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Radiation Damage and Recovery Mechanisms of Various Scintillators and Fibers

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***Abstract*— As the intensity frontier in high energy physics increases, new materials, tools, and techniques must be developed in order to accommodate the prolonged exposure of detectors to high amounts of radiation. It has been observed recently that many of the active media of detectors could survive to much lower radiation doses than initially expected. In addition to the challenges introduced by extremely high doses of radiation, there is also a significant lack of in-situ radiation damage recovery systems. In recent studies, we investigated the radiation damage to common plastic scintillators such as polyethylene naphthalate, and polyethylene terephthalate, a custom made elastomer based plastic scintillator, various special glasses and scintillating fibers together with their recovery mechanisms. Here we report on the irradiation studies and the investigation of the recovery mechanisms under various conditions.**

I. Introduction

SCINTILLATORS in particular as part of the calorimeters, are broadly used to generate photons in proportion to the energy loss of the particles traversing them. The readout of the generated light can be either by directly coupled photodetectors or by reading out the wavelength shifting fibers coupled to the scintillators. The entire optical chain, on the other hand, is subject to high level of radiation doses in the collider experiments, and this level will get considerably higher as the collision energies and luminosities of future colliders increase [1].

When plastic scintillators are exposed to radiation, they lose their transmission. This decreases the overall performance in their application, and requires continuous adjustment of calibration factors if at all possible. Some common plastics such as polyethylene naphthalate (PEN) and polyethylene terephthalate (PET) are validated to have much higher radiation tolerance compared to most of the commercial scintillators. In addition, some doped glasses also show optimal performance as scintillators and are relatively radiation hard. However, the mechanism of radiation damage still needs to be studied carefully. In a recent study, it was also validated that the dose rate effects play a critical role in addition to the total dose [2]. Therefore, any future study should involve a careful consideration of the dose rate implemented in the irradiation tests.

In a recent study, our group made elastomer based custom scintillators (ES). The purpose of this study is to obtain control over the entire parameter space of the scintillator and customize its properties with high precision. Combined tests of irradiation and performance measurements in particle beams were performed so far.

The wavelength shifting fibers should also have considerable radiation tolerance if they are used in collider detector experiments. Since they are installed inside the detector bodies in lengths of several hundred meters, the radiation damage and recovery mechanisms of the fibers should be evaluated carefully before installation.

We performed several irradiation and recovery tests on various scintillators and optical fibers. Here we report on the details of the tests and discuss the results.

II. Irradiation Facility and Experimental Setup

The scintillators and optical fiber samples were irradiated by using 6000 Ci ^{137}Cs Gamma source at the University of Iowa RadCore Facility. Figure 1 shows a picture of the irradiation hall.

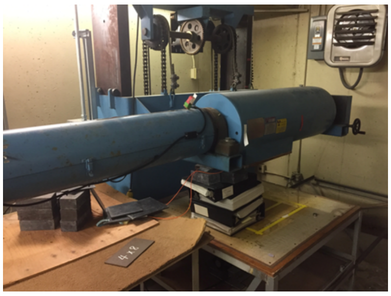

Fig. 1. Picture of the irradiation hall at the University of Iowa RadCore Facility.

We used two acrylic tables that are 8 cm and 18 cm away from the radioactive source, and the dose rate and integrated dose can be calculated and simulated accurately. The samples were prepared and characterized at the High Energy Physics Laboratory of the University of Iowa before and after the irradiation. The equipment used can be summarized as:

- Dark boxes: Light-tight enclosures with cable feedthroughs.
- Xenon light source: A fiber-coupled, broad spectrum light source used in transmission tests.

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- Ocean Optics two channel spectrometer: For the measurement of spectral response between 400 nm and 800 nm.

III. Radiation Damage and Recovery of PEN and PET

PEN and PET are bright and inexpensive intrinsically radiation-hard plastic scintillators [3]. The light yield of PEN was measured as 10,500 photons/MeV making an intrinsic blue scintillation with an emission spectrum peak of 425 nm [4]. PET has an emission spectrum that peaks at 385 nm [5].

