Quality Control and Thin Film Metrology for Future Optical Components

Presented by:

OSA Thin Films Technical Group

WELCOME TO JOIN OUR WEBINAR

QUALITY CONTROL AND THIN FILM METROLOGY FOR FUTURE OPTICAL COMPONENTS

14 May 2019 • 9:30 EDT

OSA Thin Films Technical Group

Thin Films
Technical Group

At a Glance

- Focus

– Our group focuses on the design, preparation, and characterization of optical thin films and interference coatings from fundamentals to applications.

– Our group serves over thousand global members like YOU.

- Mission

– To connect people from academia, institutions and industries in the field

– To bridge the fundamentals, the know-hows and the new developments

– To promote networking and career development through continuous learning

Find us here

- Technical Group Website: www.osa.org/ThinFilmsTG
- LinkedIn: www.linkedin.com/groups/4783616

Interested in presenting your research?
Have ideas for our group activities/events?
Please contact your committee members on the next slide. Thank you!

OSA Thin Films Technical Group

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Executive Committee Roles and Responsibilities

- **Chair –** Primary responsibilities are to guarantee the technical group is active and engaging to our community.

- **Vice Chair –** Assists the chair and works with executive committee to guide new development of activities and events.

- **Social Media Officer –** Manages the group's social media platforms, posting discussion topics and event notices on a regular basis.

- **Events Officer –** Leads technical events, poster sessions, networking events at relevant OSA Meetings. Identifies potential topics and speakers for events.

- **Webinar Officers –** Identify topics of interest to the community, solicit potential speakers and organize webinars.

WELCOME TO OUR WEBINAR PRESENTER Dr. Lars Jensen

Lars Jensen holds PhD in physics from Leibniz University Hannover, Germany and also a Diploma in technical physics from University of Hannover.

Dr. Lars Jensen has more than 15 years of experience in dielectric thin films for optical applications. In the first years he developed metrology in the field of laser-induced damage and optical losses and then developing thin film coatings for numerous application in photonics, space, lighting and astronomy.

Sine 2018 he is responsible for the Laser Components department at the Laser Zentrum Hannover.

QUALITY CONTROL AND THIN FILM METROLOGY FOR FUTURE OPTICAL COMPONENTS

Dr. Lars Jensen

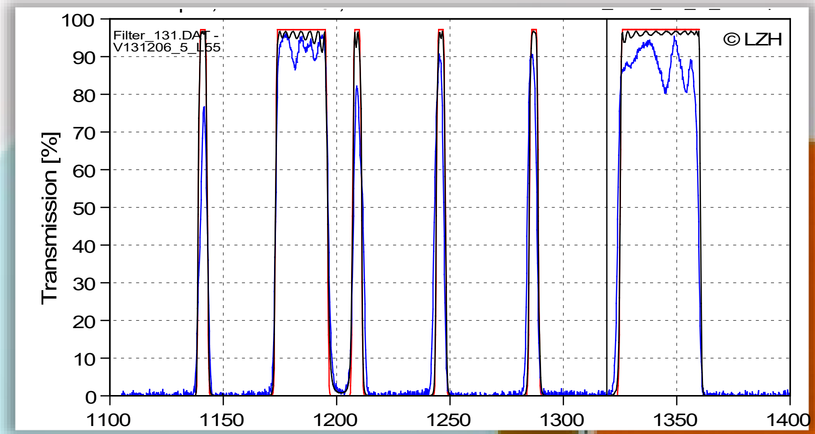
Laser Zentrum Hannover, Germany

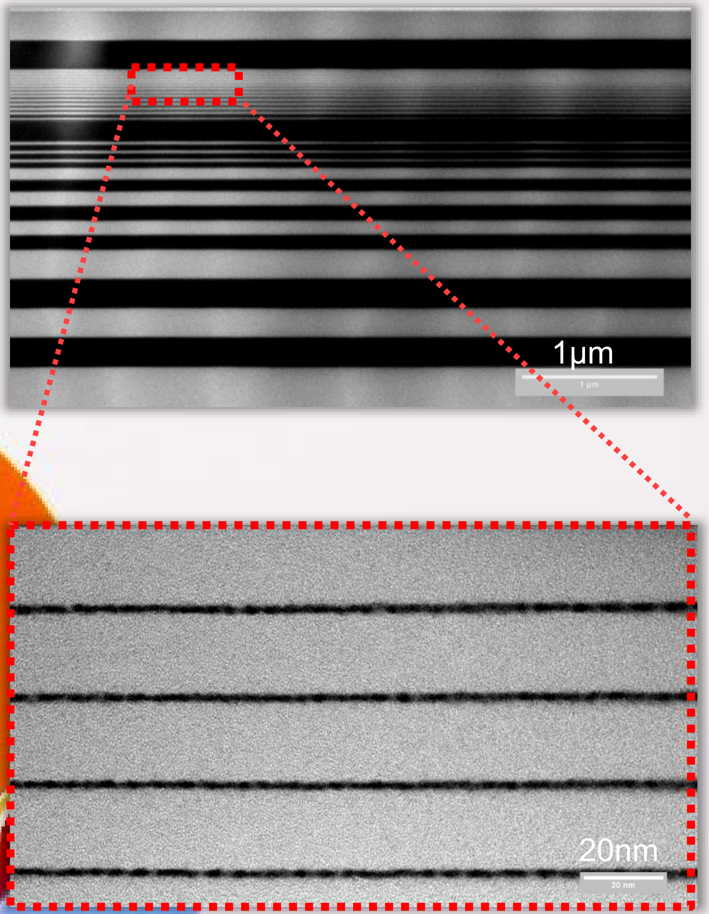
Webinar May 14th 2019
Technical Group: Thin Films

OSA® The Optical Society

LZH LASER ZENTRUM HANNOVER e.V.

PRECISION IN OPTICAL THIN FILMS

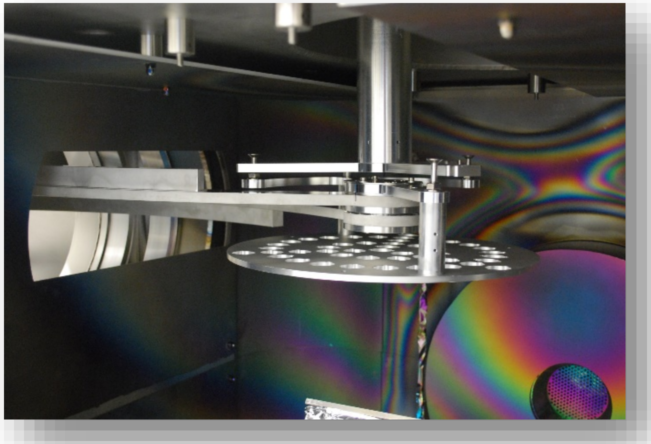




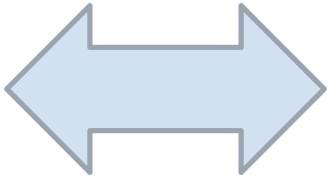
QUALITY CHECK VS. CONTROL

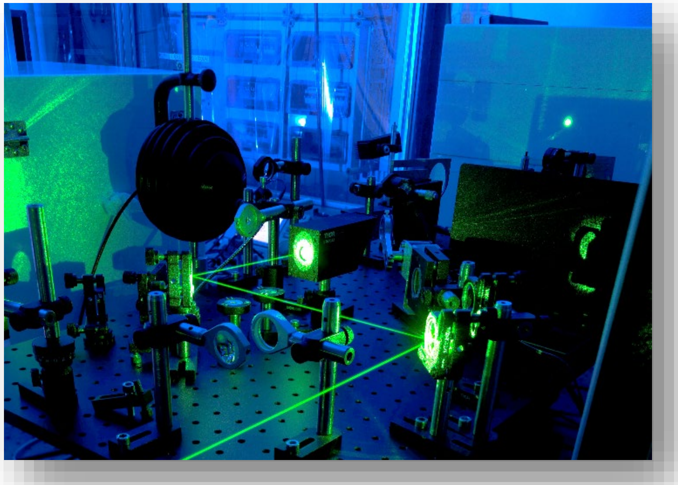
Strategies

- quality control vs mitigation
- In-situ vs ex-situ
- Accuracy
- Efficiency



Courtesy by Cutting Edge Coatings GmbH





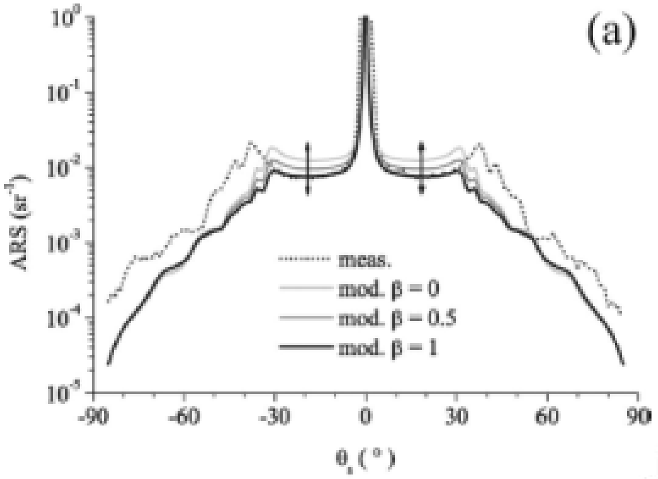
EXAMPLES FOR POST DEPOSITION METROLOGY

Losses

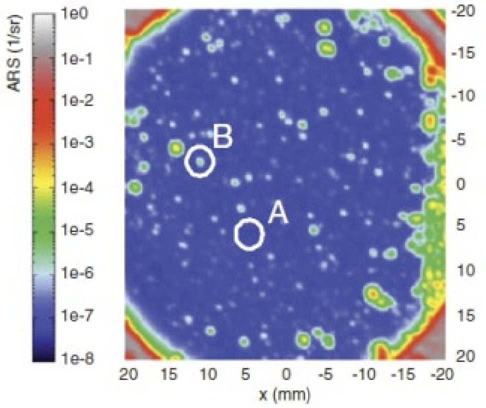
- Scatter
- Absorption
- Stress

Laser-induced Damage → lifetime

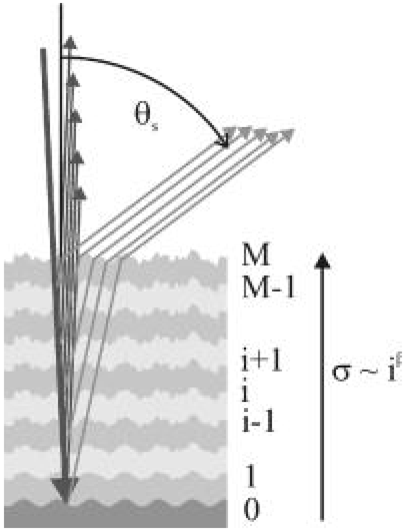
Environmental stability



Schröder et al. "Angle-resolved scattering: an effective method for characterizing thin-film coatings," Appl. Opt. **50,** (2010)



Schröder et al. AOT 2015 Vol 4 (5-6)



