Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin
Nationales Metrologieinstitut

Traceable Radiometric Calibration in the EUV/VUV Spectral Range using Synchrotron Radiation

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Michael Kolbe, Christian Laubis — EUV Radiometry
Roman Klein, Reiner Thornagel — Synchrotron Radiation Sources
Frank Scholze — Radiometry with Synchrotron Radiation (dept.)

Subtitle?

What you should expect from state-of-the-art ground based radiometric calibrations

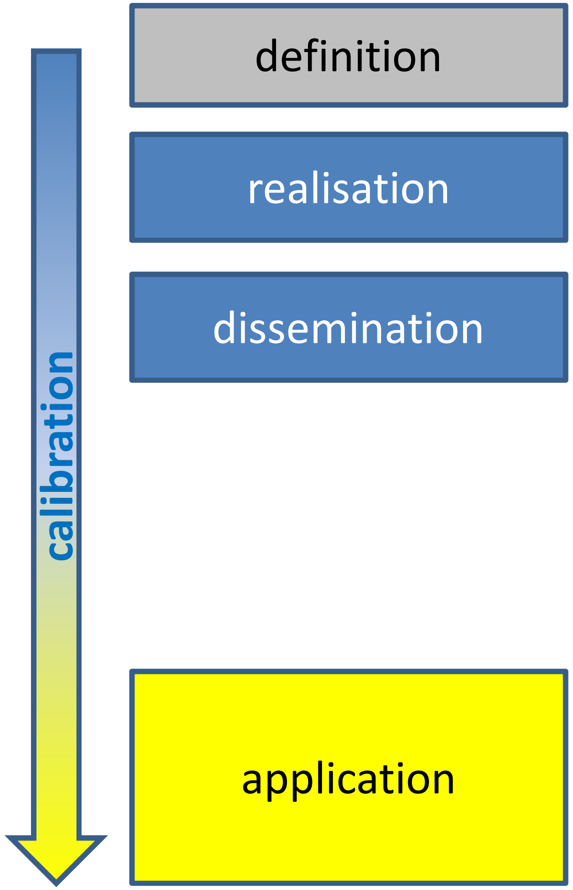
in the wavelength range from 5 nm to 200 nm

Outline

- The basic principles: Traceability in Radiometry
- How to use Synchrotron Radiation
- How to make a precision measurement
- Limits
- Examples

Traceability

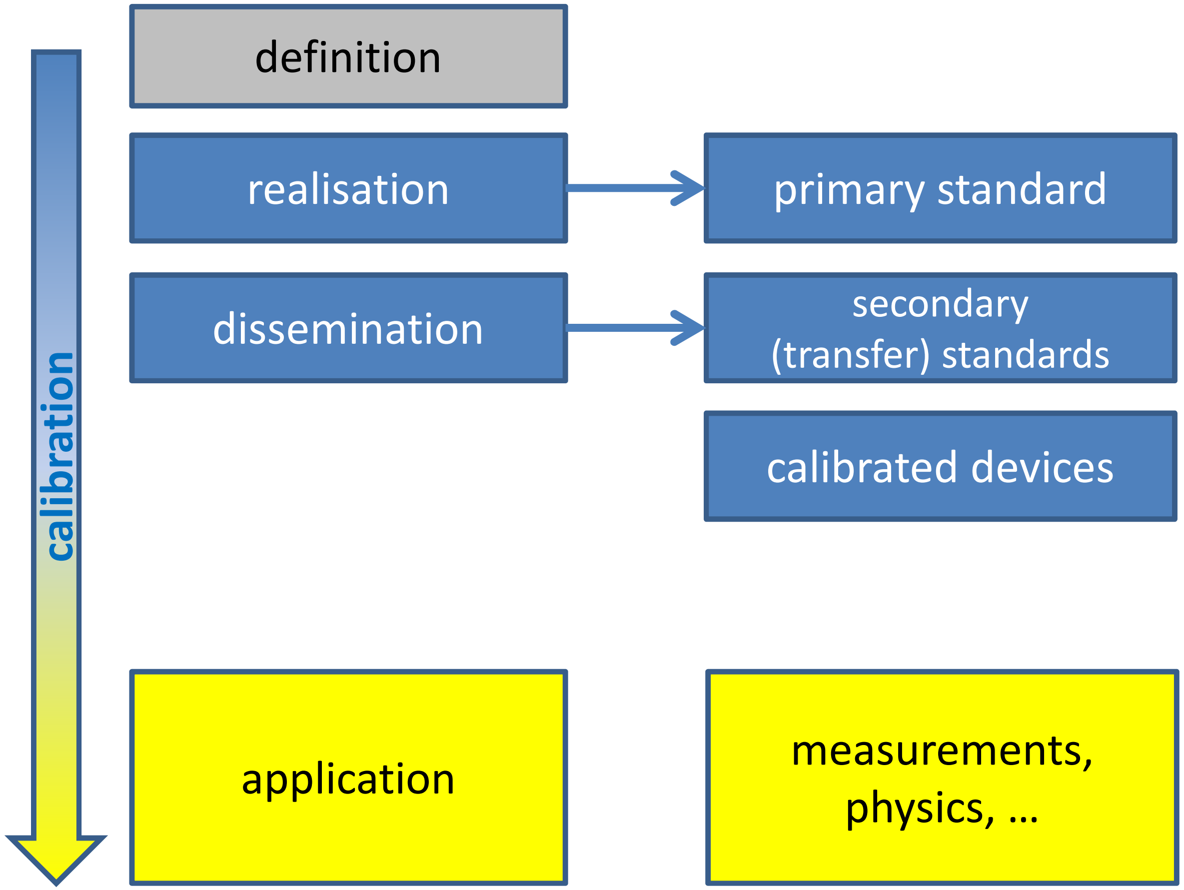
radiometric quantity, or unit



e.g. radiant power [W]
radiant intensity [W sr^{-1}]
spectral radiance [W m^{-1} sr^{-1} m^{-2}]
spectral irradiance [W m^{-1} m^{-2}]