We tested samples of PEN and PET using laser stimulated emission on separate tiles exposed to 1.4 Mrad and 14 Mrad gamma rays. PEN exposed to 1.4 Mrad and 14 Mrad emit 71.4 % and 46.7 % of the light of an undamaged tile, respectively, and maximally recover to 85.9 % and 79.5 % after 5 and 9 days, respectively. PET exposed to 1.4 Mrad and 14 Mrad emit 35.0 % and 12.2 % light, respectively, and maximally recover to 93.5 % and 80.0 % after 22 and 60 days, respectively. Figure 2 shows the percent damage after irradiation for PEN (top) and PET (bottom) samples that were irradiated to 1.4 MRad (left) and 14 MRad (right) over the course of approximately two months. The trends were fit to the sum of an exponential and a constant.

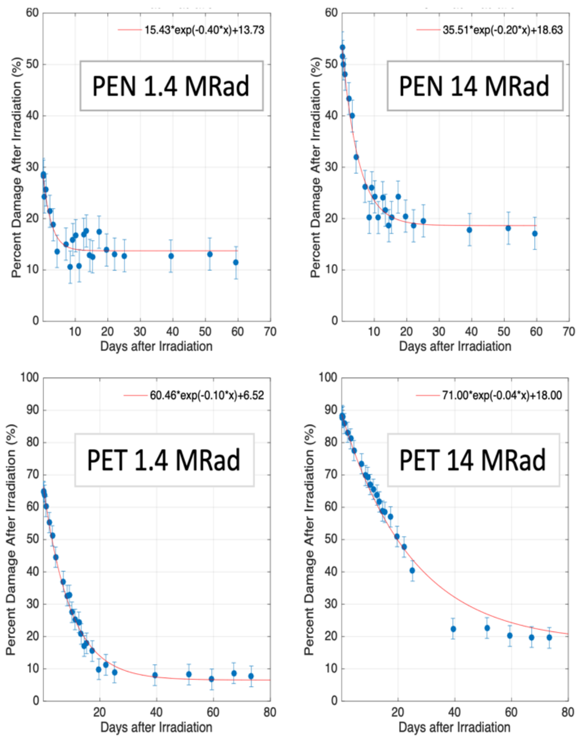

Fig. 2. Percent damage after irradiation for PEN (top) and PET (bottom) samples that were irradiated to 1.4 MRad (left) and 14 MRad (right) for a duration of approximately two months.

IV. Investigation of LED Stimulated Recovery From Radiation Damage

Scintillators have varying natural recovery properties from radiation damage. Various recovery conditions can be taken advantage of for prolonging the useful lifetime of active media. Intermittent maintenance shutdowns of collider experiments occur on the order of days, to years, which can provide sufficient time for the detector to 'cool off' and its scintillator components to recover to some extent. It has further been shown that this natural recovery can be augmented by shining visible and infrared light to the damaged area, improving and extending the lifetime of this particular scintillator [6].

We irradiated various scintillators to investigate their radiation damage and recovery characteristics. One particular sample of each kind was dedicated for LED stimulated recovery tests [7-9].

Four tiles of PEN were cut to 5 cm × 5 cm × 0.1 cm squares. Two tiles of an early version of the new elastomer scintillators composed of p-terphenyl mixed into epoxy, referred to as SiX for Scintillator-X, were prepared as 2.5 cm × 4.5 cm × 1 cm sizes [10]. Two tiles of Eljen brand [11] EJ-260 (EJN) were cut from a single tile to 2 cm × 3 cm × 1 cm sizes, and two tiles of over-doped Eljen brand EJ-260 (EJ2P) were cut from a single tile to 2 cm × 3 cm × 1 cm sizes.

Figure 3 shows the percent damage after irradiation for Scintillator-X (top), EJ-260 (middle) and EJ-260P (bottom) for 40 days following irradiation. SiX showed a significant effect, the sample on RGB LED recovering 10 % more and faster (4.5 vs 5.5 days).

Neither EJN nor EJ2P showed any significant effect from the LEDs, recovering approximately 24 % and 27 %, respectively, both for the RGB LED and dark box samples. The variation in permanent damage between the EJN RGB and EJN dark box tiles is primarily due to the systematic differences in the initial damage. The improvement of EJN recovery in the presence of LED stimulation is compatible with this difference. EJ2P does not exhibit any improvement in recovery when stimulated by RGB LEDs. The results indicate that blue scintillators respond to color spectrum but green scintillators are affected very little.

