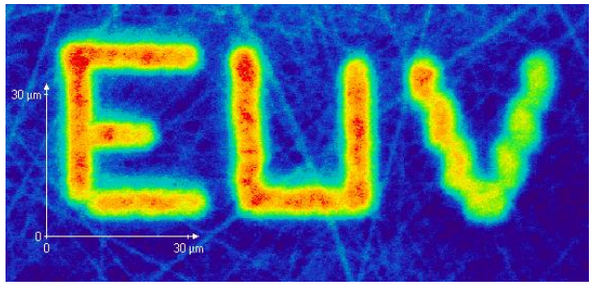


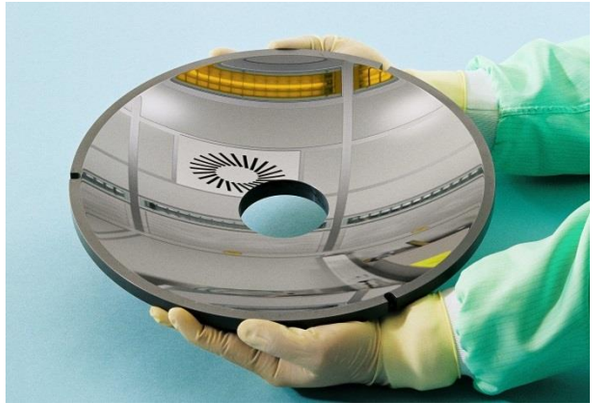

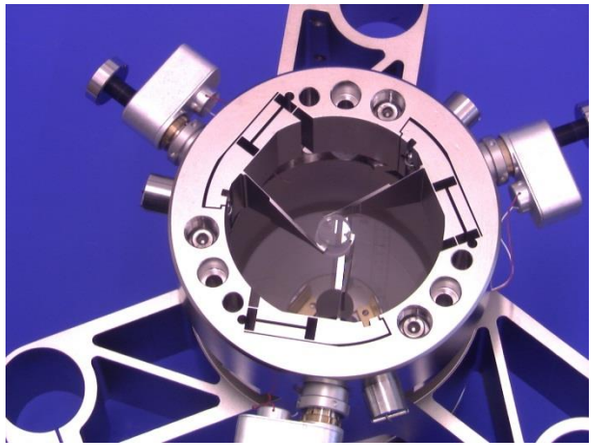

# High reflective water window collector optics

**Hagen Pauer, Marco Perske, Tobias Fiedler, Torsten Feigl**
*optiX fab GmbH, Jena*

**Christian Laubis, Frank Scholze**
*PTB, Berlin*

Enschede, Netherlands, November, 11th 2016

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# Outline

- Introduction
- Water window collector optics
- Water window graded optics
- Summary



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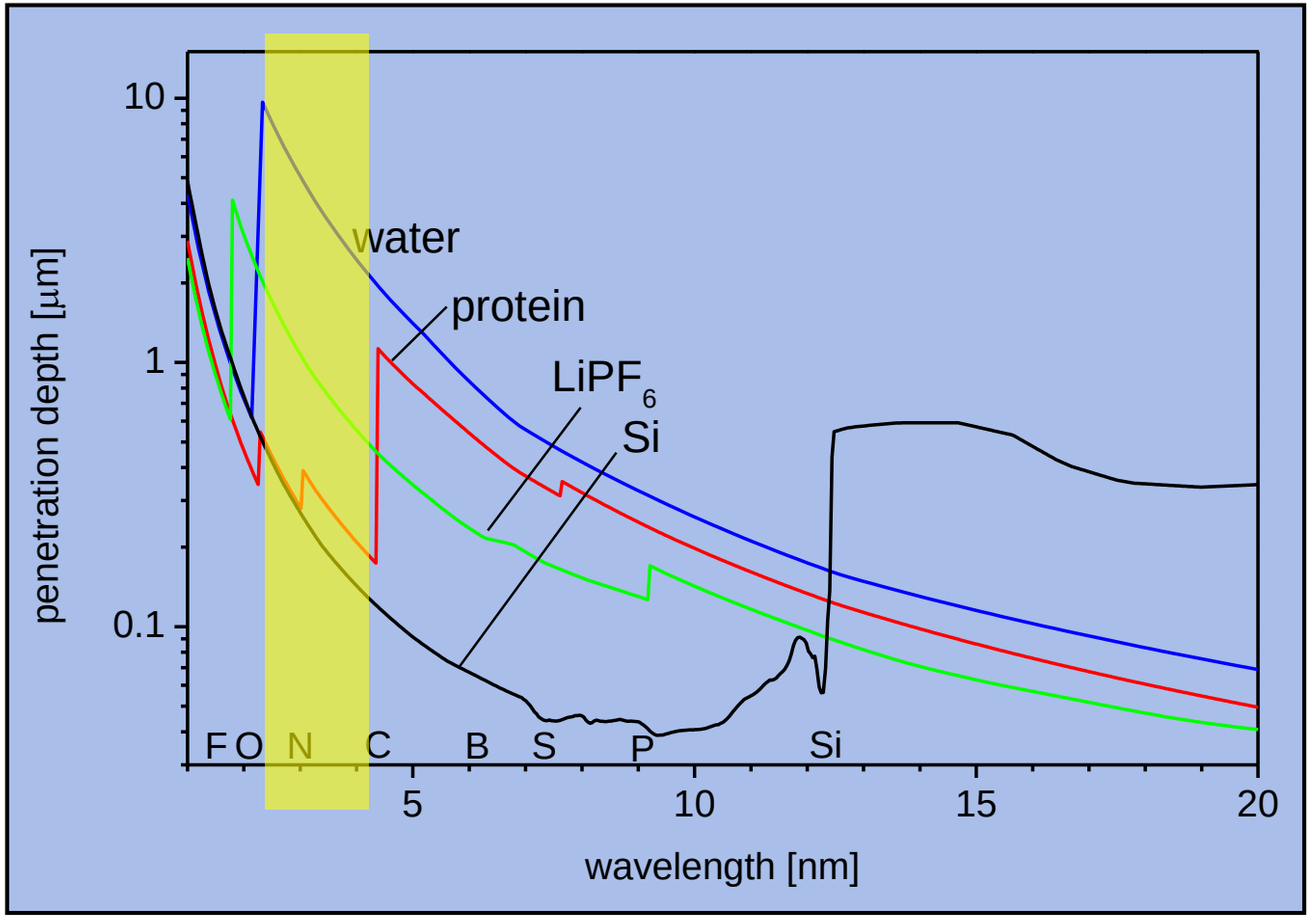
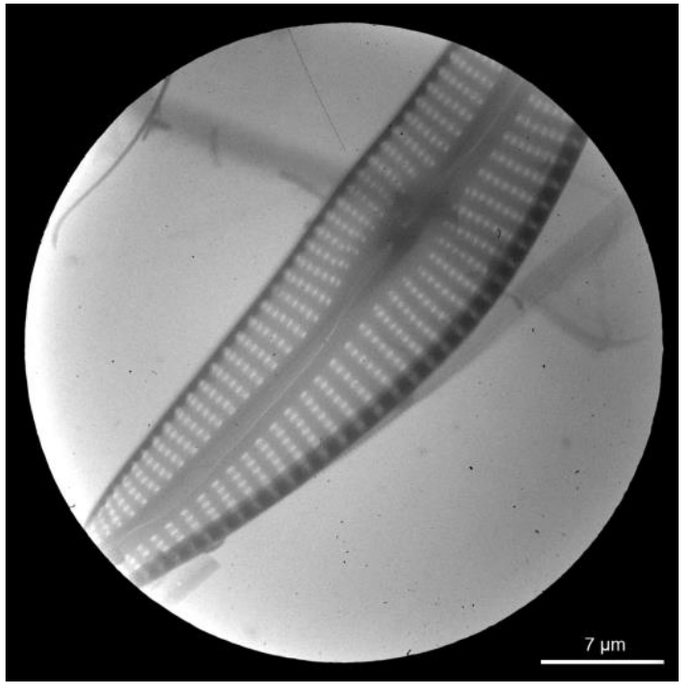
# Water window microscopy




diatom

Low absorption of water leads to

high contrast against $O_2$, $N_2$, C for $\lambda$ = 2.3 … 4.4 nm



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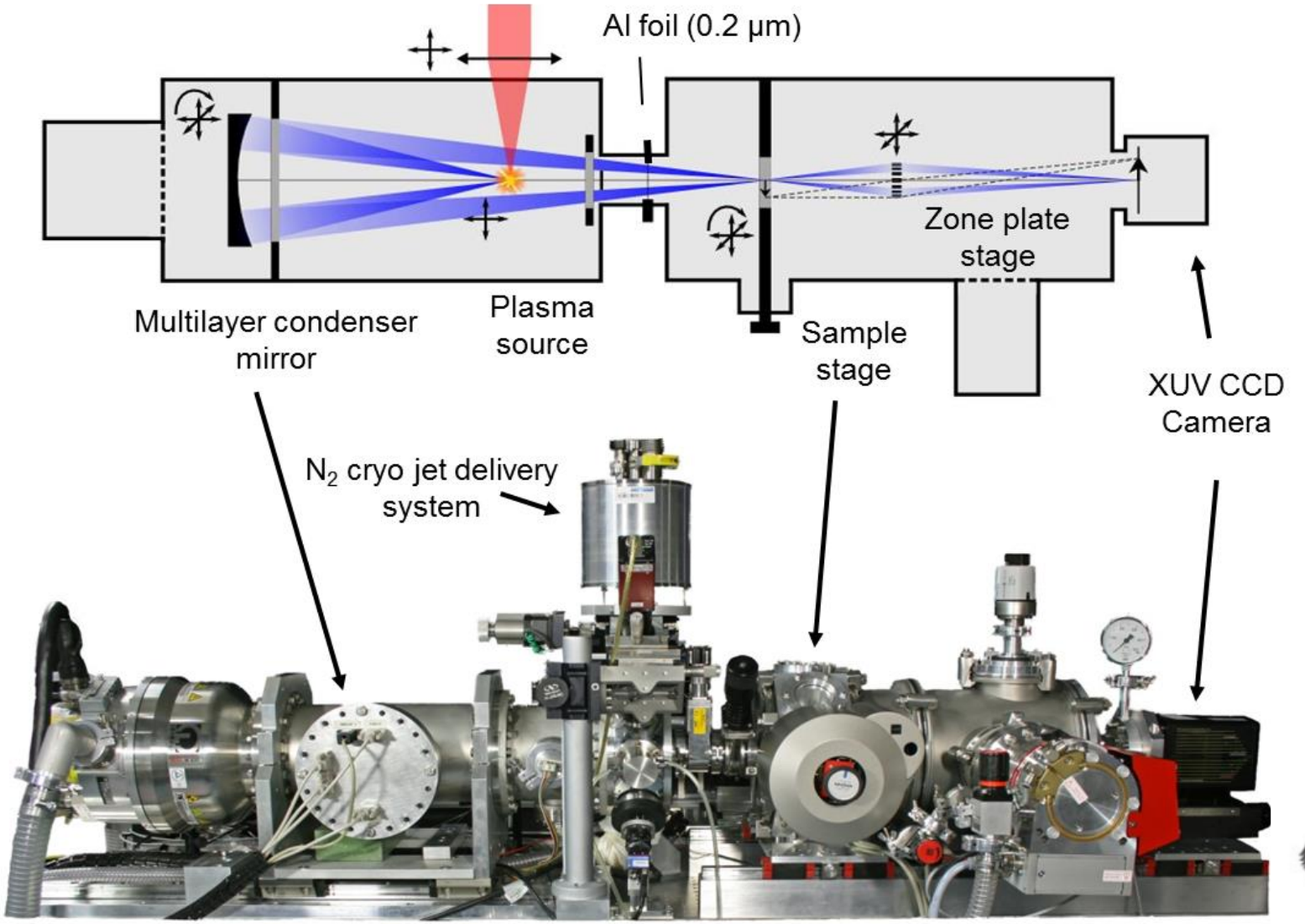
# Laboratory Transmission X-ray Microscope (LTXM)




