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[1] http://kromek.com/index.php/products/all-nuclear-products/sigma

[2] http://kromek.com/index.php/link-3/oem-solutions/ubiquitous-radiation-network-solution (last retrieved 9th July 2017)

[3] A. Giaz et al., Nucl. Instrum. Meth. A 772, 103 (2015).

List of acronyms and abbreviations

$LaBr_3$:Ce	A transparent scintillator material that offers the best energy resolution obtained so far.
$CeBr_3$	An alternative to LaBr, not exhibiting the internal radiation of La
SiPM	Silicon photomultiplier
PMT	Photomultiplier Tube
PSPMT	Position Sensitive PMT
UoY	University of York

EXECUTIVE SUMMARY

Research and development have been carried out into hybrid scintillator detectors for nuclear physics and societal applications. The focus is on the potential for the application of SiPMs for light collection. Their excellent performance has been demonstrated in terms of energy resolutions comparable to the best obtained with regular PMTs – close to 3% at 662-keV when coupled to $LaBr_3$. Moreover, specific technical issues in their deployment have been overcome through development of a bespoke temperature-stabilising bias circuit. SiPMs facilitate innovative solutions for light collection unachievable with PMTs and show excellent promise for realising the determination of point of interaction within large scintillator crystals. Hybrid prototype designs are advanced on this basis. They will be the subject of Monte-Carlo simulations. Data will be obtained with a bespoke collimated-beam scanning system, which will allow to evaluate the prototype detector performance in the next phase of the project.

0 INTRODUCTION

Hybrid detectors employing two or more scintillators are an interesting possibility for nuclear physics and societal applications. Phoswich detectors, where two different scintillators are coupled and the light is collected with a common photomultiplier tube (PMT), are a technology of long standing. This technique works best when the two scintillators differ strongly in terms of the decay time of their scintillation light output, i.e. where one is fast and the other is slow. The recent advent of fast digital data acquisition suggests scope for improvement in separating scintillation components. An alternative, so far largely unexplored in terms of hybrid detectors, is to use layers of scintillator read out by silicon photomultipliers (SiPMs). Such sensors are intrinsically compact and low profile affording the possibility of new, compact geometries for hybrid detectors. Moreover, SiPMs operate at low voltage (typically 30-60 V), and are cheap and robust compared to PMTs which have an evacuated tube.

1 SENSOR CHARACTERISATION

1.1 Choice of silicon multiplier

We have considered two choices for the SiPMs to be used in this project. The first are from Hamamatsu - a major international company based in Japan - which manufactures all kinds of photosensors including PMTs. The second option are SiPMs produced by SensL, a smaller spin-off company from University College Cork and based in Ireland. The UoY group has collaborated with SensL for the last ten years both directly and through their industrial partners, Kromek PLC. With Kromek, UoY developed a hand-held radiation detector based on a SiPM coupled to a CsI(Tl) crystal (see Figure 1) [1]. This product has latterly transformed into the D3S [2] which is a wearable system. This company has recently received a $6M order for 12000 units from the US government. The strong experience of working with SensL both directly and indirectly dictated the choice of sensor.

Figure 1: Hand-held gamma-ray spectrometer based on SiPM/CsI(Tl) combination developed by UoY for Kromek PLC.

Our initial work on the Kromek project was based on the SensL C-series SiPMs which are blue-colour sensitive and a good match to scintillators such as $LaBr_3$ and $CeBr_3$. During 2016, SensL developed the J-series in response to the needs of scintillator coupling in collaboration with UoY and Kromek. Such square SiPMs come in 3-mm or 6-mm sizes. The main characteristics to determine the efficiency of the sensor is the Photon Detection Efficiency (PDE): The PDE is the probability that a photon arriving on the SiPM surface is detected, producing an output pulse. It can be defined as the ratio between the number of detected photons over the number of incoming photons. Typical parameters of these sensors are given in Figure 2.

