# Efficient Positioning of Silicon Photomultipliers on Large Scintillation Crystals

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***Abstract*–Silicon photomultipliers (SiPMs) are attractive replacements for photomultiplier tubes (PMTs). However, many radiation detector applications require large volumes of monolithic scintillator and correspondingly large numbers of SiPMs. When multiples of SiPMs are used, the dark count noise and cost increase proportionally with the surface area covered. When too few SiPMs are used, non-uniformity of light collection degrades the energy resolution of the detector. Strategic placement of a limited number of SiPMs on a large scintillator can reduce the number of SiPMs necessary and decrease the cost-to-performance ratio. Simulations and experiments have been performed to find general guidelines regarding optimal positioning of SiPMs on large NaI(Tl) crystal scintillators. For example, if the SiPMs are placed near edges and vertices on one cuboid face, the number of SiPMs necessary to achieve adequate energy resolution need only cover 40% or less of the light output face.**

## I. Introduction

SILICON photomultipliers (SiPMs) are attractive replacements for photomultiplier tubes (PMTs) when compact geometry and low power draw are important. However, many radiation detector applications require large monolithic scintillators, which can pose a problem for the use of SiPMs in such applications. Single device SiPMs are smaller than 0.5 cm$^2$ and large scintillators require an array of SiPMs or a large number of individual units to efficiently detect the light. When multiples of SiPMs are used, the dark count noise and cost increase proportionally with the surface area covered. As of 2016, SiPMs are roughly 5x the price of PMTs on a per cm$^2$ basis. When too few SiPMs are used, non-uniformity of light collection degrades the energy resolution of the detector.

## II. The Cost Problem

Several radiation detection applications require large monolithic scintillators. Examples include SPECT imaging, nuclear facility monitoring, and public area security scanning. To date, these detectors have used PMTs as the photosensors because they can be made with large sensitive areas (>100 cm$^2$) that are suitable for covering a large optical exit area on a large scintillator. For example, a typical nuclear facility station monitor made with NaI(Tl) scintillator will have dimensions of Ø=15 cm x h=18 cm and will be coupled to a 127 mm diameter PMT. Covering the same area with SiPMs would require 350 SiPMs (of 6x6 mm$^2$ size) and cost over ten thousand euros (~€30 ea.), far more than the cost of a single PMT (< €500).

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## III. Developing an SiPM Location Strategy

### *A. Photon density at the detection surface- a thought experiment*

A strategy to reduce the number of SiPMs requires an understanding of where the photon density is highest on the light collection plane. To obtain an intuitive grasp of where the density may be the greatest, imagine a cube of scintillator with one face designated as the light output plane (called the detection plane) and the other five sides covered with perfect diffuse reflector. Fig. 1a shows the orientation.

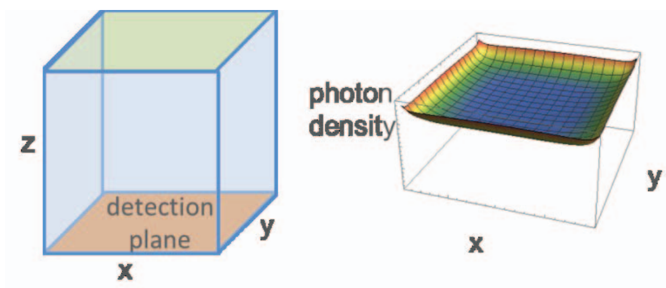


Fig. 1. a) Schematic of the thought-experiment cubic scintillator. b) Density plot of scintillation irradiance on the detection plane .

If the volume of the scintillator is uniformly filled with randomly directed light then the irradiance onto the detection plane can be considered as coming from three sources: 1) the direct light from the volume, 2) the light reflected from the top surface, and 3) the light reflected from the four standing sides. The relative irradiance from the three sources can be visualized by integrating the inverse squares of the distances from every source point to every point on the detection plane and plotting as a function of the detection plane coordinates. This function is shown in Fig. 1b. Note that the photon density is greatest near the edges and corners of the detection plane. This is because the parts of the detection plane that are close to the standing sides will have very large inverse square distance values. This immediately suggests that if one is limited in SiPM quantity, then the best positions to place them may be near the edges and corners. Such placements on a large scintillator could reduce the number of SiPMs necessary and decrease the cost-to-performance ratio.