BRUKER

Fraunhofer ILT

Fraunhofer IOF

HZB Helmholtz Zentrum Berlin

KTH Vetenskap och Konst

Bundesministerium für Bildung und Forschung



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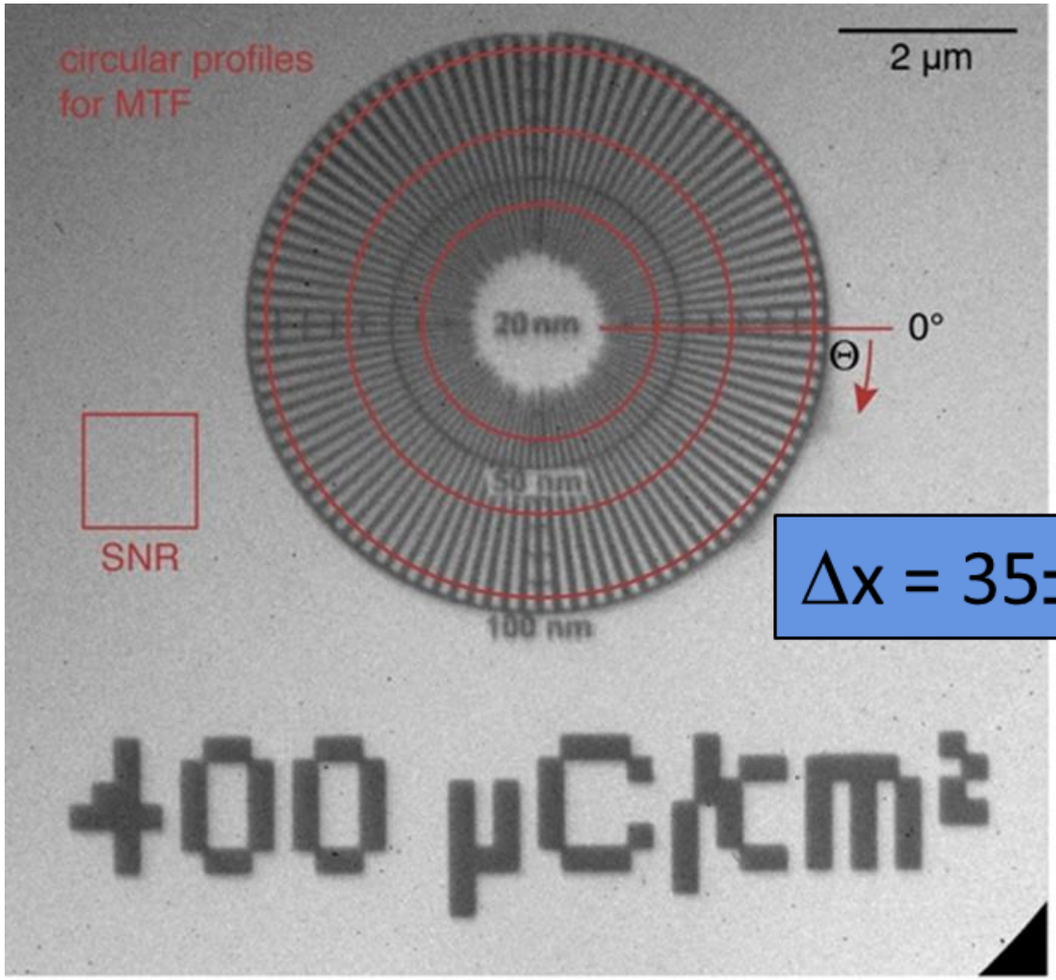
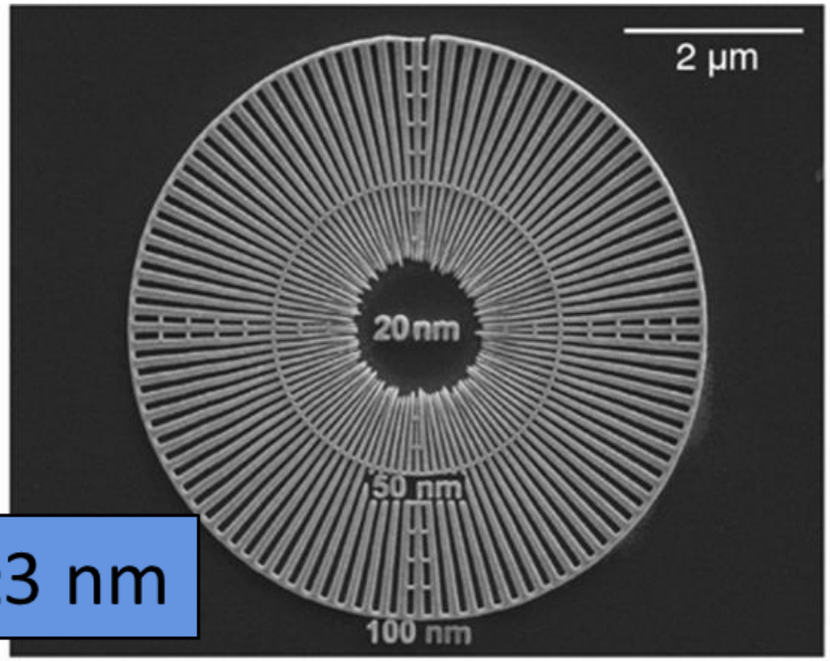
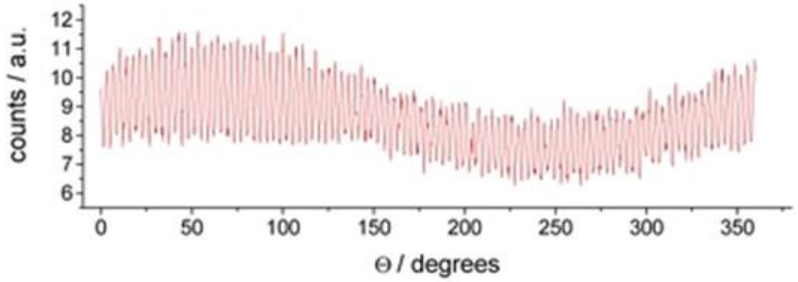
# Laboratory Transmission X-ray Microscope: Resolution




*Left*: LTXM image (magn. 1250x; exposure time: 10 min; laser power: 100 W)

*Right top*: SEM image taken at ZELMI (TUB)

*Right bottom*: Plot of the outermost red circle shown in the LTXM image

*C. Seim, H. Legall, H. Stiel et al SPIE (2013)* ***8678****, 867808*



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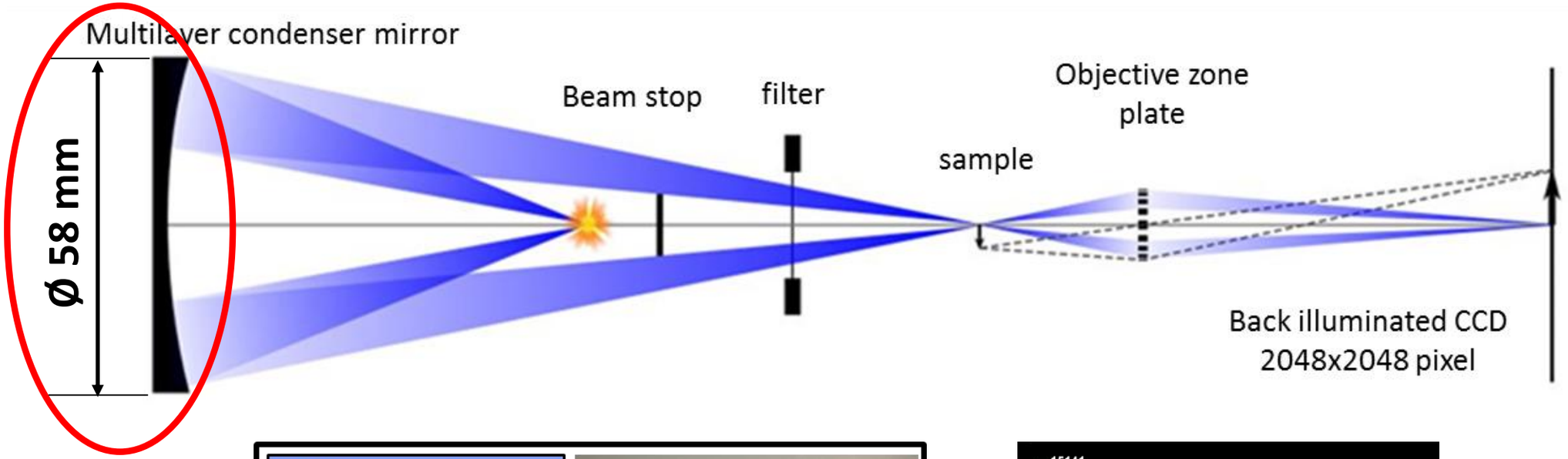
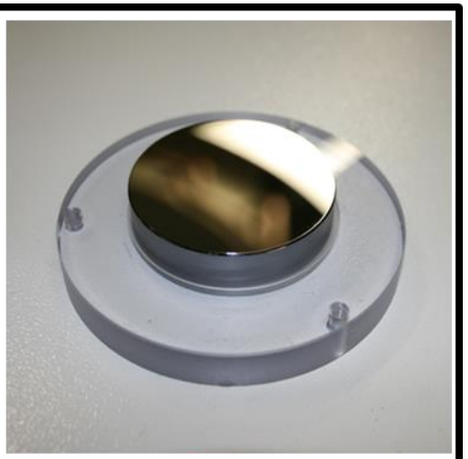
# Laboratory Transmission X-ray Microscope (LTXM)

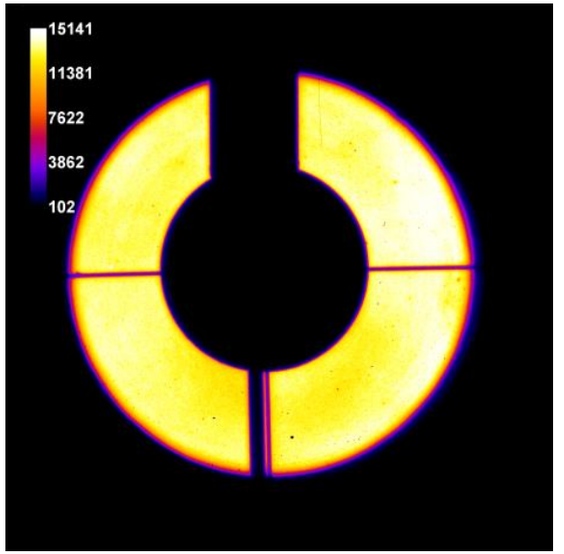



**Multilayer condenser**

Coating: Cr / V
Wavelength:
(2.478 ± 0.01) nm
Bandwidth: 8 pm
mean reflectivity:
Up to 0.6 %
Radial aperture:
54 mm
Throughput:
> $2*10^{-4}$ sr



