Neutron-Induced Radiation Damage in Fast Inorganic Crystals

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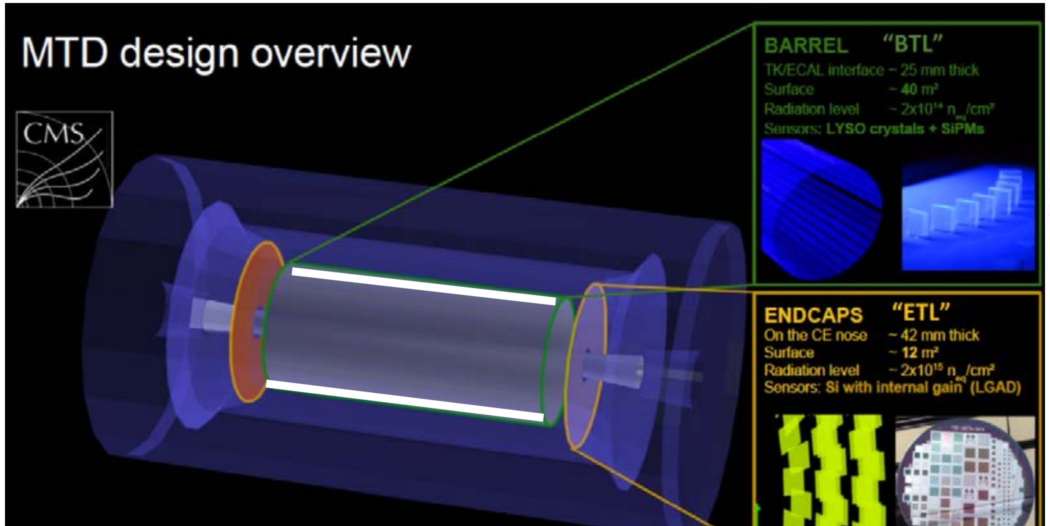
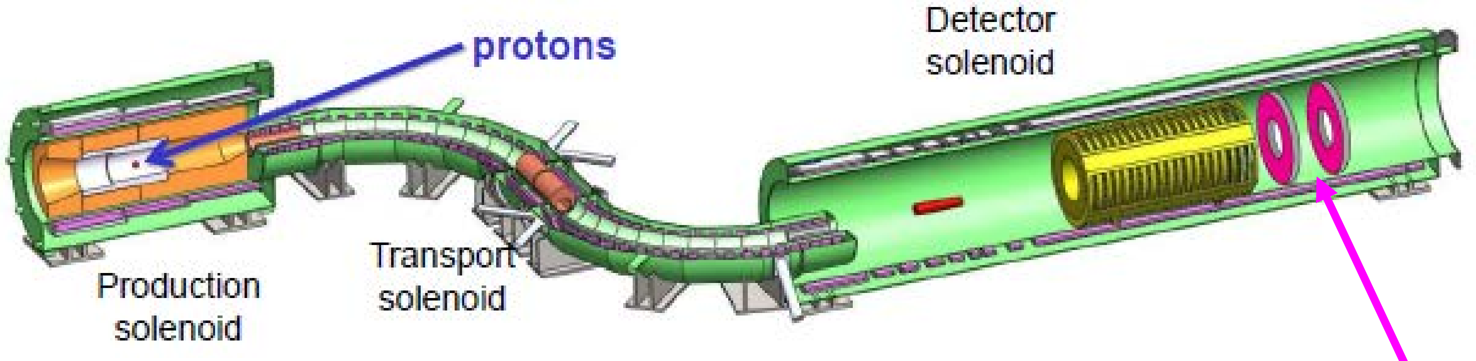
Inorganic Crystals are Widely Used in HEP

- **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, such as LYSO:Ce, at the energy frontier (HL-LHC);**
  - **Ultra-fast scintillators, such as BaF_2:Y, at the intensity frontier (Mu2e-II);**
  - **Cost-effective crystals with less than $1/cc for lepton collides (ILC/FCC/CEPC).**

Application of Fast Inorganic Crystals

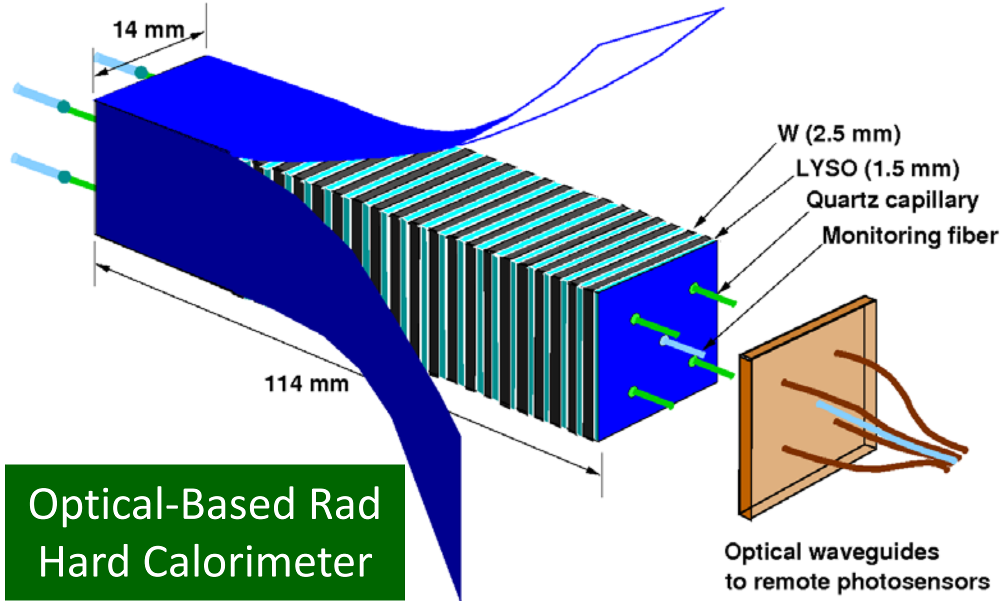


CMS BTL: An LYSO + SiPM Layer



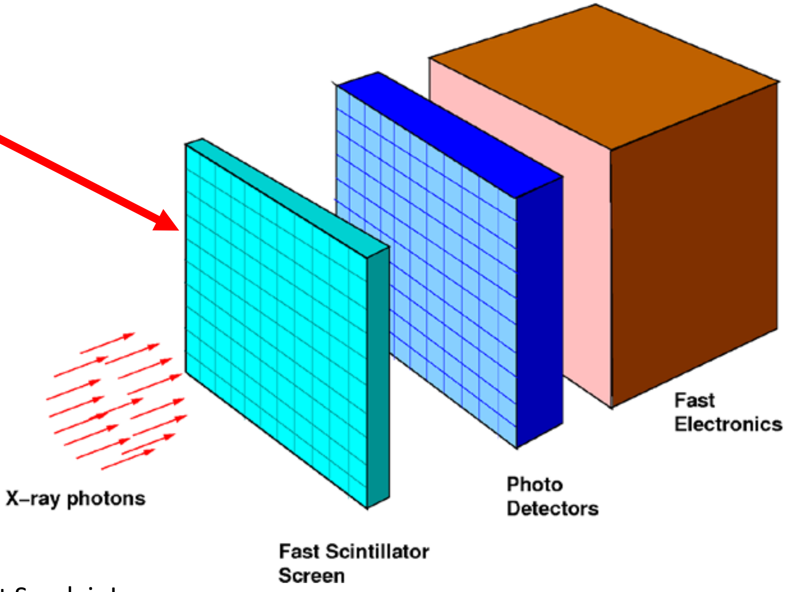
Mu2e-II: arXiv:1802.02599
See papers N37-4, N40-3