Traceability

radiometric quantity, or unit



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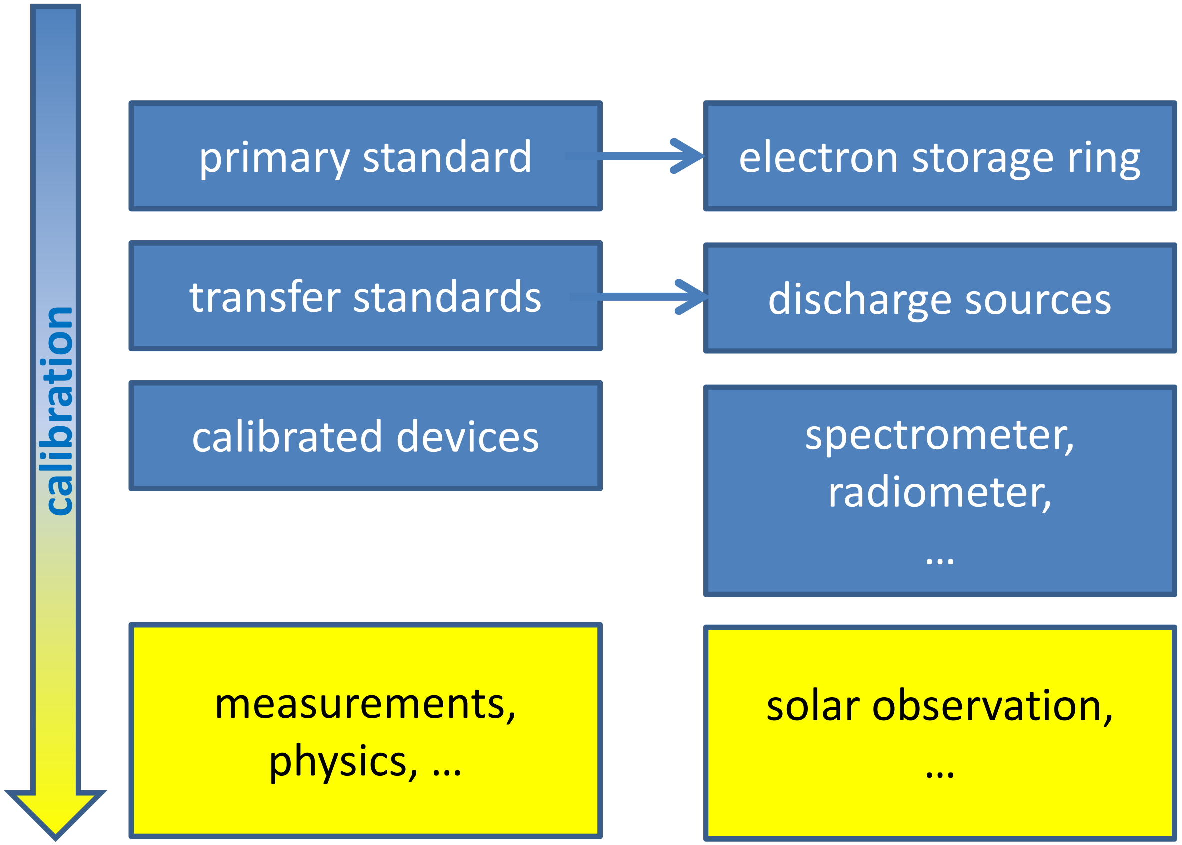
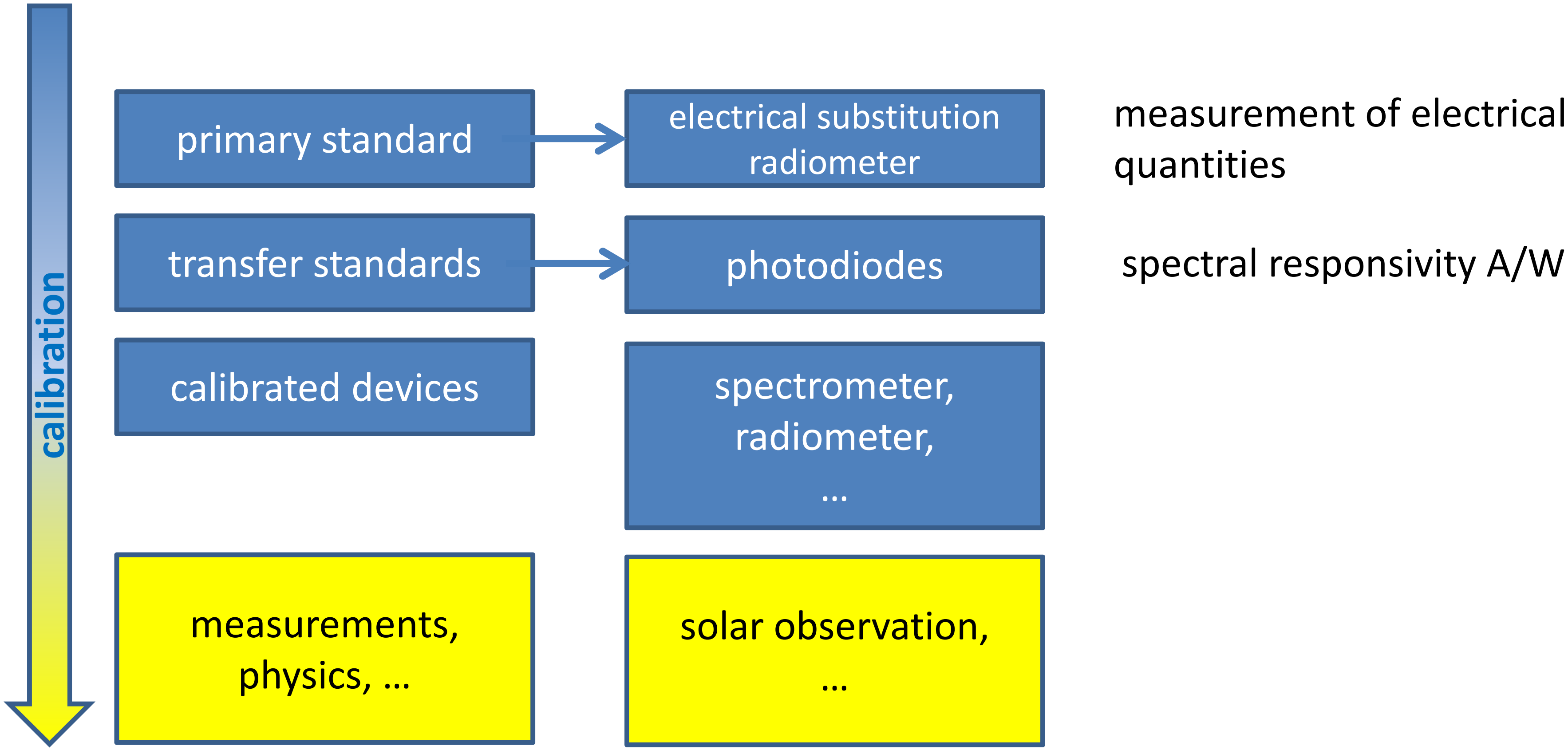
Source based radiometry



calculation by
Schwinger‘s equation (1949)

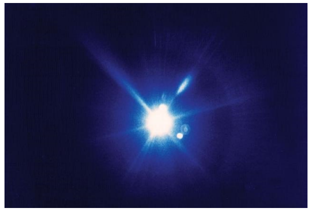
spectral radiant intensity,
spectral radiance

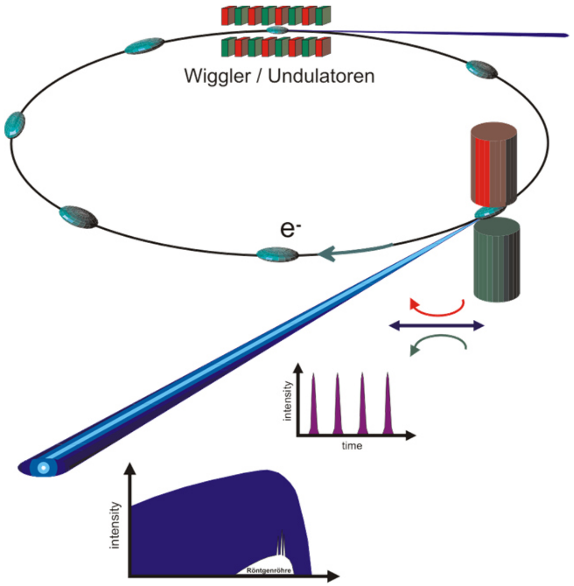
Detector based radiometry



Why synchrotron radiation ?

