Traceable Calibration of Silicon Single Photon Avalanche Diodes Using Synchrotron Radiation

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Outline

- **Electron storage rings as radiation sources with high dynamic range of the spectral radiant power
– the Metrology Light Source (MLS) of PTB**

- **Traceable calibration of Single Photon Avalanche Diodes (SPADs) using synchrotron radiation**

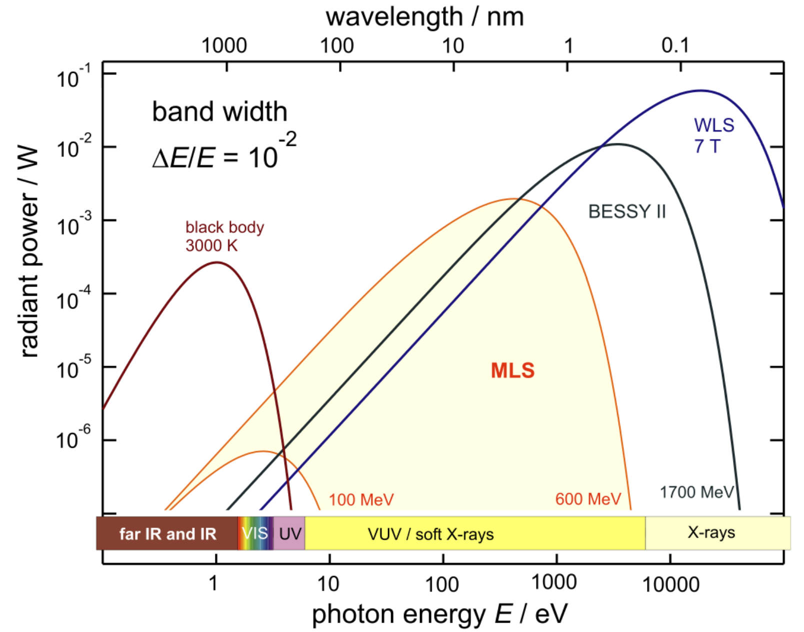
- **Outlook**

Important property of synchrotron radiation

- For *N* electrons

$$\Phi_{\lambda}^{\text{Schwinger}}(\lambda, N_{e^-}) = N_{e^-}\Phi_{e^-,\lambda}^{\text{Schwinger}}(\lambda)(1+\varepsilon(\lambda))$$

(incoherent operation)
Number of stored electrons changes radiant power by 11 orders of magnitude without changing the emitted spectrum

