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# Performance of Crystal Scintillators in a Severe Radiation Environment Caused by Protons

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**Abstract.** Future high energy physics experiments at the energy and intensity frontiers will face challenges from a severe radiation environment caused by both ionization dose and charged and neutral hadrons. This paper reports an investigation on proton induced radiation damage in various crystal scintillators. Large size BGO, LFS and PWO crystals of 18 to 22 cm long were irradiated by 800 MeV protons up to  $3 \times 10^{15} p/cm^2$  at the WNR facility of LANSCE with longitudinal transmittance measured *in situ*. LYSO plates of  $14 \times 14 \times 1.5 mm^3$  were irradiated by 24 GeV protons up to  $8.2 \times 10^{15} p/cm^2$  at the IRRAD facility of CERN. Degradations in both transmittance and light output are reported. The results show an excellent radiation hardness of LYSO/LFS crystals against charged hadrons.

## 1. Introduction

Because of their superb energy resolution and detection efficiency, crystal scintillators are widely used in HEP experiments. The CMS lead tungstate ( $PbWO_4$  or PWO) crystal calorimeter, for example, has played an important role in the discovery of the Higgs boson [1]. One crucial issue, however, is its radiation damage in a severe radiation environment, which requires precision monitoring to correct variations of crystal's transparency [2]. The proposed HL-LHC with  $5 \times 10^{34} cm^{-2}s^{-1}$  luminosity and up to  $3,000 fb^{-1}$  integrated luminosity will present an extreme severe radiation environment, where up to  $3 \times 10^{14}$  charged hadrons/cm<sup>2</sup> and  $5 \times 10^{15}$  neutrons/cm<sup>2</sup> in addition to an ionization dose of up to 130 Mrad are expected for forward calorimeters (FCAL) at  $\eta = 3$  [3]. Cerium doped lutetium yttrium oxyorthosilicate ( $Lu_{2(1-x)}Y_{2x}SiO_5:Ce$  or LYSO) [4] and cerium fluoride ( $CeF_3$ ) [5] crystals were proposed to construct a sampling Shashlik calorimeter for the CMS FCAL upgrade for the HL-LHC. The survivability of these crystals is an crucial issue. In this paper, we report proton induced radiation damage in large size BGO, LYSO and PWO crystals measured *in situ* before and immediately after 800 MeV proton irradiation at the Weapons Neutron Research facility of Los Alamos Neutron Science Center (WNR of LANSCE). Results of thin LYSO plates of  $14 \times 14 \times 1.5 mm^3$  irradiated by 24 GeV protons at CERN are also reported.

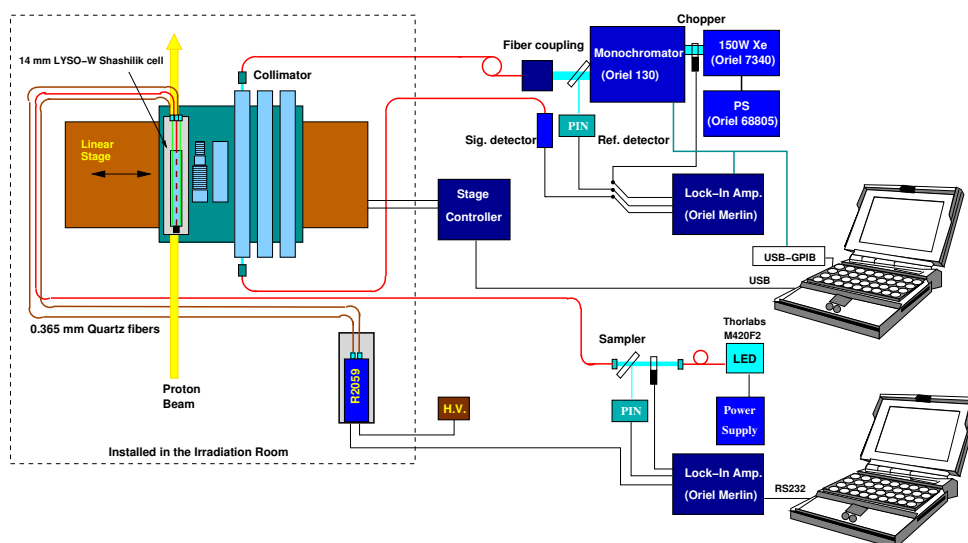


**Table 1.** Samples Irradiated at the WNR Facility of LANSCE by 800 MeV Protons

Position	Samples	Dimensions (mm <sup>3</sup> )	<i>in-situ</i> Measurement	Fluence (p/cm <sup>2</sup> )
1	Shashlik cell	34×34×215	420 nm LED, Al	1.24×10 <sup>15</sup>
2	BaF <sub>2</sub>	30×30×20	Al foil activation	2.94×10 <sup>14</sup>
2	LuAG ceramic	25×25×0.4	Al foil activation	2.94×10 <sup>14</sup>
2	10 PWOs	25×25×10	Al foil activation	2.94×10 <sup>14</sup>
2	BGO	17×17×17	Al foil activation	2.94×10 <sup>14</sup>
2	20 LFS plates	14×14×1.5	Al foil activation	2.94×10 <sup>14</sup>
3	2 Capillaries, 2 Y11s	ϕ1×200	Al foil activation	3.05×10 <sup>15</sup>
4	PWO	28.5 <sup>2</sup> ×30 <sup>2</sup> ×220	LT (350-700 nm)	1.80×10 <sup>14</sup>
5	LFS	25×25×180	LT (350-700 nm)	2.87×10 <sup>15</sup>
6	BGO	25×25×200	LT (350-700 nm)	1.77×10 <sup>14</sup>

