Radiation Hardness of LYSO and BaF_2 Crystals against γ-rays, Protons and Neutrons

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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.**
- **Total absorption crystal calorimetry performance 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 hard scintillators at the energy frontier (HL-LHC);**
  - **Ultra-fast scintillators at the intensity frontier (Mu2e-II);**
  - **Cost-effective crystals for lepton collides (ILC/FCC/CEPC).**

CMS LYSO+SiPM BTL for HL-LHC

CMS Hermetic Timing Concept

ETL: Si

BTL: LYSO/SiPM

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**

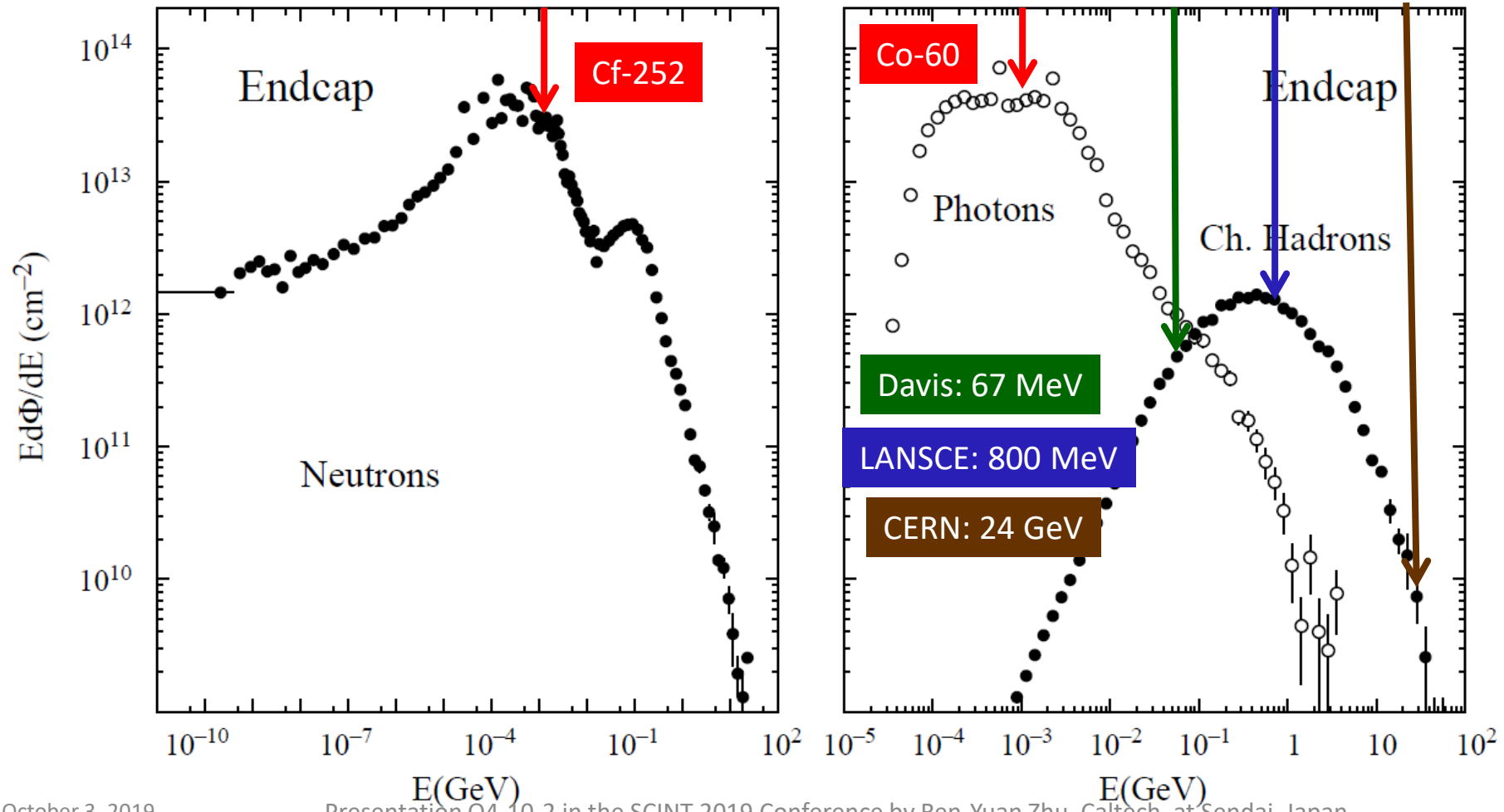
Radiation Expected by CMS BTL

MTD TDR: assuming 5×10^{34} $cm^{-2}s^{-1}$, 3,000 fb^{-1} & a safety factor of 1.5
Radiation spec: λ_{in}<3 m^{-1} for 4.4 Mrad, 2.5 x 10^{13} p/cm^2 & 3.0 x 10^{14} n_{eq}/cm^2

CMS MTD	η	n_{eq}/cm^{-2}	n_{eq} Flux ($cm^{-2}s^{-1}$)	Proton* (cm^{-2})	p Flux ($cm^{-2}s^{-1}$)	Dose (Mrad)	Dose rate (rad/h)
Barrel	0.00	2.5E+14	3.1E+06	2.2E+13	2.7E+05	2.7	122
Barrel	1.15	2.7E+14	3.4E+06	2.4E+13	3.0E+05	3.8	169
Barrel	1.45	2.9E+14	3.6E+06	2.5E+13	3.1E+05	4.4	196
Endcap	1.60	2.3E+14	2.8E+06	2.0E+13	2.5E+05	2.9	128
Endcap	2.00	4.5E+14	5.6E+06	3.9E+13	4.9E+05	7.5	338
Endcap	2.50	1.1E+15	1.4E+07	9.9E+13	1.2E+06	25.5	1148
Endcap	3.00	2.6E+15	3.2E+07	2.2E+14	2.8E+06	73.5	3308

Particle Energy Spectra at LHC

FLUKA simulations: neutrons and charged hadrons peaked at MeV and several hundreds MeV respectively. We investigate neutron and proton induced damages at East Port and Blue Room of LANSCE.

