Substrate treatment and metrology

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Essential Technologies for Einstein Telescope
27/11/2023

CONTENT

- Subaperture corrective polishing of optical elements for GW detectors
    1. Si testmass
    2. FS OMC freeform optics
- Scattering properties of structural elements
- Conclusions

Subaperture corrective polishing of optical elements for GW detectors

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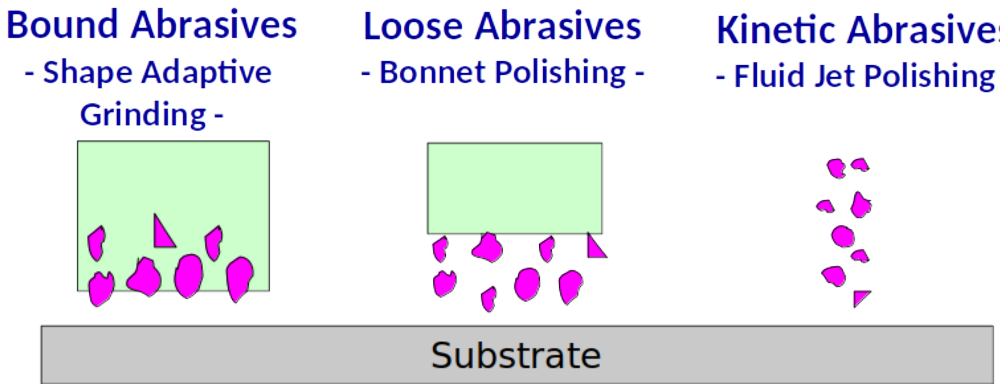
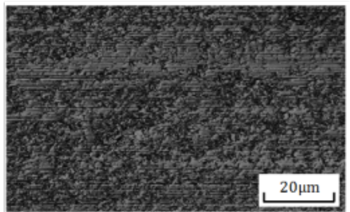
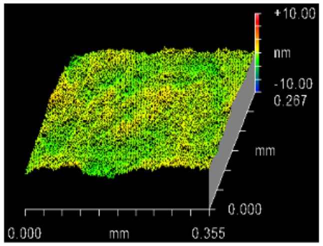
Subaperture corrective polishing

- Grinding: generation with brittle fracture (subsurface damage)
- Polishing: smoothing and figure correcting at ductile regime
- Surface pressure and dwell time

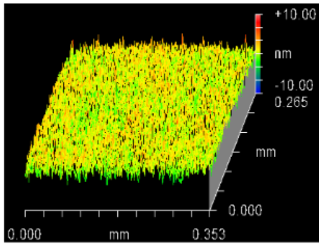




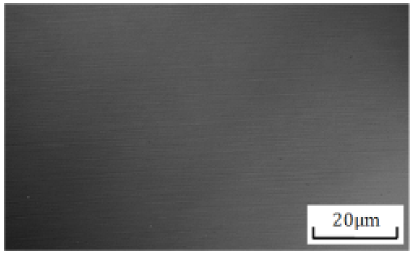
(c) Fracture mode



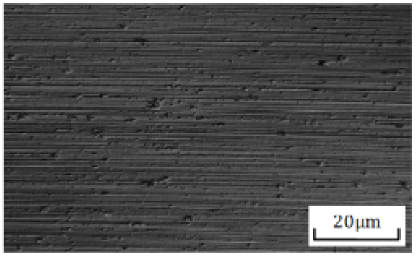
Ra :0.52nm



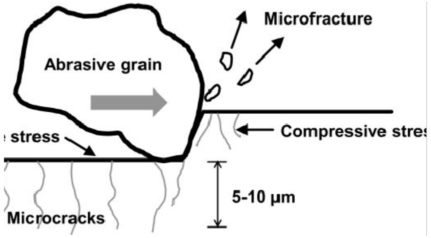
Ra :1.17nm

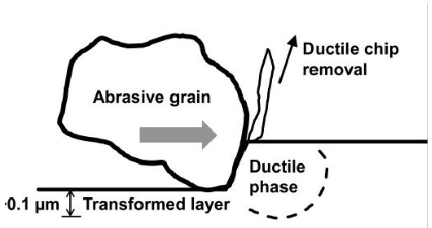


(a) Ductile mode



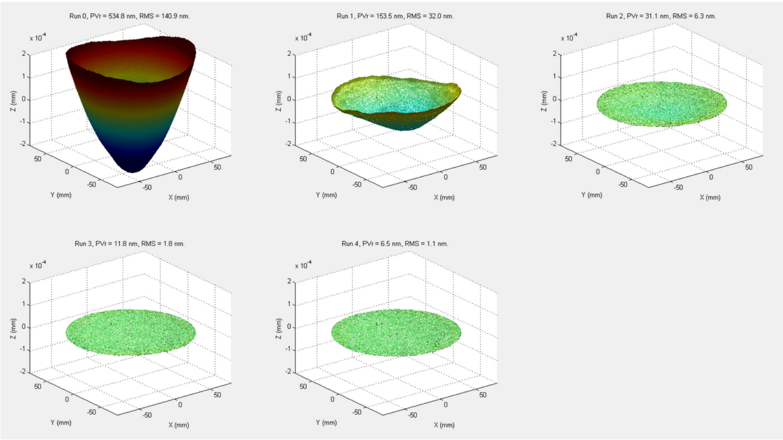
(b) Ductile and fracture mode

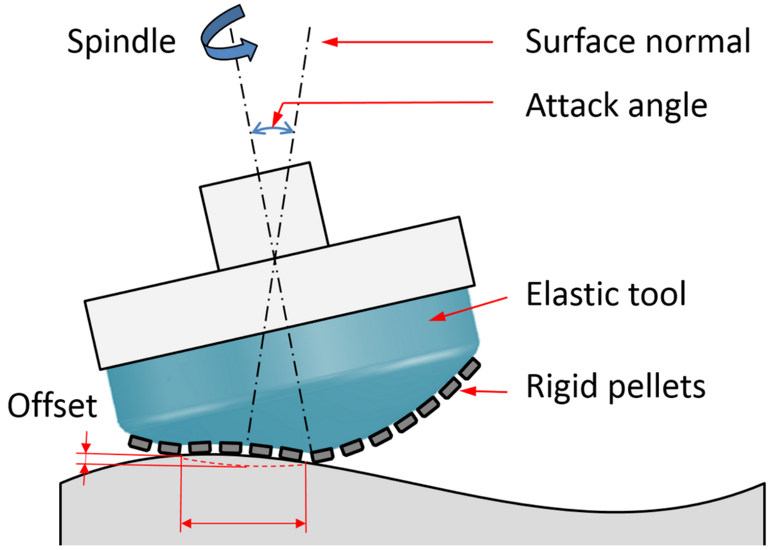




Subaperture corrective polishing

- Subaperture corrective polishing
  - Requires extended skills or CNC operated machines
  - Tool does not comply with shape
  - Requires subaperture tools
  - Requires removal function characterisation
    - Per tool type and material
    - Per process set point





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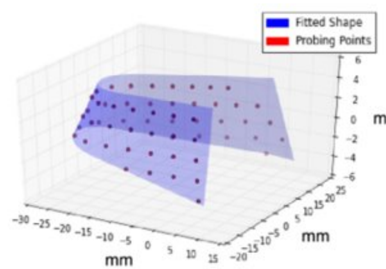
Subaperture corrective polishing

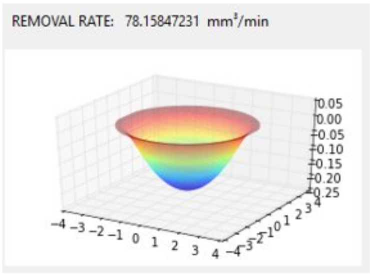
- B-PHOT: corrective multi-axis and robotic polishing

Subaperture corrective polishing

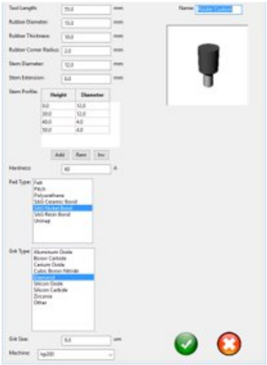
- B-PHOT: corrective multi-axis and robotic polishing
  - Sequence

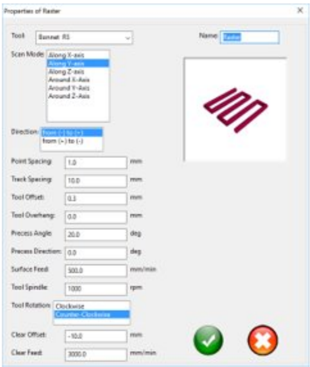


CAD entry

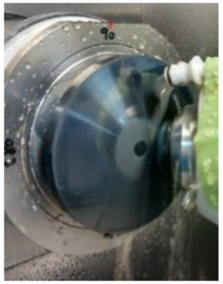


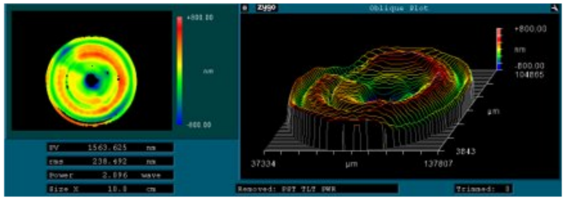
Tool and material removal study: influence functions

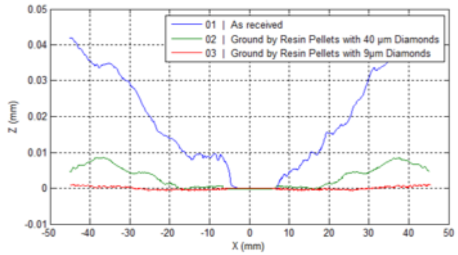


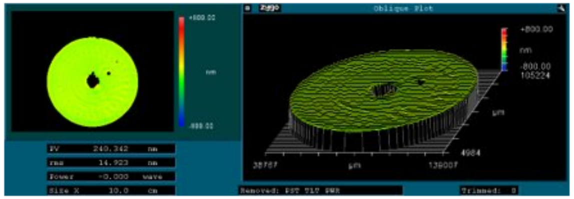


CAM toolpath generation: feed moderation







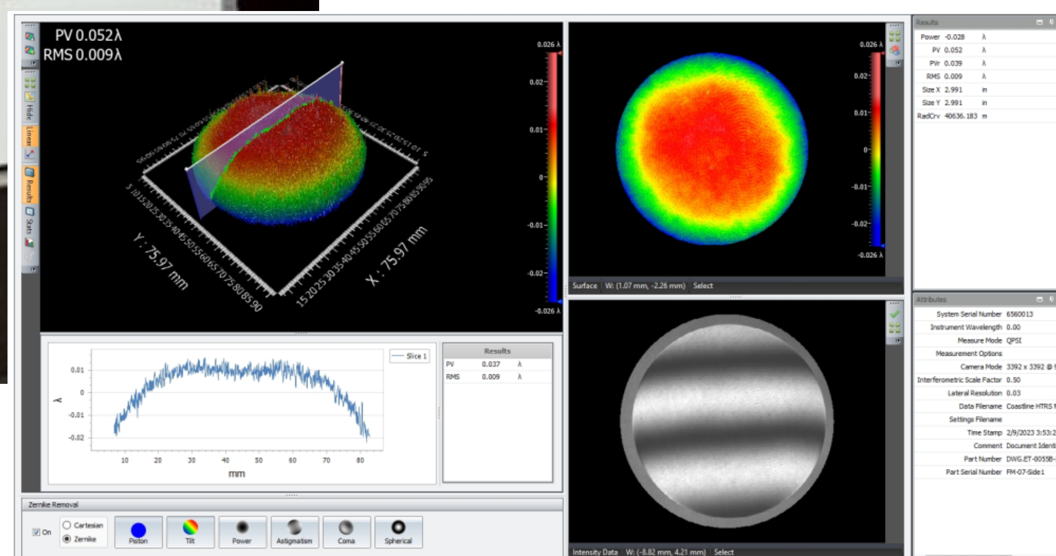


Subaperture corrective polishing

- B-PHOT: corrective multi-axis and robotic polishing
  - Metrology: full field interferometer