Sensor Size	Microcell Size	Parameter [1]	Overvoltage	Min.	Typical	Max.	Units
3mm	20µm, 35µm	Breakdown Voltage (Vbr) [2]		24.25	24.5	24.75	V
6mm	35µm						
3mm	20µm, 35µm	Recommended Overvoltage Range (Voltage above Vbr)		1		6	V
6mm	35µm						
3mm	20µm, 35µm	Spectral Range [3]		200		900	nm
6mm	35µm						
3mm	20µm, 35µm	Peak PDE Wavelength (λp)			420		nm
6mm	35µm						
3mm	20µm	PDE [4]	Vbr + 2.5V		31		%
	35µm				38		%
	20µm		Vbr + 6.0V		42		%
	35µm				51		%
6mm	35µm		Vbr + 2.5V		38		%
			Vbr + 6.0V		51		%
3mm	20µm	Dark Count Rate [5]	Vbr + 2.5V		45	75	kHz/mm²
	35µm				45	75	kHz/mm²
	20µm		Vbr + 5.0V		80	157	kHz/mm²
	35µm				80	157	kHz/mm²
6mm	35µm		Vbr + 2.5V		45	75	kHz/mm²
			Vbr + 5.0V		80	157	kHz/mm²

[1] *All measurements made at 5.0V overvoltage and 21 °C unless otherwise stated.*
[2] *The breakdown voltage (Vbr) is defined as the value of the voltage intercept of a straight line fit to a plot of √I vs V, where I is the current and V is the over-voltage.*
[3] *The range where PDE >2.5% at Vbr + 5.0V.*
[4] *PDE does not contain afterpulsing or crosstalk.*
[5] *Dark count rate is derived from dark current data.*

Figure 2: Key parameters for the SensL J-series (taken from the datasheet http://sensl.com/downloads/ds/DS-MicroJseries.pdf).

The main improvement of the J-series over the earlier C-series relates to the close packing of the SiPM arrays achieved by reading out the sensors through silicon vias. This makes them eminently suitable for coupling to large scintillator crystals (see Figure 3).

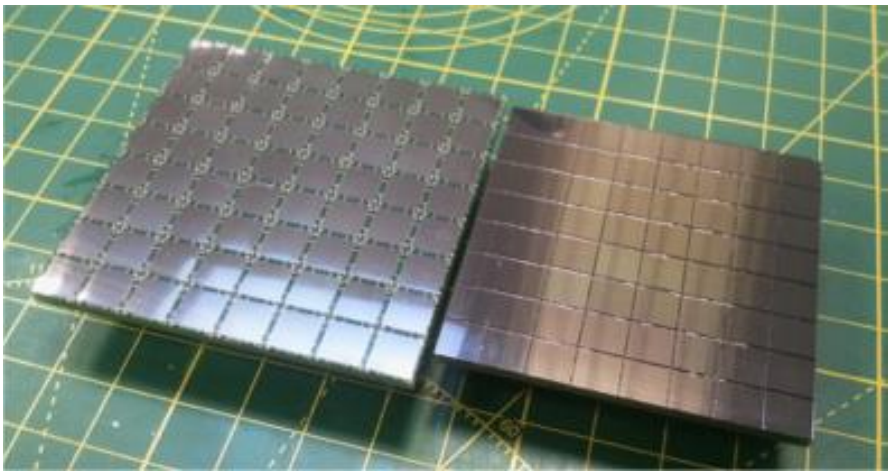

Figure 3: (left) An 8 x 8 array of 6-mm C-series SiPMs compared to the higher fill factor (right) 8 x 8 array of 6-mm J-series SiPMs.

1.2 Performance with large scintillators

We have studied the performance of the SensL SiPM arrays in configurations suitable for hybrid detectors for nuclear physics. In particular, we coupled 8 x 8 arrays of 6-mm SiPMs of both C-type and J-type to a 2” cubic LaBr3 crystal with one open end (see Figure 4).

