SiPM Single Photon Timing Resolution

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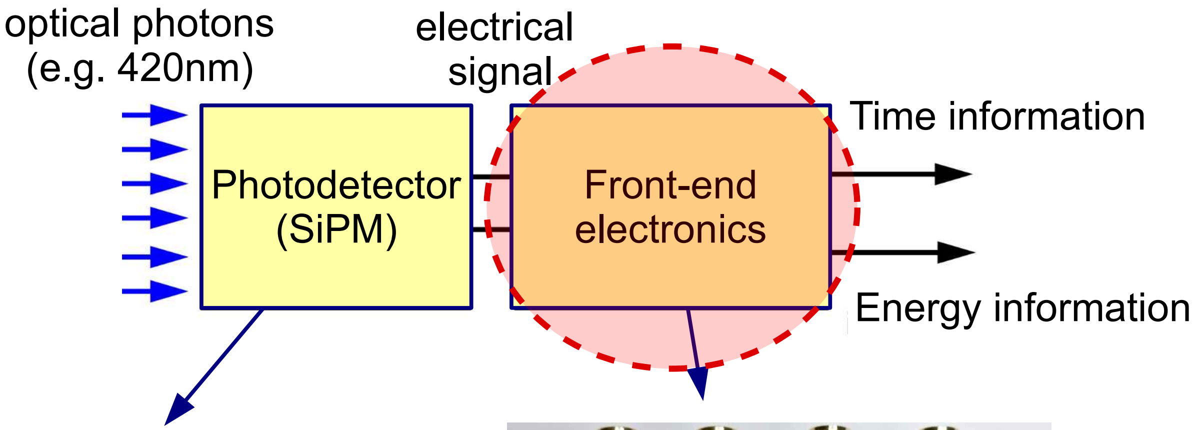
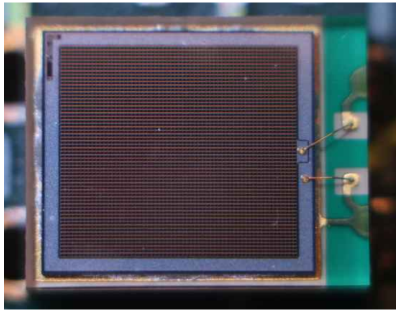
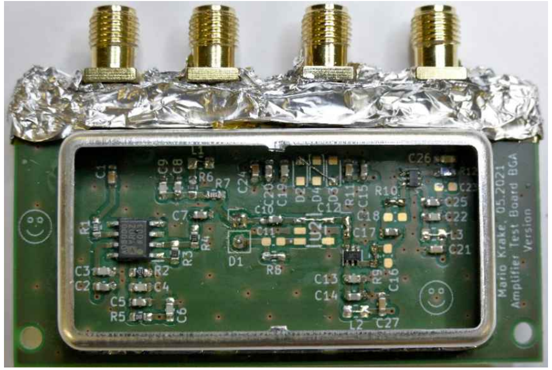
Electronic readout concepts of SiPMs

Reading the SiPM signals

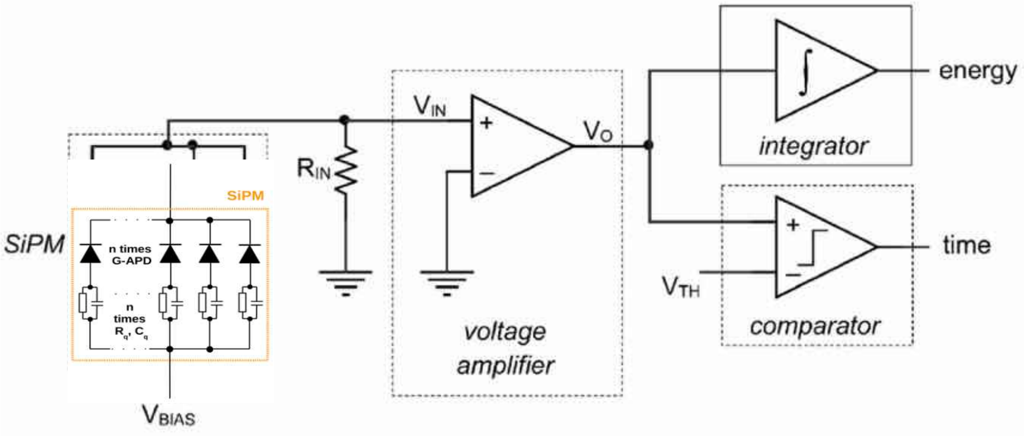


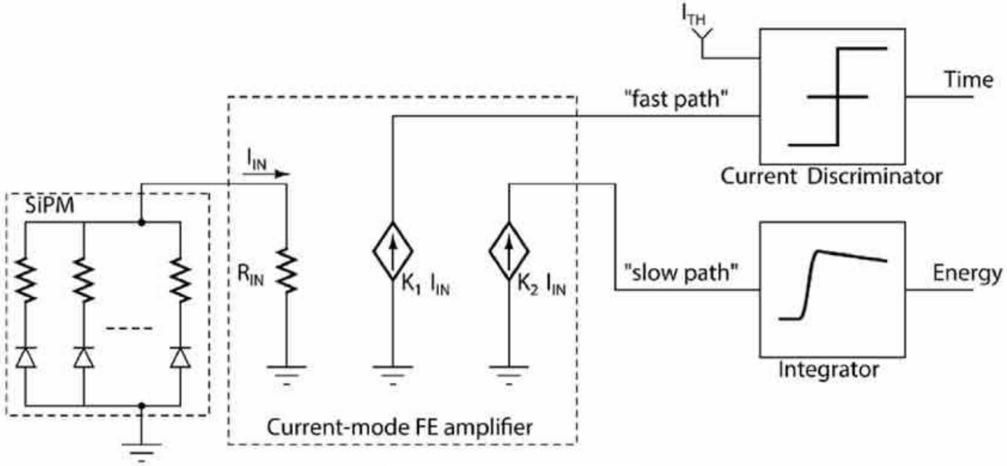




F. Acerbi and S. Gundacker, “Understanding and simulating SiPMs”, Nuclear Inst. and Methods in Physics Research, A 926 (2019) 16–35

Front-end basics





Voltage readout:

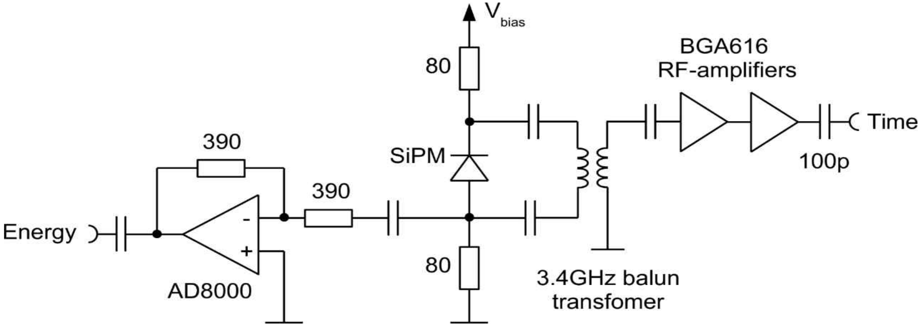
- senses the voltage drop on R_{IN}
- potentially very high bandwidth
- small signal amplitudes for large active SiPM areas
- e.g. Radioroc, **HF-readout**

Current readout:

- measures the current or charge directly
- bandwidth limited by large passive C of SiPM
- signal height theoretically not altered by SiPM active area (for low frequencies)
- e.g. TOF-PET2 ASIC, **NINO**

P. Caló, F. Ciciriello, S. Petrignani and C. Marzocca, “SiPM readout electronics”, Nucl. Instrum. Methods Phys. Res. A 926 57–68, 2019

High-frequency readout as test vehicle



This design pushed forward the state-of-the-art, especially in understanding the SPTR.

IOP Publishing Phys. Med. Biol. 63 (2018) 185022 (11pp) https://doi.org/10.1088/1361-6560/aadbcd

Physics in Medicine & Biology

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PAPER

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RECEIVED
10 January 2018

REVISED
13 August 2018

ACCEPTED FOR PUBLICATION
21 August 2018

PUBLISHED
19 September 2018

Improved single photon time resolution for analog SiPMs with front end readout that reduces influence of electronic noise

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2 European Organization for Nuclear Research (CERN), Geneva, Switzerland
3 Universitá degli Studi di Milano-Bicocca, Milano, Italy
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5 Department of Physics, Stanford University, Stanford, CA, United States of America
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Keywords: silicon photomultiplier, single photon time resolution, timing resolution

IOP Publishing Phys. Med. Biol. 64 (2019) 055012 (9pp) https://doi.org/10.1088/1361-6560/aafd52

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PAPER

CrossMark

RECEIVED
25 October 2018

REVISED
10 December 2018

ACCEPTED FOR PUBLICATION
10 January 2019

PUBLISHED
26 February 2019

High-frequency SiPM readout advances measured coincidence time resolution limits in TOF-PET

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2 CERN, 1211 Geneve 23, Switzerland

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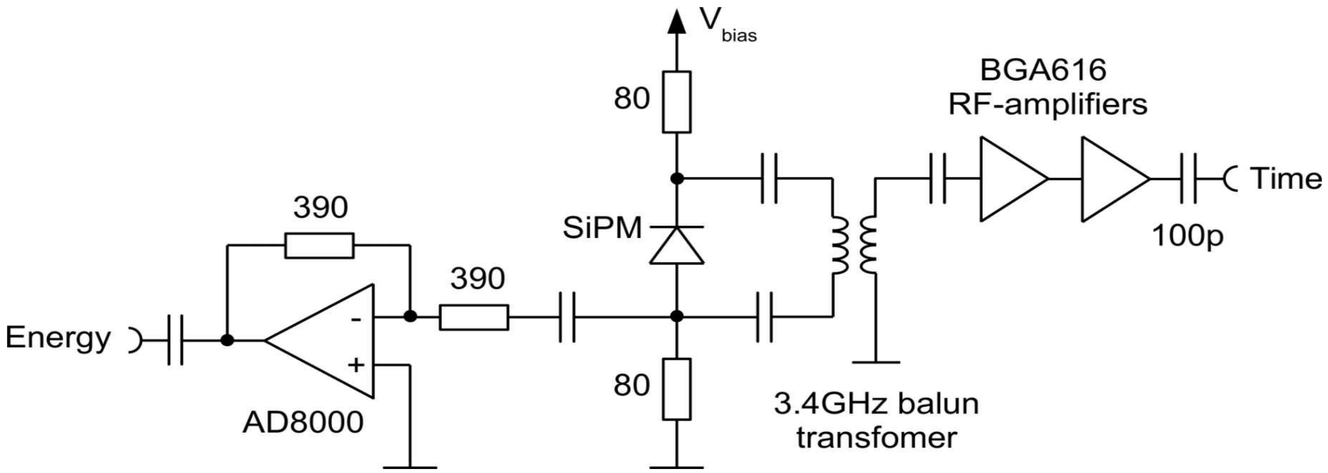
Keywords: high-frequency electronics, TOF-PET, LSO:Ce codoped with Ca, fast timing, coincidence time resolution, single photon time resolution, Cherenkov emission in scintillators

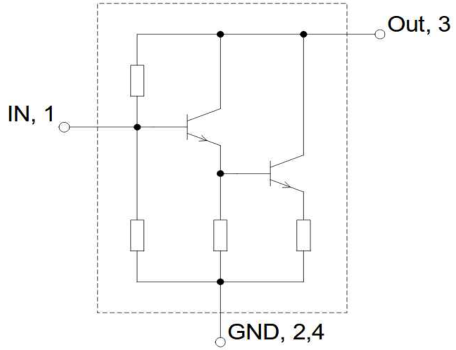
J. Cates et.al,
Phys. Med. Biol. 63 185022, 2018, https://doi.org/10.1088/1361-6560/aadbcd

