Hadron-Induced Radiation Damage in Fast Inorganic Scintillators

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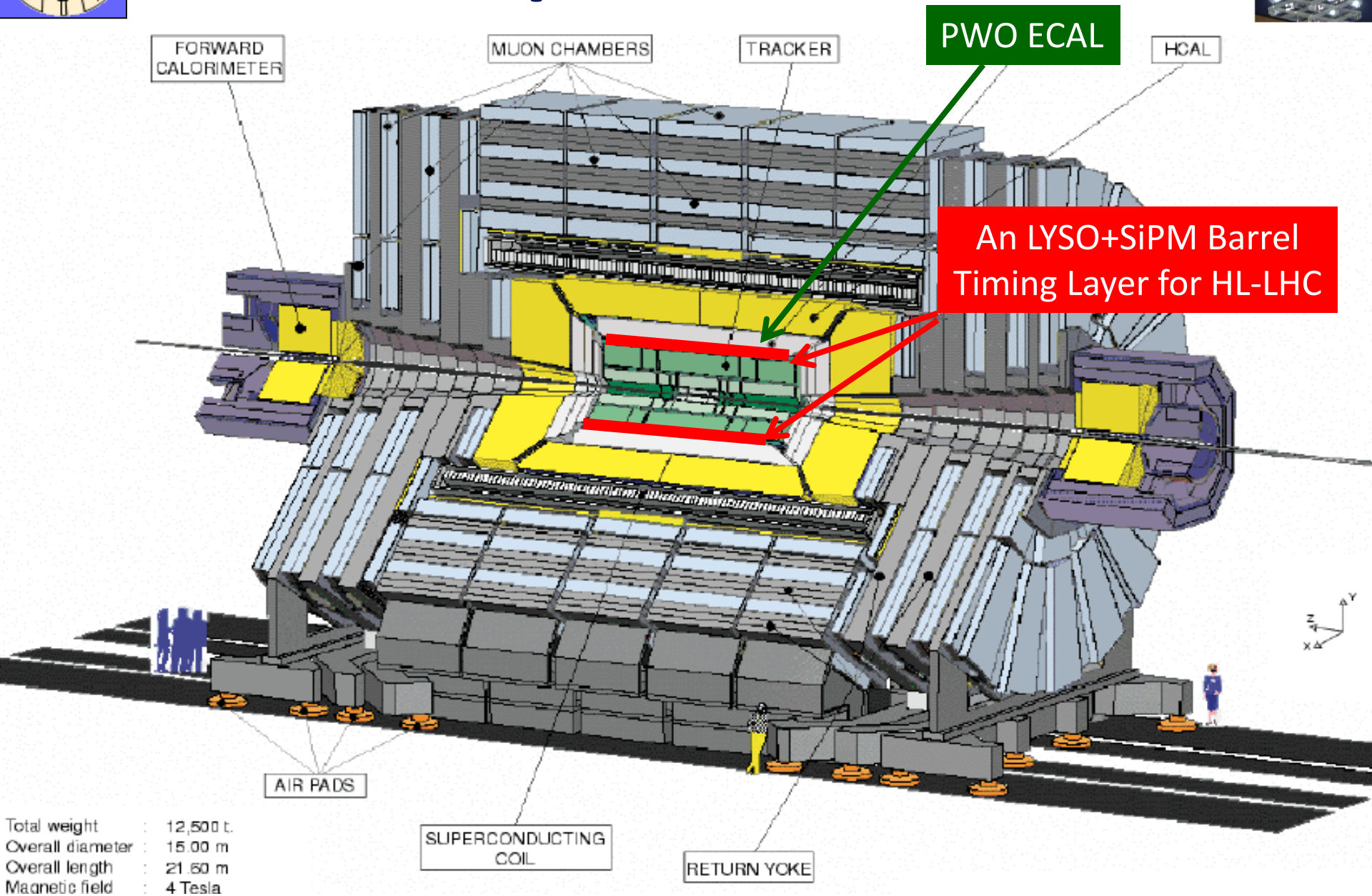
Crystals are Widely Used in HEP

- **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 Experiment at LHC



CMS Barrel Timing Layer 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**

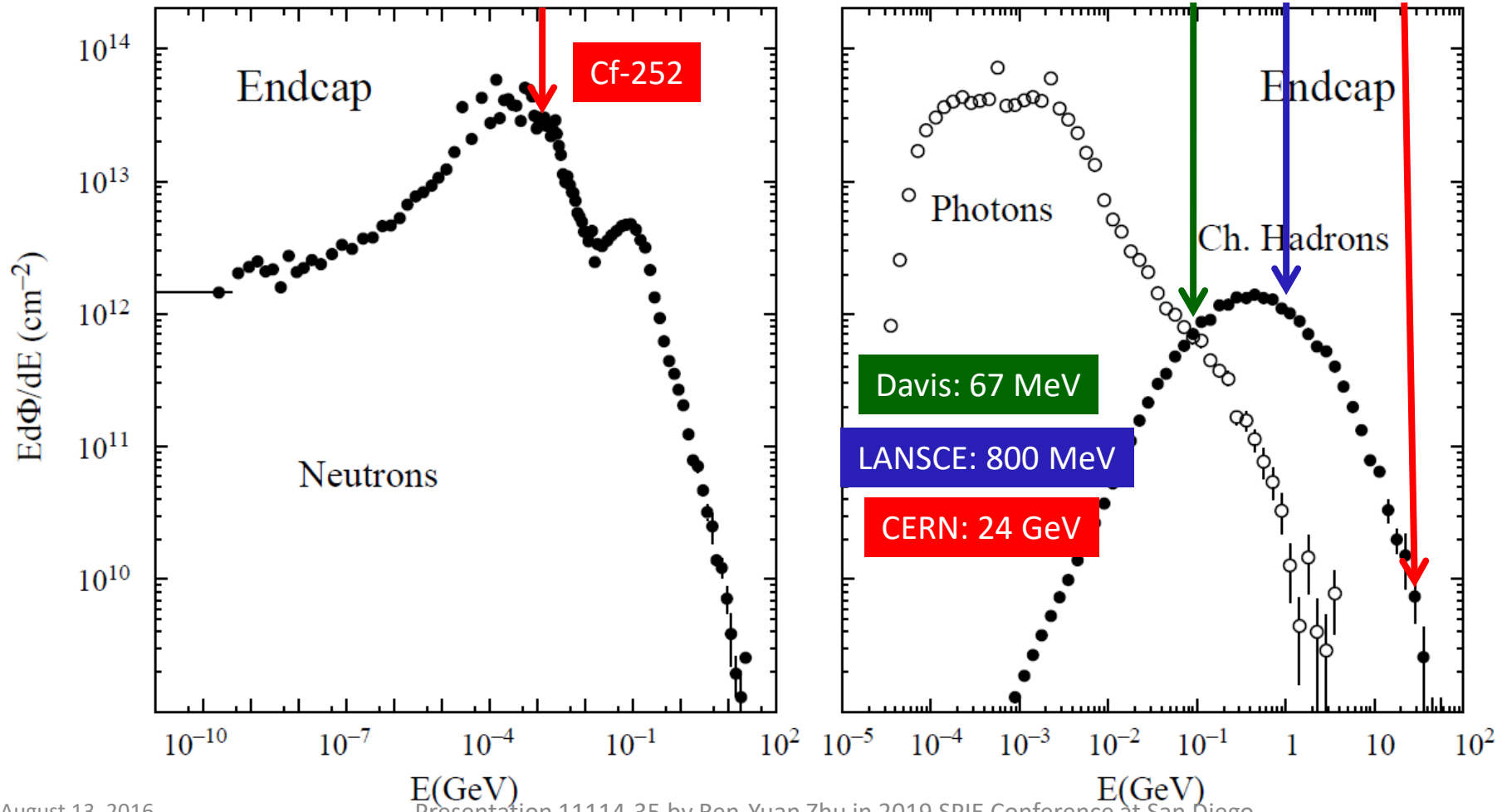
Radiation Expected by CMS BTL

From MTD TDR, assuming 5×10^{34} $cm^{-2}s^{-1}$, 3,000 fb^{-1} and a safety factor of two. CMS BTL LYSO radiation specification: induced absorption <3 m^{-1} for TID of 3.7 Mrad, TF:p of 2.5E13/cm^2 and TF:n of 3.0E14 p/cm^2.

CMS MTD	η	TF: n_{eq} (cm^{-2})	n_{eq} Flux ($cm^{-2}s^{-1}$)	TF: Proton (cm^{-2})	p Flux ($cm^{-2}s^{-1}$)	Ionization Dose (Mrad)	Dose rate (rad/h)
Barrel	0.00	2.6E+14	3.2E+06	2.2E+13	2.7E+05	2.4	108
Barrel	1.15	2.9E+14	3.6E+06	2.4E+13	3.0E+05	3.2	142
Barrel	**1.45**	**3.0E+14**	**3.8E+06**	**2.5E+13**	**3.2E+05**	**3.7**	**165**
Endcap	1.60	1.7E+14	2.1E+06	1.4E+13	1.8E+05	3.8	169
Endcap	2.00	3.6E+14	4.5E+06	3.1E+13	3.8E+05	11.3	506
Endcap	2.50	9.9E+14	1.2E+07	8.4E+13	1.1E+06	39.0	1755
Endcap	3.00	2.6E+15	3.2E+07	2.2E+14	2.7E+06	103.5	4658

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.

