Liquid scintillator tiles for high radiation environments

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Abstract

Future experiments in high energy and nuclear physics may require large, inexpensive calorimeters that can operate up to doses of 50 Mrad or more. We present the results of a study of a scintillator tile based on EJ-309 liquid scintillator using cosmic rays, test beam, and ^{60}Co irradiations that shows little degradation of output under irradiation.

Keywords: organic scintillator, liquid scintillator, radiation hardness, calorimetry

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1. Introduction

Sampling calorimeters using plastic scintillator tiles with wavelength-shifting (WLS) fibers, such as the CDF plug calorimeter[1] and the CMS Barrel[2] and Endcap[3] hadron calorimeters, are popular due to their low cost and ease of construction. Plastic scintillator is available commercially from companies like St.

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Gobain and Eljen. When irradiated, however, the performance of plastic scintillator and WLS fibers deteriorate; light self-absorption (yellowing) increases and light output decreases. The resulting loss of light output for this kind of tile has been studied [4, 5]. Generally, the light output decreases exponentially with dose, with an decay constant on order of a few Mrad. Future high energy and nuclear experiments, however, may have to operate in environments that will deliver doses of tens of Mrad. In this paper, we present the design and optimization of a liquid scintillator tile, based on EJ-309 liquid scintillator, that can operate in this kind of environment.

2. Tile design

Our tile is based on EJ-309 scintillator, from Eljen Technology, which uses naphthalene as the substrate with wavelength shifting additives. EJ-309 has a light output that is 75% of anthracene, a wavelength of maximum emission of 424 nm, a refractive index of 1.57, and a flash point of 144°C. The high flash point is important for its suitability for a collider environment.

The design of a tile to hold the liquid needs to consider light collection efficiency, light collection uniformity, and cost. The container should not leak, and there should not be interactions between the container and its contents that degrade the light output over time or compromise the integrity of the container. Figure 1 shows the mechanical construction of our prototype. The case is made of aluminum. Two transparent support tubes with outer diameter of 2 mm run through the liquid and can hold either wavelength shifting fiber or liquid wavelength shifter. The index was measured at the Quattrone Nanofabrication facility at the University of Pennsylvania to be need jeff's number. When a wavelength shifting fiber was used, the end of the fiber not connected to the photodetector was coated with Al to increase the light output unless otherwise noted. The support tube is sealed to the case with a Viton fluoroelastomer o-ring. The thickness of the top and bottom Aluminum plates is 0.5 mm. The total internal volume is 88 mm x 88 mm x 4 mm. The inner surface of the container is a lapped and polished Al-6061 available from McMaster Carr. The material comes with a plastic coating that can be used to maintain its mirror quality during the machining process and then removed before the welding step. The liquid was transfered into the containing in an inert atmosphere.

Several variations on this design were constructed. For the default design, the thickness of the liquid is 4 mm. A version with a 6 mm thickness was also made. The support tubes were quartz with an inner diameter of 1.3 mm and were used with Kuraray Y-11 fiber (doping of 200 ppm), double-clad. Quartz tubes filled with liquid wavelength shifter were also used. The quartz tubes had an outer diameter of 2 mm and an inner diameter of 1 mm (or an outer diameter of 1 mm and an inner diameter of 0.4 mm) and a measured index of need jeff's number. The liquid wavelength shifter was a prototype material from Eljen, and is not yet a commercial item. The liquid wavelength shifter has an emission maximum from between 481 and 492 nm and a decay time between 2 and 8 ns. The solvent was the same as that used for EJ-309. Sapphire tubes were also tested with both liquid and plastic wavelength shifter.

In what follows, the results shown are for the mirrored tile with 4 mm thickness, quartz support tubes, and a 0.9 mm diameter Y-11 WLS fiber unless otherwise stated.