V. In Situ Measurement of Radiation Damage in Optical Fibers

We used three different optical fibers for both the in-situ measurement of radiation damage and the successive irradiation and recovery tests. Emission of these fibers were centered in blue, green and orange regions of the visible spectrum. The dose rate for the irradiations was kept constant at 22 Gy/min.

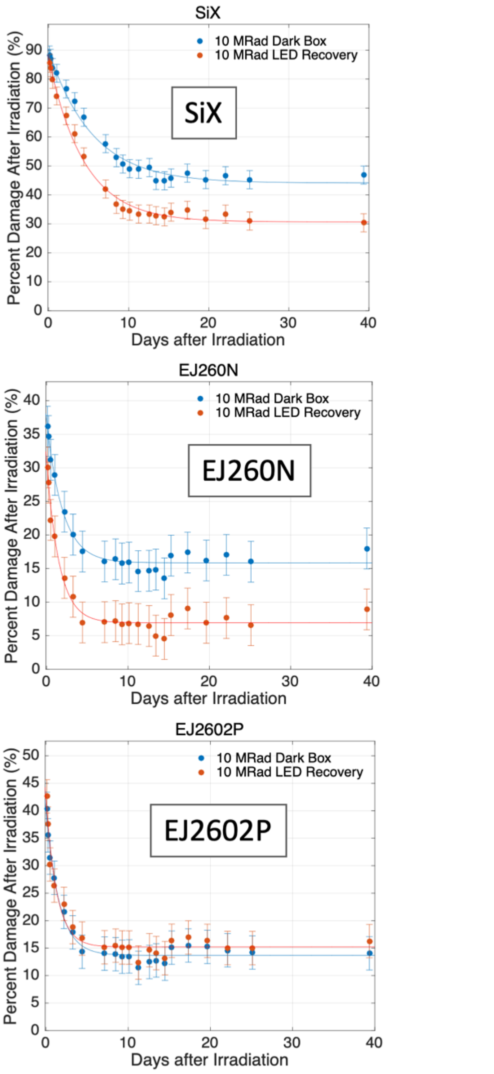

Fig. 3. Percent damage after irradiation for Scintillator-X (top), EJ-260 (middle) and EJ-260P (bottom) for 40 days following irradiation.

Figure 4 shows the transmission spectra of the blue fiber as a function of irradiation duration. The majority of the damage is in the blue region and it manifests itself within minutes of irradiation. The damage in the red-infrared region remains above 50 % for the entire duration of the irradiation and it is dramatic below 520 nm. It is also observed that the transmission peak at 480 nm disappears and a new peak at 540 nm emerges. However, the blue end of this peak gets damaged quite fast to yield less than 5 % transmission after approximately 10 hours of irradiation. There are also spectral regions with slightly less pronounced damage compared to their spectral neighborhood, around 600 nm and 650 nm.

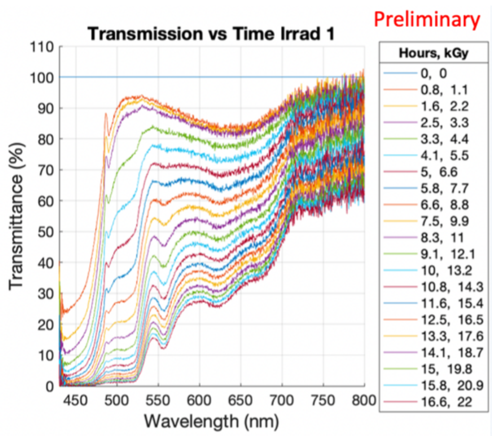

Fig. 4. The transmission spectra of the blue fiber as a function of irradiation duration.

The transmission spectra were then integrated for the spectral region of 400 nm to 800 nm, and the trend of this integral was monitored in-situ. Figure 5 shows the integrated transmission vs. time for the four consecutive irradiation campaigns for the blue fiber. After approximately four hours of irradiation which corresponds to approximately 5 kGy of total dose, the integrals can be fit to the sum of an exponential and a constant. As expected, the initial and final damages are higher for successive irradiations. The time constants for the damage are between 4.5 h to 6.7 h, decreasing with successive irradiations. Therefore, the radiation damage is faster for the previously damaged fibers. The fibers were also monitored for natural recovery in dark boxes. Therefore the initial damage of consecutive irradiations is much higher that the final damage of the previous campaign.

