Single-Photon Timing Resolution in Digital Silicon Photomultipliers

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Main objective of this talk

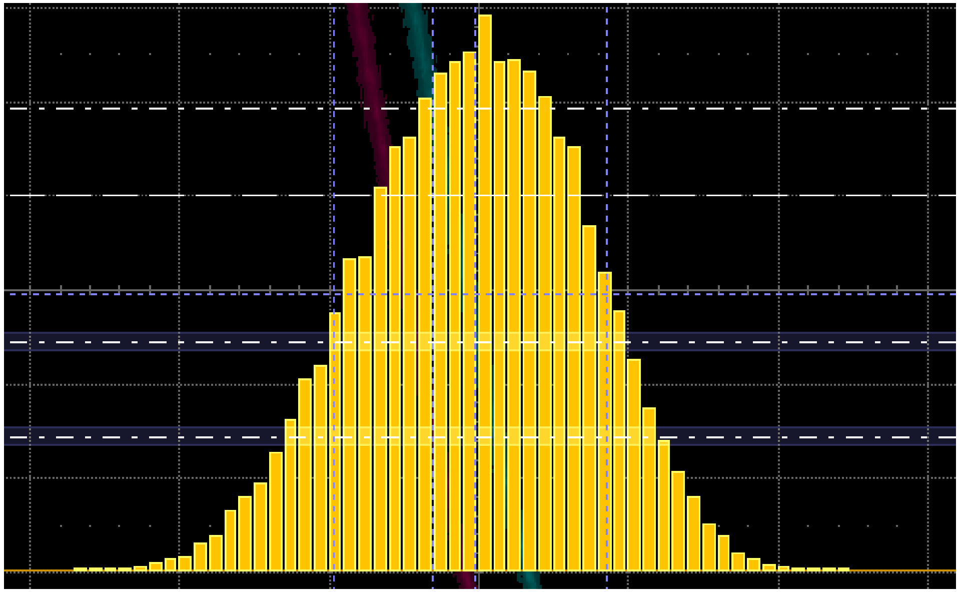
Discuss and propose a standardization methods for SPTR measurements in <u>Digital SiPMs</u>

Outline

- Definition of SPTR
- Digital SiPM architectures
- Setup examples
- Parameters and standardization
- Conclusions

Single-Photon Timing Resolution

"The timing response of a SiPM is represented as a statistical distribution characterized by its precision, accuracy, and bin size (LSB)"



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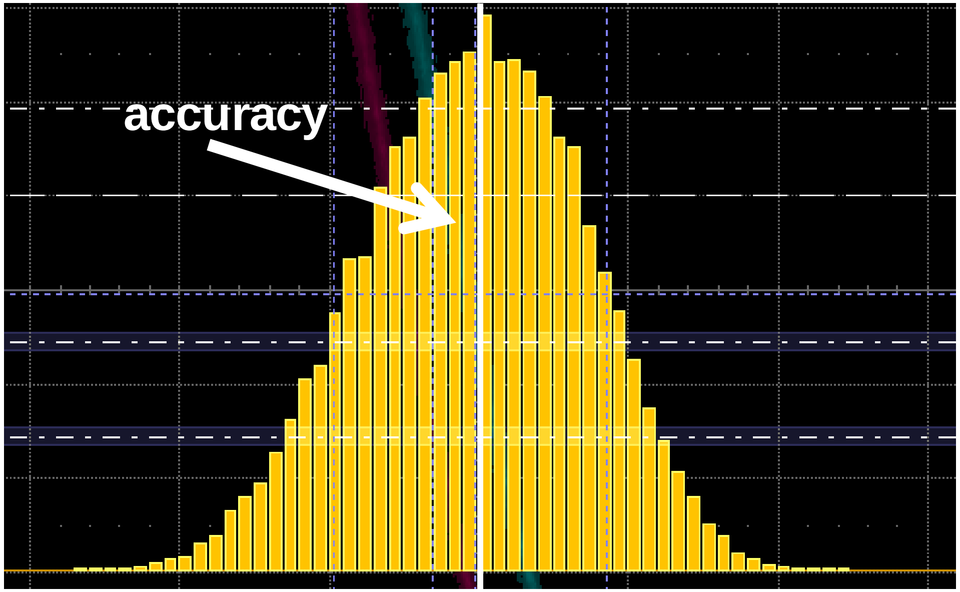

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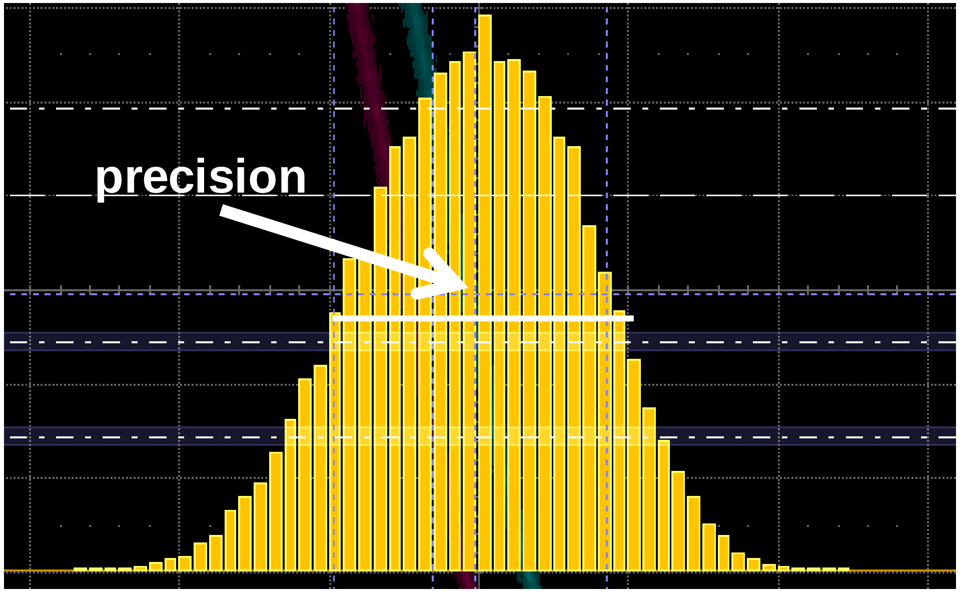

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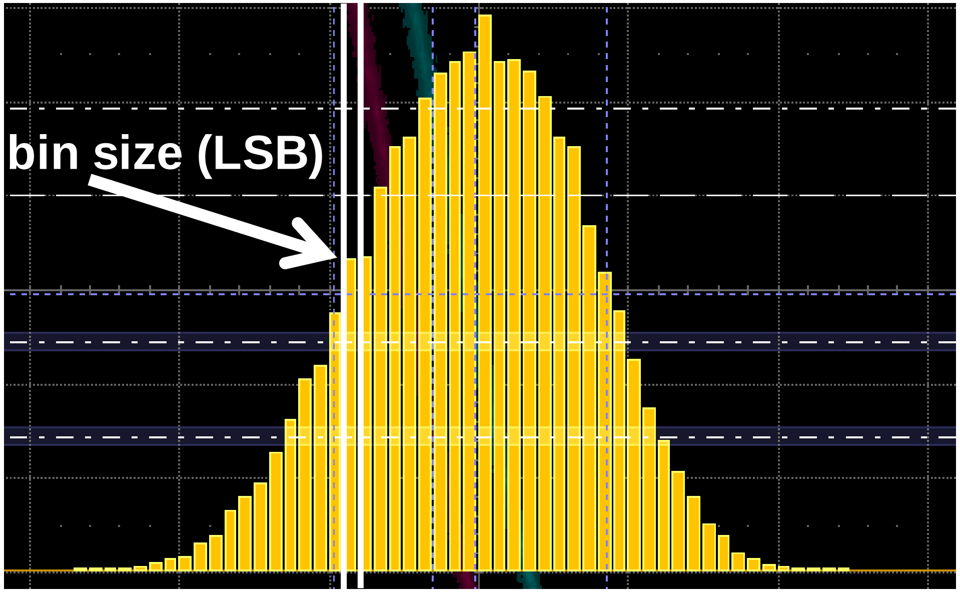
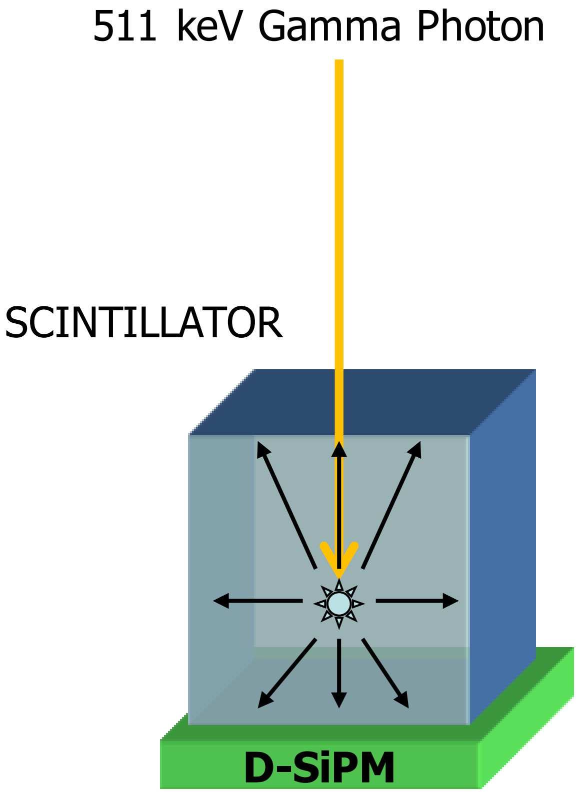


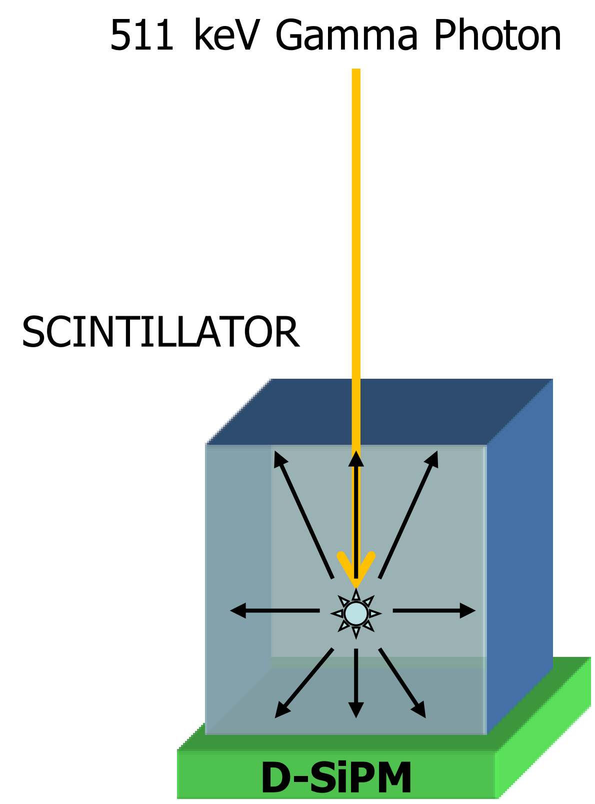
Conditions and techniques

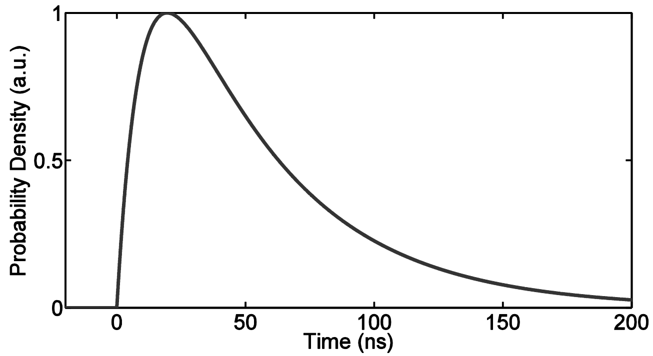
- Single-photon light level
- Uniform illumination over the sensitive area
- TCSPC measurement technique

SPTR impact on applications (PET)



SPTR impact on applications (PET)





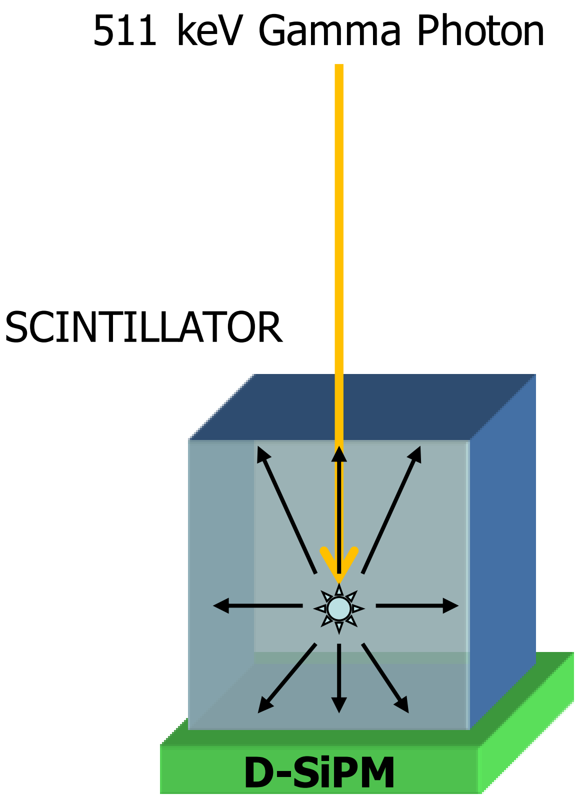
Q: total photoelectrons

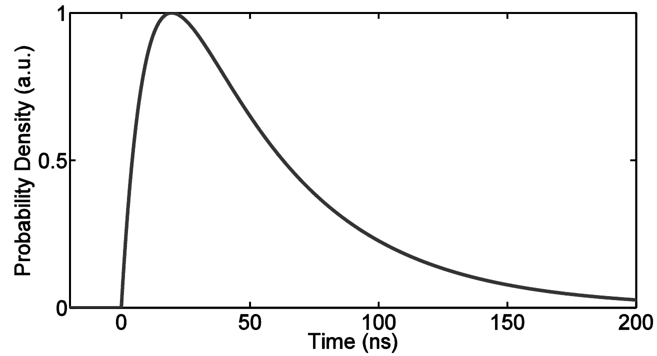
T_r: rise time

T_d: decay time

σ: SPTR

SPTR impact on applications (PET)





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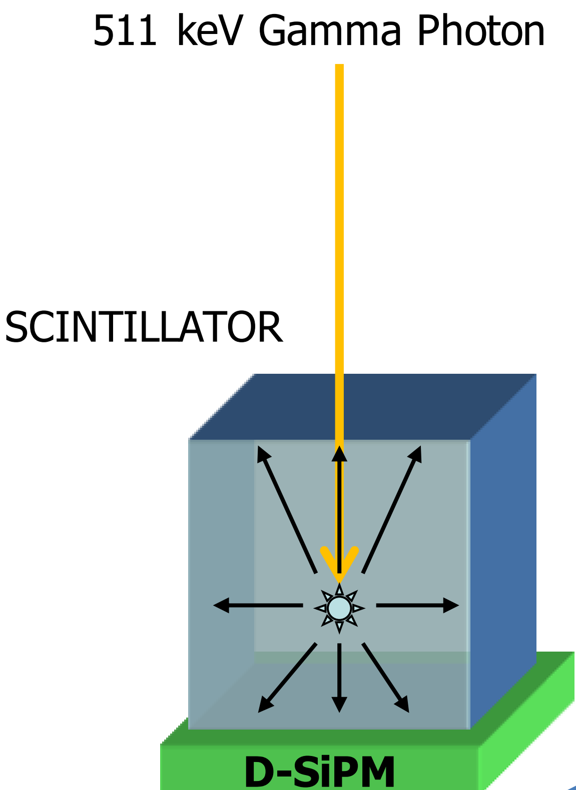
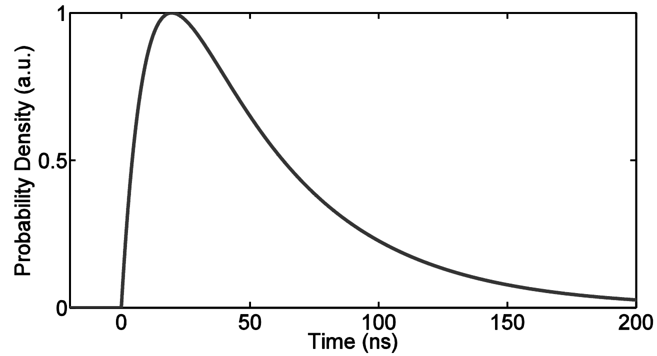
SPTR impact on applications (PET)





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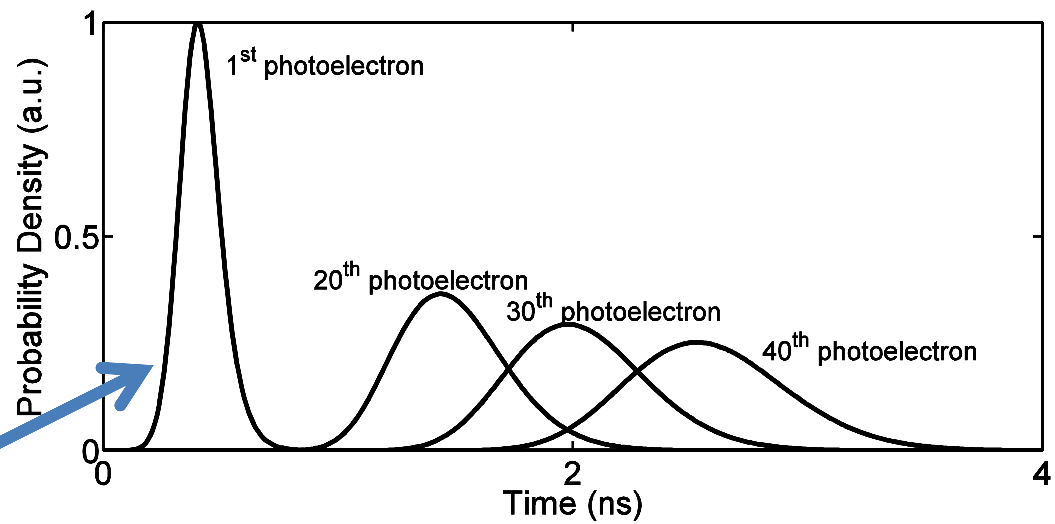


