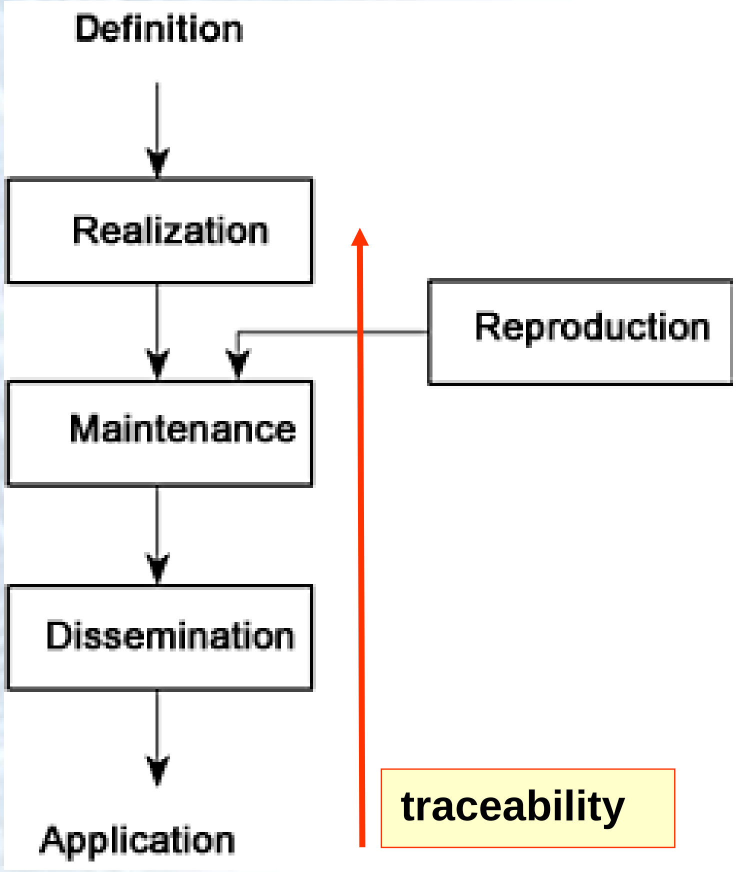
Uncertainties in traceable radiometric calibration of EUV instruments using synchrotron radiation

Alexander Gottwald (UV and VUV detector-based radiometry)
Frank Scholze (EUV detector-based radiometry)
Roman Klein (Source-based calibrations)

Traceability

… or: what metrology institutes are good for.



common radiometric SI units:

- radiant flux (power) Φ_e — W
- spectral power $\Phi_{e,\lambda}$ — $W \cdot m^{-1}$
- radiant intensity I_e — $W \cdot sr^{-1}$
- spectral radiance $L_{e,\lambda}$ — $W \cdot m^{-1} \cdot sr^{-1} \cdot m^{-2}$
- spectral irradiance $E_{e,\lambda}$ — $W \cdot m^{-1} \cdot m^{-2}$

…

$\Rightarrow$ **power ⊗ spectrum ⊗ geometry**

Traceability

traceability of radiant power

source based radiometry

traceability to:

primary source standard

emission calculable based on basic physical principles

in UV, VIS, IR: black body radiator

Planck's law, $\Phi_{e,\lambda} \sim T^4$

$T < 3800\ \mathrm{K} \Rightarrow \lambda > 200$ nm

in VUV/EUV: electron storage ring
Schwinger equation

detector based radiometry

traceability to:

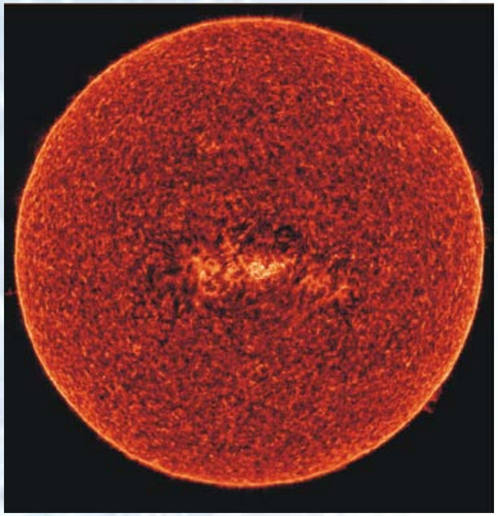
primary detector standard

(cryogenic) electrical substitution radiometer (ESR)

based on equivalence between electrical and radiative heating

radiometric measurement is traceable to measurement of electrical quantities

Examples: EUV instrument calibrations



Characterisation of space-based instruments in the VUV / EUV spectral range by PTB:

- reference source calibration
- detector calibration
- filter transmission
- mirror reflectivity
- grating efficiency
- spectrometer characterisation

Year of calibration	Wavelength range	Instrument	Mission
1994	50 to160 nm	**SUMER** *Solar Ultraviolet Measurements of Emitted Radiation*	**SOHO** *Solar and Heliospheric Observatory* launch Dec 2,1995
1994	15 to 80 nm	**CDS** *Coronal Diagnostic Spectrograph*	
1996	15 to 80 nm	**SERTS** *Solar EUV Rocket Telescope and Spectrograph* launches Nov 18, 1997 and June 24, 1999	
1998	1 to 20 nm	**SEE** *Solar EUV Experiment*	**TIMED** *Thermospere Ionosphere Mesosphere Energetics and Dynamics* launch Dec 7,2001
2004	115 to 135 nm	**TWINS** *Two Wide-Angle Imaging Neutral-Atom Spectrometers* launch June 28,2006	
2004	15 to 80 nm	**EIS** *EUV Imaging Spectrometer*	**SOLAR-B** launch Sep 22, 2006
2005	15 to 80 nm	**MOSES** *Multi-Order Solar EUV Spectograph* launch Feb 8, 2006	
2007	17 nm to 37 nm	**EUNIS** *Extreme Ultraviolet Normal Incidence Spectrometer* launches in 2006, 2007, 2008	
2004 2006	10 to 240 nm	**SOL-ACES** *Solar Auto-Calibrating EUV/UV Spectrophotometers*	**SOLAR** Solar Monitoring Observatory / ISS launch Feb 7, 2008
2002 2007	180 to 3200 nm	**SOL-SPEC** *Solar Spectral Irradiance Measurement*	
2005 2006 2007	1 to 240 nm	**LYRA** *Lyman-alpha Radiometer* **SWAP** *Sun Watching using APS detectors and image processing*	**PROBA II** *Project for On Board Astronomy* launch Nov 2, 2009
2009 2010	10 to 240 nm	**EUI** *Extreme-Ultraviolet Imager*	**Solar Orbiter** scheduled 2015 +x

