Large Plastic Scintillators with Efficient SiPM Readout

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Introduction

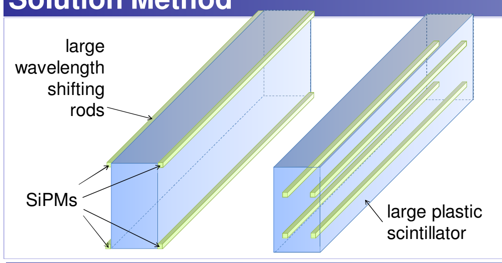
Large single pieces (~5x40x200 cm^3 = 40 liter) of plastic scintillator are routinely used for gamma ray detection of illicit nuclear materials in applications such as cargo scanning, wide area monitoring, and vehicle border crossings:

- Inexpensive
- Large efficiency×solid angle products.
- Currently use several photomultiplier tubes (PMTs) for light detection
- Can a few SiPMs be used in place of PMTs?

The Problem

- SiPMs are 3 – 5x more expensive per cm^2 than PMTs
- Too few SiPMs reduces light collected, gamma ray sensitivity and detectability
- Dark count noise increases with SiPM total area covered
- ***Advanced plastics containing high-Z additives[1] or high fluor concentrations[2] for fast neutron detection only add to problem***
  - optical scattering increased
  - optical absorption increased
  - large detector size exacerbates total attenuation
- **To enable large advanced plastic detectors a new method of scintillator light collection is needed.**

Solution Method



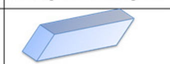
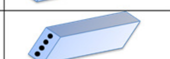
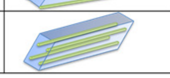
- Rods of cladded wavelength shifting (WLS) plastic are threaded through the bulk of the large scintillator monolith or coupled to an edge.
- The rod cross-sections are matched to the size of the SiPMs.
- Each end of a rod can be optically coupled to an SiPM.

- scintillation light does not need to randomly strike a small SiPM area on the surface
  - simply needs to encounter the much larger WLS rod surface and be trapped
  - can detect more light in plastics with large bulk attenuation
- average photon pathlength through the plastic monolith is reduced
- smaller probability of surface reflector absorptions
- This advantage is especially useful for advanced plastics which have high optical extinction coefficients and thus need shorter photon pathlengths for adequate performance.

configuration	collection area	trapping efficiency	effective collection area
8 SiPMs on monolith surface	8 x 0.36 cm^2 = 2.88 cm^2	na	2.9 cm^2
4 PMTs (1.125"Φ)	4x 6.4 cm2	na	26 cm^2
8 SiPMs on 4 surface rods	4 x 0.6 cm x 200 cm = 480 cm^2	8.5%	41 cm^2
8 SiPMs on 4 embedded rods	4x4 x 0.6 cm x 200 cm = 1920 cm^2	8.5%	163 cm^2

Optical Simulation Results

Simulations performed with DETECT2000

Configuration description	Configuration diagram	light collection efficiency, LCE			
2¼ x 14 x 70 in^3 PVT		no absorption	absorption length = 50 cm	absorption length = 350 cm	absorption length = 1000 cm
standard readout=4 PMT, Φ=1.125"		**38.4%**	0.7%	4.1%	10.0%
4 WLS rods on long edges, readout=8 SiPM, 6x6mm^2		21.7%	3.0%	5.1%	6.6%
4 WLS rods threaded through bulk, readout=8 SiPM, 6x6mm^2		21.4%	**4.7%**	**11.4%**	**13.1%**

Simulations of light collection efficiency (LCE)

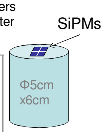
- LCE is defined as the fraction of scintillation light that reaches a photosensor (PMT or SiPM).
- The bulk plastic is PVT with dimensions 2¼ x 14 x 70 in^3 (~6x40x200 cm^3 = 48 liter).
- Several cases of differing light absorption in the bulk plastic are tabulated.

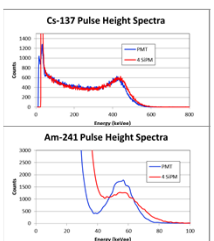
Note that as optical absorption in the bulk increases, it becomes more efficient to transport the light through wavelength shifting rods.

