Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin
Nationales Metrologieinstitut

Few photon metrology

Activities at PTB

Stefan Kück

CCPR WG-SP

22 September 2016

Contents

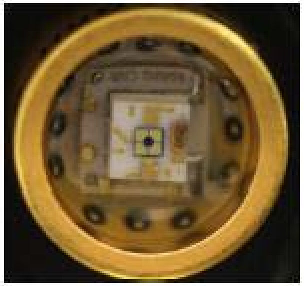
- Calibration of single-photon detectors
    - Si-SPAD
    - InGaAs
    - Superconducting nanowire single-photon detector (SNSPD)
    - Pilot studies
- Single-photon sources
    - Characterization of single-photon sources
    - Absolute single-photon source

Detection efficiency calibration
Motivation

- Single-Photon Detectors important for
  - scientific research:
    - experimental quantum optics
    - quantum cryptography
    - quantum computing
  - medicine
  - biology
  - astrophysics

Single Photon Counting Module

Sensor



$\Rightarrow$ Wherever low photon fluxes need to be measured!

Si-SPAD calibration using synchrotron radiation

IOP PUBLISHING METROLOGIA
Metrologia 49 (2012) S152–S155 doi:10.1088/0026-1394/49/2/S152

Traceable calibration of Si avalanche photodiodes using synchrotron radiation

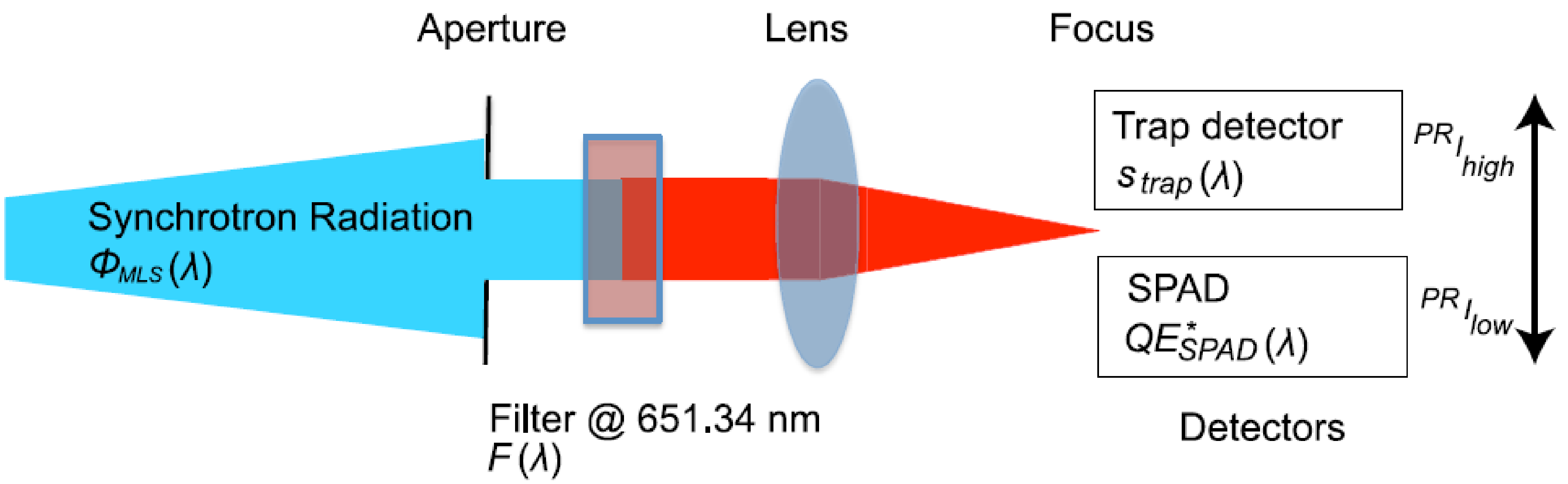
I Müller, R M Klein, J Hollandt, G Ulm and L Werner

Physikalisch-Technische Bundesanstalt (PTB), Abbestr. 2-12, 10587 Berlin, Germany

E-mail: ingmar.mueller@ptb.de

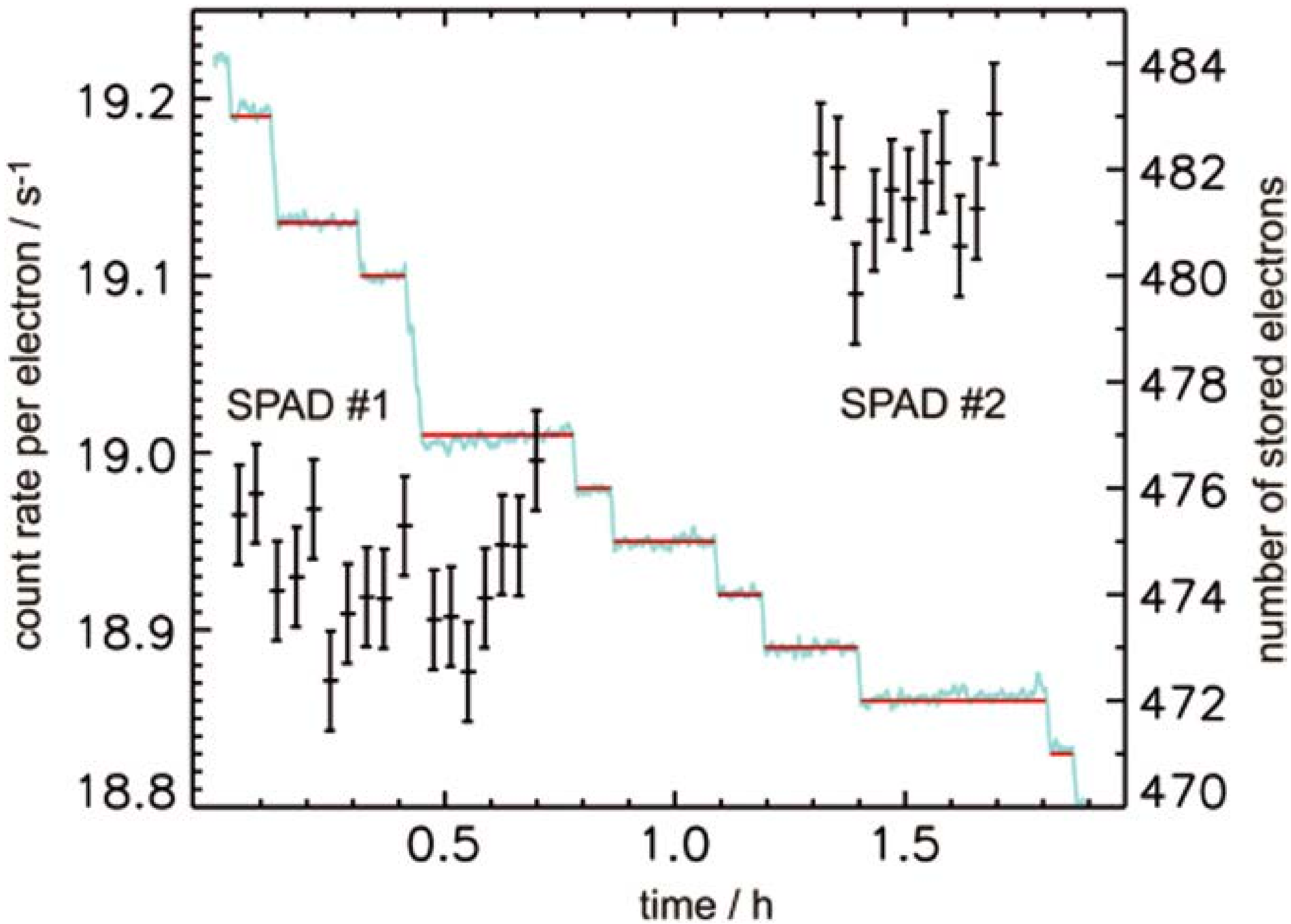
- Synchrotron radiation from Metrology Light Source (MLS) used
- Dynamic range of photon flux: 11 orders of magnitude
  - Mind the gap – bridge the gap!
- Si-SPADs calibrated at 651 nm
- Relative uncertainties of < 0.2 % traceable a cryogenic electrical substitution radiometer

Si-SPAD calibration using synchrotron radiation



I Müller, R M Klein, J Hollandt, G Ulm and L Werner, „ Traceable calibration of Si avalanche photodiodes using synchrotron radiation", Metrologia 49 (2012) S152–S155 doi:10.1088/0026-1394/49/2/S152

Si-SPAD calibration using synchrotron radiation



I Müller, R M Klein, J Hollandt, G Ulm and L Werner, „ Traceable calibration of Si avalanche photodiodes using synchrotron radiation“, Metrologia 49 (2012) S152–S155 doi:10.1088/0026-1394/49/2/S152

Si-SPAD calibration using synchrotron radiation

- Two SPADs have been traceably calibrated against a primary detector standard, the cryogenic electrical substitution radiometer
- $QE_{\mathrm{SPAD1}} = 0.6988 \pm 0.0012$ and $QE_{\mathrm{SPAD2}} = 0.7073 \pm 0.0011$.
- The results show that the uncertainties achieved with this method are of the same size as the SPDC and the substitution method [3].
- This scheme provides an independent method to calibrate SPDs traceable to a cryogenic electrical substitution radiometer at any wavelength in the spectral range of the MLS.