Synchrotron radiation is emitted when charged particles with relativistic energies are accelated in a magnetic field



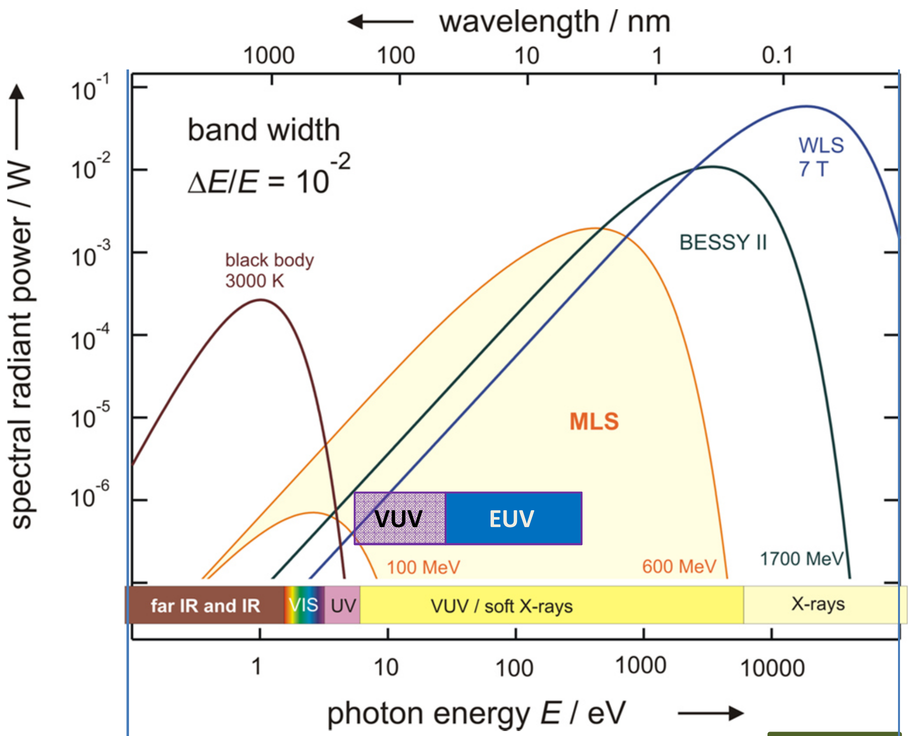


typical source:

electron storage rings = (few) GeV particle accelerators

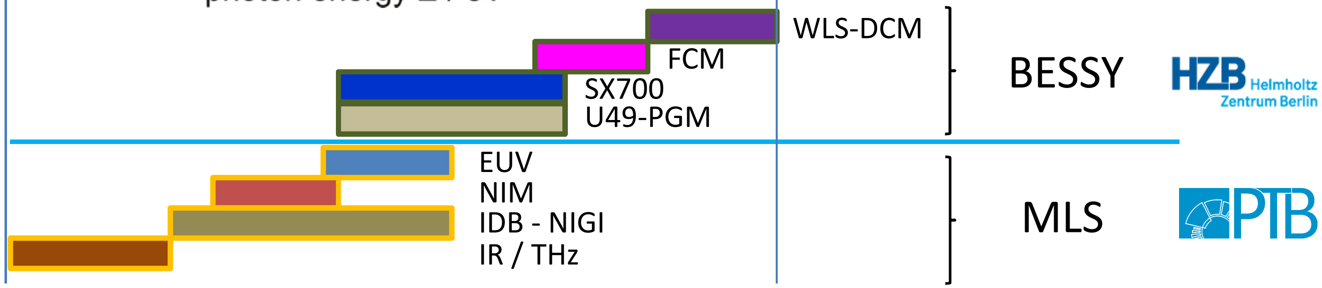
- bright > 10^{11} photons/s/0.1%BW
- brilliant > 10^{20} photons/s/mm^2/mrad^2/0.1%BW
  thus: directional emission
- „white" = broadband from IR to X-ray
  thus: **tunable with monochromators**
  also **in the EUV and VUV range**
- „clean" = UHV conditions, no debris
- emission is **calculable** from basic physical equations (Schwinger 1949):
  Thus **an electron storage ring can be operated as primary source standard.**

Synchrotron radiation available at PTB



Berlin-Adlershof

PTB monochromator beamlines:



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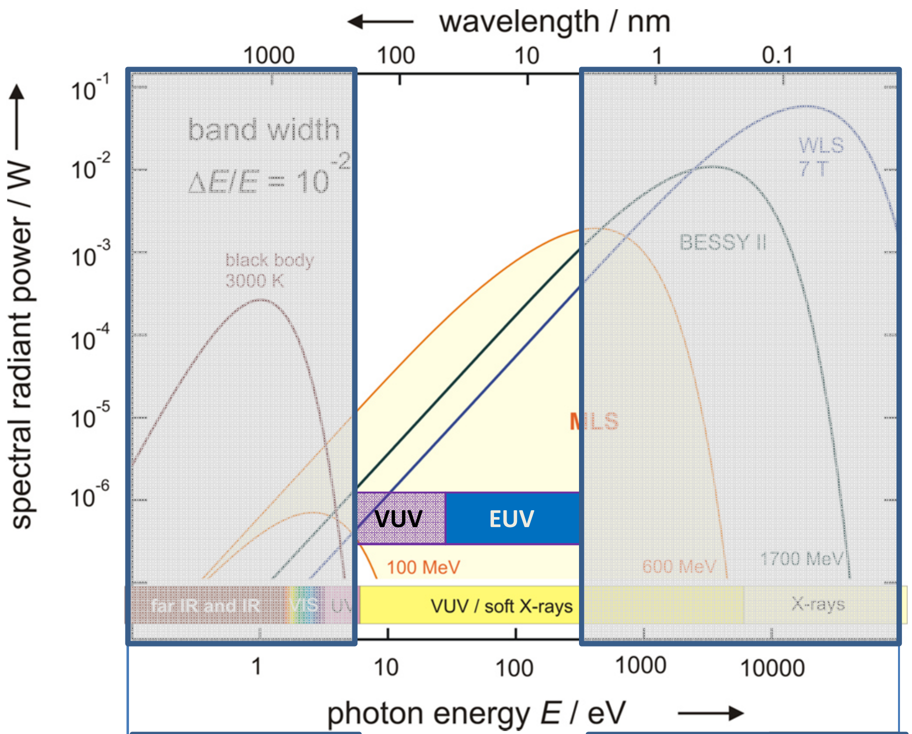
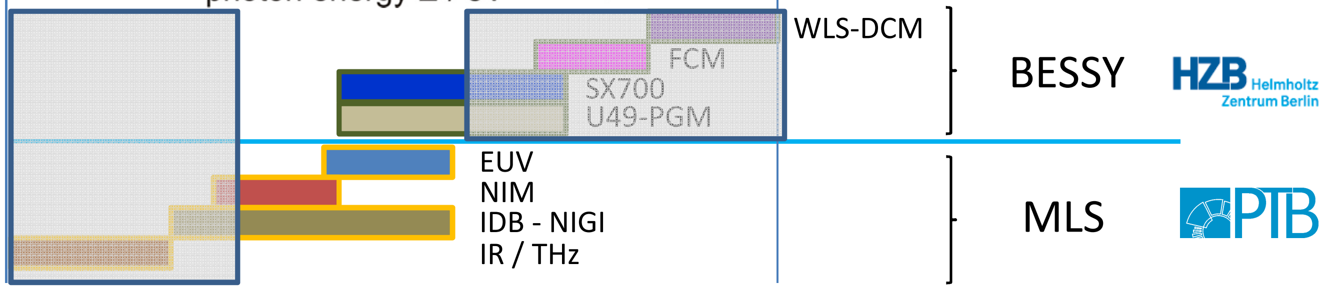