Zygo Verifire HDx interferometer

- Full-field 4" and 6" aperture
- Surface shape
- Mid-spatial frequencies



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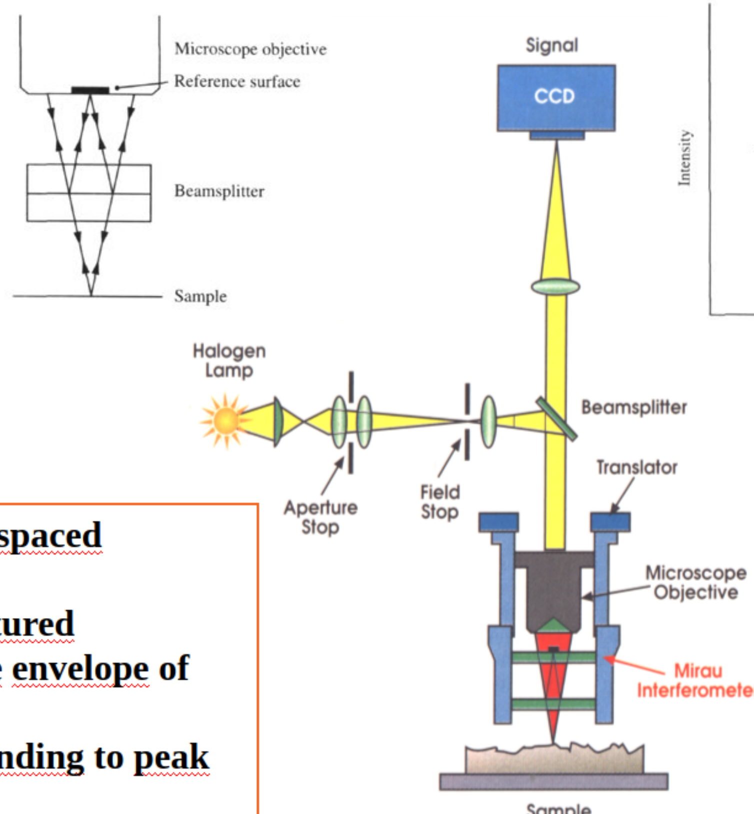
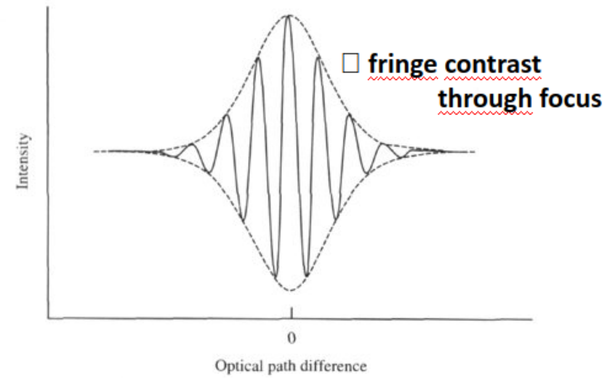
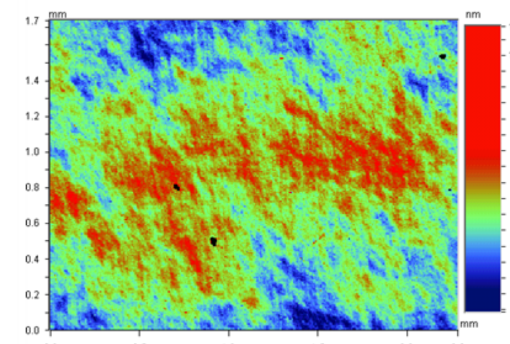
Subaperture corrective polishing

- B-PHOT: corrective multi-axis and robotic polishing
  - Metrology: white light interferometry



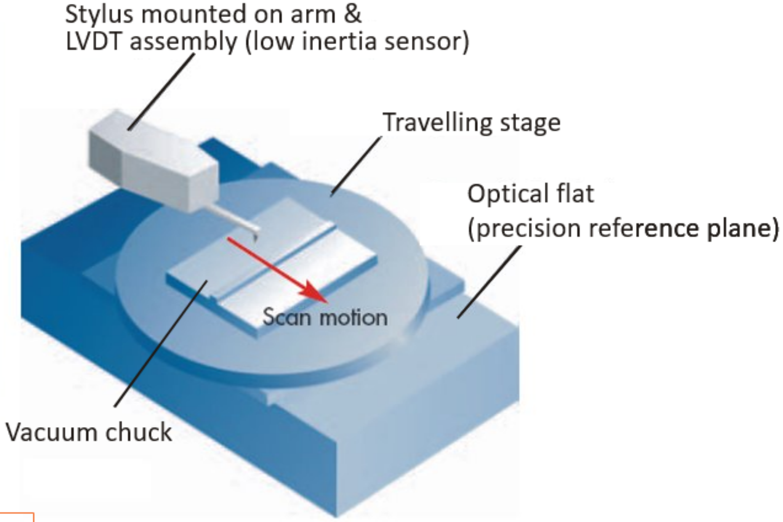


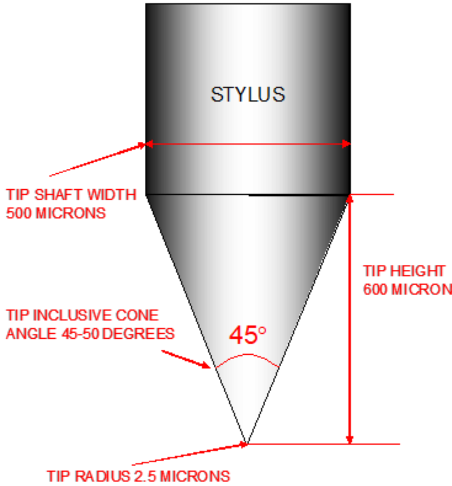


- system scans downwards @ evenly-spaced intervals
- frames of interference data are captured
- computer algorithms to demodulate envelope of fringe signal
- vertical position extracted corresponding to peak of interference signal for each point

Subaperture corrective polishing

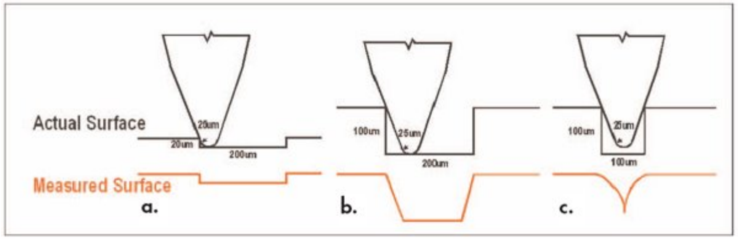
- B-PHOT: corrective multi-axis and robotic polishing
  - Metrology: surface profiling





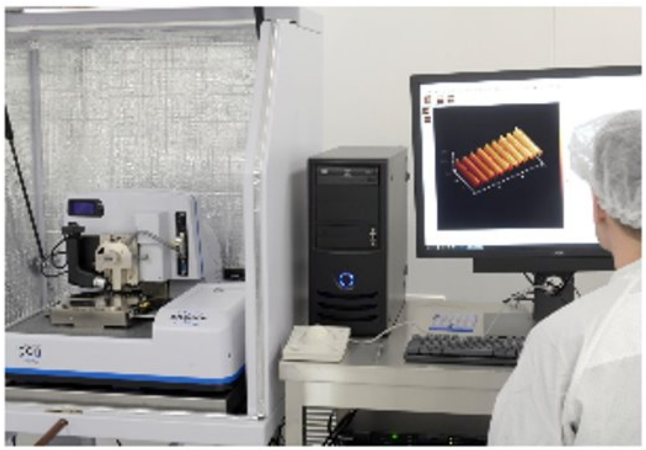
- **Linear movement of sample or stylus**
- **Map area possible**

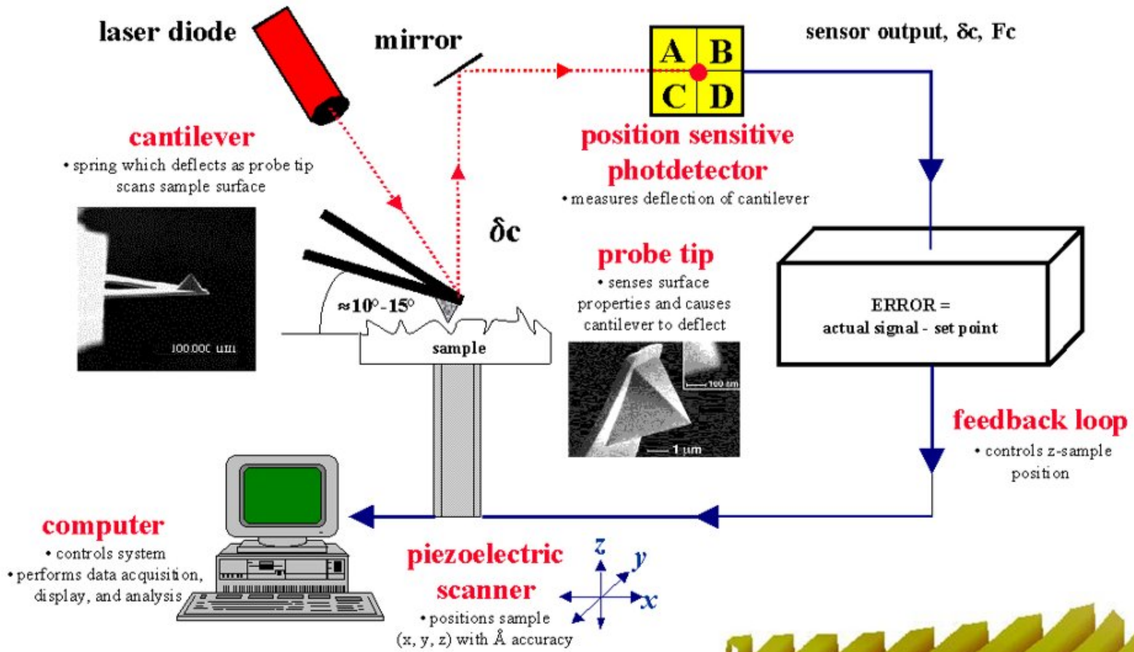
very slow – resolution depends on stylus



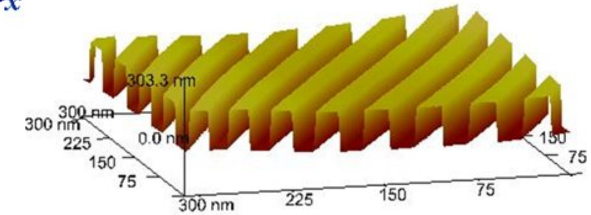
Subaperture corrective polishing

- B-PHOT: corrective multi-axis and robotic polishing
  - Metrology: atomic force microscopy





- contact, non-contact or tapping mode
- image a sample by raster scanning across the surface line by line
- three dimensional surface profile