I Müller, R M Klein, J Hollandt, G Ulm and L Werner, „ Traceable calibration of Si avalanche photodiodes using synchrotron radiation“, Metrologia 49 (2012) S152–S155 doi:10.1088/0026-1394/49/2/S152

SNSPD calibration using synchrotron radiation

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Metrologia **51** (2014) S329–S335 doi:10.1088/0026-1394/51/6/S329

Traceable calibration of a fibre-coupled superconducting nano-wire single photon detector using characterized synchrotron radiation

Ingmar Müller, Roman M Klein and Lutz Werner

- Radiometric calibration of a fibre-coupled superconducting nano-wire single photon detector at the telecom wavelength 1.55 µm by means of well-characterized synchrotron radiation is described.
- Very low uncertainties below 2 % have been achieved in the measurement of the detection efficiency of a fibre-coupled superconducting nano-wire single photon detector.

SNSPD calibration using synchrotron radiation

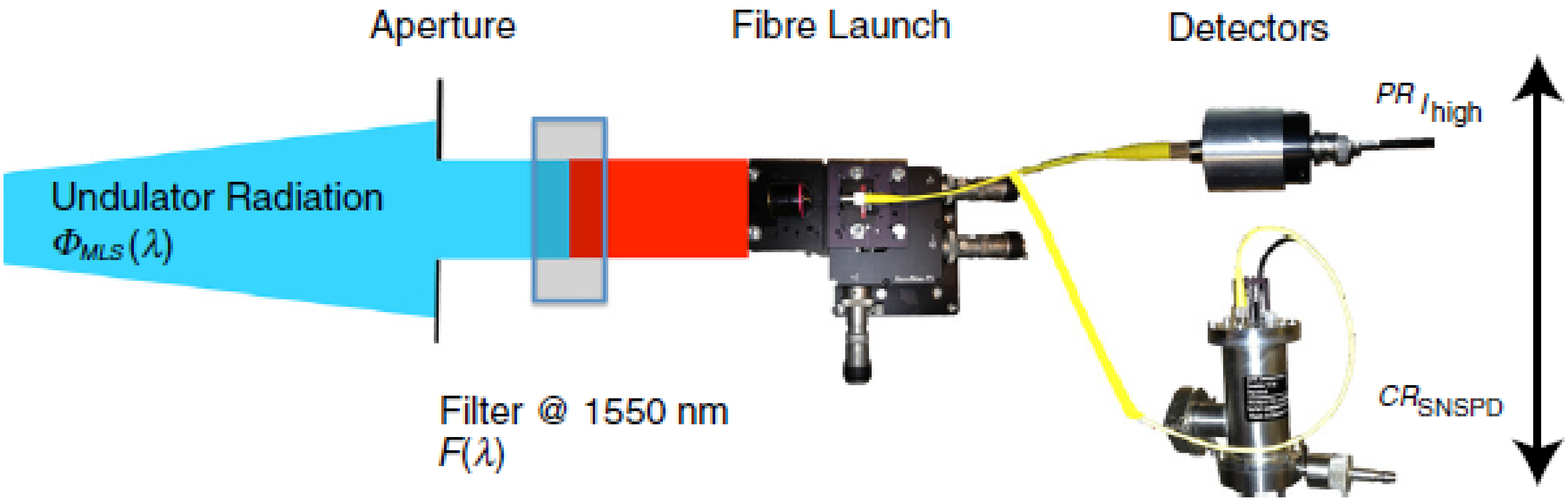


Figure 1. Schematic of the setup used to calibrate a SNSPD. The photon rate (PR_{Ihigh}) in the high ring current range is measured by a calibrated InGaAs reference detector using its known responsivity $S_{IGA}(\lambda)$. In a second step, the count rate of the SNSPD CR_{SNSPD} is measured in the low ring current range. Both detectors are, depending on the ring current, alternately connected to the same optical fibre.

Ingmar Müller, Roman M Klein and Lutz Werner, „Traceable calibration of a fibre-coupled superconducting nano-wire single photondetector using characterized synchrotron radiation“, Metrologia 51 (2014) S329–S335 , doi:10.1088/0026-1394/51/6/S329

SNSPD calibration using synchrotron radiation

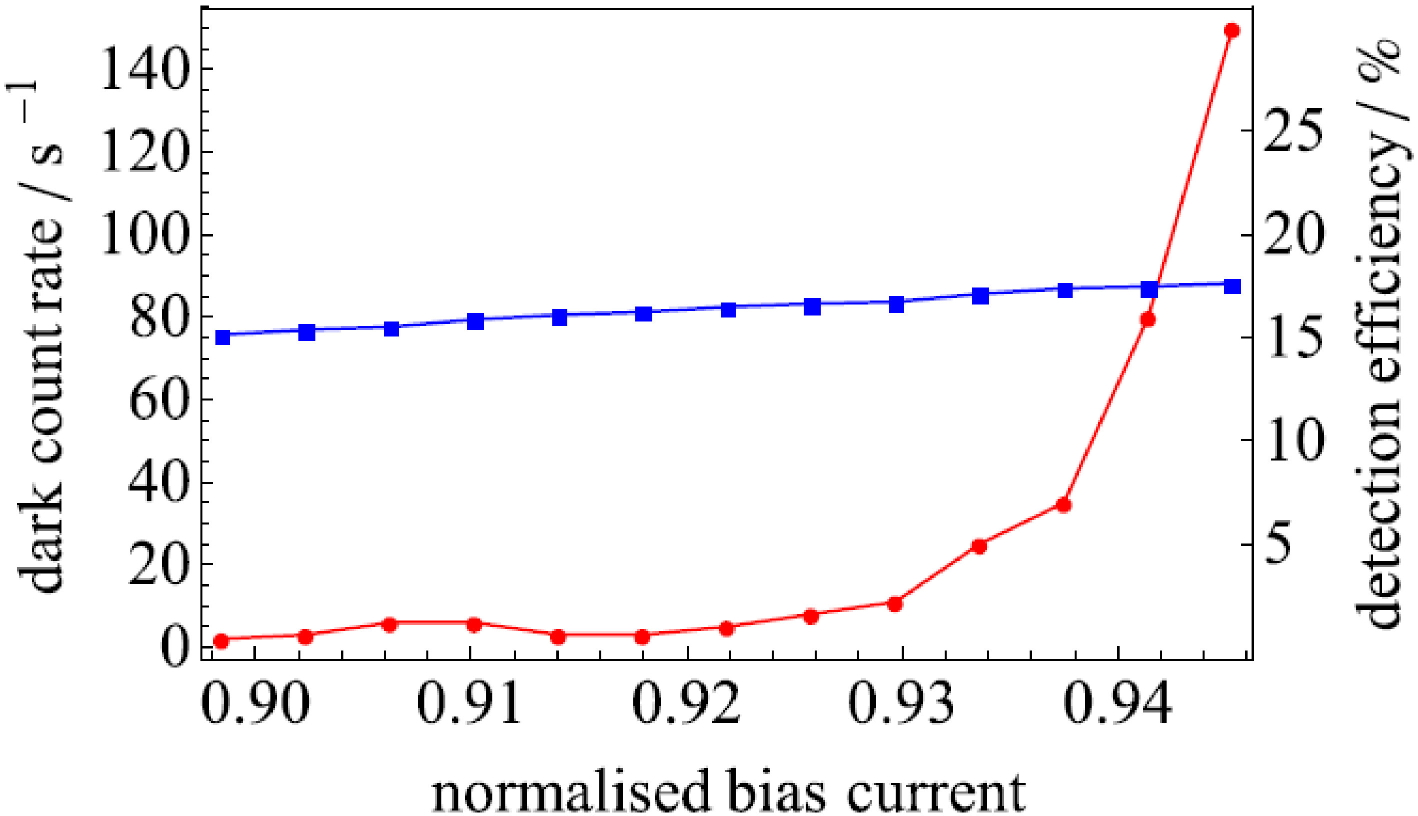


Figure 5. Measured detection efficiency (blue squares) and dark count rate (red circles) of the SNSPD plotted over the bias current normalized to the critical bias current. The uncertainty bars of the measured detection efficiency are about the same size as the blue markers.

