GANAS project - Work Package 2

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Abstract: *Novel photosensors such as APDs and SiPMs have the potential to replace conventional PMTs for nuclear physics studies and wider applications in medical imaging and elsewhere. In the present work, APDs have been evaluated in conjunction with lanthanum bromide scintillators. Typical energy resolutions of 6-7% and timing resolutions of 1-2 ns are measured. The insensitivity of the prototype systems to magnetic field has been verified.*

Introduction: Scintillation detectors are important for charged-particle and gamma-ray detection both in nuclear physics, and medical and industrial applications. Conventionally, the best performance in terms of scintillation light collection is obtained with photomultiplier tubes (PMTs). Such PMTs cannot be operated in regions of high magnetic field. This imposes a strong restriction on the efficient employment of scintillator detectors in high magnetic field environments commonly found in various apparatus of interest in nuclear physics. In addition, there is very strong interest in the medical sector in combined imaging where it is desirable to perform positron-emission tomography (PET) or single-photon emission computed tomography (SPECT), which provide *functional* information, simultaneously with MRI, which provides *anatomical* information. This means that the scintillator-based technologies associated with PET or SPECT would need to be operated within the high magnetic field of an MRI magnet. It turns out that this need from the medical side aligns very well with topical interests in nuclear physics, where gamma ray detection is required in high magnetic field environments. Imaging systems, however, have two additional constraints. One is that RF-induced noise may affect the performance of the PET system. The second is the magnetic field is more susceptible to the placement of external objects (i.e. sensors and detectors).

Project aims: This work was focused on evaluating prototype gamma-ray detector systems which could be used in high magnetic field environments. A specific project of interest is a gamma-ray detector array to be used in conjunction with a helical-orbit spectrometer such as the HELIOS spectrometer at Argonne National Laboratory [Lig10,Wuo07]. Such a spectrometer is intended to study single-particle transfer reactions in inverse kinematics. The spectrometer comprises a large solenoidal magnet (such as a redundant MRI magnet) in which light ions from the reaction follow helical orbits before being detected along the axis in a compact linear silicon array. Detection of gamma rays would assist in assigning j values to observed states and in other applications. In this case, the gamma ray array would need to have high energy resolution but be capable of operating in a magnetic field up to 3-T. With the intention of achieving the highest possible energy resolution we considered the new generation scintillator material, lanthanum bromide, which has an intrinsic resolution better than 3% for 662-keV gamma rays. For the scintillation light collection, we focused mainly on APDS since they have low noise and good temperature stability. However, SiPMs (which are arrays of APDs working in Geiger mode) were also studied for the sake of completeness.

Survey of available sensors:

The principal manufacturer of APDs is Hamamatsu. Although we used mostly Hamamatsu APDs and SIPMs for this work, it is worth mentioning that there are few other companies which make such sensors including SensL (Ireland) and Photonique SA (now available from Advatech-UK). Photonique's sensors originate from CPTA Russia. These were not particularly useful to us as their efficiency in lower wavelength (380 nm) was negligible. Some measurements were also made using SiPMs from Hamamatsu – models 10362-11-025U and 10363-33-025C which were 1mm x 1mm and 3mm x 3mm in size. The 1-mm device was not useful for making an energy measurement due to its small size and thus small light collection efficiency, but it was possible for it to be used as trigger for timing.

We also tested some of SensL's earlier devices like their 4 x 4 array (or tile) but their efficiency was again not anywhere close to being suitable for use with $LaBr_3$(Ce). These devices may, however, be used in imaging applications where the scintillation photons are longer wavelength (500-600 nm). We have future plans to build a small imaging system using 4 x 4 two dimensional arrays where we plan to do a comparison between the Hamamatsu and SensL device (4 x 4 tile) which are both sensitive to the higher wavelength region where emission takes place in LYSO and BGO.

