Surface metrology and polishing techniques for current and future-generation EUVL optics

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Contributors

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- *SLAC National Accelerator Lab*:

  Peter Stefan, Sebastien Boutet, Paul Montanez
- *Lockheed Martin Corporation:* Dennis Martinez-Galarce
- Other contributors will also be acknowledged throughout this presentation

Outline

- Overview of diffraction-limited EUVL systems
- Metrology capabilities at LLNL and LBNL
- EUVL projection optics: figure, MSFR and HSFR results and implications
- Zerodur vs. ULE as substrate materials for next-generation EUVL projection optics
- Si, SiC and other composite ceramics as candidate substrate materials for EUVL collector optics
- Novel smoothing technologies for EUVL collector substrates
- Recent advances in optic fabrication technologies for EUV solar physics and x-ray FELs and their relevance to EUVL optics
- Perspectives on 6.x nm lithography
- Summary and conclusions

- ***Unless otherwise indicated, all surface metrology results and analysis in this presentation were produced at LLNL***
- ***Any results or references to commercial vendors in this presentation do not by any means imply endorsement of these vendors or their products***

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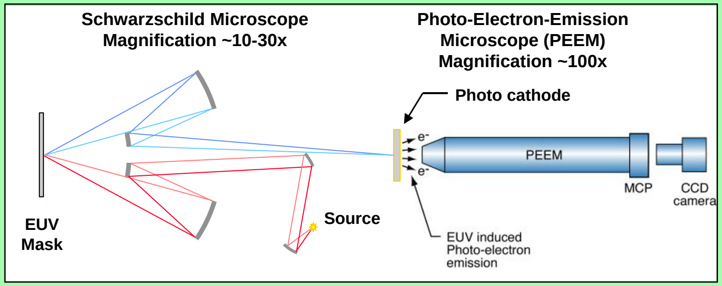
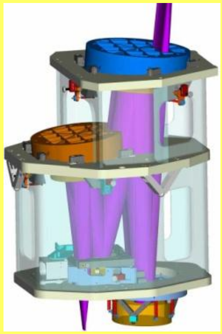
EUVL systems have greatly evolved in complexity over the past 15 years

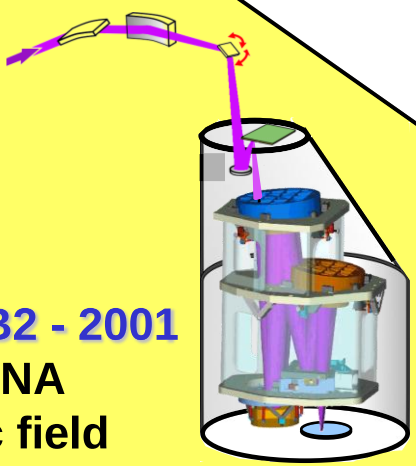
10x1 - 1996
10x2 - 1999
0.1 NA
"Microstepper"



EUV AIMs Tool
Proposed 2001

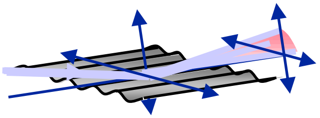
ETS POB1 - 2000
0.1 NA
Full-field scanner



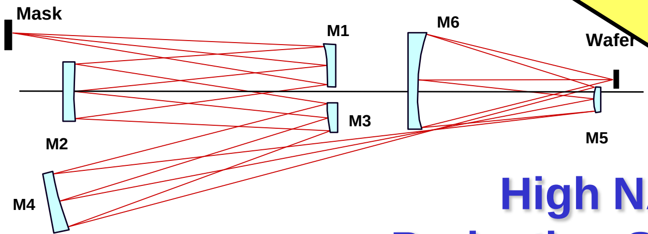


SES POB2 - 2001
0.1 NA
Static field

ETS Condenser



Ripple-Plate Condenser



High NA Projection System

MET
2002-today
0.3 NA
μstepper

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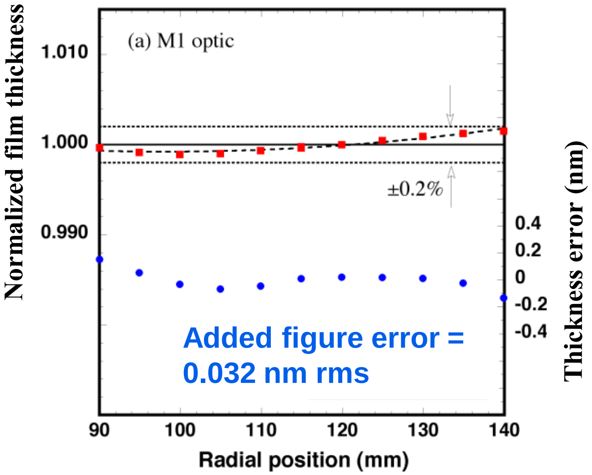
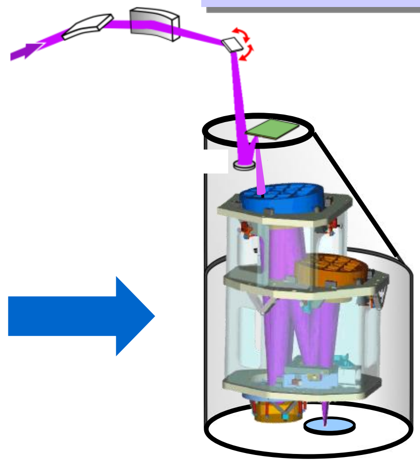
ETS and MET projection optics demonstrated multilayer-added figure errors < 0.05 nm rms and sub-diffraction-limited performance

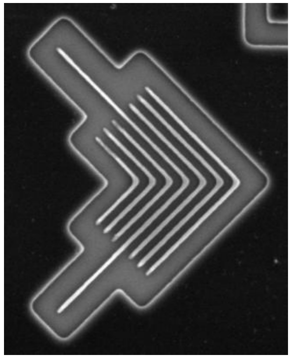
M1 mirror, PO Box 2



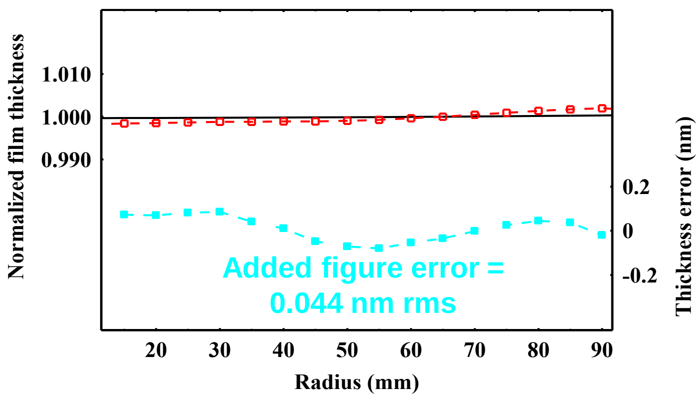
SES at ALS



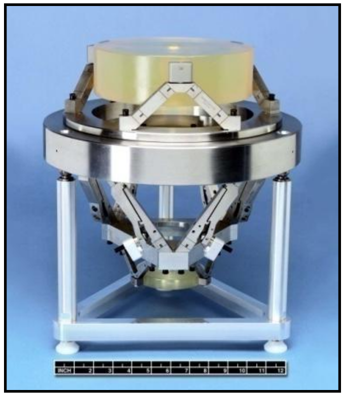
39-nm, 3:1 elbows *(Patrick Naulleau, LBNL)*



M2 mirror, MET Set 1



MET camera



Measured wavefront = 0.55 nm rms
K. A Goldberg et al, J. Vac. Sci. Technol. B 22(6), 2956-2961 (2005)

Printed 25 nm equal-line, and 29 nm isolated-line features
P. P. Naulleau et al, Proc. SPIE 5751, 56-63 (2005)

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EUVL optics: spatial frequency ranges and specifications

	Figure (rms)	MSFR (rms)	HSFR (rms)
Projection- Microfield (MET)	~0.1 nm	~0.1 nm	~0.1 nm
Projection – Scanning (α or production)	~0.1 nm (α) < 0.1 nm (prod.)	~0.1 nm (α) < 0.1 nm (prod.)	~0.1 nm (α) < 0.1 nm (prod.)
Collector	~ µrad	~0.1 nm	~0.1 nm

Critical (green): Figure for MET and Collector; MSFR for MET; Figure, MSFR and HSFR for Scanning.

Important (orange): HSFR for MET; MSFR and HSFR for Collector.