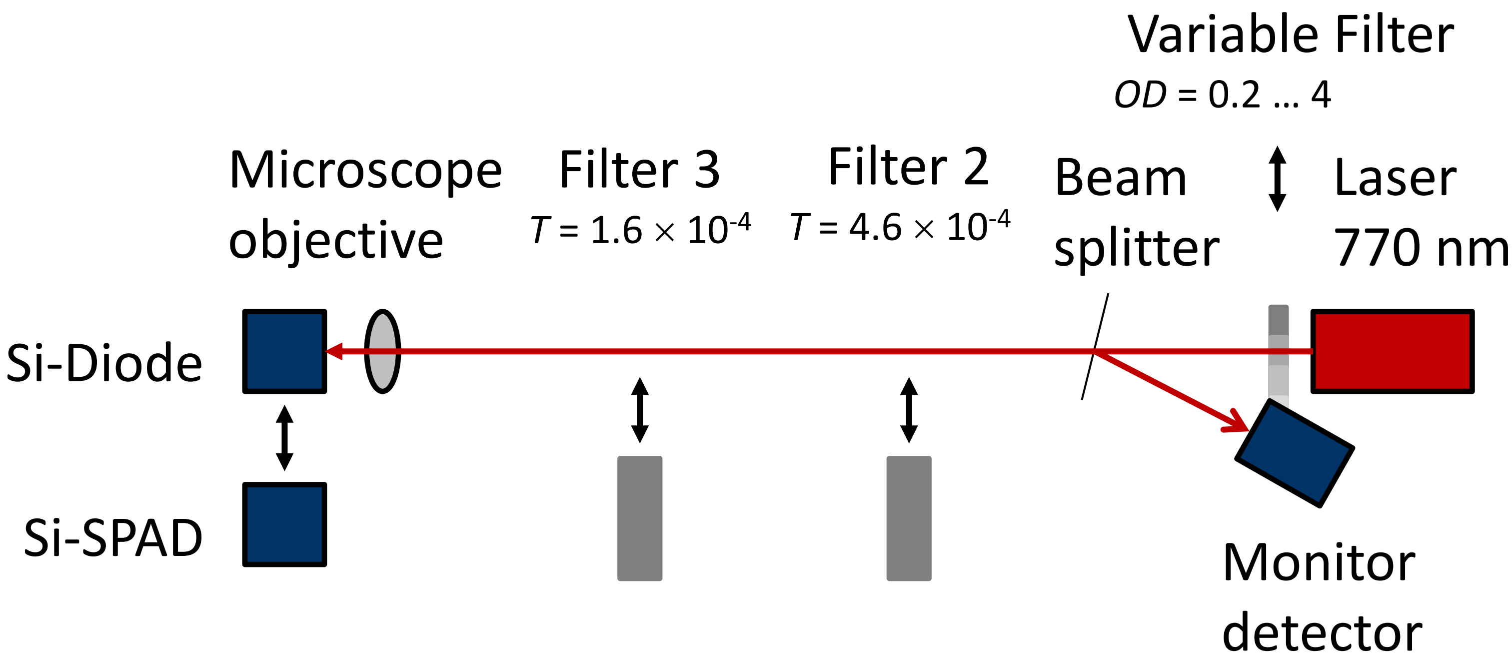
Ingmar Müller, Roman M Klein and Lutz Werner, „Traceable calibration of a fibre-coupled superconducting nano-wire single photondetector using characterized synchrotron radiation“, Metrologia 51 (2014) S329–S335 , doi:10.1088/0026-1394/51/6/S329

SNSPD calibration using synchrotron radiation

- An SNSPD has been calibrated traceable to a primary detector standard, the cryogenic radiometer, by means of the high dynamic range of the radiant power of the undulator radiation.
- The measured detection efficiency is DE_{SNSPD}(1551.97 nm) = 0.1501 ± 0.0028.
- The Metrology Light Source was used to bridge the gap in the radiant power needed to operate the classical reference detectors with low uncertainties and the photon flux that allowed low uncertainty measurements with the SNSPD.

Ingmar Müller, Roman M Klein and Lutz Werner, „Traceable calibration of a fibre-coupled superconducting nano-wire single photondetector using characterized synchrotron radiation“, Metrologia 51 (2014) S329–S335 , doi:10.1088/0026-1394/51/6/S329

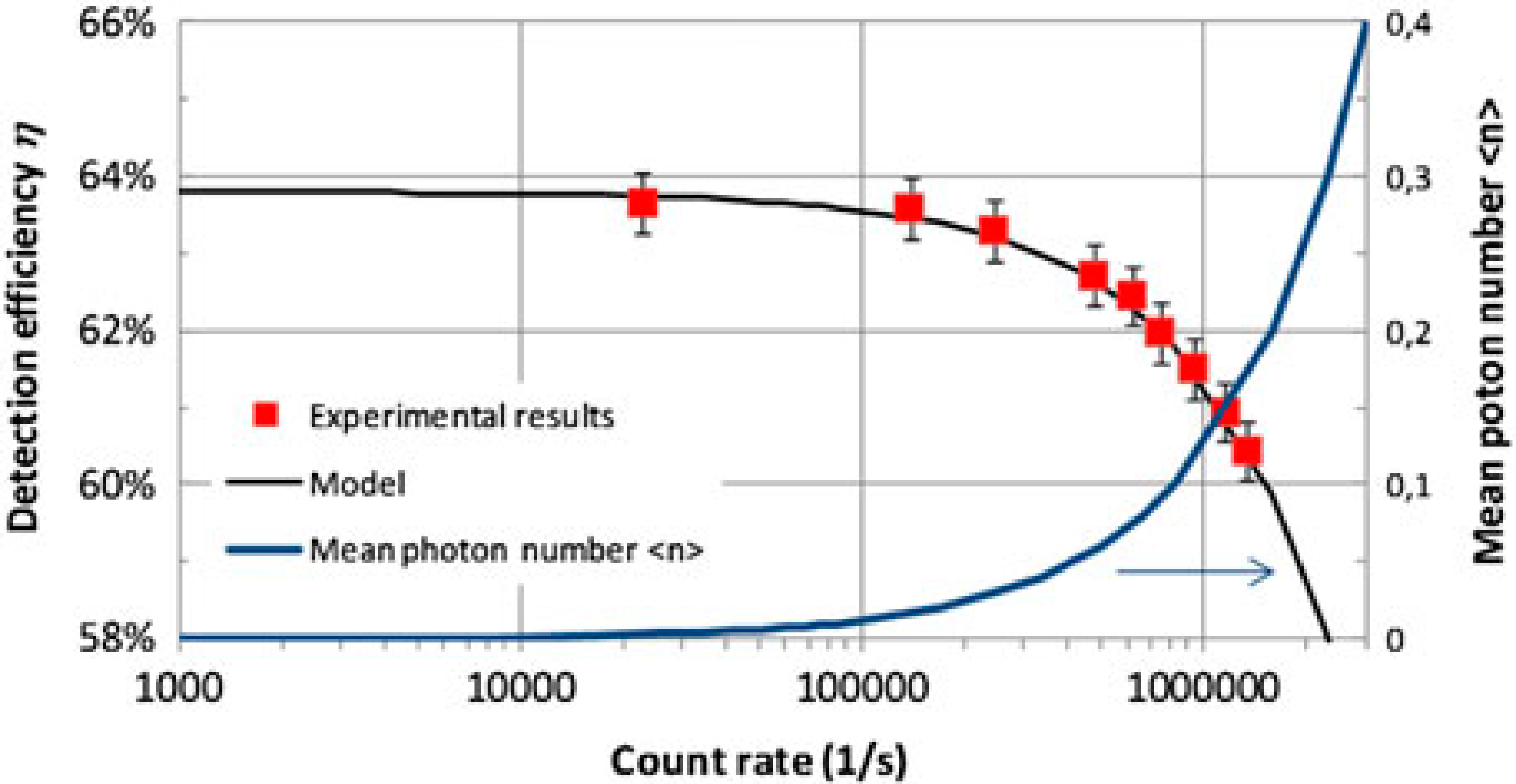
Si-SPAD calibration using double attenuator technique



$$\eta = \frac{hc}{\lambda}\frac{A_2 A_3}{A_1}\frac{\left. V_1 \middle/ V_{\mathrm{Mon1}} \right. \; \left. CR \middle/ V_{\mathrm{Mon4}} \right.}{\left. V_2 \middle/ V_{\mathrm{Mon2}} \right. \; \left. V_3 \middle/ V_{\mathrm{Mon3}} \right.} s_{Si} F_{\mathrm{filt}} = \frac{hc}{\lambda}\frac{A_2 A_3}{A_1}\frac{Q_1 Q_4}{Q_2 Q_3} s_{Si} F_{\mathrm{filt}}$$

M. López, H. Hofer, S. Kück, “Detection efficiency calibration of single-photon silicon avalanche photodiodes traceable using double attenuator technique, Journal of Modern Optics 62, S21 – S27 (2015), http://dx.doi.org/10.1080/09500340.2015.1021724.

Detection efficiency – influence of photon statistics



Detection efficiency:

$$\eta = \eta_0 \frac{1-\exp\left(-\eta_0 \langle n \rangle\right)}{\langle n \rangle}$$

Count rate at SPAD:

$$CR = \frac{1-\exp\left(-\eta_0 \langle n \rangle\right)}{t_{\text{dead}}}$$

M. López, H. Hofer, S. Kück, "Detection efficiency calibration of single-photon silicon avalanche photodiodes traceable using double attenuator technique, Journal of Modern Optics 62, S21 – S27 (2015), http://dx.doi.org/10.1080/09500340.2015.1021724.

