SiPMs Characterization for a SiPM based TOF-PET detector

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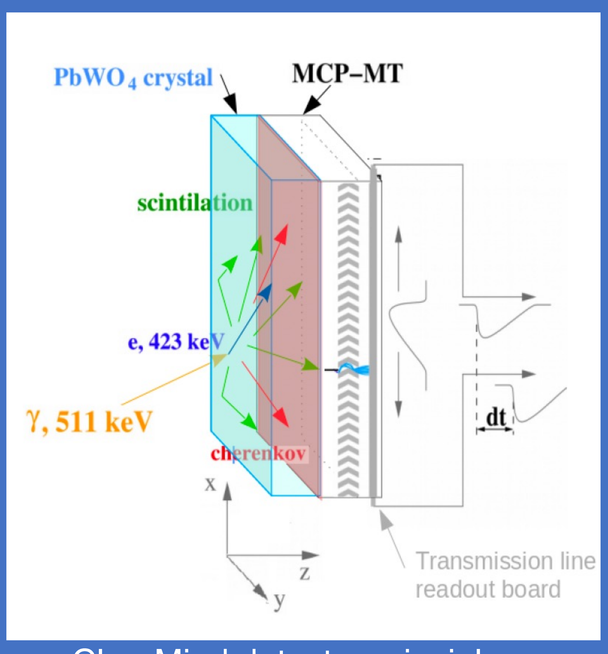
TOF-PET and the ClearMind Project

PET, a 3D medical imaging technique, is crucial in oncology, neurology, and cardiology due to its unparalleled sensitivity (1 Pico Mol) to biological activity. TOF enhances gamma annihilation position localization. developments target a 10 ps coincidence time resolution for better signal-to-noise ratio, lower doses, real-time reconstruction, and superior localization.

- The ClearMind Group develops innovative time optimized gamma detectors [1] for TOF-PET:
  - Use of $PbWO_4$ crystal to generate Cherenkov and scintillation photons
  - Direct photocathode deposition on $PbWO_4$ for improved photons transmission
  - Signal readout using transmission line
  - Pulse waveform sampling using SAMPIC [2]



ClearMind detector principle

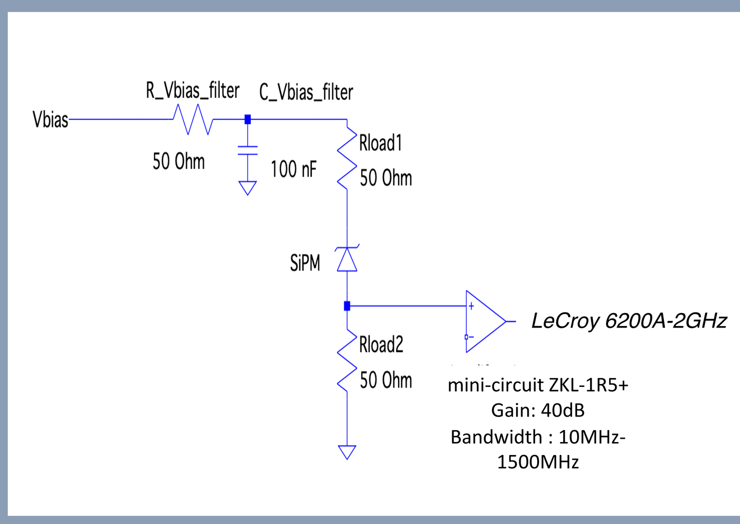
- Adding a second detection layer will improve:
  - photon detection efficiency
  - Depth of interaction estimation
  - Time resolution
- The added layer needs to be thin !
- A SiPM matrix is the natural candidate

- Different SiPM technologies are available
- Criteria: NUV sensibility, SPE fast waveform shape, noise level, time resolution
- SiPM chips need characterization to find optimal technology for our application

- **Objective:**
  - Wave form time domain characterization
  - Noise measurements
  - Time resolution measurements