EUVL requires extremely challenging specifications for the figure, MSFR and HSFR to be simultaneously met on large-area optical surfaces

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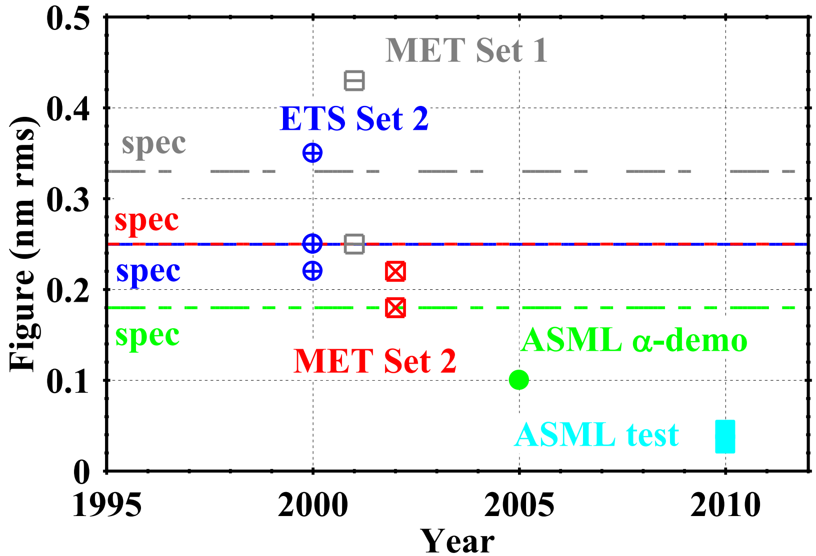
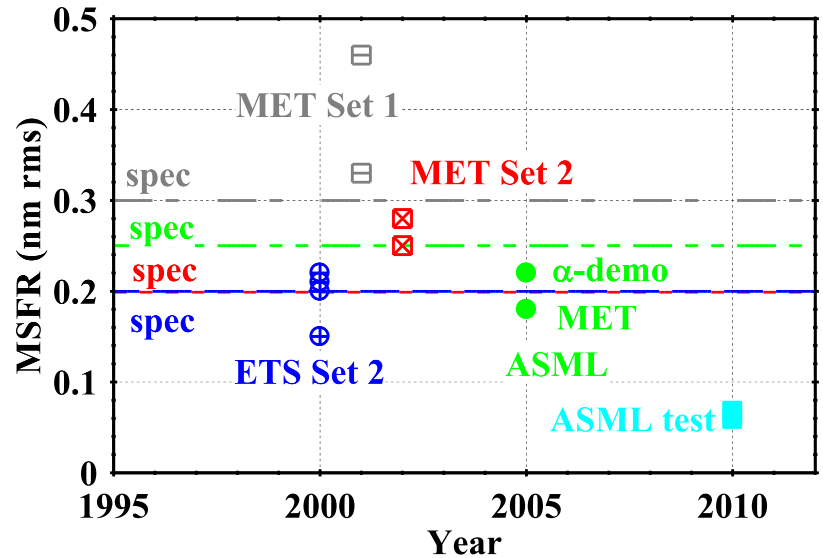
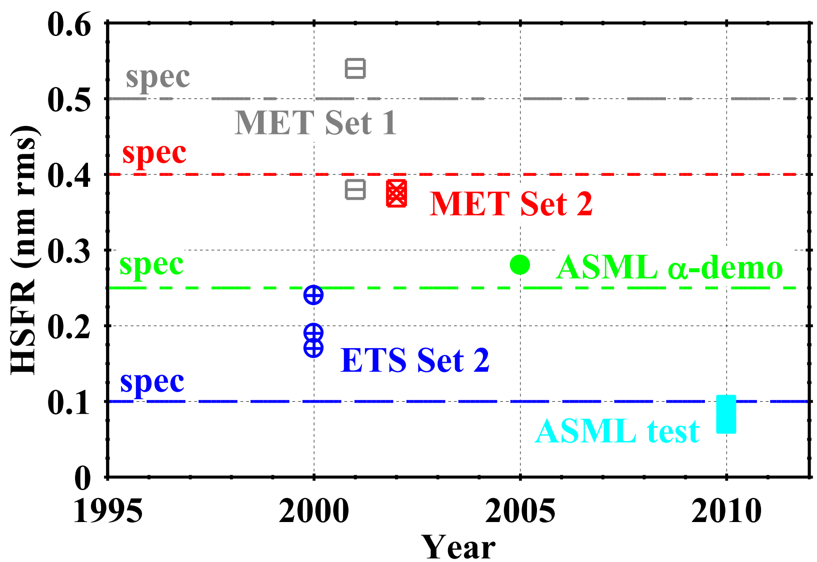
Historical evolution of figure, MSFR and HSFR of EUVL projection optics and comparison with specs



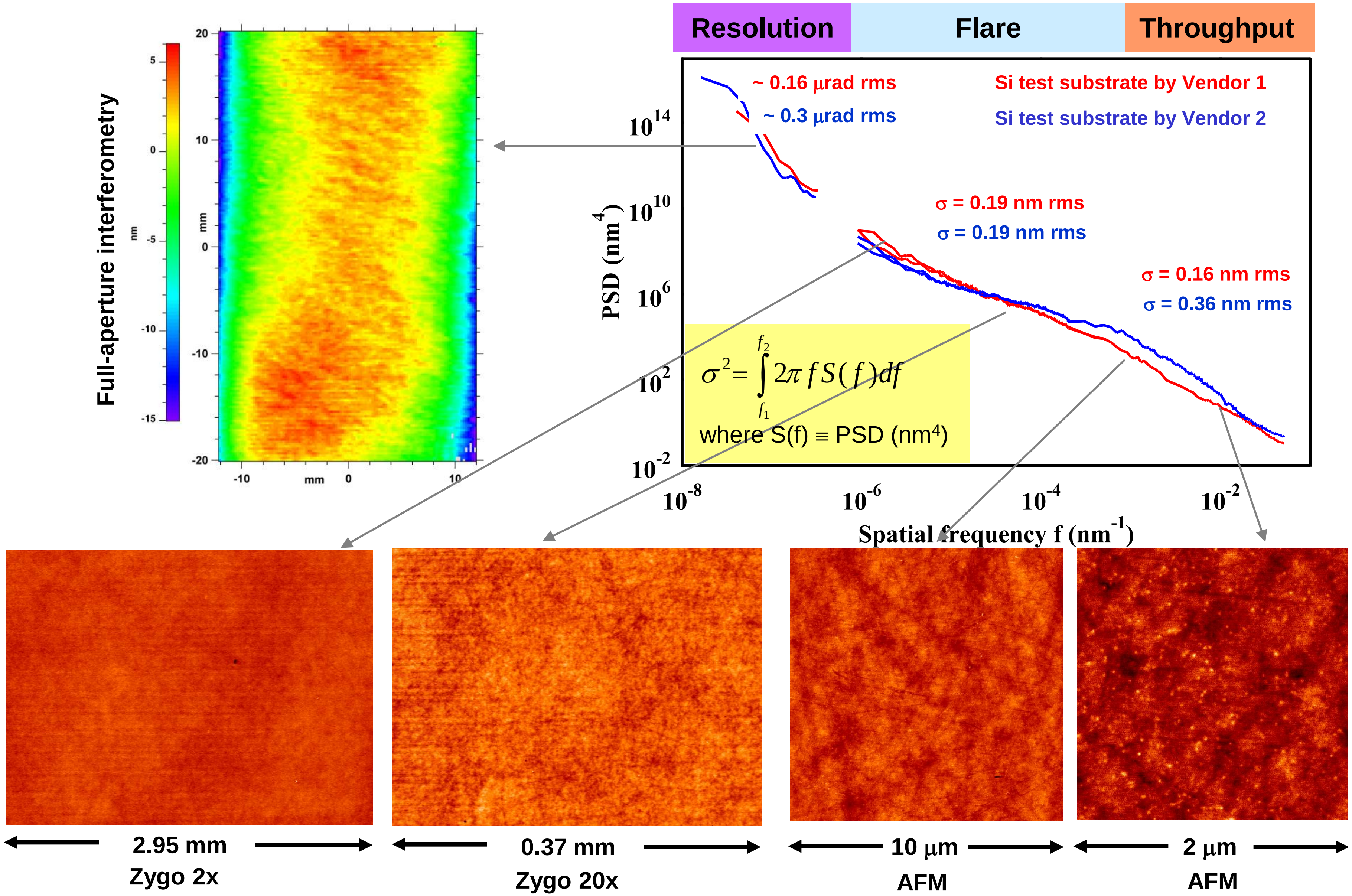




- Note that mirrors in plotted PO systems have different sizes, aspheric departures, etc
- Spatial frequency range of relevance for MSFR varies among plotted PO systems
- Nevertheless, a comparison among plotted results and specifications can reveal useful information on the evolution of polishing capabilities for EUVL projection optics

R.Soufli, et al, Proc. SPIE 4343, 51-59 (2001).
U. Dinger, et al, *Proc. SPIE* 5193, 18–28 (2004).
H. Meiling, et al, Proc. SPIE 5751 90-101 (2005).
R. Soufli, et al, Appl. Opt. 46, 3736–3746(2007).
M. Lowisch, et al, Proc. SPIE 7636, 763603 (2010).

