Hadron-Induced Radiation Damage in Fast Heavy Inorganic Scintillators

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Introduction

Future HEP experiments at the energy frontier face a challenge of severe radiation by ionization dose, as well as charged and neutral hadrons. Up to 500 Grad and 5×10^{18} 1 MeV equivalent n_{eq}/cm^2 fluence are expected at the forward calorimetry in the proposed Future Hadron Circular Collider (FCC-hh).

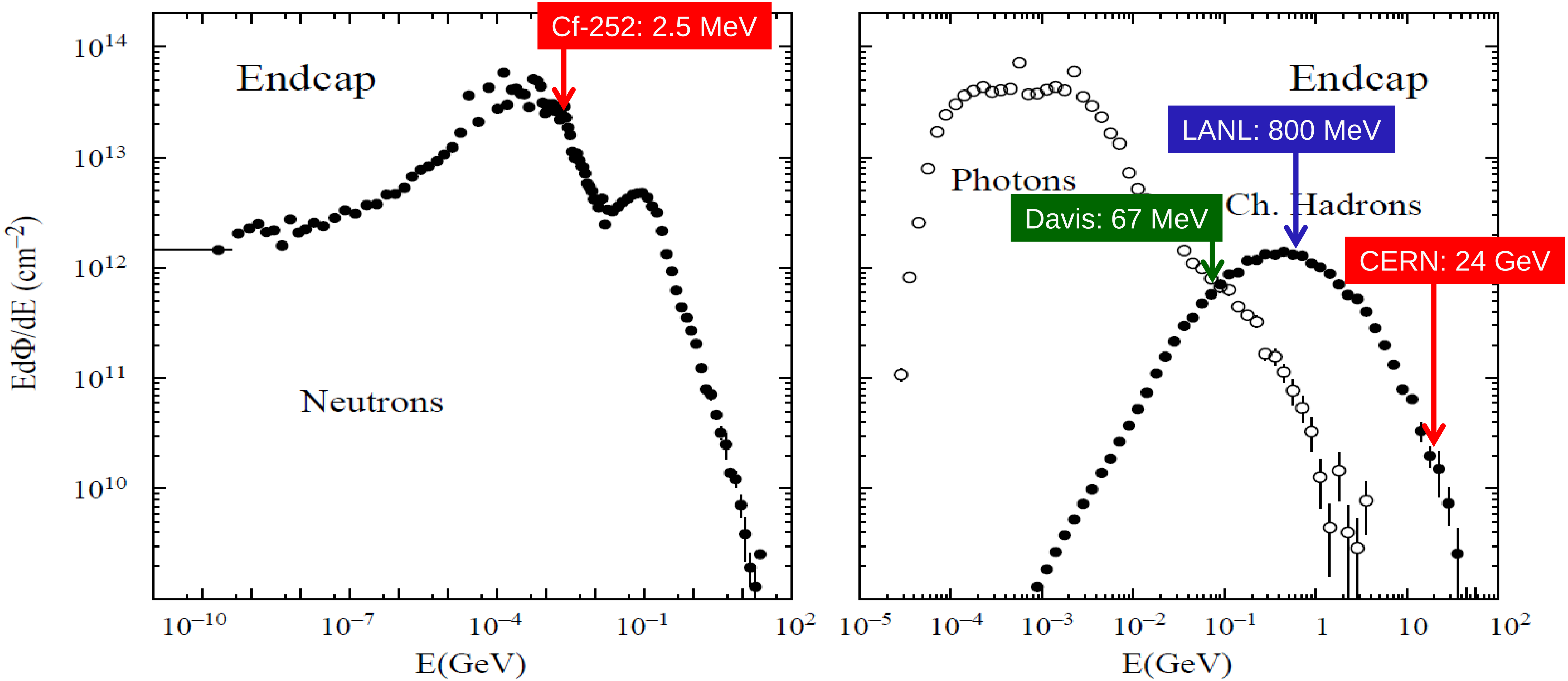
Starting from 2014 an investigation on hadron-induced radiation damage has been carried out by using 800 MeV protons and broad band neutrons respectively in the Blue Room and East Port of Los Alamos Neutron Science Center (LANSCE). Inorganic crystal and ceramic samples were irradiated up to 3×10^{15} p/cm^2 and 8×10^{15} 1 MeV equivalent n_{eq}/cm^2.

In addition, LYSO:Ce crystal and LuAG:Ce ceramic samples were also irradiated at CERN by 24 GeV protons up to $1.2 \times 10^{15}/cm^2$.

This report summarizes results obtained for LYSO:Ce crystals, LuAG:Ce ceramics and BaF_2 crystals.

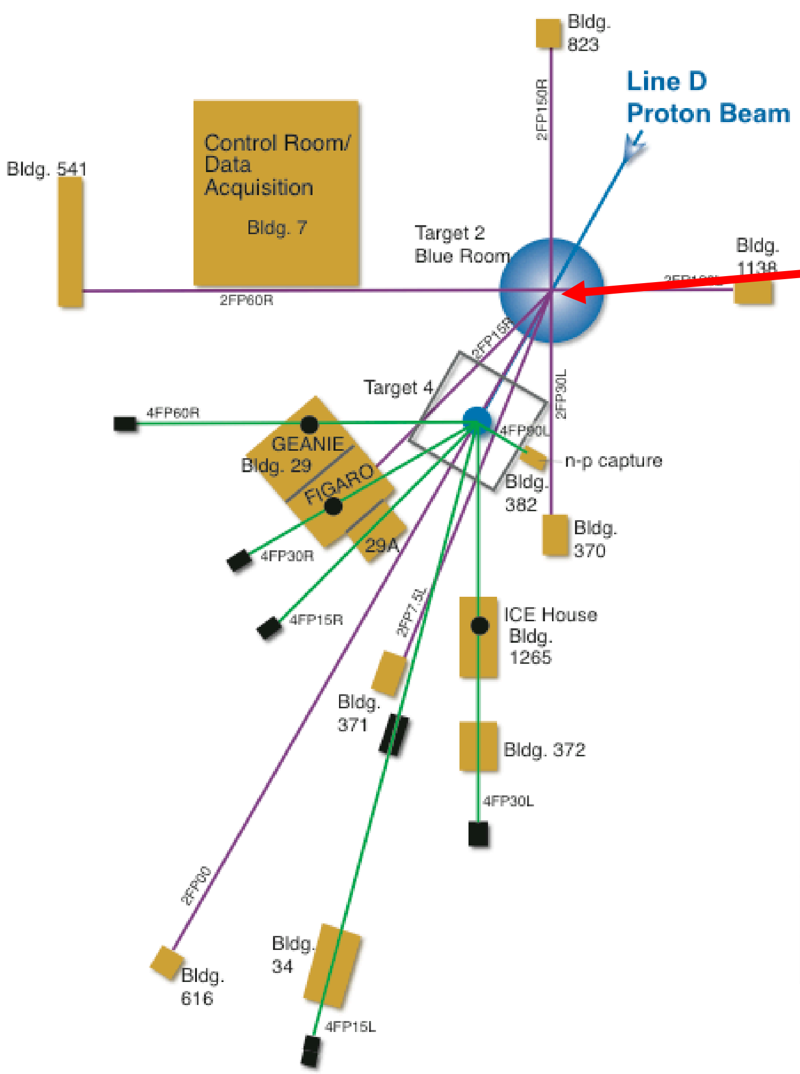
Hadron Energy Spectra at the HL-LHC

FLUKA simulations: neutrons and charged hadrons are peaked at MeV and hundreds MeV respectively
Proton and neutron irradiation was carried out in the Blue Room and East Port of LANSCE respectively



Proton Irradiation at the Blue Room

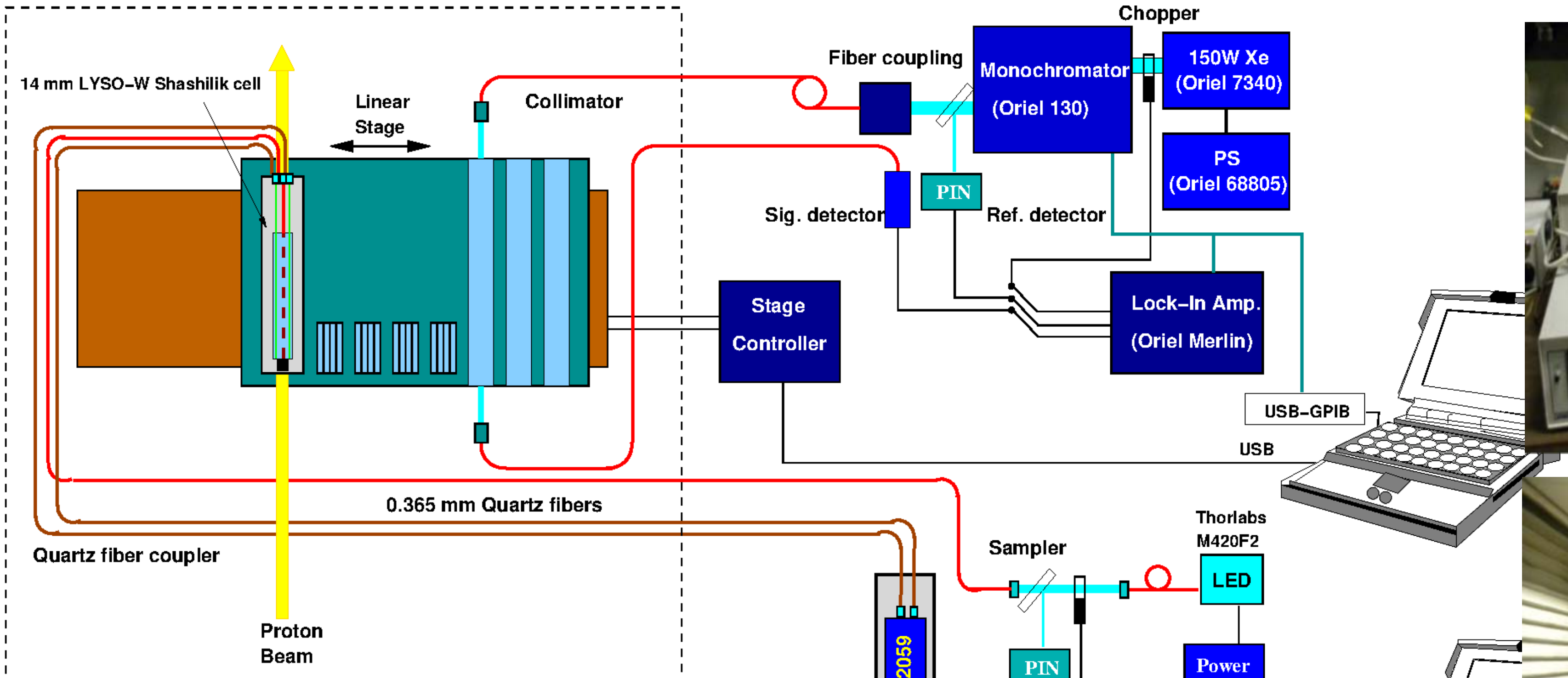
Los Alamos Neutron Science Center (LANSCE)