Description of work carried out:

The simple prototype which was the main goal of the study was constructed from a Hamamatsu APD with an $LaBr_3$(Ce) scintillator as shown in the picture. The APDs used were S8664-1010 and S8664-55 devices from Hamamatsu which had dimensions of 10mm x 10mm and 5mm x 5mm, respectively. The LaBr3(Ce) crystals are from St Gobain and are in a cylinder of 1-cm diameter and 1-cm depth encased in an aluminium canister. The APDs were mounted on a small PCB (see fig. 1) with a non-magnetic SMC connector on the back. Since the scintillator face was 10 mm, which was close to both the sensor dimensions, no light guides were used. The mounting of the APD on the scintillator was done using EJ-550 silicone gel obtained from ELJEN technologies and the sensor/detector system was wrapped in several layers of Teflon tape. Finally, they were wrapped in Al foil and then black masking tape to make them light-tight. The whole assembly was less than 1 cubic inch and connected to the preamplifier by a single cable. Mesytec unit MSI-8p was used as the preamplifier along with an Ortec 572 shaping amplifier for shaping and amplification. Power to the sensors was provided using Mesytec's MHV4 unit. Figures 2 and 3 show the performance of the sensor/scintillator system using ^{60}Co and ^{137}Cs sources, respectively.

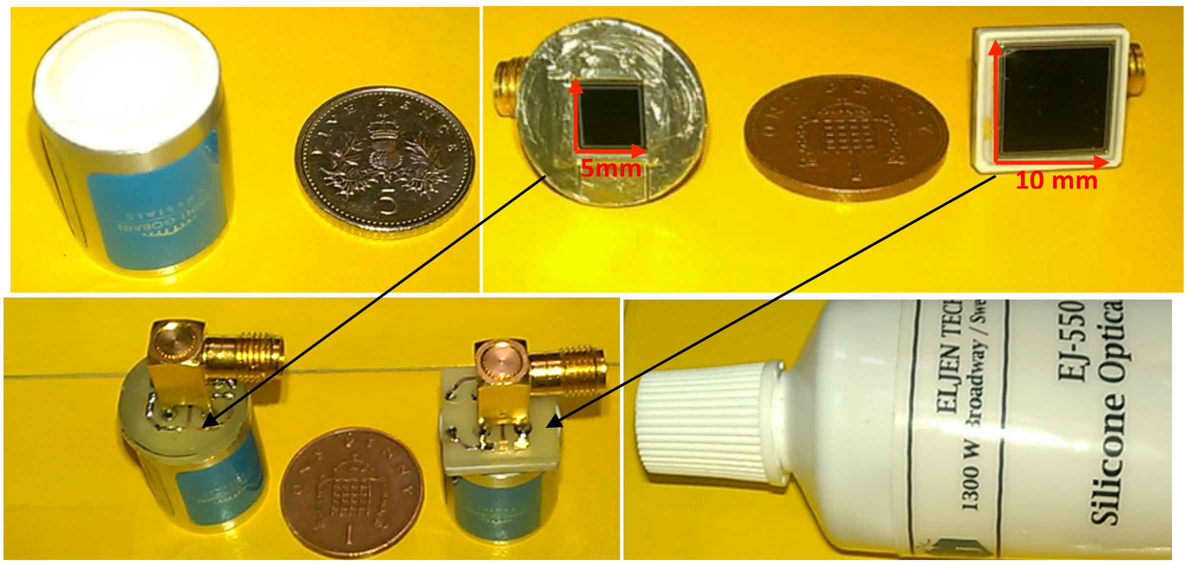

Fig1: LaBr$_3$(Ce) detector and the 5 x 5 mm and 10 x 10 mm APD sensors used for measurements.