3. Light yield and uniformity as measured in test beam

The light yield and uniformity of the tiles was measured in the H2 test beam facility at CERN using 120 GeV muons. The trigger required coincidence of two out of four plastic scintillator hodoscopes. The effective beam cross sectional area, after trigger requirements, was 14x14 cm^2. The positions of the muons was measured with five wire chambers. The position obtained from the counter closest to the prototype was used. We also required the signal in each wire chamber be consistent with that of a single muon, and that the difference in positions in sequential chambers be consistent within uncertainties. As many groups were using the same test beam, there was material upstream of our

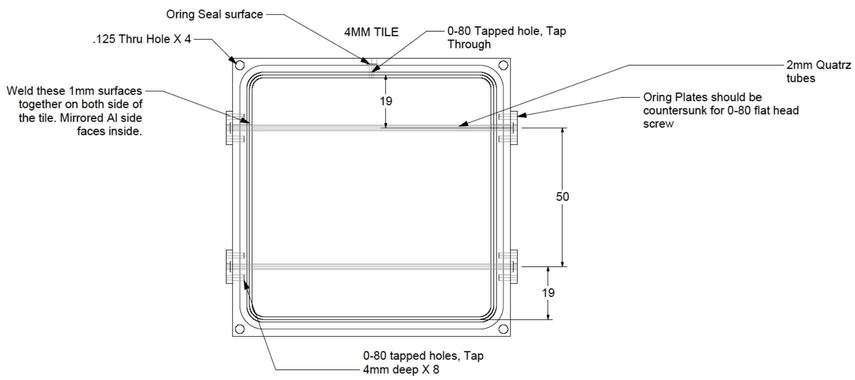

Figure 1: Mechanical design of a liquid scintillator tile. Units are [mm].

counters. For some runs, several iron blocks were used to support experiments upstream of our counters. Because the muons were high energy, the probability of a muon-induced shower was non-neglibile. (This was verified later at a test beam at FNAL that had a cleaner beam line and through simulation.) We present here the results from the runs and tiles with the smallest upstream material.

The wavelength shifting fiber was connected to a clear fiber using a connector designed at FNAL. The clear fiber was lead away from the beam line. The light output was measured using a Hamamatsu R7600U-200-M4 photomultiplier tube and a custom ASIC that integrates and digitizes the resulting charged, called the "QIE"[6]. The photomultiplier has a peak quantum efficiency of 40% at a wavelength of 400 nm and produces a clear single photoelectron (pe) peak. The integrated charge is digitized every 25 ns. Ten digitizations were recorded per muon trigger. The sum of the signal in the 4^{th} to 7^{th} sample was used.

The average number of pe's produced per minimum ionizing particle (mip) was estimated by doing a Gaussian fit to the peak centered on the pedestal. The mean number of pe's was calculated using the fraction of events in this peak, assuming a Poisson distribution. The nominal tile produced 1.7 pe's per mip. Tiles for the CMS hadron calorimeter typically produce 3 pe's per mip[2]. The results have a systematic uncertainty related to the handling of the events with showering muons. We evaluate this uncertainty by looking at the results after truncating the distribution at around 25 pe's (2500 adc counts). The results were stable to within 5%. In addition, runs taken with varying amounts of material in front of our detector, from several radiation lengths to a what was the upstream material for the best resulted in a 15% variation in light yield. We therefore take a 16% uncertainty due to upstream material.

The uniformity of the light collection was also studied at the CERN test beam. Figure 2 shows the fraction of events with at least 1 pe versus the impact position of the mip along the axis parallel to the support tubes (left) and perpendicular to the support tubes (right). As expected, there is little dependence on the coordinate parallel to the support tubes. The light yield does depend on the perpendicular distance. The light collection efficiency is maximum at for muons near the WLS fiber and is approximately 30% lower for muons in the center or edges of the tile. For most hadron calorimetry applications, we verified through simulation that this degree of nonuniformity would not aversely affect jet resolutions.

4. Light yield dependence on tile parameters

The dependence of the light yield on variations in the design parameters was studied using cosmic ray data taken at the University of Maryland. Scintillator-based counters above and below the tile were used for triggers. The tile light output was measured using a Hamamatsu R7600U-200-M4 photomultiplier tube. Fibers were connected to the tube using optical glue. Data was collected with a

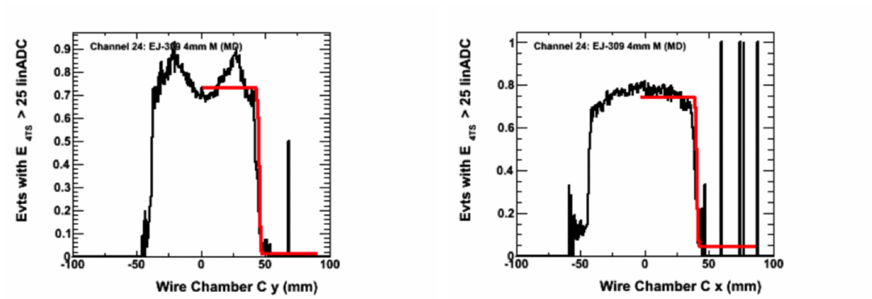

Figure 2: For the nominal liquid tile, fraction of mips with at least one pe as a function of the impact position of the mip along the axis parallel to the support tubes (left) and perpendicular to the support tubes (right).

