Proton-Induced Radiation Damage in BGO, LFS, PWO and a LFS/W/Quartz Capillary Shashlik Cell

Fan Yang, *Member, IEEE*, Liyuan Zhang, *Member, IEEE*, Ren-Yuan Zhu, *Senior Member, IEEE,*
Jon Kapustinsky, *Senior Member, IEEE*, Ron Nelson and Zhehui Wang, *Member, IEEE*

Abstract– **Future high energy physics experiments at the energy and intensity frontiers will face challenges of a severe radiation environment from both ionization dose and charged and neutral hadrons. In this paper, we report an investigation on charged hadron-induced radiation damage in BGO, LYSO/LFS, PWO and a LYSO/W/Capillary shashlik cell by using 800 MeV and 24 GeV protons at LANL and CERN respectively. Degradations in both transmittance and light output are reported. The results show excellent radiation resistance of LYSO/LFS crystals and the LFS/W/Capillary shashlik cell against charged hadrons.**

I. INTRODUCTION

CRYSTAL scintillators are widely used in HEP experiments because of their superb performances. 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 is their radiation damage in a severe radiation environment, which requires precision monitoring to correct variations of crystal's transparency [2]. During the two years of the 1st run, for example, up to 70% loss of light output in CMS PWO crystals at large rapidity was observed *in situ* at the LHC when the experiment was running at a luminosity of 5×10^{33} $cm^{-2}s^{-1}$ and a half of its designed energy [3]. The HL-LHC with 5×10^{34} $cm^{-2}s^{-1}$ luminosity and 3,000 fb^{-1} integrated luminosity presents an extreme severe radiation environment, where up to 3×10^{14} charged hadrons/cm^2 and 5×10^{15} neutrons/cm^2 are expected in addition to up to 130 Mrad ionization dose [4]. A crucial issue for these crystal based detector concepts is crystal's survivability in the expected radiation environment.

Proton-induced radiation damage was investigated for LYSO CeF_3 and PWO [5-11]. In this paper, we report proton-induced radiation damage in BGO, LFS, PWO crystals and a LFS/W/quartz capillary shashlik cell measured *in situ* and immediately after radiation by 800 MeV proton beam at LANL. Results of thin LFS plates irradiated by 24 GeV protons at CERN are also reported.

II. SAMPLES AND EXPERIMENT

Table I lists the dimension of three long BGO, LFS and PWO crystals and a LFS/W/quartz capillary shashlik cell. Also listed in the table is the fluence of 800 MeV protons went through each sample at the Weapons Neutron Research facility of Los Alamos Neutron Science Center (LANSCE).

TABLE I
SAMPLES LOADED ON THE LINEAR STAGE AND THE PROTON FLUENCE

Sample	Dimension (cm^3)	Fluence (p/cm^2)
BGO	$2.5 \times 2.5 \times 20$	1.77×10^{14}
LFS	$2.5 \times 2.5 \times 18$	2.87×10^{15}
PWO	$2.85^2\times3^2\times22$	1.80×10^{14}
Shashlik Cell	$3.4 \times 3.4 \times 21.5$	1.20×10^{15}

All samples were loaded on a linear stage with a travel distance of 1 m, as shown in Fig. 1. The stage moved each individual sample into the proton beam via a remote control. The 800 MeV proton beam has a Gaussian shape with a FWHM of about 2.5 cm and was aligned at the center of each sample. Because of the large distance between the samples multiple scattering effect to neighboring crystal was negligible.

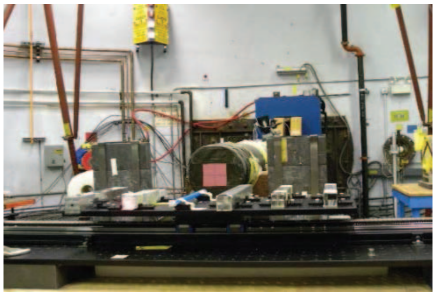

Fig. 1 A photo showing the samples loaded in a linear stage in the blue room at Los Alamos.

