Thick-wall, Liquid-filled Quartz Capillaries for Scintillation and Wavelength Shifting Applications

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Abstract:
We have been developing a readout method for Shashlik Electromagnetic Calorimetry based upon liquid-filled capillaries fabricated from radiation hard (high OH content) fused silica. The liquids are waveshifters, that currently shift scintillation light from 425nm, the emission from LYSO(Ce) crystals or conventional plastic scintillator, to wavelengths in the green (500nm). Other wavelength options are possible. While the liquid in the capillary core serves as the light source, the thick-wall of the Quartz capillaries provide the bulk of the optical path through which the wave shifted light is transmitted to photosensors. Characteristics and performance of prototype capillaries are presented, as well as plans for further development of the technique.

Approach:
Calorimeters for use in high flux and high radiation experimental conditions (for example in hadron collider experiments at the LHC) are expected to suffer significant radiation damage during the HL-LHC era and beyond. To address these challenges, we have been conducting R&D on new calorimetry techniques suitable for operation in such environments, based on scintillation and wavelength-shifting (WLS) technologies. In particular, we have focused our attention on radiation tolerant Shashlik-type EM calorimeters of very compact design with a structure consisting of alternating layers of very dense absorber and scintillating plates. [1, 2] The Shashlik modules consist of alternating layers of tungsten absorber plates 2.5mm thick and 14 x 14 mm^2 cross sectional area, and LYSO scintillation plates 1.5mm thick and identical area (see Figs. 1 and 2). This combination of materials affords a dense, compact design, with small Moliere Radius (13.7 mm) and short physical length (135 mm) corresponding to ~ 24 radiation lengths (X_0) in depth. The high brightness of the LYSO and short optical path lengths allow for a detector design that is both robust against radiation damage and event pile up, both central issues for detector operation at high luminosity.

The LYSO and tungsten layers each have five machined holes, four for readout of the detector via WLS capillaries, and one in the center for a calibration fiber. As can be seen in Fig. 2, four capillaries penetrate through the length of the Shashlik module to sample the scintillation light produced in the LYSO crystals.

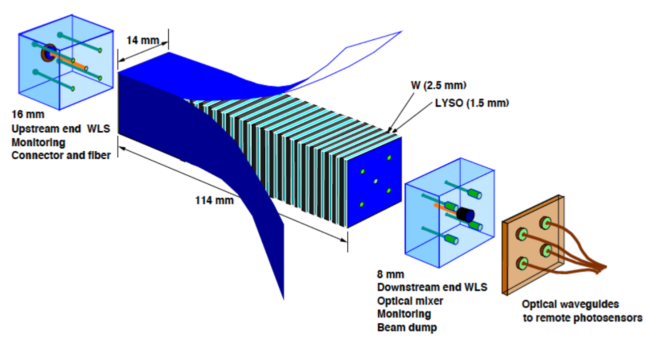

Figure 1. A Shashlik module based upon interleaved W and LYSO(Ce) layers. In this prototype structure, 29 LYSO crystals and 28 W plates comprise a module. Four WLS liquid-filled quartz capillaries are used to detect the scintillation light and transfer the light to photosensors at the downstream end of the module (right hand side in the figure). Photosensors could be located there directly or remotely with the light carried via optical waveguides, as indicated in the figure. A centrally placed fiber is used to inject laser light into the Shashlik Module for monitoring purposes.

Our choice of capillary material is high OH content fused silica, [3] selected for its radiation hardness, and based upon prior experience from the CMS forward hadron calorimeter (HF). The capillary cross-sectional dimensions are: outer diameter of 1mm and core diameter of 0.4mm, determined from a SLitrani simulation study. The capillary lengths are

185 mm, of which 114 mm lies within the active volume of the Shashlik module itself.

The liquid waveshifters under study are based on a quenched EJ309 liquid base, and containing either of the fluorescent dyes DSB1 or J2. [4] The DSB1 and J2 have fluorescence characteristics similar to the well-known Y11 (variously known as K27), but DSB1 is significantly faster in response than the other shifters by a factor of ~2.