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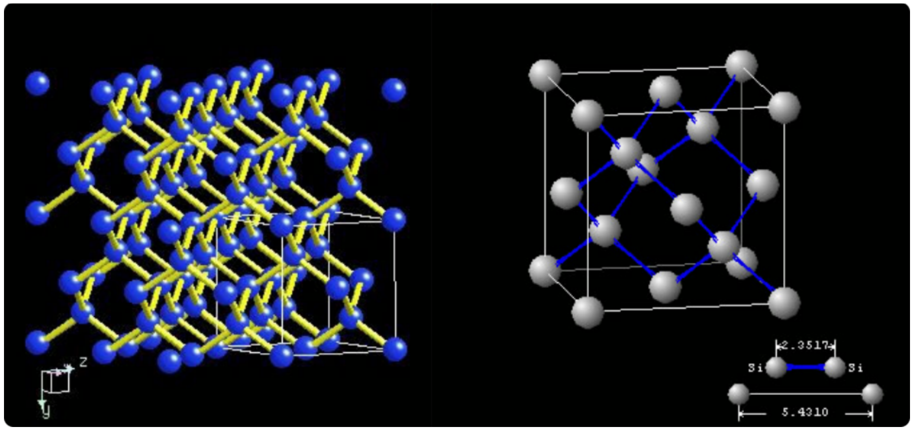
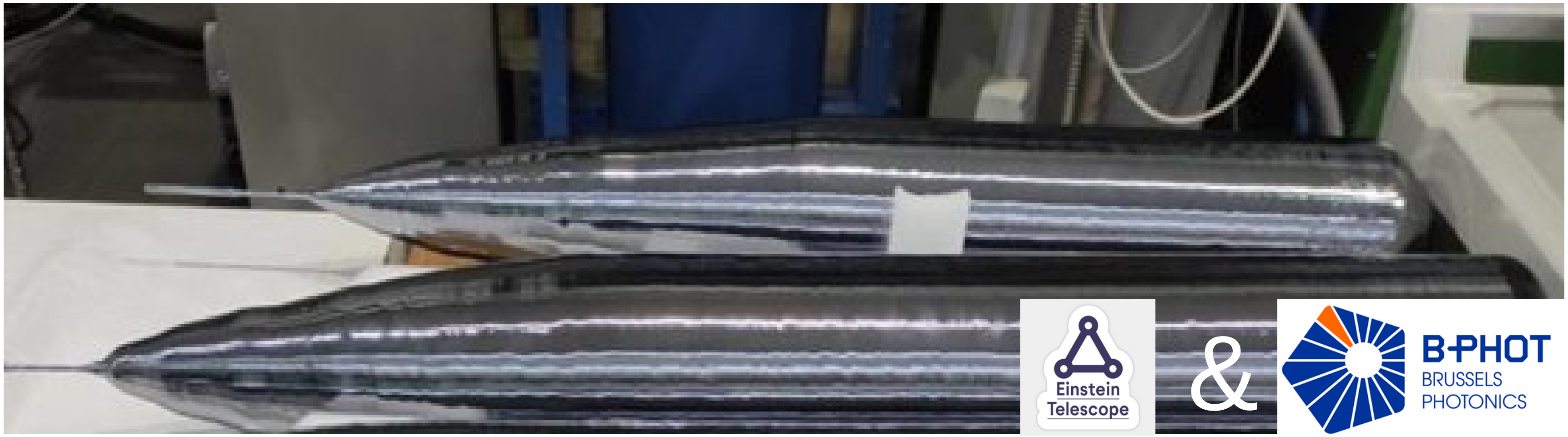
Test mass requirements (ETPathfinder)

- <100> high-purity FZ silicon (IKZ Berlin)
- D 150 mm, 80 mm thick
- Shape :
  - CC -14.5±0.1 m
  - CX +9.0±0.1 m
- Final telescope D550mm Si





Einstein Telescope & B-PHOT BRUSSELS PHOTONICS

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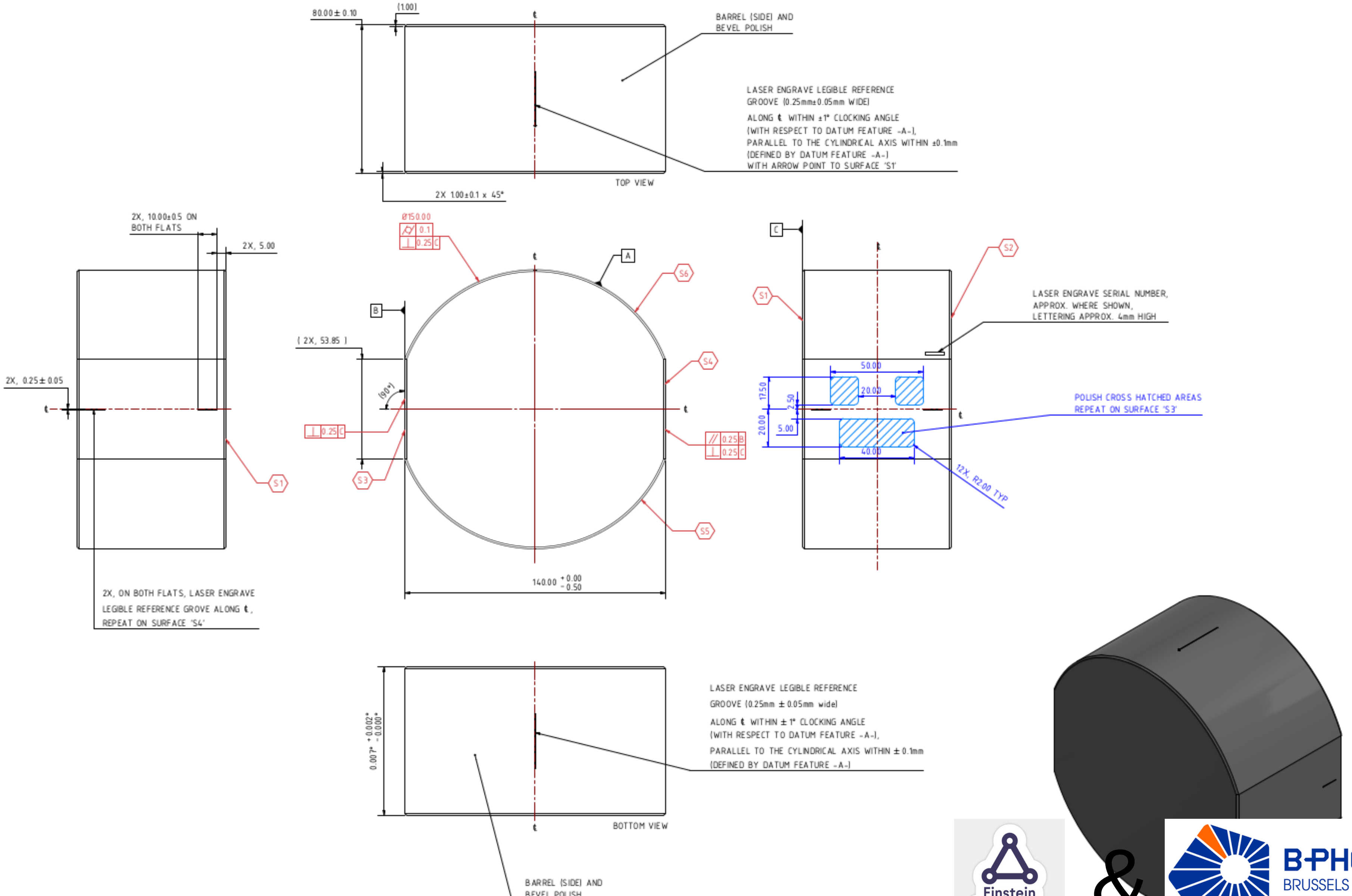
Test mass requirements



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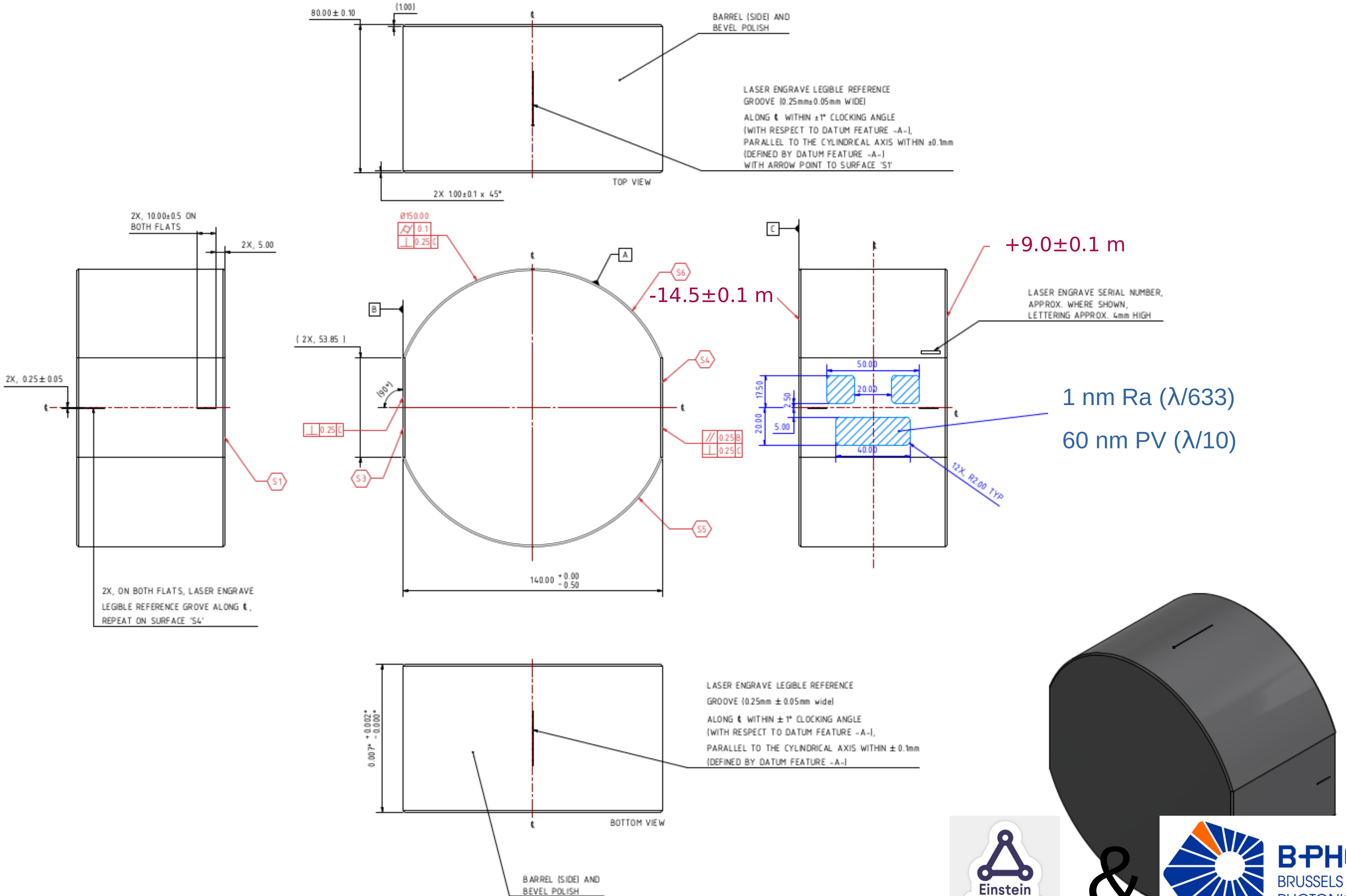
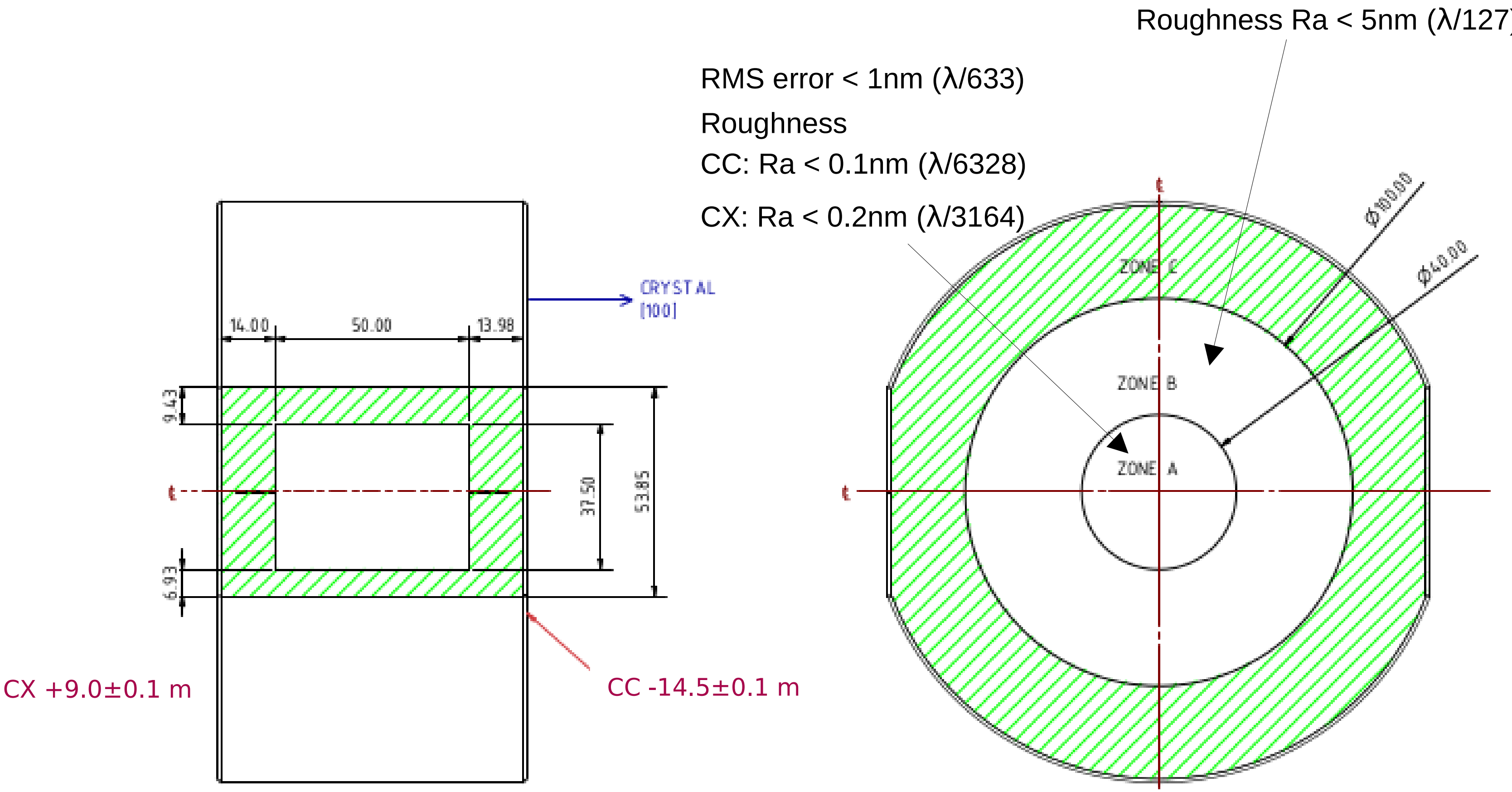