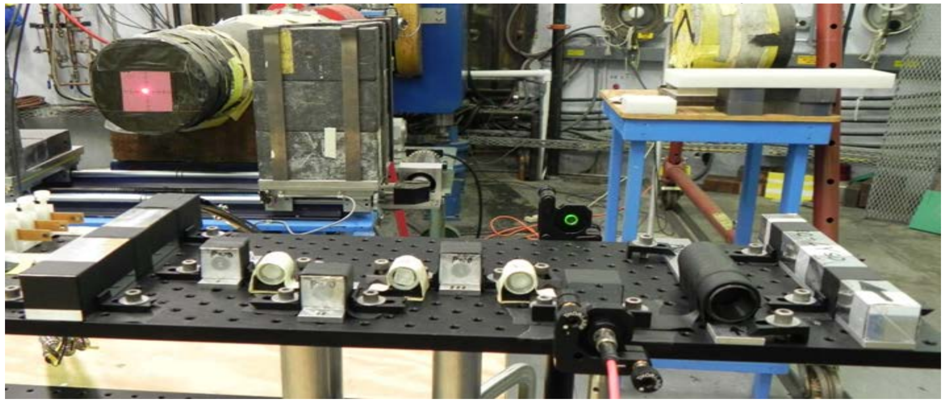


800 MeV proton beam (FWHM= 2.5 cm)

Environment/Source	Proton Flux ($p\ s^{-1}\ cm^{-2}$)	Fluence on Crystal ($p\ cm^{-2}$)
CMS FCAL (η=1.4) at HL-LHC	2.8×10^5	2.5×10^{13} / 3000 fb^{-1}
CMS FCAL (η=3.0) at HL-LHC	2.3×10^6	2.1×10^{14} / 3000 fb^{-1}
WNR facility of LANSCE	**Up to 2×10^{10}**	**Up to 3×10^{15}**

Proton Irradiation at the Blue Room

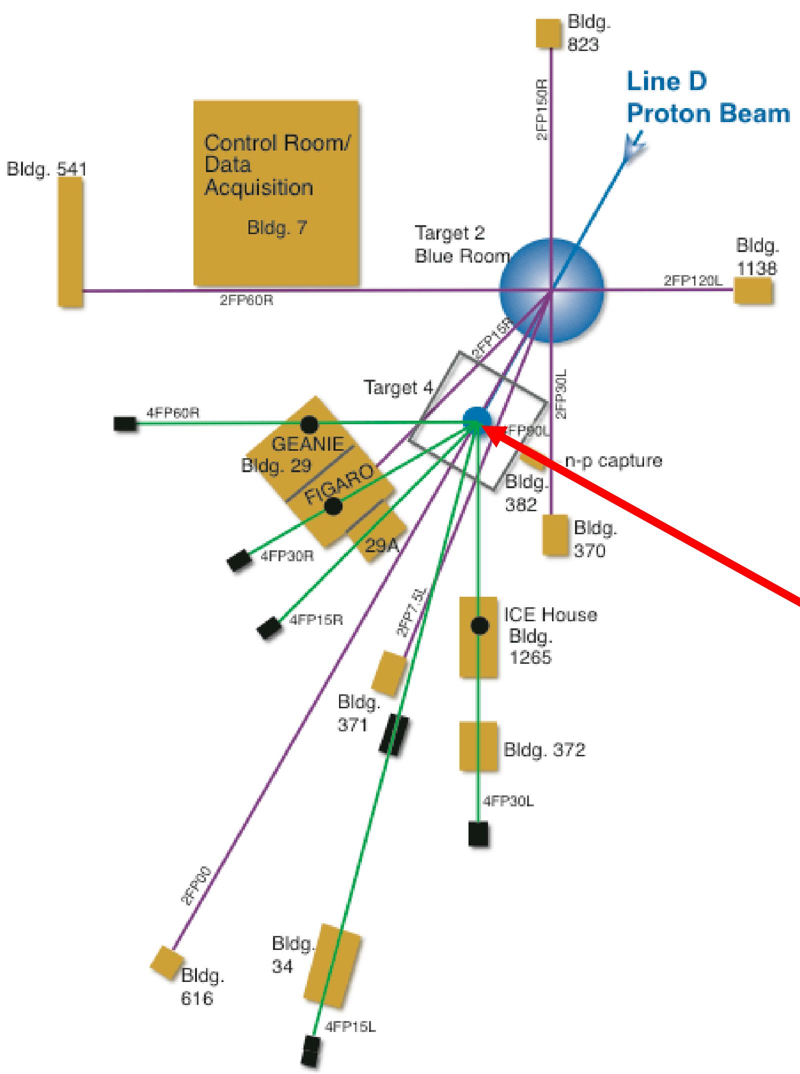




Setup of Experiment 7324

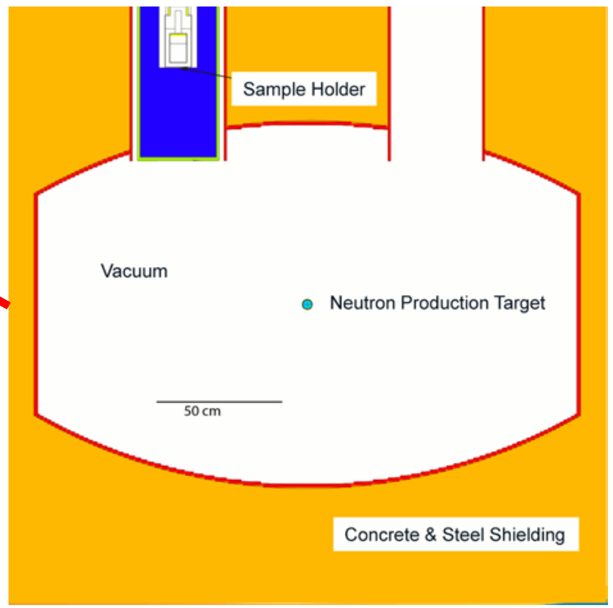
Neutron Irradiation in the East Port

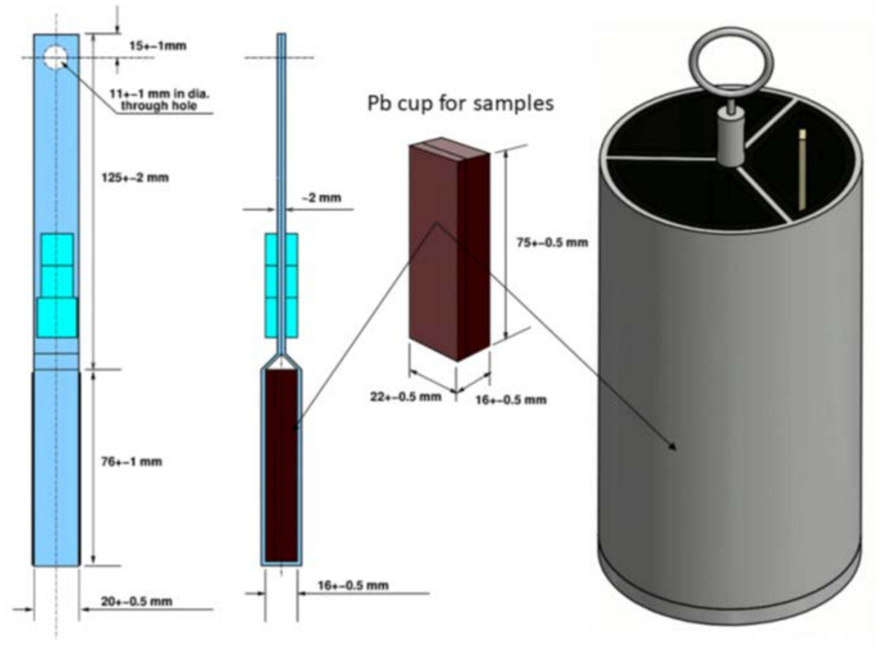
Los Alamos Neutron Science Center (LANSCE)



All samples in three groups were loaded at the beginning of beam run into the East Port of Target-4 at about 1.2 m away from the neutron production target. They were taken out one by one after reaching certain neutron fluence.