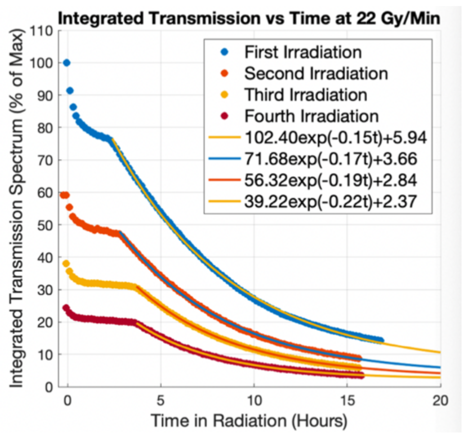

Fig. 5. The integrated transmission vs. time for the four consecutive irradiation campaigns for the blue fiber.

VI. Recovery from Radiation Damage in Optical Fibers

The same set of three fibers described in the previous section were also investigated for their recovery properties from radiation damage. Figure 6 shows the absolute transmission spectra of blue (left), green (middle) and orange (right) fibers as a function of time following the first irradiation campaign. The blue fiber exhibits the largest amount of recovery from radiation damage reaching 95 % of its initial peak intensity, but the peak is displaced from 540 nm to 618 nm. The amount of recovery in the green fiber is also dramatically high. The orange fiber recovers approximately 85 % of the radiation damage.

In total four irradiation campaigns were performed. Figure 7 shows the transmission spectra integrals as a function of duration of recovery for the blue fiber. The fiber recovers to 58 %, 38 %, 24 % and 15 % after the first, second, third and fourth irradiation campaigns respectively.

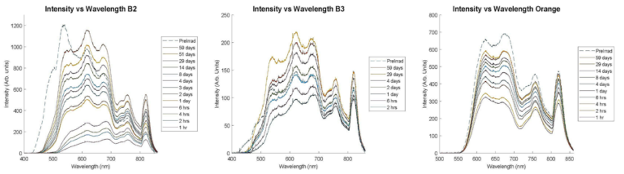

Fig. 6. The absolute transmission spectra of blue (left), green (middle) and orange (right) fibers as a function of time after the first irradiation campaign.

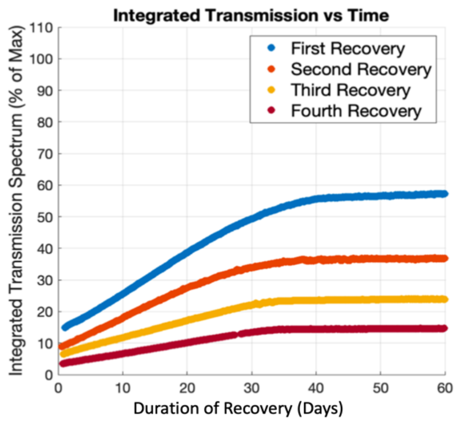

Fig. 7. The transmission spectra integrals as a function of duration of recovery for the blue fiber.

VII. Conclusions

Scintillators and optical fibers are excessively used in High Energy Physics experiments and scientific research facilities. Their response to the repeated exposure provides an important information on continuous performance. R&D on the development of radiation-hard scintillators and fibers is paralleled by the investigation of radiation damage and recovery mechanisms by our team.

Intrinsically radiation hard plastics PEN and PET remain to be feasible and cost-effective solutions as scintillators. Further investigation of their properties, also their mixtures, are needed before implementation in large-scale experiments. The options of intrinsically radiation-hard scintillators are being expanded with the addition of Scintillator-X. Different variants of Scintillator-X should be probed. With the improved production techniques, various sizes and specifications are now possible.

The darkening and recovery curves of the optical fibers provide useful information about the annealing process. The investigation of in-situ radiation damage and recovery mechanisms is critically important for future experiments. We investigated the in-situ radiation damage of optical fibers with the emission peaks in the blue, green and orange region of the visible spectrum. The time constants for the radiation damage were measured to be between 4.5 hr to 6.7 hr, decreasing with successive irradiations. The recovery from the damage ranges from approximately 60 % for the first irradiation campaign to approximately 15 % for the fourth campaign.

LED mediated recovery techniques are a possible solution to speed up radiation damage recovery. The techniques can now be implemented easily with on-detector electronics.

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