Berlin-Adlershof

PTB monochromator beamlines:



Main relative uncertainty contributions *(k=1, in %)*

source based calibration

Radiant intensity, D_2 Lamp 200 nm

electron beam current, *I*	**0.5**
electron energy, *W*	0.012
mag. Induction, *B*	0.0005
eff. vertical source size, Σ_Y	0.07
offset to orbit plane, Ψ	0.01
total [storage ring]	**0.51**

realisation

non-linearity of detector	0.3
stability within SR calibrations	**2.2**
distance difference to AP	0.21
higher diffraction orders	**0.5**
stray light	**0.5**
total [transfer monochromator]	**2.4**

dissemination

D2 source stability	**2.0**
source alignment	0.5
wavelength calibration	0.1
residual polarization of source	0.5
total [D2 Lamp]	**2.1**

calibration

total	**3.2**

detector based calibration

Spectral responsivity, Si photodiode, 13 nm

normalized heating power difference	**0.1**
radiant conversion efficiency	0.03
thermal non-equivalence	0.012
electr. calibration	0.002
total [electr. subst. radiometer]	**0.11**

measured diode photocurrent	0.1
electrometer calibration	0.06
wavelength uncertainty	0.01
spectral bandwidth	0.005
higher diffraction orders	0.03
diffuse scattered light	**0.2**
angle of incidence	0.005
total [beamline]	**0.23**

detector non-uniform responsivity	**0.2**
non-linearity	0.12
temperature dependence	0.05
polarisation	0.10
total [detector]	**0.26**

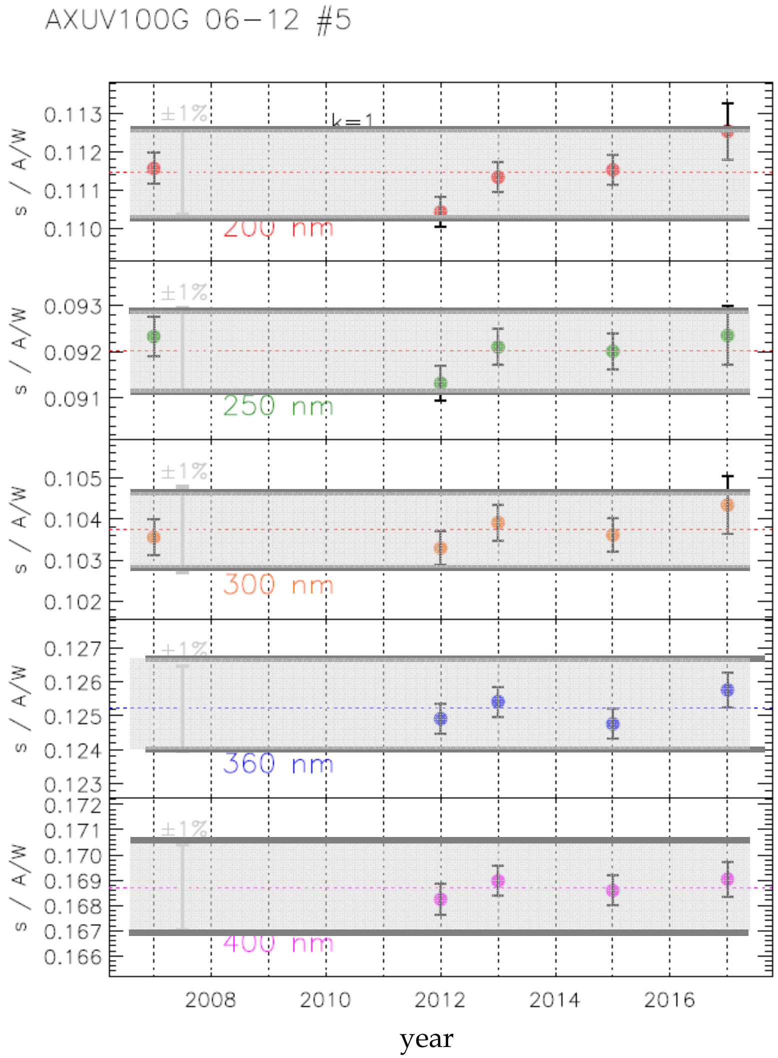
total	**0.37**

Internal Validation

Reproducibility of calibrations: calibration history

- set of own secondary standard detectors as reference
  (~ 6 individuals, different types)
- regularly re-calibrated

- **individual drifts in responsivity**
  < 1 % / 5 years for λ > 150 nm
  < 5 % / 5 years for 40nm < λ < 150 nm
  < 1 % / 5 years for λ < 40 nm
- **systematic changes: not observed**

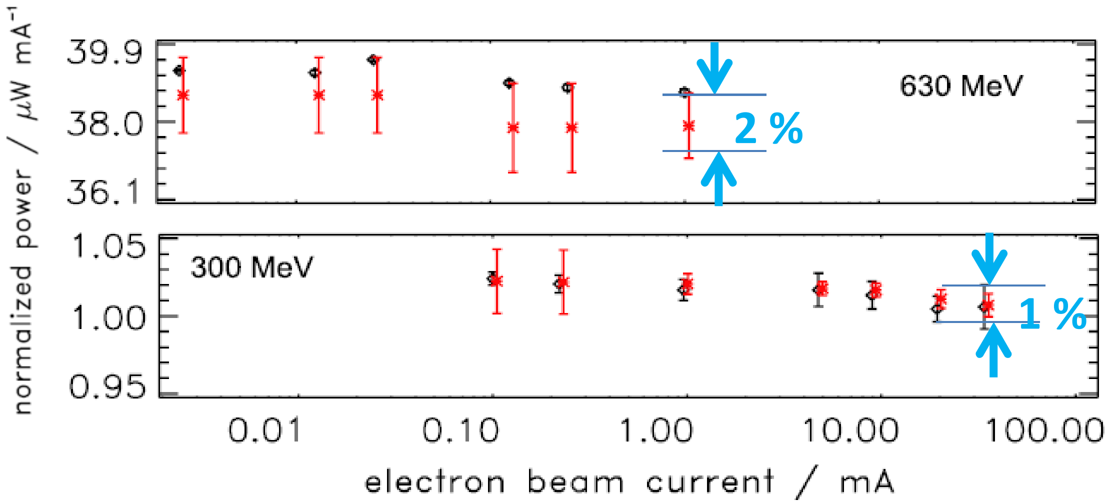


Internal Validation

How it is assured that different realisations of an unit are equivalent ?