SiPMs and their readout electronics

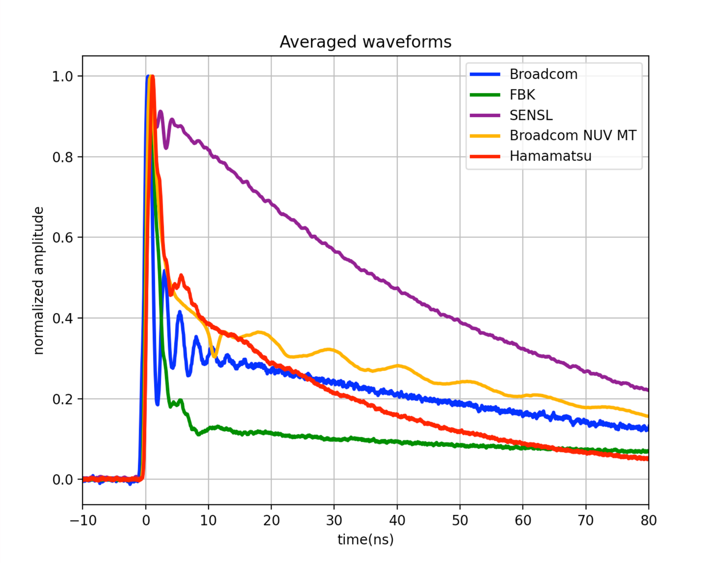
- **Devices under test:**
  - **Five** SiPMs have been tested :
    - **Hamamatsu NUV S13360 3x3mm2 50 µm pixel pitch**
    - **FBK NUV-HD 3x3mm2 40µm pixel pitch**
    - **Onsemi (SENSL) J series 3x3mm2 35 µm pixel pitch**
    - **Broadcom AFBR-S4N33C013 NUV-HD 3x3mm2 30 µm pixel pitch**
    - **Broadcom AFBR-S4N44P014M NUV-MT 4x4mm2 40 µm pixel pitch**