East Port

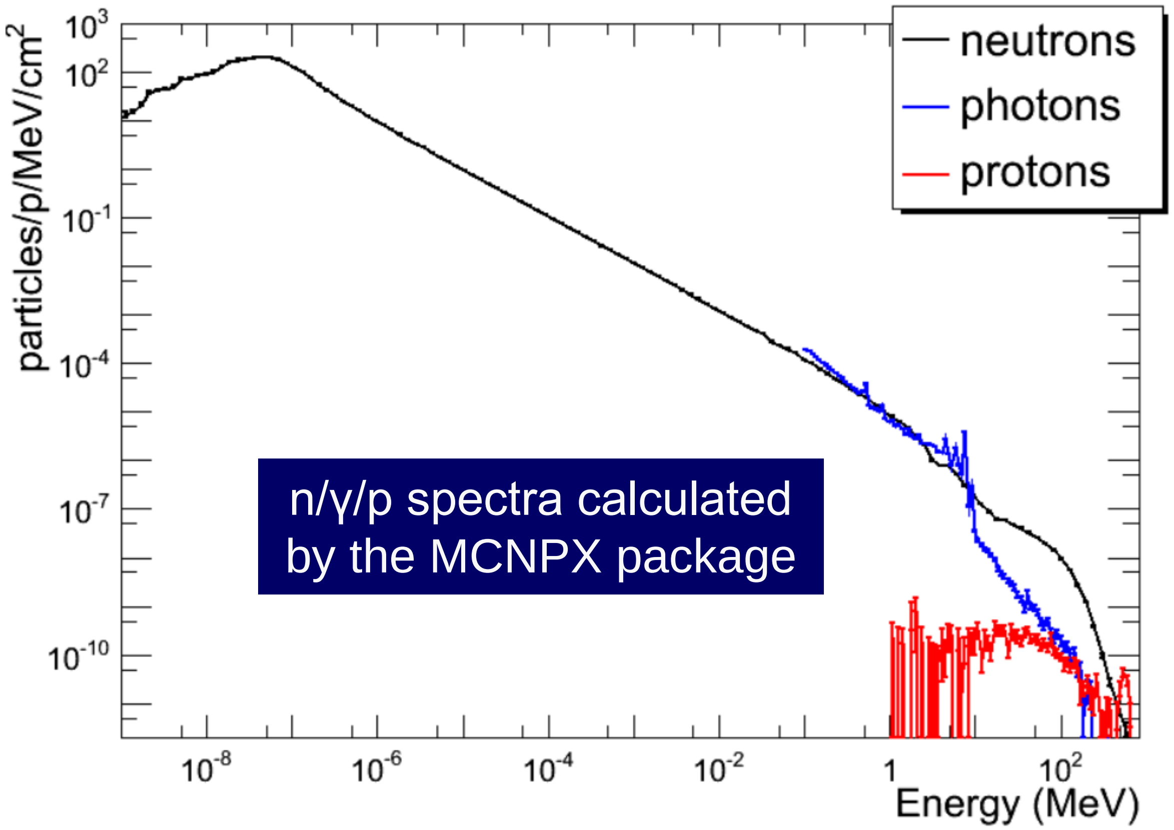


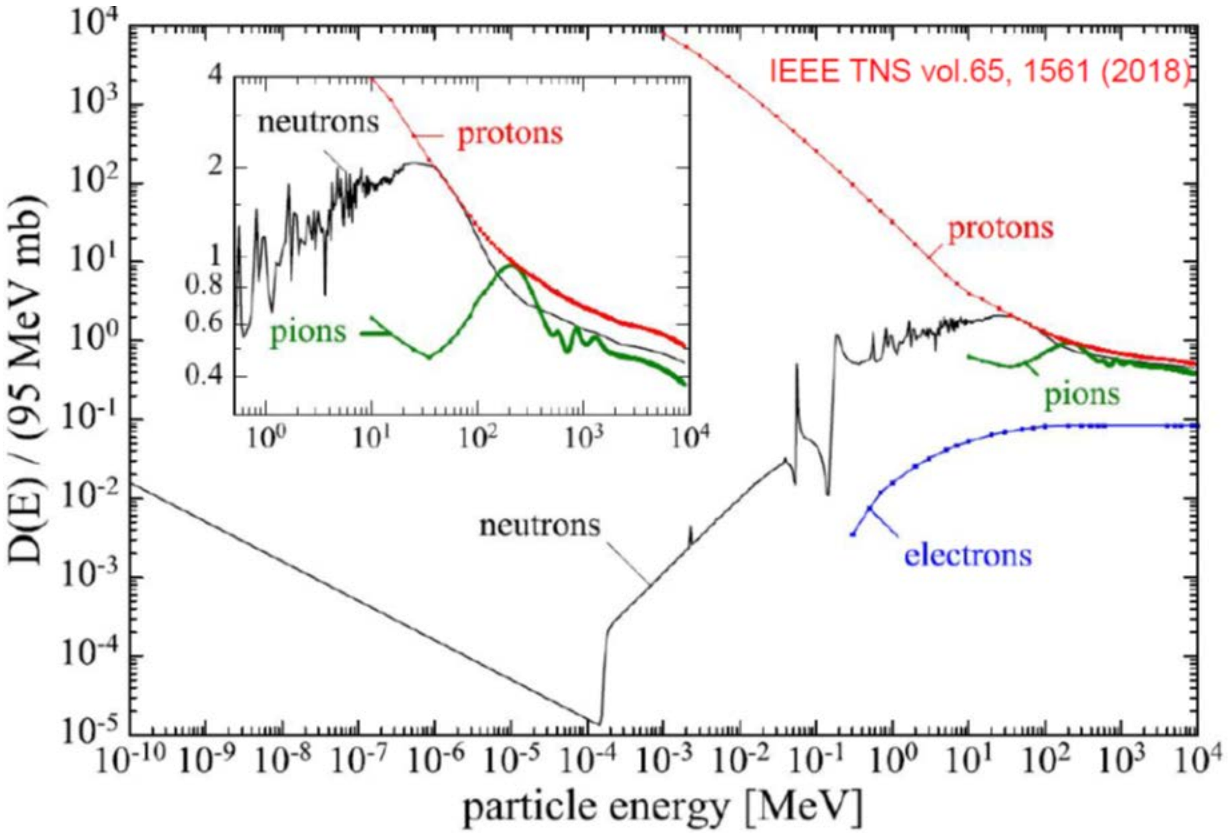


Setup of Experiment 7332

n/ɣ/p Spectra and Conversion to 1 MeV n_{eq}

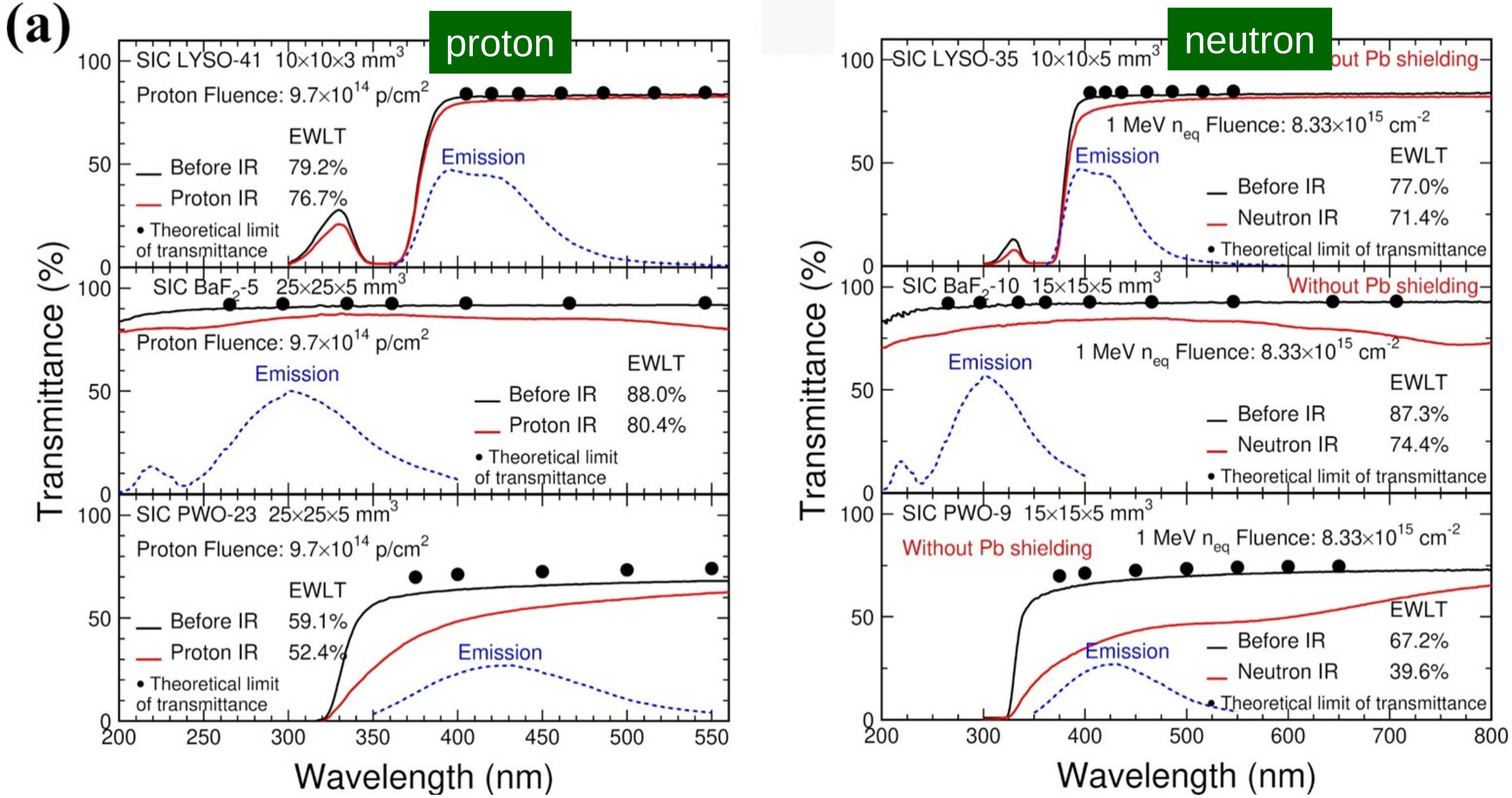
MCNPX (Monte Carlo N-Particle eXtended) package was used to calculate the n/ɣ/p spectra tallied in the largest sample volume (averaging) with 1 MeV equivalent (n_{eq}) fluence calculated by using the damage factor in Silicon





