Time-resolution with a fast plastic scintillator read out by a G-APD: a GEANT4 study

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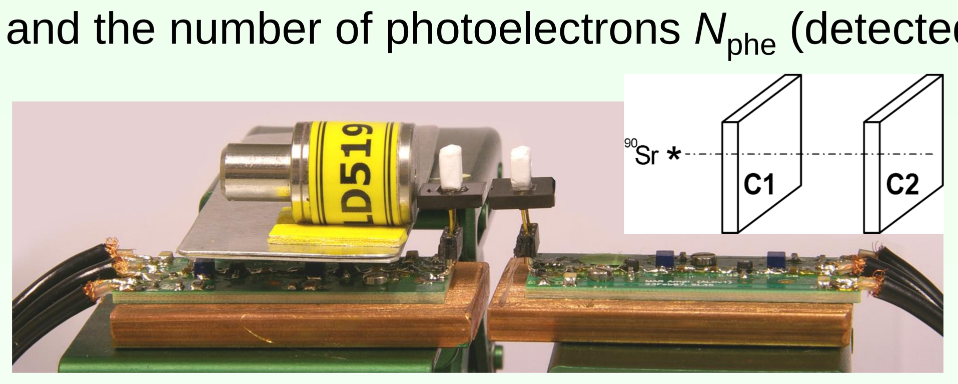
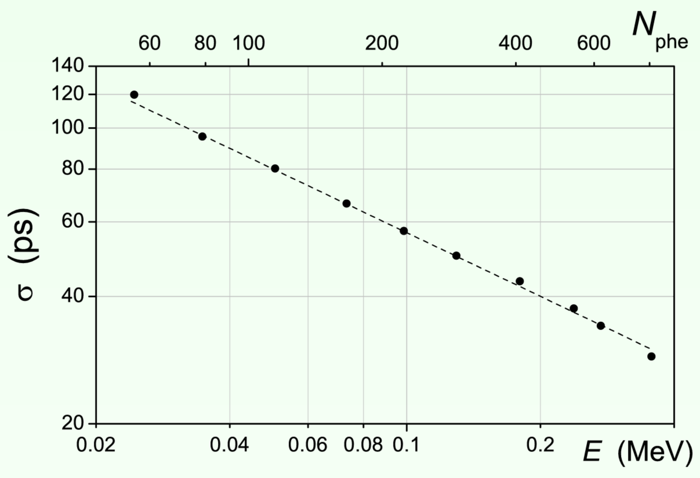
The time resolution of a fast scintillation counter, consisting of a plastic scintillator read out by a Geiger-mode Avalanche Photodiode, is studied over a wide range of the number of detected photons using the GEANT4 simulation toolkit. Different timing definitions such as first photon detection, leading edge and constant fraction discrimination are considered. In the latter case the predictions are compared with the existing experimental data.

Motivation

For our application – the High-Field μSR spectrometer [1] – we need to detect ~10 MeV/c muons and positrons in the magnetic field of 0 – 9.5 T with extremely good time resolution. We use the BC-422 plastic scintillator read out by a G-APD (Hamamatsu MPPC S10362-33-050C), and process the signals by constant fraction discriminators (CFDs). Using a dedicated setup, we estimated the limit on the time resolution of such a detector as a function of energy E deposited in the scintillator and the number of photoelectrons N_{phe} (detected photons) in the G-APD [2]:





$$\sigma = \sigma^{1MeV} / \sqrt{E} = \sigma^{1phe} / \sqrt{N_{phe}}$$

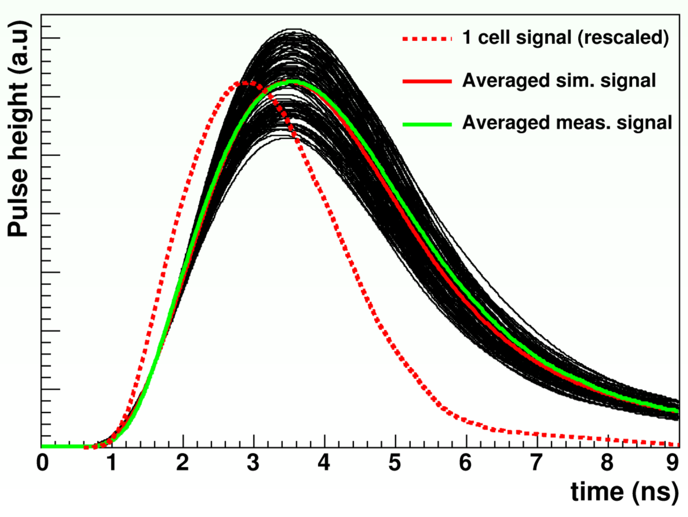
$\sigma^{1MeV} = 18 \pm 1$ ps·MeV$^{1/2}$, $\sigma^{1phe} = 850 \pm 5$ ps

[1] A.Stoykov et al., *High Field μSR instrument at PSI: detector solutions*, Physics Procedia 30 (2012) 7.