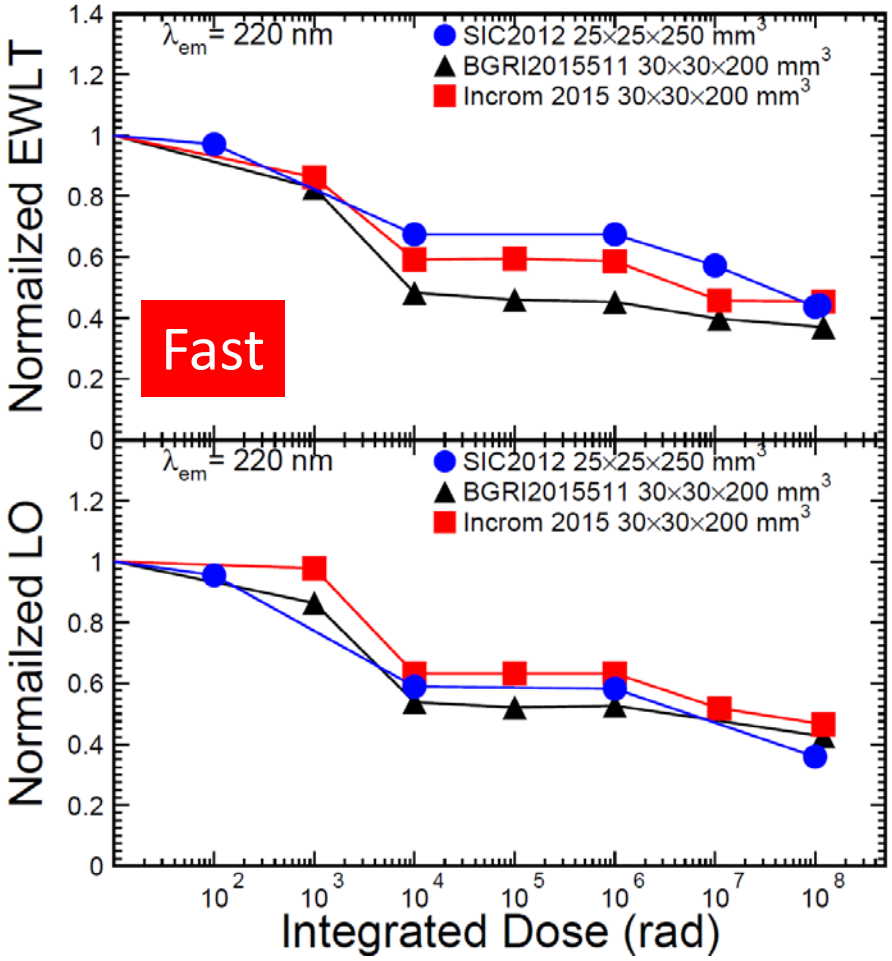


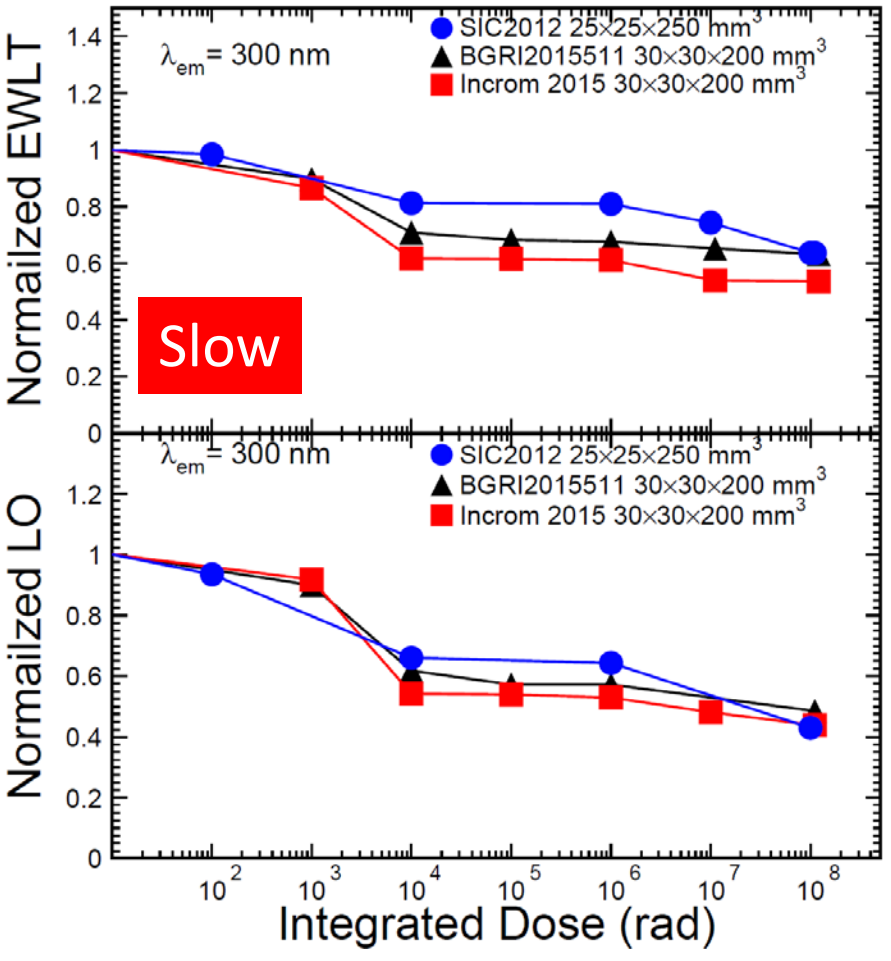
Radiation Damage in Crystals

- Possible damage effects are scintillation mechanism damage, induced absorption and phosphorescence, where induced absorption degrades crystal transparency and light output.
- Ionization dose induced damage is investigated for BaF_2, BGO, CeF_3, undoped CsI, LSO/LYSO/LFS and PWO crystals of large size by using Co-60 and Cs-137 sources at Caltech, the JPL TID facility and the Sandia GIF facility.
- Proton induced damage in crystal scintillators is investigated for BaF_2, BGO , CeF_3, LYSO and PWO crystals by using 800 MeV protons at the Blue Room of LANSCE and 24 GeV protons at CERN proton IRRAD Facility.
- Neutron induced damage in crystal scintillators is investigated for BaF_2, LYSO and PWO crystals at the East Port of LANSCE.