Transmittance: LYSO:Ce, BaF_2 and PWO

Transmittance measured before and after 9.7×10^{14} p/cm^2 and 8.3×10^{15} n_{eq}/cm^2 for LYSO:Ce, BaF_2 and PWO, showing good radiation hardness of LYSO:Ce and BaF_2



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

T(λ): Transmittance spectrum
Em(λ): Emission spectrum

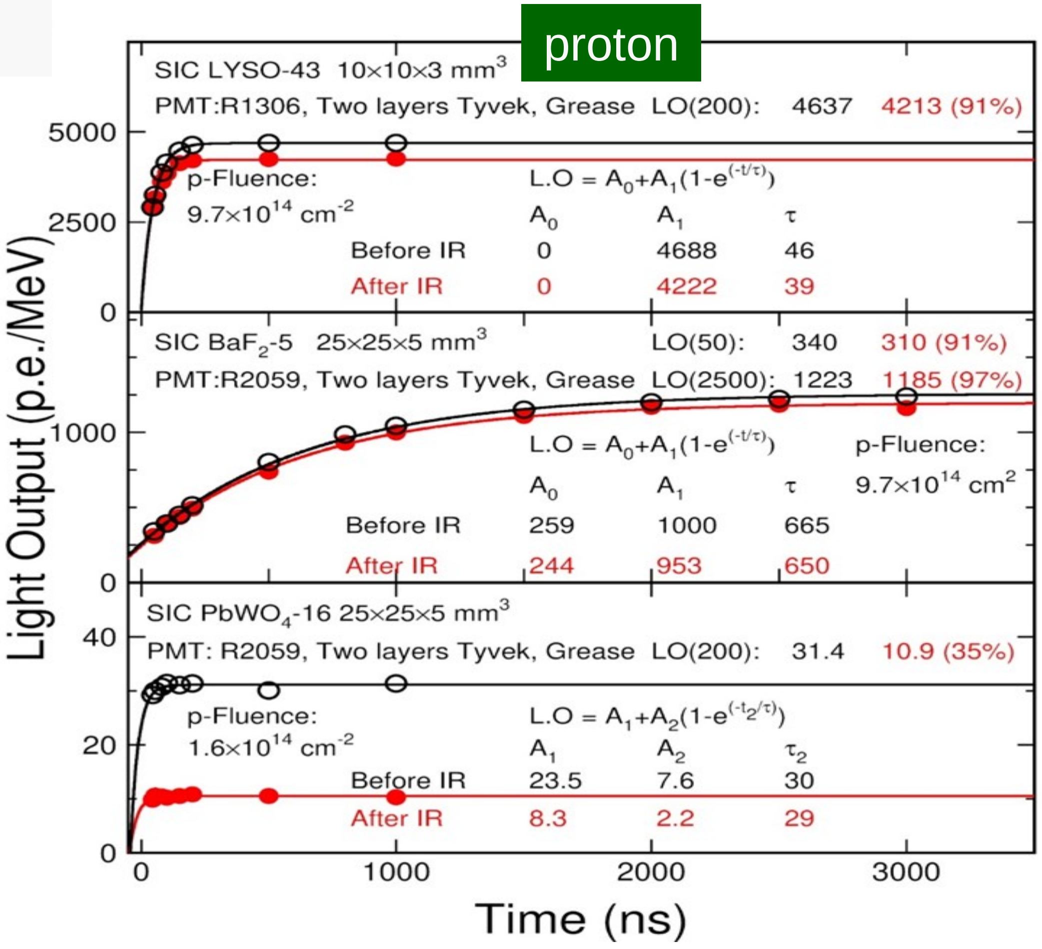
$$RIAC = \frac{1}{l}\ln\left(\frac{T_0}{T}\right)$$

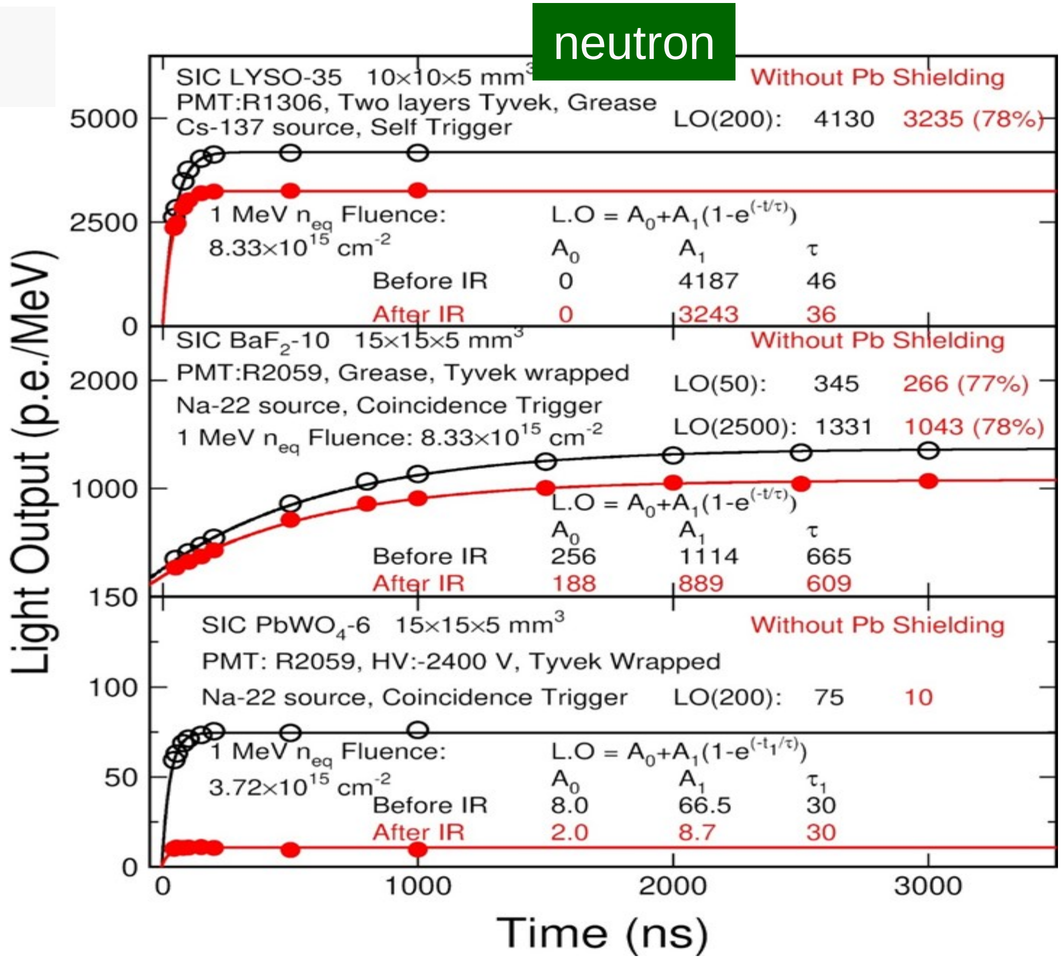
l: Crystal length
T0(λ): T before irradiation
T(λ): T after irradiation

C. Hu, L. Zhang and R.-Y. Zhu, Snowmass paper 2022, arXiv:2203.06788,

Light Output: LYSO:Ce, BaF_2 and PWO

Light output as a function of integration time measured before and after 9.7×10^{14} p/cm^2 and 8.3×10^{15} n_{eq}/cm^2, showing good radiation hardness for LYSO:Ce and BaF_2

