# Characterisation of Silicon Photomultipliers for Time-Of-Flight Applications

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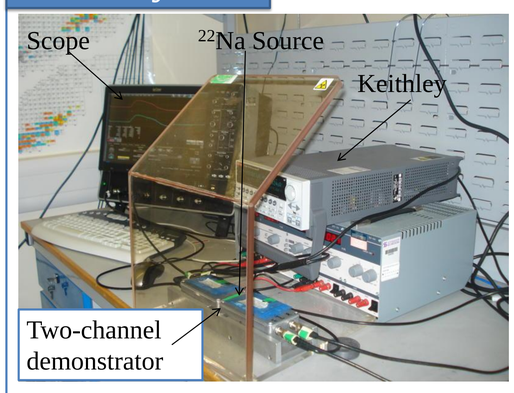
The recently developed Silicon PhotoMultiplier (SiPM) is a solid state photon detector operating in the Geiger mode. Due to avalanche nature of its signal, it has a fast response time; this makes it an ideal candidate for use in fast Time-Of-Flight (TOF) applications. This work is aimed at the application of TOF to medical imaging. In this study we characterised SiPMs from three manufacturers: breakdown voltages, dark count rates, rise times of dark noise signals and signal in response to light sources were measured. Two-channel demonstrators were built coupling SiPMs to $LaBr_3$(Ce) and LYSO crystals and their time performances were studied. The best timing resolution was measured to be 298ps (σ).

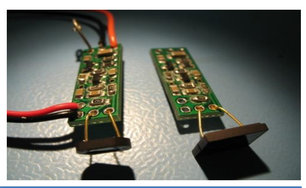
## 1. The system



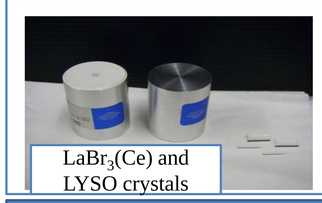

The experimental set-up for timing resolution studies

Electronics:
1. Read-out boards: preamp boards from Photonique, ~ 700ps rise time, gain 10x-20x
2. Power supply: Keithley 2612 two-channel sourcemeter 200V

DAQ: Lecroy Wave Pro 725Zi 2.5GHz oscilloscope, 40GHz sampling rate



SiPMs & Photonique boards



$LaBr_3$(Ce) and LYSO crystals

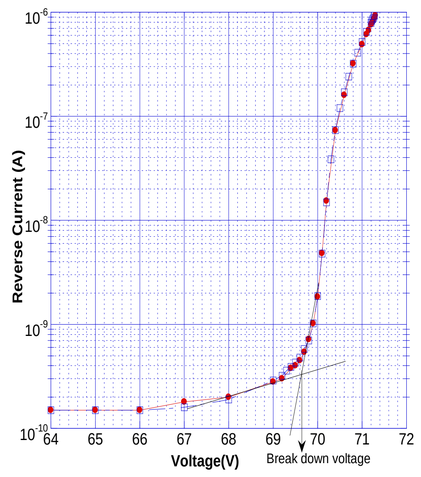
| Manufacturer | Area (mm²) | Cell Size |
|---|---|---|
| Hamamatsu | 1x1 | 25μm,50μm,100μm |
| | 3x3 | 25μm,50μm,100μm |
| Photonique | 1x1 | No information |
| | 2x2 | No information |
| SensL | 1x1 | No information |
| | 3x3 | No information |

| Crystal | Area (mm²) | Length (mm) |
|---|---|---|
| LYSO | 1x1 | 5 |
| | | 10 |
| | 3x3 | 5 |
| | | 10 |
| | | 15 |
| | 4x4 | 5 |
| | | 10 |
| $LaBr_3$(Ce) | 3x3 | 30 |

Sources:
1. For SiPM characterisation: blue (450nm peak-emission) LED and 1050nm Laser both from PicoQuant
2. For timing resolution studies of two-channel demonstrators: $^{22}$Na source