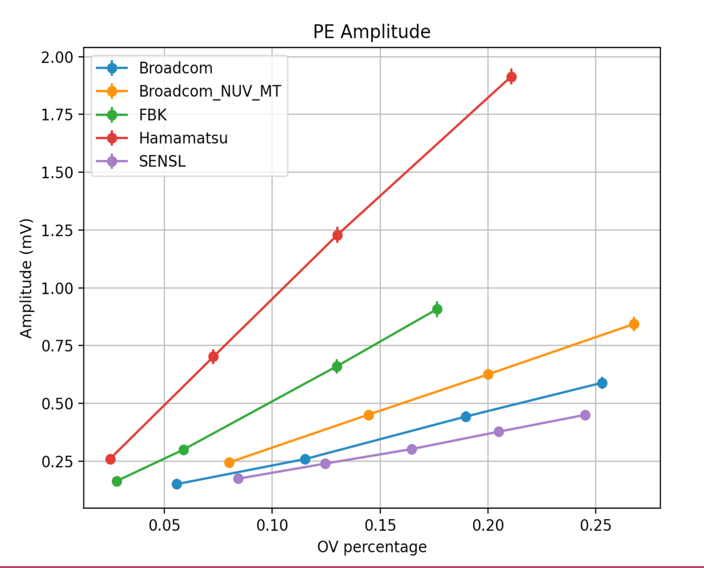


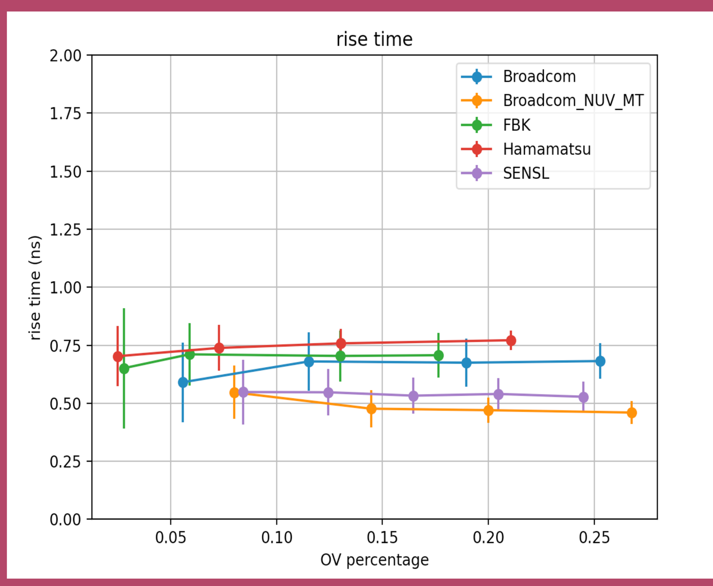
SAMPIC module

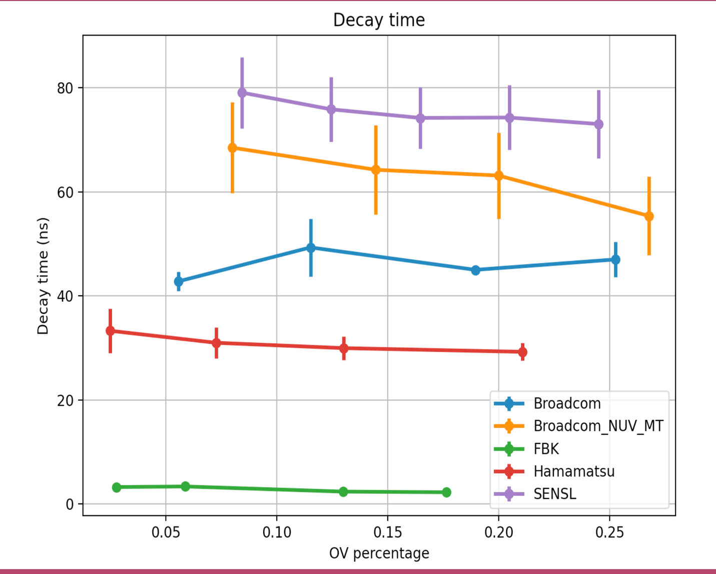
- Sampling for waveform and noise measurements using LECROY 6200A-2GHz
- Sampling for time resolution using SAMPIC 6.4 Gsp/s
- All measurements have been conducted in a light sealed black box at different OV (Overvoltage) values

Waveform characteristics









- *2000 pure 1PE waveforms averaged*
- *Some chips shows large fast pulse*
- *Oscillations are speculated to be due to line inductance*

- *Amplitude evolves linearly with OV*
- *SPAD design influences the value of amplitude*

- *Rise and decay time are OV independent and are only influenced by SPAD design*
- *Fast Rise time is observed for all chips (below 900 ps)*
- *Disparity with decay time between chips with fastest under 10 ns and slowest under 80 ps*