EUVL mirrors require state-of-the-art metrology for the figure, MSFR and HSFR



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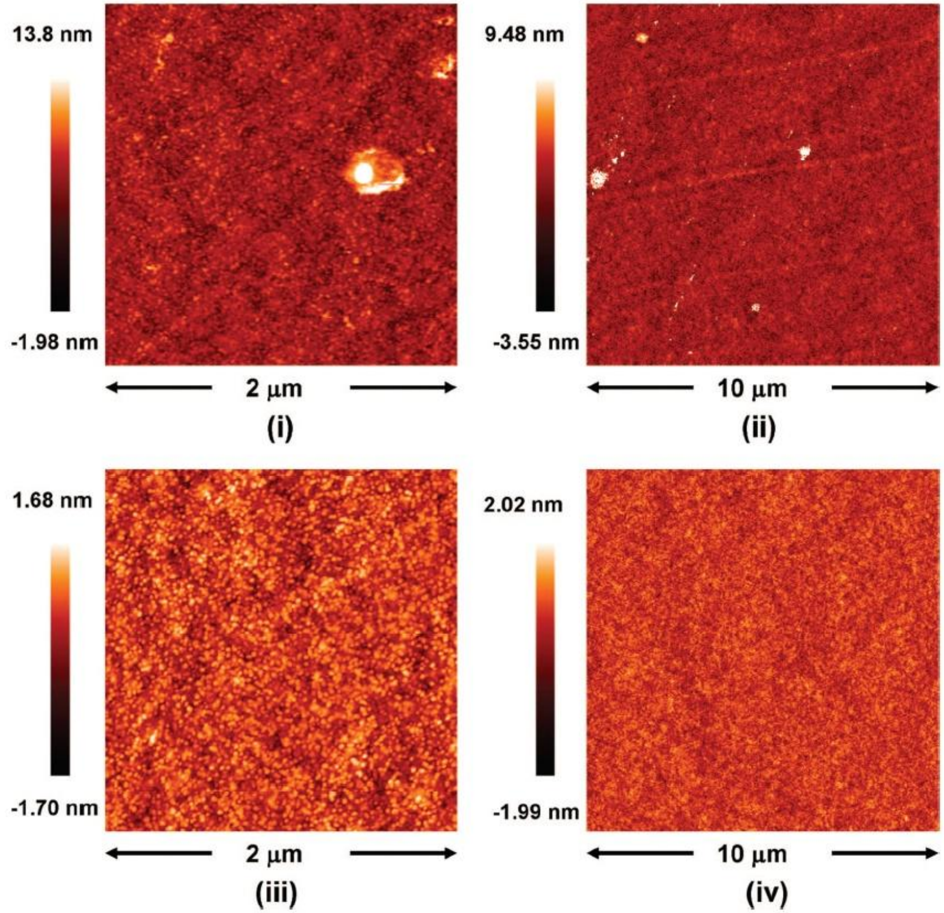
LLNL cleaning facility for optical substrates removes microscopic contamination while maintaining surface finish

Custom-developed process includes: rinsing in a water-based solution, followed by drying in N_2 environment using semiconductor-grade system (*YieldUp*™, pictured). Located next to multilayer deposition system.



LLNL AFM images on a Zerodur substrate: (i), (ii) as-received and (iii), (iv) after cleaning.

R. Soufli, S. L. Baker, *et. al*, Appl. Opt. 46, 3156-3163 (2007).

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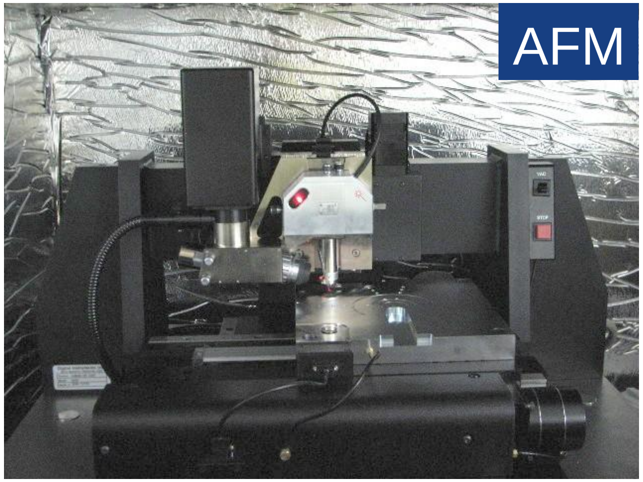
LLNL precision surface metrology lab

- *Digital Instruments Dimension 5000™* Atomic Force Microscope (AFM) includes acoustic hood and vibration isolation. *Noise level = 0.03 nm rms*
- *Zygo NewView™* Optical Profiling Microscope
- *LEO 1560* ™ Scanning Electron Microscope (SEM)
- Full aperture interferometers (not shown)



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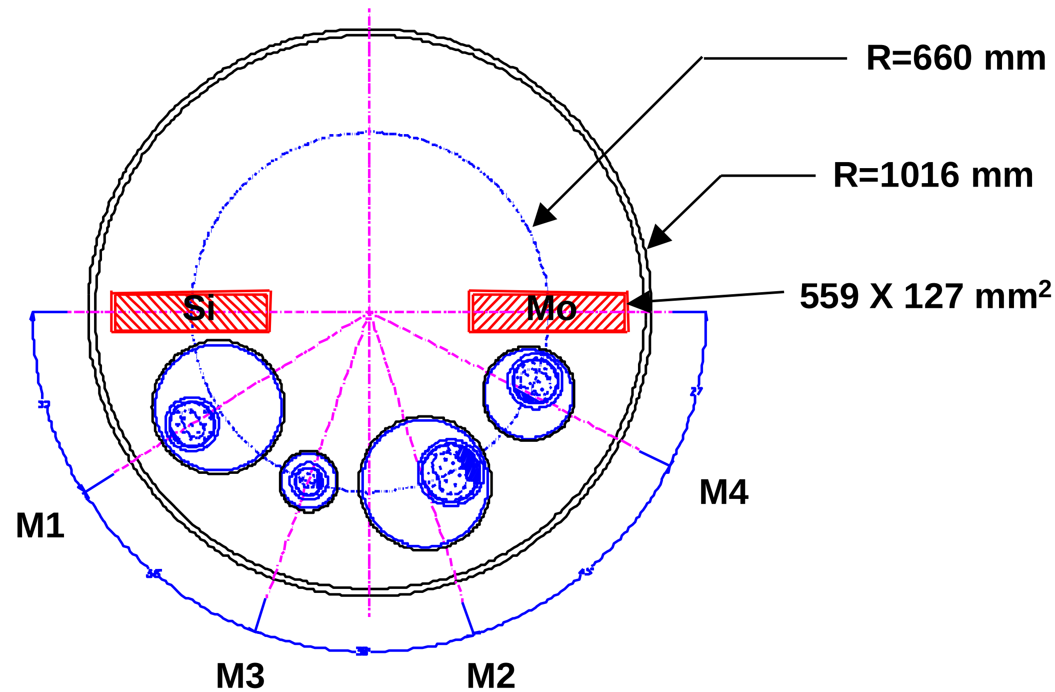
DC-magnetron sputtering is a proven deposition technique for the multilayer-coating of EUVL camera and collector optics

Underneath view of LLNL chamber lid with 5 sputtering targets



4-mirror and 2-mirror EUV cameras have been multilayer-coated in a single deposition run, achieving optic-to-optic wavelength matching within $1\sigma = 0.010$ nm. Maximum optic size that can fit in chamber is 450 mm in diameter

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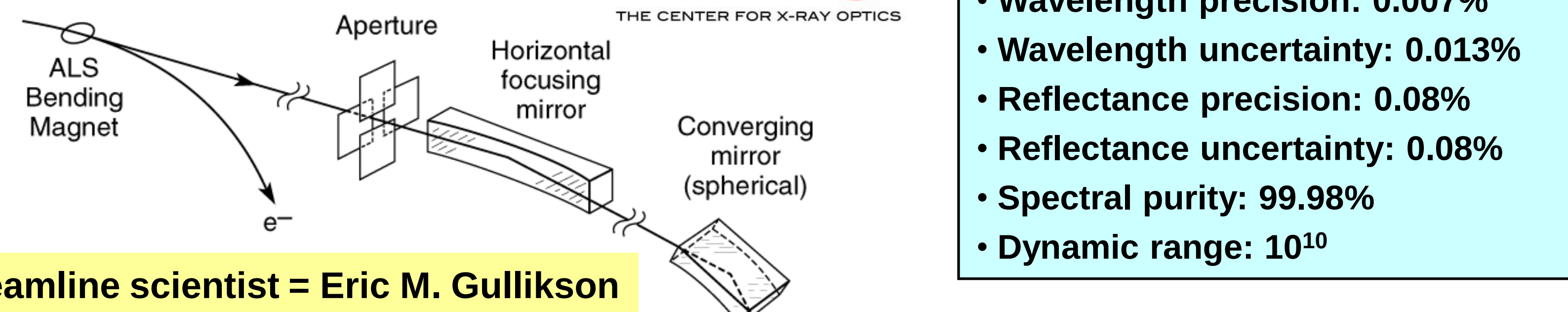
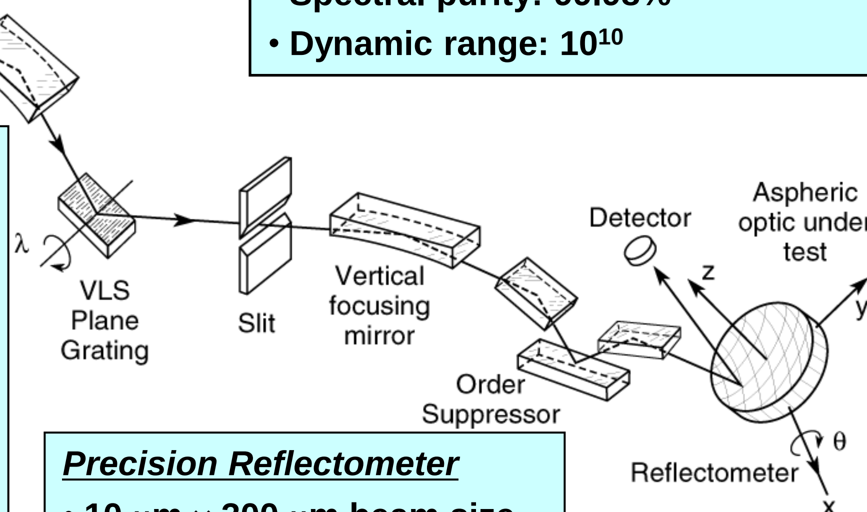
CXRO's beamline 6.3.2. at the ALS synchrotron (LBNL) is the world reference standard for EUV/x-ray reflectance, scattering and transmission measurements

