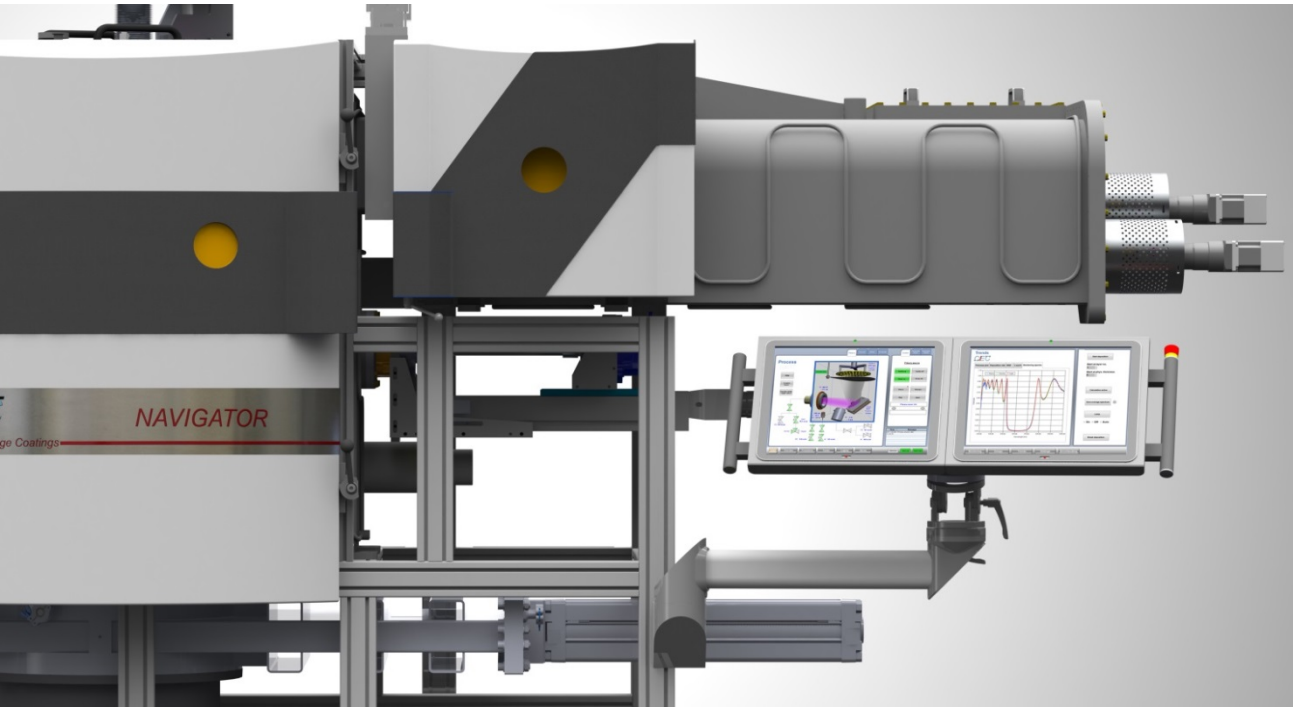
CEC

Cutting Edge Coatings



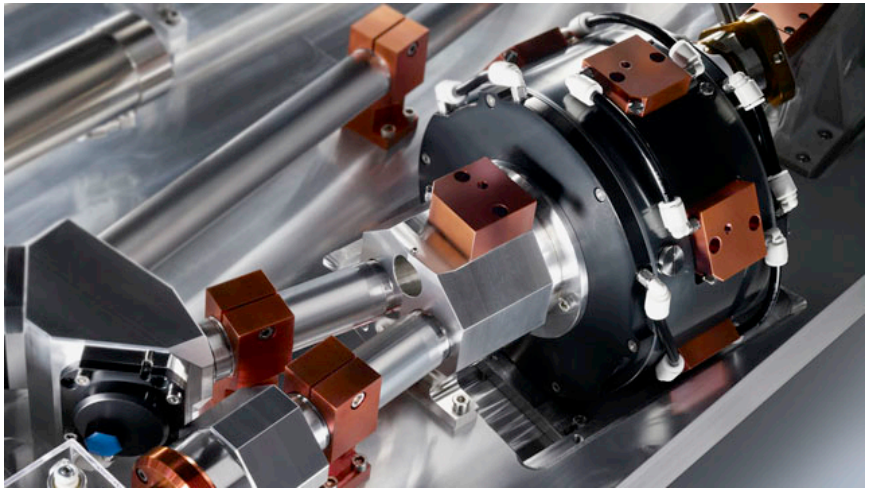
Ion Beam Sputtering - Current challenges in ultimate performance optical coatings

Dr. Kai Starke, Dr. Benjamin Lotz, Wjatscheslaw Sakiew, Stefan Schrameyer

Motivation

Cutting Edge Coatings

Industrial Applications

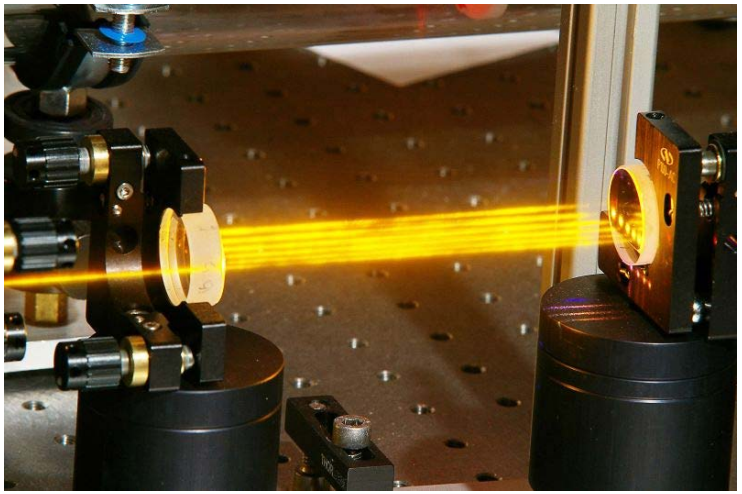


Optical System TruDisk disk laser.

www.de.trumpf.com/produkte/lasertechnik/produkte/festkoerperlaser/scheibenlaser.html

- **Highest Reflectivity**
- **Ultra-low optical losses**
- **Low particle contamination**

Fundamental Research



5 bounces of awhite-light contiuum , compressed to a few-cycle laser pulse

www.mbi-berlin.de

- **High environmental stability and laser resistance**
- **Exact spectral characteristics**

Deposition Processes

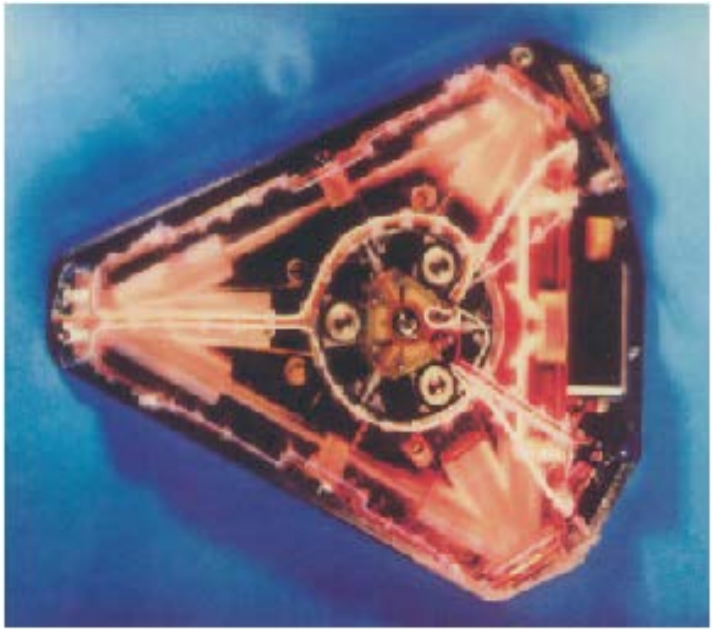
Quality parameter	e-beam	IAD	MS	IBS
Absorption [ppm]	< 10	< 10	1-2	**< 1**
Total scattering [ppm]	< 100		< 10	**< 1**
T-stability typ. [ppm/°C]	- 100	**< 10**	**< 20**	**< 10**
Stress [MPa]	< 400	**(-) 100 – 200**	(-) 200 – 400	(-) 800
Defect density [1/cm^2]	< 100			**< 1**
Substrate temperature [°C]	< 250	**50-100**	**< 50**	**< 50**
Rate [nm/s]	**1 - 10**	**1 - 10**	0.5	0.3 -0.4
Area [cm^2]	**15,000**	**15,000**	1,900	1,300
Productivity [nm cm^2/s]	**>10,000**	**7,500**	2,000	200