Results of TID:γ for BaF_2

Consistent damage in 20 cm long BaF_2 crystals from three vendors

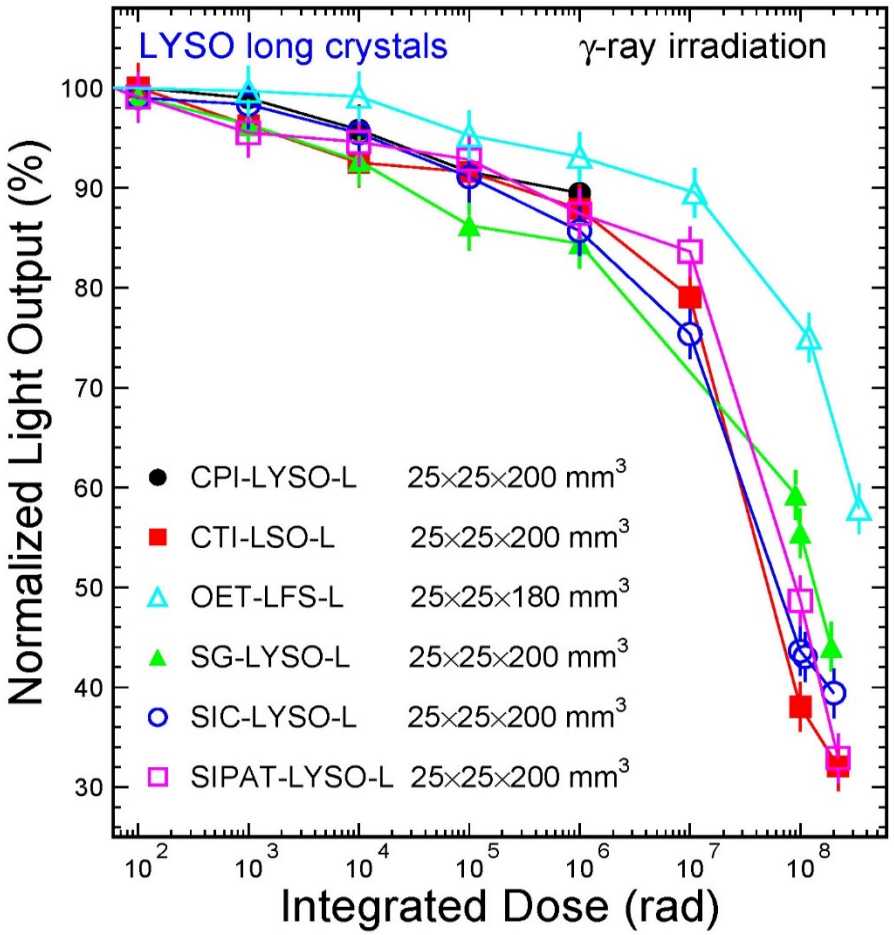


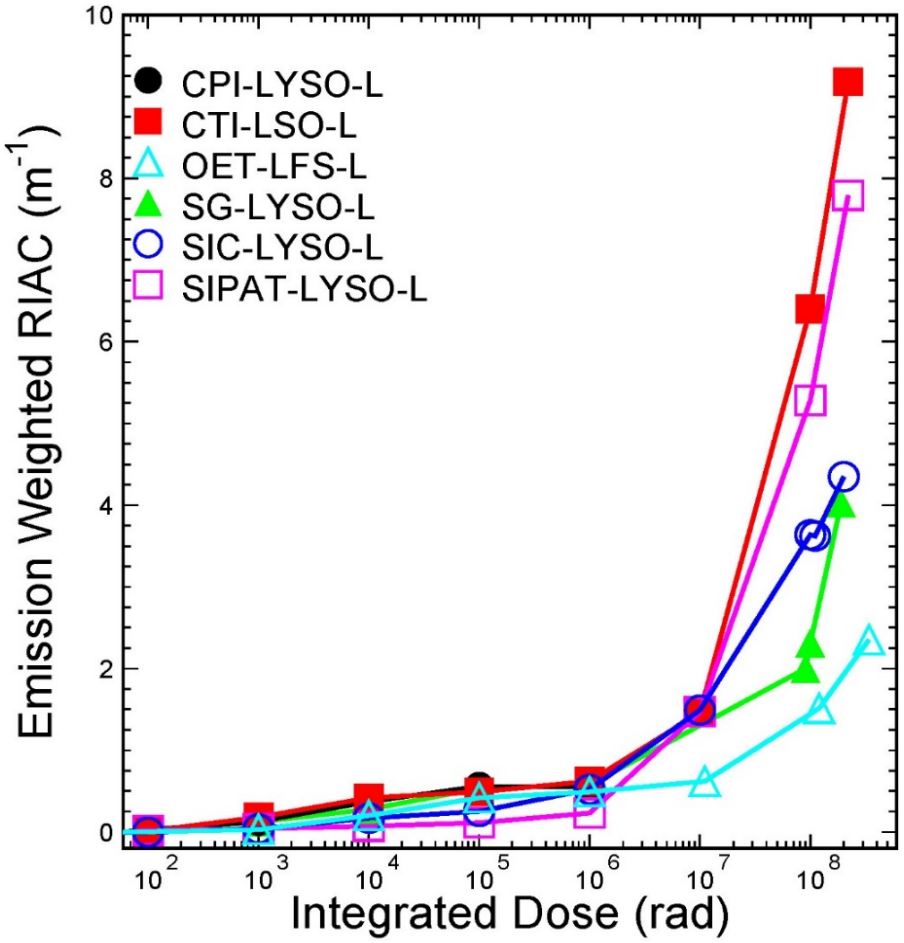


40%/45% LO loss for the fast/slow component after 120 Mrad

Results of TID:γ for LYSO

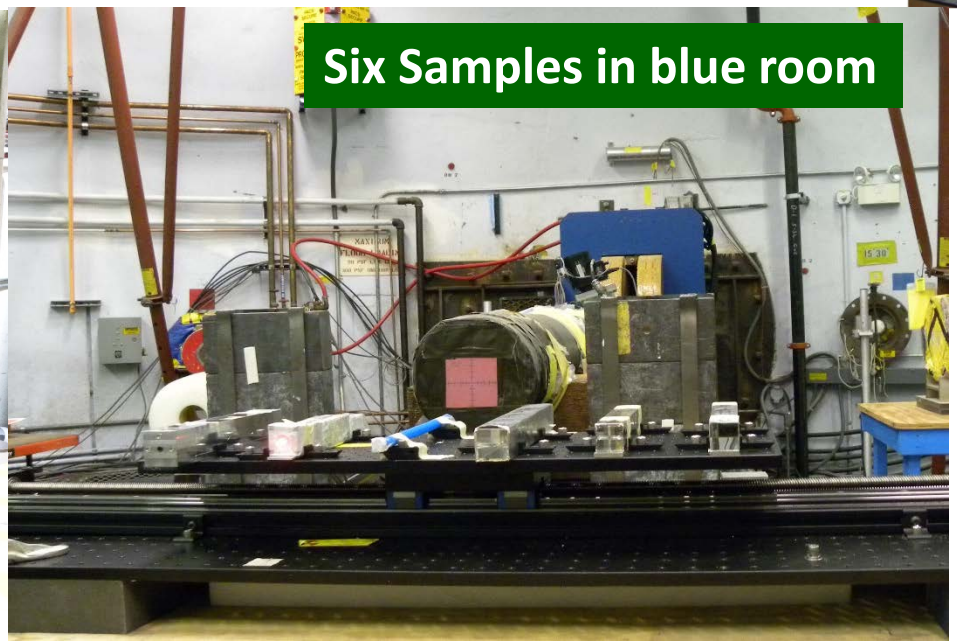
F. Yang *et al.*, *IEEE Trans. Nucl. Sci.* **63**, pp. 612-619 (2016)





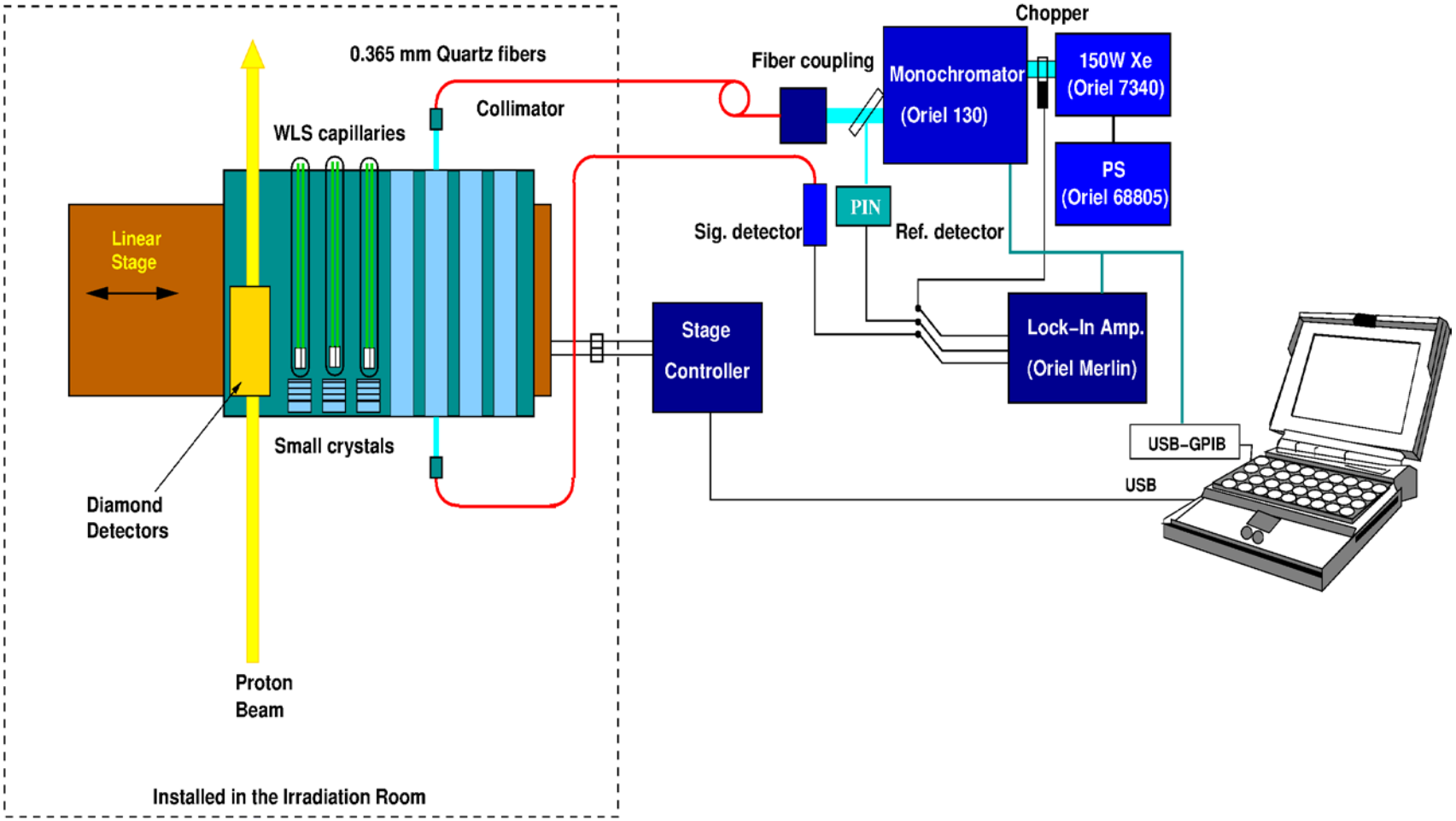
LYSO crystals from six vendors show < 3 m^{-1} after 20 Mrad