Fig. 2 shows an optical fiber and a lock-in amplifier based spectrophotometer used to measure longitudinal transmittance *in situ* before, during and after irradiation for three long crystals. A part of the chopped light from a 150 W Xe lamp through a monochromator was monitored by a reference photodiode (Thorlabs DET10A). The main part of the light was injected into the crystal sample via a ϕ0.365 mm quartz fiber and through two collimators at the front and back of the crystal, and was measured by a signal photodiode (Oriel 70336). The lock-in amplifier (Oriel Merlin) measured the ratio between the signal and reference photodetectors. The precision and stability of this ratio is better than 1%, and is free from both the radiation-induced phosphorescence background in the sample and the fluctuations of the light intensity.

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F. Yang, L. Zhang and R.-Y. Zhu are with the California Institute of Technology, Pasadena, CA 91125, USA (e-mail: zhu@hep.caltech.edu).

J. Kapustinsky, R. Nelson and Z. Wang are with the Los Alamos National Laboratory, Los Alamos, NM 87545, USA.

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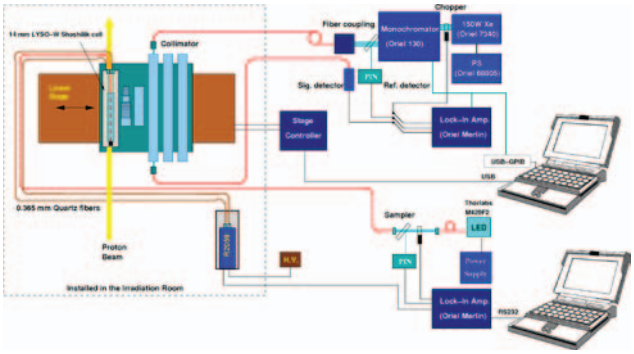

Fig. 2 A schematic showing the setup used to measure crystal’s longitudinal transmittance *in situ* at LANL.

To avoid the hadronic shower leakage effect in long crystals, LFS plates of $14\times14\times1.5$ mm^3 were also irradiated by 24 GeV proton beam with a FWHM of 12 mm up to 8.19×10^{15} p/cm^2 at CERN. Table II lists the proton fluence went through these samples.

TABLE II
PROTON IRRADIATION OF LFS PLATES AT CERN

ID	Protons (GeV)	Irradiation Set	Fluence (p/cm^2)	Error (+/- %)
BOET-6	24	2045	9.97×10^{14}	7.0
BOET-7	24	2045	9.97×10^{14}	7.0
BOET-8	24	2046	4.48×10^{14}	8.4
BOET-9	24	2046	4.48×10^{14}	8.4
BOET-10	24	2047	8.21×10^{14}	7.6
BOET-11	24	2047	8.21×10^{14}	7.6
BOET-12	24	2048	1.65×10^{15}	7.5
BOET-13	24	2048	1.65×10^{15}	7.5
BOET-14	24	2049	8.19×10^{15}	7.3
BOET-15	24	2049	8.19×10^{15}	7.3

All samples were measured at Caltech before and about 200 days after irradiation. Transmittance was measured by a Hitachi U-3210 UV/visible spectrophotometer with 0.15% precision. The corresponding precision for the radiation-induced absorption coefficient (RIAC) is 0.03 and 3.5 m^{-1} respectively for 20 cm and 1.5 mm light path length. The RIAC represent radiation damage in crystal’s transparency, and is defined as:

$$RIAC = \frac{1}{l} ln \frac{T_0(\lambda)}{T(\lambda)} \qquad (1)$$

where T_0 and T are the transmittance along crystal length l measured before and after irradiation respectively.

III. PROTON-INDUCED RADIATION DAMAGE IN CRYSTALS

Fig. 3 shows the longitudinal transmittance spectra for the 20 cm long BGO crystal measured before, after 1.77×10^{14} p/cm^2 irradiation and after recovery of 37 hours and 130 days. This 20 cm BGO sample is completely black below 400 nm after 1.77×10^{14} p/cm^2 with a flux of about 3.1×10^{14} p/cm^2/hr, but has significant recovery after 37 hours. Also listed in Fig. 3 are the RIAC values at BGO emission peak 480 nm. It was 14.7 m^{-1} after a 1.77×10^{14} p/cm^2, and was recovered to 10.1 m^{-1} after 37 hours, showing significant recovery.

