The evaluation of two InGaAsP/InP Geiger-mode avalanche photodiodes at NPL

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Why is the characterisation of photon counting systems important?

1. **Because it allows the uncertainty component associated with a particular characteristic (spectral responsivity, linearity, uniformity, temperature coefficient, etc) to be estimated and used to calculate the combined uncertainty.**

No characterisation – no uncertainty budget

2. **Suppliers of photo-detection systems exaggerate the capabilities of their products. They rely on the inability of their customers to verify their claims (Theo's 2nd Law).**

3. **There are differences in the performance of nominally identical products. It allows the selection of the detector with the best performance.**

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Parameters determining the performance of detectors

1. The relative spectral radiant power responsivity.
2. The absolute spectral radiant power responsivity.
3. The Noise Power Spectral Density and NEP/NEI
4. Spatial uniformity of response
5. Linearity/non-linearity of response
6. Temperature coefficient of response
7. Temporal of response
8. Stability with time/ageing or fatigue

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The identification of certain commercial equipment in this paper does not imply recommendation or endorsement by the authors nor does it imply that the equipment identified are the best available for the purpose.

- The performance of two nominally identical InGaAsP/InP Single-Photon Avalanche Photodiode (SPAD)-based photon counting systems was investigated.
- The two SPAD Model id400 detection systems were purchased (by my colleagues!) from id Quantique SA, Switzerland for measuring correlated photons produced by parametric down-conversion.
- Each id400 detection system is based on the PGA285 avalanche photodiode fabricated by Princeton Lightwave.
- Each id400 SPAD detection system consists of an id401-80 detection head and an id40x control unit.
- The detection head contains the InGaAsP/InP Avalanche PhotoDiode (APD) mounted on a 3-stage thermoelectric cooler capable of cooling the APD down to –40 ^{o}C.

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Description of the detectors

- Each id400 APD had a circular active area of 80 μm diameter.
- It was sensitive to wavelengths in the 900 nm to 1150 nm range.
- The APD can be operated under three different **single photon detection probability** values (7.5%, 15% and 30%), which correspond to three different **bias voltages**.
- The single photon detection probability values were calibrated by id Quantique at the 7.5%, 15% and 30% levels using a Perkin Elmer SPCM-AQR detector as a transfer standard.
- The characteristics of the id400 detection systems were investigated for 1 μs and 10 μs dead-time settings.
- Both id400 detection systems were operated in the "free-running" Geiger mode throughout this evaluation.

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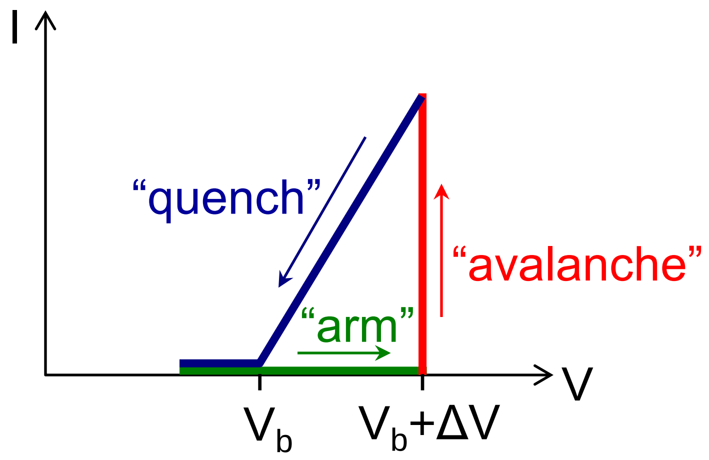
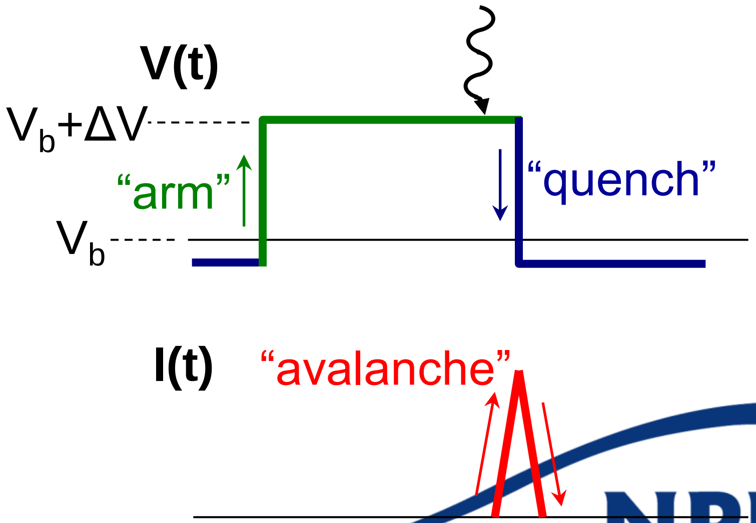
Geiger mode operation

- **Single photon avalanche diode (SPAD) operation in "Geiger mode"**
  - Photon-activated switch with purely digital output
  - "Arm": apply overbias ΔV beyond breakdown voltage V_b
  - "Avalanche": single photon induces macroscopic current pulse
    - Detect using threshold detection circuit
  - "Quench": Terminate avalanche by lowering bias below V_b

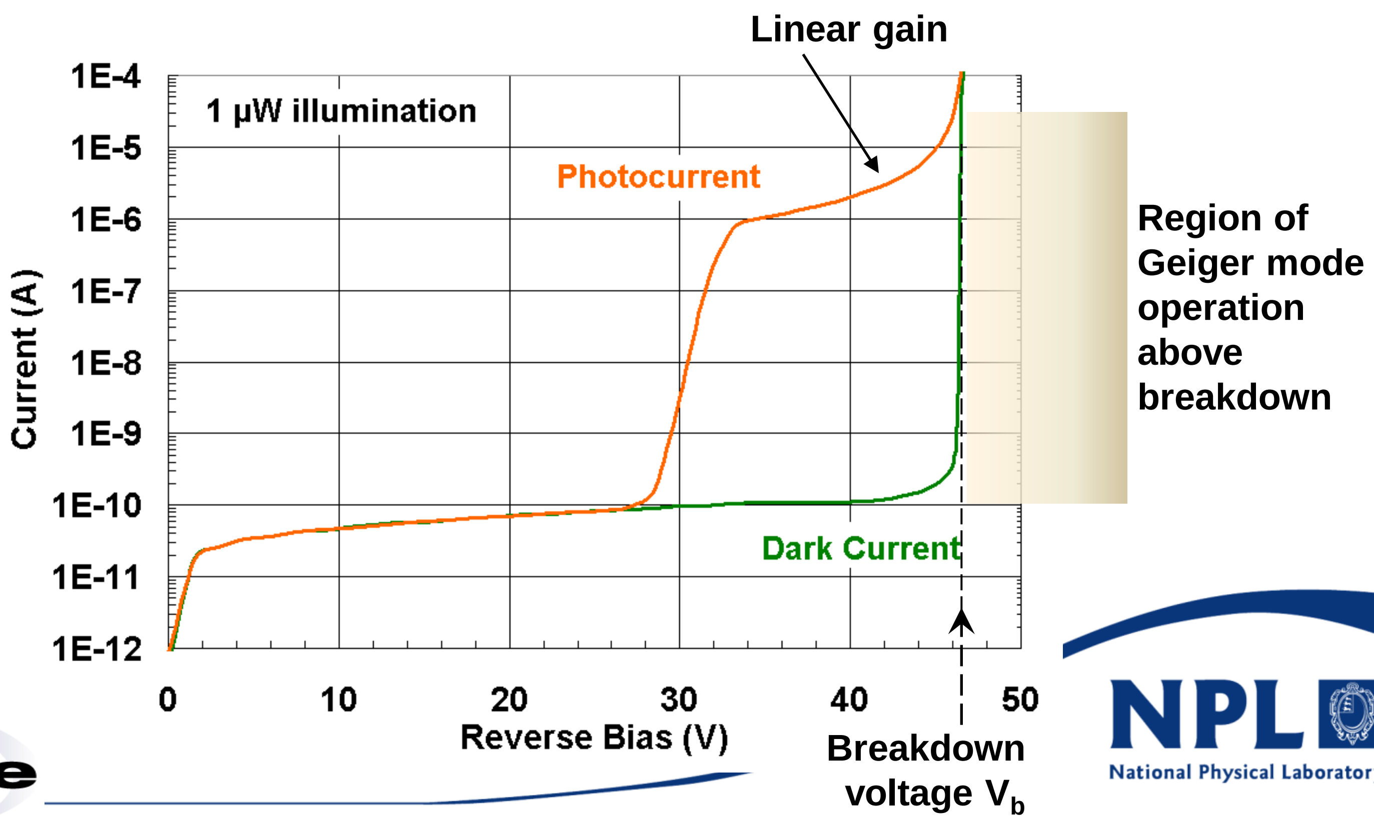




- For the benefit of this evaluation, the two nominally identical systems were designated as id400-A and id400-B detection systems.

APD Current-Voltage Characteristics

- **Linear mode performance defines behavior below breakdown voltage V_b**
  - Photocurrent below V_b is proportional to optical power
  - InP-based APD linear mode operation optimized for modest gains of 10 – 20
- **Geiger-mode performance has different device considerations**
  - Operation above V_b to achieve runaway avalanches (typically 10^6 to 10^8 carriers)



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I will not deal with spectral responsivity/quantum efficiency measurements because the customer did not pay for that service!

For information on the characterisation of the spectral responsivity of photon counting systems at NPL see:

Biller et al,

“Measurement of photomultiplier single photon counting efficiency for the Sudbury Neutrino Observatory”,

***Nuclear Instruments and Methods in Physics Research*,**

A 432, 364-373, 1999

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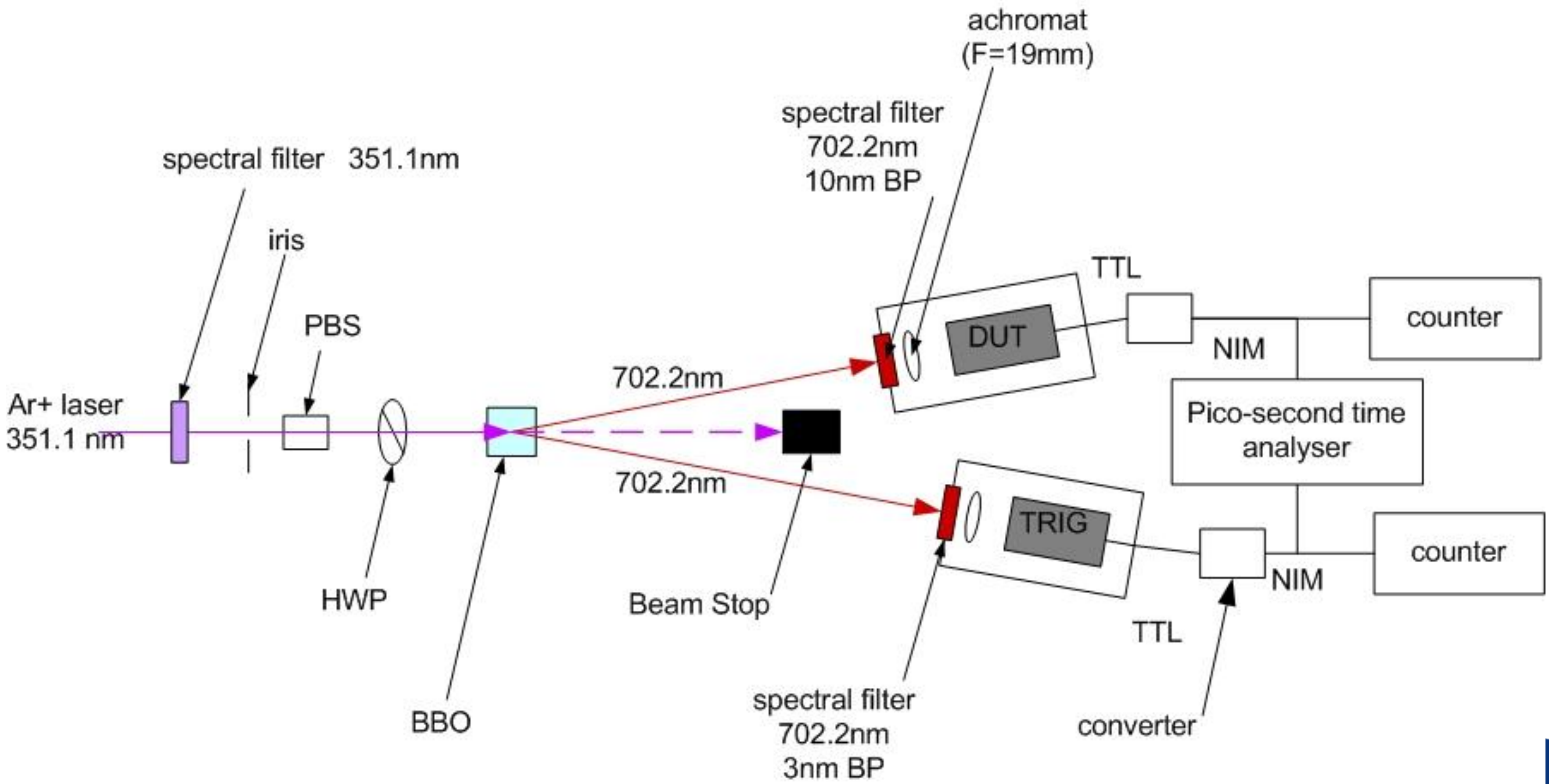
NPL quantum efficiency measurements using correlated photons

Cheung et al. "The Quantum Candela – a re-definition of the standard units of optical radiation", Journal of Modern Optics, **54**, 373-396, 2007

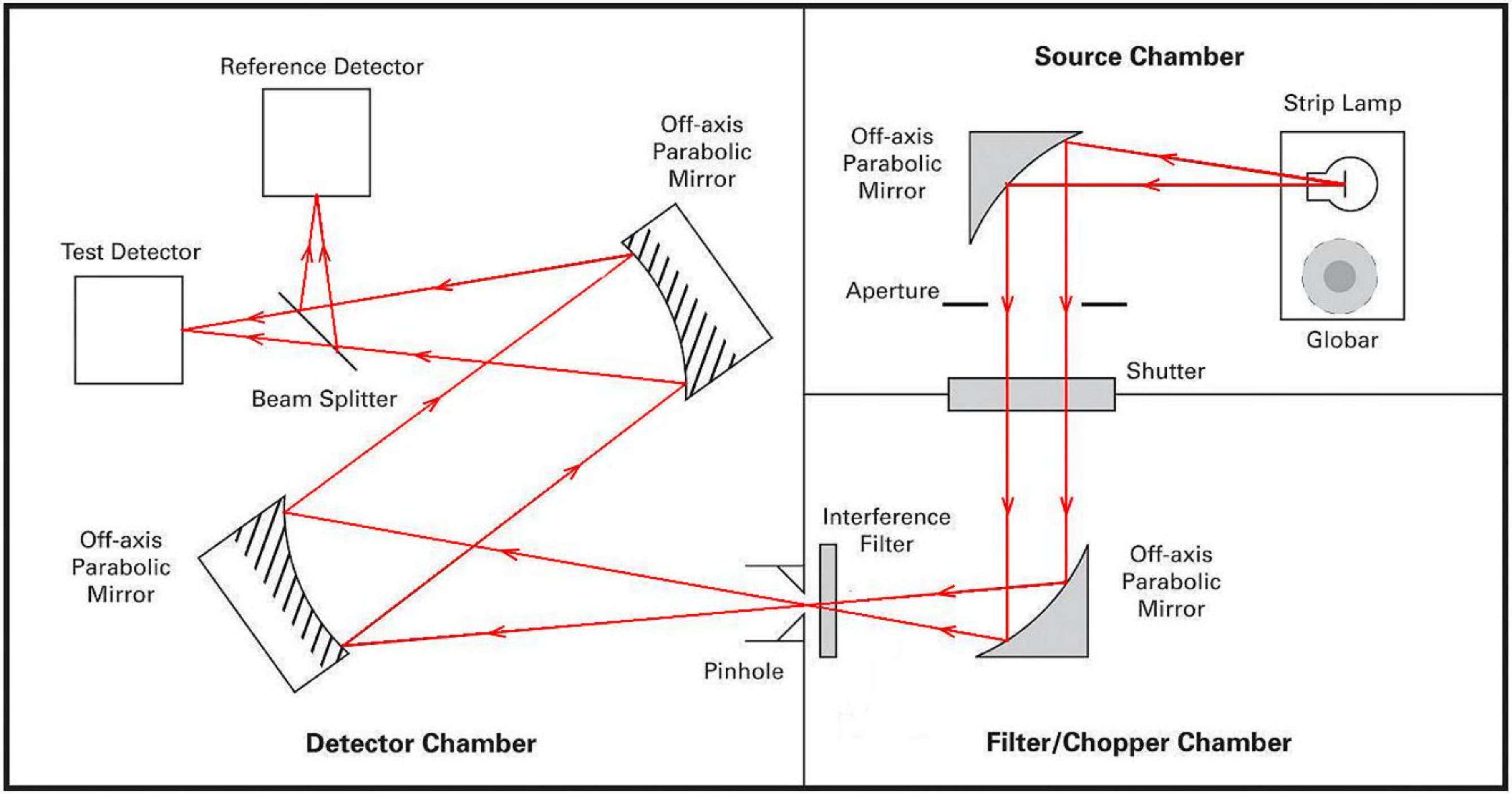


Spatial Uniformity of Response Characterisation

- **Spatial uniformity of response** defines the variations in the responsivity of a detection system at different points on its active area.