Mu2e-I: 1,348 CsI of 34 x 34 x 200 mm
Mu2e-II: 1,940 BaF_2:Y of 30 x 30 x 218 mm



Optical-Based Rad Hard Calorimeter

A BaF_2 crystal based ultrafast front imager proposed for GHz hard X-ray imaging for future FEL facility, proposed in the 2016 workshop at Santa Fe



Fast Inorganic Scintillators

	LSO/LYSO	GSO	YSO	CsI	BaF_2	CeF_3	$CeBr_3$	$LaCl_3$	$LaBr_3$	Plastic scintillator (BC 404) ①
Density (g/cm^3)	7.4	6.71	4.44	4.51	4.89	6.16	5.23	3.86	5.29	1.03
Melting point (℃)	2050	1950	1980	621	1280	1460	722	858	783	70[#]
Radiation Length (cm)	1.14	1.38	3.11	1.86	2.03	1.7	1.96	2.81	1.88	42.54
Molière Radius (cm)	2.07	2.23	2.93	3.57	3.1	2.41	2.97	3.71	2.85	9.59
Interaction Length (cm)	20.9	22.2	27.9	39.3	30.7	23.2	31.5	37.6	30.4	78.8
Z value	64.8	57.9	33.3	54	51.6	50.8	45.6	47.3	45.6	5.82
dE/dX (MeV/cm)	9.55	8.88	6.56	5.56	6.52	8.42	6.65	5.27	6.9	2.02
Emission Peak[a] (nm)	420	430	420	420 310	300 220	340 300	371	335	356	408
Refractive Index[b]	1.82	1.85	1.8	1.95	1.5	1.62	1.9	1.9	1.9	1.58
Relative Light Yield[a,c]	100	45	76	4.2 1.3	42 4.8	8.6	99	15 49	153	35
Decay Time[a] (ns)	40	73	60	30 6	650 0.5	30	17	570 24	20	1.8
d(LY)/dT[d] (%/°C)	-0.2	-0.4	-0.1	-1.4	-1.9 0.1	~0	-0.1	0.1	0.2	~0

a. Top line: slow component, bottom line: fast component.

b. At the wavelength of the emission maximum.

c. Relative light yield normalized to the light yield of LSO

d. At room temperature (20°C)

#. Softening point

1. http://www.detectors.saint-gobain.com/Plastic-Scintillator.aspx
   http://pdg.lbl.gov/2008/AtomicNuclearProperties/HTML_PAGES/216.html

The sub-ns fast scintillation in BaF_2 promises a very fast crystal calorimeter to face the challenge of high event rate expected by future HEP experiments at the energy and intensity frontiers

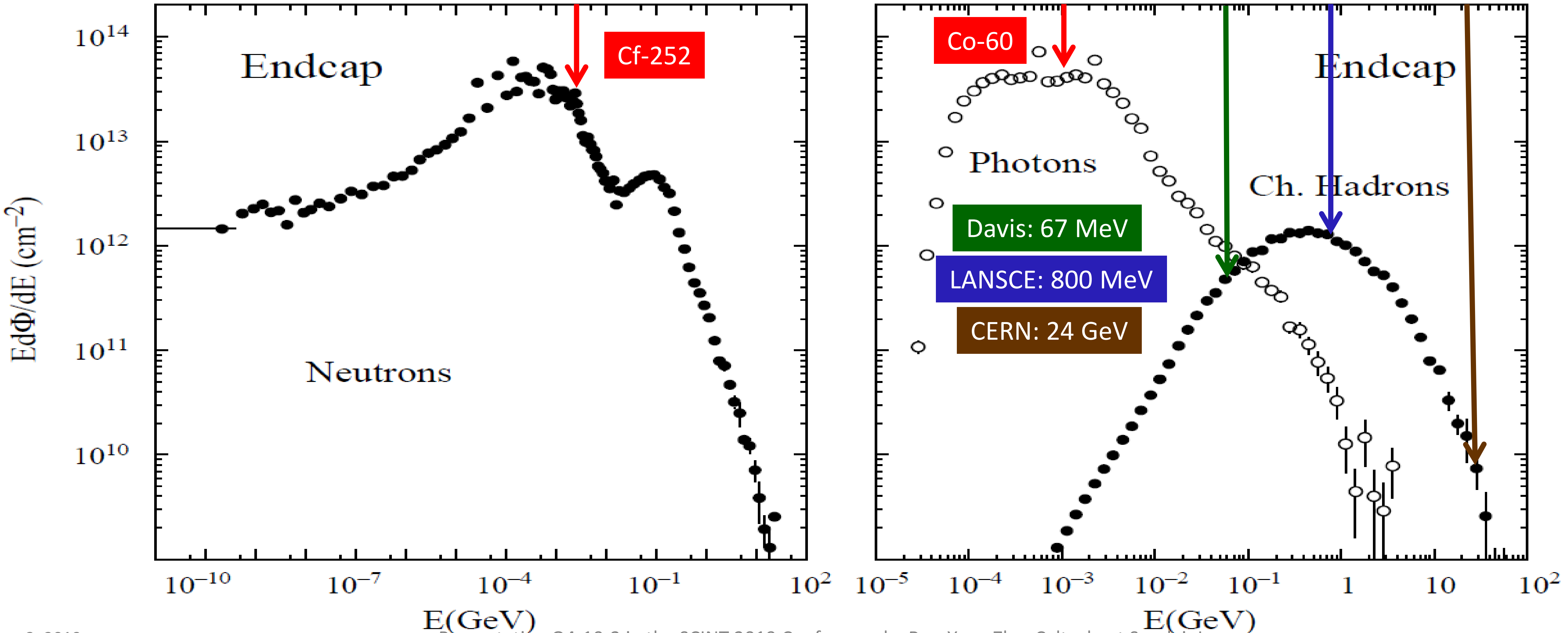
Expected Radiation at the HL-LHC

CMS MTD: 4.8 Mrad, 2.5x 10^{13} p/cm^2 & 3.2 x 10^{14} n_{eq}/cm^2
CMS FCAL: 68 Mrad, 2.1x 10^{14} p/cm^2 & 2.4 x 10^{15} n_{eq}/cm^2

CMS MTD	η	n_{eq} (cm^{-2})	n_{eq} Flux (cm^{-2}s^{-1})	Protons (cm^{-2})	p Flux (cm^{-2}s^{-1})	Dose (Mrad)	Dose rate (rad/h)
Barrel	0.00	2.48E+14	2.75E+06	2.2E+13	2.4E+05	2.7	108
Barrel	1.15	2.70E+14	3.00E+06	2.4E+13	2.6E+05	3.8	150
Barrel	**1.45**	**2.85E+14**	**3.17E+06**	**2.5E+13**	**2.8E+05**	**4.8**	**192**
Endcap	1.60	2.3E+14	2.50E+06	2.0E+13	2.2E+05	2.9	114
Endcap	2.00	4.5E+14	5.00E+06	3.9E+13	4.4E+05	7.5	300
Endcap	2.50	1.1E+15	1.25E+07	9.9E+13	1.1E+06	25.5	1020
Endcap	**3.00**	**2.4E+15**	**2.67E+07**	**2.1E+14**	**2.3E+06**	**67.5**	**2700**

Particle Energy Spectra at HL-LHC

FLUKA simulations: neutrons and charged hadrons peaked at MeV and several hundreds MeV, respectively. Neutron and proton induced damages were investigated at the East Port and the Blue Room of the Los Alamos Neutron Science Center (LANSCE), respectively