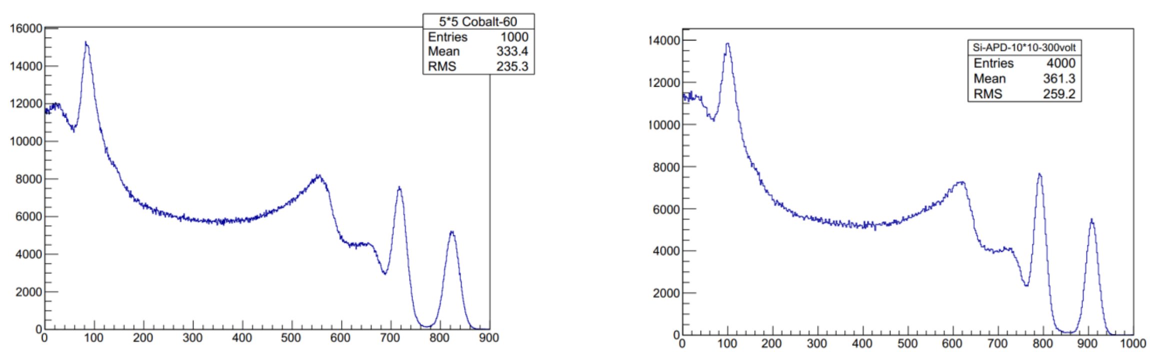

Figure 2: ^{60}Co spectra using a 5 x 5 mm and a 10 x 10 mm APD with LaBr3(Ce) scintillator with energy resolution of 4.23 % and 3.57 % at 1332-keV .

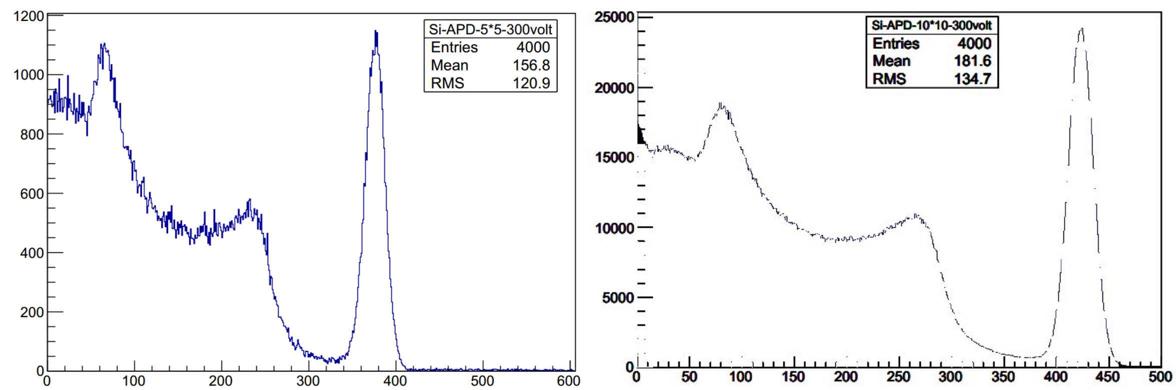

Figure 3: ^{137}Cs spectra using 5 x 5 mm and 10 x 10 mm APD with $LaBr_3(Ce)$ scintillator with energy resolutions of 7.3 % and 6.7 %, respectively, at 662-keV .

Magnetic field measurements: The performance of the prototype systems in a magnetic field was evaluated using a 1-T magnet (fig. 4) available in the Department of Physics at the University of York. The magnet belongs to the magnetic materials group and is a simple DC current magnet with sufficient in-pole gap to place the detector and APD. The preamplifier and the counting system remained on a trolley nearby. A ^{137}Cs source was used for the experiment and the measurements were done in the same setting with and without the 1-T magnetic field. The effect of the magnetic field on the performance of the detection system was found to be negligible (figure 5). These measurements were then repeated by changing the orientation of the detector with respect to the magnetic field - placing the detector axis perpendicular as well as parallel to the field axis. None of these measurements showed any deterioration in the performance in the magnetic field therefore suggesting that such a device would not be affected by the magnetic fields typically found in MRI magnets.

Fig 4: The 1-T Magnet, used for the study. The detector set-up can be seen in between the pole pieces in the bottom right figure.

Although APDs were the main focus of the tests, it was found that SiPMs showed similar insensitivity to magnetic field which is not so surprising given they are 2D array of tiny APDs and therefore, supposed to have similar characteristics.