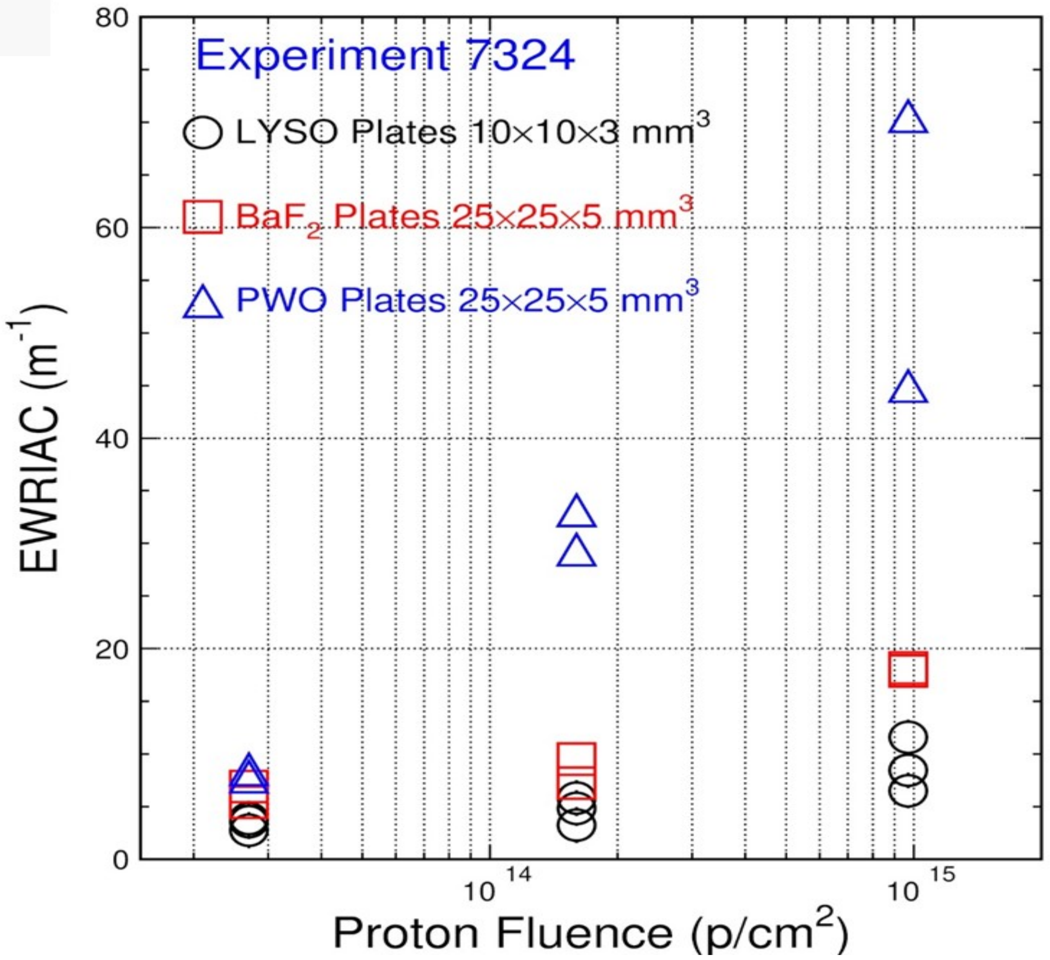




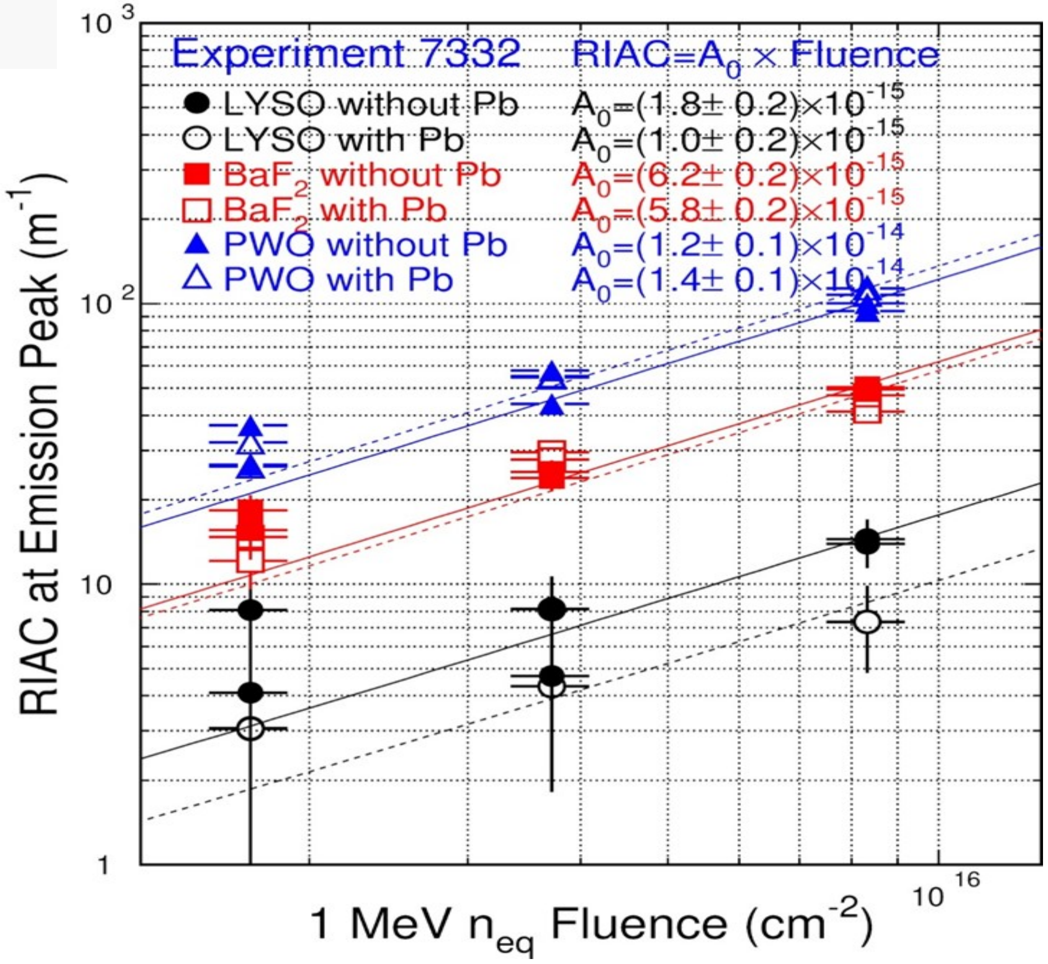
C. Hu, L. Zhang and R.-Y. Zhu, Snowmass paper 2022, arXiv:2203.06788,

RIAC: LYSO:Ce, BaF_2 and PWO

Radiation induced absorption coefficient (RIAC) as a function of fluence for 3 groups of LYSO:Ce, BaF_2 and PWO samples after up to 9.7×10^{14} p/cm^2 and 8.3×10^{15} n_{eq}/cm^2



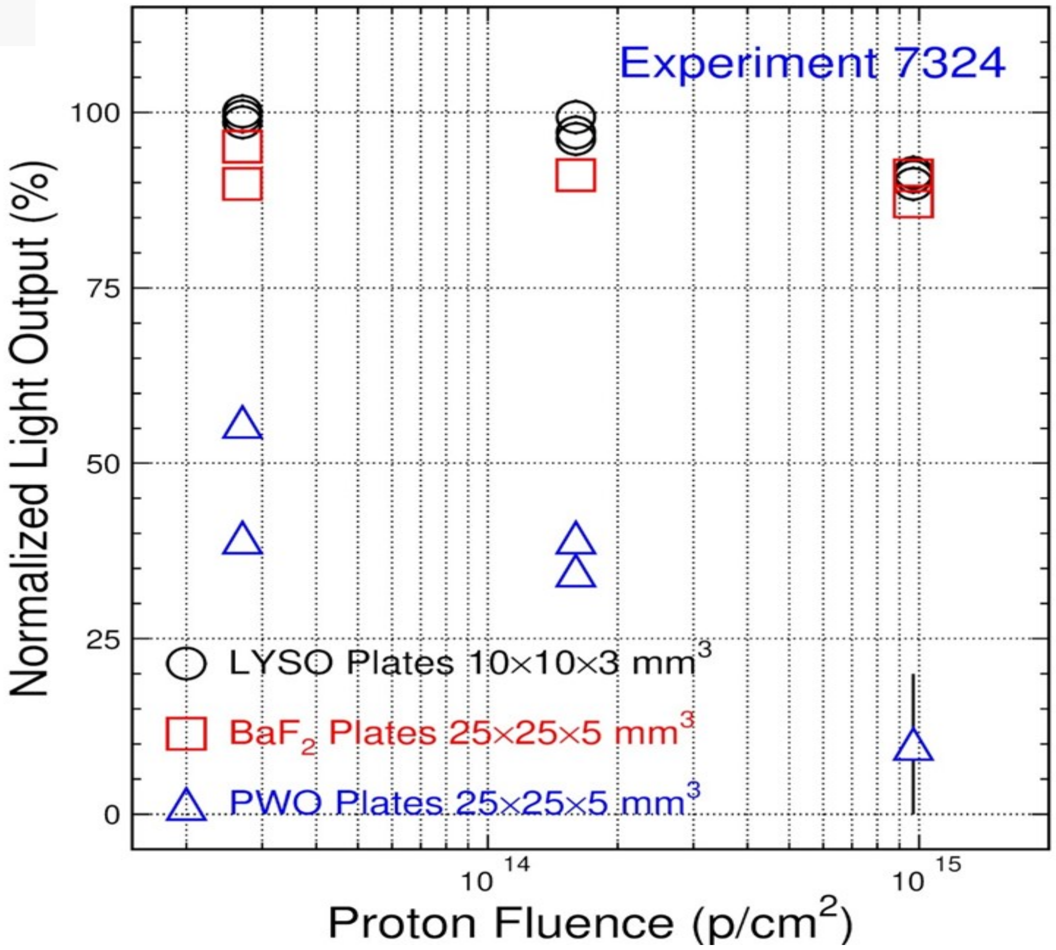
C. Hu et al., IEEE Trans. Nucl. Sci. vol. 65, pp. 1018-1024 (2018)



C. Hu et al., IEEE Trans. Nucl. Sci. vol. 67, pp. 1086-1092 (2020)

Light Output: LYSO:Ce, BaF_2 and PWO

Light output losses: ~10% after 9.7×10^{14} p/cm^2 and ~25% after 8.3×10^{15} n_{eq} /cm^2 for LYSO:Ce and BaF_2 plates of a few mm thick