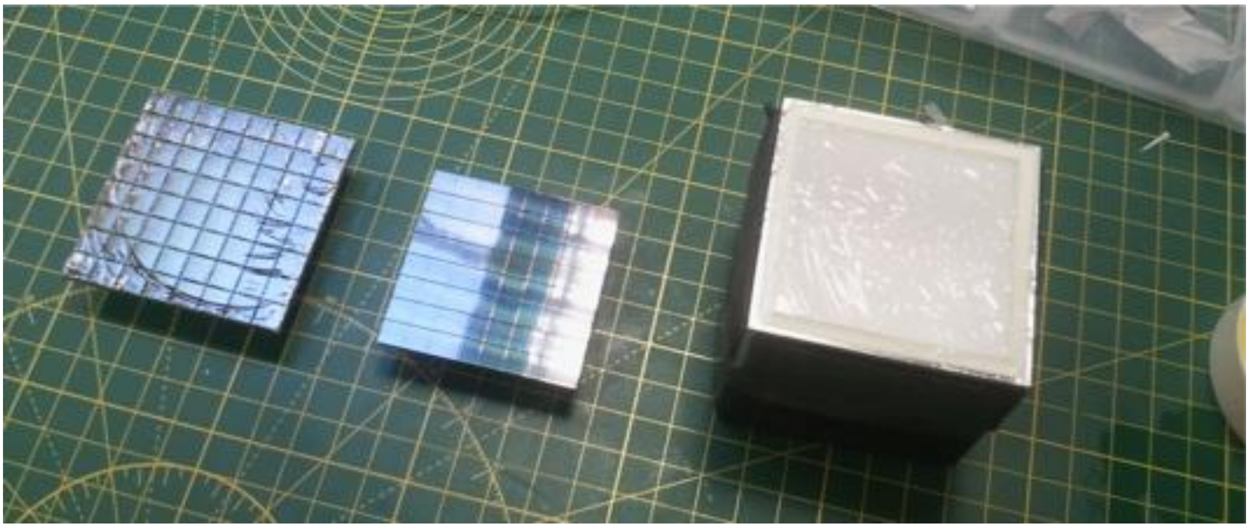

Figure 4: Sensl C-series array (left), J-series array (centre) and 2" cubic $LaBr_3$ crystal (right).

The resolution of the detectors was optimised as a function of bias voltage on the SiPMs, with 28.5 V being found to be the most appropriate voltage for room-temperature operation. The achieved energy resolutions at 662 keV were 3.8 % for C-type and 3.2 % for J-type (see Figure 5). The latter compares favourably with the best performances achieved with a photomultiplier tube for such a crystal of order 3 %. The J-series has two outputs – an energy output and a fast-timing output intended for PET applications. Timing resolutions were measured using a ^{22}Na source for the SiPM-readout detector in coincidence with a small LaBr3 crystal coupled to a fast PMT. Timing resolutions of around 1.0 ns were obtained with the fast timing output and 1.15 ns with the energy output from the J-series based on the sum of timing signals from four of the 64 elements of the SiPM array.