There was still the question of whether the insertion of the sensor and scintillator would modify the magnetic field or not. In order to investigate this aspect, we decided to perform an MRI scan of a phantom with the detector unit placed next to the phantom. The scan was performed at the York Neuroimaging Center (YNIC). Due to a restriction imposed by YNIC, it was not possible to place measuring instruments (NIM bin, preamp etc.) inside the room containing the MRI machine. It was also not possible to use radiation sources within the facility. However, it was still possible to place the detector and the cables unit within the magnet's center alongside a phantom (a plastic ball filled with paramagnetic substance + H_2O) and perform a scan to see if any distortion to the image occurs. We used a 10 x 10 mm APD mounted on a 2.5 cm x 2.5 cm CsI(Tl) crystal and 5 x 5 mm APD mounted to an $LaBr_3$(Ce) encapsulated in aluminum. The connectors had 5-m long RG58 shielded cables connected with them. The images acquired by scanning this system showed that the there was a small influence on the magnetic-field homogeneity from the detector set-up when it was placed alongside the phantom which was placed close to the axis of the magnet. The distortion caused to the image was small and it was possible to correct it using the shimming coils available in the MRI system. Placing the detection set-up far away from the axis, where most likely it would be used in a research set-up like HELIOS or in an imaging scanner (PET insert for an MRI scanner), did not show any image distortion of the scanned object.

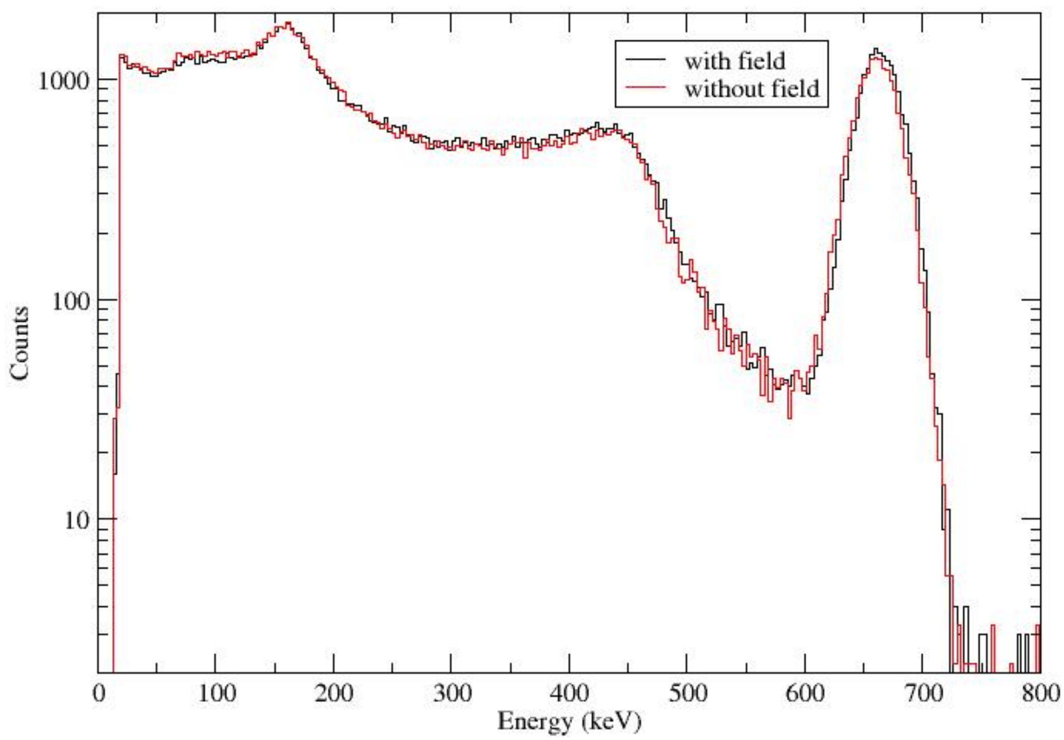

Fig 5 : A representative set of spectra for a ^{137}Cs source obtained with and without 1-T magnetic fields.

