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Time resolution of analog SiPMs: techniques and setups examples

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Introduction

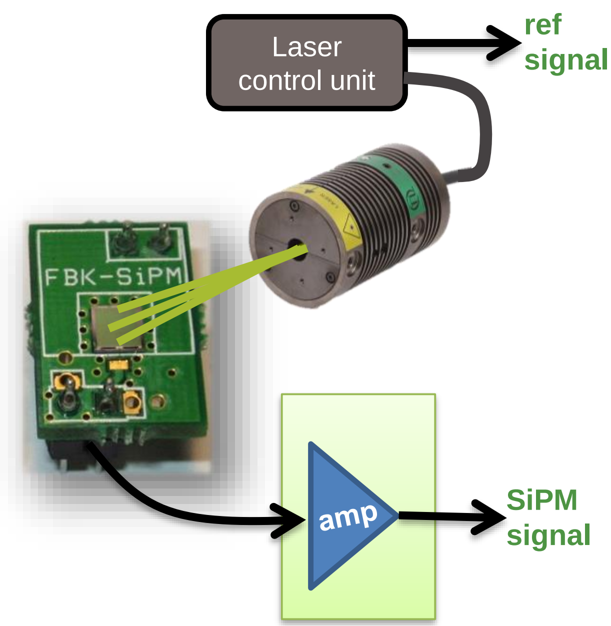
- Among others properties, **single-photon time resolution (SPTR)** is an important characteristic of the SiPMs
- Has been studied over the last few years by different groups employing **different setups and techniques.**

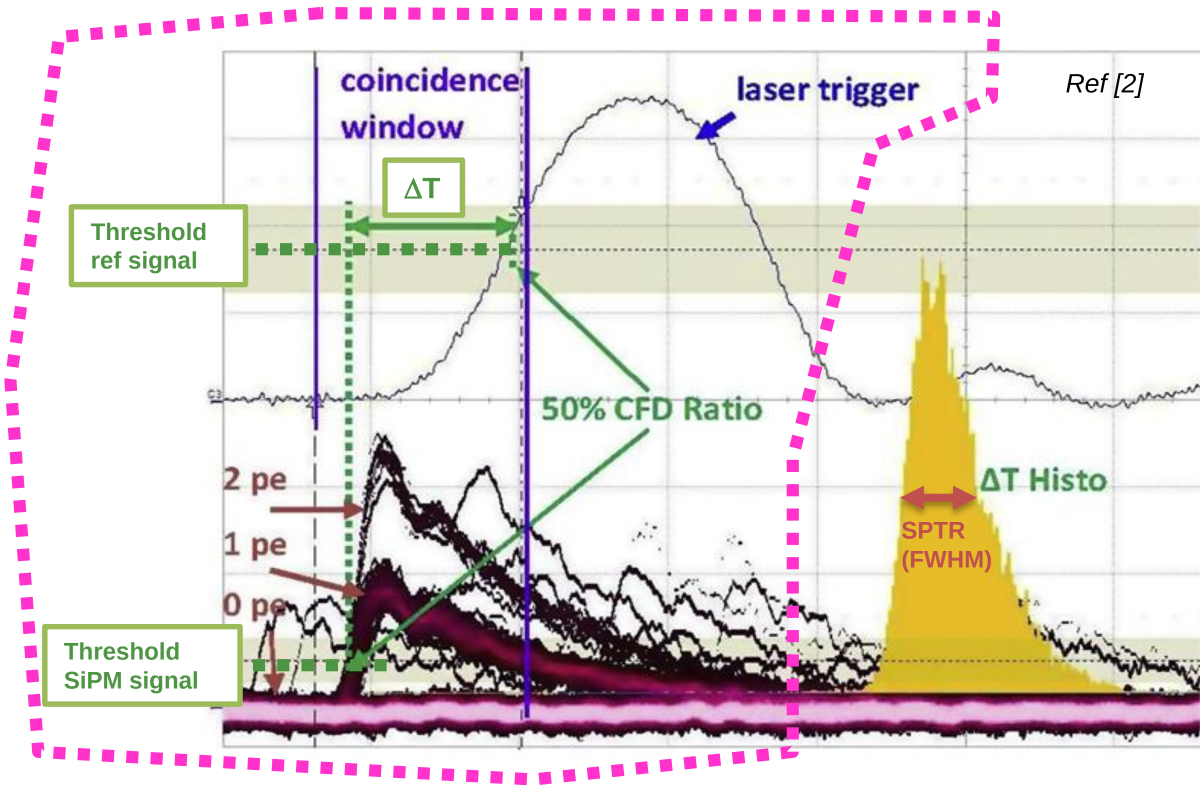
- In this contribution → ***examples and comparison of meas. setups and readout methodologies*** used by various groups to characterize the SPTR of analog SiPM.

- Discussion of some ***SPTR measurement related aspects*** such as
  - Type of laser, attenuation of light, uniformity of the light, reference signal, …
  - Identification of single photon events.
  - ***Practical considerations*** (TTS, amplifier, state-of-the-art values, etc.)

- By examining the SPTR measurement techniques for analog SiPM → we intend to have comparable parameters for the measurements performed by groups across several fields and institutions.

Single-photon time resolution (SPTR)

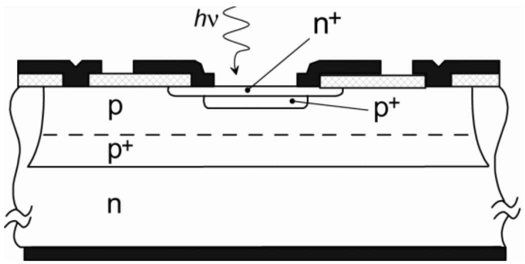




- **Single-photon time resolution (SPTR):**
  - jitter in time between photon arrival on the SiPM and detection by the front-end electronics.
  - Measurement: 2 signals → SiPM signal & reference (sync) signal
    → thresholding → histogramming → SPTR = spread of time difference

SPTR: from SPAD to SiPM

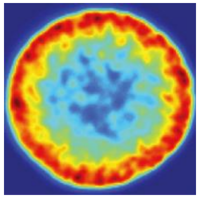
SPAD:



SPTR depends on:

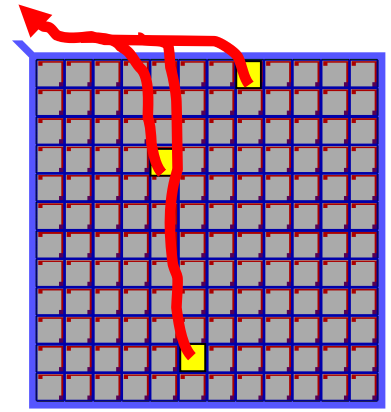
- **Avalanche build-up spread**
  (highly depend on excess bias
  → higher E-field, faster build-up times, with less spread)
- **diffusion tail**
  (particularly at high wavelength
  → diffusion of carrier photogenerated in neutral region)
- **Non-uniformity of electric field** in the active area

See ref [1] and ref [2]



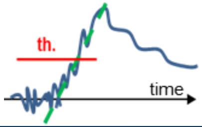
aSiPM:

(Array of many SPADs in parallel)



SPTR depends on:

- **Single-cell (SPAD) "intrinsic" time-resolution**
- **Transit time skew (TTS):** parasitic and length variation of interconnections
- **Non-uniformity between SPADs**
  (e.g. gain or amplitude variation)
  (e.g. breakdown voltage variation → different local excess biases → overall wider timing hist., worse SPTR)
- (***effect of electronic noise*** *on th. crossing time*
  → significantly affect measured SPTR, but it is not a characteristic of the detector)

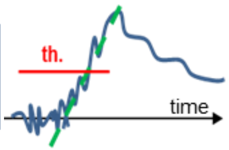


$$Jitter_{noise} = \frac{V_{noise}}{dV/dt}$$

Measured SPTR: contributing factors

$$SPTR_{meas} = SPTR_{photosensor} \oplus Jitter_{noise} \oplus Jitter_{setup} \oplus Laser\_PW \oplus Jitter_{trigger}$$

$$Jitter_{noise} = \frac{V_{noise}}{dV/dt}$$



LASER contributions:
- optical **Pulse Width (PW)**
- Electronic-to-optical signal jitter

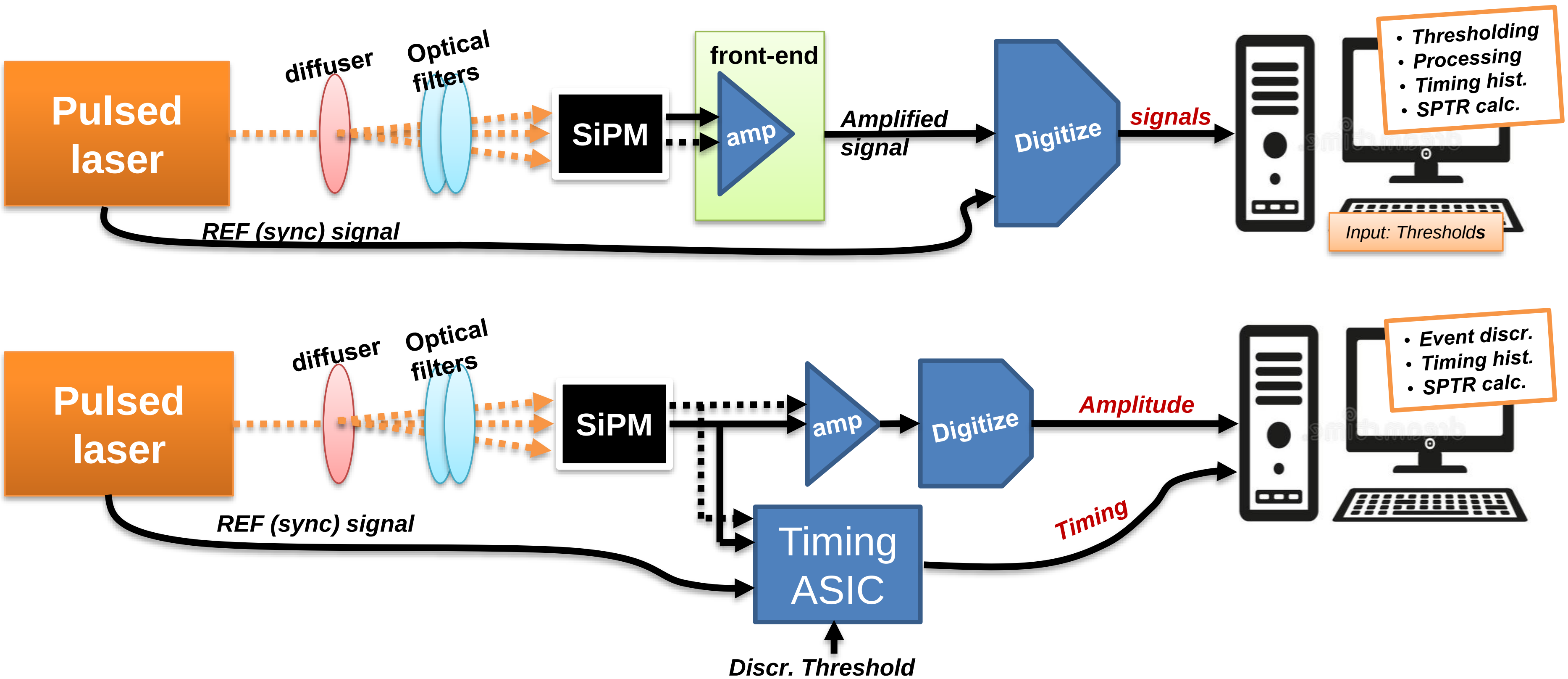
SPTR
(λ,V_{EX},V_{th})

$$SPTR_{photosensor} = SPTR_{SPAD(intrinsic)} \oplus TTS \oplus Spad\_to\_Spad\_Variation$$

$$SPTR_{SPAD(intrinsic)} = Jitter_{build-up}(V_{ex}, V_{th}) \oplus diffusion\_tail(\lambda) \oplus Jitter_{Efield\_unif.}(V_{ex})$$

- **The actual SPTR(λ, V_{EX}, V_{th}) is only the photosensor jitter ($SPTR_{photosensor}$)**
  - *setup influence, laser PW and jitter should be deconvolved* from measured data.
  - *BUT also the measured value have to be reported*
    (since estimations and deconvolutions may be not easy, and may introduce error)
- **Detector SPTR → considered intrinsic to the detector**
- **SPTR can be given with more insight (e.g. TTS, or focused-light SPTR)**

Setup for SPTR measurement

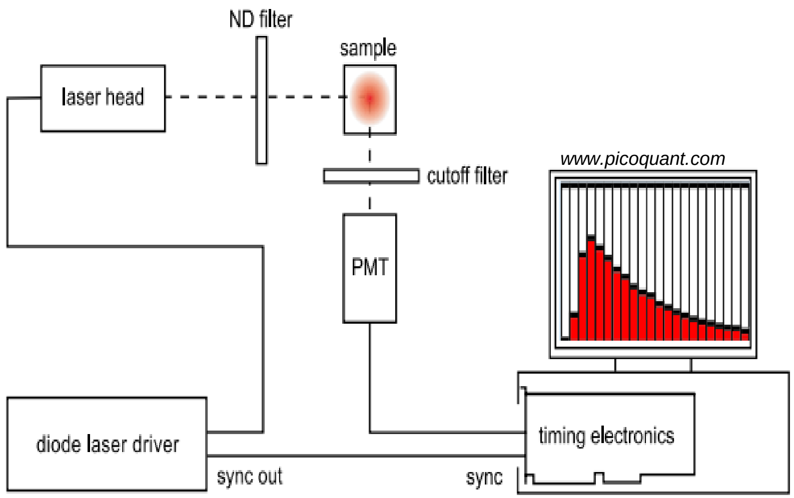


- **Two commonly used techniques to measure timing:**
  - ***Waveform acquisition*** → SiPM output is amplified, acquired directly (oscilloscope or digitizer) and the signal analyzed, appl. threshold(s), extracting timing histogram(s).
  - ***ASIC readout*** → the output is either a time stamp or a discriminated signal that can further be digitized by an external TDC.

