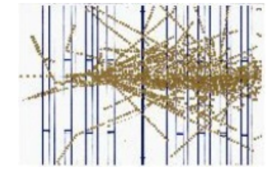


A LFS crystal of 18 cm irradiated to 2.9×10^{15} p/cm^2 in five steps with RIAC at 430 nm of 3.7 / 14.1 m^{-1} after 3.6×10^{14} / 2.9×10^{15} p/cm^2 respectively





RIAC at Emission Peak

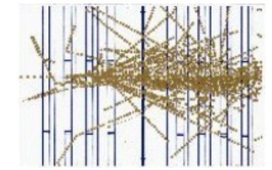


Measured Values at about E14, and extracted to 3E14 p/cm^2

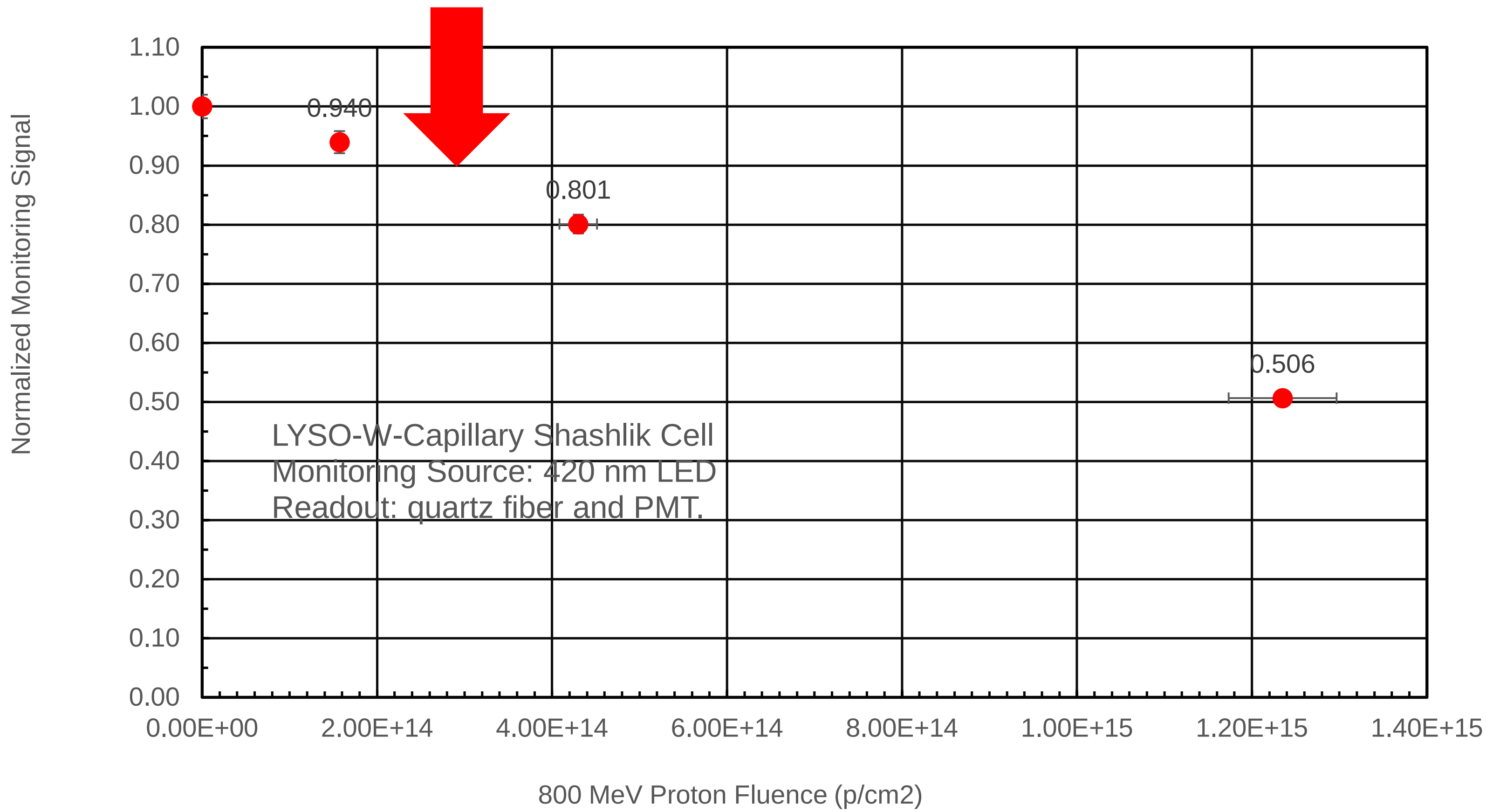
Crystal	Dimensions (mm^3)	ID	Emission Peak (nm)	Fluence (p/cm^2)	RIAC at EP (1/m)	@ 3E+14
BGO	25×25×200	SIC-BGO	480	1.77E+14	14.7	24.9
CeF_3	22^2×26^2×150	SIC-CeF	340	1.40E+14	17.4	37.3
LYSO	25×25×200	SG-LYSO	430	3.27E+14	0.86	0.8
LFS	25×25×180	OET-LFS	430	3.55E+14	3.7	3.1
PWO*	28.5^2×30^2×220	SIC-PWO	420	1.80E+14	> 36	> 60