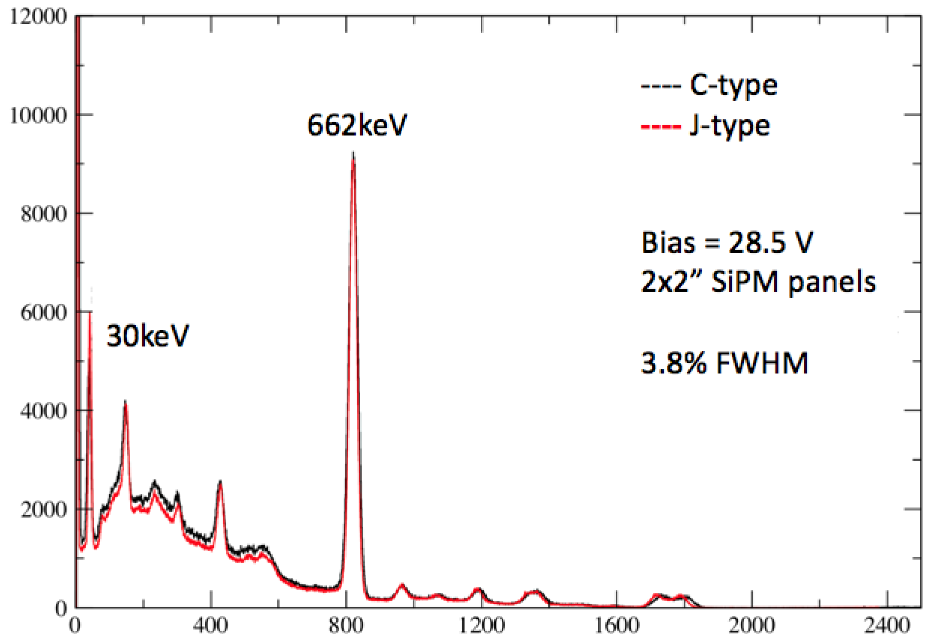

Figure 5: Comparison of performance of C-series and J-series array coupled to 2" $LaBr_3$ crystal.

An interesting possibility for a hybrid detector would be to combine the 2" cubic LaBr3 and SiPM array with a 2" x 2" x 6" NaI(Tl) crystal with conventional PMT positioned behind. This would be the same geometry as the phoswich detectors designed for the PARIS calorimeter. Such detectors comprise the two crystals permanently coupled and read out by a common PMT. In that case, typical energy resolutions for interactions solely in the $LaBr_3$ element are around 4.5 %. The performance of the SiPM-array readout is clearly superior. However, the SiPM array will introduce a small amount of dead space between the two crystals which may be important. The evaluation of the two separate crystal variant of the phoswich will take place in the next phase.

1.3 Gain stability with temperature

One of the issues in operating SiPMs as compared to PMTs is the strong change in gain as a function of temperature if the bias voltage is kept the same. We have produced our own in-house circuit using digital microprocessor-control to correct the bias voltage as a function of temperature to keep the gain fixed (see Figure 6). The device monitors the temperature close to the SiPMs and reports this back to an Arduino unit. This programmable unit is able to calculate the required bias, based on any function of temperature, and drive a power supply capable of supplying up to 50V and 30mA. The device has been tested using a 1" cubic CsI(Tl) crystal coupled to a 2 x 2 array of 6-mm J-series SiPMs (see Figure 6). Figure 7 compares a combined ^{137}Cs+^{152}Eu spectrum obtained at a fixed temperature of 20.5 °C to that obtained during a 15-minute sweep from 20 to 50 °C in a temperature controlled chamber. The energy resolution at 662-keV was 7.1 % for the fixed temperature, degrading to 7.6% for the data obtained during the sweep in temperature. The degradation in performance is expected since the dark current in the SiPMs increases strongly with temperature, doubling with every 10 °C increase in temperature.

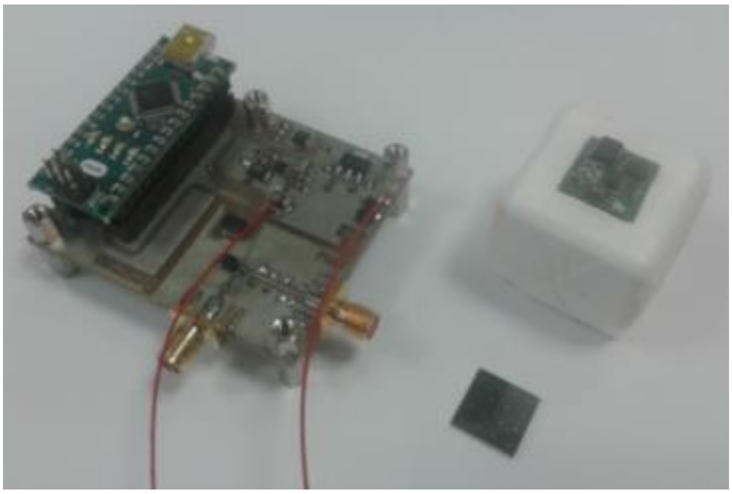

Figure 6: Temperature-compensation circuit to regulate SiPM bias voltage (built by UoY)