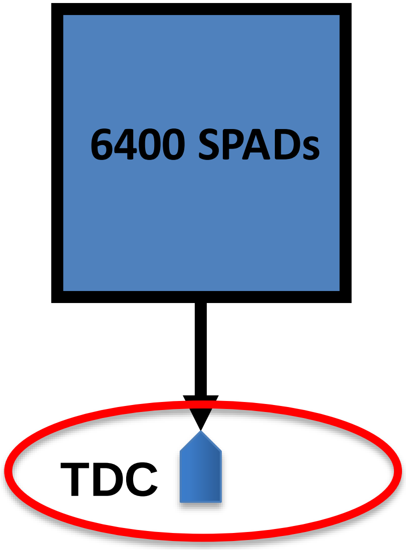
$$p_q(t) = \frac{R!}{(q-1)!(R-q)!}[1-F(t)]^{(R-q)}[F(t)^{(q-1)}]f(t),$$

SORTING PROCESS

Digital SiPM architectures

Digital SiPM concepts

digital photon counter (DPC)



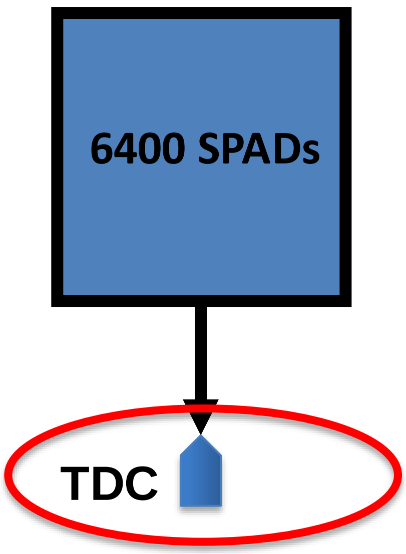
1 time stamp

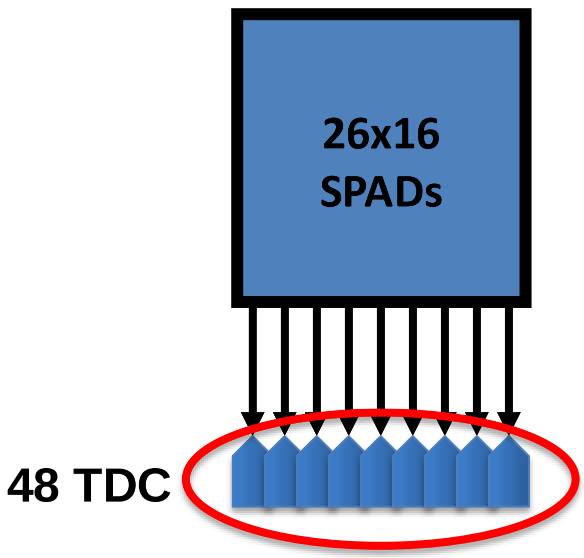
T. Frach et al., NSSMIC 2009

Digital SiPM concepts

digital photon counter (DPC)

Multichannel digital SiPM (MD-SiPM)





1 time stamp

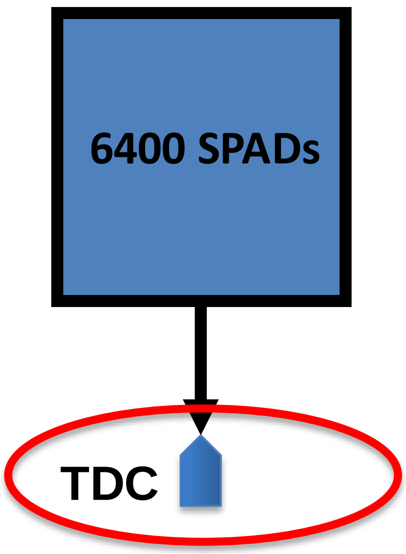
48 **individual** time stamps

T. Frach et al., NSSMIC 2009

S. Mandai et al., NSSMIC 2012

Digital SiPM concepts

digital photon counter (DPC)



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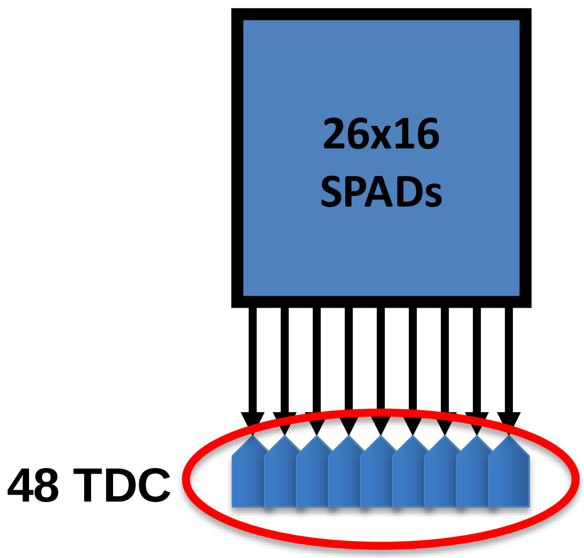
T. Frach et al., NSSMIC 2009

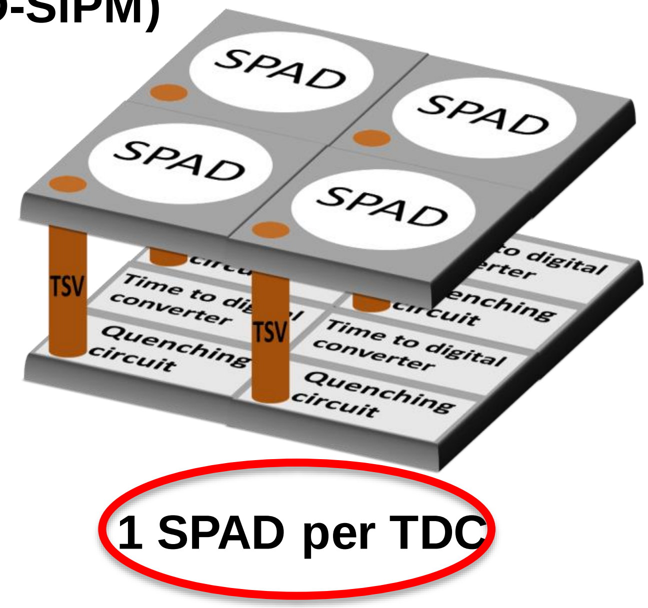
Multichannel digital SiPM (MD-SiPM)



48 **individual** time stamps

S. Mandai et al., NSSMIC 2012

3D digital SiPM (3DdSiPM)

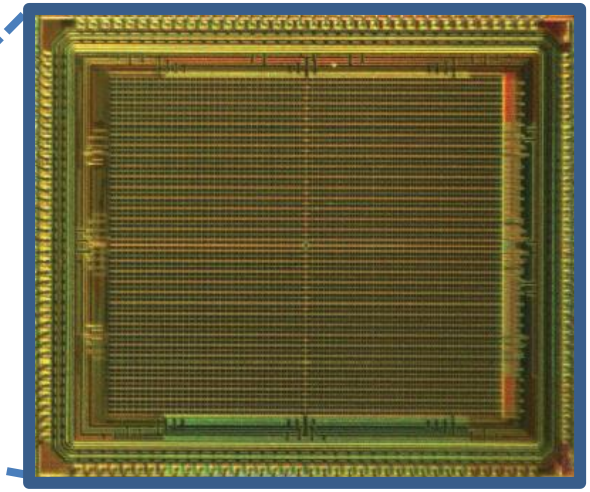


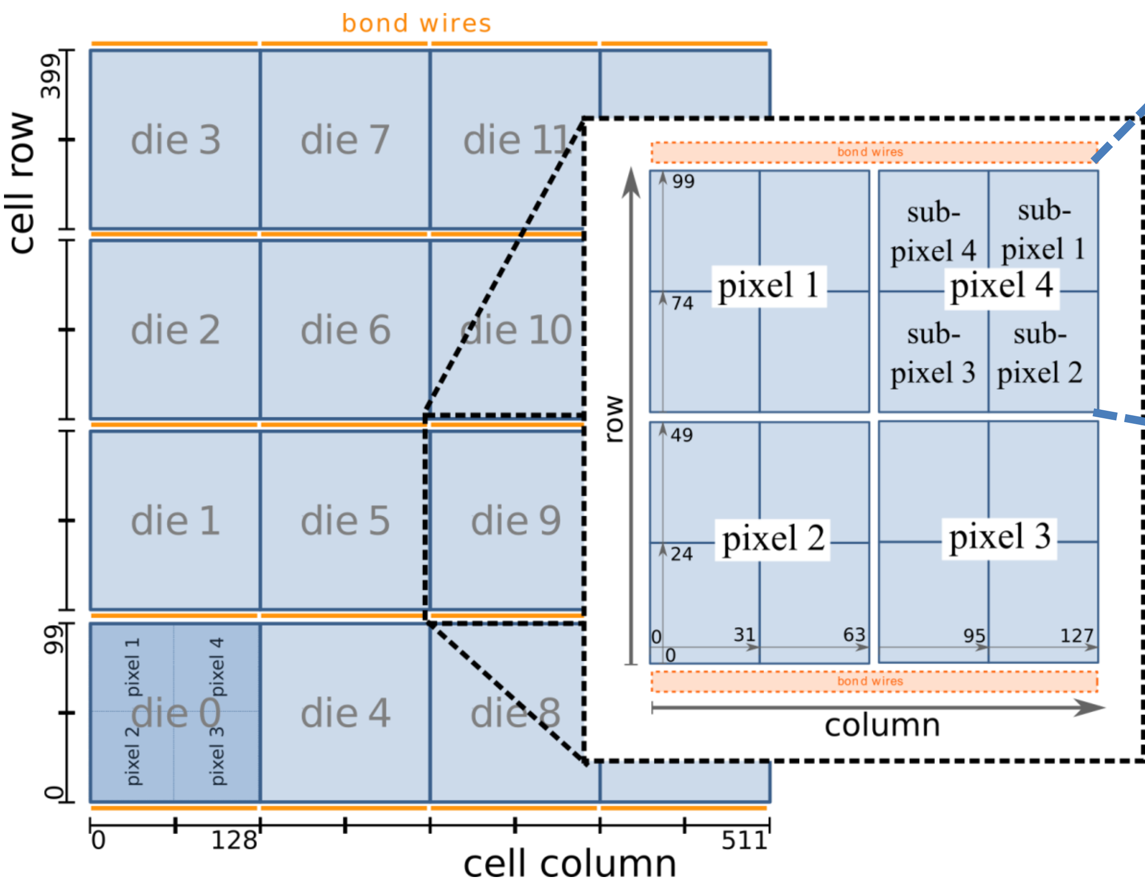
N **individual** time stamps

Pratte et al. 3DIC-IEEE 2010

Digital Photon Counter (DPC)

T. Frach et al., NSSMIC 2009

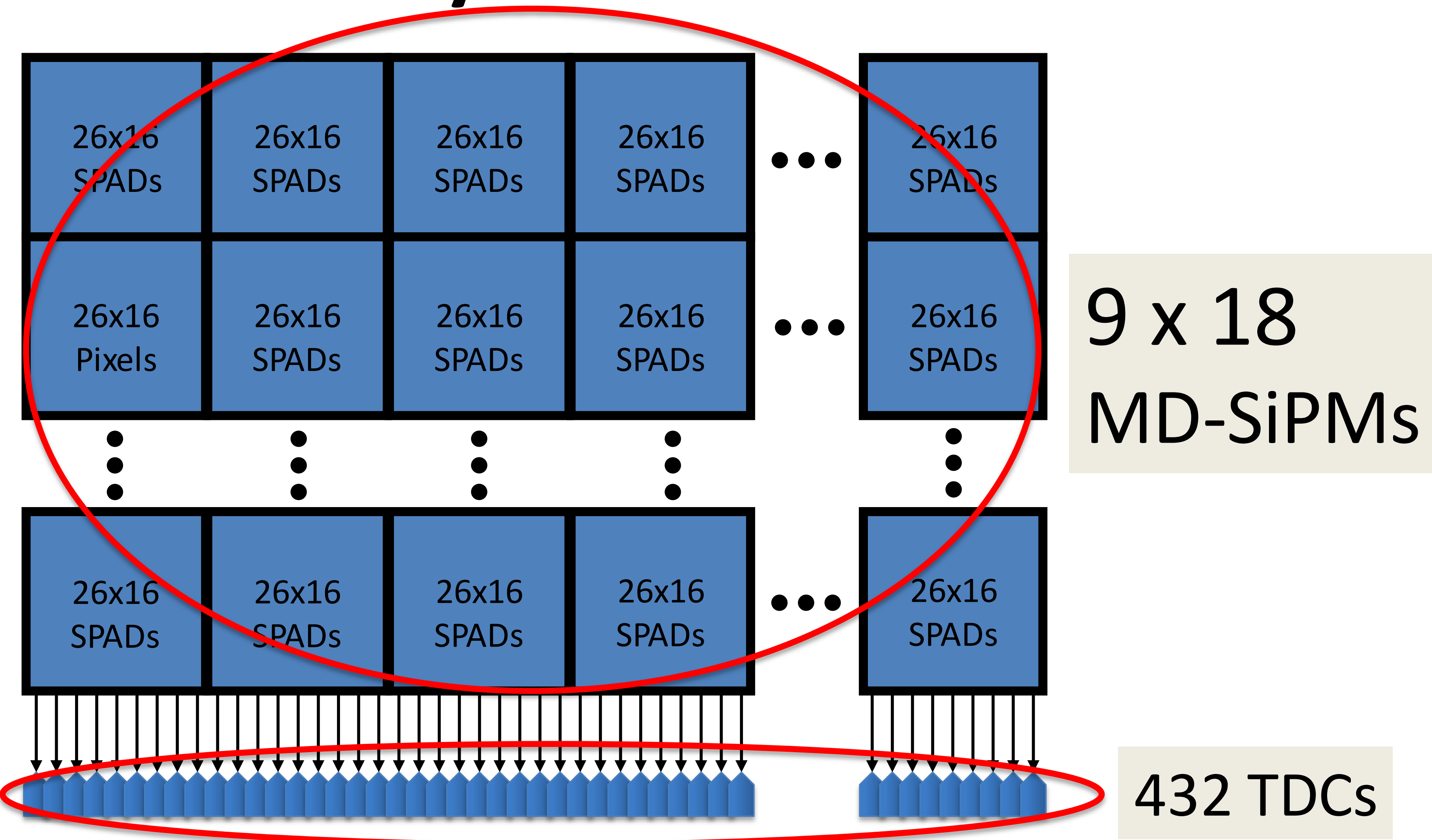


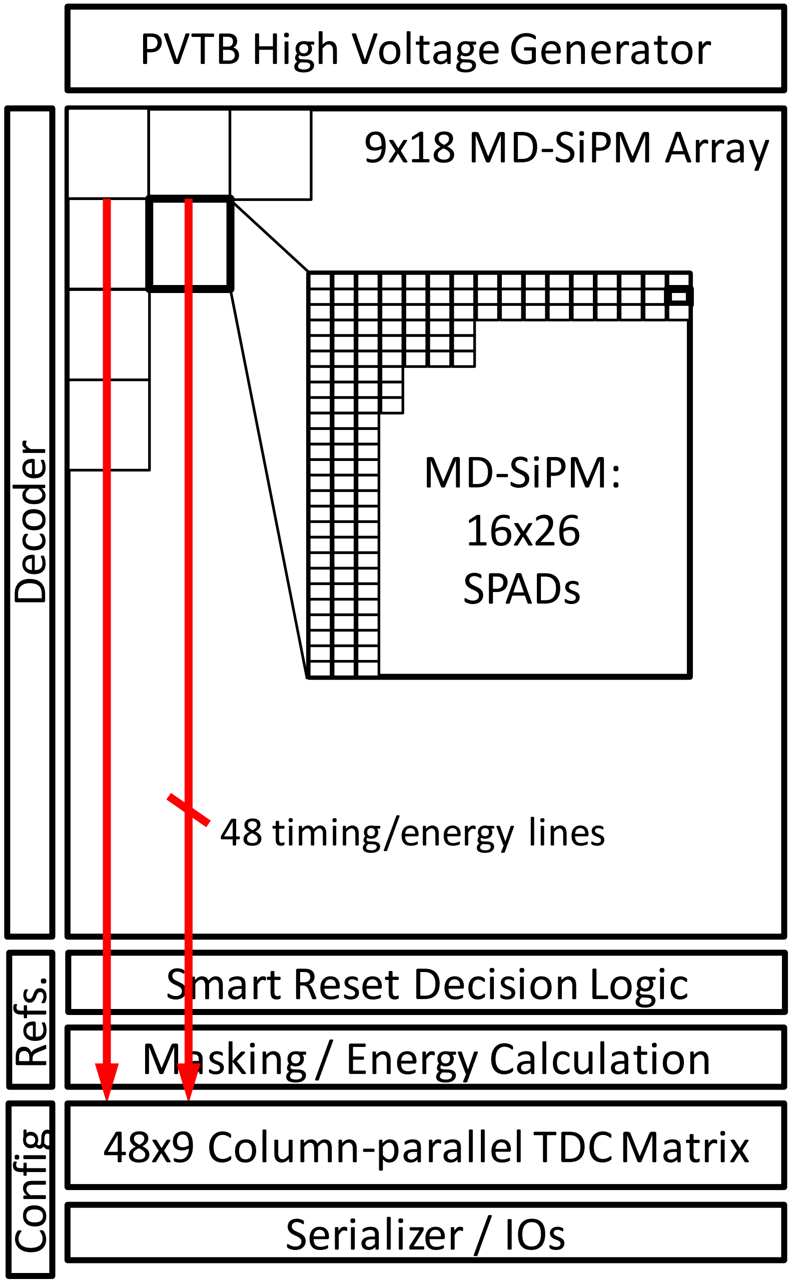


S. Brunner et al., JINST 2016

- each die has 4 pixels
- two TDCs per die
- 4 sub-pixels
- 3200 or 6400 SPADs per pixel
- programmable trigger and validation logic
- individual SPAD cell masking circuitry
- TDC bin size: 24 ps

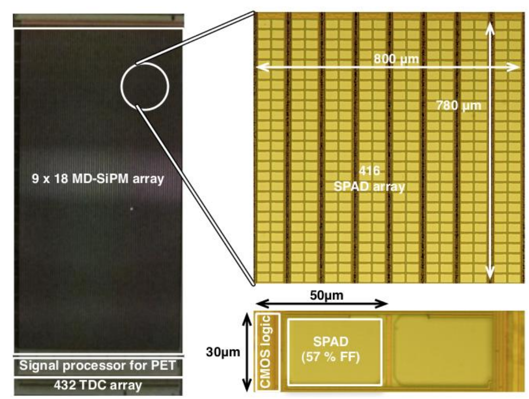
9x18 Array of MD-SiPMs





9x18 Array of MD-SiPMs architectural overview

- a 2D 9x18 MD-SiPM array.
- 9 TDC banks with each having 48 TDCs..
- configuration memory and masking registers.
- readout logic and discriminator.