&

Test mass requirements



The polish ingredients used on S1 and S2 shall not include ingredients known to increase the optical absorption of polished silicon surfaces, where possible. The mechanisms that cause higher surface absorption after polishing are largely unknown.

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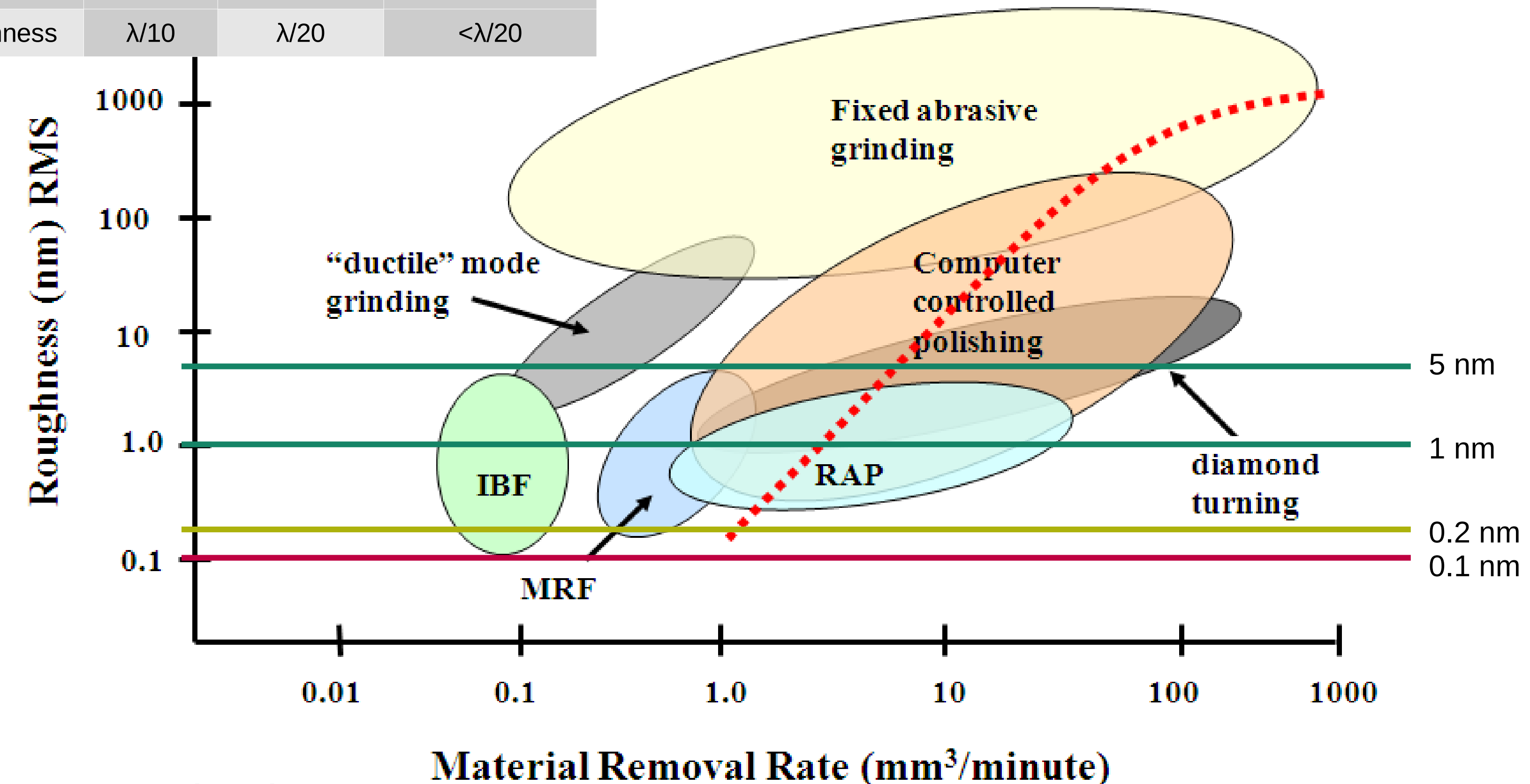
Extreme precision technologies

	Typical	Precision	High precision
PV error	λ/2	λ/4	λ/8
Ra roughness	λ/10	λ/20	<λ/20



IBF: Ion Beam Figuring

RAP: Reactive Atom Plasma

MRF: Magneto Rheological Fluid polishing

Comley, P., et al. "Grinding metre scale mirror segments for the E-ELT ground based telescope."
CIRP Annals-Manufacturing Technology 60, no. 1 (2011): 379-382.

Extreme precision technologies

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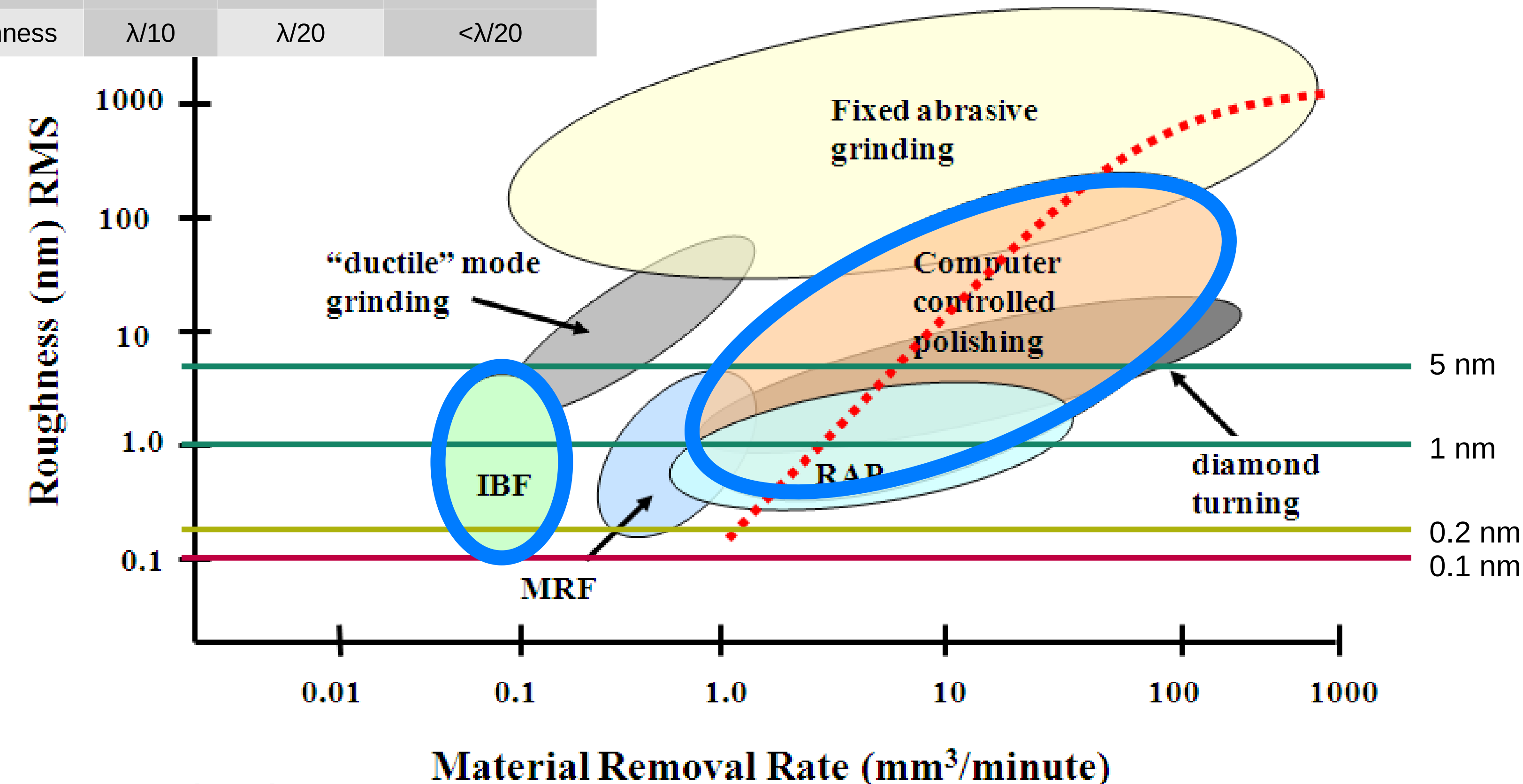

