Optimising SiPM Array Architectures and Optical Coatings for High-Efficiency ZnSe(Al,O)-Based Sr-90 Detection

A.Kolnikaj[1], K. A.A. Gamage[1], O. Popoola[1], J.Graham[2], A. Di Buono[2]

[1]University of Glasgow, University Avenue, Glasgow, G12 8QQ, UK

[2]United Kingdom National Nuclear Laboratory, Sellafield, Sellafield, Seascale, Cumbria, CA20 1PG, UK.

University of Glasgow

United Kingdom National Nuclear Laboratory

Introduction

There is a need for rapid, real-time monitoring of Sr-90 in groundwater at nuclear sites. Current methods rely on laboratory analysis of collected samples, which is slow, costly, and poorly suited to continuous field deployment. This work develops a compact ZnSe(Al,O)-based beta spectrometer using an inorganic scintillator coupled to silicon photomultipliers and custom readout electronics. A Geant4 optical model is used to study how crystal surface treatment and SiPM placement affect photon collection, detector efficiency, and overall spectroscopic performance.

Method

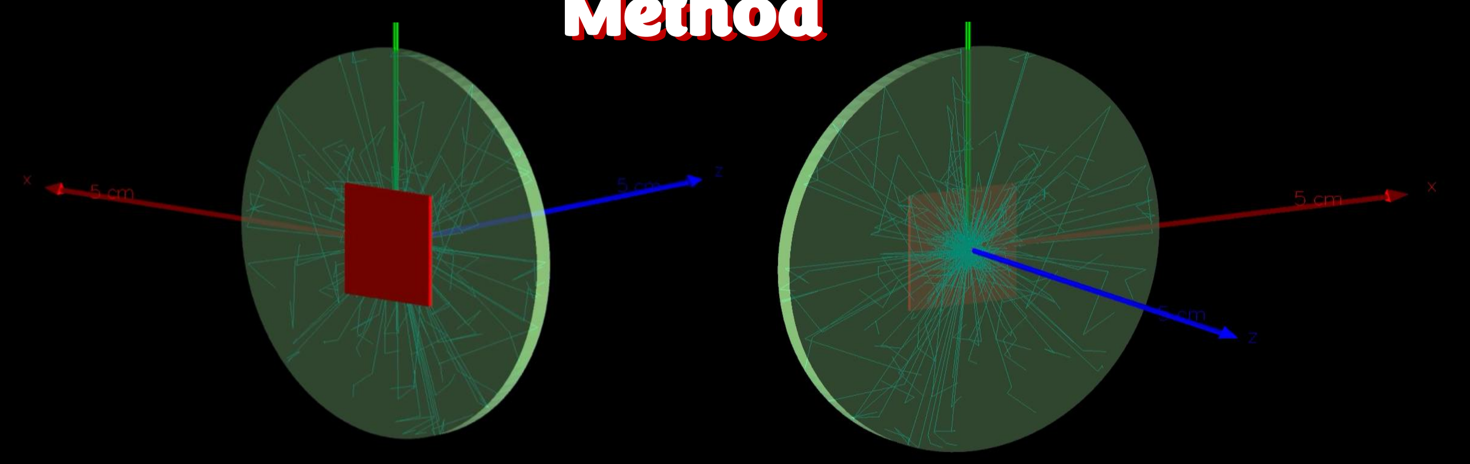


Figure 1: A screenshot from the Geant4 visualiser showing a ZnSe(Al,O) crystal optically coupled to a SiPM, with the PTFE coating . Optical photons can be seen propagating through the scintillator, being reflected and successfully contained by the coating.

A model was developed using the Geant4 Monte-Carlo toolbox [1]. This consisted of a ZnSe(Al,O) crystal with diameter of 42 mm and thickness 2.1 mm. A simulated coating was then applied, matching the contours of the crystal and measuring 20 um thick. The material was then set to either be aluminium or polytetrafluoroethylene (PTFE), both with surface reflectivity of 92%. This was then optically coupled to an array of SiPMs ranging from 1x1 to 14x14, with each SiPM having a photosensitive area of 3x3 mm^2.

