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Using LEDs to stimulate the recovery of radiation damage to plastic scintillators

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ABSTRACT

In this study, we consider using LEDs to stimulate the recovery of scintillators damaged from radiation in high radiation environments. We irradiated scintillating tiles of polyethylene naphthalate (PEN), Eljen brand EJ-260 (EJN), an overdoped EJ-260 (EJ2P), and a lab-produced elastomer scintillator (ES) composed of p-terphenyl (ptp) in epoxy. Two different high-dose irradiations took place, with PEN dosed to 100 kGy, and the others to 78 kGy. We found that the 'blue' scintillators (PEN and ES) recovered faster and maximally higher with LEDs than without. Conversely exposing the 'green' scintillators (EJ-260) to LED light had a nearly negligible effect on the recovery. We hypothesize that the 'green' scintillators require wavelengths that match their absorption and emission spectra for LED stimulated recovery.

1. Introduction

As the intensity frontier in the field of 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. Current materials are being pushed to their operational limits [1], and calibration systems are challenged with continuously having to correct for the lowering light yields of radiation damaged materials [2].

Scintillators in collider experiments, in particular calorimeters, are broadly used to generate photons in proportion to the energies of the particles traversing said media [3]. These photons can be collected directly or indirectly. Technologies such as photomultiplier tubes (PMTs) [4], hybrid photomultiplier tubes (HPMTs) [5], silicon photomultipliers (SiPMs) [6], and others, can be coupled directly to scintillators to measure the light generated within.

Often, space and other constraints require placing the photodetectors outside of the calorimeter apparatus, further requiring the generated light to be transported out of the scintillator tile and into the photodetectors by other means. Wavelength shifting (WLS) fibers provide a means of efficiently collecting scintillated light [7]. This usually requires that scintillators be machinable, or engineered to contain an optical fiber. Between the need for WLS fibers, costs, and other considerations, this is why most scintillators are made of plastic. Of note, most current WLS fibers are made of similar plastics as the scintillator tiles themselves, and are therefore similarly susceptible to radiation.

Once the light generated in the tile by a transiting particle reaches the photodetector and is transformed into a voltage signal, calibration factors are then applied to 'reconstruct' the particle's energy and position [8].

As a plastic scintillator is exposed to radiation, its effectiveness to generate the light that needs to be collected drops as it loses its ability to scintillate as brightly. In addition, its clarity darkens [9], lowering its optical transmission. This decreases its overall performance in its application, and requires continual adjustment of calibration factors, leading to higher systematic uncertainties.

Scintillators have varying levels of intrinsic resistance to radiation damage. Research is currently underway on new materials [10] which are more radiation tolerant, including polyethylene naphthalate (PEN) [11], and Eljen Technology's EJ-260 [12].

Scintillators also have varying natural recovery properties which depend on time [13], ambient atmosphere [14] and other in situ conditions. These 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 weeks, to months, and even years, which can provide sufficient time for the detector to 'cool off' and its scintillator components to recover to some extent, allowing their lifetimes to be prolonged before necessary interventions and detector upgrades have to take place.

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It has further been shown that this natural recovery can be augmented by shining visible and infrared light specifically into $PbWO_4$ [15], improving and extending the lifetime of this particular scintillating crystal, and therefore the experiment that uses it as its active medium.

It is with all of this in mind that we decided to investigate this technique using scintillator materials under consideration for the upgrade of the CMS Experiment [16], a collider detector at the Large Hadron Collider at CERN.

During our task of investigating different options for the replacement of scintillators for the CMS experiment, we irradiated PEN to test its radiation damage and recovery characteristics. One particular PEN sample was dedicated for LED stimulated recovery tests. Following the success of the LED stimulated recovery of PEN, it was decided to test the LED stimulated recovery of other types of scintillators for the CMS upgrade.

Considering the positive results shown in this paper, the process of 'bleaching' scintillators with bright lights during beam-off conditions could become standard procedure for future and upgraded experiments.

2. Experimental setup

Four tiles of Scinterex, the brand name scintillator formulation of Polyethylene Naphthalate (PEN) from Teijin Plastics [17] were cut to 5 cm × 5 cm × 0.1 cm squares from a single 8.5″×11″ sheet. Two tiles of an early version of a lab-produced elastomer scintillator composed of p-terphenyl mixed into epoxy [18], referred to as ES, were prepared as 2.5 cm × 4.5 cm × 1 cm sizes. Two tiles of Eljen brand [19] 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.

Prior to radiation, each tile was measured for scintillation properties to establish a baseline. The results of repeated measurements of like scintillators were within 5%.