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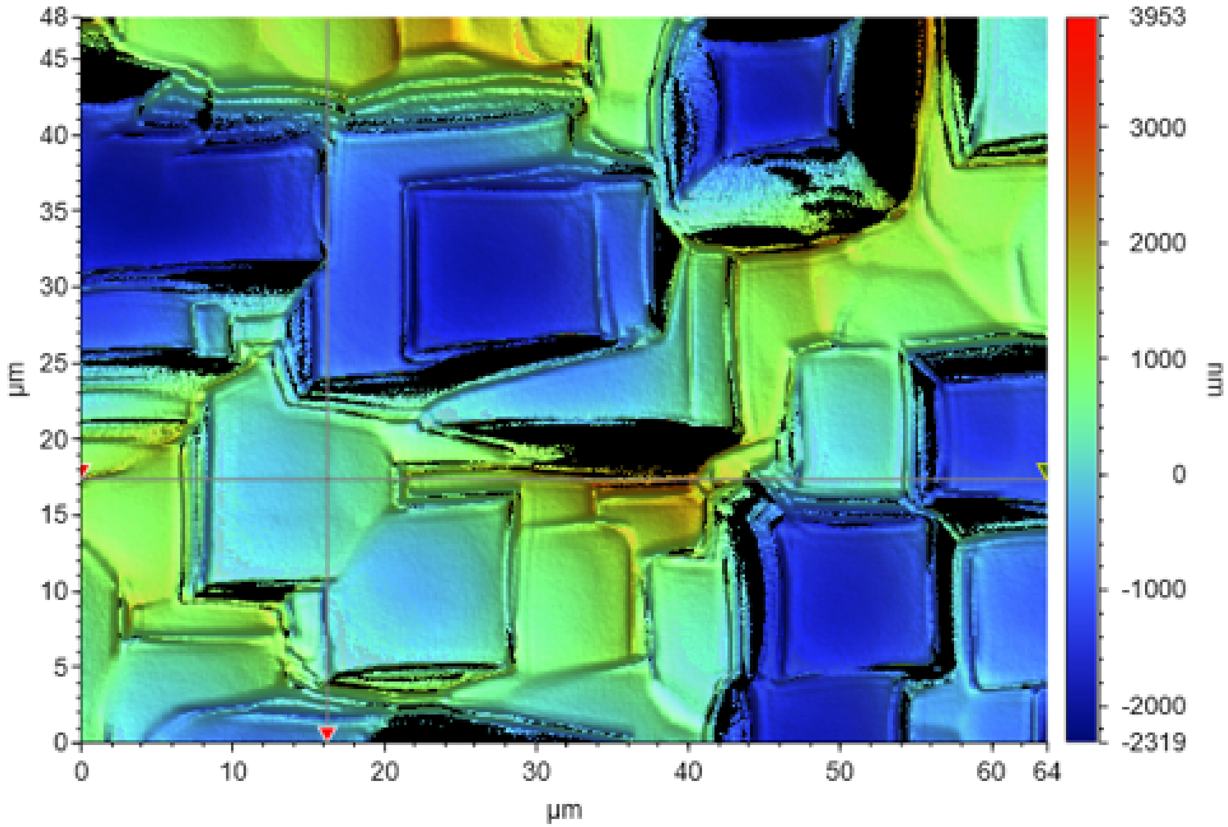
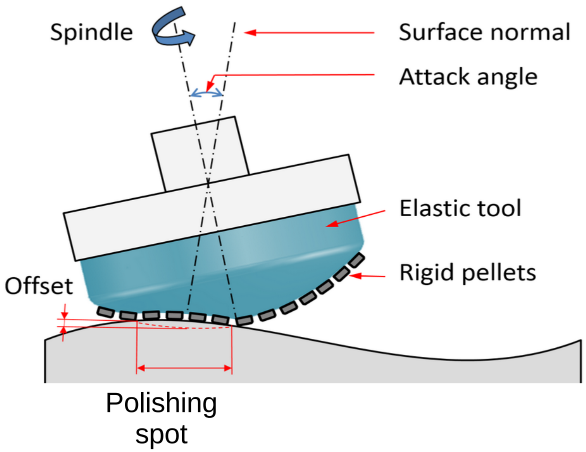
Si: initial test results

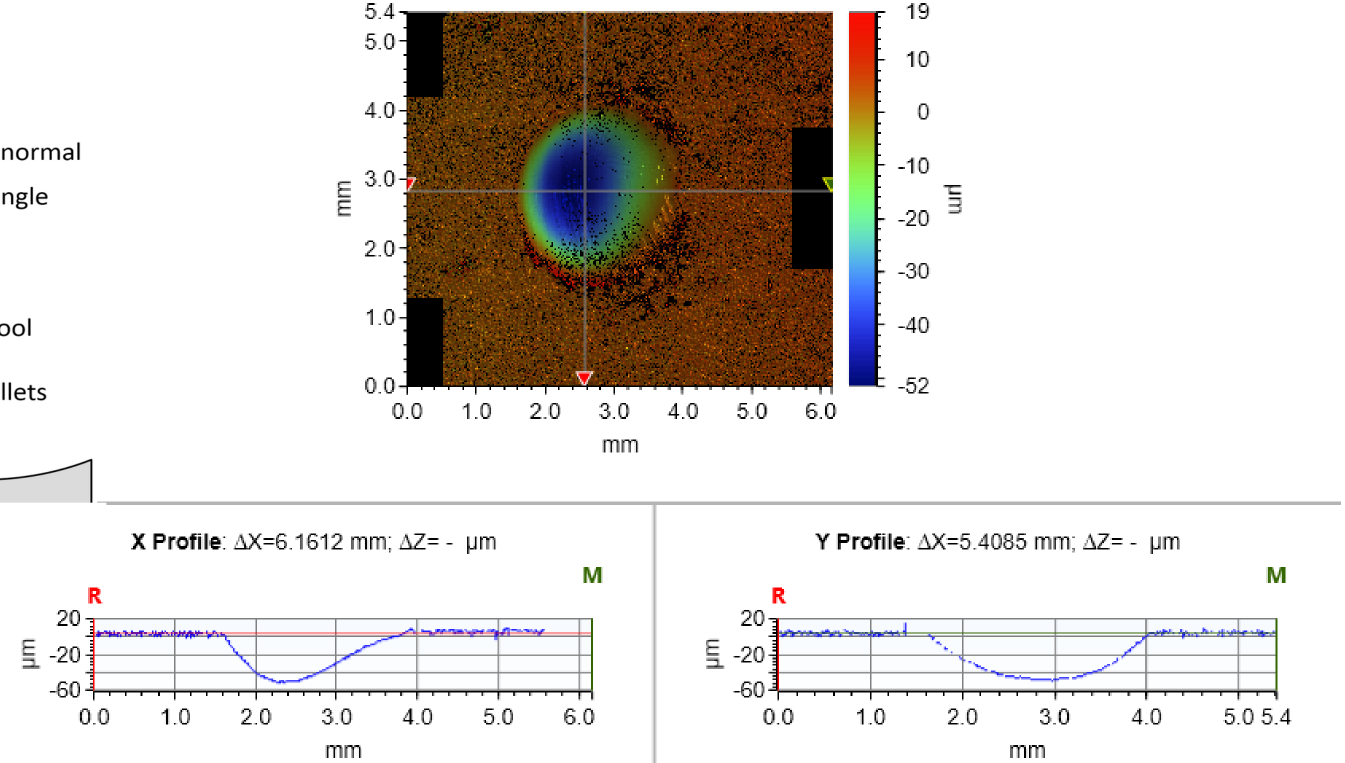
- Initial state : CZ D100mm <100> Si
  - As cut ~ 6 um R_t
  - Test samples for surface generation (grinding) and polishing strategies



Si: initial test results

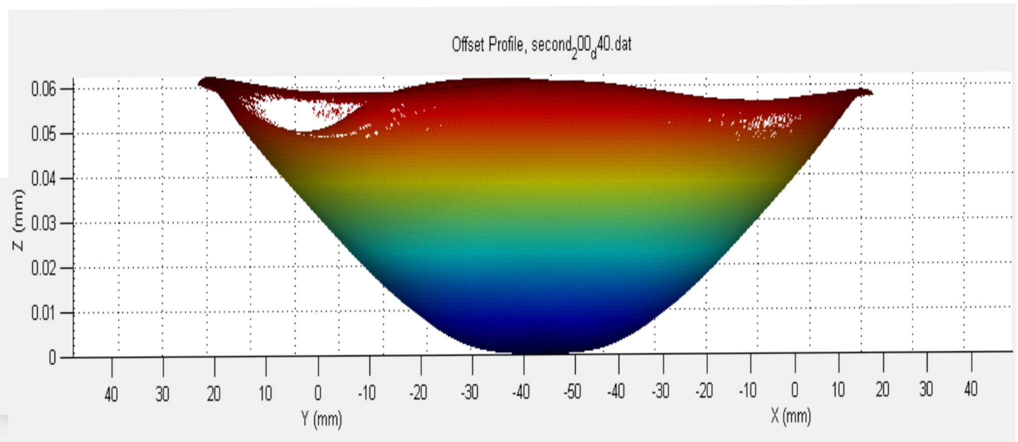
- Tool removal function characterisation
  - Nickel or resin bonded fixed diamond abrasive
  - DI water as coolant
  - Multiple grit sizes

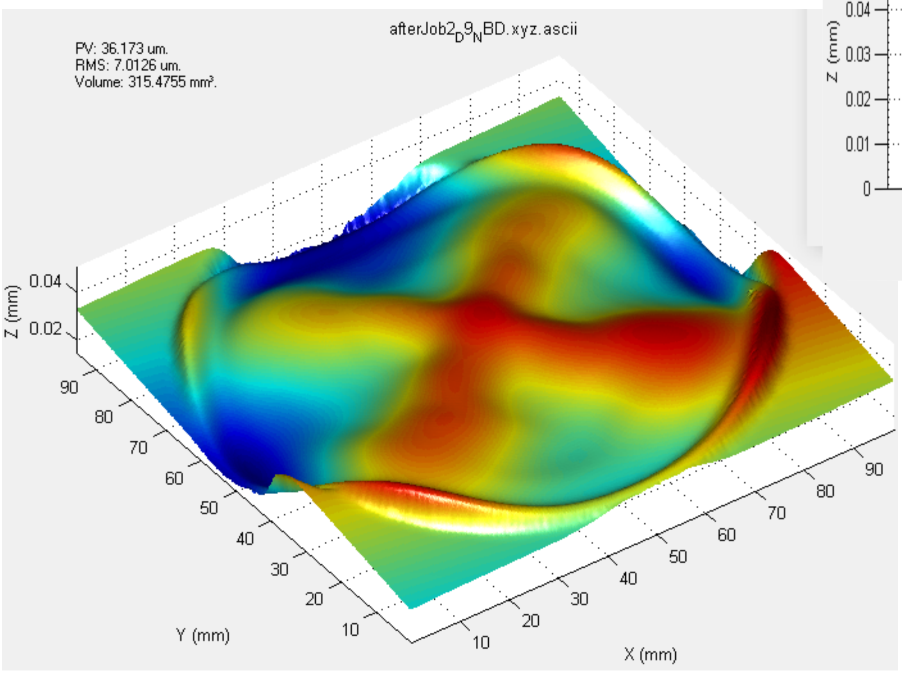




Si: initial test results

- Surface generation testing
  - D100 CC -14.5m radius (~84 um sag)
  - 80% of final sag before corrective polishing
    - 400x 40um grit
    - 20x 9um grit
  - Ra < 50 nm