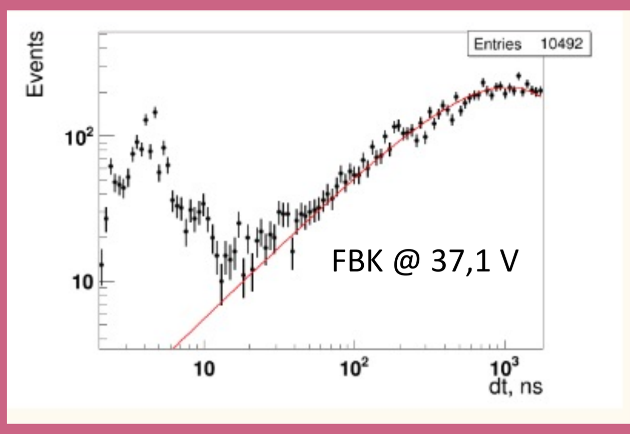
Noise Measurements

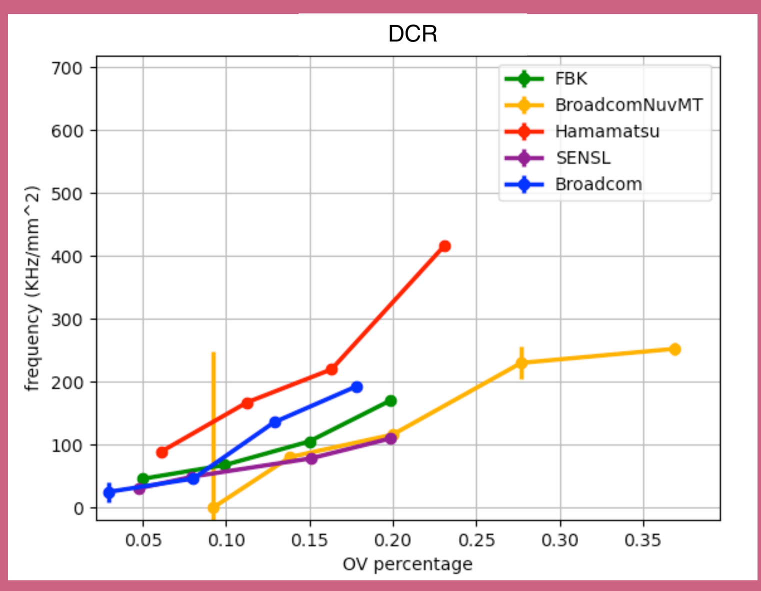
- ***SiPM Noise types:***
  - SiPMs are known to have different noise mechanisms[3]:
  - DQR, Direct cross talk, and delayed crosstalk(delayed+ External+ After pulses) have been quantified at different OV

Non correlated
- Dark count rate (DCR)
- Direct cross talk — Direct
- After pulse
- External cross talk — Delayed
- Delayed cross talk

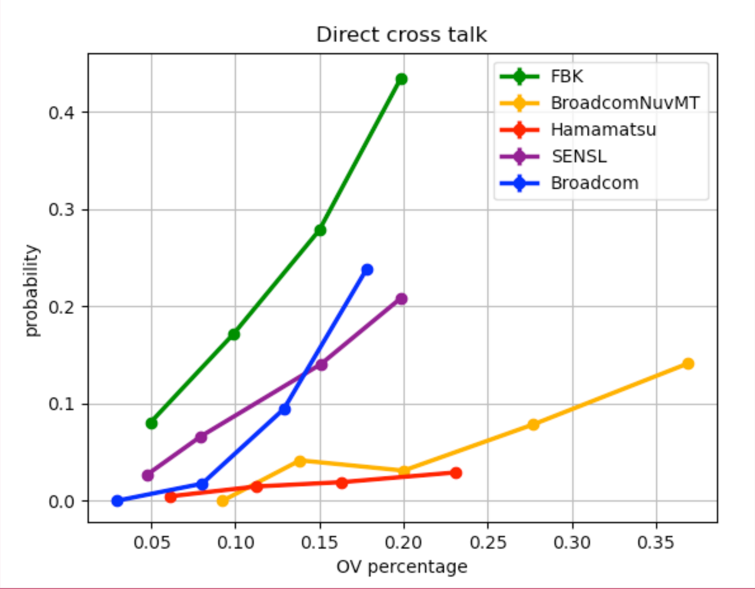
Correlated

- ***Methodology:***
  - *2 µs data waveforms are acquired*
  - *First and second pulses are detected and time difference dt is calculated*
  - *Delayed cross talk have been estimated as the probability to have events in the interval of 2ns to 100 ns after a main event*
  - *DCR is estimated using a Poisson law fitted in the interval [100ns, 1800ns]*

