X-ray Radiometry

# Absolute calibration of X-ray detectors at low energies

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X-Ray Detectors for Synchrotron Applications
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# Outline

X-ray Radiometry

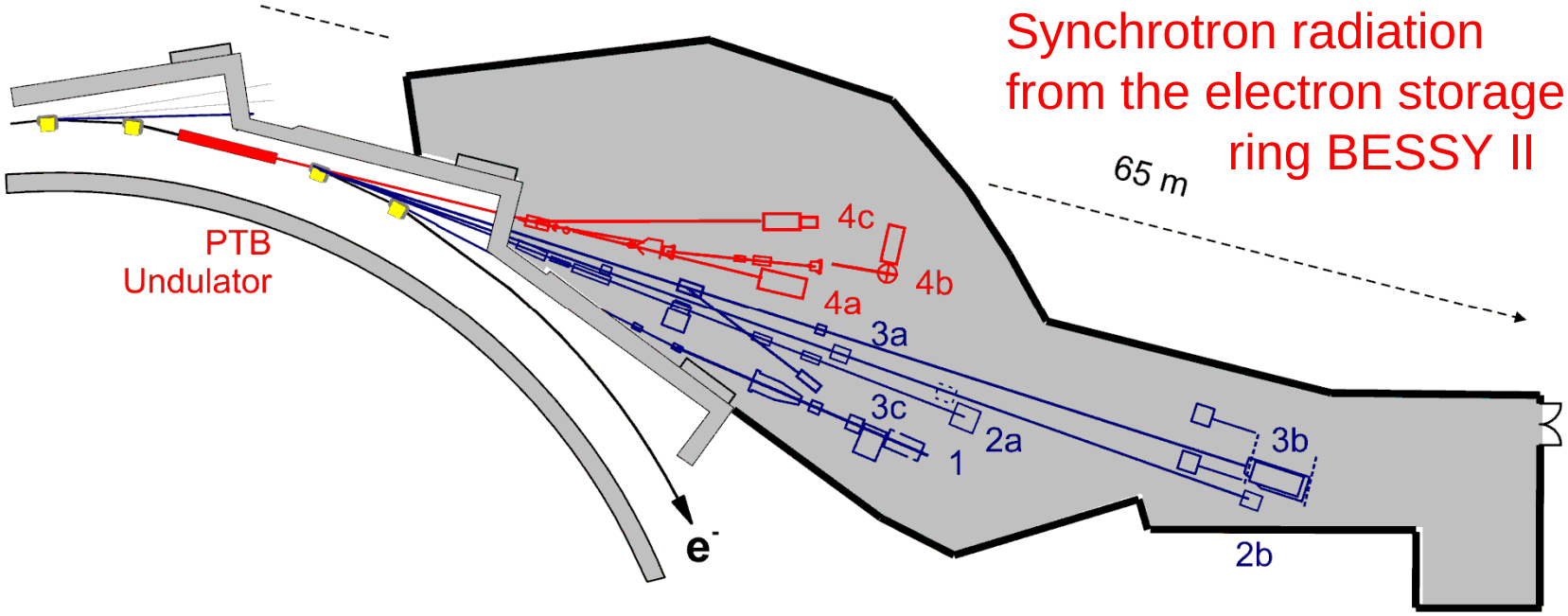
- PTB laboratory at BESSY II

- Calibration of energy-dispersive detectors against the **primary source standard BESSY II**
- Quantum detection efficiency of Si(Li) detectors and SDDs

- Detector calibration against a **primary detector standard**
- Spectral responsivity of semiconductor photodiodes
- Calibration and characterization of area detectors with monochromatic radiation:
  - energy-dispersive pnCCD
  - hybrid-pixel PILATUS detector

# PTB laboratory at BESSY II in Berlin

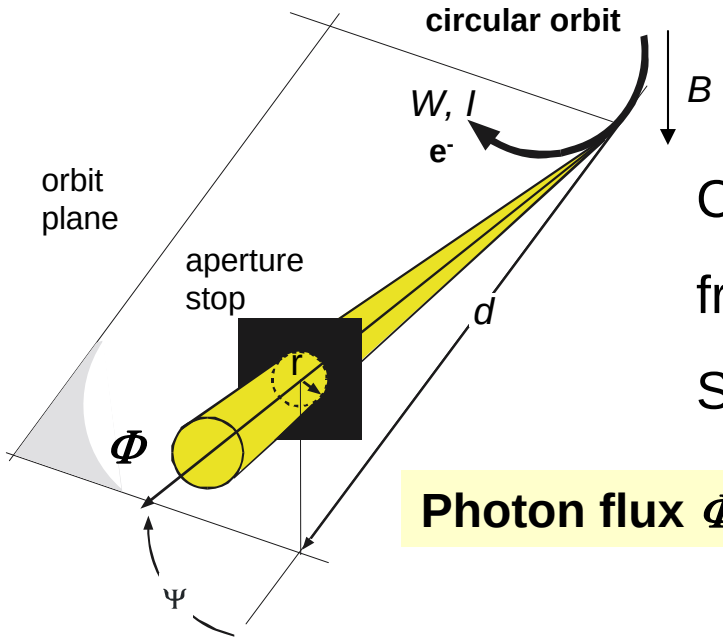
X-ray Radiometry




| | | | |
|---|---|---|---|
| 1 | plane grating monochromator SX700<br>30 eV to 1800 eV | | |
| **2a** | **four-crystal monochromator**<br>**1.75 keV to 10 keV (0.7 nm to 0.1 nm)** | 3c | deflected undispersed bending magnet radiation,<br>EUV irradiation test station |
| **2b** | X-ray pencil beam facility (XPBF),<br>astrophysics optics characterization | 4a | undispersed undulator radiation<br>Compton backscattering |
| **3a** | **undispersed bending magnet radiation** | 4b | plane grating monochromator (PGM) at undulator,<br>40 eV to 1900 eV (30 nm to 0.65 nm) |
| 3b | normal incidence monochromator<br>3 eV to 35 eV | 4c | deflected undispersed undulator radiation<br>EUVL metrology test station |