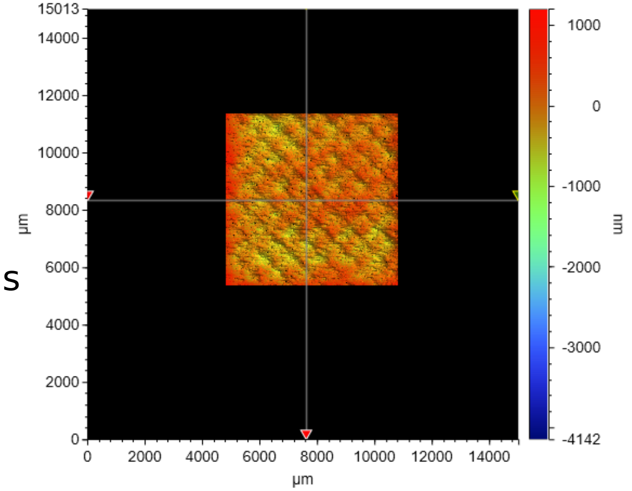


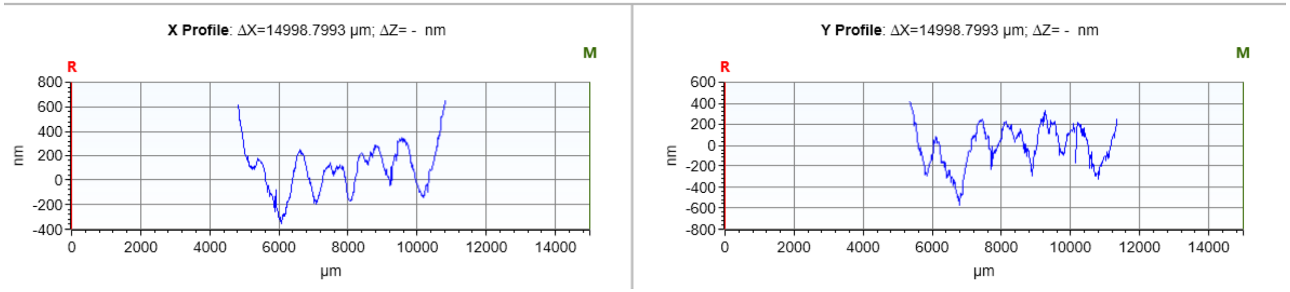
Si anisotropy requires highly dynamic correction : under investigation

Subsurface damage layer

Si: initial test results

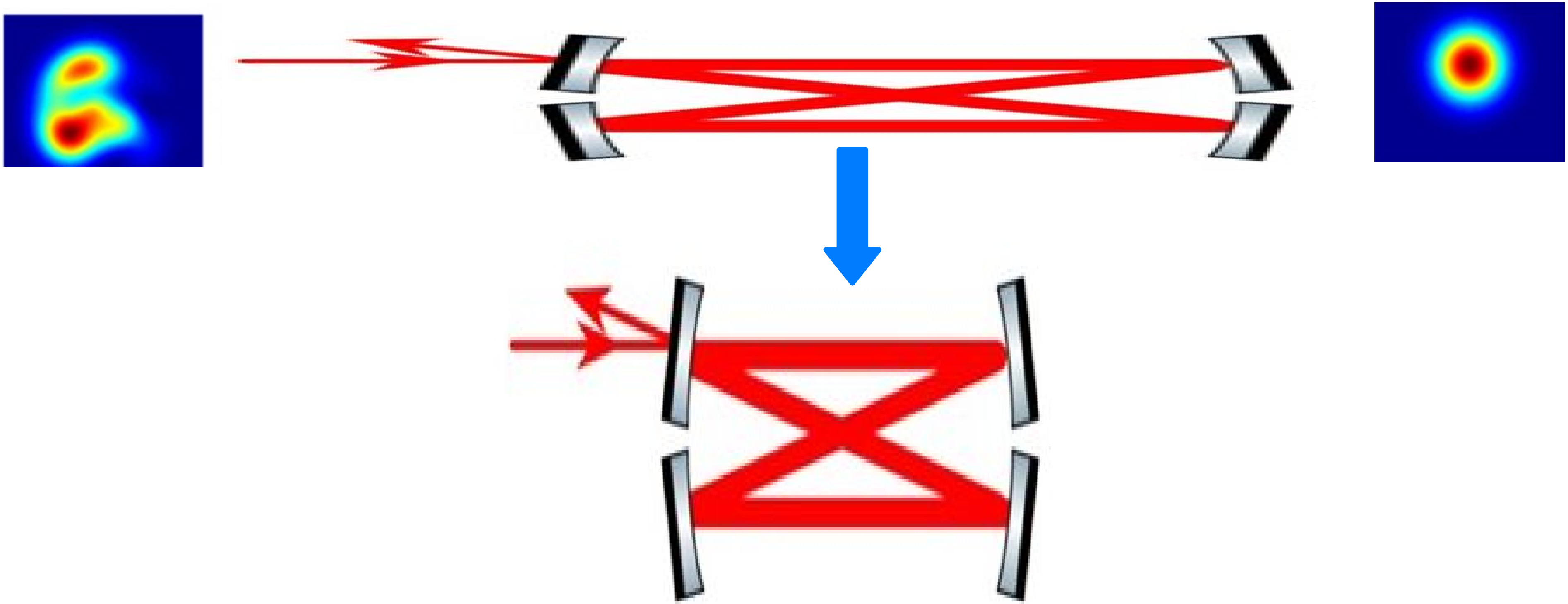
- Surface generation testing
  - D100 CC -14.5m radius (~84 um sag)
  - 80% of final sag before corrective polishing
    - 400x 40um grit
    - 20x 9um grit
  - Ra < 50 nm
  - Mid-spatial zoom shows pattern
    - Needs randomisation of toolpaths





Freeform optics output mode cleaner

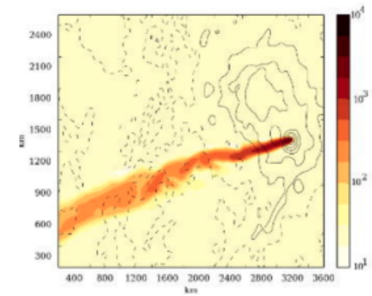
- Design: subject of iBOF
- Claim: freeform optics could **reduce the OMC form factor**
  - Reduction will lead to large optics angles = aberrations
  - Freeforms might enable more efficient mode rejection
- Base material: IR-grade fused silica (amorphous SiO_2 with very low OH-content)



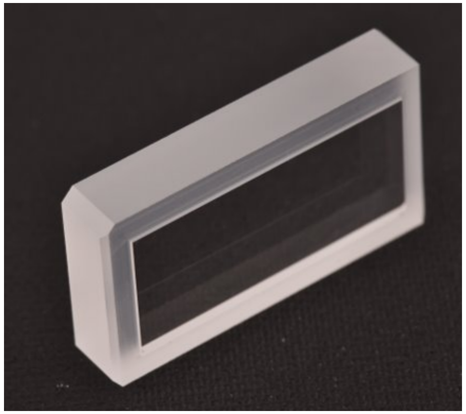
IR fused-silica freeform corrector

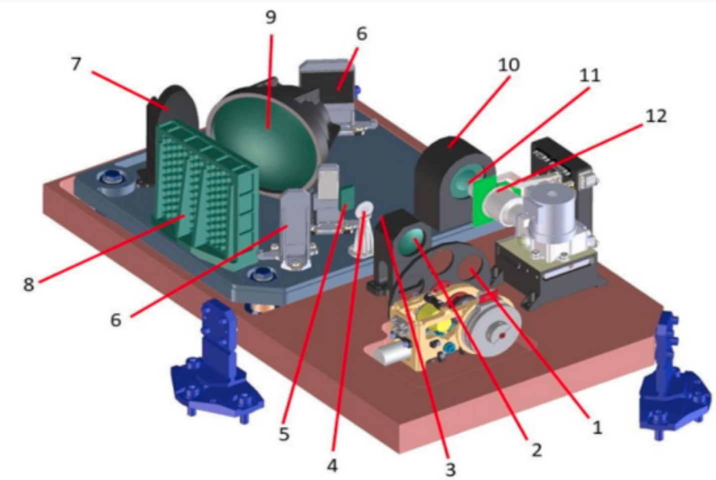
esa & B-PHOT BRUSSELS PHOTONICS

- ESA Envision VenSpec-H instrument
  - ESA/NASA EnVision planetary mission to Venus (2032)
  - Phase A and Phase B1: fully functional instrument, now towards C and D (engineering & flight)
  - Venspec-H high-resolution nadir echelle grating spectrometer instrument
    for 1.0–2.5 µm and 7.32° by 0.084° FOV (design by OIP n.v.)
  - Monitoring of volcanic activity



- Freeform IR fused-silica wavefront corrector plate
  - Compensation of downstream aberrations
  - **<λ/10 RMS surface error , <5 nm RMS roughness**
  - ~80um total sag
  - Full supply chain @ VUB B-PHOT

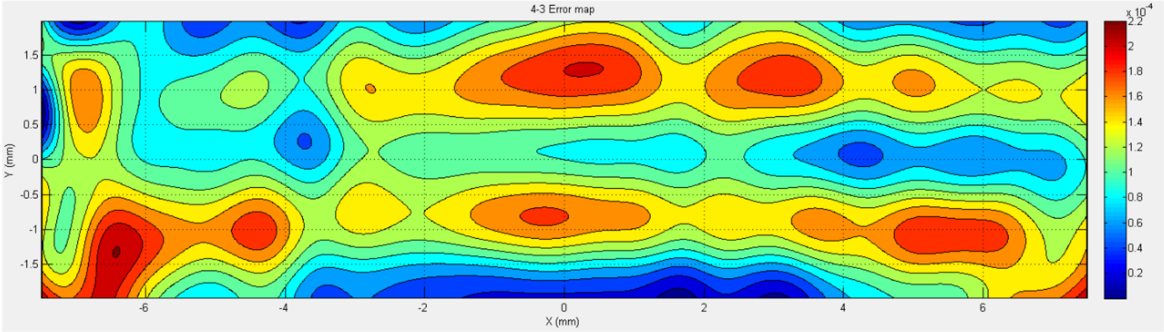


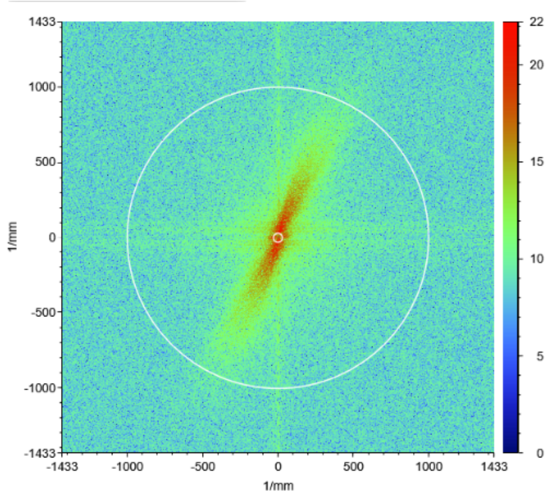


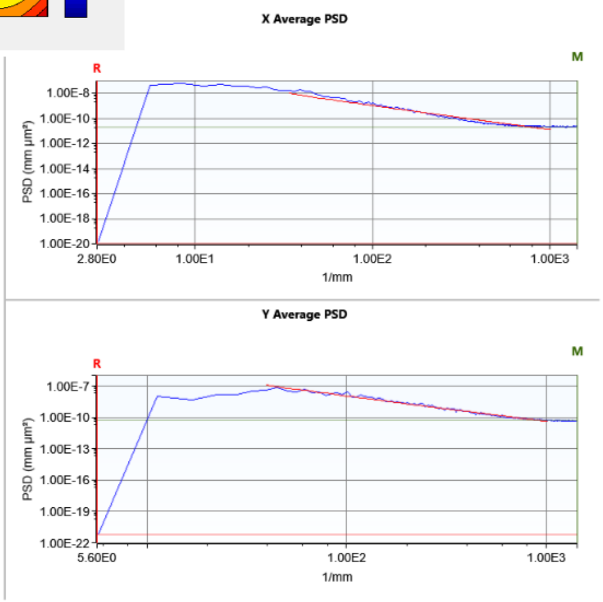
IR fused-silica freeform corrector

esa & B-PHOT BRUSSELS PHOTONICS

- Freeform IR fused-silica wavefront corrector plate
  - <λ/10 RMS surface error , <5 nm RMS roughness
  - **Reached < λ/17 RMS error and 4 nm RMS rougness**