- **Direct** comparison of the primary standards

R. Klein, A. Gottwald, et al., *Radiometric comparison of the primary source standard 'Metrology Light Source' to a primary detector standard*, Metrologia **48**, 219 (2011)



red: source (calc.)
blk: detector

standard uncertainties
(k = 1)

overall agreement ~ 1 %

integral comparison,
i.e. not spectrally dispersed !

External Validation

How to assure that realisations of an unit at different NMIs are equivalent ?

formal : Mutual Recognition Agreement (MRA) through the
International Committee for Weights and Measures (CIPM)

> "National Metrology Institutes demonstrate the international equivalence of their measurement standards and the calibration and measurement certificates they issue. "

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- **Source based radiometry**

U. Arp, R. Klein, Z. Li, W. Paustian, M. Richter, P.-S. Shaw, and R. Thornagel:
*Synchrotron radiation-based bilateral **intercomparison** of **ultraviolet** source calibrations,*
Metrologia **48**, 261 **(2011)**

range: 200 nm – 350 nm **NIST - PTB** **overall agreement < 5 %**

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- **Detector based radiometry**

F. Scholze, R. Vest and T. Saito: *Report on the CCPR Pilot* ***Comparison****: Spectral Responsivity* ***10 nm to 20 nm***,
Metrologia **47**, 02001 **(2010)**

NIST - NMIJ - PTB **overall agreement ~ 1-2 %**

A. Gottwald, M. Richter, P.-S. Shaw, Z. Li, and U. Arp: *Bilateral NIST–PTB* ***comparison*** *of spectral responsivity in the* ***VUV***, Metrologia **48**, 02001 **(2011)**

range 135 nm – 250 nm **NIST - PTB** **overall agreement ~ 1-4 %**

Limits in disseminating radiometric scales

transfer source standards

	stability
>200 nm :	
D2 lamp, FEL lamp	~ 1 %
>120 nm :	
D2 lamp MgF_2 Window	> 1 %
< 120 nm	
HC (line spectrum)	>> 5 %

transfer detector standards

(photodiodes)

stability, uniformity depending on:

- type
- wavelength
- irradiation
- storage

e.g.

Si PD with thin oxide (e.g. AXUV, S10043)

Si with metallic layer (e.g. SXUV)

B-doped Si (e.g. SPD-100UV)

Schottky (SUV100)

stability issues due to:

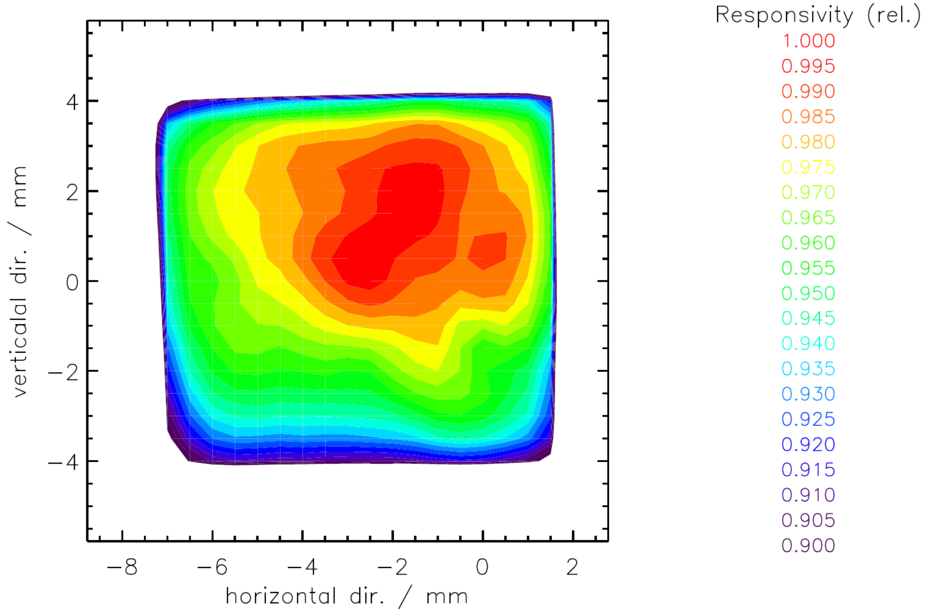
- **irradiation aging**
- **contamination**

most critical range: 50 nm to 170 nm

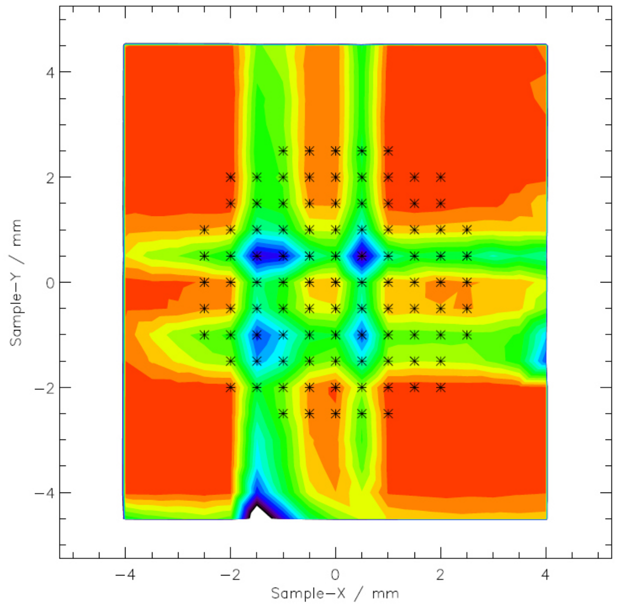
Specific photodiode problems

initial non-uniformity (wafer processing)