# Electron storage rings as primary source standards

X-ray Radiometry



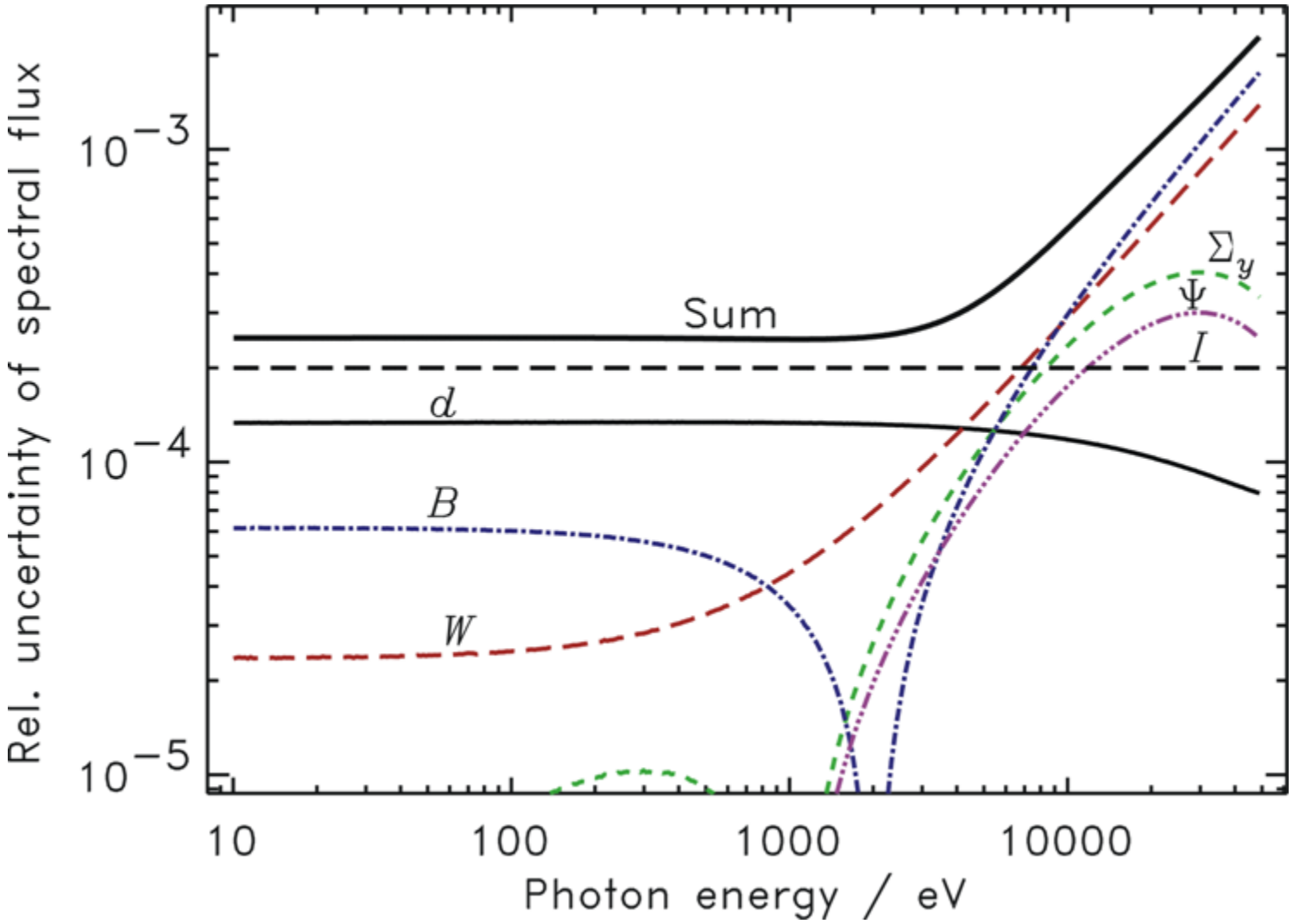

Calculable synchrotron radiation from bending magnets, Schwinger theory

**Photon flux $\Phi = \Phi\ (W, I, B, \Sigma_y, d, r, \psi)$**

- **electron beam and storage ring parameters**
  - $W$ electron beam energy
  - $I$ electron current
  - $B$ magnetic induction
  - $\Sigma_y$ vertical extension and divergence of the beam
- **geometrical quantities**
  - $d$ distance
  - $r$ radius of aperture
  - $\psi$ emission angle

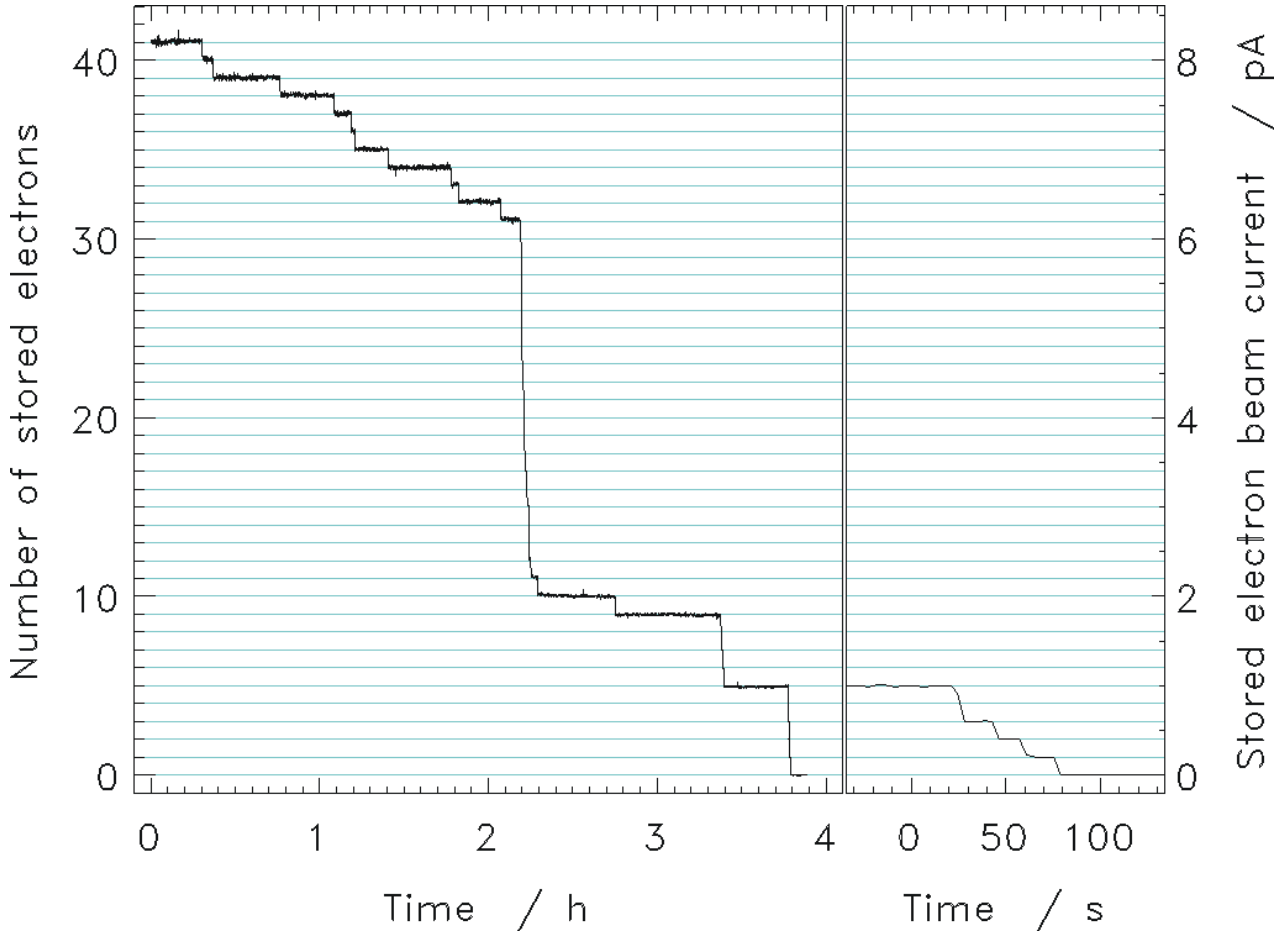
# Relative uncertainty at BESSY II bending magnet

X-ray Radiometry



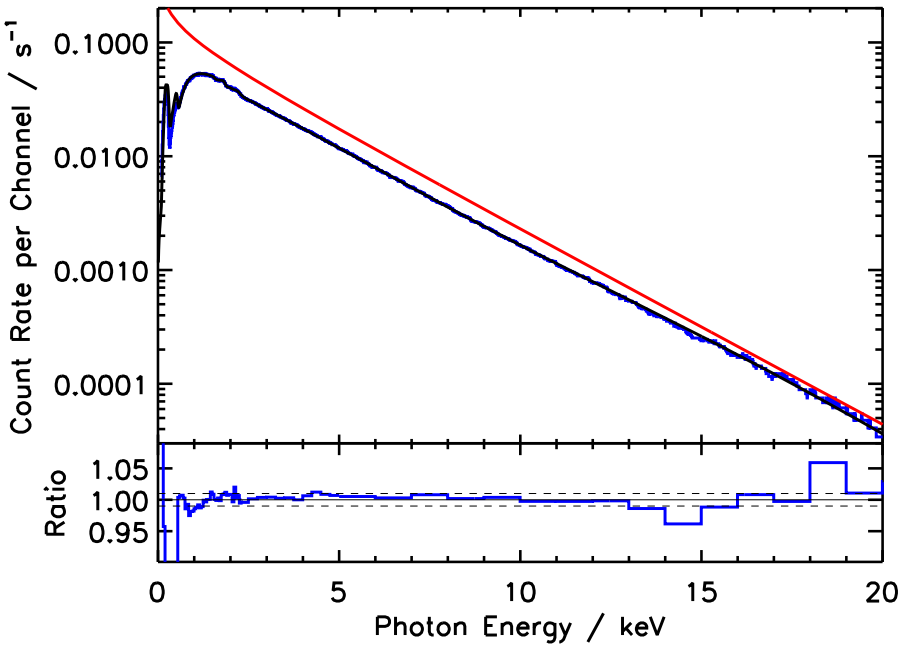
# BESSY II operation with few stored electrons