Important: photon number discrimination

***Single-photon* time resolution → only *single photon* events !**

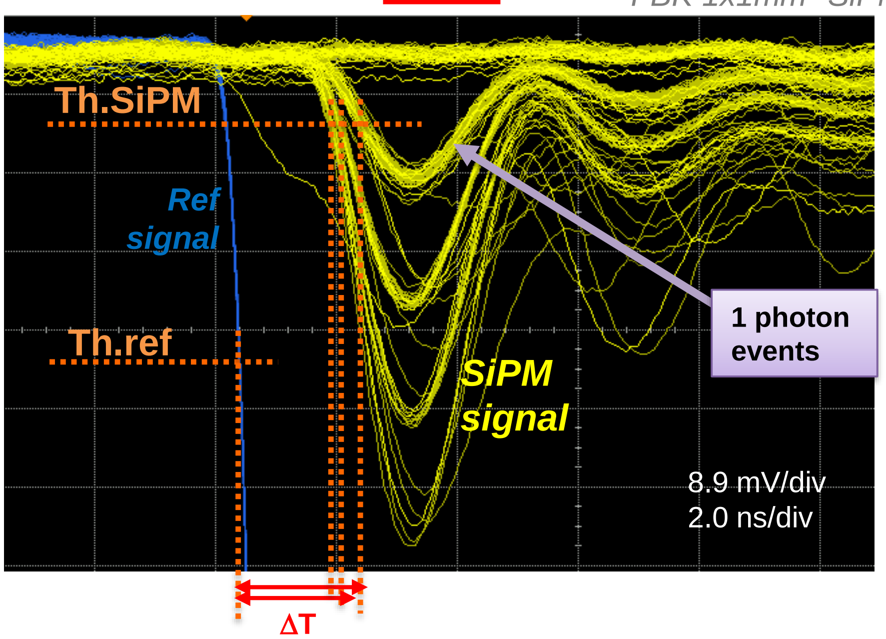
SPAD (or PMT)



- **For SPAD (or PMT) →** necessary and sufficient to operate at <5% rate (of laser rep-rate)
  - → *prob. 2ph triggering same cell negligible*

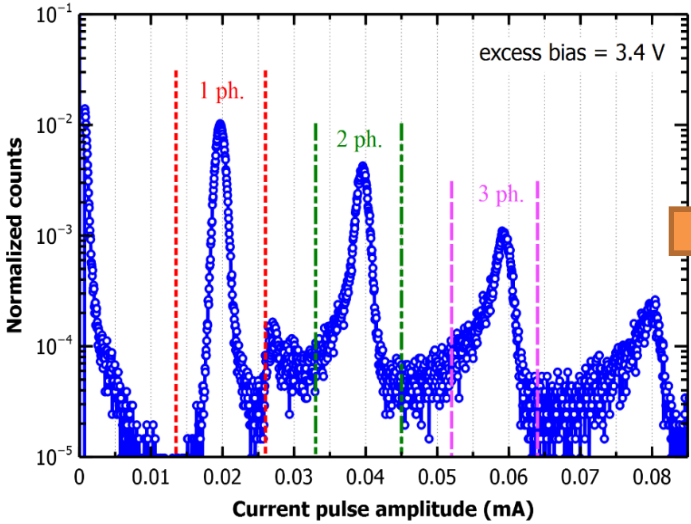
SiPM

FBK 1x1mm² SiPM

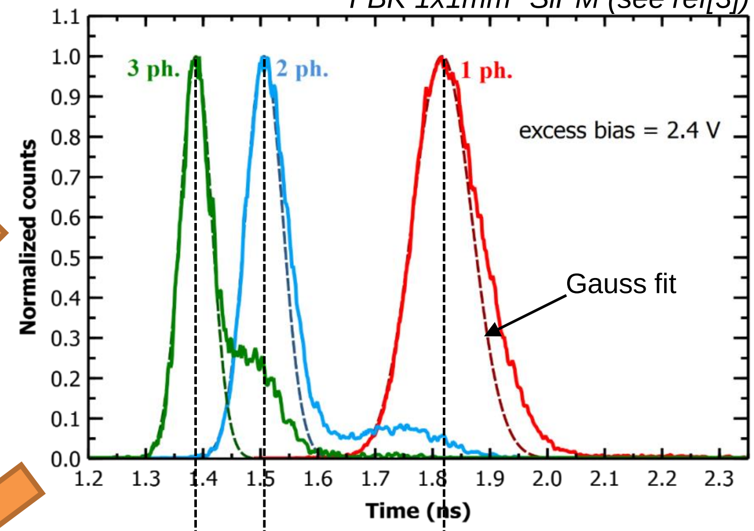


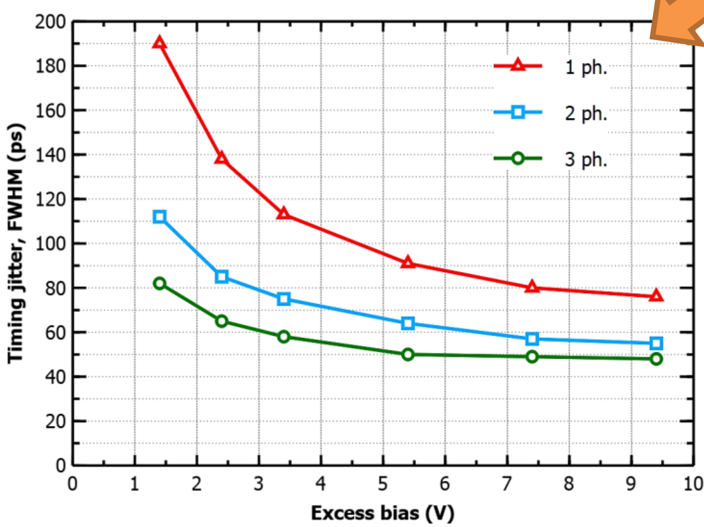
- **For SiPMs →** timing histogram & statistics ***altered by 2ph, 3ph, etc. events.***
  - *Important to consider only 1-ph events.*
  - Even if trig rate < 5% *(single photon level)* optical CT is present.

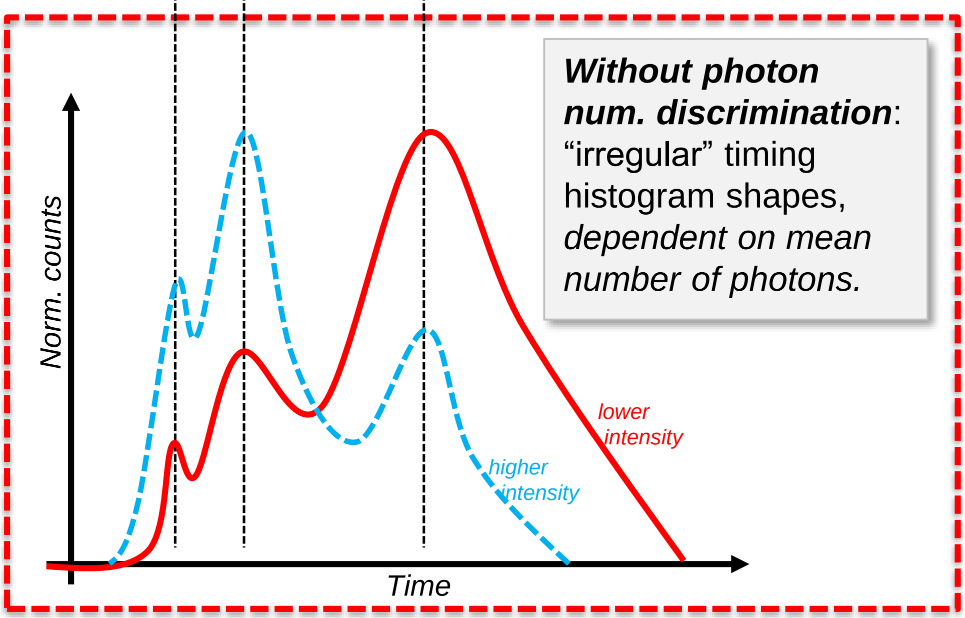
Important: photon number discrimination



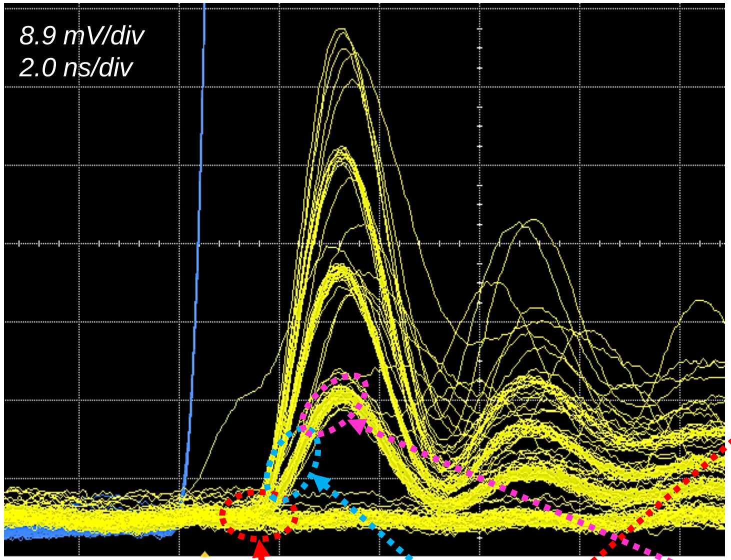
FBK 1x1mm² SiPM (see ref[3])

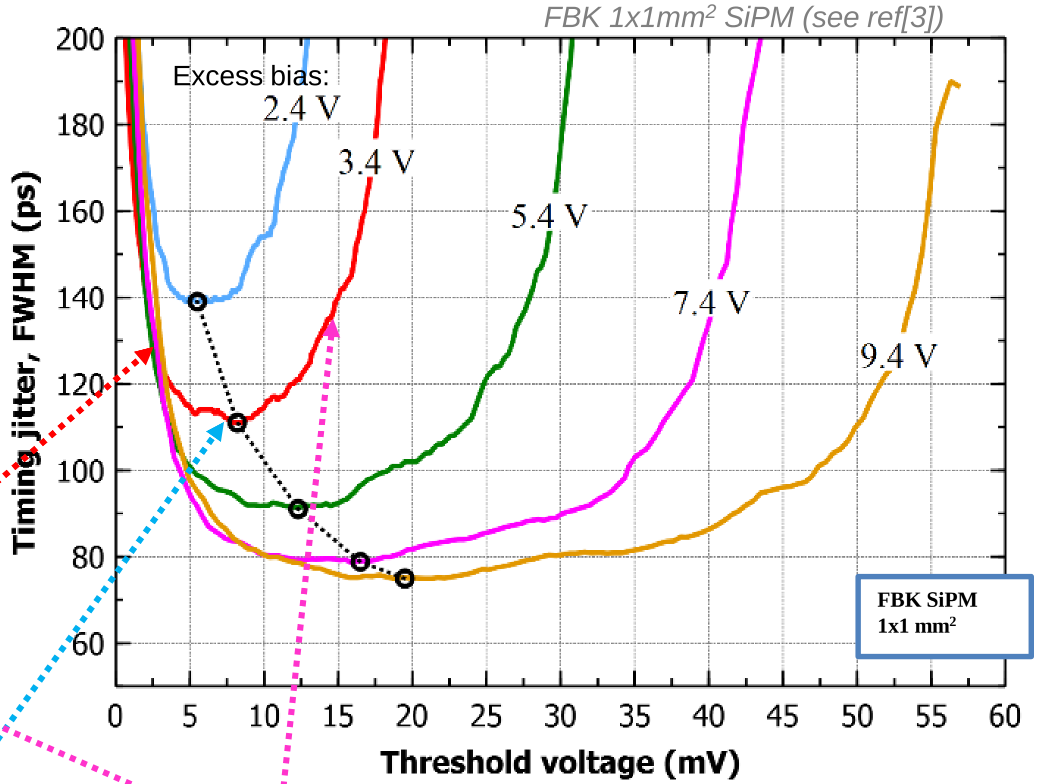






SPTR dependences of aSiPM



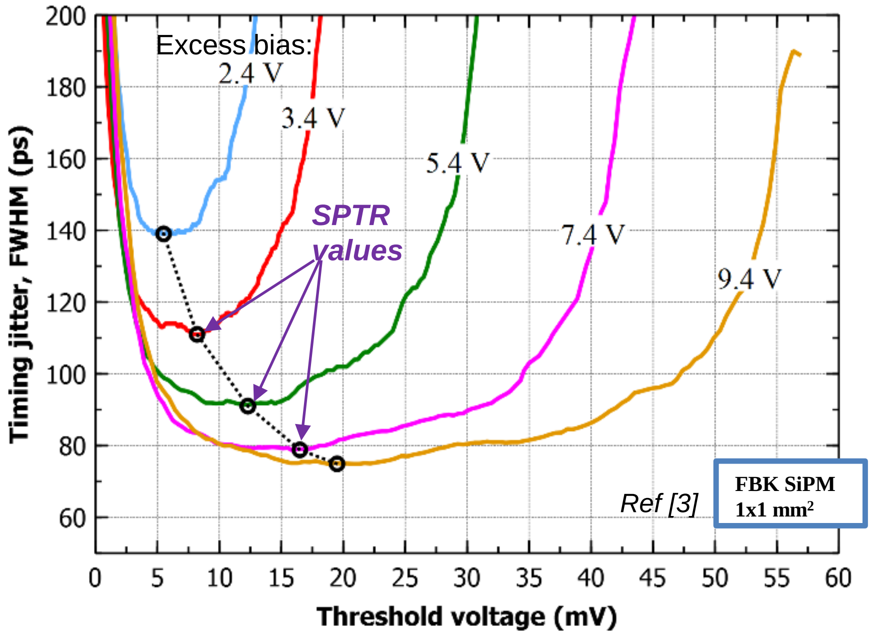


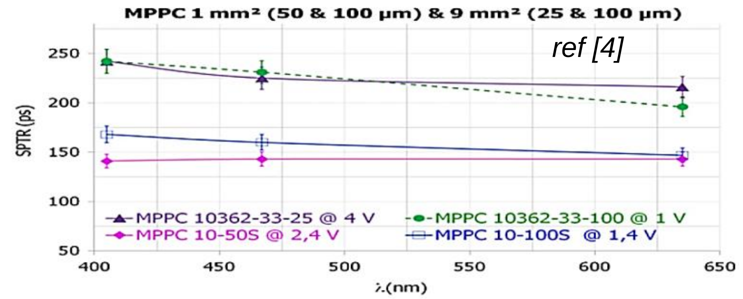
Low threshold: triggering on electronic noise and baseline fluctuations