S. Gundacker et.al.
Phys. Med. Biol. 64 055012, 2019, https://doi.org/10.1088/1361-6560/aafd52

High-frequency readout as test vehicle



BGA616 data sheet



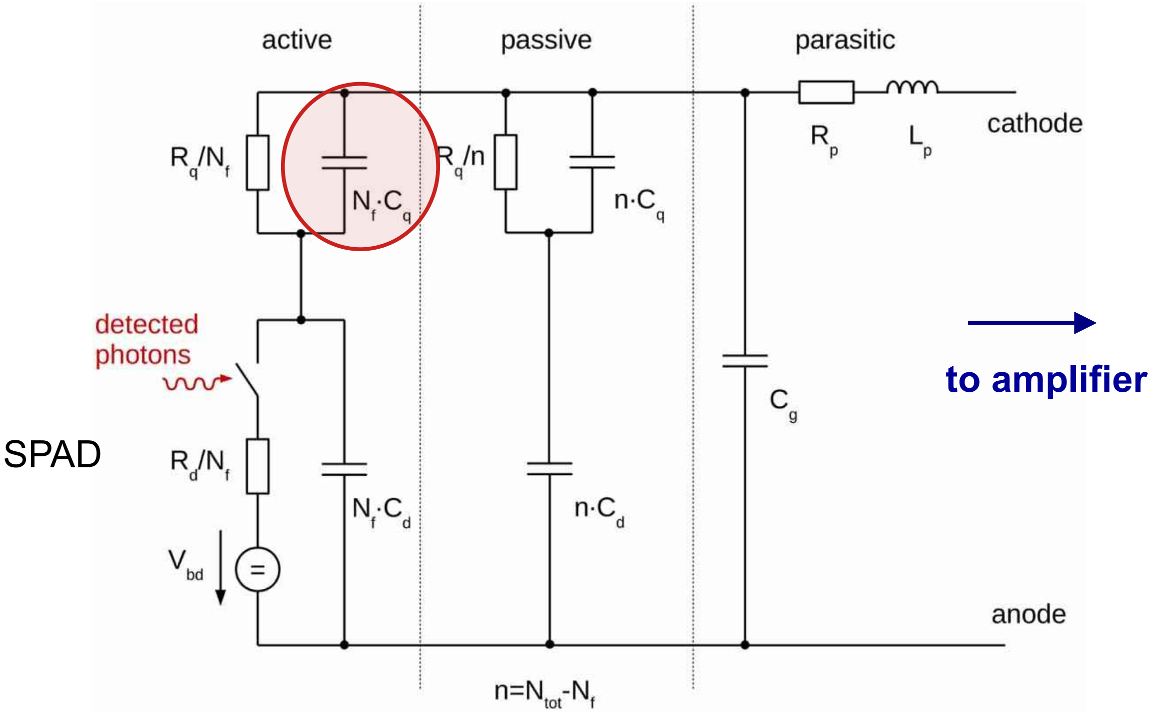
→ BGA616 RF-amplifier reads SiPM differentially via RF balun
→ High-frequency path via SPAD quenching capacitance C_q
→ High frequency for time ~1.5 GHz bandwidth

→ Minimizes the impact of electronics to the timing performance of the SiPM

J.W. Cates, S. Gundacker, E. Auffray, P. Lecoq and C.S. Levin, "Improved single photon time resolution for analog SiPMs with front end readout that reduces influence of electronic noise", Phys. Med. Biol. 63 (2018) 185022 (11pp)

High-frequency path via quenching C_q

SiPM equivalent circuit:



Working principle:

- capacitive divider of signal to SiPM anode-cathode
- signal amplitude proportional to SiPM area (terminal C)
- voltage readout with high-bandwidth MMIC, RF amplifiers
- no bandwidth limitation! (larger 1.5 GHz tested)

Too high power consumption of first prototypes

Amplifier	Supply voltage [V]	Supply current [mA]	Power [mW] (single channel)	Gain [dB]	Noise figure	Price [€/amplifier] (year 2021)
BGA616	6	48	288	19	2.5	1.36

Power consumption of first implementation of HF-amplifiers was above 290mW per channel.

M. Krake, V. Nadig, V. Schulz, and S. Gundacker, “Power-efficient high-frequency readout concepts of sipms for TOF-PET and HEP,” NIM A, vol. VCI2022 conference proceeding, submitted 2022.

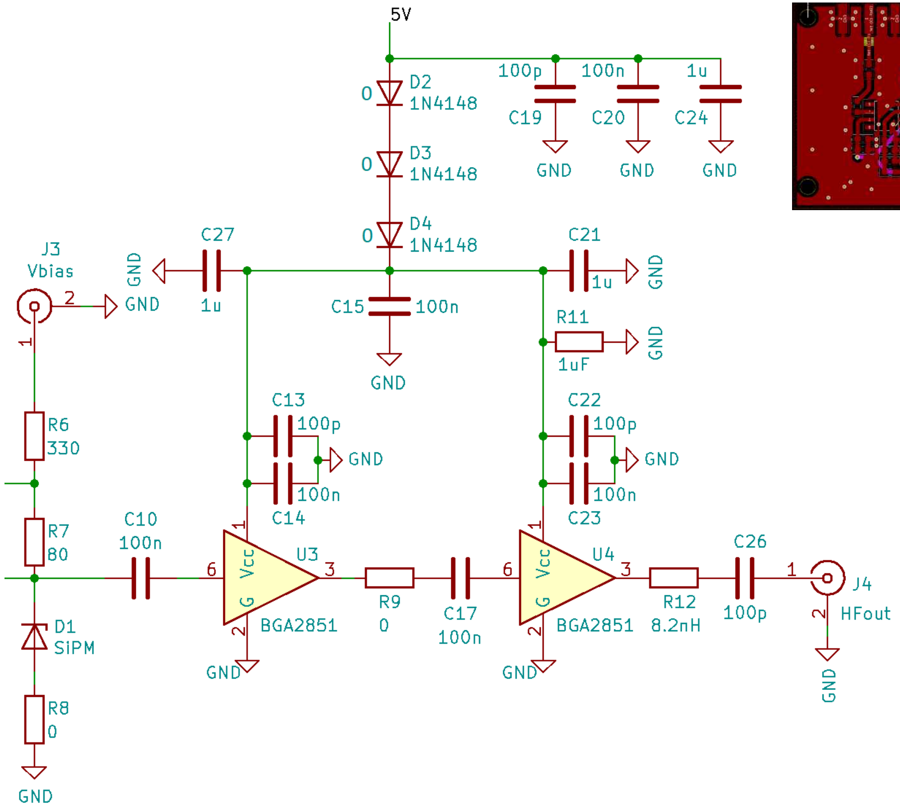
Low power amplifier types tested

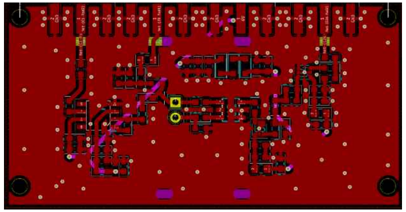
Amplifier	Supply voltage [V]	Supply current [mA]	Power [mW] (single channel)	Gain [dB]	Noise figure	Price [€/amplifier] (year 2021)
BGA616	6	48	288	19	2.5	1.36
BGA2803	**3**	**5.8**	**17**	**23.6**	**3.6**	**0.291**
BGA2851	**5**	**7**	**35**	**24.8**	**3.2**	**0.32**
BGA2869	5	24	120	31.7	3.1	0.362

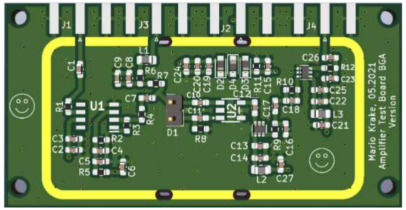
→ Bandwidth above 2 GHz for all amplifiers
→ Many more types available; a good device for a particular application can always be found

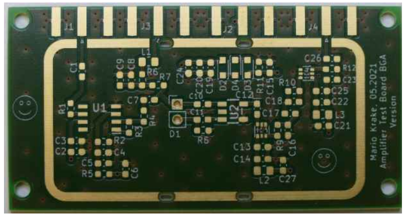
M. Krake, V. Nadig, V. Schulz, and S. Gundacker, "Power-efficient high-frequency readout concepts of sipms for TOF-PET and HEP," NIM A, vol. VCI2022 conference proceeding, submitted 2022.

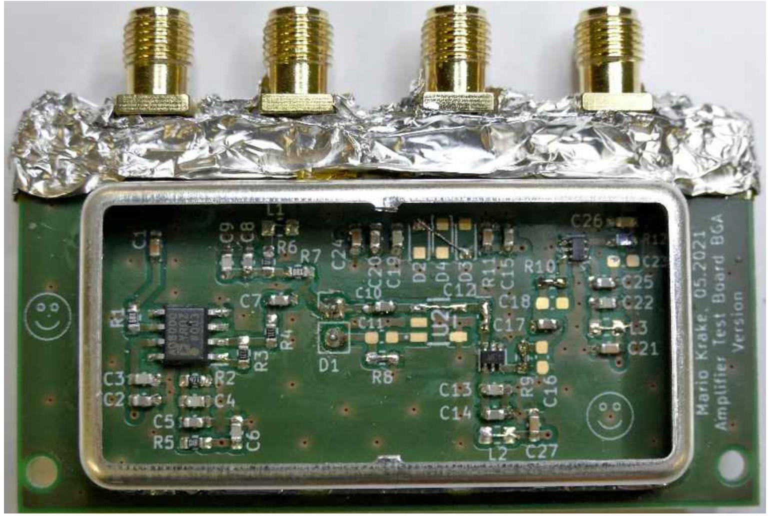
Power-efficient HF implementation





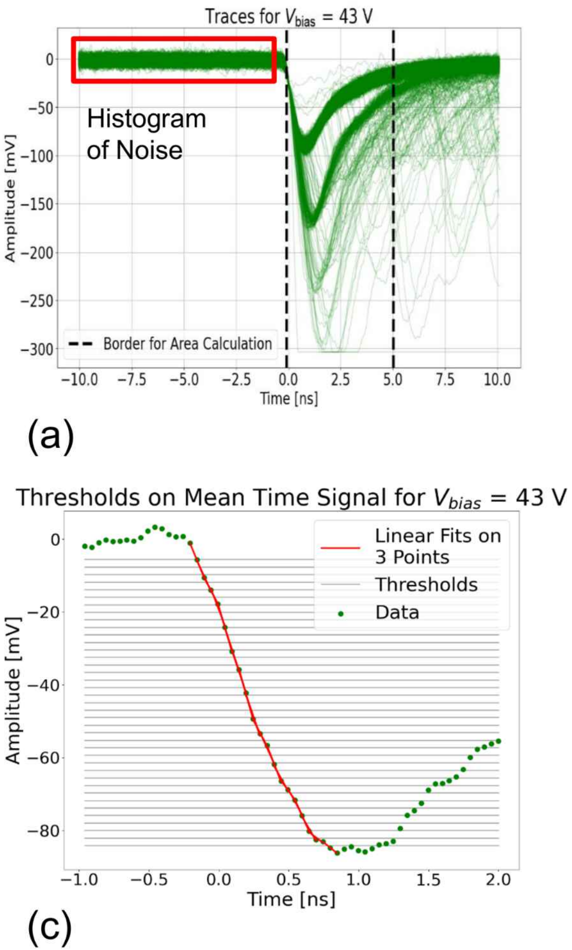






M. Krake, V. Nadig, V. Schulz, and S. Gundacker, “Power-efficient high-frequency readout concepts of SiPMs for TOF-PET and HEP,” NIM A, vol. 1039 (2022) 167032

Electronic time resolution with single photons



→ Noise amplitudes before single photon signal (a) inserted into histogram (b)

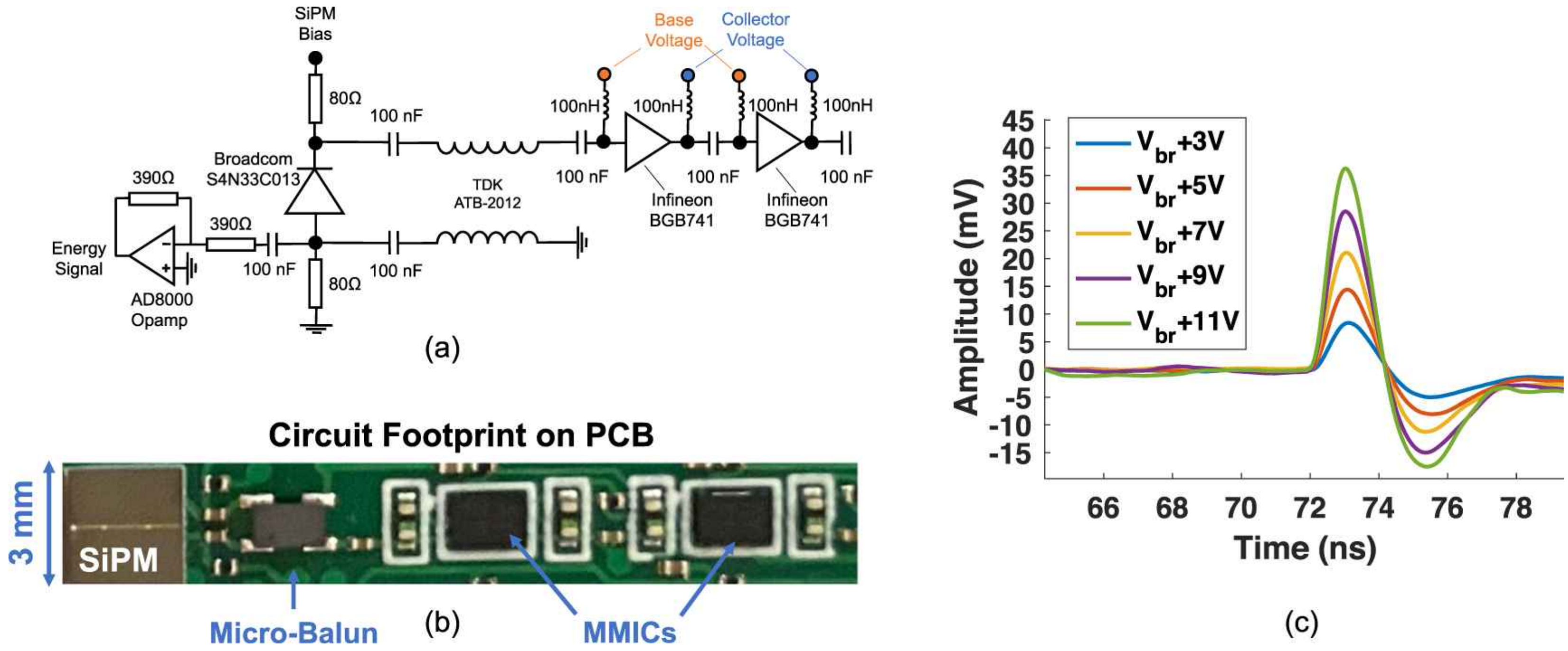
→ Single photon traces are averaged (c) and dV/dt at different thresholds calculated (d)

→ The electronic time resolution is calculated:

$$TR_{SPAD} = \frac{FWHM_{Noise}}{dV/dt_{@\,threshold}}$$

All amplifiers tested similar performance in TR_{SPAD}.