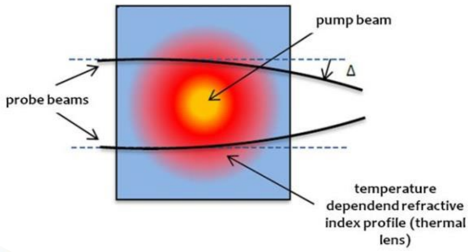
POST DEPOSITION METROLOGY - ABSORPTION

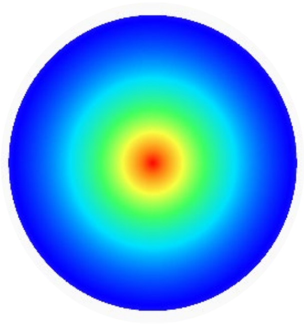
Losses

- Scatter
- **Absorption**
- Stress

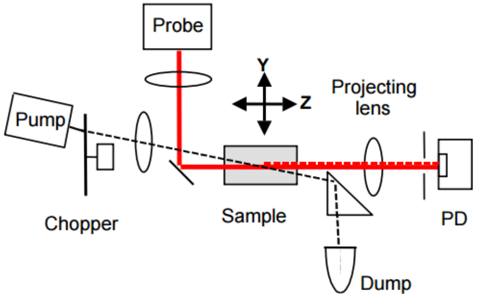
Laser-induced Damage → lifetime

Environmental stability





- Highly sensitive detection of thermal or index changes



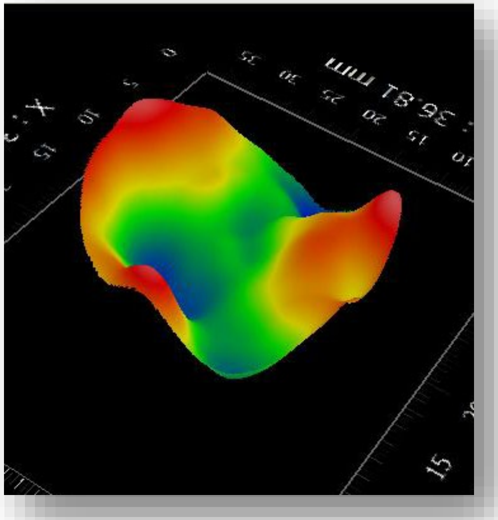
POST DEPOSITION METROLOGY - STRESS

Losses

- Scatter
- Absorption
- **Stress**

Laser-induced Damage → lifetime

Environmental stability

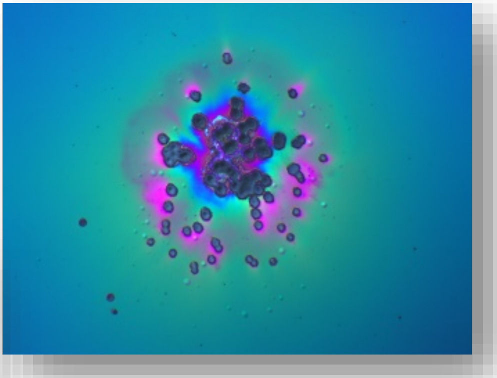


- nm accuracy on rotating mechanics not yet reliable

POST DEPOSITION METROLOGY – LASER DAMAGE/ENVIRONMENT

Losses

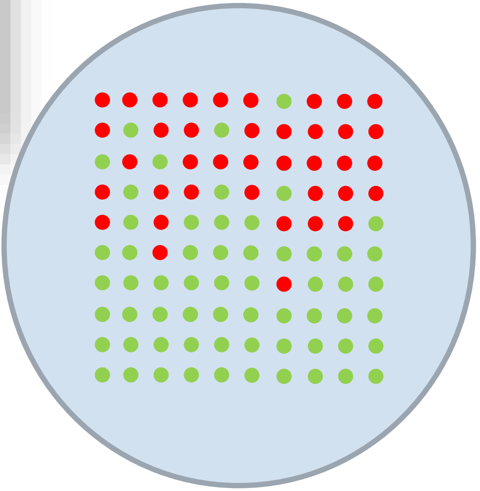
- Scatter
- Absorption
- Stress



Laser-induced Damage → lifetime

Environmental stability

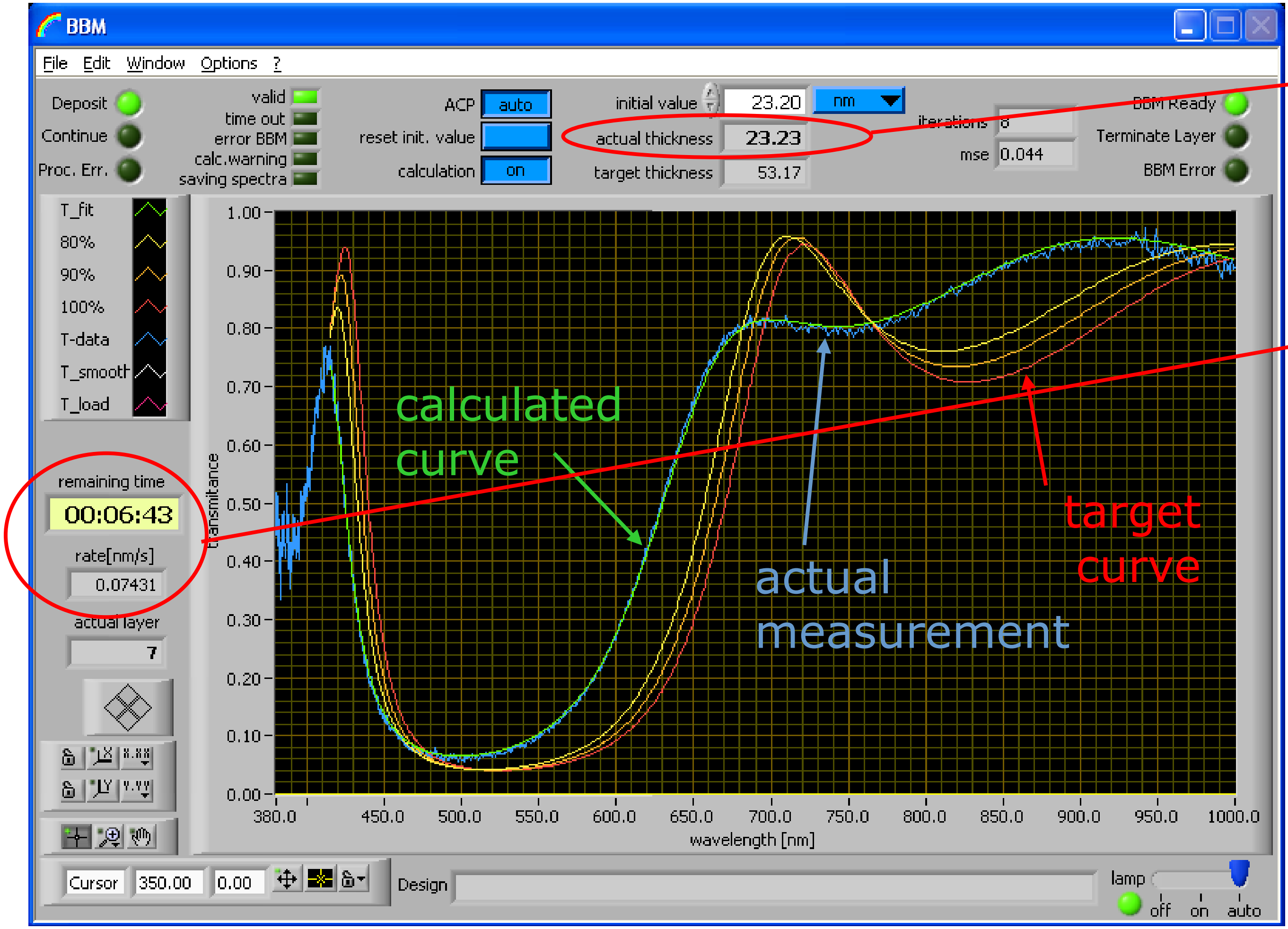
- MISSE experiment on ISS /2001+2005



QUALIFICATION VS MITIGATION

	in-situ	**ex-situ**
Spectral reflection/transmission		
Uniformity non-plane surfaces		
Film defects		

BBM: LAYER THICKNESS CONTROL I



ACP: auto

initial value: 23.20 nm

actual thickness: 23.23

target thickness: 53.17

calculation: on

iterations: 8

mse: 0.044

remaining time: 00:06:43

rate[nm/s]: 0.07431

actual layer: 7

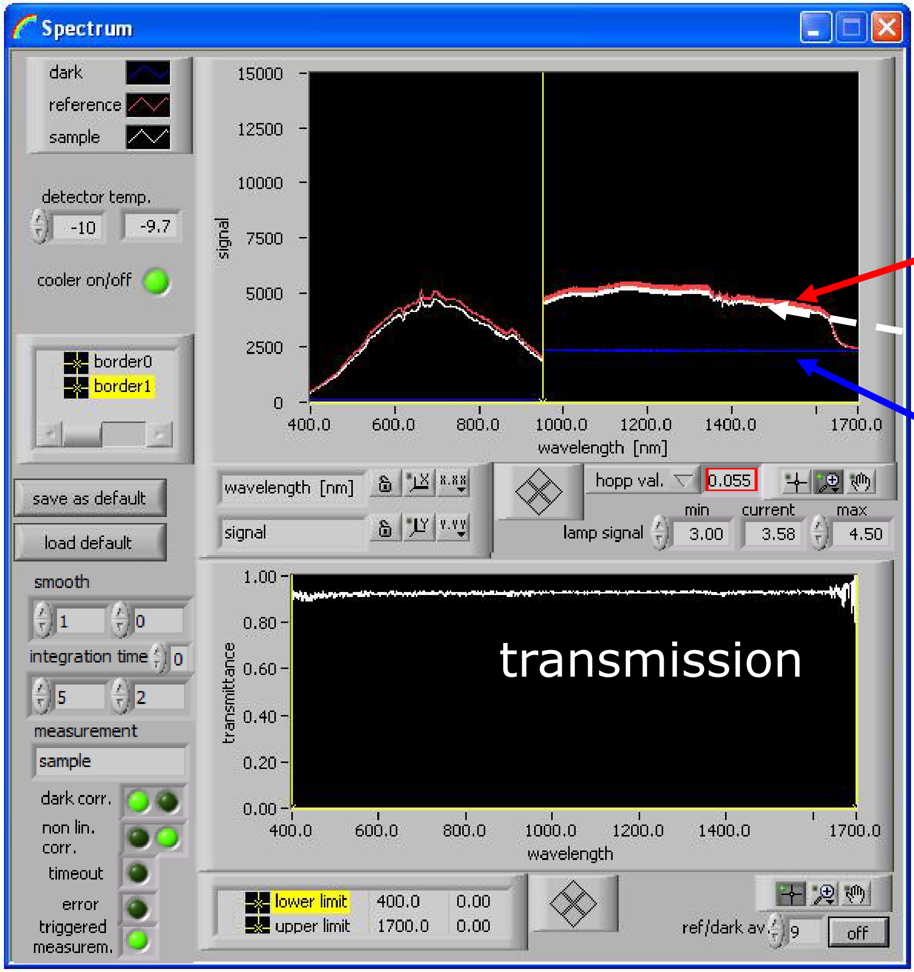
Cursor: 350.00 0.00

calculated thickness,

calculated rate and remaining time

„automatic mode" to control coating plant

BBM: ABSOLUTE MEASUREMENT



detector temp. -10 -9.7

cooler on/off

smooth 1 0

integration time 0

5 2

measurement: sample

wavelength [nm]

signal

hopp val. 0.055

lamp signal: min 3.00, current 3.58, max 4.50

lower limit 400.0 0.00

upper limit 1700.0 0.00

ref/dark av 9 off

reference measurement

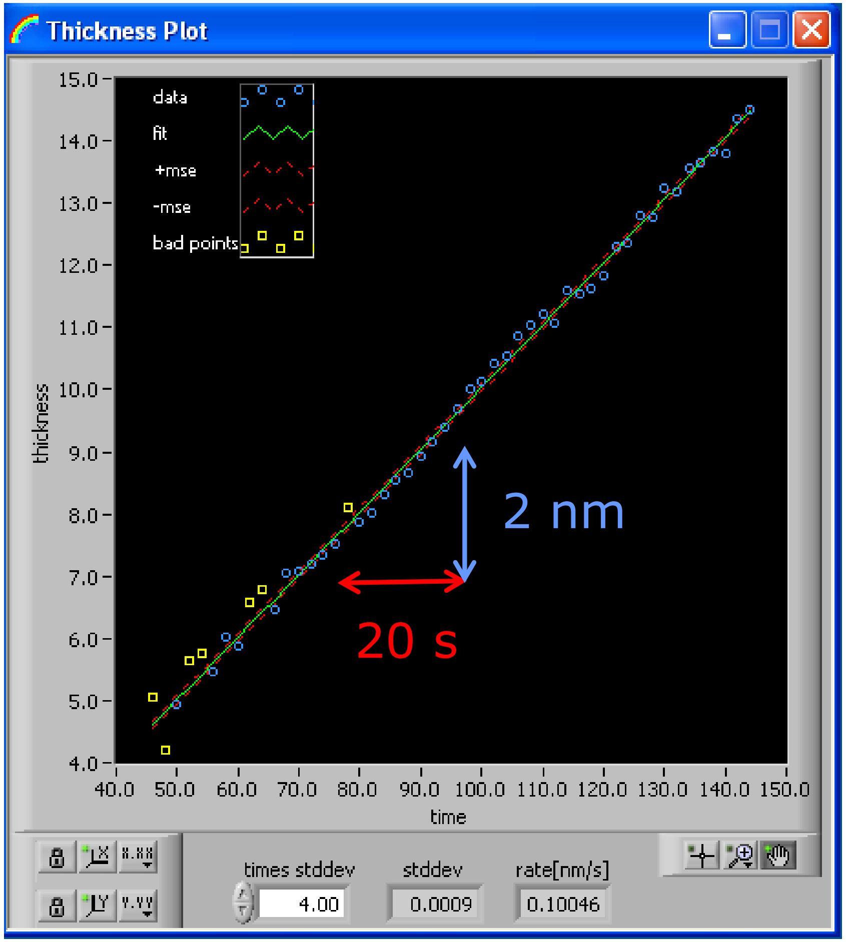
substrate measurement

dark measurement

Spectrometer module

absolute transmission by 3 measurements per revolution

BBM: LAYER THICKNESS CONTROL II



times stddev 4.00

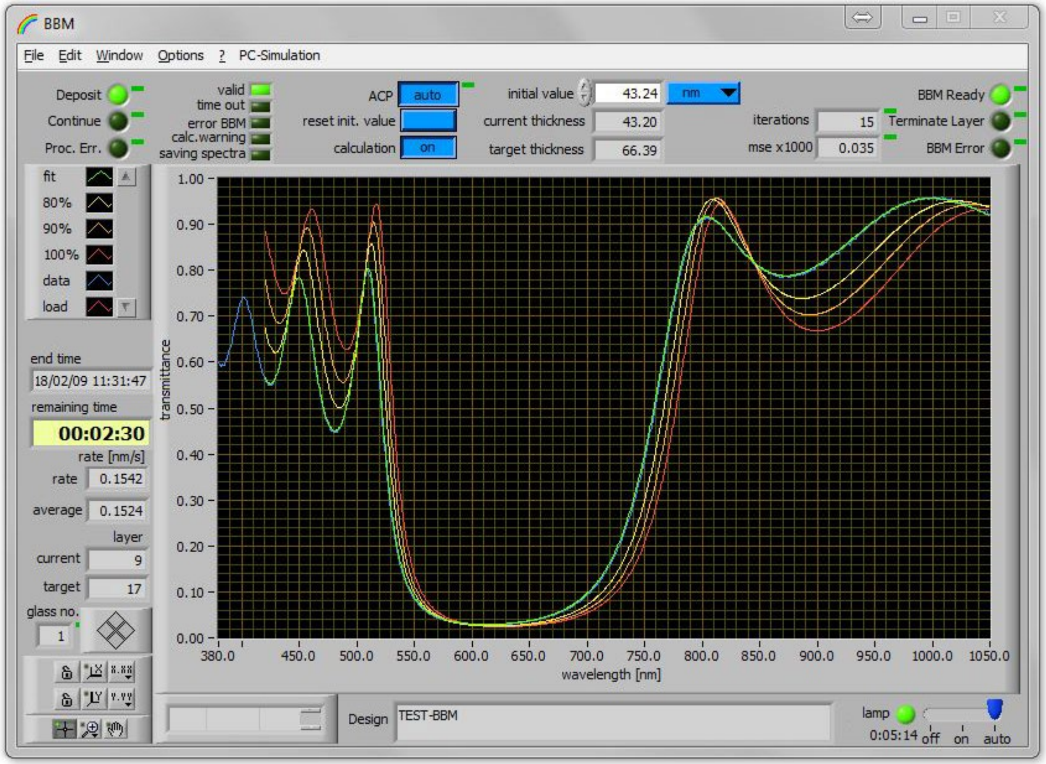
stddev 0.0009

rate[nm/s] 0.10046

Process control rate module:

averaging about several broadband measurements (history) determines rate and the termination point