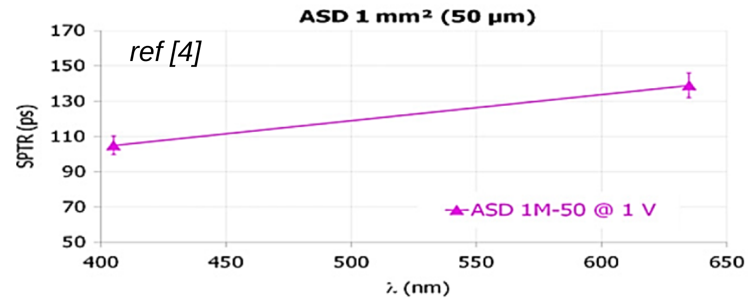
Good (intermediate) thresholds: good signal slope

High thresholds: lower signal slope and sensitive to amplitude variations

SPTR dependences of aSiPM





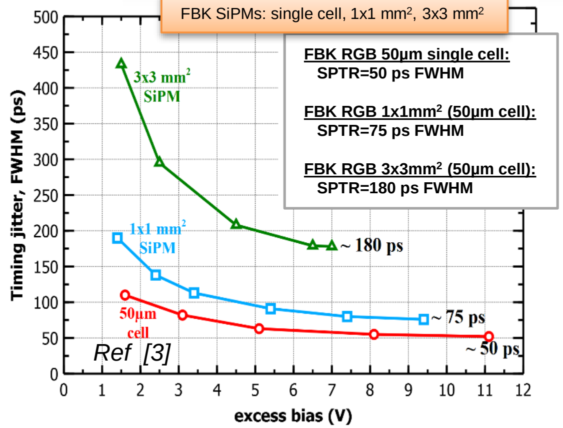


- **Measured SPTR value is highly affected by:**
  - the choice of the ***excess bias***
  - the voltage discriminating ***threshold*** (on SiPM signal)
  - Laser *wavelength* *(diffusion tail)*
  - *Temperature* *(e.g. DCR influence on $SPTR_{meas}$, or second order effects.)*
  - Repetition rate of laser (dead time?)
  - Front-end circuit (input capacitance)

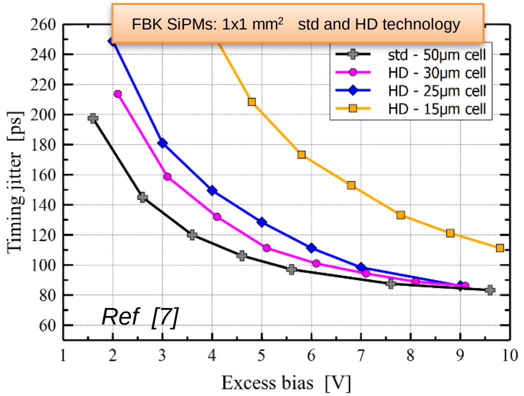
Very important to specify the values used in the measurement !

SPTR: state of the art results

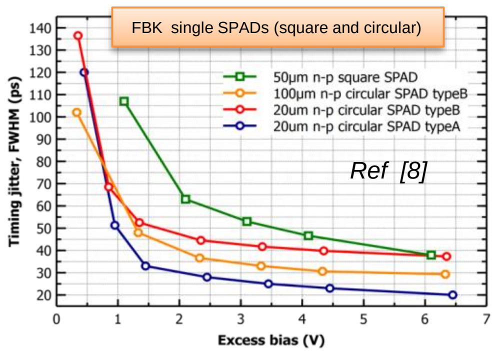
FBK SiPMs: single cell, 1x1 mm², 3x3 mm²



FBK SiPMs: 1x1 mm² std and HD technology



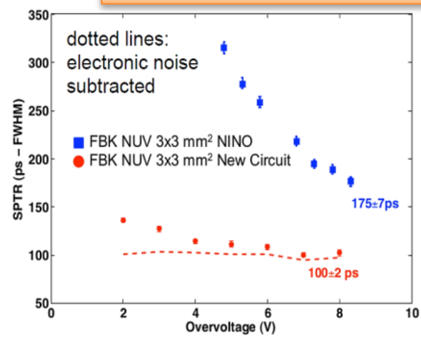
FBK single SPADs (square and circular)

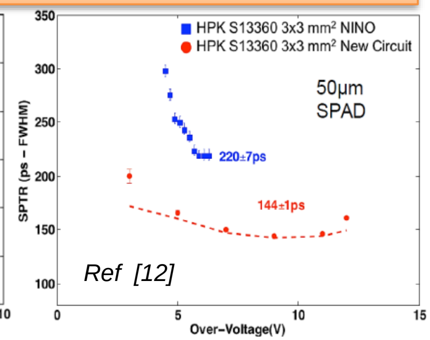


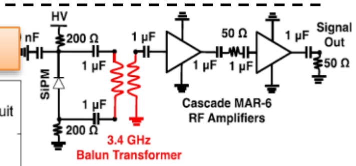
Several different SiPMs - ***tested with NINO ASIC*** *Ref [5]*

SiPM	Device area (mm²)	Cell size (μm)	Capacitance pF	SPTR FWHM	Overvoltage (V)	CT %	DCR MHz
STM	4.3 × 3.6	50	1250	200 ± 8	9.2	28	40
FBK NUVHD	4 × 4	25	610	205 ± 7	16.2	57	5.5
FBK NUV	3 × 3	40	440	175 ± 7	8.3	40	1.2
FBK NUV	1 × 1	40	55	94 ± 5	9.3	-	0.2
FBK NUV	SingleCell	40	-	75 ± 4	15.8	-	
Ham TSV	3 × 3	50	315	290 ± 7	2.6	34	0.6
Ham TSV	2 × 2	50	154	215 ± 5	3.4	30	0.8
Ham LCT2	3 × 3	50	340	220 ± 7	6.1	38	1.0
SensL JD0	3 × 3	35	790	290 ± 7	8.7	32	0.9
SensL JD4	3 × 3	20	690	270 ± 7	6.9	16	0.8
Ketek Optimized	3 × 3	50	820	330 ± 7	5.2	20	2.5

Recent results: 3x3 mm² SiPMs - ***with NEW Capacitance compensation circuit***





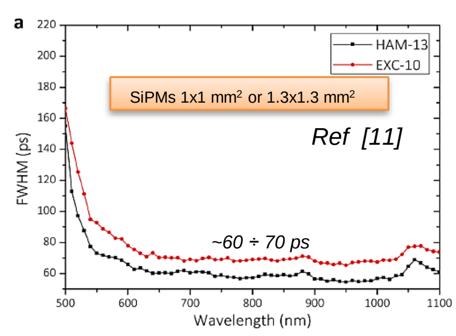


FBK NUV 3x3mm² (40µm cell)
NINO ASIC: SPTR=175ps FWHM
new circuit: SPTR=100ps FWHM

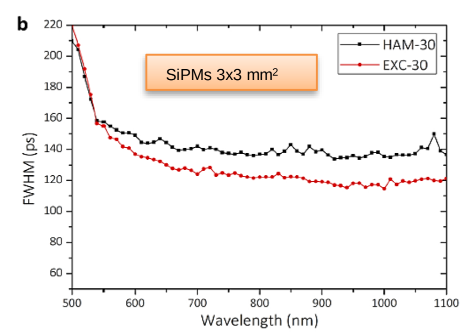
HPK 3x3mm² (50µm cell):
NINO ASIC: SPTR=220ps FWHM
new circuit: SPTR=144ps FWHM

SensL-J 3x3mm² (35µm cell):
NINO ASIC: SPTR=290ps FWHM
new circuit: SPTR=150ps FWHM

SiPMs 1x1 mm² or 1.3x1.3 mm²



SiPMs 3x3 mm²

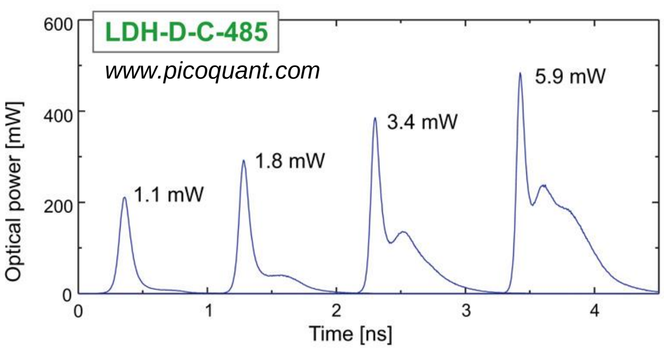


Practical considerations

Laser ?

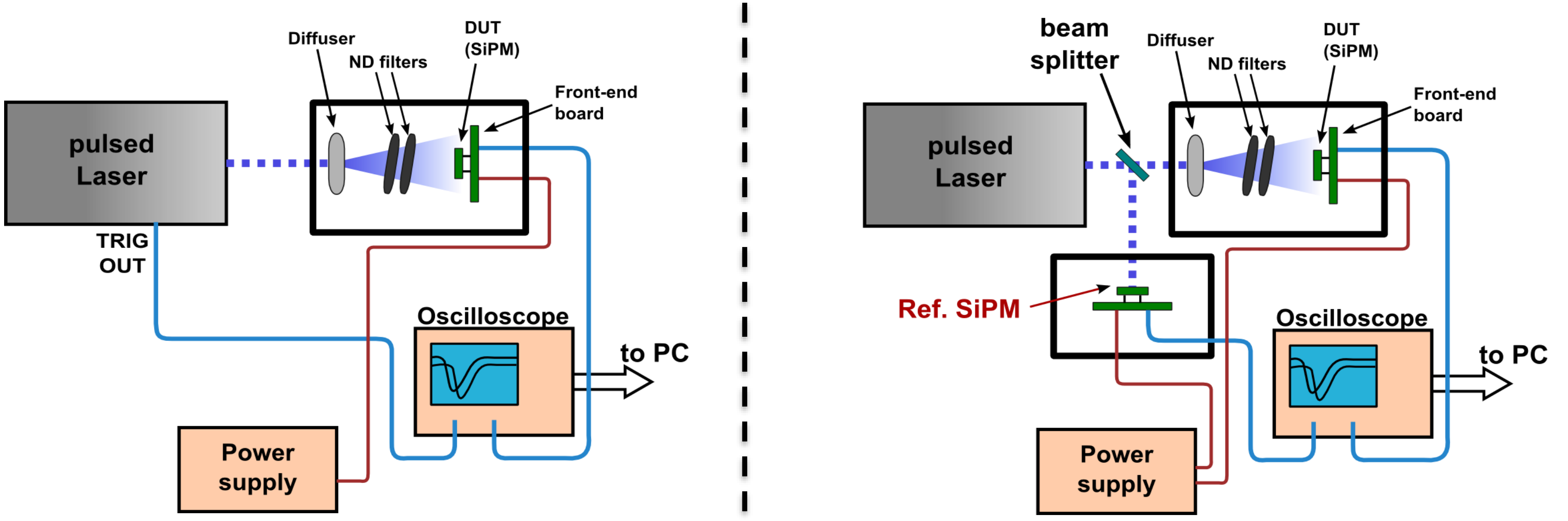
Laser type	Producer	Model	Pulse width range	Rep rate	Cost	Features
Semiconductor lasers	Picoquant	Picosecond Pulsed Sources	40-100 ps *	Adjustable (e.g. 1Hz ÷100MHz)	+	• Electrical trig-out available (but few tens ps jitter ?) • Several different laser heads (different λ) • Secondary peaks or tails ** • Compact, fiber coupled.
	ALS	PiL XXX	40-80 ps *	From pulse-on-demand up to 120 MHz		
Pulse Oscillators	Spectra physics	Mai Tai	~100 fs	80 MHz	+++	• High stability, short pulses • Tunable wavelength, limited range (e.g. 690–1040 nm) • Accessories: pulse picker, SHG, etc. • Bulky, typ. Free space.
	Coherent	Vitara	< 20 fs	80 MHz		
Femtosecond Fiber Lasers	Toptica	FemtoFErb 780	~ 90 fs	100 MHz	++	• Chirped very short pulses • Fiber coupled, compact • Only 1 wavelength, (plus SHG)
	MENLO	ELMO 780	< 100 fs	50 – 100 MHz		

*In this **table only very few examples reported** – with the only purpose of comparing the general features of the different types of laser solutions. Data taken from the relative website.*
** From general description of product or considering only the visible range*
*** See plot below.*



Practical considerations

Laser ref. signal



1) With electrical trigger out signal from laser

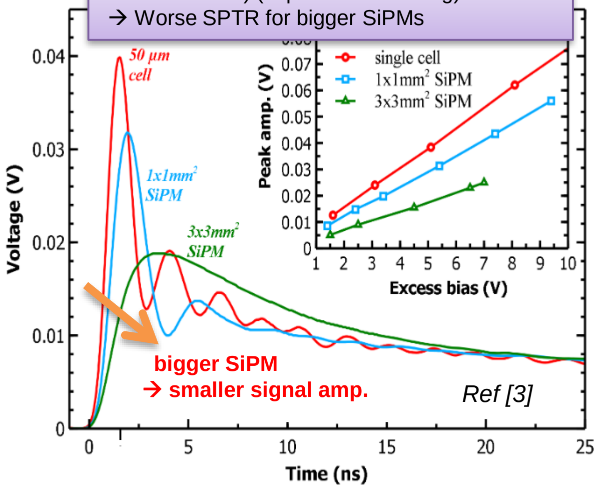
2) With reference signal from secondary detector

- **Reference signal:**
  - ***Electrical-optical jitter*** can be an issue (up to few tens of picoseconds)
  - maybe not relevant when measuring SPTR of 100ps, or when laser PW is ~70ps, but **can be eliminated** using reference signal from **secondary detector**. (with much higher light intensity, to decrease the jitter to the minimum).

