Studying Photon Number Distribution of NV-Centre Emission in Nano-Diamond

W. Schmunk[1] M. Gramegna[3] G. Brida[3] I. P. Degiovanni[3]
M. Genovese[3] H. Hofer[1] <u>S. Kück</u>[1] L. Lolli[3] M. G. A. Paris[4]
S. Peters[1] M. Rajteri[3], A. M. Racu, A. Ruschhaupt[2] E. Taralli[3] P. Traina[3]

[1]*Physikalisch-Technische Bundesanstalt, Germany*

[2]*Istituto Nationale di Ricerca Metrologica, Italy*

[3]*Universita degli Studi di Milano, Italy*

[4]*Leibniz Universität Hannover, Germany*

Motivation

Application of single photon sources …

- Quantum physics
- Quantum computing
- Quantum Key Distribution
- Biomedical physics
- Efficiency calibration of single photon detectors

Motivation

Why photon number distribution is of interest?

e.g.

- quantum key distribution:

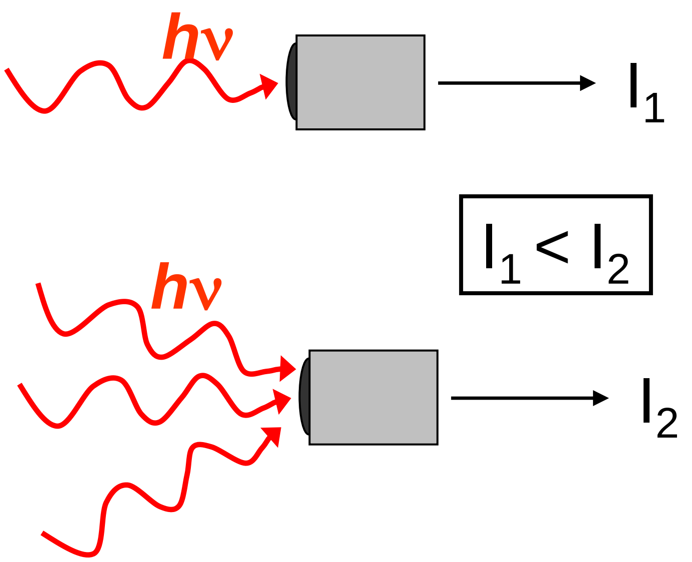
  multiphoton events vulnerable to attacks

- efficiency calibration of single photon detectors

  photon statistics affects result of calibration

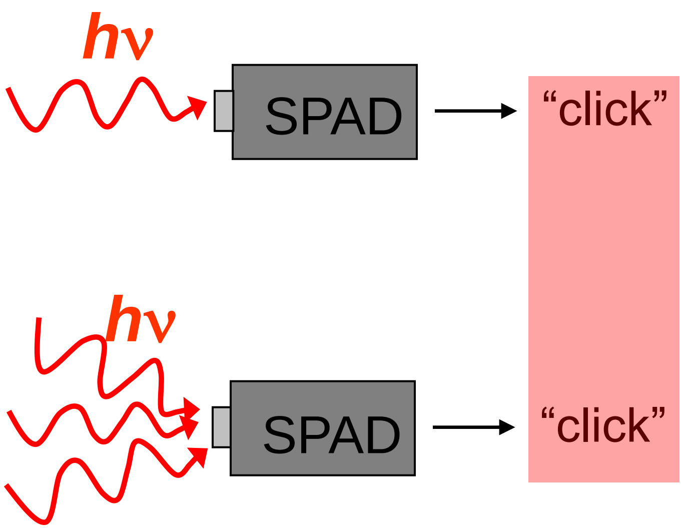
Single Photon Detector Calibration

Analogue detector



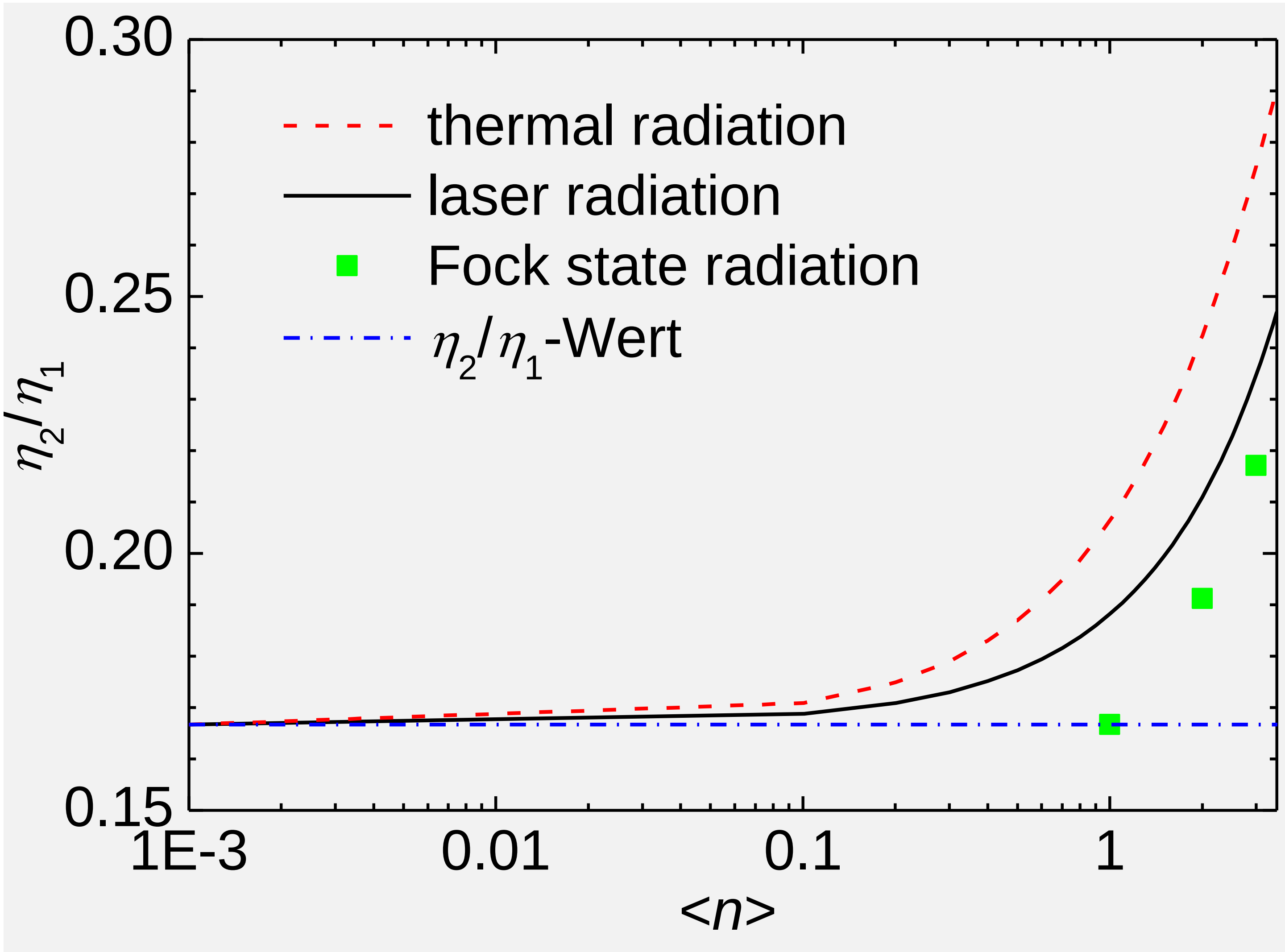
Signal ∝ Number of photons

Digital detector



Only one "click" per time

Single Photon Detector Calibration



W. Schmunk, M. Rodenberger, S.Peters, H. Hofer, S. Kück, *Radiometric Calibration of Single Photon Detectors by a Single Photon Source based on NV-centers in diamond*, J. Mod. Opt. 58, 1252 (2011)