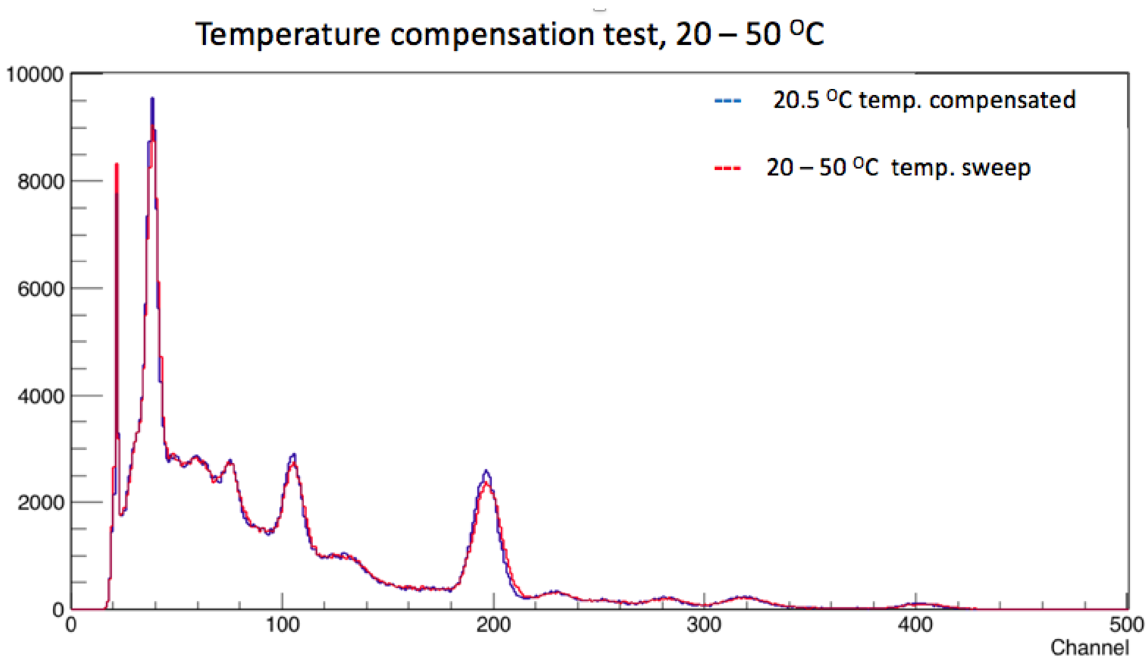

Figure 7: Temperature compensation tests with 1” CsI(Tl) crystal coupled to 2 x 2 SiPM array: The blue curve is the 137Cs/152Eu spectrum obtained at fixed temperature of 20.5 °C while the red curve is the spectrum obtained during a sweep in temperature from 20 to 50 °C.

1.4 Additional possible hybrid geometries

The possibility of SiPM readout makes all kinds of interesting geometries possible for hybrid detectors. Moreover, SiPM arrays provide an excellent opportunity for imaging where the point of interaction in the crystal is deduced from where the scintillation light is collected. Giaz et al. have shown that this is achievable even for a 3" LaBr3 detector with a position resolution of around 1 cm using a segmented photomultiplier tube [3]. This performance could, in principle, be improved upon using a SiPM array since the array elements are very uniform in performance, much more so than elements of a segmented PMT which can differ by 50% and significant corrections have to be applied to the raw signals in exploring the point of interaction. Moreover, the compact nature of SiPM arrays allows further interesting possibilities for light collection. For example, in Figure 8 where light is collected from both the rear face and one of the sides. This could allow localisation of the position of interaction in depth as well as x and y. Of course, in practice, such interactions may be multiple with Compton scattered photons and so some element of scanning the crystals and possibly machine learning will be needed to correlate measured signals with multiple points of interaction.