Experimental Results

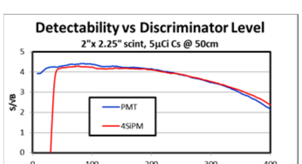
Small Detectors

- 5cm diameter x 6cm long cylinders
- Compare readout with 2" diameter PMT vs 4 SiPMs (6mm^2 ea)





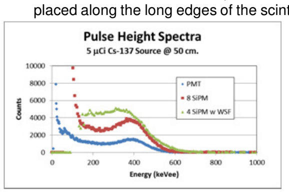
The noise edge of the SiPM readout comes into play at approximately 40 keV

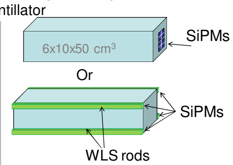


A plot of detectability vs energy threshold shows that the SiPM readout is as effective as a PMT for energies above 50 keV. Below that energy, dark counts in the SiPMs limit the sensitivity of the device

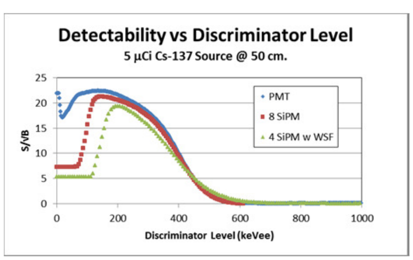
Intermediate Size Detectors

- 6cm 10cm x 50cm
- Compare readout with a single 1.125" PMT or SiPMs coupled direct to the scintillator or coupled to wavelength shifting rods placed along the long edges of the scintillator



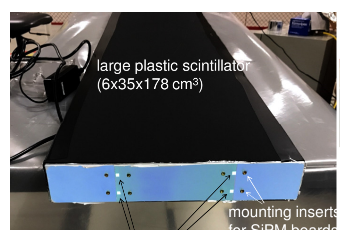


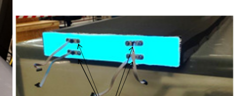
Pulse height spectra for the three readout configurations are shown above. The horizontal scales are normalized so that the ½ height of the Compton edge occurs at ~450 keVee.



The detectability plot shows that the PMT readout has good sensitivity to below 30 keV. For 8 SiPMs direct coupled to the scintillator face, the energy limit is ~ 150 keV. For SiPMs and wavelength shifting fibers the limit is about 200 keV.

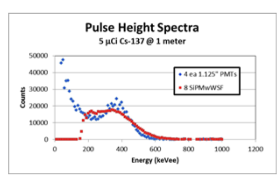
Large Sized Detectors

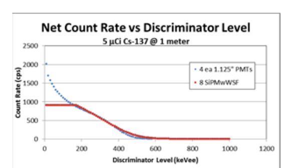


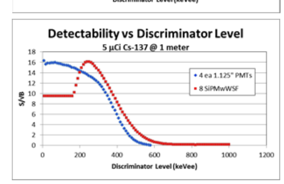


Four SiPM boards mounted at each end

embedded wavelength shifting rods







Nuclear performance of a large sized panel with embedded wavelength shifters and SiPMs closely matches that of piece read out with multiple PMTs for energies above 200 keVee. Below this energy, the low noise of the PMTs permits threshold levels as low a few keVee.

Summary and Outlook

- **Initial experiments are underway on instrumenting large plastic scintillator with a few SiPMs.**
- **Initial results indicate that efficient detection can be achieved for events depositing >200 keVee in the plastic.**
- **Methods to reduce the detection threshold such as cooling and improved signal processing techniques will be investigated.**
- **Studies of the absolute photoelectron yield will be conducted to confirm improved light collection with embedded shifters and SiPMs**
- **Experiments with highly scattering plastics such as high-Z loaded and neutron sensitive plastic to be done in coming year.**

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[1] Edgar V. van Loef, et. al., "High energy resolution plastic scintillator," Proc. SPIE 9968, Hard X-Ray, Gamma-Ray, and Neutron Detector Physics XVIII, 996803 (2016).
[2] Natalia Zaitseva, et. al., "Plastic scintillators with efficient neutron/gamma pulse shape discrimination," Nucl. Instrum. and Meth. A, Vol. 668, pp. 88–93 (2012).