Introduction

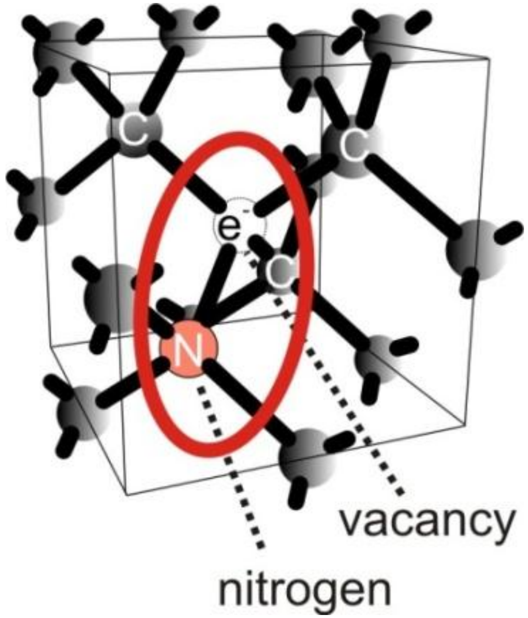
Several methods have been developed to analyze unknown photon statistics, e.g.:

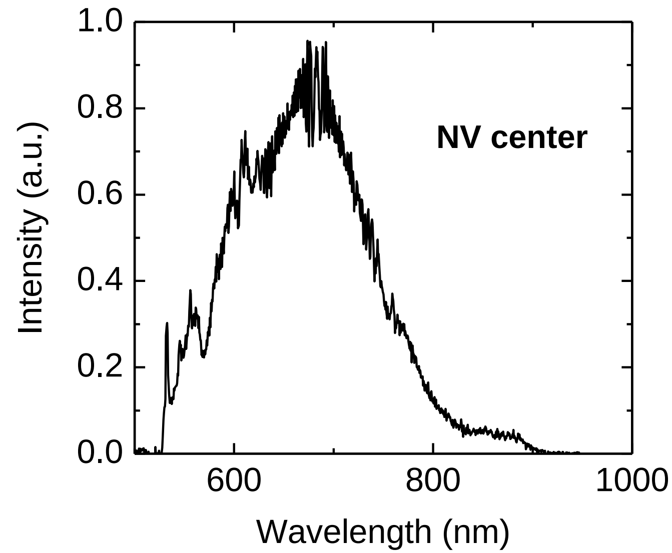
- photon number resolving detector, e.g. transition edge sensor (TES)
- “on/off-measurements”
- detector tree
- …

Here:

- NV-centre emission is studied
- results compared to the $g^{(2)}(0)$-values obtained by Hanbury-Brown & Twiss (HBT)-measurements

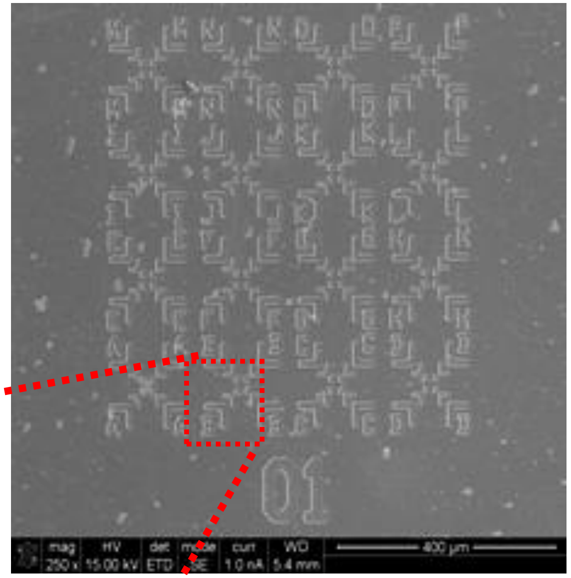
The Nitrogen-Defect (N/V) Center in Diamond

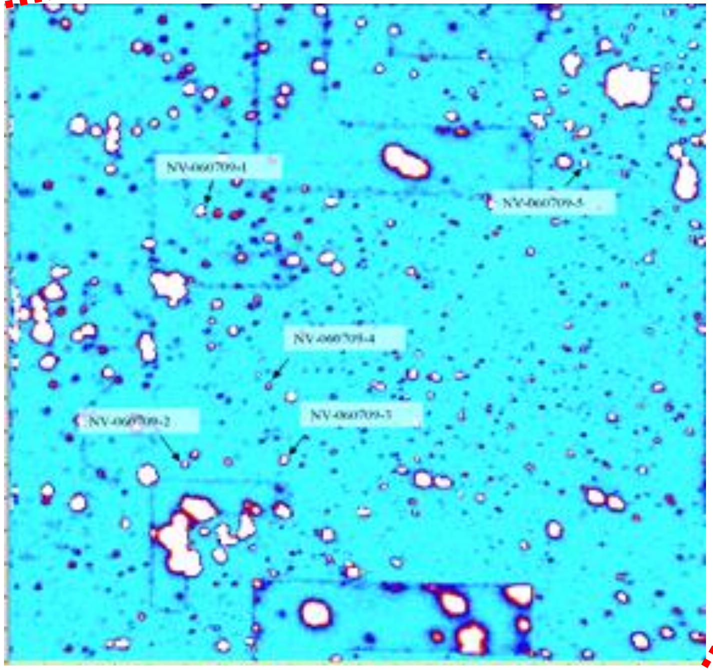




- high photo stability at room temperature
- bright emission: up to 10^6 photons per second detected
- short decay time 8 ns - 30 ns
- broad luminescence spectrum
- NV-defects in **nano diamonds**: minimization of optical limitations caused by the high refractive index of diamond

Nano-diamonds with NV-centres on Si substrate





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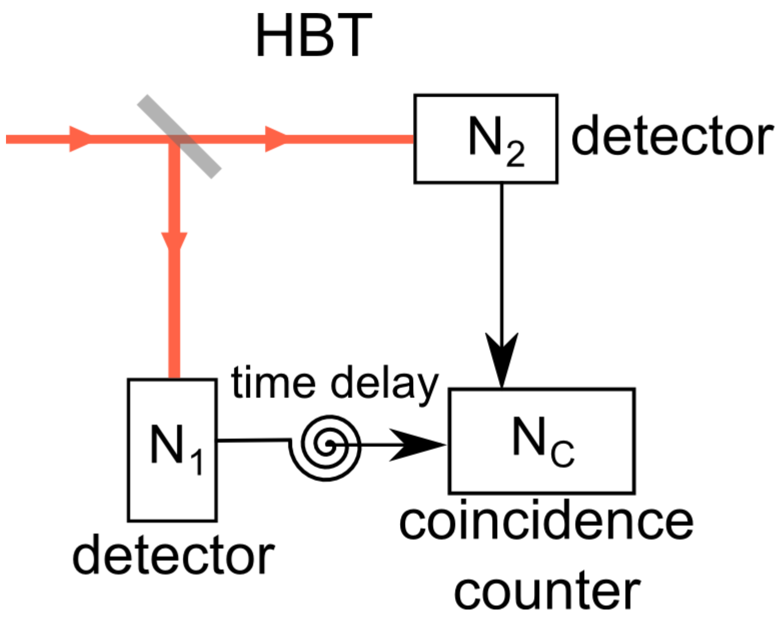
HBT Interferometer Measurements