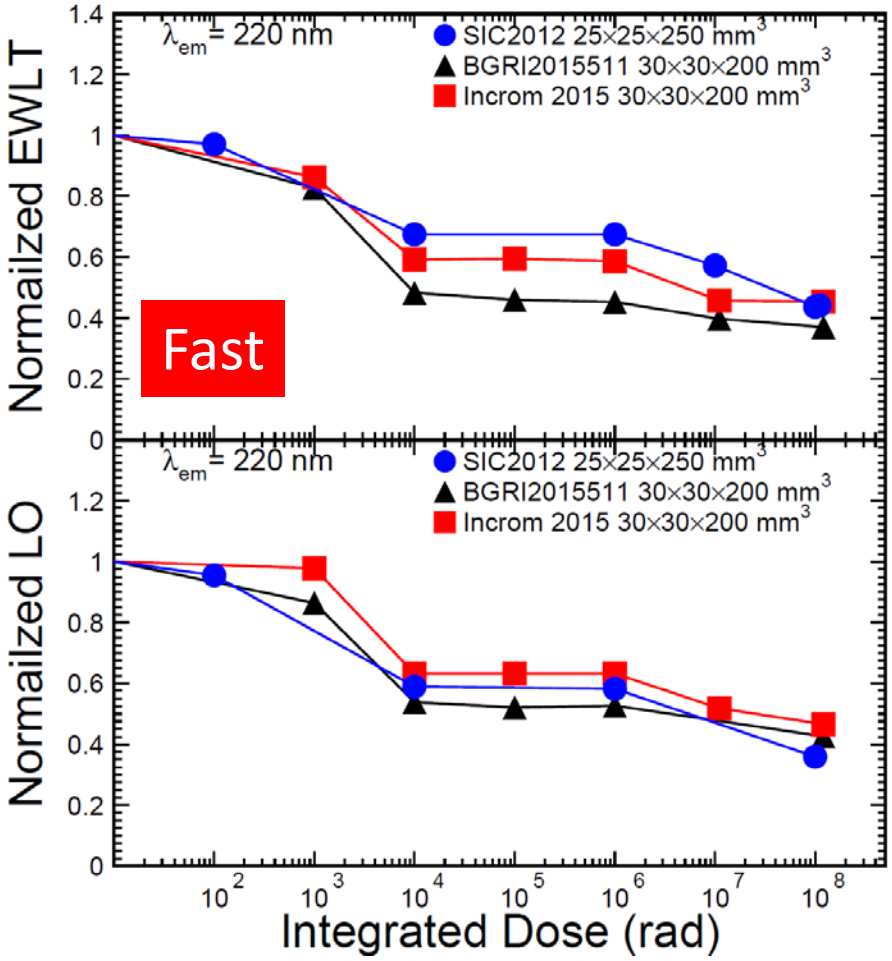


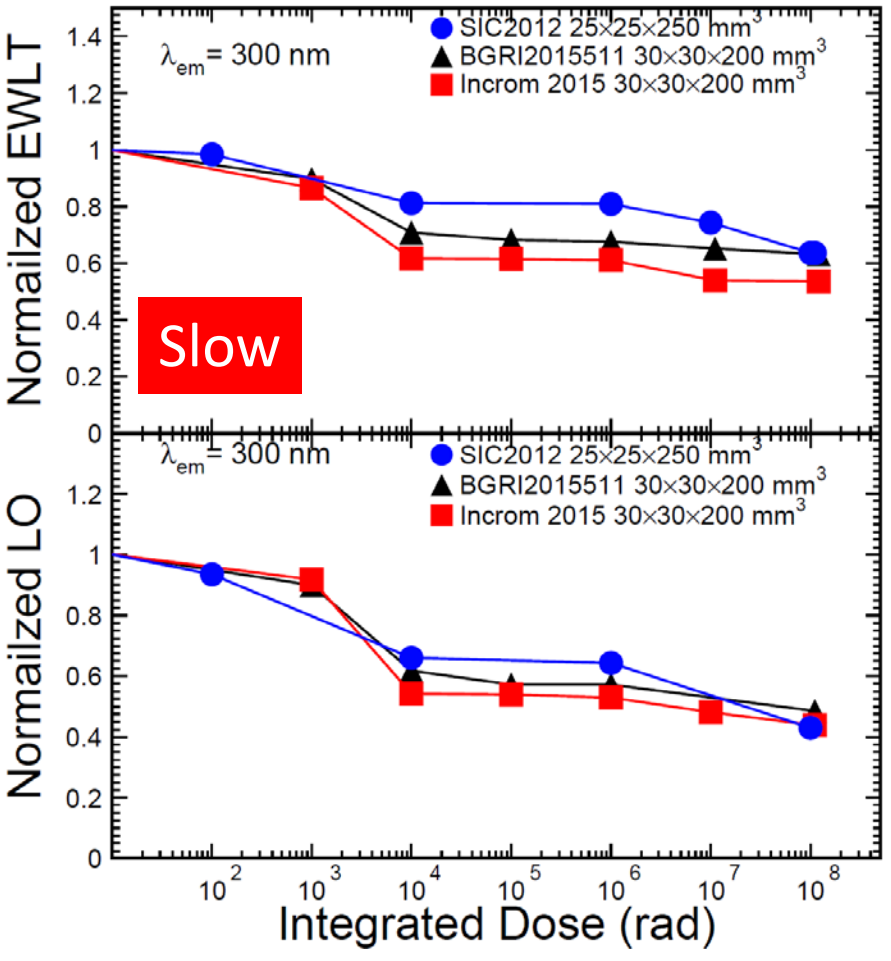
Radiation Damage in Crystals

- Possible damage effects are scintillation mechanism damage, induced absorption and phosphorescence, where induced absorption degrades crystal transparency and light output.
- Ionization dose induced damage was investigated for BaF_2, BGO, CeF_3, undoped CsI, LSO/LYSO/LFS and PWO by using Co-60 and Cs-137 sources at Caltech, as well as the JPL TID and the Sandia GIF facilities.
- Proton induced damage was investigated for BaF_2, BGO , CeF_3, LYSO and PWO crystals by using 800 MeV protons at LANSCE and 24 GeV protons at CERN IRRAD facilities.
- Neutron induced damage was investigated for BaF_2, LYSO and PWO crystals at LANSCE.
- Results of LYSO and BaF_2 crystals are presented in this report.