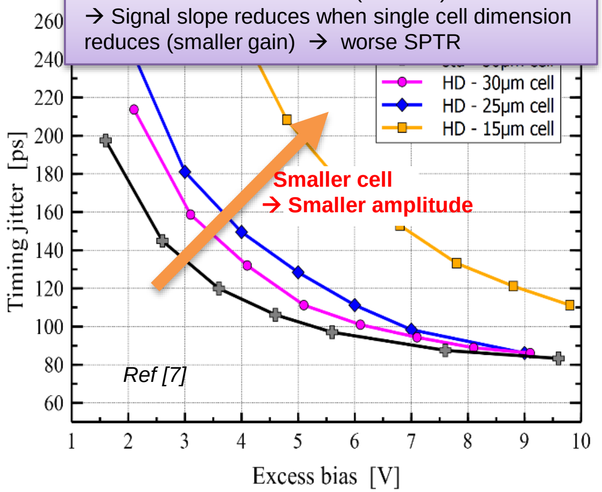
Practical considerations

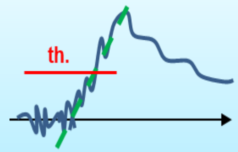
Signal slope and electronic noise

Signal slope reduces for bigger SiPMs (same cell dimension) (capacitance filtering)
→ Worse SPTR for bigger SiPMs



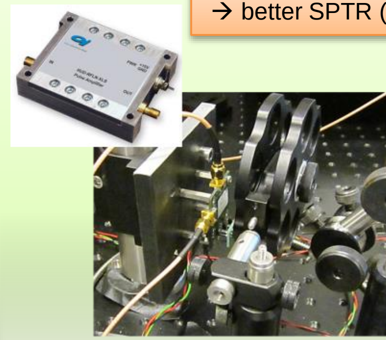
Same dimesion of the SiPM (1x1mm²)
→ Signal slope reduces when single cell dimension reduces (smaller gain) → worse SPTR

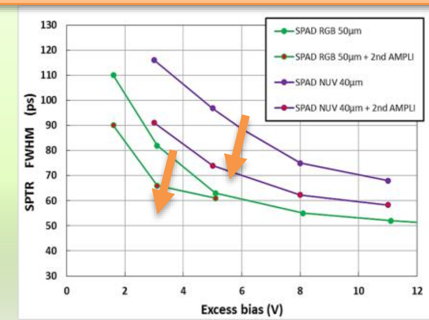


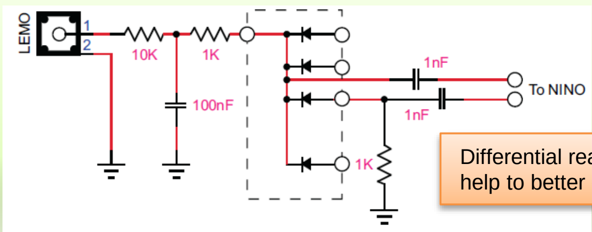


$$Jitter_{noise} = \frac{V_{noise}}{dV/_{dt}}$$

Additional RF amplifier → higher BW and gain of the signal
→ better SPTR (but high power consumption)







Ref [6]

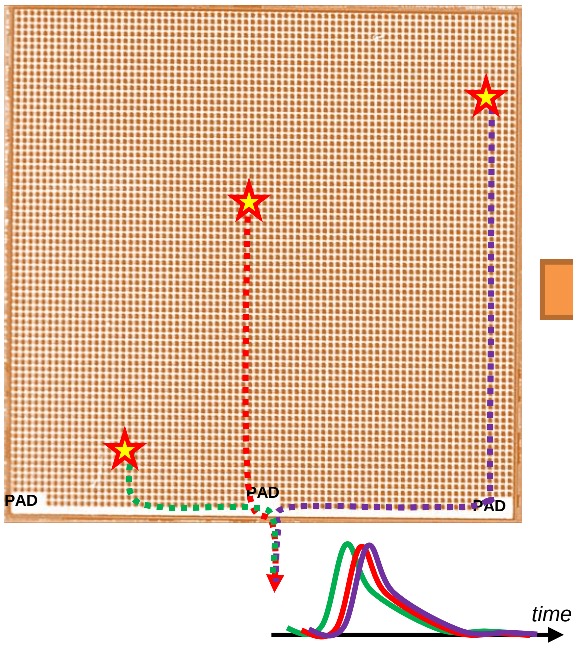
Differential readout of SiPMs can help to better extract the signal

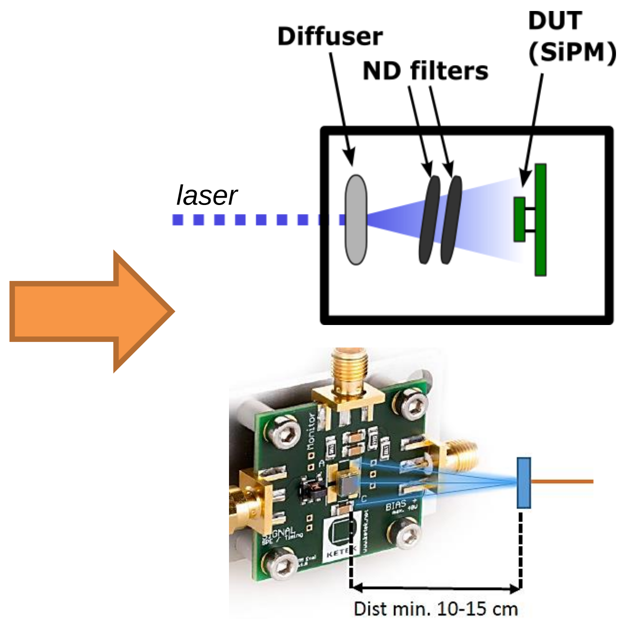
- ***Effect of electronic noise and DCR***: **often the limiting factor.**
  - ***Recommendation: high bandwidth, short trace lengths, low input impedance***.
  - *In addition, to better extract signal:*
    - *Differential readout to reduce signal filtering.*
    - *Passive or active capacitance compensation.*

Practical considerations

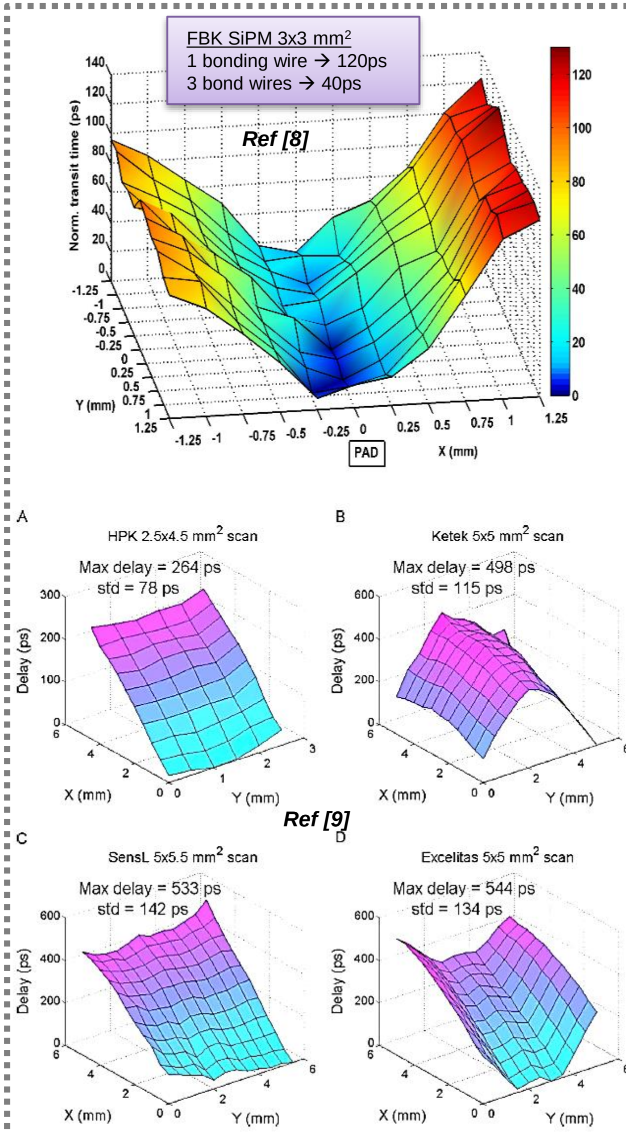
Transit time skew(1)

3x3 mm² SiPM





Measurements of TTS

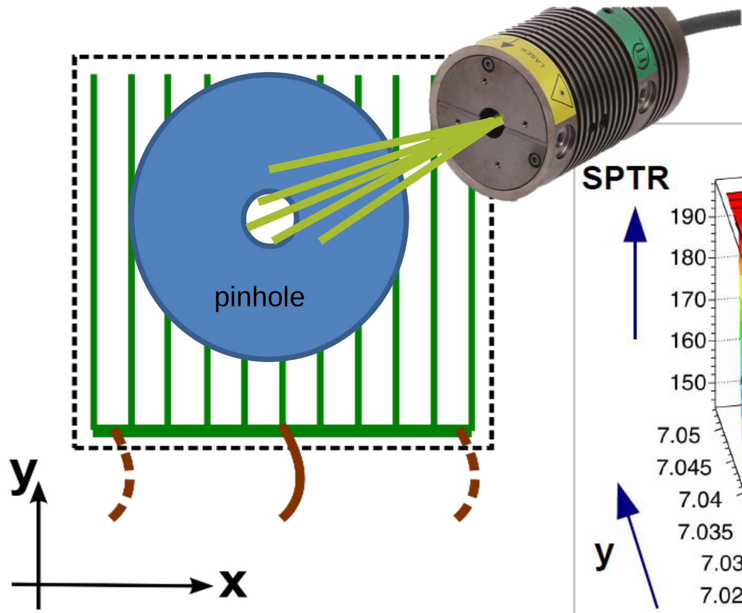


- **SPTR affected by transit time skew (TTS),** i.e. difference in signal path from triggered cells to bonding PAD(s).