BBM SIMULATOR: VIRTUAL COATING PLANT



ACP auto

calculation on

initial value 43.24 nm

current thickness 43.20

target thickness 66.39

iterations 15

mse x1000 0.035

end time 18/02/09 11:31:47

remaining time 00:02:30

rate [nm/s]

rate 0.1542

average 0.1524

layer

current 9

target 17

glass no. 1

Design TEST-BBM

lamp 0:05:14

process-phase processphase

Wait for ReCalc off

cur.layer 9

act.Monitor BBM

no.Layers 17

curr. material TIO2

name / path C:\Program Files (x86)\BBM\data\BBM-Testdesign.dsg

d_sim [nm] 42.60

d_calc [nm] 43.20

rate_sim [nm/s] 0.15000

rate_calc [nm/s] 0.15421

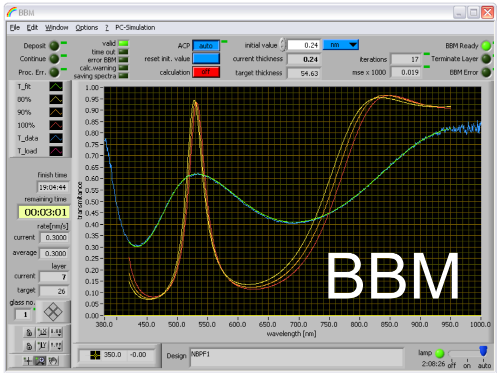
batch OFF

batch mode 10 1

Coating simulation in advance:

Verification of layer designs with increased process stability and chance of success (“real“ process control module ↔ virtual coating plant)

RECALC&REOPT: PRINCIPLE OF AUTOMATED REENGINEERING



ACP: auto

initial value: 0.24 nm

current thickness: 0.24

target thickness: 54.63

iterations: 17

mse x 1000: 0.019

calculation: off

finish time: 19:04:44

remaining time: 00:03:01

rate[nm/s] current: 0.3000

rate[nm/s] average: 0.3000

layer current: 7

layer target: 26

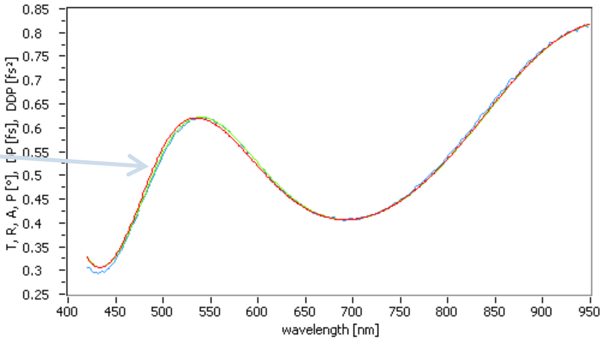
glass no.: 1

350.0 -0.00

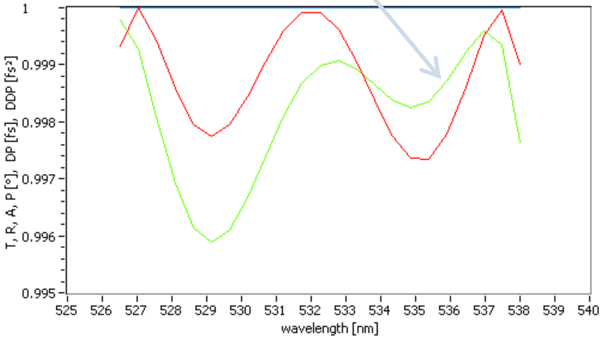
Design: NBPF1

2:08:26

transmittance
layer data
→re-calculate
thickn., disp.



given target
specifications
→current design
forecast of result



→re-optimize
residual layers

original design-path: C:\Programme\BBM\data\Design_15.02.11_110620_1359.dsg

onlinemodus

online/automatic:

layers: 26

centre wl [nm]: 532.00

LayNo <>: 1

layer No.	thickn. [QWOT] target	thickn. [QWOT] recalc	thickn. [nm] target	thickn. [nm] recalc	dt [QWOT]	dt [nm]	dt [%]	mat ID	glass	vary	active
1	1.0000	[illegible]	54.63	54.60	-0.0005	-0.03	-0.05	-3.00	1	☒☒	☒
2	1.0000	[illegible]	90.45	90.89	0.0050	0.45	0.50	-2.00	1	☒☒	☒
3	1.0000	1.0123	[illegible]	55.30	0.0123	0.67	1.23	-4.00	1	☒☒	☒
4	2.0000	1.9792	[illegible]	179.01	-0.0208	-1.88	-1.04	-2.00	1	☒☒	☒
5	1.0000	1.0243	[illegible]	[illegible]	0.0243	1.33	2.43	-5.00	1	☒☒	☒

Ø active dt: 1.05

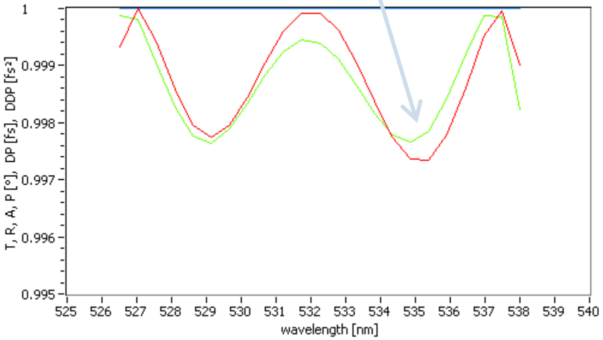
current / next layer: 6 7

equ.: 9

reopt: 3

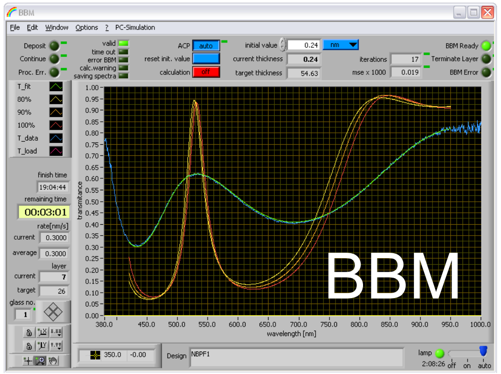
300.0 0.00

design info: NBPF1



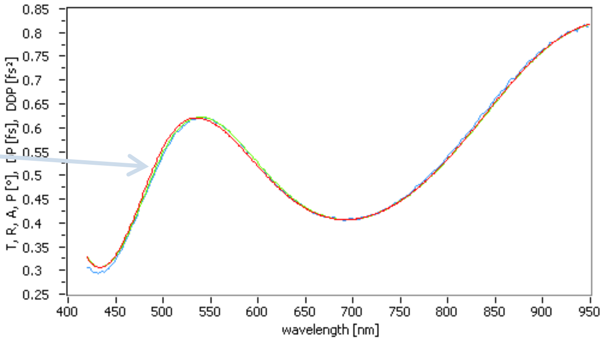
→upload optimized
design

RECALC&REOPT:
ERROR ANALYSIS FUNCTION



ACP auto
reset init. value
calculation off
initial value 0.24 nm
current thickness 0.24
target thickness 54.63
iterations 17
mse x 1000 0.019
finish time 19:04:44
remaining time 00:03:01
rate[nm/s]
current 0.3000
average 0.3000
layer
current 7
target 26
glass no. 1
350.0 -0.00
Design NBPF1
2:08:26

transmittance
layer data
→*re-calculate*
thickn., disp.



original design-path C:\Programme\BBM\data\Design_15.02.11_110620_1359.dsg
layers 26
centre wl [nm] 532.00
LayNo <> 1

layer No.	[illegible] target	[illegible] recalc	thickn. [nm] target	thickn. [nm] recalc	dt [QWOT]	dt [nm]	dt [%]	mat ID	glass	vary	active
1	1.0000	[illegible]	54.63	54.60	-0.0005	-0.03	-0.05	-3.00	1	☒ ☒	☒
2	1.0000	[illegible]	90.45	90.89	0.0050	0.45	0.50	-2.00	1	☒ ☒	☒
3	1.0000	1.0123	[illegible]	55.30	0.0123	0.67	1.23	-4.00	1	☒ ☒	☒
4	2.0000	1.9792	[illegible]	179.01	-0.0208	-1.88	-1.04	-2.00	1	☒ ☒	☒
5	1.0000	1.0243	[illegible]	[illegible]	0.0243	1.33	2.43	-5.00	1	☒ ☒	☒

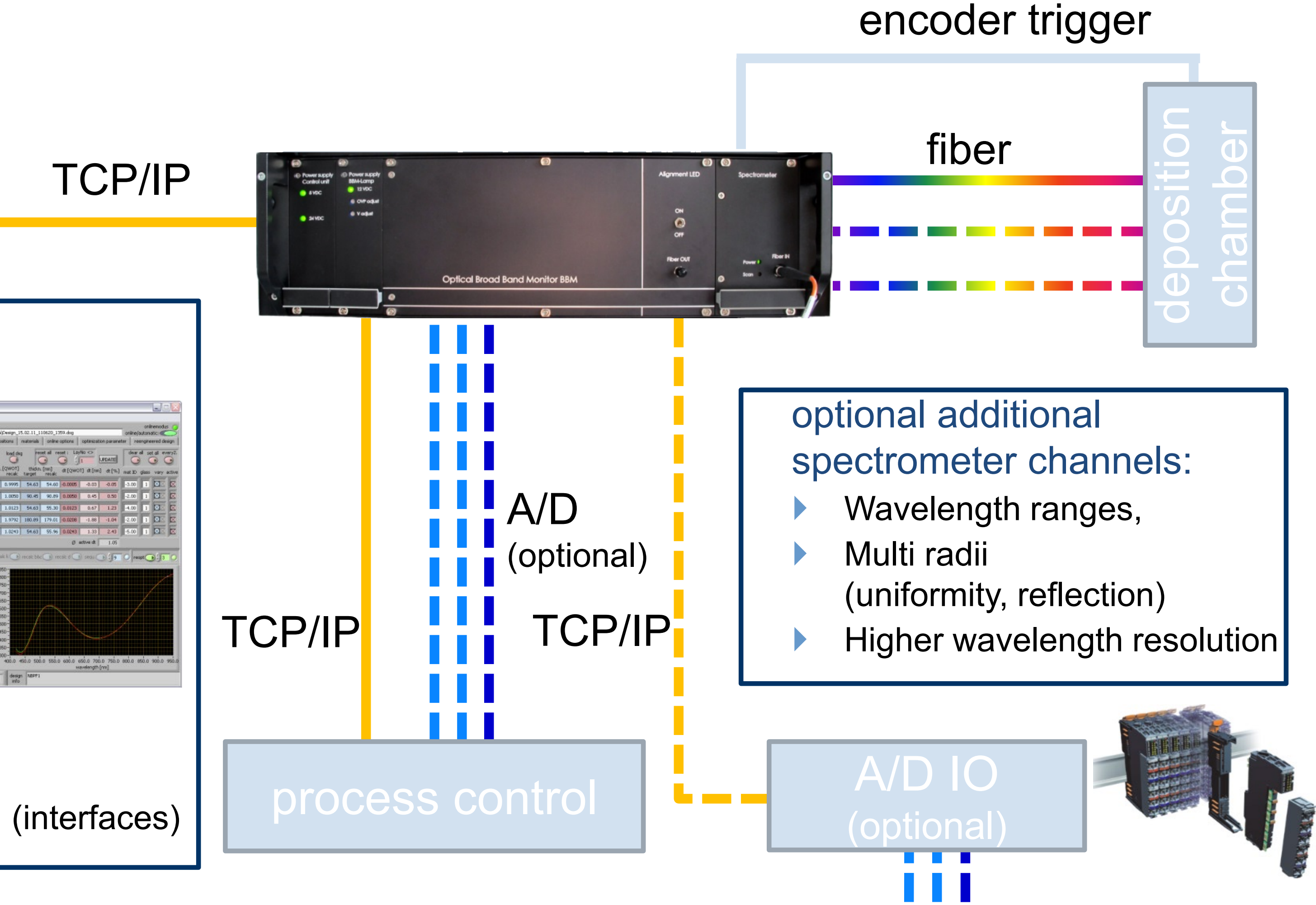
Ø active dt 1.05
current / next layer 6 7
9
reopt 3
300.0 0.00
design info NBPF1

layer thickness
deviation detected

operator decision:
continue
re-optimization
abort
…

critical deviation
→interrupt of coating
directly or after current layer

FLEXIBLE AND MODULAR BBM CONCEPT



optional additional spectrometer channels:

- Wavelength ranges,
- Multi radii (uniformity, reflection)
- Higher wavelength resolution

Software:

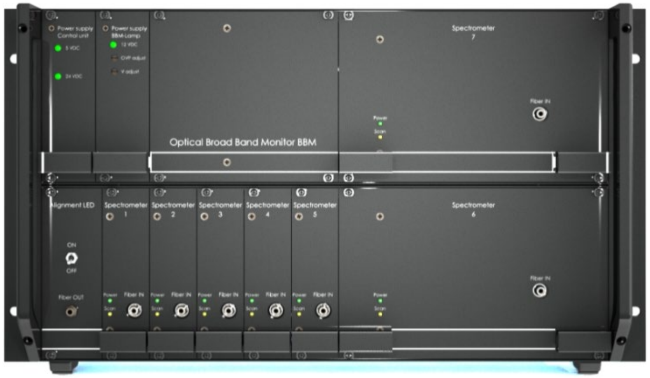
BBM & Tools

- Reengineering
- Simulation
- Individual modules (interfaces)

HIGH RESOLUTION BBM

Precise:
“Standard BBM”

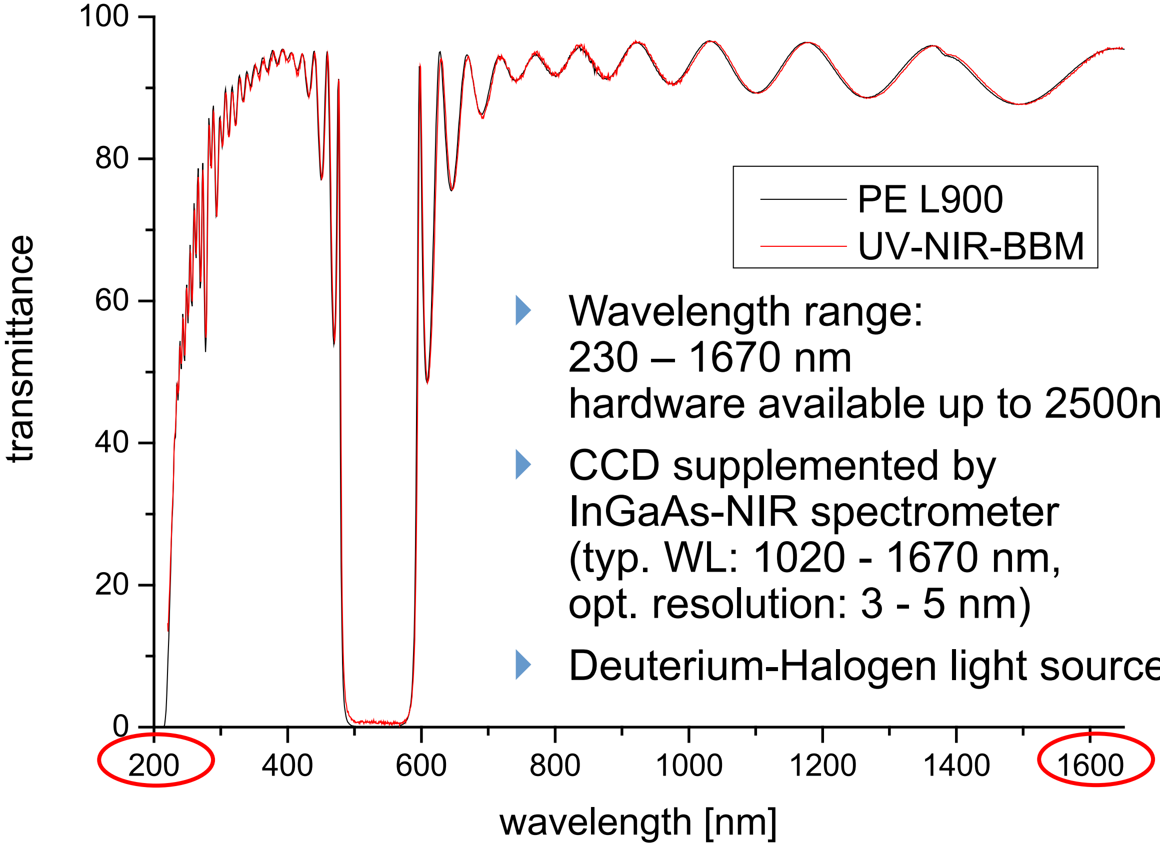
More precise:
„High Resolution BBM”



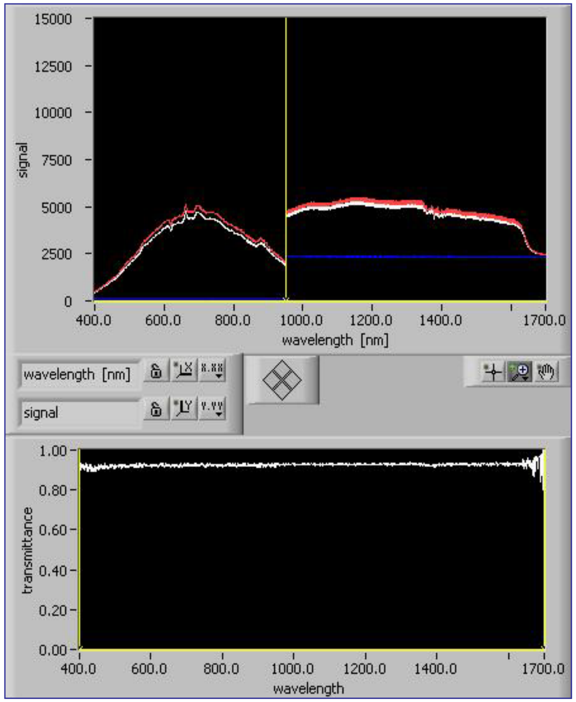
HR-BBM – “high resolution”

- Modular system with 7 spectrometers:
  wavelength range: e.g. 400-1700 nm, **spectral resolution: ~ 0.1 – 0.3nm (IR: ~ 1.5 - 3nm)**
- Application: highly complex filters
- Monitoring of the total system:
  - Usage of error self compensation effects
  - No need for complicated measurement glass changings

BBM MEASUREMENT: UV-NIR WAVELENGTH EXTENSION



- Wavelength range:
  230 – 1670 nm
  hardware available up to 2500nm
- CCD supplemented by InGaAs-NIR spectrometer (typ. WL: 1020 - 1670 nm, opt. resolution: 3 - 5 nm)
- Deuterium-Halogen light source



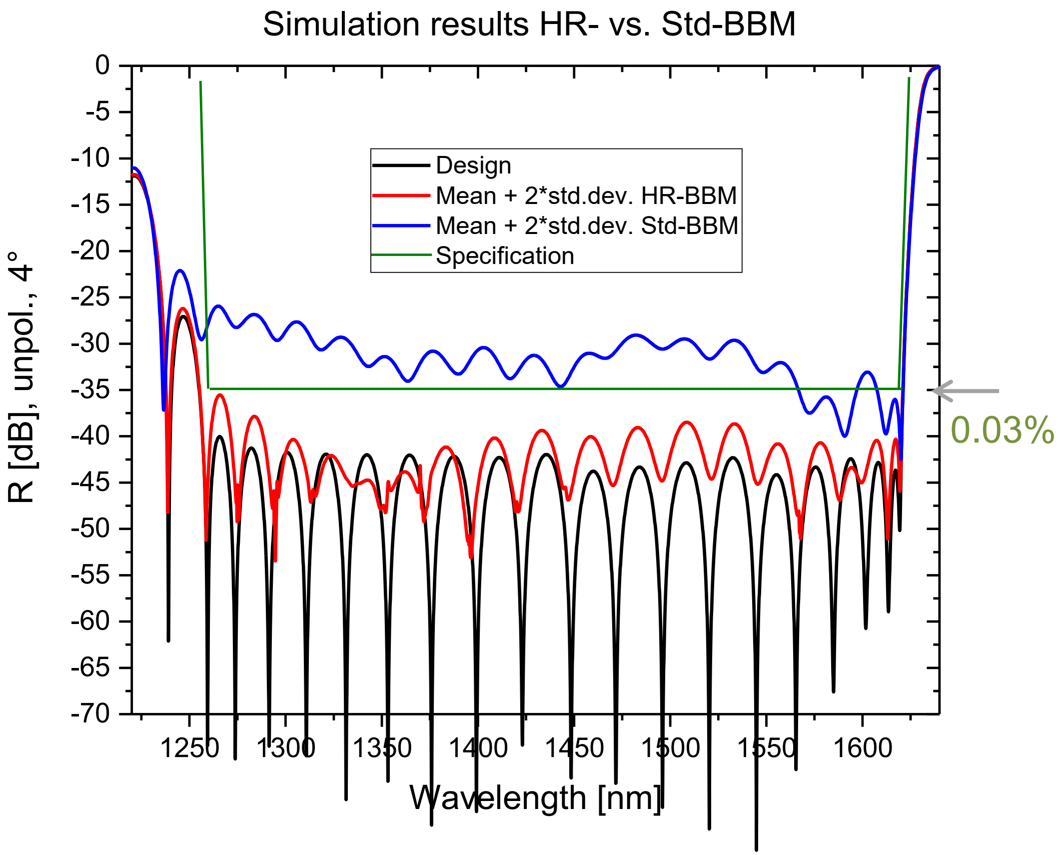
LASER ZENTRUM HANNOVER e.V.

EXAMPLE: HIGH RESOLUTION BBM

Simulation with STD- and HR-BBM

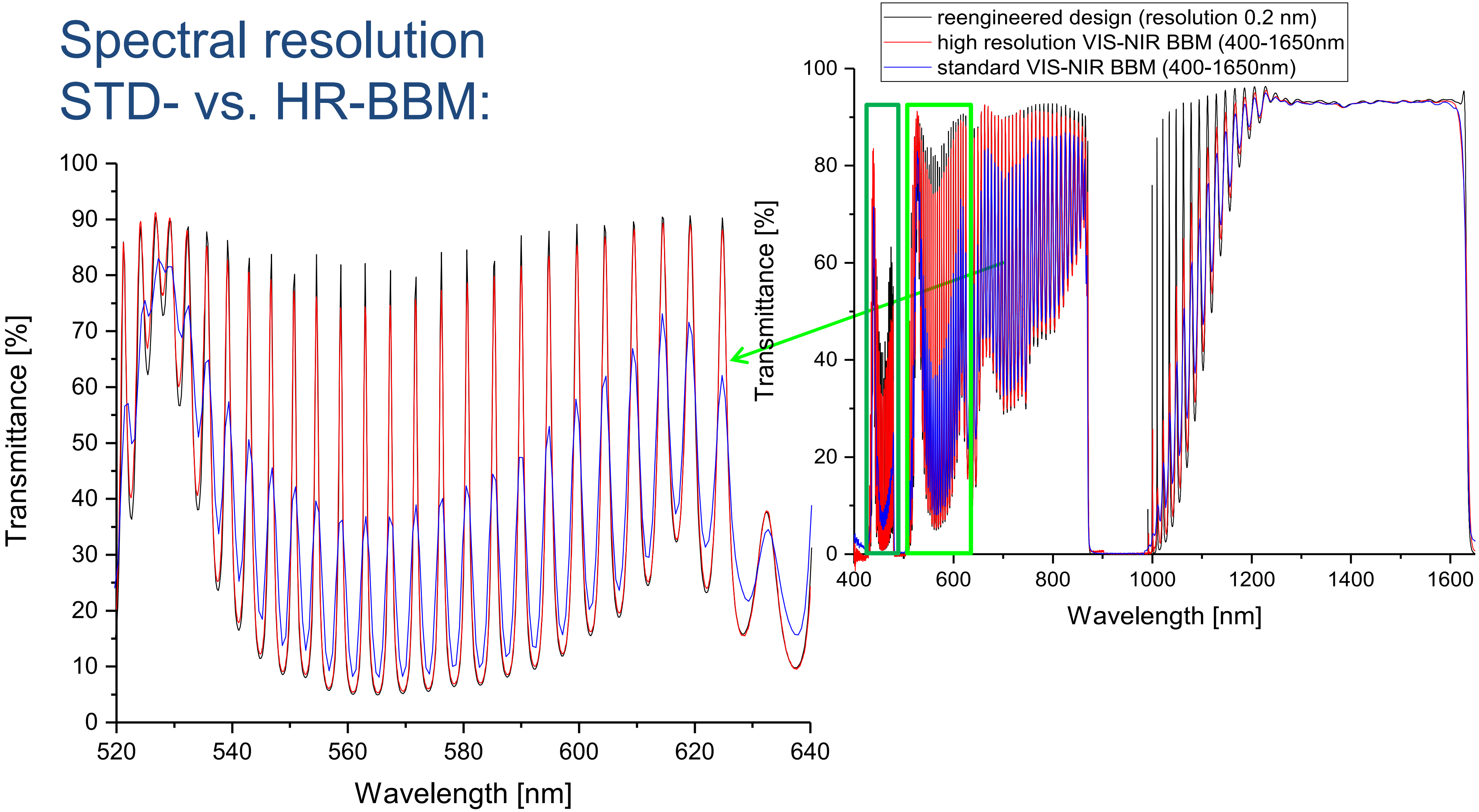
Mean results of 20 simulation runs:

- Simulation of “real” measurement resolution limit
- No process errors in dispersion assumed
- With standard BBM because of limited resolution R<-35dB@1260-1621nm not achievable

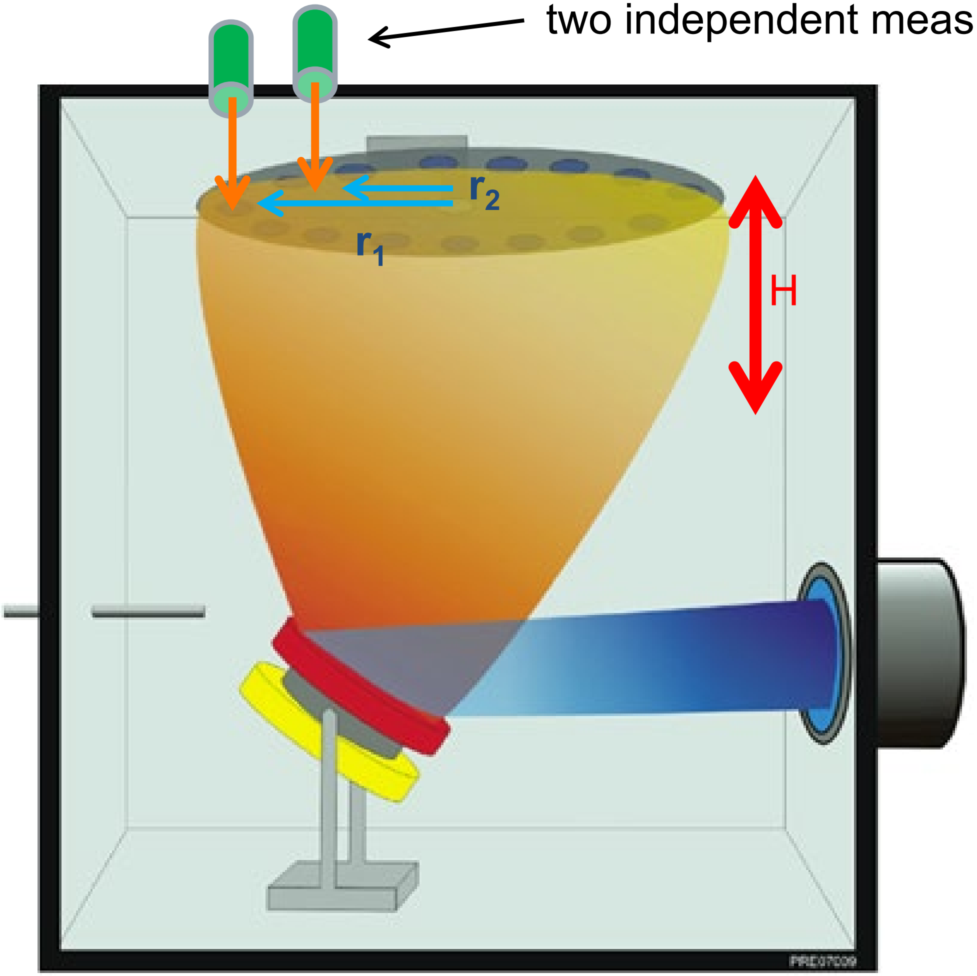


EXAMPLE: HIGH RESOLUTION BBM

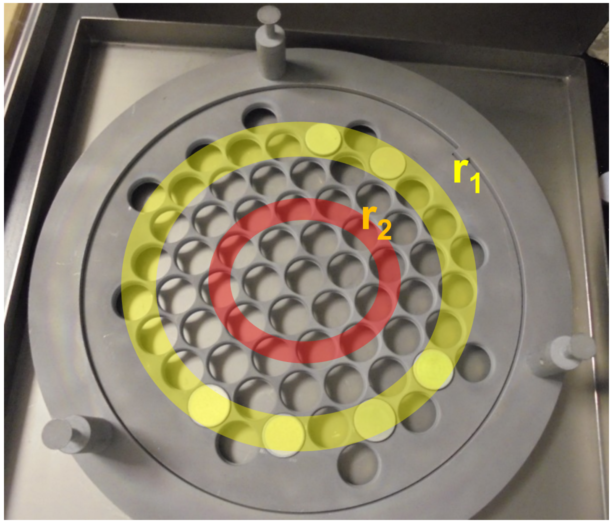
Spectral resolution STD- vs. HR-BBM:



BBM UNIFORMITY CONTROL



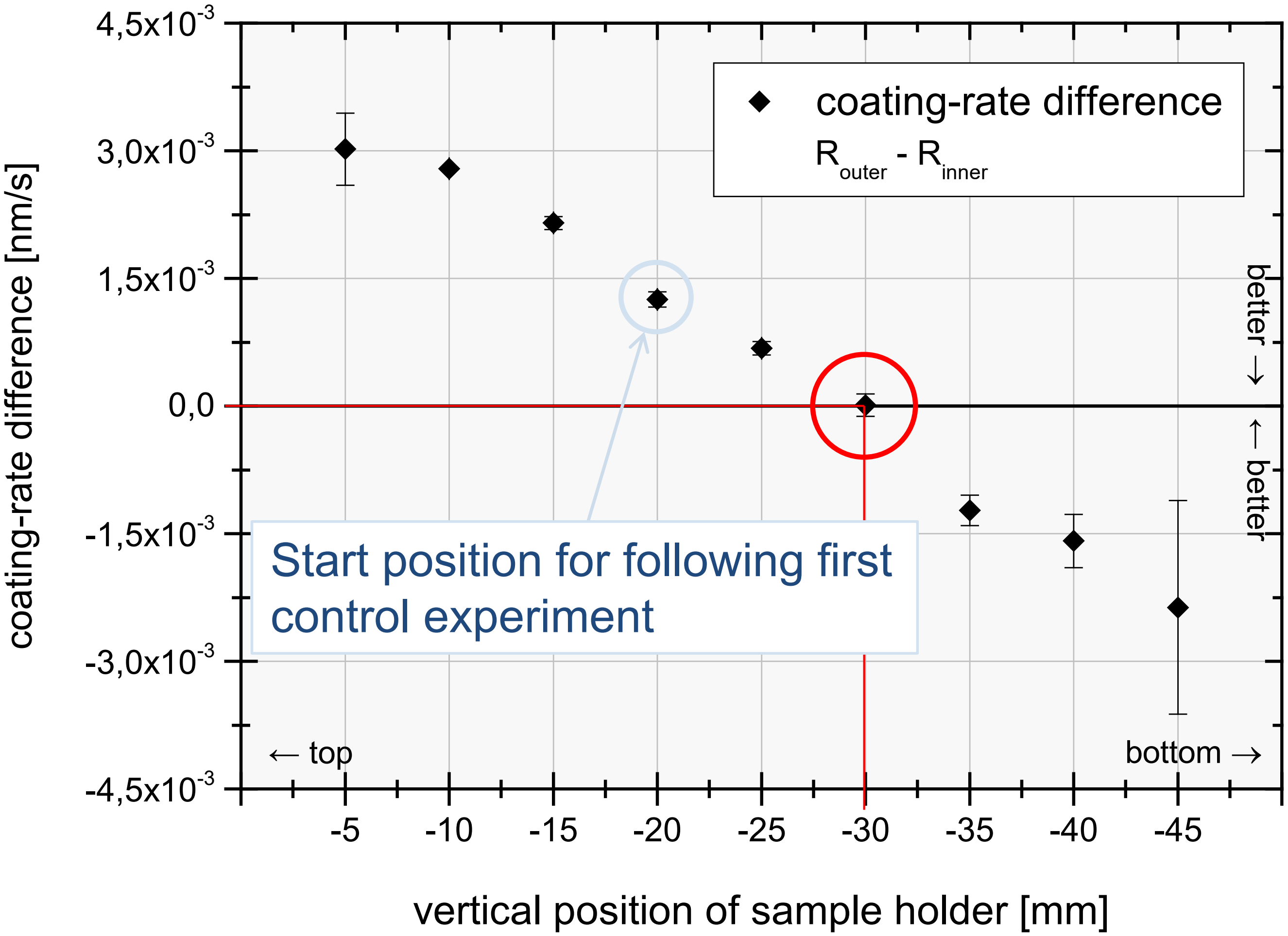
two independent measurement beams



Uniformity measurement

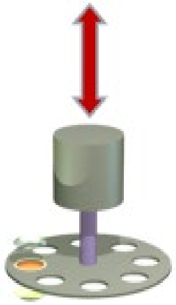
- Multi radii BBM
- Monitoring of deposition rate and thickness difference

BBM UNIFORMITY CONTROL

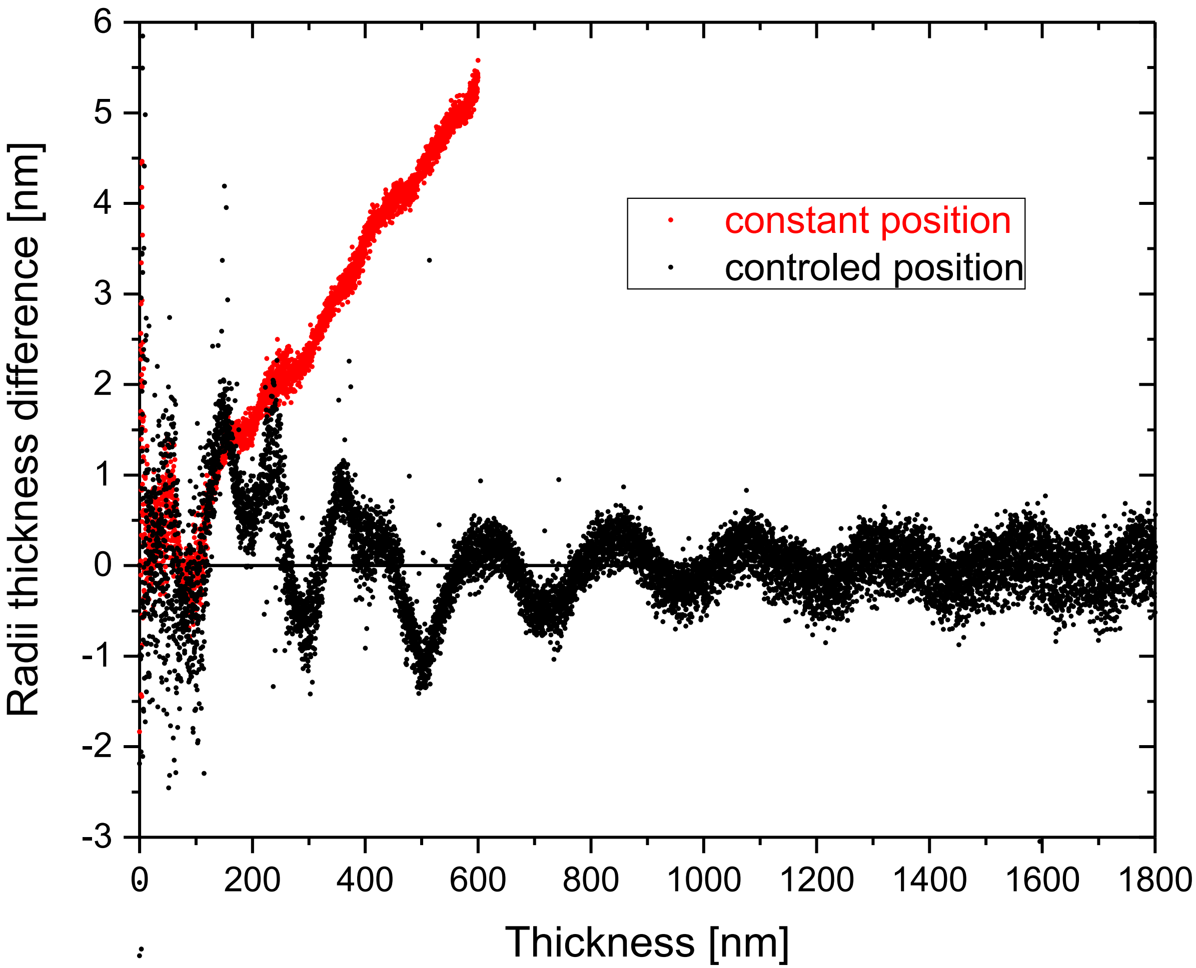


Start position for following first control experiment

- Algorithm automatically finds vertical position where coating rate difference vanishes
- For different materials this position is differing
- If process conditions are getting disturbed, control-loop is able to readjust