Proton Irradiation at LANSCE

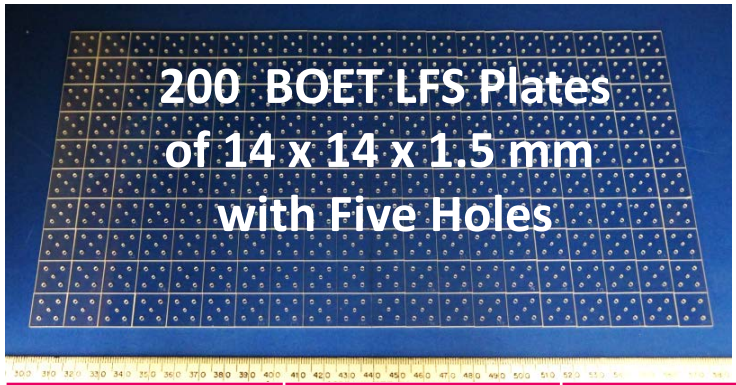


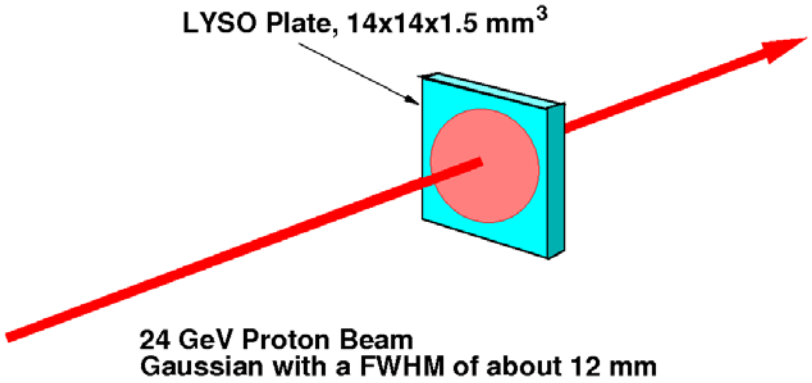
Protons: LANSCE 6990, 7324 and 8051

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



Proton Irradiation at CERN RTF

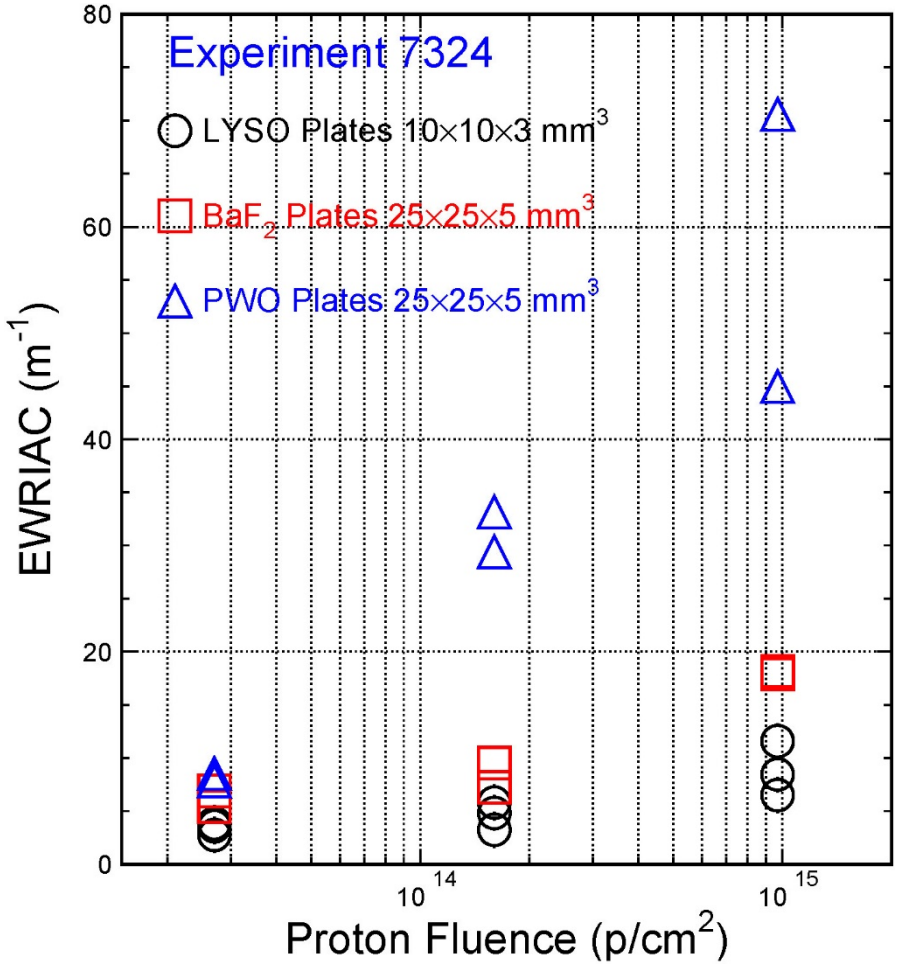


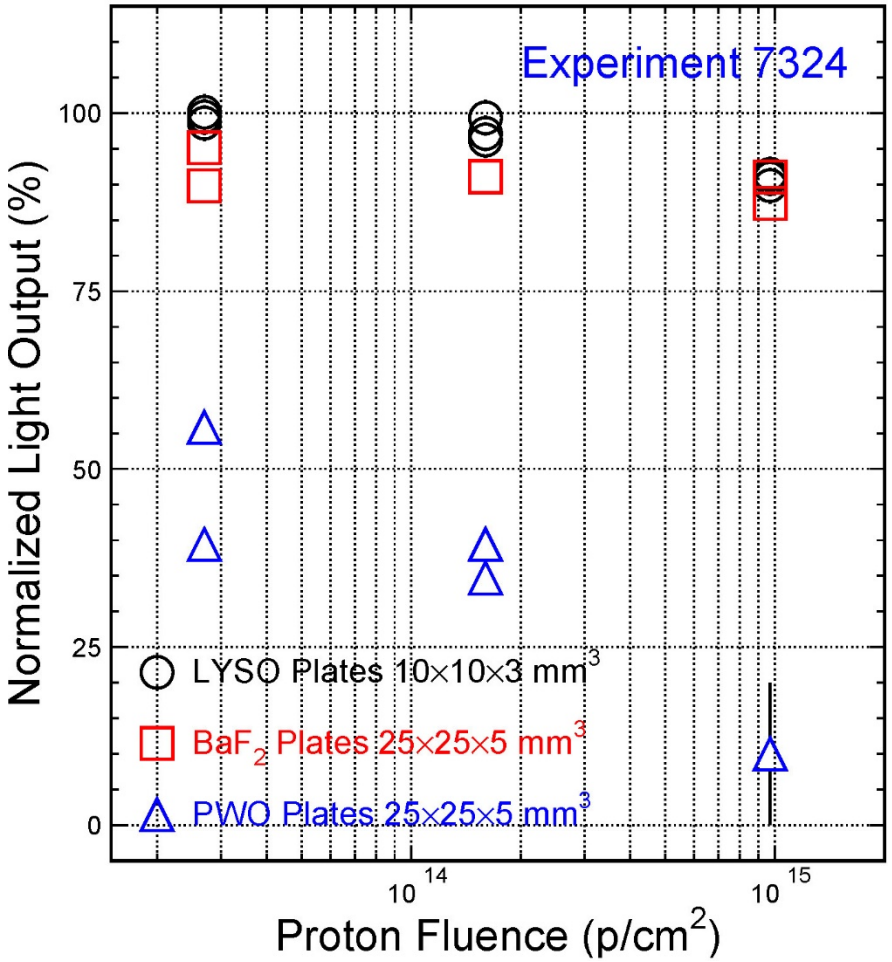


ID	Dimension (mm^3)	Facility	Protons (GeV)	Irradiation Set	Fluence (p/cm^2)	Error (+/- %)
LFS BOET-6	14×14×1.5	CERN	24	2045	9.97×10^{13}	7.0
LFS BOET-7	14×14×1.5	CERN	24	2045	9.97×10^{13}	7.0
LFS BOET-8	14×14×1.5	CERN	24	2046	4.48×10^{14}	8.4
LFS BOET-9	14×14×1.5	CERN	24	2046	4.48×10^{14}	8.4
LFS BOET-10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