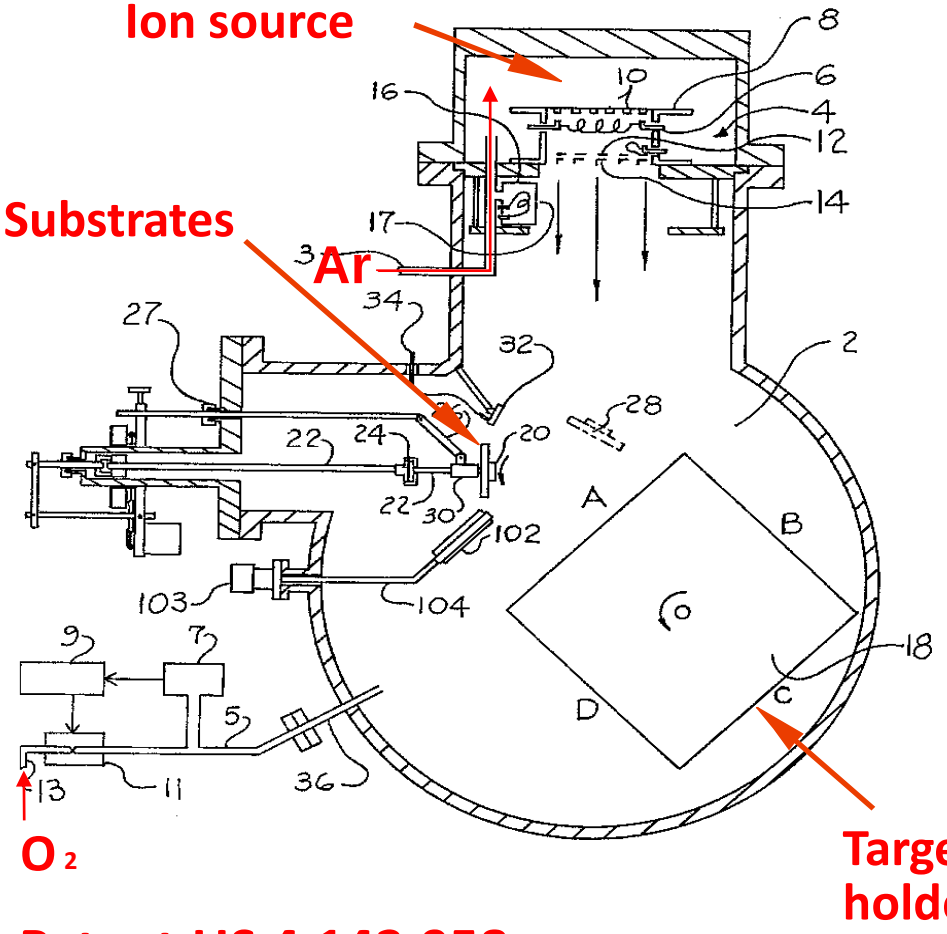
Estimated quality parameters for Nd:YAG-laser mirrors (HR 1.064 µm)
From: D. Ristau, Laser Zentrum Hannover e.V.

IBS: History

Low-loss Mirrors for gyroscopic ring lasers

- withstand HeNe-plasma
- backscattering <20ppm

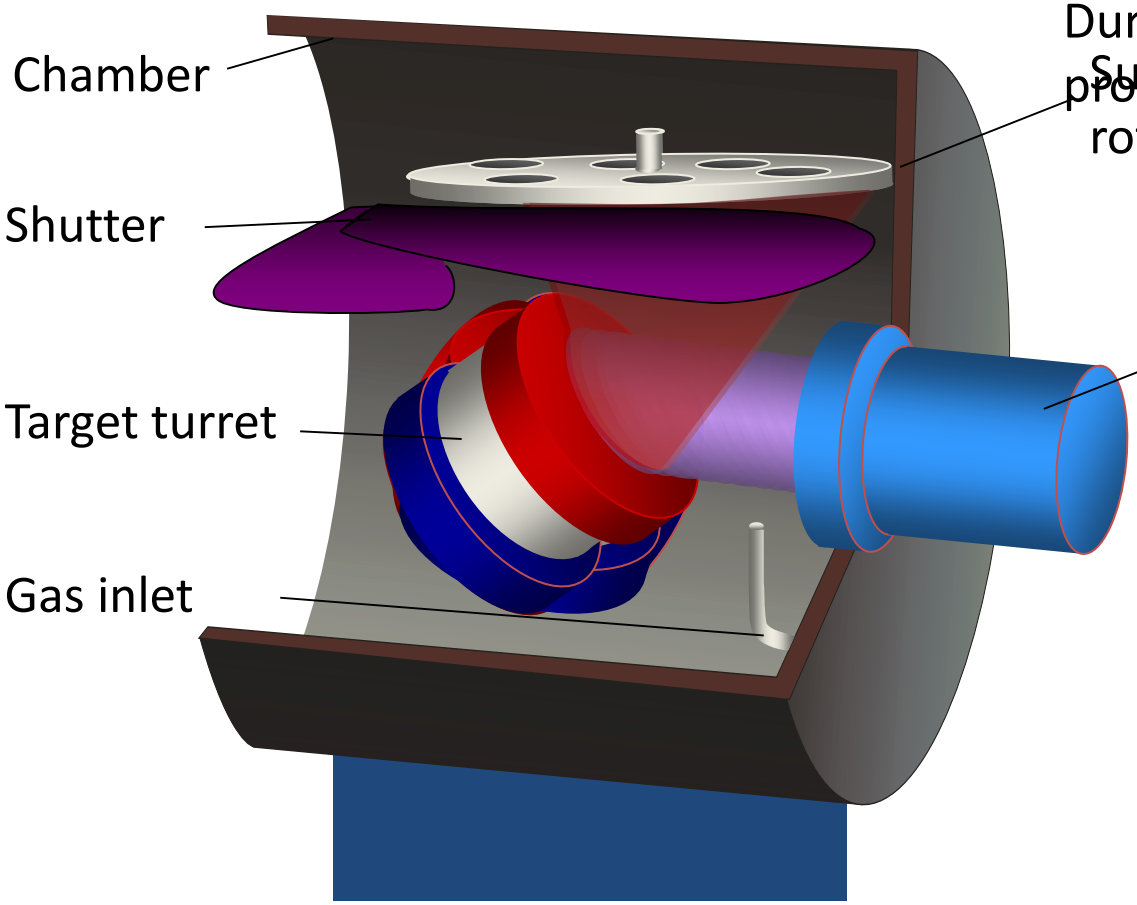




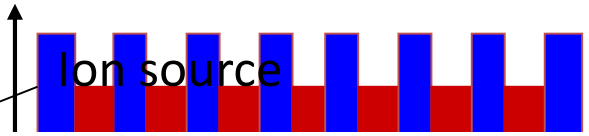
Patent US 4,142,958

1978 Litton D.T. Wei, A.W. Louderback

IBS Deposition Process



During material change, coating process is shortly interrupted



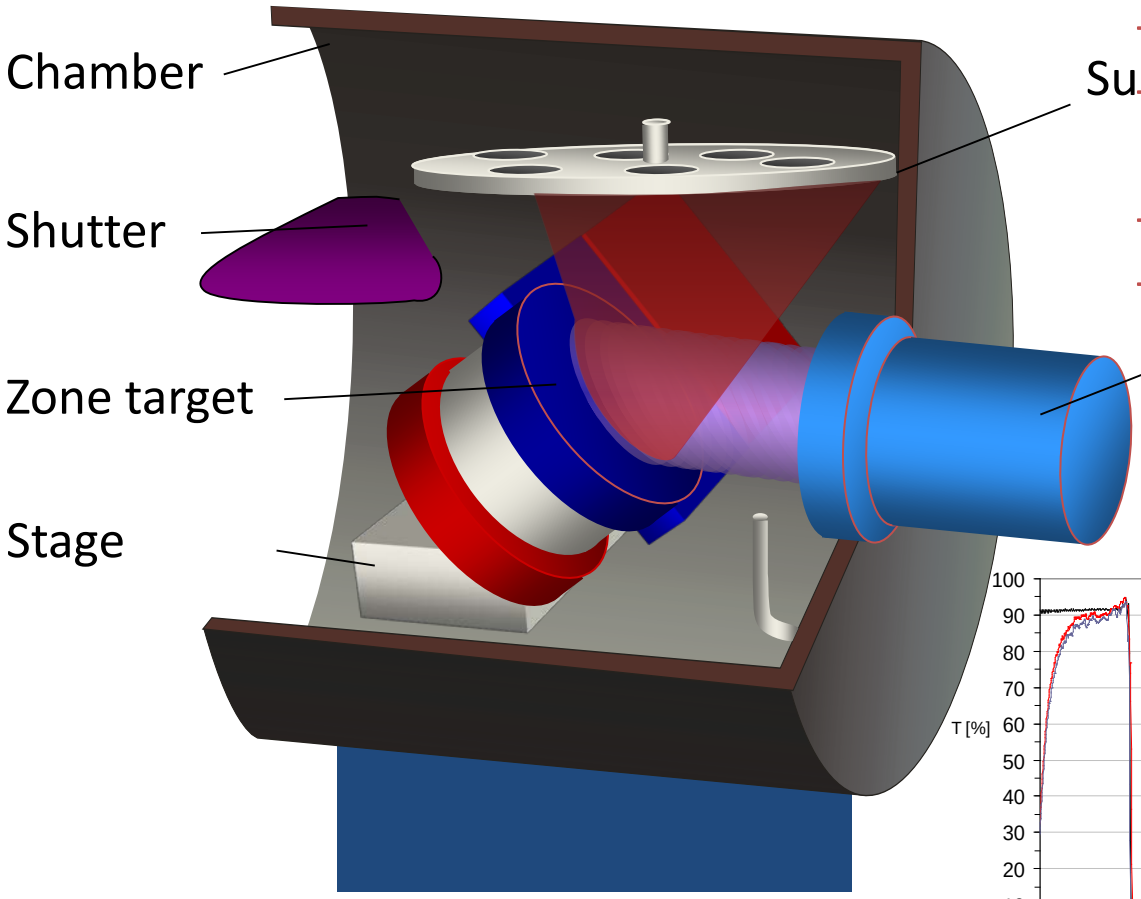
- **Ion source:**
  rf-pumped, filamentless
  Ion energy 1000-2000eV