Measurement uncertainty budget – main components

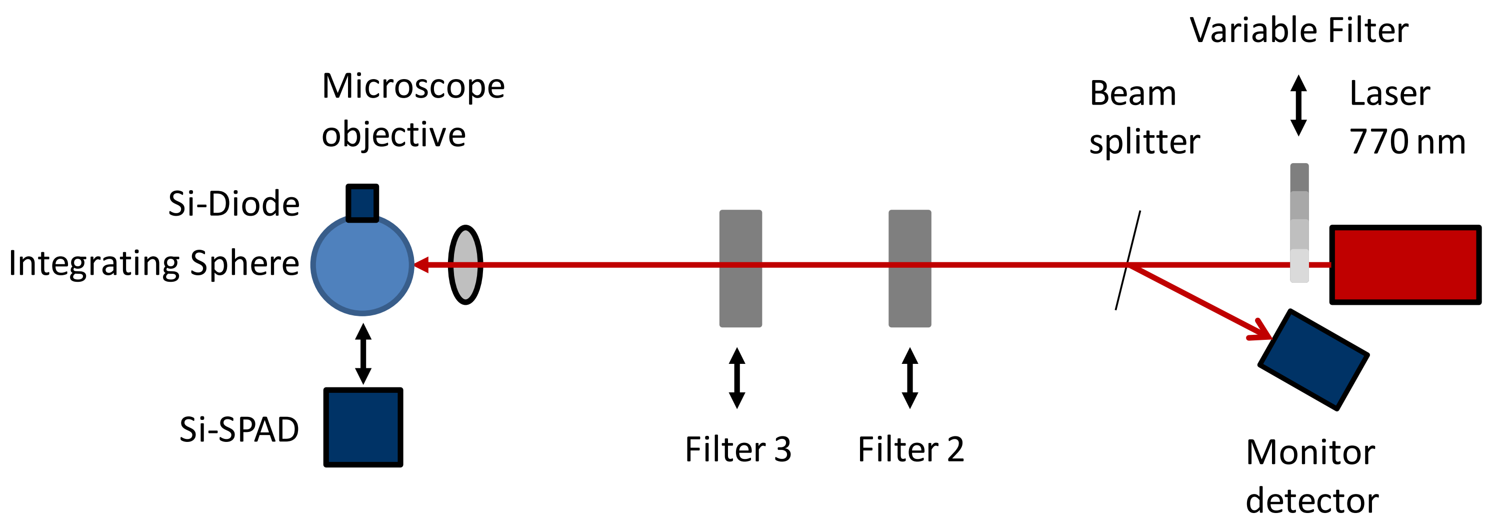
s_{Si}	A/W	Spectral responsivity of Si-Diode	0.357750 A/W	$716 \cdot 10^{-6}$ A/W	Standard	1.8	$1.3 \cdot 10^{-3}$	40.9 %
F_F	1	Factor for the use of two filters	0.99680 1	$2.31 \cdot 10^{-3}$ 1	Rectangular	0.64	$1.5 \cdot 10^{-3}$	54.8 %

- Spectral responsivity of Si-diode:
  Caused by linearity measurements and its uncertainty
- Filter transmission:
  Total filter transmission equals multiplication of two single filter transmissions?

$\eta_{\mathrm{SPAD}} = 0.6359 \pm 0.0040$ (k = 2)
$\eta_{\mathrm{SPAD}} = 0.6359 \pm 0.63$ % (k = 2)

Measurement setup – Improvements

- Standard detector:
  Integrating sphere with Si-diode instead of Si-diode only
- Automated alignment procedure



Detection efficiency – Results and Uncertainty

$$\eta = \frac{hc}{\lambda} \frac{A_2 A_3}{A_1} \frac{Q_1 Q_4}{Q_2 Q_3} s_{Si} F_{filt}$$

Uncertainty component	Uncertainty (%)
Planck constant, h	2.52×10^{-7}
Speed of light, c	0.0
Wavelength, λ	0.0075
Amplification factor, A_1	0.0021
Amplification factor, A_2	2.08×10^{-6}
Amplification factor, A_3	2.08×10^{-6}
Ratio V_1/V_{Mon1}, Q_1	0.004
Ratio V_2/V_{Mon2}, Q_2	0.015
Ratio V_3/V_{Mon3}, Q_3	0.05
Ratio $CR/V_{MonSPAD}$, Q_4	0.036
Spectral responsivity, s_{Si}	0.15
Factor for the use of two filters, F_{filt}	0.005
Combined uncertainty, u_c	0.162

Main contribution:
Standard detector

$u(\eta_{SPAD}) \geq 0.16$ %
(770 nm, 100 000 cps)

However, this is the ideal value. What will be achieved in day-to-day calibrations? 1 % seems reasonable!? See Pilot study!!!

Comparison: DE (Si-SPAD) calibrated directly against Si-Diode (CMI) and PTB-standard setup

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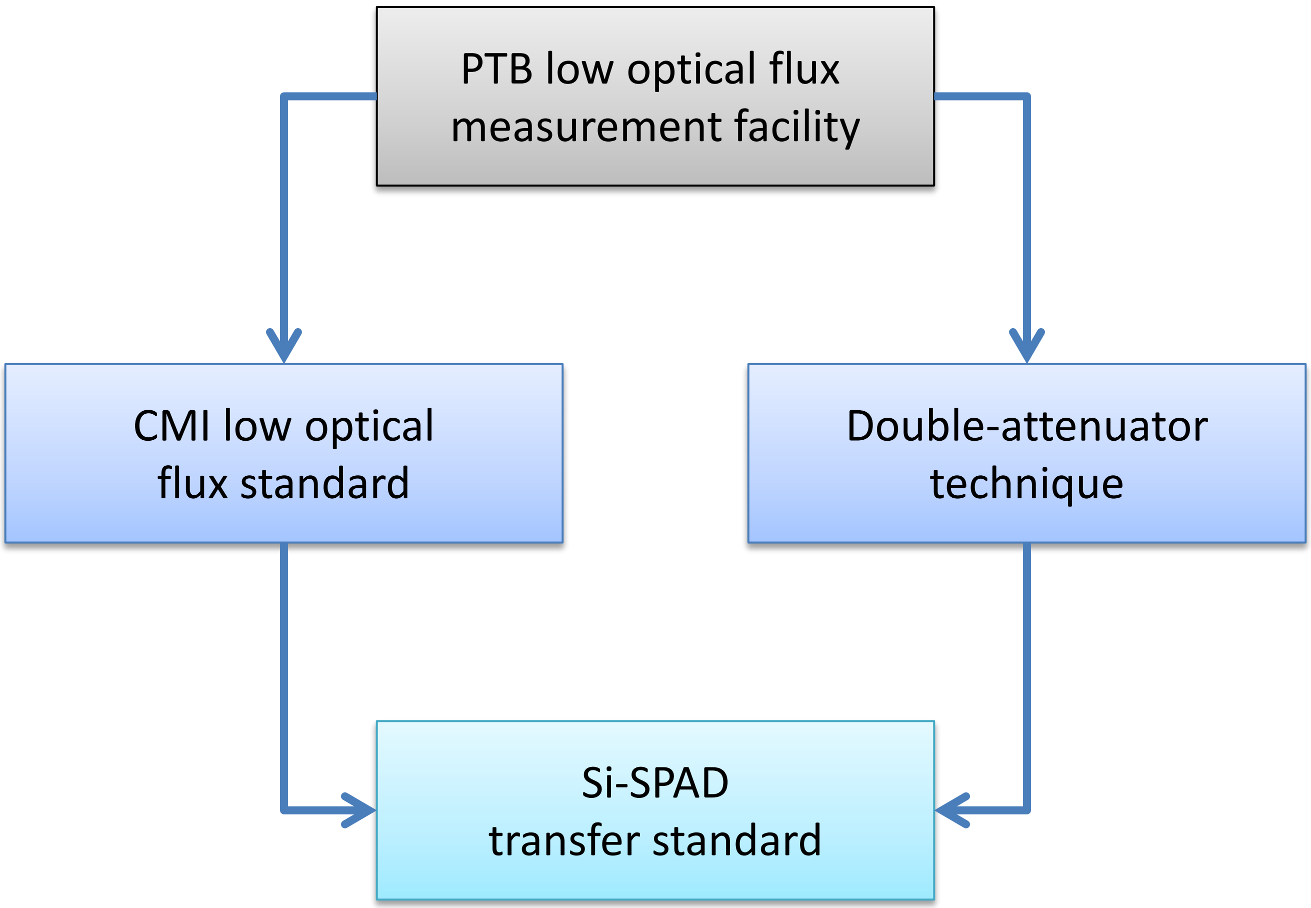
Metrologia 53 (2016) 1115–1122
doi:10.1088/0026-1394/53/4/1115

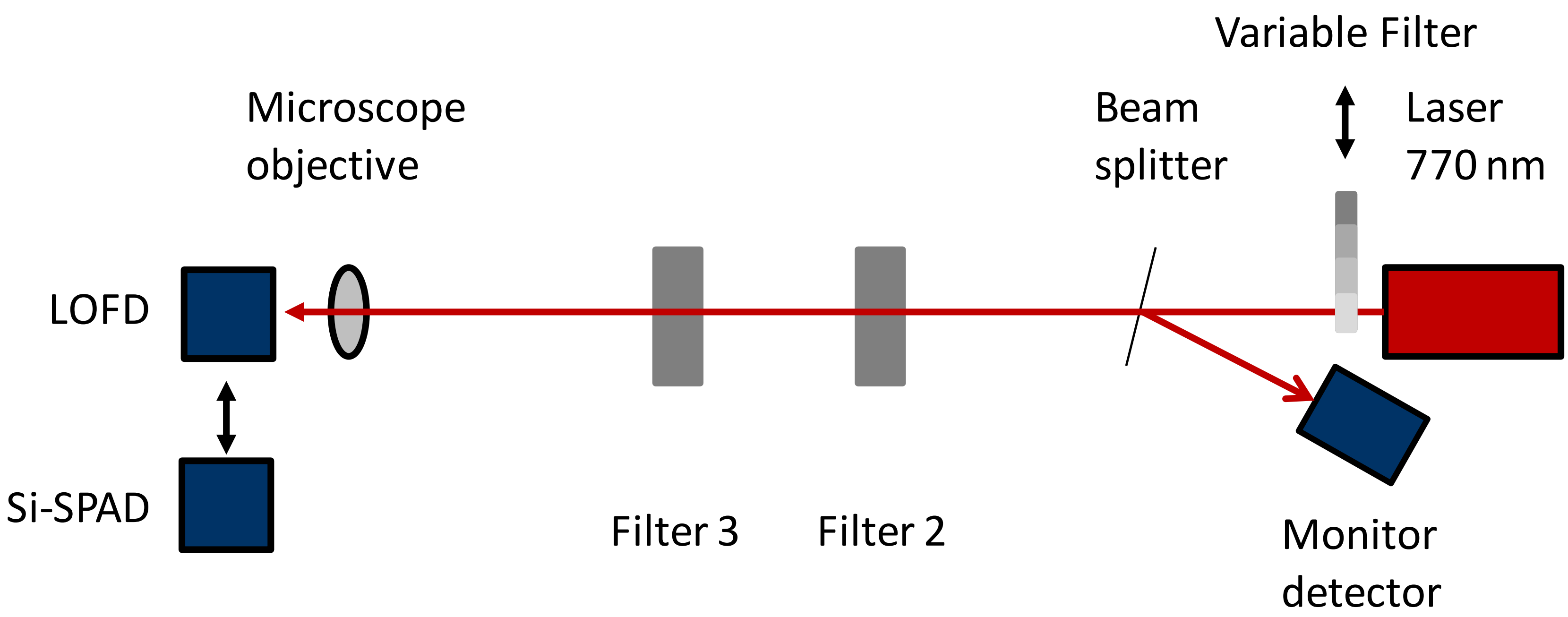
Comparison at the sub-100 fW optical power level of calibrating a single-photon detector using a high-sensitive, low-noise silicon photodiode and the double attenuator technique