LYSO is the most radiation hard among all tested at LANL

LFS/W/Capillary Tower



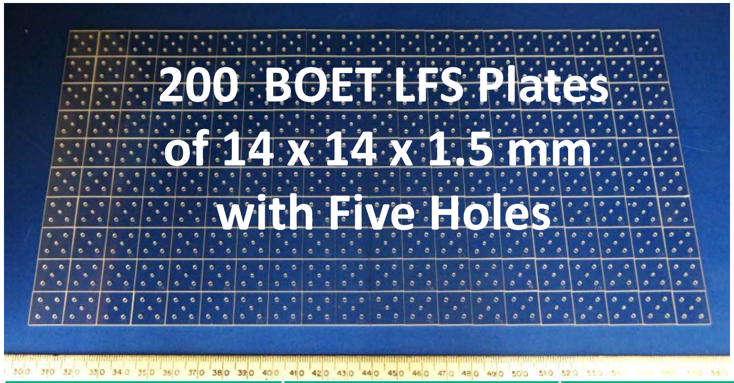
The Shashlik tower irradiated to 1.2×10^{15} p/cm^2 in 3 steps with degradation of 20%/50% after 4.3×10^{14} / 1.24×10^{15} p/cm^2

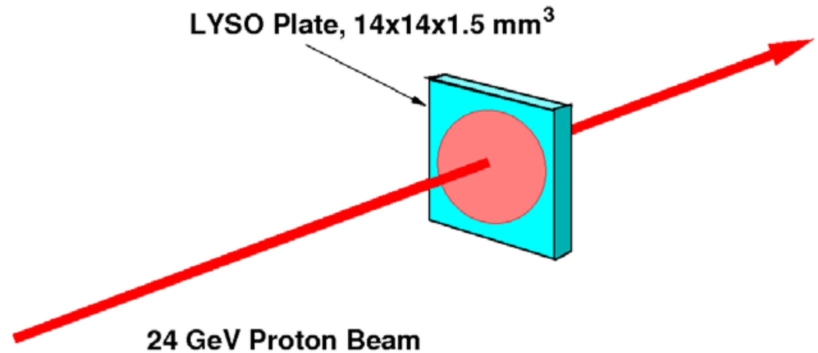


~10% light output loss in a LYSO/capillary based Shashlik tower

@ 3E14

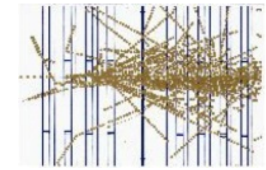