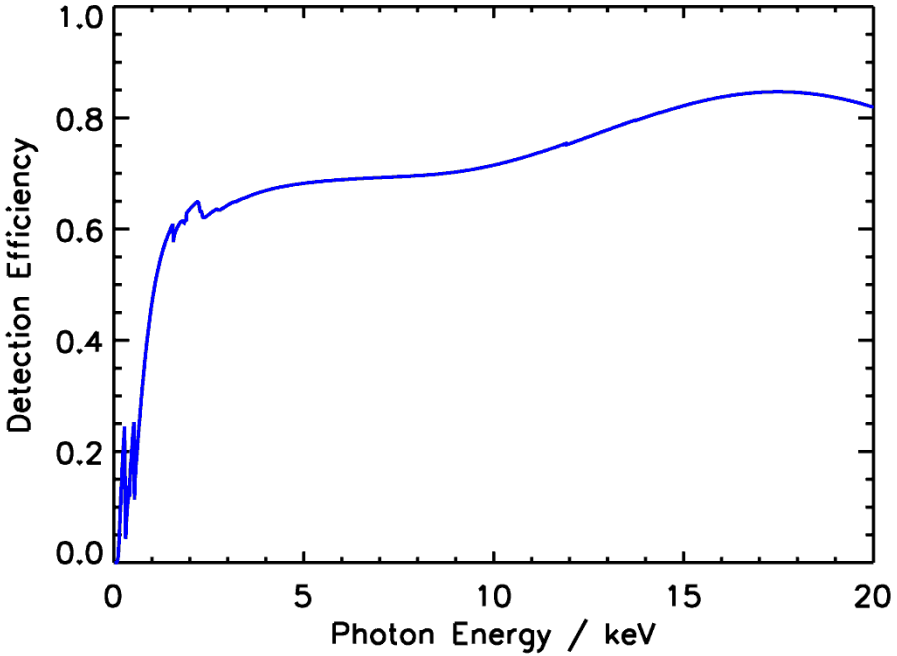
X-ray Radiometry



# Calibration of a Si(Li) detector

X-ray Radiometry



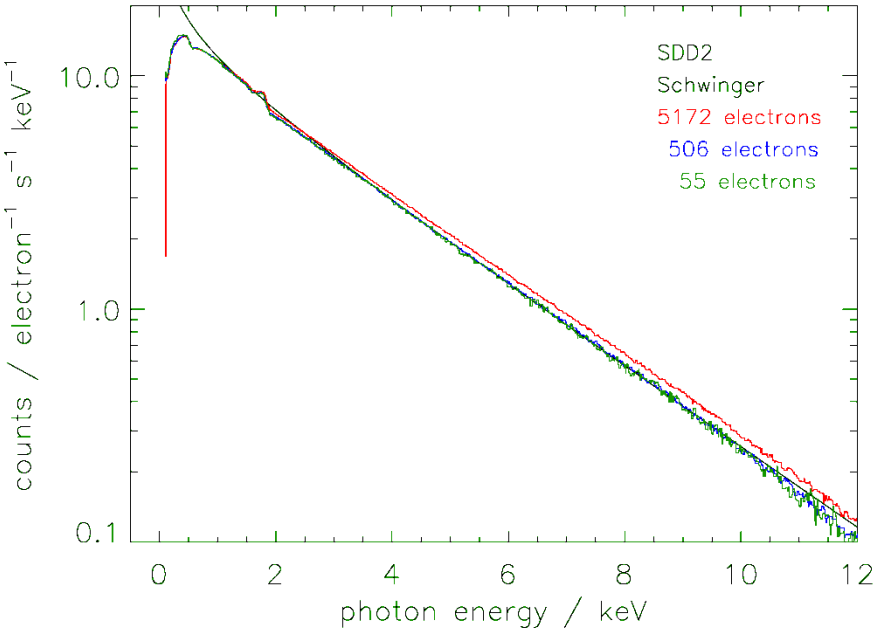

Calculated:
BESSY II bending magnet radiation
incl. detection efficiency
measured spectrum

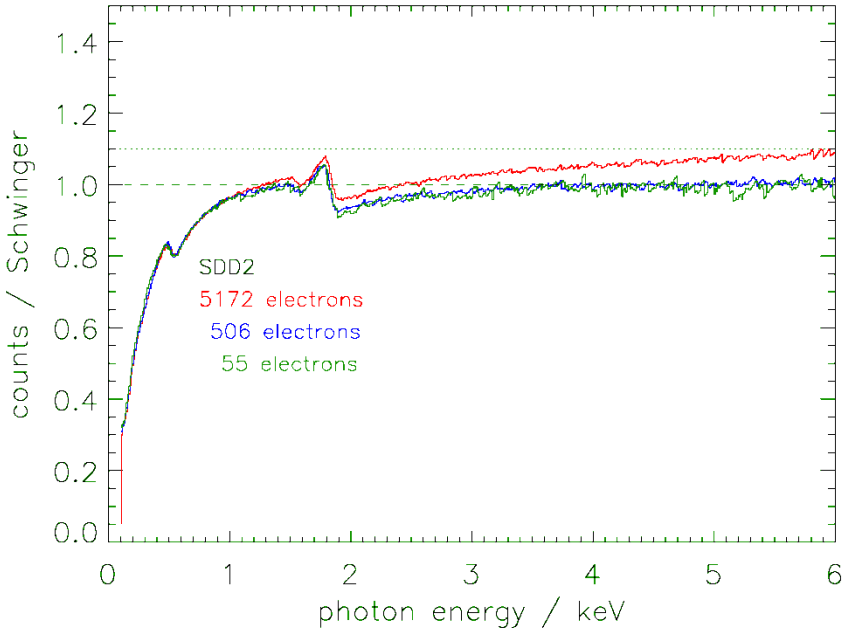
MOXTEK window
containing Al, O, C, N
Si support grid

M. Krumrey, F. Scholze and G. Ulm, Proc. SPIE **5501**, 277 (2004)

# Calibration of a silicon drift detector (SDD)

X-ray Radiometry




Calculated BESSY II bending magnet radiation

measured spectra for different cont rates:
1 kHz 10 kHz 100 kHz

Windowless SDD
Quantum efficiency close to unity

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- **Detector calibration against a primary detector standard**
- Spectral responsivity of semiconductor photodiodes
- Calibration and characterization of pixel detectors with monochromatic radiation:
  - energy-dispersive pnCCD
  - hybrid-pixel PILATUS detector