[2] A.Stoykov, R.Scheuermann, K.Sedlak, *A time resolution study with a plastic scintillator read out by a Geiger-mode Avalanche Photodiode*, Nucl. Inst. and Meth. A – in press (http://dx.doi.org/10.1016/j.nima.2011.11.011)

Geant4 study – simplified geometry

A simplified setup based on just one scintillator box (2x3x3 mm^2) and a single G-APD was implemented in Geant 4.9.5. The scintillator box was made of "G4_PLASTIC_SC_VINILTOULENE" material, its surface approximated as "polishedteflonair" defined in the Geant4 internal look-up tables.

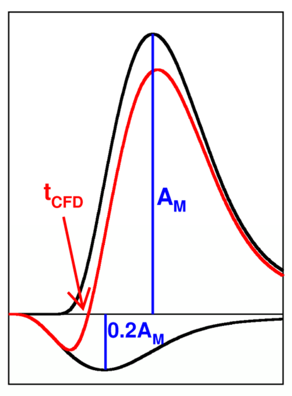


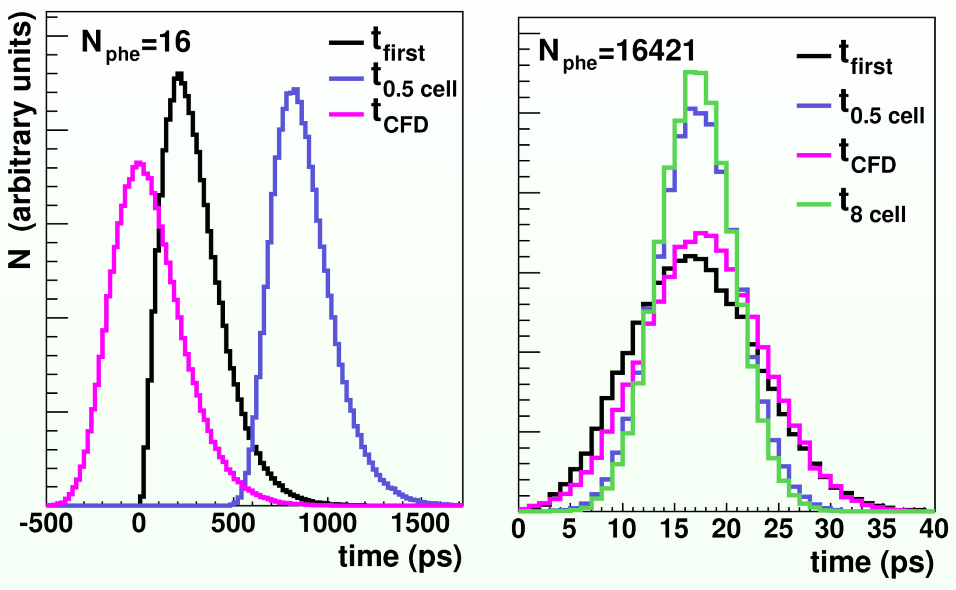
Converting photons into a G-APD signal

An averaged 1-cell signal was obtained experimentally. Every time a photon is detected in the G-APD, the 1-cell signal is added up to the final analog pulse. Several analog pulses simulated this way using e$^-$ are shown in the left plot. Only the signals corresponding to 675 – 825 photons were selected.

Definitions of timing

- t_{first} – time when the first detected photon enters the G-APD.
- t_{CFD} – time from a constant fraction discriminator triggering at 20% of the signal amplitude.
- $t_{0.5cell}$ – time when the signal reaches threshold of $0.5{\cdot}A_{1cell}$, where A_{1cell} is the average amplitude of the 1-cell signal.