- I define "spatial non-uniformity of response" as the maximum percent deviation of the response from the maximum response.

Layout of the spatial uniformity of response measurement facility



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Settings for spatial uniformity measurements

- A pinhole of 22 μm diameter was used for all measurements described in this document.
- The pinhole was (optically) de-magnified by approximately a factor of 3 by the optical system employed by the facility. This ensured that a spot of 8 μm in diameter was illuminating the active area of the test detector during the evaluation.
- The spatial uniformity plots generated, represent the convolution of the actual spatial uniformity plot of the detectors under evaluation and the spatial profile of the illuminating spot, hence the diameter of the illuminating spot was kept to 8 μm.
- The F/number of the incident beam was limited to F/30 in order to increase the "depth of field" and relax the requirement of focusing the spot on the active area of the test detector.
- The power of the incident beam was attenuated to ensured that the test detector output was well away from its non-linear range of operation.

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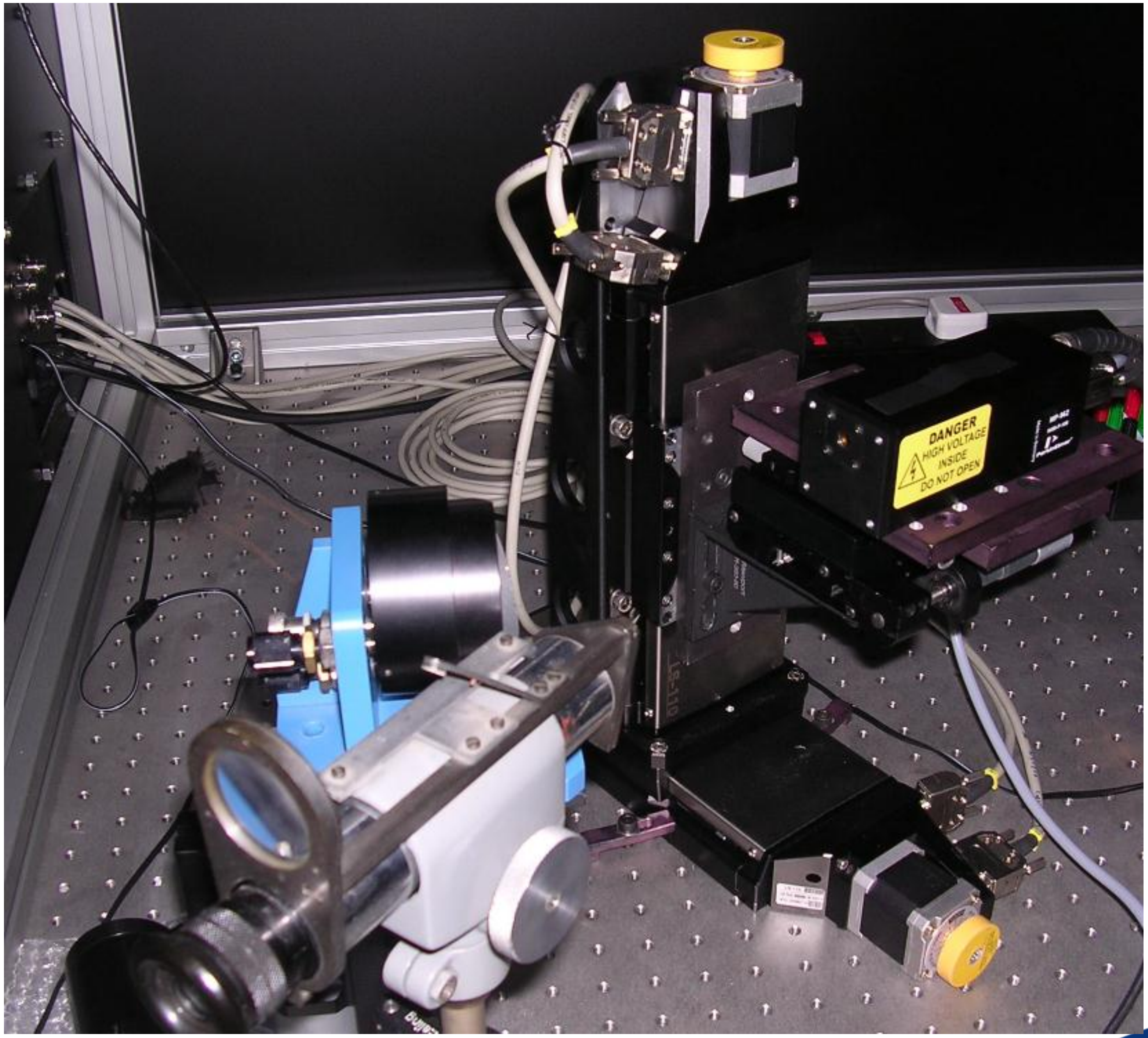
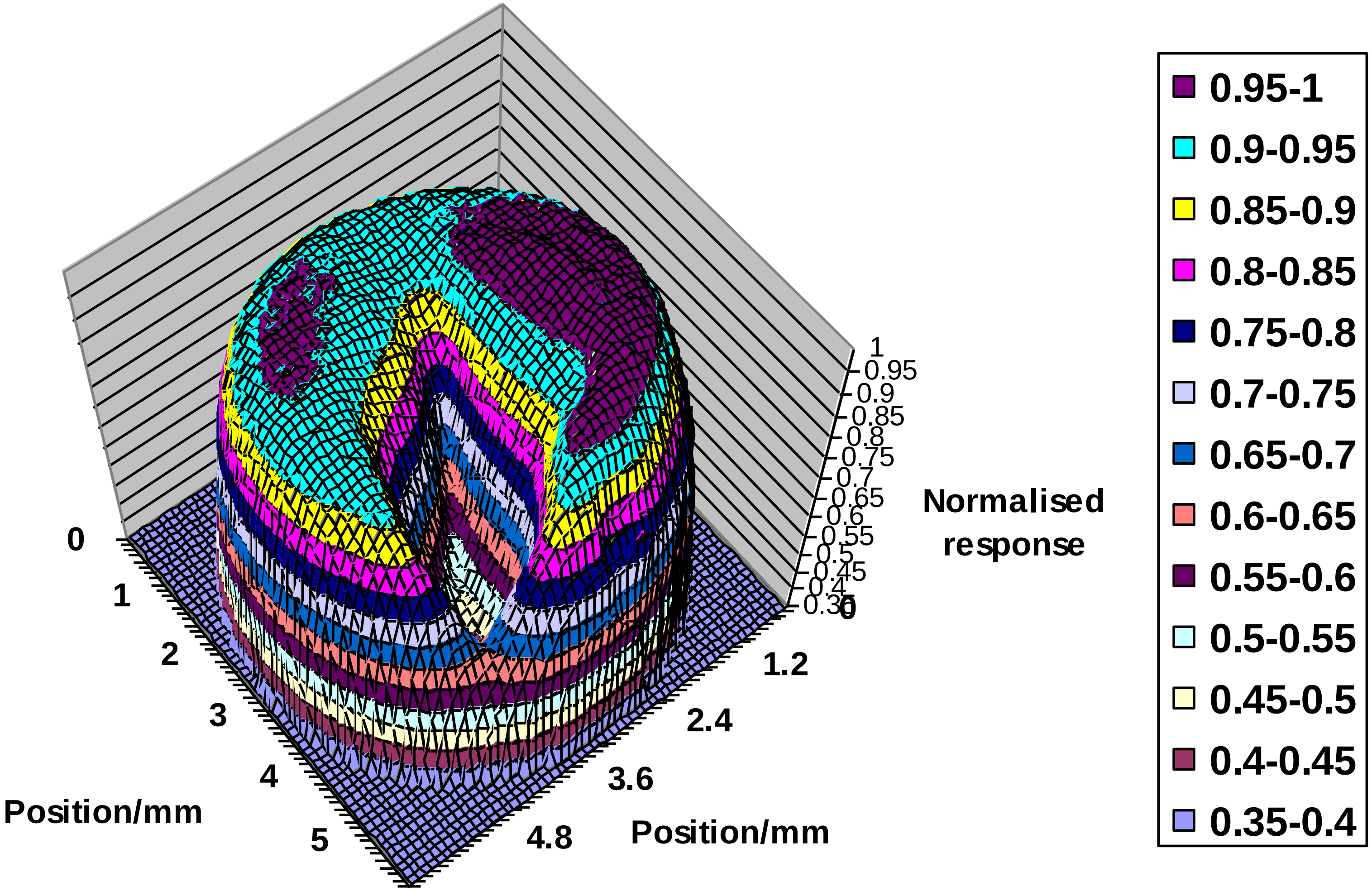
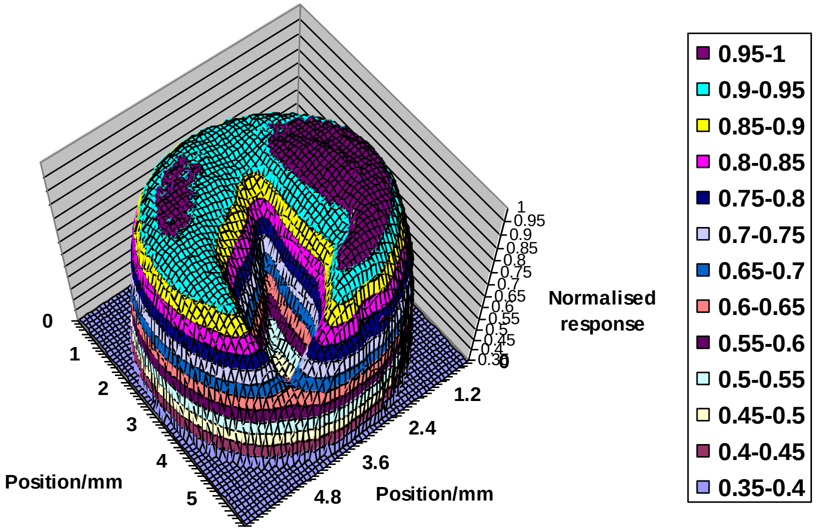
Photon counting system "linearity" evaluation

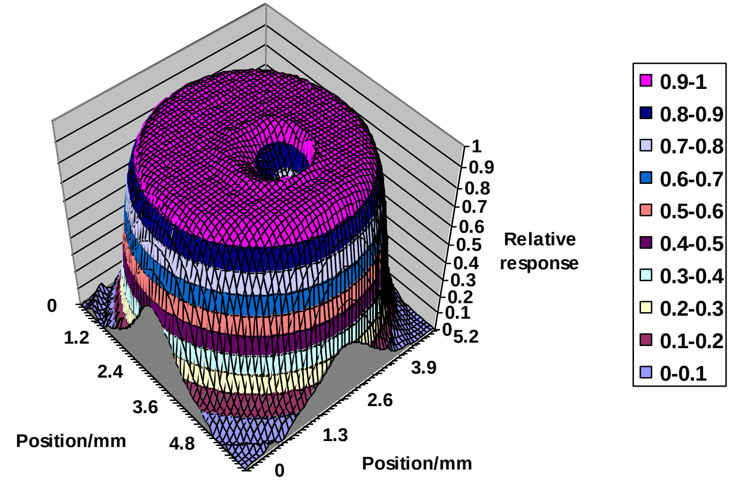


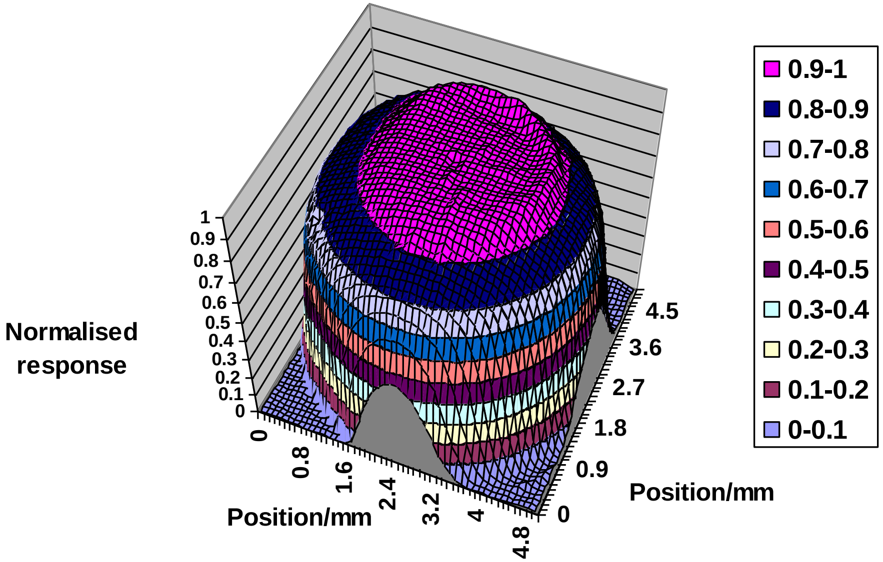
Spatial uniformity of response of the MP 962-A photon counting system at 400 nm, using a 50 μm spot.