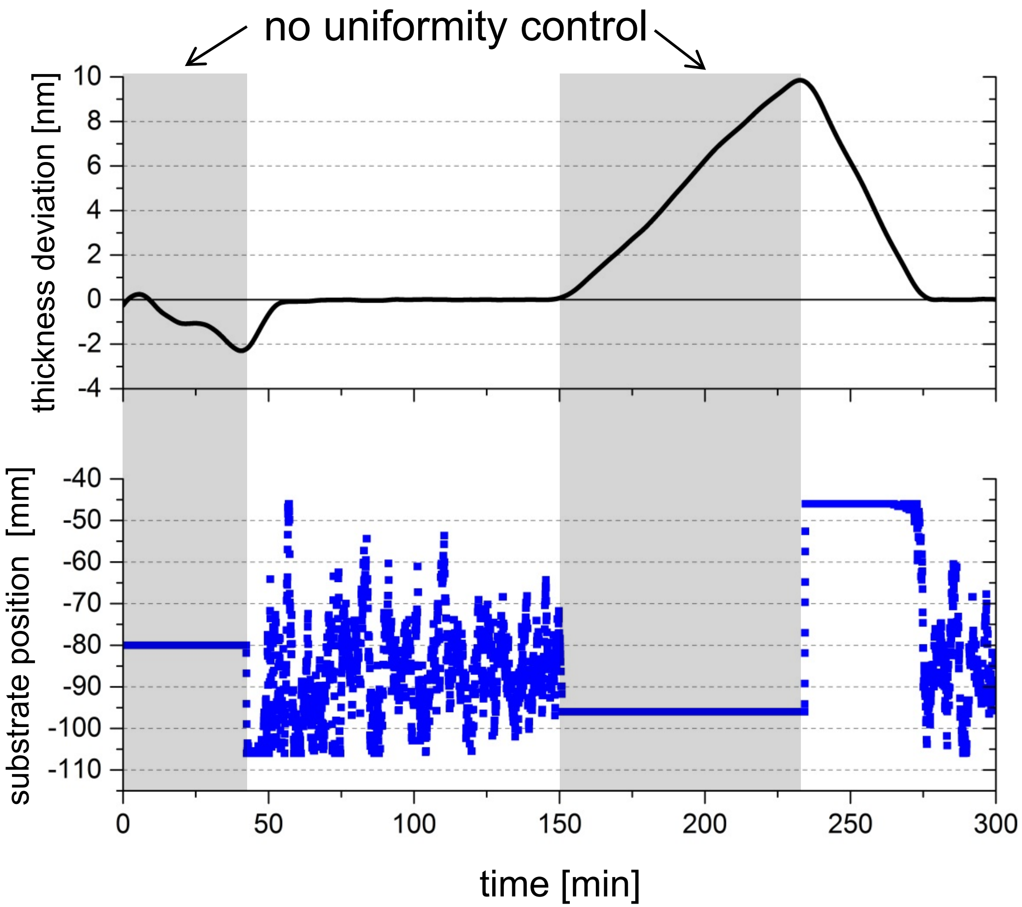


BBM UNIFORMITY CONTROL



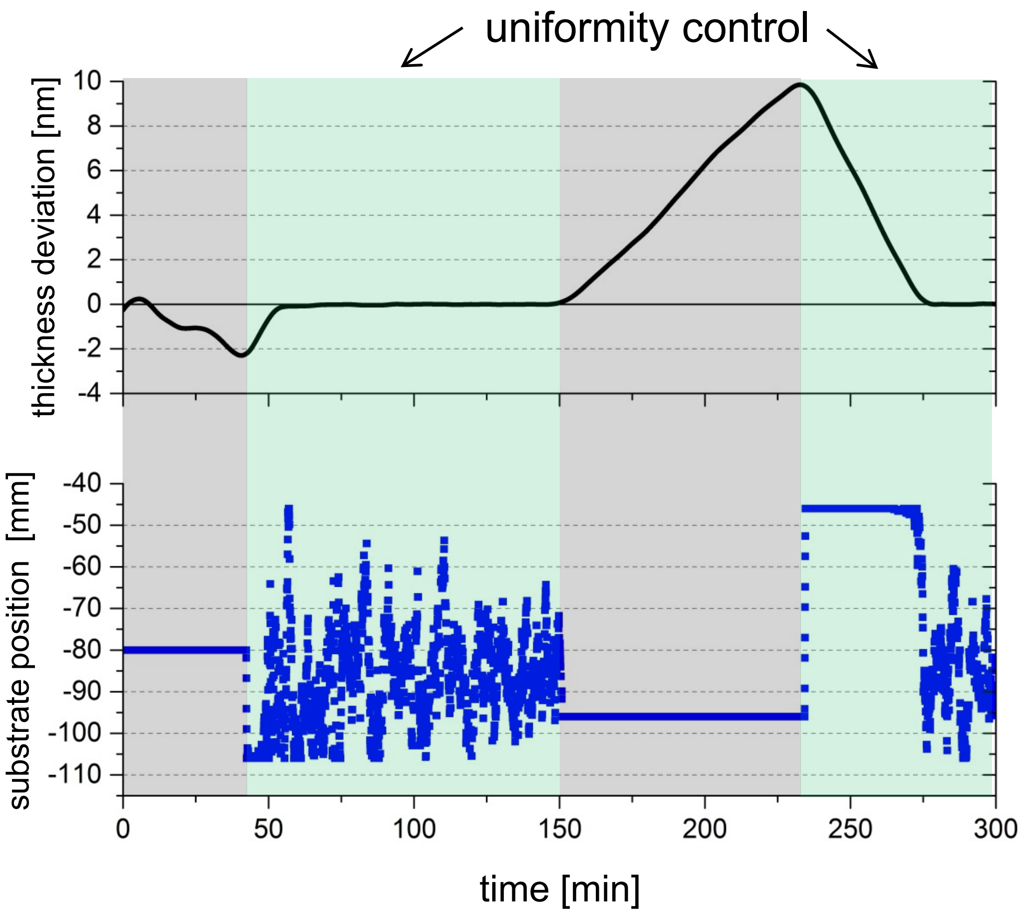
- First uniformity control attempt
- Ta_2O_5 single layer
- Coatings start at same substrate holder z-position (-20mm)
- Good uniformity around ±0.5nm with control
- Transient oscillations → control parameters still need to be optimized → controlling too late and too hard

BBM UNIFORMITY CONTROL



- Ta_2O_5 single layer
- Coating starts at inhomogeneous position (-80mm)
- Uniformity control activated after 45 min
- Uniformity control deactivated after 150 min
  → thickness deviation increases
- Reactivated at 10nm thickness deviation
  → Uniformity control compensates deviation

BBM UNIFORMITY CONTROL



- Ta_2O_5 single layer
- Uniformity control compensated thickness deviation automatically
- Uniformity control stabilizes homogeneity

Federal Ministry of Education and Research

BMBF funded research grant Pluto+ 13N13215

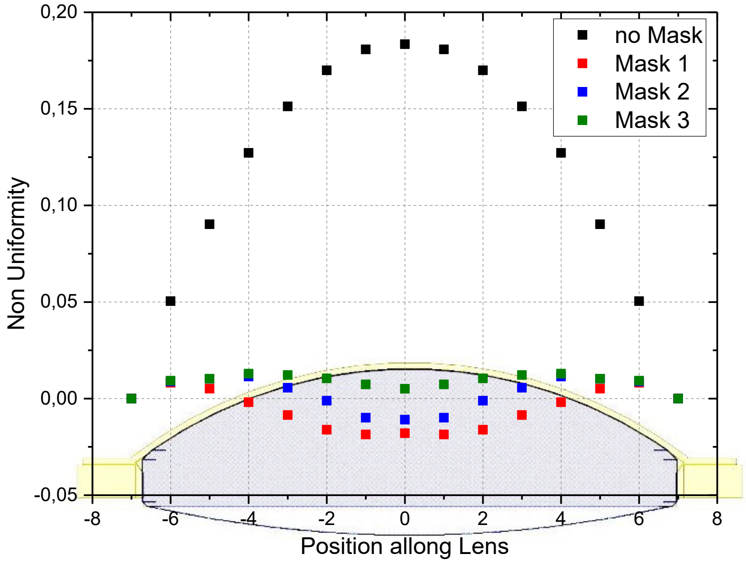
UNIFORMITY CONTROL

Task

- Establish shadow mask for individual surface
- Verify uniformity
- Process witnesses

Solution

- Dedicated jig for each surface
- Allows use of flat witness samples
  - Easy measurement of T and R
  - Readily available samples
  - Witnesses at different locations
  - Process can be checked any time without need for a lens substrate (risk mitigation, process conformity)



IN-SITU → EX-SITU

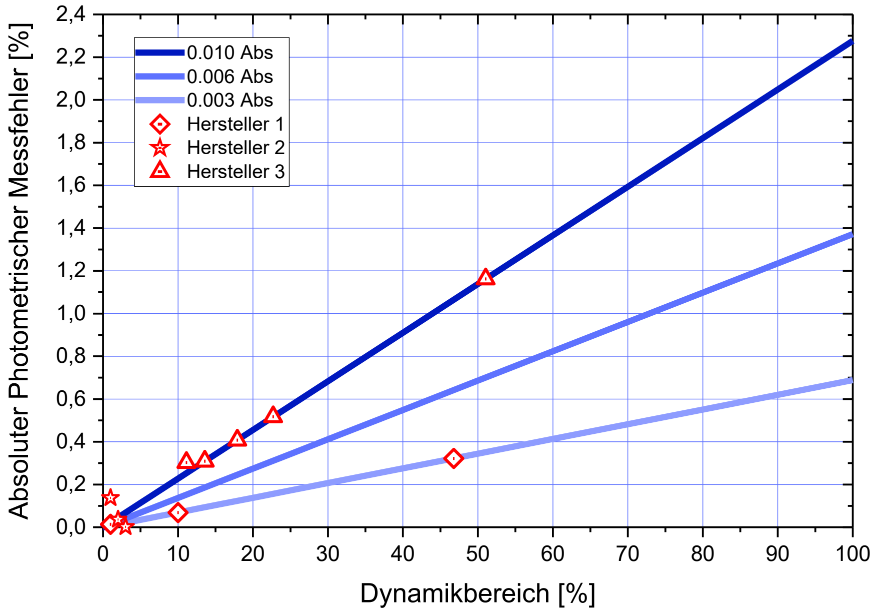
- Accuracy

Below 10^{-3} →ex-situ

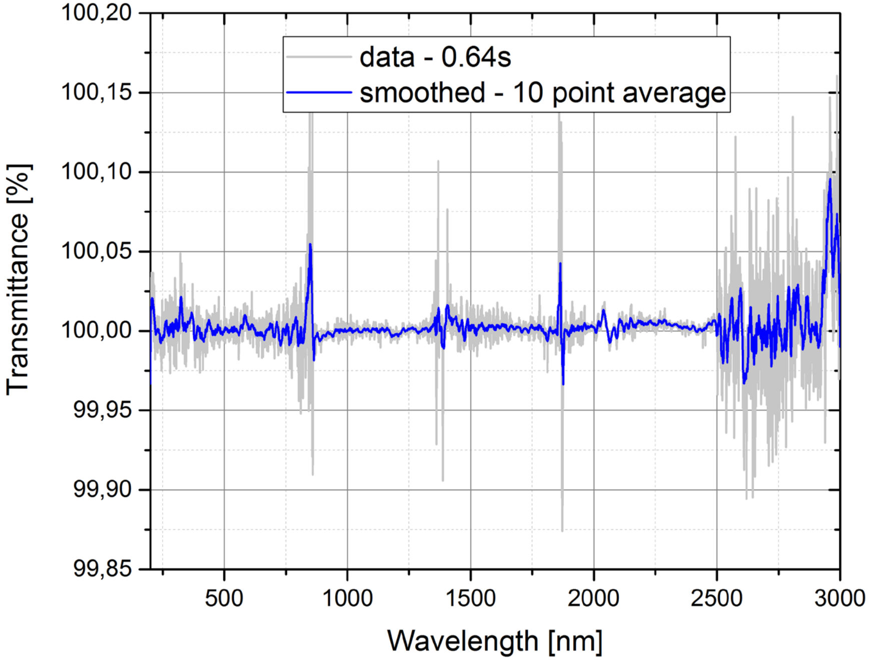
- Specification at AOI > 0°
- Polarized light
- Both
- Losses
  - Absorption - heat, thermal expansion, …
  - Scattering - imaging, surface control, ..
  - Highly precise reflection - laser…

Current Limits:

- Measurement Problem at OSA Optical Interference Coatings topical Meeting
  - Limits of commercial test instruments