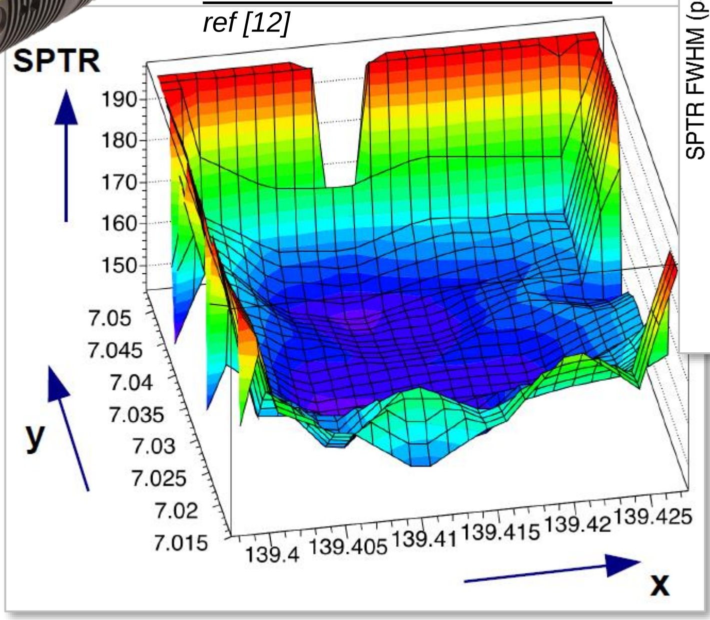
- ***SPTR measurement*** → ***ensure uniform illumination of sample***
  - e.g. use light diffuser

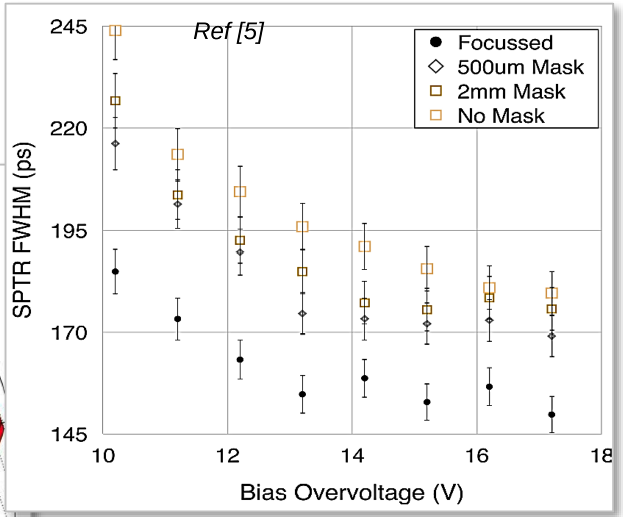
Practical considerations

Transit time skew(2)



FBK NUV SPAD – scan of microcell
ref [12]



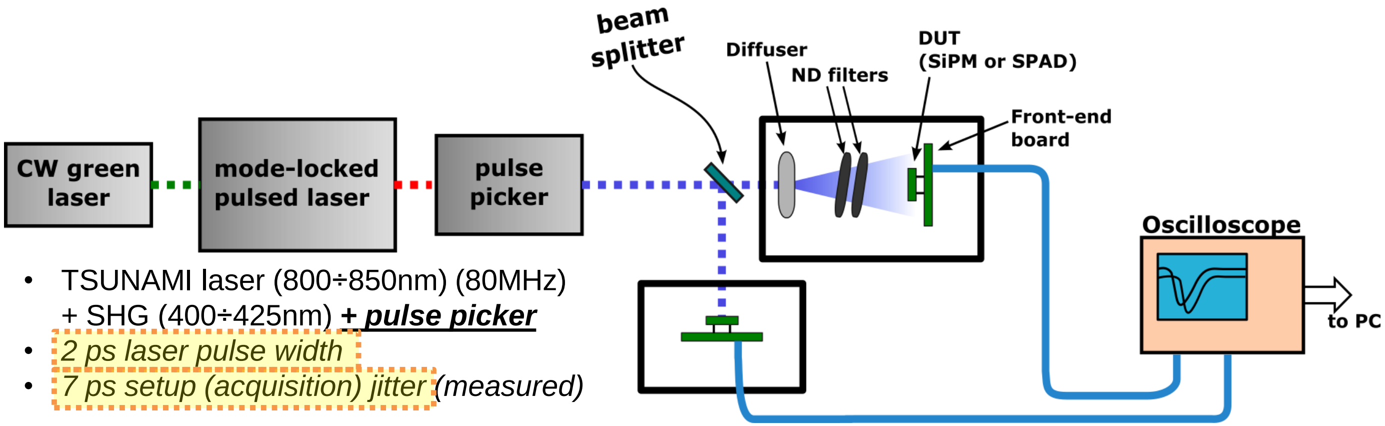


- ***Interesting additional (optional) measurement:***
  → ***SPTR with focused-light (or with pinhole) in the center (or complete scan)***
  - Useful insight of the detector
  - Interesting in some applications (which can focus light)

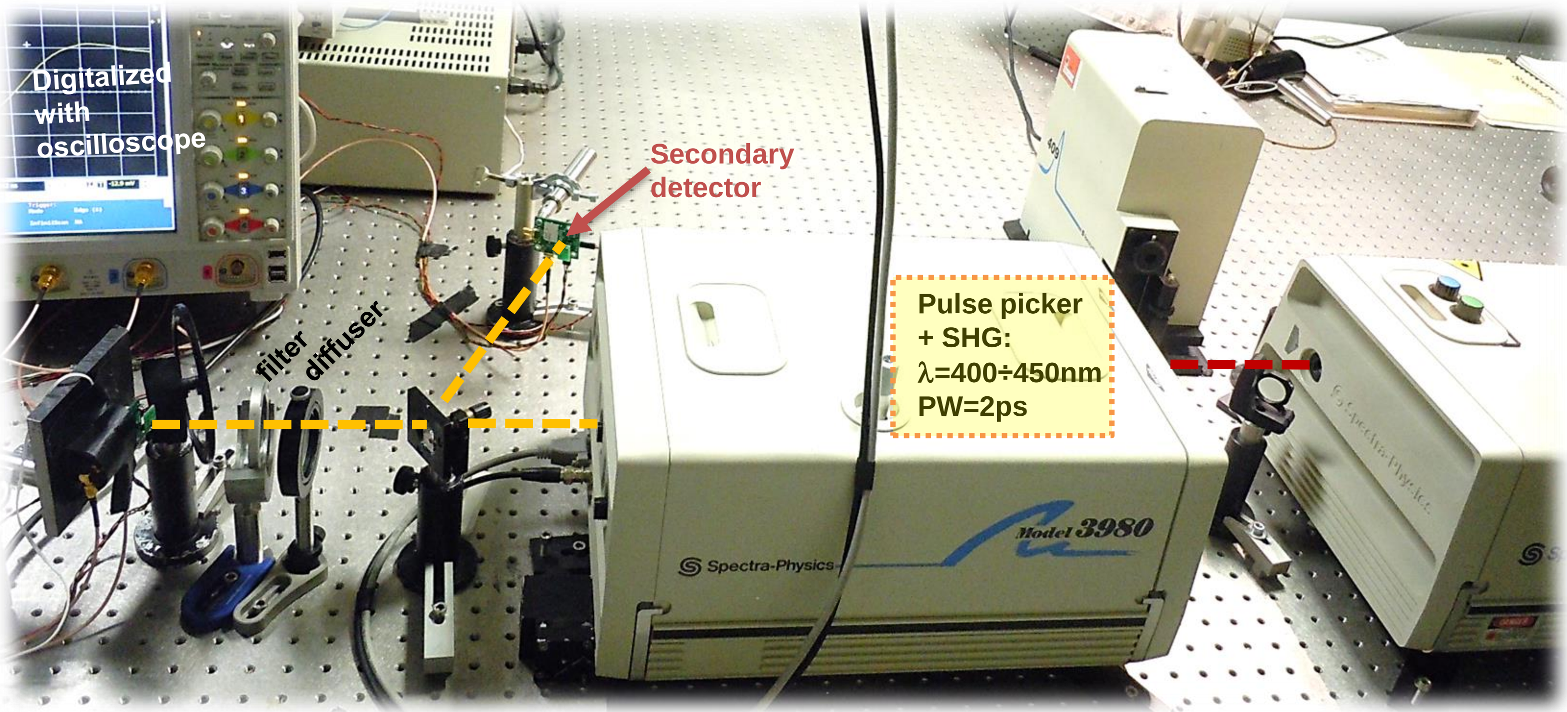
Practical examples of SPTR setups

Setup #1 (at FBK/UniTN)

Based on signal acquisition - with secondary detector

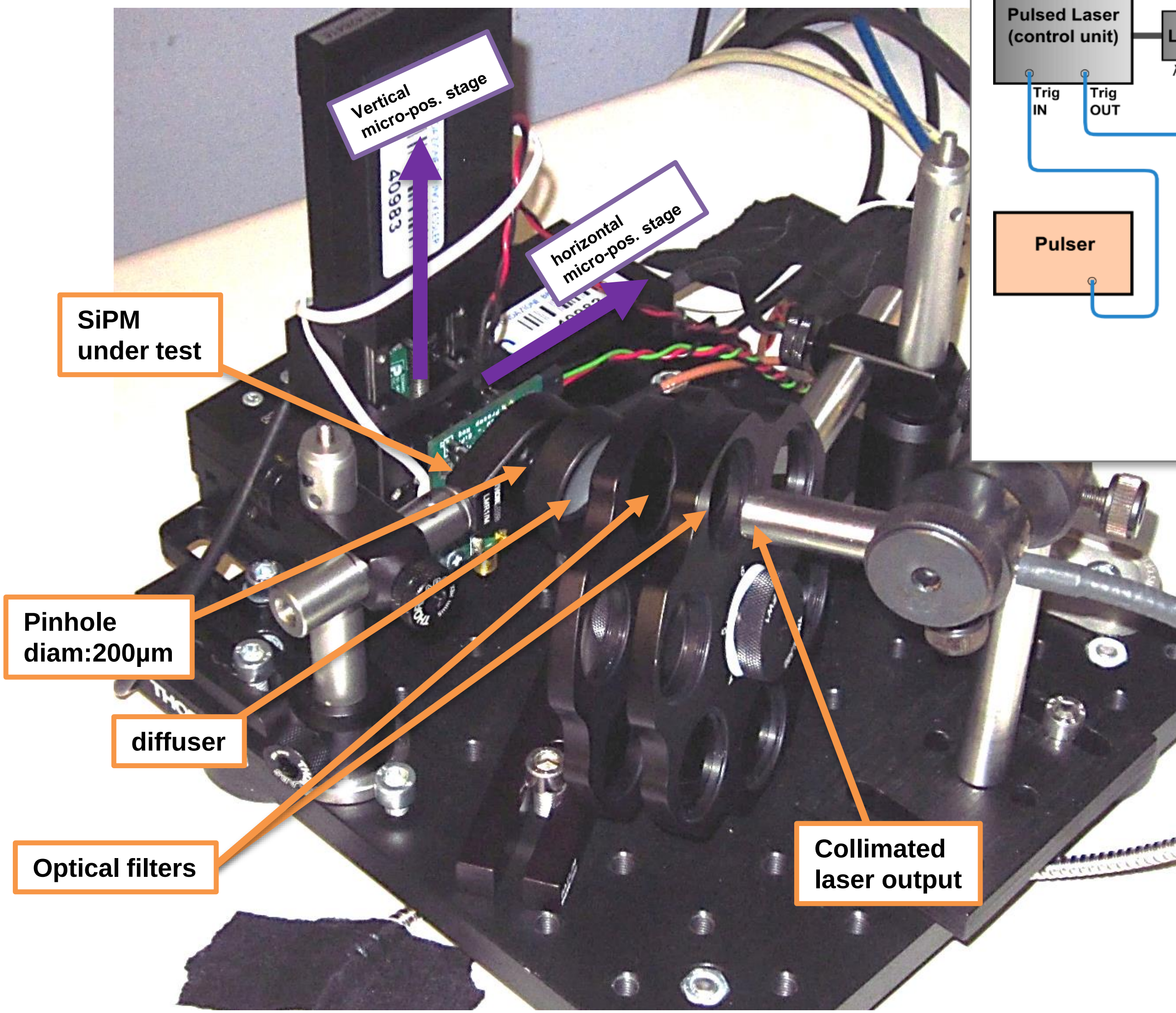


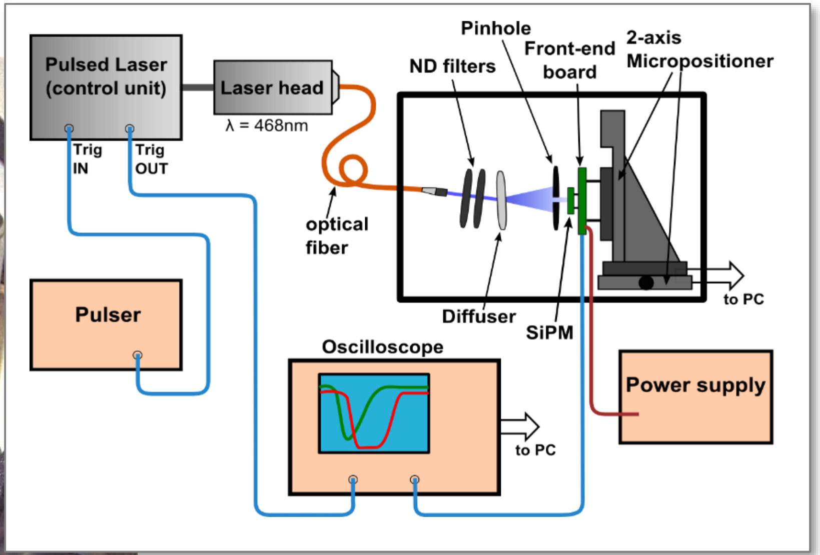
- TSUNAMI laser (800÷850nm) (80MHz) + SHG (400÷425nm) + ***pulse picker***
- *2 ps laser pulse width*
- *7 ps setup (acquisition) jitter (measured)*



Setup #2 – active area scan (with pinhole) (at FBK)