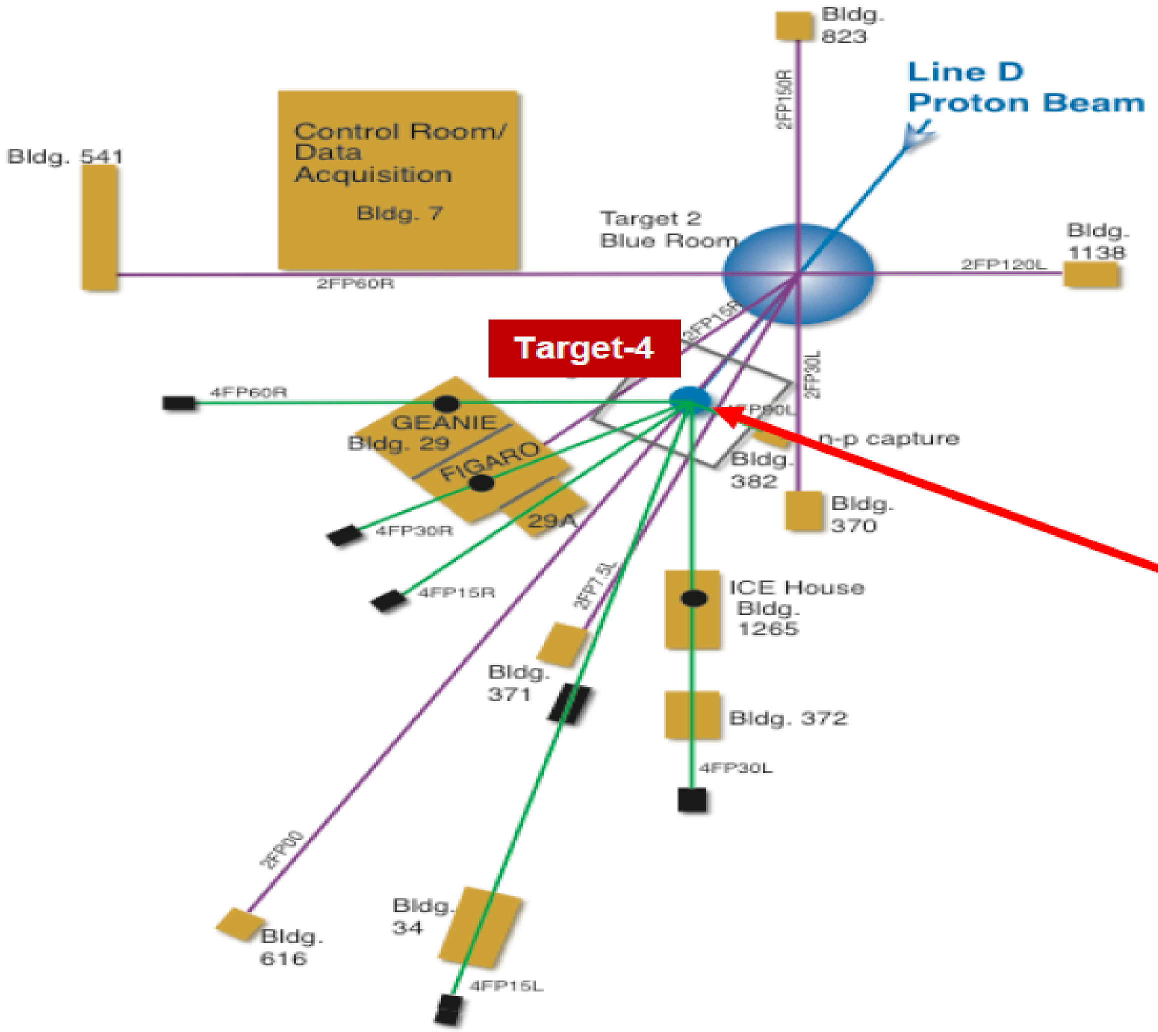


Radiation Damage in Inorganic Crystals

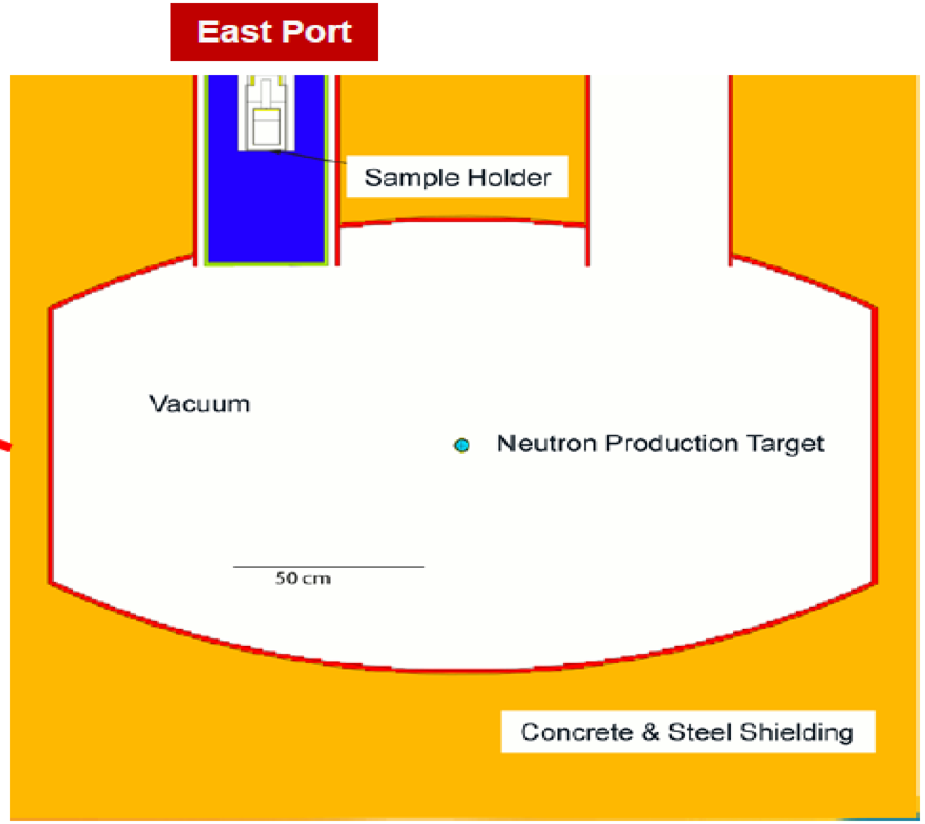
- Possible damage effects are scintillation mechanism damage, induced absorption and phosphorescence, where induced absorption degrades crystal transparency and light output.
- Ionization dose induced damage was investigated for BaF_2, BGO, CeF_3, undoped CsI, LSO/LYSO/LFS and PWO by using Co-60 and 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. Paper N2-5
- Neutron induced damage was investigated for BaF_2, LYSO and PWO crystals in three experiments since 2015 at LANSCE : 6991 (2015), 7332 (2016) and 7638 (2017). This paper reports neutron induced damage.