G Porrovecchio[1], M Šmid[1], M López[2], H Hofer[2], B Rodiek[2] and S Kück[2]

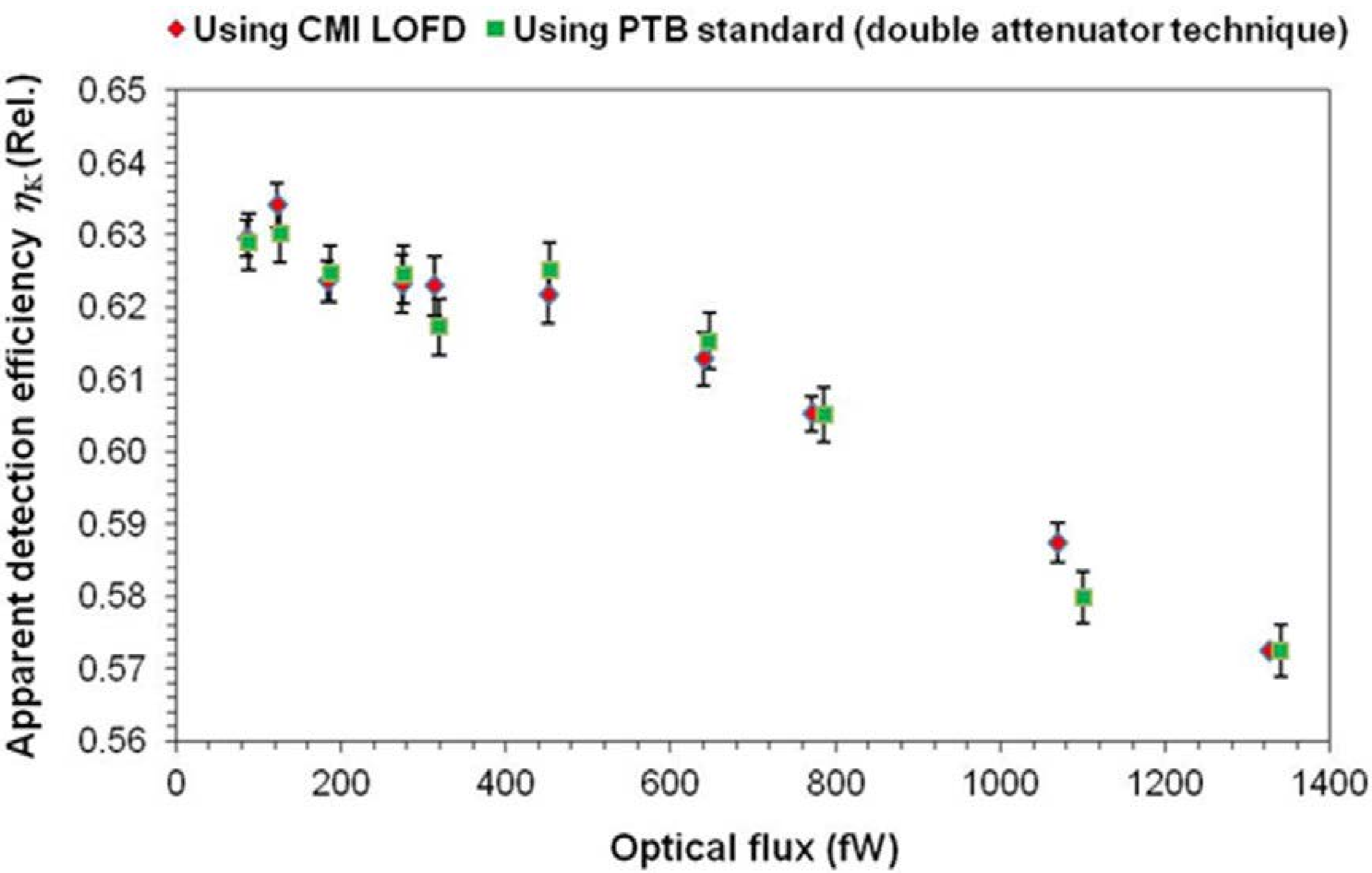
Comparison: DE (Si-SPAD) calibrated directly against Si-Diode (CMI) and PTB-standard setup



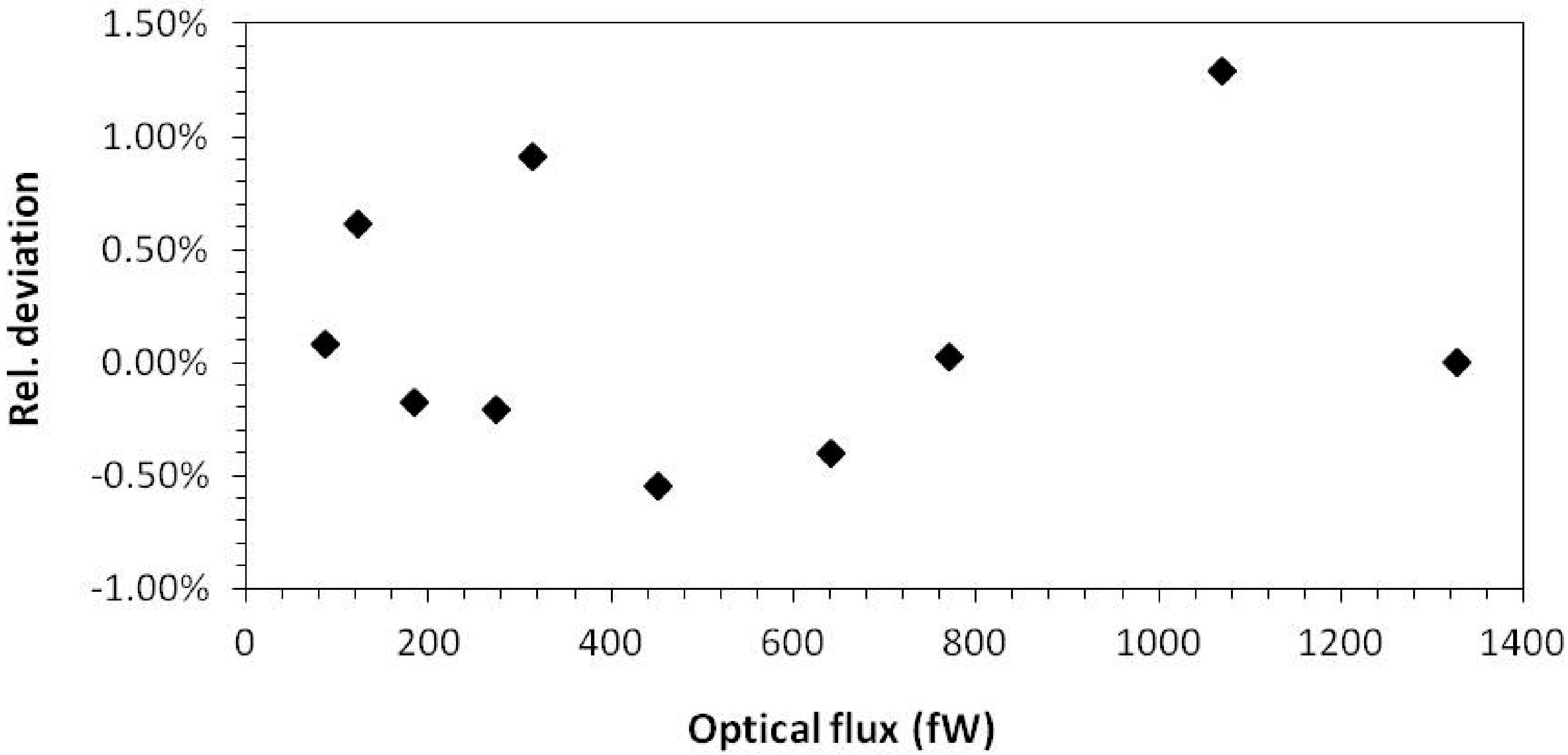
Comparison: DE (Si-SPAD) calibrated directly against Si-Diode (CMI) and PTB-standard setup



Comparison: DE (Si-SPAD) calibrated directly against Si-Diode (CMI) and PTB-standard setup