Based on signal acquisition - ref signal from laser unit

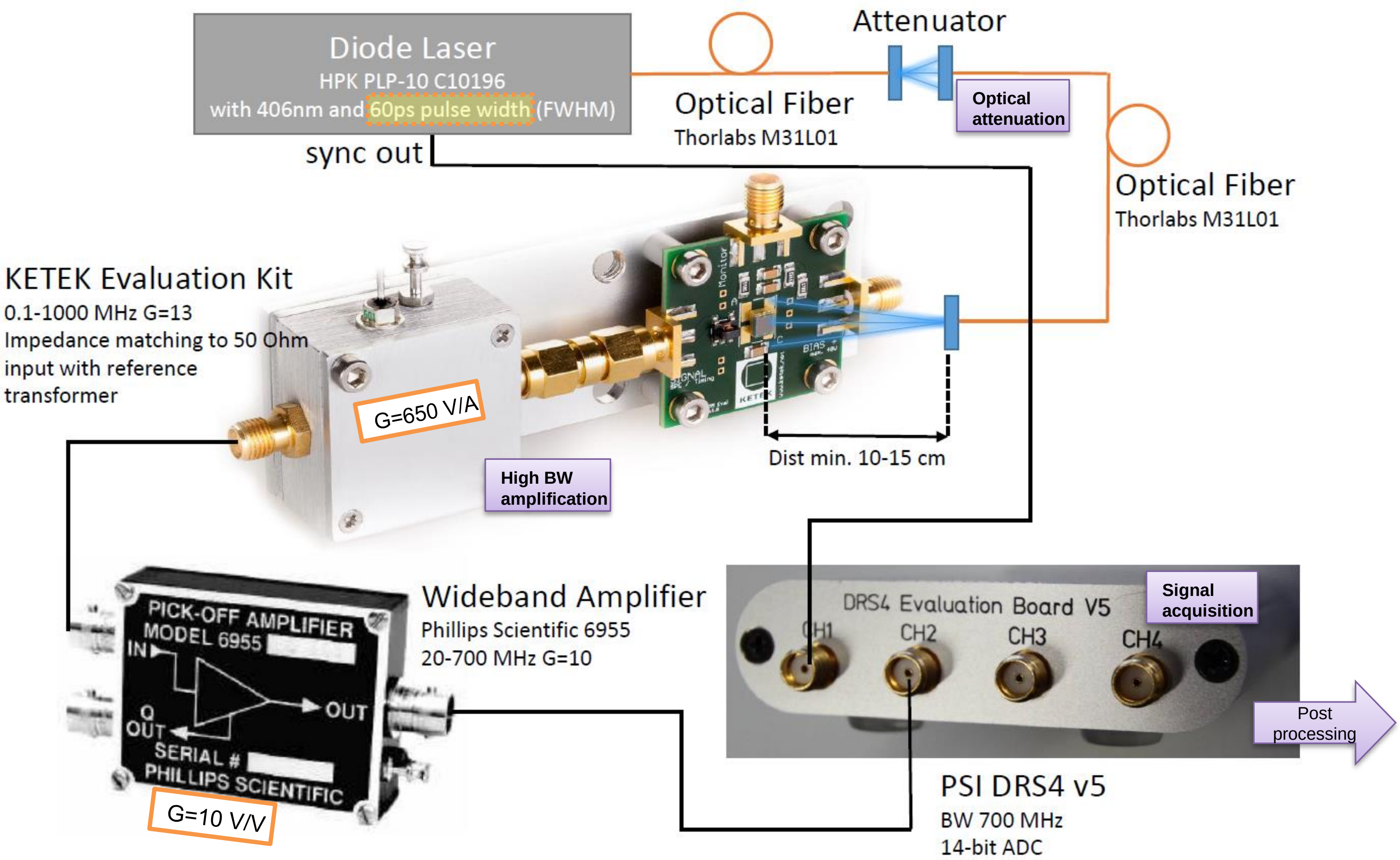




- X and Y micro-positioning stages
- "std" FBK amplifier (gain=5000 V/A)
- filters + diffuser + pinhole
- PicoQuant 470nm pulsed laser:
- 70ps pulse width
- filters + diffuser + pinhole

Setup #3 (Ketek)

Based on signal acquisition - ref signal from laser unit



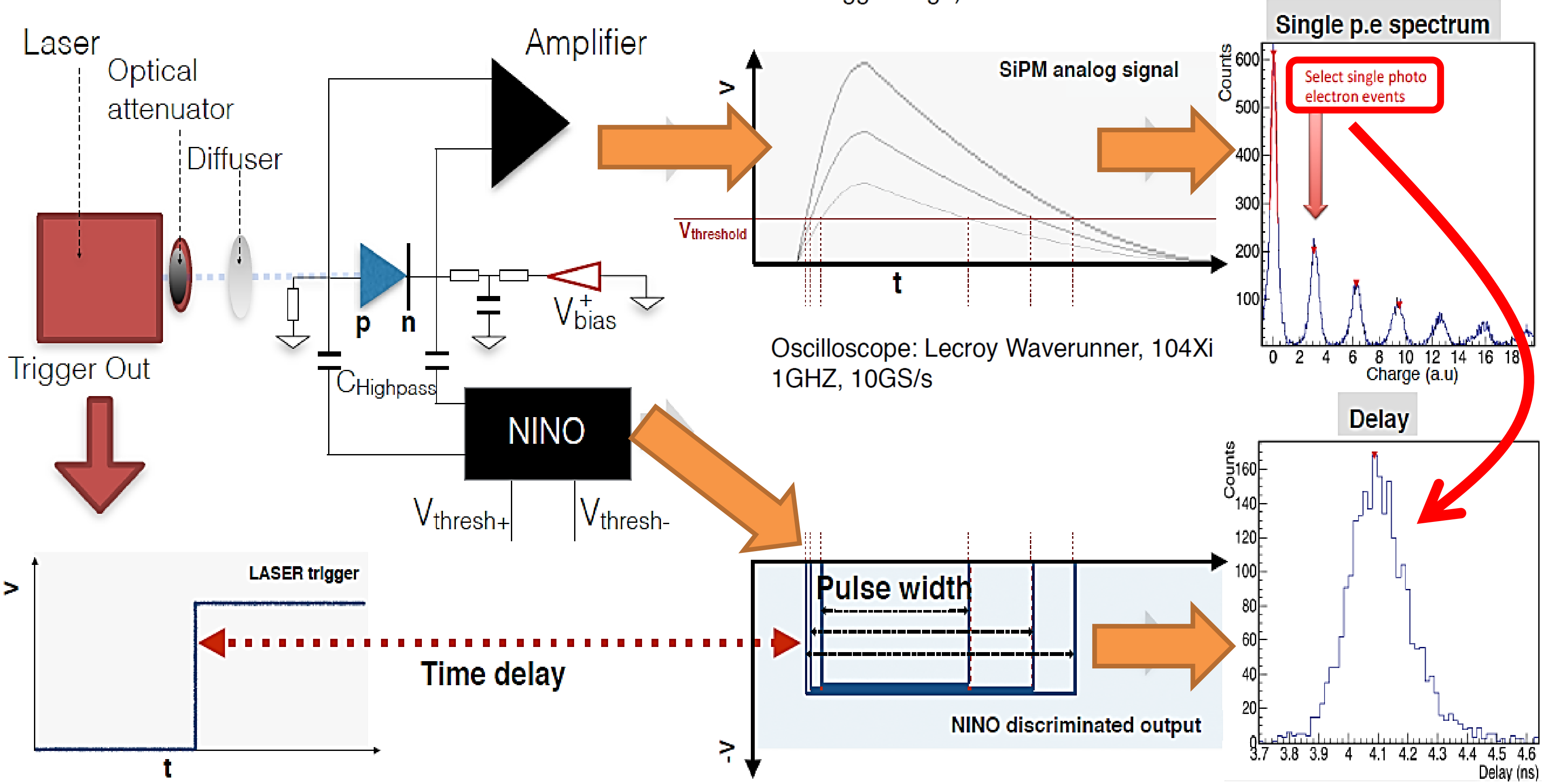
Countesy of Thomas Ganka (Ketek)

Setup #4 - with NINO ASIC (CERN)

Based on ASIC timing meas. + simultaneous signal acquisition - ref signal from laser unit

Laser :
420 nm, 42ps pulse width, 100 kHz pulse rate, 50% intensity

Acquisition jitter:
21 ps FWHM
(from NINO rising edge and the trigger edge)



Oscilloscope: Lecroy Waverunner, 104Xi 1GHZ, 10GS/s

Setup #5 (Uni. Sherbrooke)

Based on signal acquisition – ***with secondary detector***

Variable attenuator
high power optics
glen polarizer
1/2 wave plate
beam dump

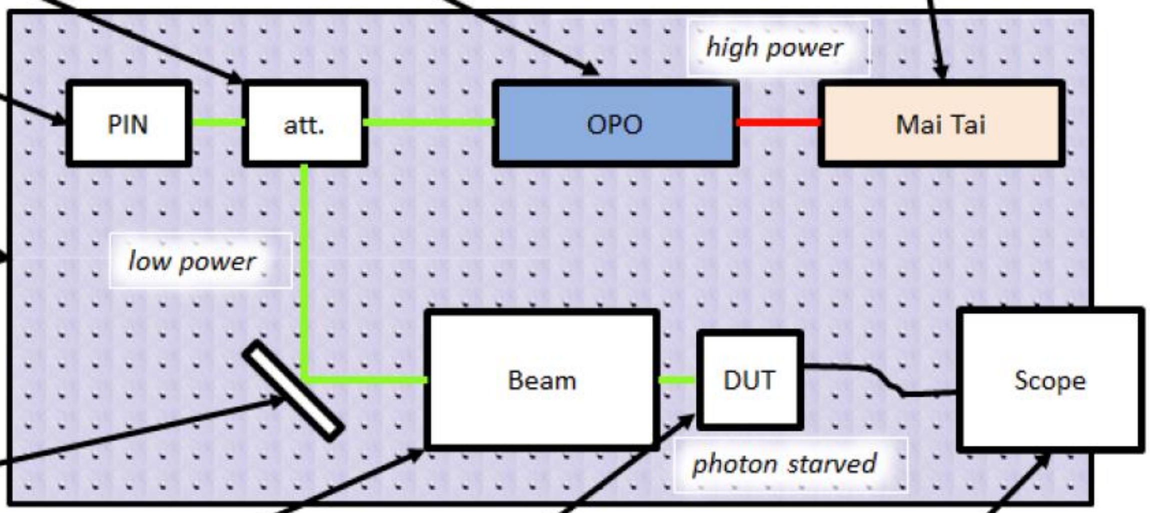
SP- Optical Parametric Oscillator
pulse width : < 100 fs
repetition rate : 80 MHz
wavelength : 345 - 2500nm
average power : 100 mW - 1.0 W

SP- Mai Tai Ultrafast Ti-Sapphire Laser
pulse width : < 100 fs
repetition rate : 80 MHz
wavelength : 690 - 1040 nm
average power : 3.0 W

Reference PIN diode
Becker-Hickl PHD-400
200 ps rise time

Opticale table
- two 2x6' tables
- one 2x8' table
- optical table shelves

Free space beam propagation
High-end newport mirrors for ultrafast laser



Beam conditionning setup
iris, shutter, filter, beam splitter, focusing optics

Sample fixture
- automated XYZ-axis stage
- manual tilt, yaw and rotation axis

Output signals
SMA cable (ref diode and DUT)
Oscilloscope
- LeCroy SDA 6000A 20 GS/s, 6 GHz
- Keysight MSOX91304A 80 GS/s, 13 GHz

Summary (Recommendations)

- **SPTR is defined as the one of the detector (SiPM)**
  - The measured value should be *de-convolved from setup, acquisition and laser related jitters*
  - SPTR value → one for each bias (and λ and temperature) → the one at the best discr. threshold.

- **Laser:**
  - Check laser electronic jitter (e.g. with multi-photon response)
    - In case split laser optical pulse and use secondary detector
  - Check laser pulse shape *(second peaks, tails, reflections, etc.)*
    - streak camera or TCSPC with SPAD?

- **SiPM:**
  - Check the detector is uniformly illuminated → To avoid TTS bias in Analog SiPMs
  - Avoid saturation of SiPM → mean number of photons: max ~5% rep rate
  - Always specify measurement conditions, particularly excess bias and discrimination threshold.
    - Best threshold, giving best SPTR, can be different for each bias, λ, temp. condition.