Hanbury-Brown Twiss Interferometer



$$g^2(\tau) = \frac{N_C}{N_1 \cdot N_2 \cdot \Delta\tau \cdot T}$$

Second order correlation function

$$g^2(t) = \frac{< I(t+\tau) \; I(t) >}{< (I(t) >^2}$$

$$g^{(2)}(0) = 1 - \frac{1}{n}$$

↓

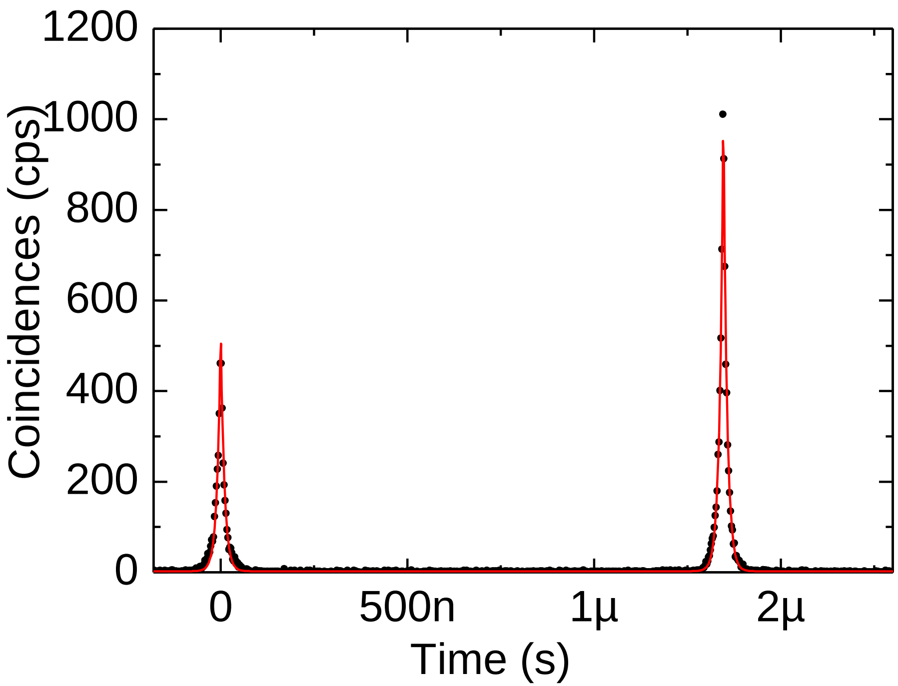
Number of single photon emitters

HBT Interferometer Measurements

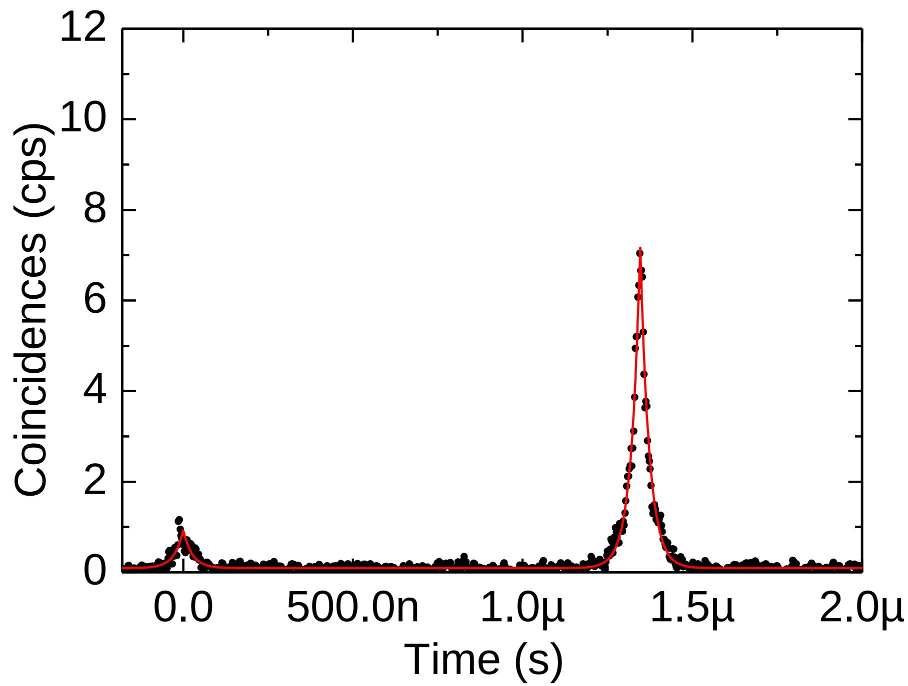
PTB

Hanbury-Brown-Twiss set up → $g^{(2)}(t)$

Centre 1: $g^{(2)}(0)$ = 0.53 ± 0.02



Centre 2: $g^{(2)}(0)$ = 0.06 ± 0.03



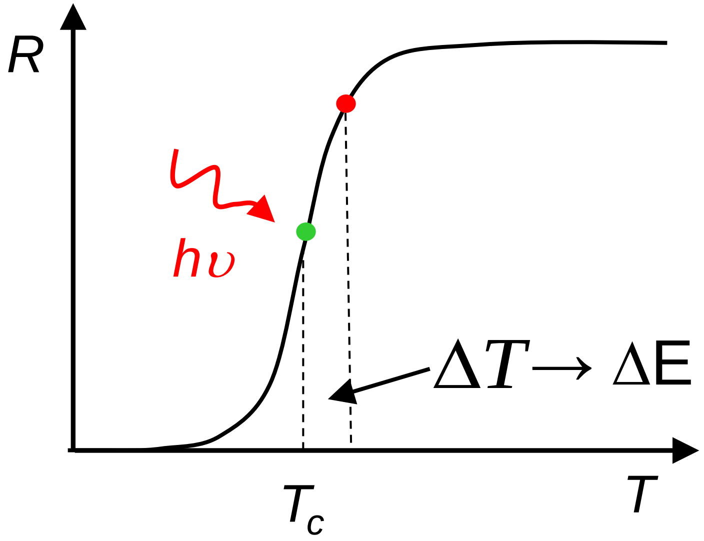
excitation: pulsed laser @532 nm, 743 kHz

emission: spectral filtering: (694 ± 37) nm

Photon Number Resolving Detector at INRIM

Transition edge sensor (TES):