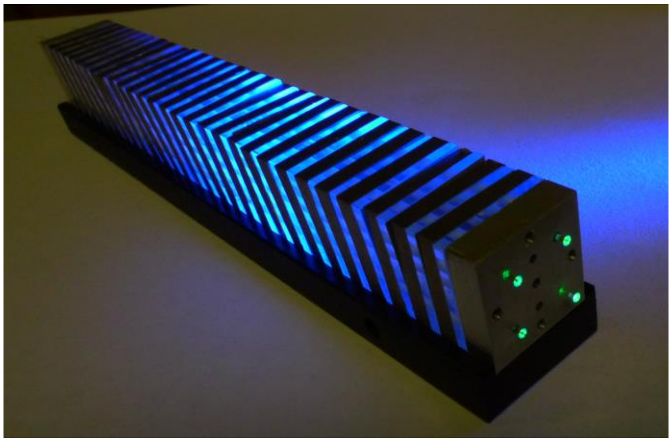

Figure 2. An assembled Shashlik Module with interleaved tungsten plates, LYSO(Ce) plates and sealed WLS capillaries containing the WLS dye DSB1. Illumination is with a UV light of 365 nm that excites the LYSO material. The LYSO emission at 425nm in turn excites the WLS dye in the capillaries, which fluoresce at 500nm. Particles from an LHC interaction would enter from the upper left. At the lower right are the readout ends of the four capillaries. These can be coupled directly to photosensors or fiberoptic waveguides that can carry the WLS light to photosensors located remotely.

The refractive indices of the core liquid and quartz are 1.57 and 1.46 respectively. The quartz capillary itself has no external cladding other than an air layer. So light propagation can occur within the liquid core only, or within the liquid/quartz combination. The light traveling within the liquid core is prevented from reaching the readout by a "core block", whereas light from the quartz/liquid combination is not. Figure 3 provides a schematic of the light collection and transmission process.

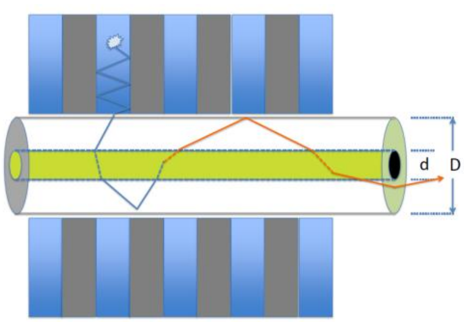

Figure 3. A schematic of the light collection approach. Scintillation light produced in LYSO tiles (blue) is waveshifted in the liquid core of a thick wall Quartz capillary, D =1mm, d = 0.4mm, and then propagates to the readout end at the right. The core light propagating only in the liquid is blocked from reaching the readout, but the light propagating predominantly in the quartz wall emerges around the core blocking. This helps to reduce the optical attenuation length of the structure and improve the performance in a high radiation environment.

Light propagation solely in the WLS liquid suffers from two issues. The first is self-absorption of light due to the WLS dye itself; the second is possible damage to WLS liquid medium due to irradiation effects. Both can in principle lead to longitudinal non-uniformity of light collection and transmission. However since the WLS liquid occupies only 16% of the volume of the capillary, the optical transmission of the WLS light occurs predominantly in the rad hard quartz material, helping to level the longitudinal response of the system.

R&D Program:

The objectives of the R&D program are to: (1) to optimize the capillary structure for uniformity of response of light collection as a function of depth in the Shashlik Modules; (2) study the behavior and performance of the capillaries as readout elements both before and after various levels and types of irradiation; (3) develop WLS liquids and optimize these for applications utilizing different scintillation materials, including ceramics. This paper addresses the first two issues.

1. Optimization of Capillary Structure. Our group has developed several methods of capillary fabrication and implementation. [5] The simplest and most practical approach is the filling of the capillaries under vacuum and then sealing them either thermally or with epoxy.

The capillary fabrication procedure involves the following steps. First, high OH content fused silica is used for the capillaries, with no external coating or cladding material on the outside surface. We refer to this as QA material, as the outer "cladding" is air. [3] Second, a spherical reservoir bubble is blown into the capillary that serves as an expansion/contraction reservoir for the WLS fluid (see Fig 4).