Results of TID:γ for BaF_2

Consistent damage in 20 cm long BaF_2 crystals from three vendors

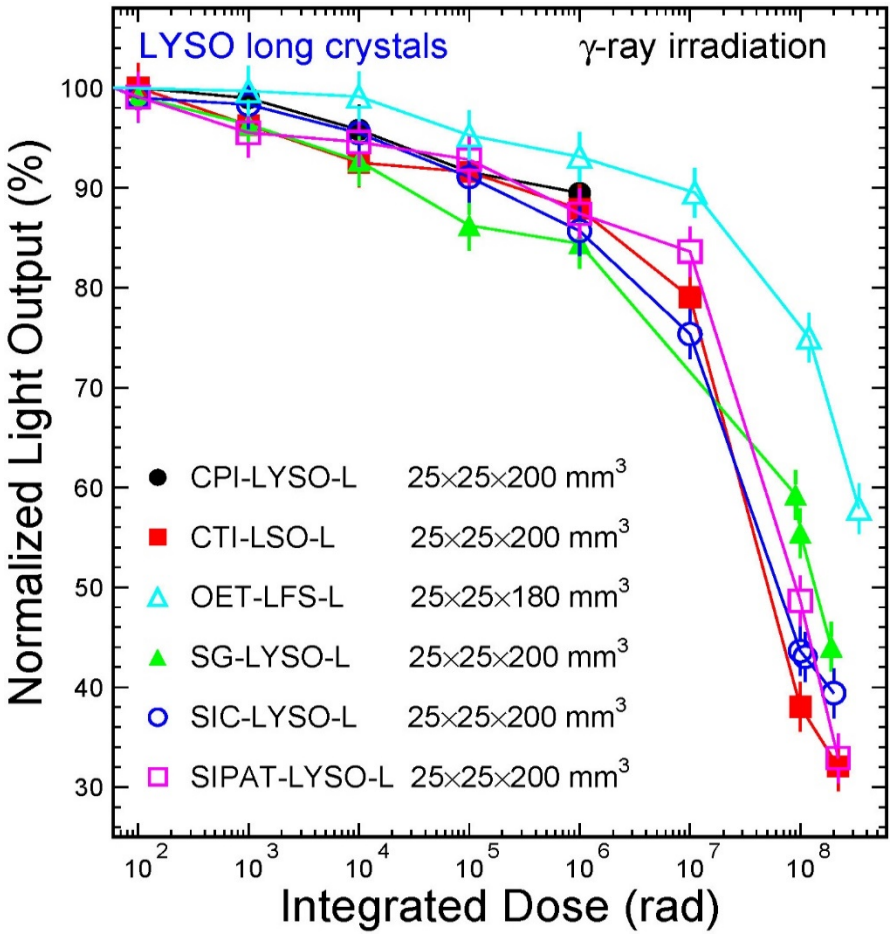


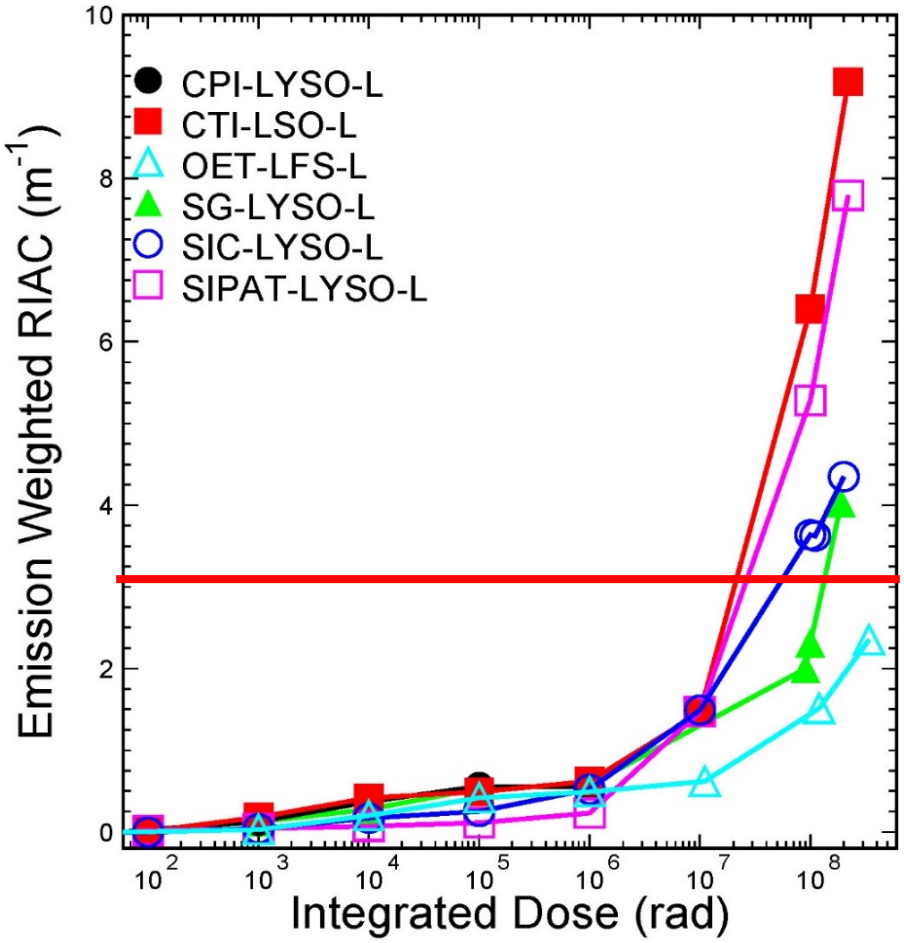


40%/45% LO loss for the fast/slow component after 120 Mrad

Results of TID:γ for LYSO

F. Yang *et al.*, *IEEE Trans. Nucl. Sci.* **63**, pp. 612-619 (2016)