PTB facilities for synchrotron radiation

1982 – 1999: BESSY I

located in (West-)Berlin, Wilmersdorf

since 1999: BESSY II

BESSY II: multi-user facility,
circumference 250 m, electron energy 1.7 GeV

located in Berlin-Adlershof

since 2008: MLS

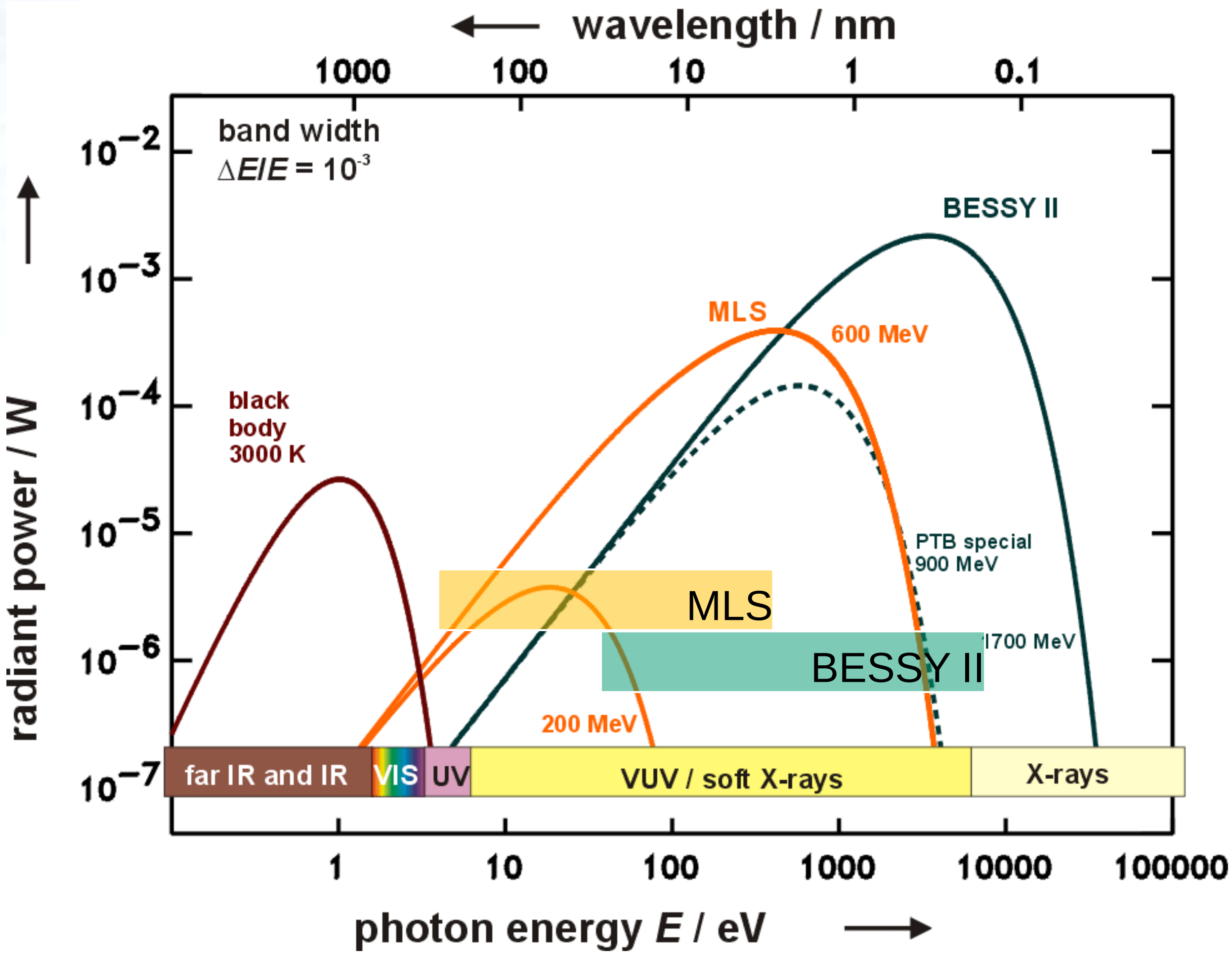
Metrology Light Source MLS: PTB-owned facility,
circumference 48 m, electron energy 100 - 630 MeV

located in Berlin-Adlershof

PTB facilities for synchrotron radiation

since 1999: BESSY II

since 2008: MLS

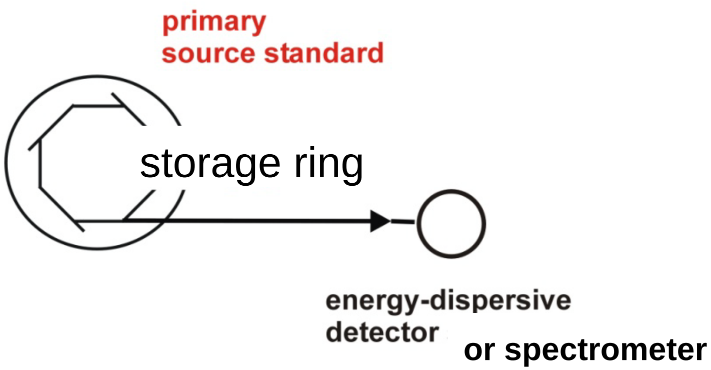


Source-based radiometry

use of electron storage ring as primary source standard (calculable radiation)

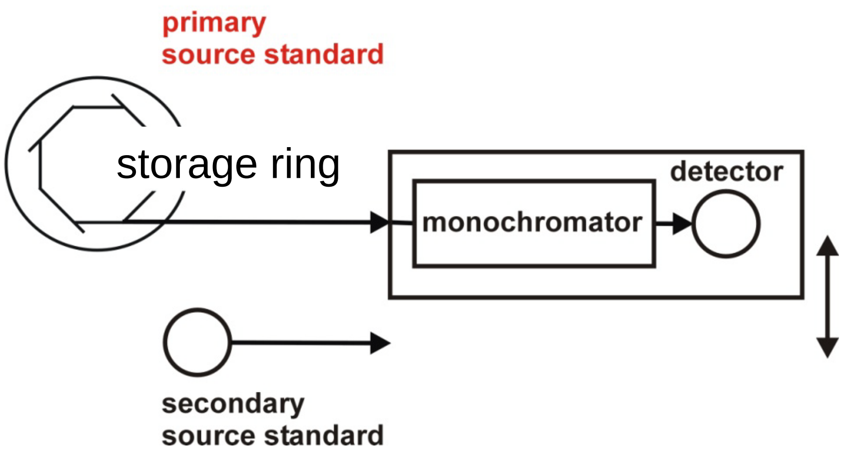
direct calibration

(a) calibration of energy-dispersive detectors & spectrometers



calibration of transfer standard

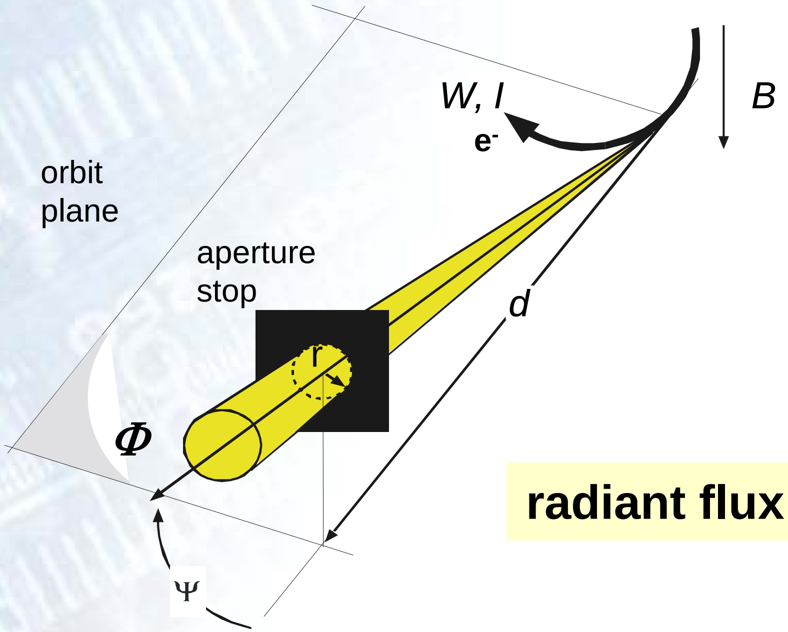
(b) calibration of radiation sources



Calculable Synchrotron Radiation

PTB

electron storage ring as primary source standard



Schwinger equation:

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

- **electron beam and storage ring parameters**

W	electron beam energy
I	electron current
Σ_y	vertical extension and divergence of the beam
B	magnetic induction