Sensitive calorimeter measuring pulse energy



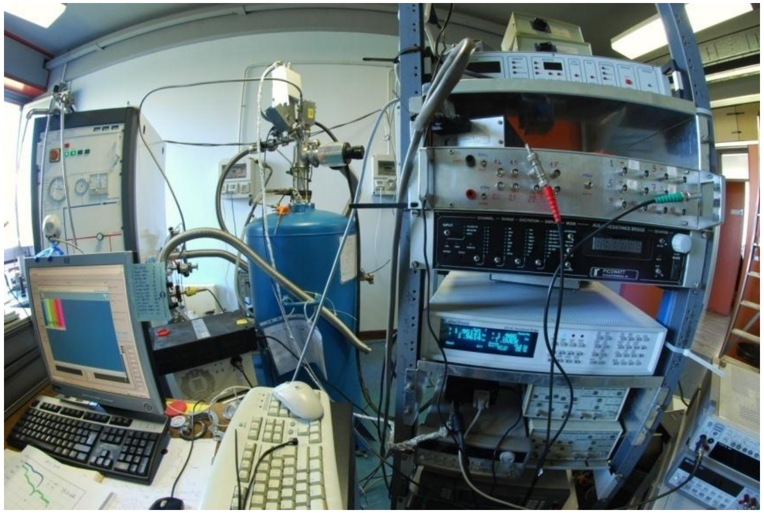
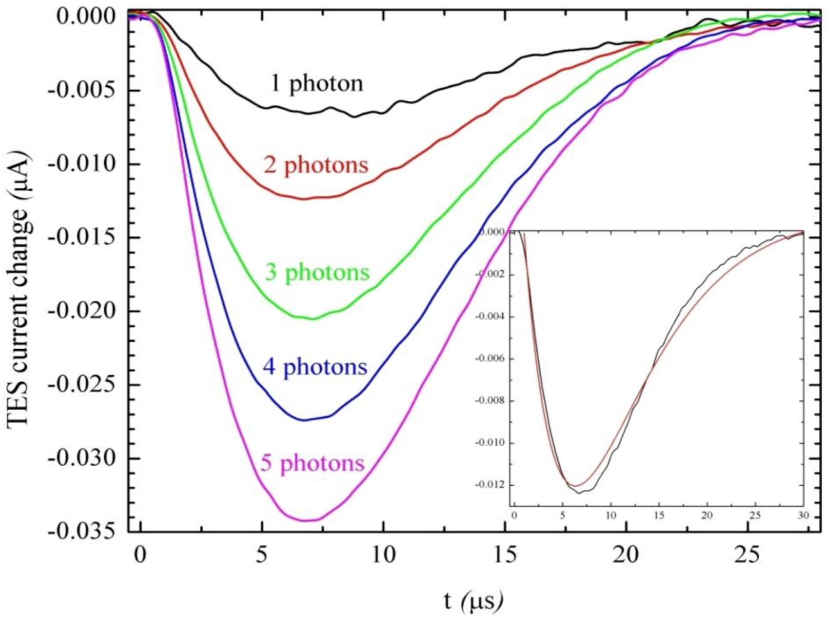


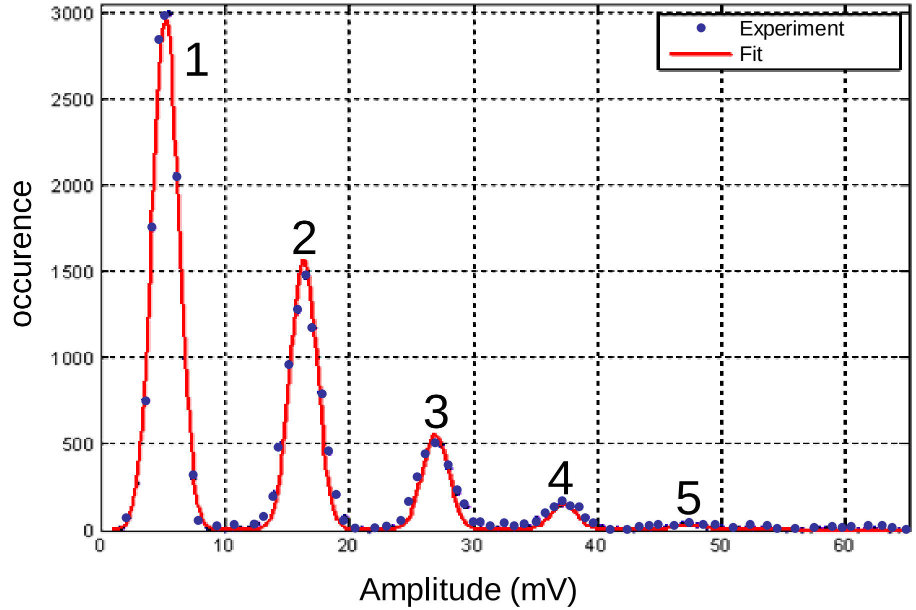
Foto: G.Brida

- Operation temperature T_c = 130 mK
- Sharp superconducting phase transition $\Delta T \sim h\nu$ = 1 mK
- Optical fibre coupling (9 µm core)