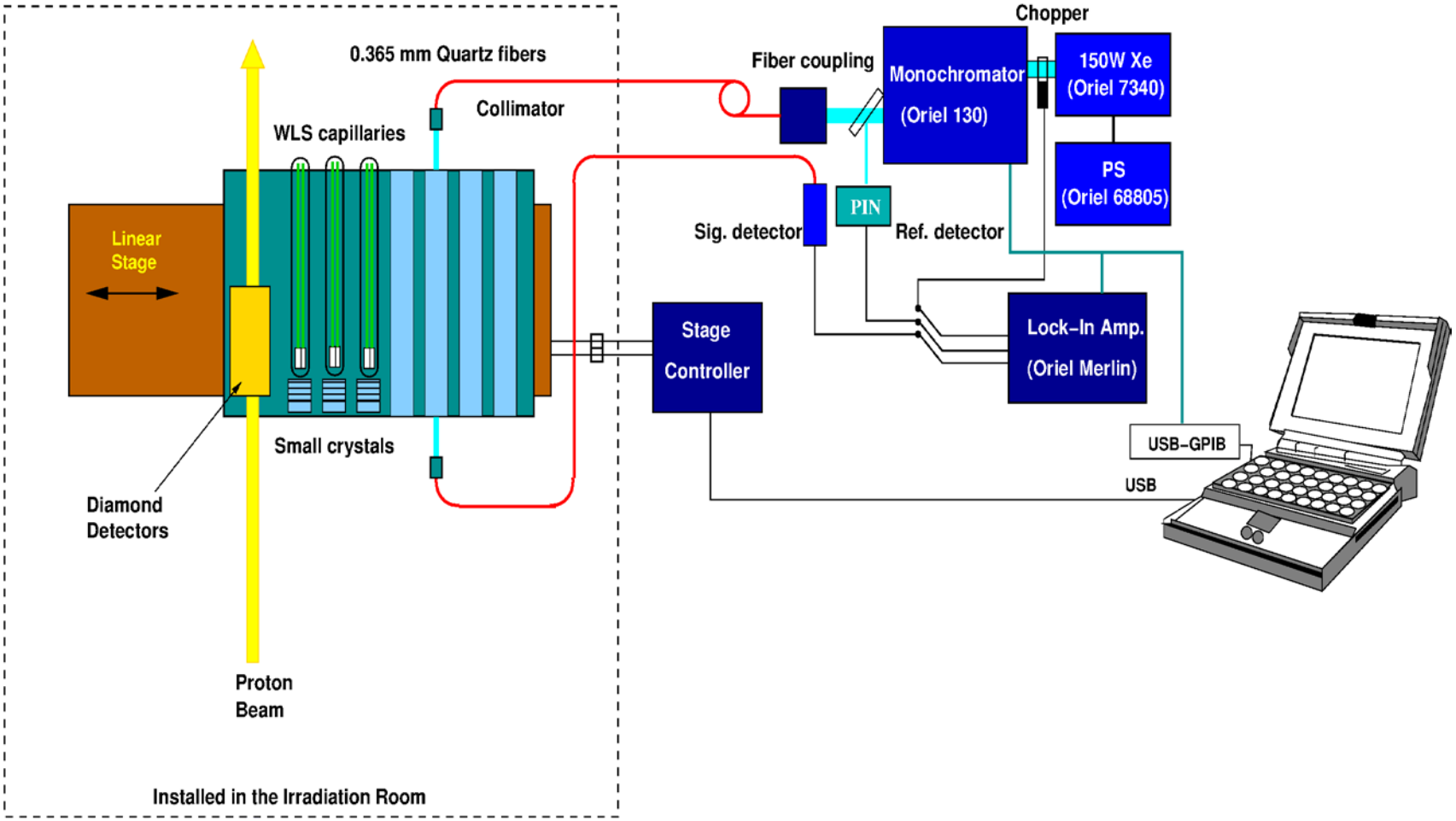




LYSO crystals from six vendors show < 3 m^{-1} after 20 Mrad

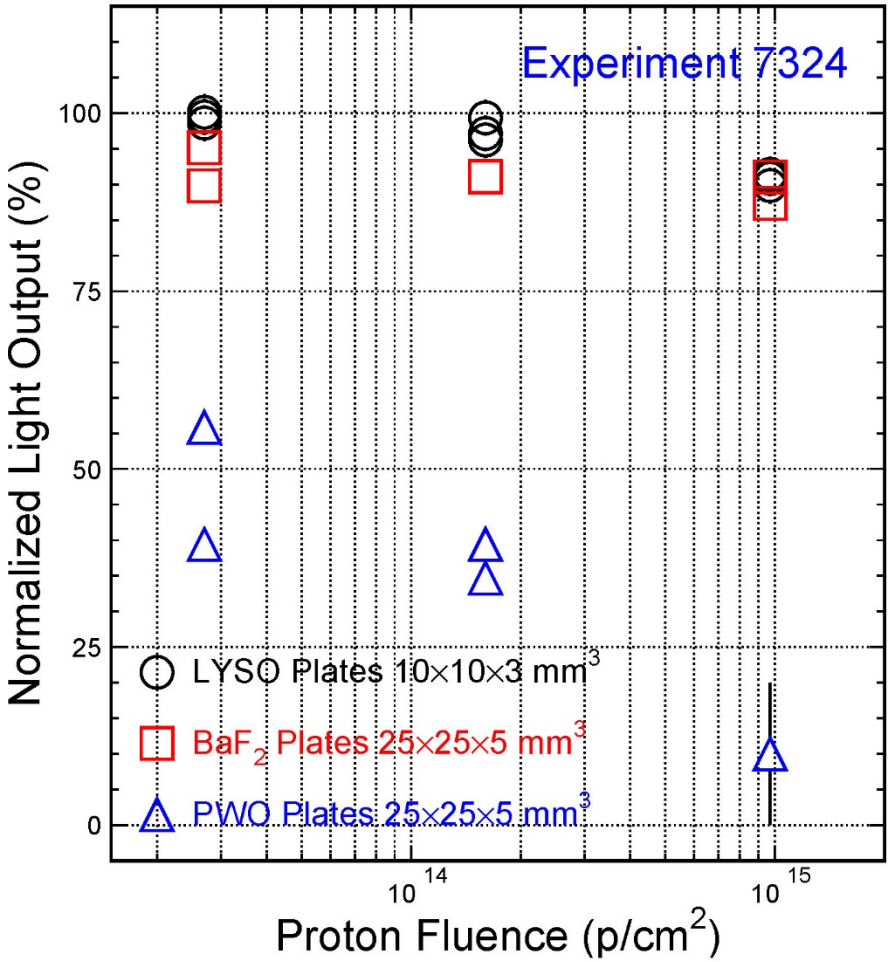
Protons: LANSCE 6990, 7324 and 8051

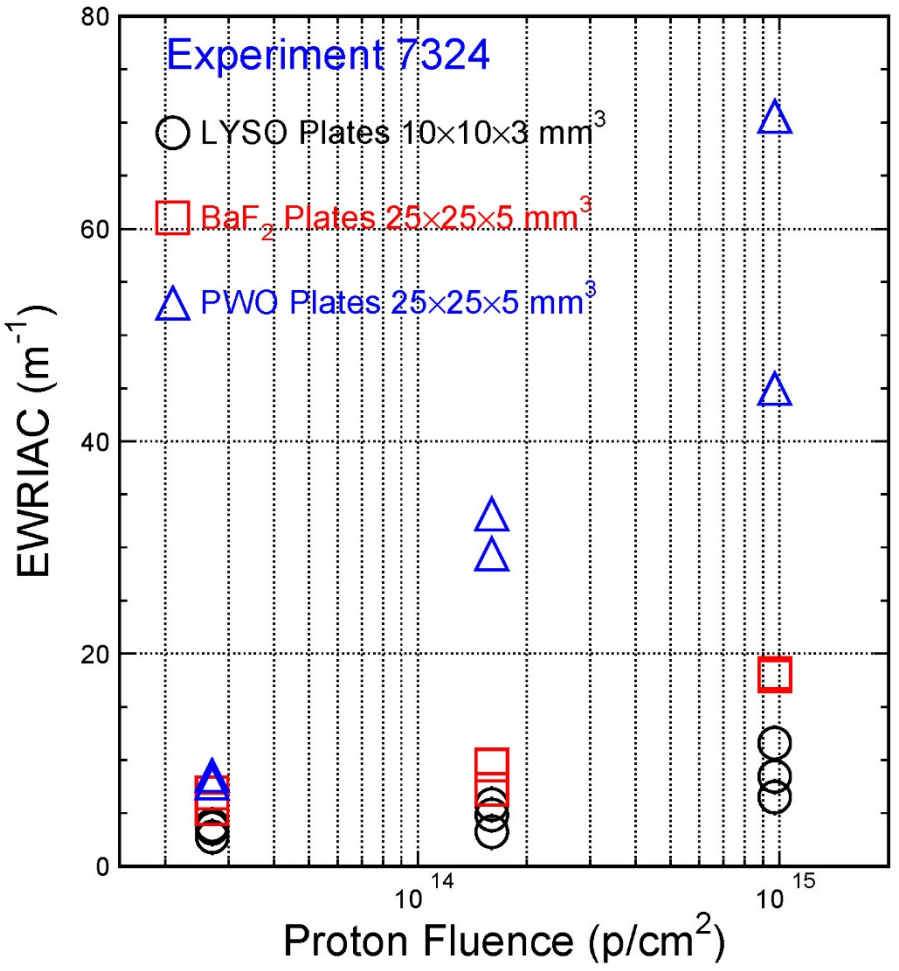
Crystals are characterized at Caltech. Transmittance was monitored by a fiber based spectrophotometer during irradiation for long samples