- **Targets:**
  Metallic/oxide materials
  e.g. **Silizium**/**Titan**,
  Reactive gas for amorphous oxides

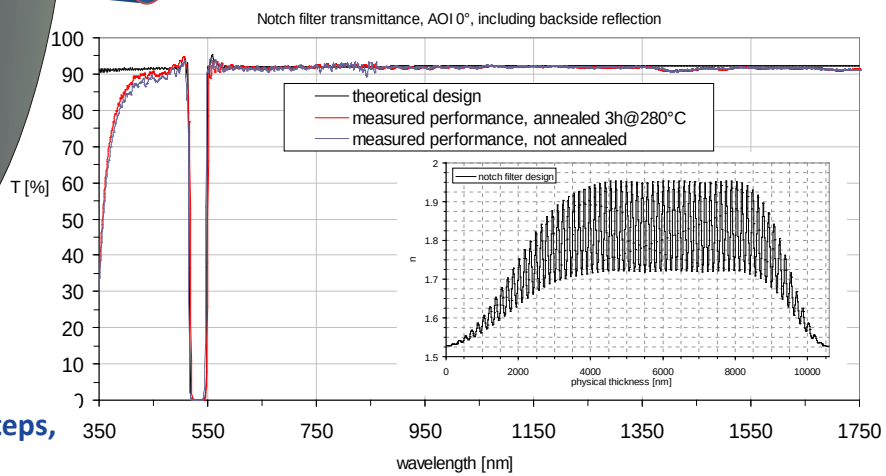
IBS Process with Zone Target

LASER ZENTRUM HANNOVER e.V.

Cutting Edge Coatings

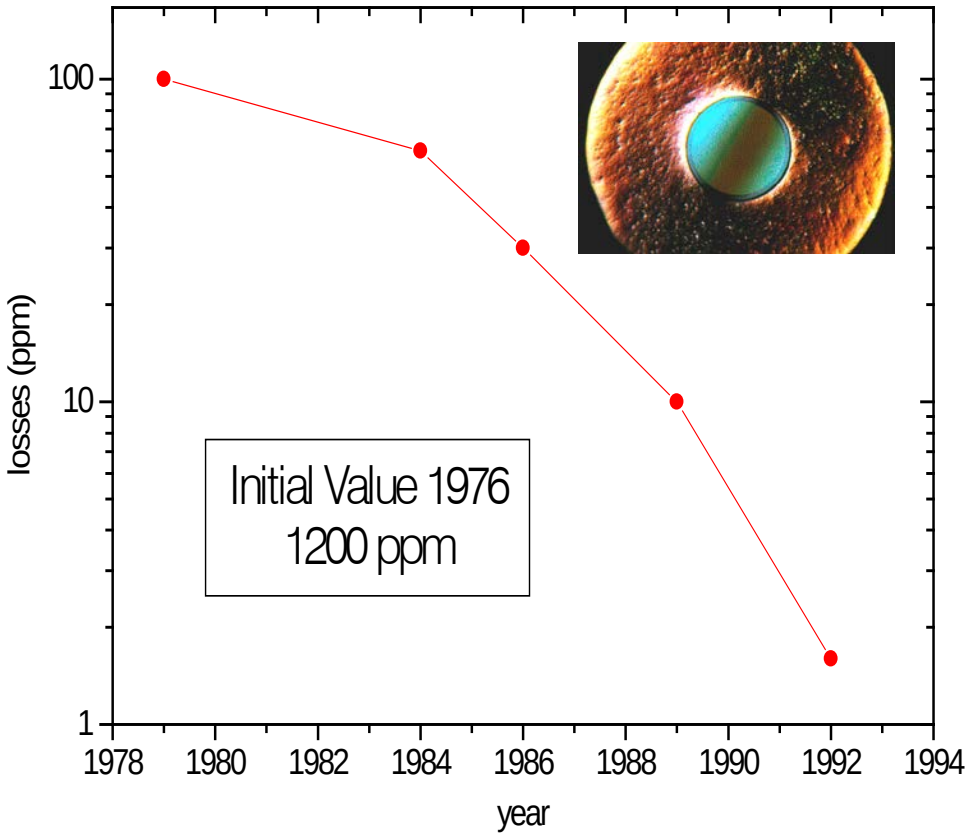


- Coating w/o interruptions!
- Intermediate refractive indices by material blending
- Intermixing on atomar basis
- Coating of complex gradient index coatings (Rugate)



761 layers, 372 index steps, total thickness 10,6µm

Low-Loss Mirrors



„Learning curve“ for total losses (λ=1.064nm)

Standard losses NAVIGATOR

HR mirror, AOI 45° s-pol
Proven with CRD measurements

- T+A+S < 20 ppm @ 633nm
- T+A+S < 10 ppm @ 1030nm

On Substrates with RMS Roughness < 1 Ang (G&H)

Low-Loss Mirrors

Cutting Edge Coatings

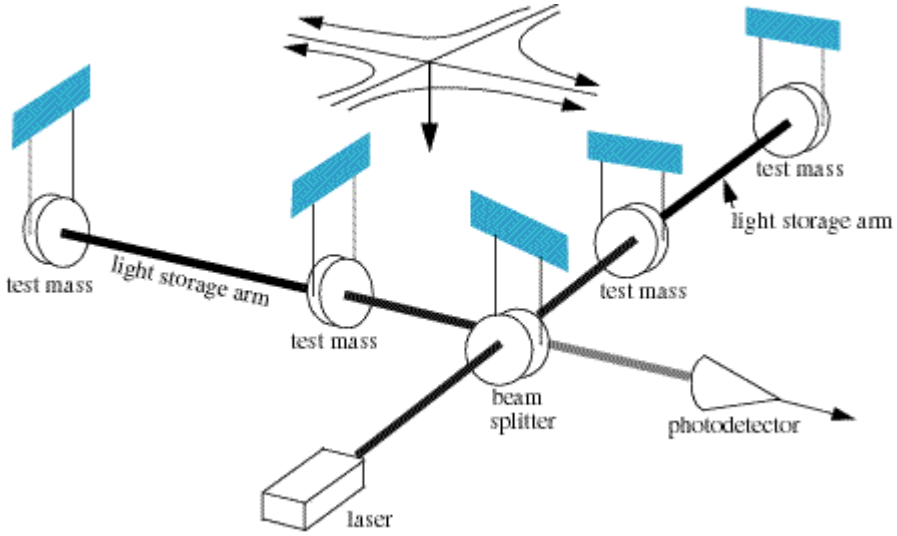
Low-loss mirrors for gravitational wave detectors (Michelson-interferometer):

Ta_2O_5-TiO_2 /SiO_2 for dielectric coatings on test masses and other optics

Optical & mechanical losses (heat dissipation, brownian movement)

Total losses during round-trip in LIGO-cavity (4km arm length) < 80ppm[1]

aus: Physicsworld.com



aus: ligo.caltech.edu

[1]: Michel, C. et al. "Realization of low-loss mirrors with sub-nanometer flatness for future gravitational wave detectors" *Proc. SPIE* 8550, Optical Systems Design 2012, 85501P (December 18, 2012); doi:10.1117/12.981766

[2]: Harry, G.M. "Advanced LIGO: the next generation of gravitational wave detectors" Class. Quantum Grav. **27** (2010) 084006; doi:10.1088/0264-9381/27/8/084006

Low-Loss Mirrors

Cutting Edge Coatings

Laboratoire des Matériaux Avancés, Lyon, France

IBS-deposition system in ISO 3 clean room

Quality Characteristics	Losses [ppm]
Absorption, 633nm [ppm]	< 5
Absorption, 1.064nm [ppm]	< 0,6
Scattering, 633nm [ppm]	1,2 (Ø 25mm)
Scattering, 1.064nm [ppm]	4 (Ø 200mm) 0,6 (Ø 25mm)