# Detector based calibration

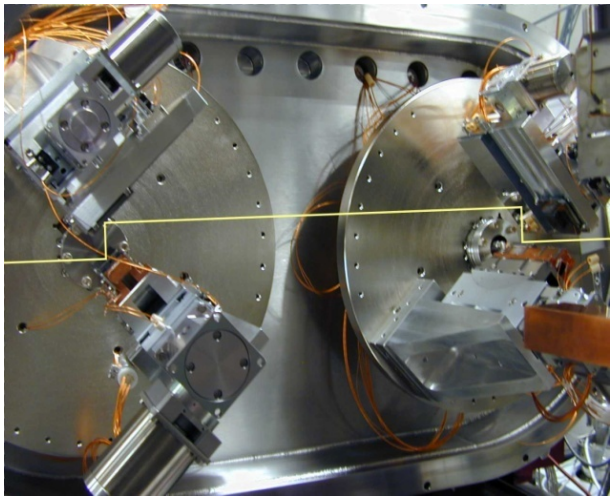
X-ray Radiometry

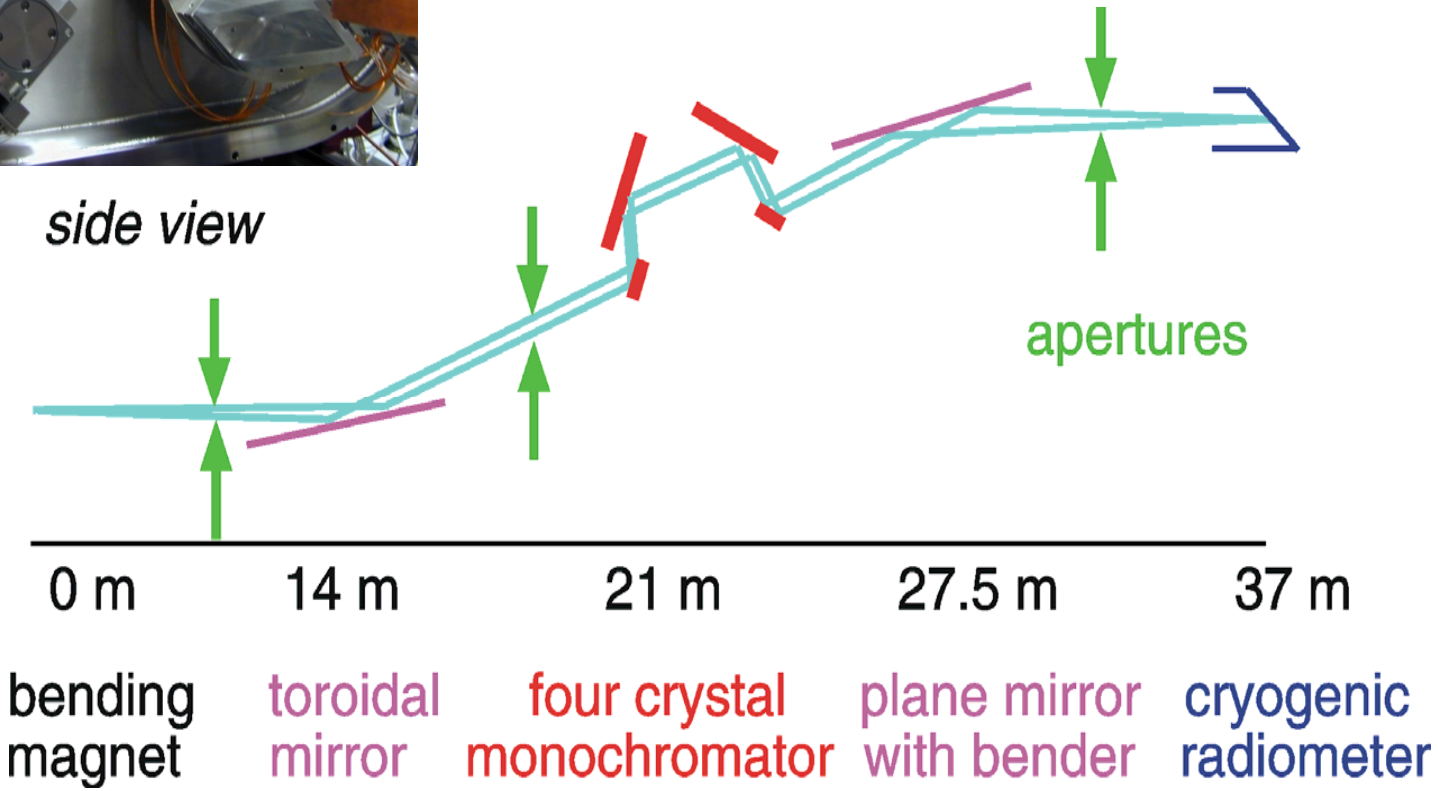
Detector calibration against a **primary detector standard** requires**:**

- Monochromatic radiation of high spectral purity, available e.g. in the range from 1.75 keV to 10 keV at the **four-crystal monochromator beamline**
- A primary detector standard to determine the radiant power with low uncertainty: **cryogenic electrical substitution radiometer**