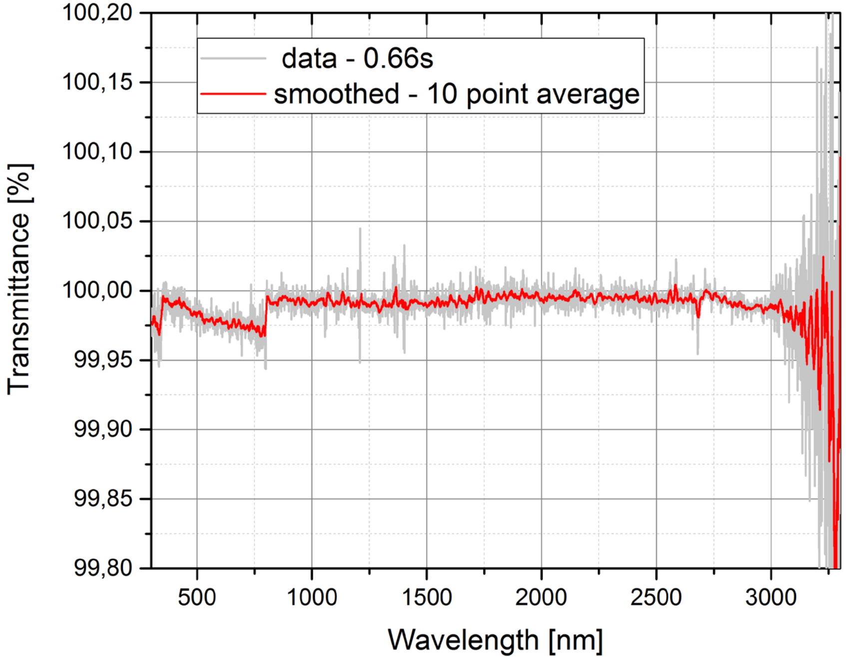
ACCURACIES UV-VIS-NIR - DEVICE 1



UV-VIS-NIR Single detector

- 200nm – 860nm
  - SD: 0.018%
  - SD smoothed:0.008%
- 860nm – 2500nm
  - SD: 0.011%
  - SD smoothed:0.004%
- 2500nm – 3300nm
  - SD: 0.040%
  - SD smoothed:0.024%

ACCURACIES UV-VIS-NIR - DEVICE 2

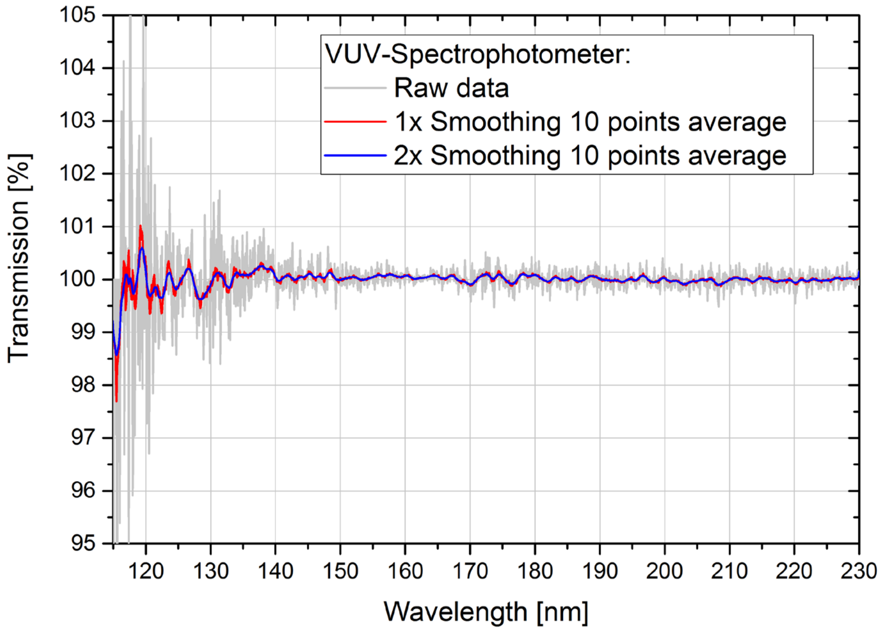


UV-VIS-NIR Single detector – Device 2

- 200nm – 860nm
  - SD : 0.011%
  - SD smoothed : 0.007%
- 860nm – 2500nm
  - SD : 0.007%
  - SD smoothed : 0.003%
- 2500nm – 3300nm
  - SD : 0.060%
  - SD smoothed : 0.031%

- Slight offset of average value: 0.02%

ACCURACIES VUV



VUV:

- 130nm-230nm:
  - SD: 0.24%
  - SD smoothed: 0.06%
- 115nm-230nm:
  - SD: 0.91%
  - SD smoothed: 0.20%

EXPECTED DIFFICULTIES

Measuring real sample:

- Sample thickness
- Measurements at AOI ≠ 0
  - Beam displacement
  - Detector size
- Jumps in T/R data at detector changes

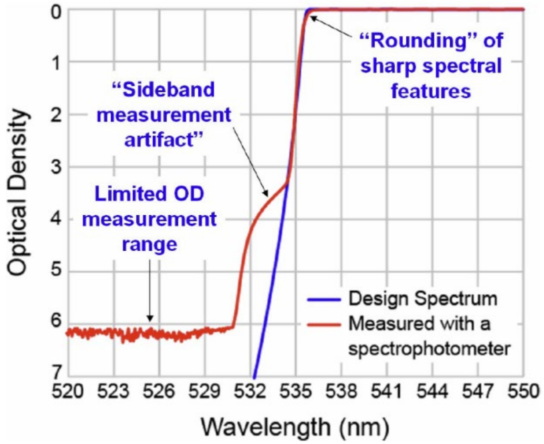
Solutions:

- Possibly: integrating spheres

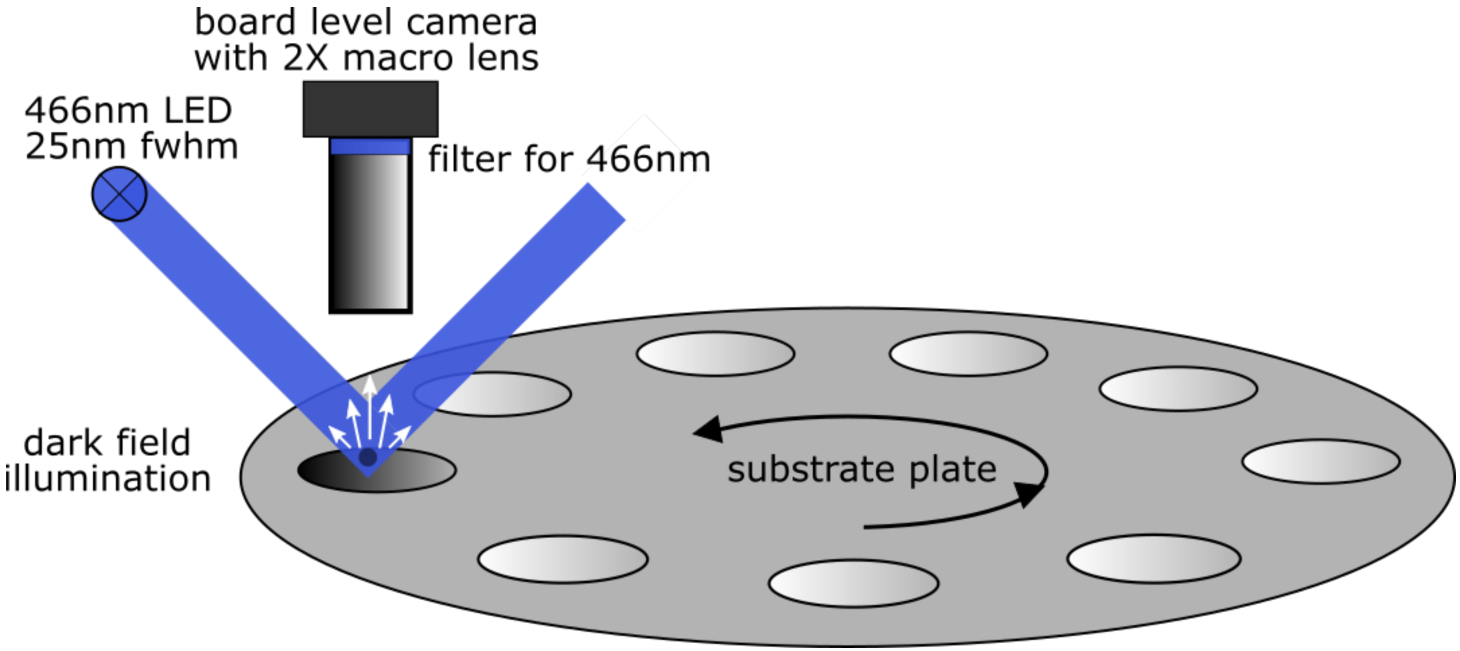
General Difficulties with a lamp/monochromator based R&T measurement:

- Low light power vs. high resolution
- Beam divergence
- Limits in Bandwidth
- Pinholes

https://www.semrock.com/measurement-of-optical-filter-spectra.aspx



IN-SITU PARTICLE DETECTION



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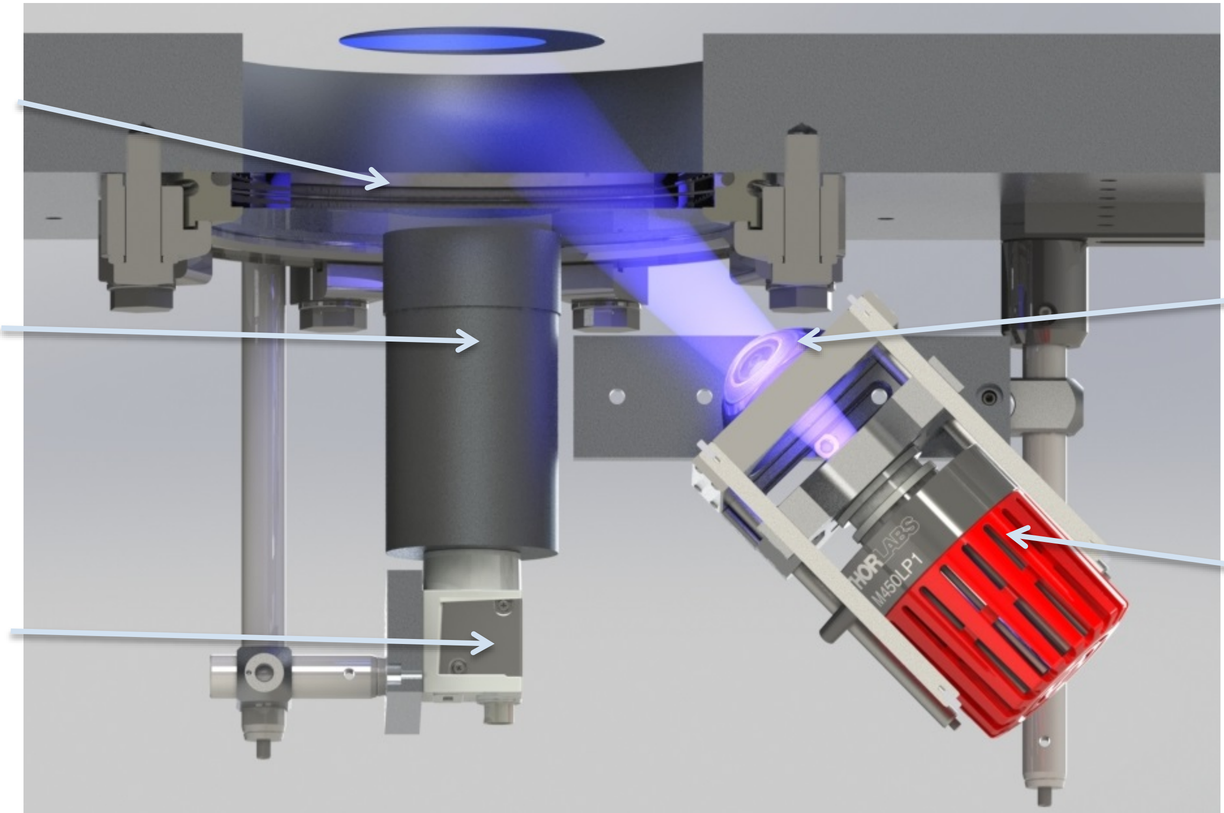
IN-SITU PARTICLE DETECTORS: DEMONSTRATOR 1 (MAGNETRON SPUTTERING)