Fraunhofer IOF



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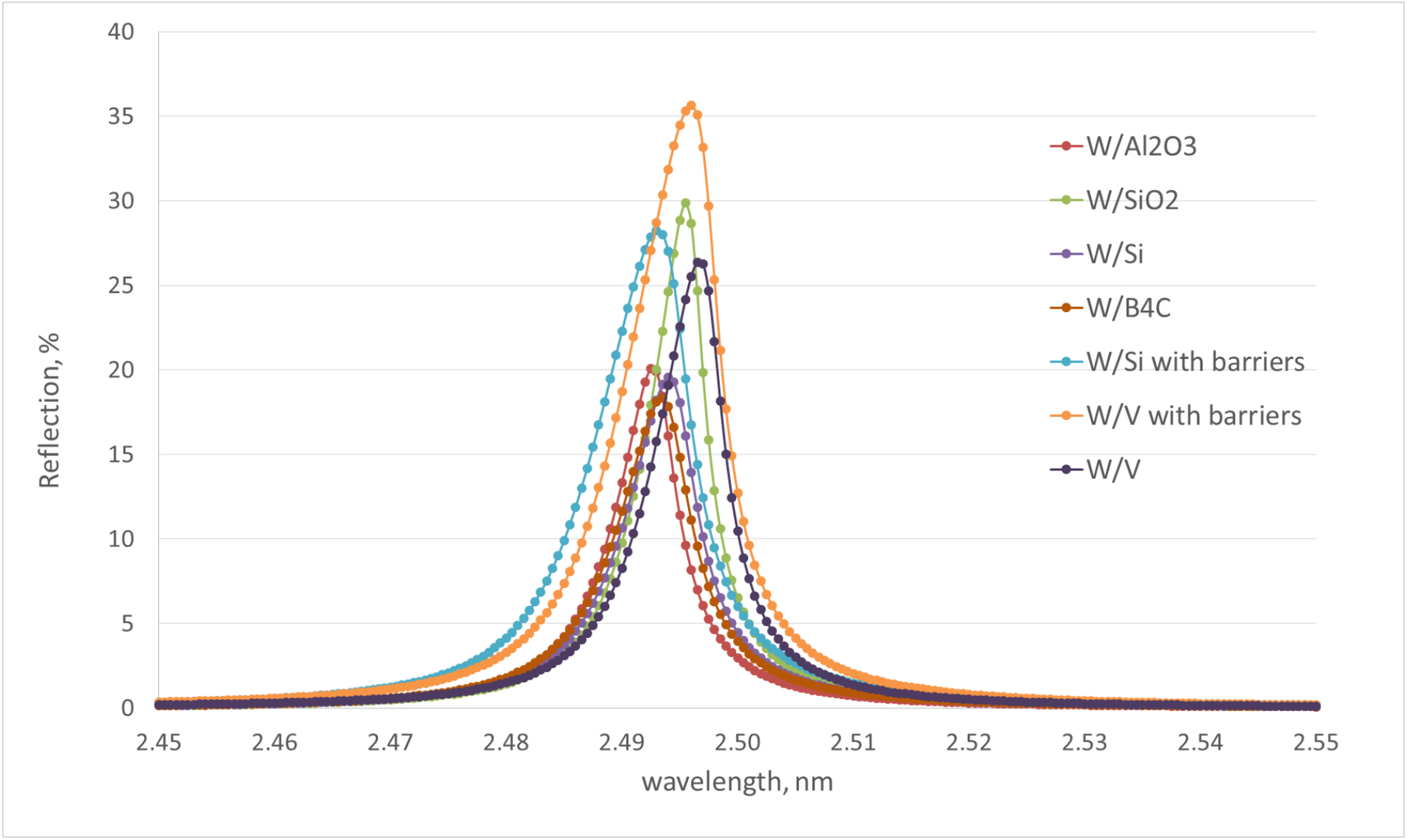
# Alternative multilayer materials: Simulation of reflectance

## Tungsten based systems (Henke constants, no interdiffusion, AOI = 1.5°)



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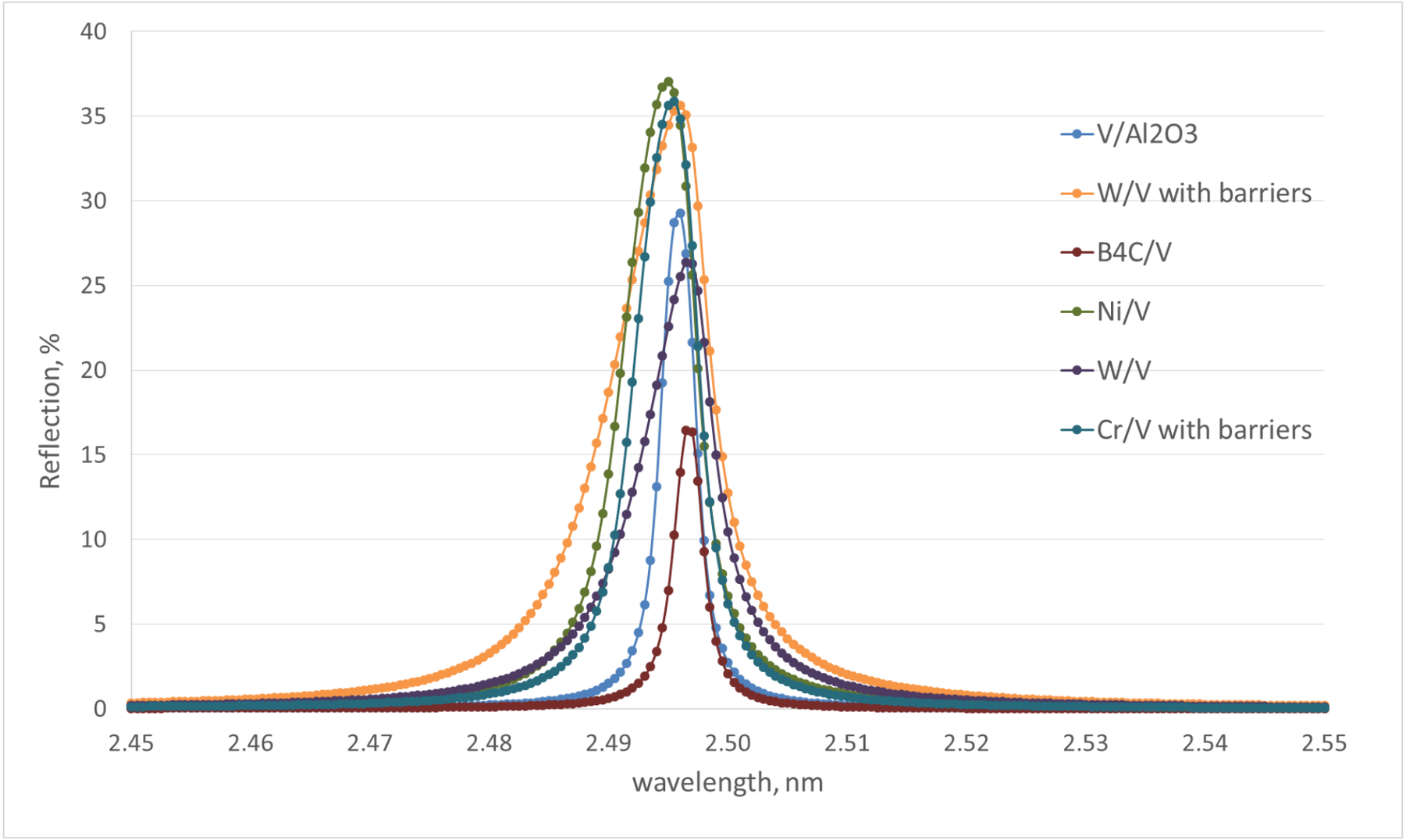
# Alternative multilayer materials: Simulation of reflectance

## Vanadium based systems (Henke constants, no interdiffusion, AOI = 1.5°)



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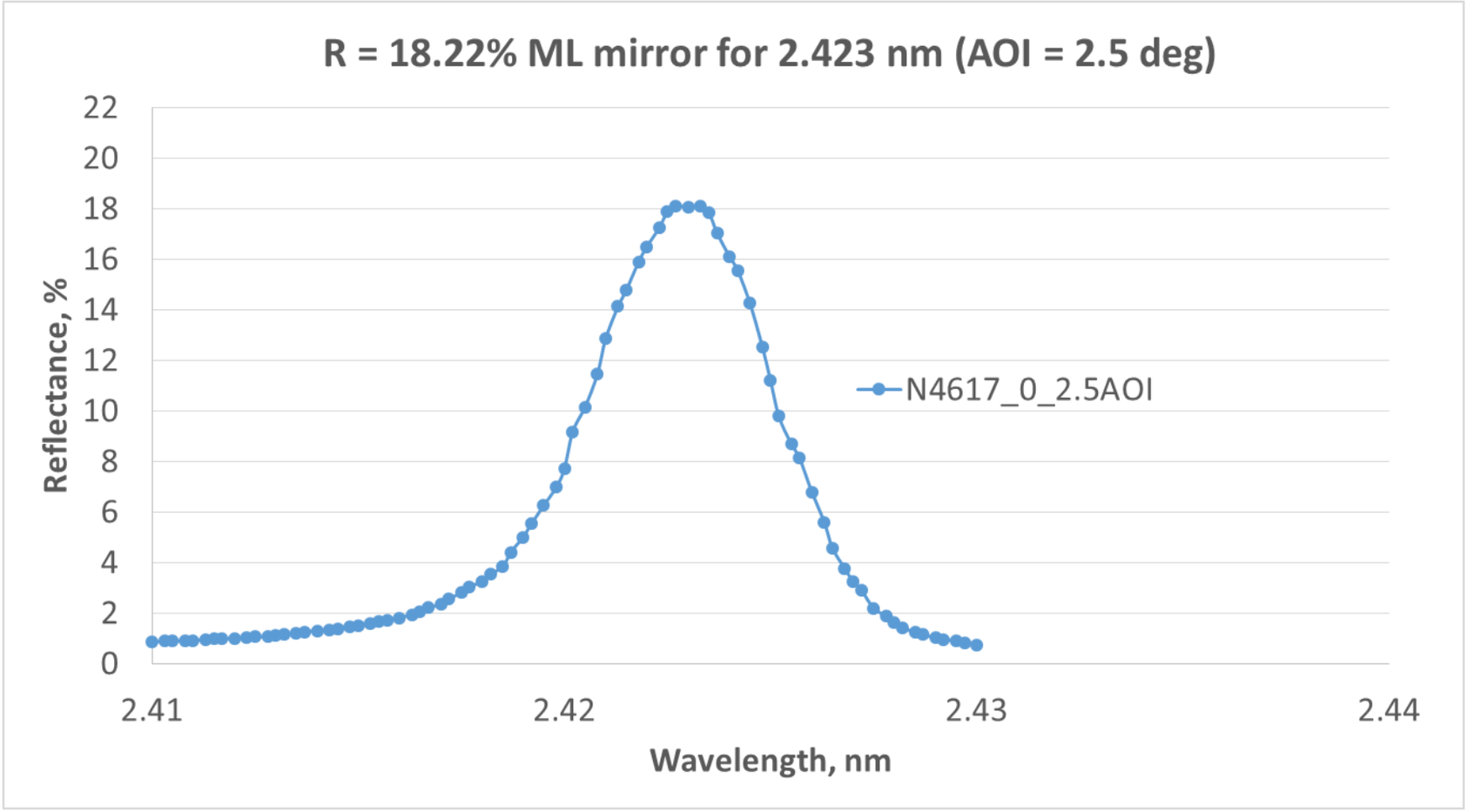
# Current water window multilayer coating: optical performance




- Cr/V multilayer system with barrier layers: **R = 18.22% @ 2.423 nm** (AOI = 2.5deg)

Measured @PTB Berlin



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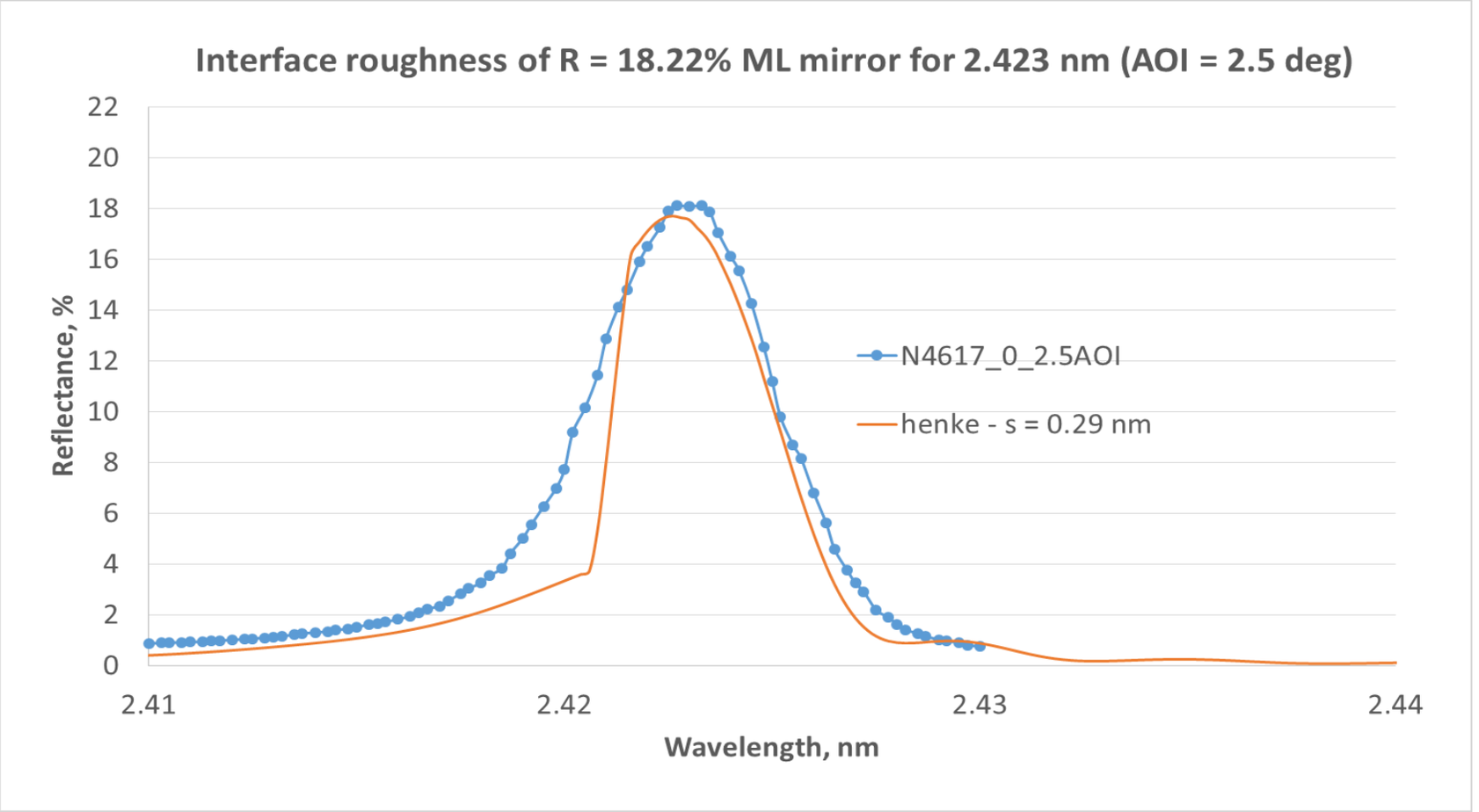
# Current water window multilayer coating: optical performance