## 2. I-V curves and breakdown voltages

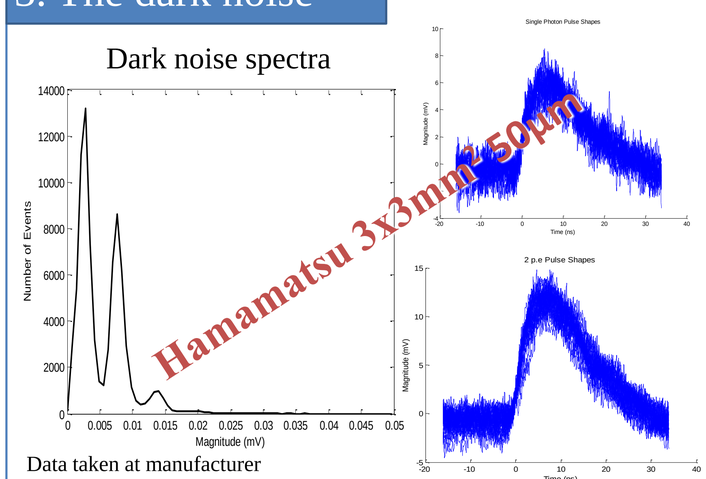
Breakdown voltages were calculated for all SiPMs.
These breakdown voltages were found to be in the range 1.0-2.0V below the operating point ($V_{bias}$) recommended by the manufacturers.




| SiPM | | Breakdown Voltage (V) | Recommended $V_{bias}$ (V) |
|---|---|---|---|
| Hamamatsu 3x3mm² 25μm | SiPM 1 | 69.60 | 71.10 |
| | SiPM 2 | 69.60 | 70.96 |
| Hamamatsu 3x3mm² 50μm | SiPM 1 | 69.60 | 71.28 |
| | SiPM 2 | 69.60 | 71.31 |
| Hamamatsu 3x3mm² 100μm | SiPM 1 | 69.40 | 70.04 |
| | SiPM 2 | 69.30 | 69.71 |
| Hamamatsu 1x1mm² 25μm | SiPM 1 | 68.60 | 70.86 |
| | SiPM 2 | 69.50 | 71.79 |
| Hamamatsu 1x1mm² 50μm | SiPM 1 | 68.20 | 69.63 |
| | SiPM 2 | 68.20 | 69.63 |
| Hamamatsu 1x1mm² 100μm | SiPM 1 | 69.20 | 70.83 |
| | SiPM 2 | 68.60 | 70.71 |
| Photonique 1x1mm² | SiPM 1 | 17.20 | 19.00 |
| | SiPM 2 | 17.30 | 19.10 |
| Photonique 2x2mm² | SiPM 1 | 26.50 | 27.50 |
| | SiPM 2 | 26.50 | 28.80 |
| SensL 1x1mm² | SiPM 1 | 28.20 | 29.60 |
| | SiPM 2 | 28.20 | 29.60 |
| SensL 3x3mm² | SiPM 1 | 27.50 | 29.60 |
| | SiPM 2 | 27.50 | 29.60 |