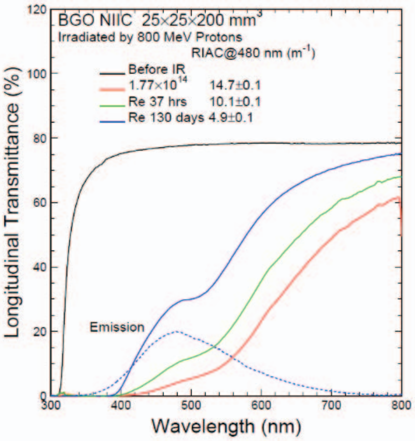

Fig. 3. Longitudinal transmittance spectra measured before and after proton irradiation and during recovery for the BGO crystal.

Fig. 4 shows the longitudinal transmittance spectra for the 18 cm long LFS crystal before and after 1.82, 3.55, 7.12, 13.0 and 28.7×10^{14} p/cm^2. The corresponding RIAC values at 430 nm are 3.7 and 14.1 m^{-1} after 3.55×10^{14} and 2.87×10^{15} p/cm^2 respectively, confirming excellent radiation hardness of LYSO crystals against charged hadrons [11]. Recovery is also observed in this LFS crystal, where the RIAC value at 430 nm is 5.7 m^{-1} after 130 days.

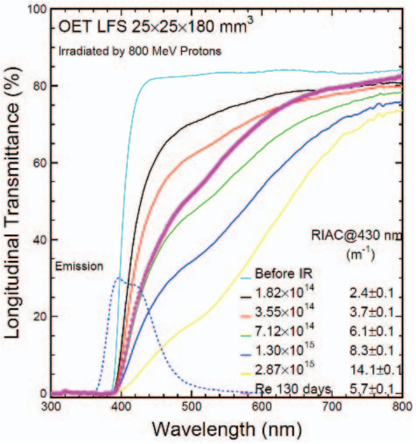

Fig.4 Longitudinal transmittance spectra measured before and after five irradiation steps followed by recovery of 130 days are shown for LFS.

Fig. 5 shows the longitudinal transmittance spectra measured for the PWO crystal before, after 1.80×10^{14} p/cm^2 and after recovery of 38 hours. This 20 cm PWO crystal is complete black below 440 nm after 1.80×10^{14} p/cm^2 with a flux of about 3.1×10^{14} p/cm^2/hr.

Fig. 6 shows the RIAC spectra for PWO, showing that the RIAC values at 450 nm was 35.7 m^{-1} after a 1.8×10^{14} p/cm^2, and was recovered to 31.7 m^{-1} after 38 hours.

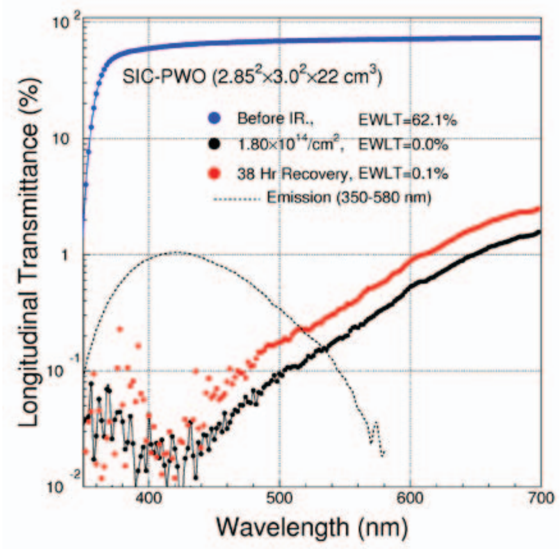

Fig.5 The longitudinal transmittance spectra measured after irradiation for the PWO crystal

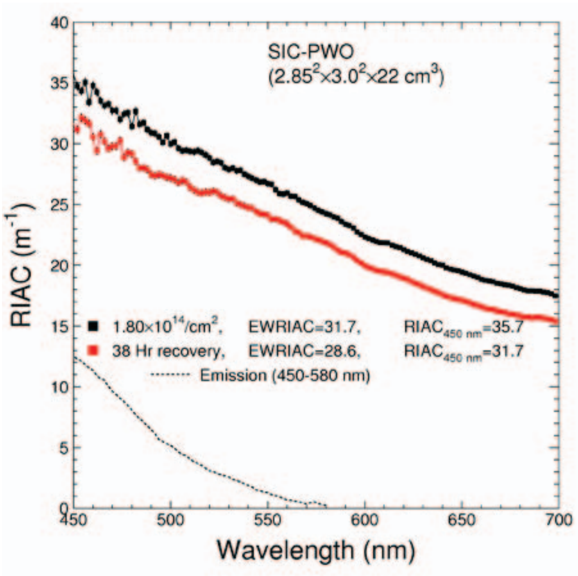

Fig. 6. The RIAC spectra after proton irradiation and the recovery for PWO crystal