# PTB four-crystal monochromator beamline

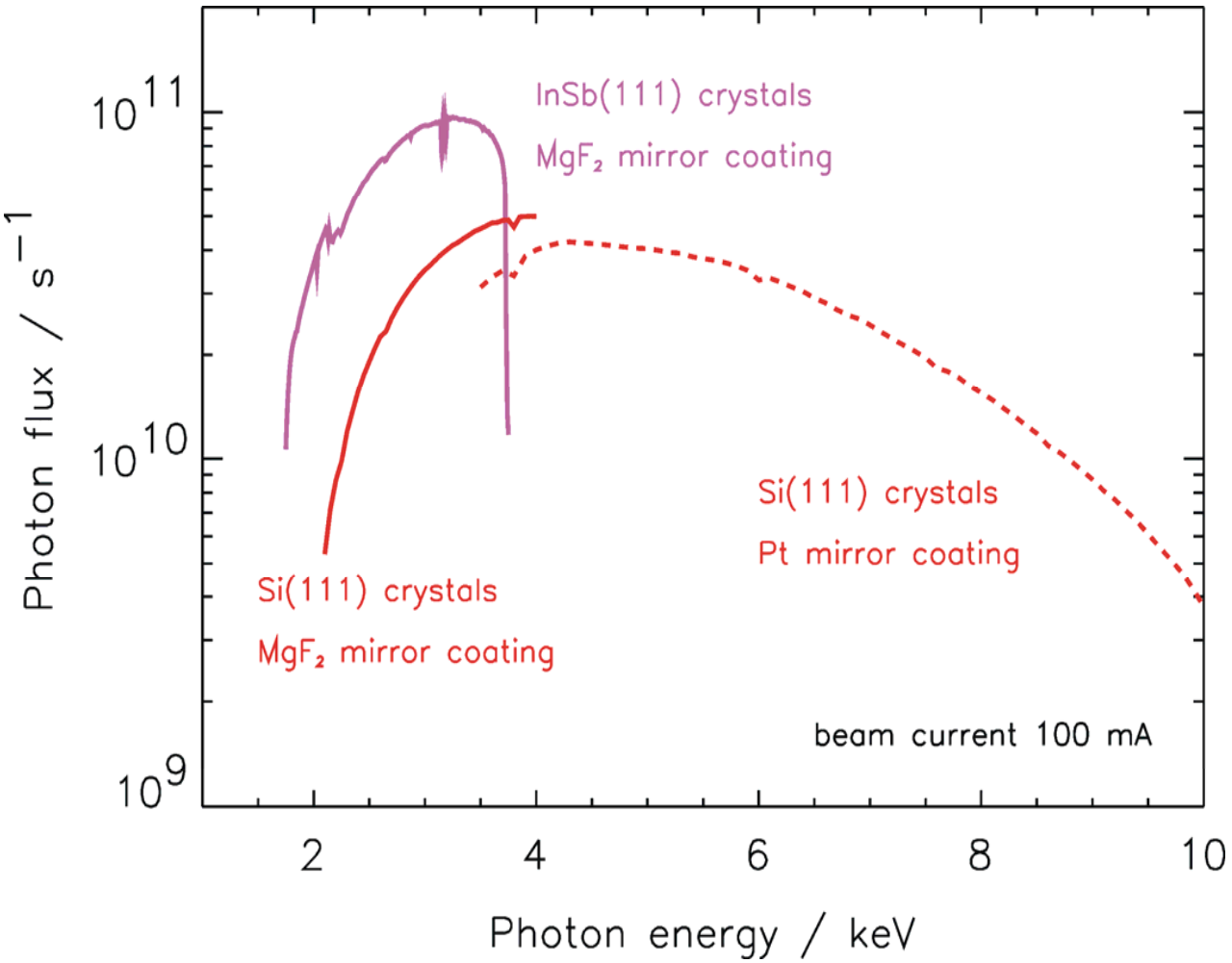
X-ray Radiometry





# Photon Flux at the FCM beamline

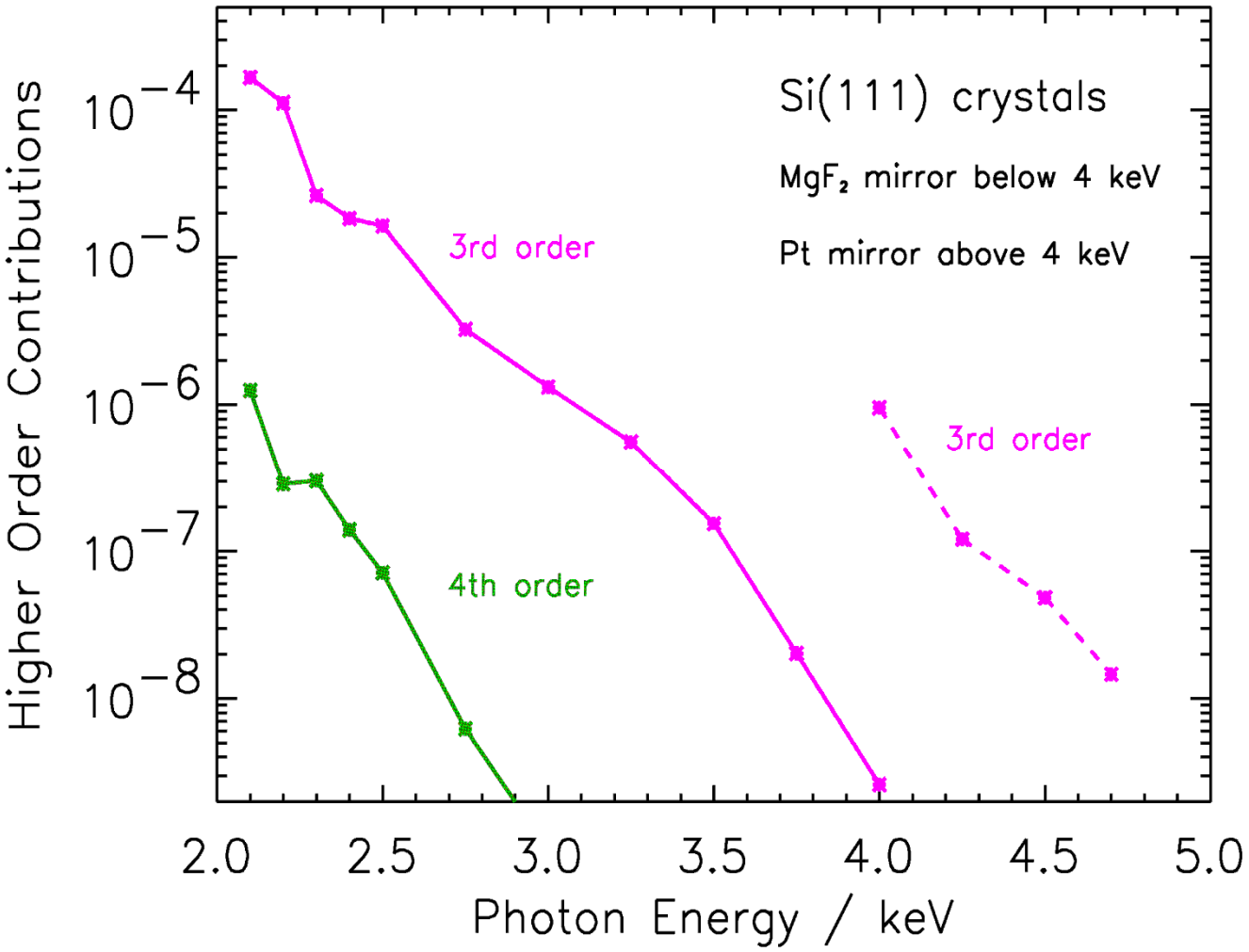
X-ray Radiometry




M. Krumrey and G. Ulm, Nucl. Instr. Meth. A **467-468**, 1175 (2001)

# FCM Beamline: Measured higher orders for Si crystals

X-ray Radiometry

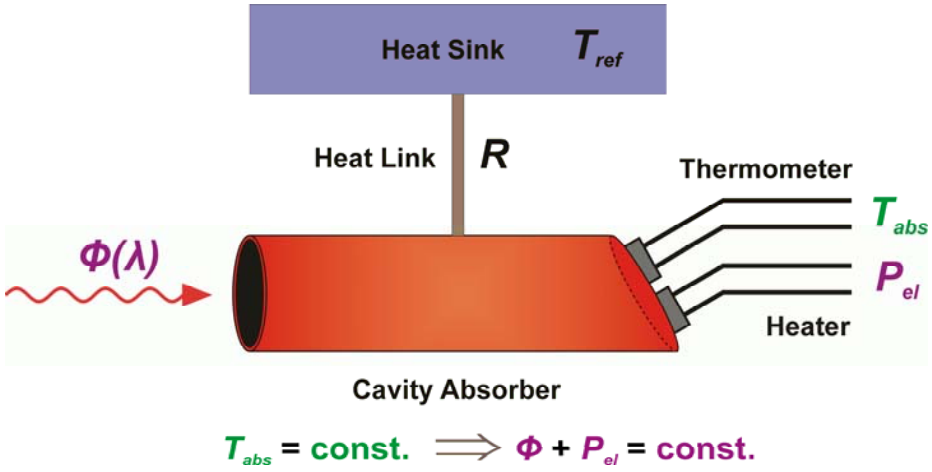


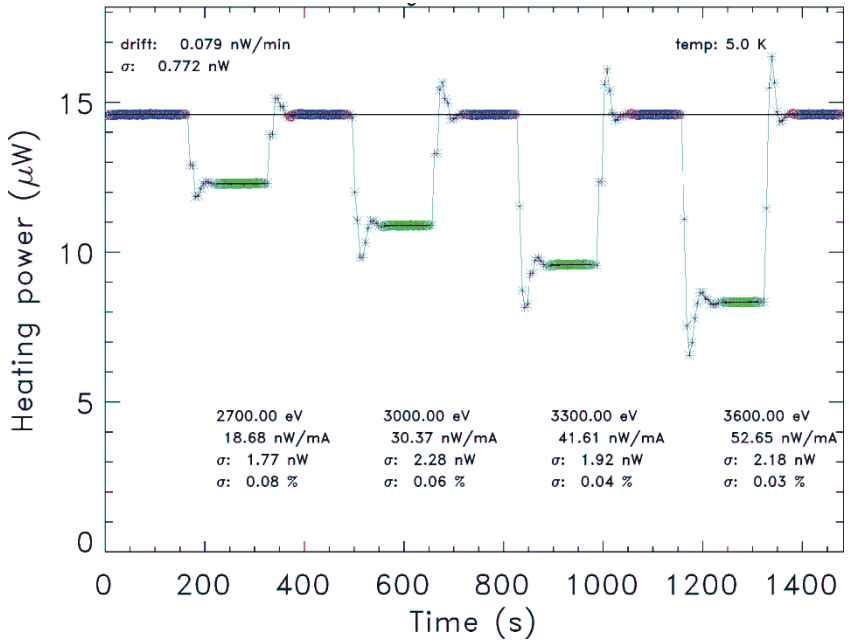

M. Krumrey and G. Ulm, Nucl. Instr. Meth. A **467-468**, 1175 (2001)

# Primary detector standard

X-ray Radiometry

## Cryogenic Electrical Substitution Radiometer



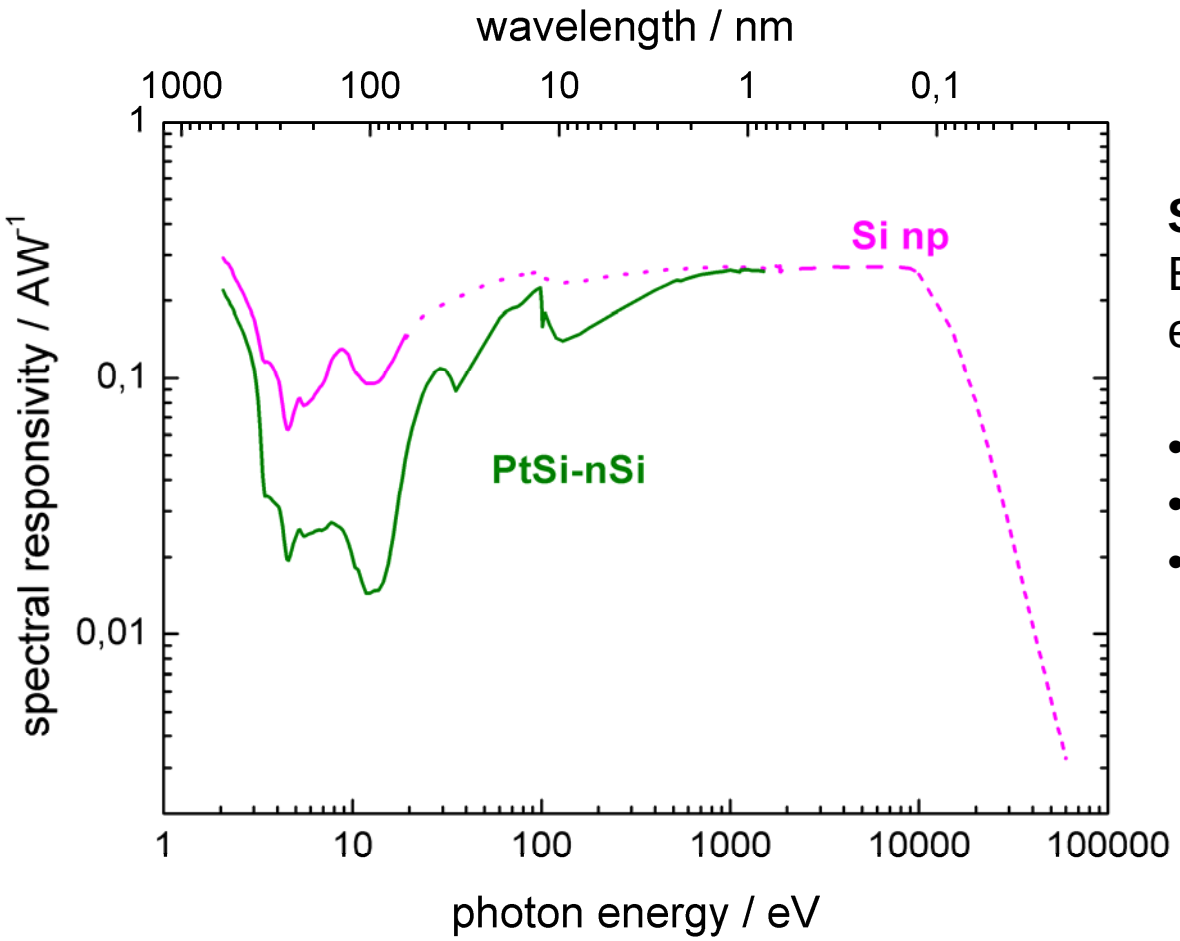

Absorber: 40 mm long, 8 mm diameter

500 µm Au base

80 µm Cu shell