Result of TF:p LANSCE 7324

C. Hu *et al.*, *IEEE Trans. Nucl. Sci.* vol. **65**, pp. 1018-1024 (2018)

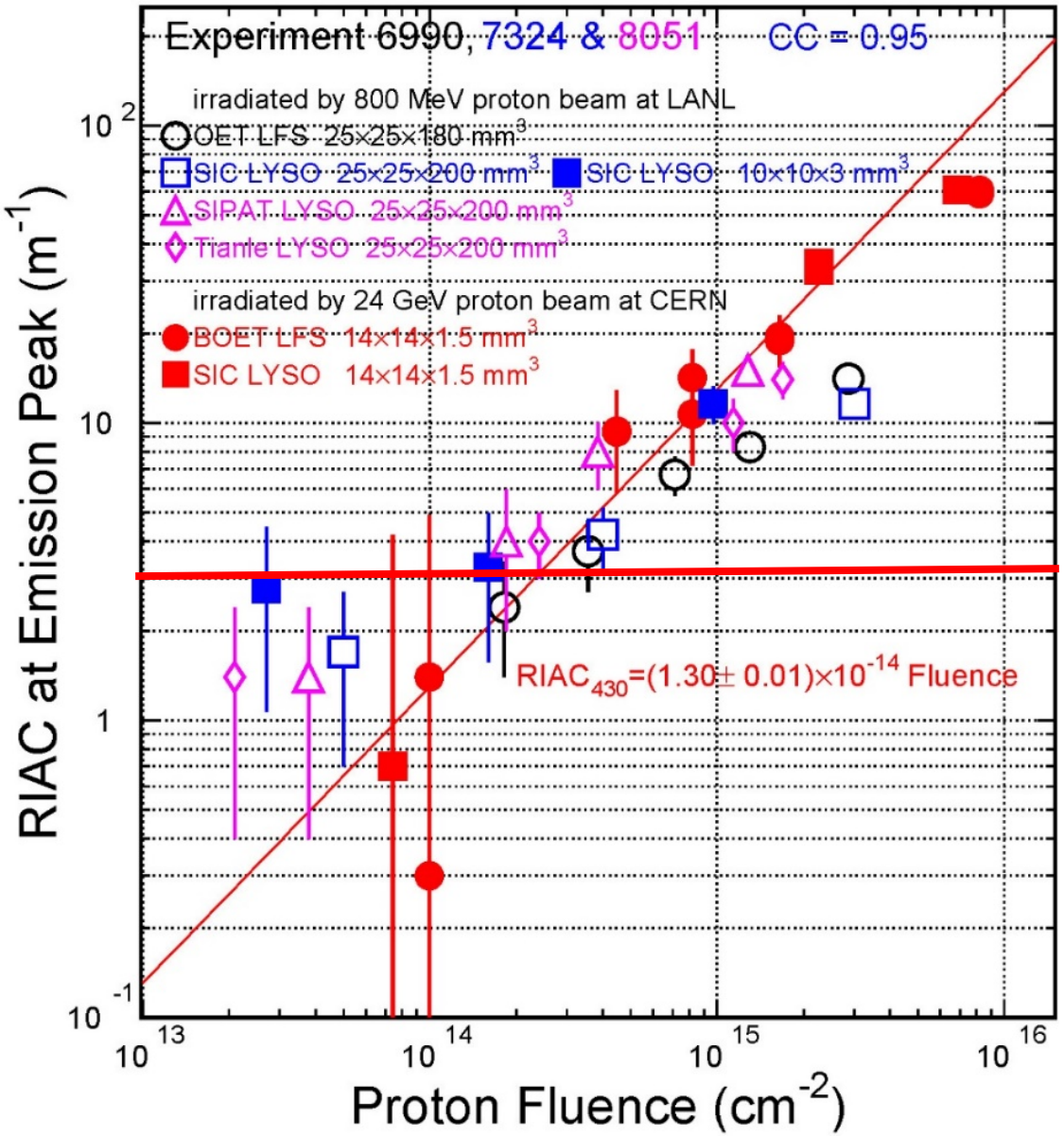




Excellent radiation hardness of LYSO and BaF_2 up to 10^{15} p/cm^2

Results of TF:p for LYSO

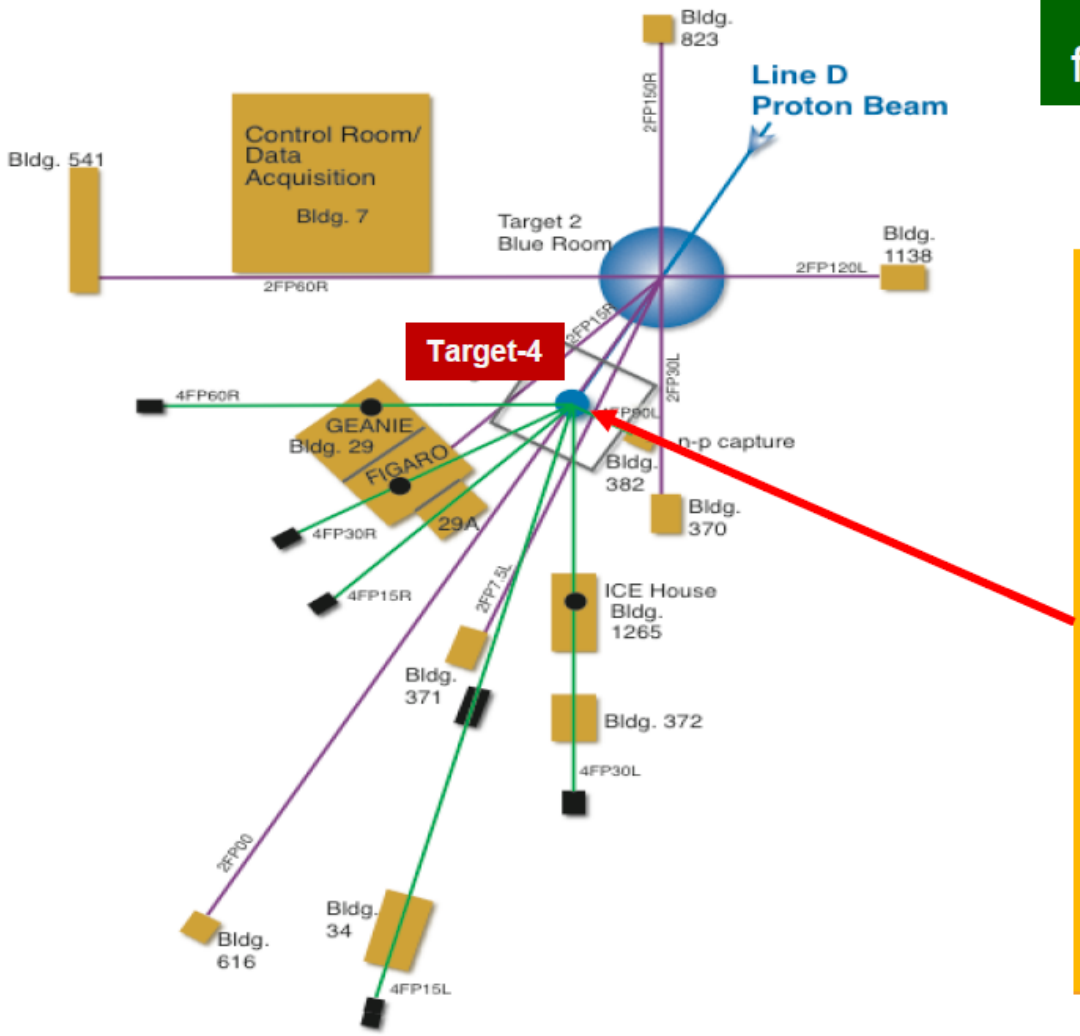
Damages induced by protons of different energies follows: $RIAC_{430} = 1.3 \times 10^{-14} F_p$ for LYSO crystals of different size and from four vendors, indicating < 3 m^{-1} after 2×10^{14} p/cm^2