## 2. Samples and experiment

Table 1 lists the samples loaded at six positions on a remotely controlled linear stage with a travel distance of 1 m at the WNR facility of LANSCE. The 800 MeV proton beam has a Gaussian shape with a FWHM of about 2.5 cm. Because of the 20 cm spacing between the samples multiple scattering effect to neighboring crystal is negligible. Optical and scintillation properties of the crystal samples were measured before irradiation at Caltech and again after samples are returned to Caltech after cooled down. The fluence listed in the table is calculated by using beam current data provided by LANSCE, and is cross-checked with the activation data measured by Al foils.

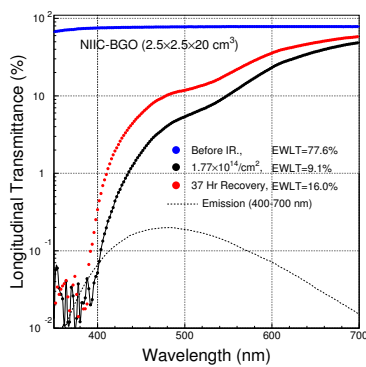


**Figure 1.** A schematic showing the experimental setup used to measure crystal longitudinal transmittance *in situ* at WNR of LANSCE.

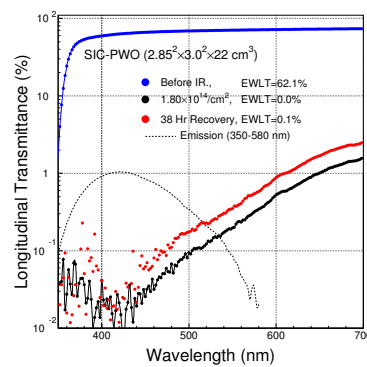
Fig. 1 shows an optical fiber based spectrophotometer used to measured longitudinal transmittance (LT) for long crystal samples *in situ* before, during and after irradiation. It uses a lock-in amplifier to mitigate the noise caused by phosphorescence in crystals after irradiation. To avoid multiple Coulomb scattering and shower leakage in long crystals, LYSO and LFS plates of  $14 \times 14 \times 1.5 \text{ mm}^3$  were also irradiated by 24 GeV protons at the IRRAD facility of CERN up to  $8.2 \times 10^{15} \text{ p/cm}^2$ . Transmittance was measured at Caltech by using PerkinElmer Lambda 950 spectrophotometer with 0.15% precision. The corresponding precision for the radiation induced absorption coefficient (RIAC) is about  $3.5 \text{ m}^{-1}$  for 1.5 mm thick LYSO plates. Light output was measured as the intensity of photoluminescence excited by a 365 nm LED for LYSO and LFS plates before and after irradiation with a systematic uncertainty of about 1.5%, where the sample was surrounded by a Teflon box and read out by four Y-11 wavelength shifting (WLS) fibers. Similarly, a lock-in amplifier was used to mitigate the residual phosphorescence.

### 3. Results and discussions

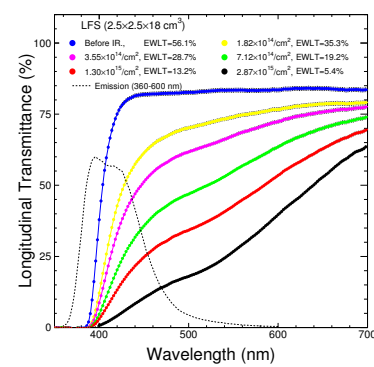
Fig. 2 and 3 show the LT spectra measured *in situ* before and after  $1.8 \times 10^{14} \text{ p/cm}^2$  irradiation for the BGO and PWO samples respectively. The BGO and PWO samples are completely black below 400 and 450 nm respectively. Recovery of radiation damage was observed in both BGO and PWO with the RIAC values at 480 and 450 nm recovered from 15 and 36 to 10 and 32  $\text{m}^{-1}$  in 37 and 38 h respectively. LYSO was found radiation hard against proton irradiation in the 2014 test [6]. Fig. 4 shows the LT spectra measured for the LFS sample up to  $2.9 \times 10^{15} \text{ p/cm}^2$  in five steps with RIAC values at 430 nm of 3.7 and 14.1  $\text{m}^{-1}$  after  $3.6 \times 10^{14}$  and  $2.9 \times 10^{15} \text{ p/cm}^2$  respectively, confirming excellent radiation hardness.