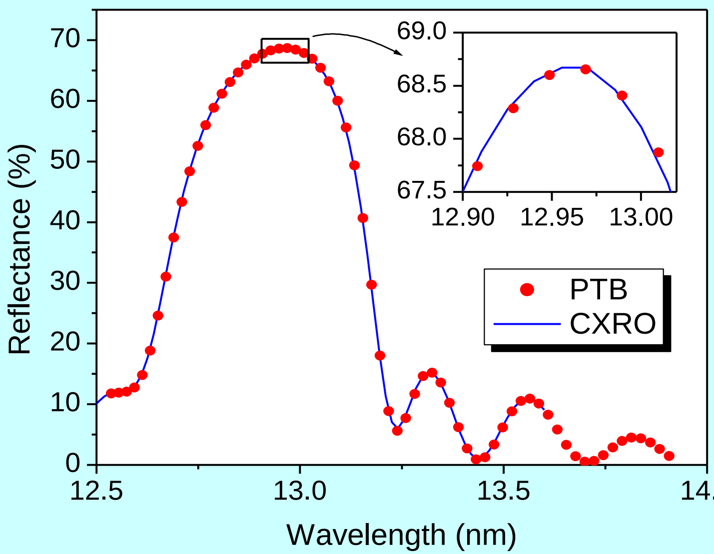
1-50 nm wavelength range

Beamline Specifications

- **Wavelength precision: 0.007%**
- **Wavelength uncertainty: 0.013%**
- **Reflectance precision: 0.08%**
- **Reflectance uncertainty: 0.08%**
- **Spectral purity: 99.98%**
- **Dynamic range: 10^{10}**

Beamline scientist = Eric M. Gullikson



Cross-calibration results are shown between beamline 6.3.2 (CXRO) and PTB, BESSY synchrotron (Berlin, Germany)

Precision Reflectometer

- **10 μm × 300 μm beam size**
- **10 μm positioning precision**
- **Angular precision 0.01 deg**
- **6 degrees of freedom**
- **Sample size up to 200 mm**

LG156

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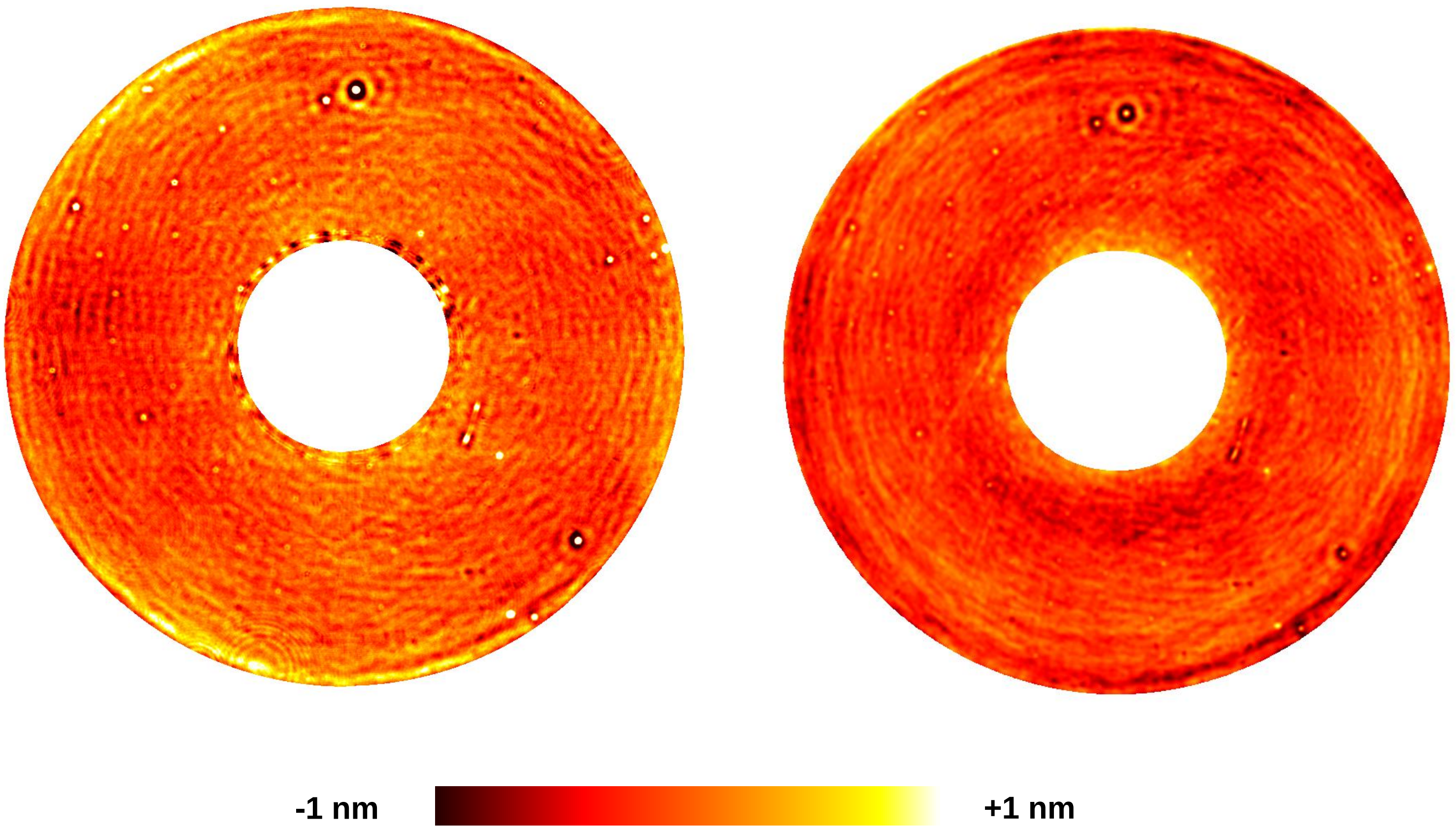
Side-by-side comparison of the Zeiss and LLNL full-aperture interferometry for the MET primary substrate figure

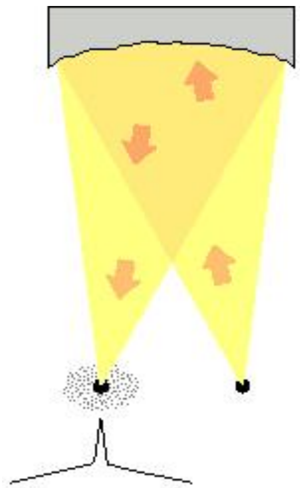
Zeiss interferometer
Flipped and rotated to register
0.22 nm rms when clipped and binned

LLNL Phase-shifting diffraction (PSDI) interferometer
Magnification adjusted fractionally by 1.7×10^{-5}
0.29 nm rms when clipped and binned



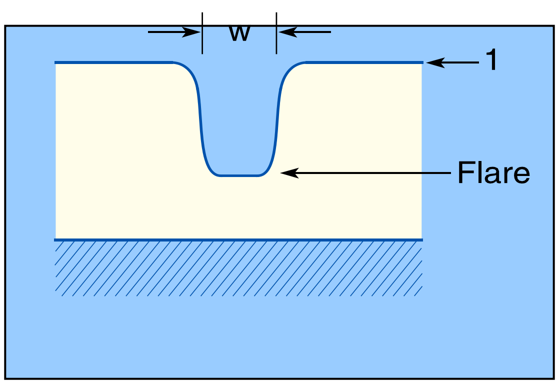
G. E. Sommargren, D. W. Phillion, M. A. Johnson, N. Q. Nguyen, A. Barty, F. J. Snell, D. R. Dillon, L. S. Bradsher, "100-picometer interferometry for EUVL", Proc. SPIE 4688 316-328 (2002).