Augusto Carimatto; Shingo Mandai; Esteban Venialgo; Ting Gong; Giacomo Borghi; Dennis R. Schaart; Edoardo Charbon. ISSCC, 2015

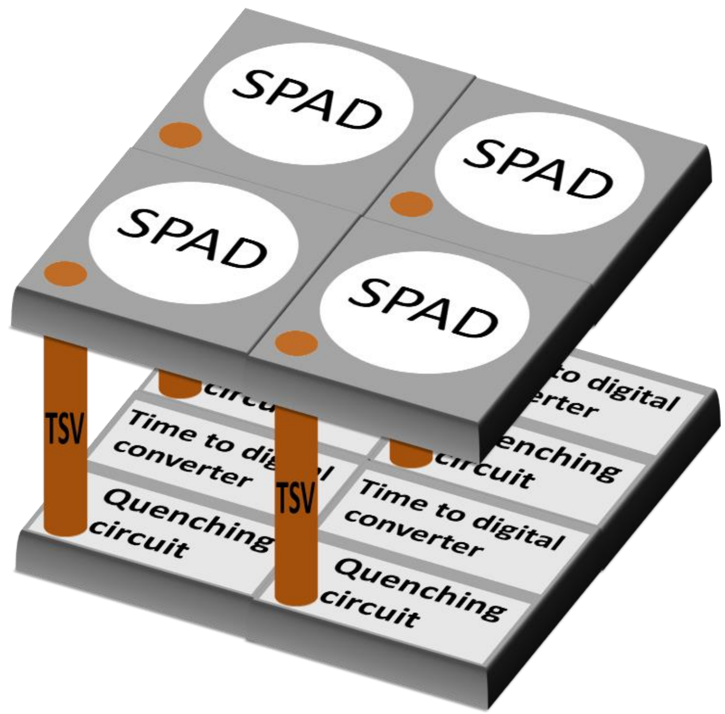
3D digital SiPM

3D Integration

- high fill factor
- heterogeneous technologies integration

Pratte et al. 3DIC-IEEE 2010

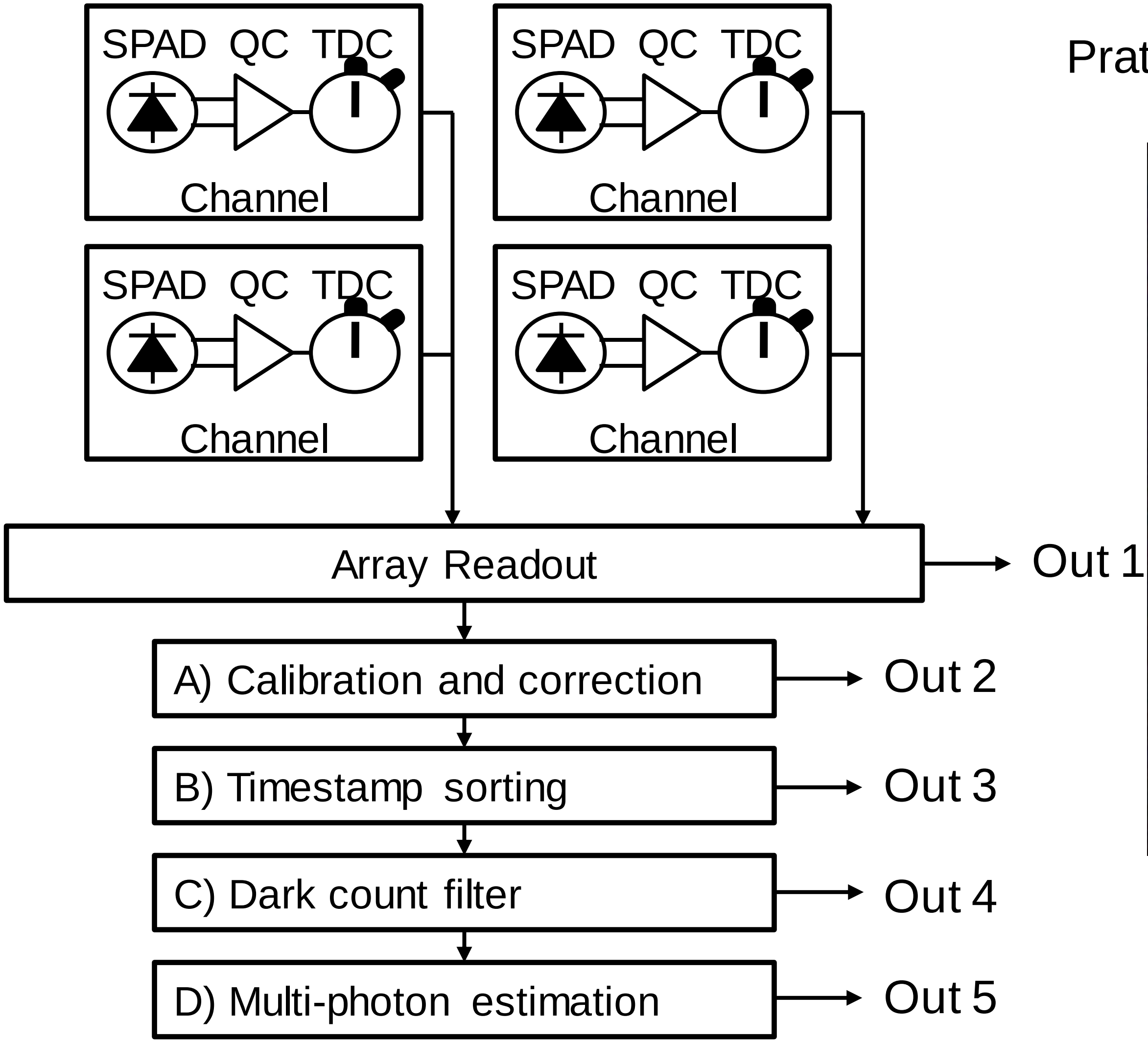
Teledyne Dalsa
Custom process



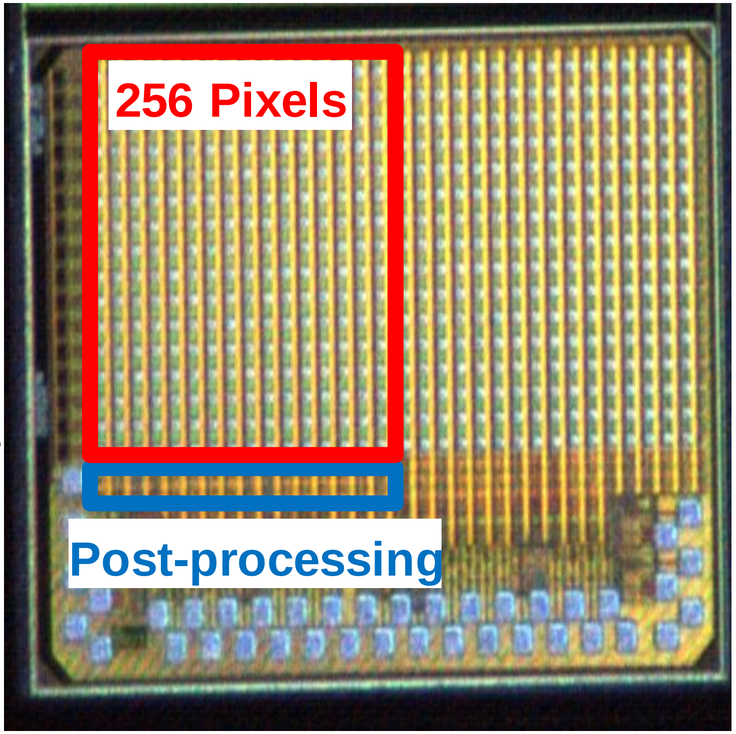
TSMC CMOS 65 nm

256 SPAD readout ASIC

Digital SiPM overview



Pratte et al. 3DIC-IEEE 2010

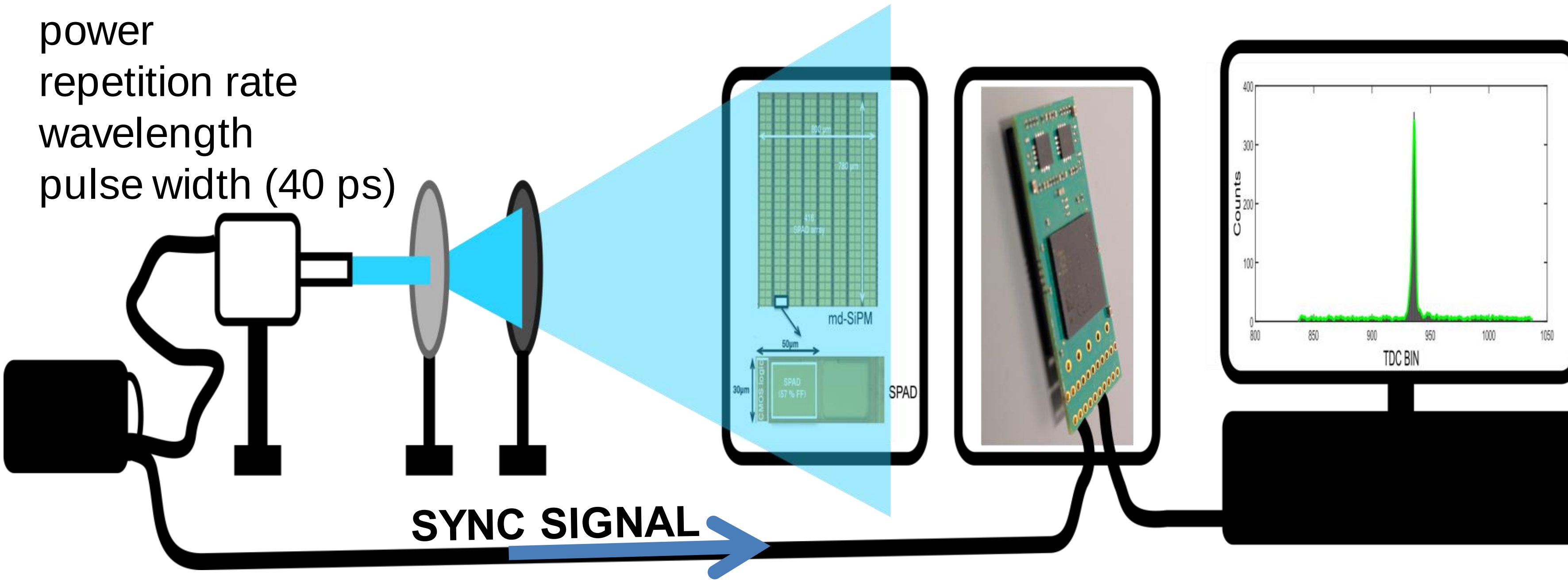


Setup examples

Typical setup (MD-SiPM)

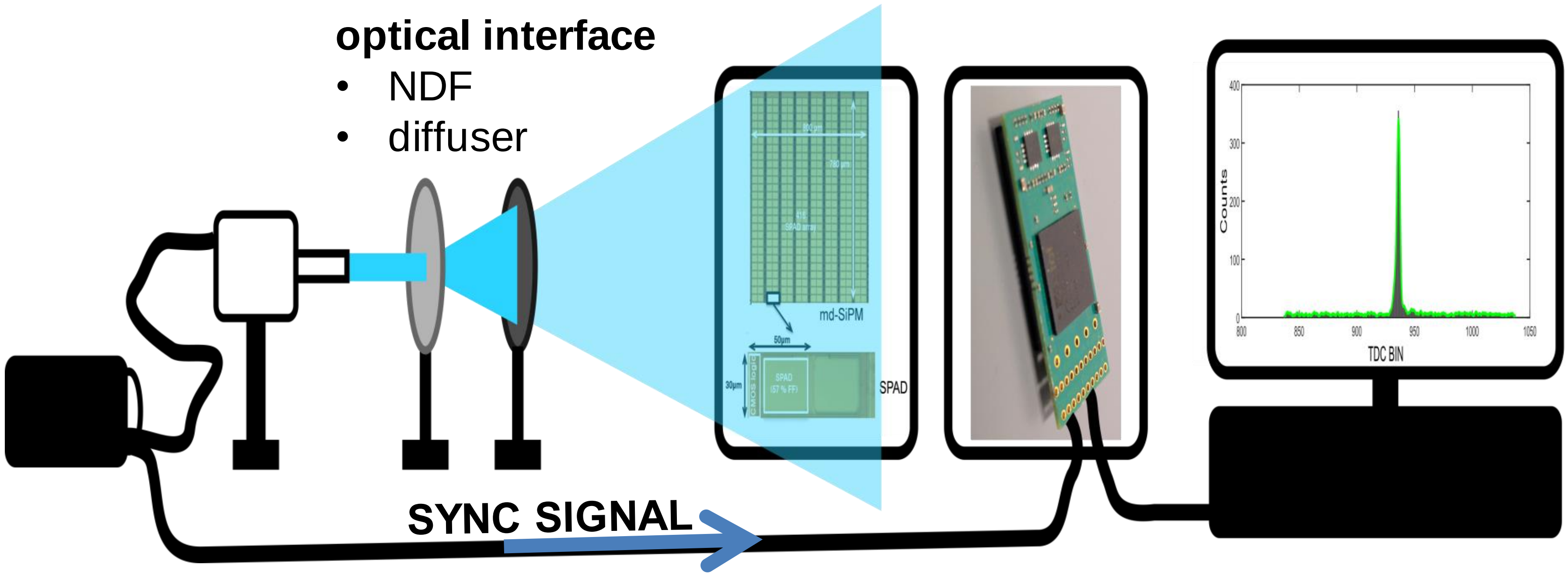
picosecond Laser

- power
- repetition rate
- wavelength
- pulse width (40 ps)



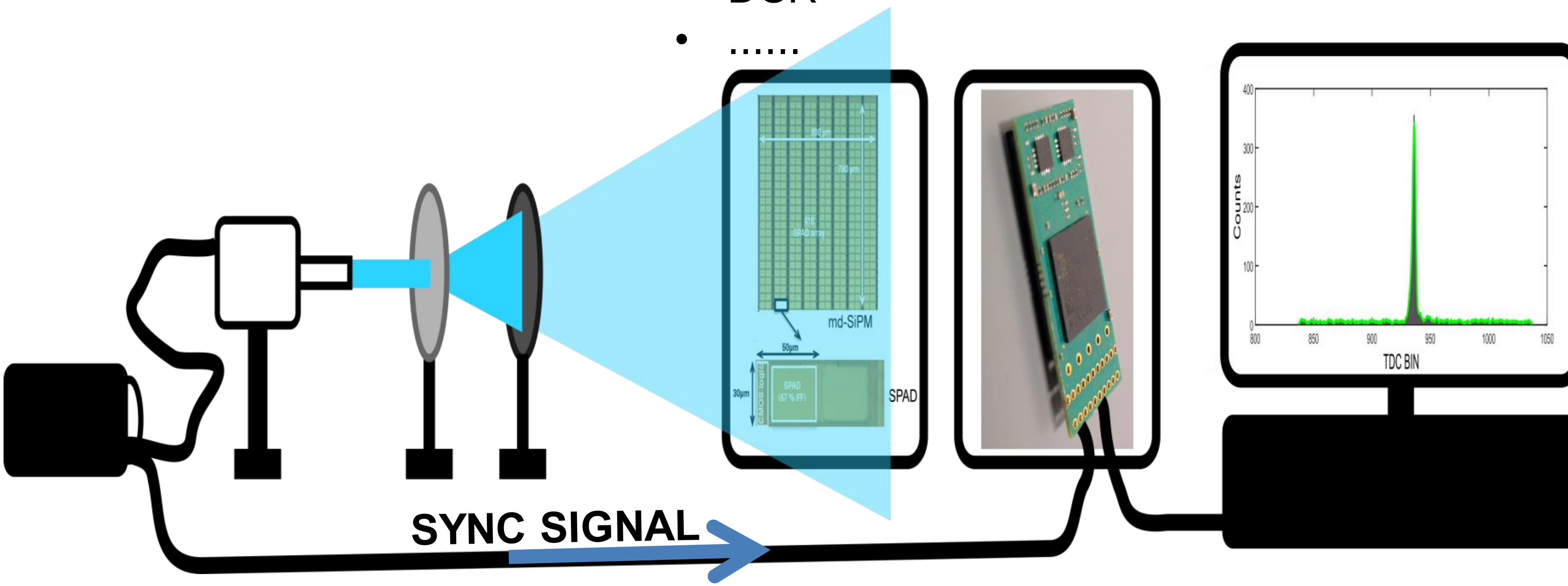
Advaced laser diode systems. EIG1000 AF. Head**:** PiL040F, 405 nm, SANYO laser diode DL-5146-152

Typical setup (MD-SiPM)



Typical setup (MD-SiPM)

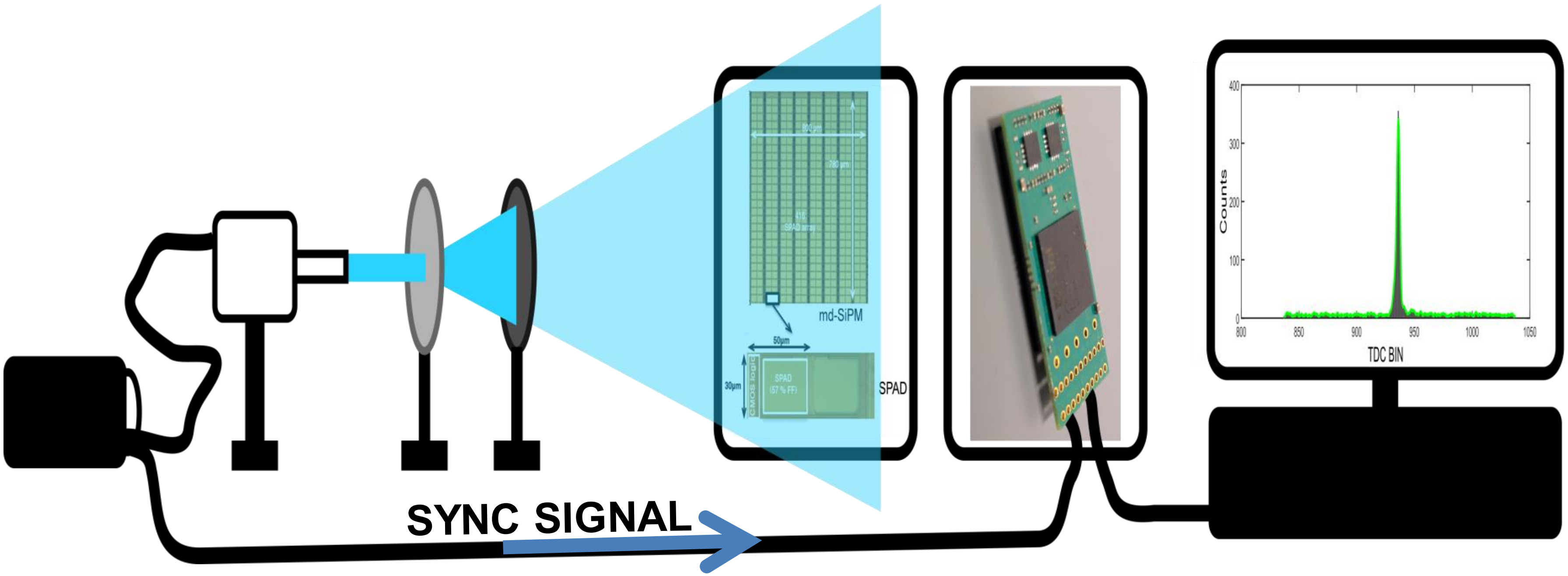
MD-SiPM
- bias voltage
- temperature
- DCR
- ......