- **geometrical quantities**

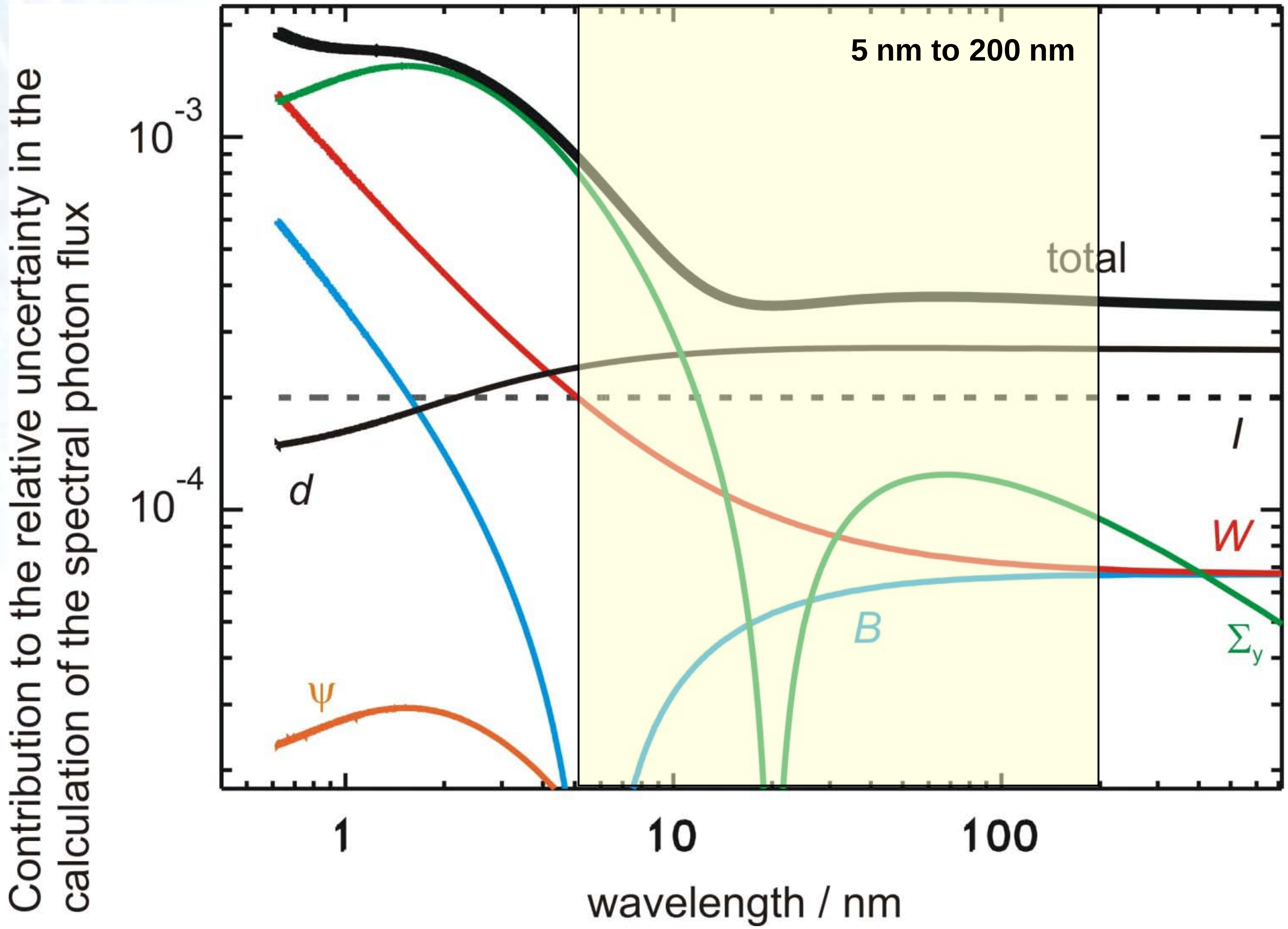
d	distance
r	radius of aperture
ψ	emission angle

Uncertainty Budget

PTB

Example: MLS

W	electron energy
I	electron current
B	magnetic induction
d	distance
Σ_y	vert. beam size
ψ	emission angle



The spectral radiant power is available with rel. uncertainties well below 0.1 %

R. Klein et al., Phys. Rev. STAB ***11*** *(2008) 110701*

Direct calibration

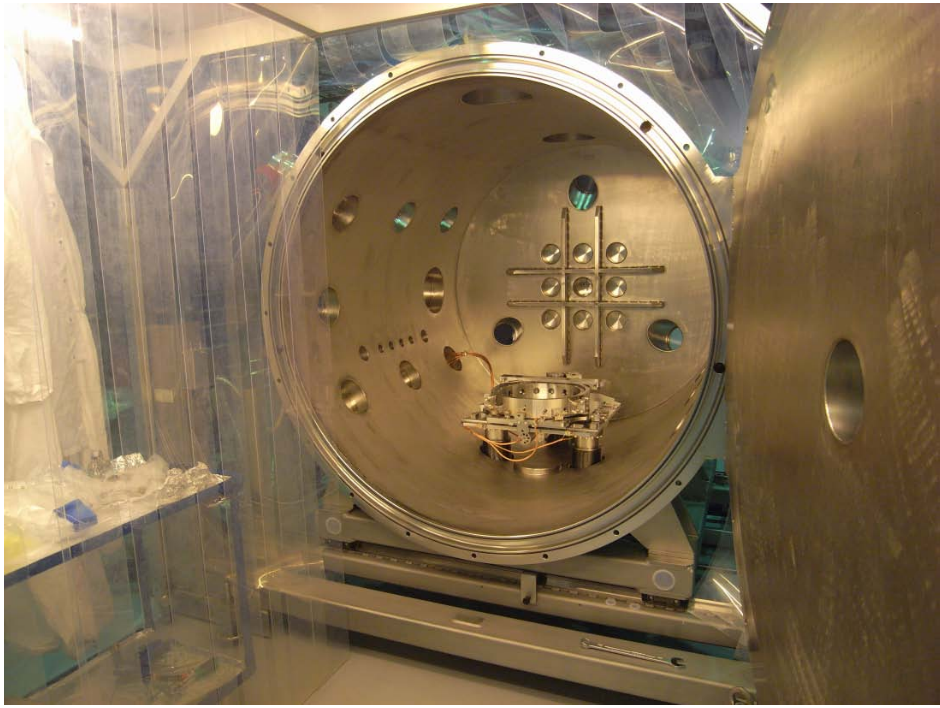
direct calibration:

- spectrometer must fit at the beamline **(!)**
- spectrometer must not vignette incident beam
- divergent beam, source is not ∞
- white beam: higher orders with grating spectrometer
- SR is (strongly) linear polarised

will add uncertainties "+ X %"

depending on the individual instument

so far not done at PTB for <u>external</u> partners



new instrumentation @ PTB
"space tank" : max. 1,50 m length, 100 kg weight

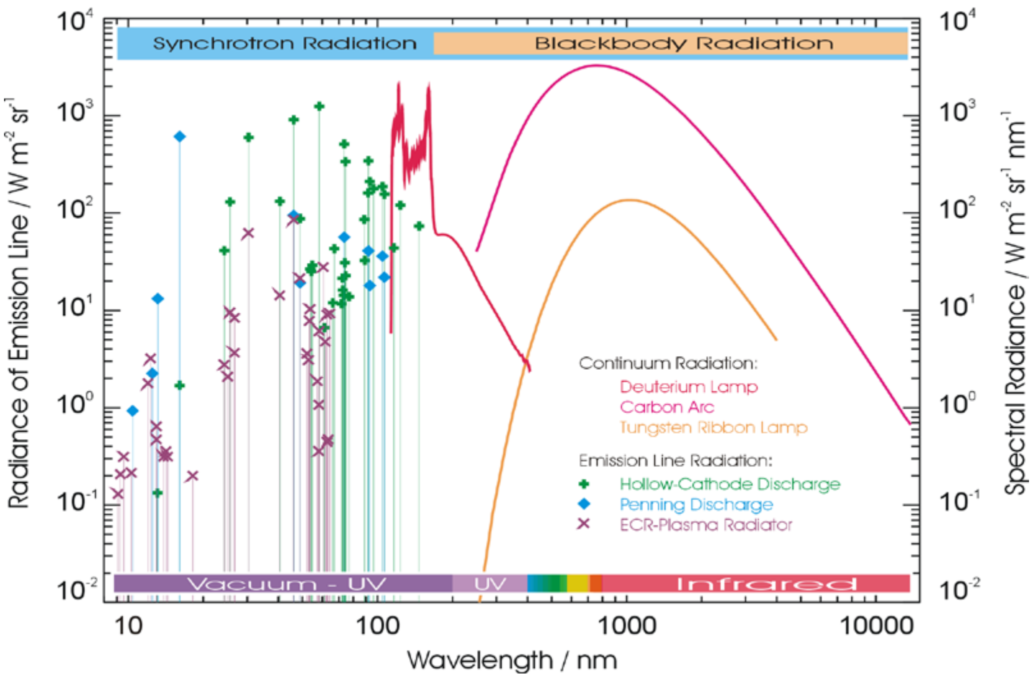
Transfer source calibration

PTB

Calibration of transfer standards

D_2 lamp (λ > 120 nm) cont. spectrum
HC (λ < 100 nm) discrete spectrum

- "One step more"
- transfer standard itself adds (high) uncertainty
- t.s. has only limited spectral width
- t.s. has only limited "lifetime" (aging)



typical uncertainties (HC), k=2:

12 - 16 % radiometric calibration
incl. 10 % reproducibility (40 h operation)

Advantages:

- transfer standard available at your lab
- re-calibration campaigns possible

*Hollandt et al., Metrologia **30** (1993) 381-388*

well-known examples: SUMER- , CDS source.