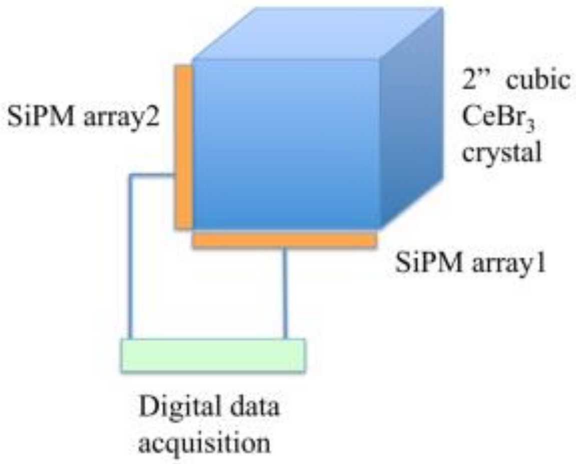

Figure 8: SiPM array readout on two faces of a crystal.

An alternative scheme for a hybrid detector would be to place individual sticks on to each SiPM on the array so that the elements are optically isolated – a "voxellated" detector. This is somewhat akin to the way that PET systems work. This would ensure interaction in a unique crystal but the sum of the individual volumes could add up to a large bulk crystal. An example scheme is shown in Figure 9.

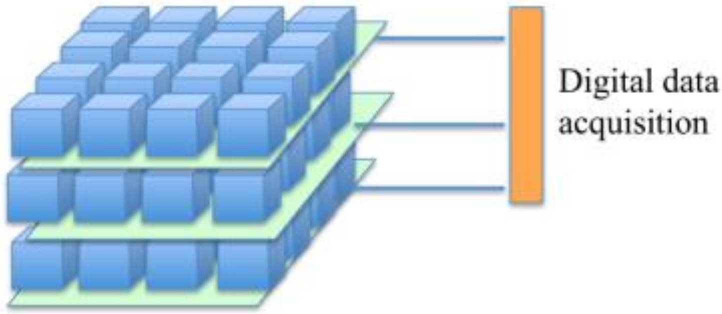

Figure 9: Possible hybrid geometry with individual cubes of scintillator assembled onto layers of SiPM arrays.

The designs described here have several advantages in position sensitivity. Firstly, if the point of first interaction can be extracted then this immediately constrains the opening angle to the radiation source which in many applications is well localised to a beam spot striking a thin target foil. Determining the first point of interaction requires an energy-dependent algorithm to be developed based on the well-known modes of gamma-ray interaction of photoelectric absorption, Compton scattering and pair production. The knowledge required is quite similar to that used in the gamma-ray tracking employed with the AGATA germanium array. In applications where the point of gamma-ray emission is not well localised, which could imply a fast-recoiling ion or in a societal application, a source distributed in the field, then the Compton camera approach could be highly relevant. Given the measurement of the total energy deposited and the positions of interaction, then the Compton camera reconstruction permits the determination of a cone from where the gamma ray originated. Intersection of such cones defines the point of emission, or characterising the distribution of the source in the field.

There are other specific advantages of the “voxellated” detector. For example, it should have very high rate capability since the light emission from, e.g., $CeBr_3$ is very fast – typical decay times of 20 ns and so each individual element may count at very high rates without feeling the effects of pile-up. In addition, some level of Compton suppression may be applied event-by-event since the probability for low energy (< 100 keV) photons to penetrate to the centre of a large composite detector, e.g. 50-mm cubic, is small and if such gamma rays are detected in the central 80% of the detector then they could be rejected. As an aside, this increases sensitivity to the 60-keV gamma ray from Am-241 in the presence of other gamma-ray fields, which is of high interest in homeland security applications.