- **Electronics:**
  - Recommended high bandwidth, short trace lengths, low input impedance…
  - Determine the electronic noise or electronic IRF (test-pulses, by illuminating with a large number of photons (MPTR, illuminating with 10 photons)
  - Baseline correction (e.g. pole-zero or high-pass filtering) or constant fraction methods are applicable

References

1) M. Assanelli et. al. "Photon-Timing Jitter Dependence on Injection Position in Single-Photon Avalanche Diodes", J quant. Elec. v.47, n.2, 2011
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3) F. Acerbi et. Al. "Characterization of Single-Photon Time Resolution: From Single SPAD to Silicon Photomultiplier" IEEE Transaction on Nuclear science v.61, n.5, 2014.
4) V. Puill et. Al. "Single photoelectron timing resolution of SiPM as a function of the bias voltage, the wavelength and the temperature" NIMA 695(2012)354–358
5) M.V. Nemallapudi et. al., "Single photon time resolution of state of the art SiPMs" 2016 JINST 11 P10016
6) K. Doroud et al. "Differential-readout:Thetechnique to optimize timing in a monolithic MPPC array" NIMA 717(2013)5–10
7) F. Acerbi et. al. "High-Density Silicon Photomultipliers: Performance and Linearity Evaluation for High Efficiency and Dynamic-Range Applications" IEEE journal of quantum electronics, v54, n.2, 2018
8) F. Acerbi et. al., "Analysis of transit time spread on FBK silicon photomultipliers" (2015) JINST 10 P07014
9) S. Dolinsky et al. "Timing resolution performance comparison of different SiPM devices" NIMA 801 (2015) 11–20
10) S. Gundacker et. al., "State of the art time resolution in TOF-PET detectors for various crystal sizes and types" 14th VCI, 18 February 2015
11) E. Martinenghi et. al., "Spectrally-Resolved Single-Photon Timing of Silicon Photomultipliers for Time-Domain Diffuse Spectroscopy" IEEE Photonics Journal, v.7, n.4 (2015)
12) S. Gundacker et. al. "Single Photon Time Resolution (SPTR) improvement" slides from FAST, Ljubljana, 8th Jan 2018

FONDAZIONE
BRUNO KESSLER

Time resolution of analog SiPMs: techniques and setups examples

Fabio Acerbi

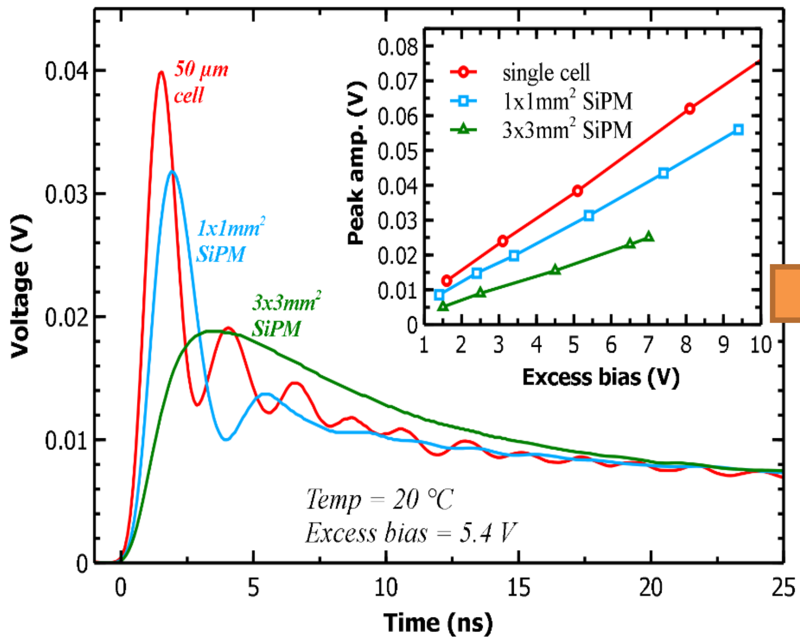
(on behalf of the ICASiPM timing group:
S Gundacker, S. Brunner, A. Gola, E. Venialgo, E. Popova,
T. Ganka, J.F. Pratte, M.V. Nemallapudi, S. Dolinsky, S. Vinogradov)

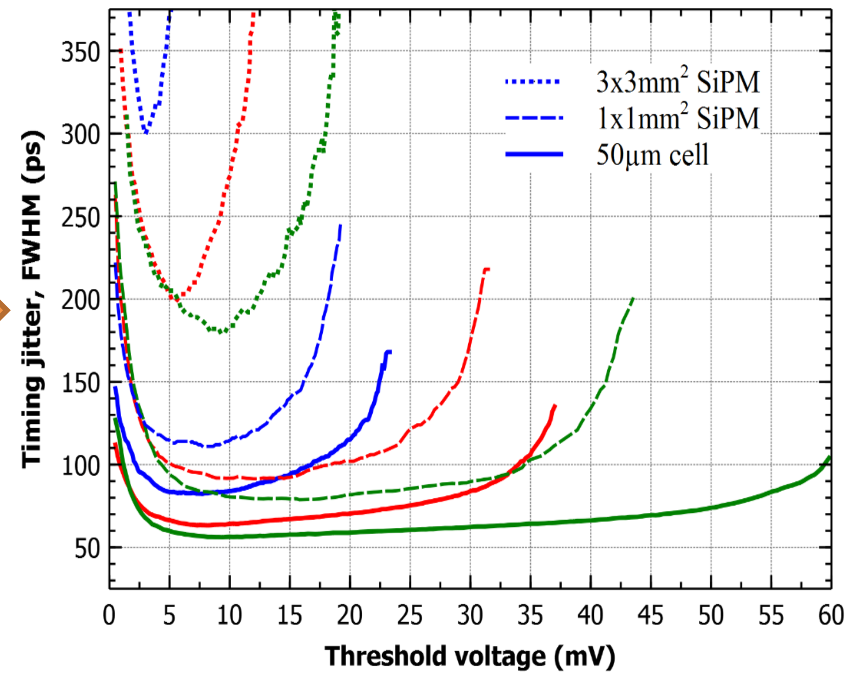
International Conference on the
Advancement of Silicon Photomultipliers
11.6.2018 - 15.6.2018 Schwetzingen, Germany

backup

SPTR dependences of aSiPM

FBK SiPMs and SPADs (see ref[3])
Same cell layout: but just one cell, 1x1mm2 SiPM containing many of these cells, or 3x3mm2 SiPM containing many of these cells



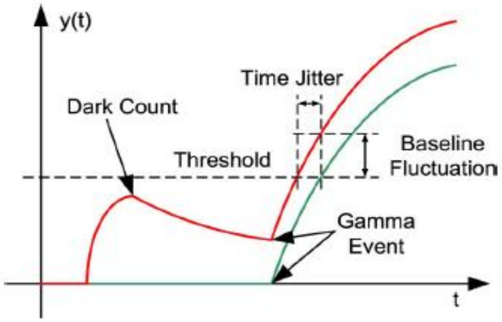


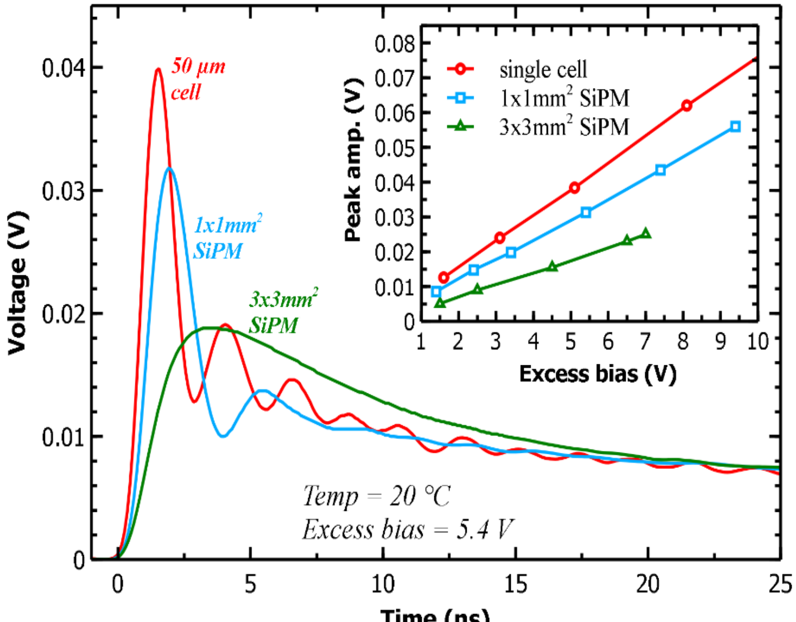
- With single cell → Higher signal → larger voltage-threshold region with good SPTR values → less affected by amplitude variations or electronic noise in the measured values.

Effect of electronic noise (baseline fluctuation)

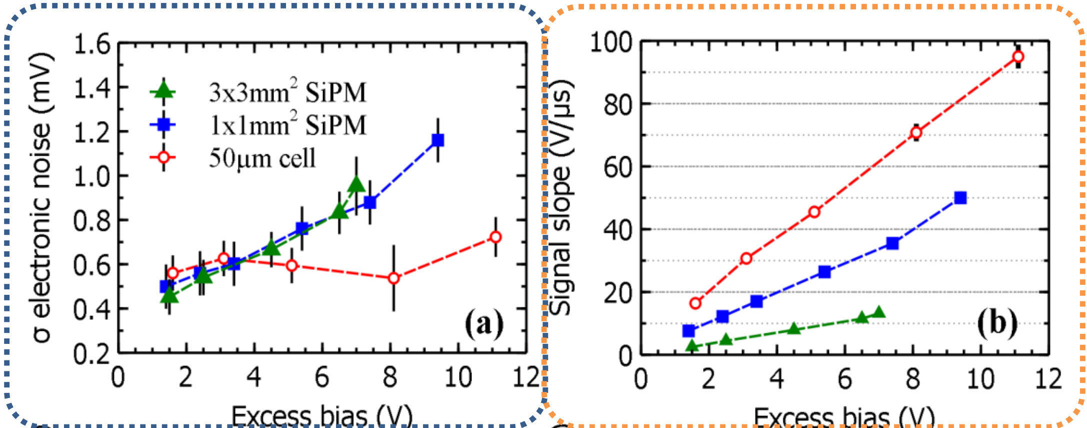
the spread in threshold crossing time (σ_n), i.e. **timing jitter**, is proportional to the **amplitude of electronic noise (σ_a)** divided by the **slope of signal**, at the threshold crossing point"

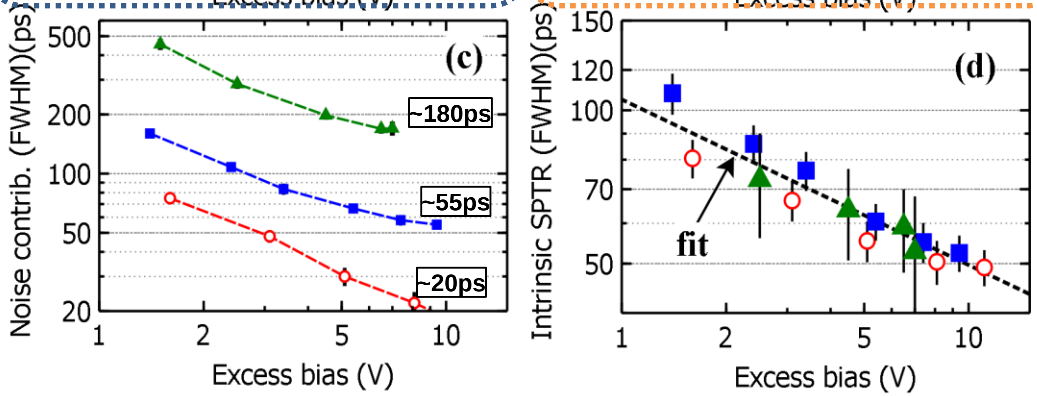
$$\sigma_n \propto \frac{\sigma_a}{f'_{th}}$$



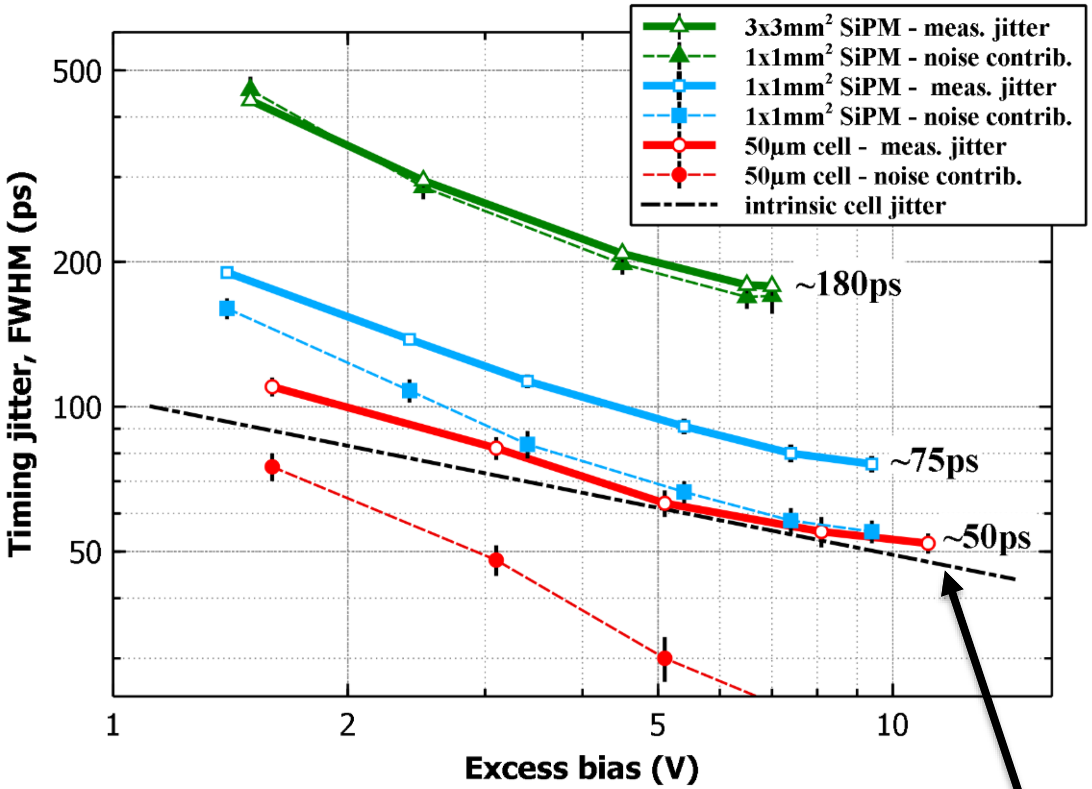


Reduced rising-edge slope for bigger devices
(higher capacitance and parasitics)



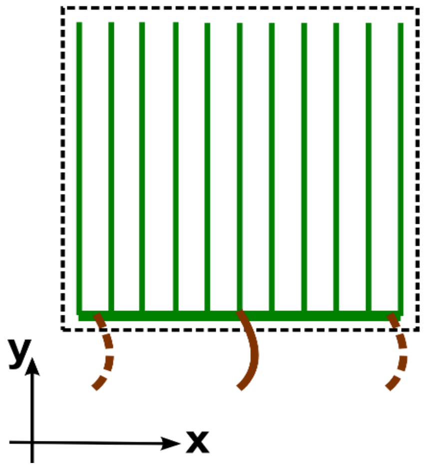


Effect of electronic noise (baseline fluctuation)