Tektronix MSO 5204 oscilloscope. No attempt was made to select minimum ionizing muons. The muons thus are low energy and will produce more light than those studied at the CERN test beam. We found an average of 2.88 ± 0.05 pe for the nominal tile. A similar tile but without the mirroring yielded 1.98 ± 0.03 pe, a reduction of a factor of 1.45. A tile with a 6 mm thickness of liquid, non-mirrored, yielded 2.61 ± 0.05 pe, an increase over the 4 mm non-mirrored tile of a factor of 1.32.

The light yield was also studied using a capillary quartz tube, filled with liquid wavelength shifter, instead of a plastic WLS. The capillary quartz tube had an outer diameter of 2 mm, and an inner diameter of 0.6 mm. The quartz support tube, which contained the plastic WLS fibers, and created an air gap between the tube itself and the fiber, was entirely replaced by the quartz capillary. In this configuration, there is no air gap between the liquid scintillator and the liquid wavelength shifter. The two materials have a very similar index of refraction (1.57), while the quartz capillary, with a lower index of refraction, allows light to be captured within the liquid WLS material. Figure 3 shows a comparison between the plastic and liquid WLS configuration. The light collection efficiency drops from 92% to 45%, and the average light yield halves as well. However, we shall note that the setup with a quartz capillary is significant step towards a radiation-tolerant calorimetry cell. The light output of the capillary setup has not been optimized as a function of the index of refraction of the quartz capillary, thus possibly leaving some space for improving the performance of the capillary setup.

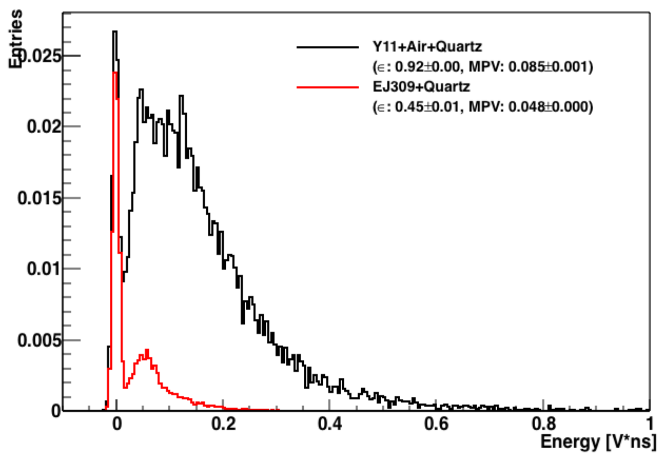

Figure 3: Comparison between the light output of a liquid scintillator tile equipped with a plastic WLS fiber, and a capillary filled with liquid WLS. The two distributions are normalized to have the same number of events in the pedestal.

5. Radiation hardness tests

Several different tests were made using irradiations with a ^{60}Co source coated at the University of Maryland. Performance of the tile under irradiation in a proton-proton collision environment will be the subject of a future paper.

The most striking test is the light-output and efficiency comparison between two samples of liquid used in the same tile, shown in Figure 4. A dark-glass vial containing 125 ml of liquid scintillator had been irradiated with γ-rays up to a dose of 50 Mrad, at a dose rate of 1 Mrad/hr.

Both the efficiency and light output from the two measurements are consistent within the uncertainty, indicating that EJ-309 is radiation-tolerant to γ-ray irradiations.

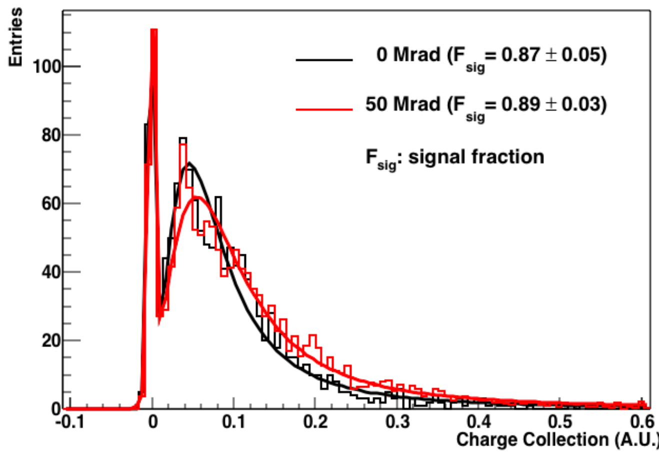

Figure 4: Comparison between the light output of a liquid scintillator tile filled with unirradiated (black) and irradiated (red) liquid scintillator. The two distributions are normalized to have the same number of events in the pedestal.

