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 $5 \times 10^{18}$ 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 $3 \times 10^{15}$ p/cm$^2$ and $8 \times 10^{15}$ 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.

CERN: 24 GeV
LANL: 800 MeV
Davis: 67 MeV
Cf-252: 2.5 MeV

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})

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

Setup of Experiment 7324
Neutron Irradiation in the East Port

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.
MCNPX (Monte Carlo N-Particle eXtended) package was used to calculate the $n/\gamma/p$ 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 $9.7 \times 10^{14}$ p/cm$^2$ and $8.3 \times 10^{15}$ neq/cm$^2$ for LYSO:Ce, BaF$_2$ and PWO, showing good radiation hardness of LYSO:Ce and BaF$_2$.

\[ E_{\text{EWLT}} = \int T(\lambda) E_{m}(\lambda) d\lambda \]

\[ R_{\text{IAA}} = \frac{1}{l} \ln \left( \frac{T_0(\lambda)}{T(\lambda)} \right) \]

$l$: Crystal length

$T_0(\lambda)$: T before irradiation

$T(\lambda)$: 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 $9.7 \times 10^{14}$ p/cm$^2$ and $8.3 \times 10^{15}$ 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,
Radiation induced absorption coefficient (RIAC) as a function of fluence for 3 groups of LYSO:Ce, BaF$_2$ and PWO samples after up to $9.7 \times 10^{14}$ p/cm$^2$ and $8.3 \times 10^{15}$ 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: $\sim$10% after $9.7 \times 10^{14}$ p/cm$^2$ and $\sim$25% after $8.3 \times 10^{15}$ n$_{eq}$/cm$^2$ for LYSO:Ce and BaF$_2$ plates of a few mm thick.

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 vs. RIAC: LYSO:Ce and BaF$_2$

Light output of LYSO:Ce and BaF$_2$ crystals irradiated by $\gamma$-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.
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 = $1.3 \times 10^{-14} F_p$ and $1.4 \times 10^{-15} F_{neq}$, showing a lower damage by neutrons.

C. Hu, L. Zhang and R.-Y. Zhu, in the Proceedings of TIPP conference (2021)
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 $1.2 \times 10^{15}$ p/cm$^2$. 

C. Hu et al., IEEE Trans. Nucl. Sci. vol. 69, pp. 181-186 (2022)
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$^2$. 

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