Neutron Irradiation at LANSCE

Los Alamos Neutron Science Center (LANSCE)

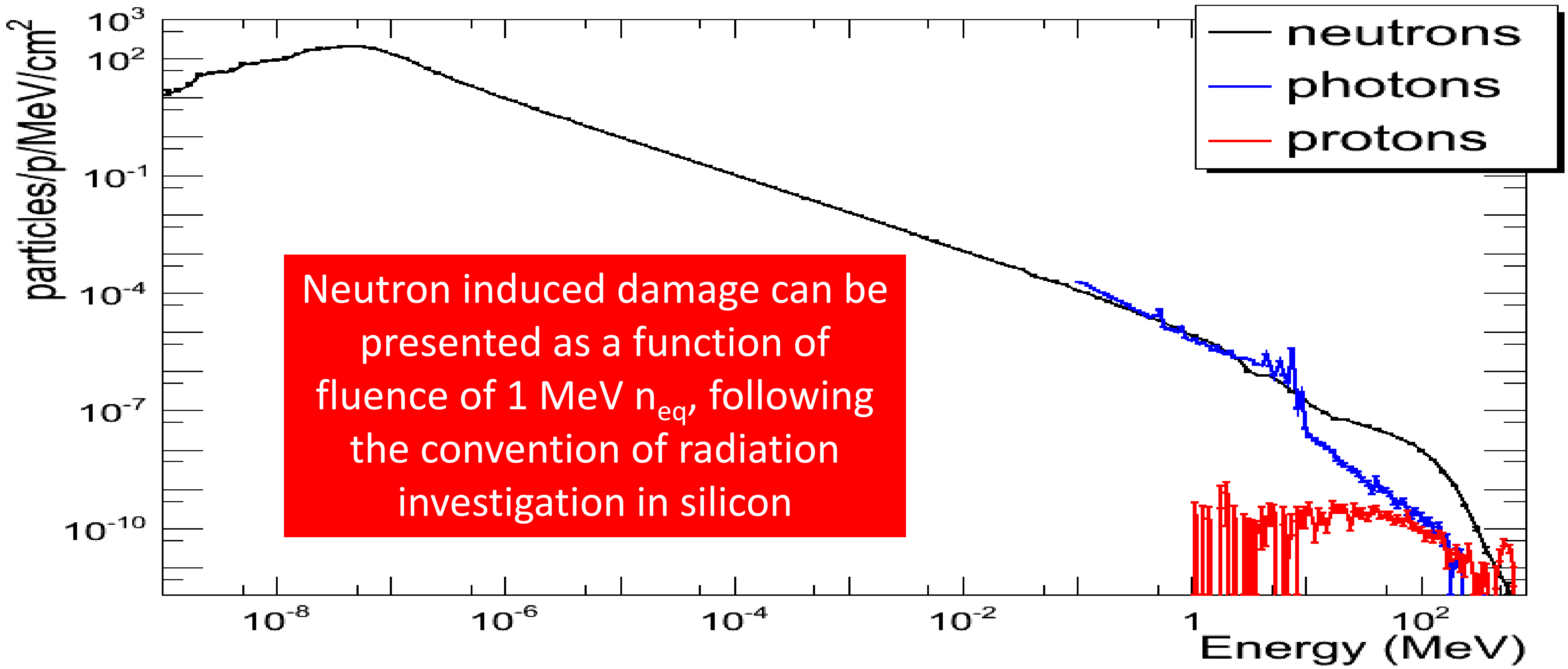


Samples are located at East Port in the Target-4, about 1.2 m away from the neutron production target



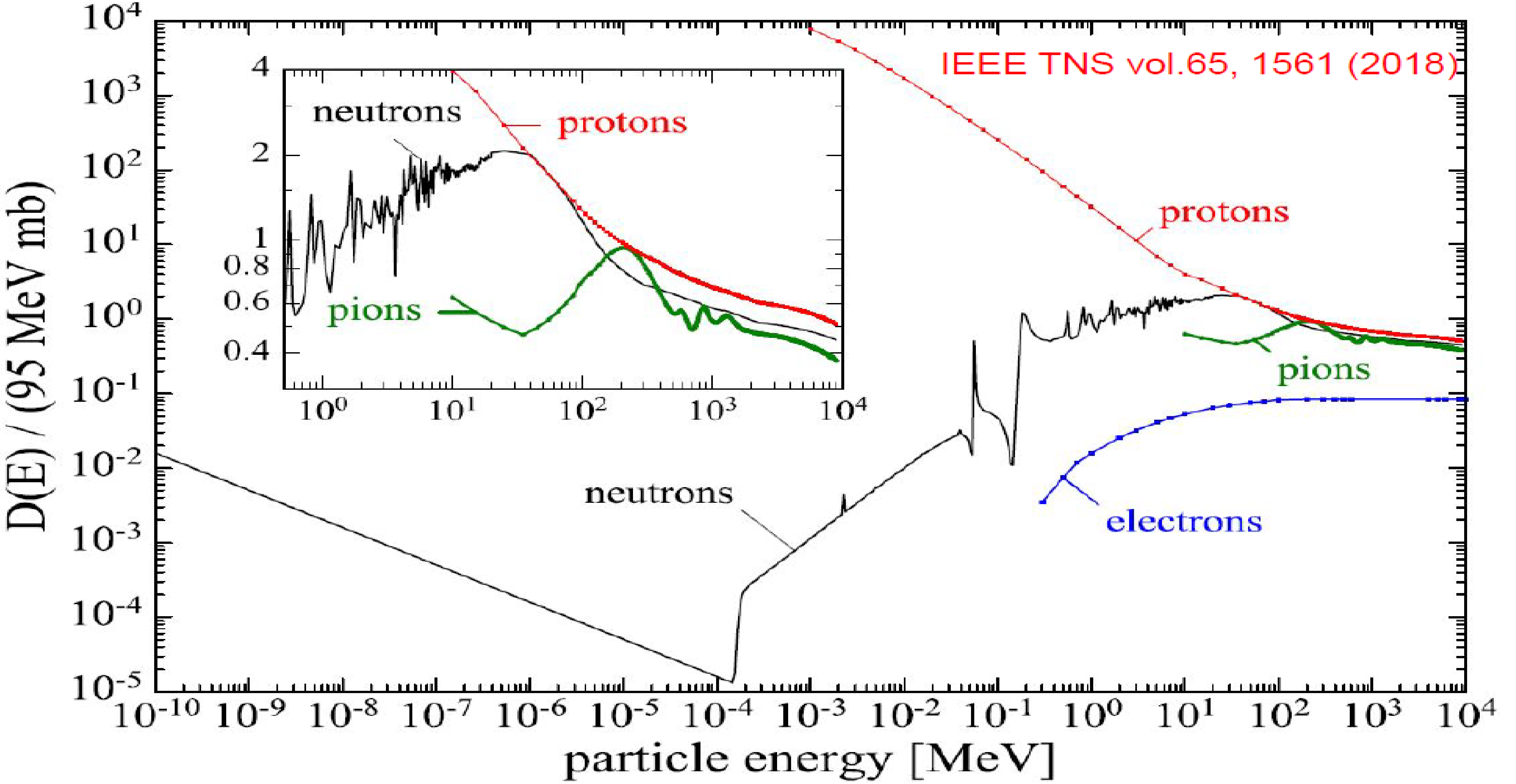
n/ɣ/p Spectra: LANSCE 6991,7332 and 7638