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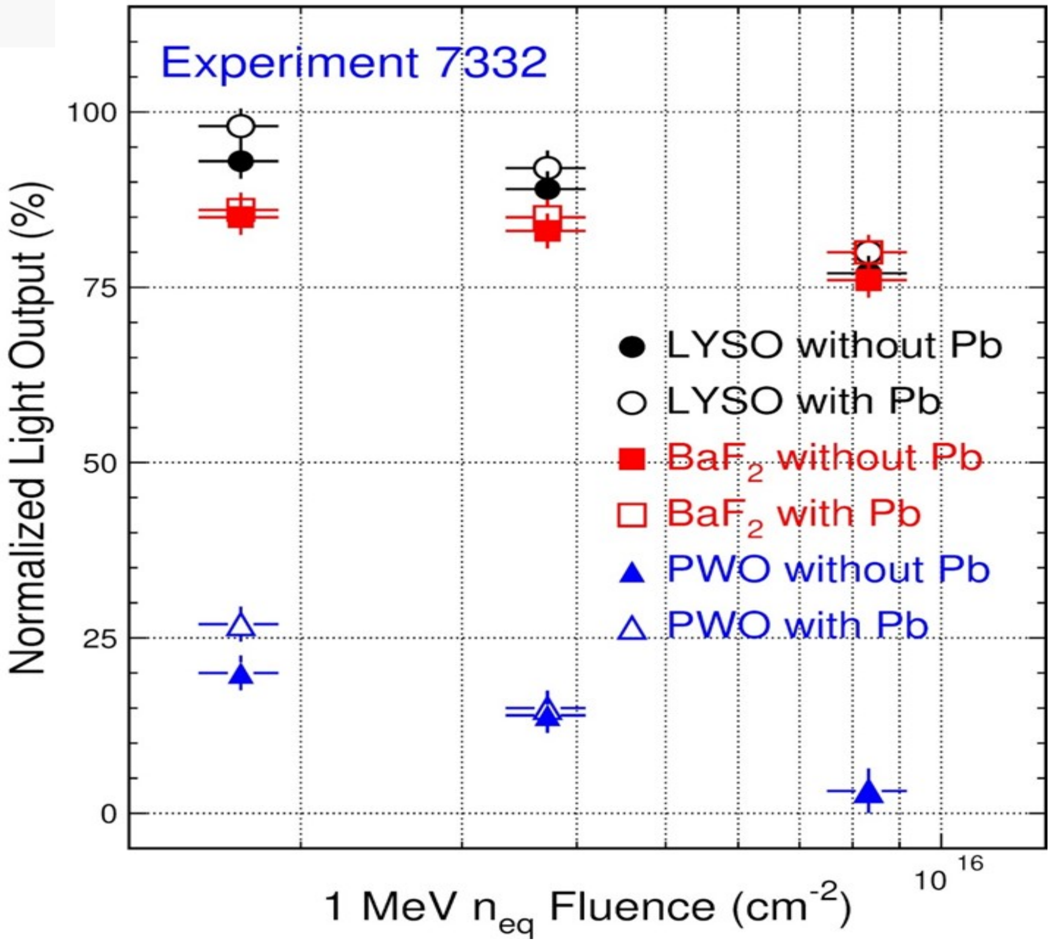
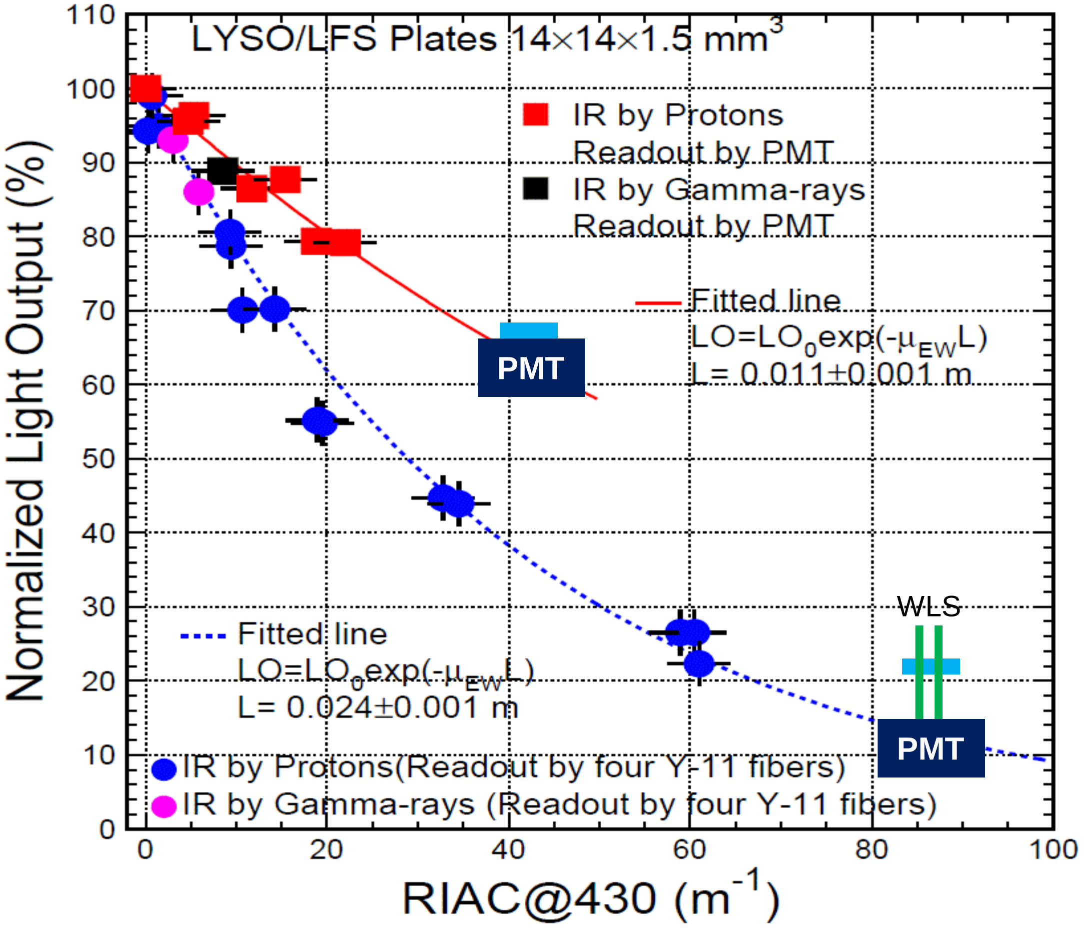
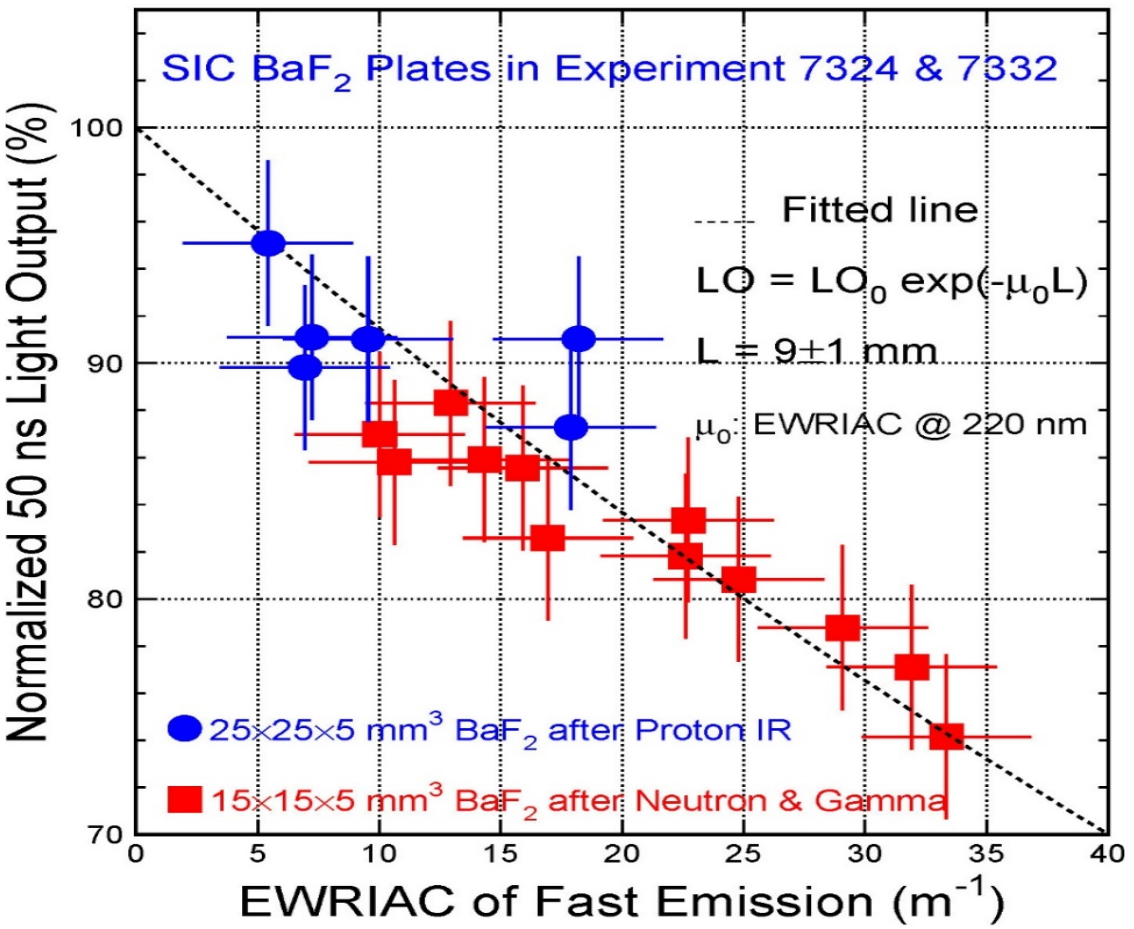


C. Hu et al., IEEE Trans. Nucl. Sci. vol. 67, pp. 1086-1092 (2020)

Light Output vs. RIAC: LYSO:Ce and BaF_2

Light output of LYSO:Ce and BaF_2 crystals irradiated by ɣ-rays, protons and neutrons show consistent relation with the RIAC values, indicating hadron induced damage can be monitored and corrected for by a precision light monitoring system