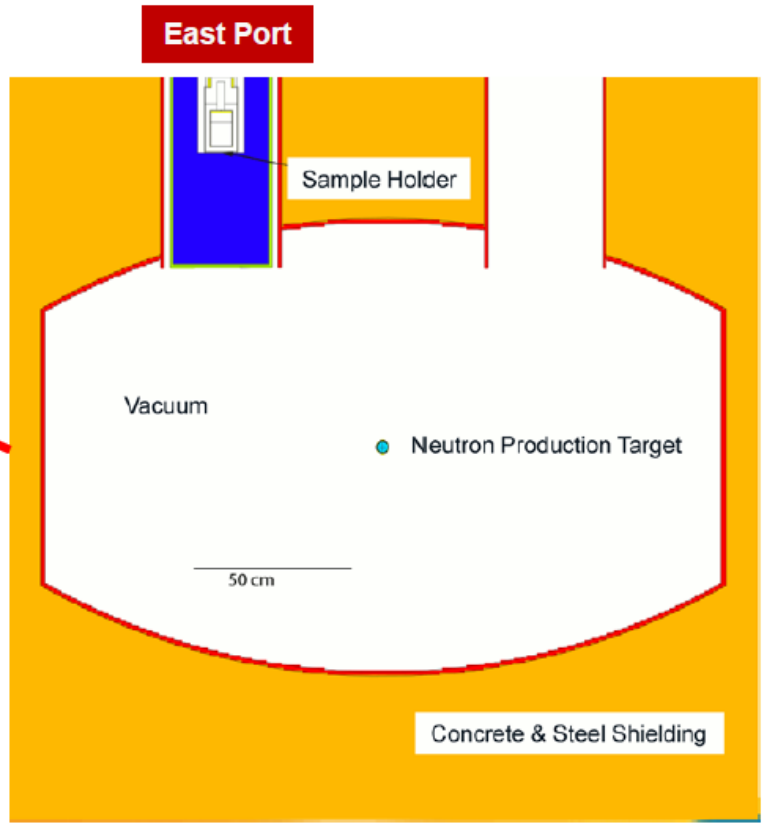


Neutron irradiation at LANSCE

Los Alamos Neutron Science Center (LANSCE)

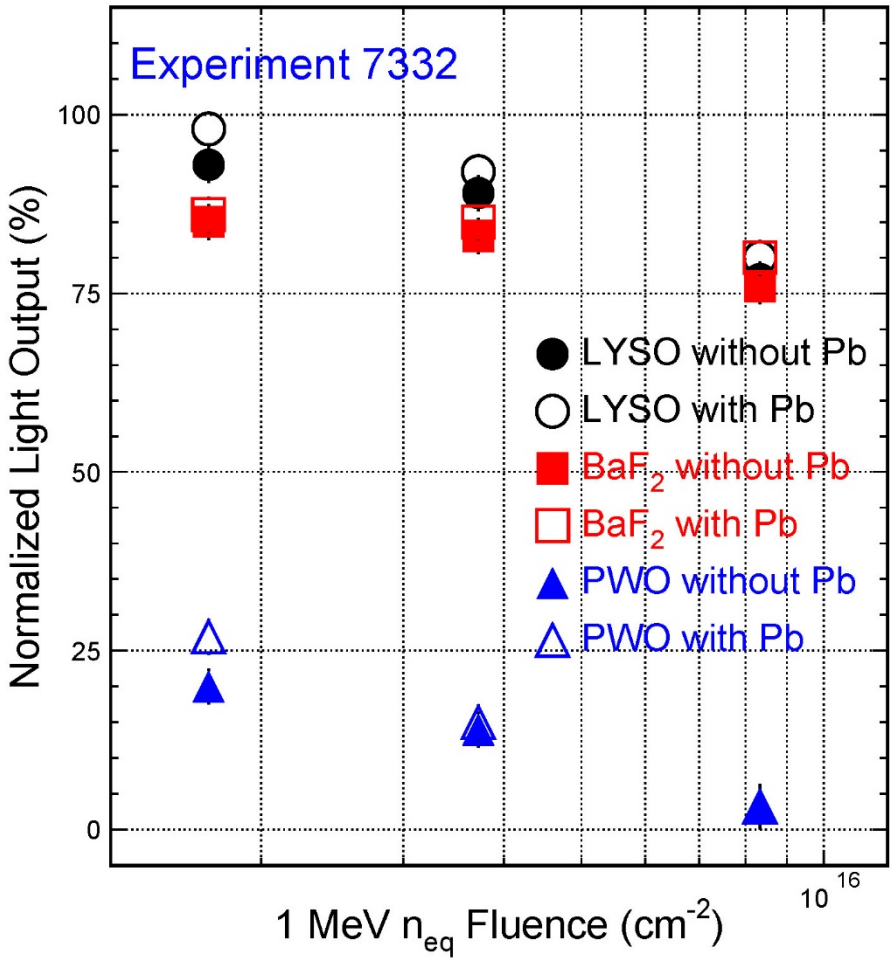
Samples are located at East Port in the Target-4, about 1.2 m away from the neutron production target