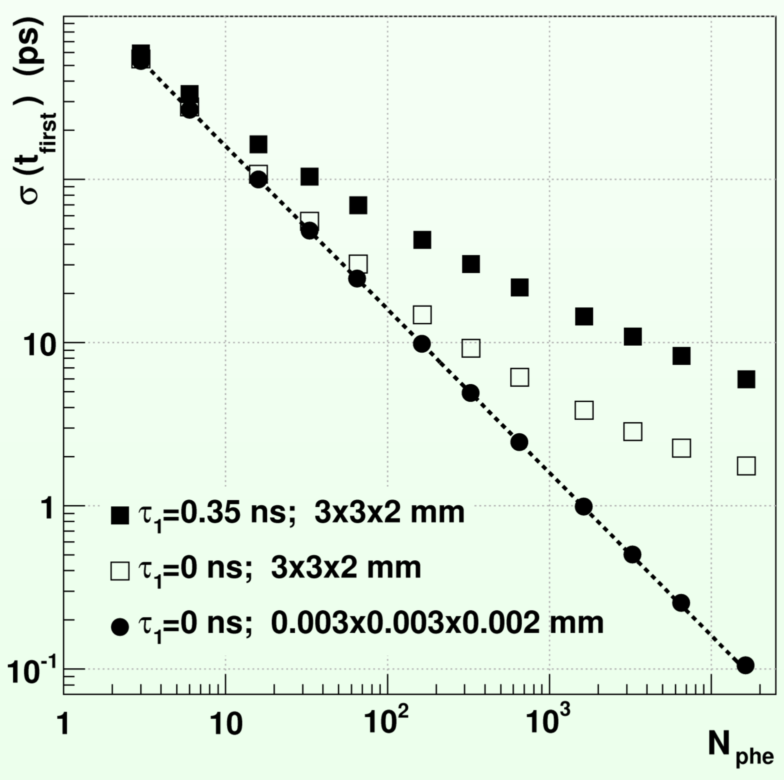




Figures on the left show the simulated time distributions for two extreme cases of 16 and 16421 detected photons (N_{phe}) in the single counter. The distributions were shifted to match their mean values in the case N_{phe} = 16421.

We define the time resolution, $\sigma(t_{det})$, as the standard deviation of a given time distribution.

First photon study



Theoretically [3], the time resolution $\sigma(t_{first})$ should follow the dependence:

$\sigma(t_{first}) = \tau_2 / N_{phe}$

for a scintillator with zero rise time (τ_1 = 0) and the decay time τ_2 (in our case 1.6 ns).

The left plot confirms this dependence for a scintillator with zero rise time and for an infinitely small size. Both finite rise time and finite scintillator size (just in a mm range!) significantly deteriorate the time resolution at large N_{phe}.

(An ideal G-APD was assumed here – see later.)

[3] R.F.Post, L.I.Schiff, *Statistical limitations on the resolving time of a scintillator counter*, Phys. Rev. 80 (1950) 1113.