Results II

Figure 4 quantifies the effect of SiPM array size on collection efficiency for uncoated, aluminium-coated, and PTFE-coated ZnSe(Al,O) crystals.

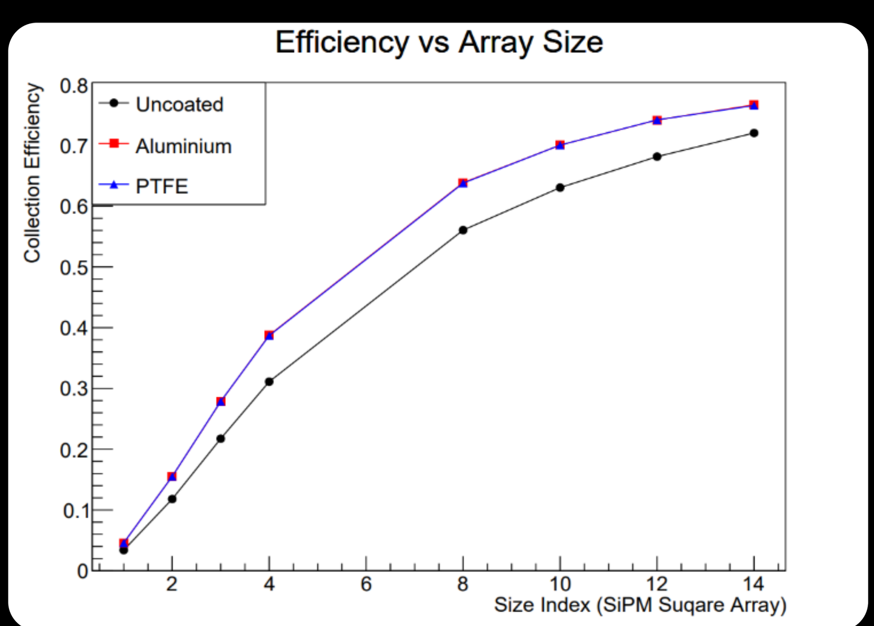


Figure 4: Simulated collection efficiency as a function of SiPM array size for uncoated, aluminium-coated, and PTFE-coated ZnSe(Al,O) crystals.

- Collection efficiency increases rapidly up to an 8 by 8 array, then begins to plateau. This indicates diminishing returns beyond this array size.
- Coated crystals show consistently higher collection efficiency than the uncoated crystal. Aluminium and PTFE give near-identical results in the model because similar reflectivity values were used.

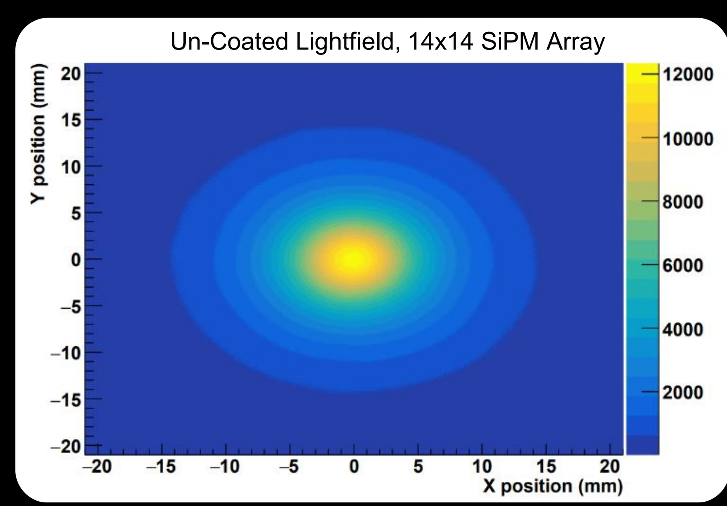
Conclusion

Geant4 simulations show that ZnSe(Al,O)-SiPM detector performance is strongly governed by optical transport, surface treatment, and SiPM coverage. Reflective coatings improve photon collection, while larger SiPM arrays produce a more stable and proportional detector response. Collection efficiency begins to plateau beyond an 8 by 8 array, suggesting that further sensor coverage gives diminishing returns. These results support an optimised coated-crystal and SiPM-array design for compact Sr-90 beta spectroscopy.