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



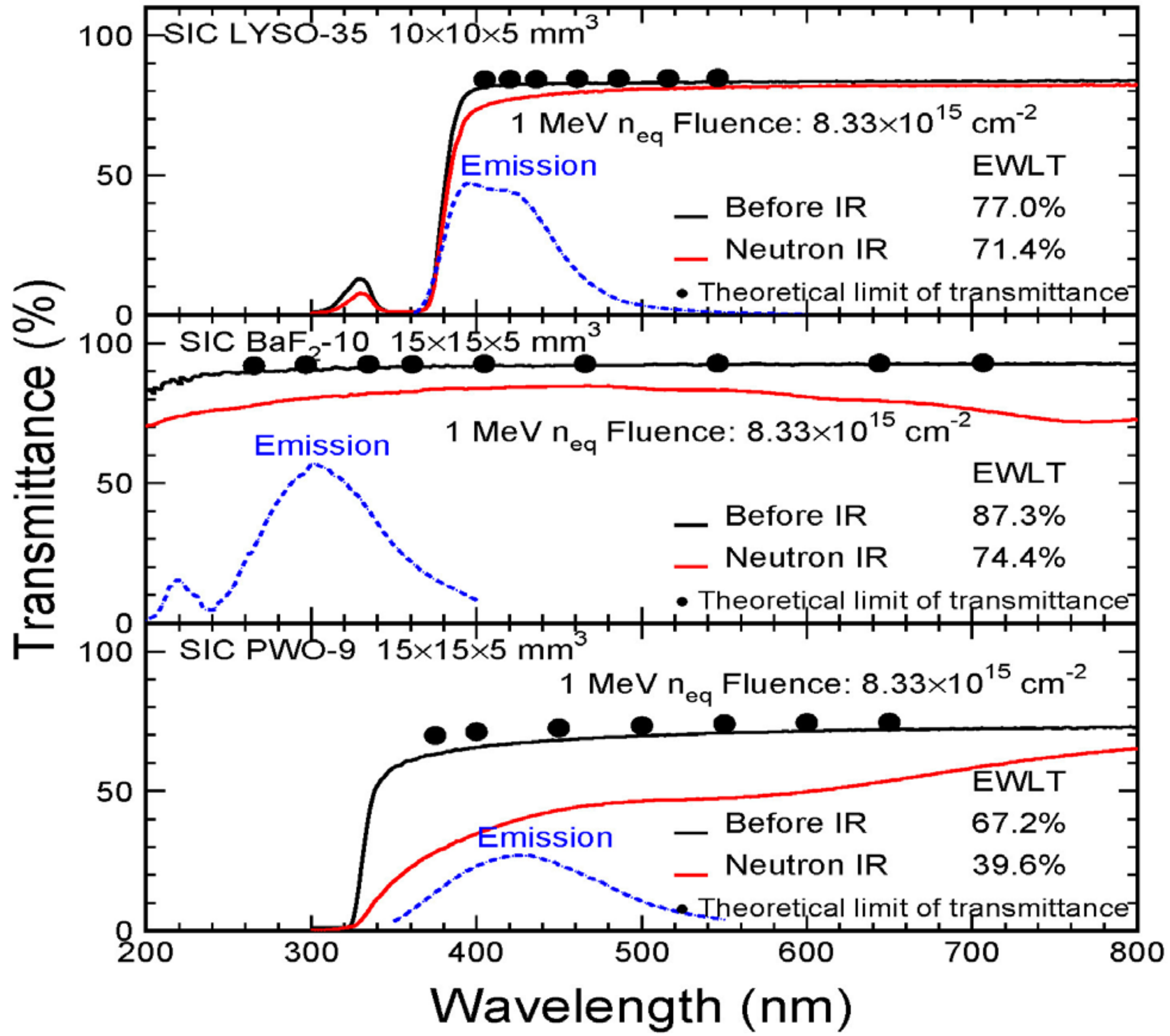
Neutron induced damage can be presented as a function of fluence of 1 MeV n_{eq}, following the convention of radiation investigation in silicon