6. Comparison with simulation, and optimization

We use the GEANT4 [7] package to simulate the optics of our tile. GEANT4's optical package includes simulations of refraction, reflection, wave length shifting, and light attenuation. A variety of options for the reflection are available. We used the "Specular Spike" option for the Al and an absorption length of 2 m for the EJ-309. When simulating the WLS fiber, an air gap was included between the fiber cladding and the support tube, while no such gap exists for the simulation of the capillary. An index of refraction of 1.57 is used for the EJ-309. The index for sapphire used was 1.77. For quartz, values between 1.46 and 1.55 were used. Photons are generated at random positions inside the liquid volume, with a wavelength corresponding to the emission maximum of EJ-309.

As shown in Figure 5 left, we find the simulation reproduces the light collection nonuniformity when a reflectivity of 0.9 is used for the mirrored Al.

We find that the light collection efficiency is a strong function of the reflectivity of the Al (Figure 5 right).

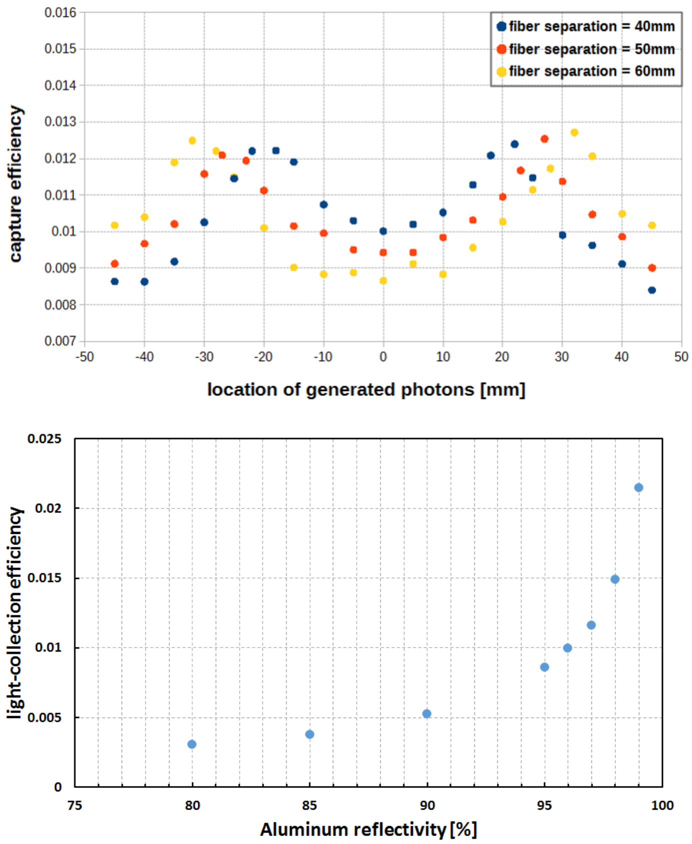

Figure 5: (left) Ratio of light yield to maximum light yield from simulationed tile as a function of the distance perpedicular to the support tubes. figure is place holder until Zishuo gives right one (right) Light collection efficiency vs Aluminum reflectivity Zishuo can you make this a ratio plot? pick some point and divide the rest by it?

We find the best light collection comes when the support tube has the lowest possible index of refraction for liquid WLS. The opposite is true for a fiber with an air gap (and plastic WLS). For a 1mm diameter for the WLS, the light collection efficiency increase by a factor of Zishuo please add this number going from an index of 1.55 to 1.46 for liquids. Presumably this difference would decrease as the reflectivity of the Al increases. For a fiber with an air gap, the efficiency decreases by a factor of Zishuo please add this number going from an index of 1.77 to 1.46.

7. Conclusions

We presented results for a liquid scintillating tile using wavelength shifting fiber readout. For our nominal design, 1.7$\pm$0.2 pe's were produced for minimum ionizing particles.

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