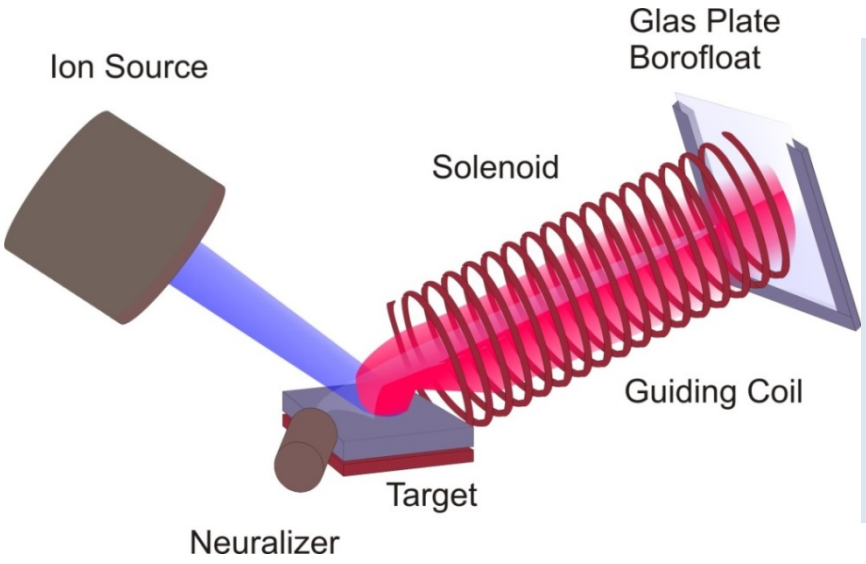
lma.in2p3.fr/Activites/loss.htm

Large size substrates >30cm diameter, 20cm thickness, 40kg weight, roughness <1,6Å rms
two substrates coated in one run [1,3]

[2]Harry, G. M. et al. "Advanced LIGO: the next generation of gravitational wave detectors" Class. Quantum Grav. 27 084006 (2010)
[3]Harry, G. M. "History of Advanced LIGO Coating Research" LIGO Magazine issue 4 March (2014)

Low-loss Coatings by Phase Separation

Combination of E and B fields for filtering sputtered molecules



Theoretical Limits:

Scattering: world record roughness: 0,18 $Å_{rms}$
TS: 4,5*10-8 ⇔ 0,045 ppm

Absorption: bulk material absorption:
$aSiO_2$<10^{-7} 1/cm, $aTiO_2$<10^{-4} 1/cm
A: 2*10^{-9} ⇔ 0,002 ppm

Total losses: approx. 0,05 ppm ⇔ R: 99,999995%

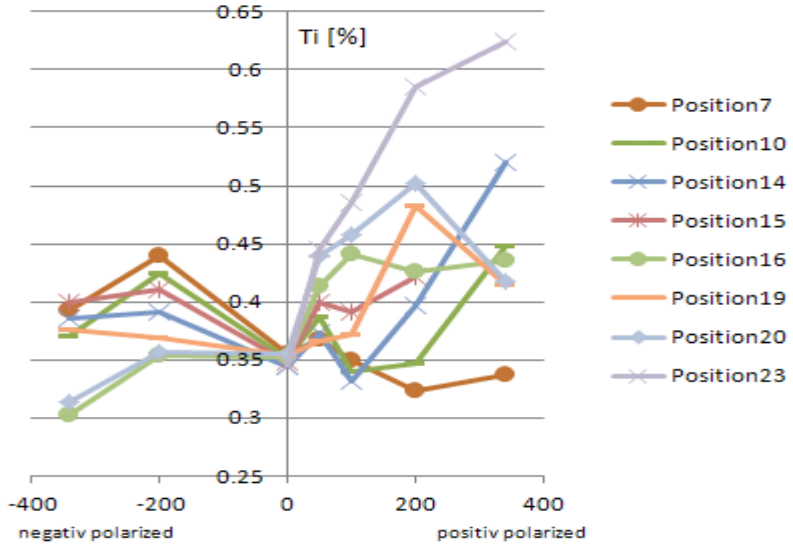
Goal: Total losses: <0.1ppm

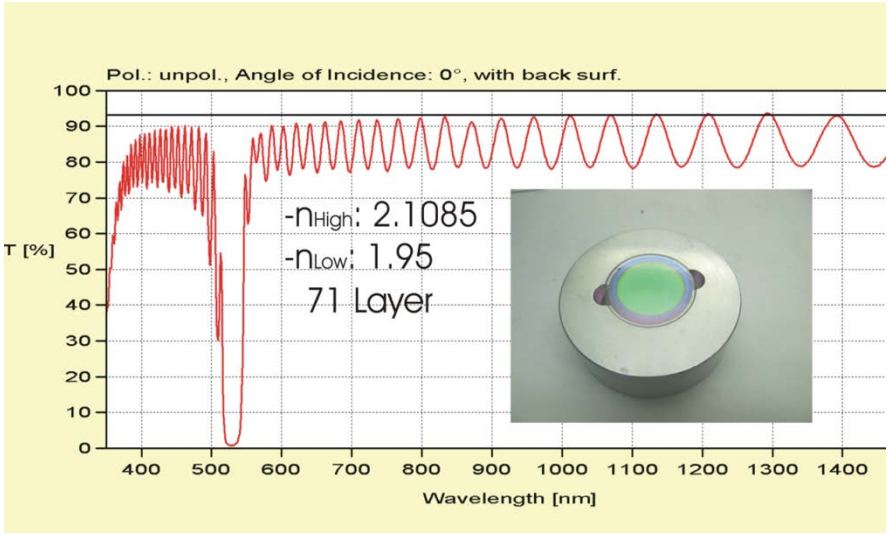
Malobabic, S. et al. “Investigations in the guiding efficiency in a modified Ion Beam Sputtering process” Appl Opt. 2013 Dec 1;52(34):

Innovative Concepts

Phase-Separator with Zone Target

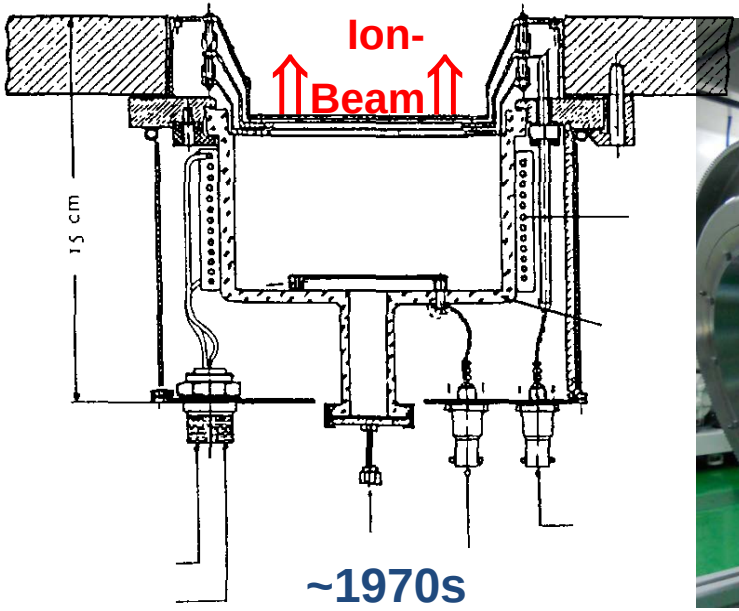
- Ionization of sputtered species
- Concentration of Ti/Al in the mixture controllable with B-field
- Material change without movement of mechanical parts
- Most simpliest variant: Reversed B-field direction





RF Ion Sources

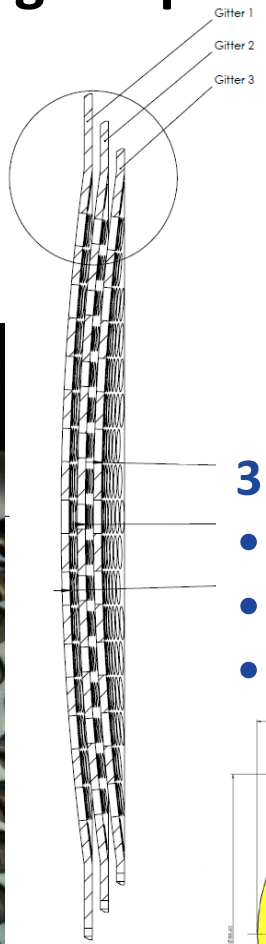
Cutting Edge Coatings

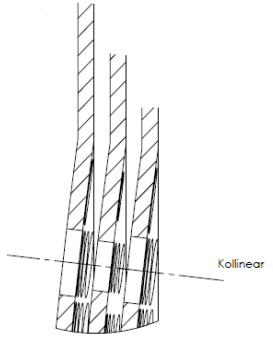


Characteristics	Specification
Plasma-Excitation	RF induktive (2 MHz), filament-less
Operating gas	Ar, Xe, O2 (seperate or as mixture)
Extraction grid system	3 Titanium grids, spherical, Ø 10-15cm pattern
Neutralization	RF Neutralizer, filament-less
Ion energy, beam current	1200-2000eV, 500 mA (>700mA im Labor)