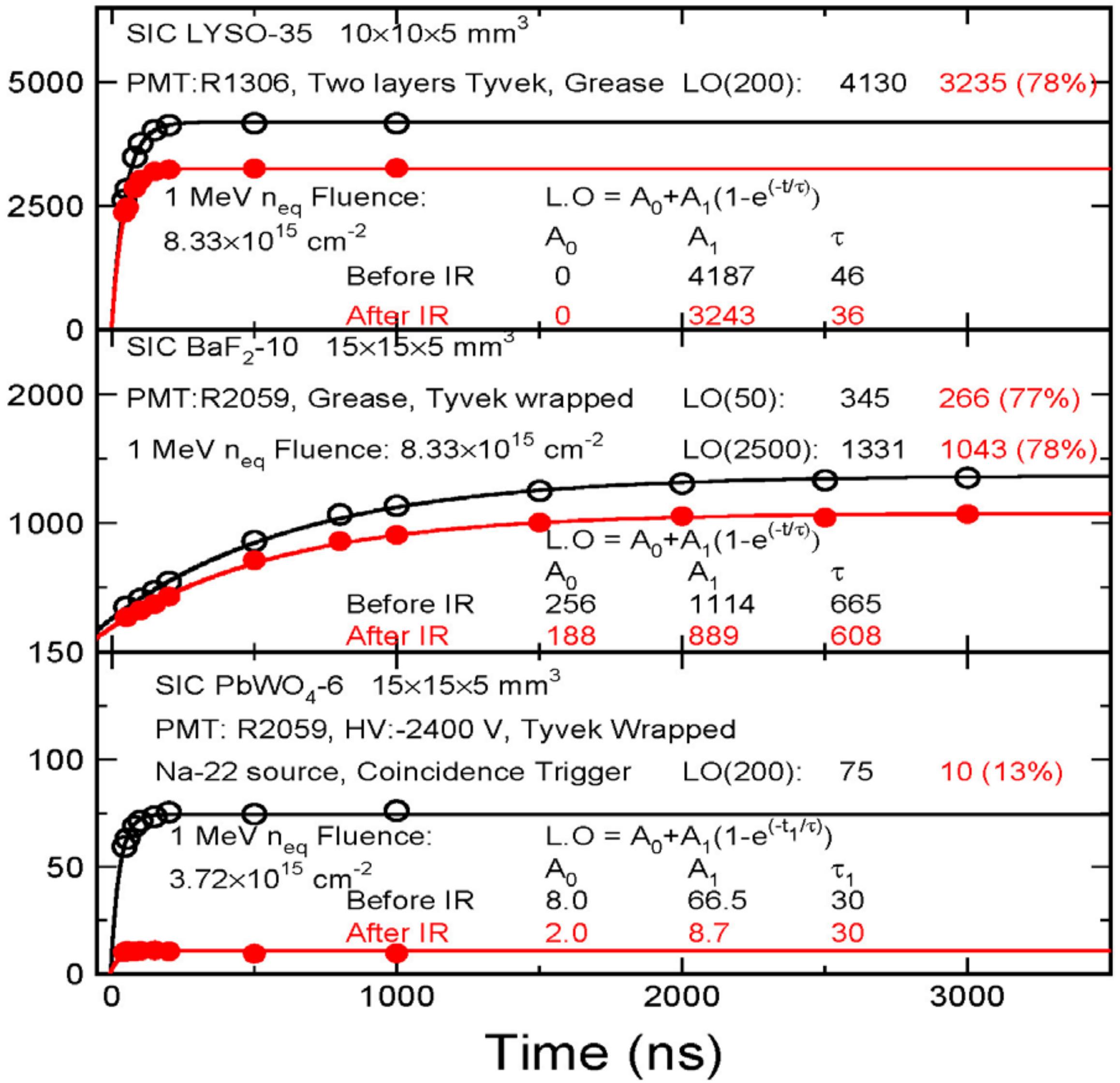
Conversion Neutron to 1 MeV n_{eq}



Transmittance and Light Output

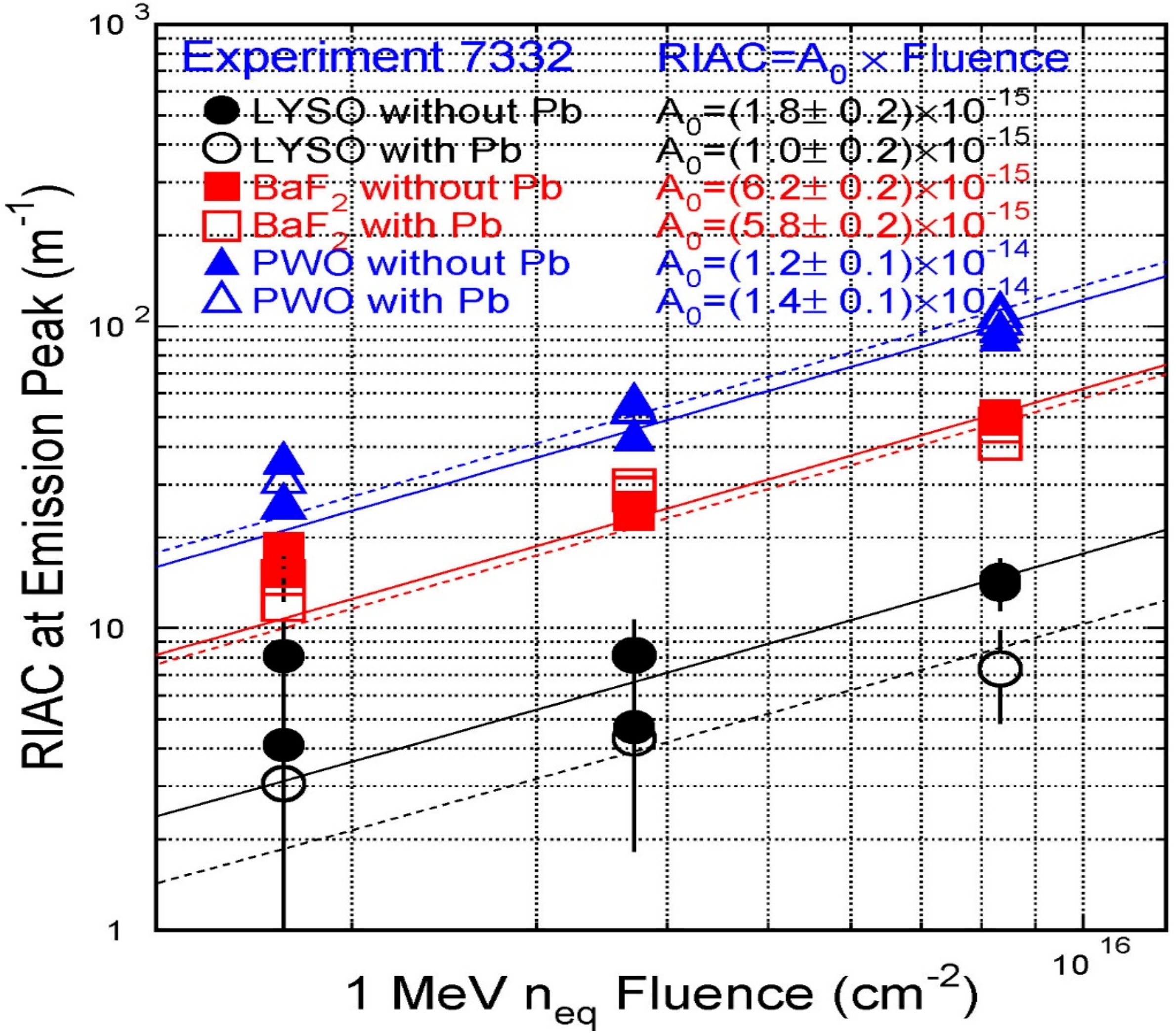
LYSO, BaF_2 and PWO irradiated up to 8 .3×10^{15} n_{eq}/cm^2