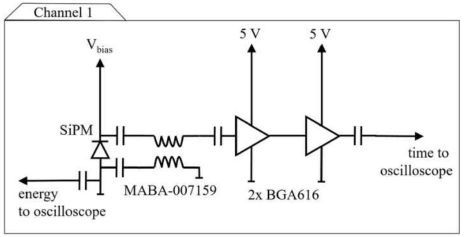
Another example of low power implementation



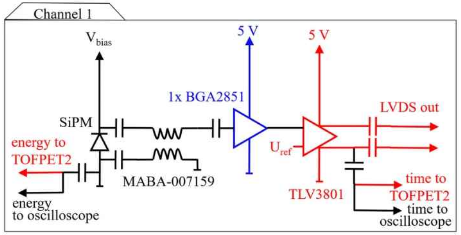
Excellent performance down to 15 mW power consumption per channel.

J. W. Cates and W-S. Choong, "Low power implementation of high frequency SiPM readout for Cherenkov and scintillation detectors in TOF-PET", Phys. Med. Biol. 67 (2022) 195009

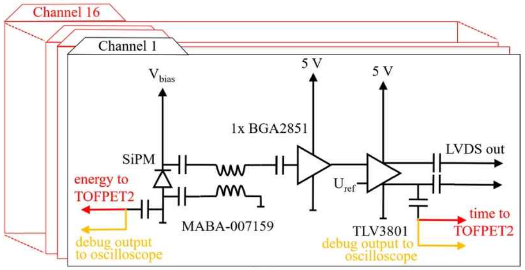
Next step: multichannel HF-readout



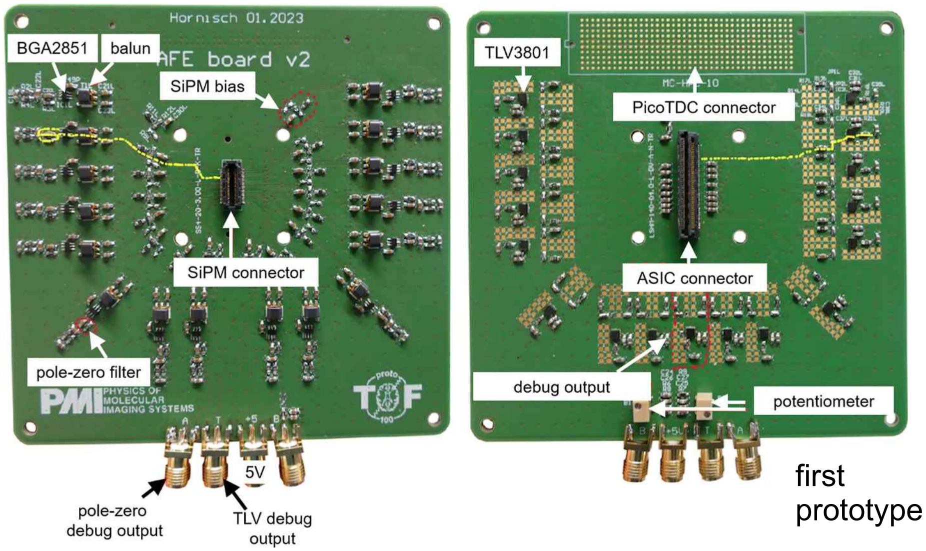
(a)



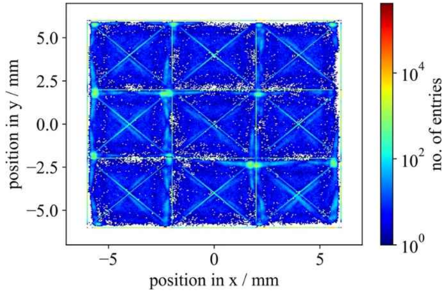
(b)

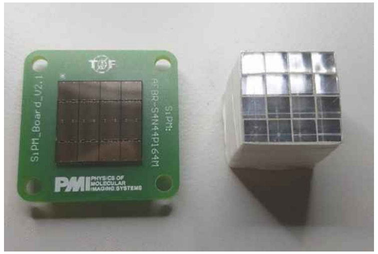


(c)



first prototype

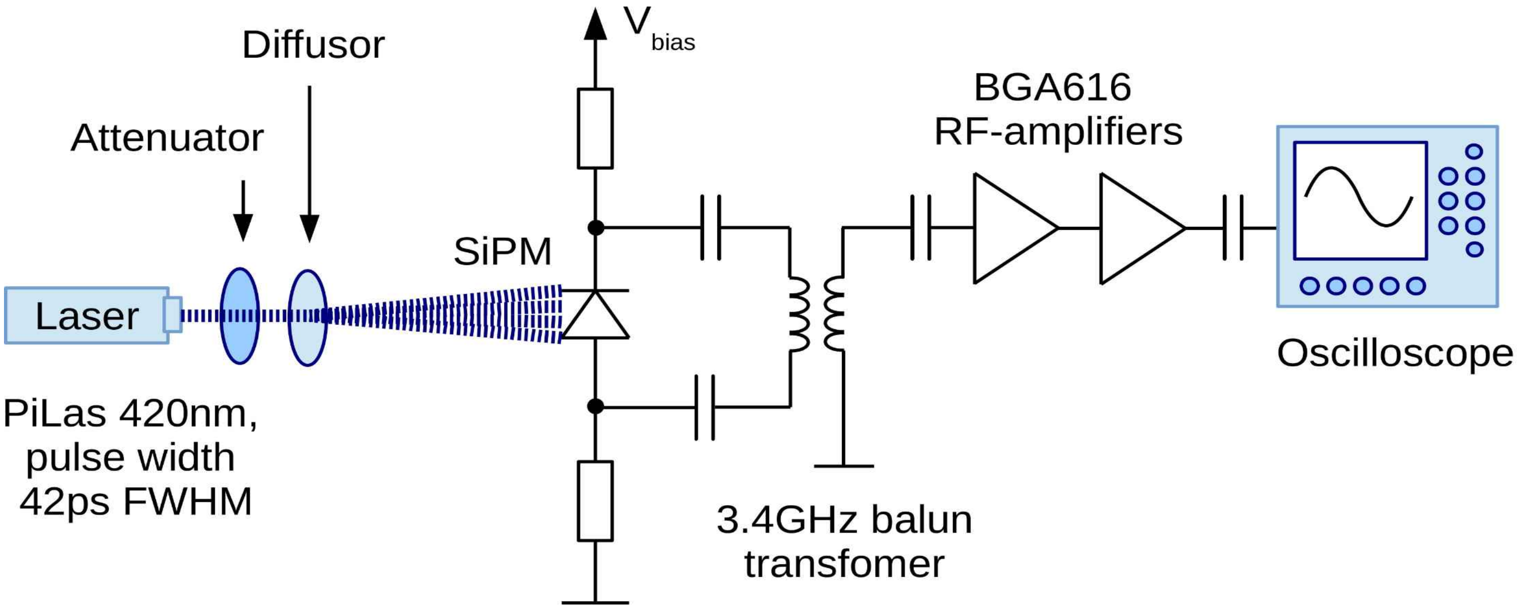




V. Nadig et.al, "16-channel SiPM high-frequency readout with time-over-threshold discrimination for ultrafast time-of-flight applications", EJNMMI Physics (2023) 10/76

SPTR measurement with laser

Single photon time resolution (SPTR) setup



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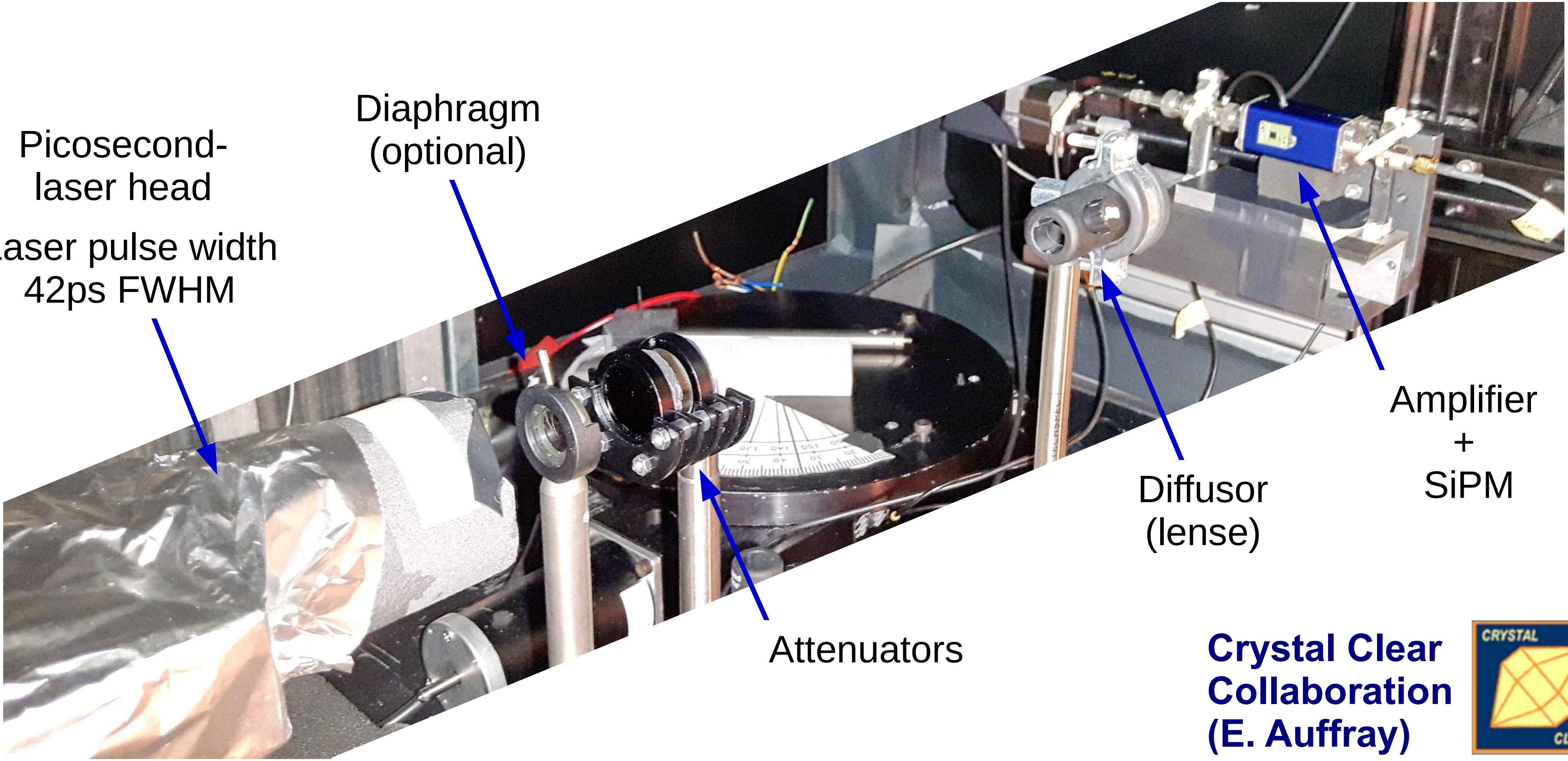
S. Gundacker et.al, “Experimental time resolution limits of modern SiPMs andTOF-PET detectors exploring different scintillators and Cherenkov emission,” Physics in Medicine & Biology, vol. 65, p. 025001, Jan 2020.