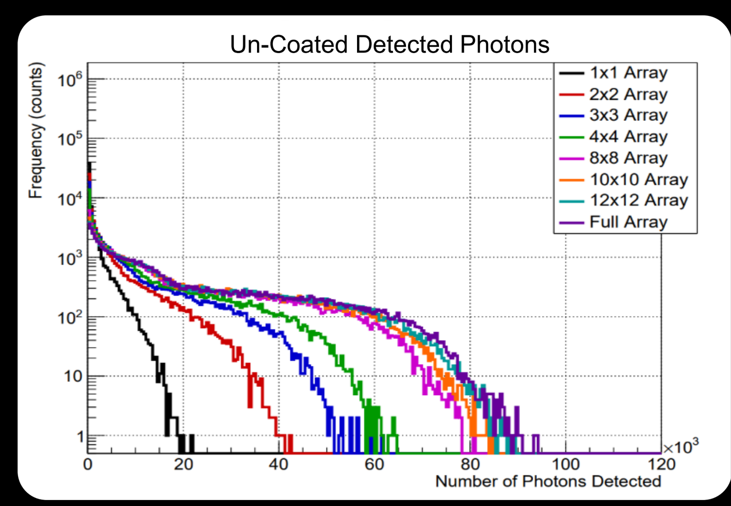
References

[1] S. Agostinelli et al. Geant4—a simulation toolkit, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 506, Issue 3, 2003, Pages 250-303, ISSN 0168-9002, https://doi.org/10.1016/S0168-9002(03)01368-8.