- Magnetron sputter system EOSS at Fraunhofer IST: chamber geometry allows for short working distance and detection from atmosphere side



viewport

camera lens for working distances of a few cm

10MP b/w camera

collimation lens

455nm high power LED

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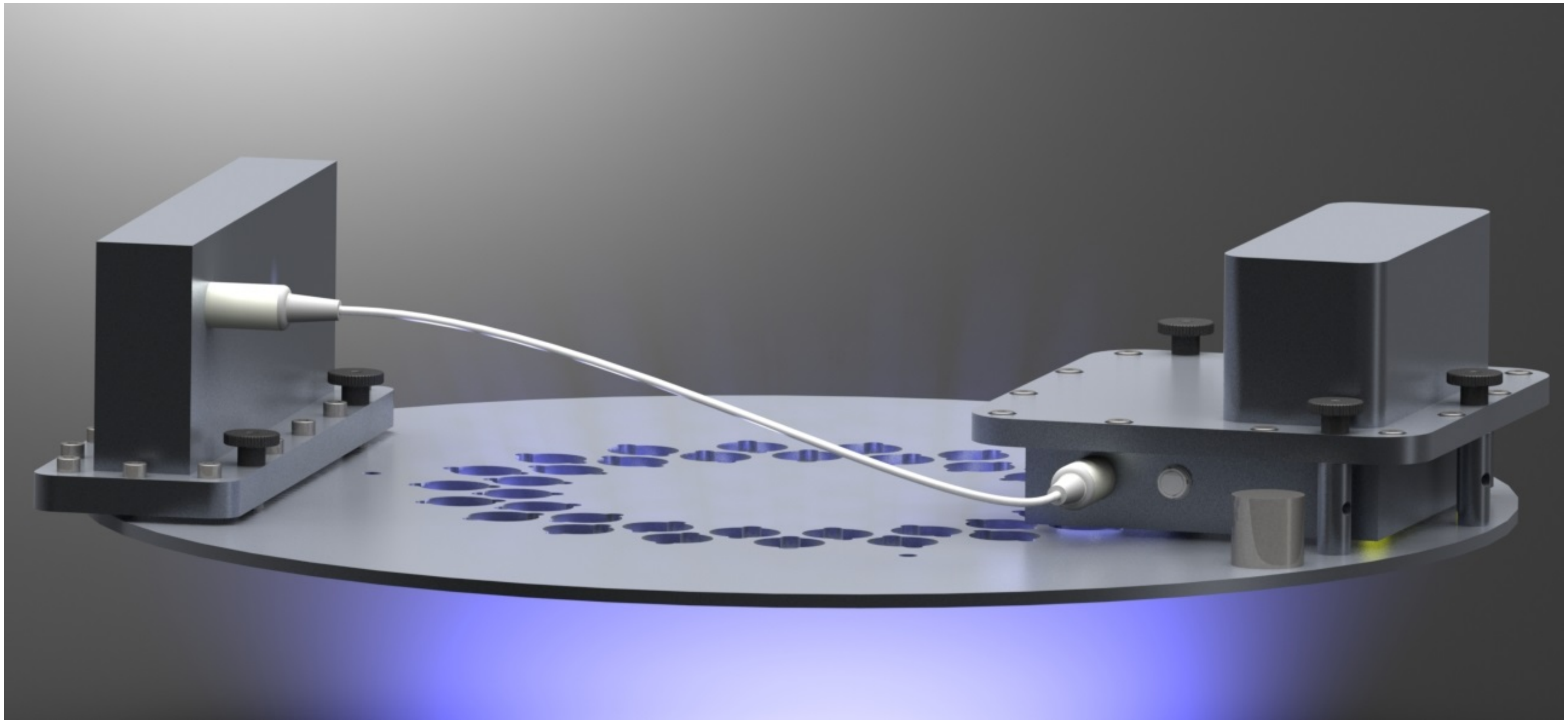
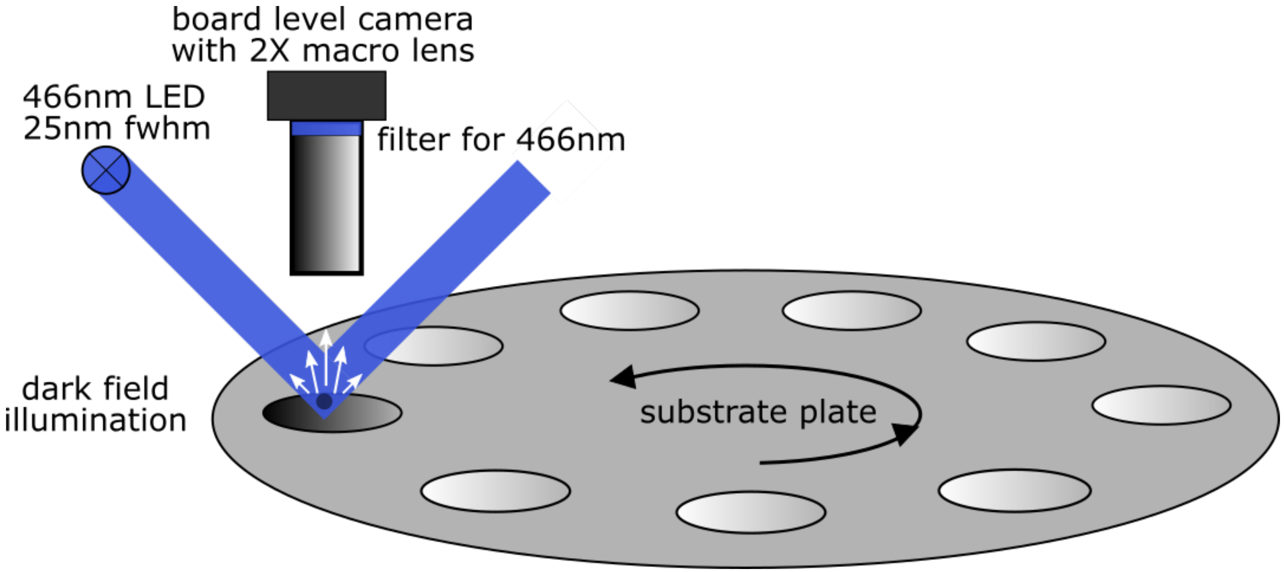
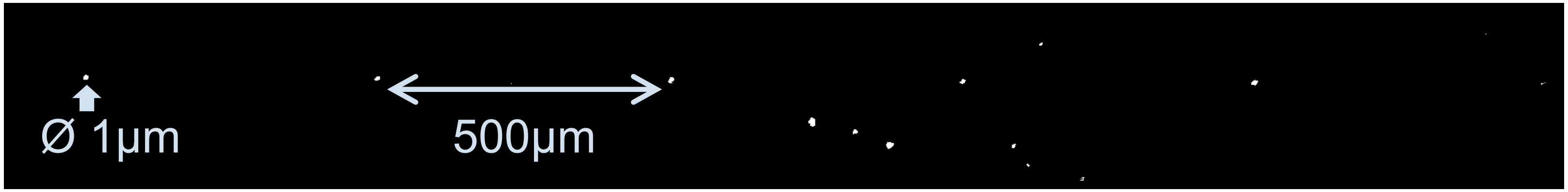
IN-SITU PARTICLE DETECTORS: DEMONSTRATOR 2 (ION BEAM SPUTTERING)



IN-SITU PARTICLE DETECTION





- 1µm diameter on defect reference sample can be detected in-situ

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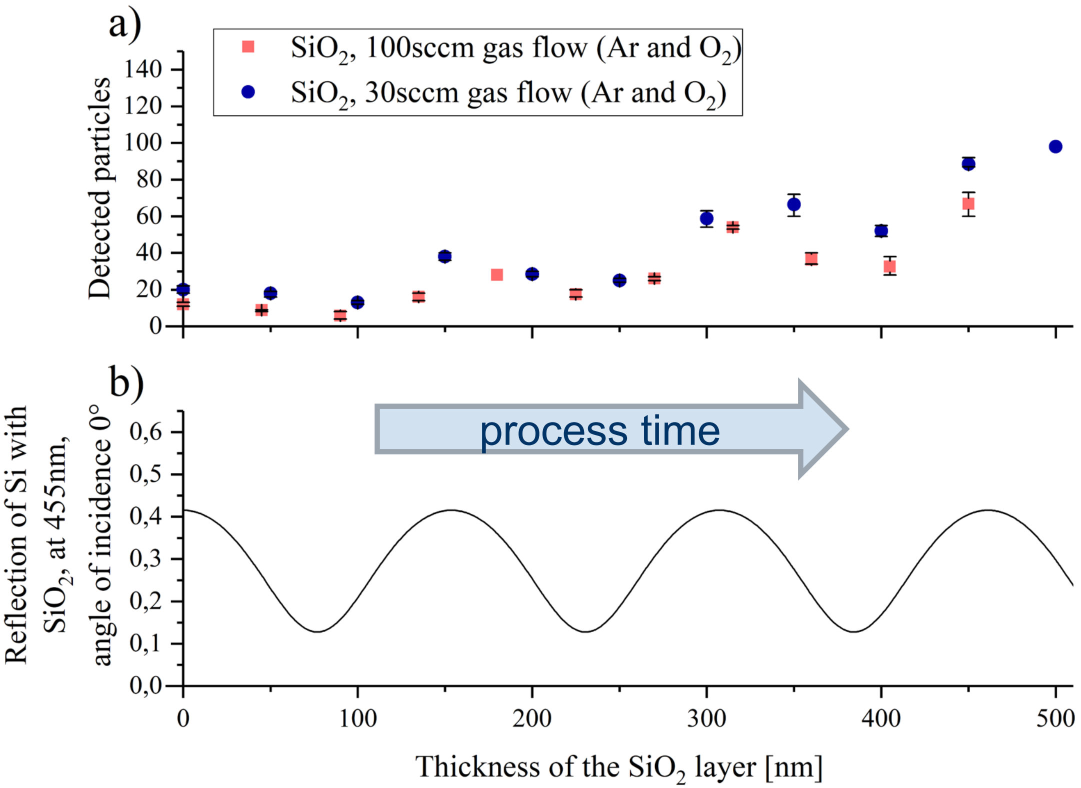
IN-SITU PARTICLE COUNTING (MAGNETRON SPUTTERING): DETECTED PARTICLES (fig. a) ↔ REFLECTION (fig. b)



- **2 coating runs SiO2 (single layer) on silicon substrates**
  - Normal gas flow (30sccm)
  - Tripled gas flow
- **Increase** and **oscillation** in **particle count** with increasing physical layer thickness
- Maximum detection at maximum reflection @ detection wavelength
  - Brightness of particles enhanced by thin film → Exceeding software detection threshold

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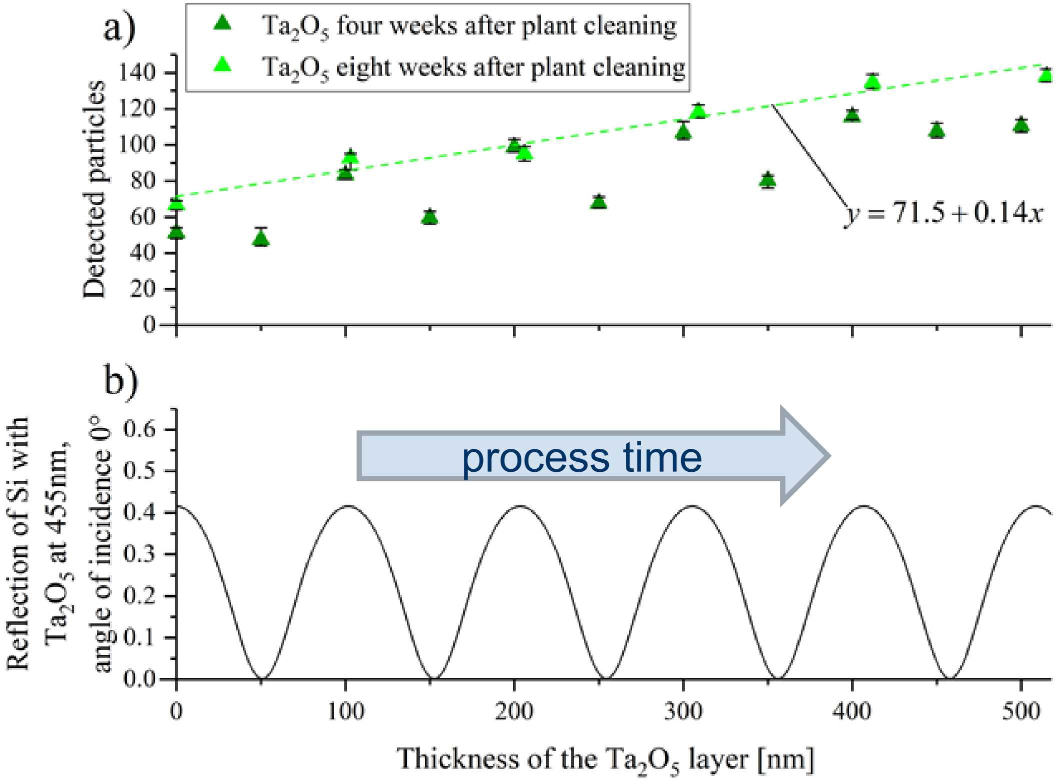
IN-SITU PARTICLE COUNTING (MAGNETRON SPUTTERING): LINEAR INCREASE



- **2 coating runs Ta_2O_5 (single layer) on silicon substrates**
  - Identical process
  - 4 weeks / 8 weeks after cleaning
- Oscillation in particle count with reflection of thin film @ detection wavelength
- **Linear increase** in particle count

A.K. Rüsseler, I. Balasa, H.-U. Kricheldorf, M. Vergöhl, L. Jensen, D. Ristau, "Time resolved detection of particles during thin film deposition", Proc. SPIE 10691, 106910H (2018)

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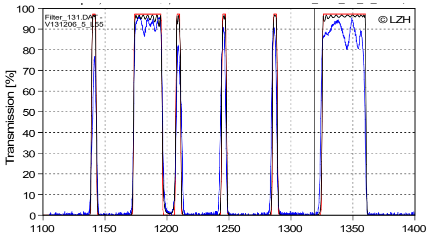
QUALIFICATION VS MITIGATION

	in-situ	**ex-situ**
Spectral reflection/transmission	process control	high accuracy
Uniformity non-flat surfaces	prepare conditions for ex-situ control	actual measurement
Film defects	identification of defect origin	highly sensitive detection

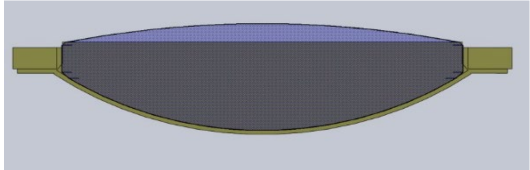
SUMMARY

Applications define strategy for quality control

- Stable process → quality control
- Need for online process control
- Specific non standard test parameters → ex-situ (angle, polarization, …)



- Thin film uniformity – controlable on plane substrates
- Complex coating geometry – measureable only ex-situ



- Need to analysis of process steps & sequence → e.g. defects
- Calibrated defect qualification → ex-situ inspection

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- Henrik Ehlers
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