Single photon time resolution setup at CERN

Picosecond-
laser head

Laser pulse width
42ps FWHM

Diaphragm
(optional)



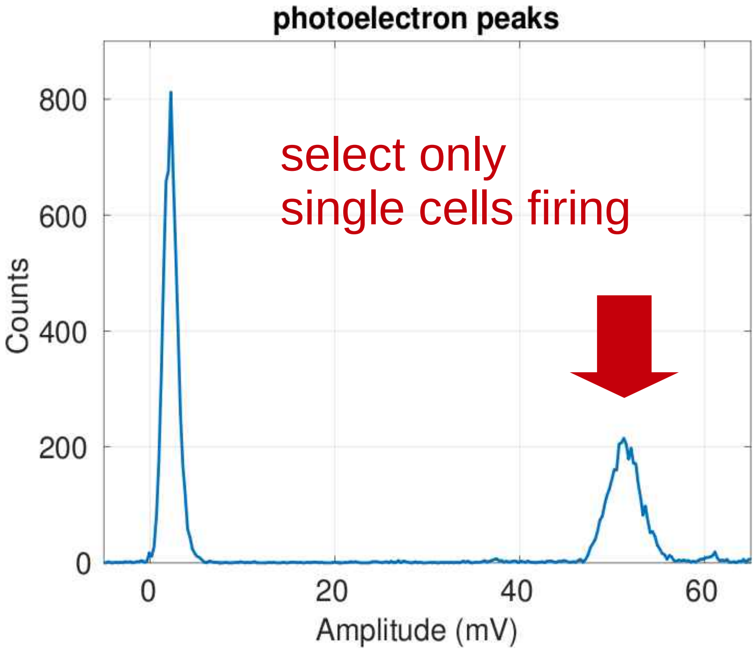
Attenuators

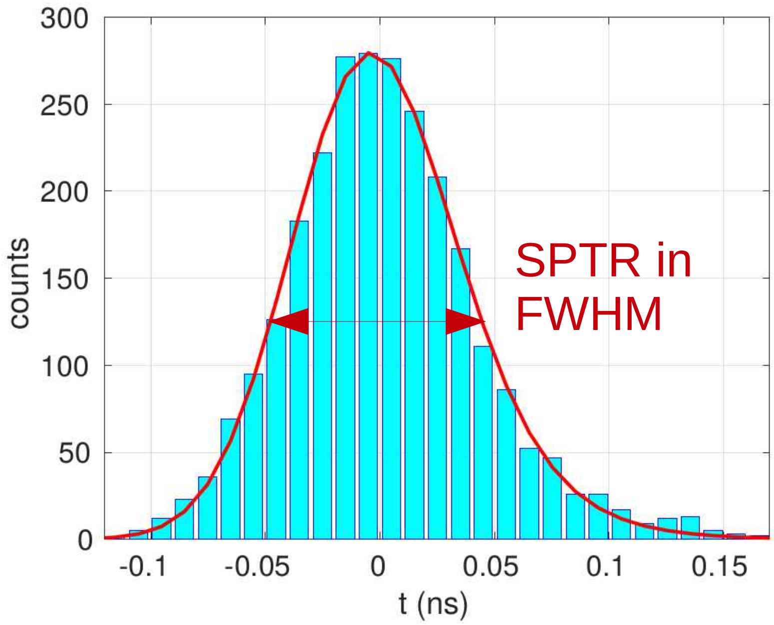
Diffusor
(lense)

Amplifier
+
SiPM

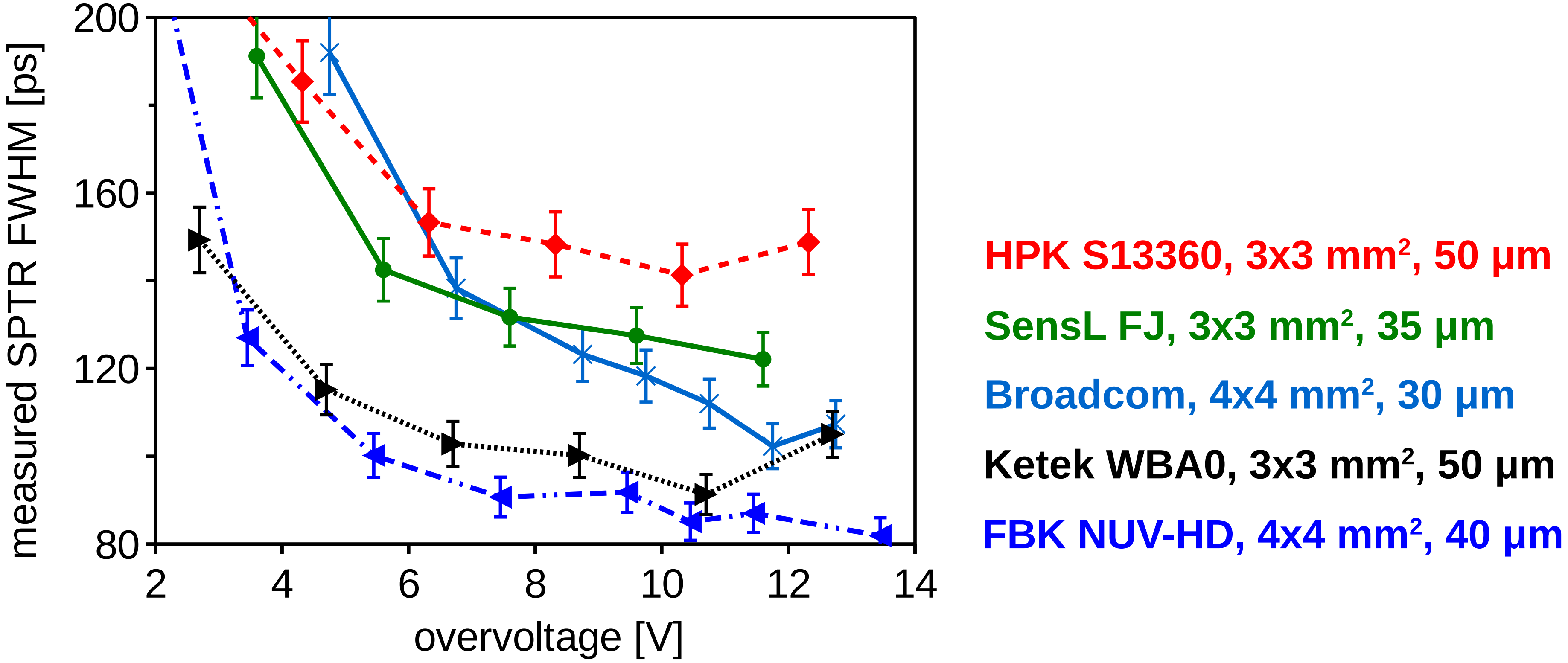
Crystal Clear Collaboration (E. Auffray)

SPTR data analysis



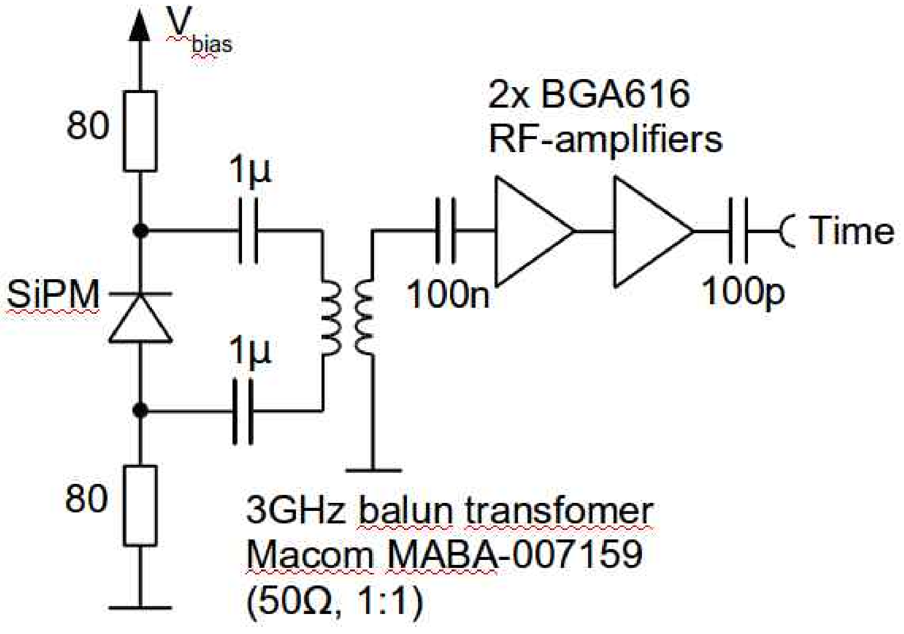


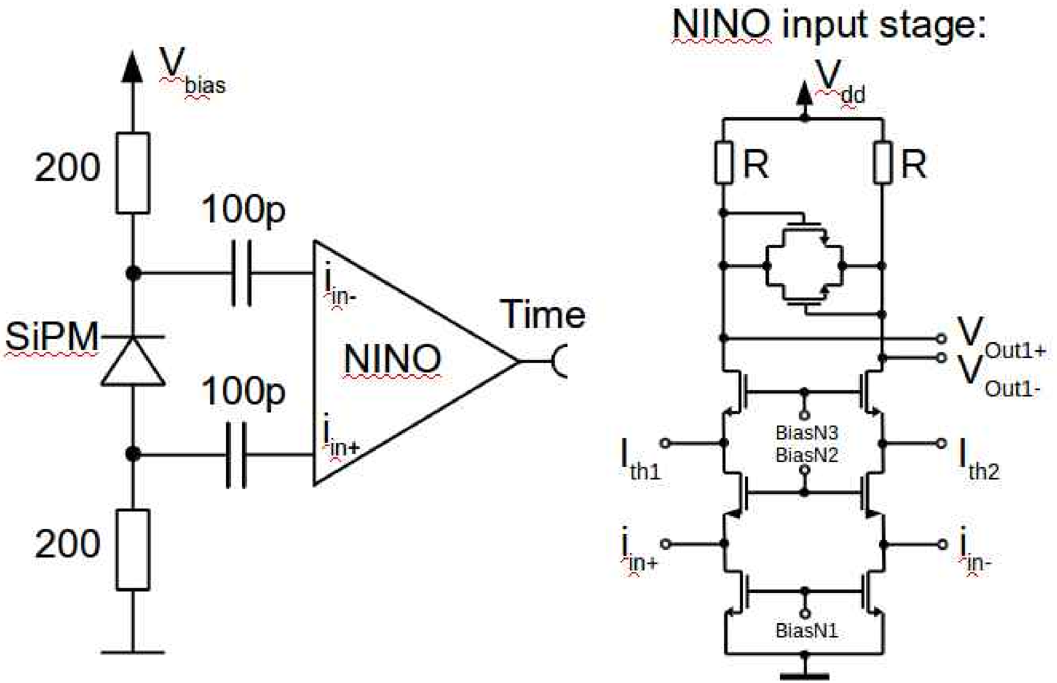
SPTR for different producers with HF-electronics



S. Gundacker et.al, "Experimental time resolution limits of modern SiPMs andTOF-PET detectors exploring different scintillators and Cherenkov emission," Physics in Medicine & Biology, vol. 65, p. 025001, Jan 2020.

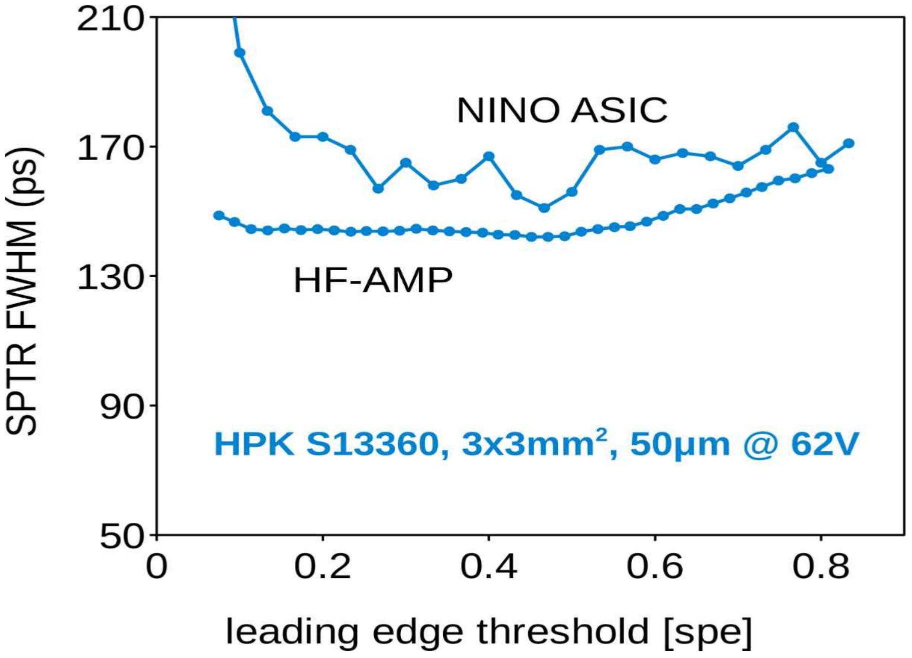
Comparing HF-electronics with NINO ASIC

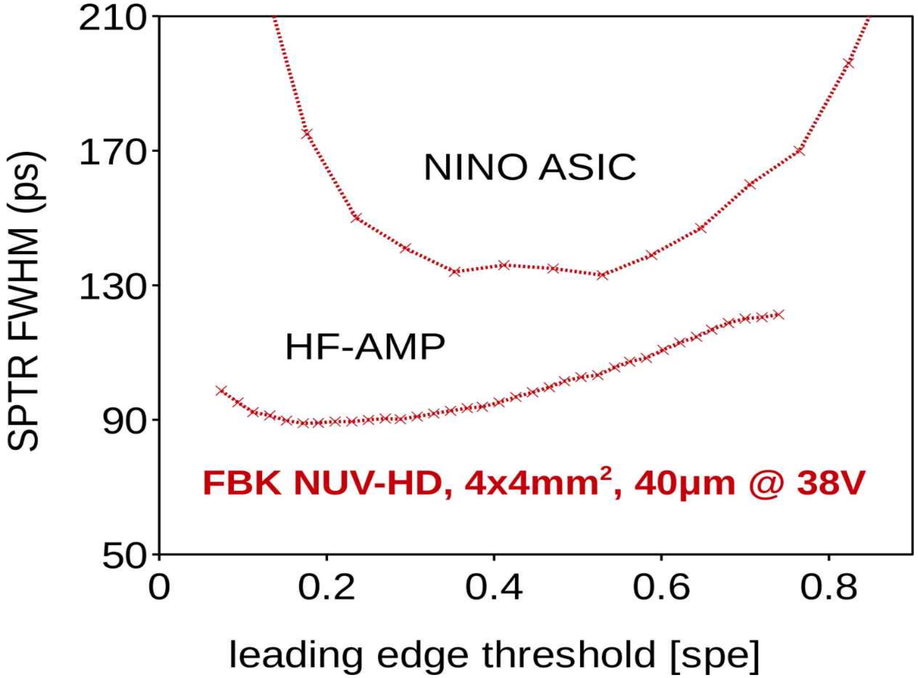




Anghinolfi F, Jarron P, Krummenacher F, Usenko E and Williams M 2004 NINO: aN ultrafast low-power front-end amplifier discriminator for the time-of-flight detector in the ALICE experiment IEEE Trans. Nucl. Sci. 51 1974–8