Validation

PTB

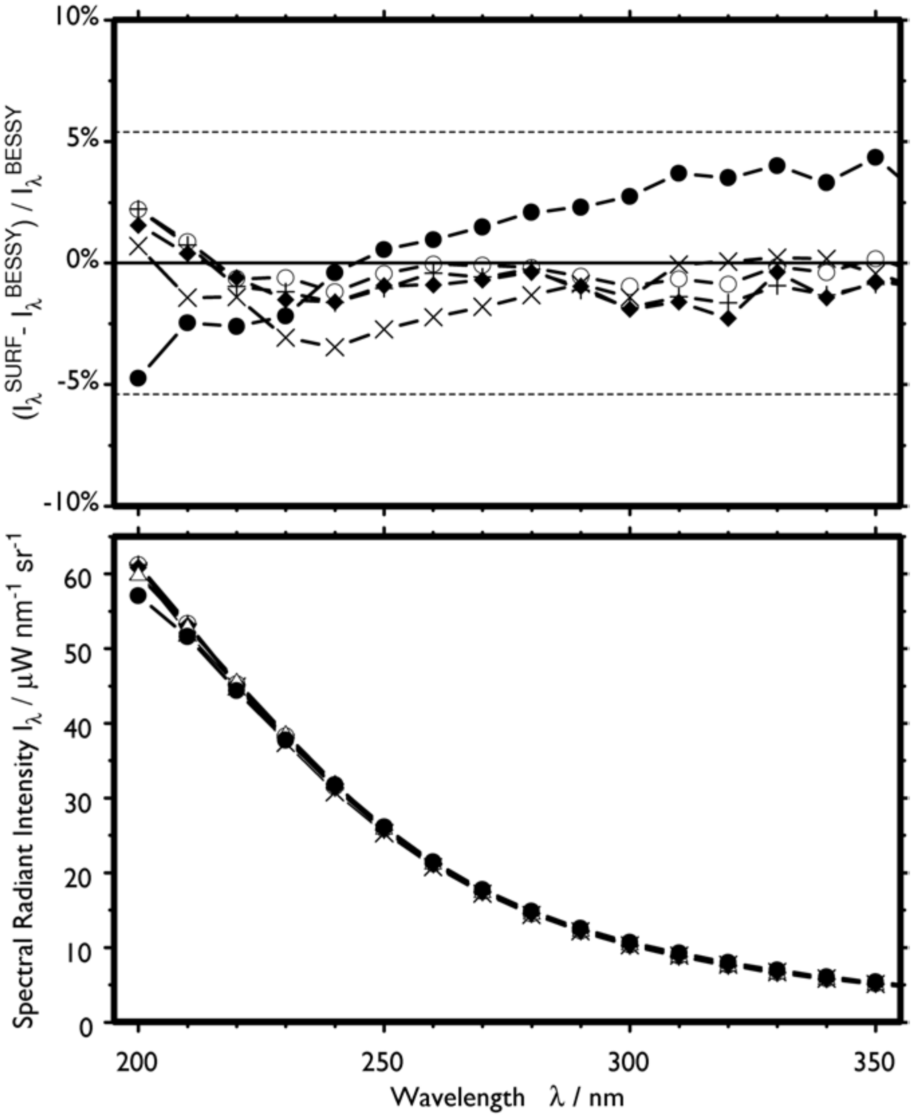
Bilateral PTB – NIST comparison

spectral radiant intensity of
deuterium lamps 200 nm – 350 nm

(NIST: spectral irradiance)

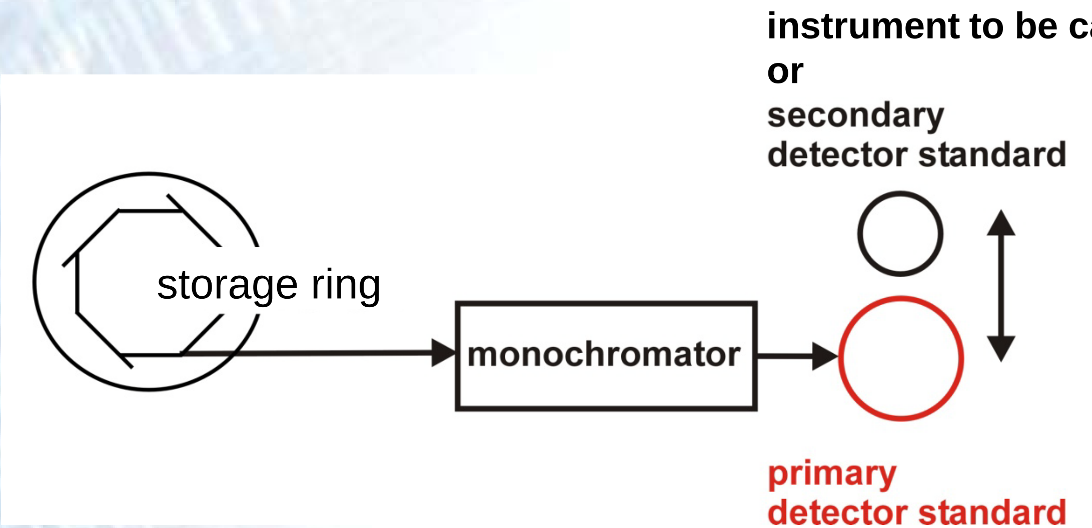
combined uncertainty *U* (*k*=2): 5.4 %

Agreement of calibrations
(= scales of spectral radiant intensity)
within combined uncertainty ≈ 5 %



Arp et al., Metrologia ***48*** *(2011) 261-267*

Detector-based radiometry



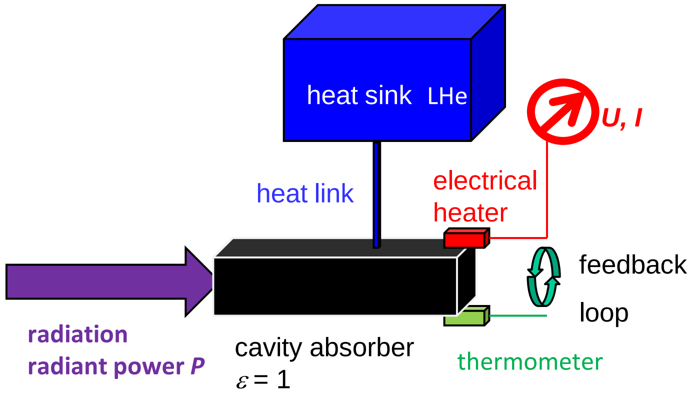
primary detector standard:
(cryogenic) electrical substitution radiometer

- Optimized for VUV radiation (40 nm to 400 nm)
- 100 mK/µW sensitivity
- 120 s time constant