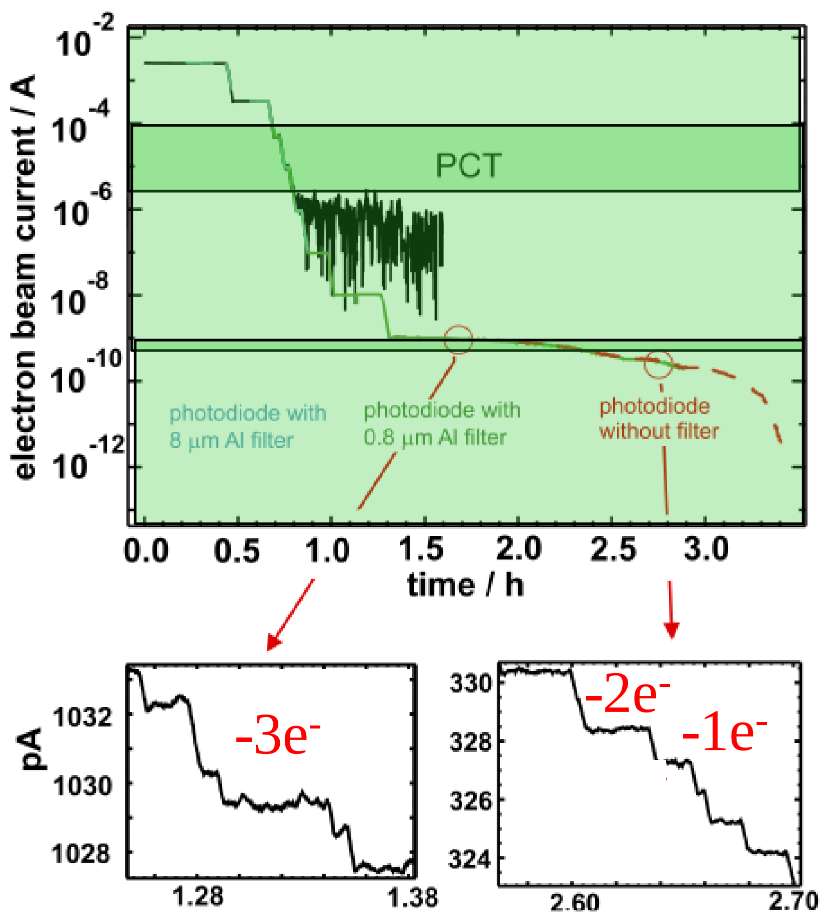


- *ε(λ)* correction for finite vertical source size (at MLS **<u>well below 10^{-4}</u>**)

*Schwinger J 1949 Phys. Rev. **75** 1912

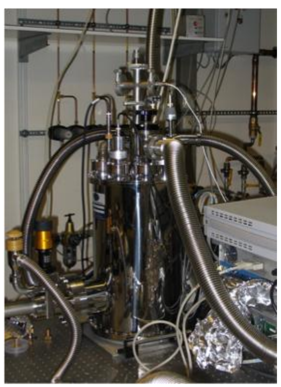
Measurement of the ring current

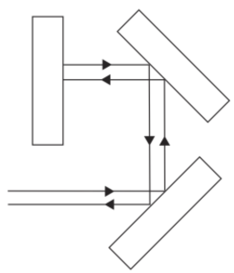
- Ring current range 200 mA to 1 mA
  - parametric current transformators
  - rel. uncertainty $2 \cdot 10^{-4}$
- Ring current range 1 mA to 1 nA
  - windowless Si-photodiodes with Al-filters
  - rel. uncertainty 2%
- Ring current < 1 nA
  - direct counting of electrons by discrete steps due to electron losses