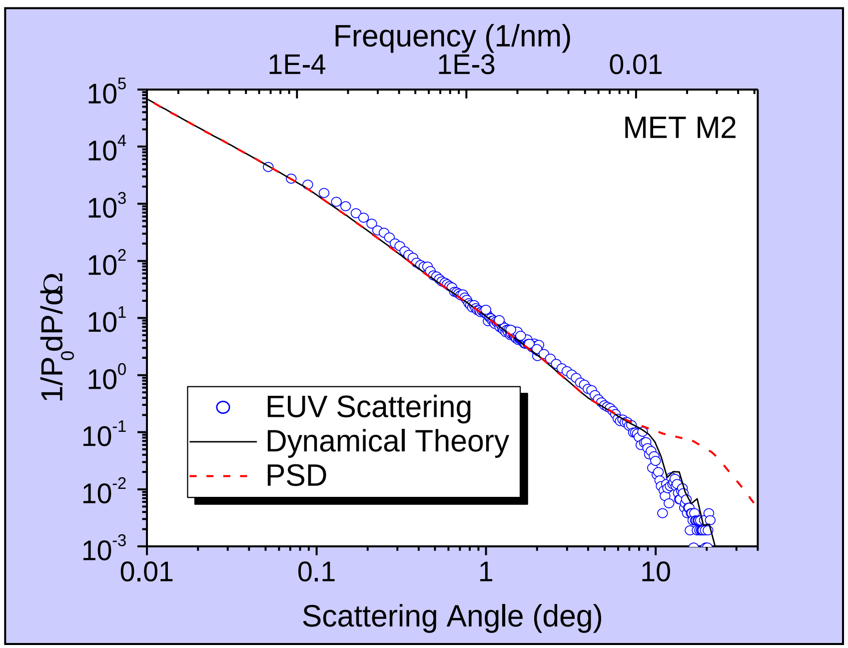
EUV optics are especially susceptible to roughness and scattering



Scattered light leads to reduced contrast and throughput

- As the wavelength λ is reduced, scattering increases with $1/\lambda^2$.
- Roughness of EUV optics must be controlled, otherwise scattering will result in loss of contrast or Flare.
- The scattering angular distribution has been measured and can be predicted from the surface roughness.





Courtesy E. M. Gullikson (LBNL)

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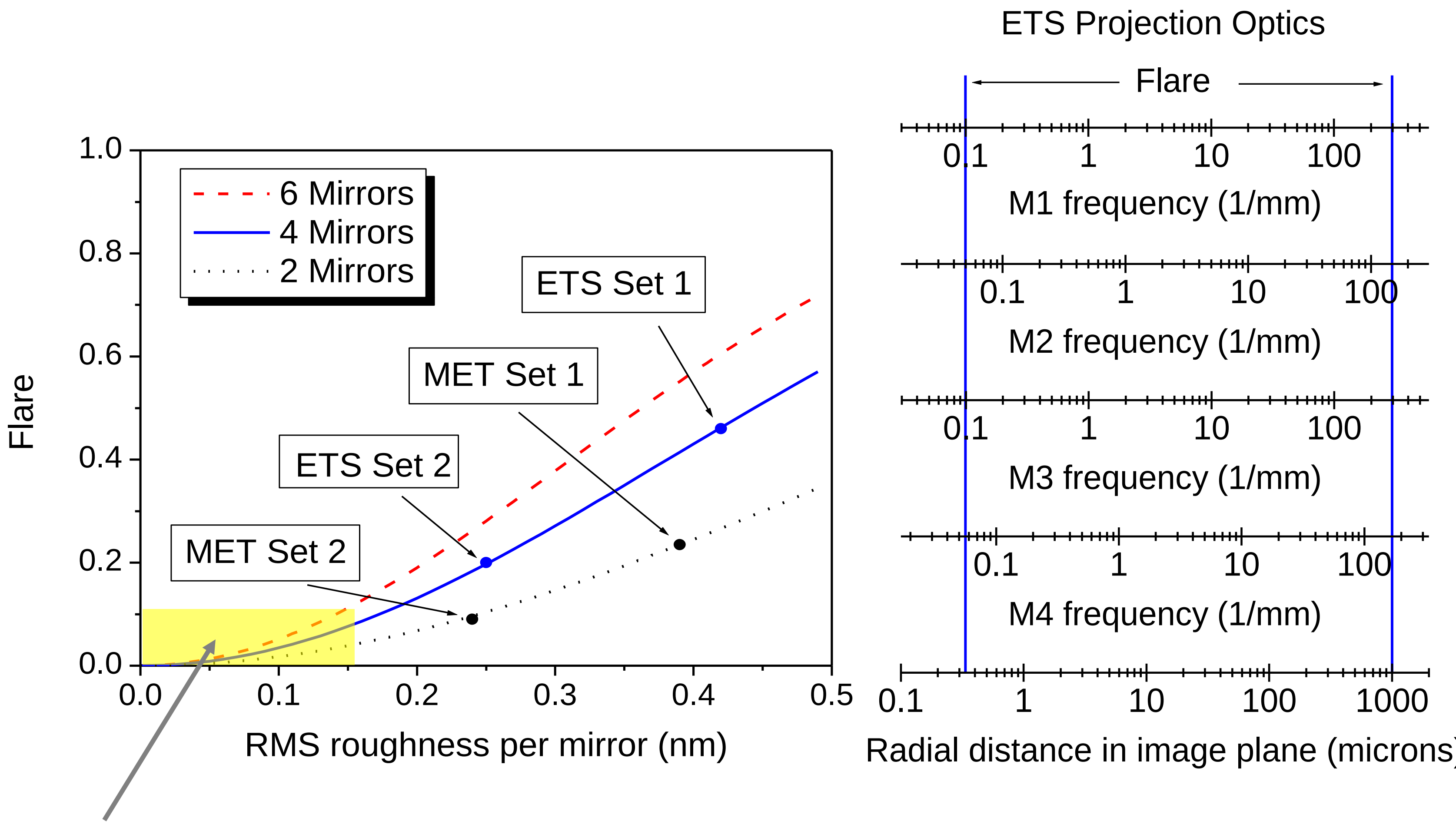
Improved MSFR leads to lower flare



< 10 % flare for a 6 or 8-mirror system requires MSFR < 0.15 nm rms

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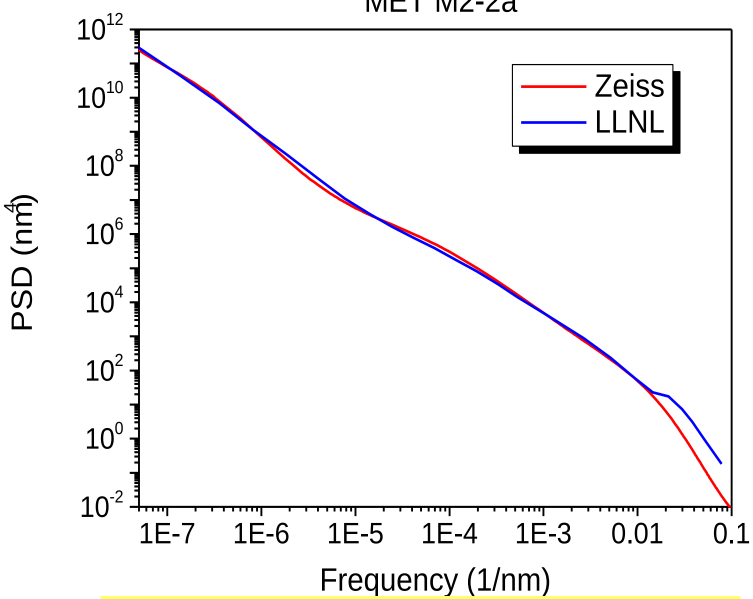
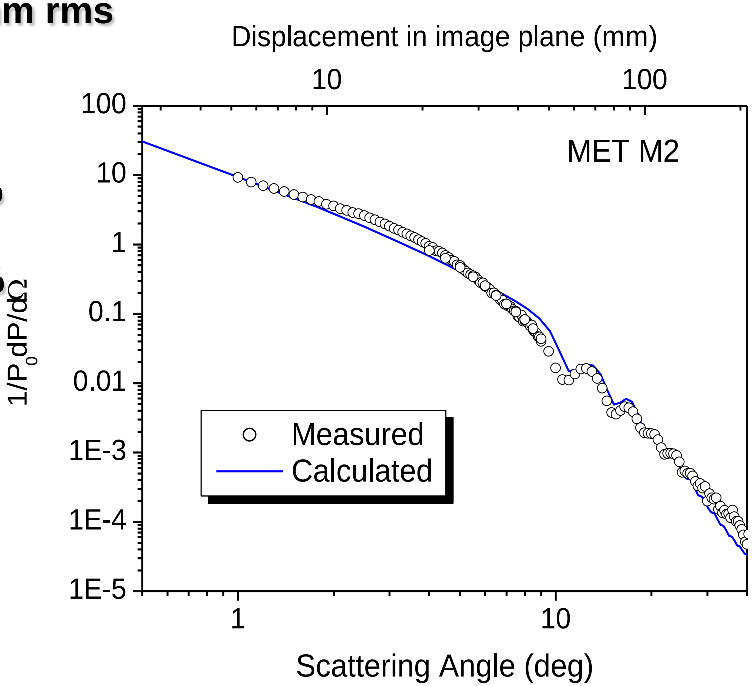
Metrology cross-validation between different facilities and independent measurements and models

	MET 1 (primary)	MET 2 (secondary)
Substrate HSFR	0.37 nm rms	0.32 nm rms
Expected loss ΔR	6.1%	5.2%
Measured R	61.2%	62.4%
R + ΔR	67.3%	67.6%



LLNL / Zeiss metrology validation



LLNL metrology / scattering model / ALS scattering measurements validation

R. Soufli *et al*., *Appl. Opt.* 46, 3736-3746 (2007)

D. G. Stearns, "Stochastic model for thin film growth and erosion," Appl. Phys. Lett. 62, 1745-7 (1993).
E. M. Gullikson, "Scattering from normal incidence EUV optics", Proc. SPIE 3331, 72-80 (1998).
D.G. Stearns *et al*, "Non-specular x-ray scattering in a multilayer-coated imaging system", J. App. Phys. 84, 1003-1028 (1998).