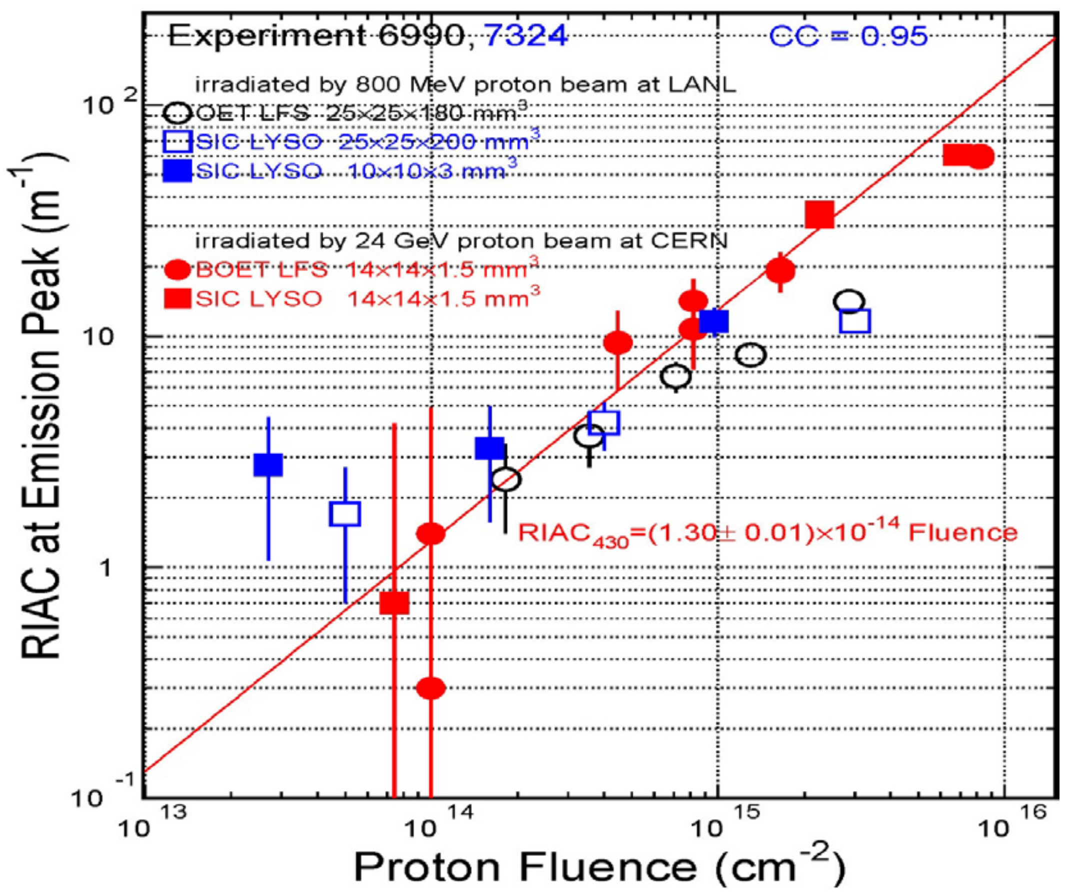


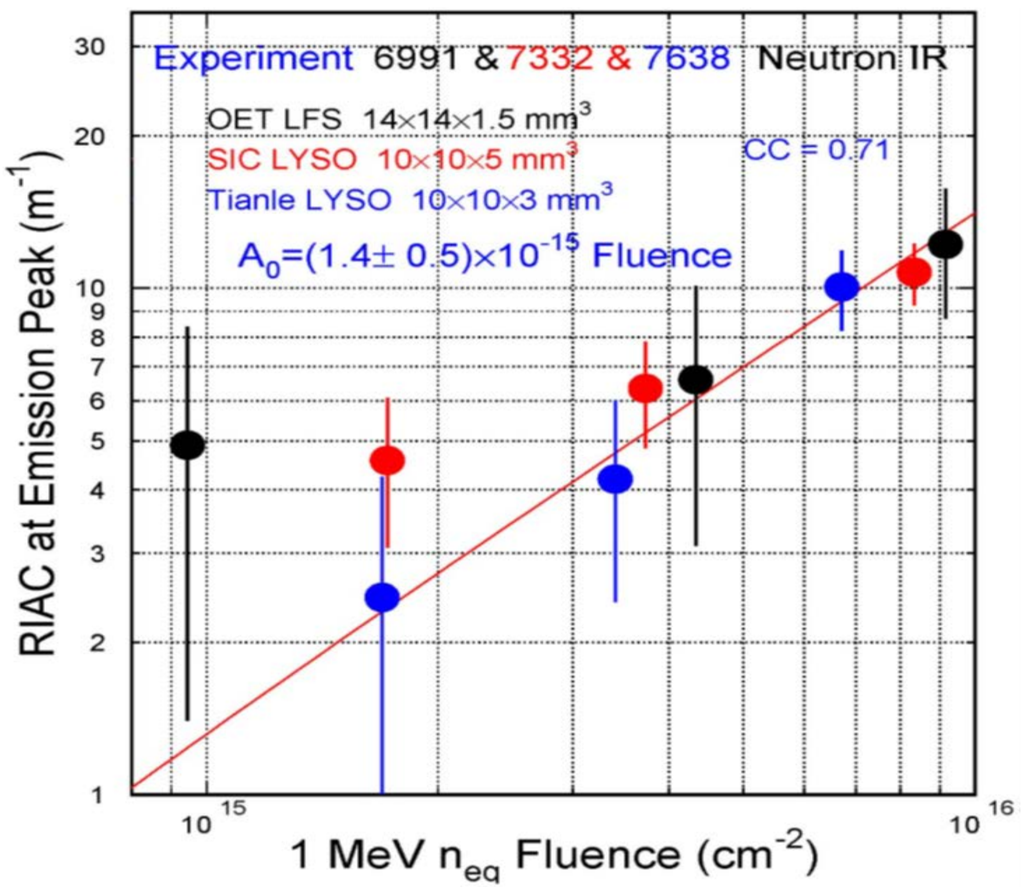


C. Hu et al., IEEE Trans. Nucl. Sci. vol. 65, pp. 1018-1024 (2018)

RIAC as a Function of Fluence for LYSO:Ce

Consistent damage observed for LYSO:Ce after irradiation by 800 MeV and 24 GeV protons
RIAC @ 430 nm = 1.3 x 10^{-14} F_p and 1.4 x 10^{-15} F_{neq}, showing a lower damage by neutrons