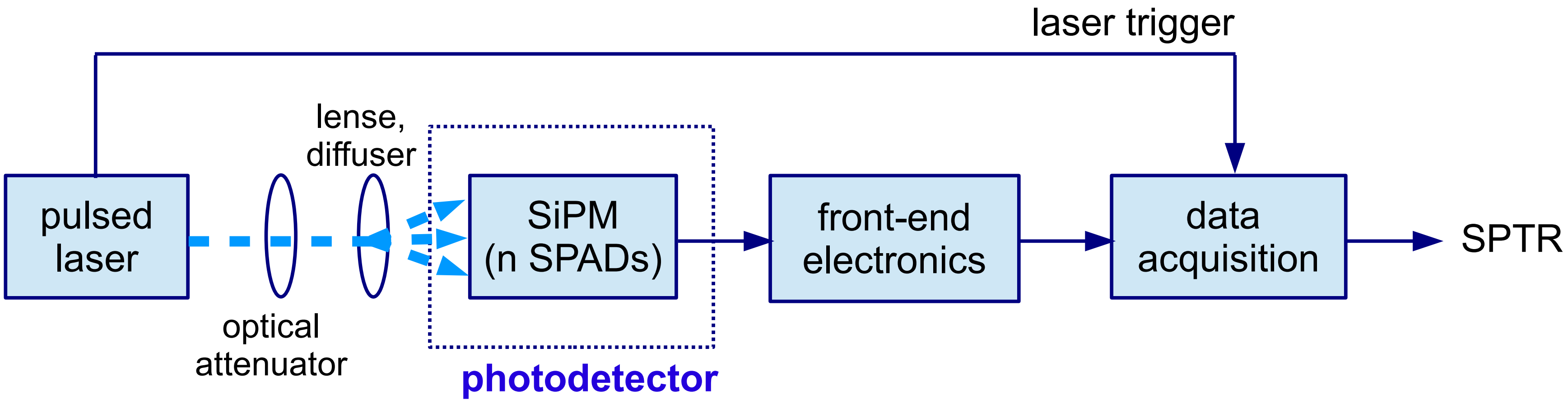
SPTR with NINO & HF-electronics





S. Gundacker et.al, "High-frequency SiPM readout advances measured coincidence time resolution limits in TOF-PET", Phys. Med. Biol. 64 (2019)

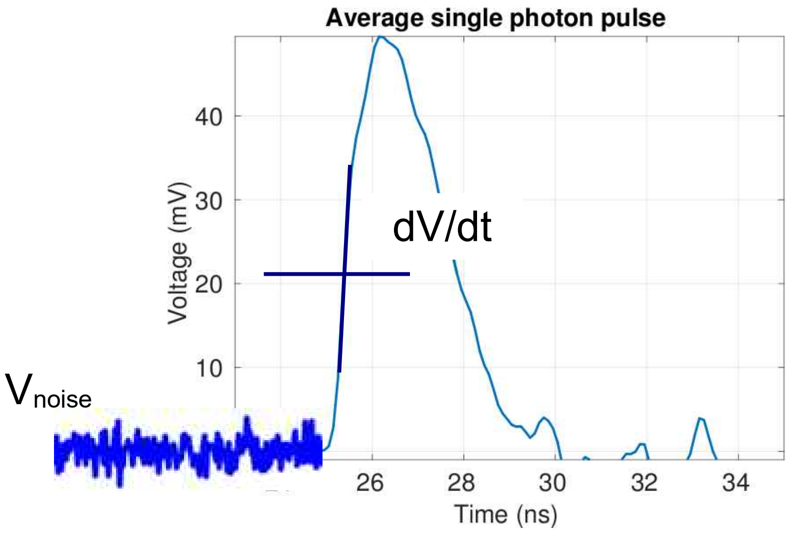
Intrinsic single photon time resolution (SPTR)



$$SPTR_{measured} = SPTR_{intrinsic} \otimes \text{electronic noise jitter}\left(\frac{V_{noise}}{dV/dt}\right) \otimes \text{aquisition jitter} \otimes \text{laser pulse shape} \otimes \text{laser trigger jitter}$$

Laser pulse width is 42 ps FWHM (measured with streak-camera).

Electronic noise jitter

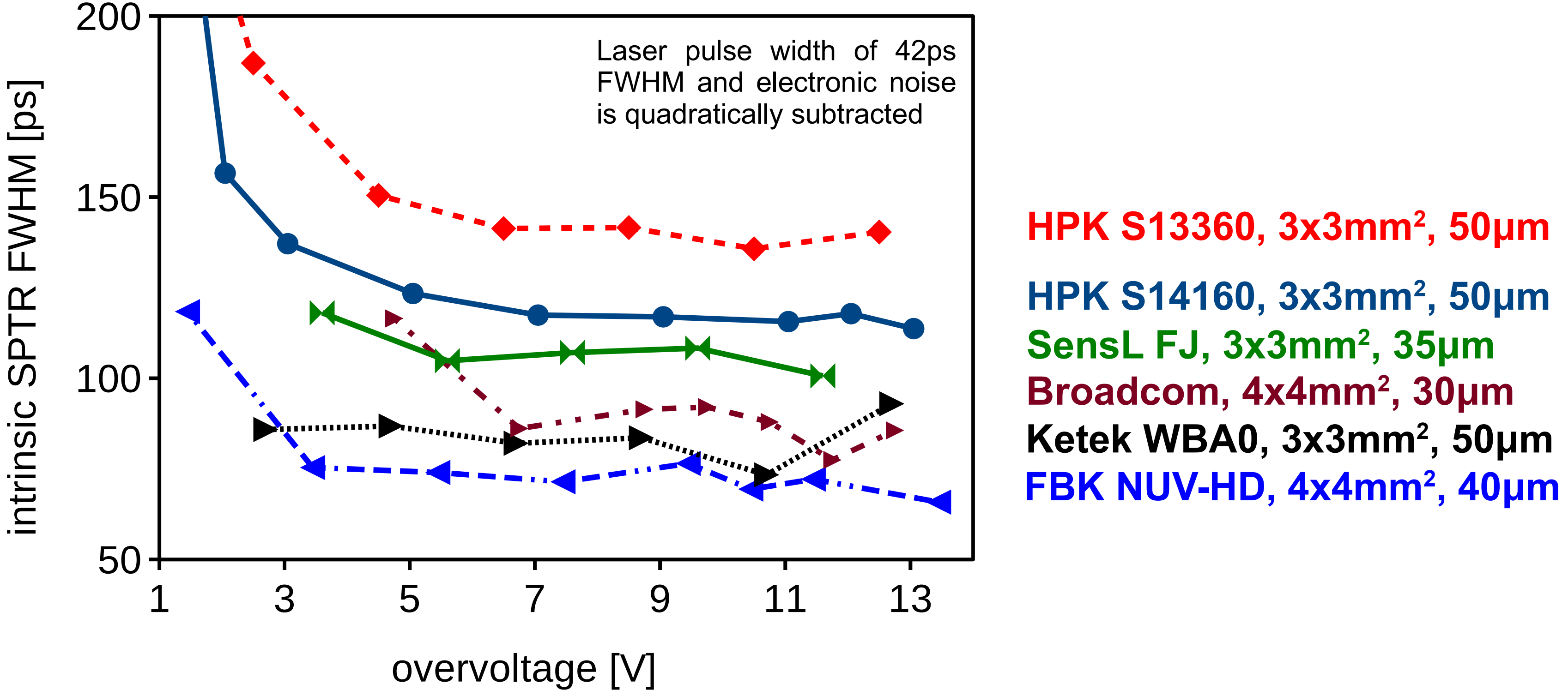


$$\text{electronic noise jitter} = \left(\frac{V_{noise}}{dV/dt} \right)$$

<u>FBK-NUVHD 4x4 mm² and 40 µm SPAD:</u>

→ 10% to 90% rise time of single cell signal is ~700 ps
→ maximum dV/dt = 90 V/µs
→ noise floor: V_{noise} = 1.07 mV rms
→ $SPTR_{measured}$ = 85 ps FWHM @ 39 V bias ($SPTR_{intrinsic}$ = 70 ps FWHM)

Intrinsic SPTR (SiPM uniformly illuminated)



S. Gundacker et.al, “Experimental time resolution limits of modern SiPMs andTOF-PET detectors exploring different scintillators and Cherenkov emission,” Physics in Medicine & Biology, vol. 65, p. 025001, Jan 2020.

Overview of SiPM performances

SiPM producers	*PDE [%]*	*SPTR intrinsic [ps]*
HPK S13360 3x3mm² (50µm)	59 ± 3	135 ± 8
HPK S14160 3x3mm² (50µm)	57 ± 3	117 ± 6
Ketek PM 3325 (WBA0) 3x3mm² (25µm)	53 ± 3	161 ± 9
Ketek PM 3350 (WBA0) 3x3mm² (50µm)	51 ± 3	74 ± 6
SensL FJ 30035 3x3mm² (35µm)	50 ± 3	108 ± 7
Broadcom AFBR-S4N44C013 (30µm)	55 ± 3	88 ± 6
FBK NUV-HD 4x4mm² (40µm)	59 ± 3	68 ± 6
FBK NUV-HD 4x4mm² (40µm) no resin	**59 ± 3**	**69 ± 6**

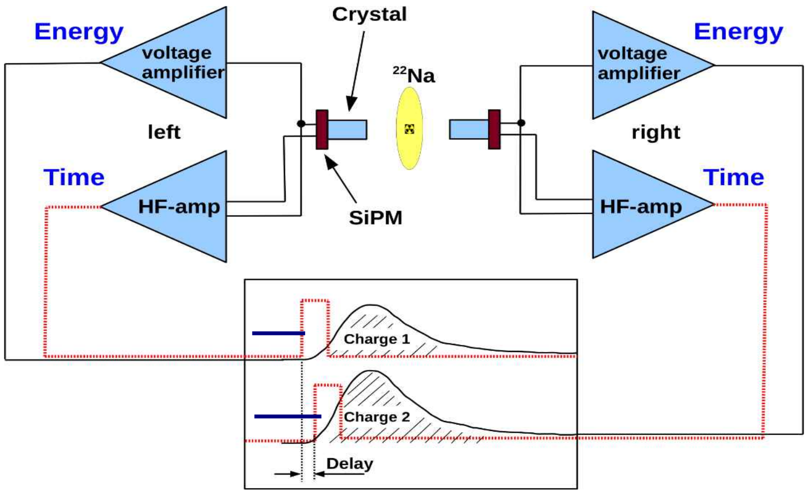
S. Gundacker et.al, “Experimental time resolution limits of modern SiPMs andTOF-PET detectors exploring different scintillators and Cherenkov emission,” Physics in Medicine & Biology, vol. 65, p. 025001, Jan 2020.

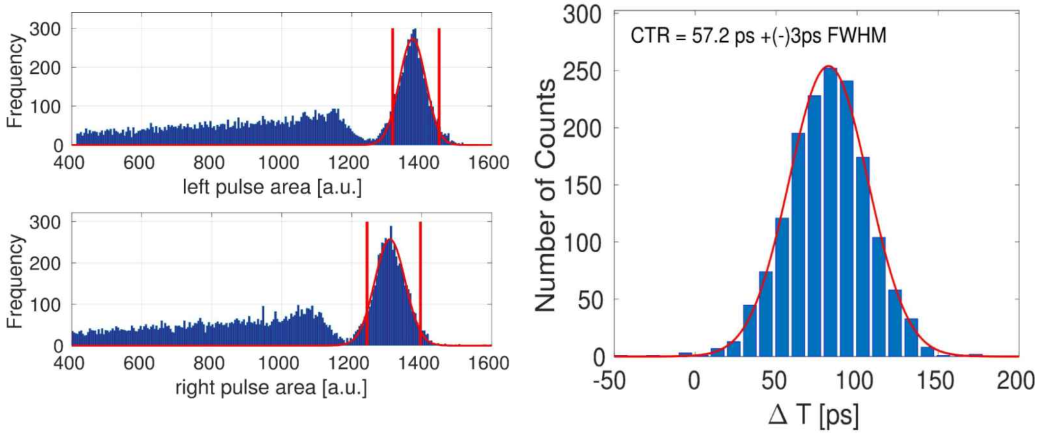
Another way to measure the SPTR?