Comparison: DE (Si-SPAD) calibrated directly against Si-Diode (CMI) and PTB-standard setup



$$E_n = \frac{\left|\eta_{k,SPAD,PTB} - \eta_{k,SPAD,CMI}\right|}{\sqrt{U\left(\eta_{k,SPAD}\right)^2_{CMI} + U\left(\eta_{k,SPAD}\right)^2_{PTB}}} = 0.00 \ldots 0.60$$

WG-KC TG 11 Few photon radiometry

- ✓ Nov 2015: draft of the technical protocol for the pilot study
- ✓ Jan 2016: technical protocol agreed

CCPR WG-SP TG 11

Pilot study on the detection efficiency of single-photon detectors

CCPR.PR-PS xx

Technical Protocol

Participants:

PTB (Germany), NIM (China), CMI (Czech Republic), INRiM (Italy), NMIJ-AIST (Japan), KRISS (Korea), VNIIOFI (Russia), METAS (Switzerland), NPL (UK), NIST (USA)

Single-Photon Sources

Applications of single-photon sources:

- Quantum Key Distribution / Quantum Cryptography
- Quantum Computing
- Quantum Enhanced Measurements (QEM)

- Last, but not least: Radiometry!
  - New standard source!
  - Ideal source for detection efficiency determination of single-photon detectors

Single-Photon Sources as standard source

Number of photons

Photon energy

- Constants of nature
- Wavelength

Power

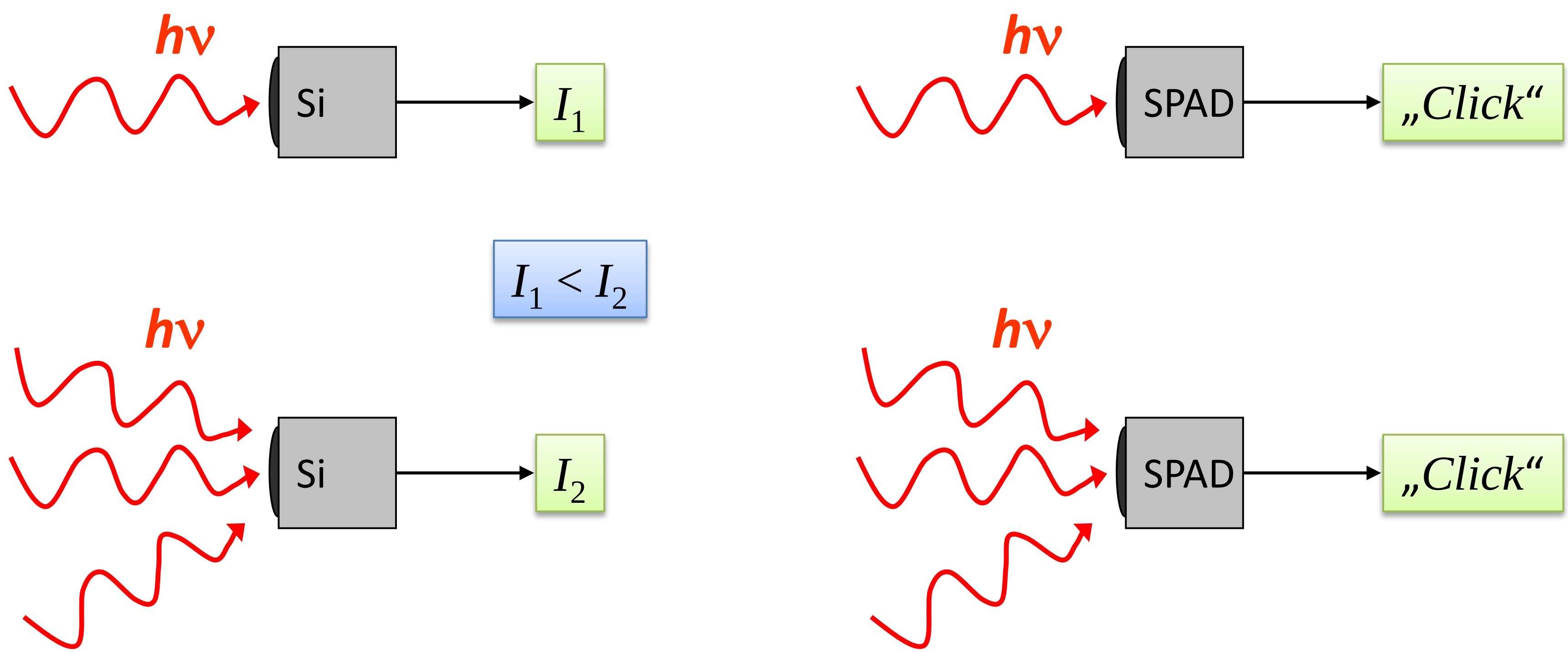
$$\Phi = \frac{n}{t}\frac{hc}{\lambda}$$

Time

Single-Photon Sources for detector DE calibration

Analogue detector

Digital detector



Signal ∝ Number of photons

Only one "click" per time

Single-Photon Source

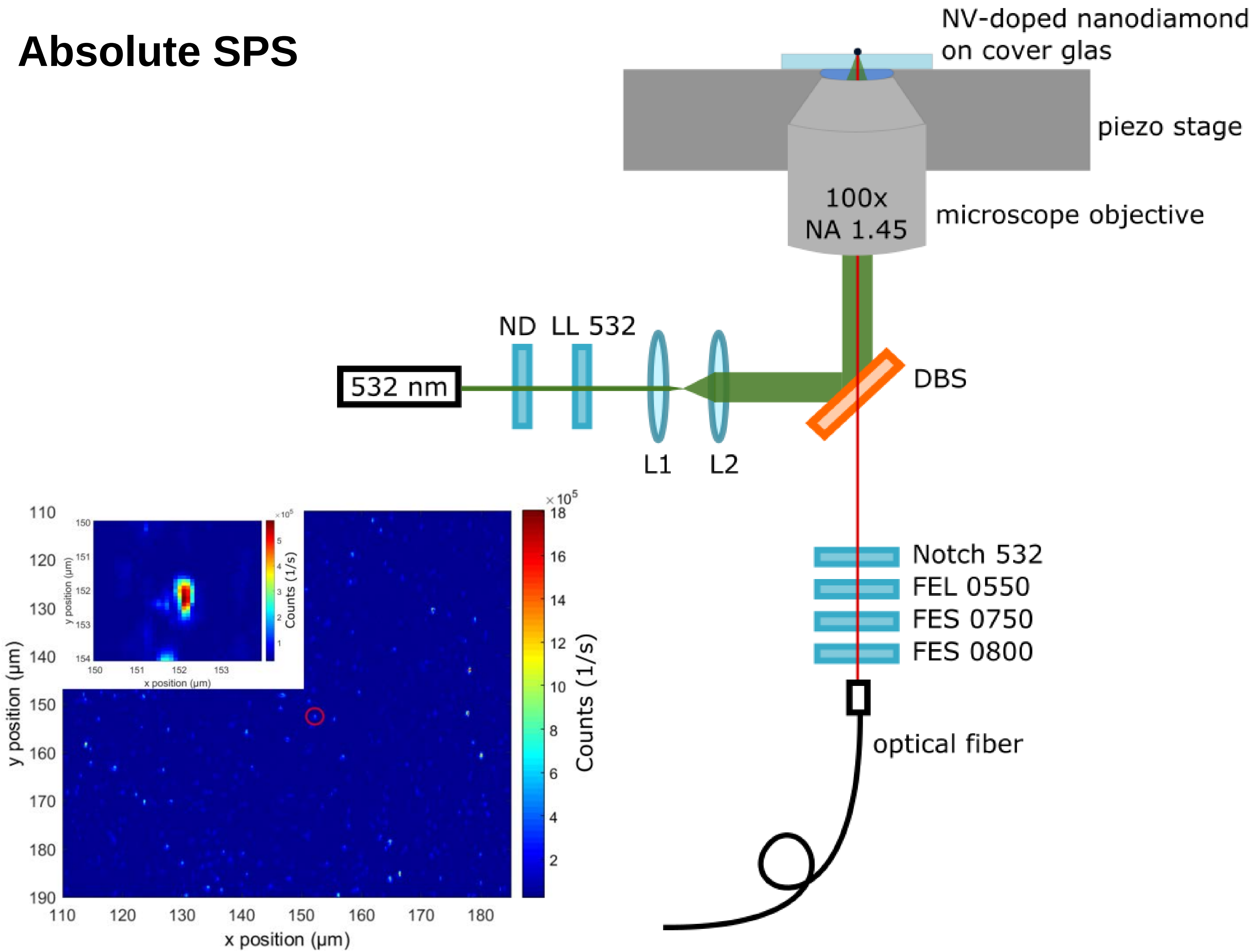
No single-photon source existed that fulfilled all the requirements needed!