Uncertainty in power determination

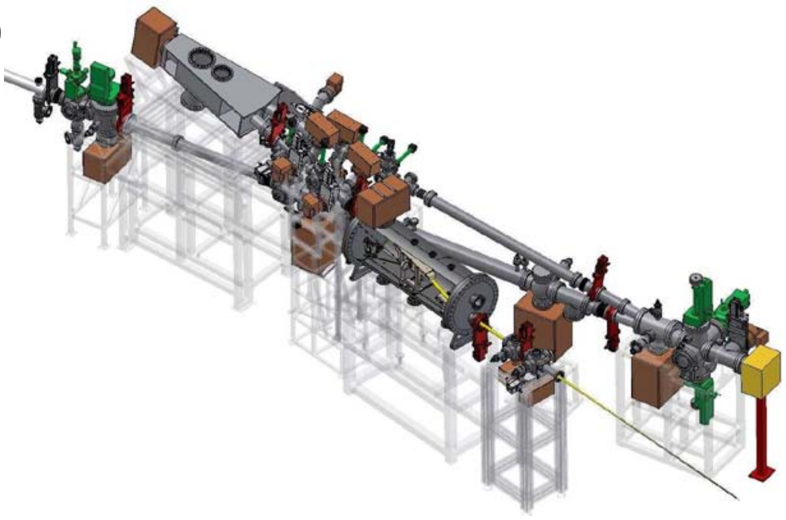
main contributions from ESR (@ 200 nW)

non-equivalence correction	0.17 %
temperature deviations	0.05 %
electrical calibration	0.03 %
…	
total	**0.19 %**



main contributions from SR radiation (@ 60 nm)

false light (higher orders)	0.15 %
wavelength & bandpass	0.02 %
stability	0.18 %
…	
total	**0.24 %**



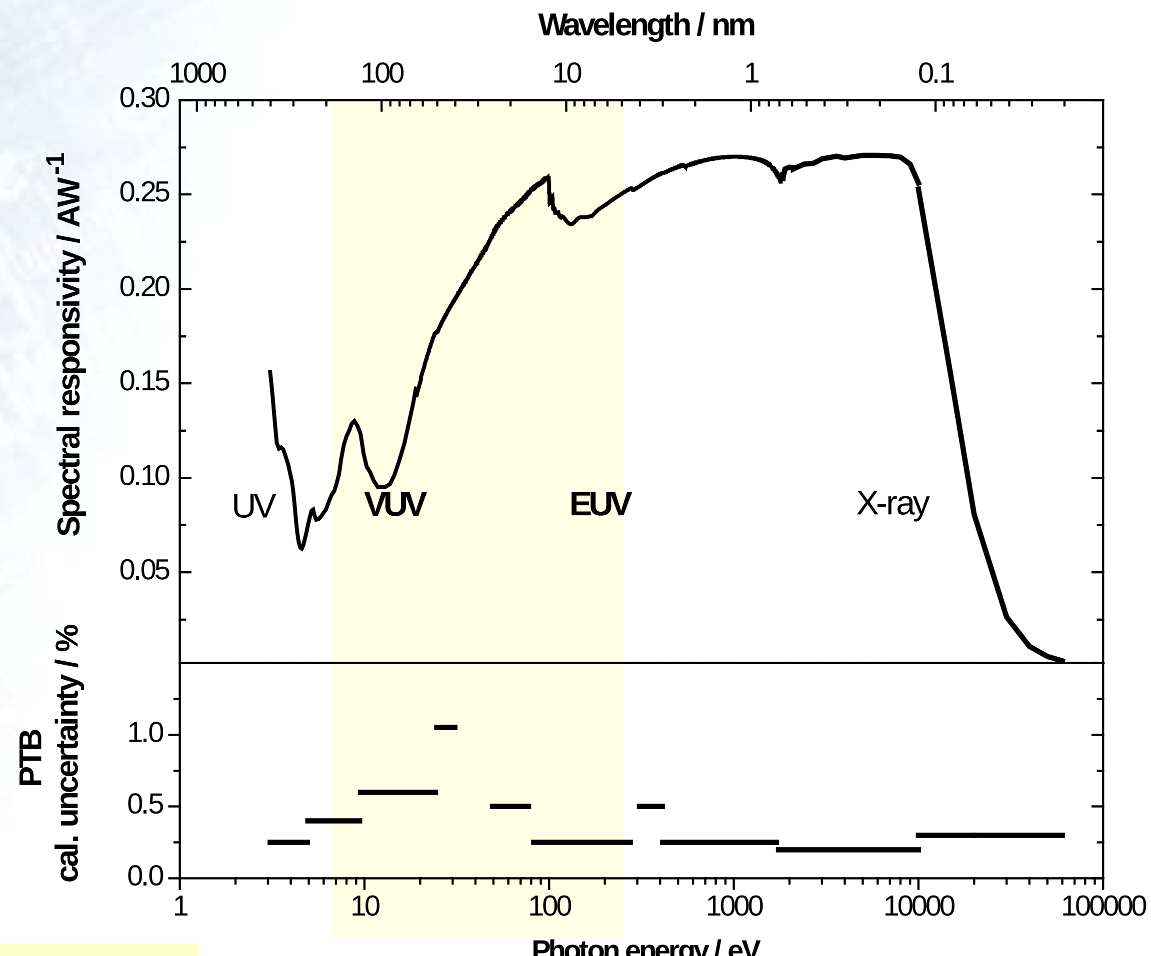
PTB's VUV beamline 40 nm – 400 nm

Gottwald et al., Meas. Sci. Technol. ***30*** *(2010) 381-388*

Scale of spectral responsivity

… as realised at PTB from UV to X-ray using synchrotron radiation

… using "well-behaving" (?) semiconductor photodiodes as secondary standards



why u > 0.5 % for λ < 120 nm ?

The weak point

main contributions from "good" secondary detector (@ 60 nm)

photocurrent measurement	0.30 %
dark current variability	<0.01 %
thermal stability	<0.01 %
spatial uniformity	0.20 %
polarisation dependence	0.05 %
…	
total	**0.37 %**

largest contribution to total uncertainty

for wavelengths 25 nm < λ < 140 nm :

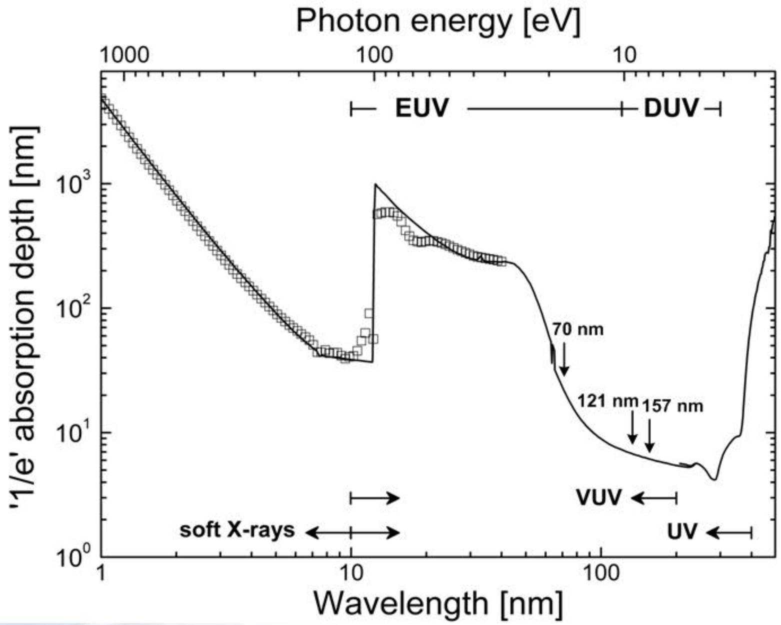
- available radiant power low (< 300 nW)
- detector responsivity low
- strong detector non-uniformities

detector aging still not covered (!) in <u>calibration</u> uncertainty budget

… as it will occur in use of the detector after the calibration.