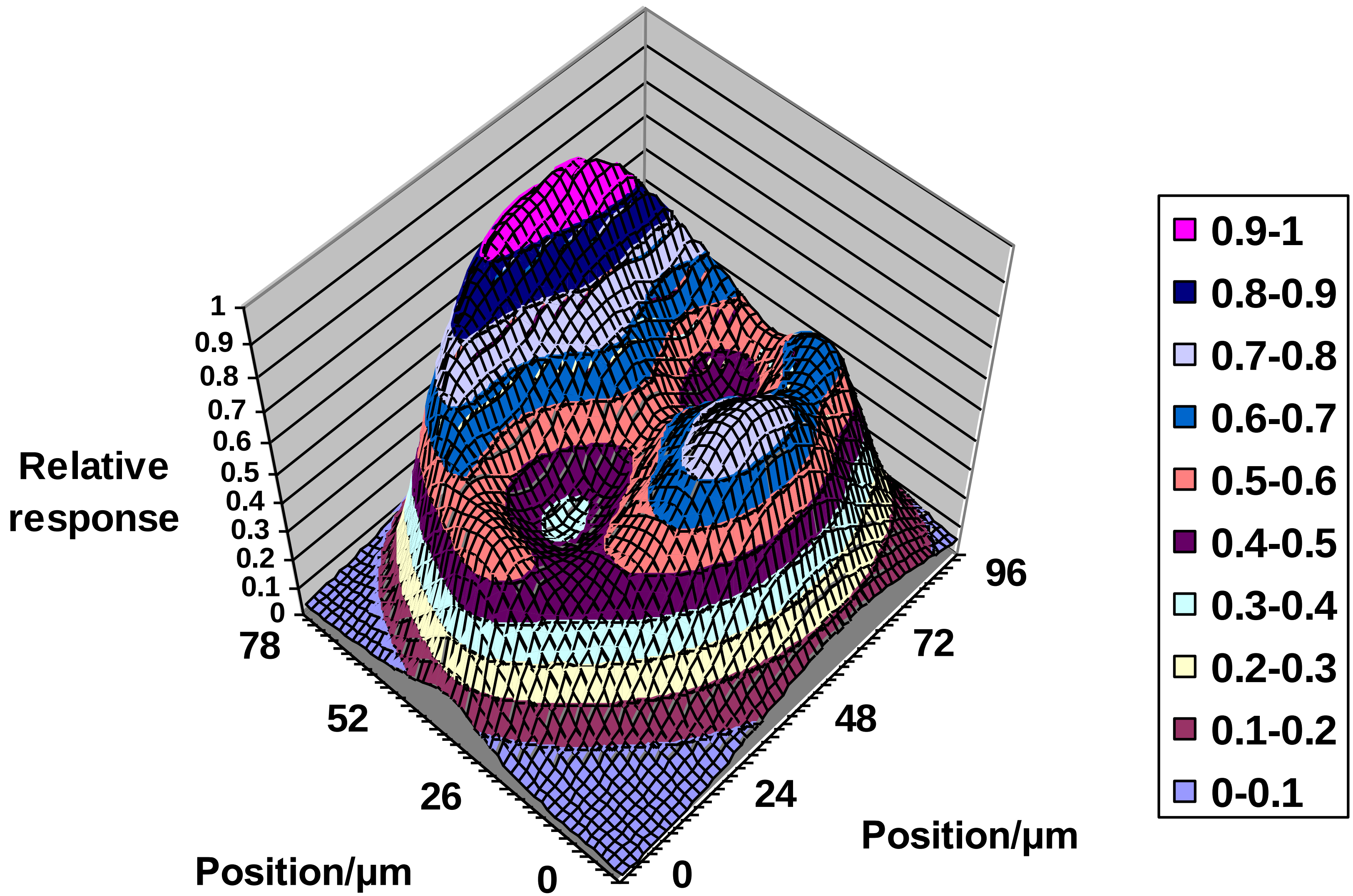
Spatial uniformity of response of the MP 962-A, -B and -C photon counting systems at 400 nm, using a 50 μm spot.



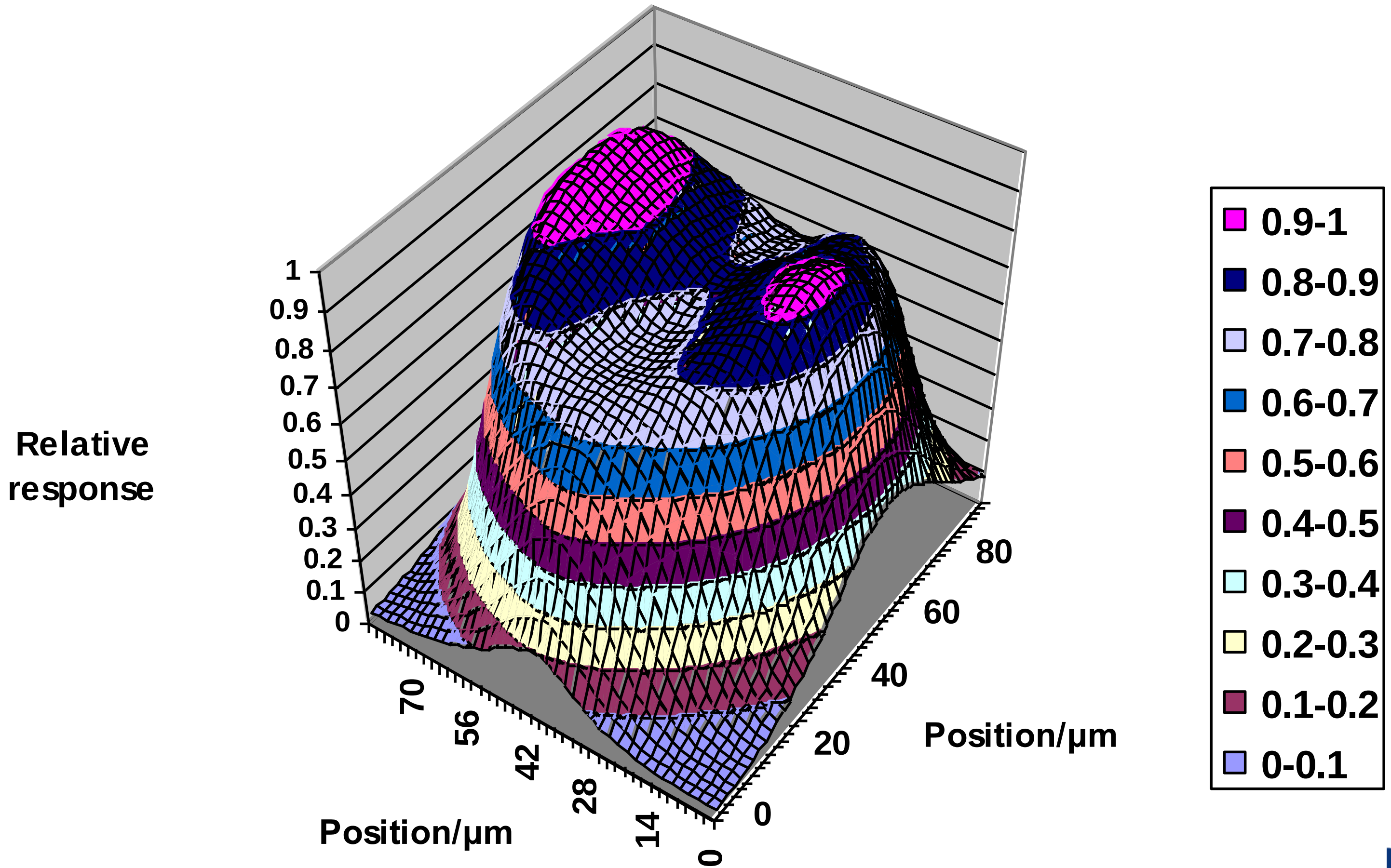




The spatial uniformity of response of the id400-A InGaAsP/InP photon counting system, measured at 1064 nm, with 10 μs dead-time and a 7.5% single photon detection probability value.



The spatial uniformity of response of an id400-A InGaAsP/InP photon counting system, measured at 1064 nm, with 10 µs dead-time and a 15% single photon detection probability value.



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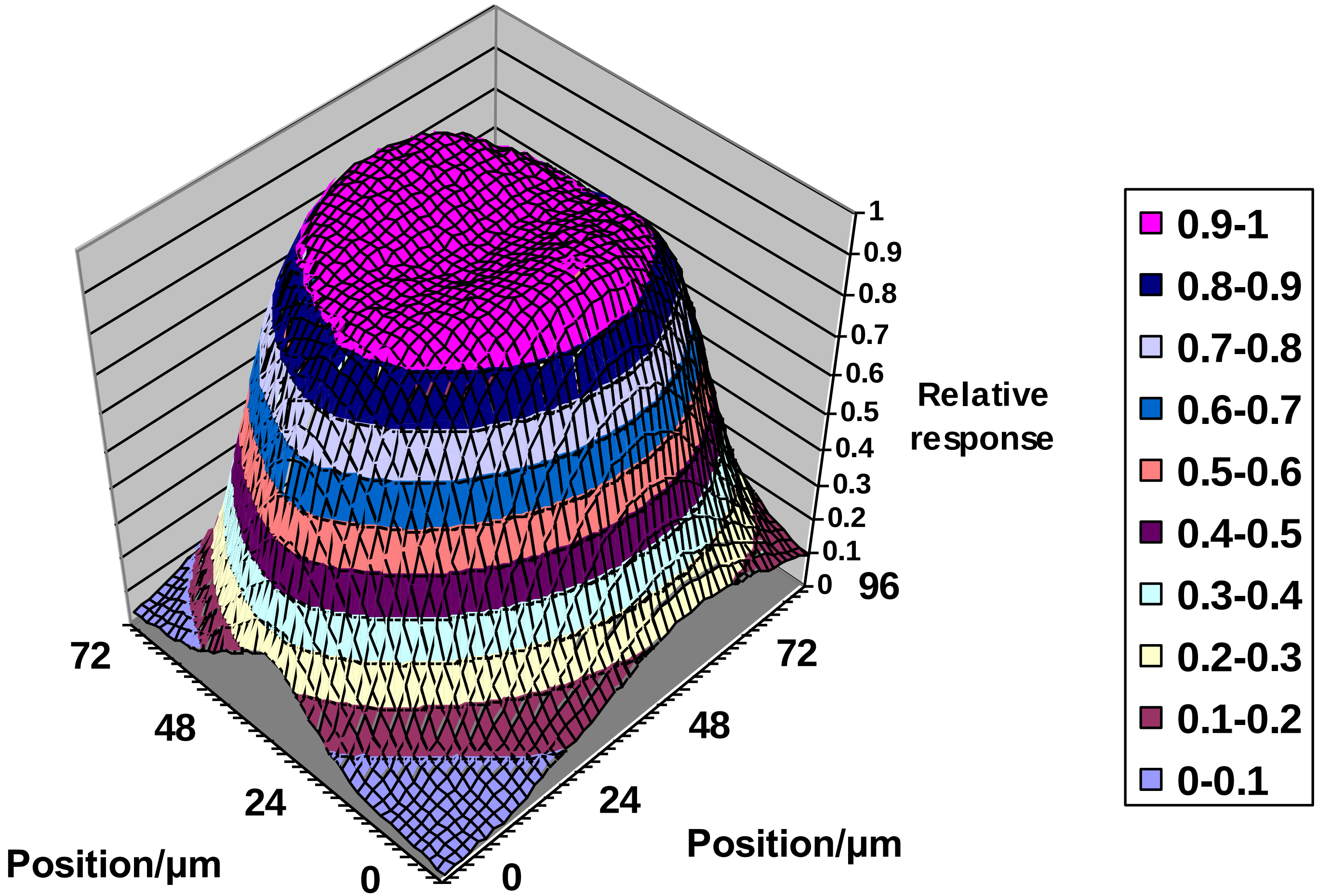
The spatial uniformity of response of the id400-A InGaAsP/InP photon counting system, measured at 1064 nm, with 10 μs dead-time and a 30% single photon detection probability value.



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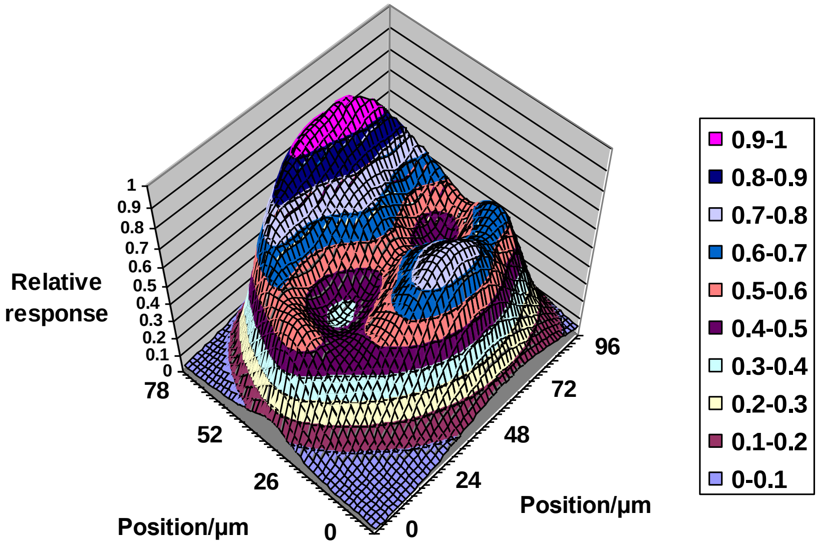
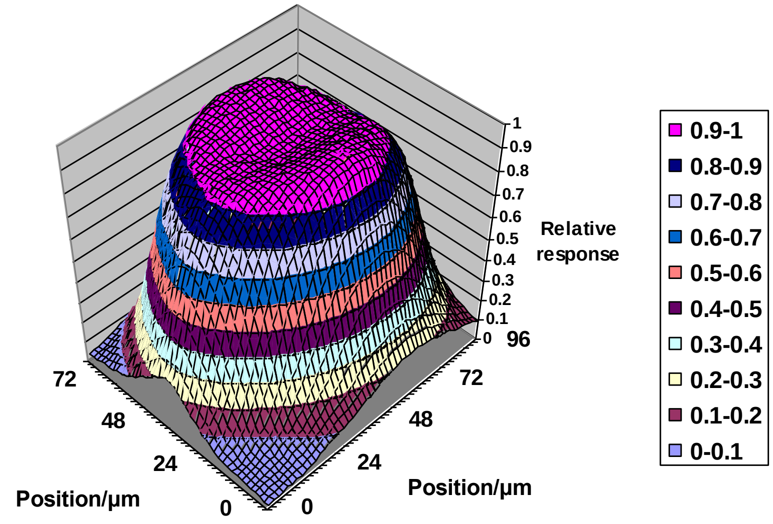
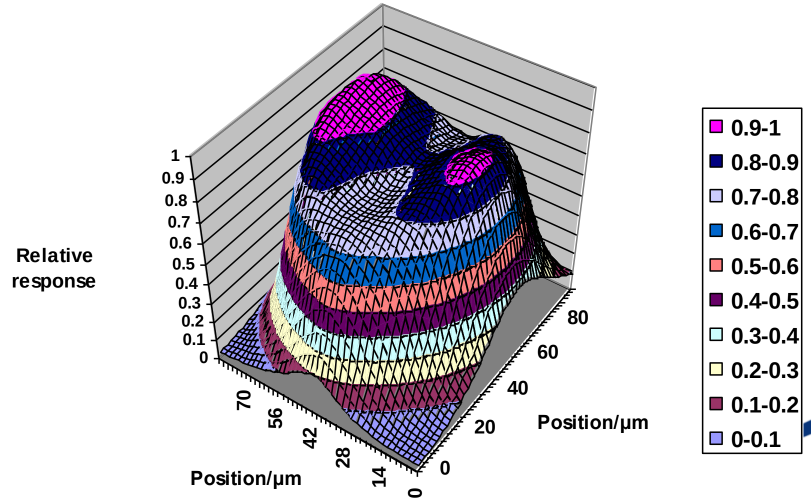
The spatial uniformity of response of an id400-A, measured at 1064 nm, with 10 μs dead-time and 7.5%, 15% and 30% single photon detection probability values.