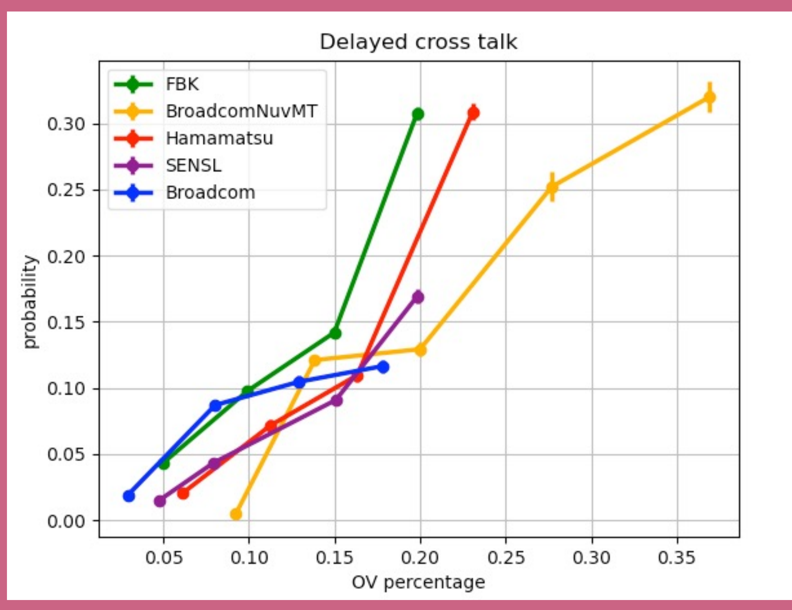




- *DCR increases with OV*
- *DCR levels varies from one chip to another*



- *Direct cross talk have been estimated as the probability to numerous prompt events*
- *increases with OV*
- *deep metal trenches, optical windows Have influence*