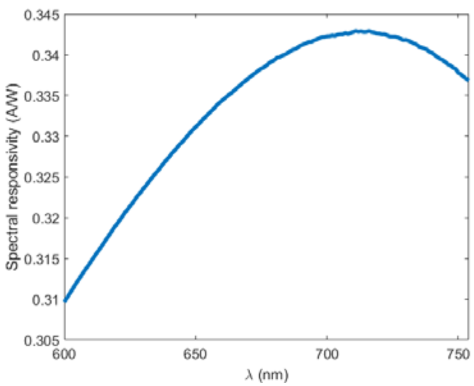
$\Rightarrow$ European Joint Research Project

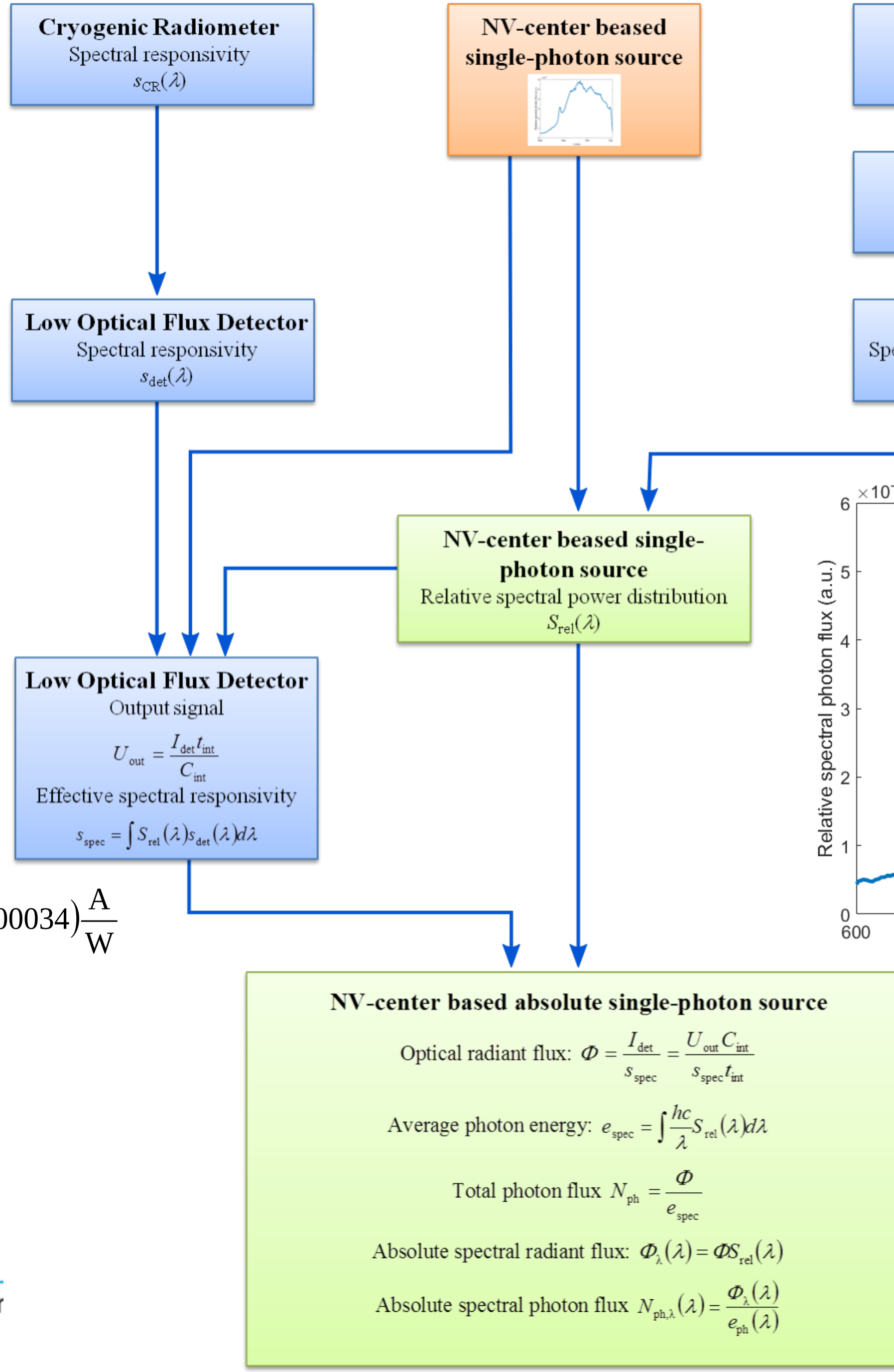
- EMRP Call 2012 on Open Excellence
- SIQUTE: Single-Photon Sources for Quantum Technologies
- Coordinated by PTB

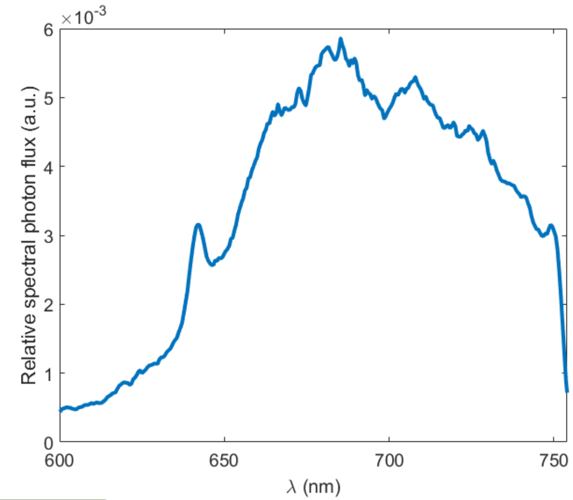
EMRP
European Metrology Research Programme
Programme of EURAMET
The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

Absolute SPS









$$s_{spec} = \int S_{rel}(\lambda) s_{det}(\lambda) d\lambda = (0.33798 \pm 0.00034) \frac{A}{W}$$

Absolute Single-Photon Source

NV-center based absolute single-photon source

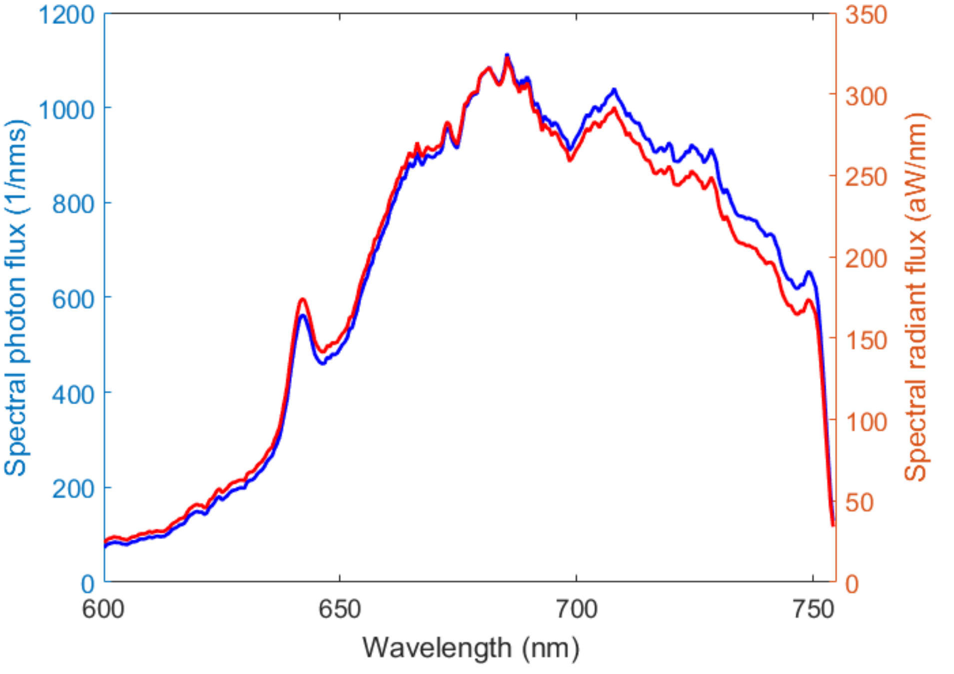
Optical radiant flux: $\Phi = \frac{I_{\text{det}}}{s_{\text{spec}}} = \frac{U_{\text{out}} C_{\text{int}}}{s_{\text{spec}} t_{\text{int}}}$ = 55 fW to 75 fW

Average photon energy: $e_{\text{spec}} = \int \frac{hc}{\lambda} S_{\text{rel}}(\lambda) d\lambda$ $= (2.8855 \pm 0.0029) \times 10^{-19}\ \text{J}$

Total photon flux $N_{\text{ph}} = \frac{\Phi}{e_{\text{spec}}}$ = 190 000 ph/s to 260 000 ph/s