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

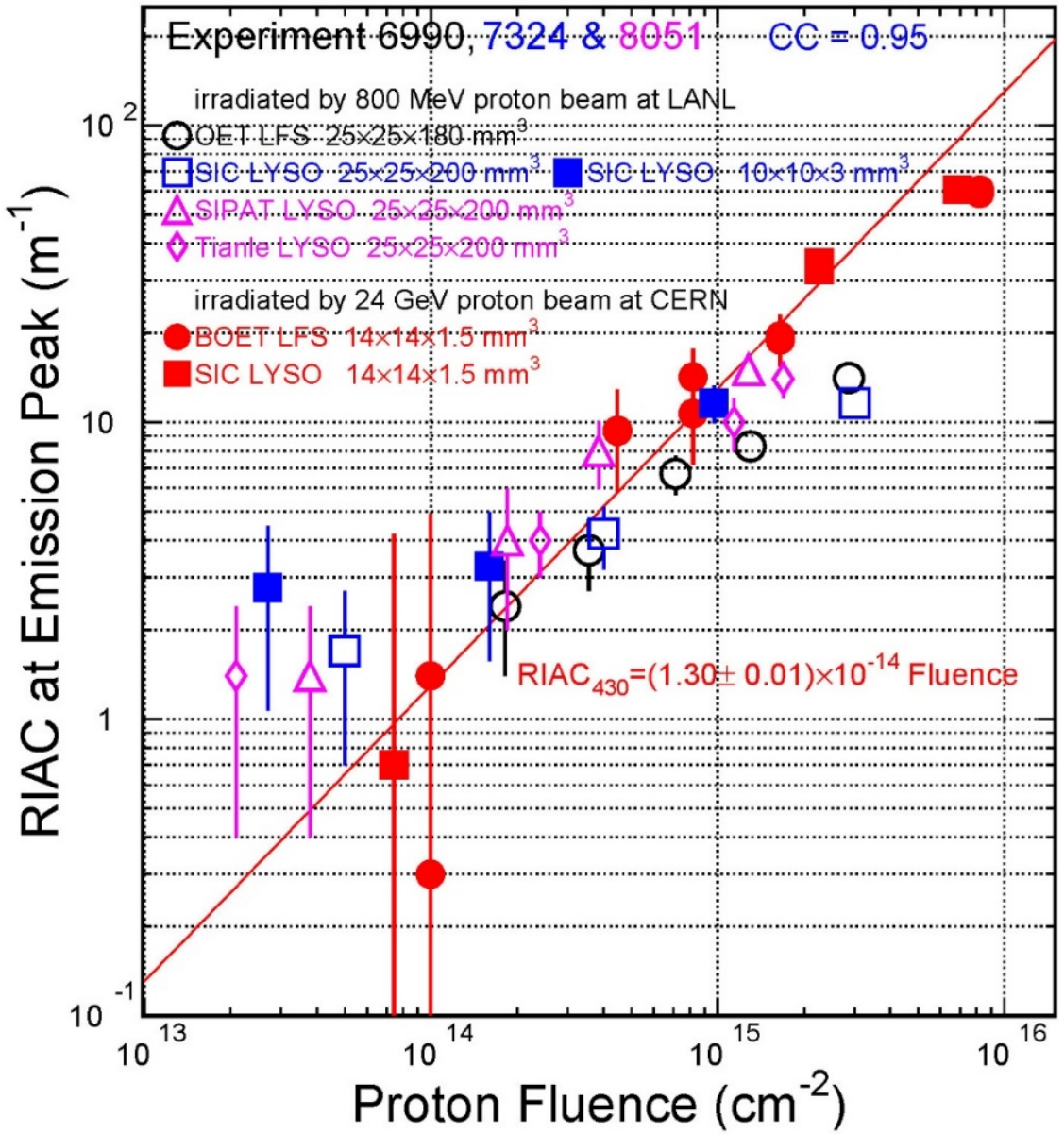
Results of TF:p for LYSO

Damages induced by protons of different energies follows a relation:

$RIAC_{430} = 1.3 \times 10^{-14} F_p$

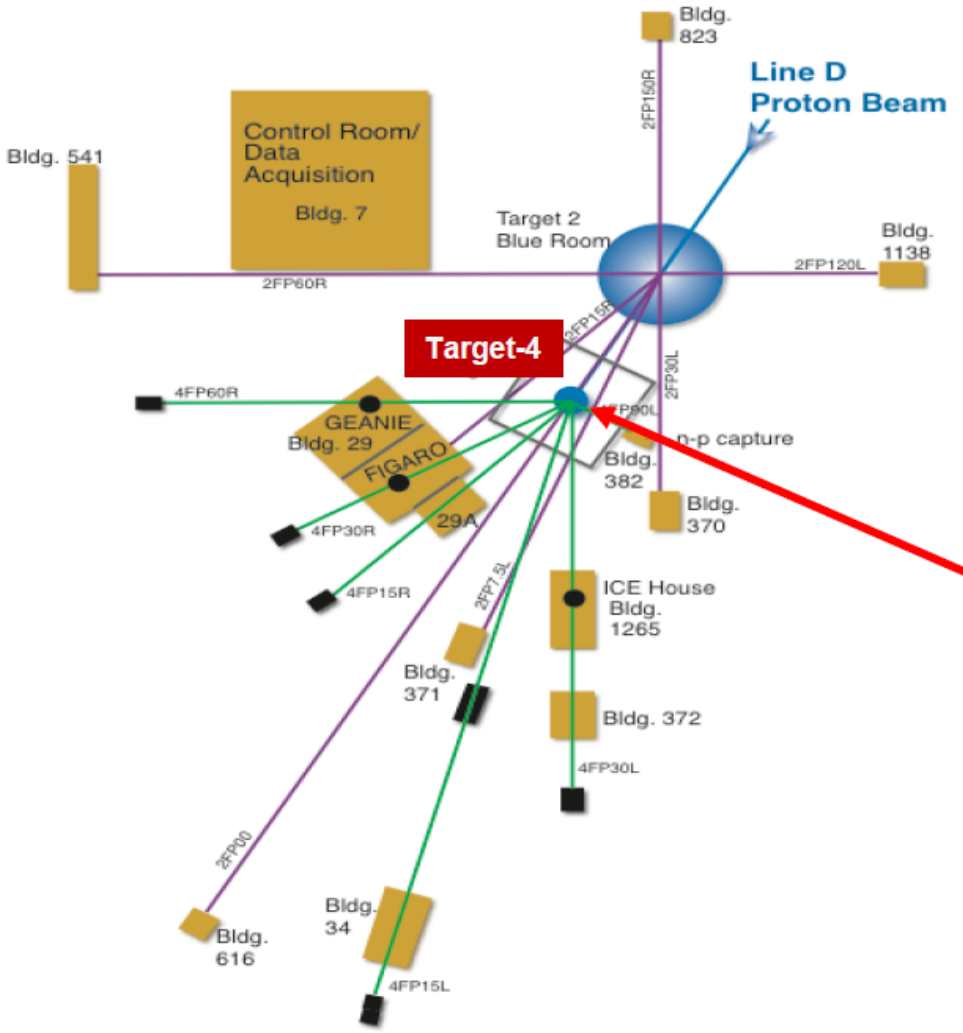
for LYSO crystals of different size and from different vendors

LYSO crystals from four vendors show < 3 m^{-1} after 2 × 10^{14} p/cm^2

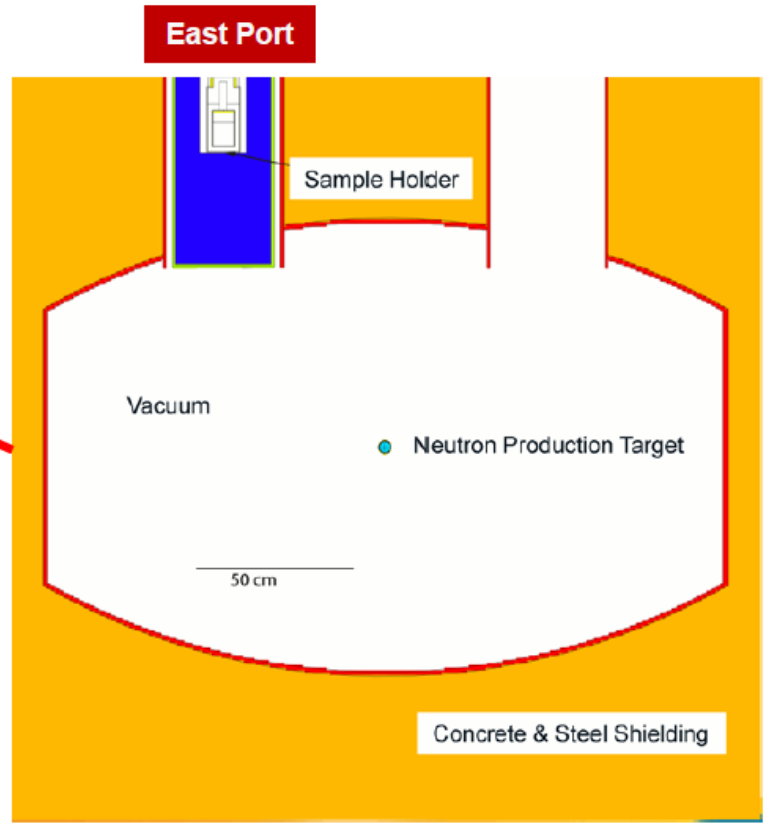


Neutron irradiation at LANSCE

Los Alamos Neutron Science Center (LANSCE)



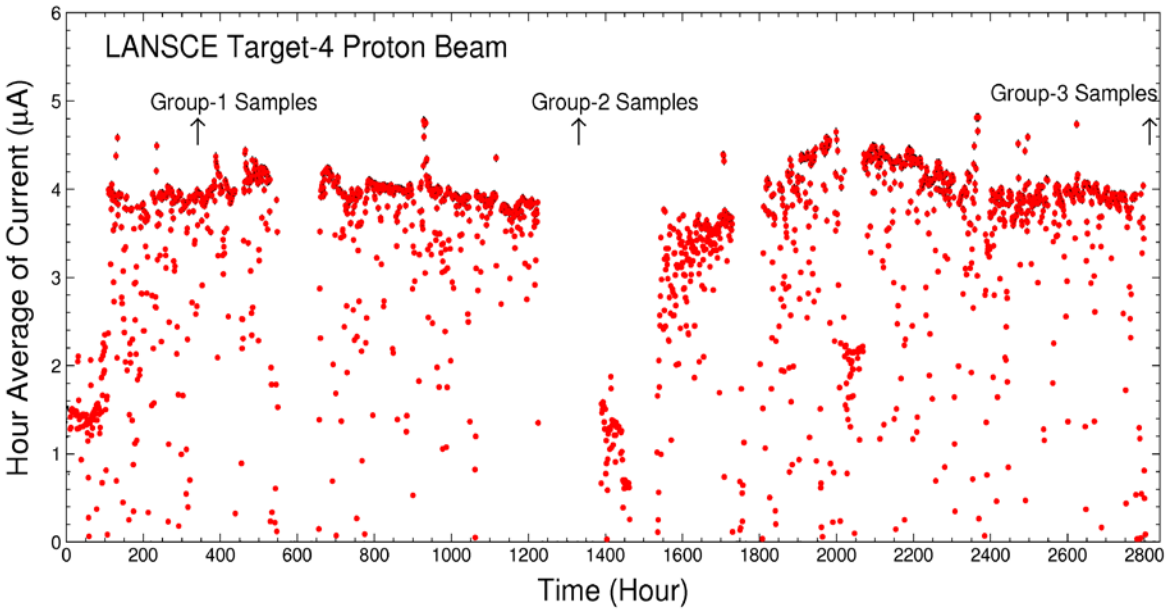
Samples are located at East Port in the Target-4, about 1.2 m away from the neutron production target