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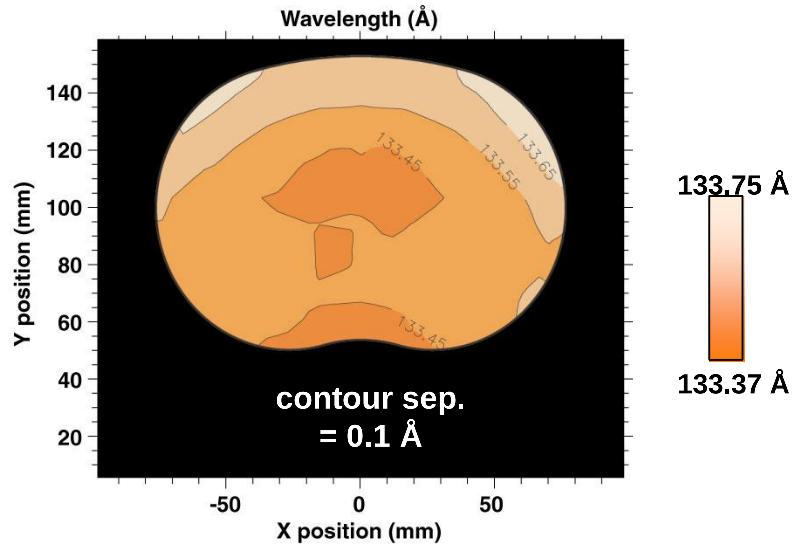
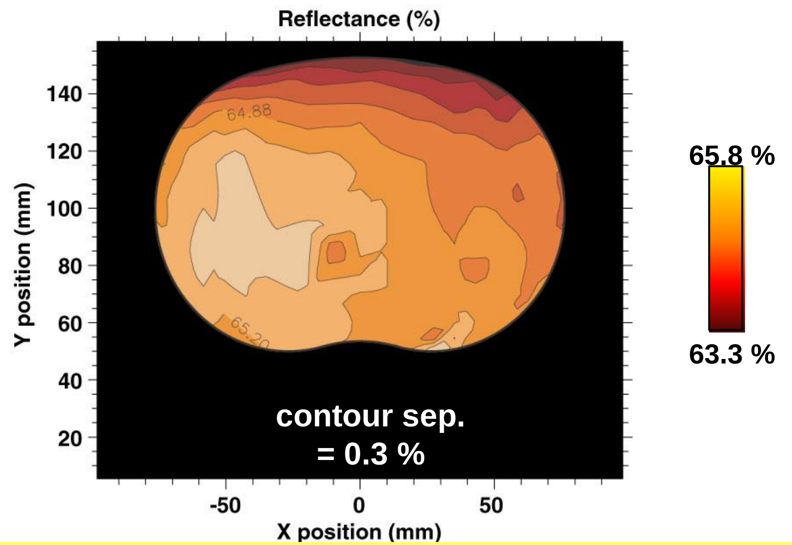
Accurate EUV reflectance measurements provide an additional method to verify substrate HSFR uniformity





2D contour maps of ETS optic M2 obtained at ALS beamline 6.3.2

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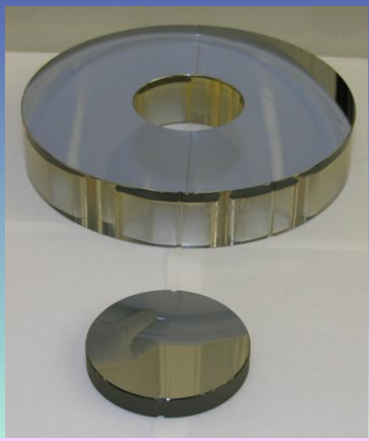
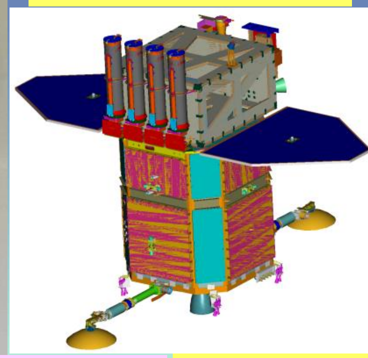
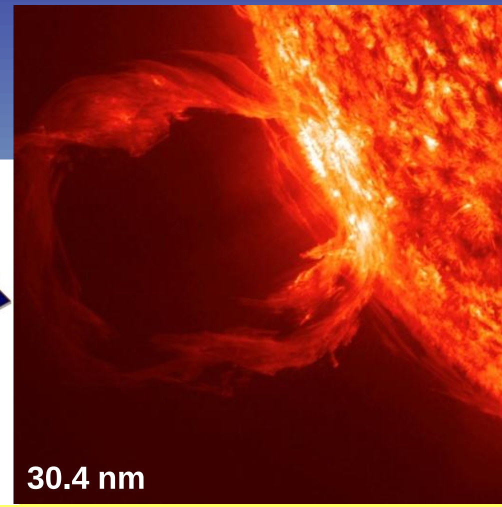
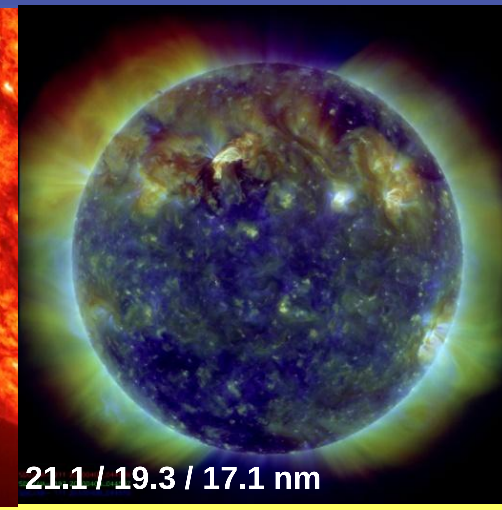
We have developed EUV multilayer optics and precision metrologies for next-generation solar physics and space weather satellites



7 EUV wavelengths
(9.4 nm to 33.5 nm)

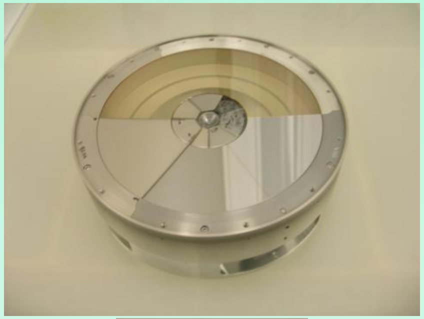


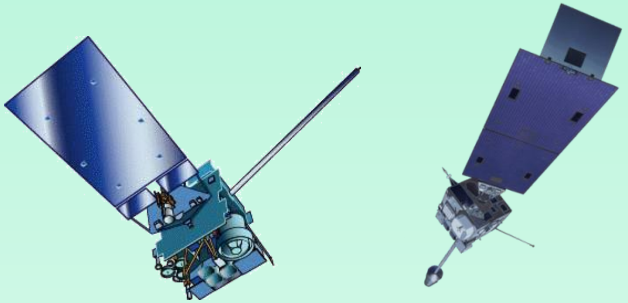


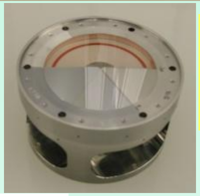


R. Soufli, *et al*, Proc. SPIE 5901, 59010M (2005).
R. Soufli, *et al*, Appl. Opt. 46, 3156-3163 (2007).
P. Boerner *et al*, Solar Physics (2011).
J. R. Lemen *et al*, Solar Physics (2011).

NASA's Solar Dynamics Observatory (SDO). Launch date: February 11, 2010.
http://sdo.gsfc.nasa.gov





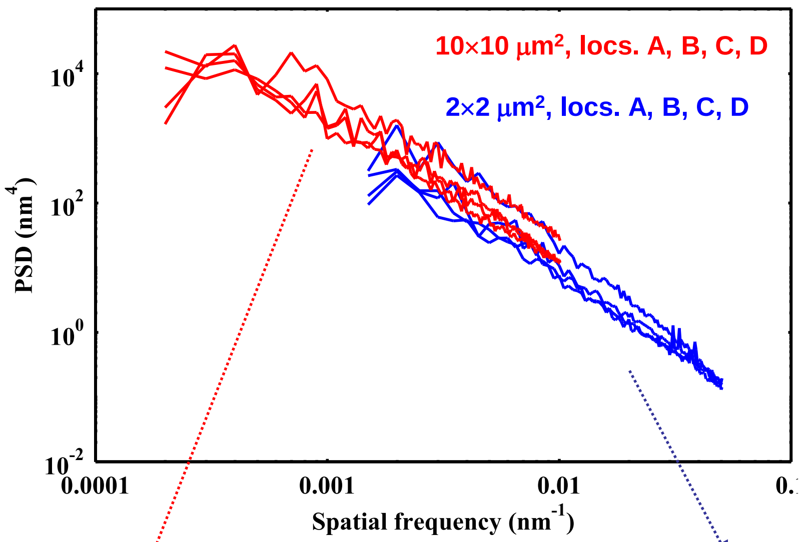


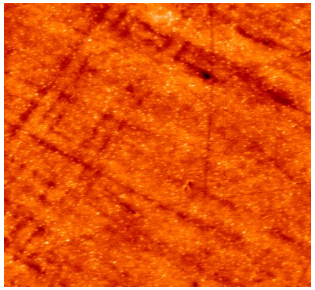
Multilayer-coated test mirrors for NASA/NOAA's GOES-R space weather satellite. 6 EUV wavelengths , 9.4 nm to 30.4 nm.
Launch date: 2014