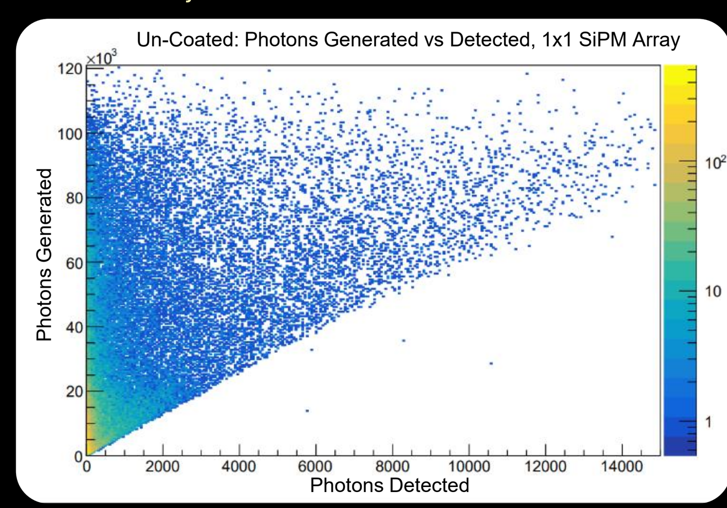
Results I



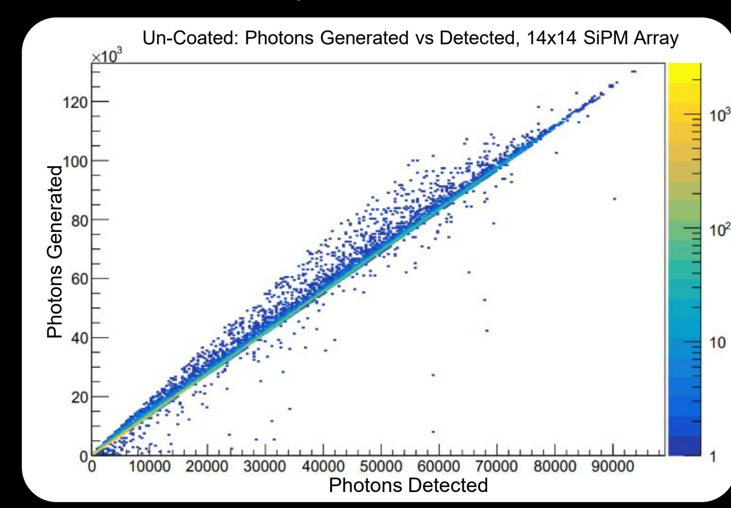
(a) Photon distribution produced by the crystal when coupled to a 14x14 array of SiPMs with Sr-90 source incident.



(b) Frequency of photons detected by the SiPM array ranging from a 1x1 to 14x14 array.



(c) Photons generated vs detected for a 1x1 array with heat map of frequency of detected events.

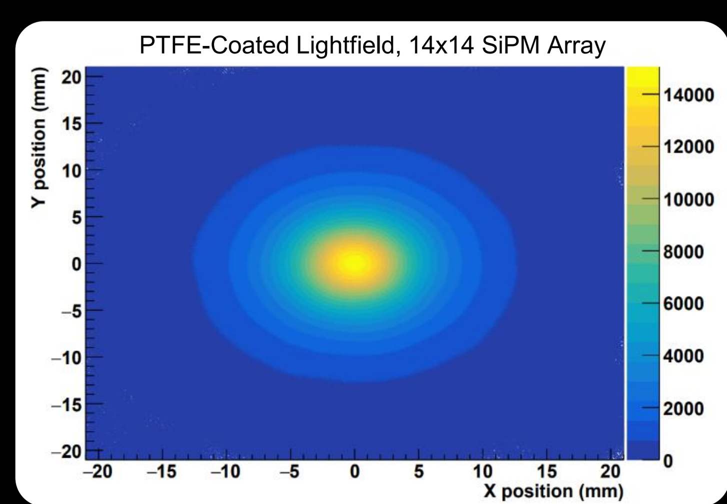


(d) Photons generated vs detected for a 14x14 array with heat map of frequency of detected events.

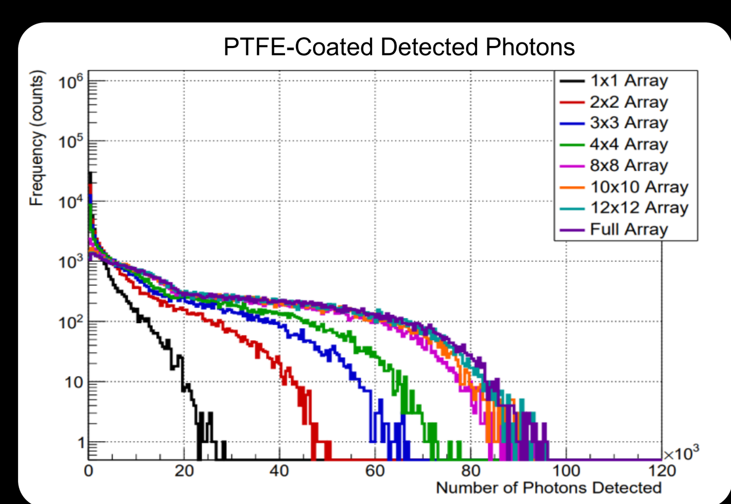
Figure 2: Collection of results for varying sized SiPM arrays coupled to an un-coated ZnSe(Al,O) crystal.

Figures 2 and 3 compare the optical response of uncoated and PTFE-coated ZnSe(Al,O) crystals coupled to different SiPM array sizes. Aluminium-coated crystals were also simulated but are not shown because the model produced near-identical photon collection behaviour.