@193 nm



@121 nm



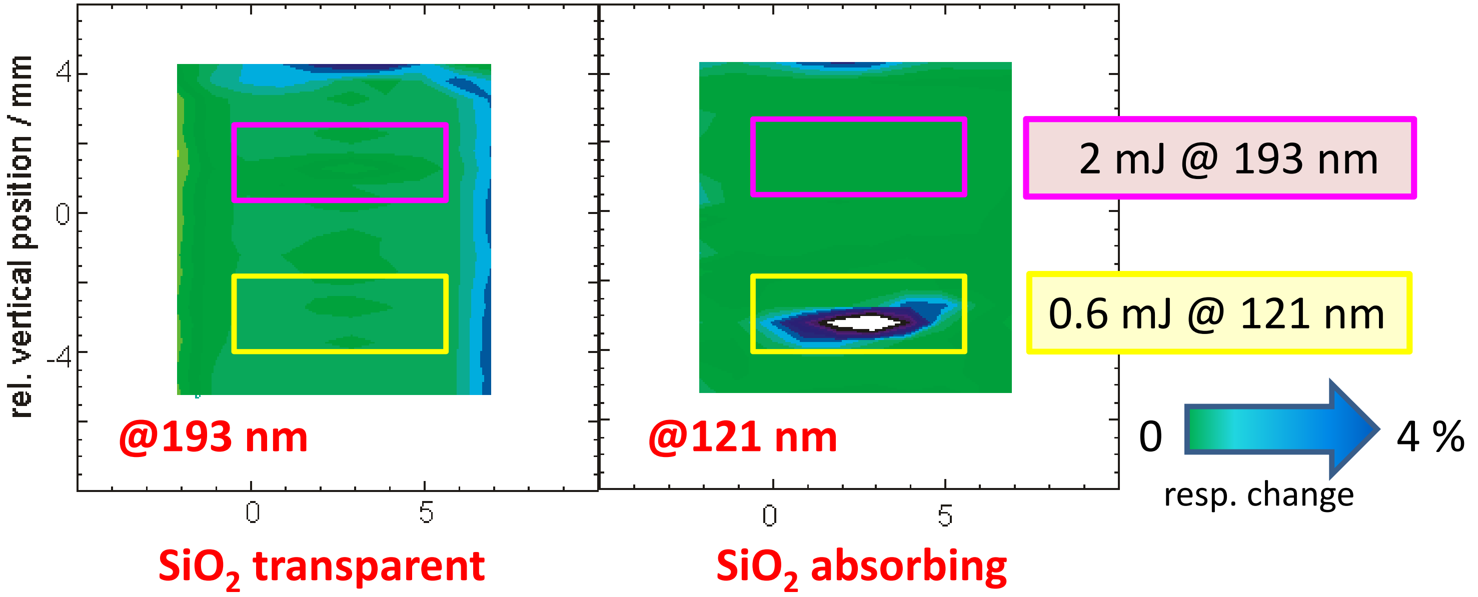
Bor-doped Si PD (SPD100-UV):
Doping profile (ion implant + diffusion)

Si PD (AXUV100G):
recent series (> ~ 2016):
line structures in thin oxide layer
(> 10 % 70 nm)

Example for ageing: Si photodiode

AXUV-100G photodiode 10 mm x 10 mm

Relative spectral responsivity map:

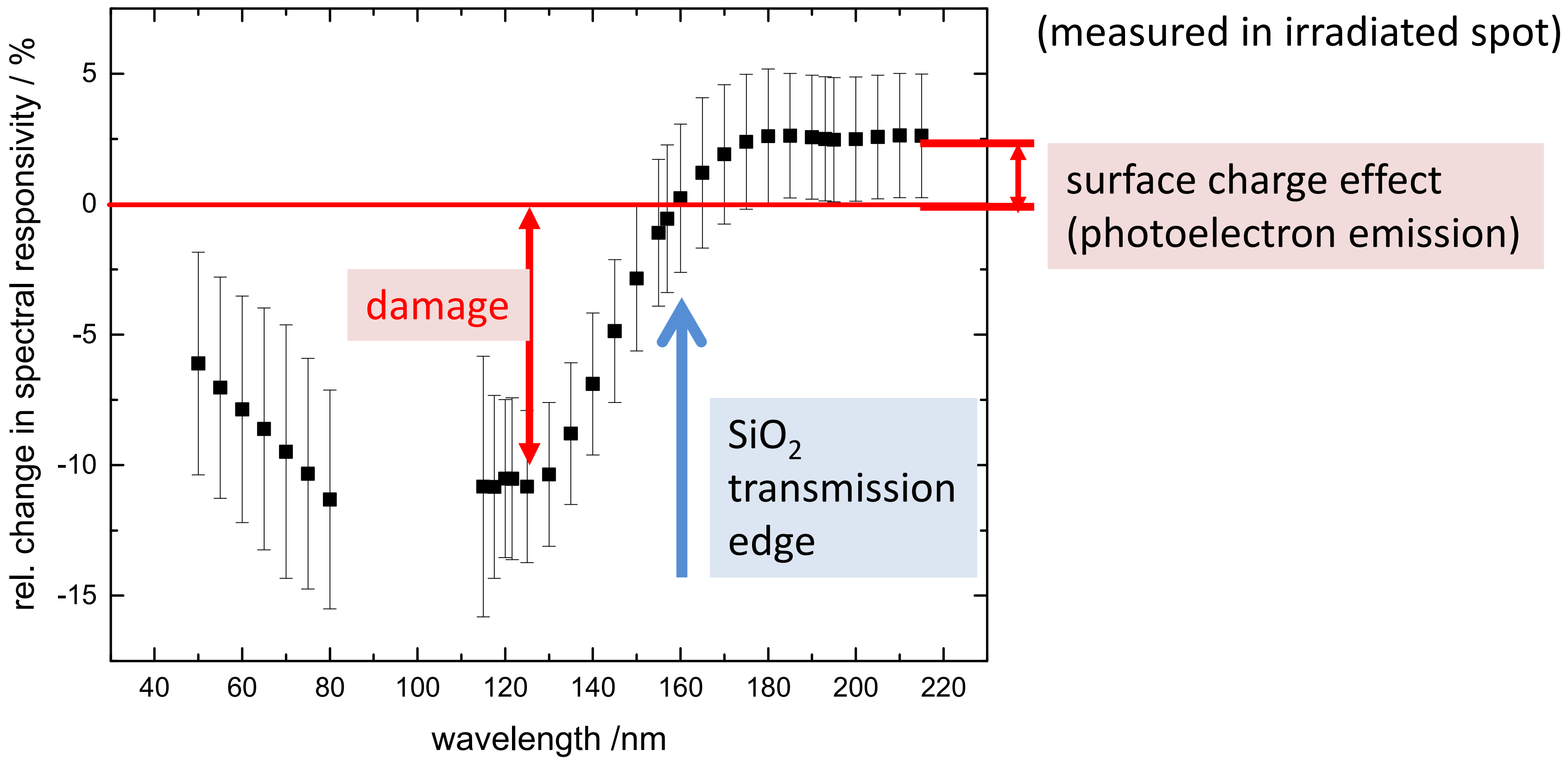


- weak effect of 193 nm irrad.