**30%** of theoretical reflectivity limit

- Cr/V multilayer system with barrier layers: **R = 18.22% @ 2.423 nm** (AOI = 2.5deg)
- interdiffusion roughness $\sigma$ = 0.29 nm (simulated with Henke constants)

Measured @PTB Berlin



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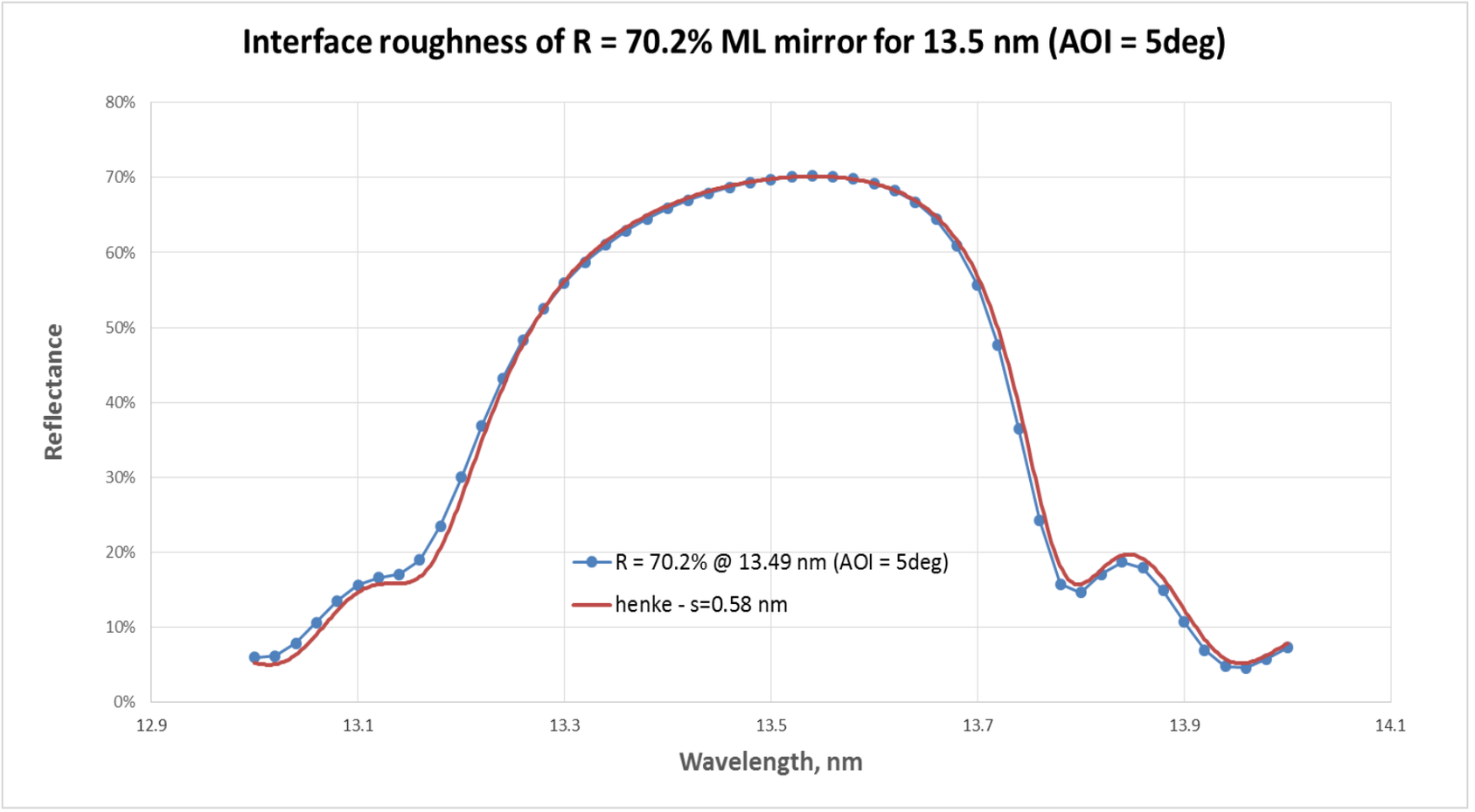
# Current EUVL multilayer coating for 13.5 nm: optical performance




**95%** of theoretical reflectivity limit

- best Mo/Si system (with barrier layers): **R = 70.20% @ 13.48 nm** (AOI = 5.0deg)
- interdiffusion roughness $\sigma$ = 0.58 nm (simulated with Henke constants)

Measured @PTB Berlin



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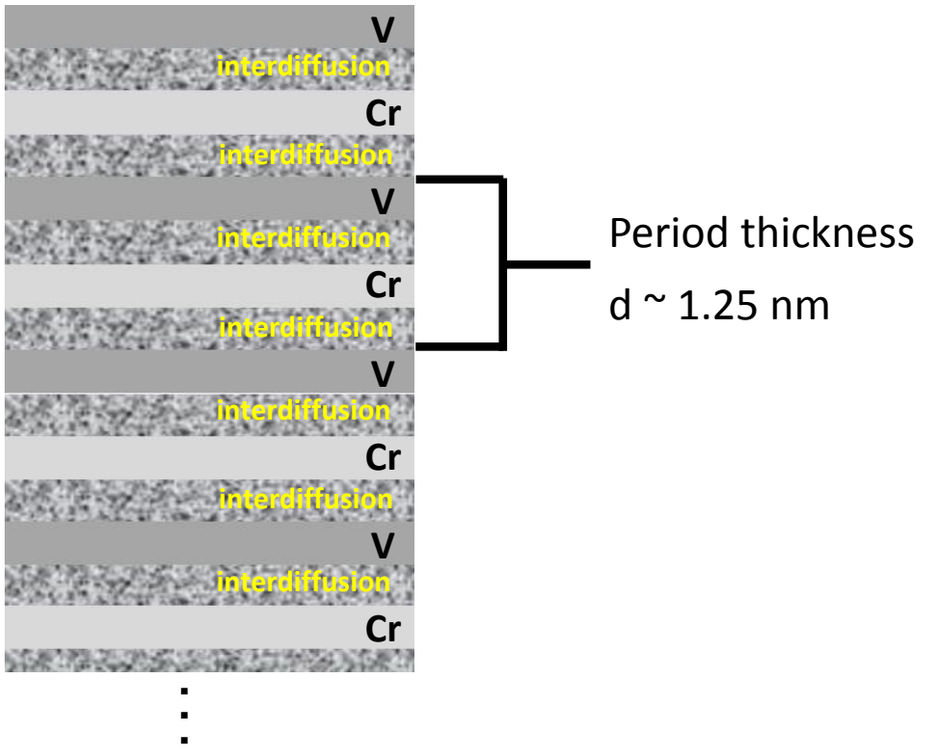
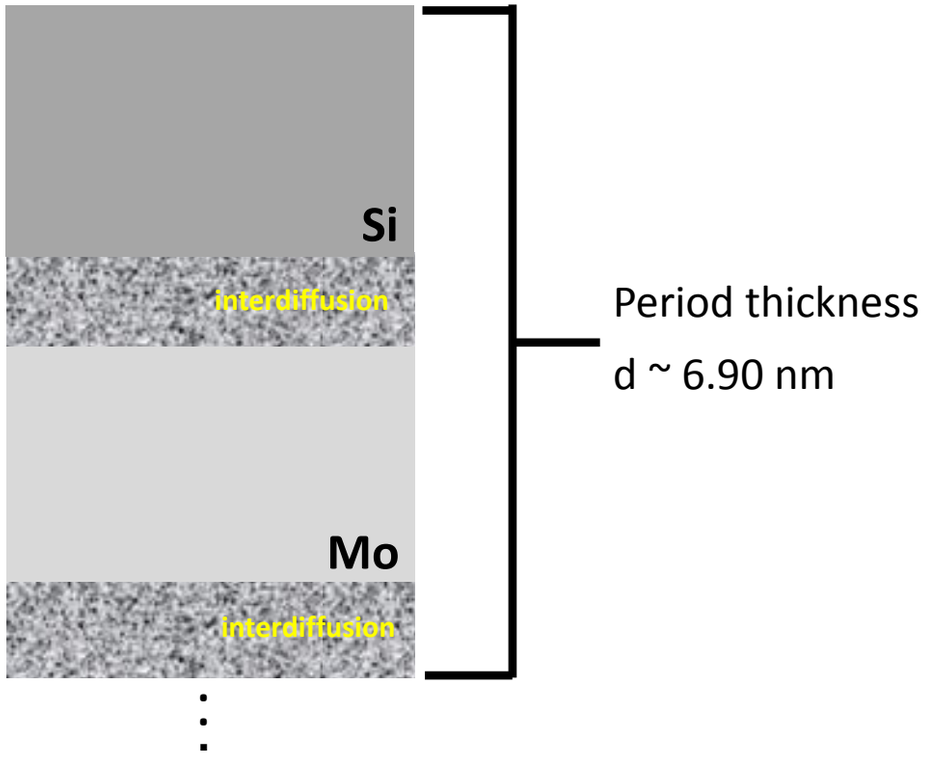
# Interdiffusion of multilayer systems

best Cr/V based system for 2.48 nm




best Mo/Si based system for 13.5 nm




**Ratio interdiffusion/ period thickness**

Cr/V multilayer with barriers: **0.5**

Mo/Si multilayer with barrier layers: **0.2**



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# Development of HR water window multilayer systems

## Main challenges

- Material choice
- Gamma ratio
- First/ last layer (adhesion, oxidation on surface)
- **Interdiffusion zones (roughness ← → absorption behaviour)**

- **Leads to investigation of barrier layers (interface engineering):**

  - Barrier layer materials, process parameters…
  - Barrier layer thickness
  - Barrier layer after spacer/ absorber/ both?