Samples and Beam History

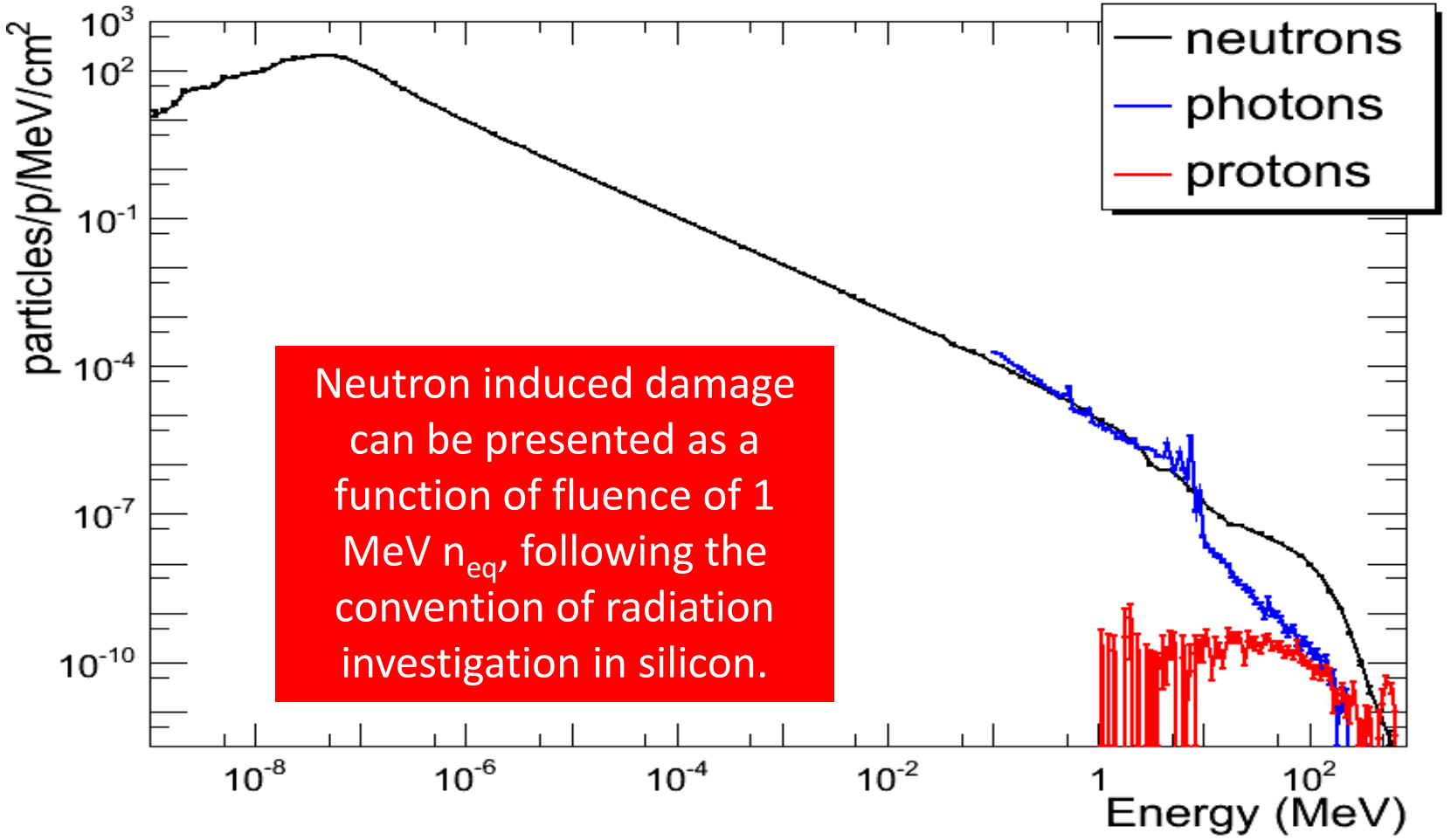
Samples were downloaded into East Port, and were extracted in three groups, e.g. after 13.4, 54.5 and 118 days for the experiment LANSCE 7332, and were measured at Caltech.

LANSCE target-4 proton beam data provided by the LANSCE team.