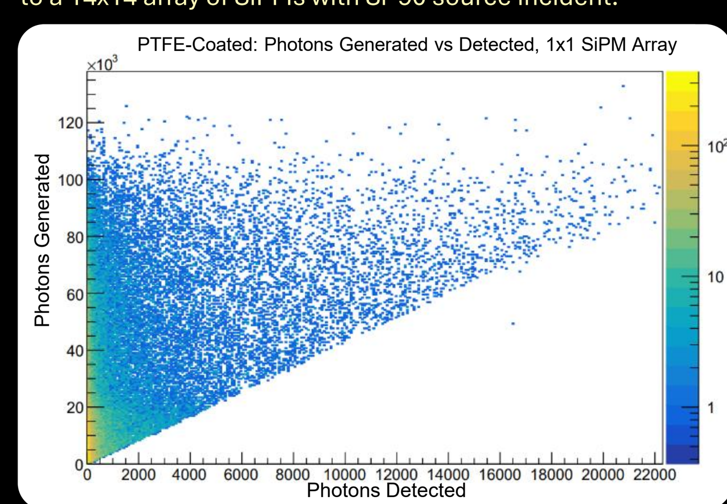
- The simulated light fields shown in **2a** and **3a** is strongly concentrated near the centre of the crystal. The PTFE-coated crystal produces a higher photon density than the uncoated crystal, indicating improved photon retention through reflection at the crystal boundaries.



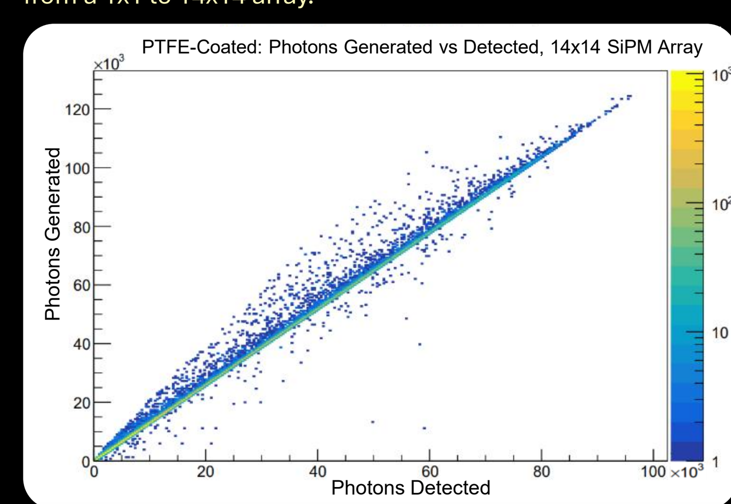
(a) Photon distribution produced by the crystal when coupled to a 14x14 array of SiPMs with Sr-90 source incident.



(b) Frequency of photons detected by the SiPM array ranging from a 1x1 to 14x14 array.



(c) Photons generated vs detected for a 1x1 array with heat map of frequency of detected events.



(d) Photons generated vs detected for a 14x14 array with heat map of frequency of detected events.

Figure 3: Collection of results for varying sized SiPM arrays coupled to PTEFE-coated ZnSe(Al,O) crystal.

- Figures **2b** and **3b** show detected-photon distributions for SiPM arrays from 1 by 1 to 14 by 14 under Sr-90 irradiation.
- Larger arrays shift the response towards higher photon counts and retain more of the high-photon tail. For the same array size, the PTFE-coated crystal detects more photons than the uncoated crystal.
- Figures **2c** and **3c** show broad, unstable responses for the 1 x 1 arrays, while Figures **2d** and **3d** show tighter diagonal bands for the 14 x 14 arrays.
- This indicates a more proportional relationship between generated and detected photons. This is needed is for spectroscopy because the detector response becomes more predictable and better correlated with deposited energy.