Irradiation for LYSO Plates, 2015



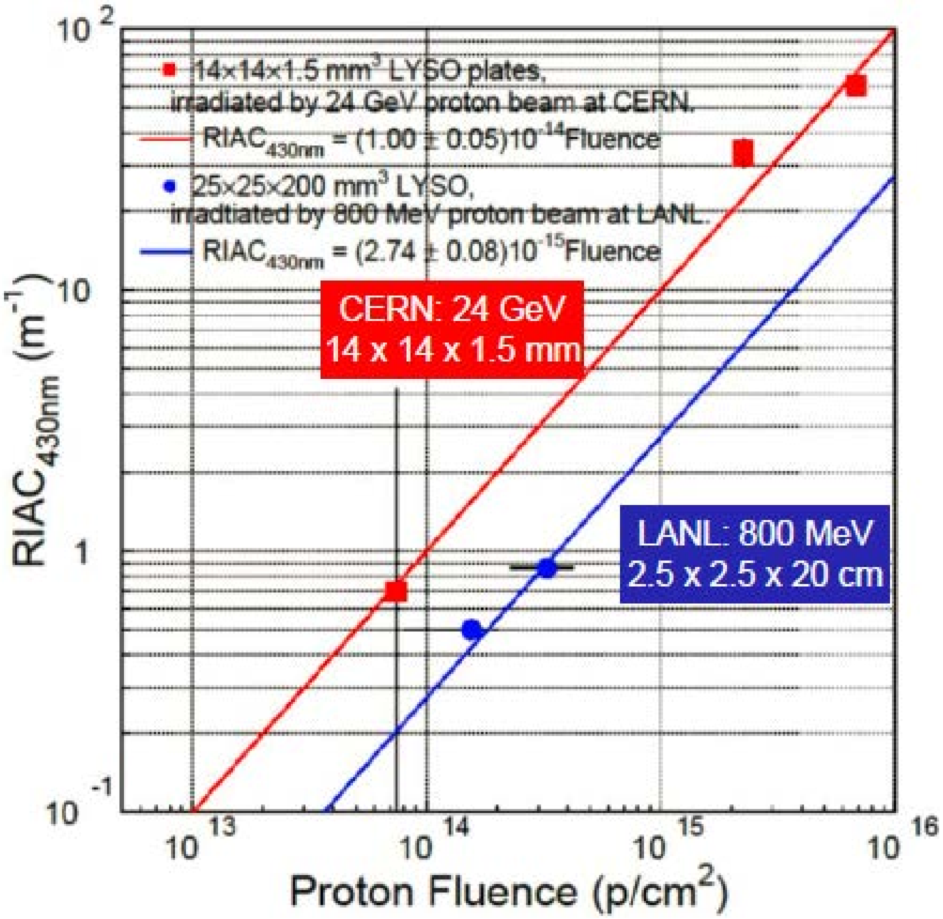


ID	Dimension (mm³)	Facility	Protons (GeV)	Irradiation Set	Fluence (p/cm²)	Error (+/- %)
LFS BOET-6	**14×14×1.5**	CERN	24	2045	9.97×10^{13}	7.0
LFS BOET-7	**14×14×1.5**	CERN	24	2045	9.97×10^{13}	7.0
LFS BOET-8	**14×14×1.5**	CERN	24	2046	4.48×10^{14}	8.4
LFS BOET-9	**14×14×1.5**	CERN	24	2046	4.48×10^{14}	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