Physical reasons

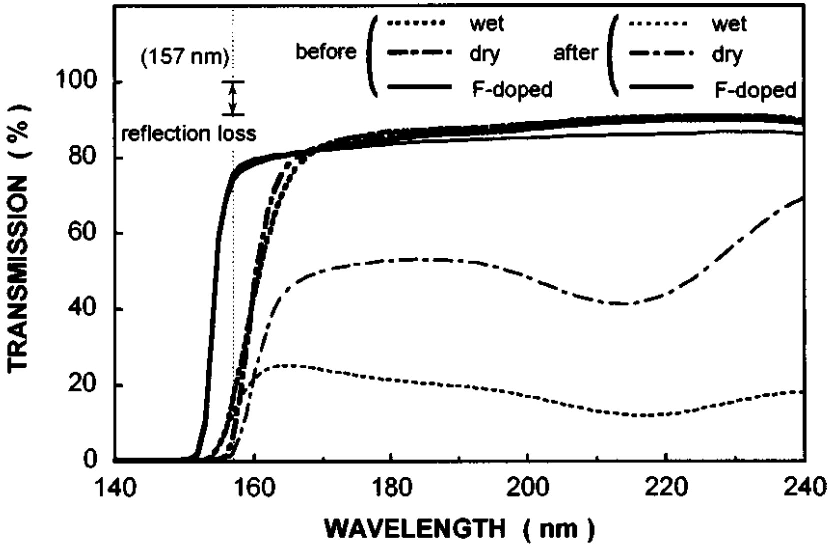
Si absorption length



L.Shi et al., (data from Palik, Henke)

IEEE Transactions on Electron Devices 59, 2012, 2888

SiO_2 absorption



VUV absorption of synthetic quartz glasses

Hosono et al., Appl. Phys.Lett. ***74*** *(1999) 2755*

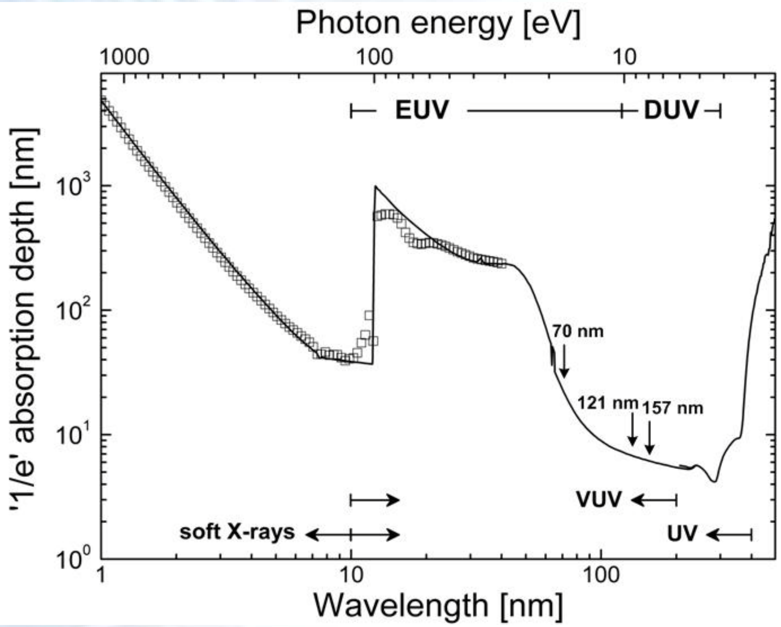
In particular for 70 nm < λ < 200 nm :

- absorption of radiation within top layer **< 10 nm**
- photon energy sufficient to create photoelectrons

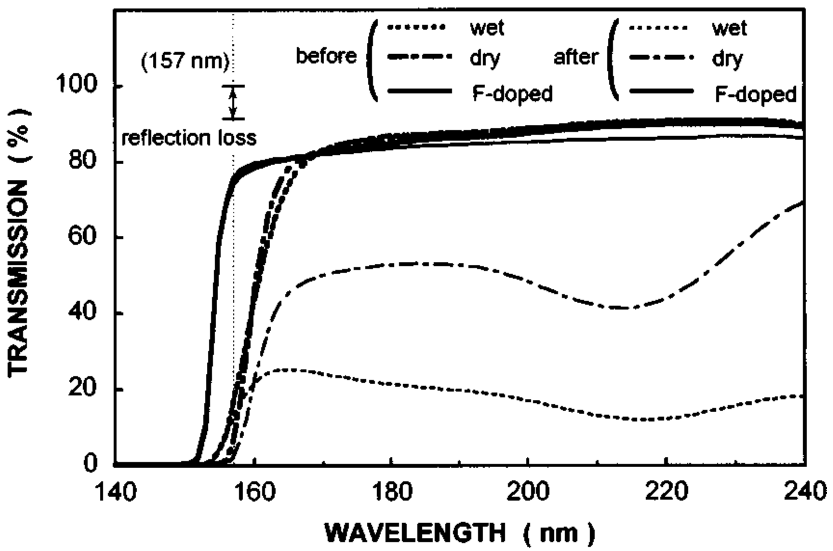
Physical reasons

PTB

Si absorption length



SiO2 absorption

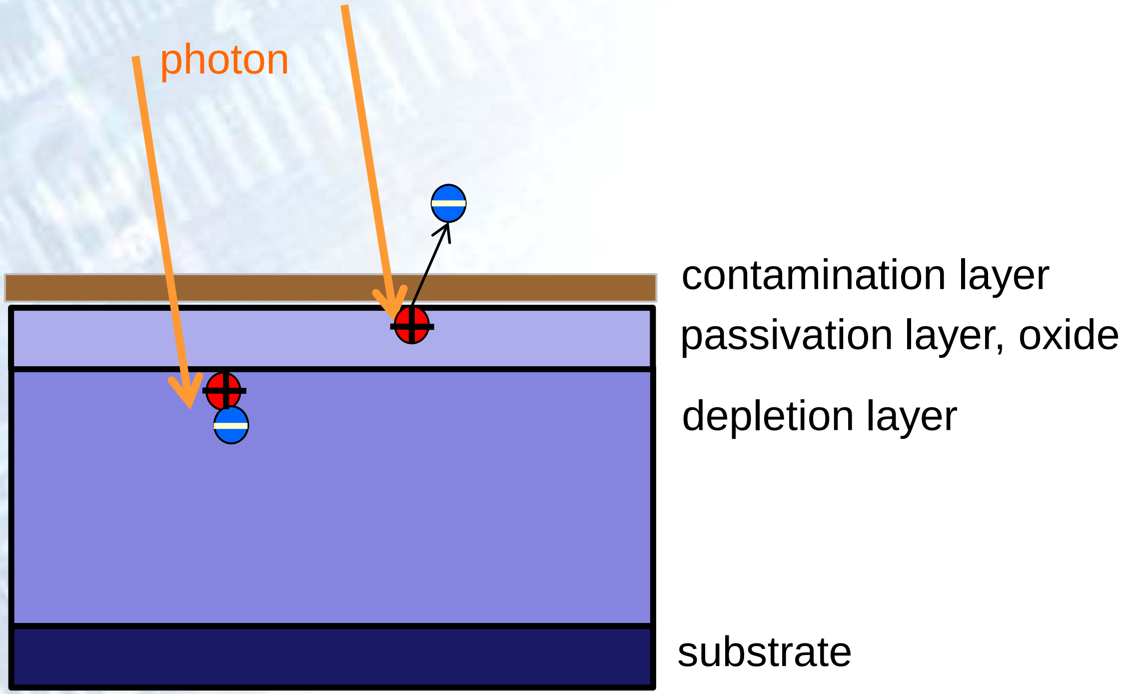


⇒ **In particular for 70 nm < λ < 200 nm :**

- **high surface sensitivity**
- **high degradation potential**

not only for detectors, but for any optical component (filter, mirror, grating)

Photon-detector interaction



- absorption within the first few nm
- condensates, adsorbates, carbon growth
- photoemission → secondary effects, chemistry
- surface charging (oxide)
- radiation damage (chemical bond-breaking)
- recombination losses → **loss in responsivity**

The ideal detector?