M.Rajteri et. al. Metrologia 46, 2009, 283 - 287

TES Signal





Pulse amplitude ~ *n*/wavelength

Time constants

- electrical rise time ~ 5.2 µs
- thermal response time ~ 32 µs

Energy resolution

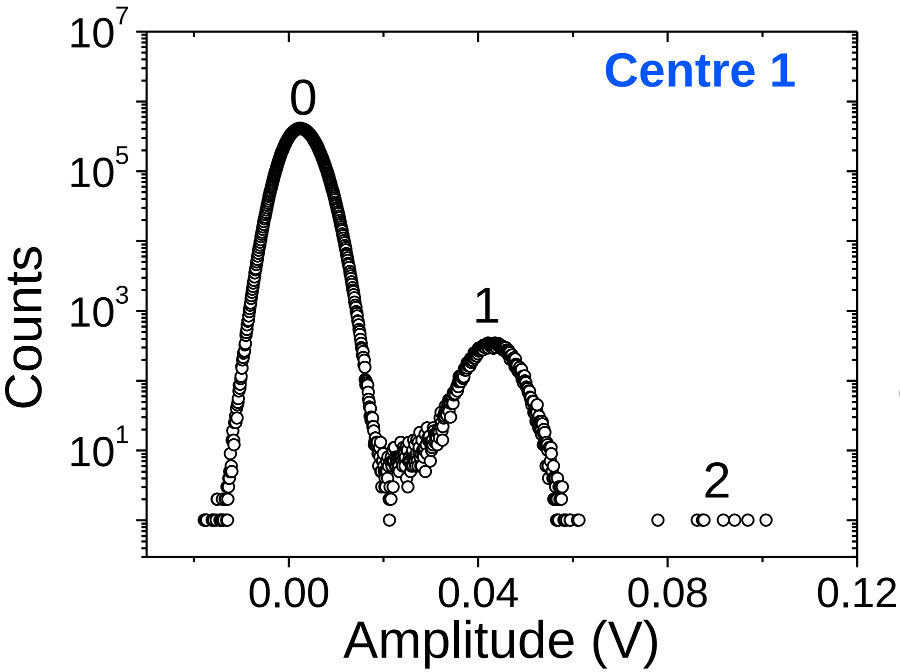
ΔE = 0.41 eV @ 690 nm

TES – Measurement Results

$g^{(2)}(0)$-values: TES results agree with values measured by the HBT

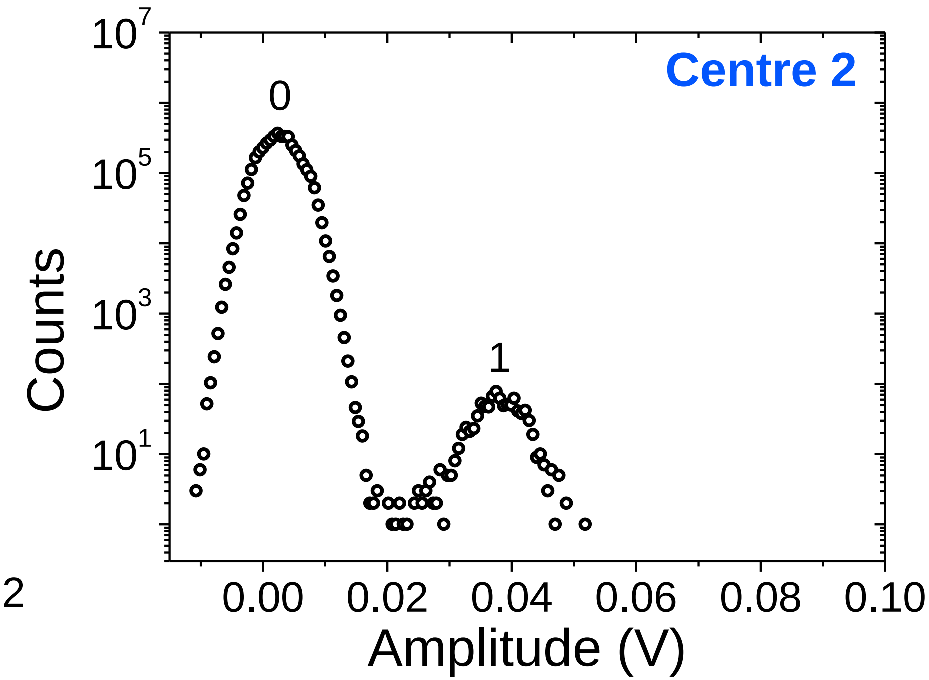
TES: $g^{(2)}(0) = 0.5 \pm 0.1$

HBT: $g^{(2)}(0) = 0.53 \pm 0.02$



TES: $g^{(2)}(0) = 0.0 + 0.1$

HBT: $g^{(2)}(0) = 0.06 \pm 0.03$



$$g^{(2)}(0) = \frac{\sum_n (n^2 P_n - n P_n)}{(\sum_n n P_n)^2}$$

‘On/Off’ Photon Statistic Reconstruction

Partial reconstruction of photon statistics by varying detection efficiency

‘No-click’ probability p_0 for a binary detector of **detection efficiency** η_ν hit by a quantum optical field with **density matrix** ρ:

$$p_0(\eta_\nu) = \sum_n (1-\eta_\nu)^n \underbrace{<n|\rho|n>}$$

diagonal elements
of the density matrix

Photon number distribution and $g^{(2)}(0)$-value can be obtained by:

- Maximum Likelihood estimation
- least square fit

‘On/Off’ Measurements

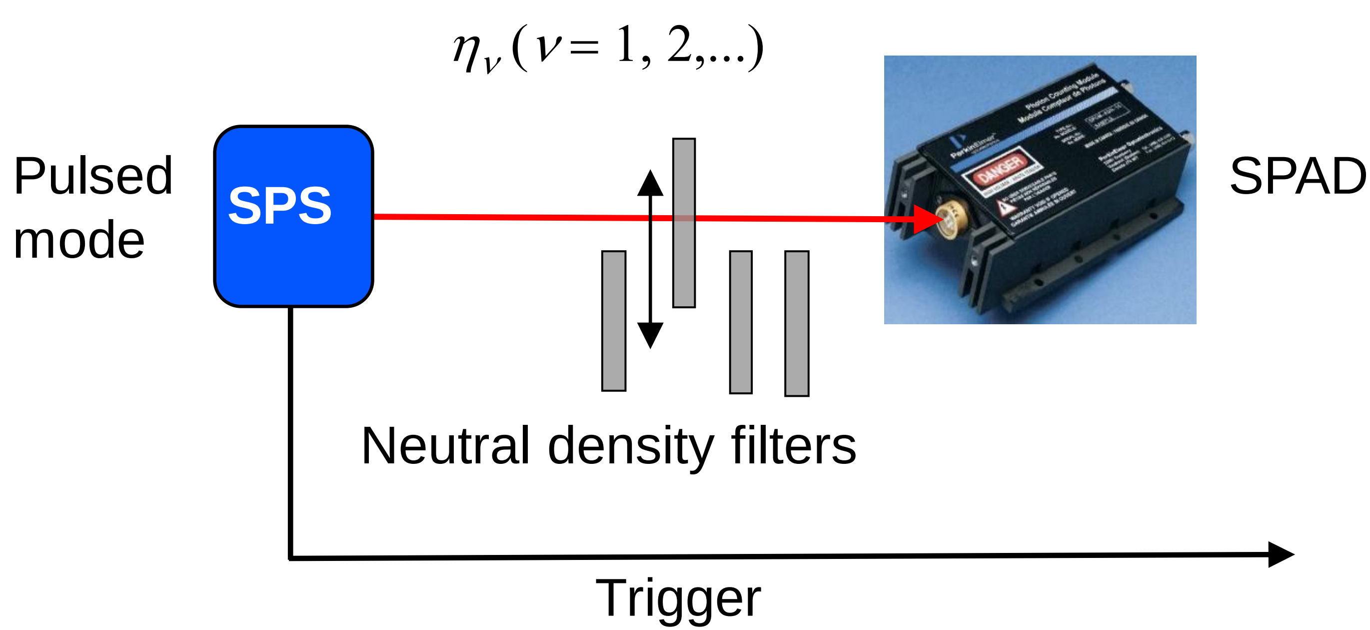
Information on the photon number distribution is gained from the ratio:

$$f_\nu(\eta_\nu) = \frac{n_{0,\nu}}{n_\nu}$$

variable detection efficiency

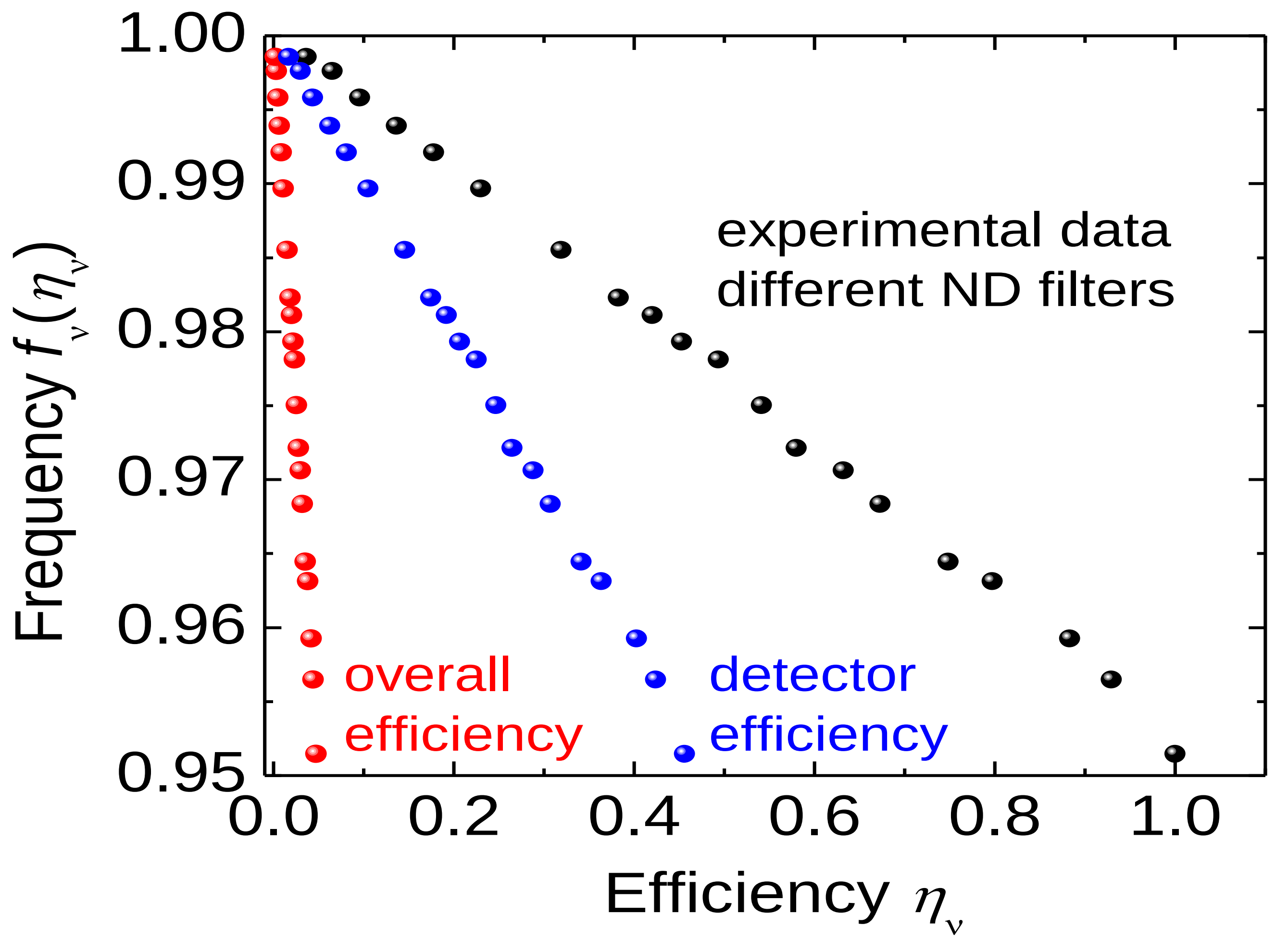
$n_{0,\nu}$: number of "no-click" events