Precise Machining of Spherical Grids

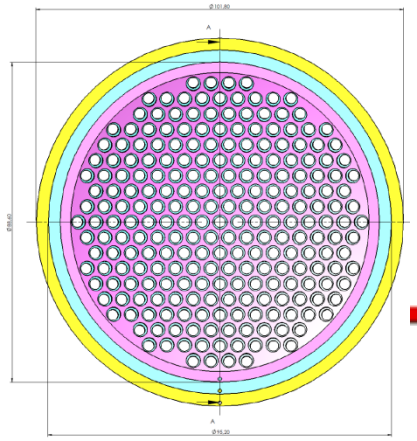
Issue: Contamination by erosion in dished grid elements (Titanium) from non-co-linearity of beam-let holes



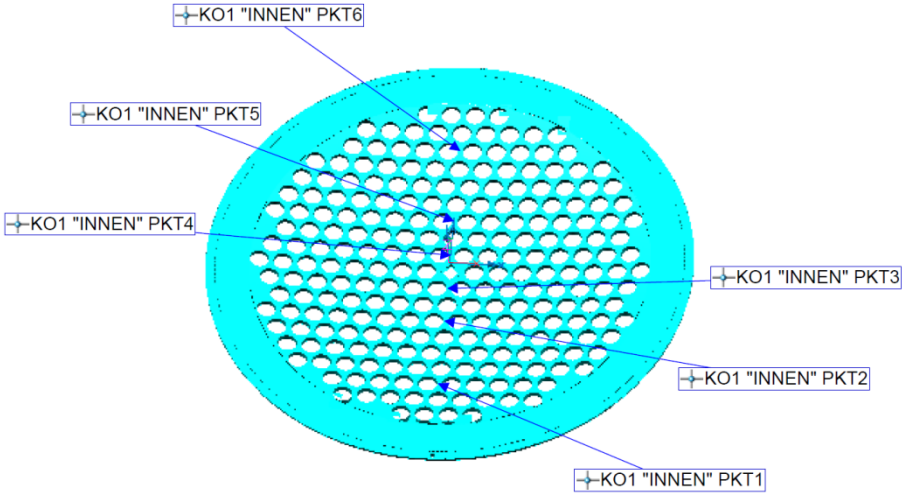


3D-CAD design of grids

- collinear hole arrangement
- uniform hole distribution
- uniform material thickness



High Precision achieved of 3D-Hole Pattern



Deviation design/measured

- location of holes
- spherical contour

less that **± 3/100 mm** for all test sites on grid element

Referenz	Sollwert	Istwert	Tol -	Tol +	Abw.	Aus. Tol.
KO1 "INNEN" PKT1 Punkt A.Fl.	Auf SOLLWERT 0.000	0.020	-0.030	0.030	0.020	
KO1 "INNEN" PKT2 Punkt A.Fl.	Auf SOLLWERT 0.000	0.013	-0.030	0.030	0.013	
KO1 "INNEN" PKT3 Punkt A.Fl.	Auf SOLLWERT 0.000	0.008	-0.030	0.030	0.008	
KO1 "INNEN" PKT4 Punkt A.Fl.	Auf SOLLWERT 0.000	0.007	-0.030	0.030	0.007	
KO1 "INNEN" PKT5 Punkt A.Fl.	Auf SOLLWERT 0.000	0.009	-0.030	0.030	0.009	
KO1 "INNEN" PKT6 Punkt A.Fl.	Auf SOLLWERT 0.000	-0.003	-0.030	0.030	-0.003	

Measuring device:

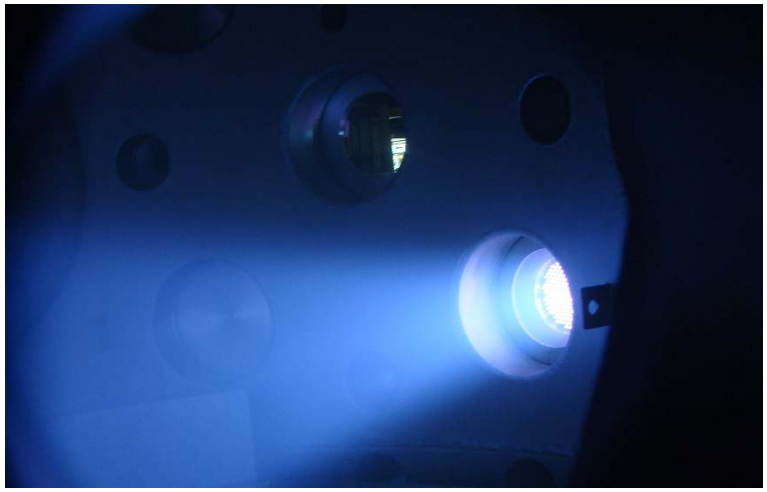
Mitutoyo 3D CNC EURO APEX 776

RF Ion Sources

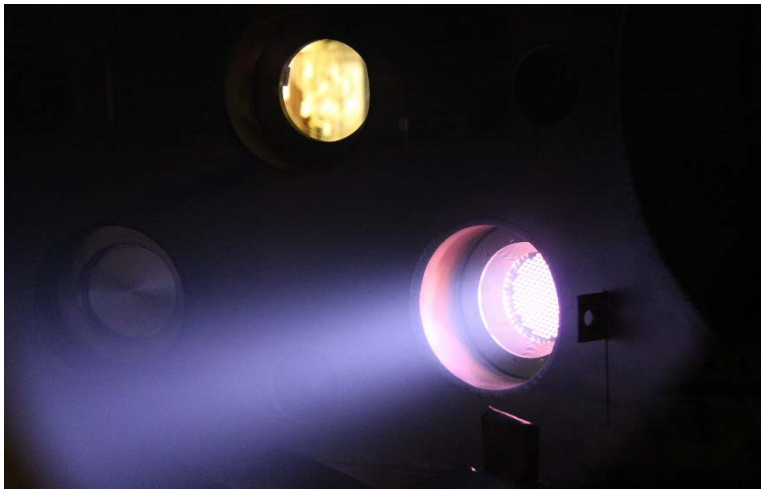
eurostars™ EUREKA

Assist Source operating in IBS system at LZH

Investigations on increase of stoichiometry, etching/chemical cleaning



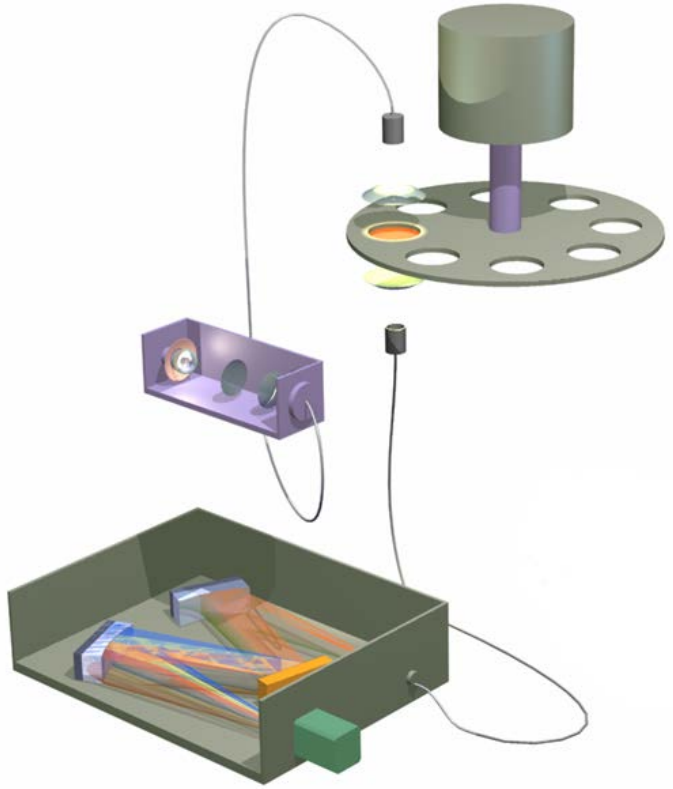
Assist Source operated with Oxygen



Assist Source operated with Argon

- **No negative impact on substrates measureable during process assistance**

Optical Monitoring



LZH-type Broadband Monitoring System

- R&D started late 90s, well-established
- Spectrum of rotating substrate
- Spectrum range > 1 octave
- DUV option: Spectra down to 230nm
- IR option: Spectra up to 1700nm
- Typical accuracy few nm
- Reoptimization / Virtual coating machine