- **massive effect of 121 nm irradiation**
- **irreversible damage of the SiO_2 passivation layer** cannot be removed by surface cleaning

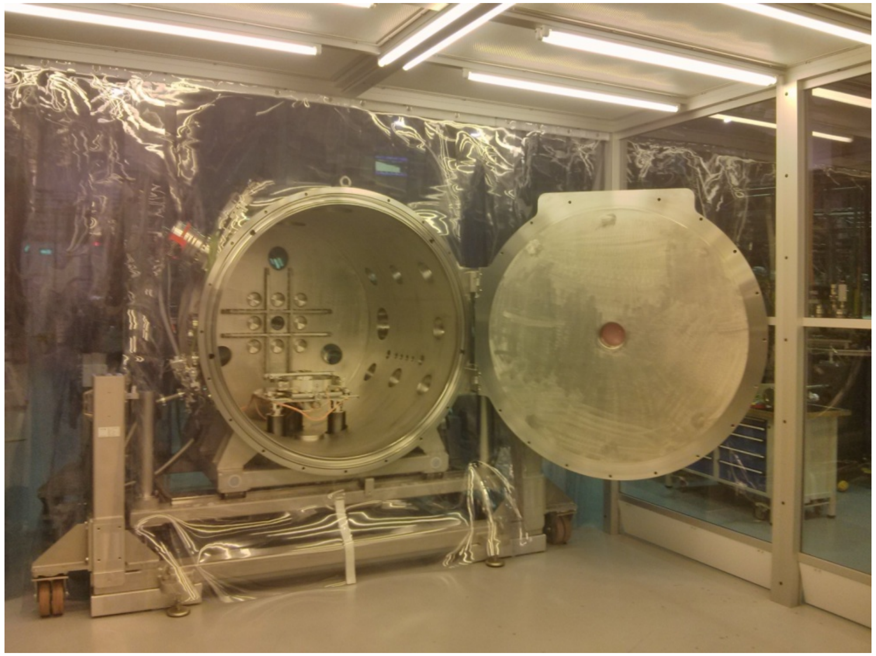
Example for ageing: Si photodiode

AXUV-100G photodiode 10 mm x 10 mm
change of spectral responsivity with wavelength **after 121 nm irradiation**



Calibration of spectrometers

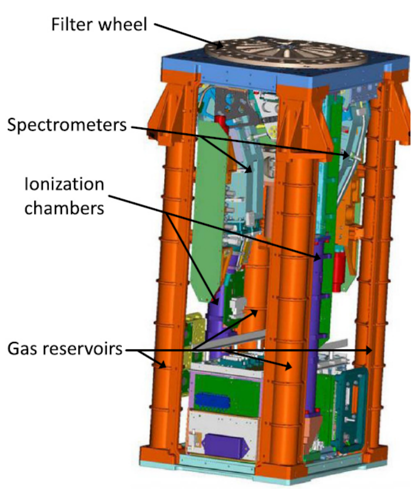
- located at PTB's Metrology Light Source (MLS) in Berlin-Adlershof
- clean room ISO class 5 specification
- UHV compatible vacuum vessel, lubricant-free
- instrumentation up to 0.6 m x 0.6 m x 1.2 m (width x height x length)
  100 kg weight



Examples for full-instrument calibration

- **SolACES**
- **PROBA/LYRA II**
- **SPICE**
- **EUI**

SolACES with Fraunhofer IPM Freiburg

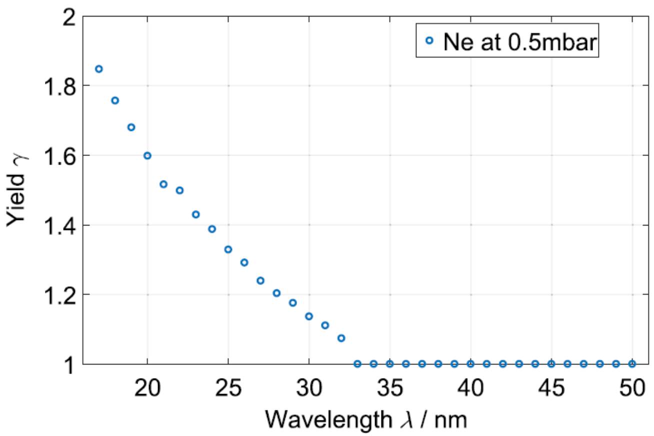


detector based

According to ist auto-calibrating principle,
no pre-flight radiometric calibration was requested.

however:

- filter transmission measurement
- AXUV photodiode characterisation
- full instrument test at 17 – 130 nm (- 240 nm)



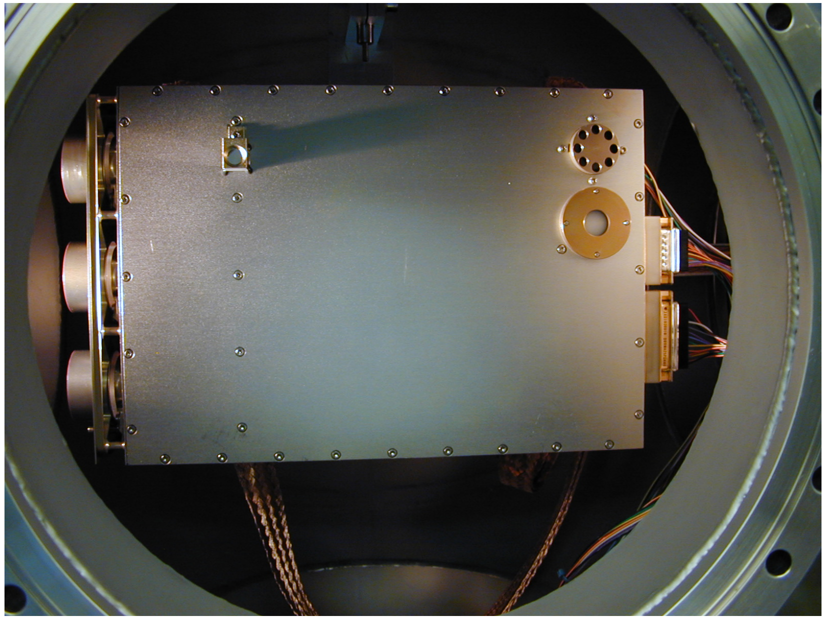
*R. Schäfer et al., Appl. Opt. **57**, 6851 (2018)*

2015: DIC spare measurements

(R. Schäfer)

- higher-order effects (double ionization) in ionisation chamber: yield measurement
- revision of uncertainty budget