Calibration chain

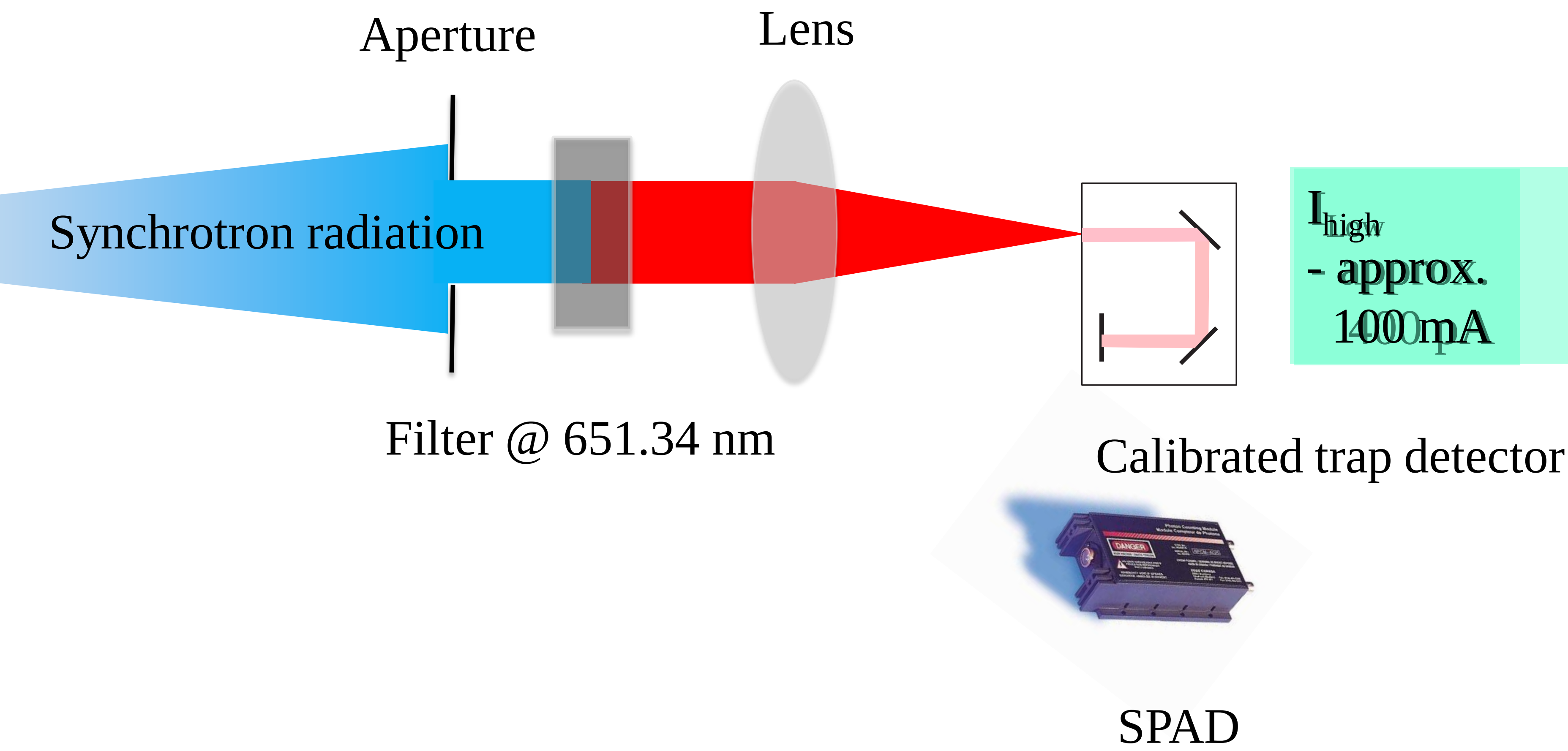
Laser based Cryogenic Radiometer → Trap Detector → Metrology Light Source → SPAD





- Huge dynamic range of the MLS (1 e^- to10^{11} e^- stored)
- Exploitation of the strict proportionality of ringcurrent and emitted radiation