➢ **Realization of complex designs**

➢ **Test coating runs obsolete**

➢ **Fully automated production**

Optical Monitoring

Cutting Edge Coatings

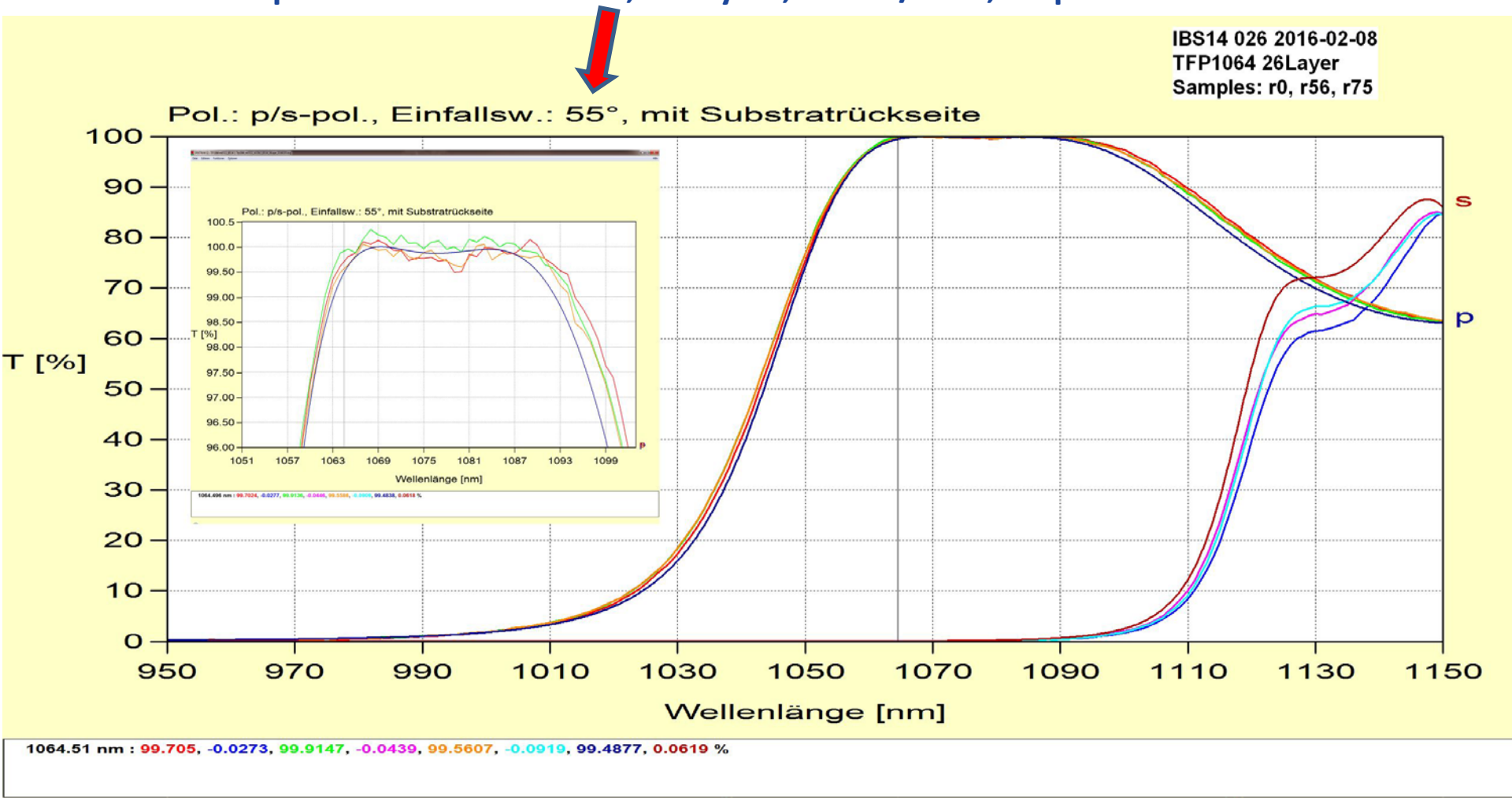
CEC's Broadband Monitoring System

- Same hardware setup
- Real-time PLC control
- Industrial interface to deposition system control
- Layer thickness / rate / ending time prediction by **Optilayer** algorithms (Opti-ReOpt)