Typical setup (MD-SiPM)

readout FPGA

- CLK source
- STOP/START

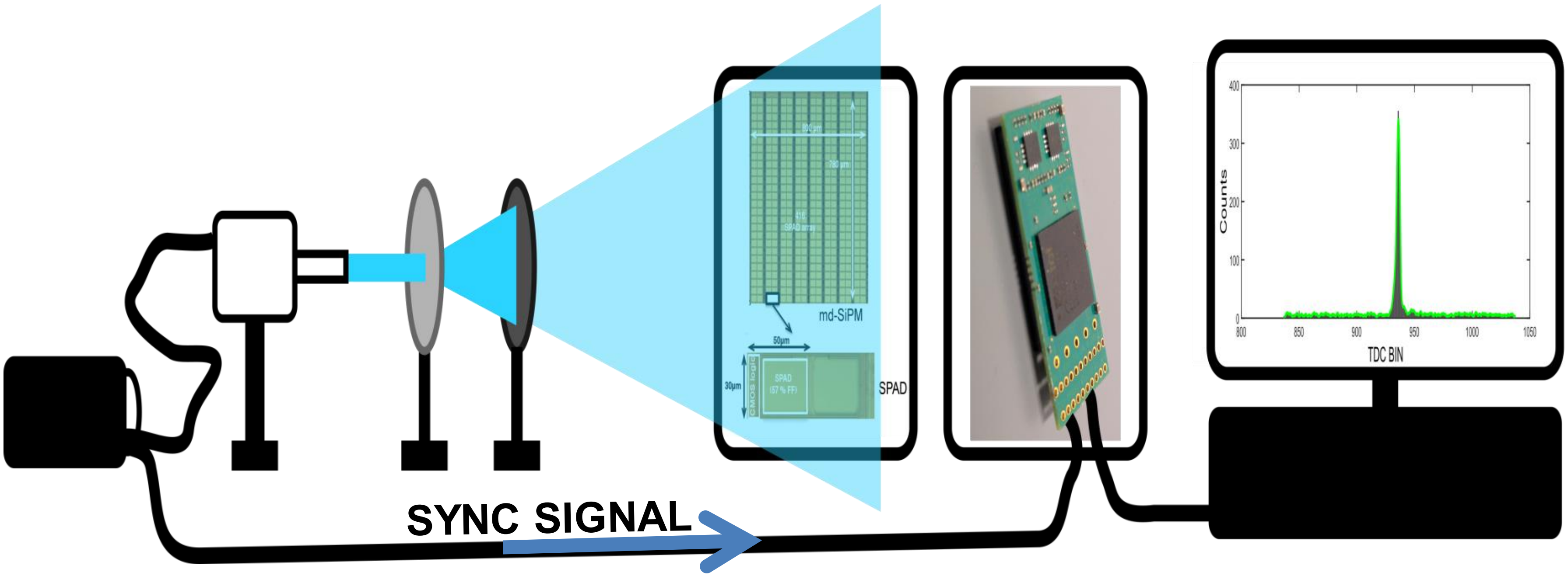


- ML507 Xilinx, Virtex-5
- human data [XCM-206Z]Xilinx Spartan-6 FGG676
- custom Microsemi AGL1000V2−CS281 board

Typical setup (MD-SiPM)

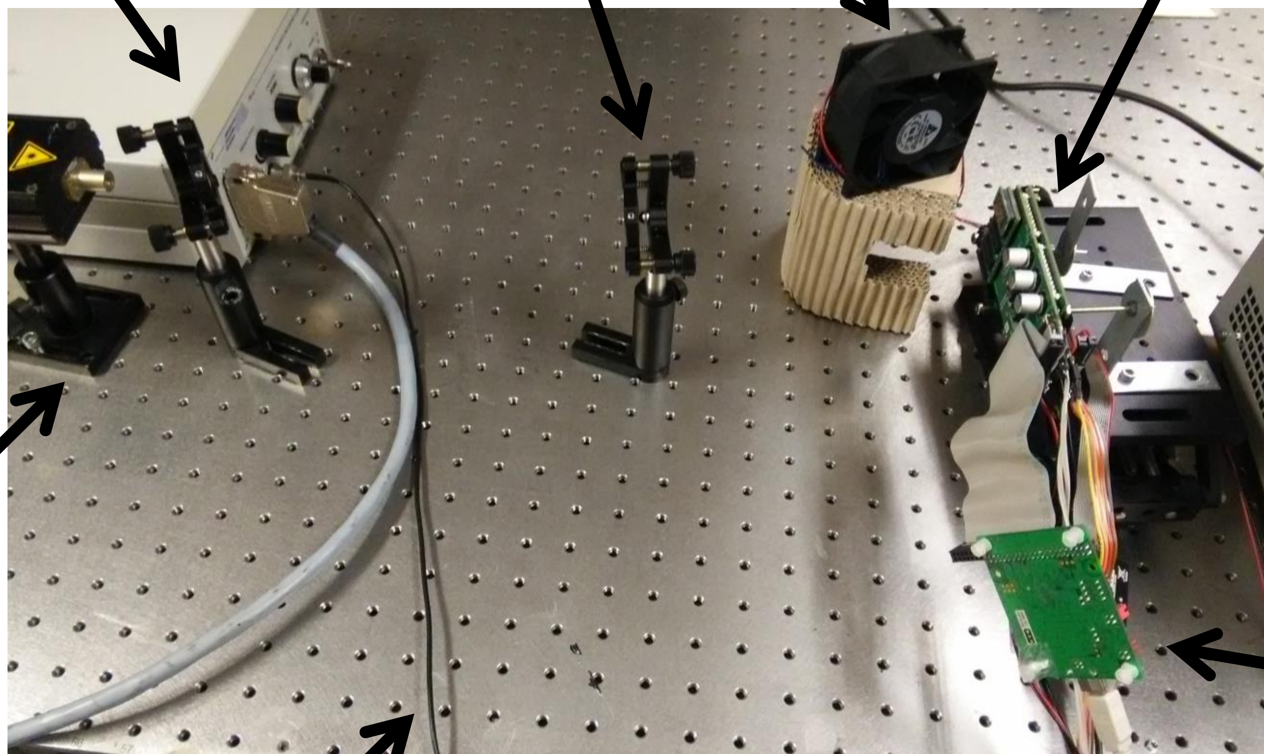
acquisition computer

- KDE
- measurement error
- calibration procedures

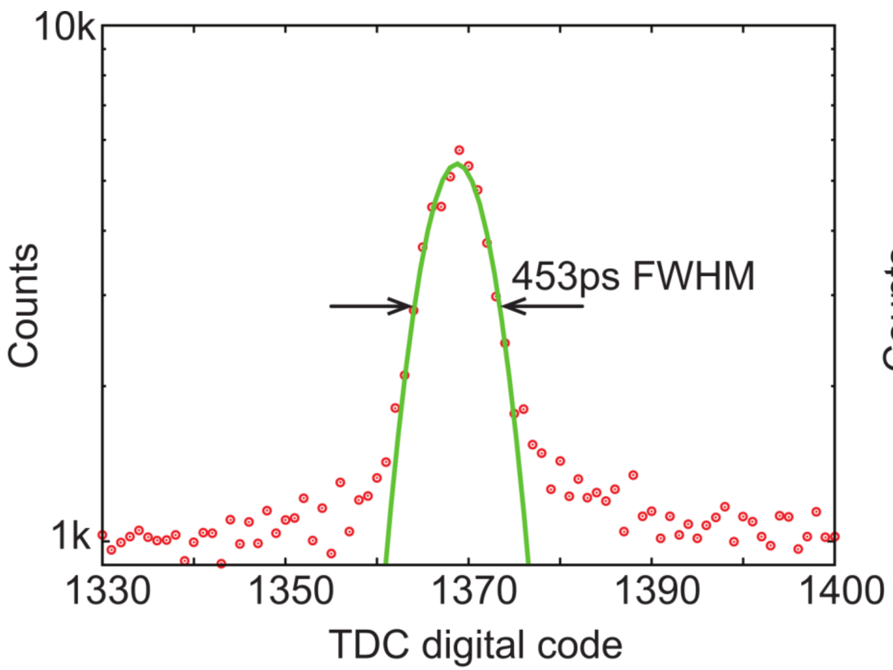


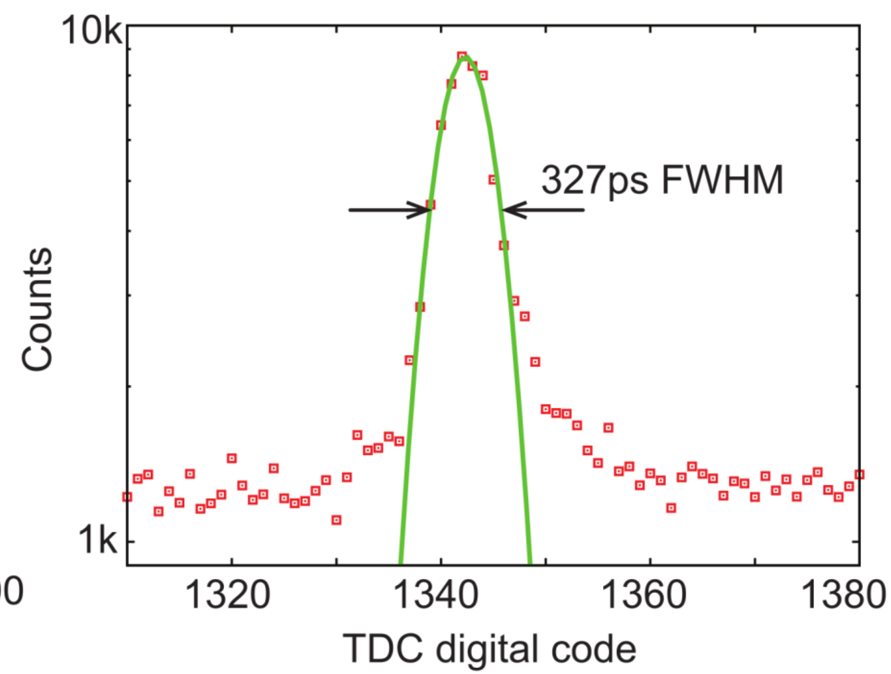
- custom USB-2.0 interface
- ethernet 1Gbps
- matlab/Linux

Typical setup (MD-SiPM)



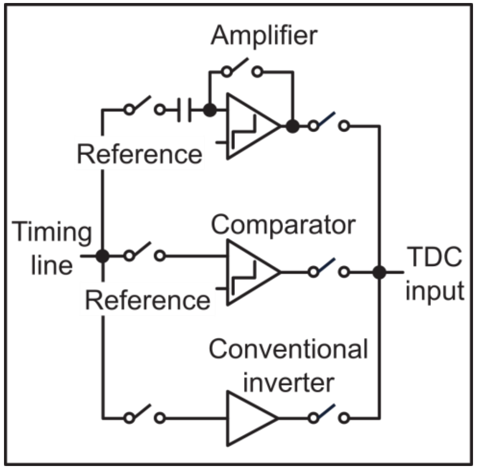
SPTR measurement MD-SiPM





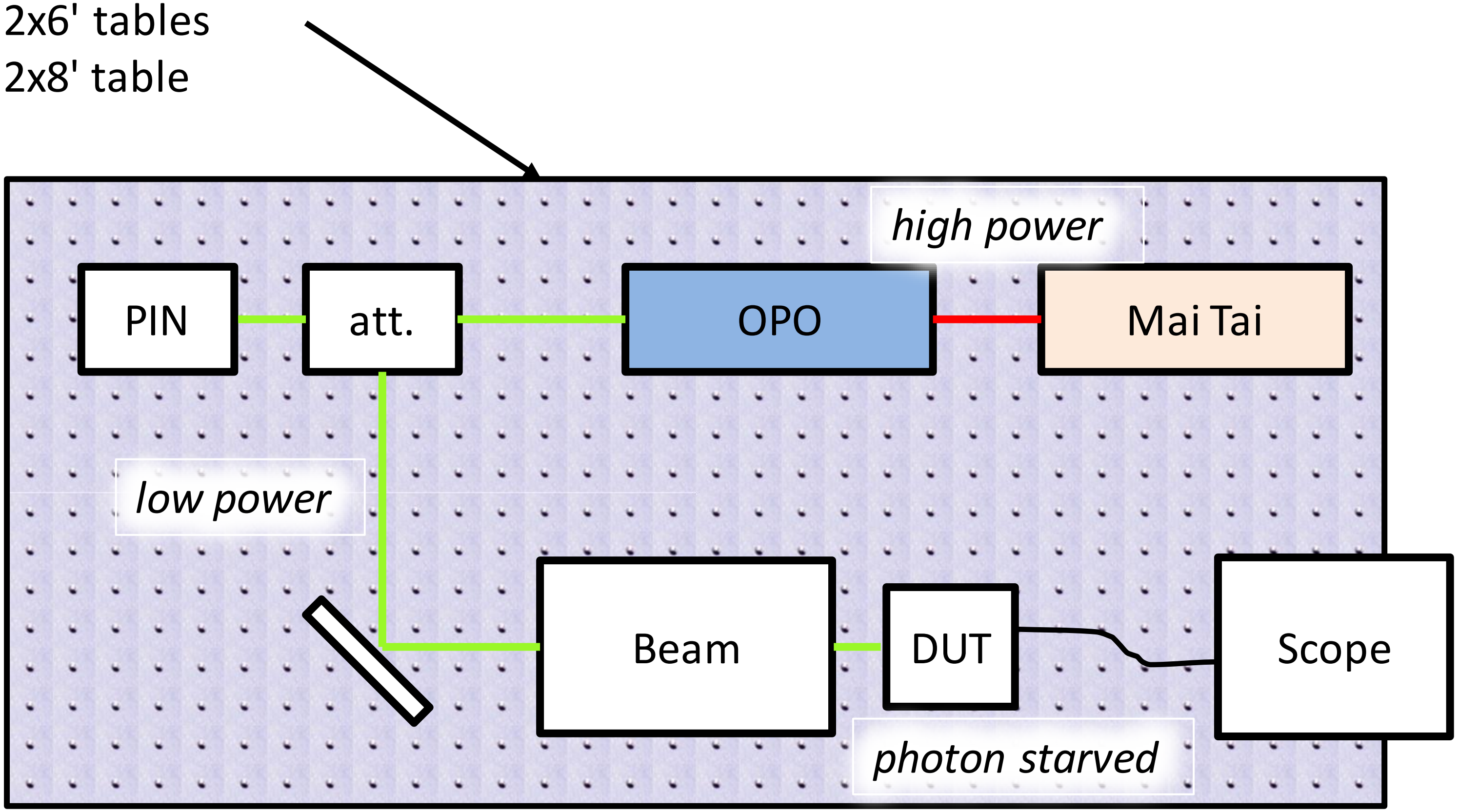
- **excess bias voltage**
- **timing line settings**

S. Mandai, PhD. Thesis, TU-Delft ,2014



Sherbrooke's SPTR setup

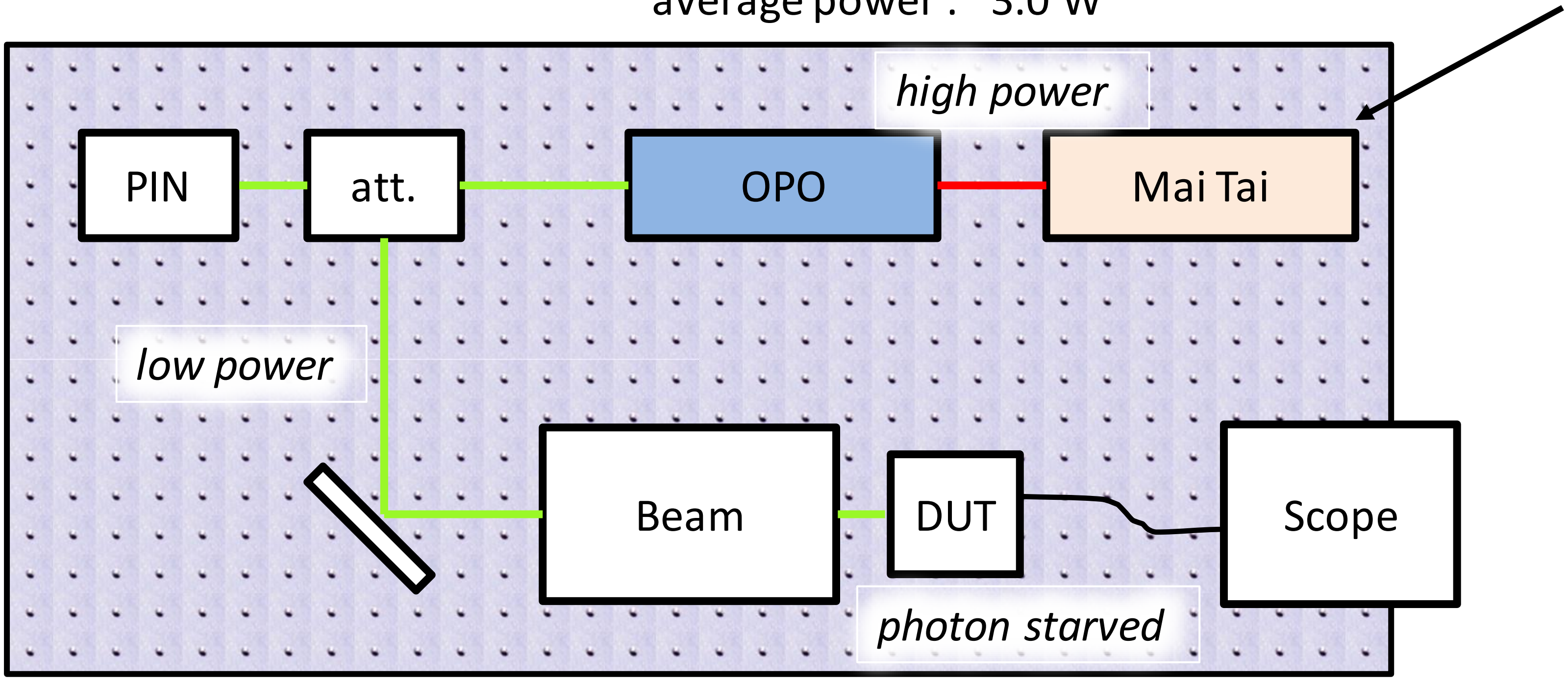
<u>optical table</u>
two 2x6' tables
one 2x8' table