2) Single-cell (SPAD)
"intrinsic" time-resolution

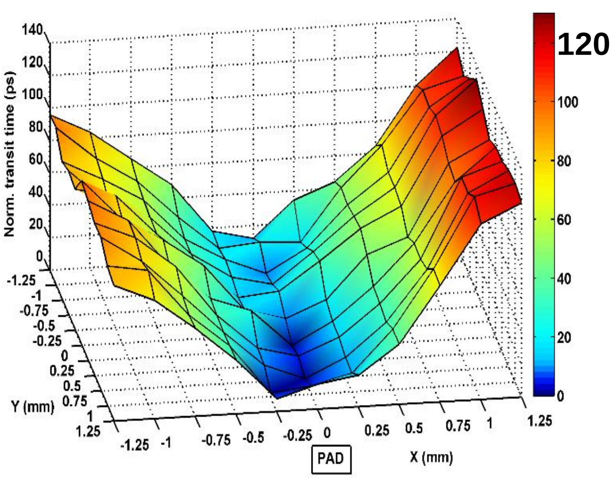
Transit time skew contribution



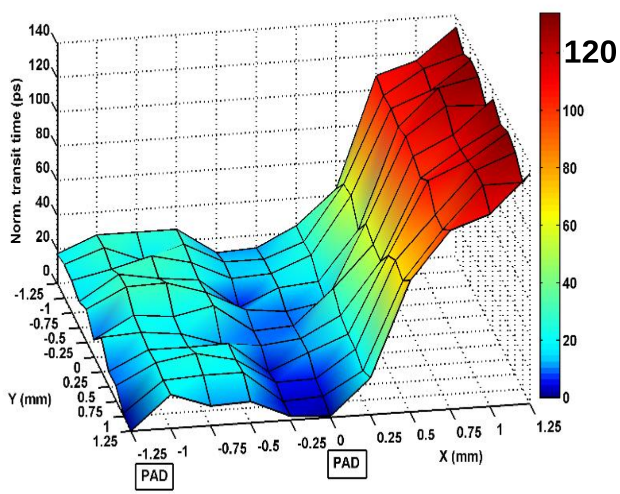
Pulsed LASER
SCAN over SiPM surface

- RGB (nonHD) 3x3mm^2 SiPM
- 50µm cell

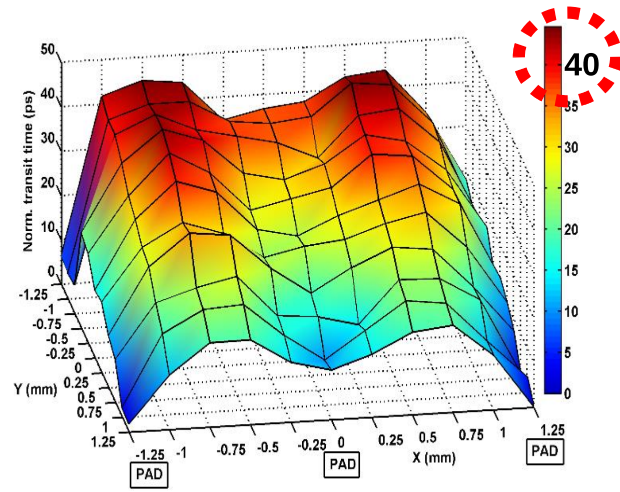
1 bonding wire (center)



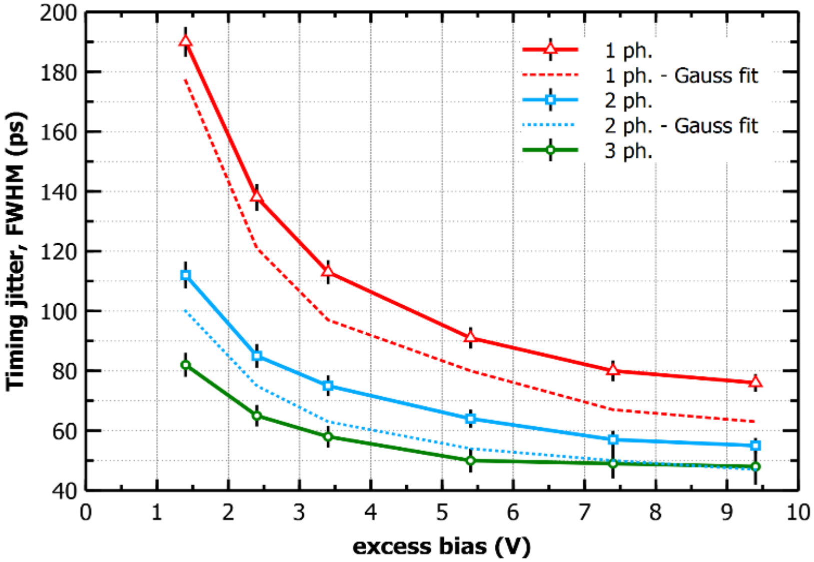
2 bonding wires



3 bonding wires



Few-photons timing jitter

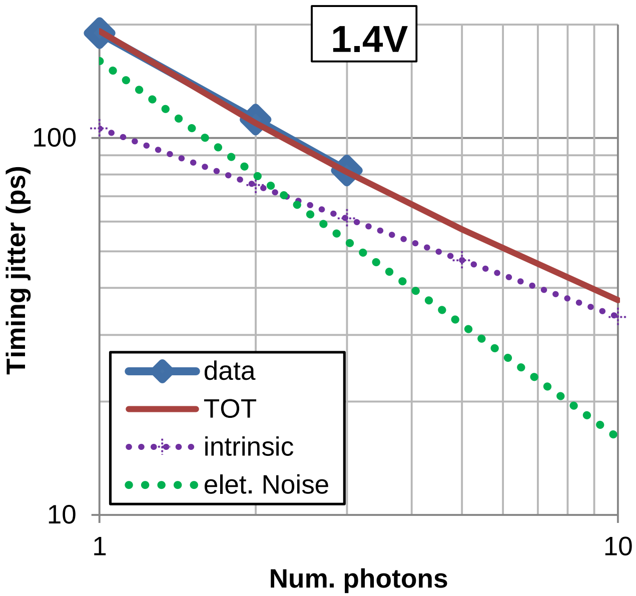


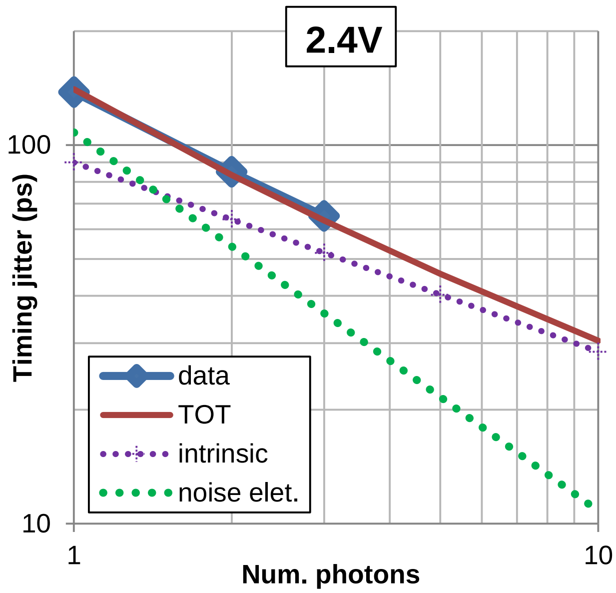
- <u>Higher num. of photons → lower timing jitter</u>
  - **Intrinsic time resolution**: reduction with square root of num. of photons
  - **Electronic noise contribution**: reduction with number of photons

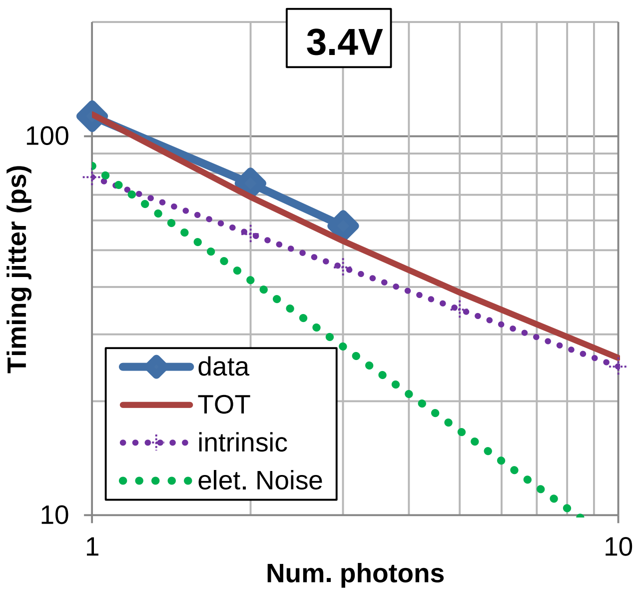
R. Vinke, NIMA 610 (2009)

$$\sigma_t = \sqrt{\boldsymbol{\sigma_i^2} + \boldsymbol{\sigma_n^2} + \sigma_{ccv}^2 + \sigma_{ttv}^2 + \sigma_{setup}^2}$$

$$\boldsymbol{\sigma_i} \propto \frac{\mathbf{1}}{\sqrt{\boldsymbol{N_{phot}}}} \qquad \boldsymbol{\sigma_n} \propto \frac{\mathbf{1}}{\boldsymbol{N_{phot}}}$$



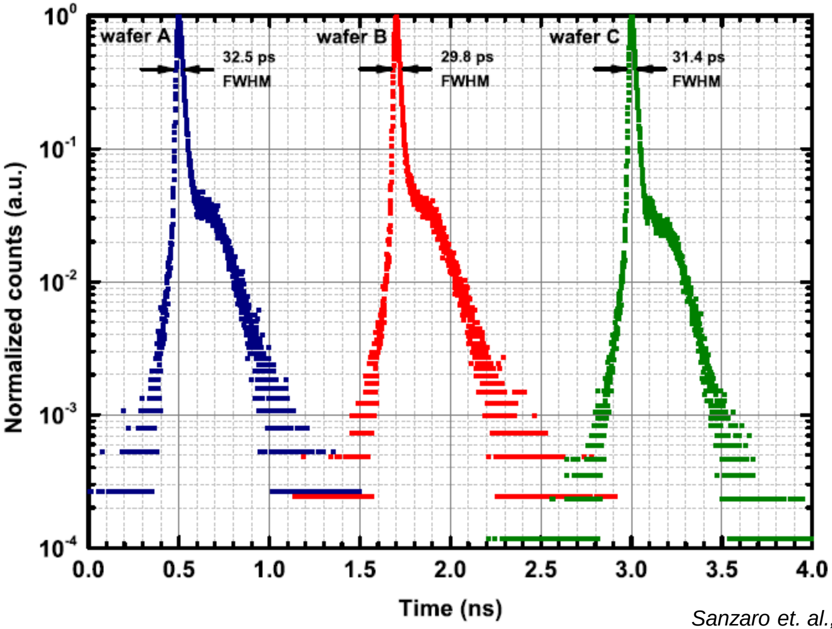




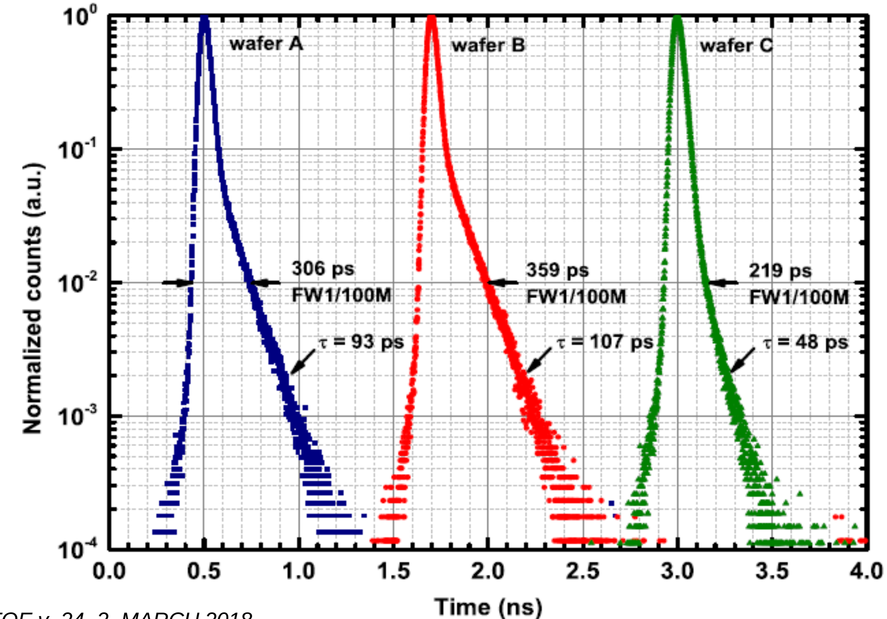
SPTR measurement with secondary peaks

Example: measurement on single SPADs in CMOS process

1st measure: laser "high intensity"



2nd measure: laser "low intensity"



Sanzaro et. al., JSTQE v. 24, 2, MARCH 2018
Antel MPL-820 laser module

- ***Lasers can have important secondary peaks or tails***
  - *Set for high intensity (but then attenuated): narrow peak, but secondary peak*
  - *Set for low intensity (but then attenuated): wider main peak but no secondary peak*
- ***Possible technique → characterize separately the SiPM/SPAD FWHM and diffusion tail.***