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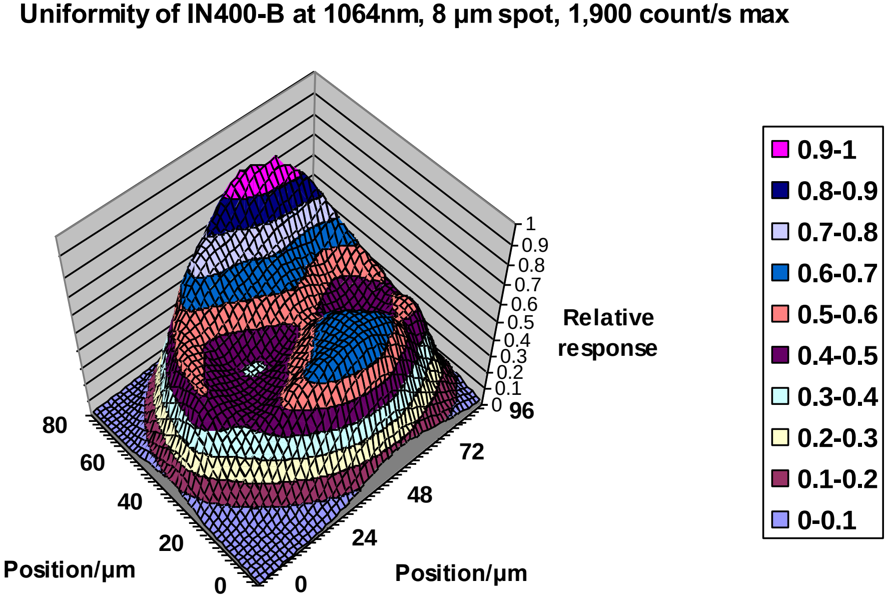
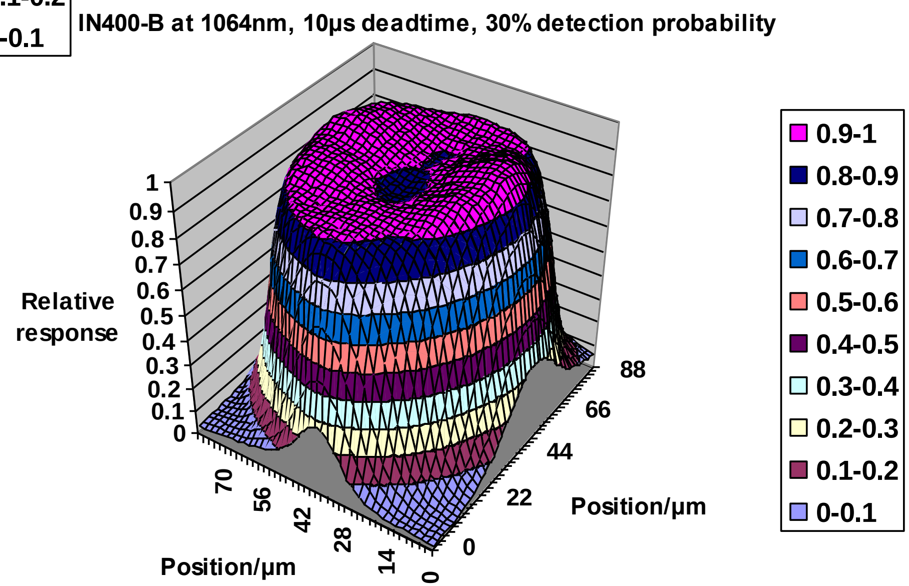
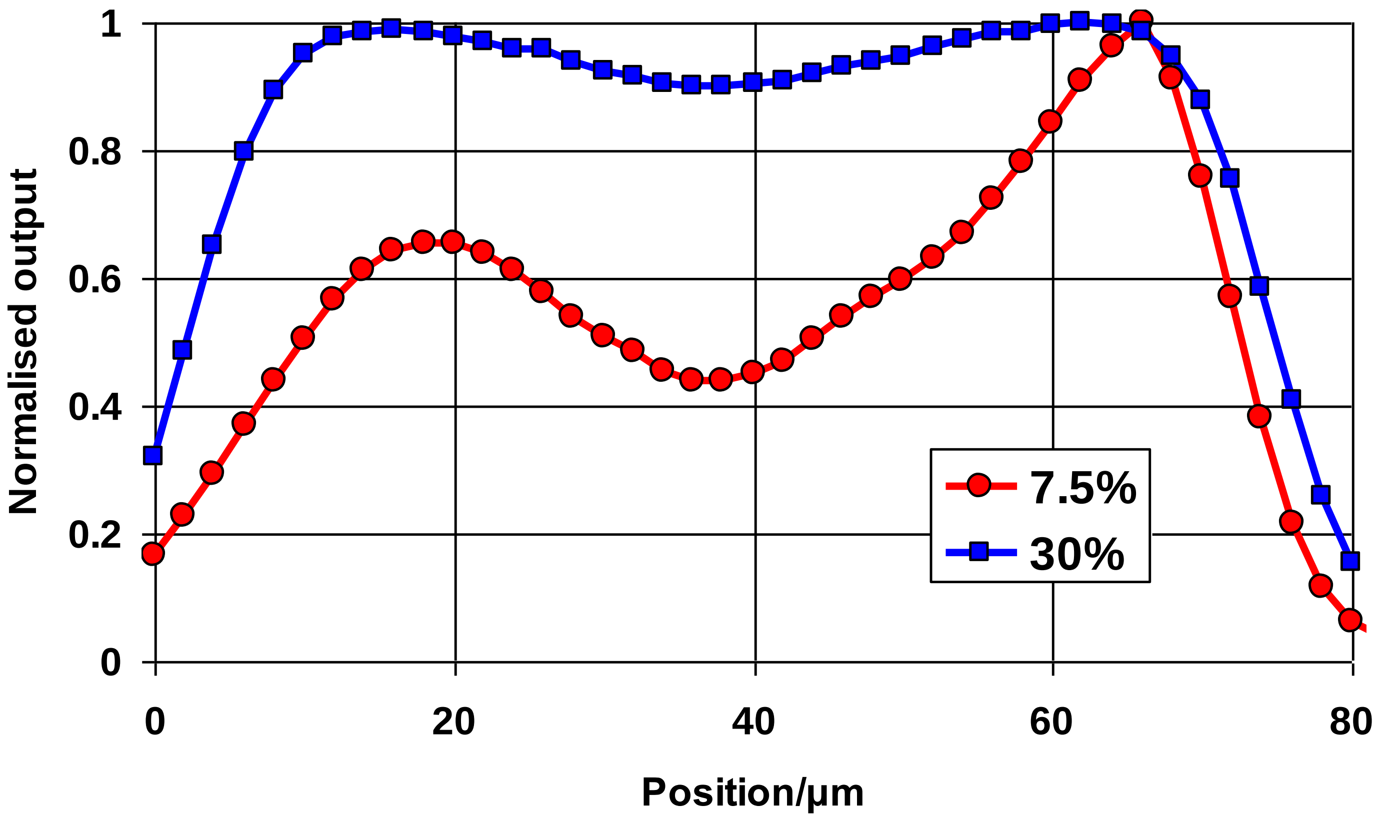
The spatial uniformity of response of the id400-B photon counting system, measured at 1064 nm, with 10 μs dead-time and a 7.5% and 30% single photon detection probability values.





Normalised output count rate of detector id400-B when the 8 μm diameter spot was scanned in one direction through the centre of the active area of the detector for a 7.5% and a 30% single photon detection probability.



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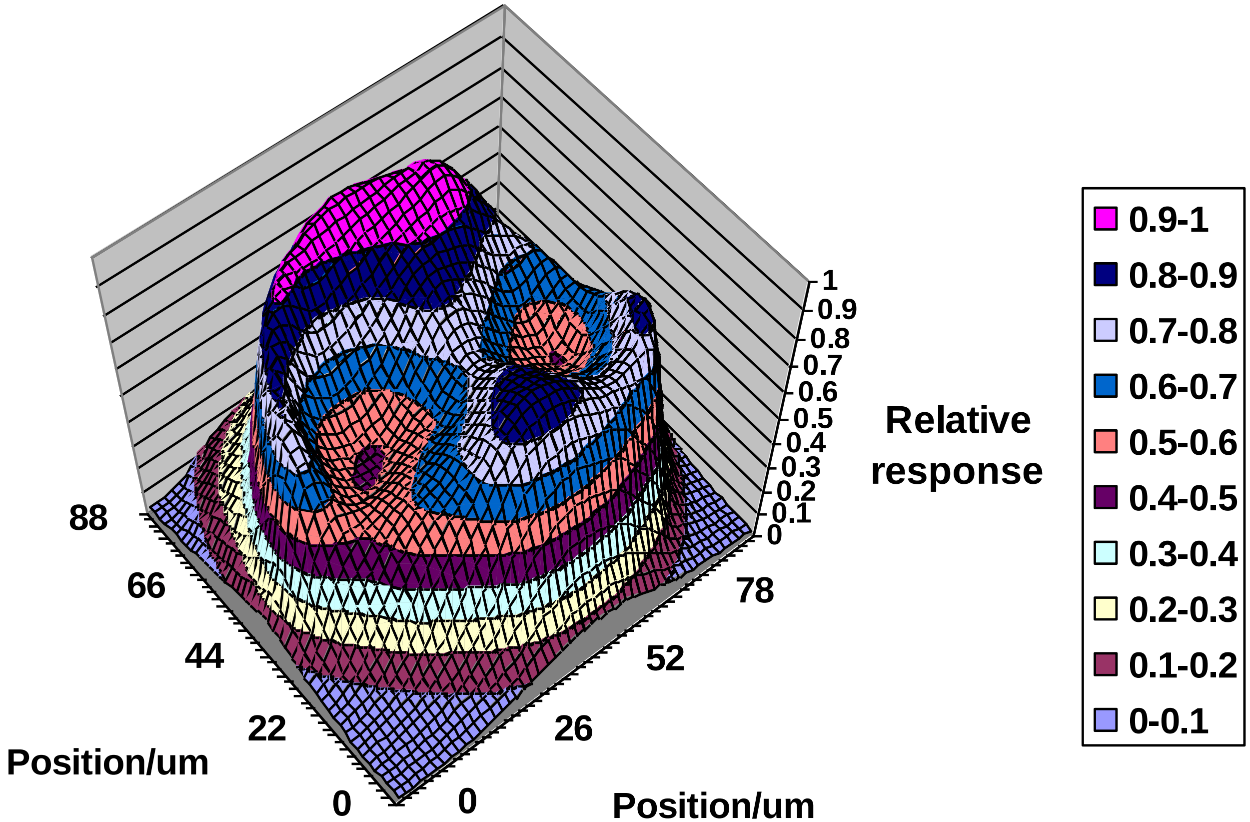
The spatial uniformity of response of the id400-A detector measured at 900 nm, with 10 μs dead-time and a 7.5% single photon detection probability value.



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Discussion on spatial uniformity of response measurements

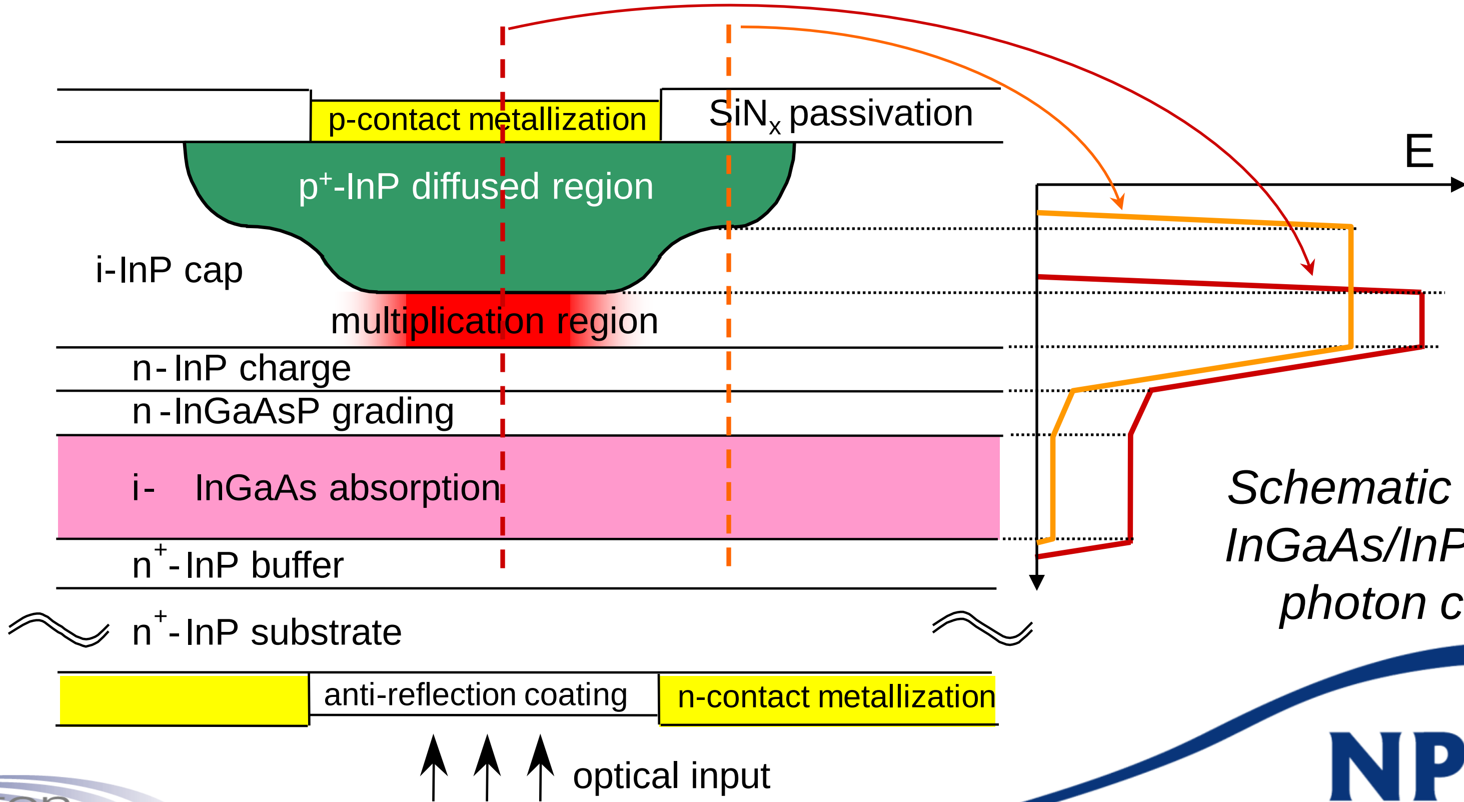
- **The observed spatial non-uniformity of response can be linked to non-uniformity in the breakdown voltage V_b across the active area of the Single Photon Avalanche Photodiode.**

- The planar diode structure is fabricated using a dopant diffusion technique, and a quasi-cylindrical junction profile that forms at the perimeter, tends to enhance the local electrical field amplitude.

- **Due to the very sensitive dependence of avalanche gain on electric field, this local field enhancement in the device periphery leads to higher avalanche gain at the device edge and to the so-called "edge breakdown" effects.**

Avalanche photodiode structure

- **Impact ionization process provides internal gain (avalanche multiplication)**
- **Separate absorption, grading, charge, and multiplication (SAGCM) structure**
  - Carrier collection in absorber: low but finite E-field to minimize dark carriers
  - Multiplication region: high field to create gain impact ionization
- **Control of 3-D electric field distribution to avoid edge breakdown**



Schematic design for InGaAs/InP SPAD for photon counting

Princeton Lightwave

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Discussion on spatial uniformity of response measurements: B

- Various techniques have been developed to suppress edge breakdown.
- **For the diodes characterized in this study, edge breakdown is reduced by implementing a pair of concentric dopant diffusions that provide a junction profile with a recessed peripheral region that corresponds to a wider avalanche region.**
- However, **any misalignment in the photolithography process** used to create the diffusion masks for these two diffusion steps **can lead to non-concentricity of the diffusions**.
- A resulting non-uniformity in the peripheral junction profile can then lead to non-uniformity in V_b.