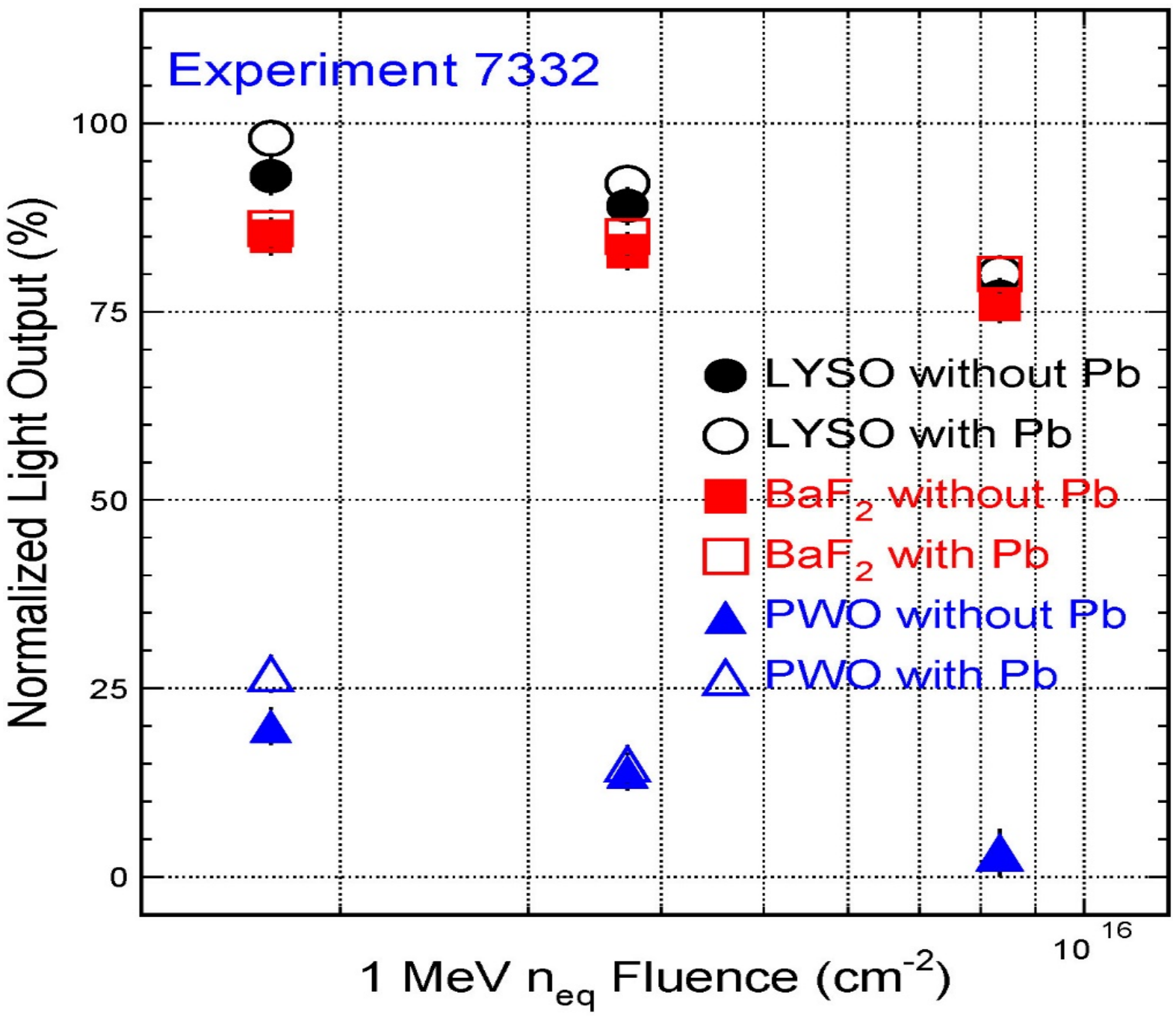




Result of TF:n LANSCE 7332

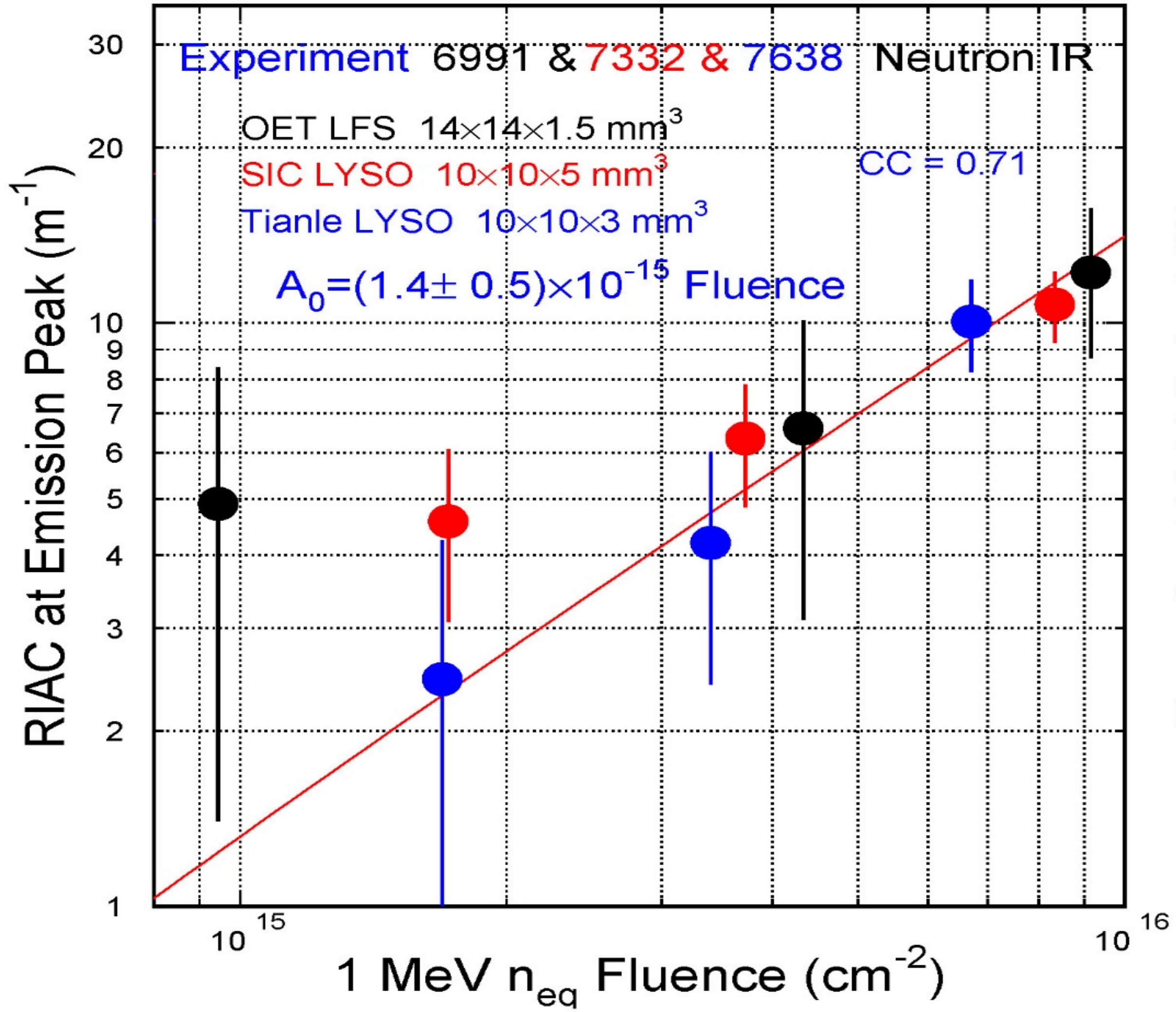
LYSO and BaF_2 are radiation hard up to 8.3 ×10^{15} n_{eq}/cm^2