Calibration - setup

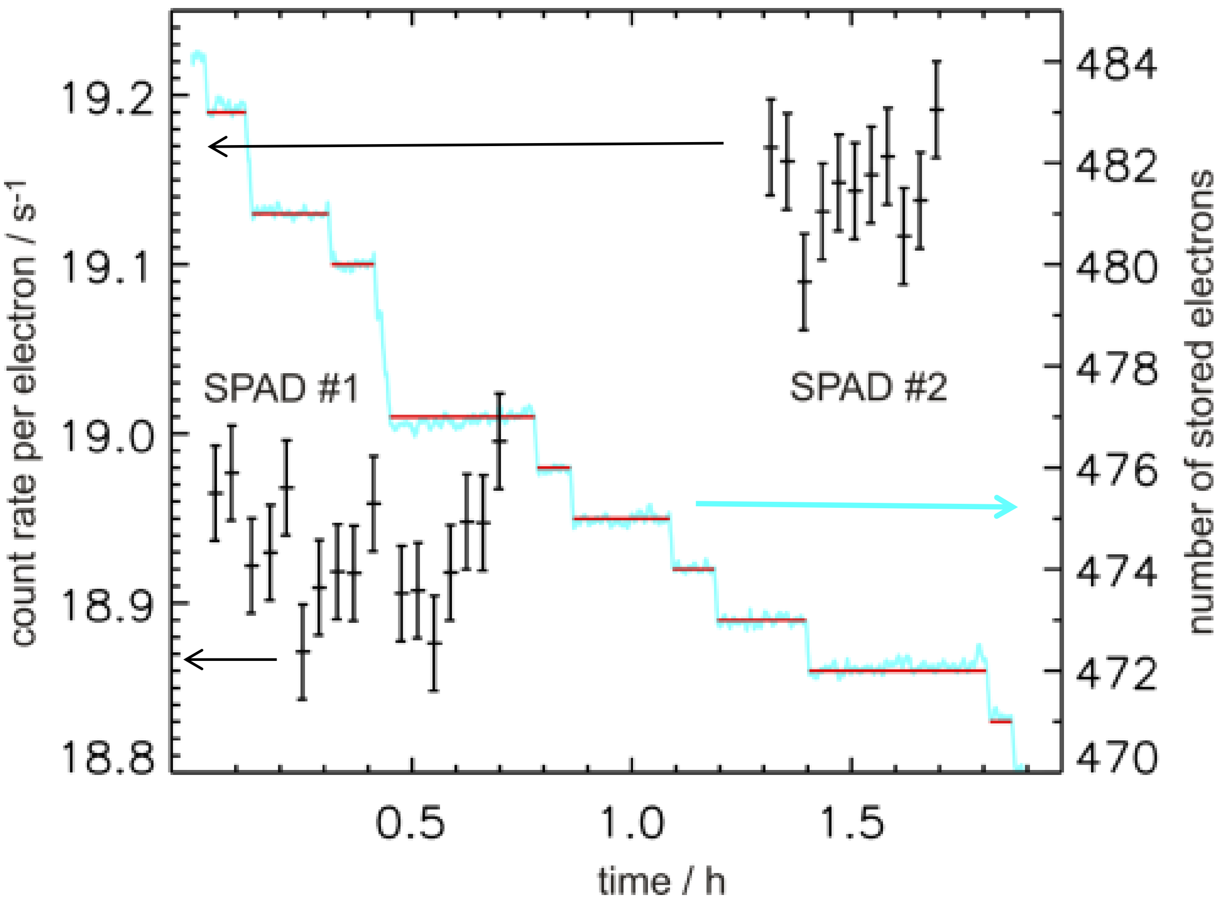


$$photon\ rate_{Trap}\ /\ number\ of\ stored\ electrons\ (I_{high})$$

Calibration – quantum efficiency

$$QE^{*}_{SPAD} = \frac{count\ rate_{SPAD} / number\ of\ stored\ electrons(I_{low})}{photon\ rate_{Trap} / number\ of\ stored\ electrons(I_{high})}$$

Uncorrected quantum efficiency (*QE**)