Problems of picosecond lasers:

- laser head noise pick-up
- sometimes difficult to exactly know the laser pulse shape

Coincidence time resolution (CTR) setup



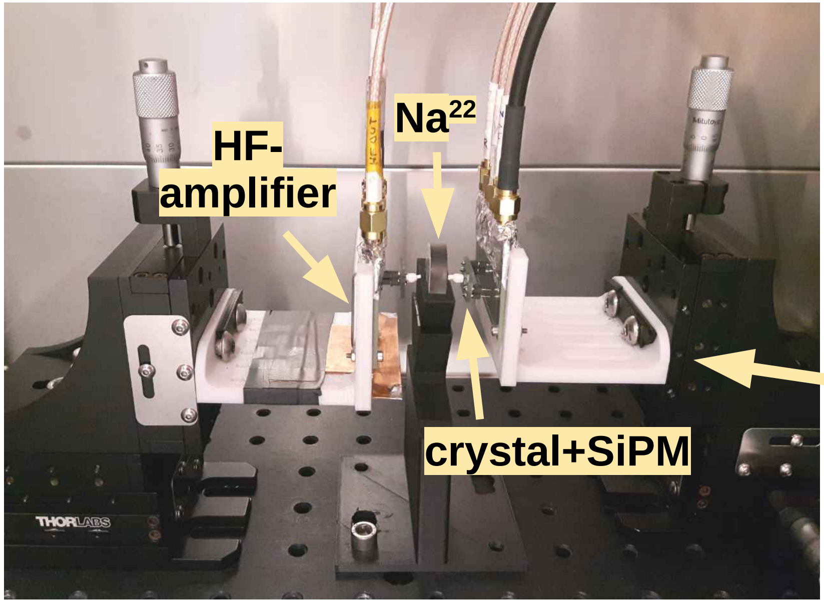


Teledyne LeCroy oscilloscope with 4 GHz bandwidth and 20 Gs/s sampling rate.

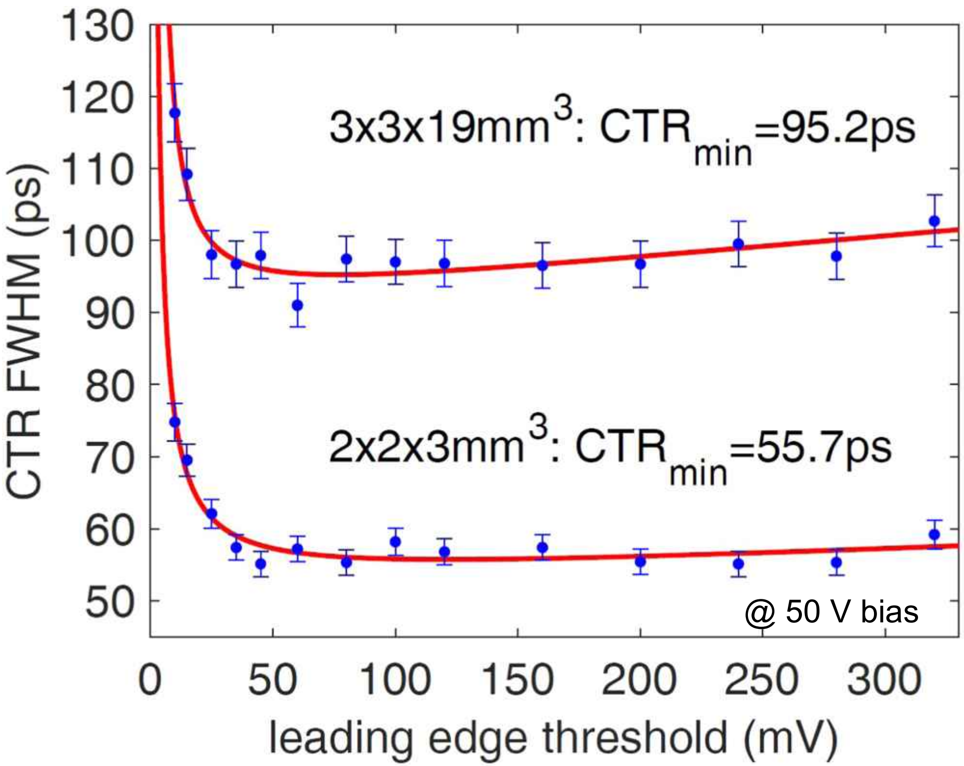
Temperature stabilized at 16°C.

S. Gundacker et.al, "High-frequency SiPM readout advances measured coincidence time resolution limits in TOF-PET", Phys. Med. Biol. 64 (2019)

Some impressions from the lab



CTR with Broadcoam NUV-MT



SiPM active area 3x3 mm^3, LYSO:Ce,Ca from TAC of 2x2x3 mm^3 and 3x3x19 mm^3

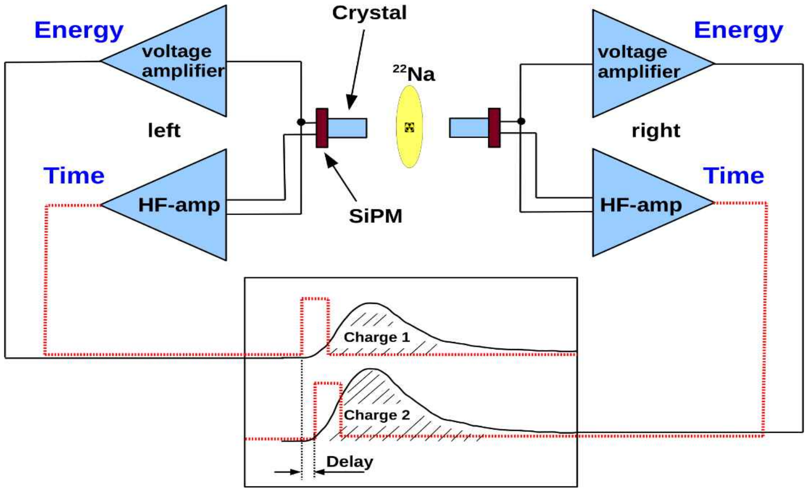
3x3x20 mm^3 LYSO:Ce,Ca
CTR=95 ps FWHM

2x2x3 mm^3 LYSO:Ce,Ca
CTR=56 ps FWHM

→ **Detector time resolution: CTR/√(2)=39 ps**

V. Nadig et.al, “Timing advances of commercial divalent-ion co-doped LYSO:Ce and SiPMs in sub-100 ps time-of-flight positron emission tomography”, Phys. Med. Biol. 68 (2023) 075002

Cherenkov radiation in PbF_2



→ standard CTR setup with reference detector on left side: CTR=56-66 ps FWHM

→ on device under test glued (Meltmount) and black painted PbF_2 crystal of 2x2x3 mm³ size (negligible photon transfer spread)

→ select to single photon, subtract DTR of reference and the electronic noise jitter

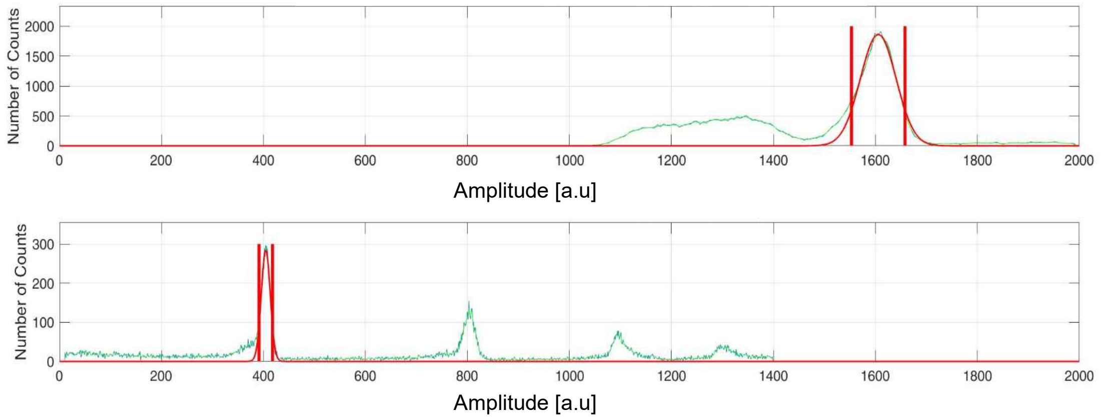
$$SPTR_{measured} = SPTR_{intrinsic} \otimes CTR/\sqrt{2} \otimes electronic\ noise\ jitter\left(\frac{V_{noise}}{dV/dt}\right)$$

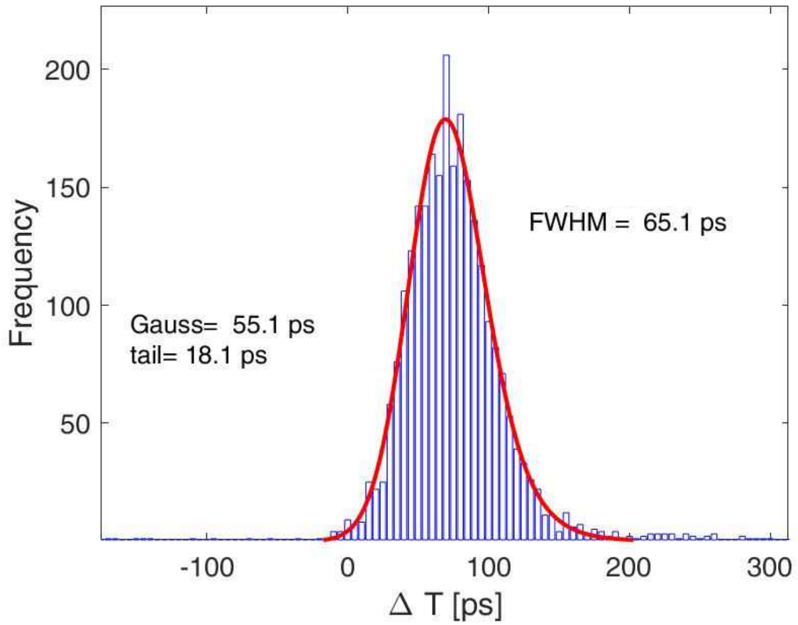
black PbF_2

N. Kratochwil, S. Gundacker and E. Auffray, "A roadmap for sole Cherenkov radiators with SiPMs in TOF-PET", Phys. Med. Biol. 66 (2021) 195001

S. Gundacker et.al, "On timing-optimized SiPMs for Cherenkov detection to boost low cost time-of-flight PET", Phys. Med. Biol. 68 (2023)

SPTR example plot & analysis

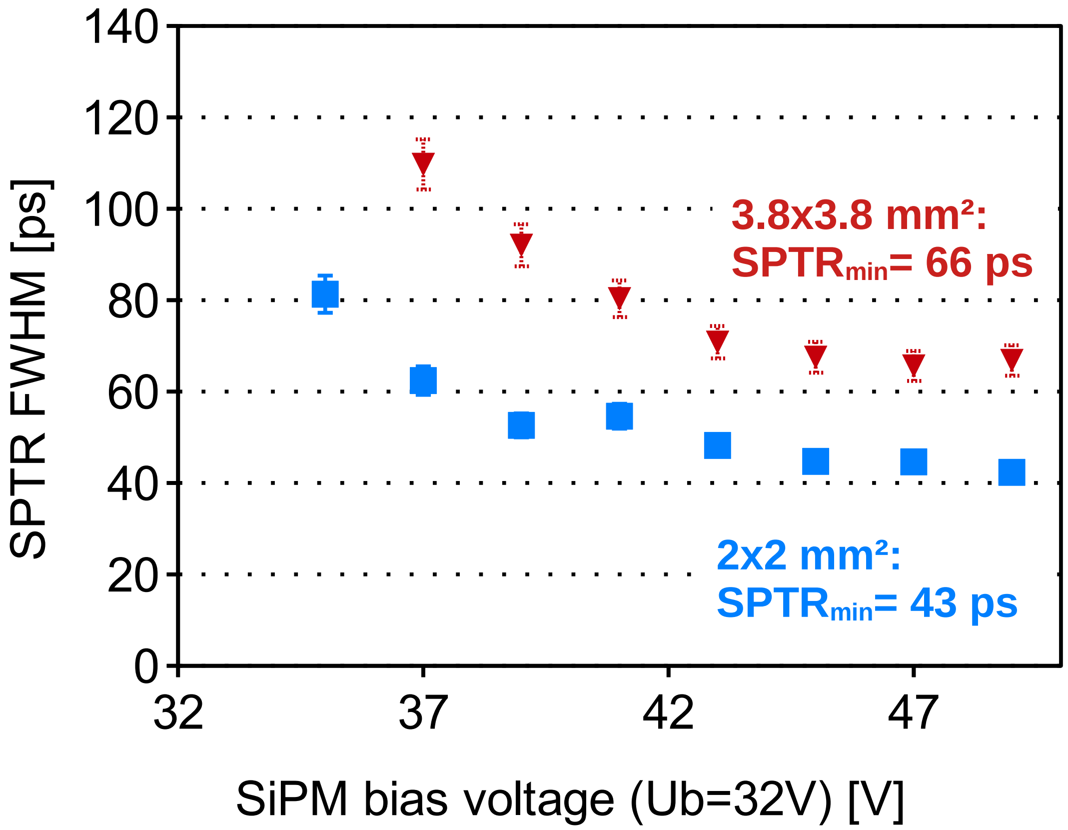




$$SPTR_{intrinsic} = \sqrt{FWHM_{measured}^2 - DTR^2 - (electr.noise)^2}$$

S. Gundacker et.al, "On timing-optimized SiPMs for Cherenkov detection to boost low cost time-of-flight PET", Phys. Med. Biol. 68 (2023)

SPTR with Broadcom NUV-MT and black PbF_2



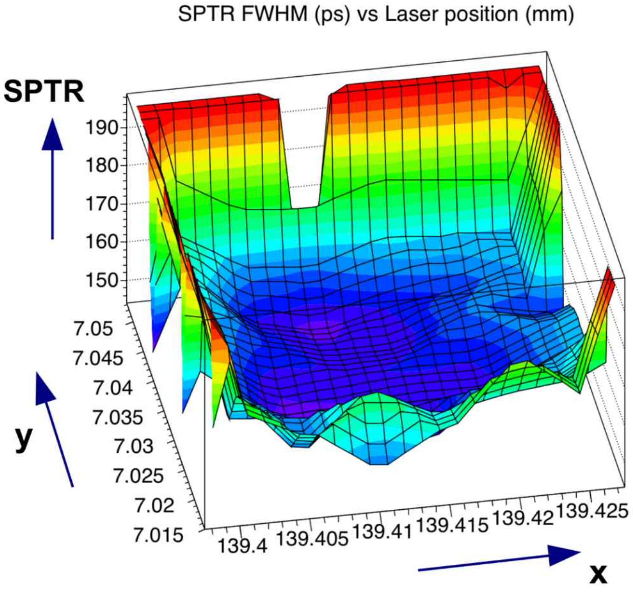
NUV-MT SiPM (AFBR-S4N44P014M), 40µm SPAD pitch from Broadcom, active area 2x2 mm² and 3.8x3.8 mm³.