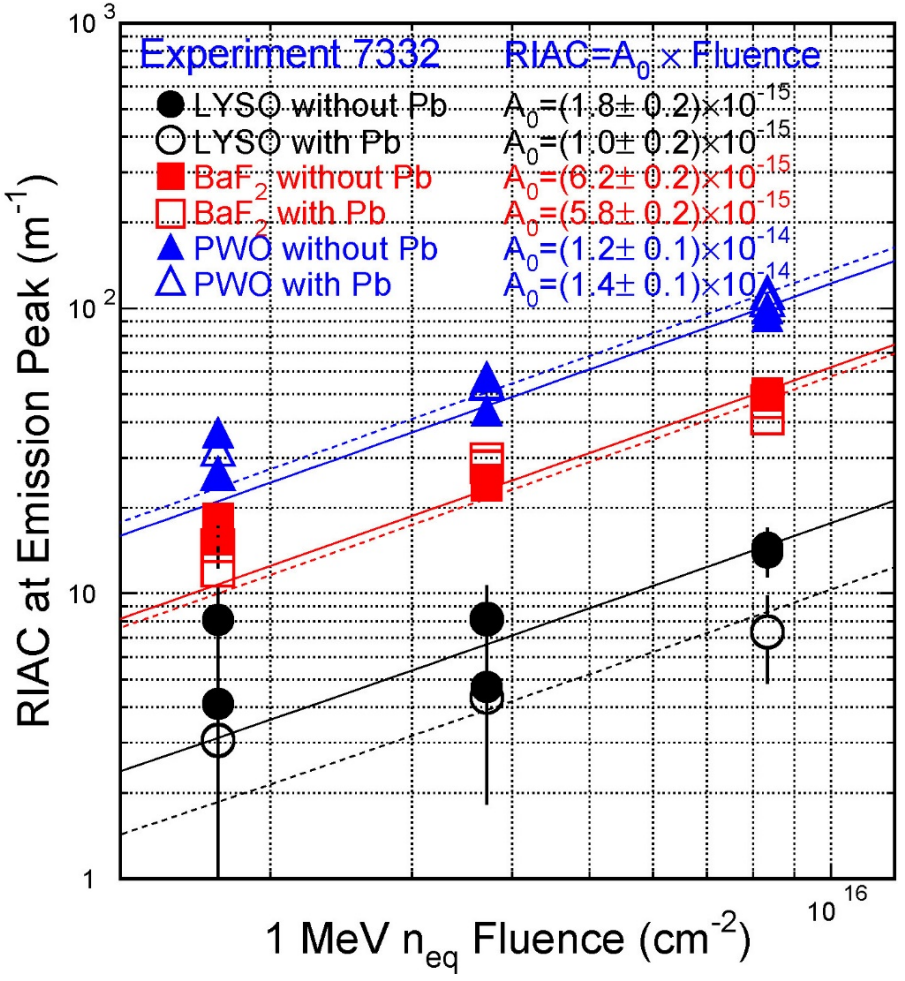




Result of TF:n LANSCE 7332

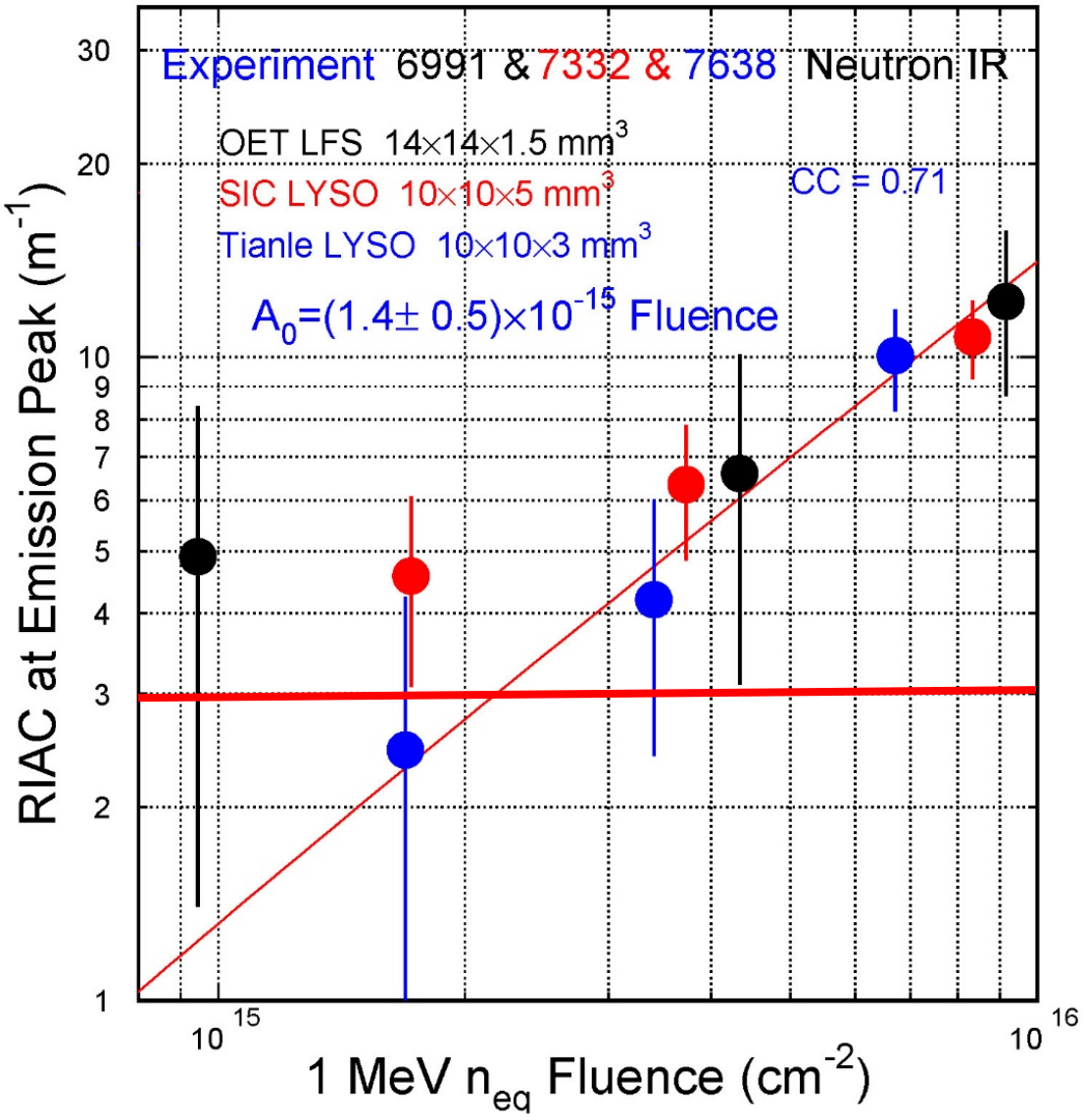
C. Hu *et al.*, *J. Phys.: Conference Series* **1162**, 012020 (2019)





LYSO, BaF_2 and PWO irradiated up to 8 ×10^{15} n_{eq}/cm^2

Results of TF:n for LYSO



Neutron induced damage follows a relation: $RIAC_{430} = 1.4 \times 10^{-15} F_n$

in LYSO crystals from three different vendors, indicating $< 3\ m^{-1}$ after $2 \times 10^{15}\ n/cm^2$

On the face value, neutron induced damage is about one order of magnitude smaller than protons.

Summary

- Radiation damage in inorganic scintillators is investigated up to 340 Mrad, 8 x 10^{15} p/cm^2 and 8 x 10^{15} n_{eq}/cm^2. LYSO crystals show the best radiation hardness among all tested crystals. About 5% light output loss is found in 14 x 14 x 1.5 mm plates after 200 Mrad, 3 x 10^{14} p/cm^2 and 3 x 10^{15} n/cm^2.
- BaF_2 is promising: 40%/45% of fast/slow light output loss is observed after 120 Mrad for 20 cm long crystals.
- While both protons and neutrons cause damage in inorganic scintillators, damage induced by protons is an order of magnitude larger than that from neutrons, presumably due to contributions from ionization energy loss.
- Commercial LYSO crystals are expected to meet CMS BTL radiation hardness specification: Induced absorption <3 m^{-1} for TID:γ of 4.4 Mrad, TF:p of 2.5 x 10^{13} p/cm^2 and TF:n of 3 x 10^{14} p/cm^2. Qualification for vendors is under way.