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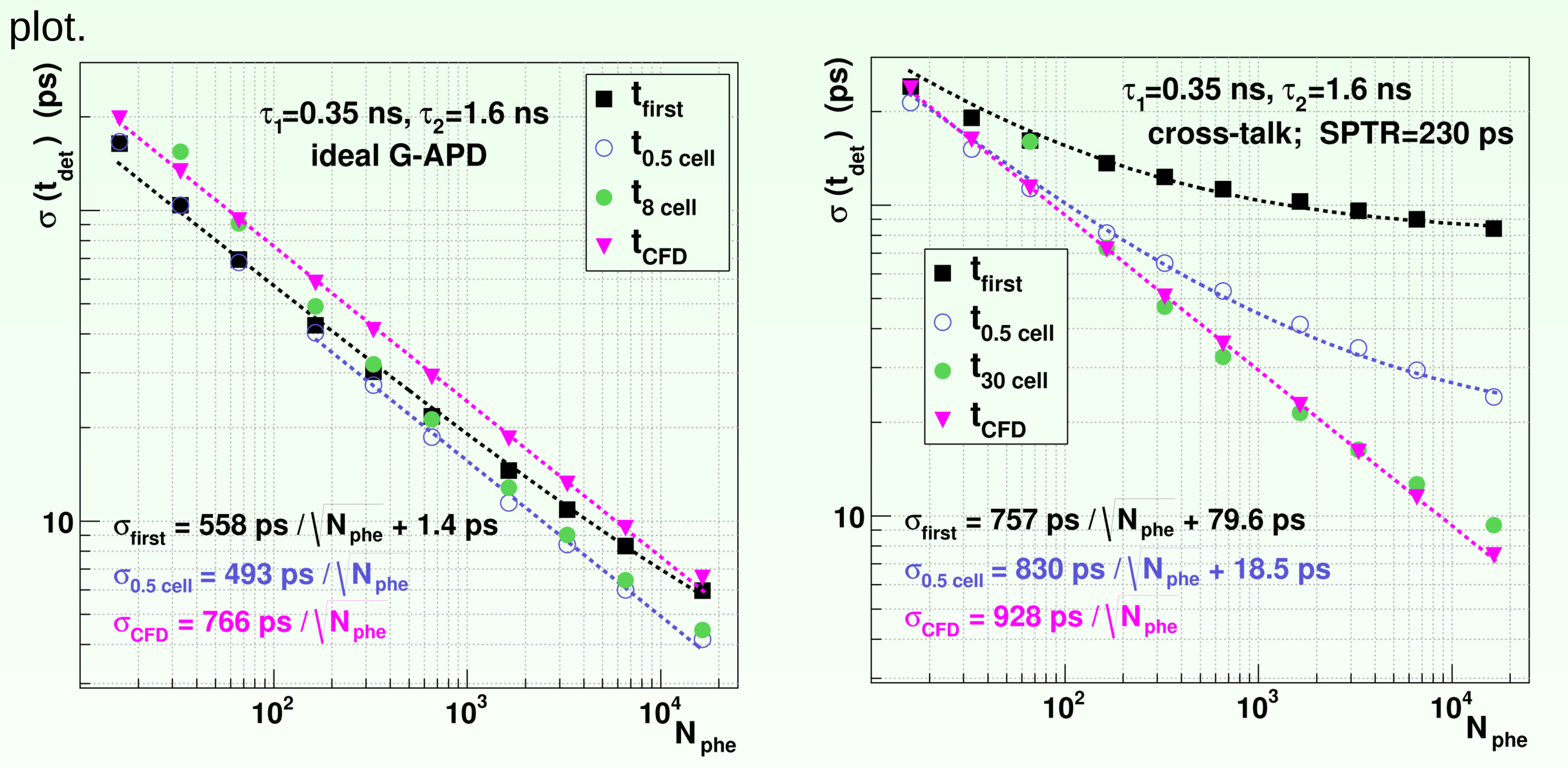
Ideal vs. realistic G-APD

Any real G-APD device has a finite number of cells, suffers from a crosstalk and from a time jitter of each individual cell, the so-called "single photon time resolution" (SPTR). To understand how these effects influence the time resolution, we started from an ideal G-APD with no cross-talk, infinite number of cells and SPTR=0 ps (see the left plot), and subsequently added the above mentioned effects. The predictions for the G-APD with a cross-talk of 12% and a realistic SPTR are shown in the right plot.



In case of the ideal G-APD the best timing is achieved with $t_{0.5cell}$ (note that $t_{0.5cell}$ and t_{first} are not equivalent). The CFD timing t_{CFD} gives the worst result.

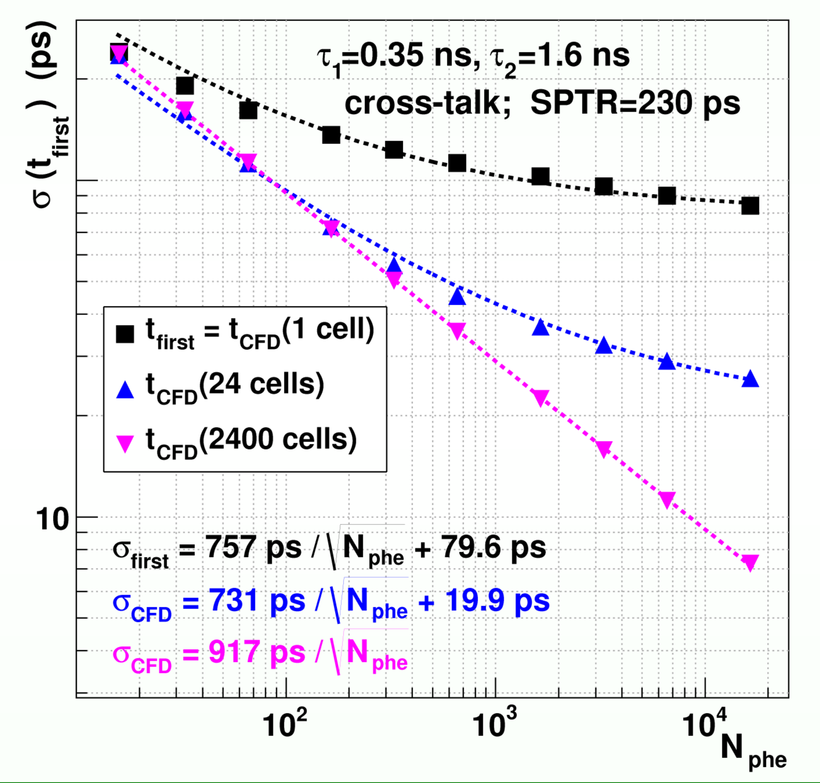
Once the crosstalk and SPTR are included, the timing based on any time definition deteriorates. The CFD timing becomes the best – together with the leading-edge discrimination at $30{\cdot}A_{1cell}$ threshold*.