**Figure 2.** LT of NIIC-BGO before and after  $1.8 \times 10^{14} \text{ p/cm}^2$ , as well as after 37 hours recovery.

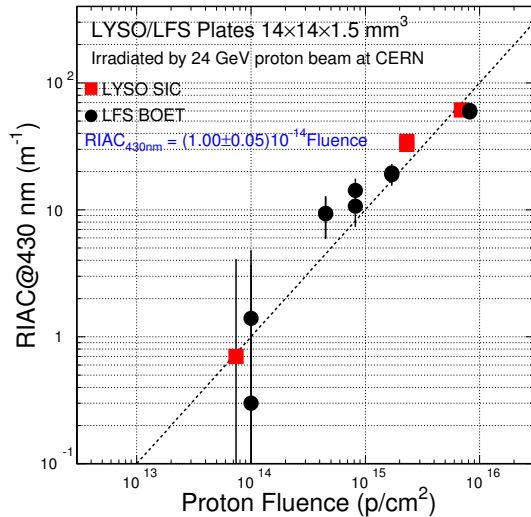


**Figure 3.** LT of SIC-PWO before and after  $1.8 \times 10^{14} \text{ p/cm}^2$ , as well as after 38 hours recovery.

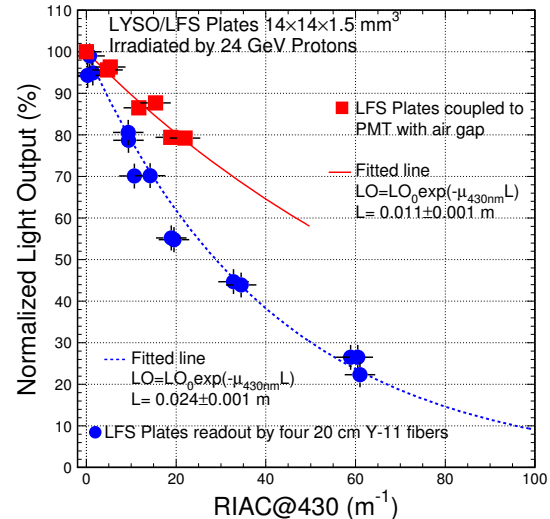


**Figure 4.** LT of LFS before and after the irradiation in five steps, 0.18, 0.36, 0.71, 1.3 and  $2.9 \times 10^{15} \text{ p/cm}^2$ .

Consistent RIAC values at 430 nm are observed in LYSO and LFS plates irradiated by 24 GeV protons up to  $8.2 \times 10^{15} \text{ p/cm}^2$  at CERN in 2014 and 2015 as shown in Fig. 5, indicating an excellent radiation hardness of these crystals against charged hadrons. Fig. 6 shows the normalized light output (LO) of the LYSO/LFS plates measured with four Y11 WLS fibers as a function of the RIAC values at 430 nm. The exponential fit for the LO versus the RIAC values at 430 nm indicates an average of 2.4 cm path length, consistent with what observed under  $\gamma$ -ray irradiation [7]. A LO loss of about 6% was observed for LYSO/LFS plates with WLS readout after  $3 \times 10^{14} \text{ p/cm}^2$  irradiation.



**Figure 5.** RIAC values at 430 nm are shown as a function of 24 GeV proton fluence for LYSO/LFS plates of  $14 \times 14 \times 1.5 \text{ mm}^3$ .



**Figure 6.** LO of LYSO/LFS plates of  $14 \times 14 \times 1.5 \text{ mm}^3$  is shown as a function of the RIAC values at 430 nm.

#### 4. Summary

A 20 cm long BGO crystal, a 18 cm long LFS crystal and a 22 cm long PWO crystal were irradiated by 800 MeV protons at LANSCE up to  $1.8$ ,  $1.8$  and  $29 \times 10^{14} \text{ p/cm}^2$  respectively with crystal's longitudinal transmittance measured *in situ*. After  $1.8 \times 10^{14} \text{ p/cm}^2$ , PWO became completely dark at its emission peak 420 nm, BGO and LFS showed RIAC values of 14.7 and  $2.4 \text{ m}^{-1}$  respectively at their emission peak of 480 and 430 nm. After  $2.9 \times 10^{15} \text{ p/cm}^2$ , the long LFS sample showed a RIAC value of  $14 \text{ m}^{-1}$  at 430 nm. LYSO and LFS plates of  $14 \times 14 \times 1.5 \text{ mm}^3$  show consistent RIAC values at 430 nm after proton irradiation with a loss of light output about 6% after  $3 \times 10^{14} \text{ p/cm}^2$  with Y-11 readout. These results provide important information for understanding charged hadron induced radiation damage in fast crystal scintillators and their use in future HEP experiments at the energy and intensity frontiers.

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