# Responsivity of silicon photodiodes

X-ray Radiometry




**Semiconductor photodiodes**, Best suited type depending on energy range due to

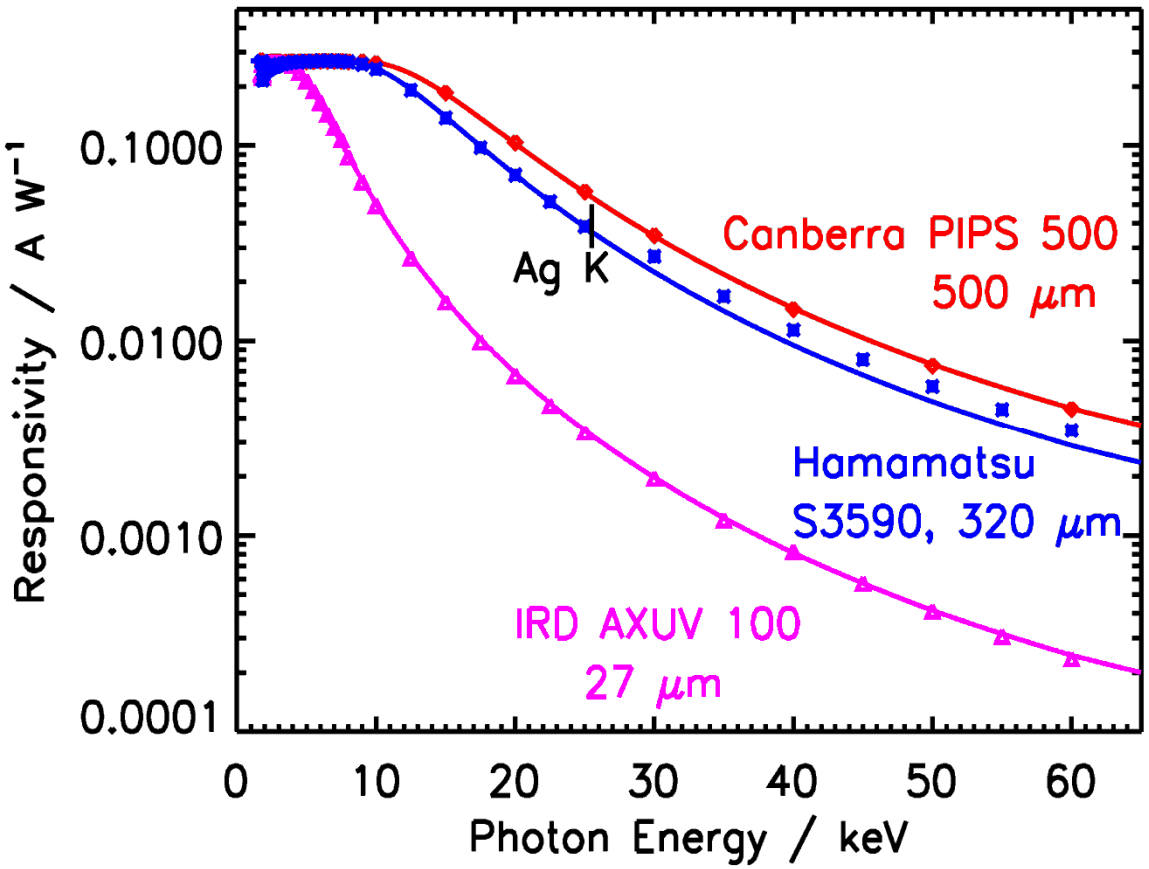
- stability
- linearity
- spatial uniformity

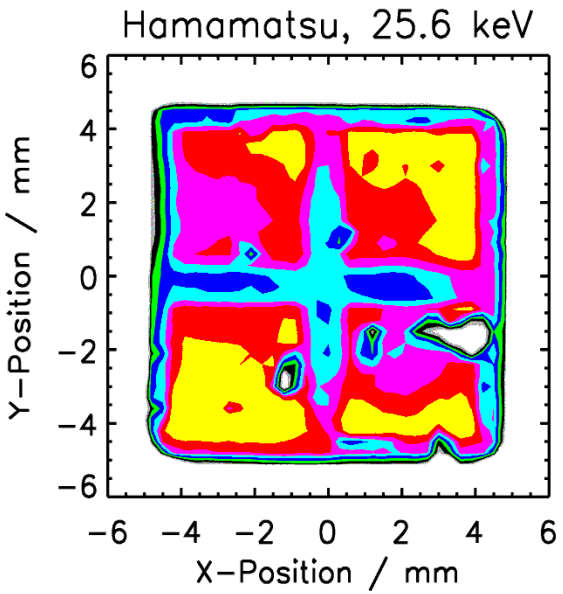
relative uncertainty ≤ 1 %

A. Gottwald, U. Kroth, M. Krumrey, M. Richter, F. Scholze and G. Ulm
Metrologia **43**, S125 – S129 (2006)

# Responsivity of silicon photodiodes

X-ray Radiometry




Diodes calibrated for:
ESRF
SOLEIL
Diamond
APS
…

M. Gerlach, M. Krumrey, L. Cibik, P. Müller, H. Rabus and G. Ulm
Metrologia **45**, 577-585 (2008)

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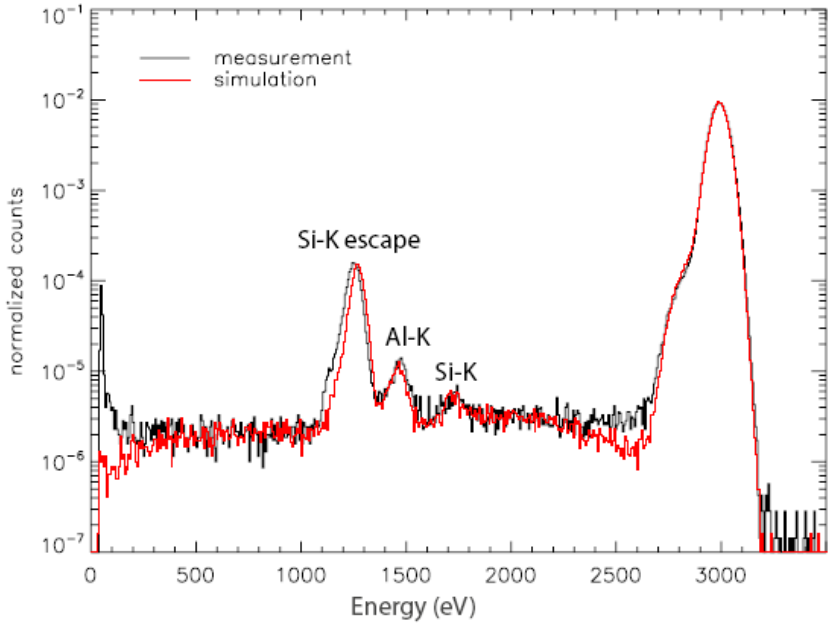
# Characterization of the pnCCD for eROSITA