Sherbrooke's SPTR setup

<u>SP- Mai Tai Ultrafast Ti-Sapphire Laser</u>

pulse width :	< 100 fs
repetition rate :	80 MHz
wavelength :	690 - 1040 nm
average power :	3.0 W



Sherbrooke's SPTR setup

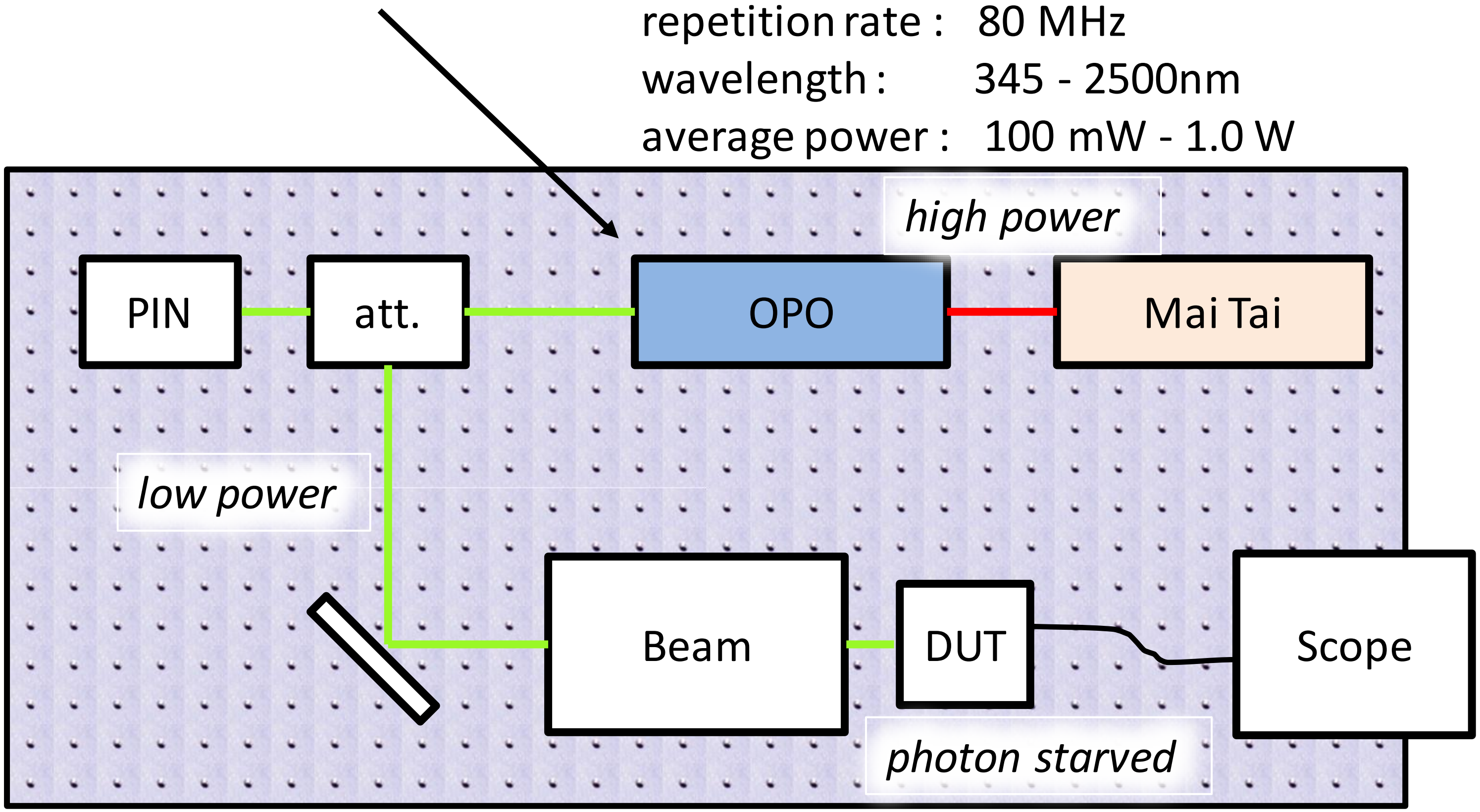
SP- Optical Parametric Oscillator

pulse width : < 100 fs

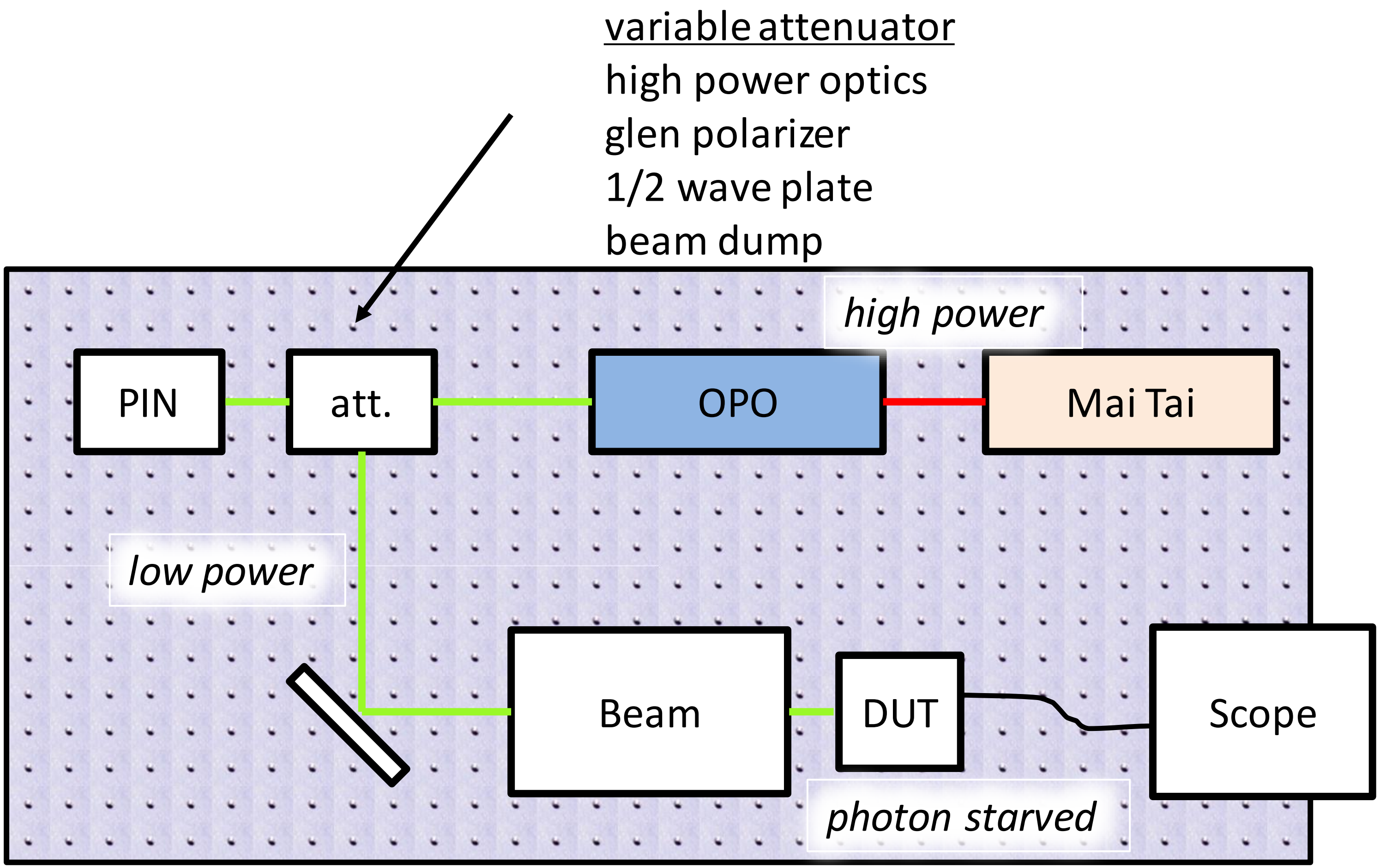
repetition rate : 80 MHz

wavelength : 345 - 2500nm

average power : 100 mW - 1.0 W

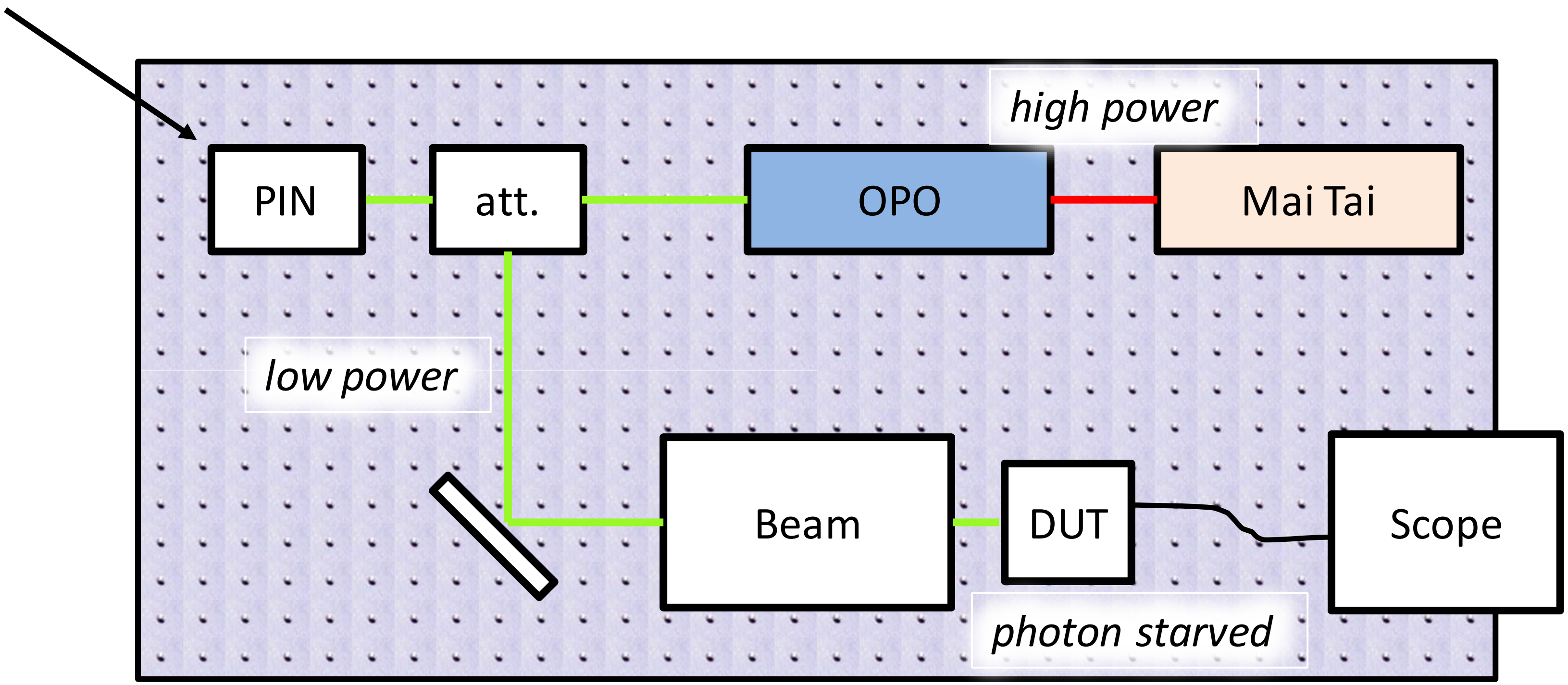


Sherbrooke's SPTR setup

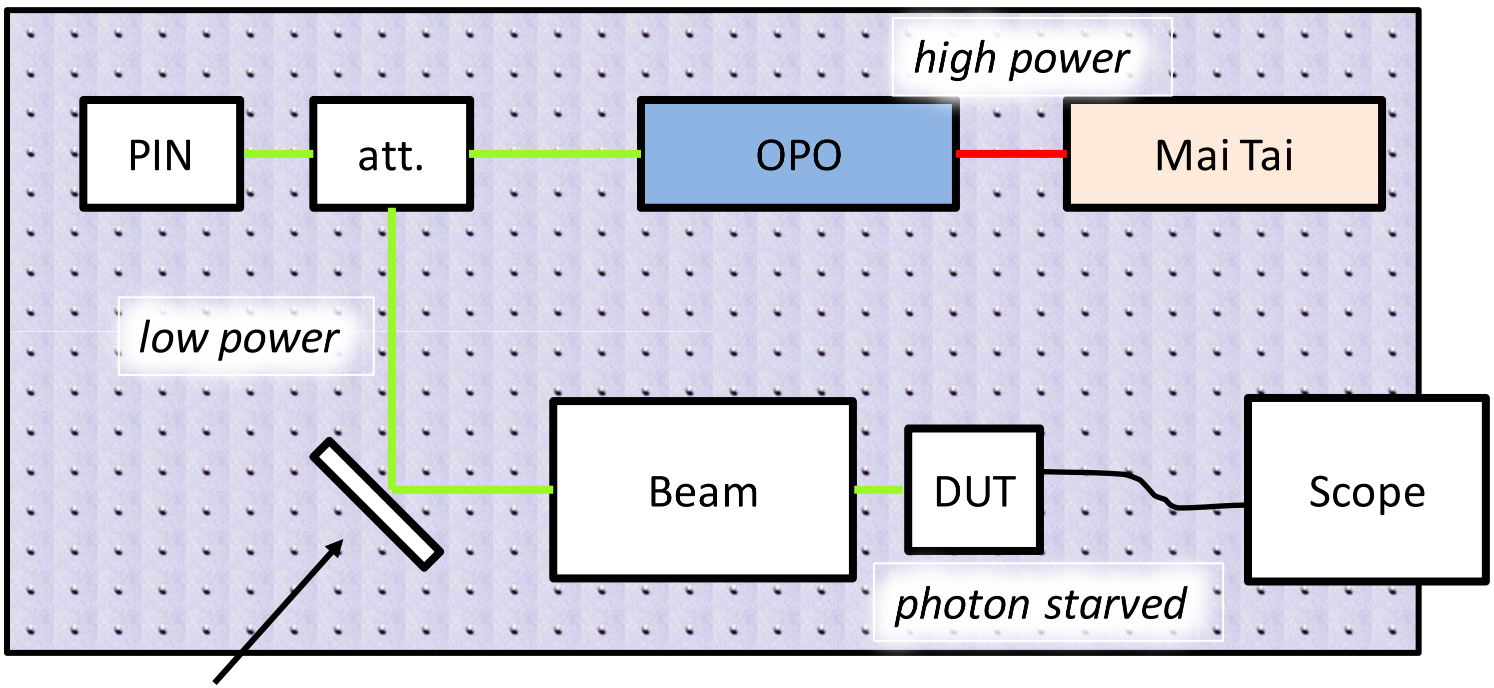


Sherbrooke's SPTR setup

reference PIN diode
Becker & Hickl PHD-400
200 ps rise time



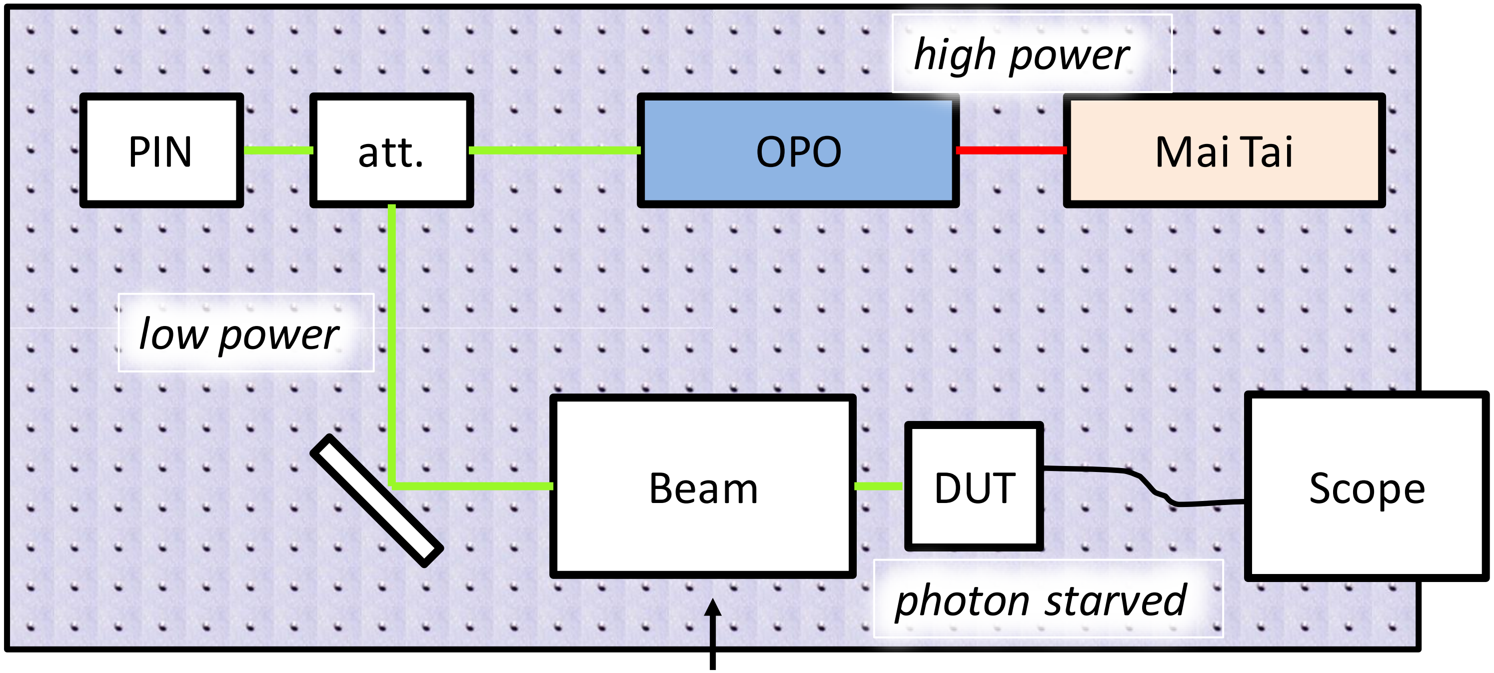
Sherbrooke's SPTR setup



free space beam propagation

high-end Newport mirrors for ultrafast laser

Sherbrooke's SPTR setup



beam conditioning setup
iris, shutter, filter, beam splitter, focusing optics

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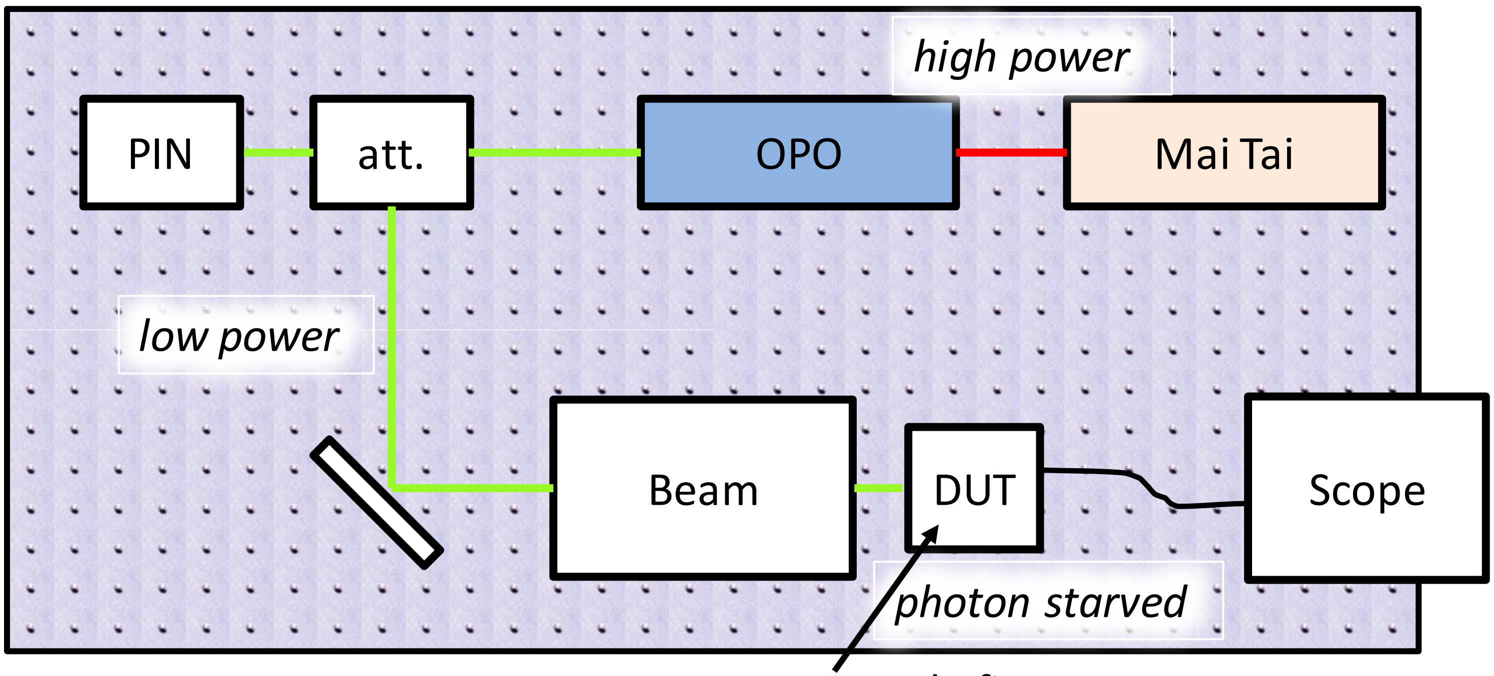
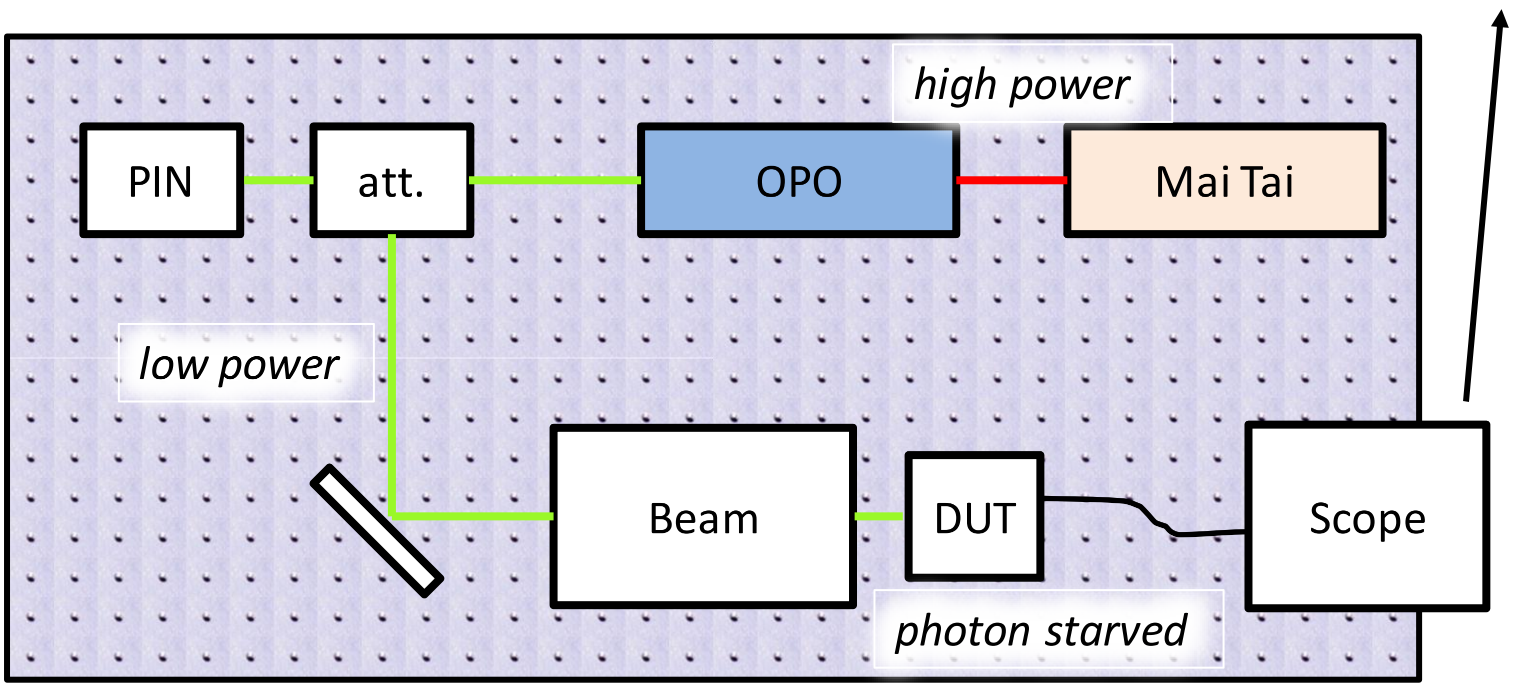