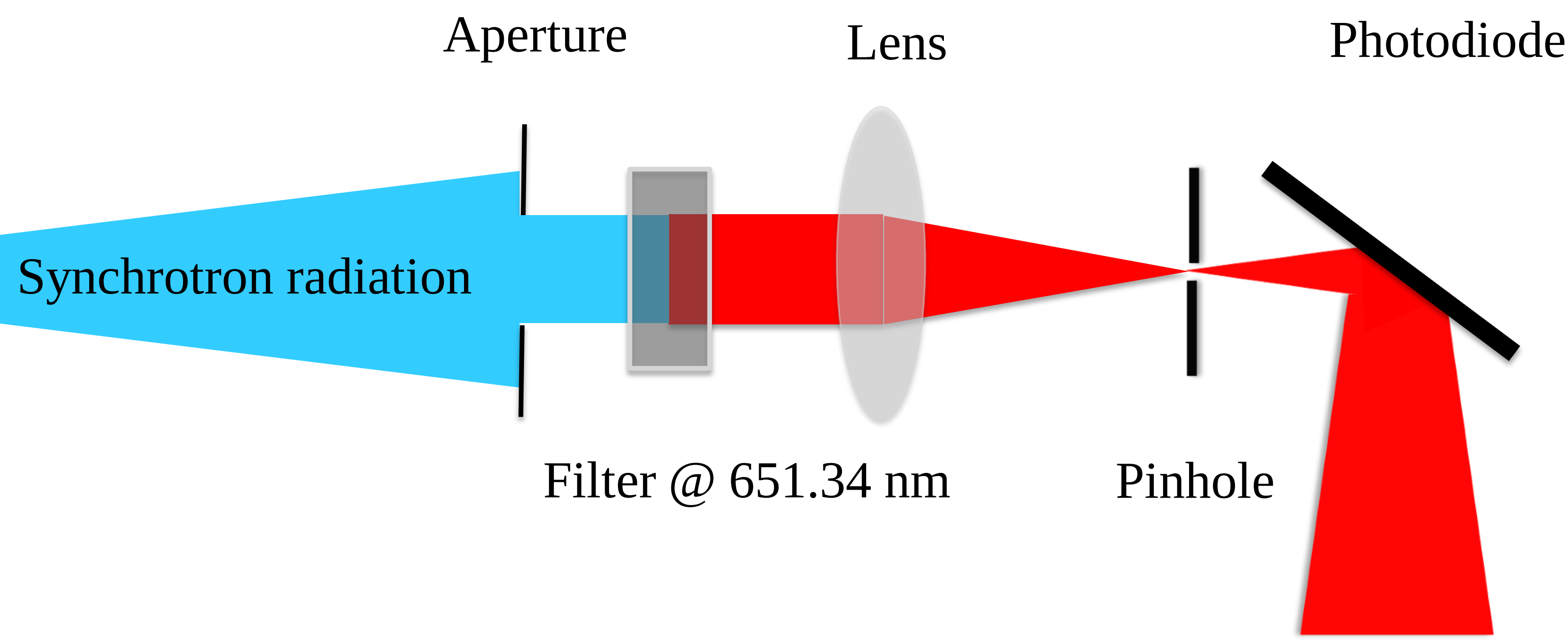


Uncorrected *QE** @ 651.34 nm:
SPAD1: 67.63 %
SPAD2: 68.39 %

Corrections

- **Different detector sizes of SPAD / trap detector**
- **Afterpulsing probability**
- **Bandwidth**
- **Dead time**
- **Photon statistic**