Readout with power-efficient HF-electronics (Krake et.al., NIM A vol. 1039 (2022)).

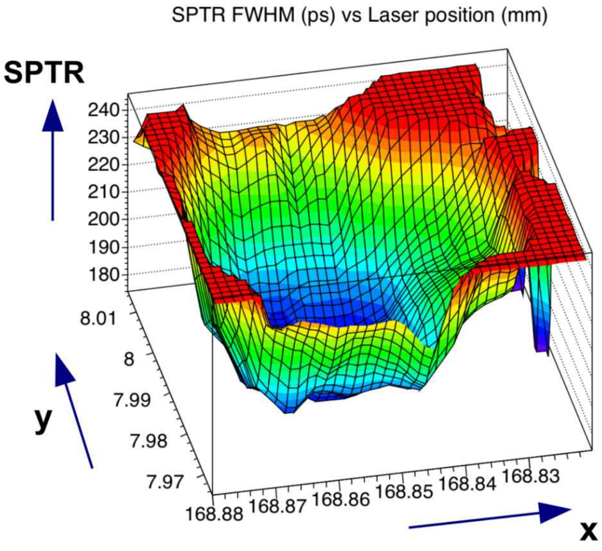
Electronic noise not subtracted, but almost negligible due to high SiPM overvoltage.

Prospects of the SPTR

Edge effects in SPADs and masking



FBK NUV



HPK TSV

→ **Masking of edges (FBK SiPMs of different types)**

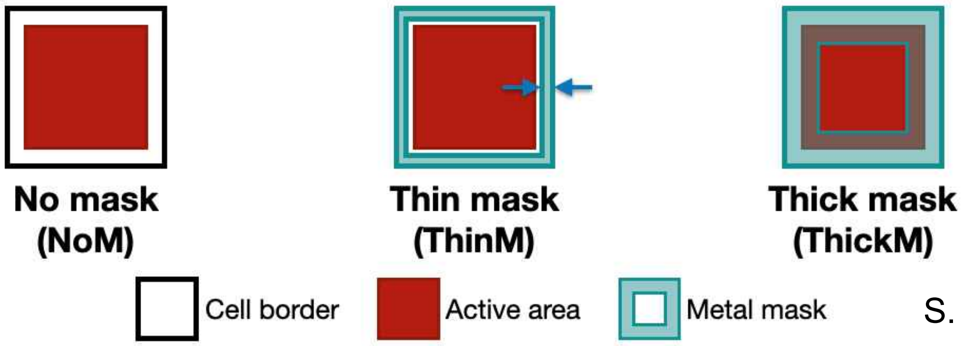
→ Improved SPTR and improved signal quality due to higher C_q

M.V. Nemallapudi, S. Gundacker, P. Lecoq and E. Auffray, “Single photon time resolution of state of the art SiPMs”, October 2016. JINST 11 P10016, DOI:10.1088/1748-0221/11/10/P10016

S. Gundacker et.al, “On timing-optimized SiPMs for Cherenkov detection to boost low cost time-of-flight PET”, Phys. Med. Biol. 68 (2023)

Differently masked SiPMs tested

→ Different **devices from FBK**: With and without SPAD masking (devices 4x4 mm² and 3x3 mm² active area, 40 μm SPAD pitch)



S. I. Kwon et.al. IEEE NSS/MIC 2021

→ measure the single photon time resolution (**SPTR**) with black painted PbF_2

S. Gundacker et.al, “On timing-optimized SiPMs for Cherenkov detection to boost low cost time-of-flight PET”, Phys. Med. Biol. 68 (2023)

Tests with timing optimized 3x3 mm² SiPMs

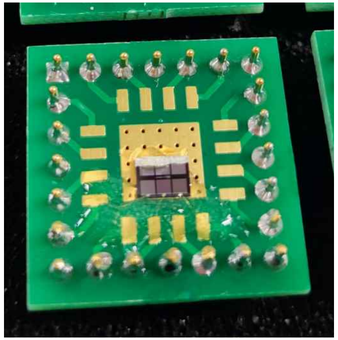
SiPM types (active area 3x3mm²)	*SPTR FWHM intrinsic [ps]*
FBK SF (standard)	68 ± 4
FBK LF2	65 ± 4
FBK LF2 M0	50 ± 3
FBK LF2 M1	47 ± 3
FBK LF2 M3	***42 ± 3***
Broadcom AFBR-S4N44C013 (commercial)	65 ± 4
HPK S14160-3050HS (commercial)	125 ± 5

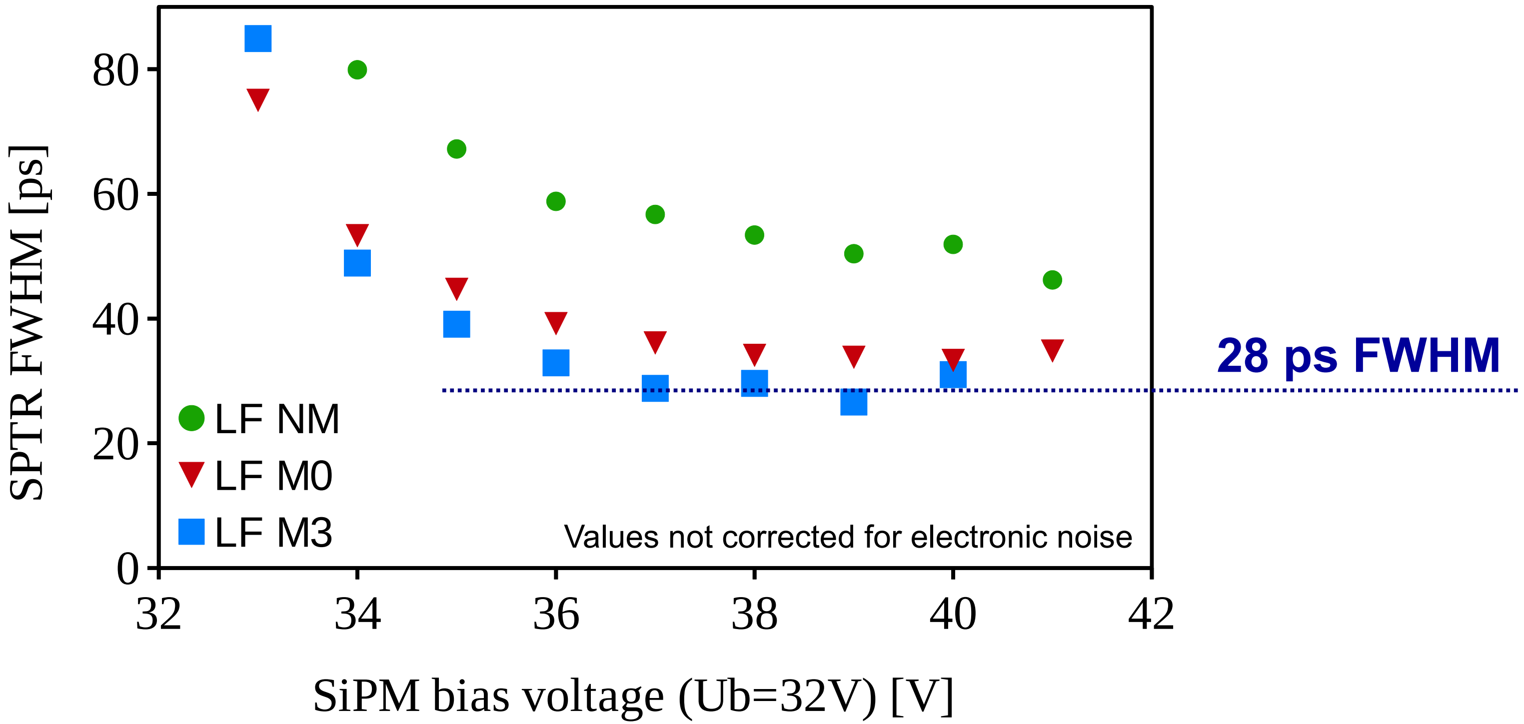
FBK … Fondazione Bruno Kessler, Trento, Italy

Speed of light: 3.3 ps/mm in vacuum.
40 ps → 1.2 cm resolution (single photon)

S. Gundacker et.al, "On timing-optimized SiPMs for Cherenkov detection to boost low cost time-of-flight PET", Phys. Med. Biol. 68 (2023)

SPTR with 1x1 mm² SiPMs



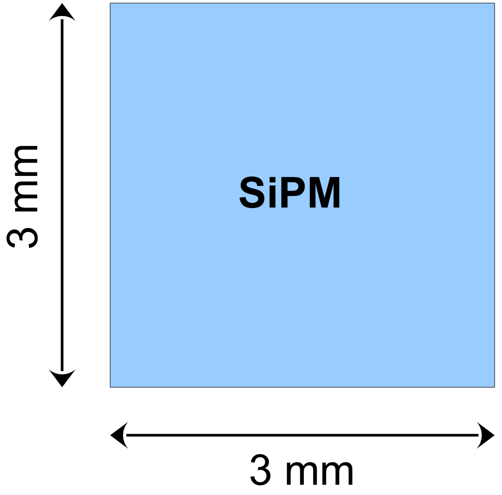


S. Gundacker et.al, "On timing-optimized SiPMs for Cherenkov detection to boost low cost time-of-flight PET", Phys. Med. Biol. 68 (2023)

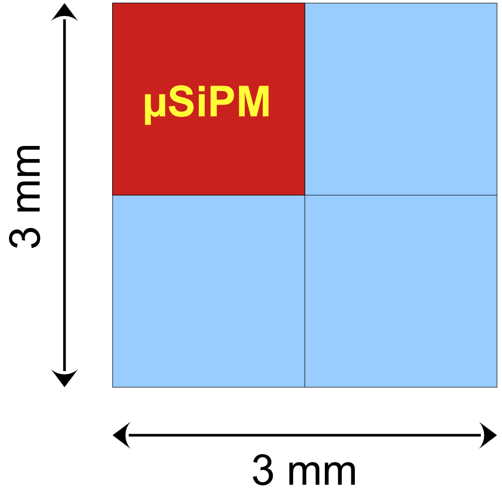
SPTR insights within the DIGILOG project

Segmenting the SiPM into µSiPMs for BGO PET

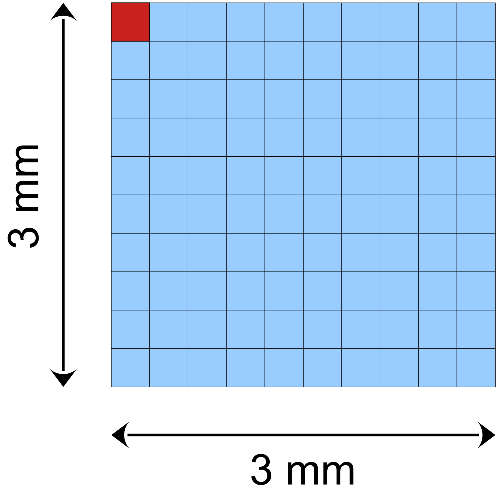
SiPM: 3x3 mm²
SPAD: 50 x 50 µm²
1x1 µSiPM array
(3600 SPADs per SiPM)



SiPM: 3x3 mm²
SPAD: 50 x 50 µm²
2x2 µSiPM array
(900 SPADs per µSiPM)