## 3. The dark noise

Dark noise spectra



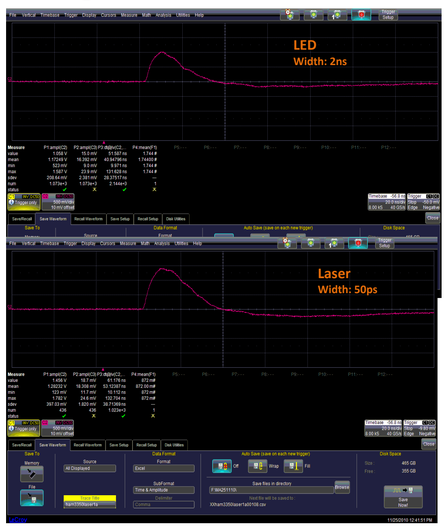

Data taken at manufacturer recommended $V_{bias}$

Dark count rates

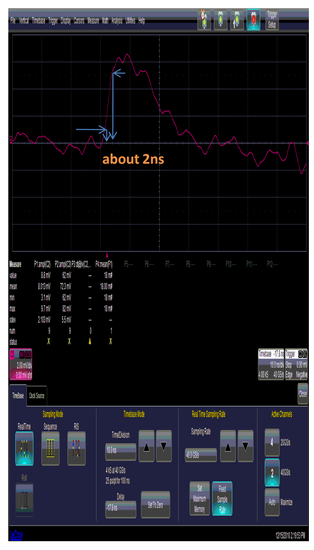
| SiPM | Measure dark count rates (MHz) | Manufacturer data (MHz) |
|---|---|---|
| Hamamatsu 1x1mm² 25μm | 0.40 | 0.30 |
| Hamamatsu 1x1mm² 50μm | 0.72 | 0.40 |
| Hamamatsu 1x1mm² 100μm | 0.66 | 0.60 |
| Hamamatsu 3x3mm² 25μm | 1.50 | 1.50 |
| Hamamatsu 3x3mm² 50μm | 4.00 | 3.00 |
| Hamamatsu 3x3mm² 100μm | 3.54 | 3.50 |
| Photonique 1x1mm² | 9.00 | - |
| Photonique 2x2mm² | 17.27 | - |
| SensL 1x1mm² | 1.40 | - |
| SensL 3x3mm² | 6.28 | - |
| SensL 3x3mm² new 8'' wafer | 3.35 | - |

## 4. Rise time studies

Light sources




Dark noise




➢ For all other SiPMs pe⁻ peaks were not visible

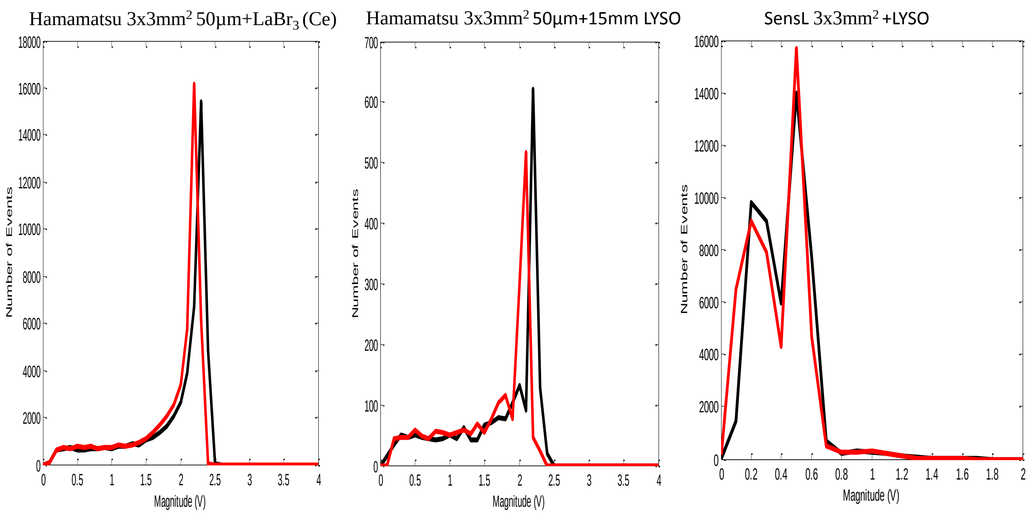
Rise time from LED and Laser

| SiPM | Rise time (ns) | |
|---|---|---|
| | LED | Laser |
| Hamamatsu 1x1mm² 25μm | 2.4 | 2.3 |
| Hamamatsu 1x1mm² 50μm | 4.8 | 5.3 |
| Hamamatsu 1x1mm² 100μm | 5.9 | 6.1 |
| Hamamatsu 3x3mm² 25μm | 4.1 | 4.7 |
| Hamamatsu 3x3mm² 50μm | 4.2 | 5.3 |
| Hamamatsu 3x3mm² 100μm | 6.2 | 6.2 |
| Photonique 1x1mm² | 1.8 | 1.8 |
| Photonique 2x2mm² | 2.7 | 2.6 |
| SensL 1x1mm² | 5.4 | 5.9 |
| SensL 3x3mm² | 6.6 | 7.1 |