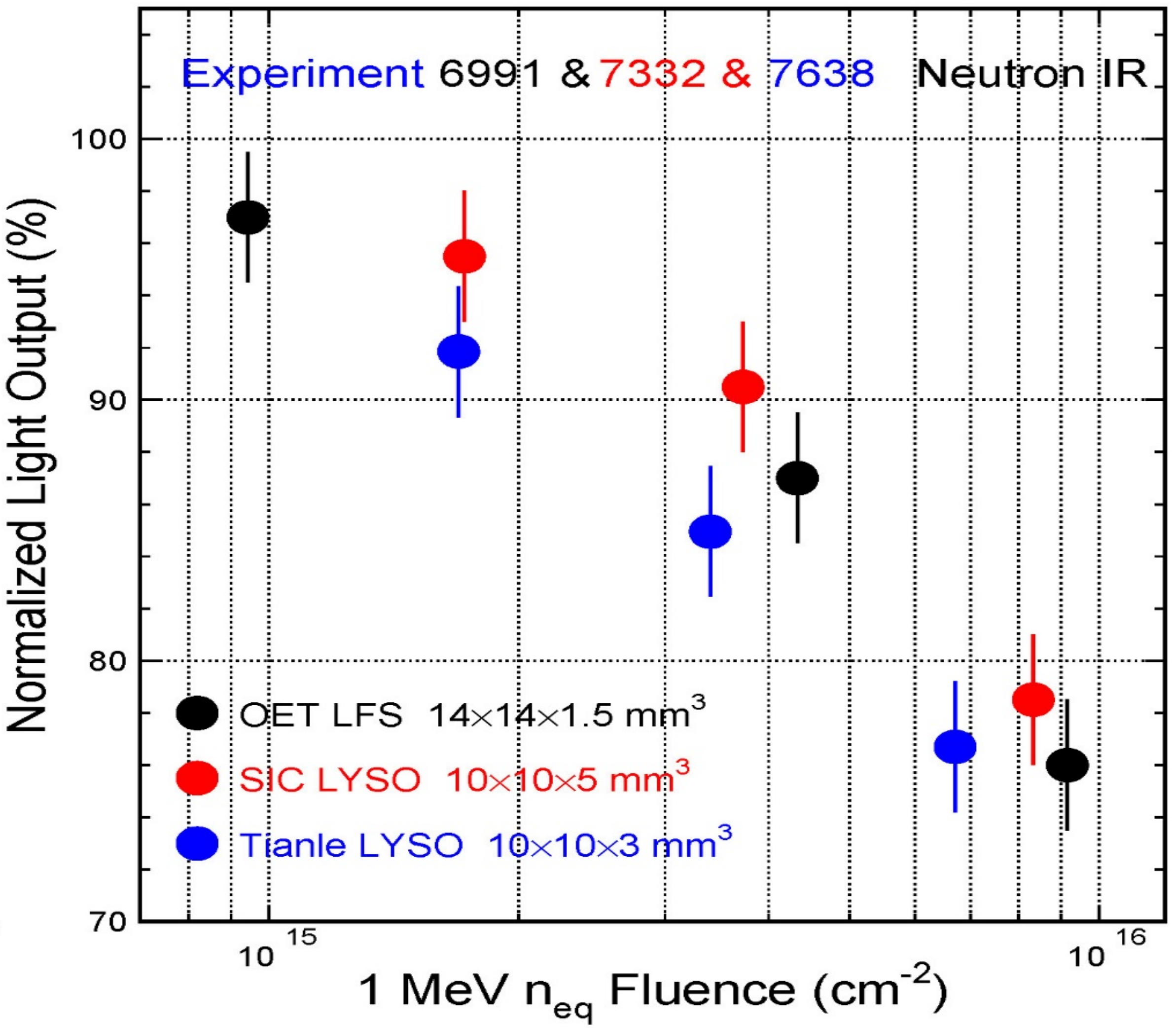




Combined Neutron IR for LYSO

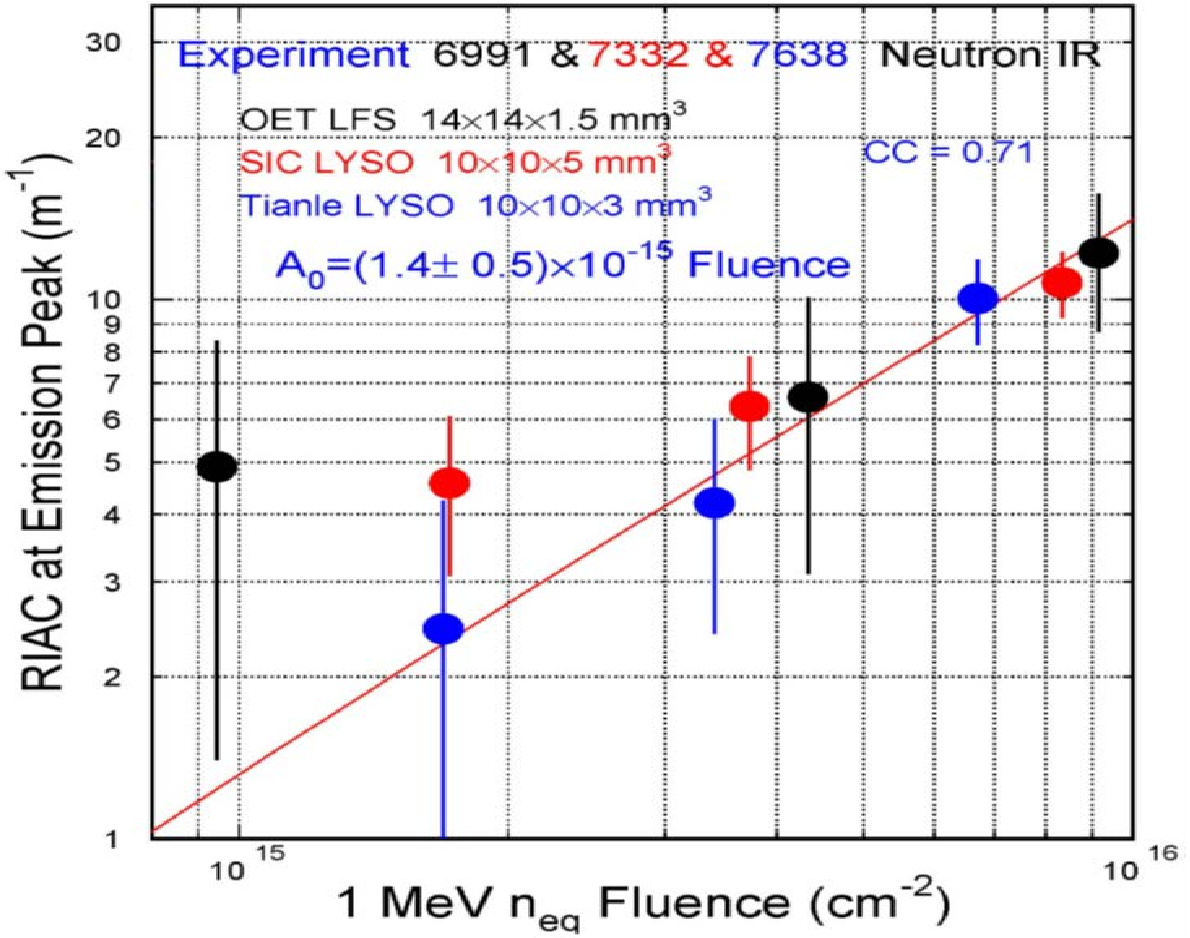
Consistent result obtained from three experiments

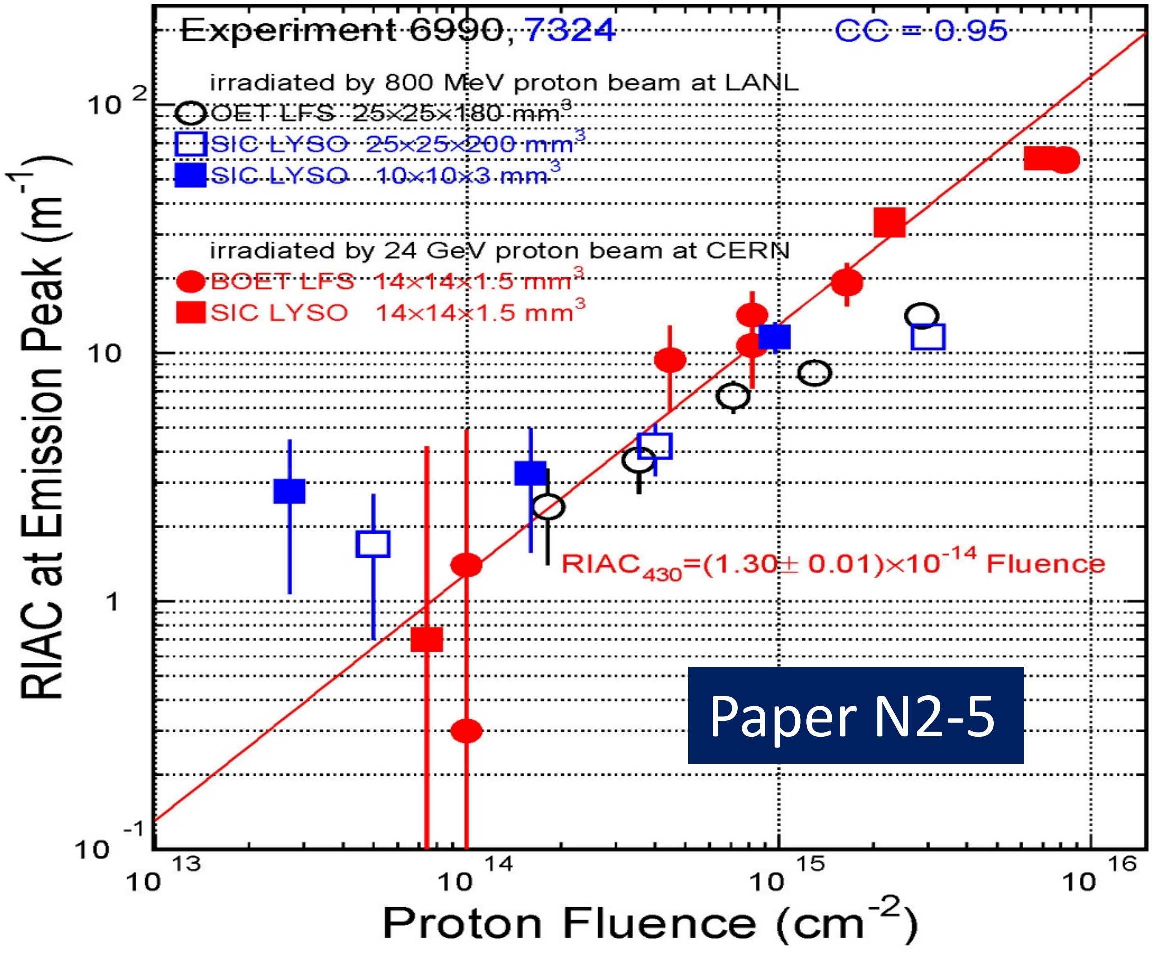




Neutron and Proton Induced RIAC in LYSO

LYSO crystals from different vendors show consistent damage for 1 MeV_{eq} neutrons with RIAC @ 430 nm = 1.4 x 10^{-15} F_n, a factor of ten less than protons





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Summary

- 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 8 x 10^{15} n_{eq}/cm^2. BaF_2 shows a similar radiation hardness to LYSO at high fluence. Investigation continues on BaF_2:Y crystals, and to compare damage in various inorganic crystal scintillators induced by ionization dose, protons and neutrons.
- 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 TF:n of 3 x 10^{14} n/cm^2 and TF:p of 3 x 10^{13} p/cm^2.

Acknowledgements

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