- **Substrate roughness as low as possible (HSFR $\sigma$ < 0.1 nm RMS)**



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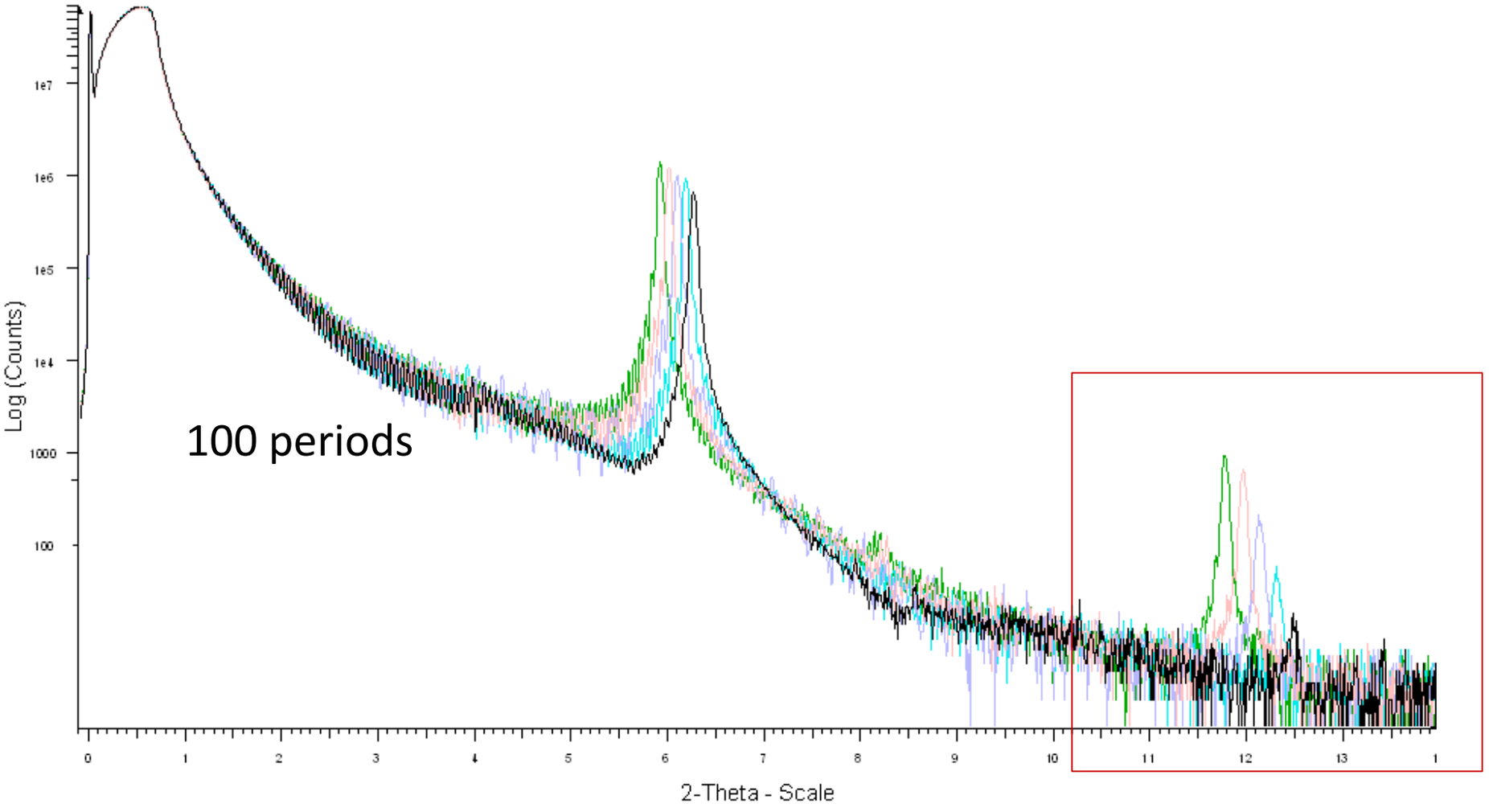
# Development of HR water window multilayer systems

XRR measurements of Cr/V multilayers with different barrier thicknesses



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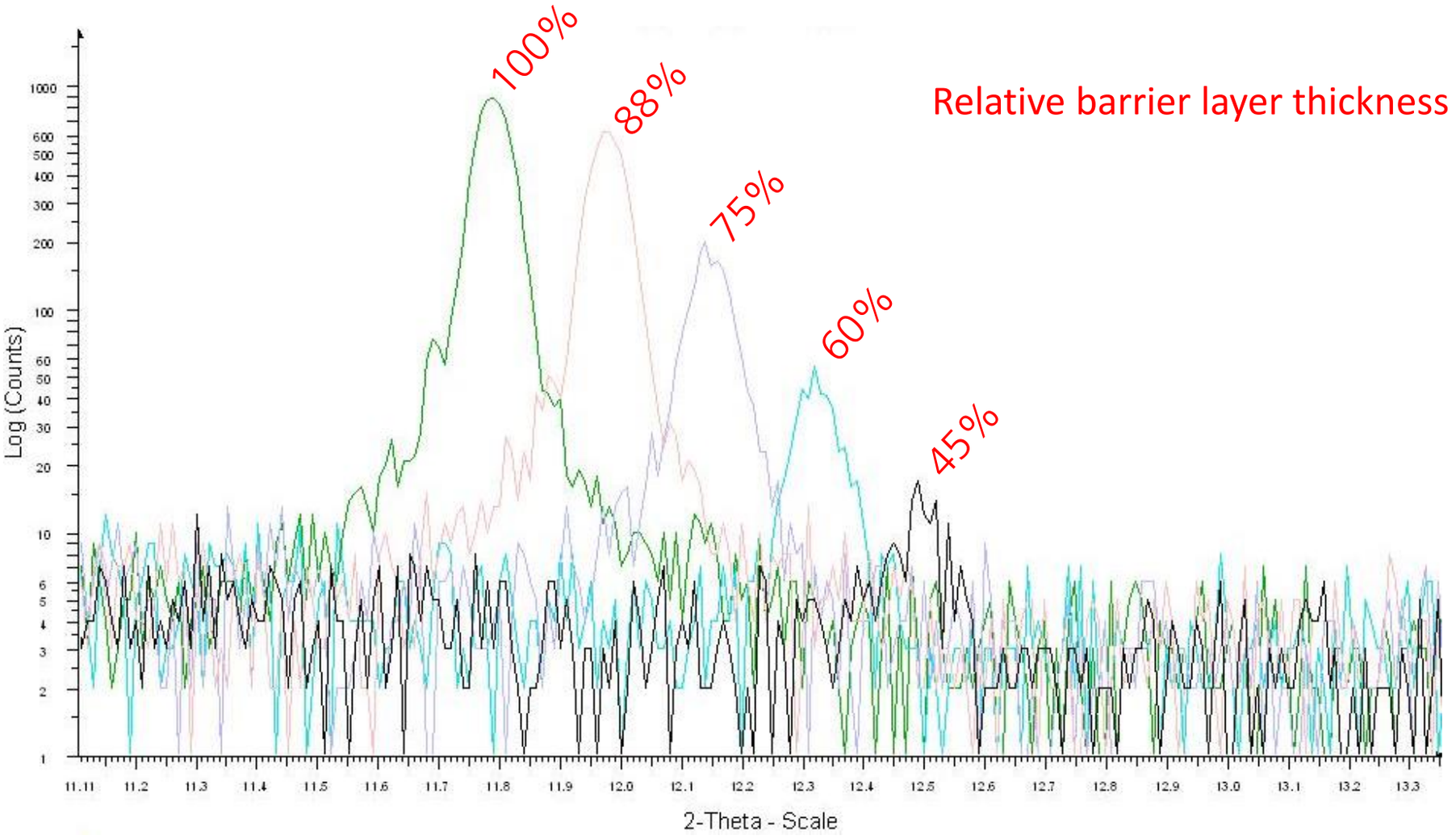
# Development of HR water window multilayer systems

XRR measurements of Cr/V multilayers with different barrier thicknesses



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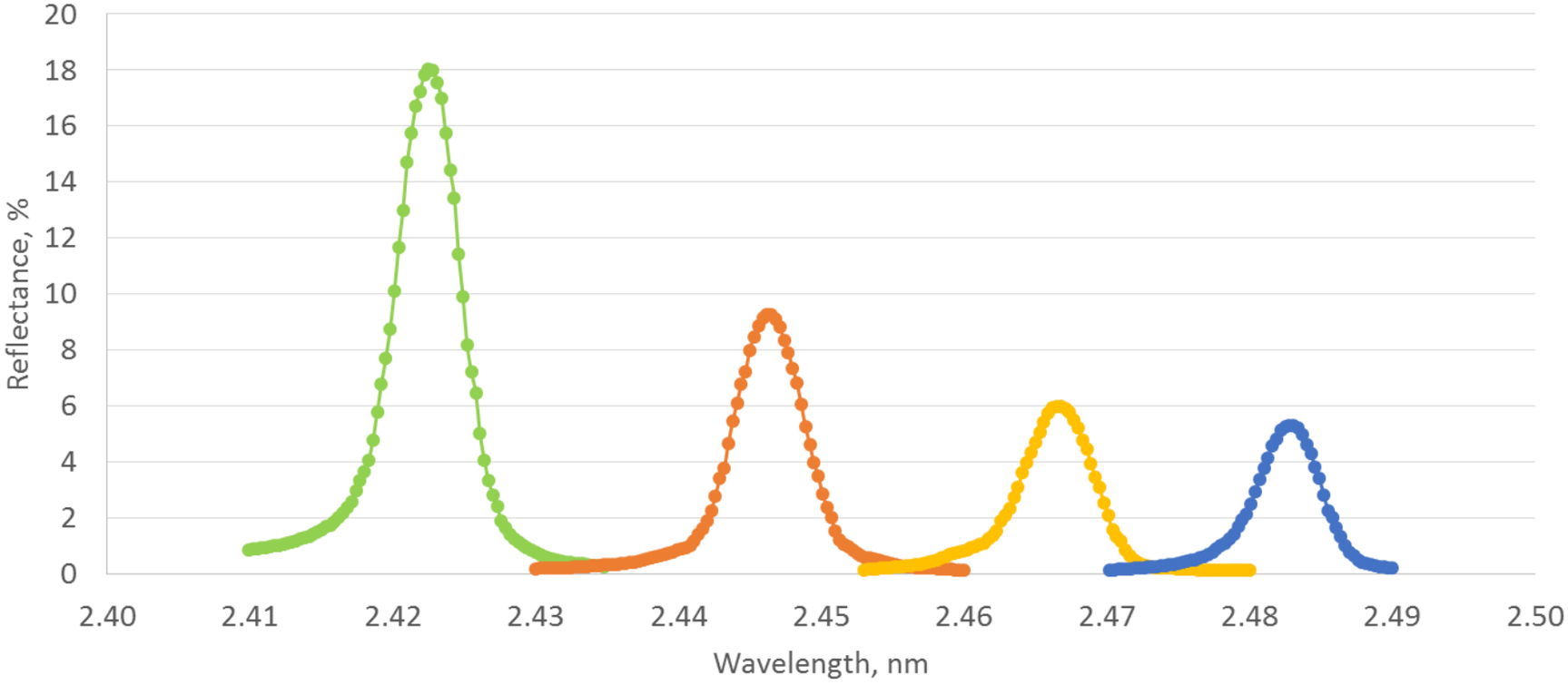
# Multilayers for the water window (Cr/V with barriers)




| Wavelength | AOI | Reflectance | FWHM |
|---|---|---|---|
| 2.4225 nm | 1.5 deg | 18.04 % | 0.054 nm |
| 2.4463 nm | 1.5 deg | 9.28 % | 0.057 nm |
| 2.4666 nm | 1.5 deg | 6.01 % | 0.058 nm |
| 2.4792 nm | 1.5 deg | 5.21 % | 0.057 nm |