Rise time from dark noise

| SiPM | Rise time (ns) | | |
|---|---|---|---|
| | 1pe⁻ | 2pe⁻ | 3pe⁻ |
| Hamamatsu 1x1mm² 50μm | Comparable with noise | 4.6 | 5.3 |
| Hamamatsu 3x3mm² 50μm | 2.8 | 4.4 | No peak |

## 5. Timing resolution studies for two-channel demonstrators



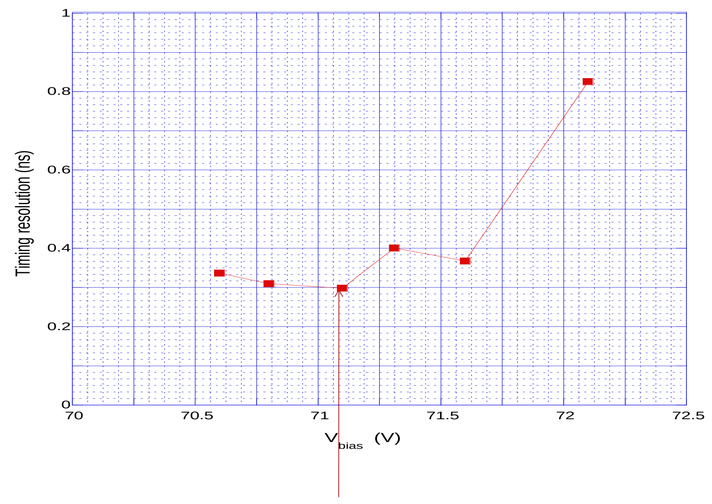

Output signals of three different two-channel demonstrators, clearly showing the 511 keV peaks from $^{22}$Na

Timing resolution at fixed $V_{bias}$

| SiPM | Crystal | Crystal size (mm³) | Timing resolution (σ) (ns) |
|---|---|---|---|
| SensL 3x3mm² | LYSO Hilger Analytical Limited | 3x3x15 | 1.509 |
| | LYSO Saint-Gobain | 3x3x10 | 1.483 |
| SensL 3x3mm² new 8'' wafer | LYSO Hilger Analytical Limited | 3x3x15 | 1.420 |
| | LYSO Saint-Gobain | 3x3x10 | 1.416 |
| Hamamatsu 3x3mm² 50μm | LYSO Hilger Analytical Limited | 3x3x15 | 0.363 |
| | LYSO Saint-Gobain | 3x3x10 | 0.358 |
| | LYSO Saint-Gobain | 3x3x5 | 0.321 |
| | $LaBr_3$(Ce) Saint-Gobain | 3x3x30 | 0.400 |

➢ Timing resolutions at SiPM fixed $V_{bias}$ recommended by manufacturers:
- The best timing resolution is 321ps (σ), obtained for 5mm length LYSO + Hamamatsu 3x3mm² 50μm

Timing resolution -vs- $V_{bias}$




Best timing resolution 298ps (σ)

➢ Timing resolution as function of SiPM $V_{bias}$:
- Carried out only for $LaBr_3$(Ce) + Hamamatsu 3x3mm² 50 μm
- Best timing resolution of 298ps (σ) measured at 0.2V below recommended $V_{bias}$

## 6. Conclusions and future work

A preliminary characterisation of SiPMs was carried out using a simple data acquisition system based on a fast oscilloscope. Breakdown voltages, dark count rates and signal rise times were measured for all SiPMs. The timing resolutions of two-channel demonstrators were measured and the best one was found to be 298ps (σ). This preliminary result is comparable to other ones reported in literature. Based on our results we identified our system limitation in the read-out electronics, which we are in the process of upgrading. We are expecting further improvements in the timing performances with properly engineered two-channel demonstrator systems and set-ups.

Plan for future work:
- Acquire faster pre-amplifiers for the Hamamatsu 1x1mm² 50μm and Hamamatsu 3x3mm² 50μm SiPMs that are better matched to their capacitance and repeat measurements with these devices.
- Investigate the effects on the timing resolution of the crystal size and of the Ce concentration in the case of $LaBr_3$(Ce).

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