Discussion on spatial uniformity of response measurements: G

- **Micrographs of the fabricated devices confirm the existence of a relative offset of ~2 μm between the two diffusions, whereas devices from different fabrication runs that do not exhibit such edge peaking have diffusion misalignments no greater than ~0.5 μm.**

- **Wafer-level characterisation of the epi-structure by Fourier Transform Infrared (FTIR) spectroscopy indicates that epi-layer thicknesses are uniform across the 50 mm diameter wafer to better than ±0.5%, and so it is very unlikely that epitaxial variations could give rise to the observed response variations on the scale of the diameter of a single device.**

Paper describing our work on the two id400 InGaAsP/InP Geiger-mode avalanche photodiodes

E. Theocharous et al.,

"The characterisation of the linearity of response and spatial uniformity of response of two InGaAsP/InP Geiger-mode avalanche photodiodes"

IEEE Journal of Quantum Electronics, 46, 1561-1567, 2010.

Princeton Lightwave manufactures the id400 InGaAsP/InP Geiger-mode avalanche photodiodes

- Princeton Lightwave offered NPL more (this time FREE) samples for evaluation (provided they get the results).
- NPL declined the offer
- Princeton Lightwave have assembled their own Spatial Uniformity of Response characterisation facility and use it as part of their quality control.
- **Copying is the best form of flattery!**

Linearity of response evaluation

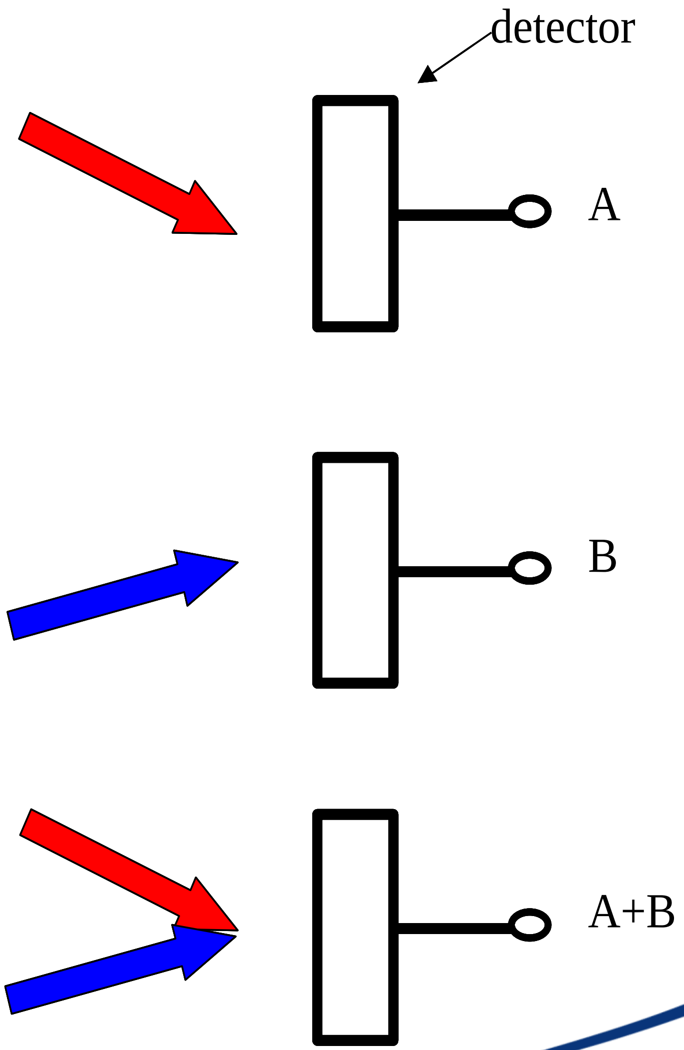
A detection system is linear if the output is directly proportional to the input

Linearity is a seriously neglected parameter

Linearity is almost always assumed (and rarely measured)

At NPL we favour ABSOLUTE linearity measurement methods based on power/irradiance superposition.

Accomplished by superimposing two beams.



Definition of the Linearity Factor

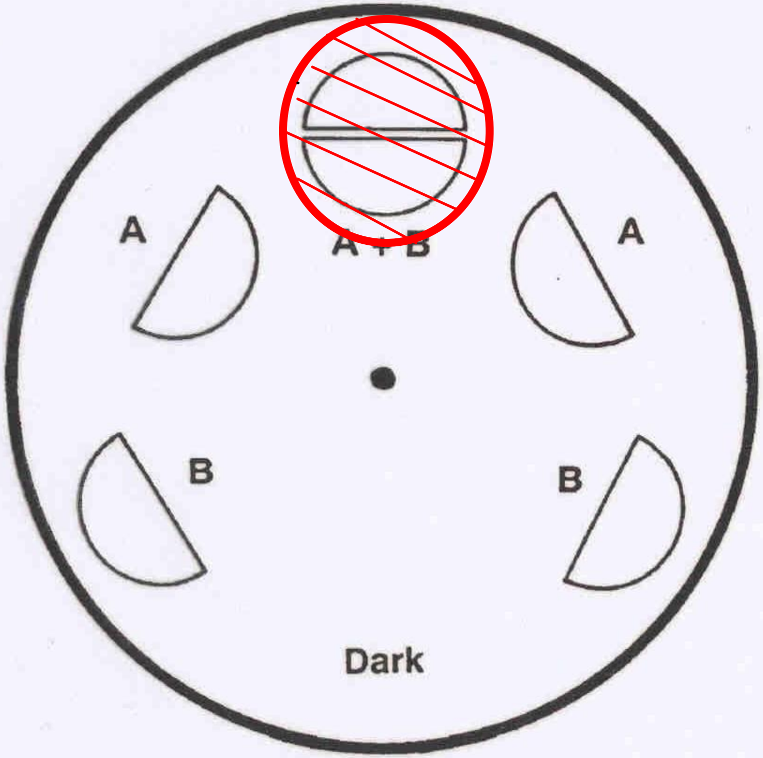
It represents a measure of the linearity of the detector for an output of $(N_A+N_B)/2$ and its value is calculated from:

$$L(N_{A+B}) = \frac{N_{A+B}}{(N_A + N_B)}$$

Where N_A and N_B represent the dark-corrected output count-rates from the photodetection system when two optical signals A and B illuminate the photodetection system respectively, whereas N_{A+B} represents the corresponding output when the two optical signals A and B illuminate the photodetection system at the same time. N_A is chosen to be approximately equal to N_B.

For a truly linear photodetection system, the value of $L(N_{A+B})$ will be equal to unity. Where $L(N_{A+B})$ deviates from unity, it can be used to estimate correction factors to apply for different count-rates to transfer the absolute responsivity calibration of a detection system from one output count-rate to another.

Double-aperture disk

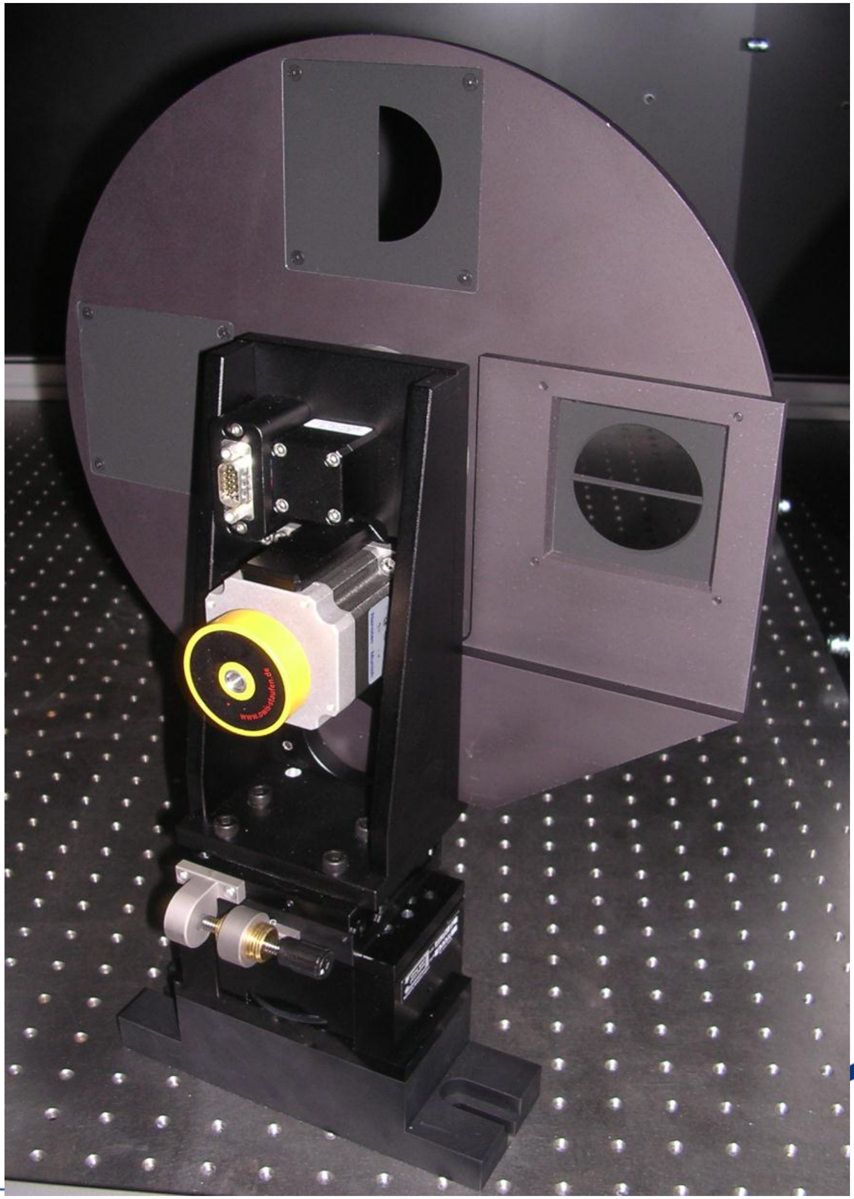


Linearity Wheel

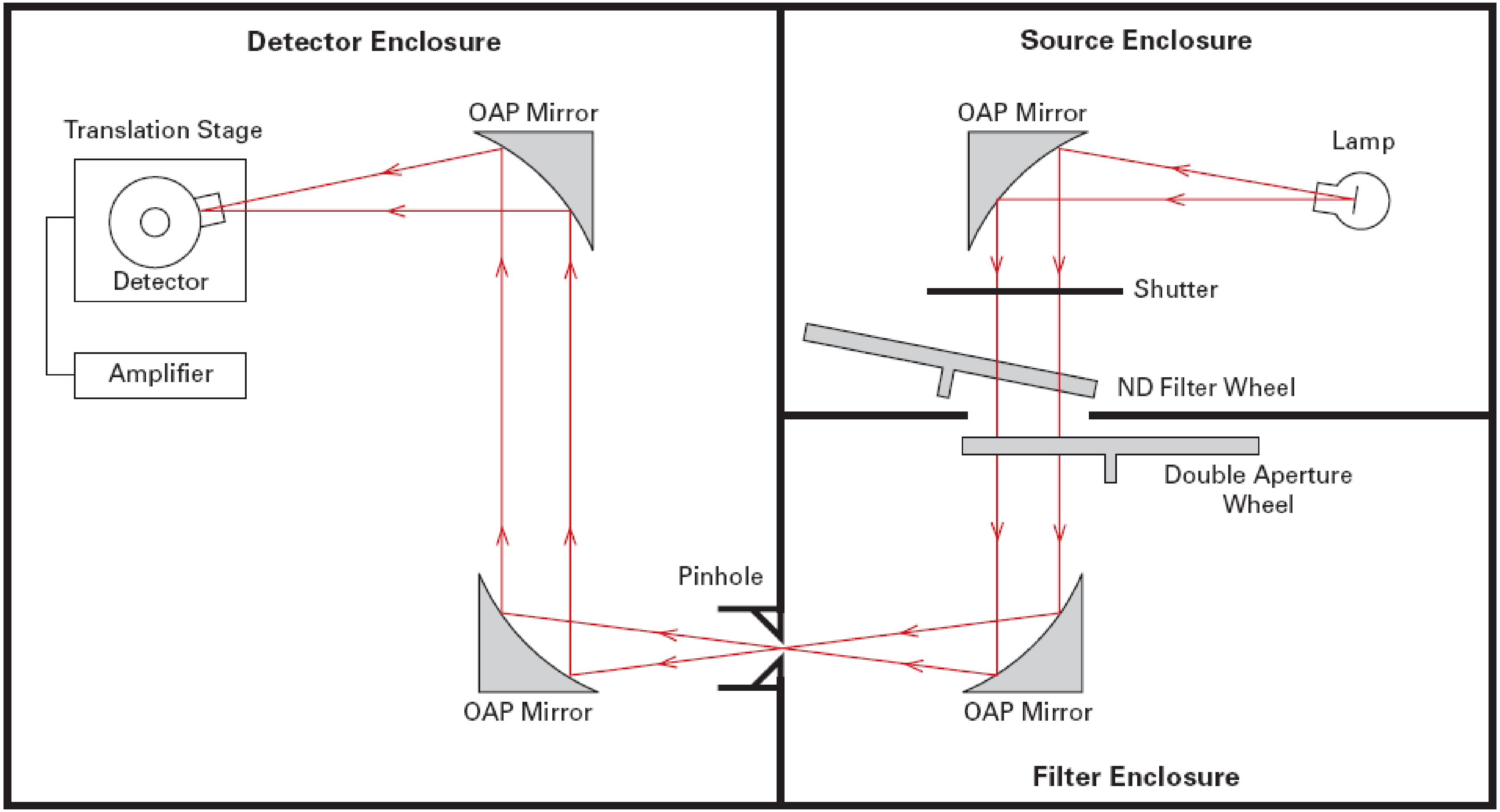
Linearity Factor = $S_{A+B} / (S_A + S_B)$