*B. Photon density at the detection surface- simulation*

An actual scintillation detector will, of course, have much more complex optics than the simple thought experiment described above. A real scintillator will have dissipative losses, Fresnel reflections, trapped light, etc. To gain more realistic information about photon density variation on the detector plane, optical simulations were performed [1].

Below are results of optical simulations of where scintillation photons strike the end surface of a large NaI(Tl) crystal cuboid (10x10x40 $cm^3$). The model includes a Teflon reflector wrapping on five faces, appropriate values for the refractive indices, and the bulk attenuation of NaI. Fig. 2 shows the density of the photons as they strike a 10x10 $cm^2$ face. Warmer colors indicate higher photon density. Note that the greatest densities occur near the vertices and edges of the face. This suggests that placing SiPMs in those positions would be more favorable than placing an equal number in the center of the face. Table I shows schematics of the SiPM placements on a 10x10 $cm^2$ face and lists the simulated light collection efficiency and the non-uniformity of light collection as a function of SiPM number and placement. The size of each SiPM is 6x6 $mm^2$.

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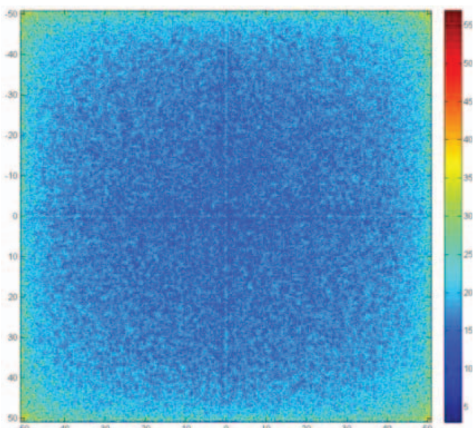


Fig. 2. Simulated density plot of photon strikes on the optical exit surface .

The light collection efficiency is the percentage of photons that strike the SiPMs. The photon detection efficiencies (PDE) are not taken into account. The calculation of volumetric light collection non-uniformity is illustrated with the help of Fig. 2. Fig. 2 shows the volumetric distribution of simulated light collection efficiencies for the second configuration in Table I. Scintillation pulses containing many thousands of photons were generated with uniform spatial distribution and allowed to optically propagate through the system. The relative probability of a photon being received at an SiPM as a function of its position of origin is shown in the plot. The warmer the color, the greater the probability of collection. Ideally, the entire volume would be uniform in color, indicating no difference in the percentage of photons collected as a function of their birth place. The non-uniformity is quantified by creating a histogram of the collection percentages from each voxel and taking the full-width at half-maximum (FWHM) of the curve. This value will add in quadrature with the other components of energy resolution such as the Poisson statistical spreading, the scintillator's intrinsic resolution, and the dark counts. This non-uniformity value is equivalent to the transfer resolution in [2].

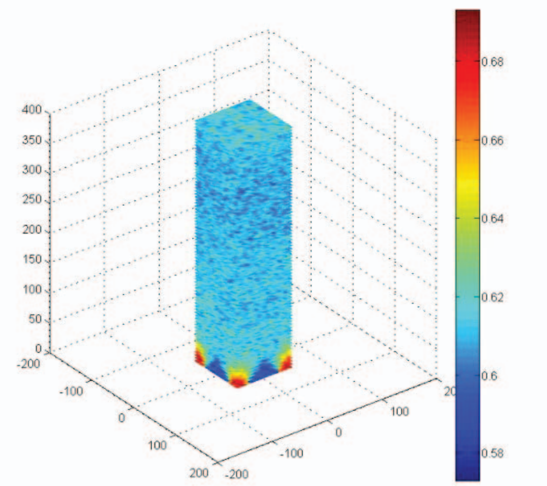


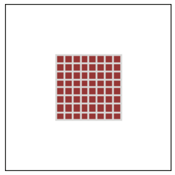
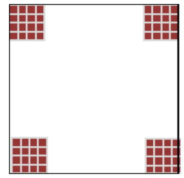
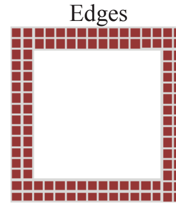
Fig. 3. Simulated volumetric distribution of light collection efficiency for corner SiPM readout .