Figure 6: The 3-T MRI magnet at the York Neuroimaging Centre. The detectors are placed on the side of circular cage shown in the centre of the magnet. The cables from the detectors can be seen stretching along the bed.

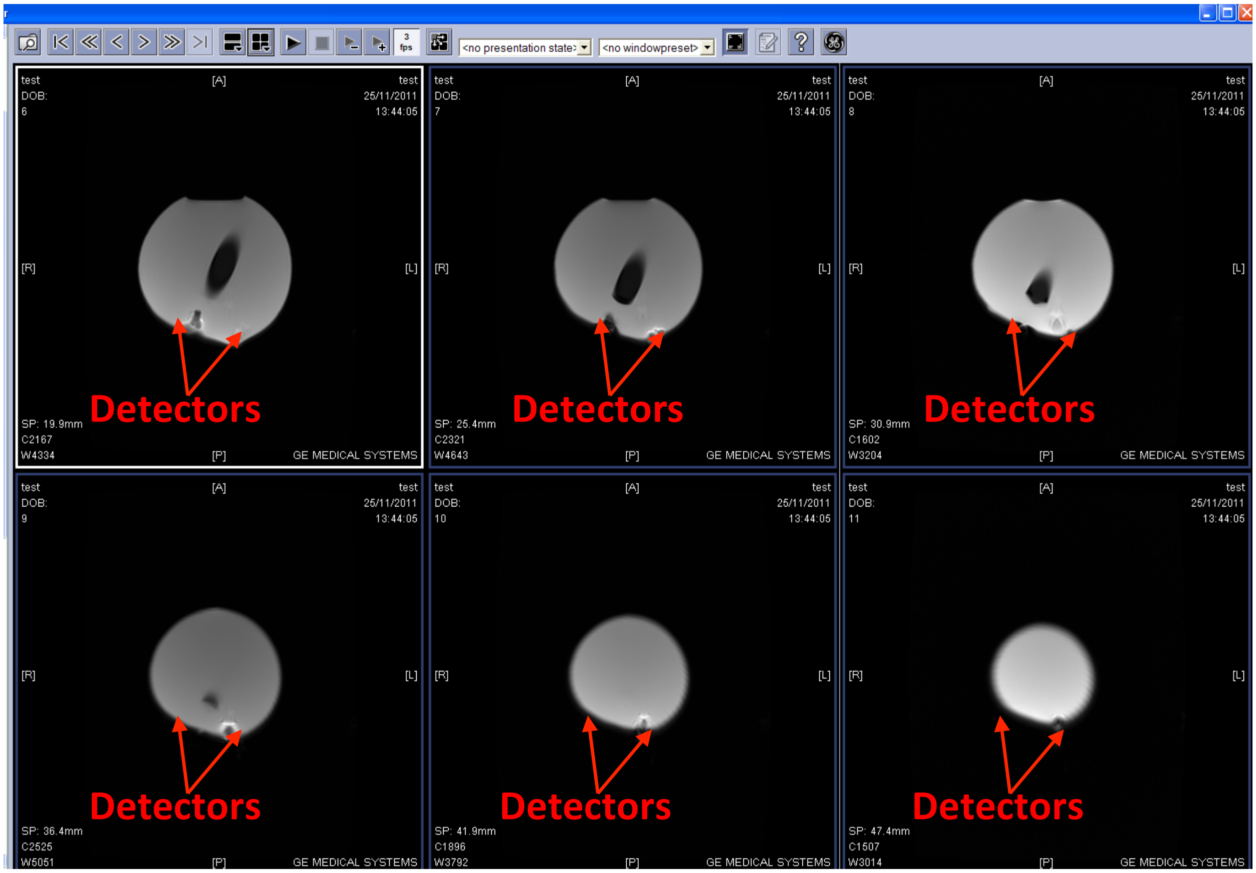

Figure 7: The MRI scan shows various cross sectional images of a phantom, taken at several depths along the magnetic field axis. The distortion of the magnetic field due to the detectors is apparent from the distortion in the images. This distortion can easily be corrected by shim coils in an MRI system. In normal use, the detectors will generally lie much further out and would cause minimal distortion to the field.