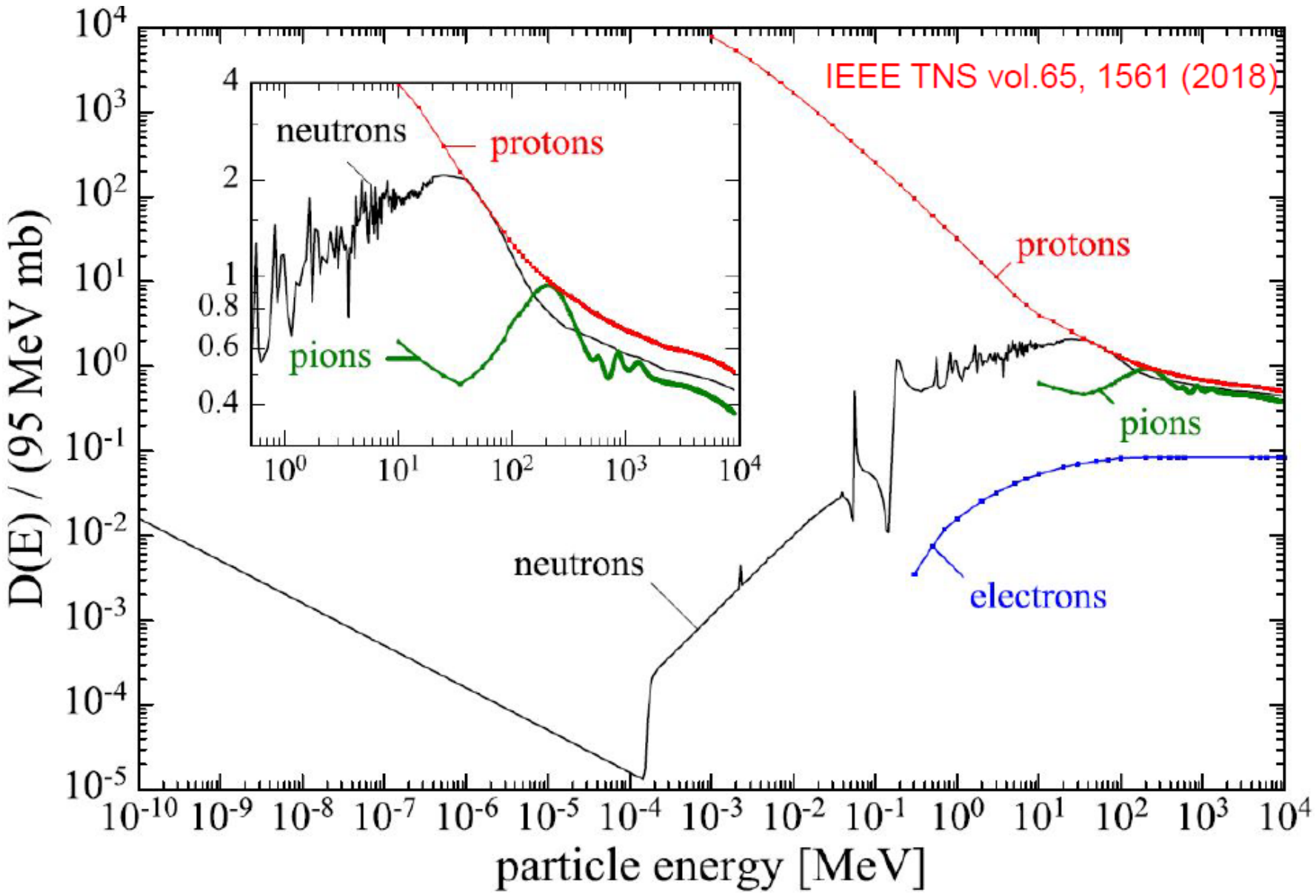


n/ɣ/p: LANSCE 6991,7332 and 7638

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

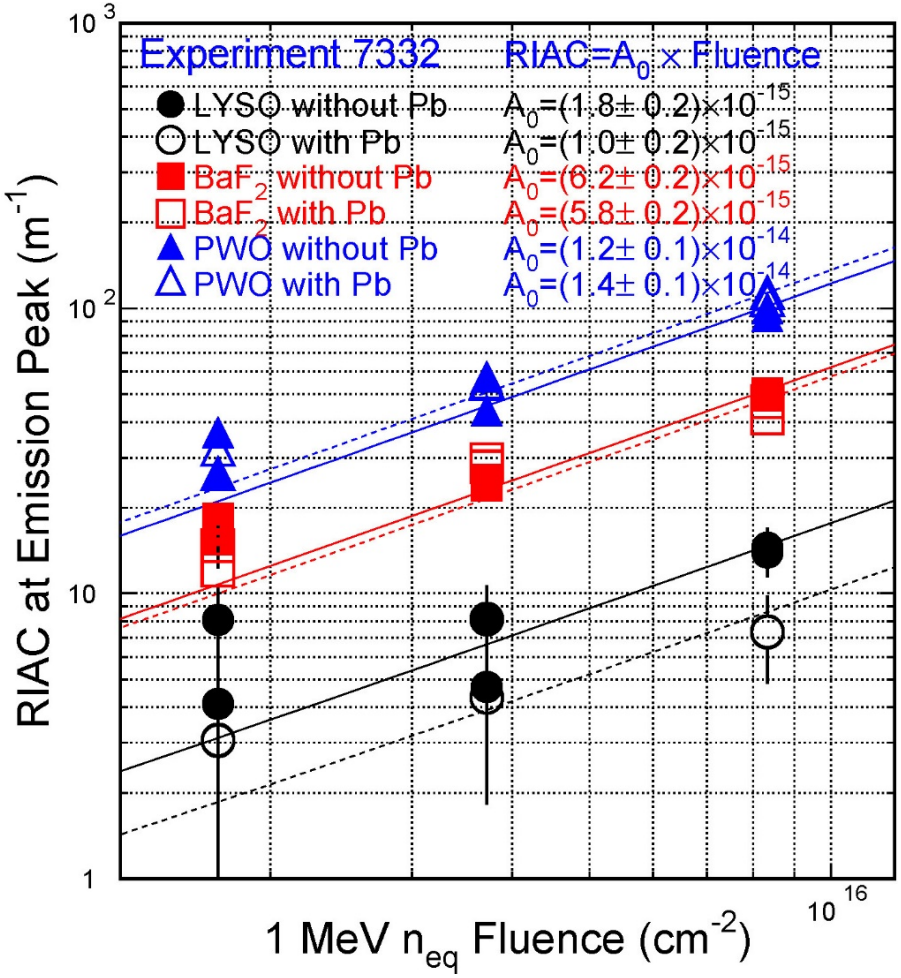


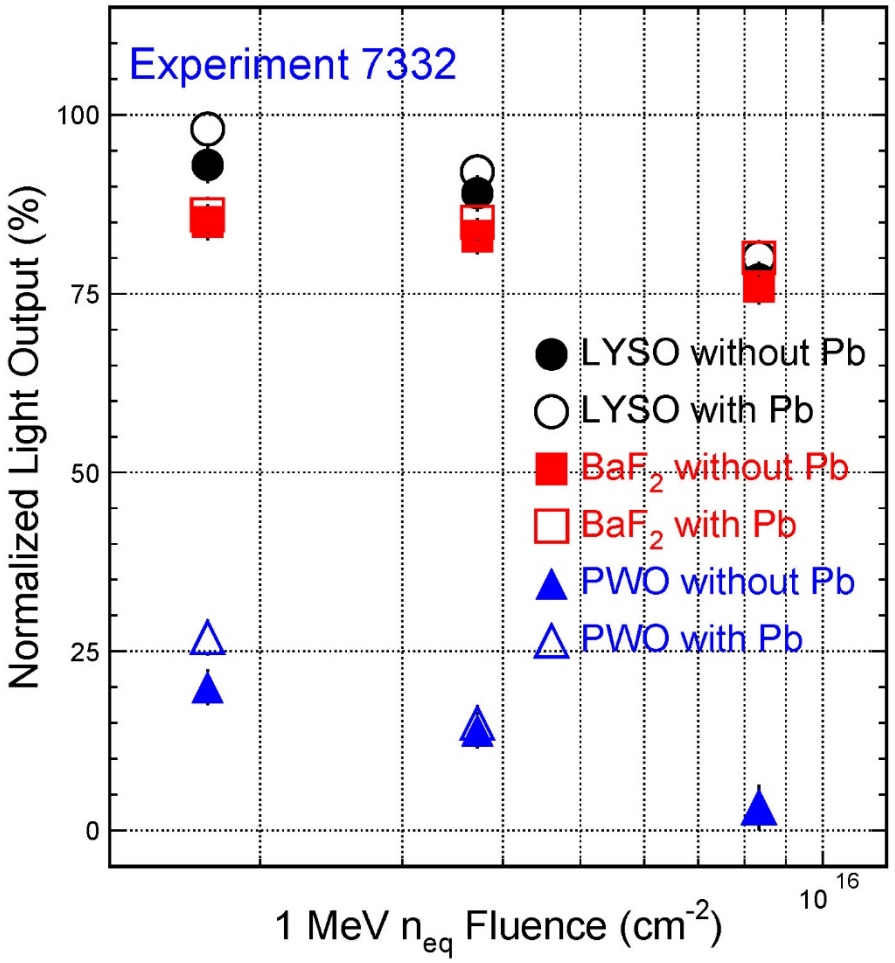
Conversion Neutron to 1 MeV n_{eq}



Result of TF:n LANSCE 7332

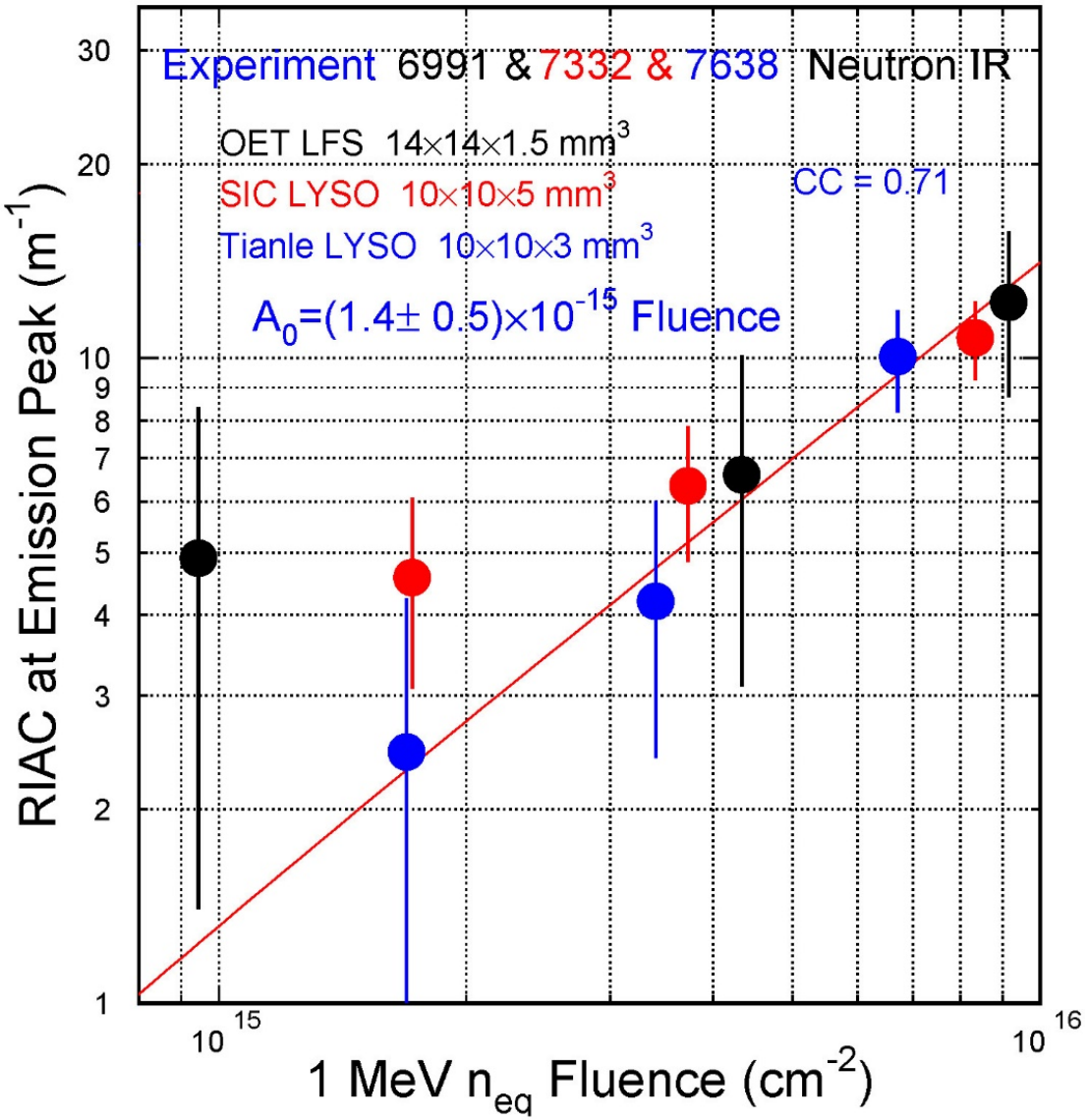
C. Hu *et al.*, *J. Phys.: Conference Series* **1162**, 012020 (2019)





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 different vendors, which is one order of magnitude smaller than protons.

LYSO crystals from three vendors show < 3 m^{-1} after 2×10^{15} n/cm^2

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 additional contribution from ionization energy loss.
- Commercial LYSO crystals are expected to meet CMS BTL radiation hardness specification: Induced absorption <3 m^{-1} for TID of 3.7 Mrad, TF:p of 3 x 10^{13} p/cm^2 and TF:n of 3 x 10^{14} p/cm^2. Qualification for vendors will be carried out.

Acknowledgements

Drs. Chen Hu, Fan Yang, Liyuan Zhang of Caltech and Drs. Jon Kapustinsky, Michael Mocko, Ron Nelson and Zhehui Wang of LANL contributed to the results presented in this report.