Sherbrooke's SPTR setup



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

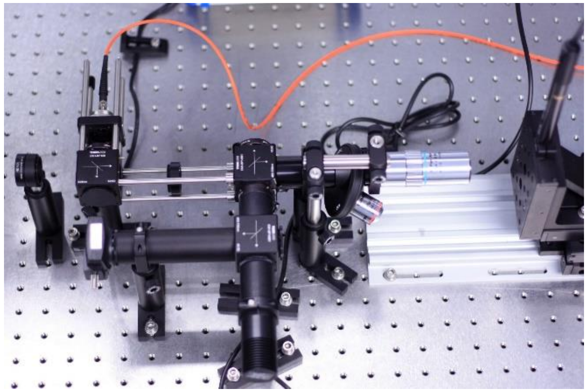
Sherbrooke's SPTR setup

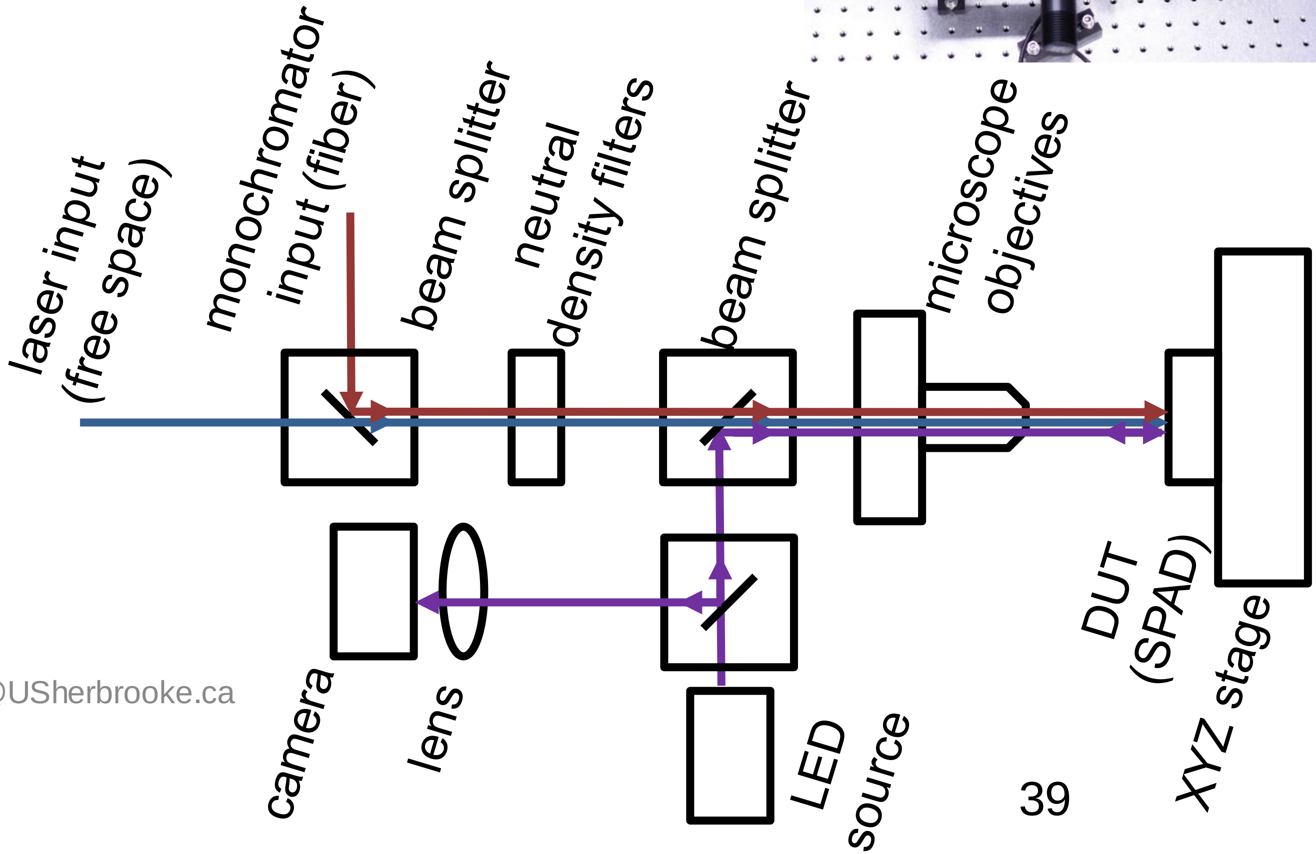
<u>output signals</u>
SMA cable (ref diode and DUT)
oscilloscope
- LeCroy SDA 6000A 20 GS/s, 6 GHz
- Keysight MSOX91304A 80 GS/s, 13 GHz



Beam conditioning setup

- laser input for SPTR measurements
- neutral density filters (photon starved)
- beam focusing (down to ~2um spot size)
- XYZ motorized stage (array sweep, ~1um step)





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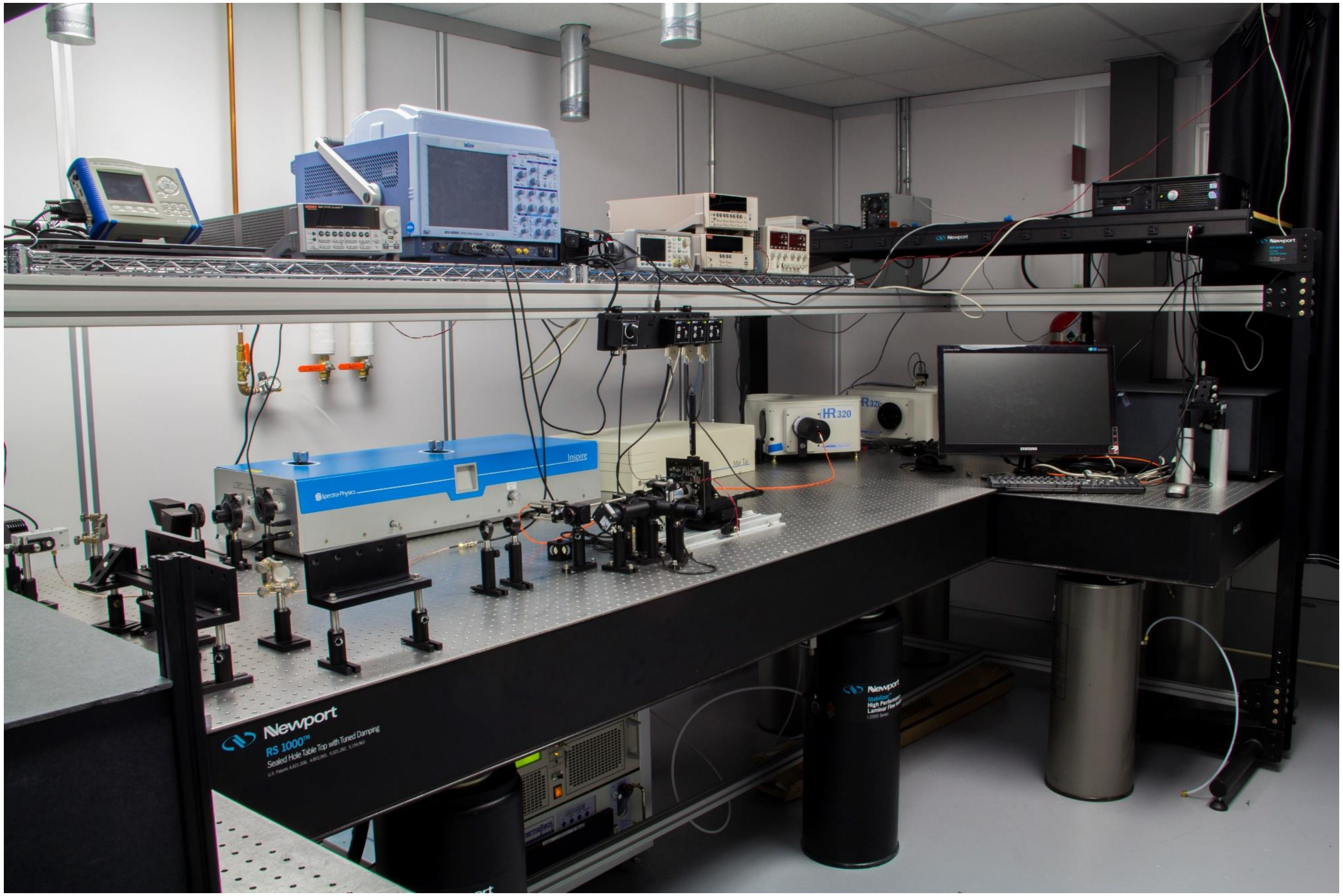
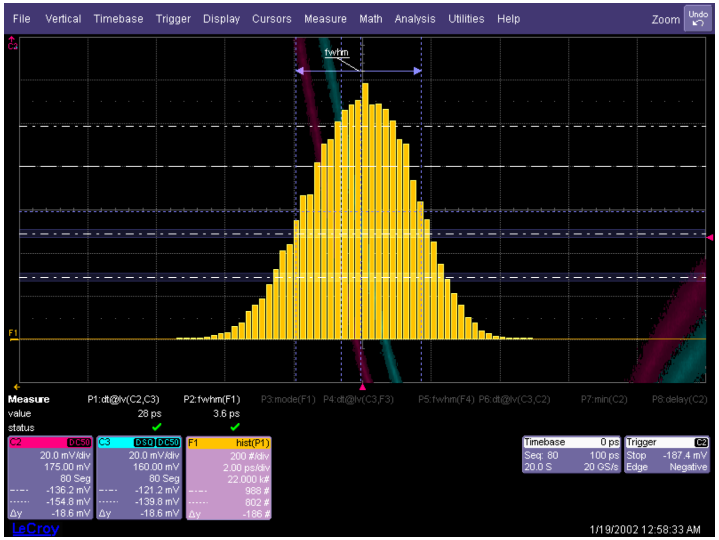
Sherbrooke's SPTR setup



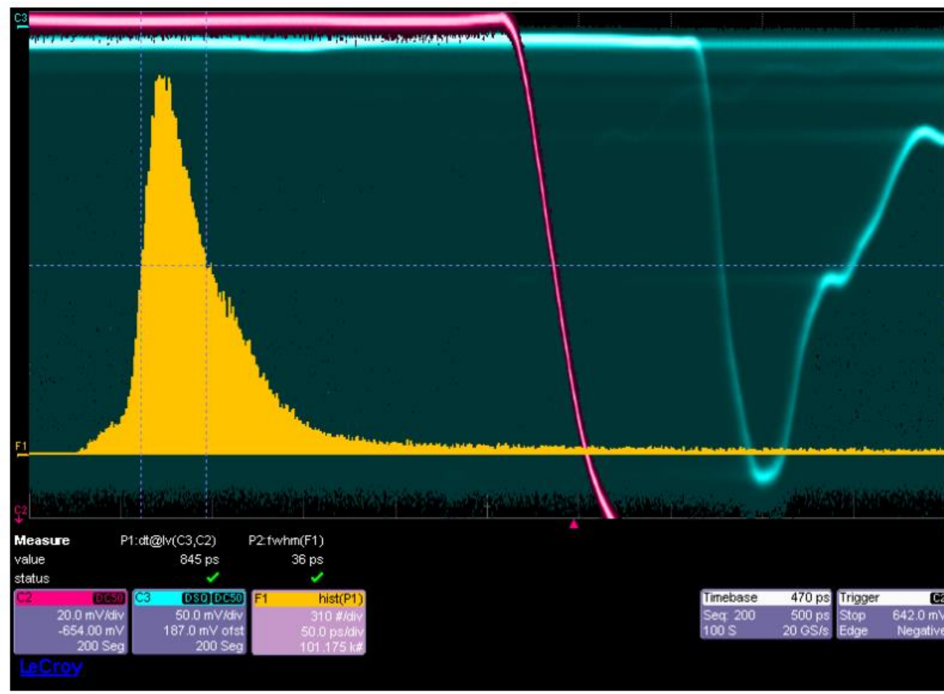
Typical SPTR acquisition



<u>A SPAD SPTR acquisition</u>

- time delay between the SPAD output (pink) and the ref. signal (blue)
- histogram building (100k events)
- FWHM extract

$$\sigma^2_{\text{mesured}} = \sigma^2_{\text{setup}} + \sigma^2_{\text{detector}}$$