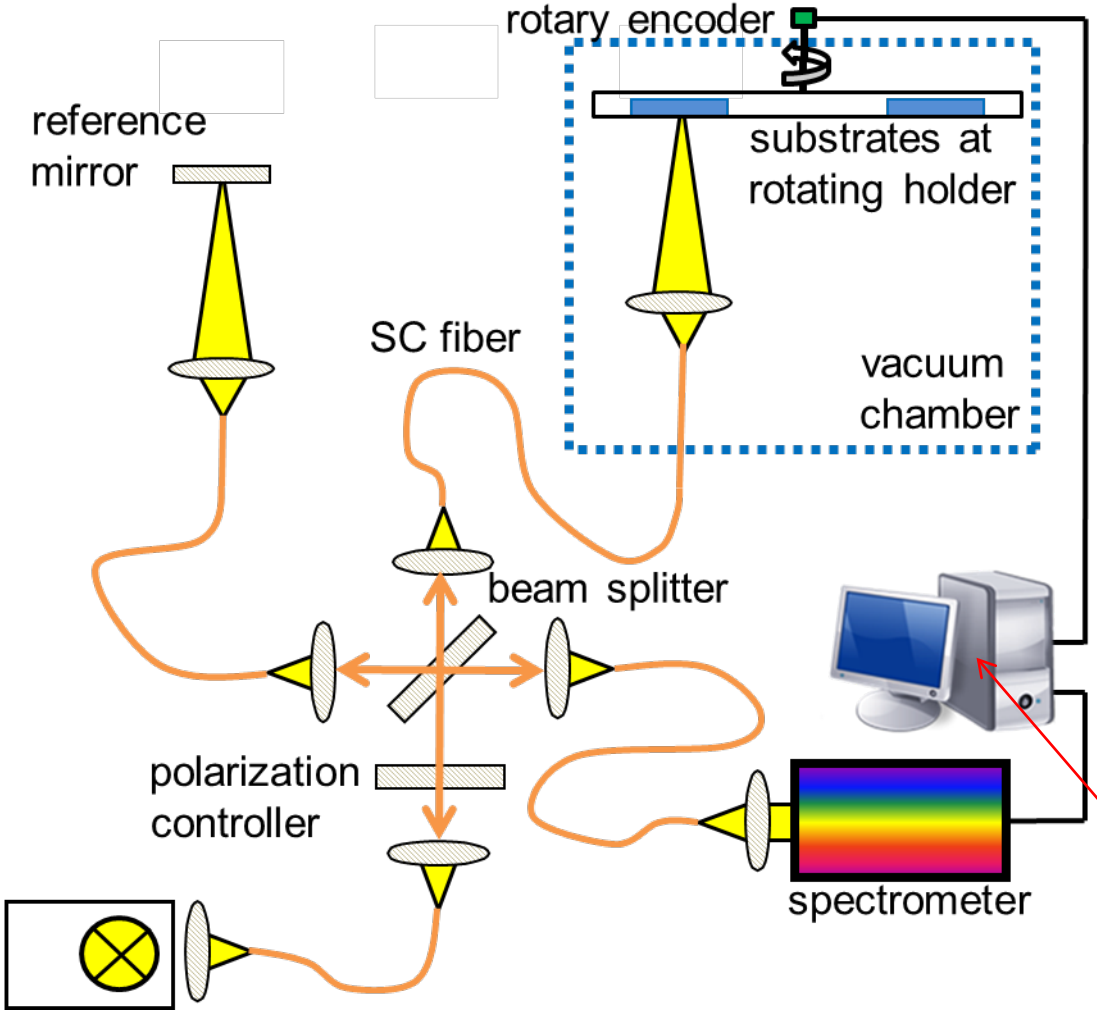
Optical Monitoring

Cutting Edge Coatings

Example: Thin Film Polarizer, 26 layers, Ta2O5/SiO2, 3.7µm total thickness



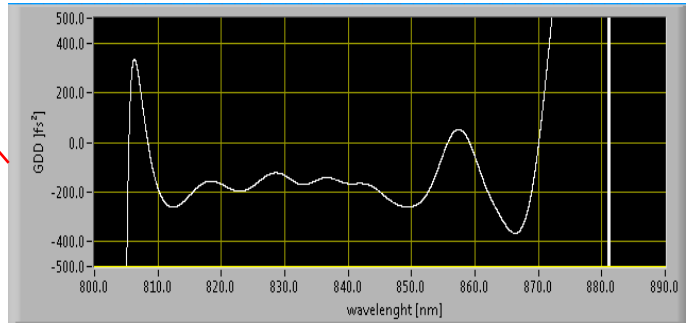
Optical Monitoring



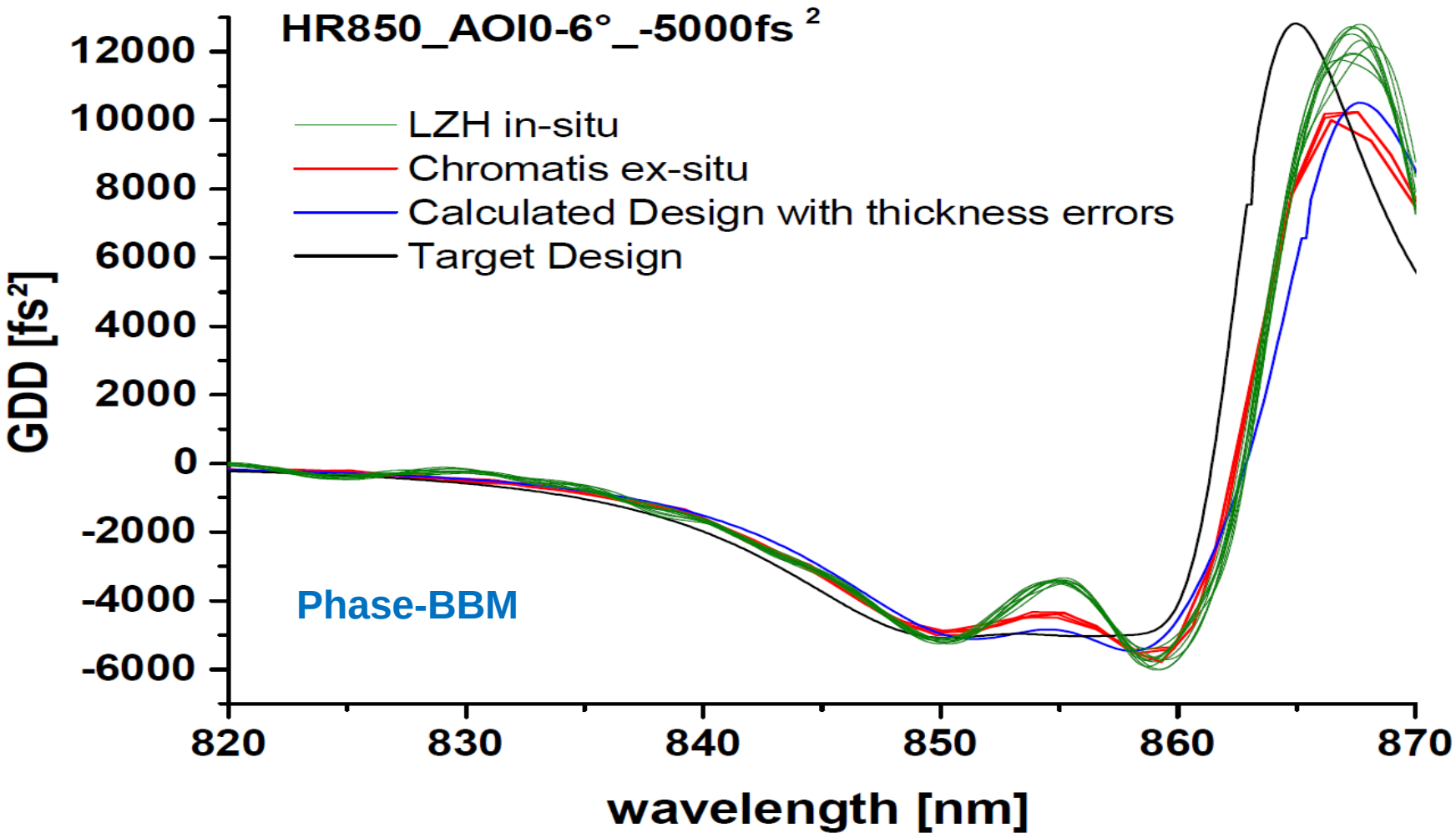
Issue: Limitation of BBOM sensitivity for wide-band reflecting filters.

Phase-BBM

- **Fourier-domain White-light interferometry**
- **implemented in IBS**
- **direct access to GDD**
- **advanced control**



Optical Monitoring

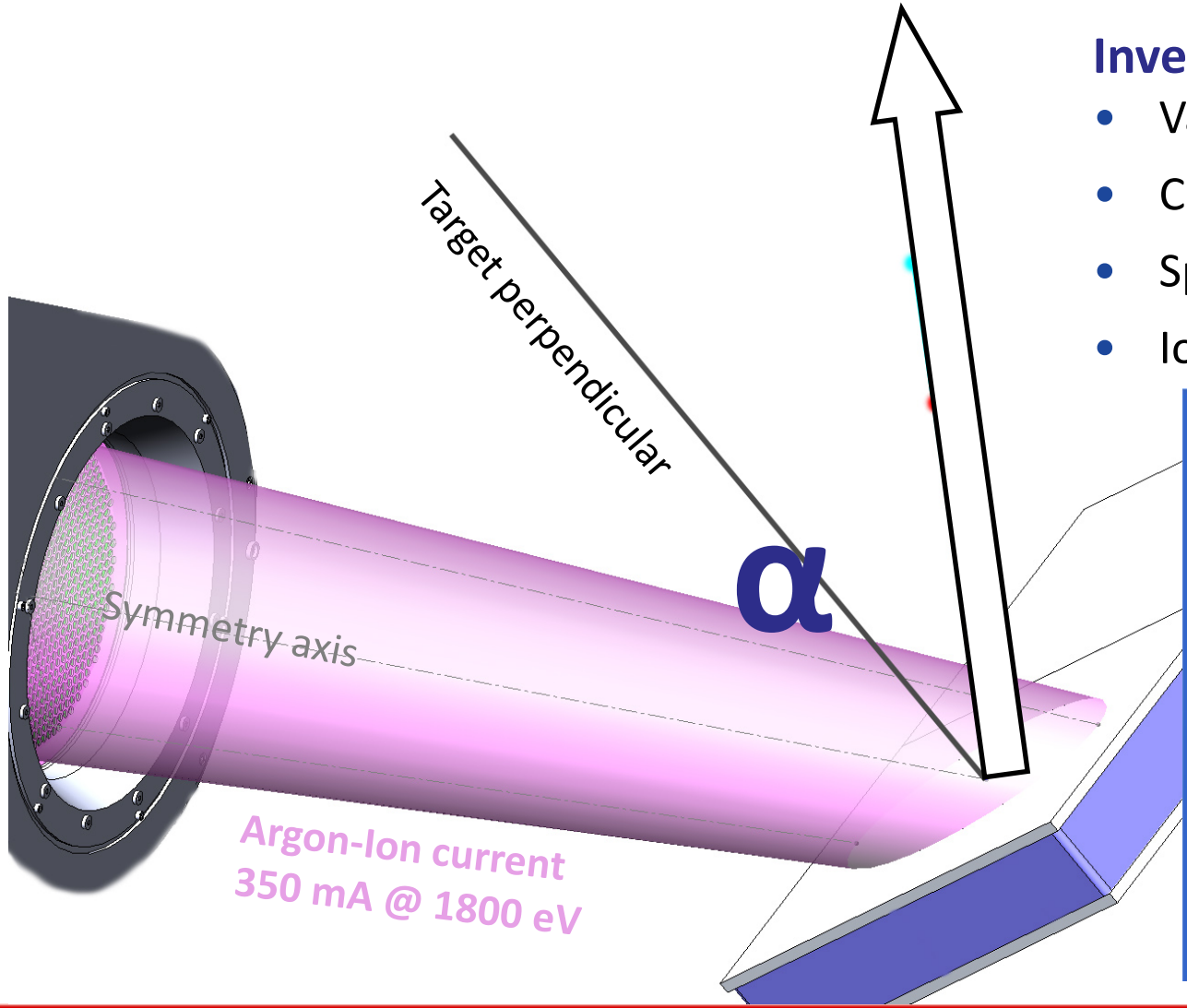


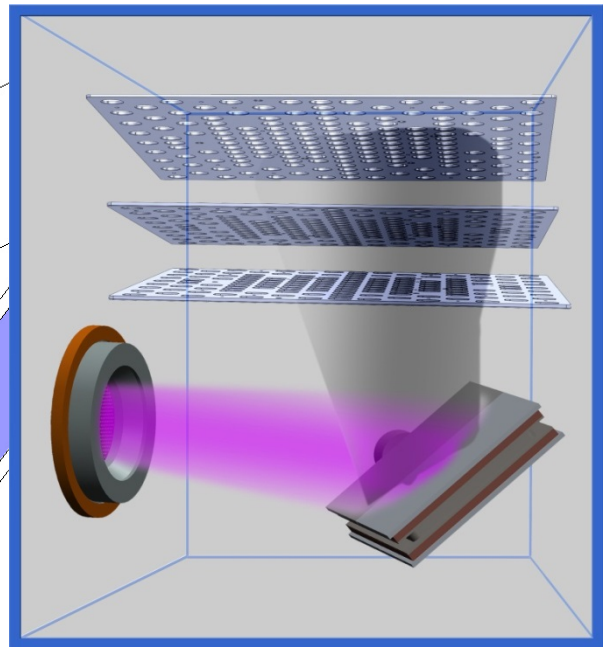
Lateral Uniformity

Cutting Edge Coatings

Investigations Ta_2O_5:

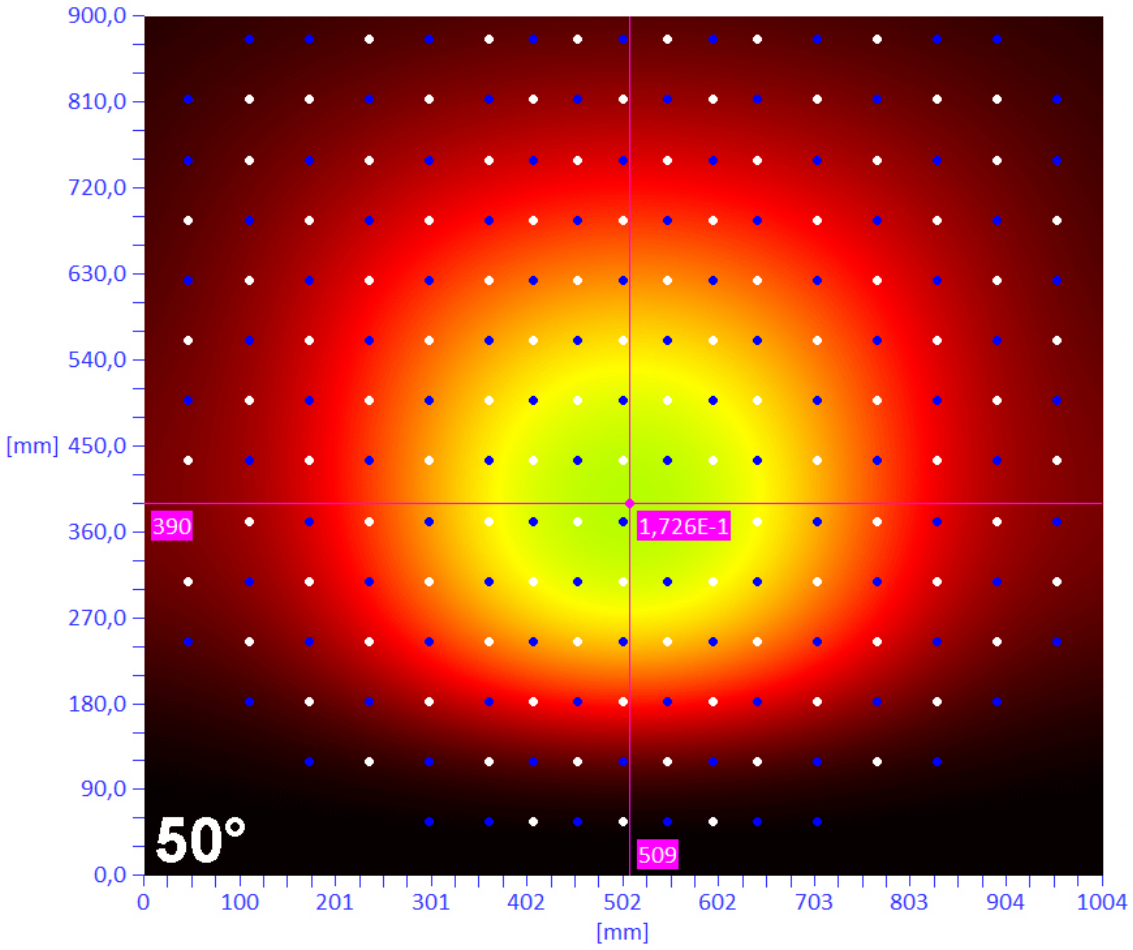
- Variation target angle
- Coating materials
- Sputter gases
- Ion beam parameters





Lateral Uniformity

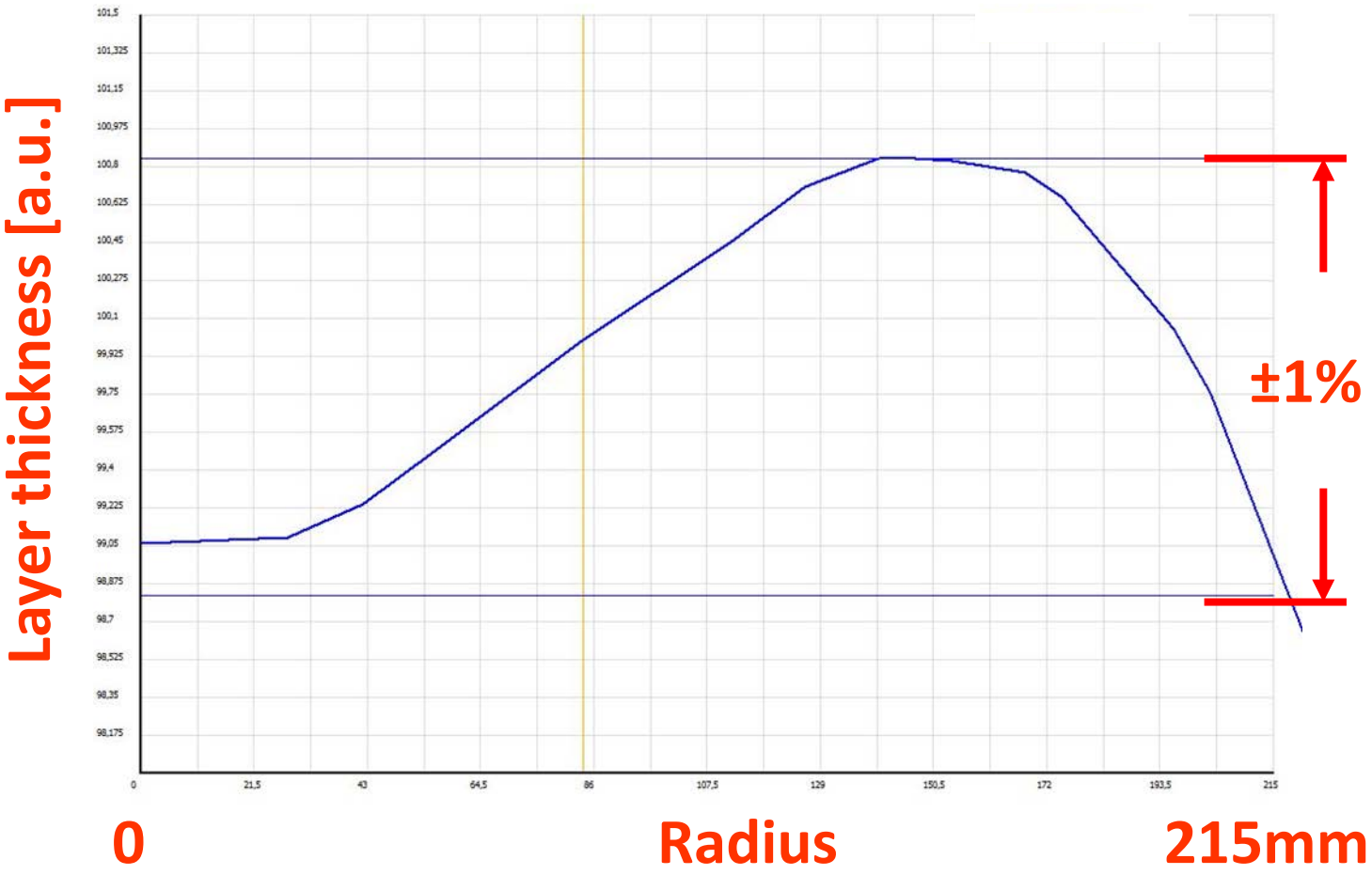
Cutting Edge Coatings



Lateral Uniformity

Cutting Edge Coatings

Uniformity of TiO_2 layers Ø430mm without shaping masks



CEC's Showroom

NAVIGATOR demonstration & R&D coating system

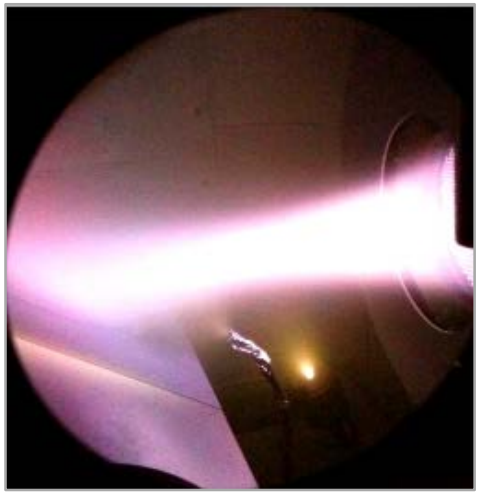
- Customer applications center
- Prove of principle investigations
- Research projects

- coating performance
- productivity
- ion source improvement
- monitoring and process stabilization concepts

➢ **Ask for free trial runs !**

Summary

- IBS is still reference for precise low-loss-coatings
- NAVIGATOR: high-performance, customized configurations
- New developments: long-life grids, optical monitoring, large uniformity (mask-less)



Acknowledgements

GEFÖRDERT VOM

Bundesministerium für Bildung und Forschung

VDI Technologiezentrum

German Ministry of Education and Research (BMBF) Project OptiKontrol, 13N12516

GEFÖRDERT VOM

Bundesministerium für Bildung und Forschung

DLR Projektträger

German Ministry of Education and Research (BMBF) Project CELL-UV, E!7721 (EUROSTARS)

GEFÖRDERT VOM

Bundesministerium für Bildung und Forschung

VDI Technologiezentrum

German Ministry of Education and Research (BMBF) Project PluTO+, 13N13207

Acknowledgements

Cutting Edge Coatings

Laser Components GmbH
Dr. Lars Mechold

Qioptiq Photonics GmbH+Co. KG
Dr. Martin Bischoff

Université de Neuchâtel
Prof. Thomas Südmeyer, Dr. Martin Saraceno

LMU München,
Munich-Center for Advanced Photonics
Dr. Vladimir Pervak, Florian Habel