III. PROTON-INDUCED RADIATION DAMAGE IN SHASHLIK CELL

An LYSO/W shashlik cell consisting of 30 LFS plates of 14×14×1.5 mm³ and 29 tungsten plates of 14×14×2.5 mm³ interleaved with 15 µm thick Al foils was constructed [12]. Al foils is chosen as the reflective layer for LFS plates because of its excellent radiation hardness. The scintillation light in LFS plates was wavelength shifted and transported through four capillaries of 1 mm diameter. To allow the capillaries through the cell, four holes of 1.3 mm diameter were drilled through the LYSO and W plates at four positions with distances of 3.5 mm to the edges of the plate. An additional hole of 0.9 mm diameter was drilled at the center of the LFS and W plate to introduce a leaky quartz fiber through which monitoring light was injected into the shashlik cell.

Fig.7 shows responses of the LFS/W/quartz capillary shashlik cell measured *in situ* after irradiation up to 1.24×10¹⁵ p/cm² in three steps. The degradation of monitoring signal is 6, 20 and 50% after 1.8×10¹⁴, 4.3×10¹⁴ and 1.24×10¹⁵ p/cm², indicating that the proposed LYSO and quartz capillary based shashlik calorimeter is radiation hard against charged hadrons.

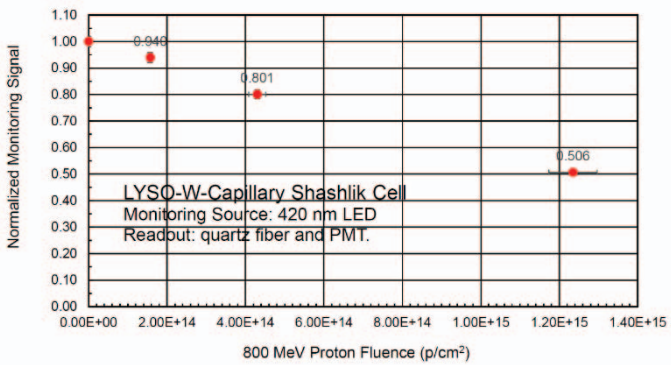

Fig. 7 Monitoring responses are shown as a function of proton fluence for a LFS/W/quartz capillary shashlik cell.

IV. PROTON-INDUCED RADIATION DAMAGE IN LFS PLATES

Ten 14×14×1.5 mm³ LFS plates were irradiated by 24 GeV protons at the CERN IRRAD proton facility. The plates were divided into five groups. Each group has two plates and was irradiated to the same fluence at the same time as shown in Table II. Consistent damages are observed in each pairs of the LFS samples. The average RIAC values at 430 nm are 0.9, 9.4, 12.5, 19.2 and 59.7 m⁻¹ respectively after 9.97×10¹³, 4.48×10¹⁴, 8.21×10¹⁴, 1.65×10¹⁵ and 8.19×10¹⁵ p/cm² of 24 GeV protons. Fig.8 shows the RIAC values at 430 nm as a function of proton fluence for the LYSO and LFS plates irradiated before [11] and this time, respectively. Damages caused by protons in LYSO and LFS plates are consistent. A linear fit to the RIAC values at 430 nm as a function of fluence shows 3 m⁻¹ for 14×14×1.5 mm plates after 3×10¹⁴ p/cm², which is in an excellent agreement with the 20 cm LFS crystals irradiated by 800 MeV protons at Los Alamos.