Note two things about these data. The first is that simply moving SiPMs from the center of the face to the corners improves both the light collection efficiency and the non-uniformity of light collection. Both eventually contribute to a better energy resolution. This is a benefit that SiPMs have over monolithic PMTs; SiPMs are separable and can be arranged to take advantage of where the exit light flux is greatest. The second is that when SiPMs cover 39% of the face (last column), 78% of the light is collected, and the non-uniformity is only 1.8%. These are the same values as those calculated for a large PMT (Ø=90 mm) positioned in the center, which would cover 60% of the face and is a standard product offered by Saint-Gobain Crystals.

*C. Experimental results of edge/corner SiPM placement*

Experiments to verify this predicted behavior were performed with a 5x5x5 $cm^3$ NaI(Tl) crystal coupled to a 5x5 $cm^2$ SiPM array with 64 SiPMs in an 8x8 pattern (SensL 60035-64P-PCB). SiPMs in the array were either coupled to the crystal or covered with reflector to vary the number and pattern. Fig. 4 shows performance comparisons of positioning the SiPMs in the corners versus the center as a function of the amount of face covered by SiPMs. Fig. 4a compares pulse heights (PH) of the 662 keV photopeak from a $^{137}$Cs gamma ray source. PH is proportional to light collection efficiency, and is in general greater in the corners than in the center. Fig. 4b compares the 662 keV energy resolution and verifies that the volumetric non-uniformity is lower when light is collected from near the corners.

TABLE I. OPTICAL SIMULATION CONFIGURATIONS AND RESULTS

| | SiPM configuration | | |
|---|---|---|---|
| | Center | Corners | Edges |
| |  |  |  |
| Number of SiPMs (6x6 mm$^2$) | 64 | 64 | 112 |
| Fraction of surface covered | 22% | 22% | 39% |
| Light collection efficiency | 52% | 61% | 78% |
| Light collection non-uniformity (FWHM) | 2.9% | 2.3% | 1.8% |