The different hybrid schemes will be the subject of Monte-Carlo simulation. A GEANT4 model has been developed for scintillators and SiPMs which incorporates the transport and reflection of optical photons (see Figure 10).

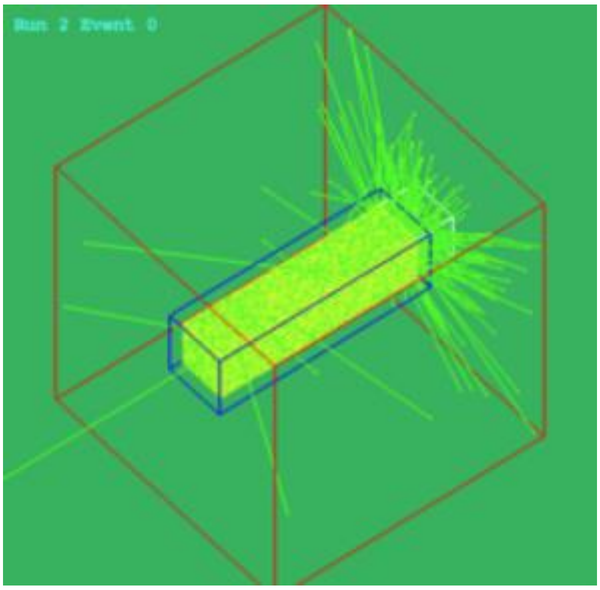

Figure 10: Visualisation of a GEANT4 simulation of a stick of CsI(Tl) wrapped with one open end. The optical photons are the green lines.

Different hybrid geometries may be explored with CsI(Tl) as a scintillator since this is not hygroscopic but it is also possible to assemble hygroscopic crystals in different combinations with SiPMs using a very low humidity glove box at UoY (see Figure 11) either to test directly in that environment or to can the detectors for testing outside.

Figure 11: Low humidity glove box at the University of York.

1.5 Scanning scintillator modules

In the next phase, we will scan prototype hybrid detectors using a strong, highly-collimated ^{137}Cs source. A special cabinet enclosure is being built in the workshop at UoY (see work in progress in Figure 12). This will contain a moveable shelf with an automated x-y scanning table on it. Prototype detectors may be placed on it under the gamma beam. The data may be collected via either an analogue or digital data acquisition. Data collection will take place in the latter half of 2017 and will interface with machine learning to deduce the position sensitivity for different hybrid geometries.

Figure 12: Collimated source enclosure under construction in the UoY workshop (July 2017).

2 Publications and Outreach

2.1 Published papers:

2.2 Conference contributions and Outreach:

- David Jenkins "Next-generation gamma ray detectors for nuclear physics based on large scintillators coupled to silicon photomultipliers".
  ANSRI - Application of Novel Scintillators for Research and Industry.
  Dublin, Ireland, May 11-13 2016.

Conclusion

Research and development have been carried out into hybrid scintillator detectors for nuclear physics and applications. The focus is on the potential for the application of SiPMs for light collection. Their excellent performance has been demonstrated in terms of energy resolutions comparable to the best obtained with regular PMTs. Moreover, specific technical issues in their deployment have been overcome through development of a bespoke temperature-stabilising bias circuit. SiPMs facilitate innovative solutions for light collection unachievable with PMTs and show excellent promise for realising the determination of point of interaction within large scintillator crystals. Hybrid prototype designs are advanced on this basis. They will be the subject of Monte-Carlo simulation. Data will be obtained with a bespoke collimated-beam scanning system which will evaluate the prototype detector performance in the next phase of the project.

Annex