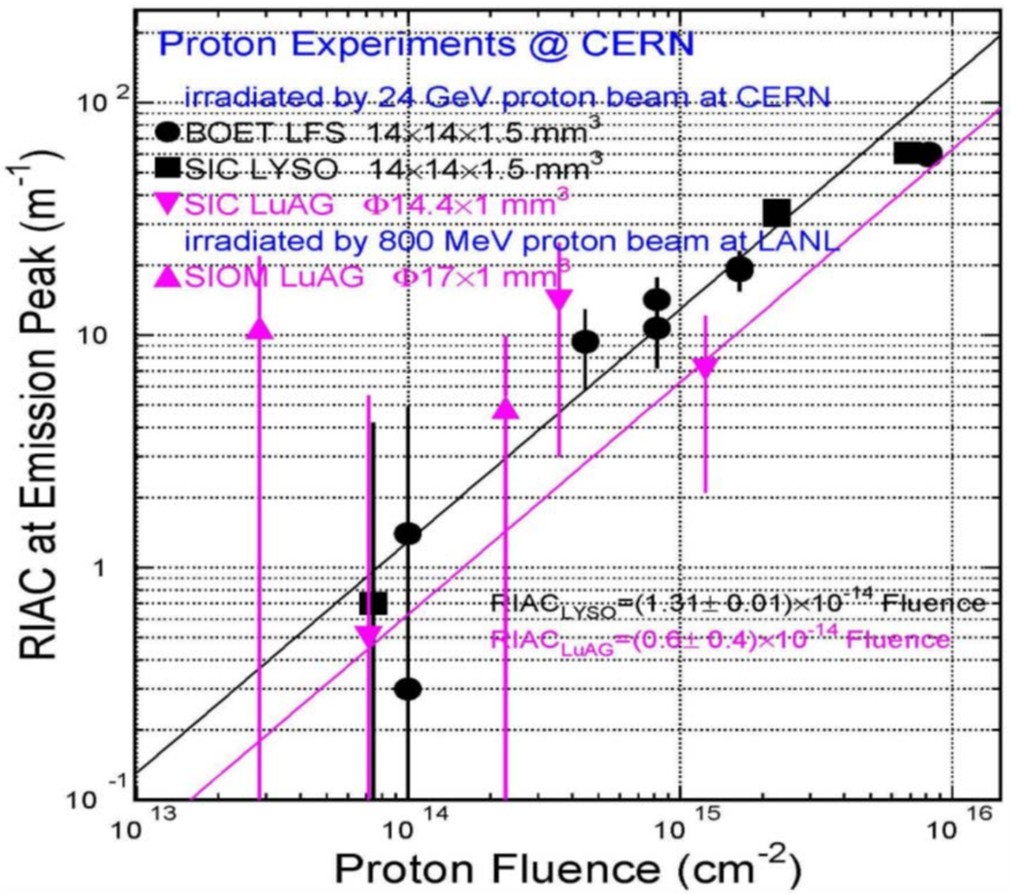


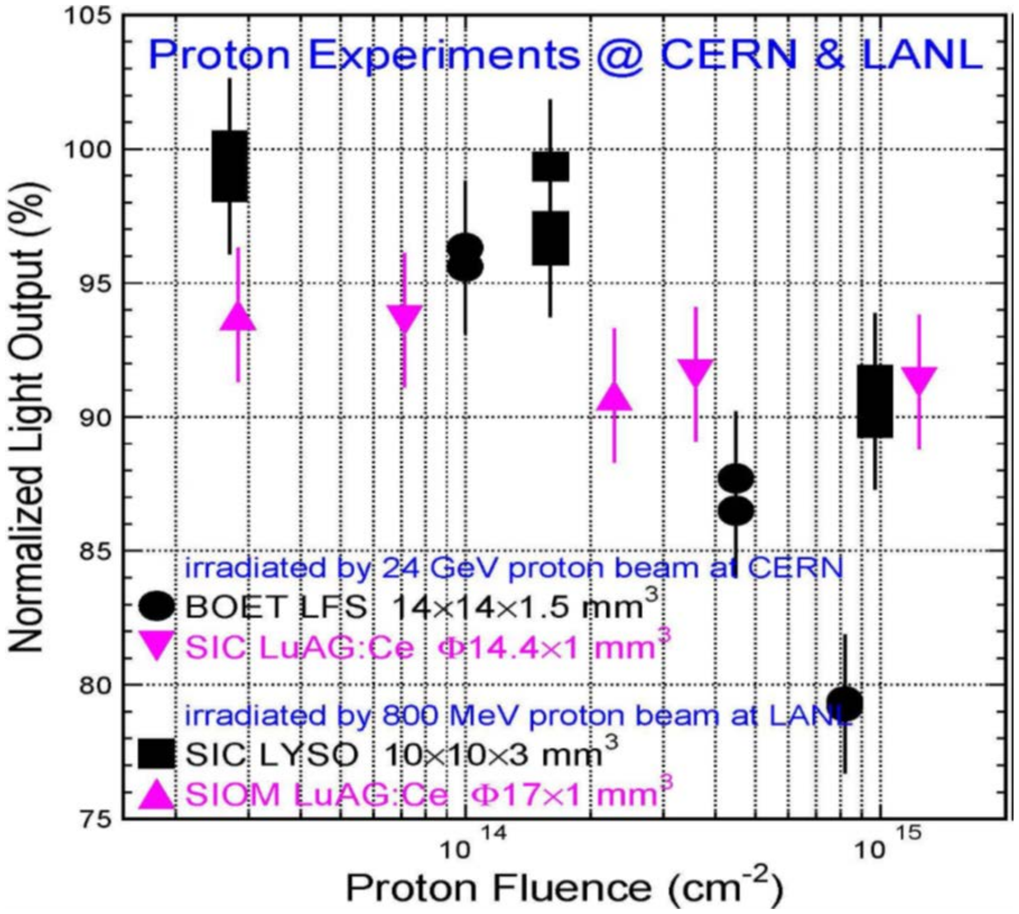


C. Hu, L. Zhang and R.-Y. Zhu, in the Proceedings of TIPP conference (2021)

Proton Damage: LYSO:Ce vs. LuAG:Ce

LuAG:Ce ceramics show about a factor of 2 smaller RIAC than LYSO:Ce crystals
90% light remains in 1 mm thick LuAG:Ce ceramics after 1.2×10^{15} p/cm^2

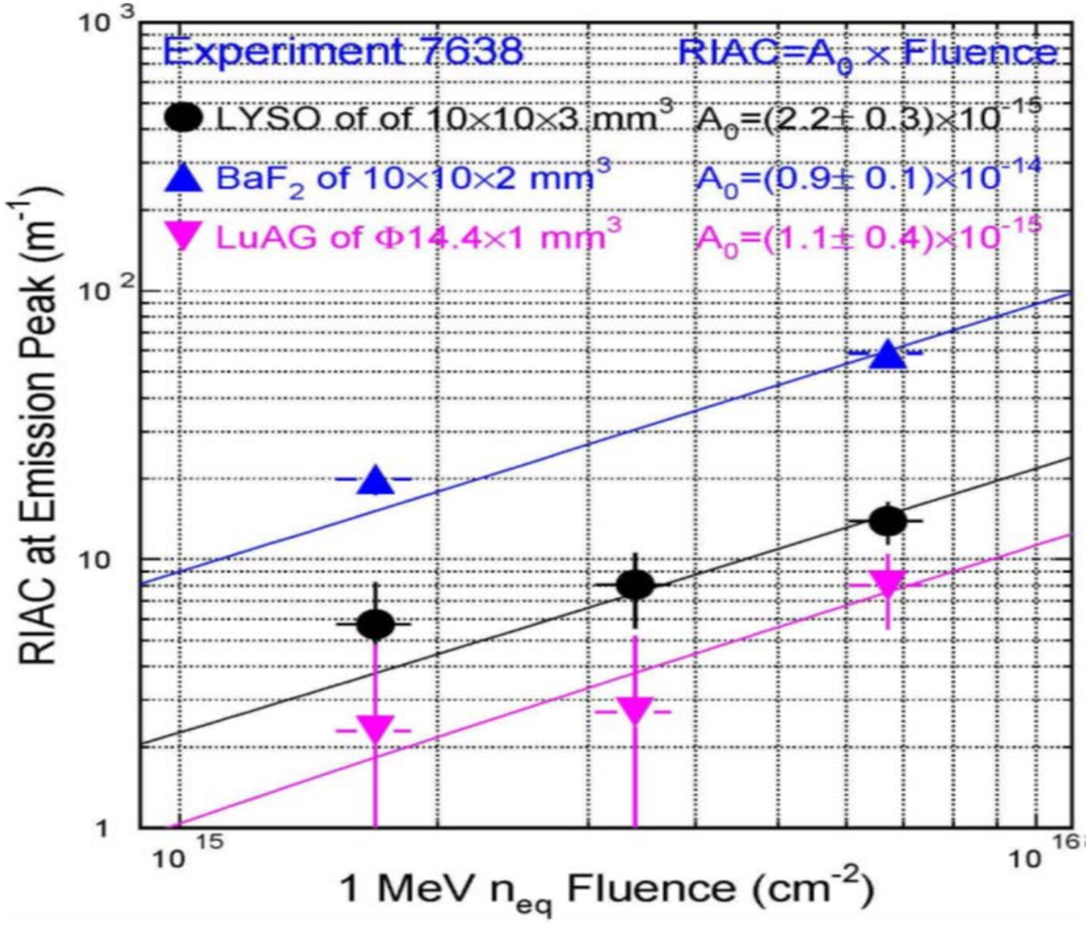


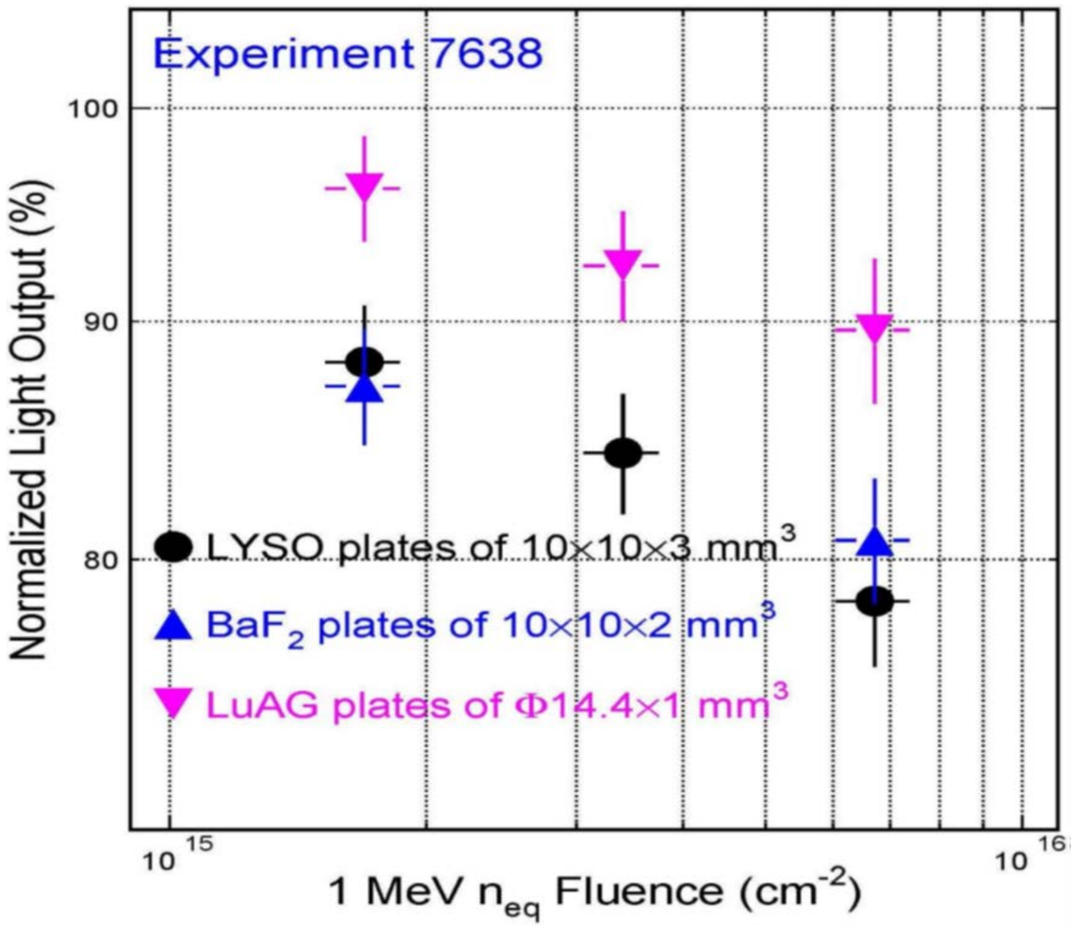


C. Hu et al., IEEE Trans. Nucl. Sci. vol. 69, pp. 181-186 (2022)

Neutron Damage: LYSO:Ce, LuAG:Ce & BaF_2

LuAG:Ce ceramics show ~2 smaller RIAC than LYSO:Ce crystals against neutrons
90% light remains in 1 mm thick LuAG:Ce ceramics after $6.7 \times 10^{15}\ n_{eq}/cm^2$





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Summary

Fast heavy crystal scintillators were irradiated by 800 MeV protons and neutrons at the Blue Room and East Port of LANSCE respectively and by 24 GeV protons at CERN. Damage induced by protons is larger than that from neutrons, presumably due to ionization energy loss, in addition to displacement and nuclear breakup.

LYSO:Ce crystals from different vendors show consistent damage level from protons of 800 MeV and 24 GeV. It is chosen to construct the CMS BTL for the HL-LHC.

LuAG:Ce ceramics show a factor of two smaller RIAC than LYSO:Ce crystals against both neutrons and protons. BaF_2 show similar radiation hardness to LYSO:Ce at high hadron fluence.

Investigations will continue to further improve optical quality, F/T ratio and radiation hardness for LuAG:Ce and BaF_2:Y crystals, and to understand damage in various inorganic crystal scintillators induced by ionization dose, protons and neutrons.

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