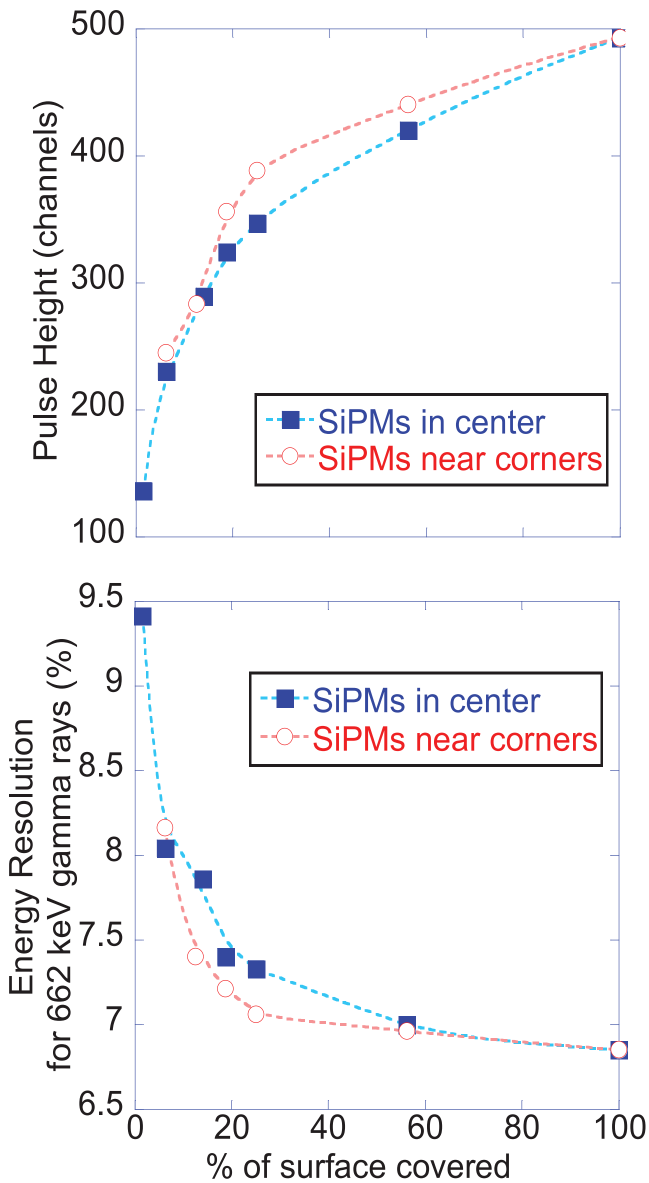



Fig. 4. Experimental results from a 5x5x5 cm$^3$ NaI(Tl) crystal patterned with various coverages of SiPMs.

Additional experimental verification was provided by a 5x10x40 cm$^3$ NaI(Tl) crystal, whose energy resolution data are shown in Fig. 5. Four, 16, and 64 SiPMs (SensL 60035J) were coupled to either the center section or in the corner regions of a 5x10 cm$^2$ face. Also plotted are the performance results of two PMTs (diameters = 50 mm or 90 mm) located in the center of the same face. As shown in this figure, SiPMs can approach the performance of large PMTs with less of the surface covered, especially when strategically placed in the edge/corner regions of a cuboid face.

Examination of Figs. 4 and 5 indicate that once 20-40% of the light exit surface is covered, then gains in performance come more slowly, and in this region the performance-to-cost ratio is likely to be maximized.

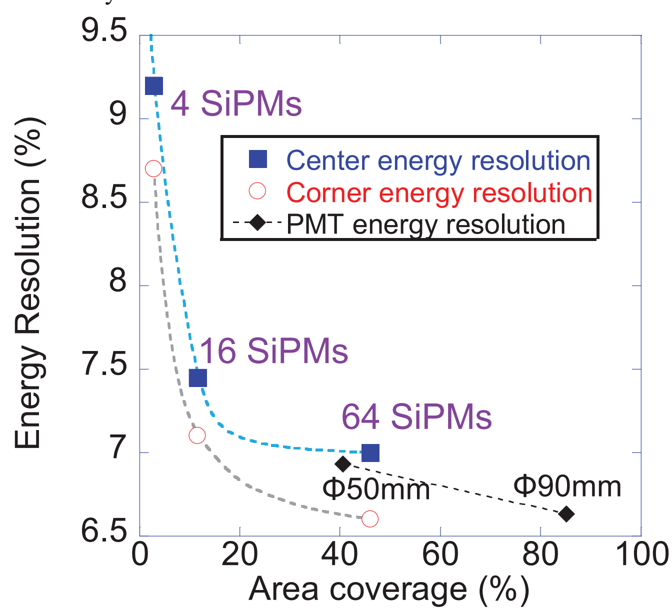



Fig. 5. Experimental results from a 5x10x40 cm$^3$ NaI(Tl) crystal patterned with various coverages of SiPMs and PMTs.

*D.SiPMs on more than one face*

Another issue is whether an advantage exists for placing SiPMs on more than one cuboid face. The compactness of SiPMs makes doing this much more reasonable than with

PMTs, which would drastically increase the size of the detector for most geometries. This issue was addressed through two additional simulations like the one shown in Fig. 3. The first new simulation added an additional 64 SiPMs in the corners of the opposite face of a 10x10x40 $cm^3$ crystal, and the second completely covered the edges with 112 SiPMs on only one face. Fig. 6 shows the configurations and volumetric non-uniformity maps of the two new simulations. Table II lists the performance results.

As expected, Table II shows improved behavior for doubling the number of SiPMs (first column vs. second column), but the third column shows that the extra SiPMs are better put to use all on one face. The performance of 112 SiPMs on one face is slightly better than 128 SiPMs split between two faces.