Calibration – detector size correction

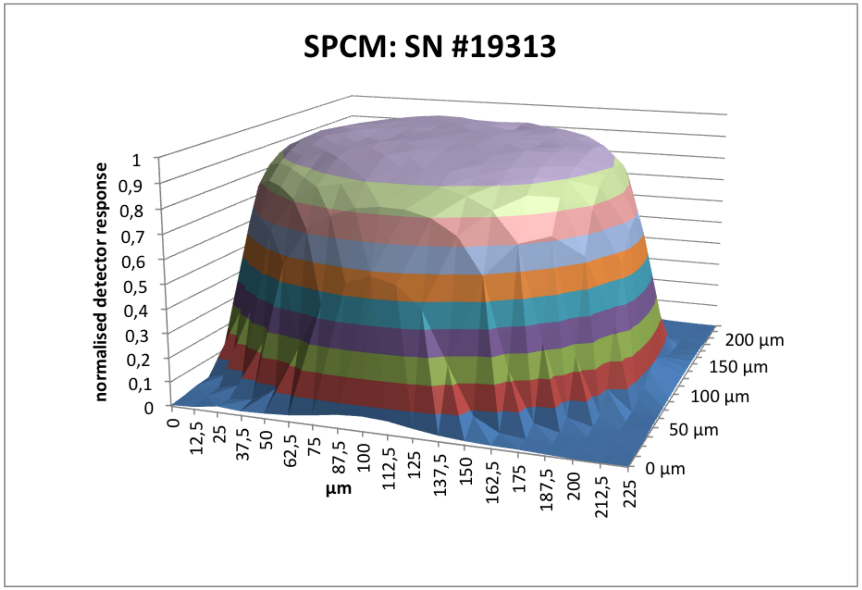


Pinhole Ø	∞	196 µm	149 µm
Losses	0%	3.7%	4.6%

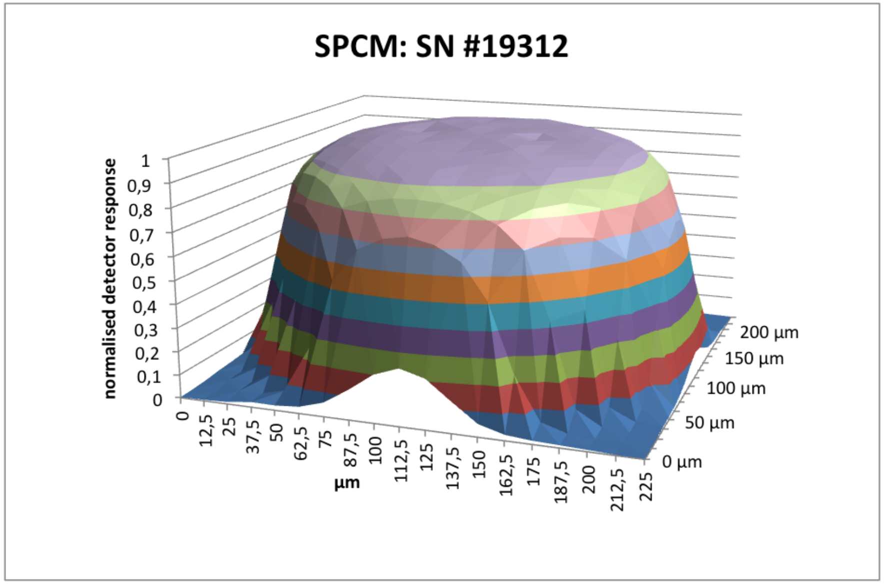
Data sheet: SPAD-diameter approx. 180 µm