Timing measurements: Timing measurements were also performed using APDs. Since the timing of $LaBr_3(Ce)$ is << 1ns, almost all of the timing resolution is contributed by the APD sensors and the electronics. The setup used for the timing is as shown in the figure 8. Using this circuit, TAC spectra for a coincidence between the two APD+$LaBr_3(Ce)$ were obtained. The timing resolution for the APD was found to be about 1.6 ns (see fig 9). We also realized the need to study timing spectra using an SiPM as these could be potentially useful device in the PET systems where energy resolution is not of very prime importance. For the SiPM, a TAC was generated using SiPM+$LaBr_3(Ce)$ in coincidence with a BaF_2+Photomultiplier. A timing resolution of 2.2 ns was obtained (see fig 9) for this.

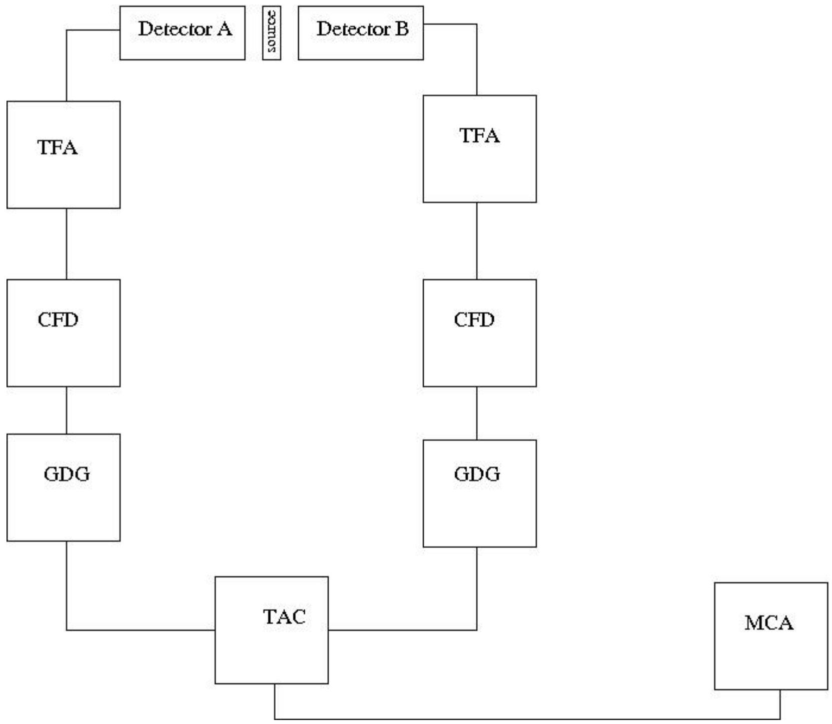

Fig 8: A general schematic representation of the set-up used for timing studies. The source used was ^{22}Na generating two gamma rays of 511 keV emitted near back-to-back.