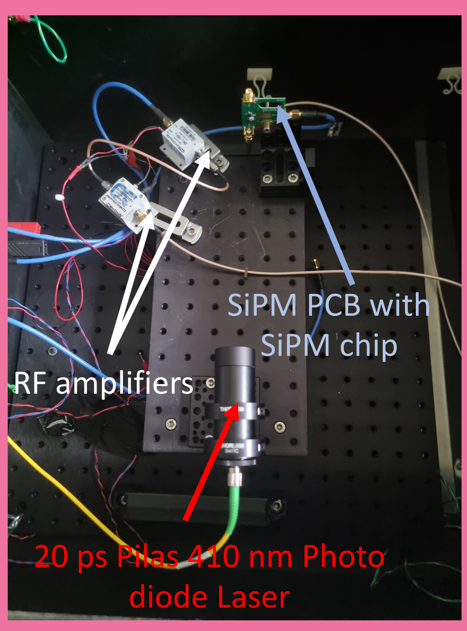


- *Delayed cross talk probability increases with OV*

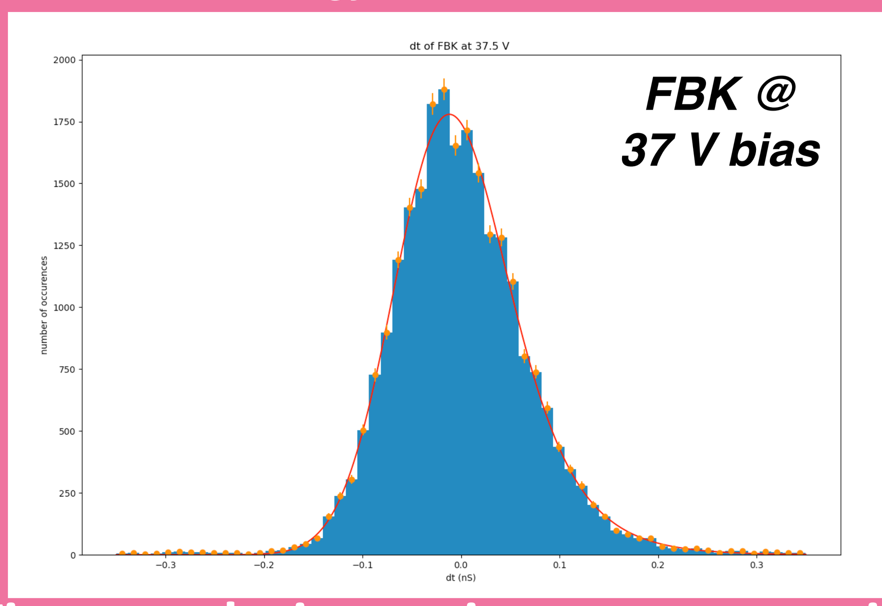
Single photon Time resolution

- ***Experimental setup:***

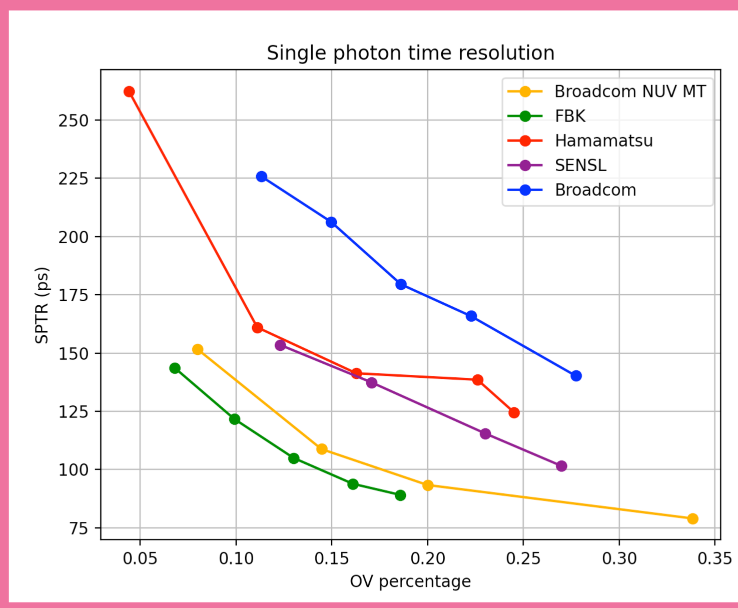
- *Attenuators used for amplitude matching with digitizer*



- ***Methodology***
  - *Time resolution is estimated on events with 1 or 2 PE amplitudes.*
  - *CFD(Constant fraction discriminator) algorithm is utilized for time estimation Time distribution is fitted using a decaying exponential convolved with a normal distribution.*



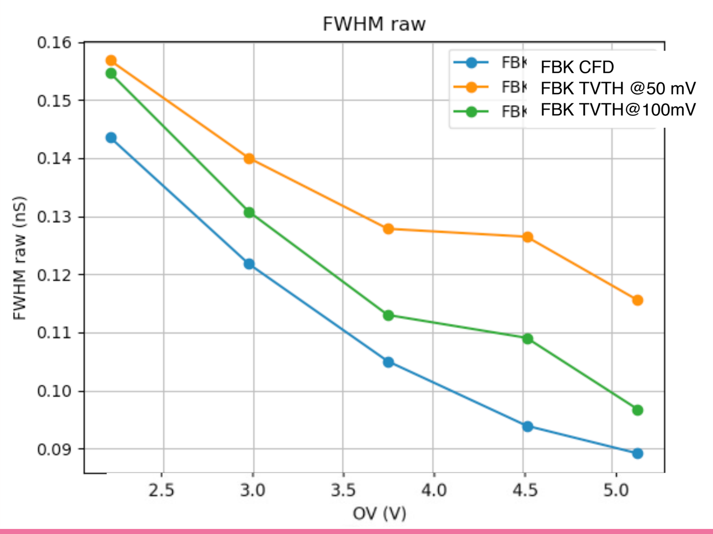
- ***Results for 1 PE events***
  - *SPTR improves with increasing OV*
  - *Broadcom NUV MT holds best resolution of 79 ps at 34 % OV*