Measured @PTB Berlin



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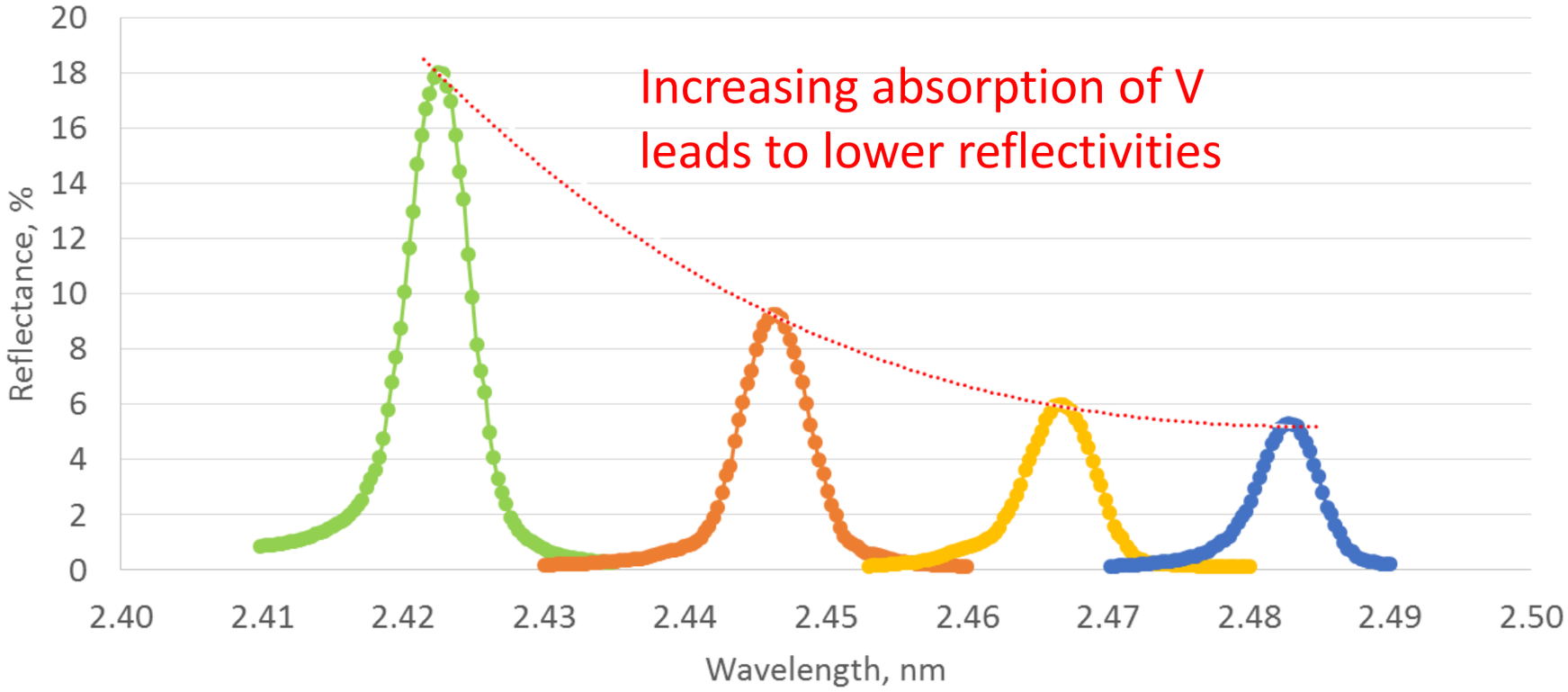
# Multilayers for the water window (Cr/V with barriers)




| Wavelength | AOI | Reflectance | FWHM |
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| 2.4792 nm | 1.5 deg | 5.21 % | 0.057 nm |

Measured
@PTB Berlin



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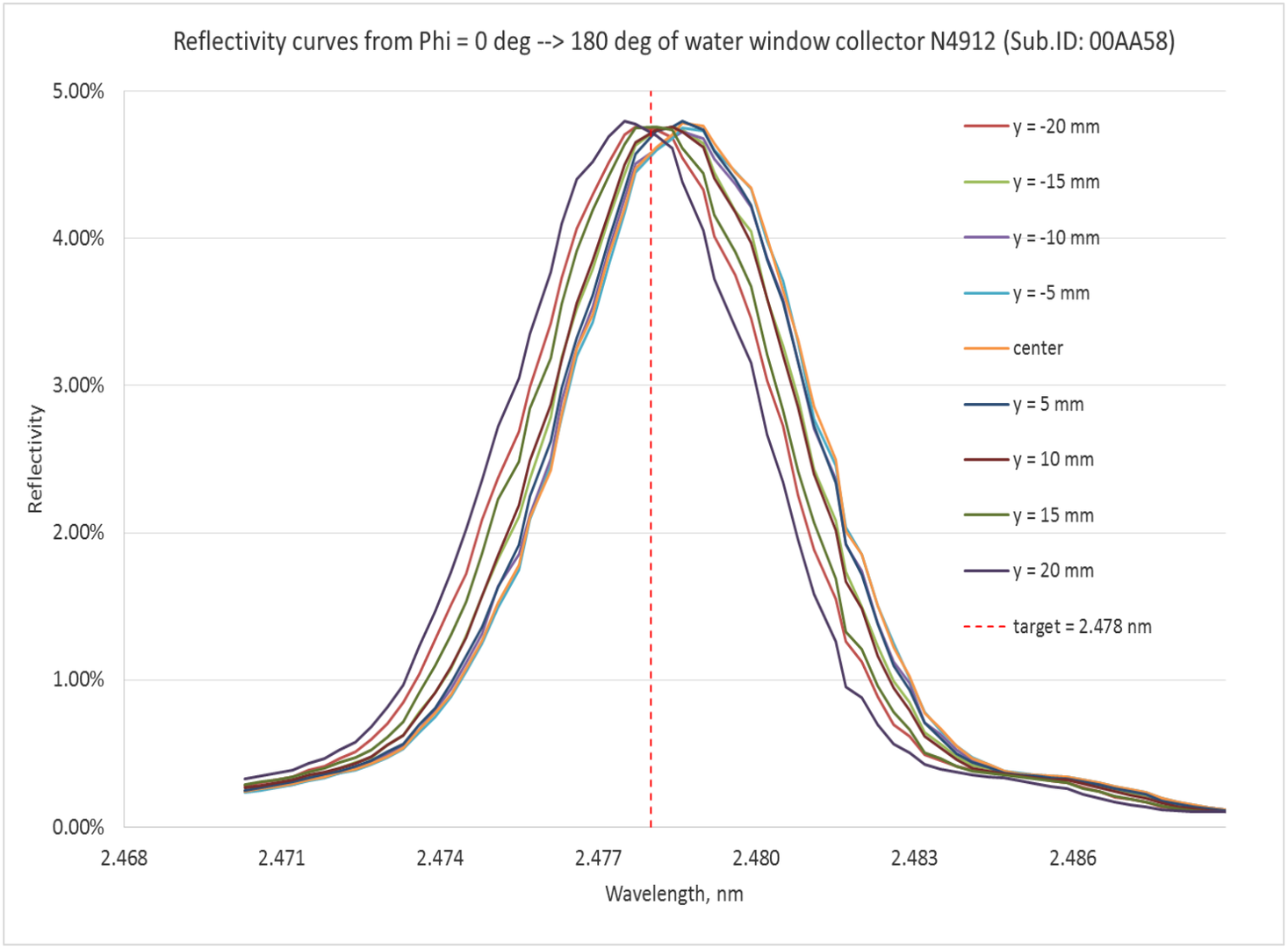
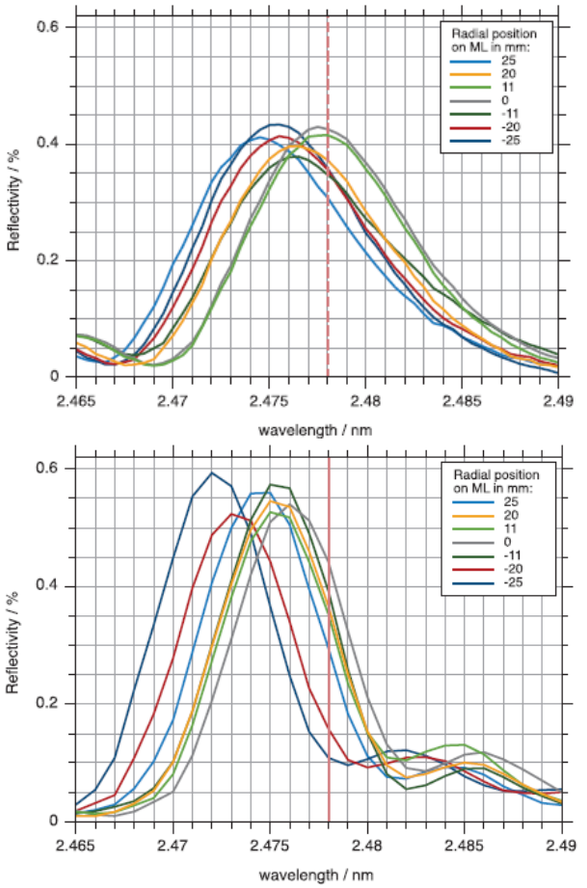
# New multilayer collector mirror: EUV reflectance at different radii




Past: R ~ 0.4 %

Now: **R ~ 4.6 %** **x10!**

*all:* $\lambda = 2.478$ *nm*




Measured @PTB Berlin



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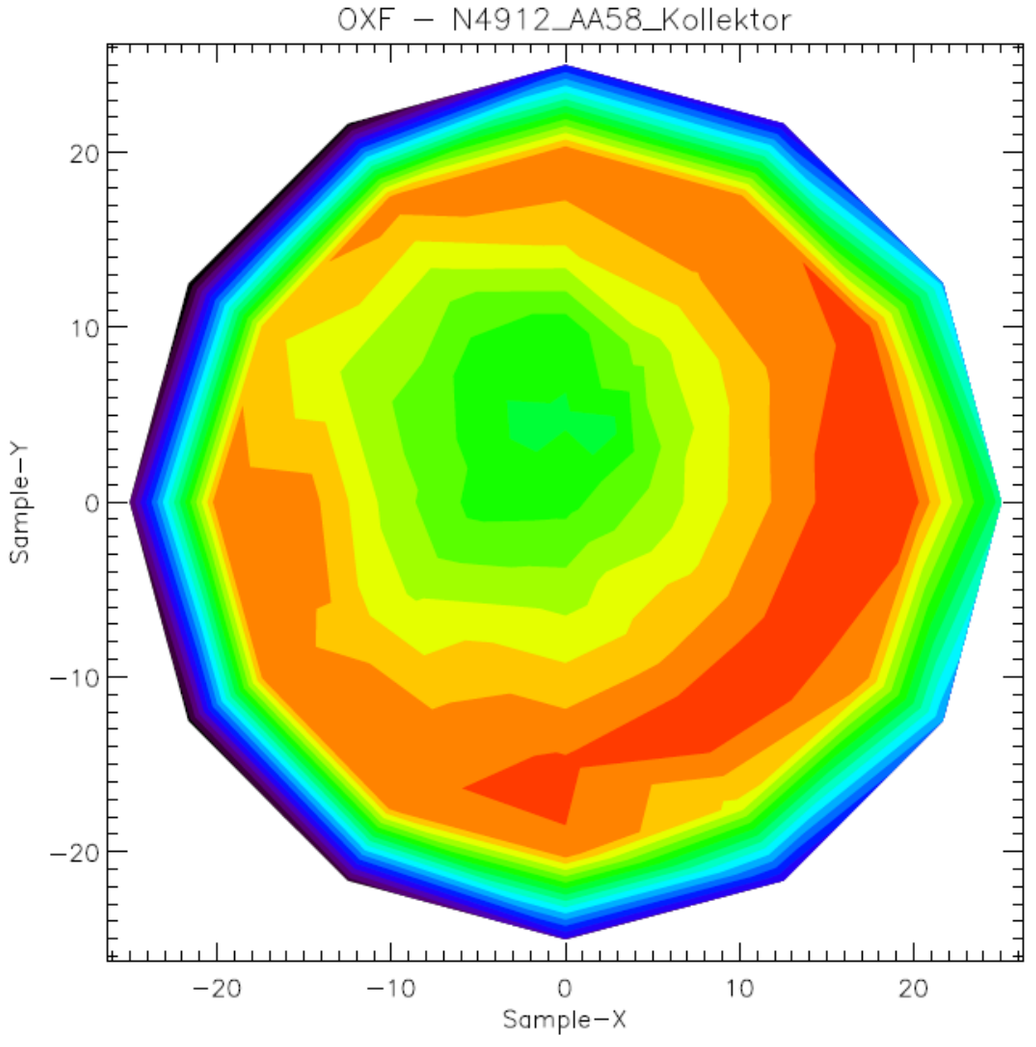
# Collector mirror: Reflectance mapping at λ = 2.478 nm




#00090 / #00089 / #00091
I0_m=0.99936 I0_std=0.00014

AOI=1.500deg

Color change = 0.041%
Max(color)=4.787%
Min(color)=4.013%
Max(data)=4.787%
Min(data)=4.013%

λ=2.478nm

4.013%
4.054%
4.095%
4.136%
4.176%
4.217%
4.258%
4.299%
4.339%
4.380%
4.421%
4.462%
4.502%
4.543%
4.584%
4.625%
4.665%
4.706%
4.747%
4.787%

**R = 4.58 %**

**λ = 2.478 nm**

**FWHM = 0.005 nm**

AOI = 1.5 deg.