Acknowledgements

Drs. Aaron Kenna of JPL and Sally Seidel of UNM helped ɣ-ray irradiation at JPL and Sandia, respectively. Drs. David Bailleux and Federico Ravotti helped proton irradiation at the CERN IRRAD facility. Drs. Jon Kapustinsky, Michael Mocko, Ron Nelson and Zhehui Wang helped proton and neutron irradiations at LANSCE.

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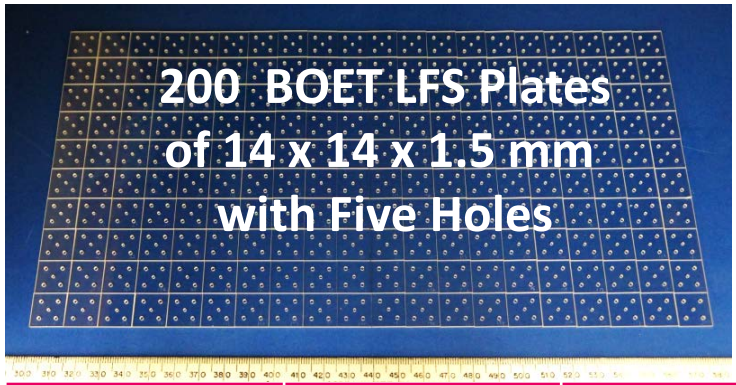
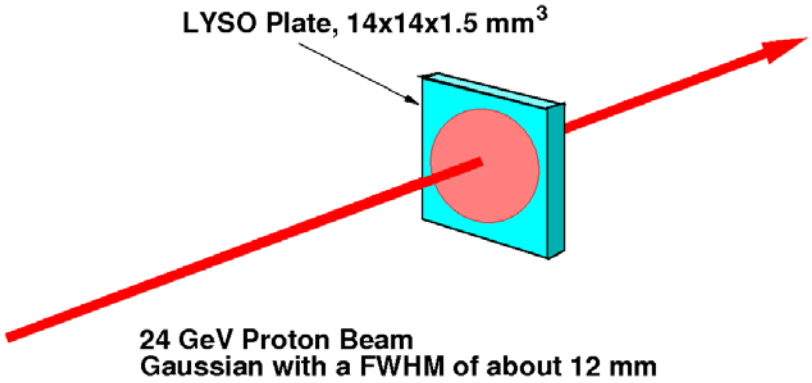
Proton Irradiation at CERN RTF

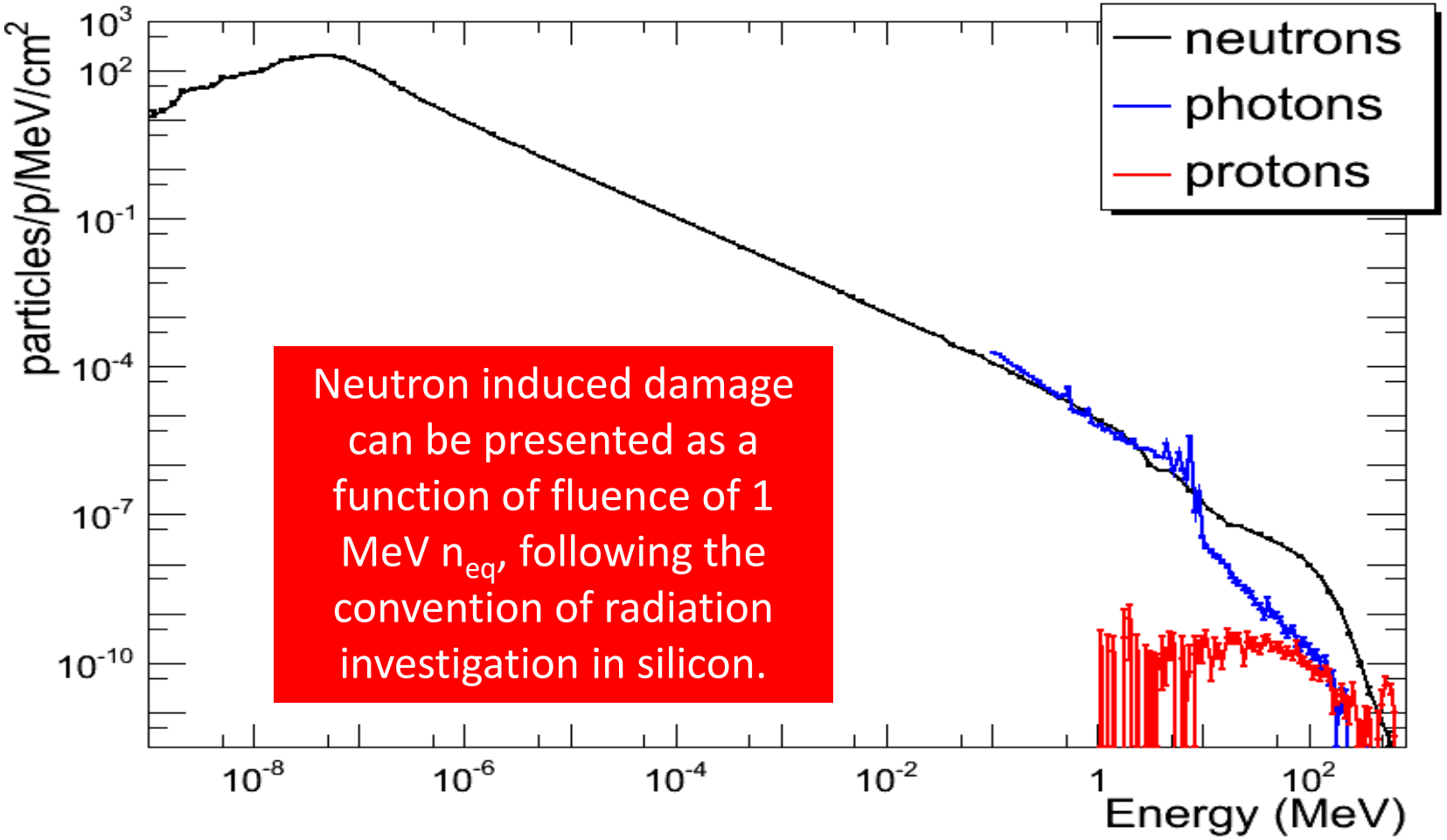




ID	Dimension (mm^3)	Facility	Protons (GeV)	Irradiation Set	Fluence (p/cm^2)	Error (+/- %)
LFS BOET-6	14×14×1.5	CERN	24	2045	9.97×10^{13}	7.0
LFS BOET-7	14×14×1.5	CERN	24	2045	9.97×10^{13}	7.0
LFS BOET-8	14×14×1.5	CERN	24	2046	4.48×10^{14}	8.4
LFS BOET-9	14×14×1.5	CERN	24	2046	4.48×10^{14}	8.4
LFS BOET-10	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

n/ɣ/p: LANSCE 6991,7332 and 7638

n/ɣ/p spectra calculated by using MCNPX (Monte Carlo N-Particle eXtended) package tallied in the largest sample volume (averaging).



Neutron induced damage can be presented as a function of fluence of 1 MeV n_{eq}, following the convention of radiation investigation in silicon.

Conversion Neutron to 1 MeV n_{eq}