n_ν: total number of runs



‘On/Off’ Measurement Results

- Low efficiency of the optical detection set up (~ 3 % – 4 %)
- Low signal to noise ratio → high order photon component has a high error
- High zero photon component

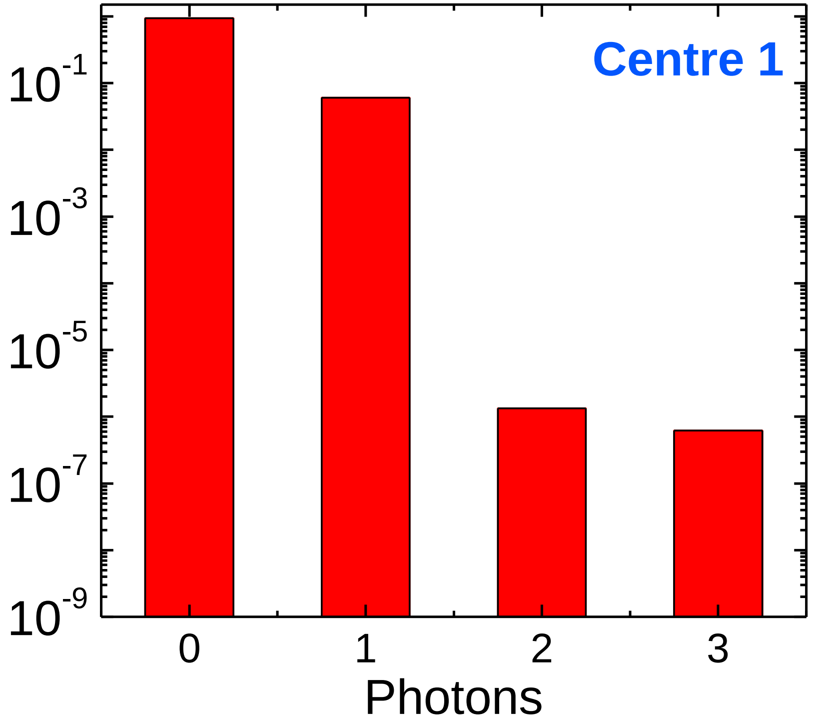


‘On/Off’ Measurements Results

“On/Off”: $g^{(2)}(0) = 0.5 \pm 0.1$

TES: $g^{(2)}(0) = 0.5 \pm 0.1$

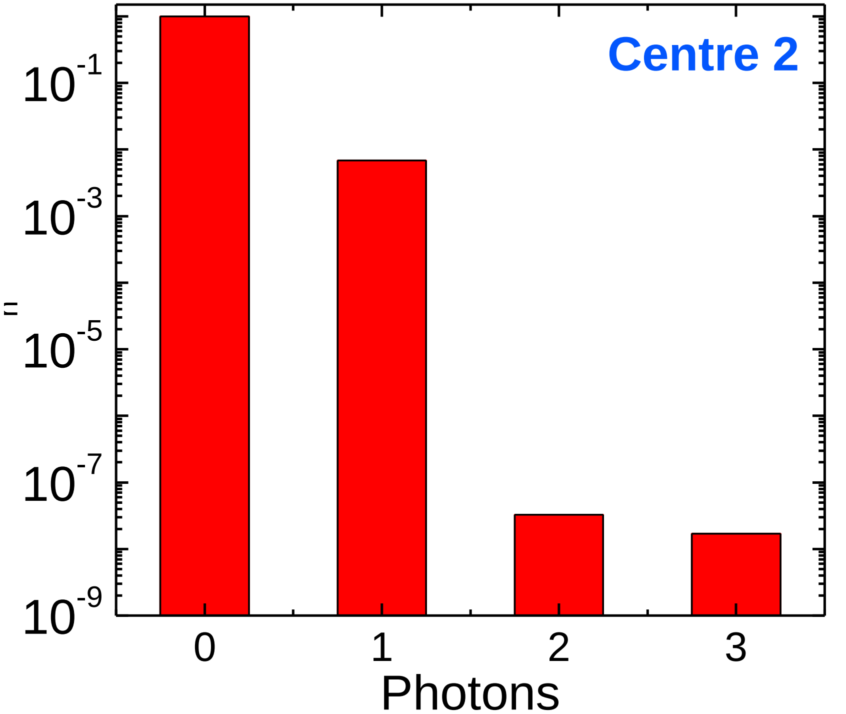
HBT: $g^{(2)}(0) = 0.53 \pm 0.02$



“On/Off”: $g^{(2)}(0) = 0.02 \pm 0.05$

TES: $g^{(2)}(0) = 0.0 + 0.1$

HBT: $g^{(2)}(0) = 0.06 \pm 0.03$



$$g^{(2)}(0) = \frac{\sum_n (n^2 P_n - nP_n)}{(\sum_n nP_n)^2}$$

Summary

Photon number distribution of NV-centre emission …

- measured by TES detector and 'On/Off' measurements
- results exhibit high zero photon components

  → low overall efficiency of the used single photon source
- $g^{(2)}(0)$-value calculated from photon number distribution compared to HBT interferometer values

  → good agreement for TES- and "On/Off"-results

Further 'On/Off' measurements will be performed for brighter NV-centres

→ to study the applicability of the method for determination of the photon statistics of single photon sources in general