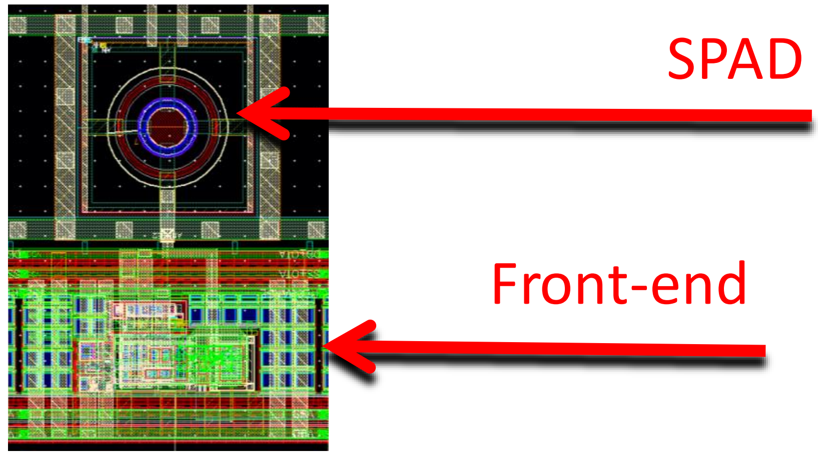


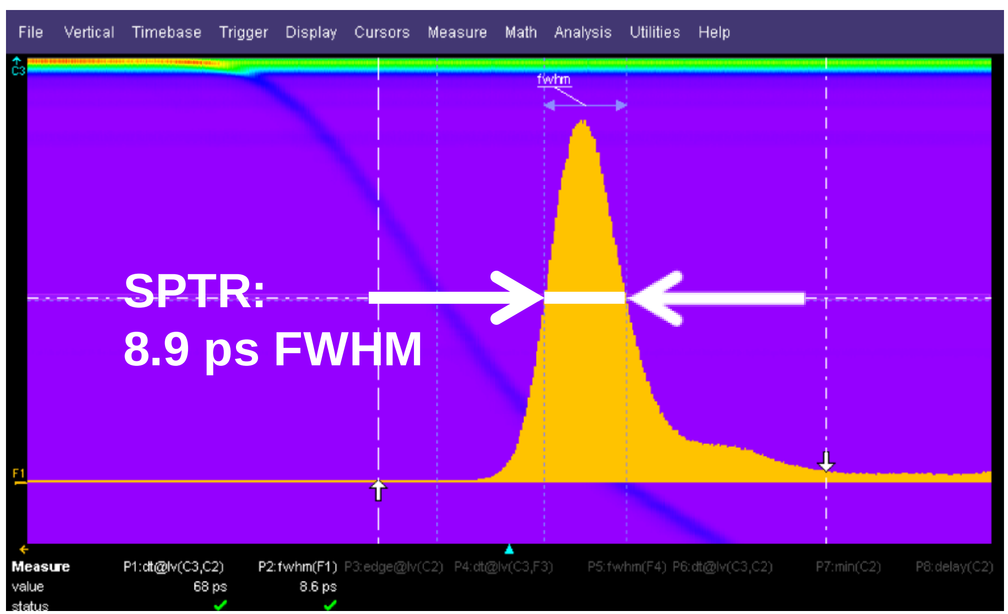
<u>Setup jitter</u>

- PIN ref diode pulse to pulse jitter
- include electronic jitter (SMA, scope)
- include Mai Tai / OPO pulse to pulse jitter (negligible)
- Value : 3-4 ps FWHM

SPAD + front-end SPTR

- TSMC 65 nm
- SPAD implemented for test purpose (and fun)
- 20 µm diameter





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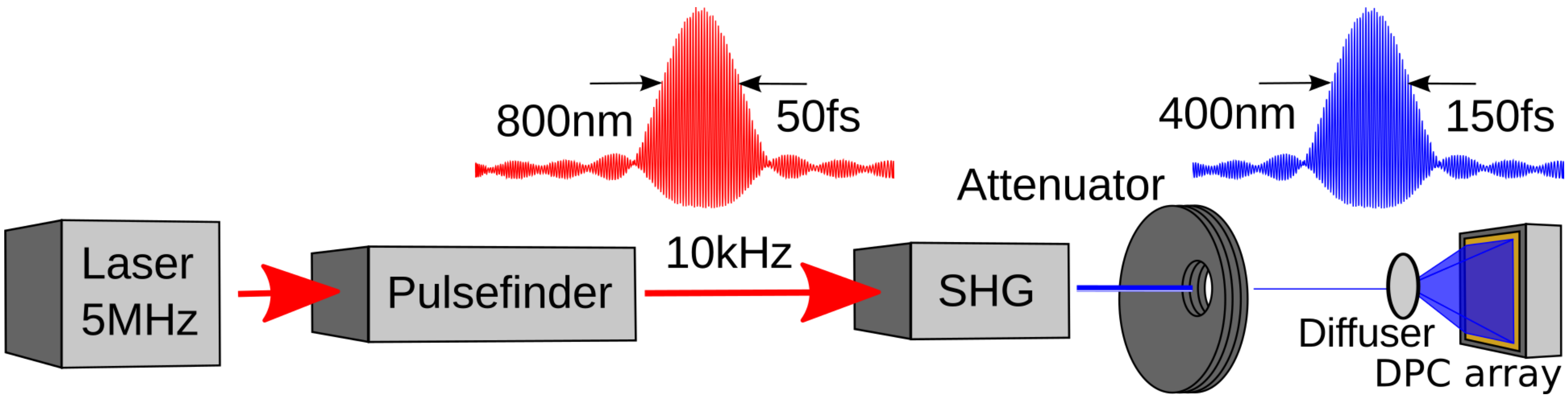
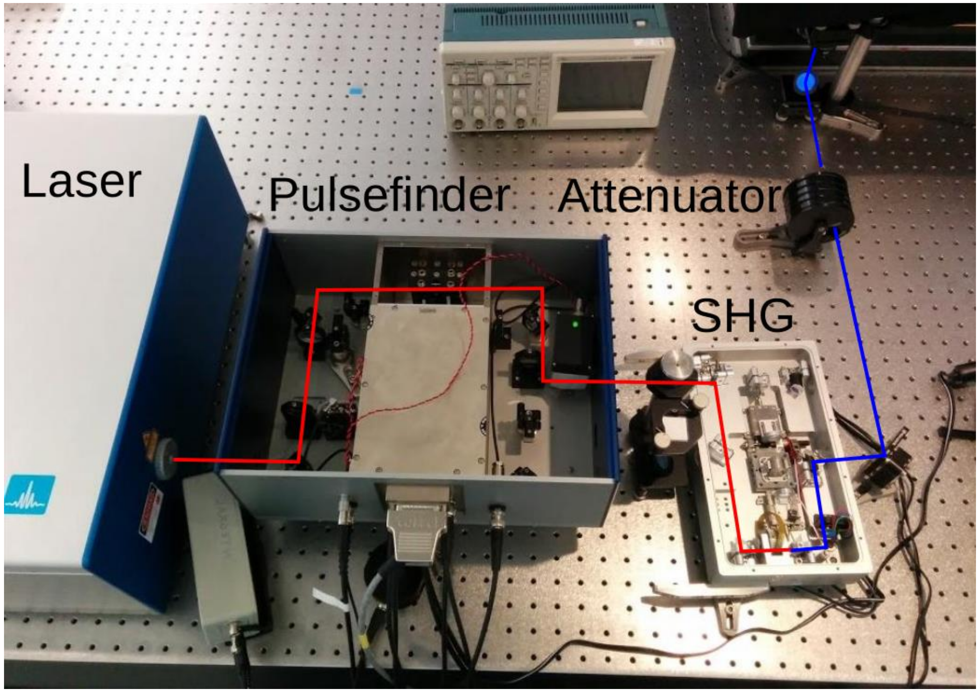
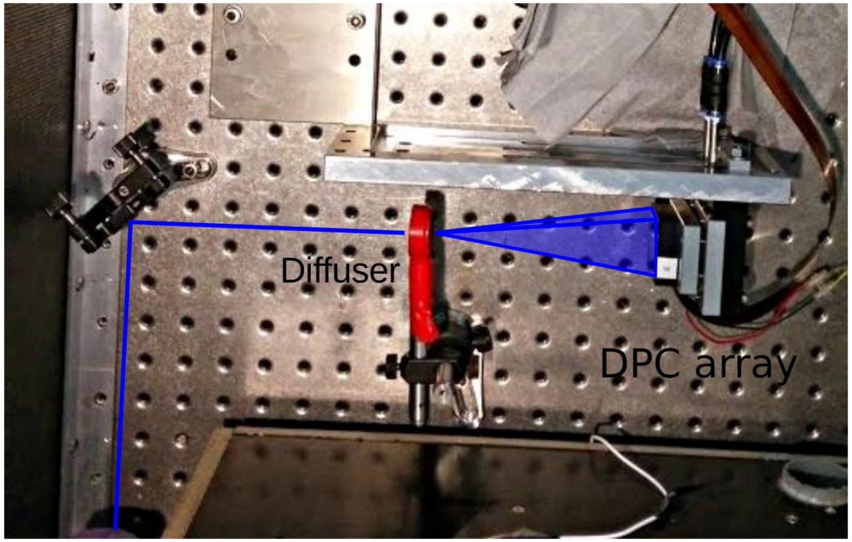
DPC SPTR (measurement setup)







S. Brunner et al., JINST 2016

DPC SPTR (results)

DPC	Active area	Temp. [°C]	Inactive cells [%]	SPTR FWHM [ps]	System TR FWHM [ps]
3200	die	0	0	187 $\pm$5.9	47 $\pm$1.9
3200	die	0	20	168 $\pm$3.0	42 $\pm$0.8
3200	die	0	50	153 $\pm$2.3	45 $\pm$0.6
3200	pixel	10	20	101 $\pm$2.8	16 $\pm$2.4
3200	pixel	20	20	113 $\pm$3.5	14 $\pm$3.1
6400	die	0	20	247 $\pm$3.0	40 $\pm$0.4

S. Brunner et al., JINST 2016

DPC SPTR (results)

DPC	Active area	Temp. [°C]	Inactive cells [%]	SPTR FWHM [ps]	System TR FWHM [ps]
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3200	pixel	10	20	101 ±2.8	16 ±2.4
3200	pixel	20	20	113 ±3.5	14 ±3.1
6400	die	0	20	247 ±3.0	40 ±0.4

Temperature °C

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DPC SPTR (results)

DPC	Active area	Temp. [°C]	Inactive cells [%]	SPTR FWHM [ps]	System TR FWHM [ps]
3200	die	0	0	187 ±5.9	47 ±1.9
3200	die	0	20	168 ±3.0	42 ±0.8
3200	die	0	50	153 ±2.3	45 ±0.6
3200	pixel	10	20	101 ±2.8	16 ±2.4
3200	pixel	20	20	113 ±3.5	14 ±3.1
6400	die	0	20	247 ±3.0	40 ±0.4

Active area

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DPC SPTR (results)

DPC	Active area	Temp. [$^\circ$C]	Inactive cells [%]	SPTR FWHM [ps]	System TR FWHM [ps]
3200	die	0	0	187 ±5.9	47 ±1.9
3200	die	0	20	168 ±3.0	42 ±0.8
3200	die	0	50	153 ±2.3	45 ±0.6
3200	pixel	10	20	101 ±2.8	16 ±2.4
3200	pixel	20	20	113 ±3.5	14 ±3.1
6400	die	0	20	247 ±3.0	40 ±0.4

Masking level

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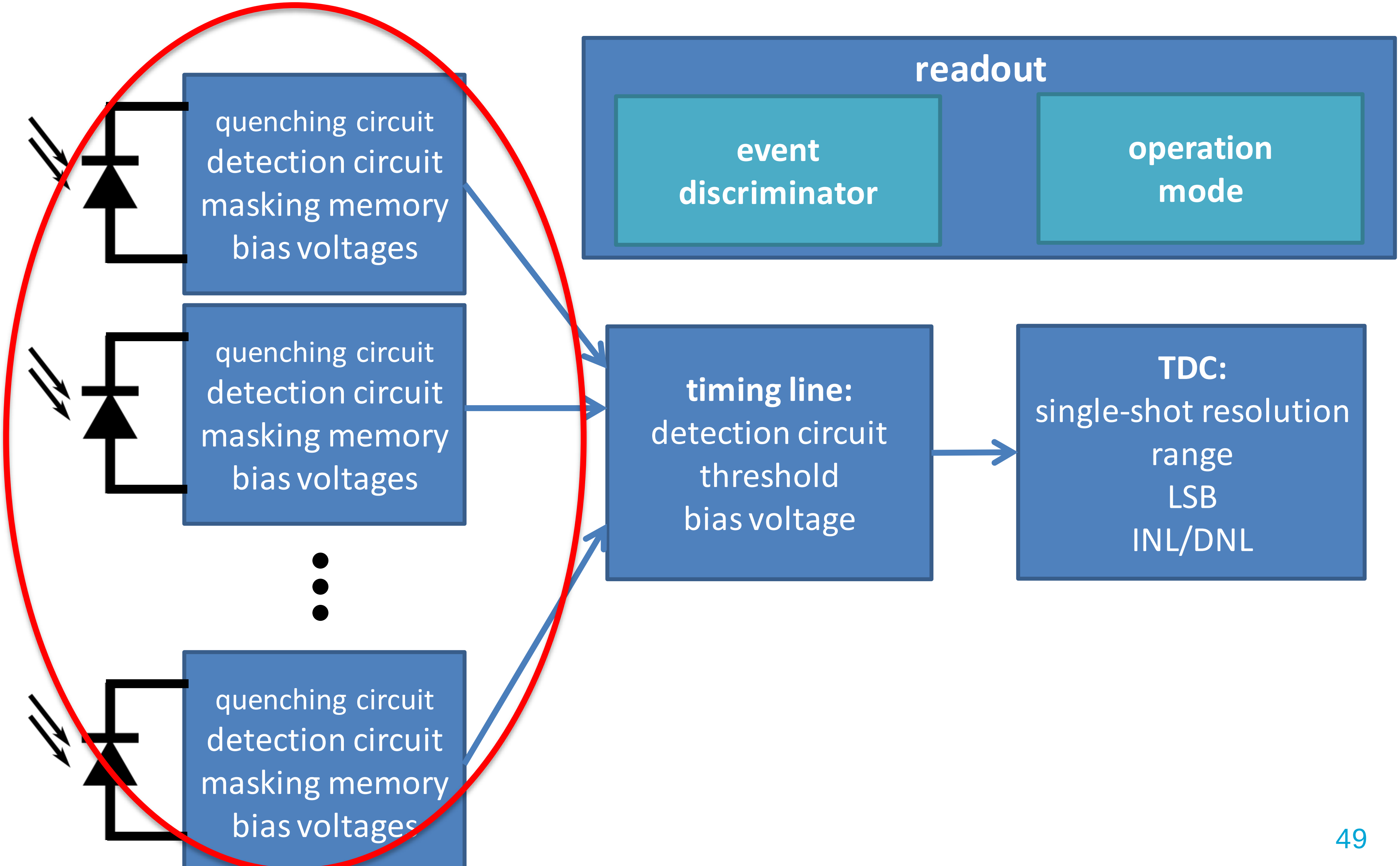
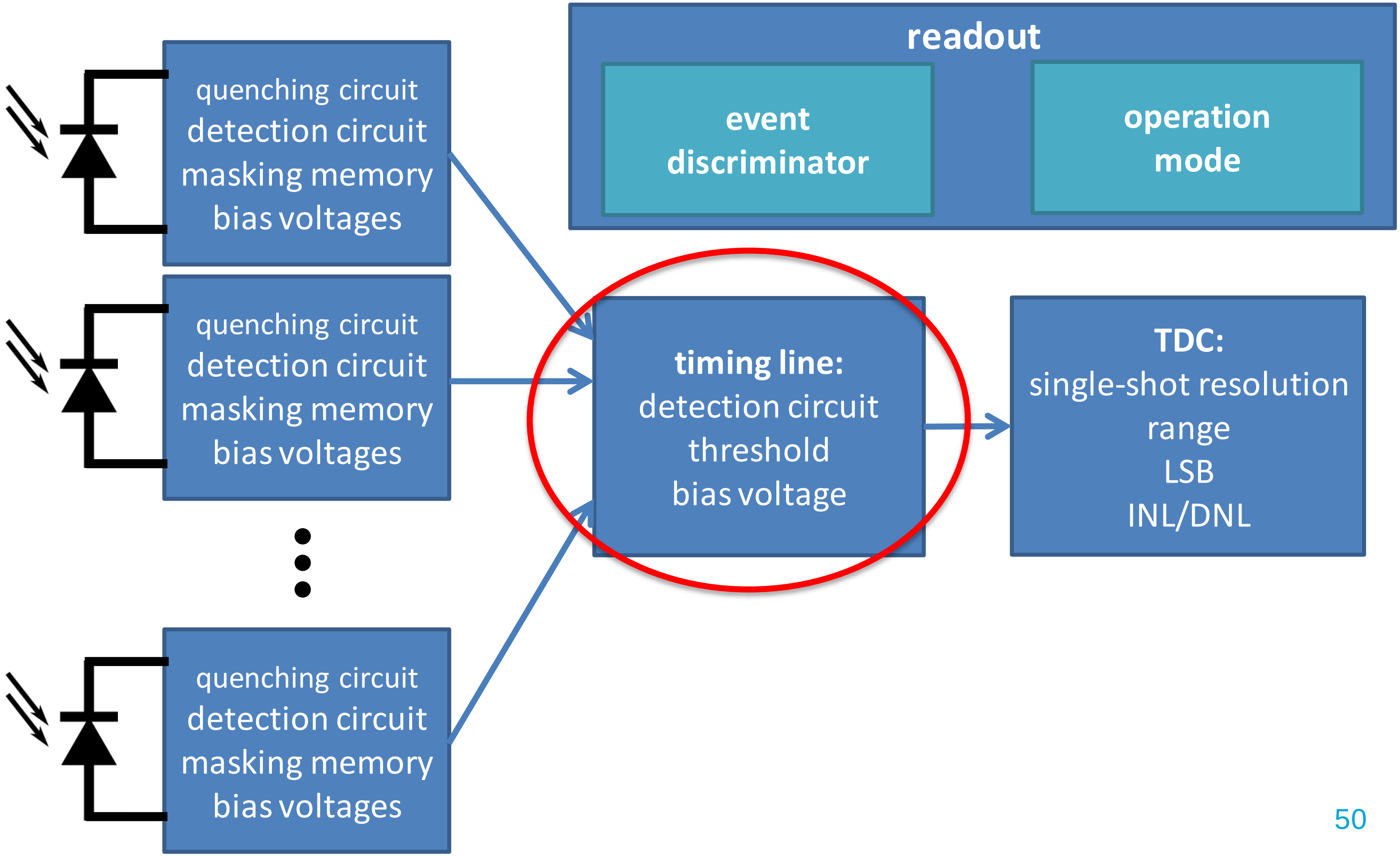
Parameters and standardization