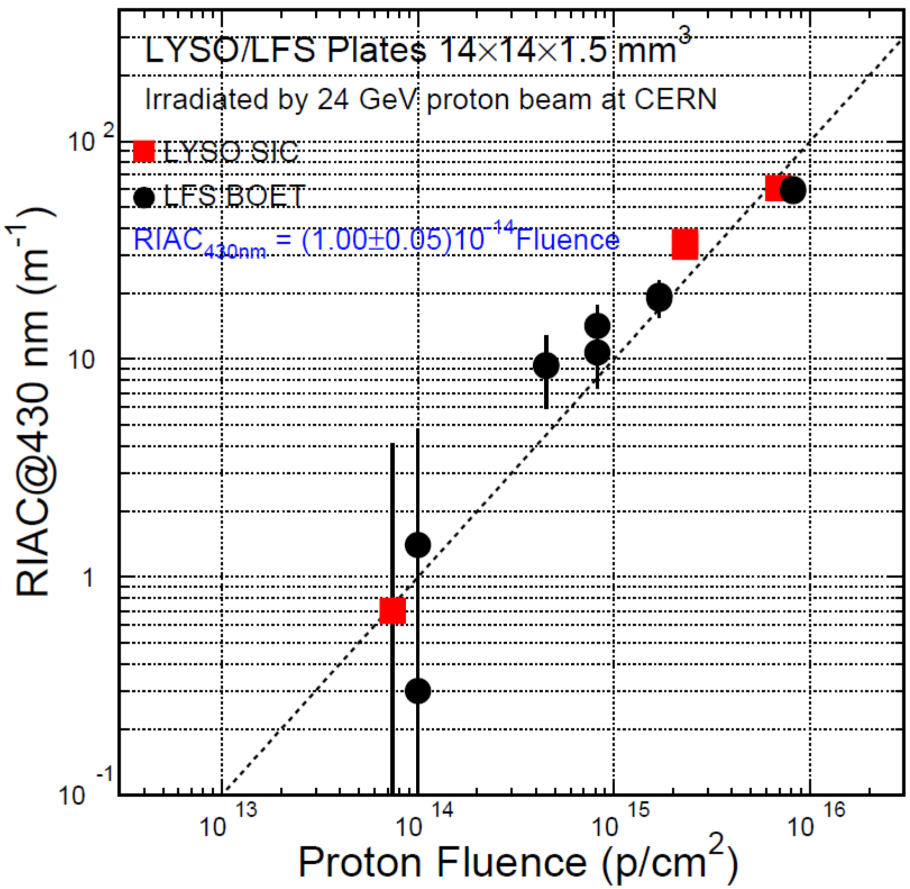
RIAC@ as a function of Fluence



2014 Data



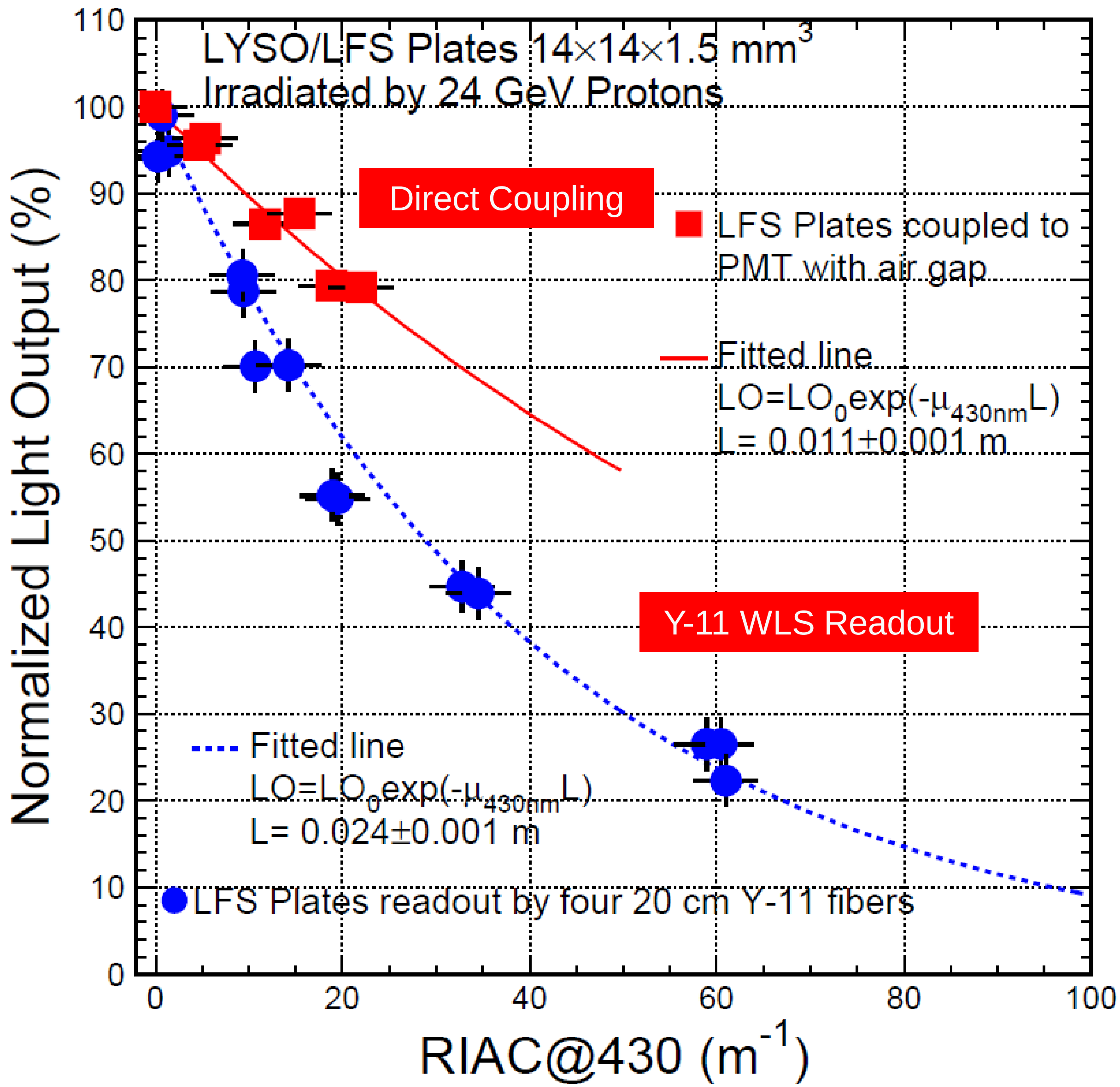
2015 Data



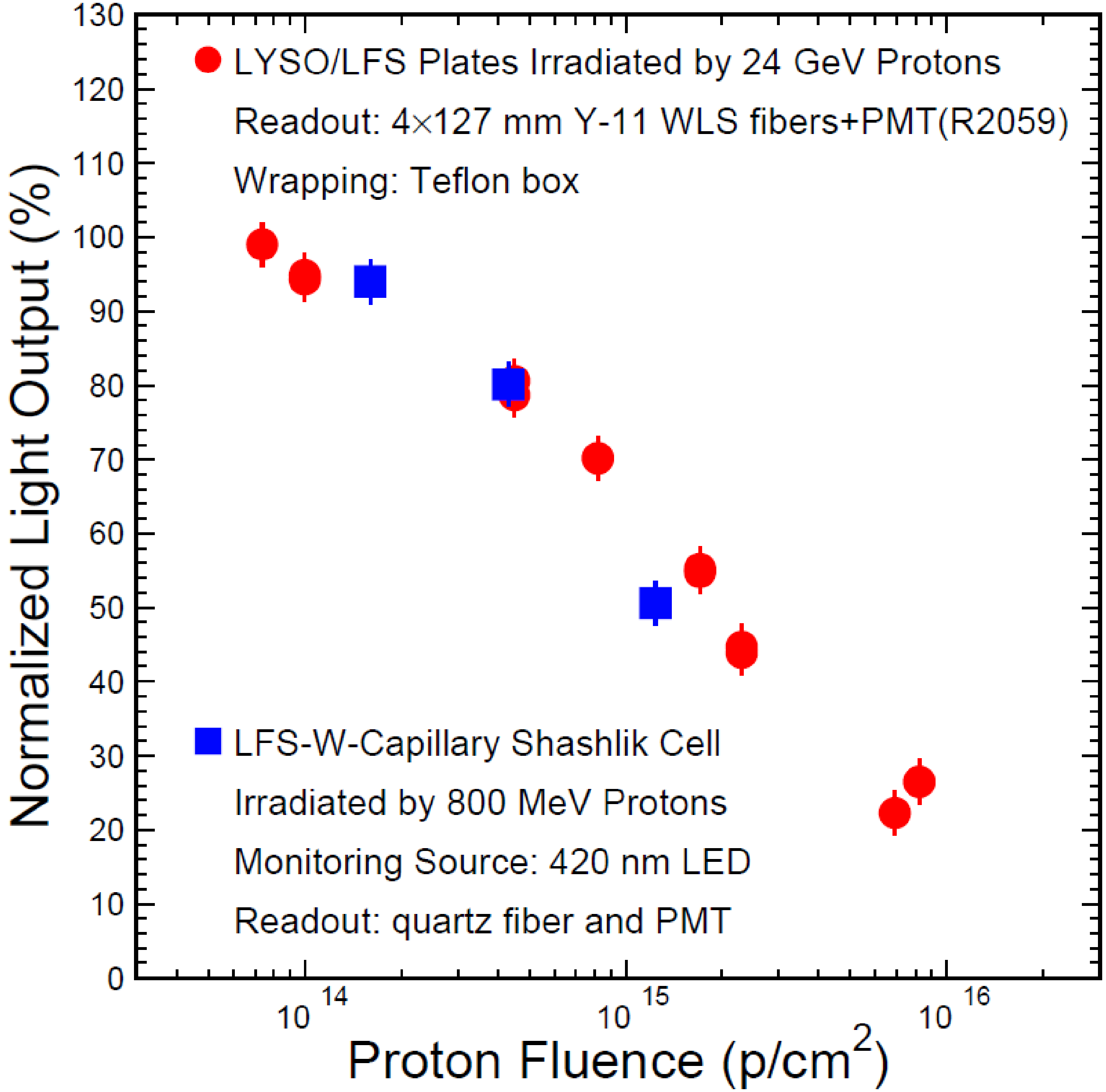
Consistent damage in LFS and LYSO

LO of LYSO/LFS Plates

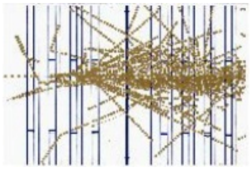
Data consistent with average light path length of 1.1 and 2.4 cm at 430 nm for direct and Y-11 readout respectively



6990: Plates & Shashlik Cell



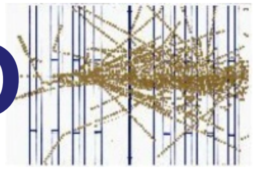
Consistent damage for plates and a Shashlik cell indicates small degradation in quartz capillaries & no difference between protons of 800 MeV and 24 GeV



Summary

- Crystal transmittance and Shashlik response were measured during proton irradiation up to 3 x 10^{15} p/cm^2.
- After 2 x 10^{14} p/cm^2 PWO and CeF_3 are black at their emission peak, BGO has a RIAC value of 15 m^{-1}. LYSO and LFS crystal shows good radiation hardness, about 1 to 3 m^{-1} after 3 x 10^{14} p/cm^2.
- A LFS/W/Capillary Shashlik cell shows 10% LO loss after 3×10^{14} p/cm^2, indicating a good stability of the proposed LYSO and quartz capillary based Shashlik calorimeter against charged hadrons.
- The damage observed at Los Alamos by 800 MeV protons is consistent with LYSO plates irradiated by 24 GeV protons at CERN in 2014 and 2015.
- Investigations will continue to compare damage by ionization dose, protons and neutrons.