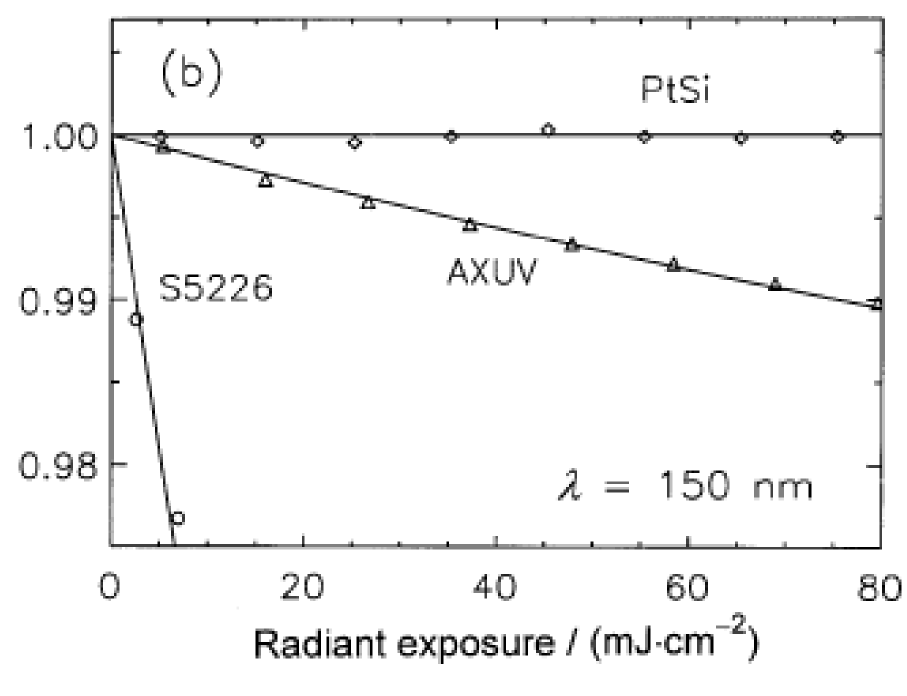
Si n – p with thin (6 nm) nitrided oxide layer	+ highest responsivity + high uniformity + "100% internal QE"	- **STRONG** degradation
Si n – p with metal/nitride filter	+ high stability	- low responsivity
PtSi-nSi Schottky	+ high irradiation stability + contamination removal	- low responsivity - low uniformity - high dark current - electrically instable
Boron technology p – n , "PureB-diode" <10 nm dead layer	+ high stability + high responsivity	- low uniformity - availability (?)

- **So far, all available detectors for this spectral region have drawbacks**
- **The PureB technology has the potential to overcome this**