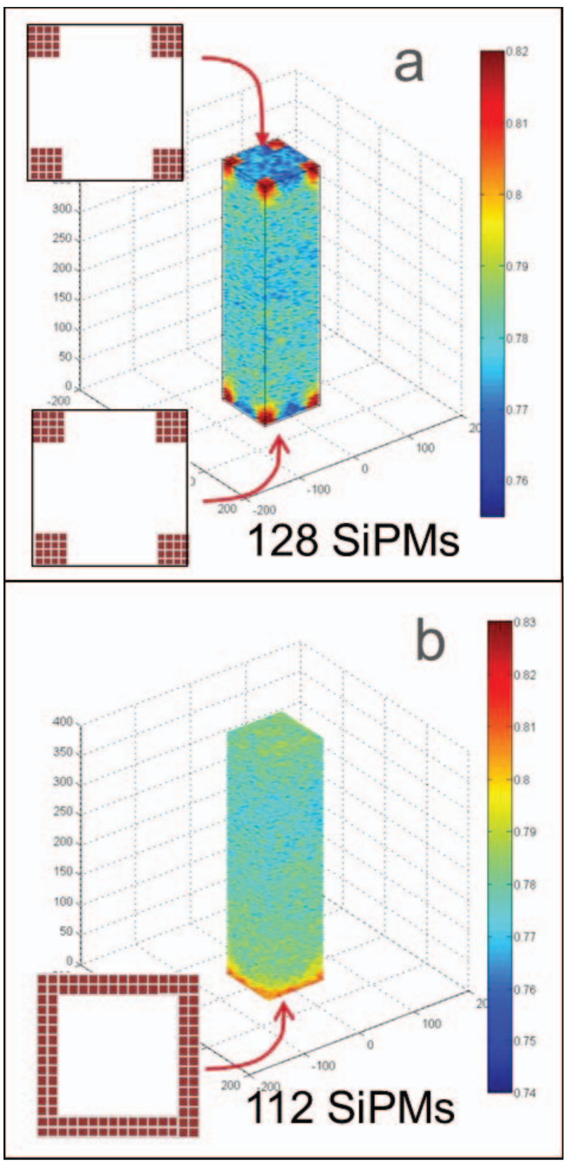



Fig. 6. Simulated SiPM configurations on a 10x10x40 $cm^3$ NaI(Tl) crystal and their respective volumetric uniformity maps. a) result for 16 SiPMs placed in 8 corners in opposing faces. b) result for 112 SiPMs covering the edges of one face in 2 rows. Table II tabulates the quantitative data for these simulations.

TABLE II. EFFECT OF SIPM PLACEMENT ON ONE OR TWO FACES

| | 64 SiPMs on 1 face | 128 SiPMs on 2 faces | 112 SiPMs on 1 face |
|---|---|---|---|
| light collection efficiency (%) | 61% | 78% | 78% |
| light collection non-uniformity (FWHM) | 2.3% | 1.9% | 1.8% |

## IV. CONCLUSIONS AND FUTURE WORK

Simulations and experimental tests show that large NaI(Tl) crystals instrumented with a limited number of SiPMs can achieve best performance-to-cost ratios when the SiPMs are placed near the edges and corners of the light extraction surface. The amount of light collected is greater, and the volumetric light collection non-uniformity is better vis-à-vis placement in the center. This holds for typical cuboid shapes and aspect ratios (length/width) ranging from 1 to at least 3. Two general guidelines are drawn from this work: 1) coverage of the light extraction surface only needs to be 20-40% to achieve PMT-like results, and 2) if challenged with only being able to cover 20-40%, it is better to place this limited number of SiPMs on a single surface than divide them between two surfaces.

The results presented in this report are far from comprehensive. The number of possible scintillator geometries and SiPM configurations is enormous, and the intention here is to provide starting points for further optimization.

What has worked in this report for NaI(Tl) may not work in the same way for high performance scintillators such as $LaBr_3$(Ce), $SrI_2$(Eu), or CLLB [3]-[5]. NaI(Tl) has a poorer intrinsic energy resolution and is therefore less sensitive to inefficiencies and non-uniformities in light collection [2]. However, these NaI(Tl) results are extremely pertinent because large ($\gtrsim$2000 $cm^3$) monolithic inorganic scintillators are almost always NaI(Tl) detectors.

Continued work in this area will look at performance at low gamma ray energies where SiPM dark counts are expected to have a significant effect. Surface roughness and reflector strategies will be examined to provide further optimization. Other scintillating materials will be investigated, including very large ($\gtrsim$20000 $cm^3$) organic scintillators.

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