Analytical Results

Label	Value	Units
PSD High Cutoff	1	1/µm
PSD Low Cutoff	30	1/mm
PSD Rms	1.3246	nm
X Rms	0.6885	nm
Y Rms	1.6966	nm

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Scattering properties of structural elements

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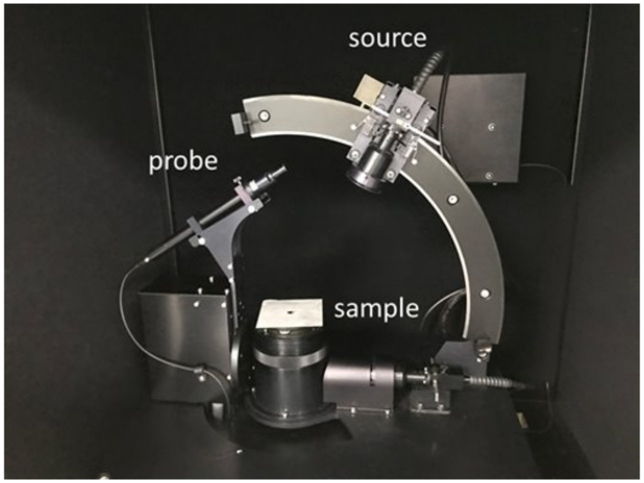
Surface roughness induced light scattering

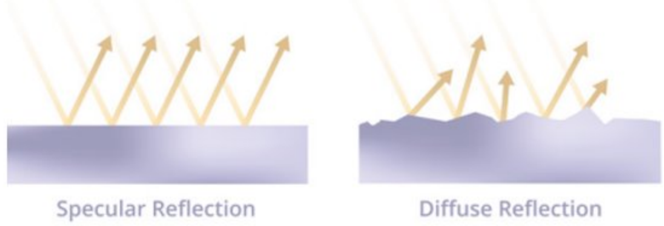
- Workflow

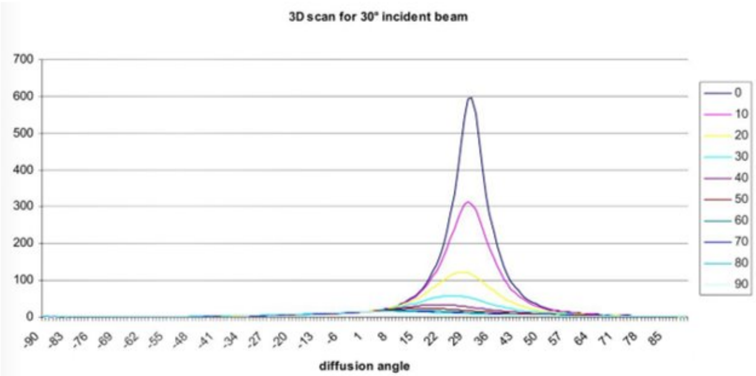
1. Surface analysis
   - Geometrical: 1D and 2d surface profile at microscopic level, surface roughness, surface Power Spectral Distribution function
   - Optical: measures of scattering, transmittance, reflectance
2. Mathematical description of optical properties of surfaces
   - Surface roughness, Power Spectral Distribution function (PSD)
   - Bidirectional Scattering Distribution Function (BSDF)
   - Wavelength scaling
3. Ray-tracing simulations
   - Description of scattering properties with dedicated software tools
   - CAD representation of objects of interest
   - Specialised techniques for fast accurate simulations

Surface roughness induced light scattering

- B-PHOT: surface roughness induced light scattering
  - Metrology: scatterometry







- illumination: white light source with filters
- transmission and reflection
- detection: integrated flux or spectral analysis
- calculation of BRDF/BTDF

400 – 1700 nm

Surface roughness induced light scattering

- The ultimate goal is to calculate the **Bidirectional Scattering Distribution Function (BSDF)** of a surface

$$BSDF = \frac{scattered\,radiance}{incident\,irradiance} = \frac{P_s/\Omega_s}{P_i \cos(\theta_i)}$$

  - P = light flux (Watts); i=incident, s=scattered ; Ω = solid angle
  - Describes how light incident from different angles is reflected (scattered) by a surface, in all directionsPerfectly specular reflection is an idealization
  - A fraction, if not all, of the incident light is reflected away from the specular direction (scattering)
  - The smoother a surface, the closer to an ideal specular reflector
- Two options to determine the BSDF
  1. **Directly from scattering measurements**
  2. **By using scatter theories**
     - when the sample does not fit into the scatterometer, or
     - when the wavelength of interest is not available in the lab.
     - Scattering theories determine BSDF from surface analysis

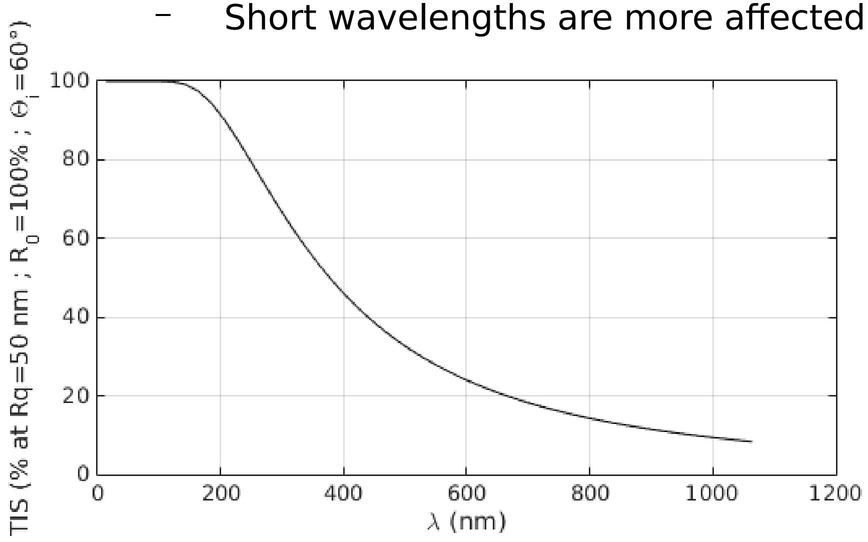
A quantity which is easily calculated from surface metrology and gives a first indication of the scatter properties of a surface is the
Total Integrated Scatter

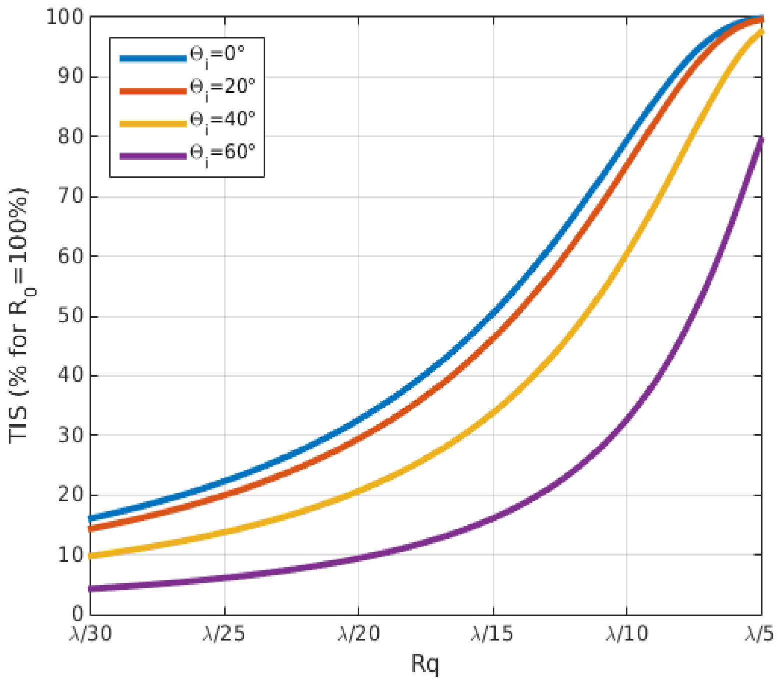
Surface roughness induced light scattering

$$TIS(R_q) = R_0\left(1 - e^{-\left(\frac{4\pi R_q \cos\theta_i}{\lambda}\right)^2}\right)$$

R_q : *RMS roughness*
R_0 : *theoretical reflectance*
θ_i : *angle of incidence on the surface*
λ : *wavelength*

- Low roughness requirements in optics
  - Scattered light reduction (halo and ghost effects, power loss & damage)
  - Mirrors (high reflectivity): more affected
  - Grazing angles: are less critical
  - Short wavelengths are more affected (UV!)





H.E. Bennett et al. "Relation Between Surface Roughness and Specular Reflection at Normal Incidence,"JOSA 51, 123, 1961.

Surface roughness induced light scattering

$$TIS(R_q) = R_0 \left(1 - e^{-\left(\frac{4\pi R_q \cos\theta_i}{\lambda}\right)^2}\right)$$

R_q : *RMS roughness*
R_0 : *theoretical reflectance*
θ_i : *angle of incidence on the surface*
λ : *wavelength*

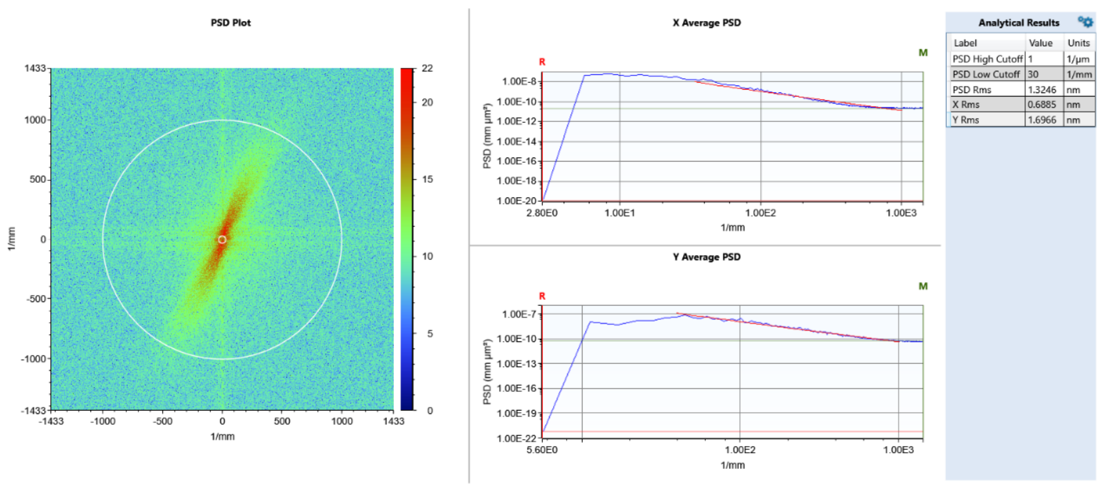
- Low roughness specification
  - A surface is considered smooth if (smooth surface criterion): $\left(\frac{4\pi R_q \cos\theta_i}{\lambda}\right)^2 \ll 1$
  - Schröder: $\frac{R_q \cos\theta_i}{\lambda} < 0.02$
  - Astronomical telescope : Rq<0.1 nm, smoothness criterion <10^{-4} ; TIS 7 10^{-5}%
  - Metallic, rough, surface : Rq=1.5 um, TIS 100% : diffuse scattering

S. Schröder et al., "Modeling of light scattering in different regimes of surface roughness," Opt. Express 19, 9820-9835 (2011).