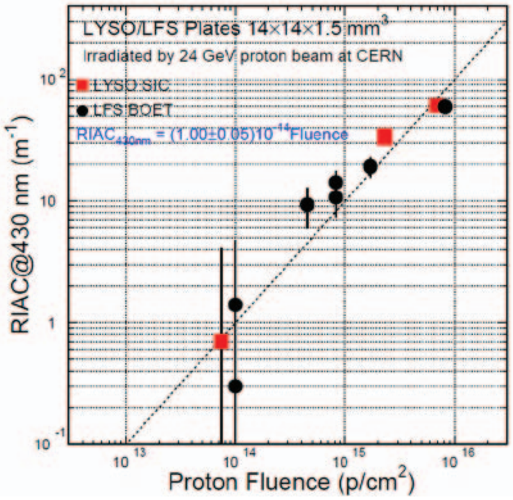

Fig. 8. RIAC values at 430 nm are shown as a function of proton fluence

Fig. 9 shows light output of LYSO/LFS plates measured by direct coupling to PMT (red and black squares) and through four Y-11 WLS fibers (blue and pink dots) as a function of the RIAC values at 430 nm. The data comes from the LYSO/LFS plates irradiated by proton (red and blue) and γ-rays (black and pink). It is interesting to note that damage caused by protons and γ-rays are consistent in LYSO/LFS plates. Also shown in Fig. 9 are exponential fits, which extract average optical path length of 2.4 and 1.1 cm for these two approaches of light output measurements, respectively.

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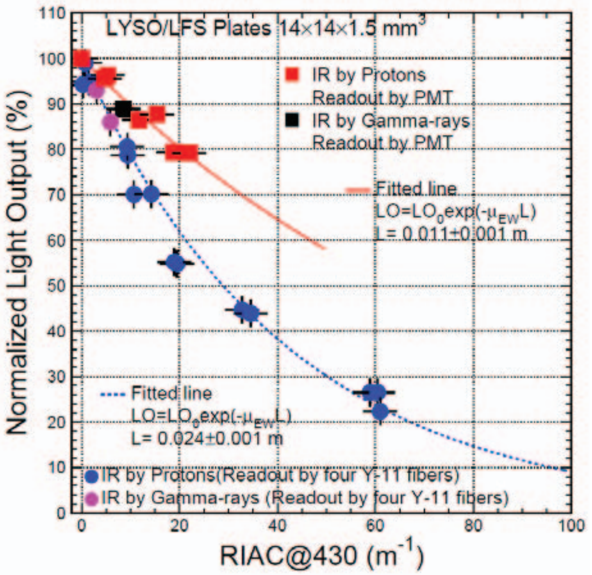

Fig. 9 Normalized light output readout by directly coupling to PMT (red and black squares) and through four Y-11 WLS fibers (blue and pink dots) are shown as a function of the RIAC values at 430 nm for LYSO/LFS plates.

V. SUMMARY

Long BGO, LFS and PWO crystals were irradiated by 800 MeV protons at LANL up to 1.77×10^{14}, 2.87×10^{15}, 1.80×10^{14} p/cm^2 respectively, with crystal's longitudinal transmittance measured *in situ*. Radiation-induced absorption measured immediately after 1.8×10^{14} p/cm^2 is 14.7 and 31.7 m^{-1} respectively for BGO and PWO around their emission peak, indicating poor radiation hardness of these samples against protons. The radiation-induced absorption are 3.7 and 14.1 m^{-1} after 3.55×10^{14} and 2.87×10^{15} p/cm^2 respectively in the 18 cm long LFS crystal, confirming excellent radiation hardness of LYSO crystals against charged hadrons.

A LYSO/W/Capillary Shashlik cell was irradiated to 1.24×10^{15} p/cm^2 in 3 steps. The degradation of monitoring signal is 6%, 20% and 50% after 1.8×10^{14}, 4.3×10^{14} and 1.24×10^{15} p/cm^2, indicating that the proposed LYSO and quartz capillary based Shashlik calorimeter is radiation hard against charged hadrons.

Ten 14×14×1.5 mm^3 LFS plates were irradiated by 24 GeV protons at CERN up to 8.19×10^{15} p/cm^2. Damages caused by protons in LYSO and LFS plates are also consistent. A linear fit to the RIAC values at 430 nm as a function of fluence shows 3 m^{-1} for 14×14×1.5 mm^3 plates after 3×10^{14} p/cm^2, which is in a good agreement with that of the long LFS sample. It is also interesting to note that damage caused by protons and γ-rays are consistent in LYSO/LFS plates.

The result of these experiments provide important information for understanding proton induced radiation damage in fast crystal scintillators and their use in future HEP experiments at the energy and intensity frontiers.

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