Irradiation was done at the University of Iowa RadCore Facility, using a ^{137}Cs gamma ray source [20]. Three of the four PEN tiles were irradiated 93.0 h, for a total dose of 100 kGy, with one tile being left not irradiated as a control sample.

Two of the three irradiated PEN tiles were kept in a dark box after irradiation and between tests. One of the three irradiated PEN tiles was placed onto an array of RGB LEDs controlled with an Arduino Uno [21]. The Arduino was programmed to continuously cycle through four settings independently: only red, only green, only blue, and all colors simultaneously. Each of the four color settings were held for 3 s.

Each tile was placed directly onto six RGB LEDs in a 2 × 3 array, with the LEDs in close contact with each other. The LEDs used were SloanLED SL995RGBCU with red/green/blue luminosity ratings of 1200/3700/700 mcd and emittance wavelengths of 627/517/472 nm, respectively [22].

The sample placed onto the LEDs was covered with a piece of 3 M Vikuiti ESR [23] highly reflective film to reflect the LED light back into the tile. The entire setup was further covered with a piece of DuPont Tedlar [24] in order to prevent any ambient light from infiltrating the tile.

The irradiated PEN samples were measured 3 days after irradiation, and 7 days after irradiation by directing a 3 ns pulse-width 337 nm nitrogen laser beam through the tile perpendicular to its surface. The scintillated light was collected from the edge of the tile using a Hamamatsu R7600 PMT [25]. The data acquisition was triggered by the laser pulse using a Hamamatsu R7525 PMT [26] placed perpendicular to the tile surface. Fig. 1 shows a sketch of the test setup.

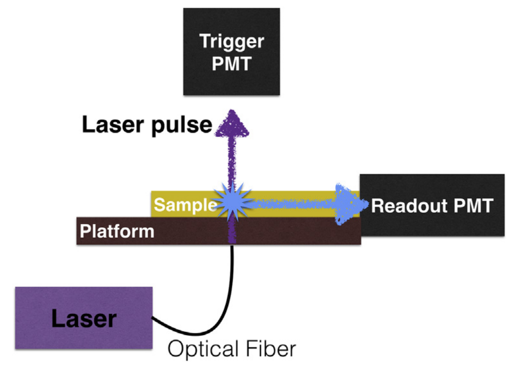

Fig. 1. Sketch of the setup used to measure the scintillation performance of the tested scintillators.

In a separate irradiation, two tiles each of ES, EJN, and EJ2P tiles were irradiated simultaneously for 67.6 h, for a total of 78 kGy. These tiles were tested immediately after irradiation, and in regular intervals up to 40 days post irradiation.

3. Experimental results

3.1. PEN Irradiated up to 100 kGy

Initially after irradiation, all three samples of PEN experienced the same amount of damage, within 5%. After three days, the recovery yield of the PEN sample placed on the RGB LED array (PEN-RGB) began to clearly separate from the two kept in the dark box, as seen in Fig. 2. The PEN-RGB sample recovered to 26% light yield, while the other two dark box samples remained at 21% of the reference tile.

After seven days, the PEN-RGB tile recovered to 72%, and the two dark box tiles recovered to 40% of the reference tile, Fig. 3.

As described in the introduction, once irradiation is stopped, plastic scintillators begin to 'heal' themselves, regaining lost light yield over time. These results show that this recovery can be augmented with off-the-shelf LEDs.

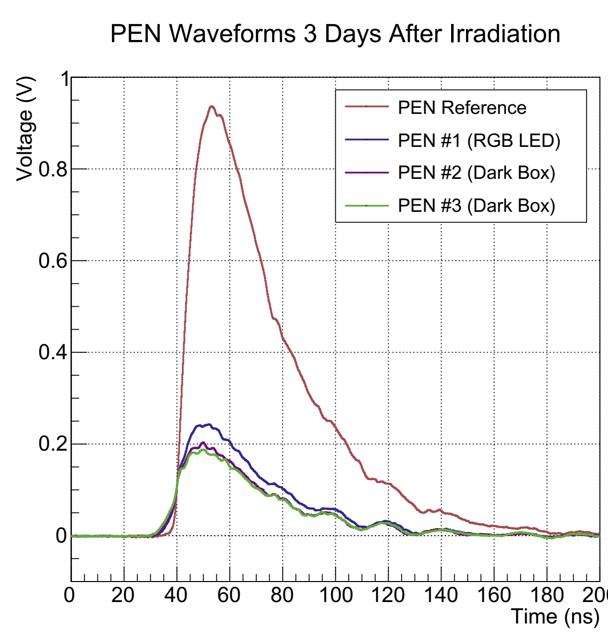

Fig. 2. PEN average waveforms three days after 100 kGy irradiation.