Determination detector size SPADs

He-Ne laser @ 633 nm, focus diameter < 15 µm



SPAD1

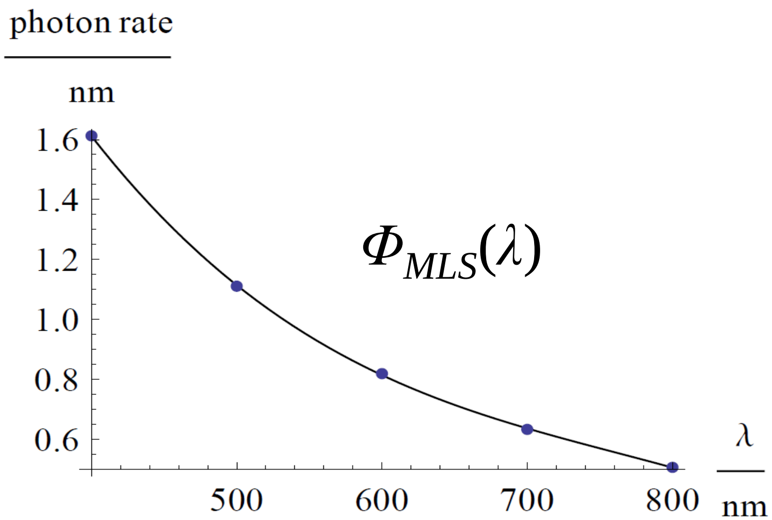


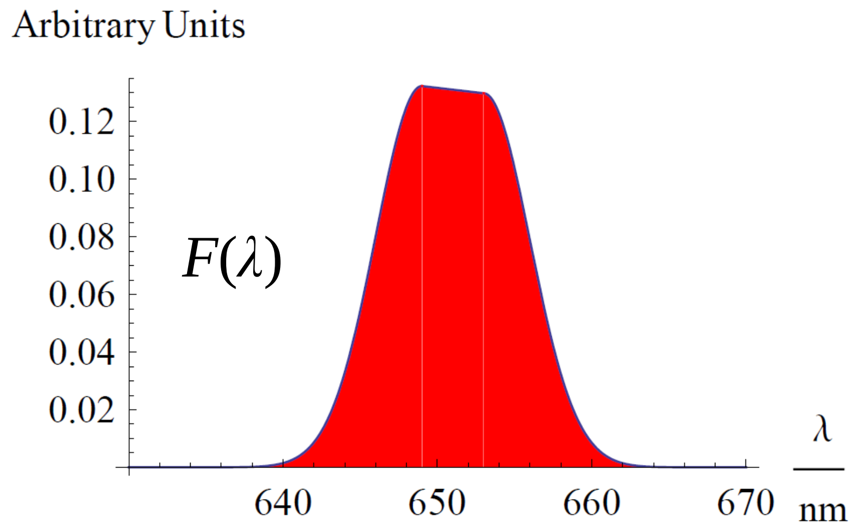
SPAD2

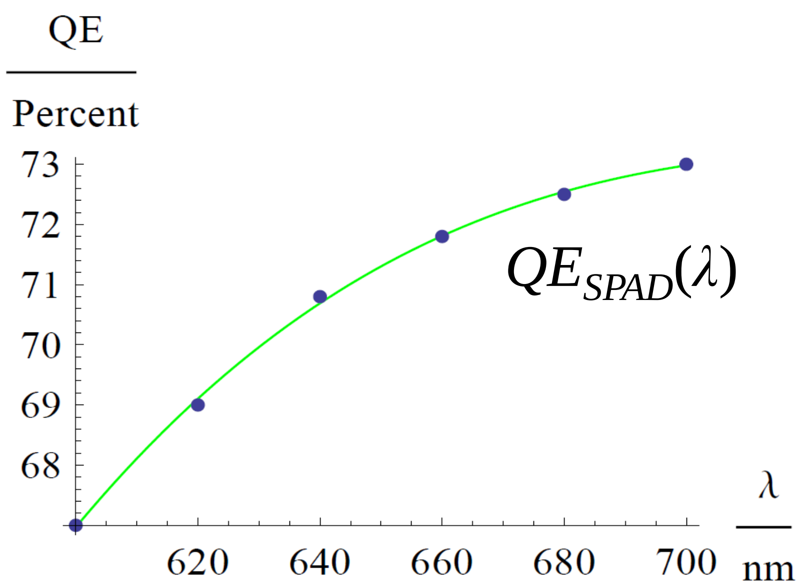
FWHM = 210 µm

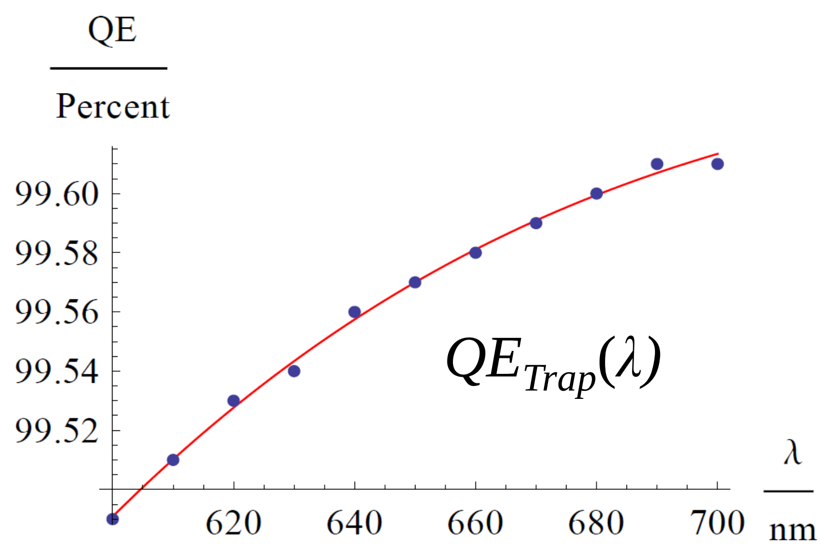
→ Correction factor detector sizes of SPAD and trap detector: 1.035

Bandwidth correction









Bandwidth correction

$$c_{Trap} = \frac{\int_{\lambda} \Phi_{MLS}(\lambda) \cdot F(\lambda) \cdot QE_{Trap}(\lambda) \cdot d\lambda}{QE_{Trap}(651.34nm) \cdot \int_{\lambda} \Phi_{MLS}(\lambda) \cdot F(\lambda) \cdot d\lambda}$$