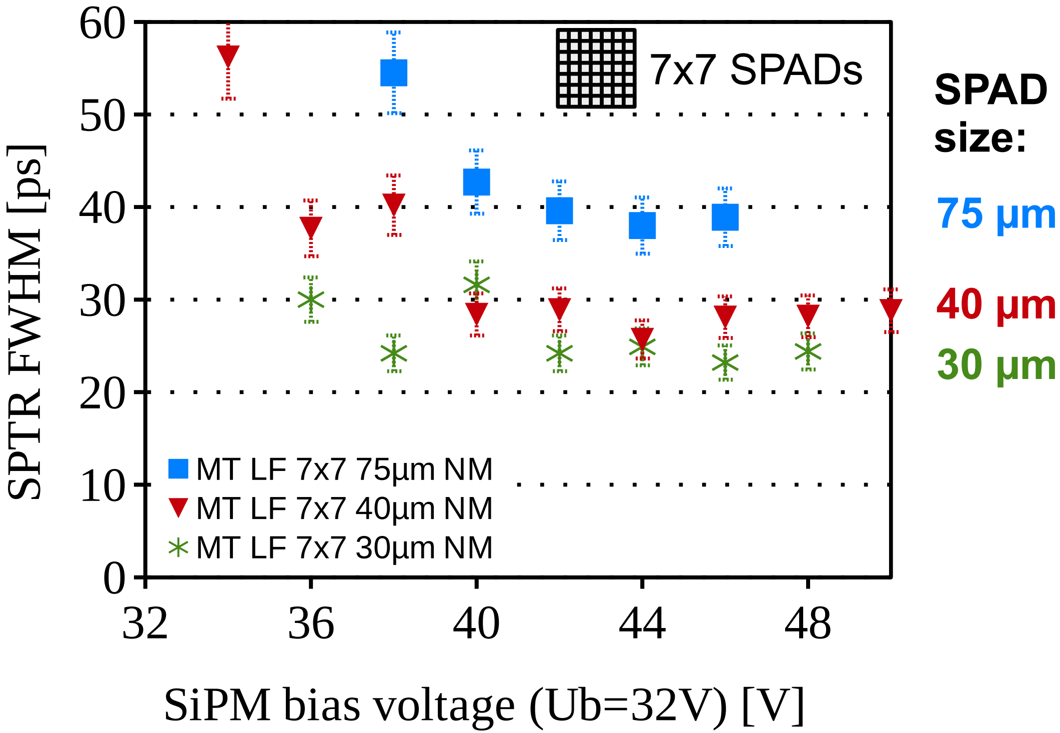


SiPM: 3x3 mm²
SPAD: 50 x 50 µm²
10x10 µSiPM array
(36 SPADs per µSiPM)



- Lower capacitance C → higher electrical signal
- smaller SiPM size → better SPTR

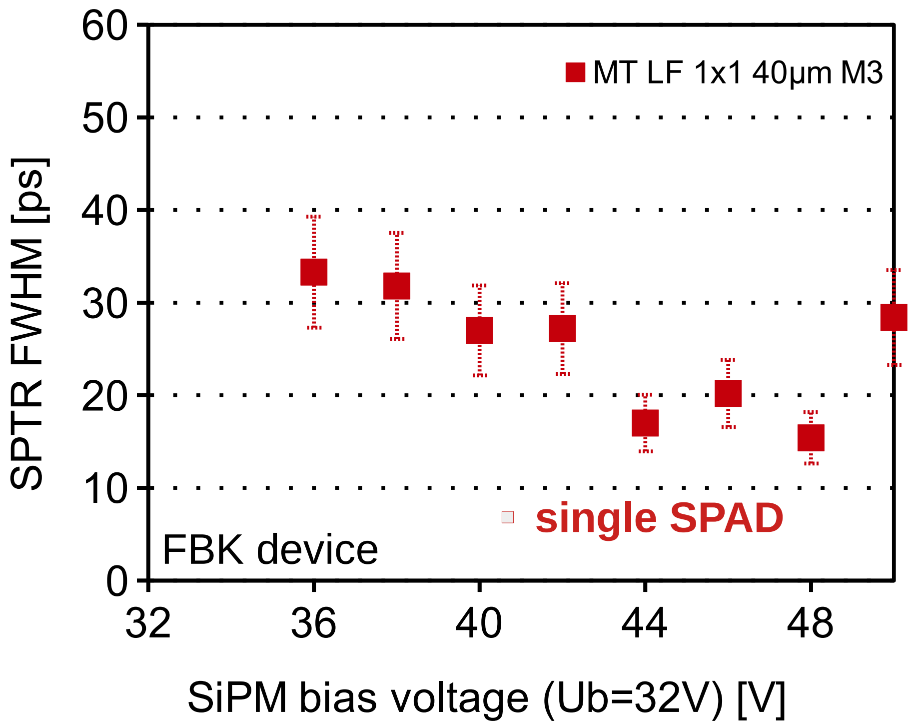
SPTR with different SPAD sizes



- µSiPM consisting of 7x7 SPADs
- SPADs are <u>not</u> masked
- SPTR performance deteriorates with SPAD size
- Best value ~ 25 ps FWHM

DIGLOG

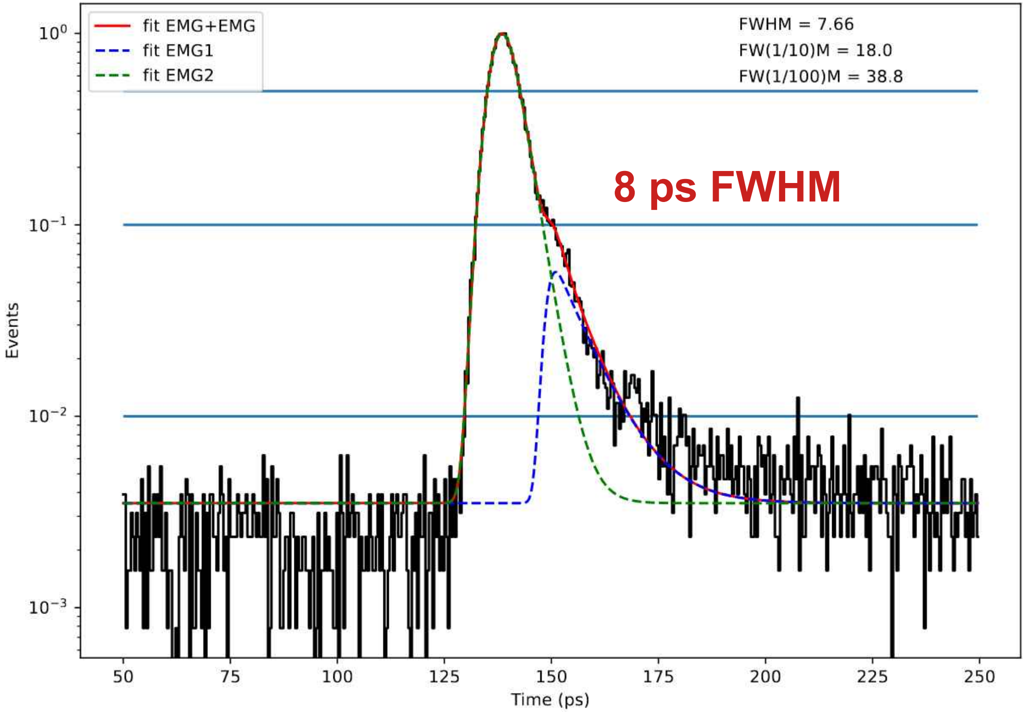
SPTR limits of single analog SPADs



- Single 40µm^2 SPAD can reach an **SPTR of well below 20 ps FWHM if masked**.
- Exact value starts to be limited by resolution of our measurement method.

See also: M.V. Nemallapudi, S. Gundacker, P. Lecoq and E. Auffray, "Single photon time resolution of state of the art SiPMs", October 2016. JINST 11 P10016, DOI:10.1088/1748-0221/11/10/P10016

"Digital" SPADs achieve even sub-10 ps



- Sherbrooke, Canada and EPFL (AQUA), Switzerland achive sub-10 ps with with digital-readout.
- See work of J. F. Pratte and E. Charbon

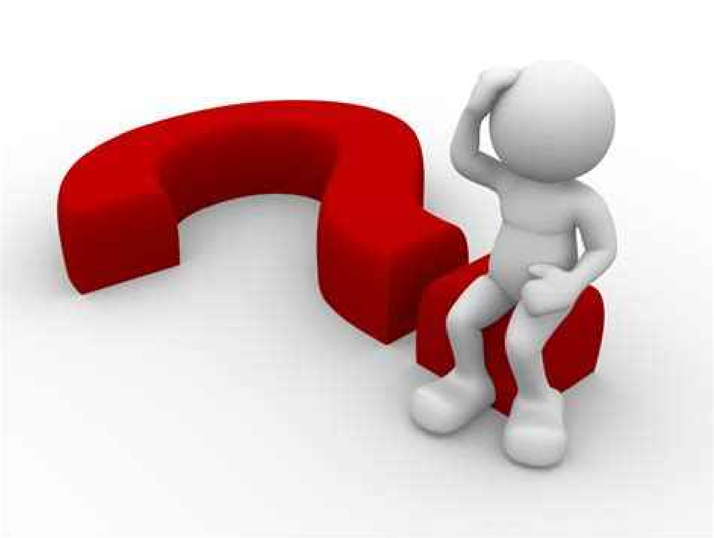
F. Nolet et.al, “Quenching Circuit Discriminator Architecture Impact on a Sub-10 ps FWHM Single-Photon Timing Resolution SPAD”, MDPI Instruments, 2023, 7, 16

F. Gramuglia et.al, “A Low-Noise CMOS SPAD Pixel With 12.1 Ps SPTR and 3 ns Dead Time”, IEEE Journal of Selected Topics in Quantum Electronics , vol. 28, no. 2, March/April 2022

Conclusions

- HF-readout allows to study intrinsic SPTR, also for larger devices (3x3mm²).
- Power-efficient (<20mW) high-bandwidth amplifiers work well, which can be used for studying system related effects in multi-channel experiments.
- Best SPTR of commercial devices:
  - ✓ **SPTR of 66ps FWHM for Broadcom NUV-MT** (3.8x3.8mm² SiPM) and **SPTR of 117ps FWHM for HPK** (3x3mm² SiPM). Difference due to different SPAD structure.
  - ✓ **SPTR of 43ps FWHM for Broadcom NUV-MT (2x2mm² SiPM).**
- Masked SiPMs with 3µm mask overhang from FBK:
  - ✓ **SPTR of 42ps FWHM (3x3mm² SiPM).**
  - ✓ **SPTR of 28ps FWHM (1x1mm² SiPM).**
- SPAD size influences SPTR with worse performance for larger SPADs.
- SPAD limits **below 20ps FWHM (analog) and below 10ps FWHM (digital).**

I am happy to answer your questions



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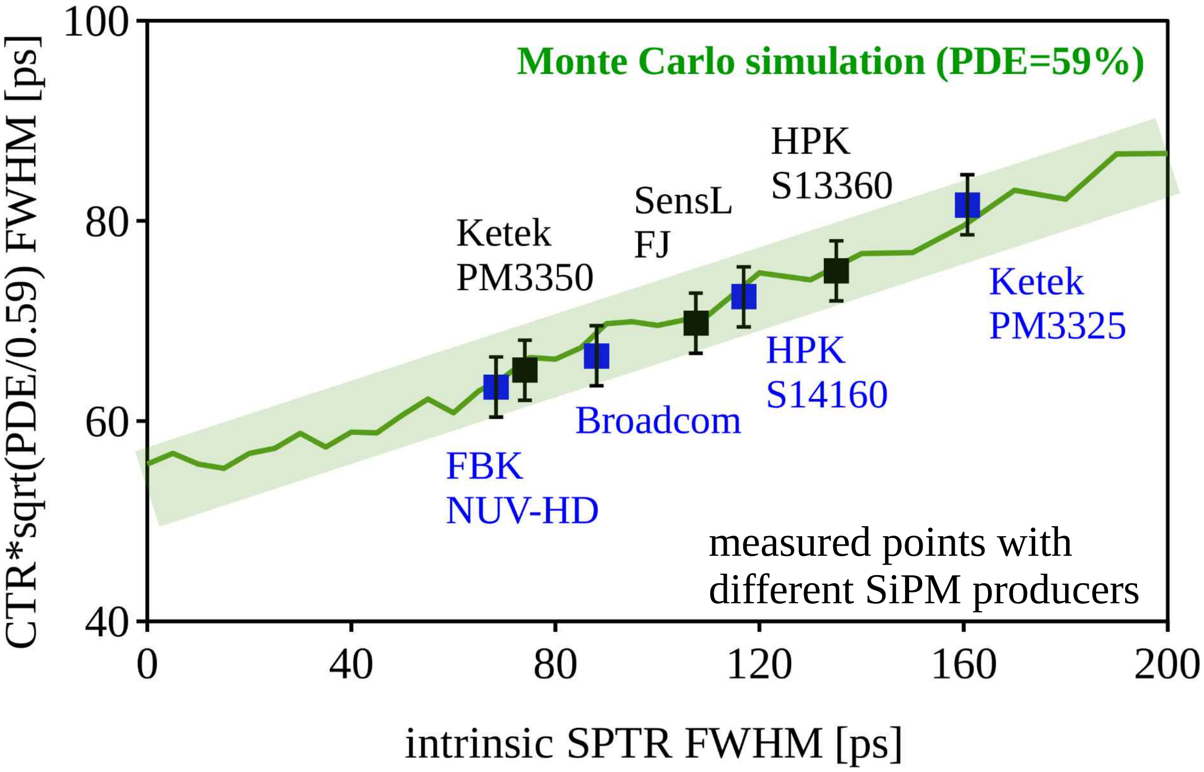
The impact of the SPTR to the CTR



CTR measured with 2x2x3 mm^3 LSO:Ce codoped 0.4%Ca.

CTR corrected for measured PDE to 59%

S. Gundacker et.al, “Experimental time resolution limits of modern SiPMs and TOF-PET detectors exploring different scintillators and Cherenkov emission,” Physics in Medicine & Biology, vol. 65, p. 025001, Jan 2020.