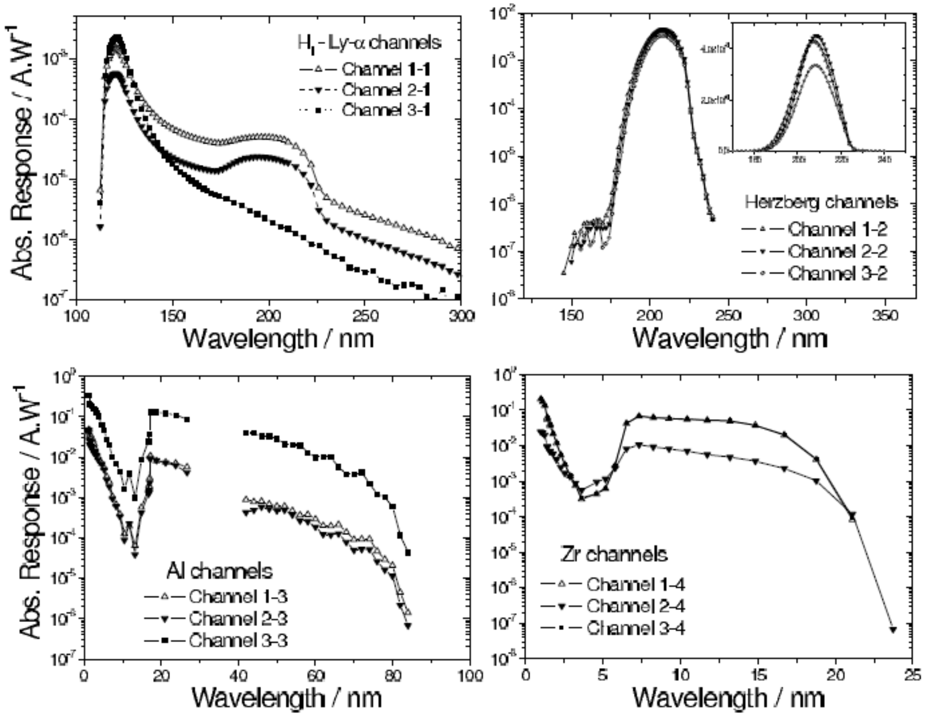
PROBA2/LYRA with ROB



*BenMoussa et al., A&A **508**, 1085 (2009)*

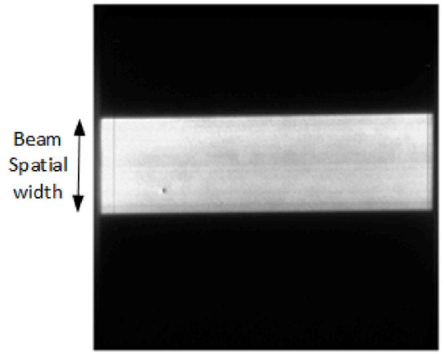
detector based

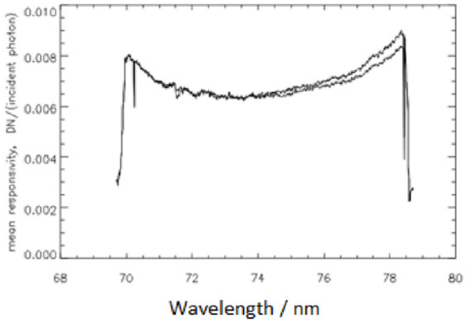
- development/test of detectors
- filter transmission calibration
- pre-flight at-wavelength calibration



SPICE with MPS / RAL

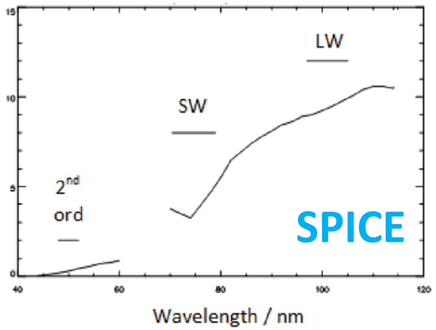
(R. Klein)

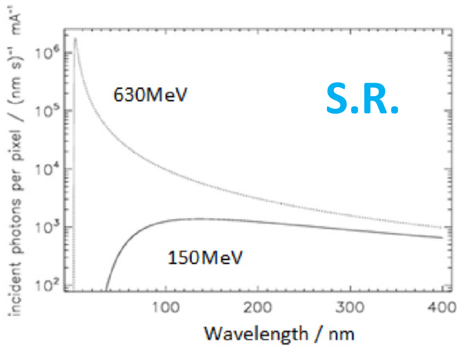




(a)

spectral profiles (calc.)





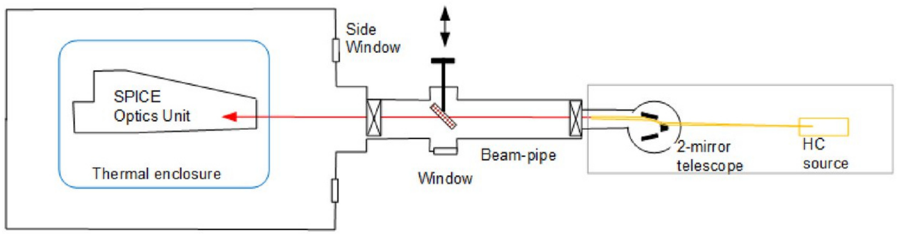
(b)

source based (mainly)

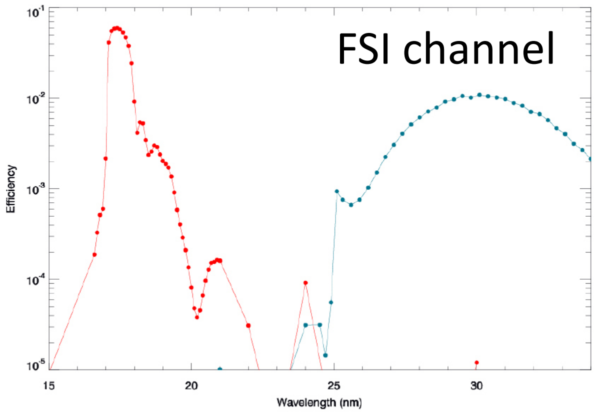
- grating efficiency calibration (ongoing activities on witness grating)
- EM calibration direct against S.R.
- FM calibration by transfer source
  (HC source at RAL; SOHO-CDS ~1995 , EIS ~2006)

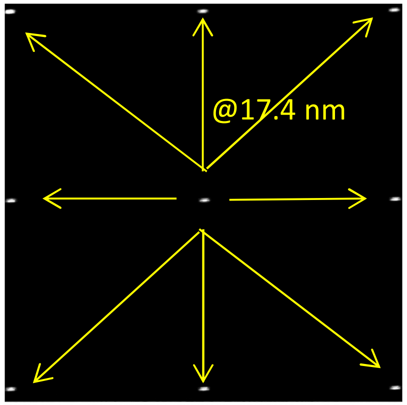
- CDS source recently re-calibrated against S.R., with regard to deviating operation conditions (discharge current)

*Caldwell et al., SPIE Vol. **10397**, 1039708 (2017)*



EUI with MPS / CSL





Halain et al., SPIE 10699H (2018)

detector based

- FM at-wavelength calibration
  FSI 17.4 nm, 30.4 nm
  HRI_{EUV}, $HRI_{Ly\text{-}\alpha}$
- FOV characterization

What PTB can provide

Calibration & characterisation of

optical components:

- filters

spectral transmission

- mirrors

spectral reflectance

- gratings

diffraction efficiency

detectors:

- photodiodes
- photoemissive/ photocathodes
- photoconductive
- imagers CCD, APS

spectral responsivity

spectrometers:

- dispersive type (grating)
- filter radiometer type

spectral responsivity

Conclusions

1. Radiometric scales in EUV and VUV are defined with standard uncertainties of **~ 1 %**

2. Radiometric scales can be disseminated /compared with standard uncertainties of **few %** only: limited by availability and stability/reproducibility of transfer standards.
   particularly: spectral range < 150 nm

3. Direct calibration of instruments at S.R. facility:
   source based against storage ring („white“ S.R.) as primary source standard
   detector based using secondary detector standards and monochromatized S.R.

   special premise needed (design, optics, size, weight, …)
   uncertainty typically then limited by the instrument itself

4. Referencing to the absolute radiometric scale:
   monitoring of aging processes (witness samples), …

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