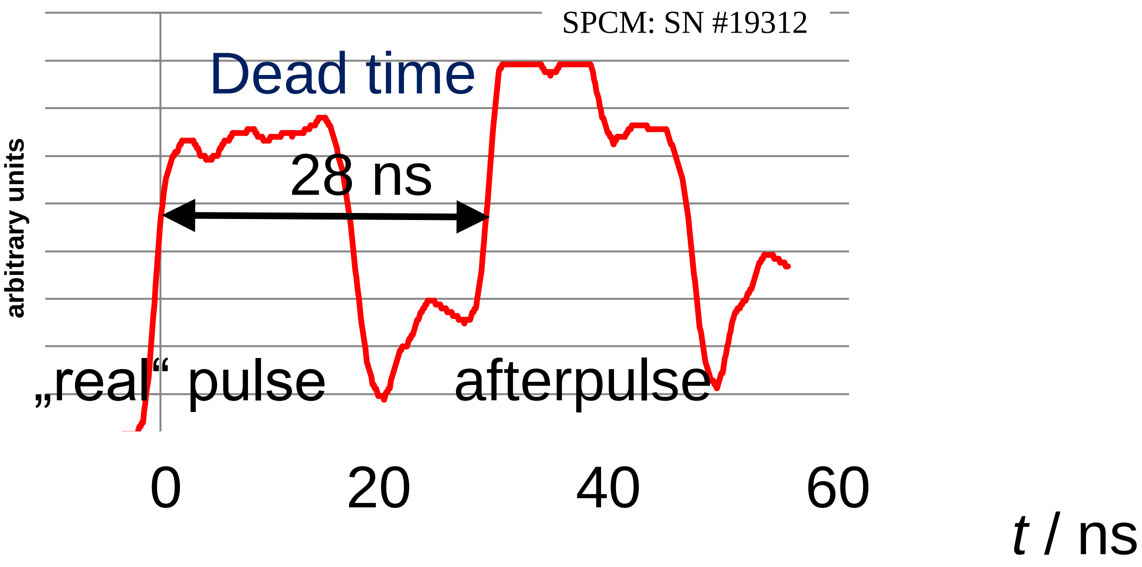
$$c_{SPAD} = \frac{\int_{\lambda} \Phi_{MLS}(\lambda) \cdot F(\lambda) \cdot QE_{SPAD}(\lambda) \cdot d\lambda}{QE_{SPAD}(651.34nm) \cdot \int_{\lambda} \Phi_{MLS}(\lambda) \cdot F(\lambda) \cdot d\lambda}$$

$$c_{BW} = \frac{c_{SPAD}}{c_{Trap}} = 1.0004$$

Afterpulsing and dead time

- Afterpulsing probability
  - 0.14 % (SPAD1)
  - 0.07 % (SPAD2)

- Dead time
  - 28 ns



Uncertainty budget

Source of uncertainty	Correction factor	SPAD1	SPAD2
Count rate/e-		0.049%	0.047%
Ratio photocurrent trap detector to ring current, Type A		0.051%	0.051%
Ringcurrent measurement		0.048%	0.048%
Spectral responsivity		0.045%	0.045%
SPAD-positioning		0.020%	0.020%
Bandwidth	1.0004	0.019%	0.019%
Detector sizes	1.035	0.09%	0.09%
Statistic	1.00018	0.018%	
	1.00018		0.018%
Afterpulsing	0.998571	0.098%	
	0.999333		0.071%
Combined rel. uncertainty		**0.18%**	**0.16%**

Result

	SPAD1	SPAD2
Quantum efficiency @ 651.34 nm	0.6984	0.7069
Relative standard uncertainty	0.18%	0.16%

- First determination of QE of SPADs with synchrotron radiation
- Method works in wide spectral range
- Measurement uncertainties comparable with the two existing methods:
  - SPDC: NIST 0.18%*, NPL 0.3%†
  - Substitution Method: NIST 0.17%*, NPL 0.2%‡

*S. Polyakov and A. Migdall, Optics Express, 15, 1390, 2007, †J. Y. Cheung, Journal of Modern Optics, 54:2-3, 373-396, ‡ JRP qu-Candela

Outlook

PTB

- **Exploitation of method with fiber coupled detectors**
  - EMRP JRP IND-06 „Metrology for Industrial Quantum Communication“
- **Calibrations at telecom wavelengths**
- **Usage of superconducting single photon detectors**

Thank you for your attention