AFM measurements reveal surface morphology related to specific polishing techniques

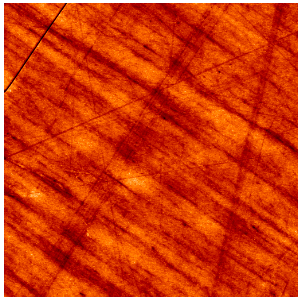
Atmospheric Imaging Assembly (AIA) instrument, Solar Dynamics Observatory (SDO)

Vendor 1, Zerodur substrate



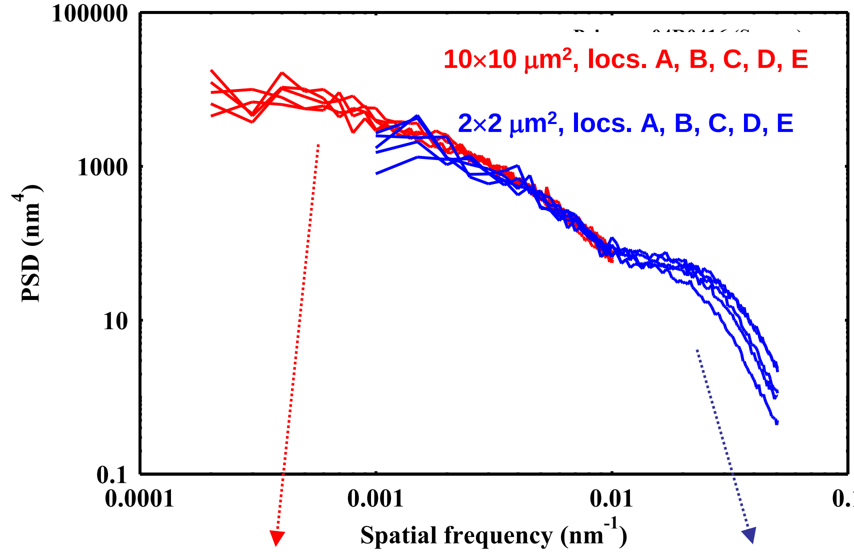


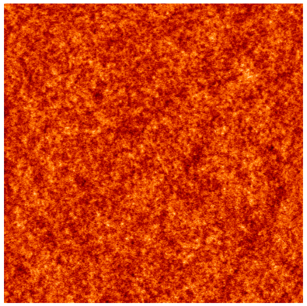
10×10 μm², loc. B



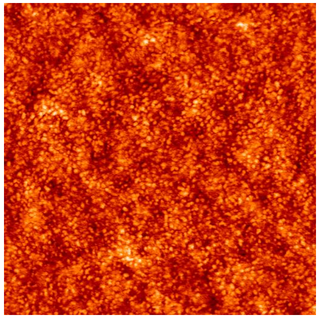
2×2 μm², loc. B
σ = 0.14 nm rms

Vendor 2, Zerodur substrate





10×10 μm², loc. E



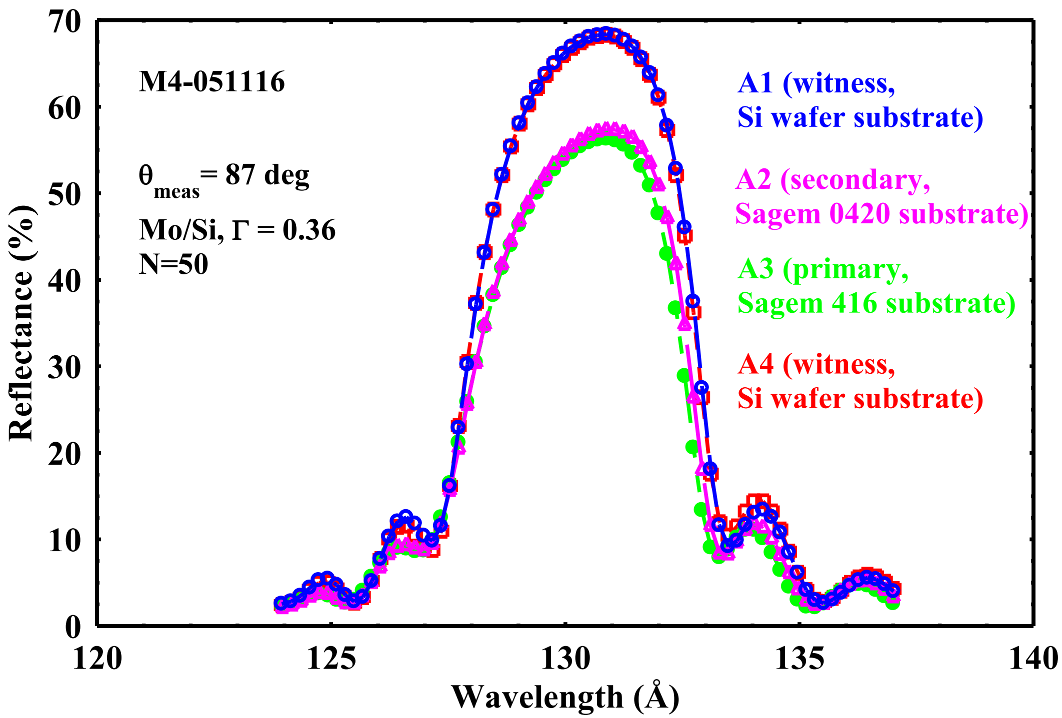
2×2 μm², loc. E
σ = 0.51 nm rms

$$\sigma^2 = \int_{f_1}^{f_2} 2\pi f S(f) df$$

where S(f) ≡ PSD (nm^4),
$f_1 = 10^{-3}\ nm^{-1}$, $f_2 = 5\times10^{-2}\ nm^{-1}$

R. Soufli, S. L. Baker, D. L. Windt, E. M. Gullikson, J. C. Robinson, W. A. Podgorski, L. Golub, Appl. Opt. 46, 3156-3163 (2007)

EUV reflectance of multilayer-coated mirrors is consistent with substrate roughness measured by AFM



Flight mirror	Primary (Sagem 04R0416)	Secondary (Sagem 04R0420)
Substrate roughness (Å rms)	5.0	5.2
R_{peak} (%)	56.2	58.8
ΔR* (%, absolute)	8.5	8.4
R_{peak} +ΔR	64.7	67.2

***ΔR** = predicted reflectance loss due to high-spatial frequency roughness, based on AFM measurements of the substrate and on a multilayer growth model. Calculation performed by E. M. Gullikson, LBNL.

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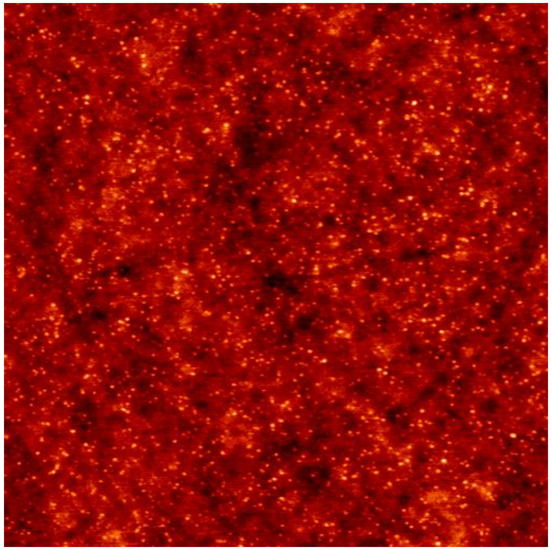
Zerodur as substrate material for EUVL projection optics

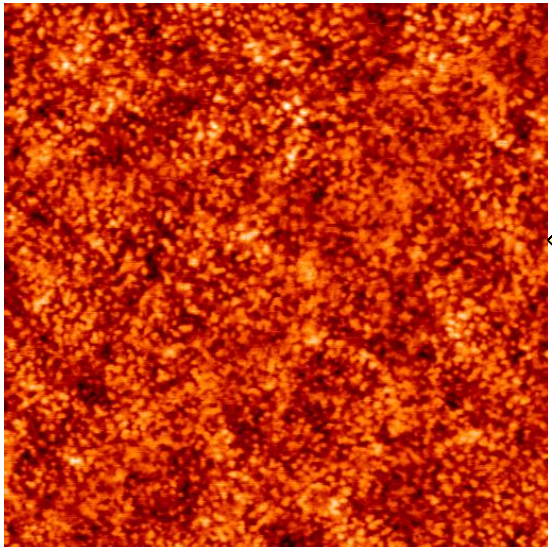
- Zerodur® (Schott) is an ultra-low-expansion glass ceramic
- 2-phase material: fused silica (amorphous) and quartz (crystalline).
- It has been used to make the most accurate projection/imaging optics for EUVL, EUV solar physics (TRACE, SDO, GOES-R, etc), x-ray astronomy (Chandra), and other applications
- Lowest achievable HSFR and MSFR may be ultimately limited due to dual phase of the material