where : S_{A+B} = Signal A + B
S_A = Signal A
S_B = Signal B

The “double aperture” wheel



Layout of the NPL linearity of response measurement facility



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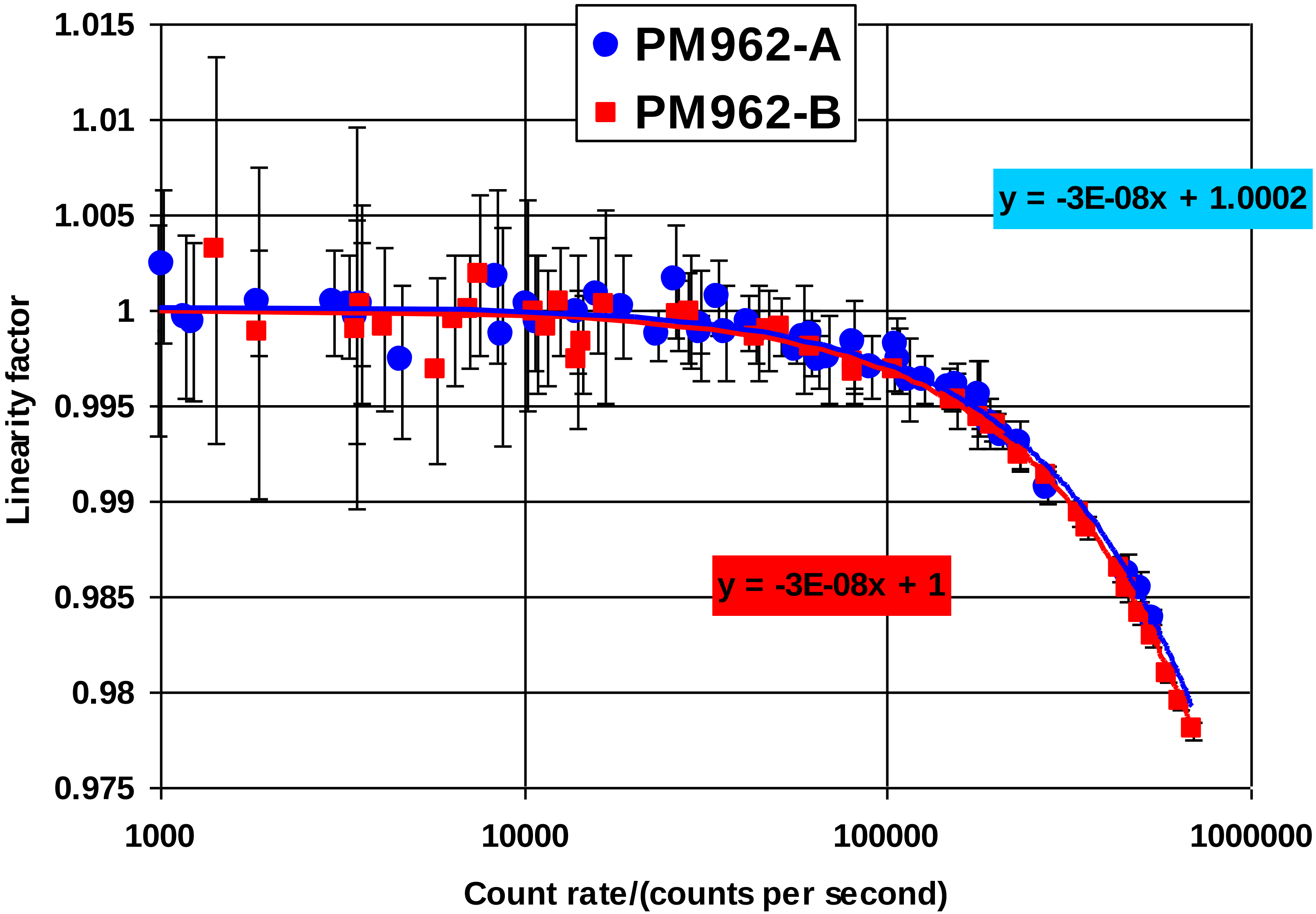
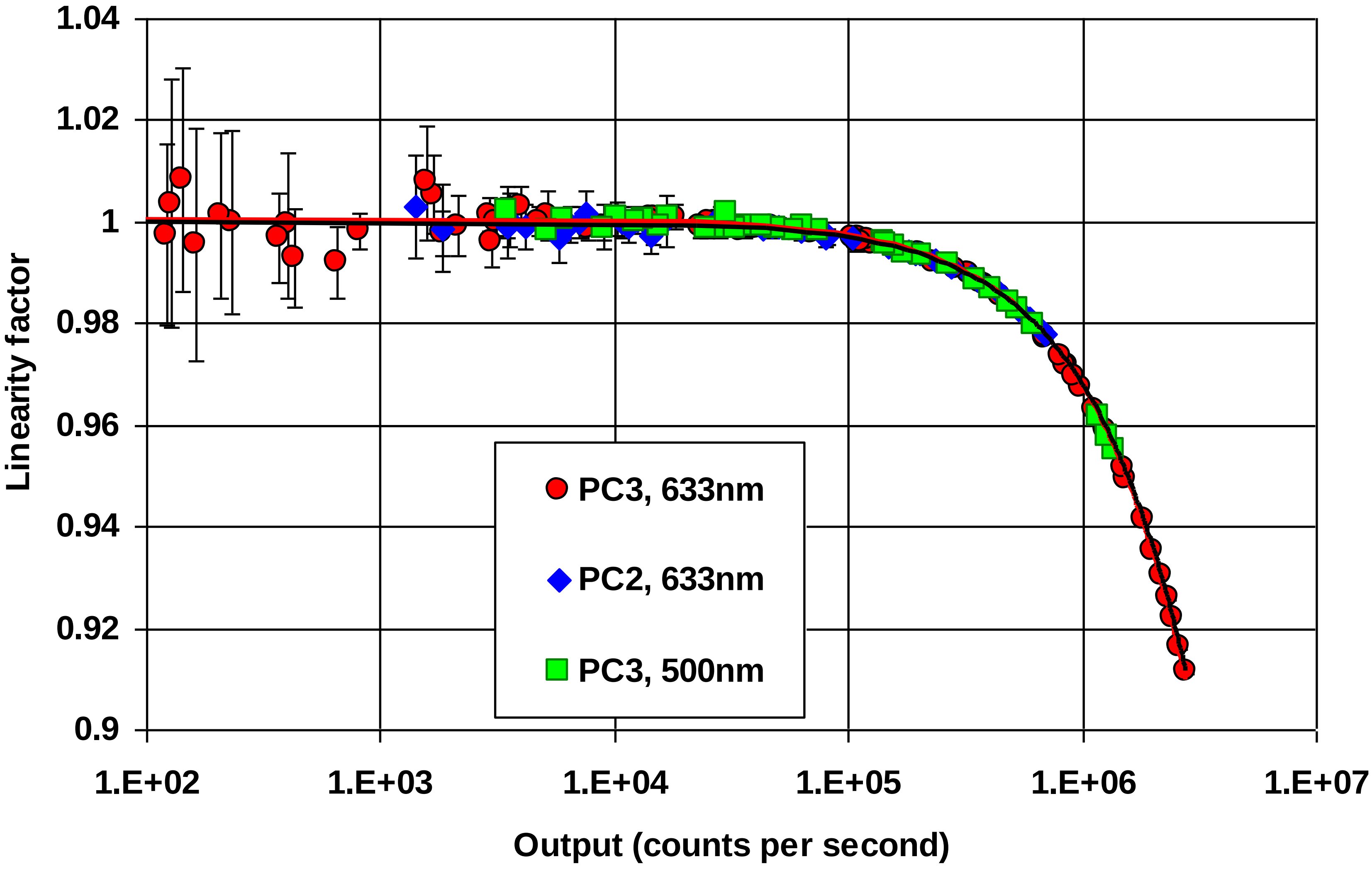
Advantages of the NPL linearity measurement facility

- It provides an **ABSOLUTE** linearity measurement.
- Ensures linearity characterisation in terms of **irradiance**.
- Uses reflective optics so it can cover a very wide spectral range (**250 nm to 25 µm** wavelength range).
- **It is fully automated.**
- The use of neutral density filters to change the radiant power means that the detector is illuminated with the **same angular characteristics** for all the radiant power levels (compare with the use of apertures to vary the radiant power/irradiance reaching the detector under test).

Linearity factor of PM962-A and PM962-B PC systems for radiation of 633 nm wavelength (logarithmic abscissa)

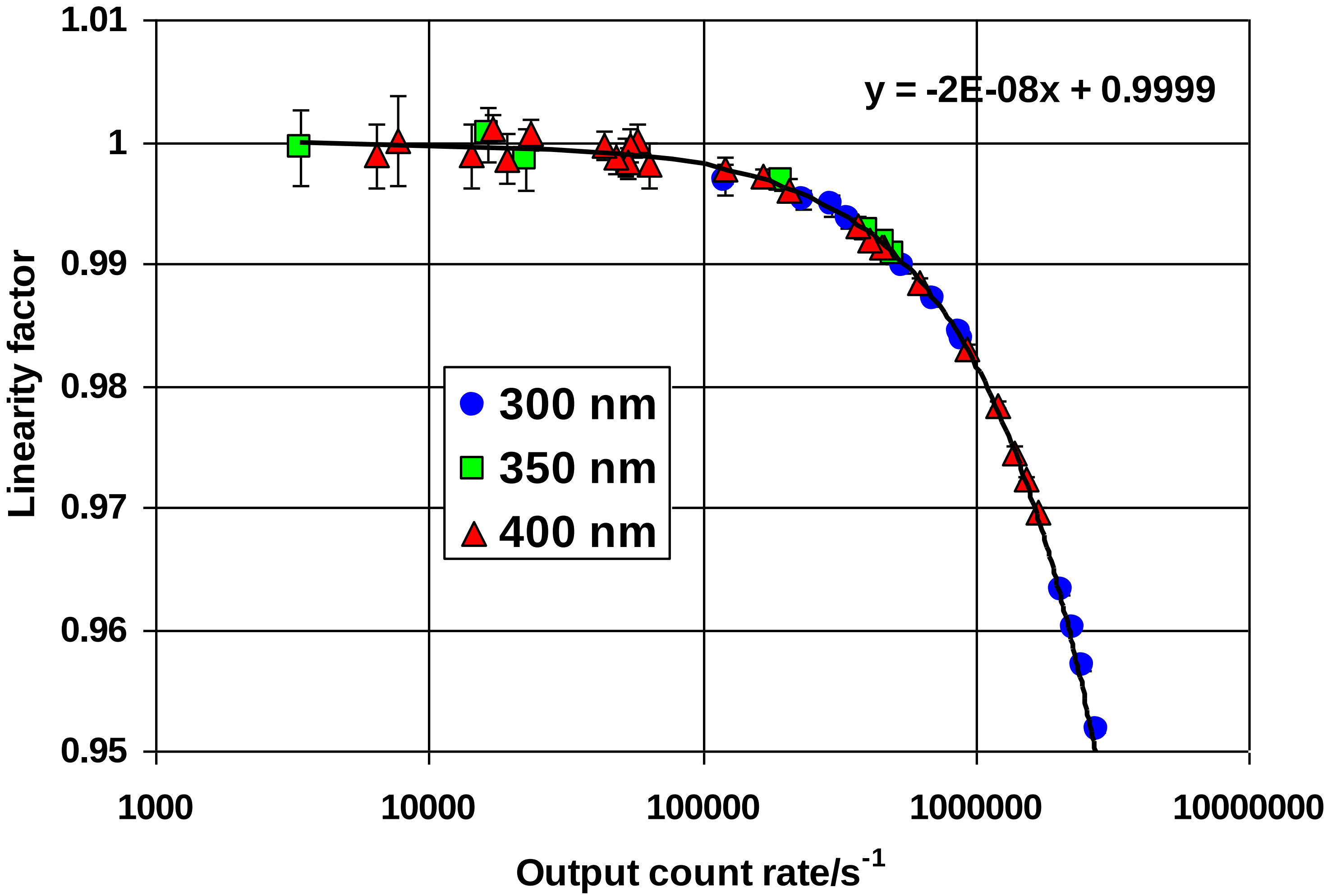


Linearity factor of PM962-B and PM962-C PC systems as a function of the output count rate at 633 nm and 500 nm



Linearity factor of the ET 9107WB PC system as a function of the output count rate measured at 300 nm, 350 nm and 400 nm.

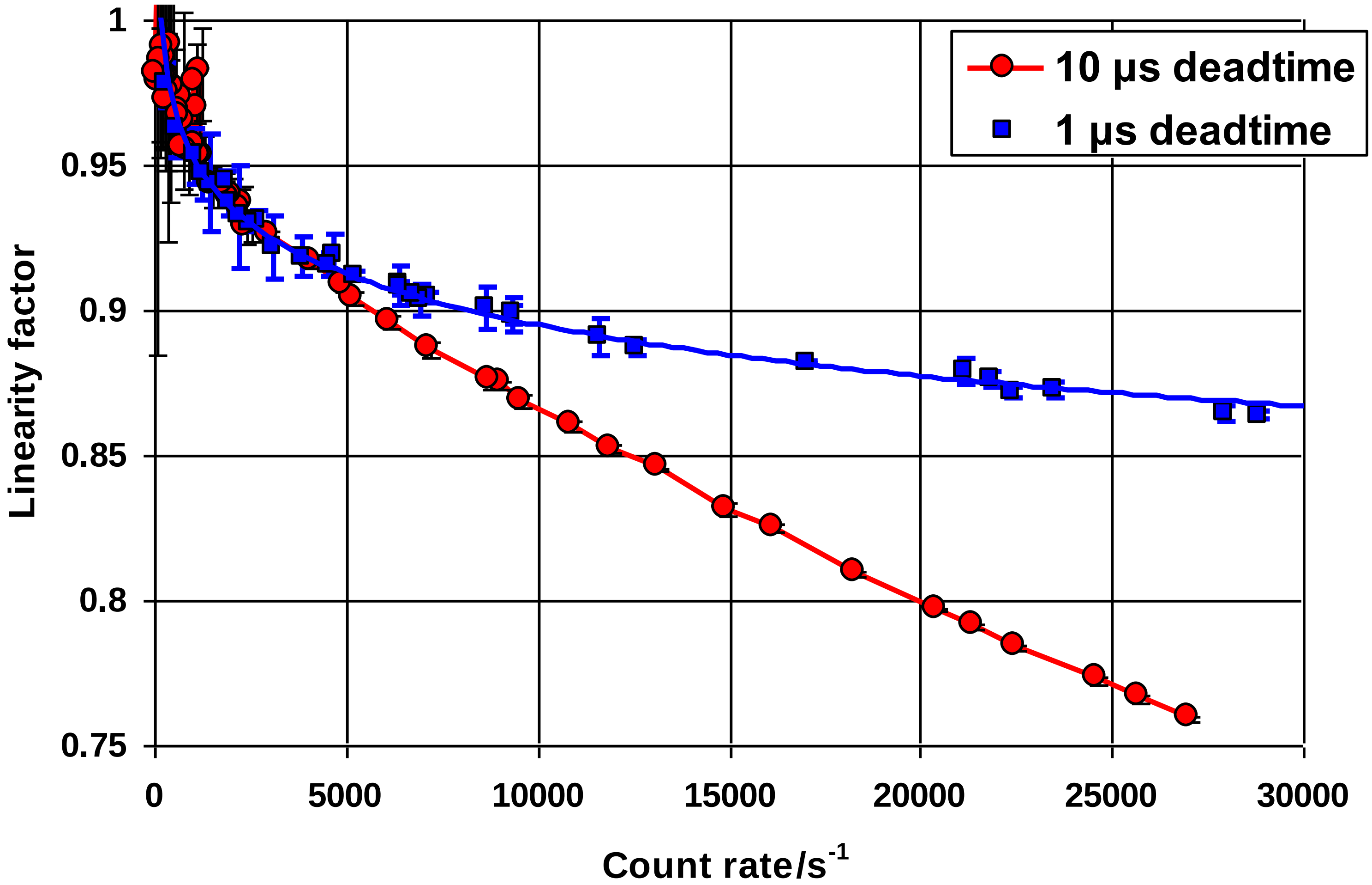
Also shown is the equation of the linear fit to the 400 nm data.