Measured @PTB Berlin



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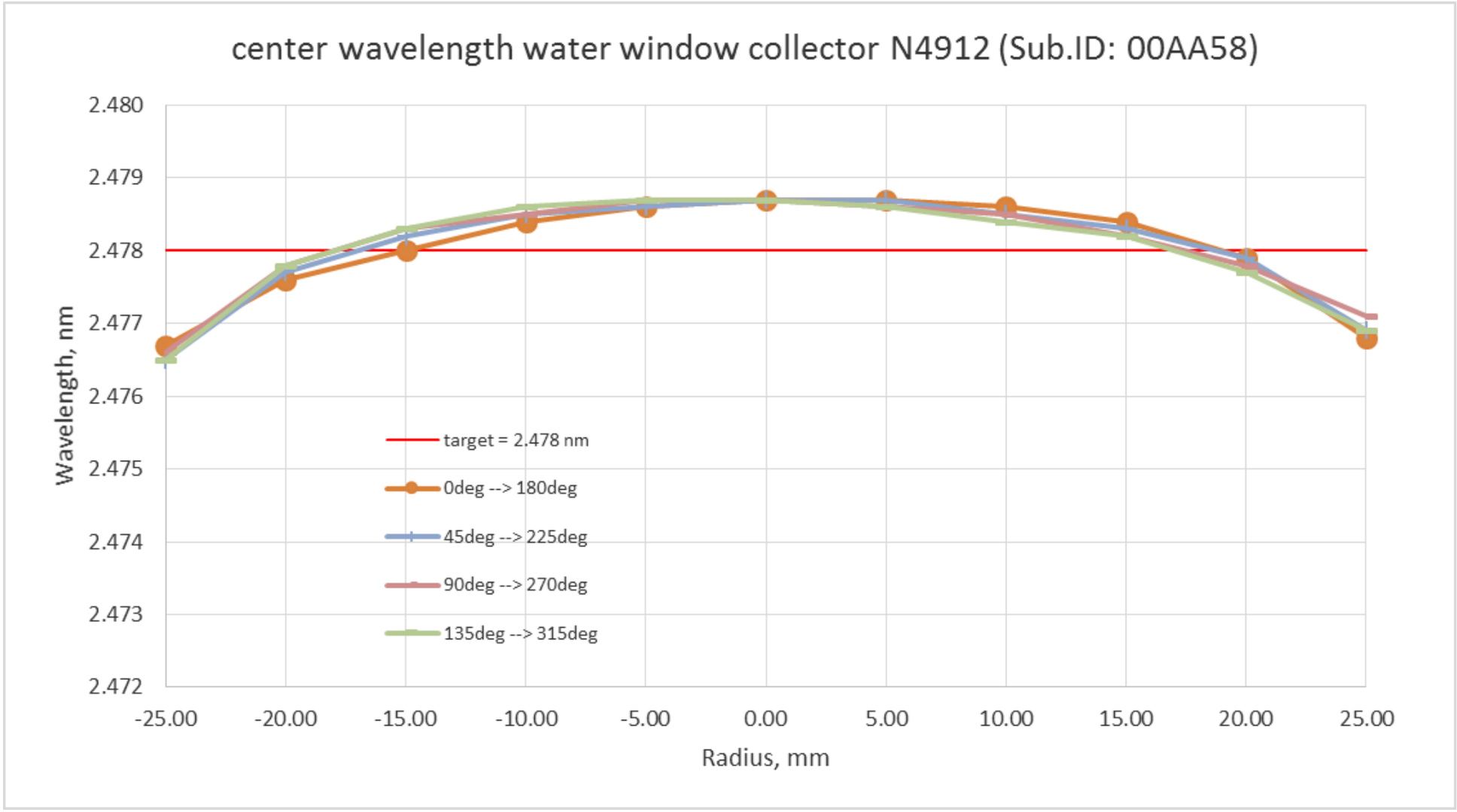
# Collector mirror: Center wavelength at different positions




Measured @PTB Berlin



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# Outline

- Introduction
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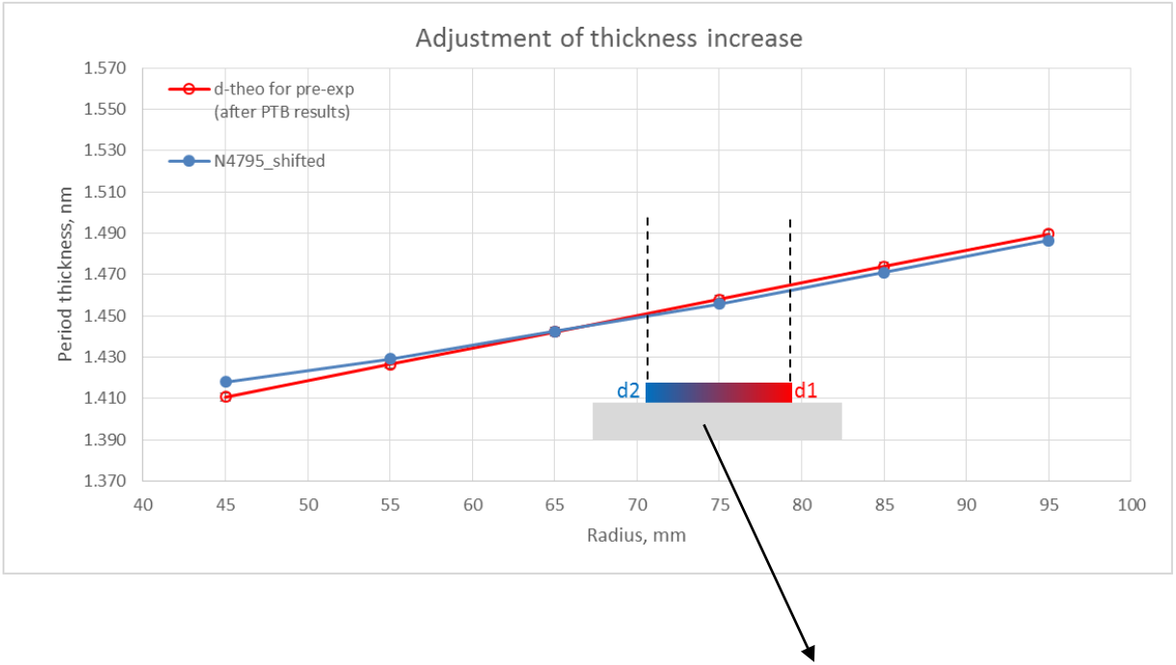
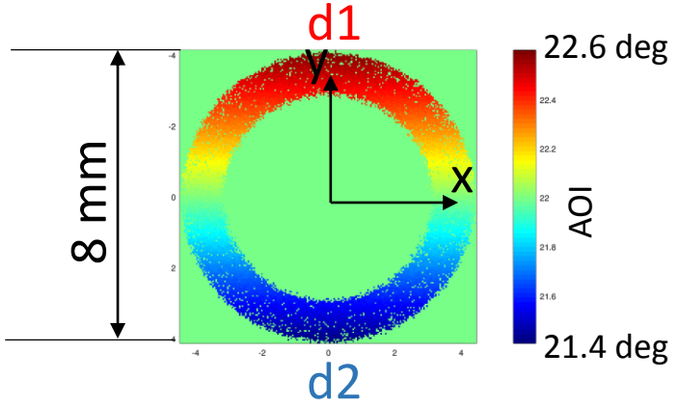
# Graded multilayer mirror for λ = 2.74 nm

- Graded multilayer coating for turning mirror




**Period thickness**

**d1 > d2 according to AOI**

- Diameter of plane Si substrate: 25.4 mm
- Increasing of thickness gradient: ~ 1% per 10 mm



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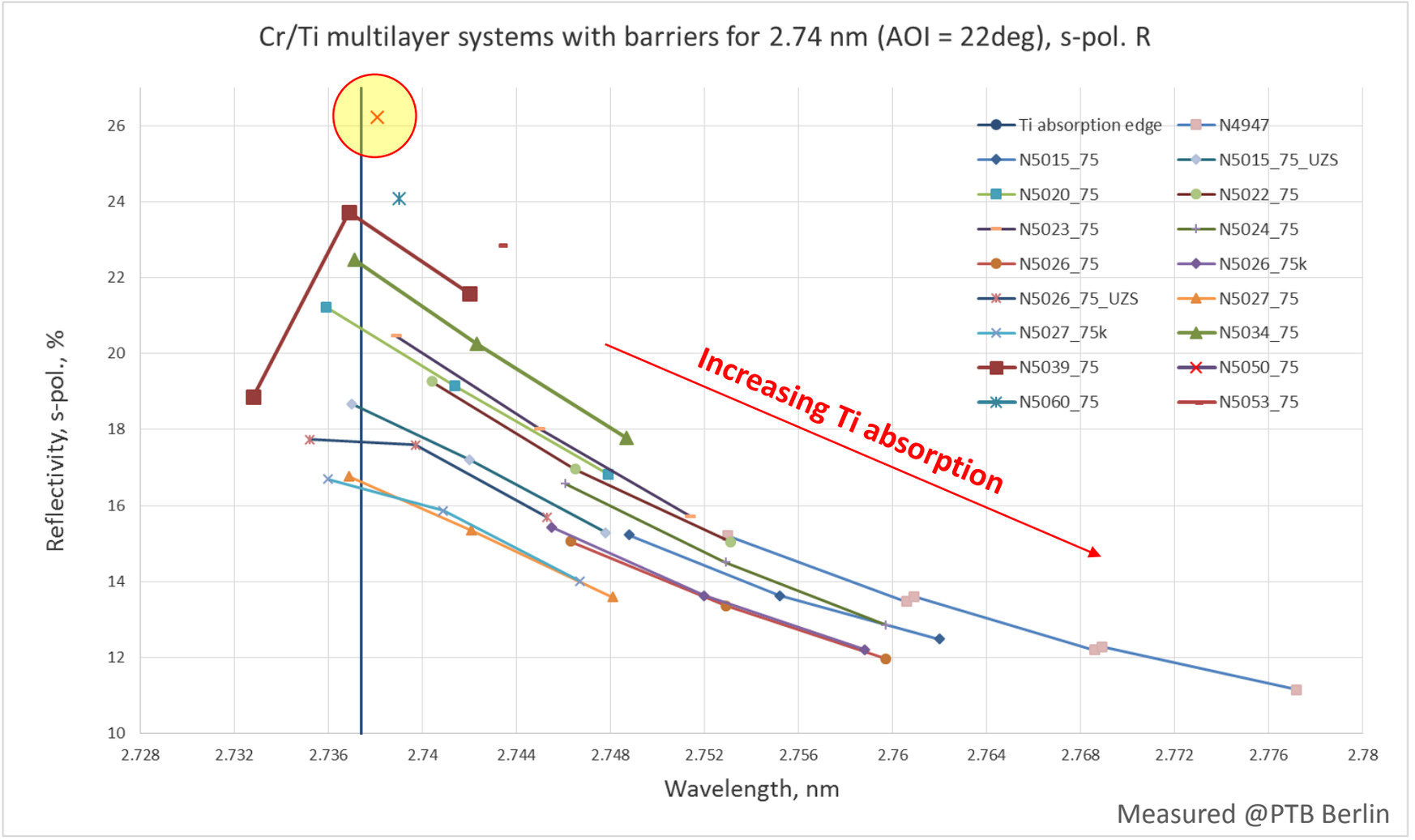
# Graded multilayer mirror for λ = 2.74 nm




- Cr/Ti multilayer system with barrier layers: **$R_{max}$ = 26.22% @ 2.738 nm** (AOI = 22deg)