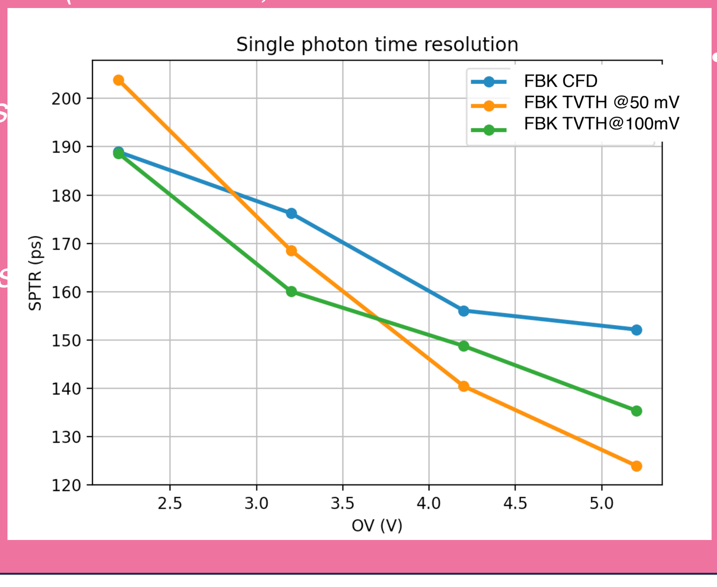
Time resolution estimators comparison

CFD at 30% amplitude and time at voltage threshold (TVTH) at 50 mV and 100 mV performances were compared for different events amplitude (1 PE events, 2 PE events and 1PE vs 2 PE comparison)

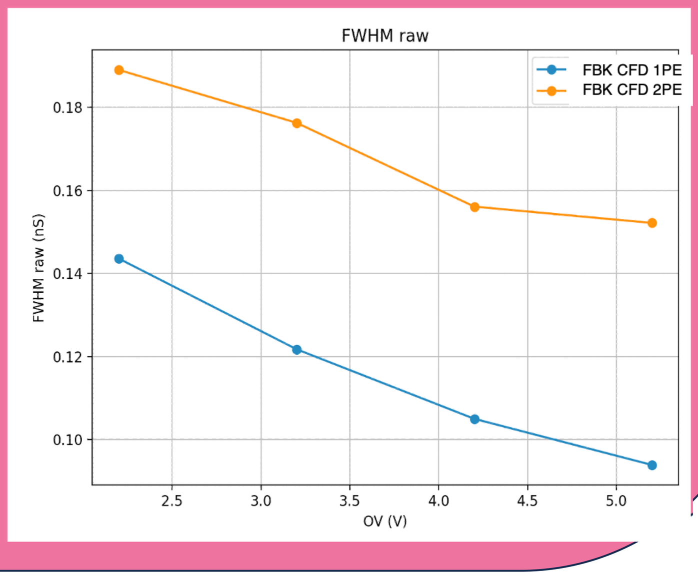
- ***1PE Events***
  - *CFD shows superior performance across various OV values.*
  - *TVTH at 100 mV outperforms TVTH at 50 mV.*
  - *TVTH performance at 50 mV and 100 mV is similar for low OV values.*



- ***2PE Events***
  - *At low OV values TVTH at 50 mV yields better results.*
  - *At high OV values TVTH at 100 mV performs better.*
  - *Complex wave shapes of 2 PE worsen CFD performances.*



- ***CFD :1PE vs 2 PE***
  - 1 PE events with CFD outperforms, 2 PE events with any algorithm.
  - 1PE : ~ 75% of statistic. This is a quality criteria.
  - Work on optimizing time estimator



Conclusion

In conclusion, rise time, quenching, and recharge time remain stable regardless of overvoltage, while amplitude, time resolution, and noise levels vary significantly with overvoltage.
ClearMind project second layer detects single photon. Our selection criteria are low direct cross talk, DCR, good SPTR and fast pulse shapes. In this regard Broadcom NUV MT seems the most adequate chip for our application
Time estimation algorithm influences SPTR estimation. CFD performs better on 1 PE events while time at voltage threshold yields better results on 2 PE events and at a high overvoltage.

References

[1]- D. Yvon et al., 'Design study of a "scintronic" crystal targeting tens of picoseconds time resolution for gamma ray imaging: the ClearMind detector', Journal of Instrumentation, vol. 15, no. 07, p. P07029, Jul. 2020.
[2]- E. Delagnes, D. Breton, H. Grabas, J. Maalmi, P. Rusquart and M. Saimpert, "The SAMPIC Waveform and Time to Digital Converter," *2014 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC)*
[3]- F. Acerbi and S. Gundacker, 'Understanding and simulating SiPMs', Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. 926, pp. 16–35, 2019.