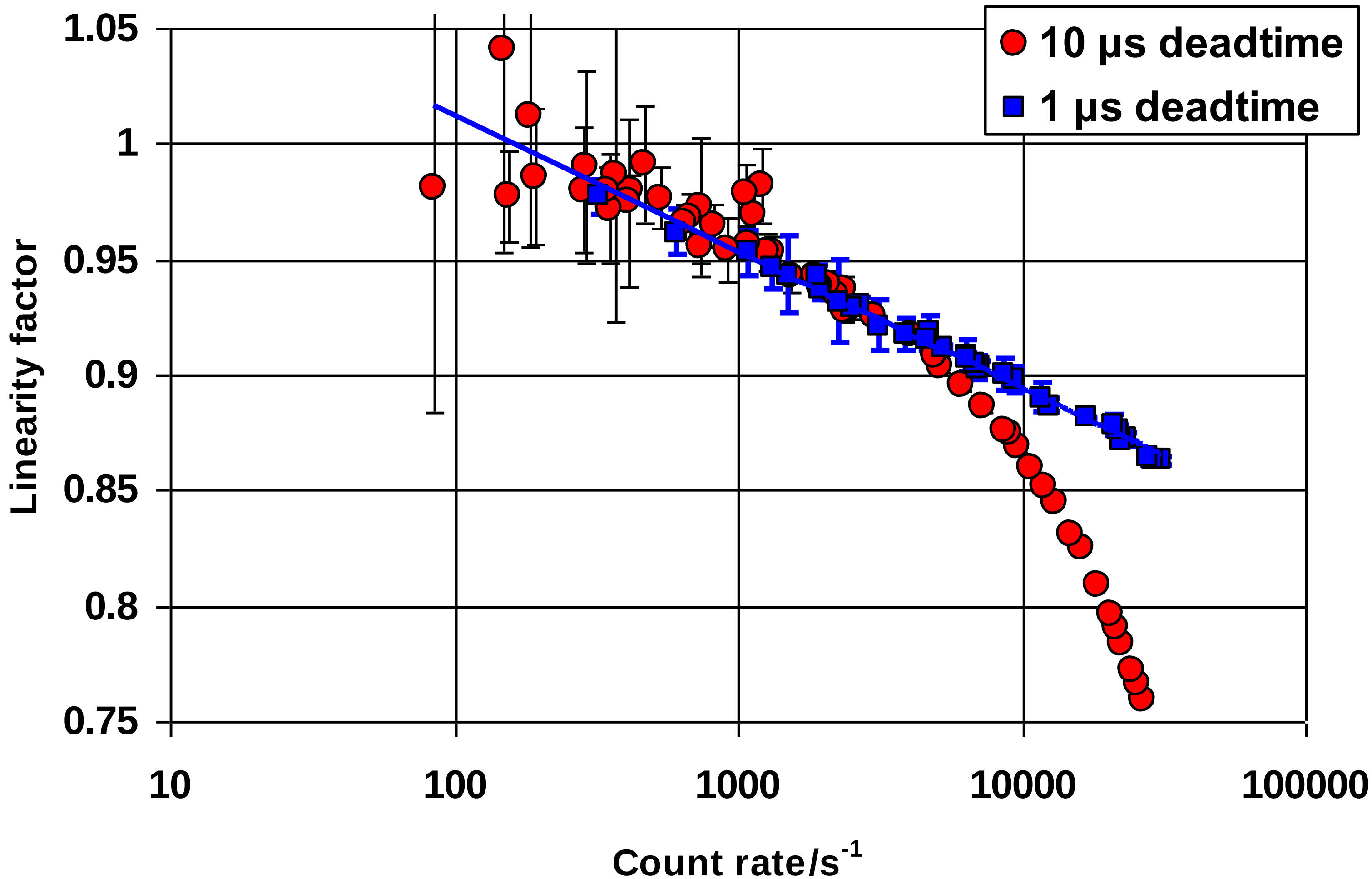
Discussion on linearity of response measurements

- Each photon incident on a photon counting system will produce an output pulse of a certain time duration.
- If two photons arrive so that the output pulse corresponding to the second photon overlaps with that of the first photon, then only a single output pulse will be produced and the two photons are read as one. This phenomenon is referred to as “pulse collision”.
- This means that the linear range of operation of any photon counting system is limited by the finite response time of the photodetection system (dead-time) which gives rise (when the output count rate is sufficiently high) to overlapping pulses and therefore to a lower output count rate.

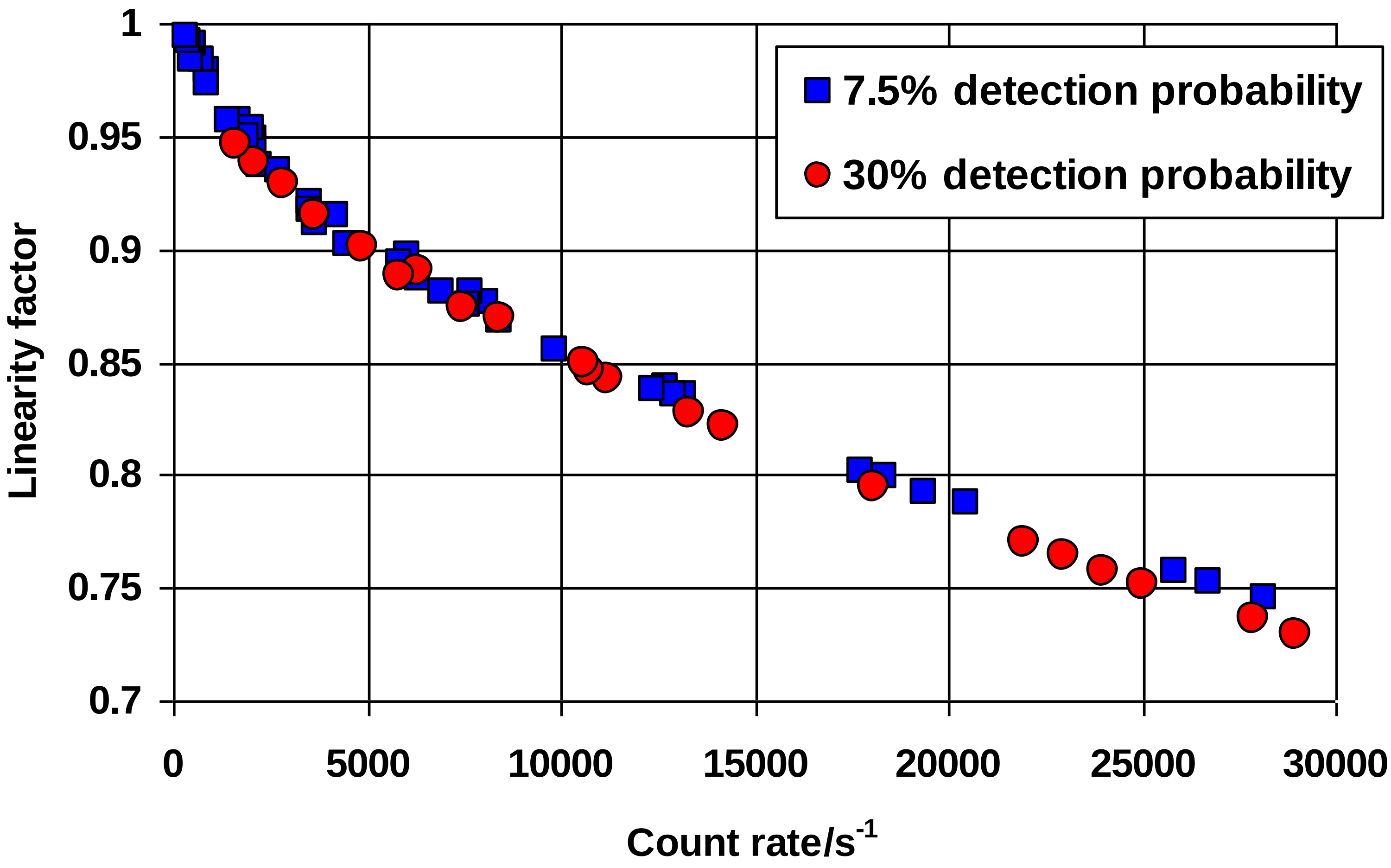
The linearity factor of the InGaAsP/InP id400-A detector measured at 1064 nm, with the dead-time set at 1 μs and 10 μs (single photon detection probability set to 7.5% for both plots)



The linearity factor of the id400-A detector measured at 1064 nm, with the dead-time set at 1 µs and 10 µs (single photon detection probability set to 7.5% for both plots).

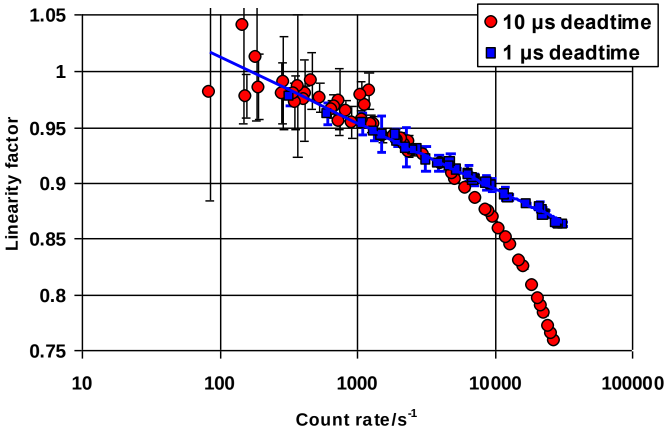


Linearity characteristics of the id400-B detector, measured at 1064nm with a 7.5% (blue trace) and a 30% (red trace) single photon detection probability value. Both plots were acquired using a 10 μs dead-time.



Discussion on linearity of response measurements

- Our data indicate that there are two sources giving rise to the non-linear behaviour of the id400-A & B SPAD detection systems.
- The first mechanism is logarithmic and occurs for all output count rates evaluated, when the dead time was set to 1 μs.
- The same mechanism was also observed for output count rates below 4000 counts per second when the dead time was set to 10 μs.
- However, for output count rates higher than 4000 counts per second (and 10 μs dead time), a second, stronger non-linear mechanism becomes apparent.



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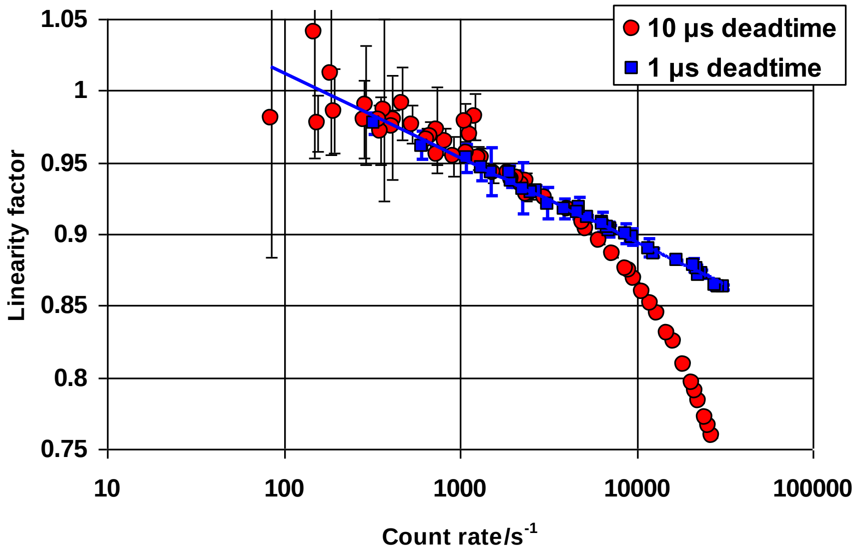
- A clue to the origin of the larger non-linearity observed for output count rates higher than 4000 counts per second is provided by treating the linearity factor measured for a 1 μs dead-time as a background, i.e. it is subtracted from the non-linearity measured for a 10 μs dead-time.
- The difference was shown to arise due to pulse collisions for the 10 μs dead time, assuming Poisson statistics for the photon arrivals.
- However, the origin of the non-linear response for count rates below 4000 counts per second is not currently understood.



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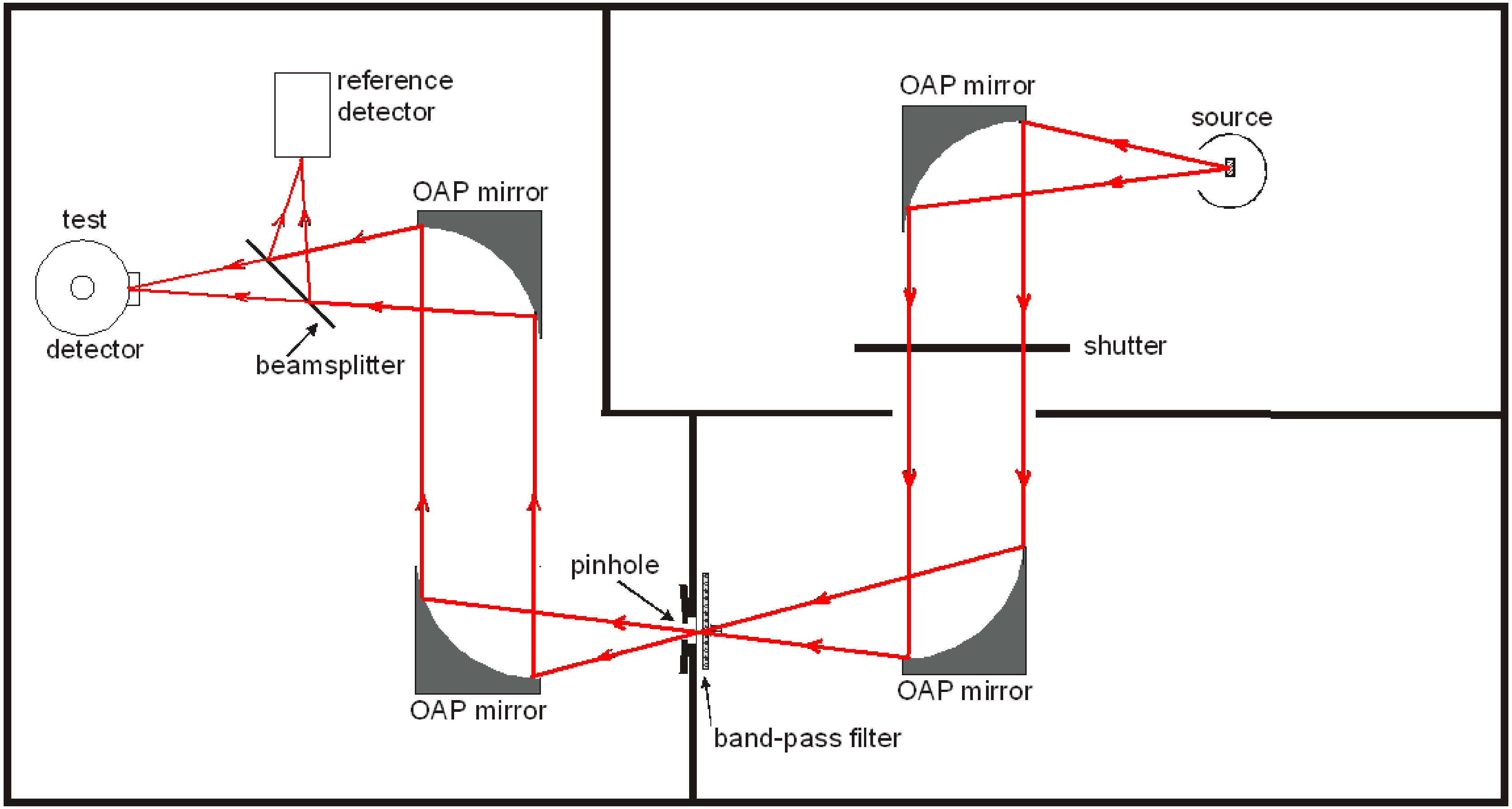
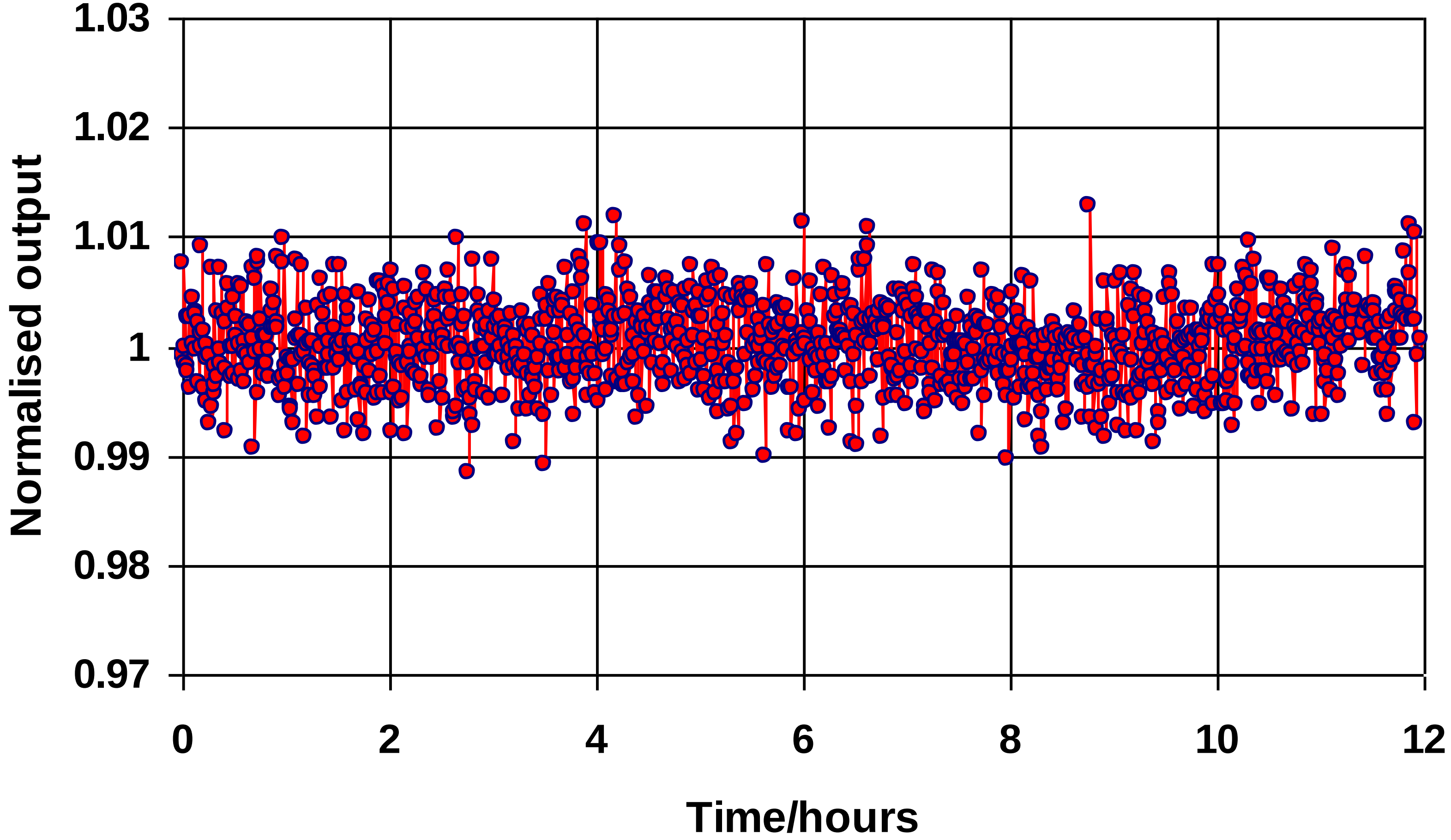
Layout of the NPL facility for the characterization of the stability of response of photon counting systems