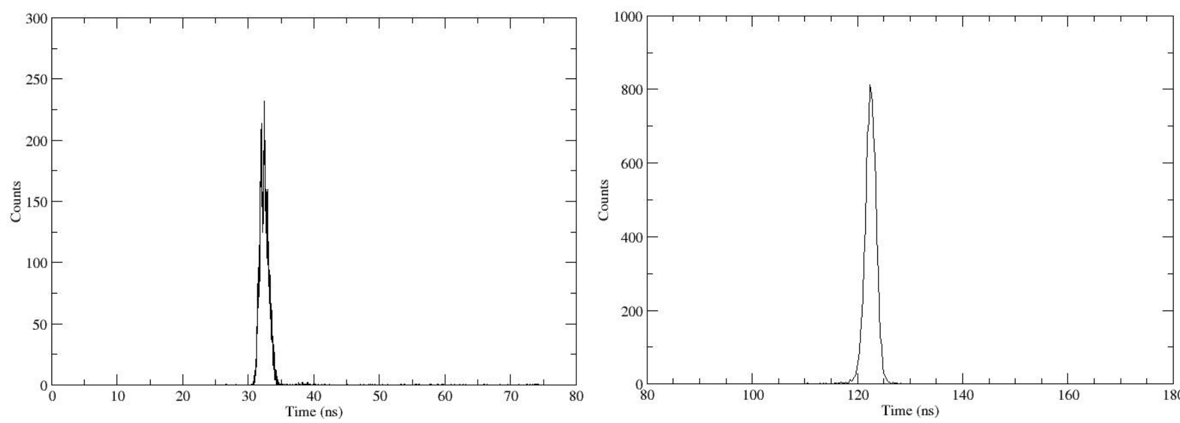

Fig 9: (left) TAC spectrum from coincidence between two Hamamatsu APDs (S8664). One of them was 5 x 5 mm while the other was 10 x 10 mm. A timing resolution of 1.6 ns was obtained. (right) TAC spectrum from coincidence between a SiPM + $LaBr_3$, and BaF_2 + photomultiplier. A timing resolution of 2.2 ns was obtained.

SiPM used low energy background reduction: As stated earlier, SiPMs were the less favorable devices for study as their use in spectroscopic energy measurement is limited by the problems like the higher levels of dark current related noise and temperature instability. Non-spectroscopic applications like PET/SPECT systems are possible places where these could still be used effectively. There are indeed ways to overcome the problems to some extent. The temperature can be reduced and made more stable using Peltier-cooled devices which are the new version of devices being made available now by Hamamatsu. Another possible way to reduce the effect of the noise related background in the SiPM is to read the light output from a given event using two light sensors. A coincidence between the two would occur when a genuine event (interaction) would generate scintillation light in the detector. In the case of noise the signal from one of the sensors would generally not show a coincidence with the signal from the other sensor. Thus the coincidence technique would be able to clean up the lower energy background.

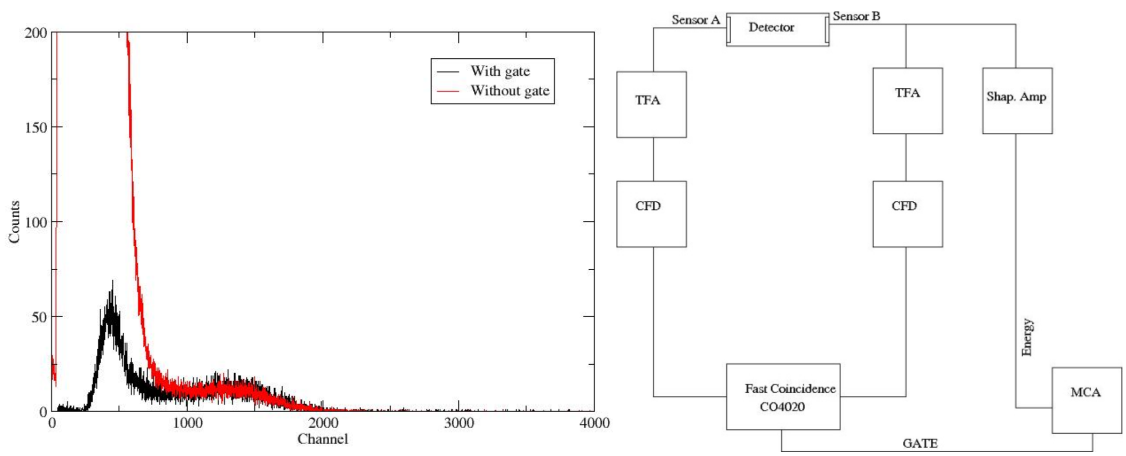

Fig 10: (on the left) energy spectrum from ^{137}Cs source using a 1 " x 1 " face CsI(Tl) with 3 x 3 mm SiPM sensor (shown in red) and the same (in black) when in coincidence with another sensor of 1 x 1 mm was demanded. This is to demonstrate that coincidence with another sensor helps in removing the lower energy noise. The schematic of the circuit used is shown on the righ-hand side.