Detector stability

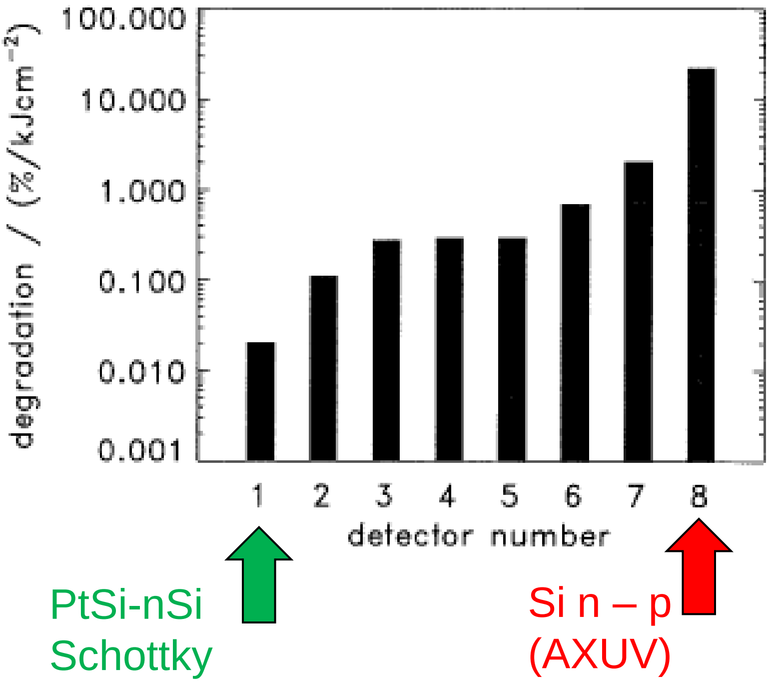
… under VUV irradiation

@ synchrotron



Kuschnerus et al., Metrologia 35, 1998, 355

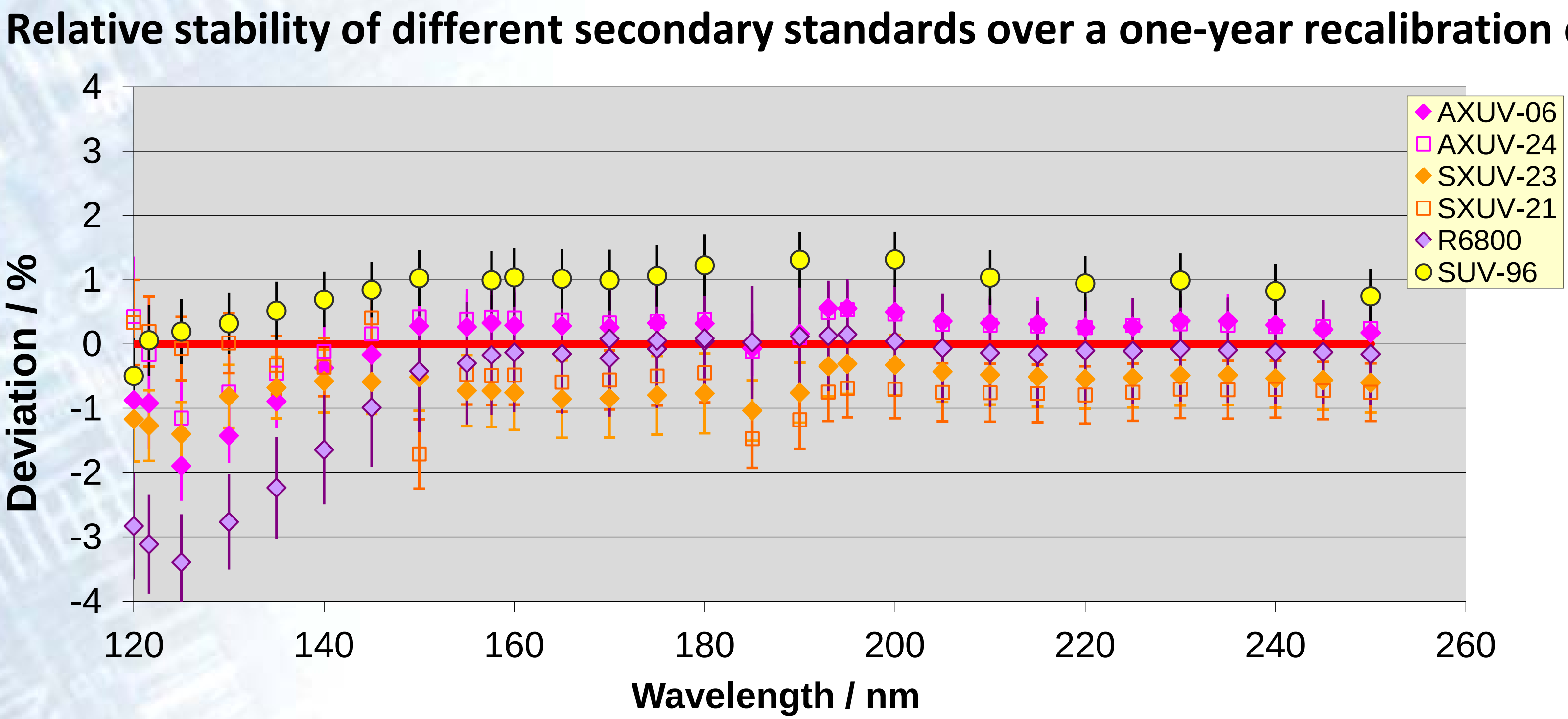
with 157 nm F_2-Laser



Richter et al., Appl. Opt., 2002, 7167

Detector stability

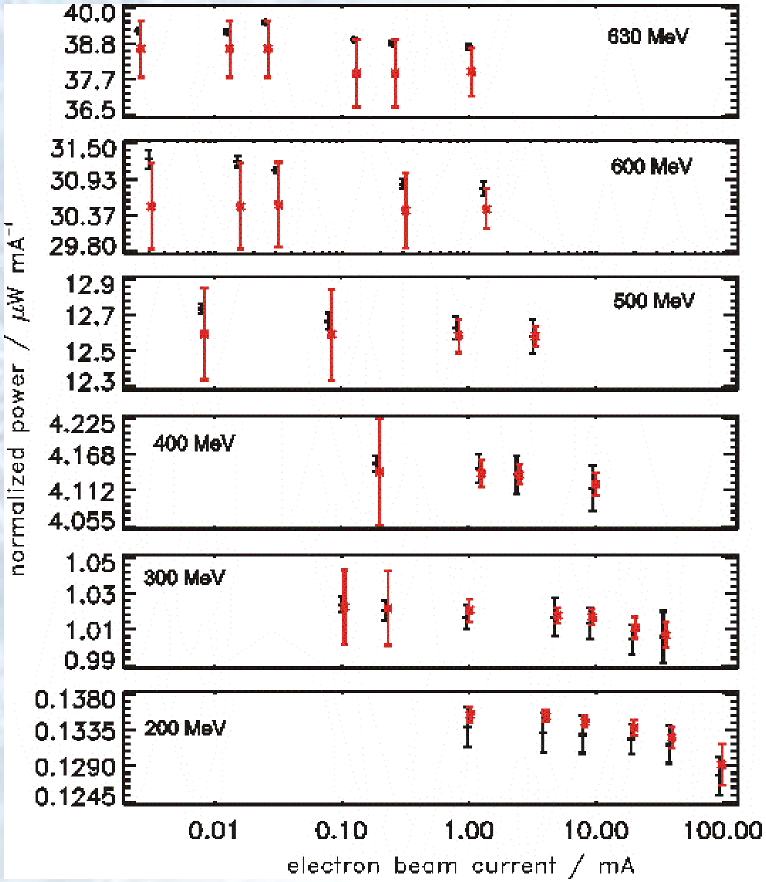
… when stored (1-year recalibration cycle)

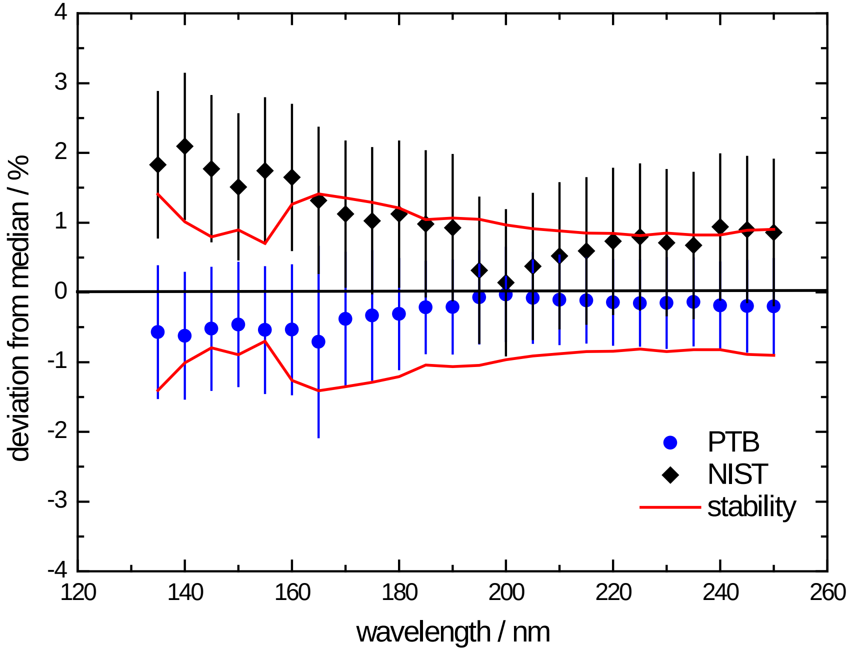


- no common behaviour: wavelenght/type/individual dependant
- **calibration can not be better than drift of secondary standard**

Validation by comparisons

- PTB internal comparison source vs. detector standard *Klein et al., Metrologia **48** (2011) 219*
- CCPR comparison PTB-NIST 135 nm – 250 nm *Gottwald et al., Metrologia **48** (2011) 02001*
- CCPR comparison PTB-NIST-NMIJ 10 nm – 20 nm *Scholze et al., Metrologia **47** (2010) 02001*





Agreement
within combined uncertainties < 2 %

Best calibration stategy ?

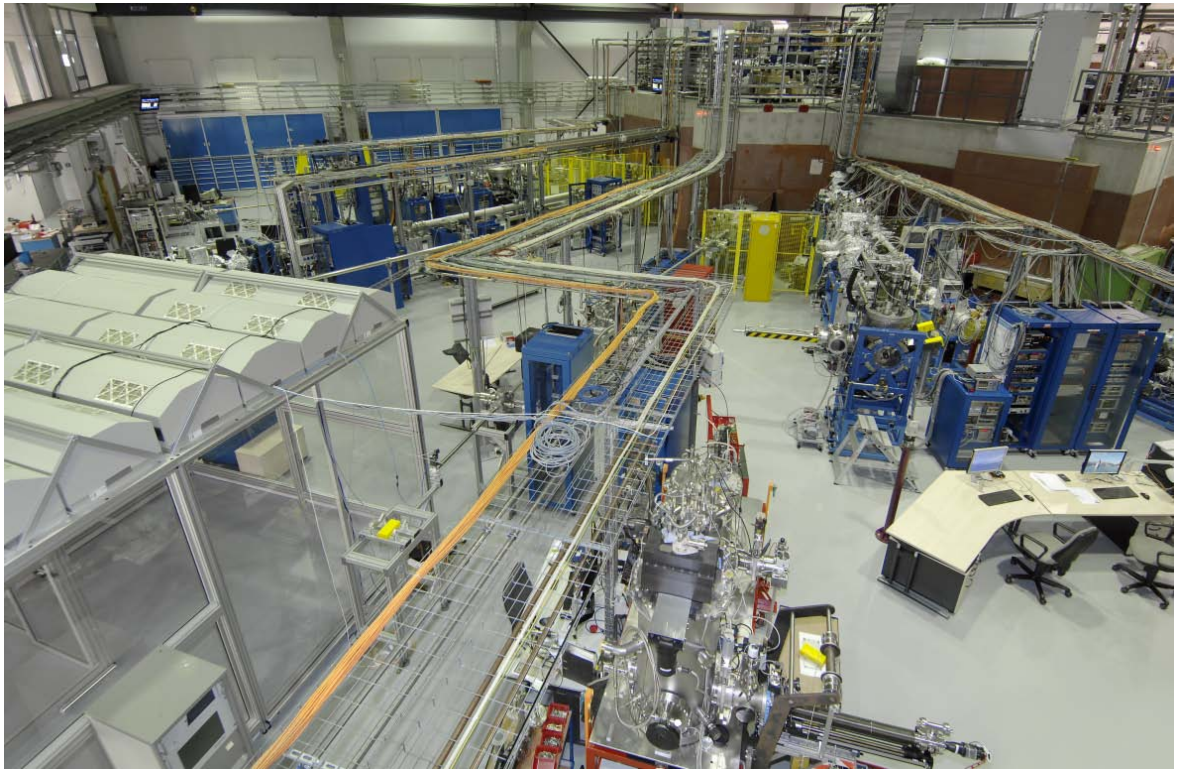
- Realization of the radiometric scale(s) by NMIs is available with low uncertainties

HOWEVER

- Dissemination of the scale by secondary (transfer) standard adds (large) uncertainties
- Direct calibration of instruments adds (large) uncertainties due to "non-equivalence" between calibration and measurement (beam) conditions
- Secondary standards as well as the instruments itself are affected by ageing (degradation) issues

- Instruments should be designed in a way that they are suitable for direct calibration with synchrotron radiation
- For the VUV range, development/improvement/commercialisation of stable transfer standards is urgently needed
- Ageing (& contamination) must be handled (witnessed. avoided. removed.)

Thank you for your attention.



View of the MLS experimental hall