Single Photon Detector Calibration

$$Q_{\text{Laser}}(\langle\bar{n}\rangle) = \sqrt{\frac{(1-e^{-\alpha\eta_D\langle\bar{n}\rangle})(1-e^{-(1-\alpha)\eta_D\langle\bar{n}\rangle})}{(1-e^{-\alpha\eta_S\langle\bar{n}\rangle})(1-e^{-(1-\alpha)\eta_S\langle\bar{n}\rangle})}}$$

$$Q_{\text{therm.}}(\langle\bar{n}\rangle) = \frac{\eta_D}{\eta_S}\sqrt{\frac{(1+\alpha\eta_S\langle\bar{n}\rangle)(1+(1-\alpha)\eta_S\langle\bar{n}\rangle)}{(1+\alpha\eta_D\langle\bar{n}\rangle)(1+(1-\alpha)\eta_D\langle\bar{n}\rangle)}}$$

$$Q_{\text{Fock }\langle\bar{n}\rangle} = \sqrt{\frac{(1-(1-\alpha\eta_D)^{\langle\bar{n}\rangle})(1-(1-(1-\alpha)\eta_D)^{\langle\bar{n}\rangle})}{(1-(1-\alpha\eta_S)^{\langle\bar{n}\rangle})(1-(1-(1-\alpha)\eta_S)^{\langle\bar{n}\rangle})}}$$

$$Q_{SPS} = \frac{\eta_D}{\eta_S}$$

‘On/Off’ Measurements

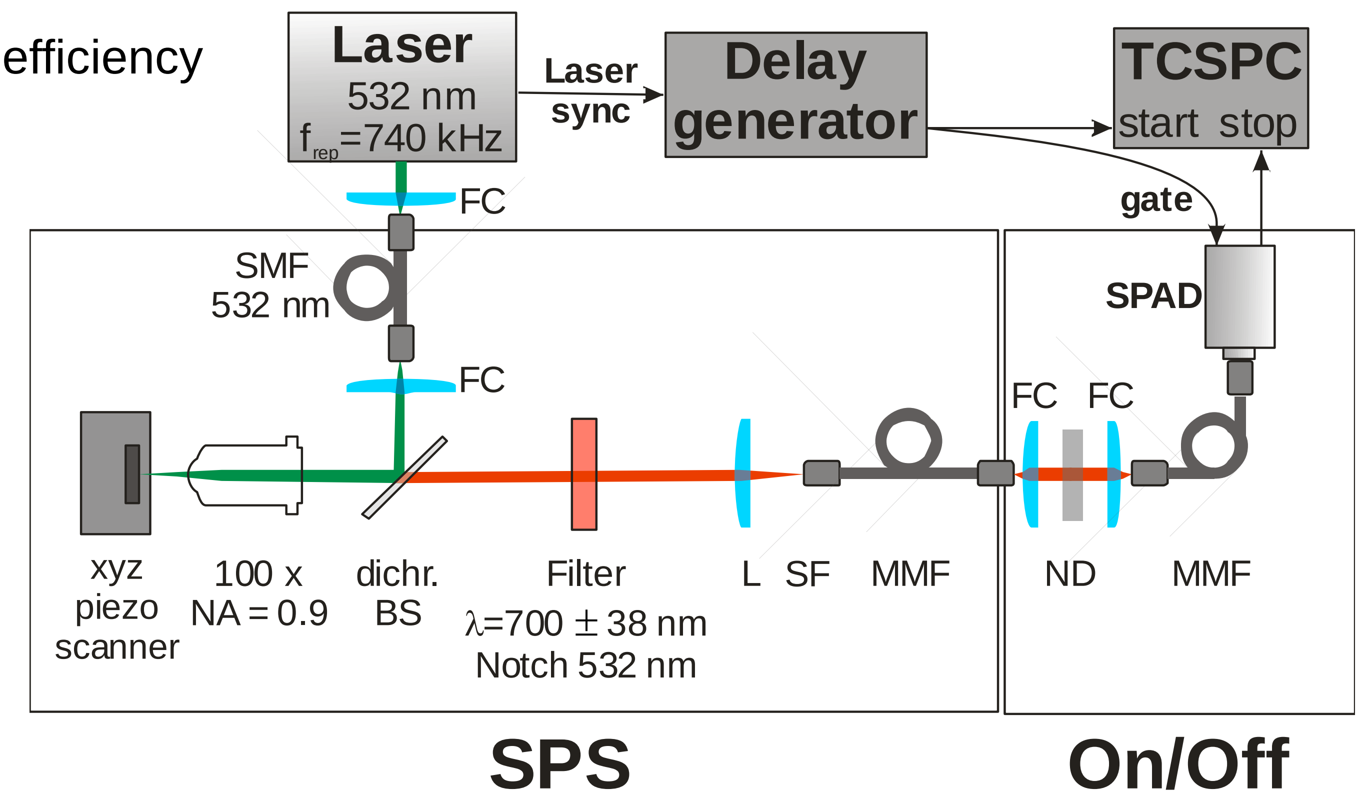
Information on the photon number distribution is gained from the ratio

$$f_\nu(\eta_\nu) = \frac{n_{0,\nu}}{n_\nu}$$

variable detection efficiency

$n_{0,\nu}$: number of "no-click" events

n_ν: total number of runs



Photon Statistics Reconstruction by On/Off measurements

Non-click probability for an on/off detector (APDs, ecc.) of quantum efficiency η_ν hit by a quantum optical fieldwith density matrix ρ:

$$P_\nu = p_0(\eta_\nu) = \sum_n A_{\nu n}\rho_n \qquad \begin{cases} A_{\nu n} = (1-\eta_\nu)^n \\ \rho_n = \langle n|\rho|n\rangle \end{cases}$$

η_ν = quantum efficiency

ρ = density matrix

Maximum-likelihood based constrained Log-likelihood probability function (on a truncated *N*-dimensional Hilbert space for the quantum optical field):

$$L_\beta = \sum_{\nu=1}^{K} f_\nu \cdot \log\left(\frac{P_\nu}{\sum_\lambda P_\lambda}\right) - \sum_{n=1}^{N} \beta\, n\rho_n$$

f_ν = fraction of non-click events

β = energy constraint

Obtained iterative solution (the apex (*i*) indicates something depending on the ρ_n at the *i*-th iteration):

$$\frac{\partial L_\beta}{\partial \rho_n} = 0 \quad \Rightarrow \quad \rho_n^{(i+1)} = \frac{\rho_n^{(i)}}{\sum_m \rho_m^{(i)}} \cdot \sum_{\nu=1}^{K}\left(\frac{A_{\nu n}}{\sum_\lambda A_{\lambda n} + \beta\, n\left(\frac{\sum_\gamma P_\gamma^{(i)}}{\sum_\mu f_\mu}\right)} \cdot \frac{f_\nu}{P_\nu^{(i)}}\right)$$

[1] Zambra et al. PRL **95**, 063602 (2005)

