Optimisation of SiPM intrinsic and coincidence time resolution using digital techniques

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Introduction

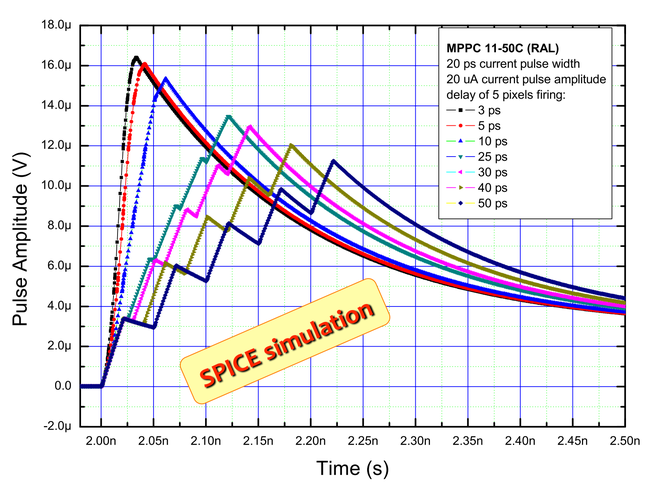
A variety of modern physics applications, ranging from medical to high energy physics, requires very fast light sensors, characterised by a response in the range of tens of picoseconds. Silicon Photomultipliers (SiPMs, or Multi pixel photon counters (MPPCs)) are a relatively new solid-state pixelated detector type that satisfies this requirement, with the advantage of being compact, cheap, operating at low bias and insensitive to magnetic fields. Moreover, their high photon detection efficiency (PDE) and high signal to noise ratio (SNR) make them suitable candidates as scintillating crystal readout detectors, in place of traditional Photomultiplier Tubes (PMTs).

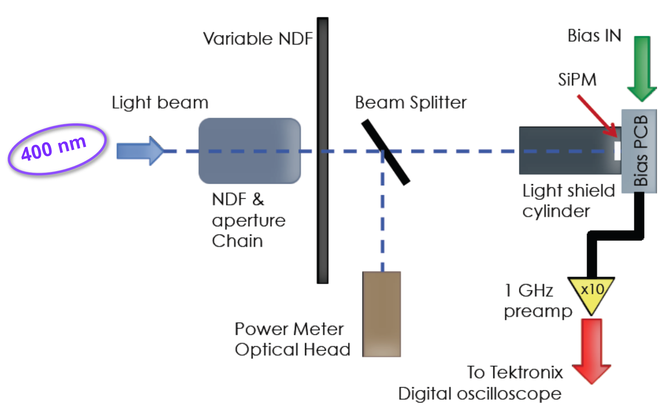
A SiPM is a matrix of Avalanche Photodiodes working in the Geiger mode region (GM-APD), connected on the same silicon substrate. Every time a photon is absorbed in the Si bulk, it can create by impact ionisation daughter carriers, which in turn can be accelerated and create further carriers. An avalanche is settled in the APD, which is quenched by a resistance connected in series to the pixel. Hence, a firing pixel generates a standard pulse, behaving actually as a binary device. The total SiPM pulse is however, the summation over all the firing pixels, giving in this way an output proportional to the number of sensed photons. A drawback of this sensor is then the limited dynamic range, given by the total number of pixels in the device. The detector is also affected by dark noise, due to its solid-state nature, and a very high capacitance that can deteriorate its timing performances.

Motivations and Experimental setup

Using the *superposition principle*, the pulse generated by a fixed number of photons with arrival time shifted of few ps was simulated with SPICE and it was found that:

- ***Non-coherent photon beams*** deteriorate the timing performances of the system because of
  - Longer rise time
  - Smaller pulse amplitude
  - → Worse Timing Jitter (σ_j)
- ***Coherent light*** improves all the timing performances allowing single photon timing with very low noise contribution even using standard quality electronics.





The ***photon beams*** are generated by a Ti:Sapphire ultra-fast laser with 100 fs pulse width and 250 kHz repetition rate, at 400 nm wavelength.