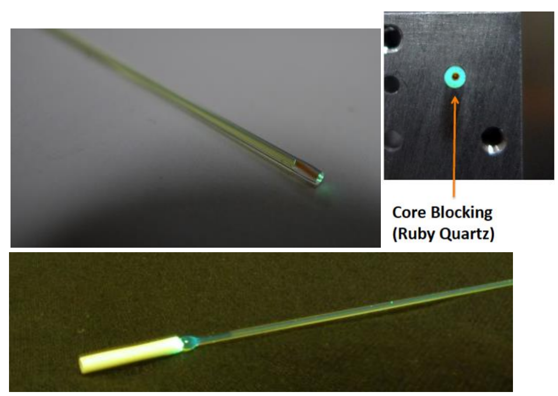

Figure 4. Upper Left: Close up of the downstream (readout) end of a capillary with a fused ruby quartz insert that provides core-light blocking. Upper Right: End-on view of the capillary, showing that the WLS light in the core is blocked by the fused ruby insert, while the thick wall of the quartz capillary transmits the WLS light (cyan coloration) to the photosensor readout. Middle: Side view of the upstream (non-readout) end. The capillary is filled from this side and then either thermally or epoxy sealed. A spherical bubble can be seen, that has been blown into the capillary to act as a reservoir for expansion and contraction of the WLS liquid. A white plastic sleave is glued onto the capillary over the sealed end for protection and to facilitate handling of the capillary. Lower: In this view, the TiO_2 diffusive reflective paint can be seen, which has been applied to the side wall of the capillary near the reservoir bubble.

Third, a ruby quartz "plug" of ~ 3mm length is inserted and thermally fused into the end of the capillary opposite to the reservoir bubble. This end is then ground to a high optical finish and serves as the readout end of the structure (Fig. 4). Fourth, the open end near the reservoir is attached to a vacuum system, which evacuates the capillary, and the capillary is then filled with the WLS fluid. Lastly, the capillary is then sealed either by fusion sealing or epoxy sealing.

2. Study of the Optical Behavior of the Capillaries. Once fabricated, the capillaries are subjected to quality control testing, by excitation through the quartz sidewall with an LED of wavelength λ = 425nm, and measuring the amount of light collected at the readout end by means of a P/N diode. This allows measurement of the overall light level and optical attenuation length. An example of such a measurement is shown in Figure 5, with the gray data points indicating the capillary light collection behavior just after fabrication

Next, a 4mm-wide thin overcoat (band) of TiO_2 paint is applied extramurally to the capillary near the reservoir end (refer to Fig. 4). As the red data points in Figure 5 show, the TiO_2 banding improves significantly the light collection from locations furthest from the readout end, but also benefits light collection overall.

Next, the capillary is exposed to gamma radiation from a ^{60}Co source at the Notre Dame Radiation Chemistry Laboratory, and measured for its optical transmission after an initial 50Mrad dose, administered over a 2½-day interval. As shown by the green data points in Figure 5, two important effects are observed: the overall light level rises from the middle to the far end; and the slope in the optical attenuation at the near (readout) end is suppressed. Note that in an actual Shashlik module configuration, light is collected from LYSO tiles situated within the range 25mm to 140mm of capillary length as displayed in the figure.

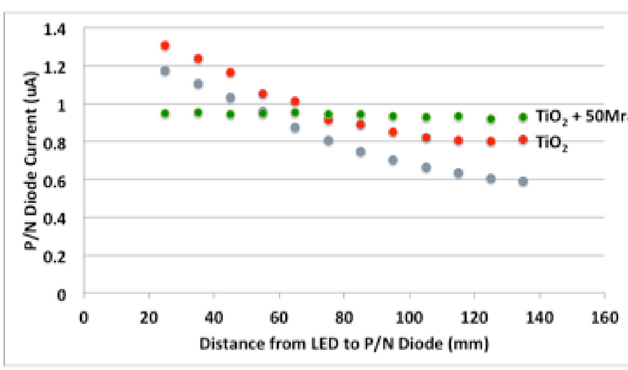

Figure 5. Measured light level in a P/N diode at the readout end of a quartz capillary as a function of the longitudinal distance from the diode to the exciting light from an LED positioned to inject its light though the sidewall of the capillary. (1) Gray data points: measured after initial fabrication and unirradiated. (2) Red data points: After TiO_2 sidewall band coating at the reservoir end near the160mm position and unirradiated. (3) Green data points: after exposure to 50Mrad of gamma irradiation.

While this situation is under detailed study, we have made some preliminary observations. The increase in light level appears to be created by a change of the optical excitation spectrum of the DSB1 waveshifting liquid in the 380-450nm range under 50 Mrad of gamma irradiation (see Fig.6). This results in improved waveshifting of 425nm light from the LED, and would correspondingly improve the light collection from LYSO(Ce) scintillator tiles, which emit at this wavelength.