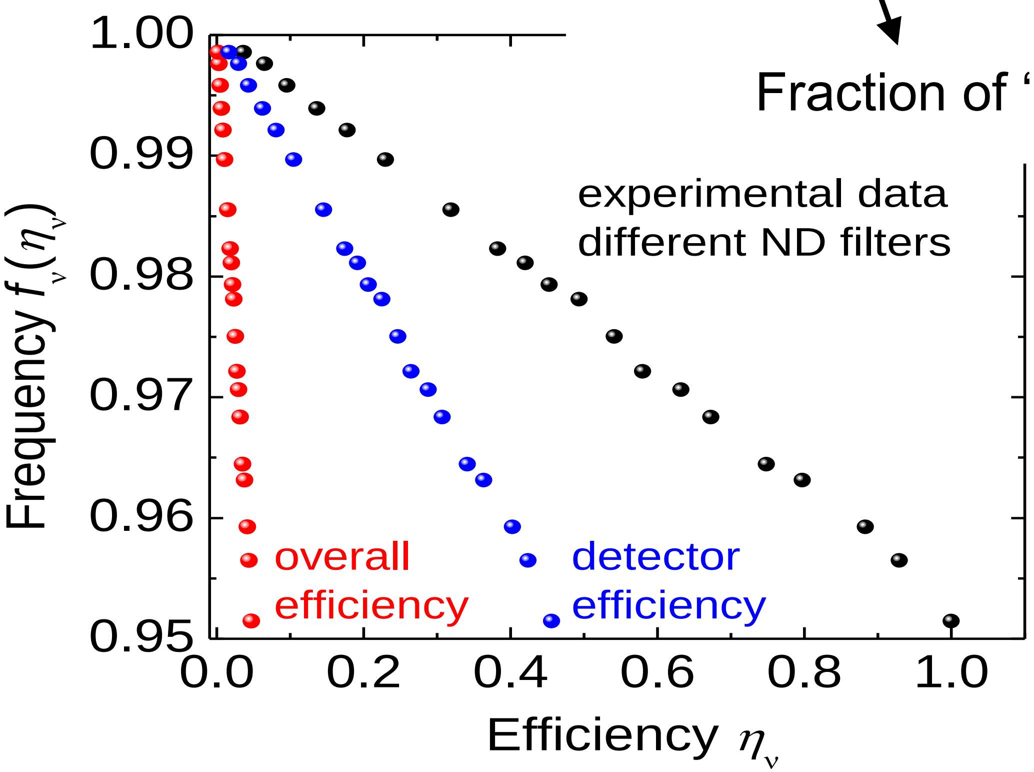
Maximum-likelihood estimation

… based on constrained **Log-likelihood probability** function

$$L_\beta = \sum_{\nu=1}^{K} f_\nu \log\left(\frac{p_0(\eta_\nu)}{\sum_\lambda p_0(\eta_\lambda)} \right) - \sum_{n=1}^{N} \beta \; n < n \,|\, \rho \,|\, n >$$

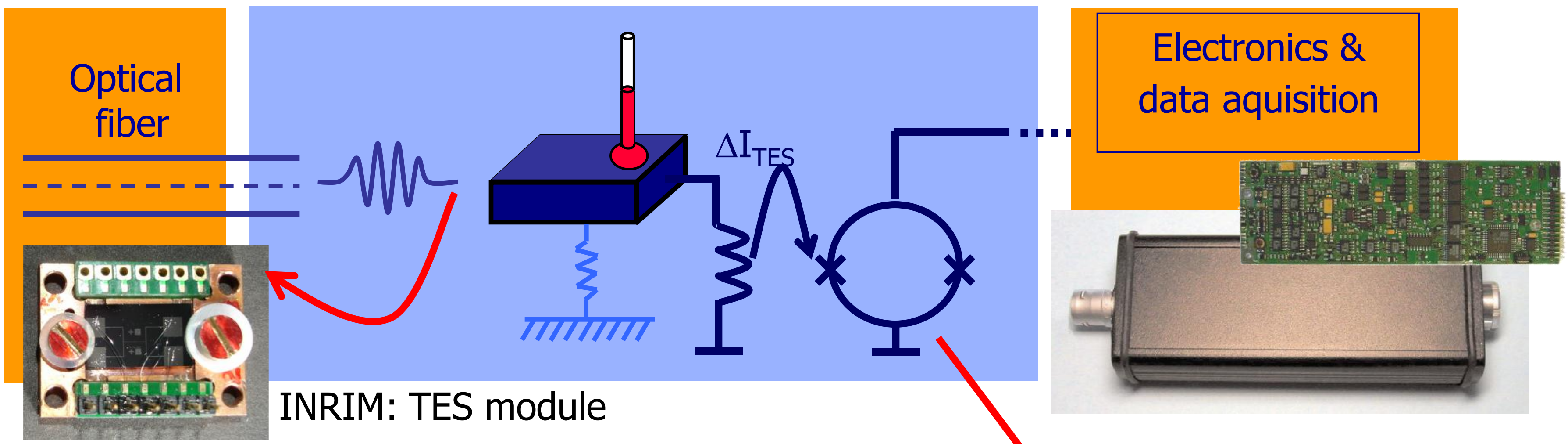
Fraction of ‘no-click’ events

Diagonal elements of the density matrix

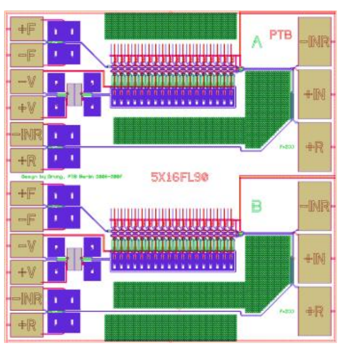


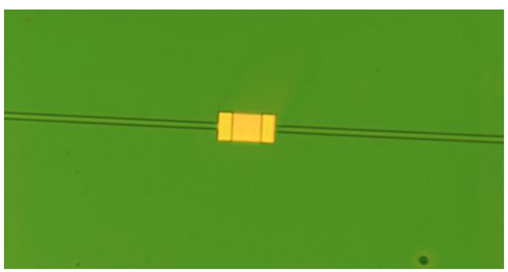
Zambra G. et. al. PRL, 2005, 063602

TES – Transition Edge Detector



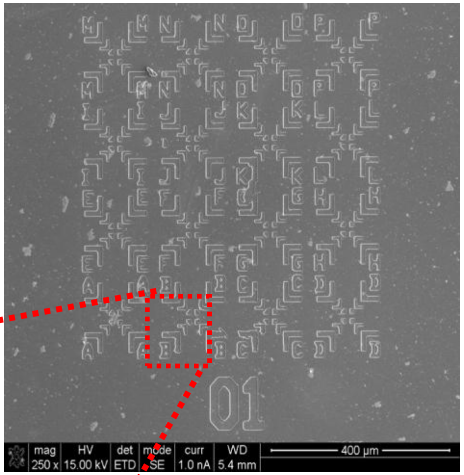
INRIM: TES module

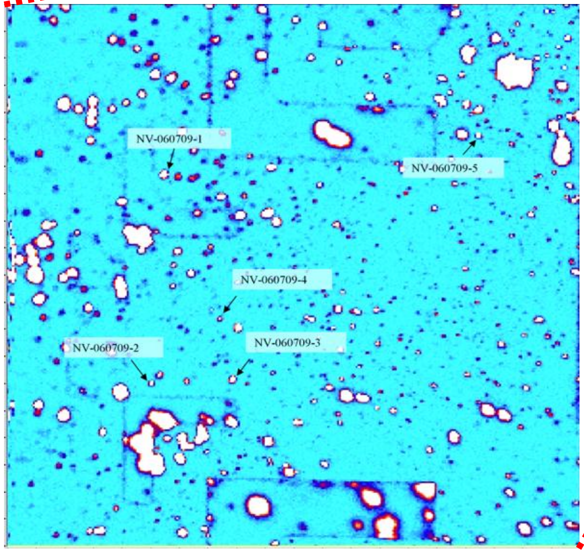




20 µm x 20 µm

Nano-diamonds with NV-centres





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