Three pairs of ***Hamamatsu MPPC*** 1125C, 1150C and 3325C were used. Their pulses are:

- *digitised and stored* using a digital phosphor oscilloscope Tektronix 7254B, 2.5 GHz bandwidth and 20 GS/s sampling rate;
- *amplified* using a 1 GHz bandwidth, 20 dB gain ZFL Mini-Circuits LN current preamplifier;
- *analysed off-line* using suitably developed LabVIEW routine.

Digital filtering and time stamp pick-up algorithms

The recorded pulses were filtered against high frequency noise affecting the signals and introduced by the electronic readout chain. In fact, this high frequency noise, increasing the timing jitter, increases also the width of the Gaussian-shape distribution of the signals time difference. Three different low-pass filters were used:

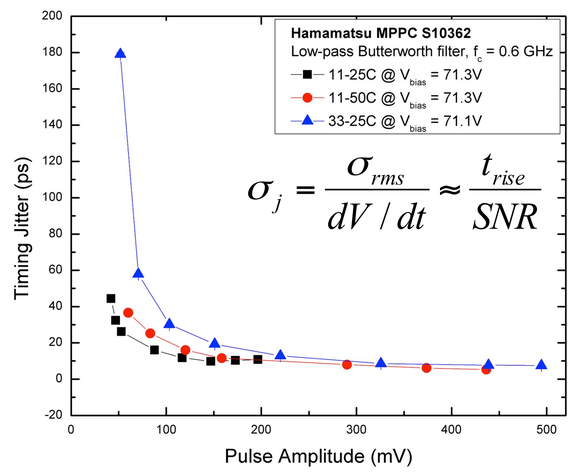
- *Butterworth*
- *Chebyshev*
- *Bessel,*

with the higher cut-off frequency, f_c, and the order, n, as filter parameters.

	11-25	11-50	33-25
t_{rise} – no filter (ps)	543.1 ± 0.4	552.8 ± 0.2	1017.3 ± 0.3
t_{rise} – filter (ps)	725.3 ± 0.2	713.81 ± 0.06	1086.26 ± 0.05
σ_j – no filter (ps)	19.45 ± 0.05	11.05 ± 0.02	17.03 ± 0.02
σ_j – filter (ps)	9.750 ± 0.013	5.309 ± 0.007	7.531 ± 0.007

Digitally filtering signals results in a slower rising edge t_{rise}, but with a factor of ~2 better timing jitter.

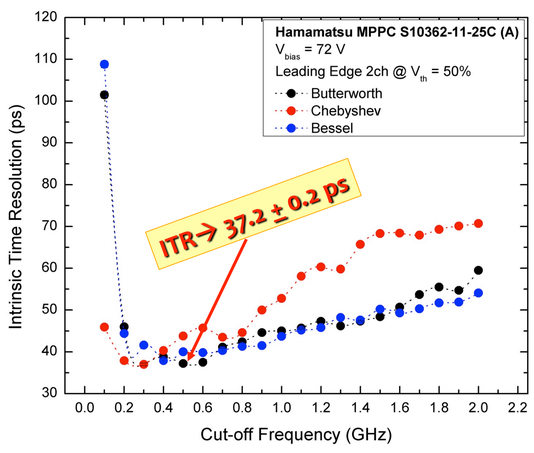
The results reported in the table above refer to the best values obtained using a Butterworth filter with f_c = 600 MHz and n = 2.
The plot on the right refers to σ_j measured at different light intensities, at the operative voltage for each MPPC.



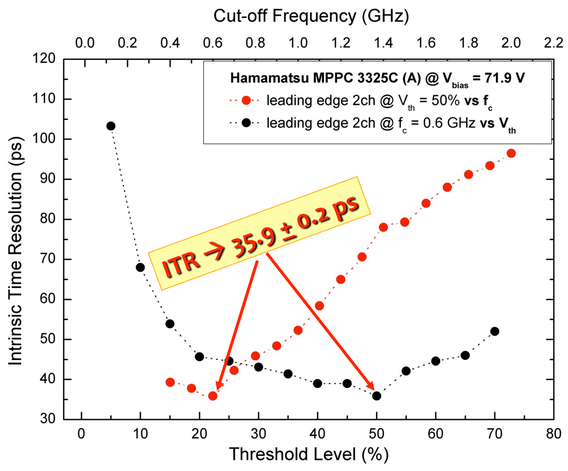
Three different algorithms were used for the time stamp pick-up for the measurement of the time resolution:

- **Fixed threshold** → a reference voltage is fixed for both pulses;
- **Leading Edge on one channel** → the reference voltage is defined as the percentage of the amplitude of the pulses on one channel;
- **Leading Edge on two channels** → two reference voltages are defined as percentage of the pulse amplitude for each channel. The values can be different for the two channels and effectively *this algorithm is a digital Constant Fraction Discriminator.*

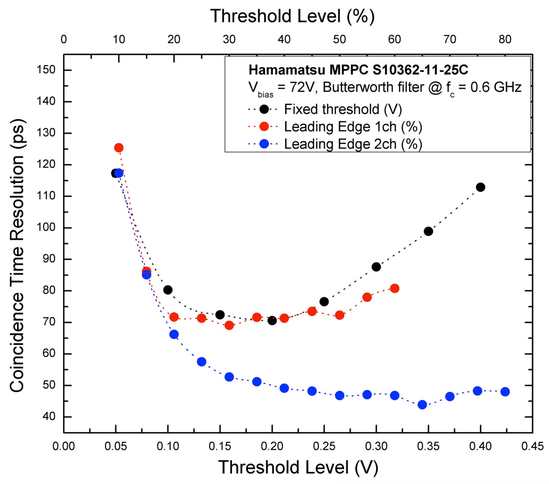
Intrinsic and Coincidence Time Resolution

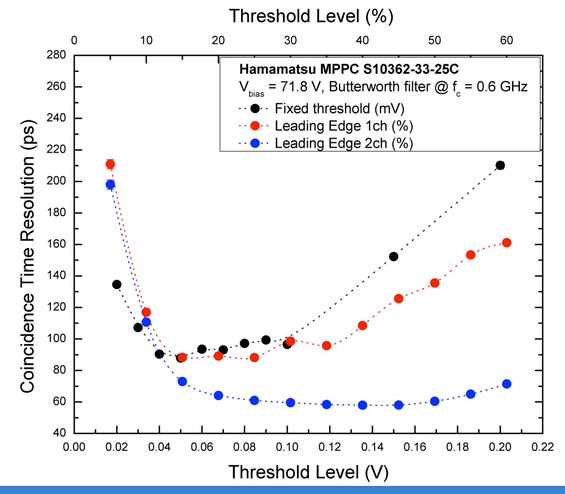


The ***Intrinsic Time Resolution (ITR)*** is the spread in the time the detector takes to generate an output signal under a light stimulus. The measurement of this parameter was performed with a coincidence between the trigger of the laser and the MPPC signal. The ITR refers to the FWHM of the distribution of the time difference at a certain threshold level.



The ***Coincidence Time Resolution (CTR)*** is the minimum resolving time with which a pair of detectors can discriminate the time of occurrence of a certain event. This parameter was measured directing the same amount of light to the two MPPCs under test. The CTR is the FWHM of the distribution of the time difference at a certain threshold level.





The table in the right summarizes the *best values for the CTR* (in ps) for both MPPCs under test using a Butterworth filter with f_c = 600 MHz.

MPPC	Fixed threshold	Leading Edge 1ch	Leading Edge 2ch
11-25C	70.6 ± 0.3 @ 200 mV	69.1 ± 0.2 @ 30%	43.9 ± 0.2 @ 65%
33-25C	87.9 ± 0.5 @ 50 mV	88.2 ± 0.5 @ 25%	58.0 ± 0.1 @ 40%

Conclusions and further developments

The intrinsic and coincidence time resolution for two MPPCs were measured using a very fast laser at 400 nm wavelength. It was demonstrated how the use of digital filters reduces the high-frequency noise introduced by the electronics. It was demonstrated as well how the values of the time resolution are dependent on the choice of the time stamp pick-up algorithm. The optimisation of the filter and algorithm parameters gives the best intrinsic and coincidence time resolution. This implies that very fast timing can be obtained using commercial electronic components and a waveform digitiser, avoiding in this way the use of the conventional NIM instrumentation used in timing experiments. A drawback of this method is of course the use in a realistic system with more than four channels, where digitisation might not be the optimum choice on an economical point of view.
Further developments to this work are the study of the timing performances of a system of MPPCs coupled to LYSO crystals and the determination of the scintillator contribution to the timing of the final response.

References

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