X-ray Radiometry

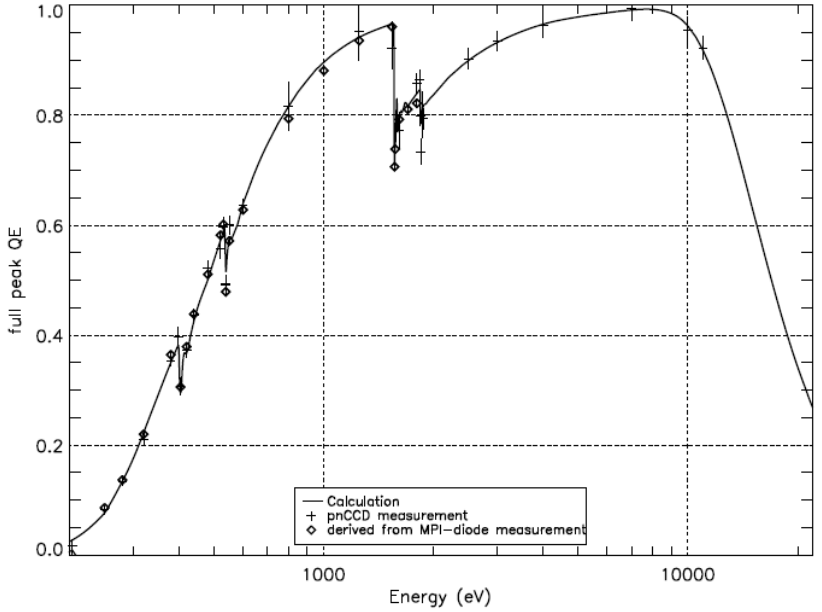
**e**xtended **Ro**entgen **S**urvey with an **I**maging **T**elecope **A**rray
X-ray astrophysics mission, launch 2013
On board: 7 fully depleted back-illuminated pnCCD, 450 µm Si thickness
384 x 384 pixels, pixel size 75 x 75 µm², area 29 x 29 mm²

## Response function




S. Granato *et al.*,
IEEE 2011 Nuclear Science Symposium Conference Record, 122 – 128 (2011)

## Full peak quantum efficiency

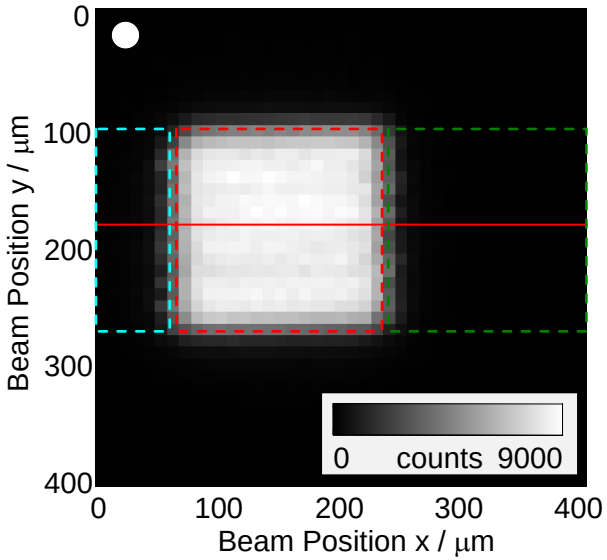


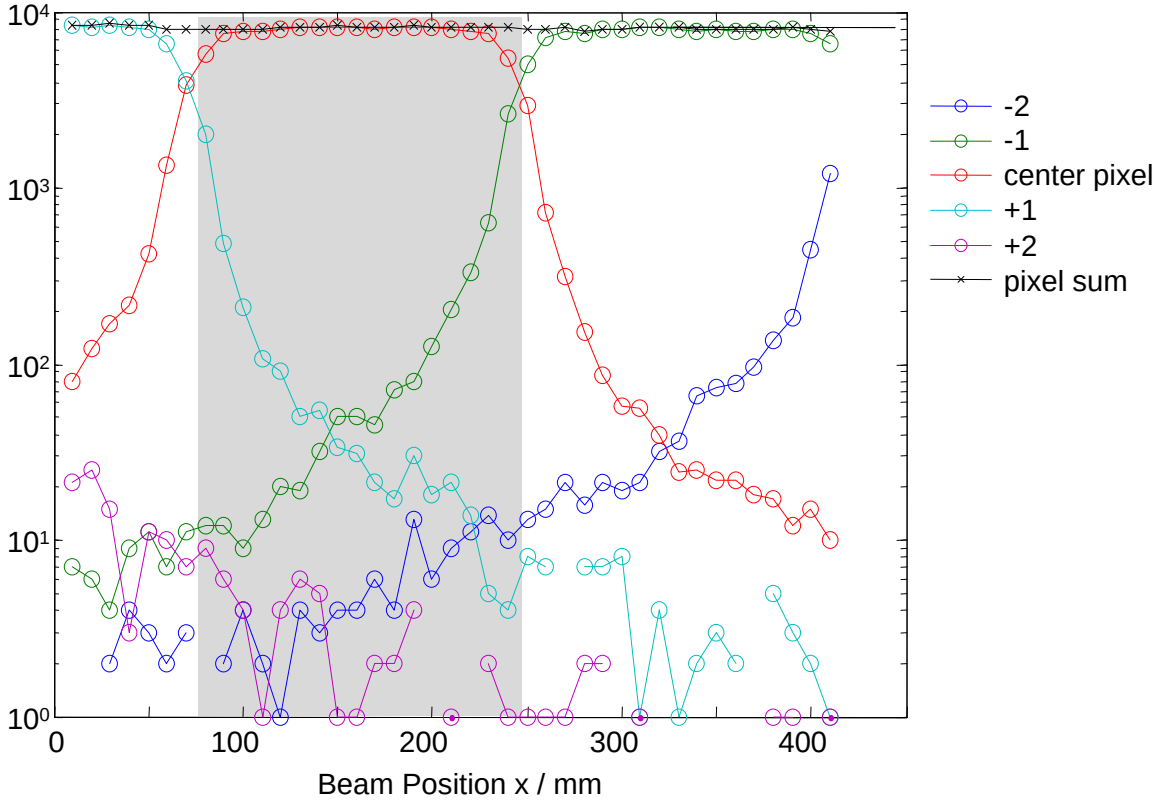

S. Ebermayer *et al.*,
Proc. SPIE 7742, 77420U (2010)

# Point spread function of a PILATUS detector

X-ray Radiometry

Pilatus 100k module, 320 µm Si thickness
487 x 195 pixels, pixel size 172 x 172 µm², area 84 x 34 mm²