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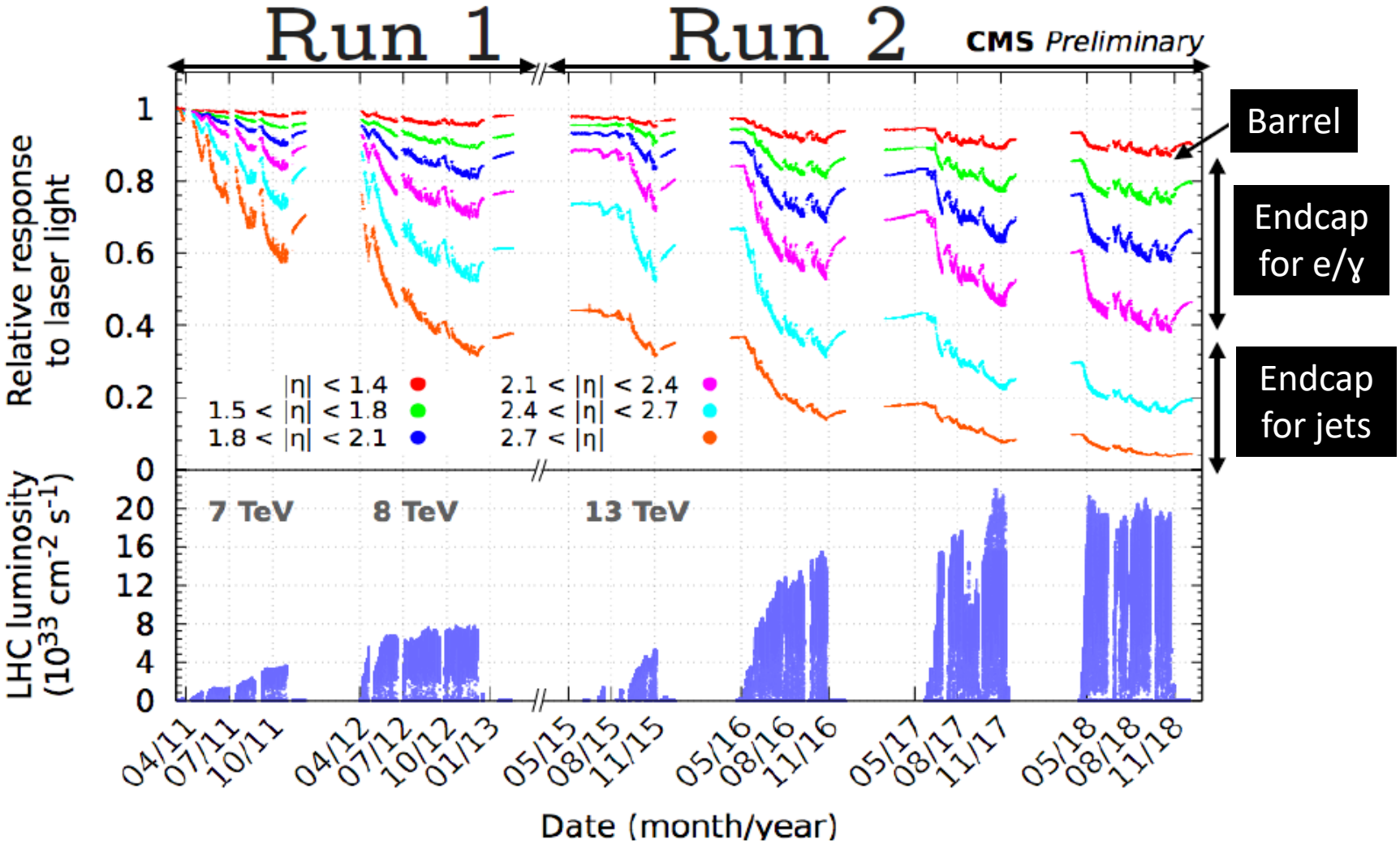
Monitoring Response of PWO

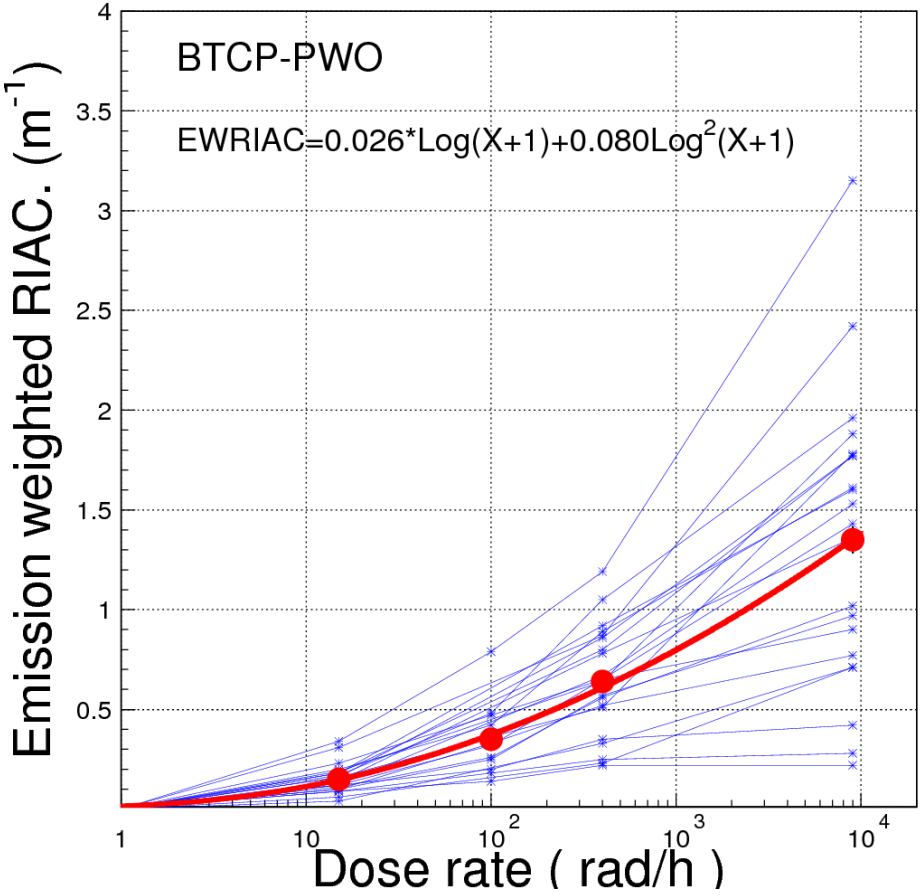
A. Zghiche, in ICNFP 2019 Conference



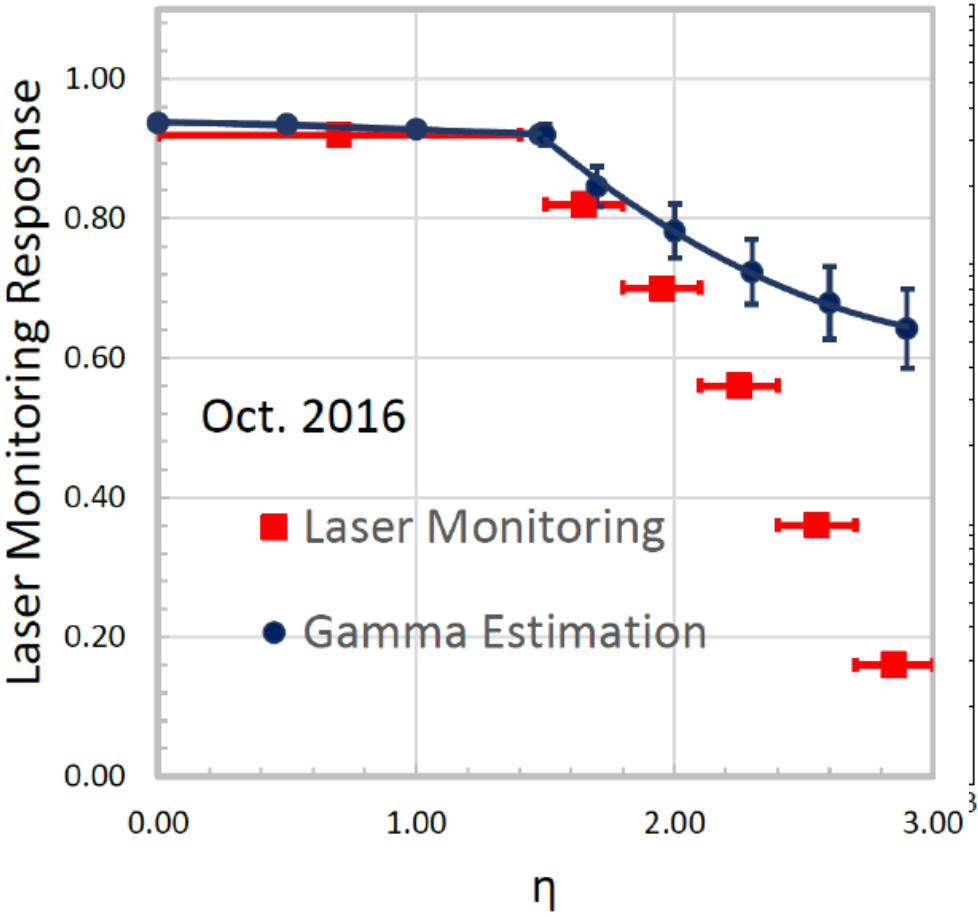
Observed damage can not be explained by ionization dose alone

Hadron Damage Required for LHC Data

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



Talk in CMS ECAL Meeting, 10/28/2016



VPT ageing and hadron induced damage observed in the LHC data