Surface roughness induced light scattering

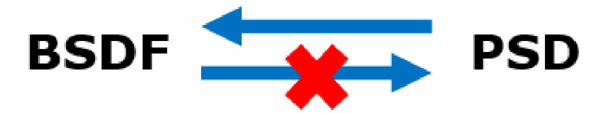
- Scatter theories: **about 30 methods** (Elfouhaily 2004)
- Parent models:
  - **Rayleigh-Rice** (1951): only for smooth surfaces, any incident or scatter angle
  - Beckmann-Kirchhoff (1963): rough surfaces but not for large angles
  - Harvey-Schack (1976): no roughness limitations, only small angles
  - **Generalized Harvey-Shack** (2011): generic model\

- Rayleigh-Rice and generalized Harvey-Shack requires
  PSD characterisation of the surface | FFT{z(x,y)}² |



Smooth surfaces
BSDF is proportional to the PSD
BSDF characterisation at a given wavelength
can be converted to any other wavelength

Rough surfaces
PSD can be used to calculate the BSDF
BSDF cannot be used to infer the PSD



Elfouhaily and Guerin, “A critical survey of approximate scattering wave theories from random rough surfaces”, 2004

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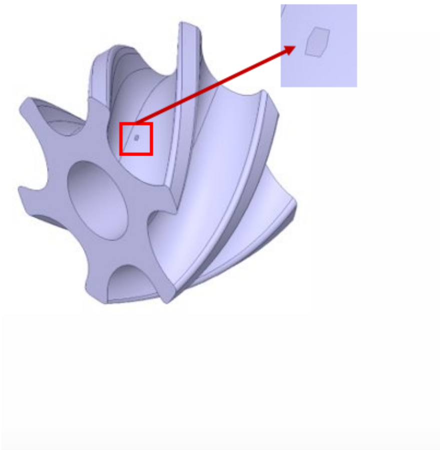
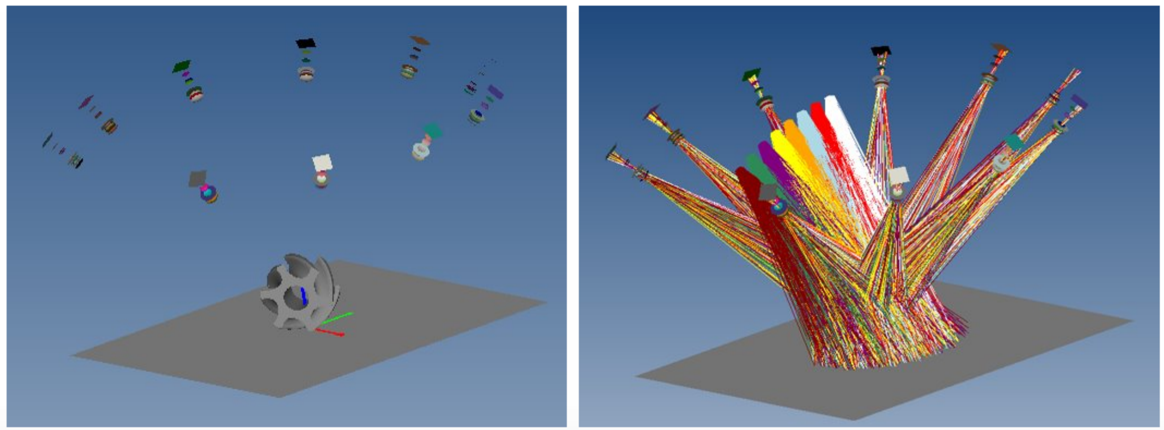
Simulated scattering example

- Goal: digital twin of a machine vision system for defect monitoring
- Method: PSD and BSDF characterisation of the surface elements
- Simulation: physical raytrace model of the full structural element

Defect is about 2 x 1 mm^2
Low reflectance (10%), diffuse scatter



10 Cameras are arrayed on a ring, to image the sample when it is illuminated by an array of LEDs arranged on an arc



System parameters

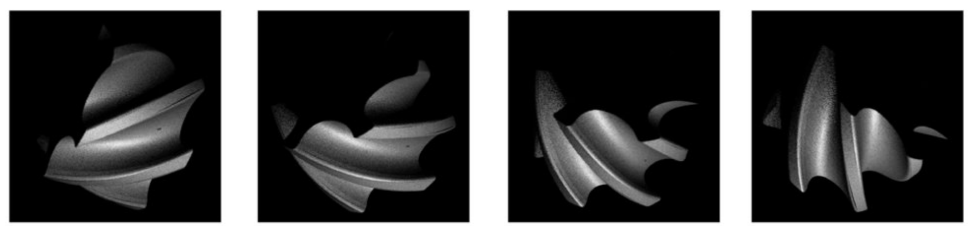
10 LEDs on, cameras' elevation 45°

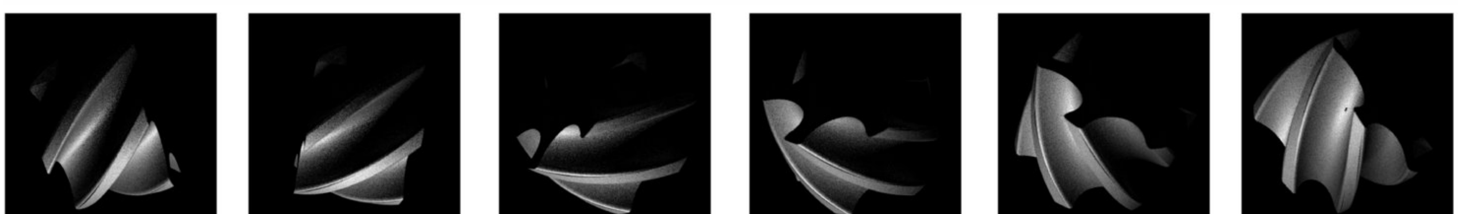
10 cameras on a ring, equally spaced

Camera has f/8, 35 mm focal length

Detector 16 x 16 mm, 1 Mpixels

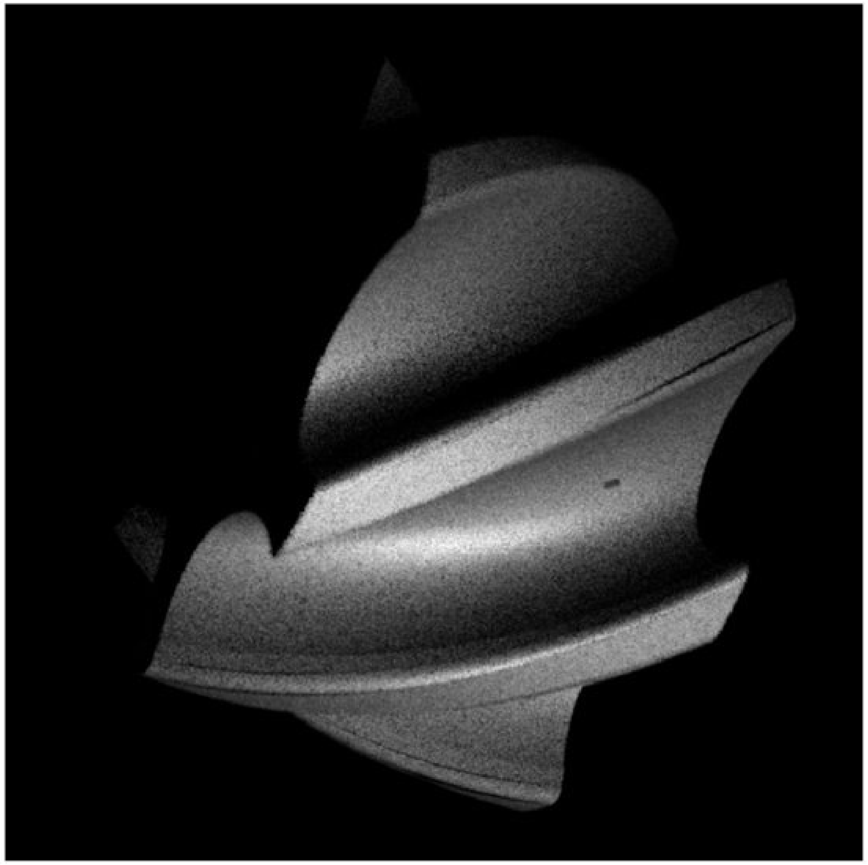
10 images in about 1 hour, using targeted scattering

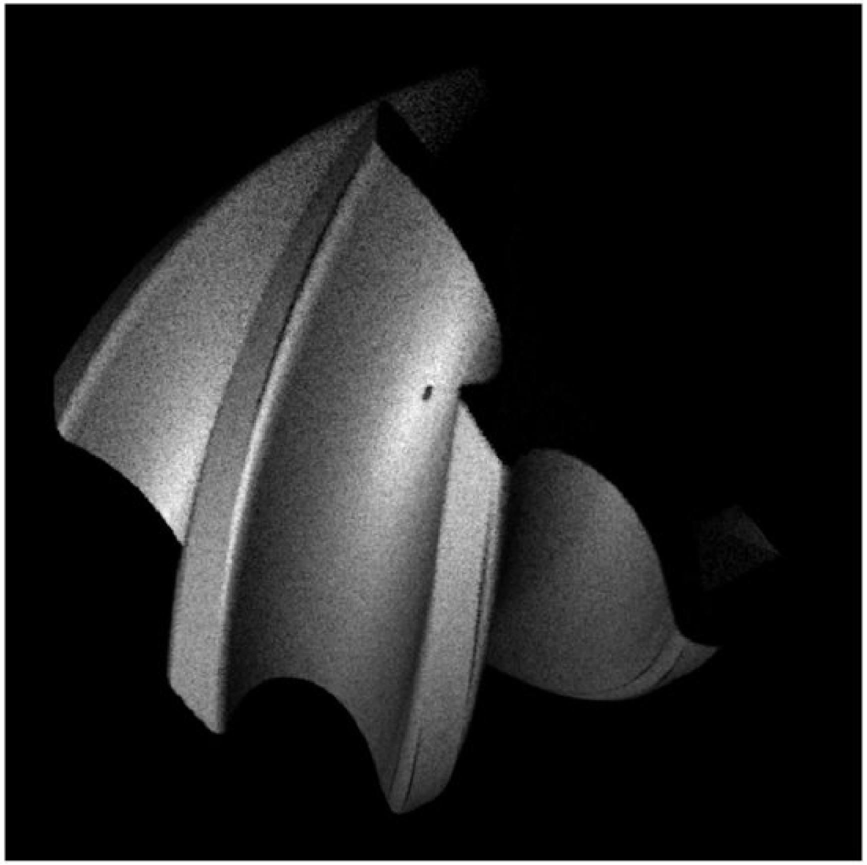




Simulated scattering example

- Goal: digital twin of a machine vision system for defect monitoring
- Method: PSD and BSDF characterisation of the surface elements
- Simulation: physical raytrace model of the full structural element (this is not a CGI rendering approach!)





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Conclusions

- Si surface generation: ongoing work, generation method is established
- OMC IR FS Freeform optics: proven supply chain for <λ/10 RMS surface error
- Scattering on structural elements: workflow from PSD to digital twin