Stability of the zero-corrected output of an id-400 InGaAsP/InP single-photon avalanche photodiode-based photon counting system, measured at 1064 nm over 12 hours.

The data corresponded to an output of approximately 20,000 counts per second



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Conclusions

- **The linearity of response and spatial uniformity of response characteristics of two commercially-available SPAD detection systems were experimentally investigated.**
- **Both id400 SPAD systems were shown to have a spatially non-uniform response, with the degree of non-uniformity depended strongly on the single photon detection probability setting of these systems.**
- **The experimentally observed spatial uniformity of response behaviour of these detectors is explained in terms of the spatial non-uniformity in the breakdown voltage V_b across the active area of the device.**

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Conclusions (cont.)

- **Both SPAD detection systems were shown to exhibit a non-linear response.**
- **The single photon detection probability setting had no influence on the linearity characteristics of the two detectors.**
- **The dead-time setting was shown to be critical on the linearity of the two id400 detection systems evaluated.**
- **The experimentally observed linearity of response characteristics of these detectors at high count rates can be explained in terms of "pulse collisions".**
- **However, the origin of the experimentally observed linearity of response characteristics of the same detectors at low count rates is currently unknown.**

Thank you for listening

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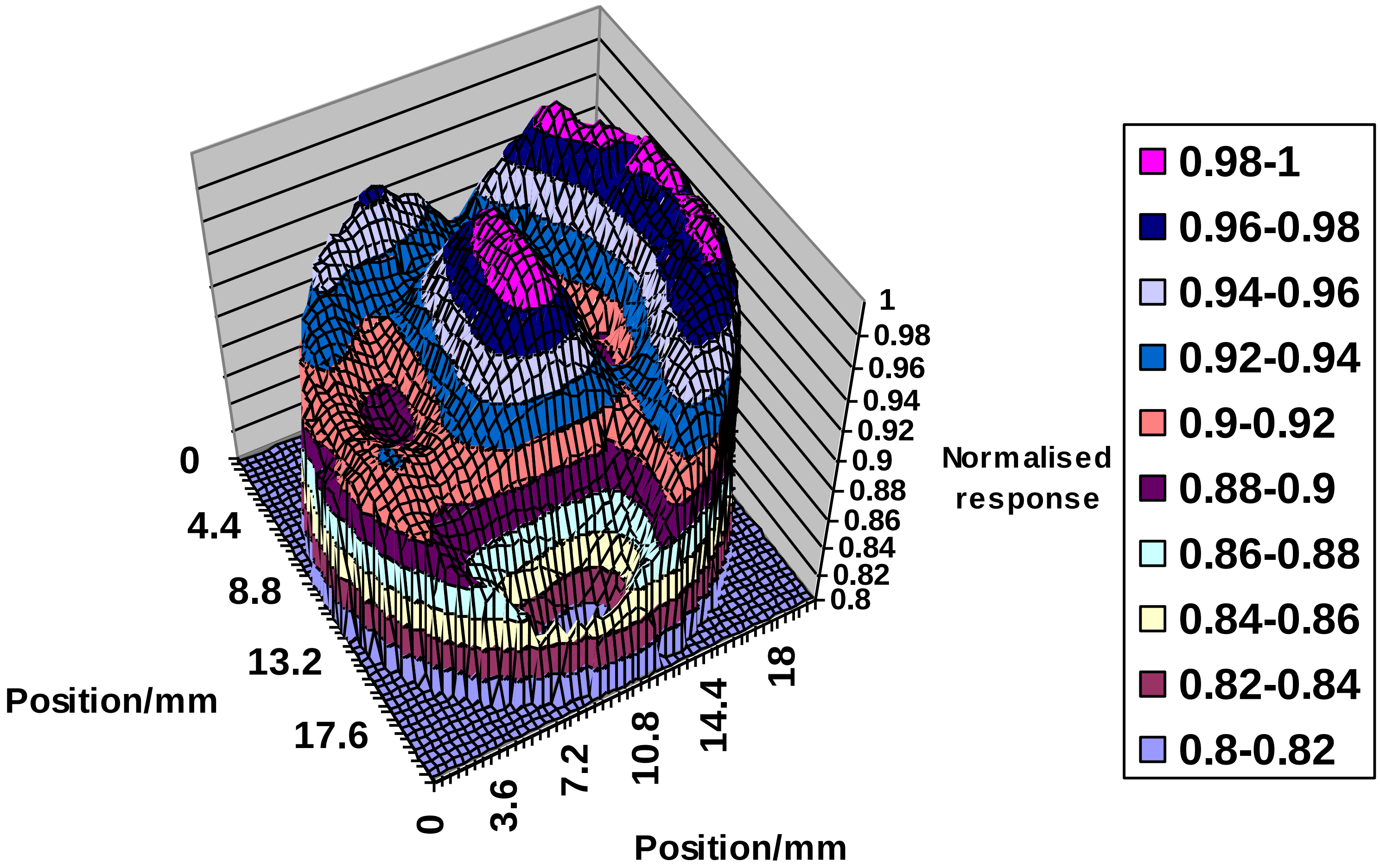
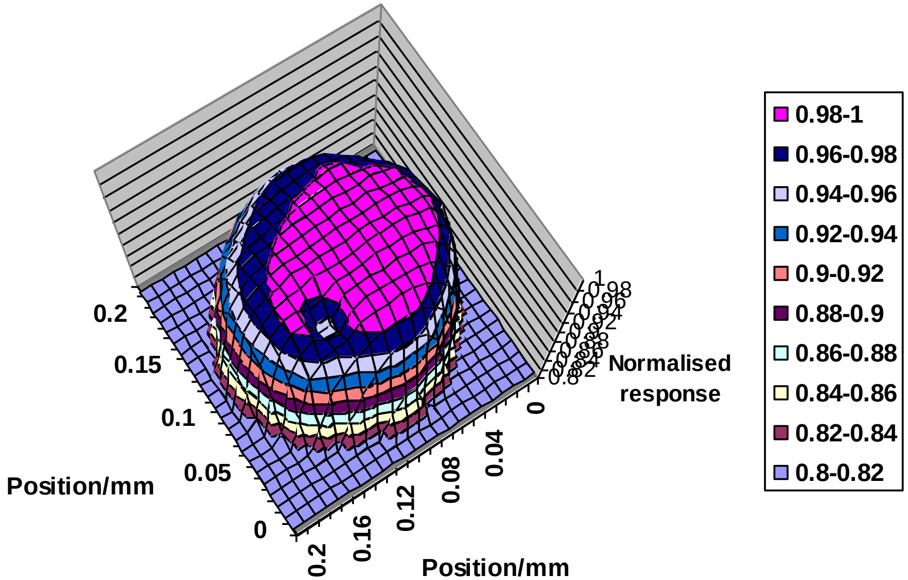
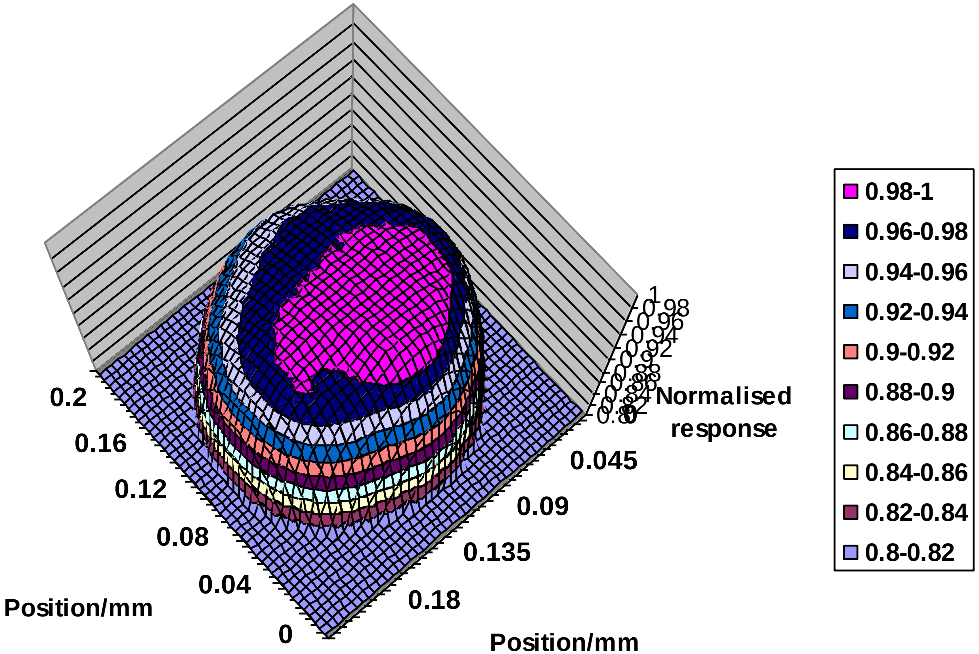
Spatial uniformity of the ET 9107WB photon counting system measured at 350 nm using a 0.4 mm diameter spot.

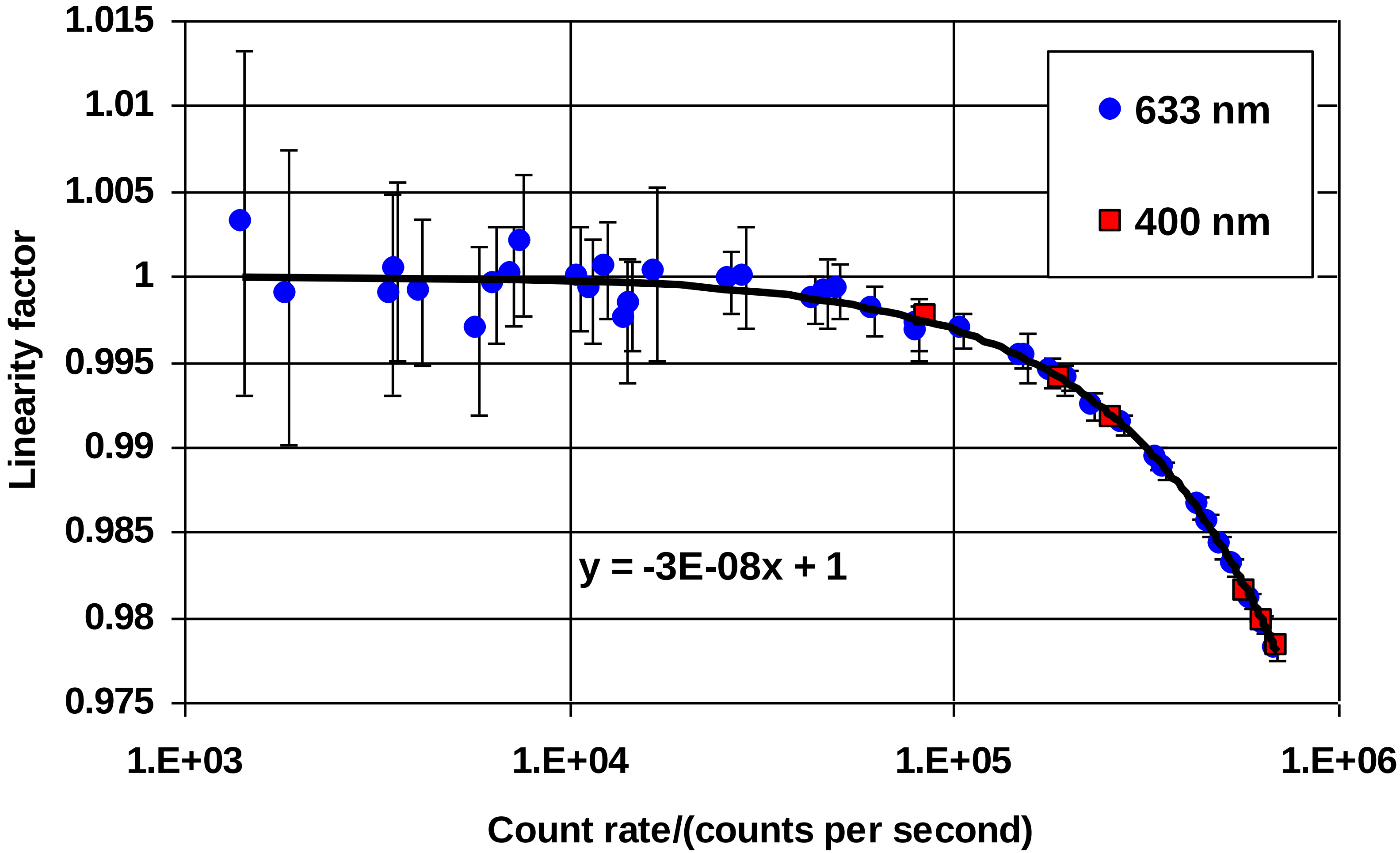


Spatial uniformity of response of the EG&G SPCM-AQR-13 photon counting system at 400 nm and 700 nm, measured using a 22 μm diameter spot.





Linearity factor of PM-962-B PC system as a function of the output count rate for radiation of 400 nm and 633 nm wavelength



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