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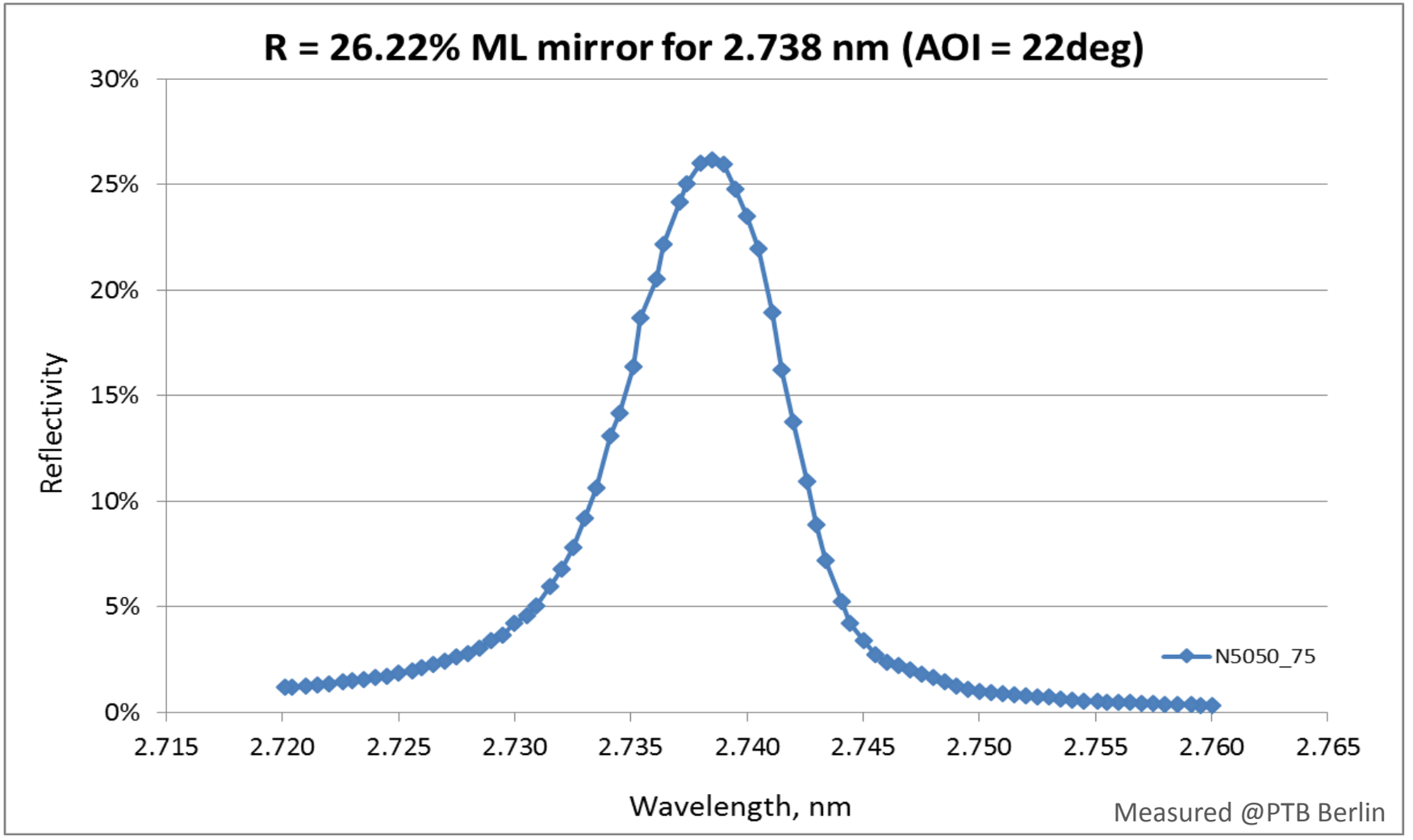
# Graded multilayer mirror for λ = 2.74 nm




- Cr/Ti multilayer system with barrier layers: **$R_{max}$ = 26.22% @ 2.738 nm** (AOI = 22deg)



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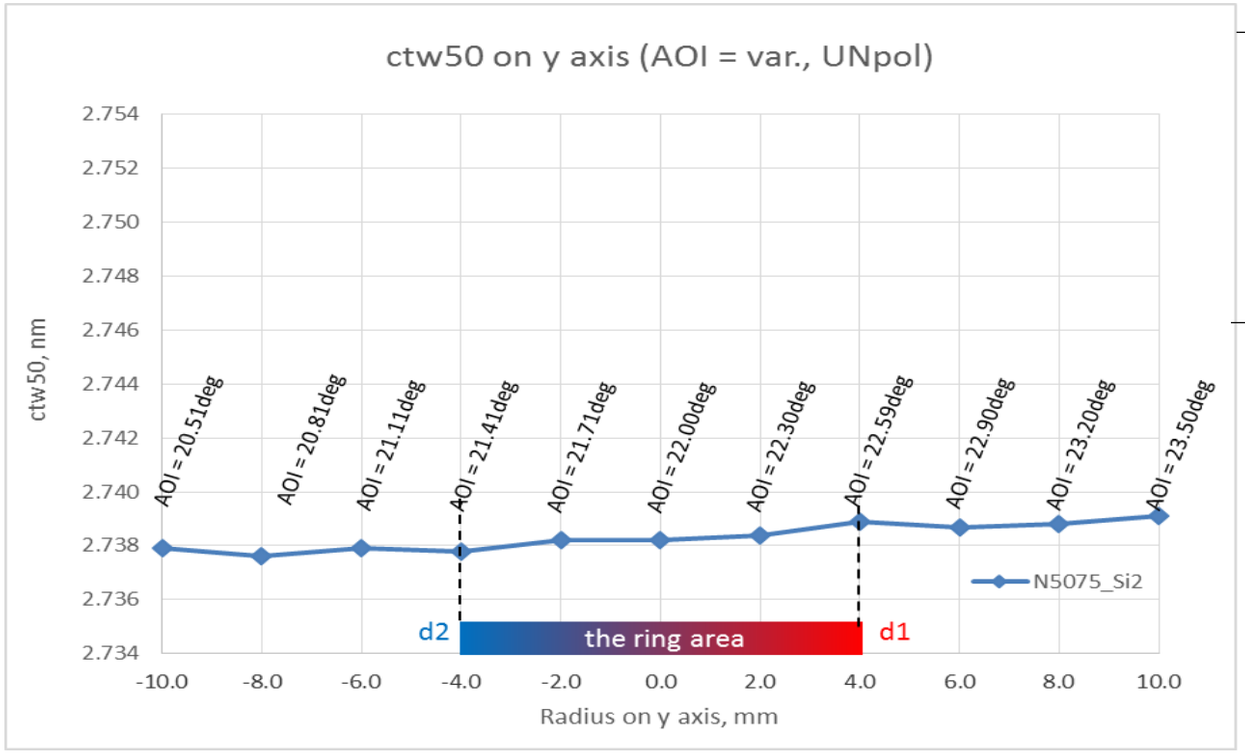
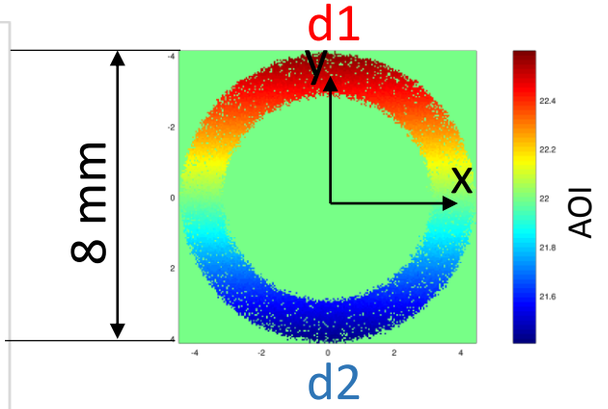
# Graded multilayer mirror for λ = 2.74 nm

- PTB results on mirror (wavelength y axis):




**Period thickness**

**d1 > d2 according to AOI**

- Center wavelength within the ring area: λ = (2.7383 ± 0.0006) nm

Measured @PTB Berlin



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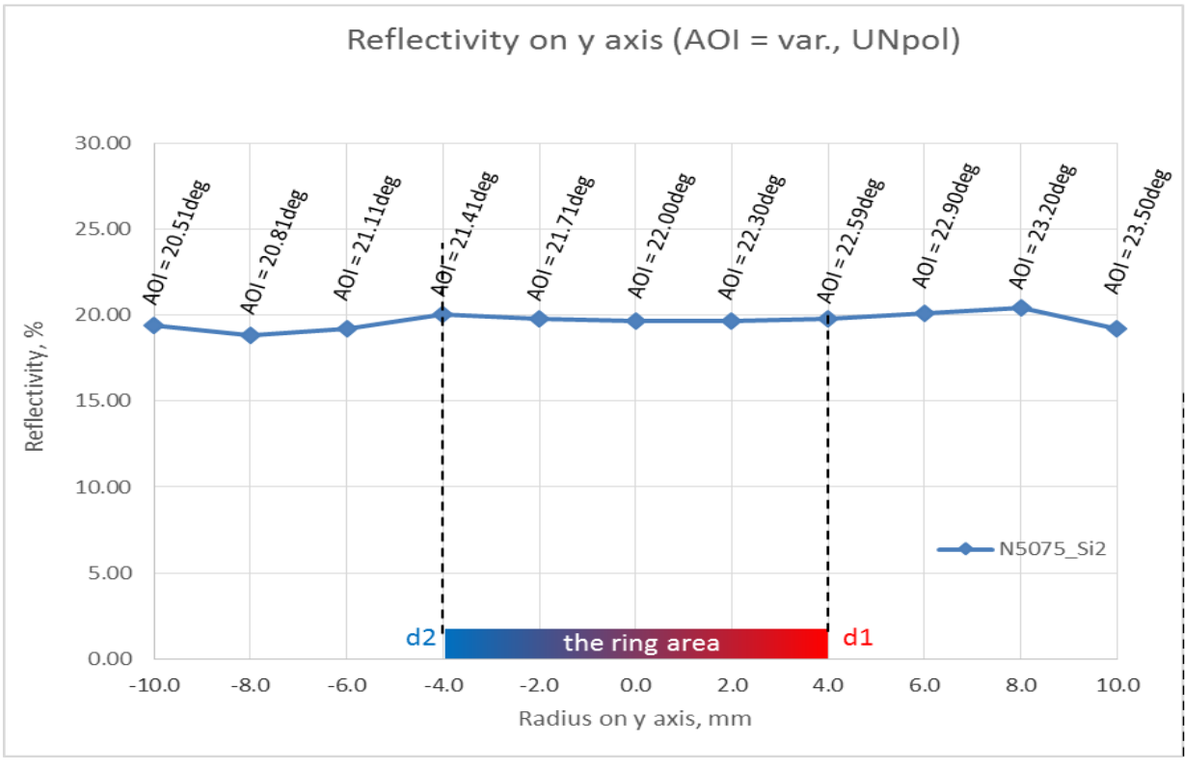
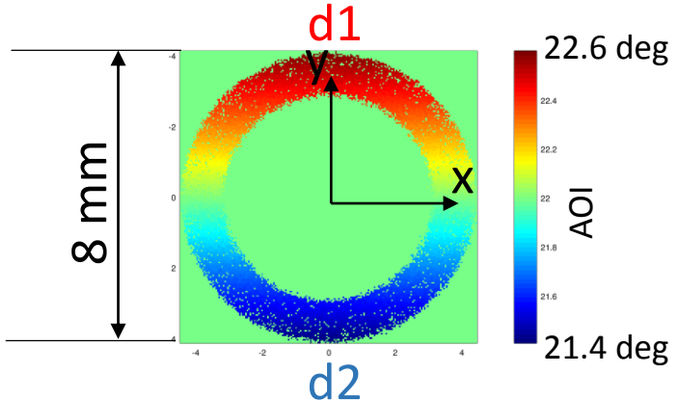
# Graded multilayer mirror for λ = 2.74 nm

- PTB results on mirror (UNpol. reflectivity y axis):




**Period thickness**

**d1 > d2 according to AOI**

- Peak reflectivity within ring area: $R_{unpol}$ = (19.82 ± 0.20) %

$R_{s\text{-}pol}$ = 24.1 % @ AOI = 22 deg

Measured @PTB Berlin



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# Summary

- Fabrication of customized EUV multilayer optics from 2 nm to 100 nm
- Fabrication of customized hard and soft X-ray optics
- reflectance level for water window region:

  R = 18.22 % @ 2.422 nm (AOI = 2.5deg; s-pol.) – Cr/V based (V absorption edge)
  R = 26.22 % @ 2.738 nm (AOI = 22deg; s-pol.) – Cr/Ti based (Ti absorption edge)

- Homogenous reflectence level for water window collector:

  R = 4.58% @ 2.478 nm (AOI = 1.5deg; s-pol) – Cr/V based ($N_2$ liquid source)



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- **KTH Stockholm:**
  Hans Hertz, Emelie Fogelqvist

- **MBI Berlin:**
  Holger Stiel

- **PTB Berlin:**
  Frank Scholze, Christian Laubis and team

- **Fraunhofer IOF Jena:**
  Thomas Müller, Michael Scheler, Steffen Schulze

# Thank you.

# optiX fab.

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