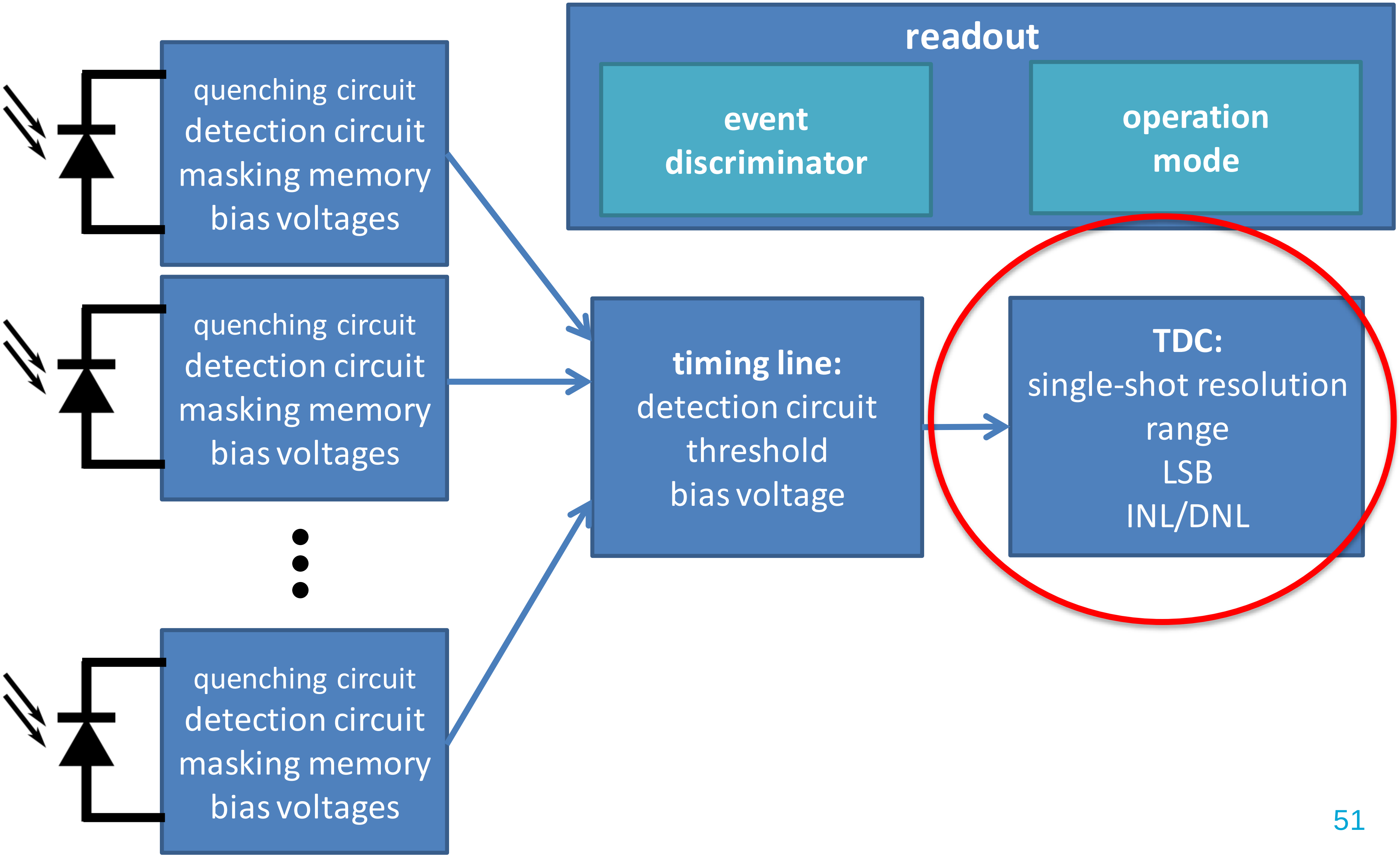
Timing propagation (architecture)



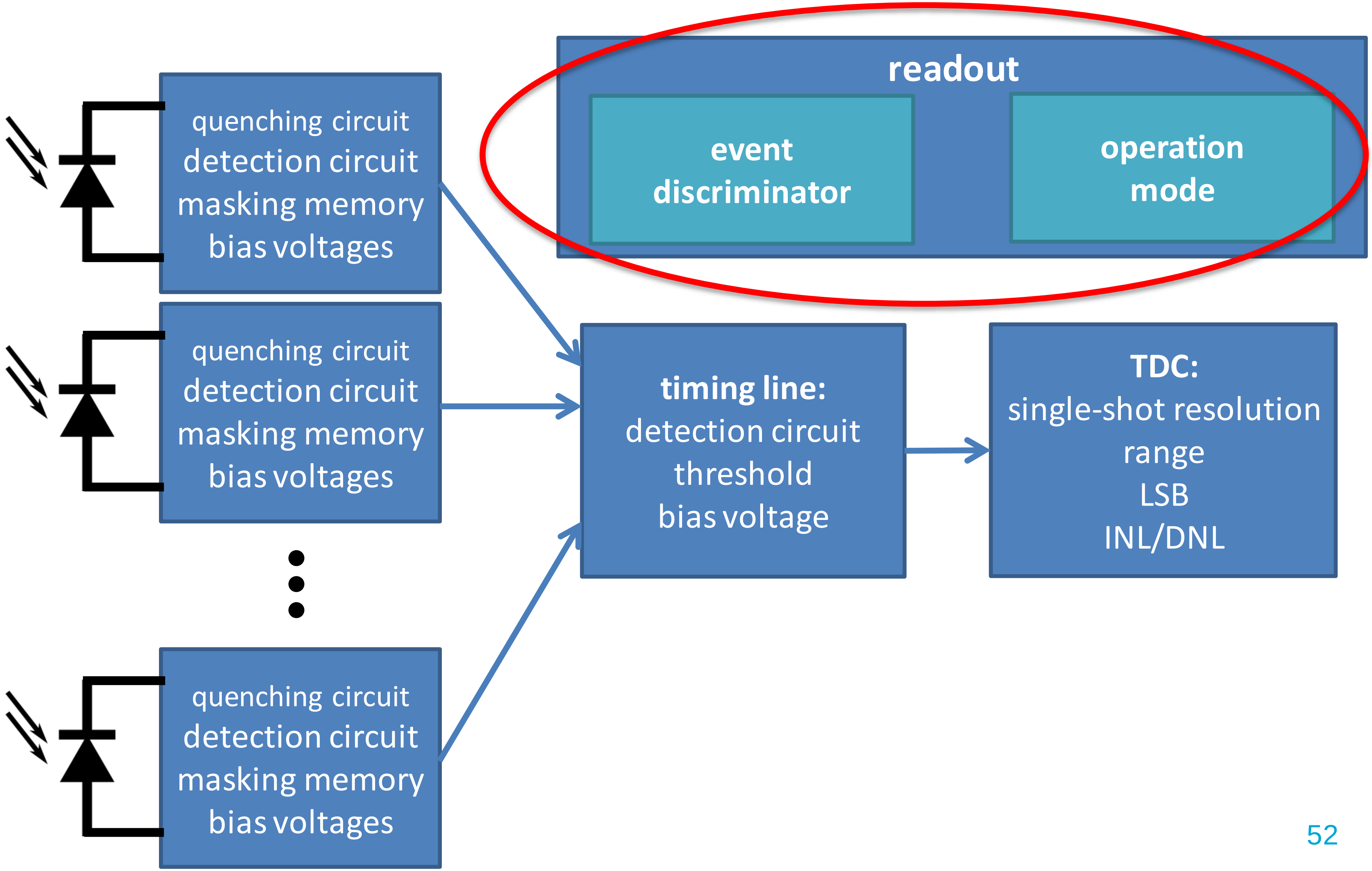
Timing propagation (architecture)



Timing propagation (architecture)



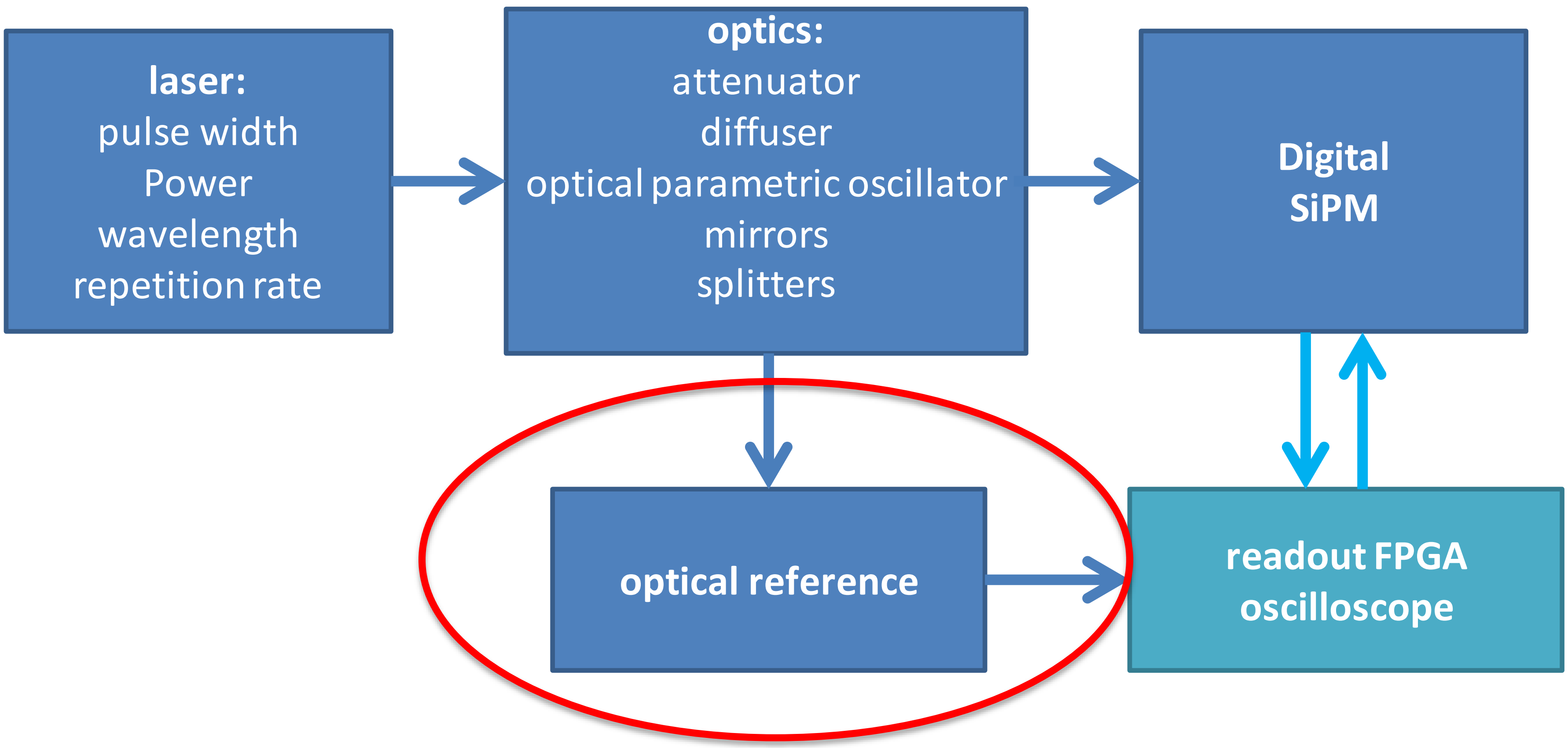
Timing propagation (architecture)



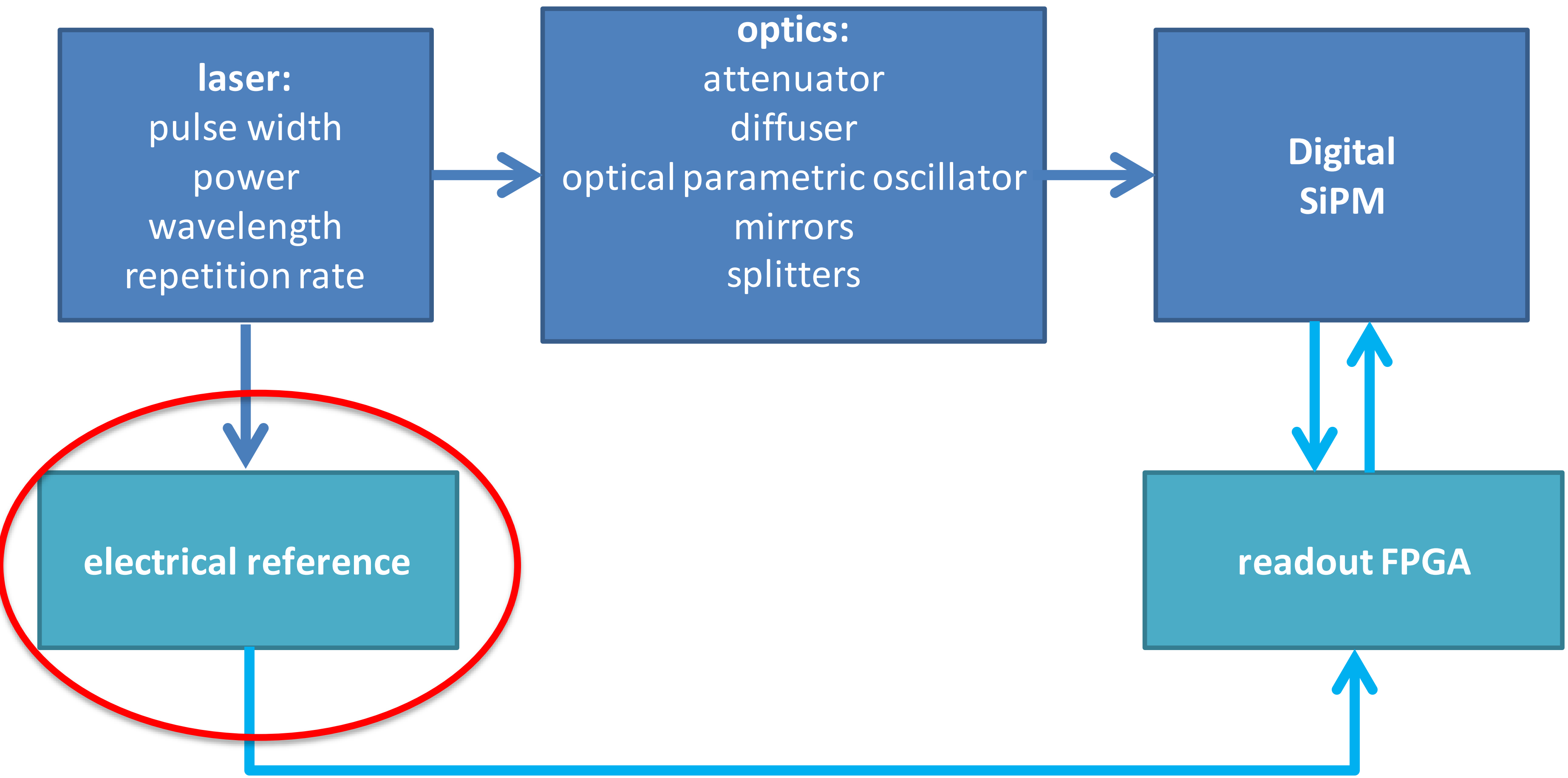
Common architectural components

- Time-to-digital converters (LSB, INL, DNL, SSR)
  - several TDCs: best, worst, and median
- Operation mode
  - event discriminator, triggering system, reset system, measurement range
- SPAD-cell operation
  - masking [%], excess bias, quenching, TH, activated area
- Timing line settings and characterization
  - inverter, comparator TH, preamplifier

Timing measurement (setup)



Timing measurement (setup)



Common setup components

- Optical components
  - light attenuator (SPAD rate, single-photon level)
  - light diffuser (uniformity). SPAD camera measurement
  - etc
- Laser system
  - pulse width, wavelength, CLK jitter, repetition rate
- D-SiPM controller and synchronization system with respect to the laser pulse
  - optical/electrical
- Measurement conditions: temperature, power, heatsinks, etc

Conclusions

- Digital SiPM standardization relies on two main aspects: the D-SiPM architecture and the measurement setup
- In a standardization procedure, the common architectural parameters are established and specific features related to timing are also reported.
- The measurement setup can be divided into two types: high timing resolution (<100 ps) and standard timing resolution (>100 ps)

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References

- S. Mandai and E. Charbon, "Multi-channel digital SiPMs: Concept, analysis and implementation," *2012 IEEE Nuclear Science Symposium and Medical Imaging Conference Record (NSS/MIC)*, Anaheim, CA, 2012, pp. 1840-1844. doi: 10.1109/NSSMIC.2012.6551429
- L. H. C. Braga *et al*., "An 8×16-pixel 92kSPAD time-resolved sensor with on-pixel 64ps 12b TDC and 100MS/s real-time energy histogramming in 0.13µm CIS technology for PET/MRI applications," *2013 IEEE International Solid-State Circuits Conference Digest of Technical Papers*, San Francisco, CA, 2013, pp. 486-487. doi: 10.1109/ISSCC.2013.6487826
- T. Frach, G. Prescher, C. Degenhardt, R. de Gruyter, A. Schmitz and R. Ballizany, "The digital silicon photomultiplier — Principle of operation and intrinsic detector performance," *2009 IEEE Nuclear Science Symposium Conference Record (NSS/MIC)*, Orlando, FL, 2009, pp. 1959-1965. doi: 10.1109/NSSMIC.2009.5402143
- Bérubé, Benoit-Louis, et al. Development of a single photon avalanche diode (SPAD) array in high voltage CMOS 0.8 µm dedicated to a 3D integrated circuit (3DIC). In: *Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC), 2012 IEEE*. IEEE, 2012. p. 1835-1839.
- BRUNNER, S. E., et al. A comprehensive characterization of the time resolution of the Philips Digital Photon Counter. *Journal of Instrumentation*, 2016, 11.11: P11004.
- A. Carimatto *et al*., "11.4 A 67,392-SPAD PVTB-compensated multi-channel digital SiPM with 432 column-parallel 48ps 17b TDCs for endoscopic time-of-flight PET," *2015 IEEE International Solid-State Circuits Conference - (ISSCC) Digest of Technical Papers*, San Francisco, CA, 2015, pp. 1-3. doi: 10.1109/ISSCC.2015.7062996
- FISHBURN, Matthew W.; CHARBON, Edoardo. System tradeoffs in gamma-ray detection utilizing SPAD arrays and scintillators. *IEEE Transactions on Nuclear Science*, 2010, 57.5: 2549-2557.
- SEIFERT, Stefan; VAN DAM, Herman T.; SCHAART, Dennis R. The lower bound on the timing resolution of scintillation detectors. *Physics in Medicine & Biology*, 2012, 57.7: 1797.
- VENIALGO, Esteban, et al. Time estimation with multichannel digital silicon photomultipliers. *Physics in Medicine & Biology*, 2015, 60.6: 2435.