No Neutron Damage in PWO

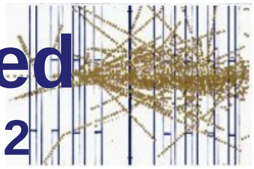


5.2 Radiation damage effects under neutron irradiation

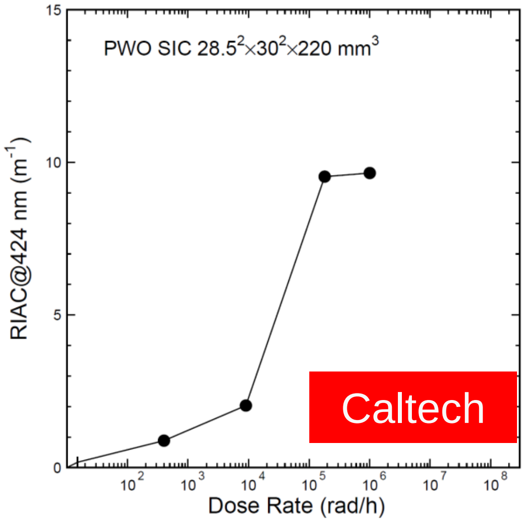
In view of the intense neutron flux expected in CMS (see section 2) the effects on lead tungstate of neutron exposure were studied in nuclear reactors [47, 48]. The neutron fluxes and energies in these exposures were comparable to those expected in CMS. However, in reactors there is a strong associated 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].

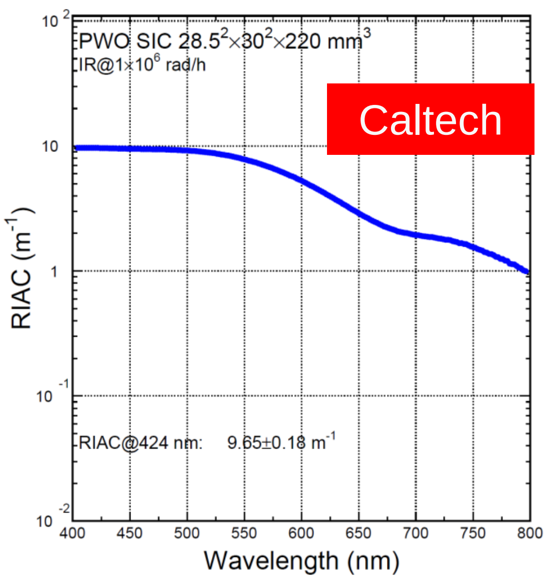
The CMS Electromagnetic Calorimeter Group, ***Radiation hardness qualification of $PbWO_4$ scintillation crystals for the CMS Electromagnetic Calorimeter***, 2010 JINST 5 P03010

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



Gamma Irradiation at JPL





7.8×10^{18}/1.2×10^{19}/4.0×10^{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

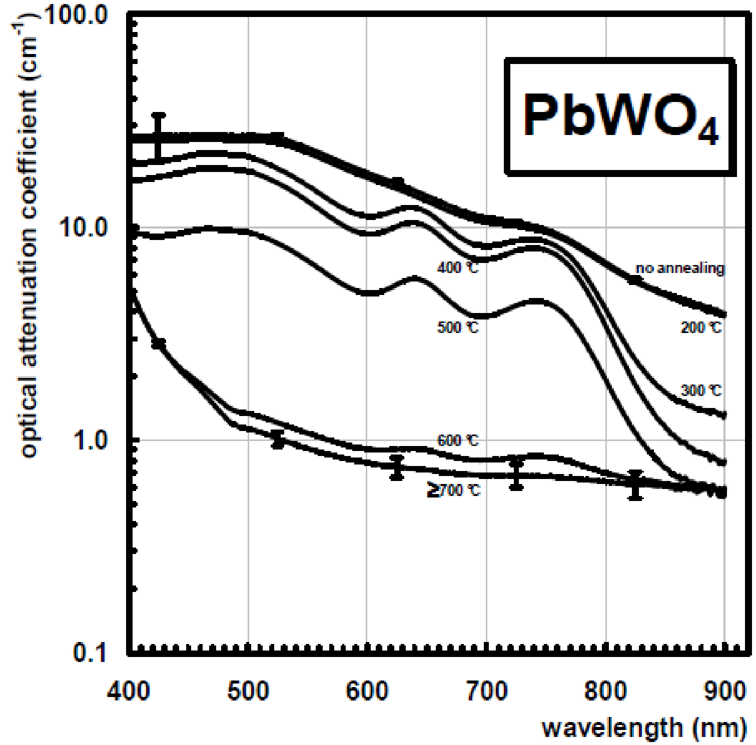


Fig. 2. Optical attenuation coefficient of the irradiated sample before annealing and after successive annealing temperatures.

[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