The effectiveness of this technique could decrease with increasing voltage on the sensors as more and more random coincidences would then start appearing within the coincidence window due to larger amount of dark current. We did a preliminary investigation to test this. Although $LaBr_3$(Ce) was a good candidate scintillator to test such a technique but it was not possible to put the two sensors together on the small size crystal we had. Consequently we tried this technique using CsI(Tl) crystal which has two 1 inch faces available. Figure 10 shows the schematic of the set-up used and the spectra obtained using with and without coincidence gates. Hamamatsu 10362-11-025U (1 x 1 mm) and 10362-33-025C (3 x 3 mm) SiPM devices were used for this measurement. The result showed significant improvement in the background for lower energies. One would need more rigorous tests with various scintillators and sensor combinations as well as tests with various bias voltages in order to establish it as a useful technique.

Conclusions: The following discussion describes our general conclusions about the two available possibilities:

APD-based set-up: We aimed to build a simple prototype unit which could be used for spectroscopic energy and timing measurement in physics experiments. The use of APD in place of photomultiplier would allow for such a device to be used in high magnetic field. The device built using an APD and $LaBr_3$(Ce) fulfilled the minimum requirements for such a system. The energy resolution of 6-7 % and timing resolution of 1-2 ns would allow discrete gamma-decay studies to be carried out in coincidence with a charged particle detection set-ups like HELIOS without being affected by the magnetic field.

SiPM-based set-up: This work also allow us to gain understanding which is applicable in a variety of applications of APD as well as SiPM. SiPM have less energy resolution compared to the APD. The energy resolution requirements of a PET imaging system are less stringent than those for spectroscopy work, therefore, a setup built using the prototype unit of APD would obviously work in scanning system. However, one of the main issues in the PET insert MRI is the high noise arising due to high-power RF and thus the best solution is to use electronics components close to the sensors. Customized ASICs could be the answer to such a problem. On the basis of this short discussion we feel SiPM can replace the APD both in the spectroscopic as well as the imaging applications only if their major pitfalls are taken care of. For the imaging application, one would need customized ASIC-based electronics which is close to the sensors. In research applications leading to spectroscopy this is not a problem but the inherent noise needs to be removed to gain sufficient energy resolution from the SiPM. This can be achieved by using Peltier cooled SiPM combined with a coincidence gating technique mentioned earlier. Therefore the use of SiPM in both research and industrial applications, would need to be carefully considered and optimised. Once used in this way, SiPM could be excellent devices as they have sufficient efficiency for the lower wavelength scintillation (see fig 11).

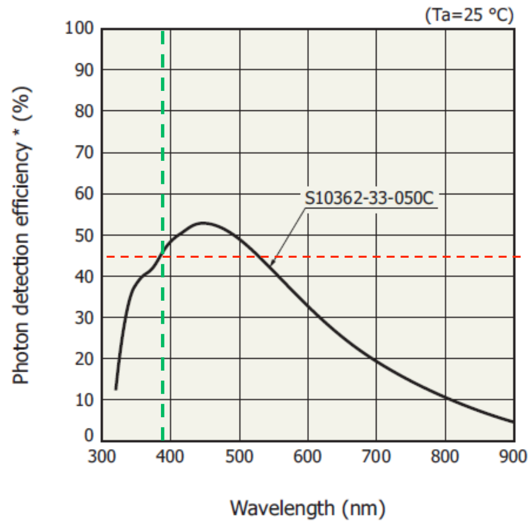

Fig 11: A plot of photon detection efficiency of Hamamatsu SIPM (S10362 series). At 380 nm it has an efficiency of 40%-50%.

References:

[Lig10] J.C. Lighthall et al., NIM A 622, 97 (2010).

[Wuo07] A.H. Wuosmaa et al., NIM A 580, 1290 (2007).