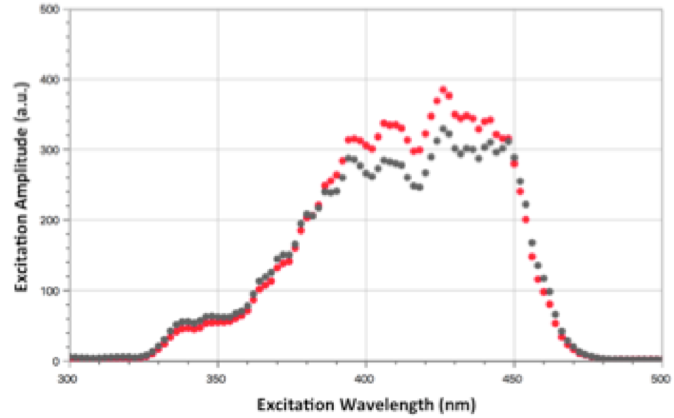

Figure 6. Excitation spectrum of the DSB1 liquid waveshifter befor (gray dots) and after (red dots) 50 Mrad of gamma irradiation. These spectra correspond to WLS emission at 500nm. Measurements using a Varian Cary Eclipse Fluorescence Spectrometer.

Under further doses of radiation in 50Mrad steps, the overall light level from the capillary drops, but in a fashion consistent with an overall scale factor of about ~25% in light reduction per 50Mrad of dose up to 200Mrad of total dose, the limit of current measurements. Figure 7 indicates this behavior, with the green data points corresponding to the first 50 Mrad of exposure as shown previously in Figure 5 above. For reference, 150Mrad is the maximum total ionization dose expected in Shashlik modules near η = 3 for integrated luminosity of 3000fb^{-1}. [6]

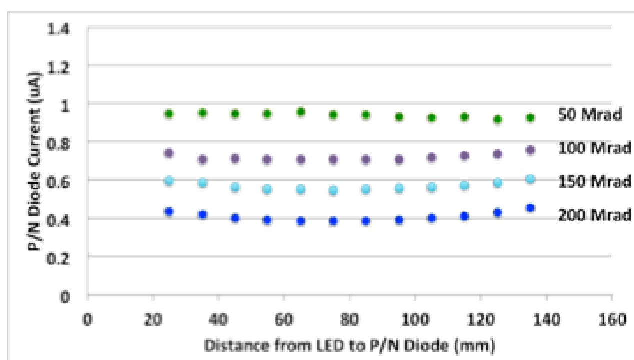

Figure 7. Continued optical measurements of the same capillary as shown in Fig. 5 but for additional levels of gamma irradiation. Green data points: after exposure to 50Mrad – same data shown in green in Fig.5. Purple data points: after exposure to 100Mrad of gamma irradiation. Light Blue data points: After exposure to 150Mrad of gamma irradiation. Dark Blue data points: After exposure to 200Mrad of gamma irradiation.

3. Ongoing and Future Studies. Significant effort is underway to test with electron beam the Shashlik Modular structure in a 4x4 array. Figure 8 shows the assembly of such an array under preparation for testing at the CERN H4 Beam Line for a June 2016 data run.