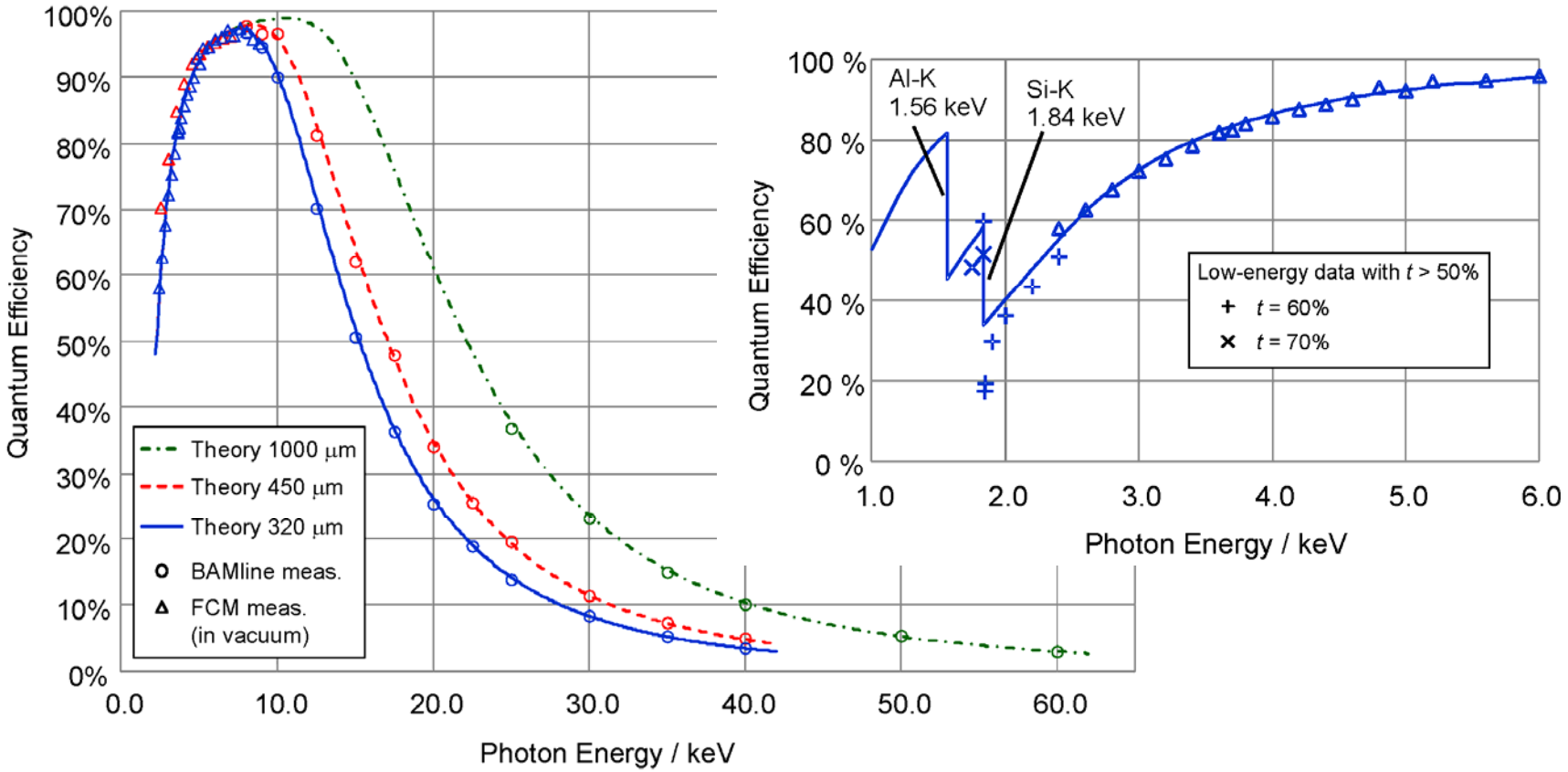

measured in vacuum
3.3 keV

T. Donath et al.,
11th International Conference on Synchrotron Radiation Instrumentation
Lyon, 9 – 13 July 2012

# Quantum Efficiency of a PILATUS detector

X-ray Radiometry

Pilatus 100k module measured in vacuum and in air



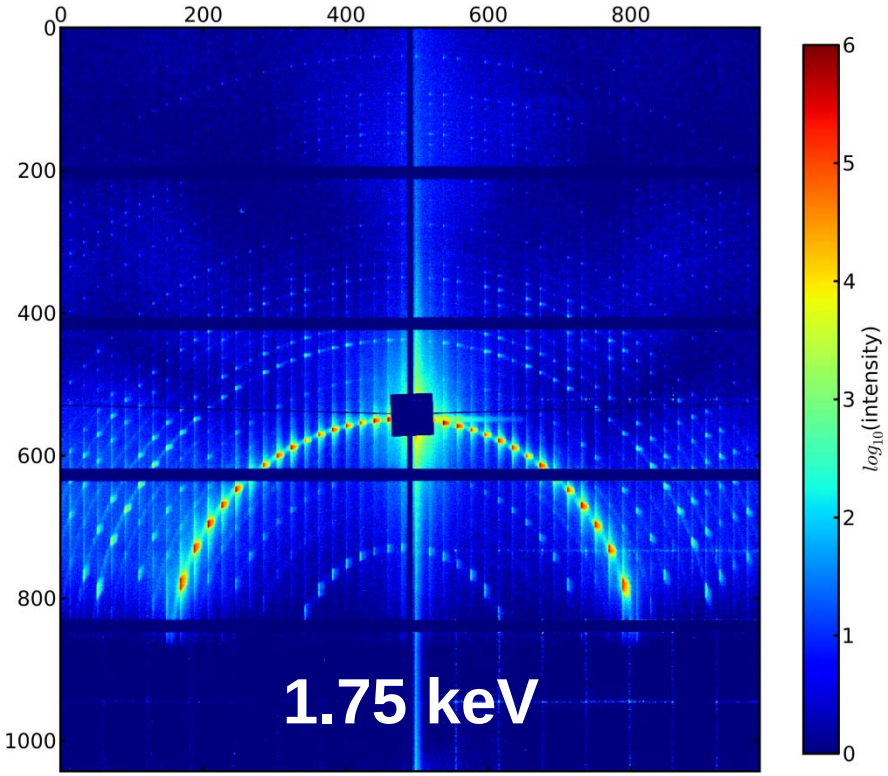

T. Donath et al.,
11th International Conference on Synchrotron Radiation Instrumentation
Lyon, 9 – 13 July 2012

# PILATUS detector for low-energy applications

X-ray Radiometry

Pilatus 1M vacuum version, 320 µm Si thickness
981 x 1043 pixels, pixel size 172 x 172 µm², area 169 x 179 mm²


GISAXS, grating structure



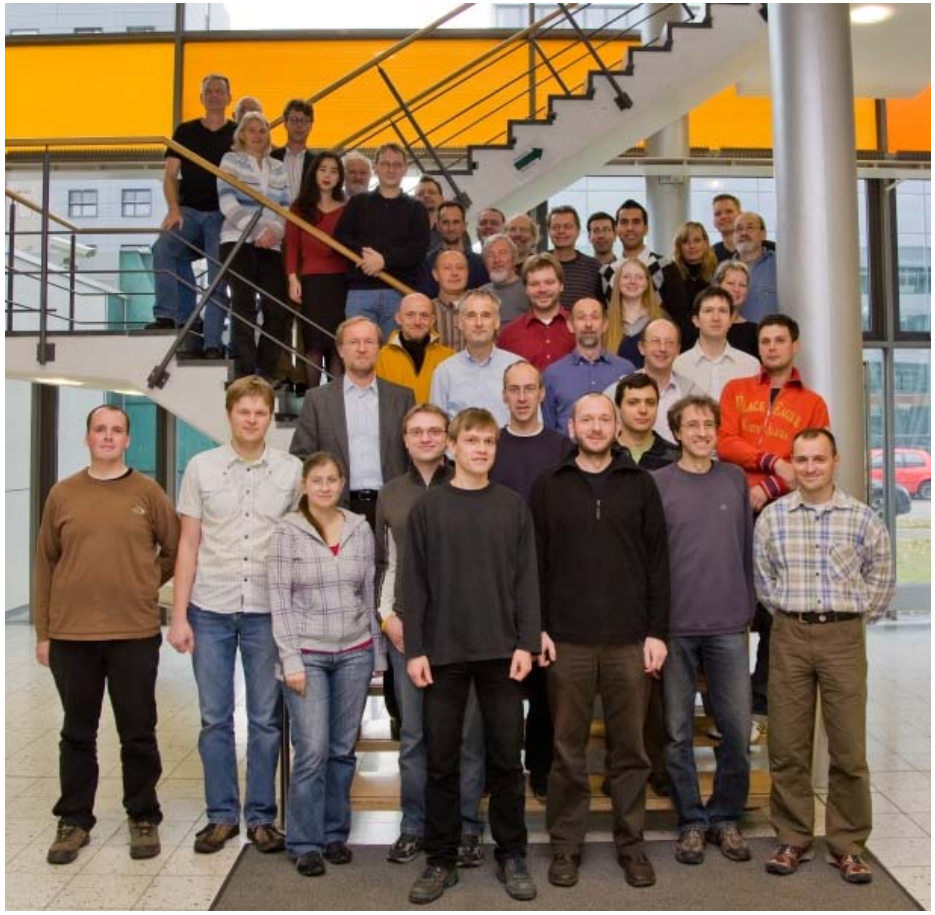
# Conclusion

X-ray Radiometry

- X-ray detectors can be characterized and calibrated in the PTB laboratory at BESSY II in a wide energy range from 50 eV to 60 keV
- Energy-dispersive detectors (Si(Li)s, SDDs) can be calibrated directly against the primary source standard BESSY II
- All other detectors can be calibrated in monochromatic radiation against a cryogenic electrical substitution radiometer as primary detector standard (using calibrated silicon photodiodes as transfer standards)
- Relative uncertainties for the responsivity or the quantum efficiency down to 1 % can be reached
- Area detectors are characterized and applied also at low X-ray energies

# Acknowledgements

X-ray Radiometry



DECTRIS
Next Generation X-Ray Detectors

**A quarter-century of metrology using synchrotron radiation by PTB in Berlin**
B. Beckhoff, A. Gottwald, R. Klein, M. Krumrey, R. Müller, M. Richter, F. Scholze, R. Thornagel and G. Ulm
physica status solidi B **246**, 1415 – 1434 (2009)