*The leading edge discrimination, however, requires a time correction based on the signal amplitude. In our case the correction is perfect, since we have zero bin widths in N_{phe}.

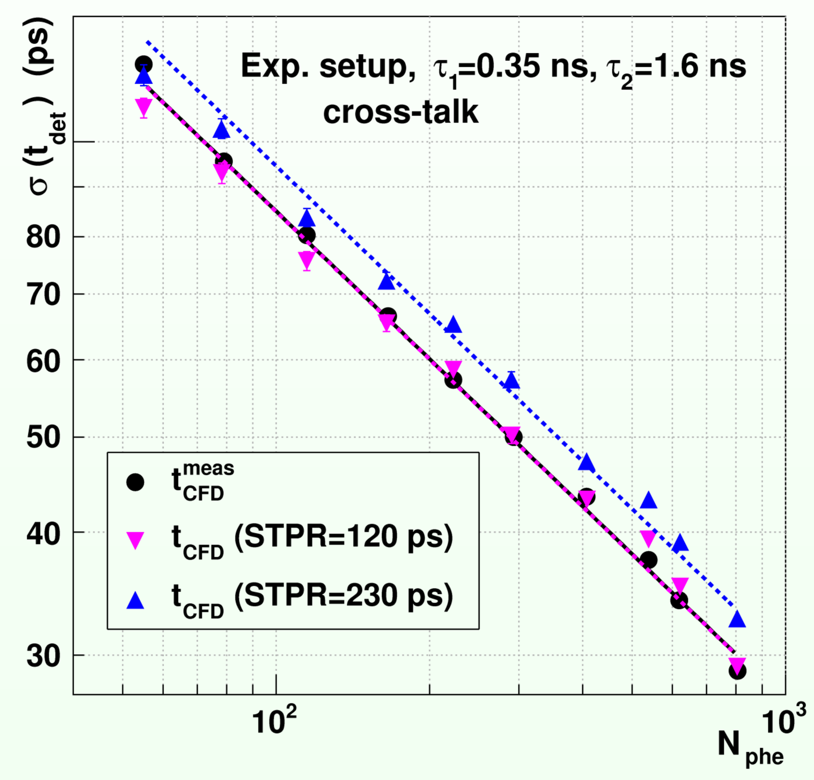
Finite number of cells

If the number of cells is very large (in our case 2400 cells are optically coupled to the scintillator), the effect of the finite number of cells becomes negligible in our range of number of detected photons N_{phe}<17000.

If the number of cells is substantially reduced, the time resolution gets worse, especially at large N_{phe}. In the limit case of just a single cell in the G-APD, the timings based on t_{first}, t_{CFD} and $t_{0.5cell}$ become identical.



Comparison with the real experiment



Finally we compared the simulation (this time reproducing the geometry of two counters) with the real measurement. In case of SPTR=120ps, the Geant4 prediction reproduces the measurement rather well.

Conclusions

- The timing at large N_{phe} in a counter with a realistic G-APD can be significantly deteriorated by the single photon time resolution (SPTR). Most affected by this parameter are the first photon detection and the leading edge discrimination with the lowest threshold.
- The simulation confirms the theoretically predicted dependence of the time resolution for the first photon: $\sigma(t_{first}) = \tau_2 / N_{phe}$. This dependence is valid only in idealised conditions (breaks down for a finite rise time or finite scintillator size).
- In a real scintillation counter using the fastest plastic scintillator (BC-422) and, to our opinion currently best suited for its readout G-APD (Hamamatsu MPPC S10362-33-050C), the CFD timing method yields practically the best result. In principle, a slightly better timing could be achieved with a well tuned leading edge discriminator (but requires a time correction based on the signal amplitude).