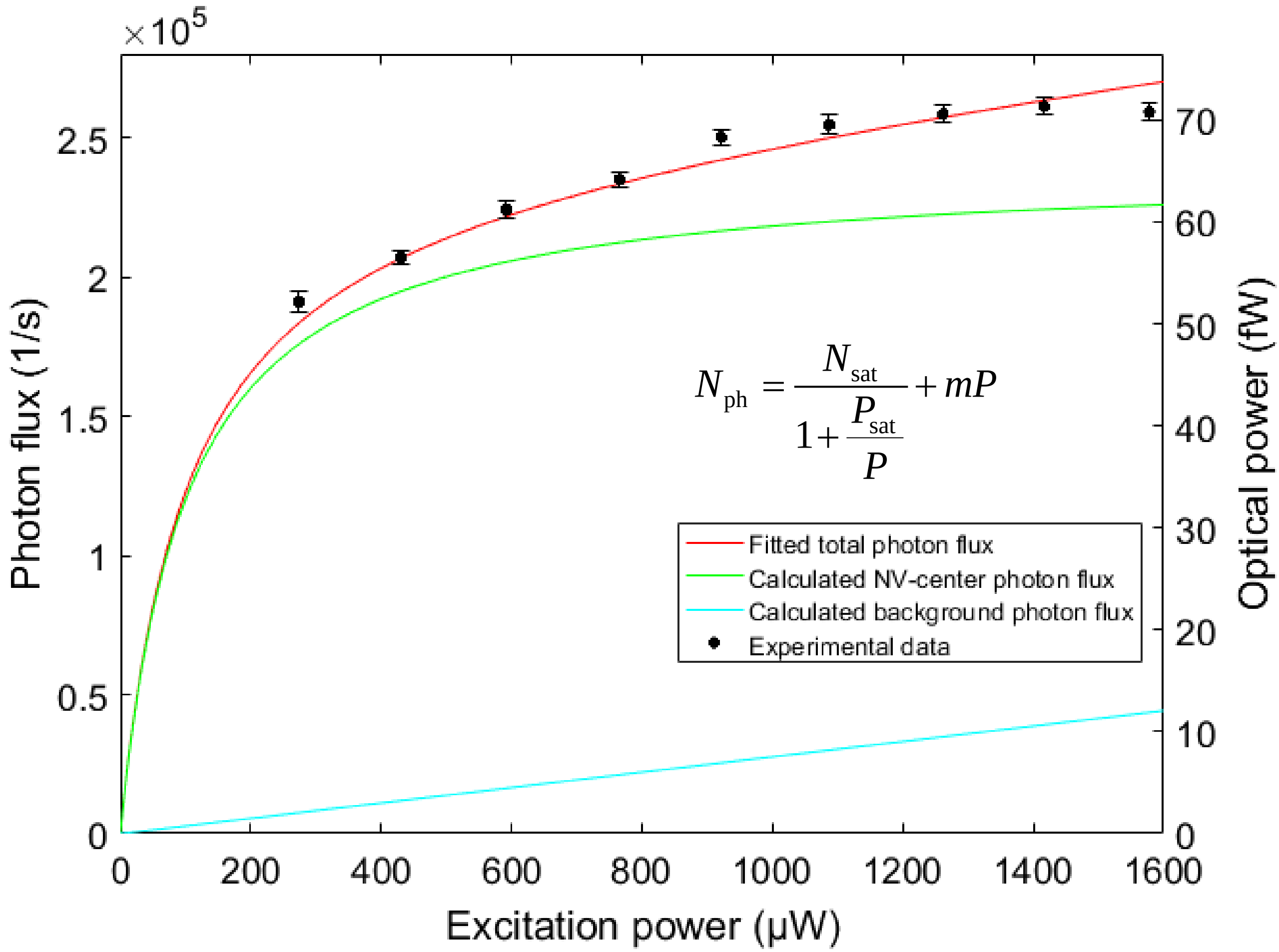
Absolute spectral radiant flux: $\Phi_\lambda(\lambda) = \Phi S_{\text{rel}}(\lambda)$

Absolute spectral photon flux $N_{\text{ph},\lambda}(\lambda) = \frac{\Phi_\lambda(\lambda)}{e_{\text{ph}}(\lambda)}$

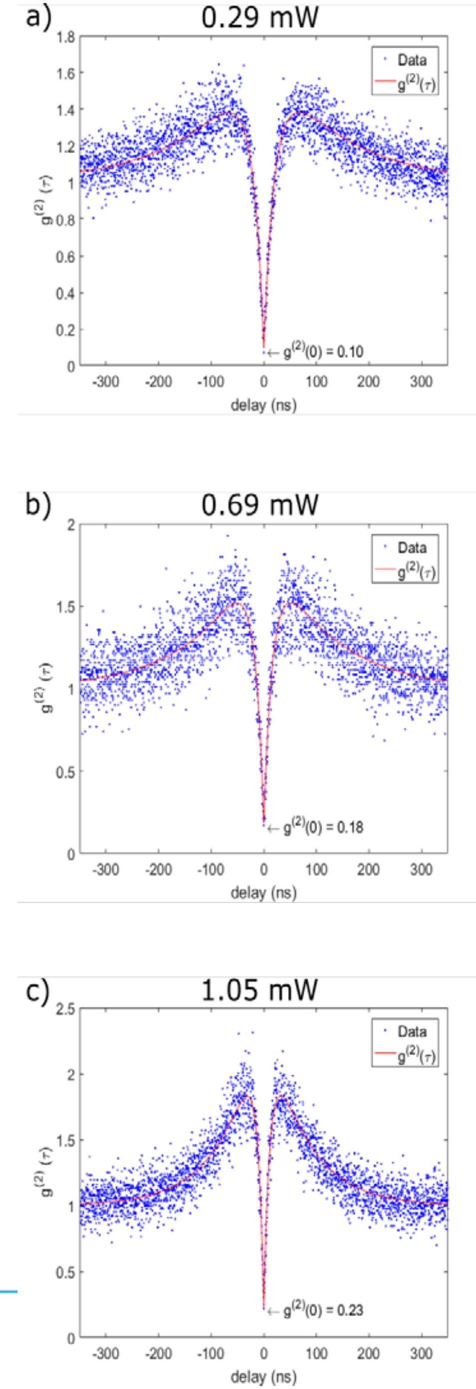


Absolute SPS

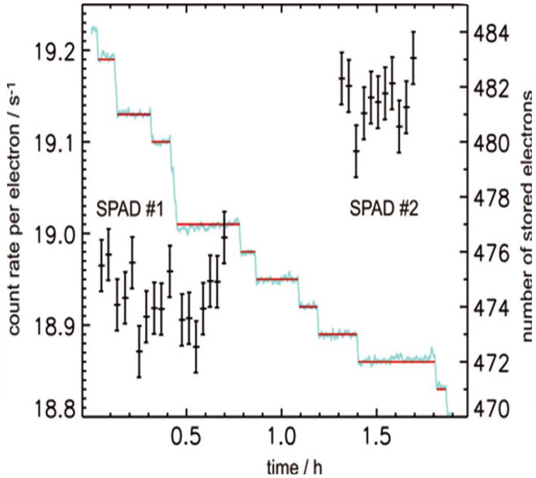
$$g^{(2)}(\tau) = 1 + c_2 \exp\left(-\frac{|\tau|}{\tau_2}\right) + c_3 \exp\left(-\frac{|\tau|}{\tau_3}\right)$$



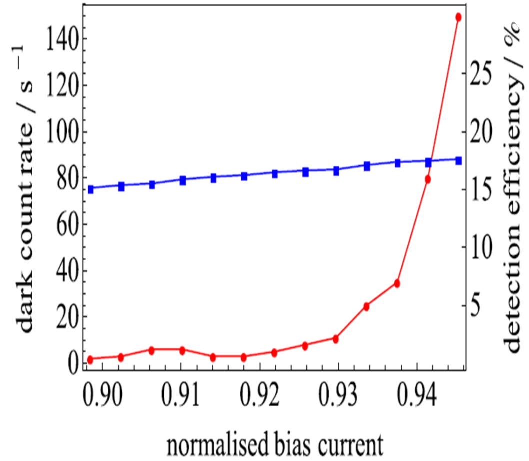
$$N_{\mathrm{ph}} = \frac{N_{\mathrm{sat}}}{1 + \frac{P_{\mathrm{sat}}}{P}} + mP$$



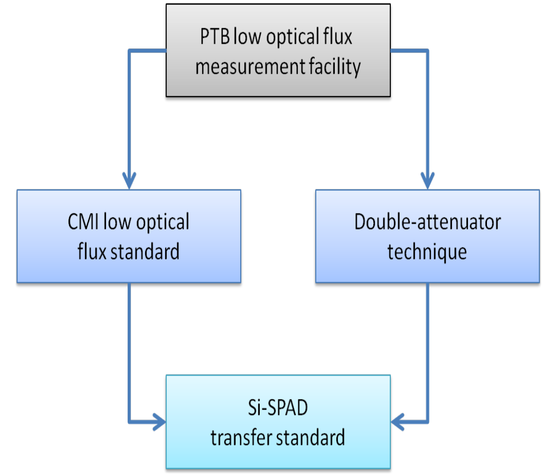
N_{sat} = 240 000 s^{-1}, P_{sat} = 100 µW and m = 27.6 $µW^{-1}s^{-1}$.



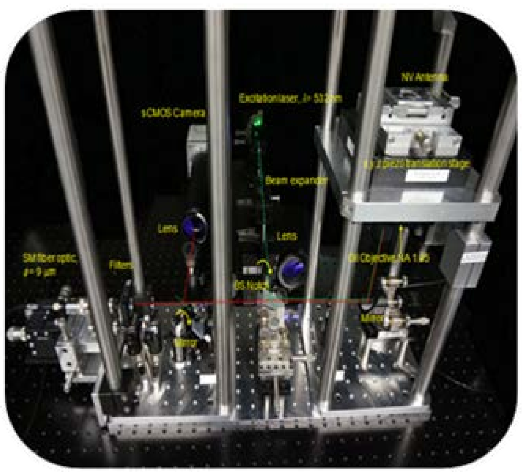
Metrology Light Source



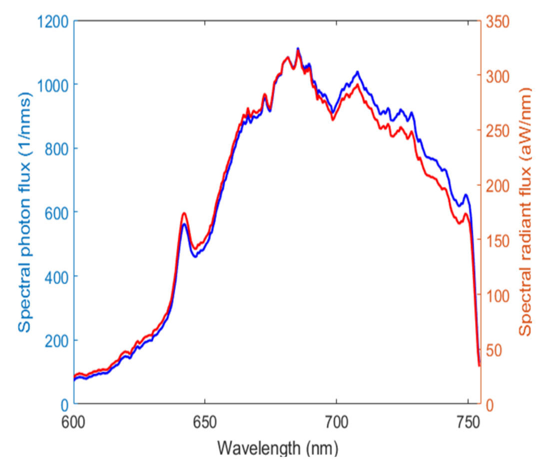
SNSPD calibration



Sub 100 fW comparison



Single-photon sources



Absolute single-photon source