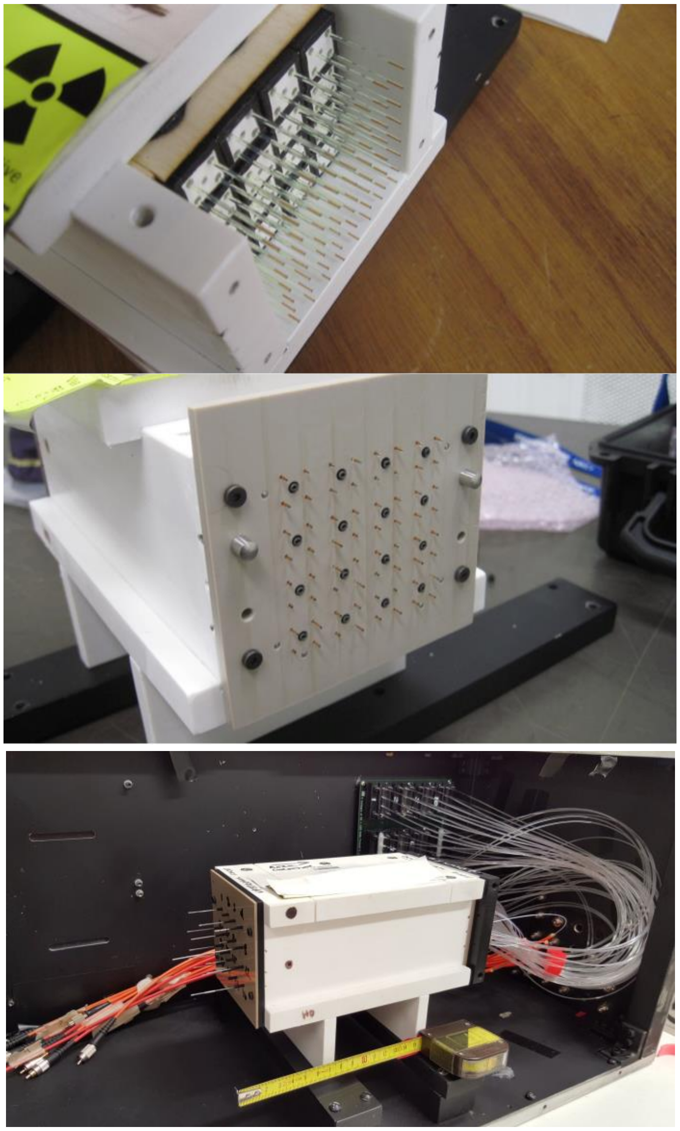

Figure 8. Views of a Shashlik 4x4 array using WLS Capillary readout. Upper, capillaries threaded through the 4x4 stack; Middle, end plate attached. Lower, optical waveguides connected to convey light to SiPM photosensors. Dimension scale in foreground indicates 15cm length. Incoming beam into the array enters the picture from the left.

A Shashlik Module of the type shown in Figures 1 and 2 was exposed to a proton beam at Los Alamos National Laboratory, exposures up to 1.2 x 10^{15} protons/cm^2.

further the radiation studies to higher doses and also to hadron irradiations. We are additionally initiating study of Quantum Dots as WLS materials. Further detailed irradiation studies and beam tests are planned to characterize and optimize the performance of the Shashlik modules.

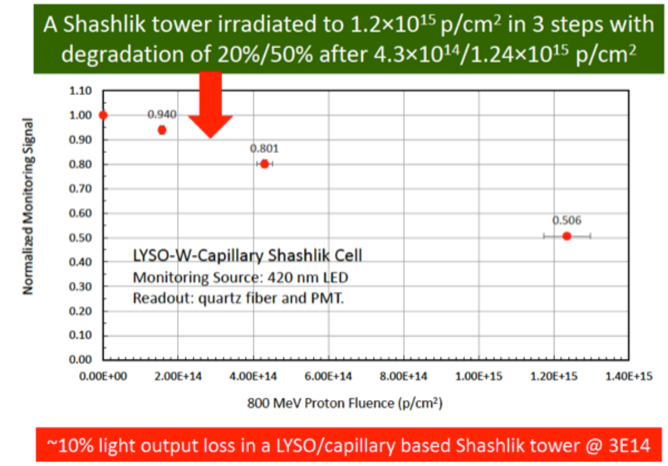

Figure 6. Exposure of a Shashlik Module to proton irradiation at LANL. These results indicate that the detector elements with capillary readout are will withstand the integrated doses expected at the LHC at high luminosity up to 3000fb^{-1} in end cap calorimeters.

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References

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[2] R. Ruchti, et al, *High Performance, Radiation Hard Light-Based EM Calorimetry for Particle Physics Applications*, CPAD Instrumentation Frontier Meeting, 5-7 October 2015, University of Texas at Arlington. *https://indico.hep.anl.gov/indico/conferenceOtherViews.py?view=standard&confId=625*

[3] Capillaries tubes are produced by Polymicro Technologies, Molex, LLC, Phoenix, AZ.

[4] DSB1 and J2 are commercially available organic fluorescent dyes and EJ309 is a scintillating liquid base developed by Eljen Technology, Inc, Sweetwater, TX.

[5] B. Baumbaugh, et al, *Development of Wavelength-shifting Liquid-Filled Quartz Capillaries for Readout of Optically based Calorimetry*, IEEE/NSS2015, Conference Record.