Polished by computer controlled grinding/polishing



AFM 2×2 μm^2, HSFR = 0.14 nm rms

Polished by ion beam



AFM 2×2 μm^2, HSFR = 0.48 nm rms

In both AFM images, lighter-color areas represent quartz crystallites protruding within amorphous silica

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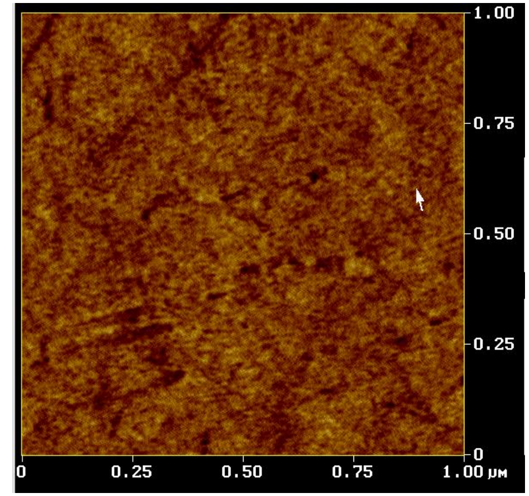
ULE as candidate substrate material for EUVL projection optics

- ULE® (Corning) is an ultra-low-expansion glass
- ULE = titania silicate = SiO_2 (> 90%)+ TiO_2 (< 10%)
- It has been used to make super-polished mask blanks for EUVL, optics for astronomy (Hubble, Gemini) and other applications
- Striae and inhomogeneities have been preventing its use as substrate for EUVL projection optics

Courtesy: Chris Walton and Cindy Larson (LLNL)



AFM 1×1 μm^2, HSFR = 0.16 nm rms. Obtained on ULE mask blank

HSFR =0.06 nm rms has been measured on ULE at LLNL [P. Mirkarimi et al, Appl. Opt. 40, 62-70 (2001)].

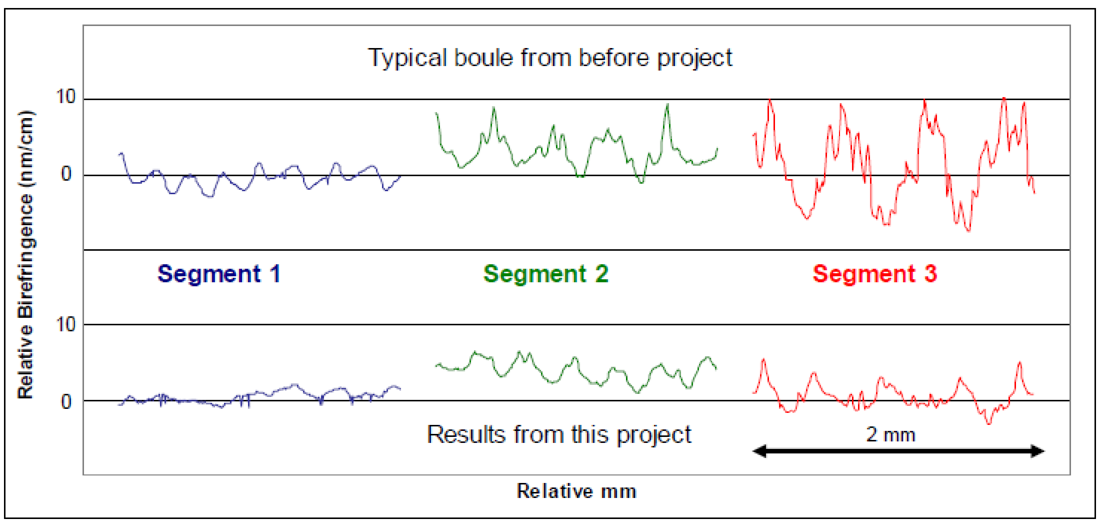


Figure 8: Striae differences showing a recently formed boule to one that was formed before this project was started.

Recent progress in diminishing striae is promising towards use of ULE for EUVL projection optics

W. Rosch, L. Beall, J. Maxon, R. Sabia, R. Sell, "Characterization of striae in ULE® for EUVL optics and masks" Proc. SPIE 6151, 615122 (2006).

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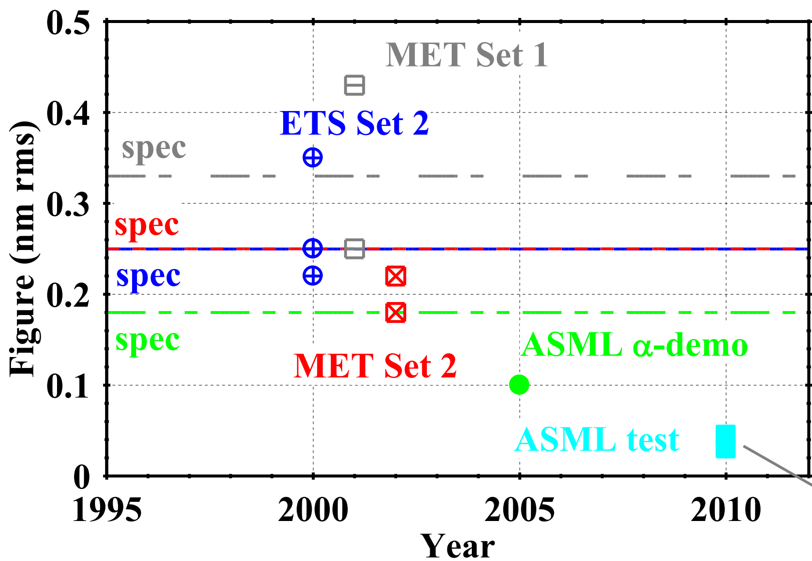
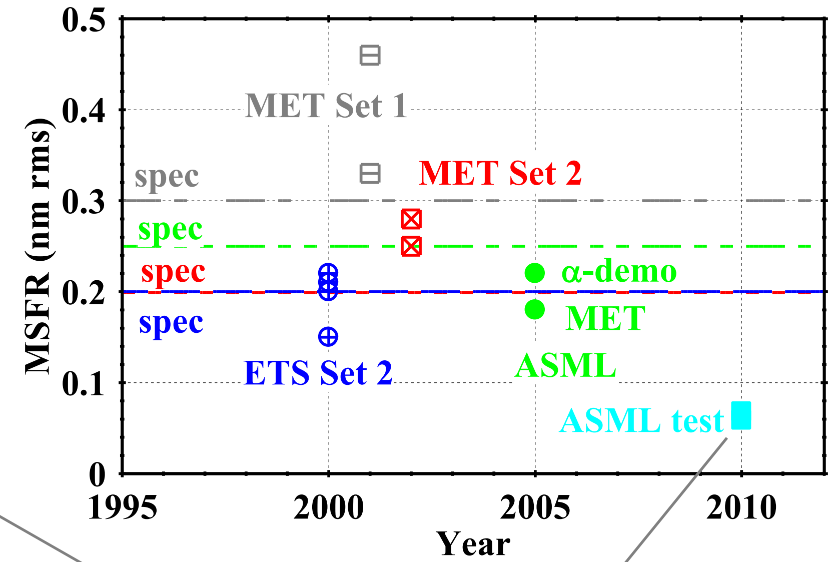
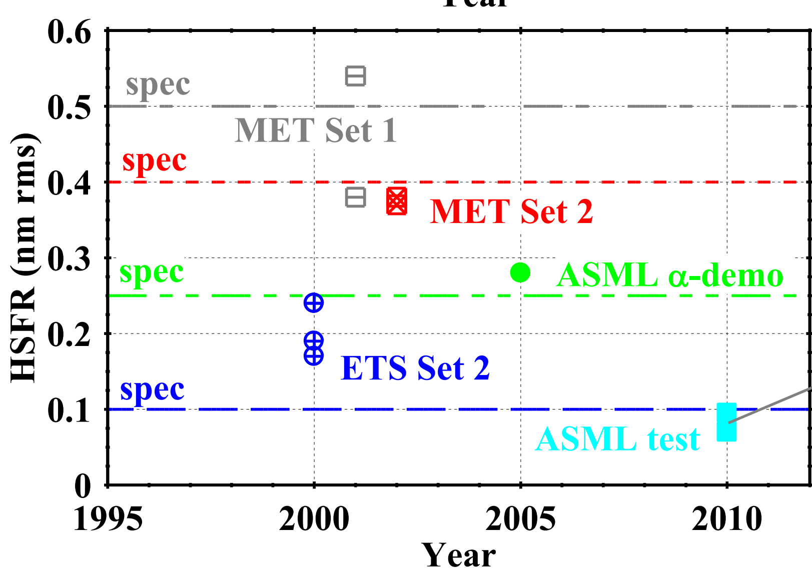
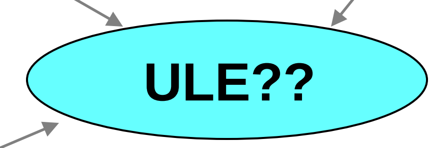
Historical evolution of figure, MSFR and HSFR of EUVL projection optics and comparison with specs



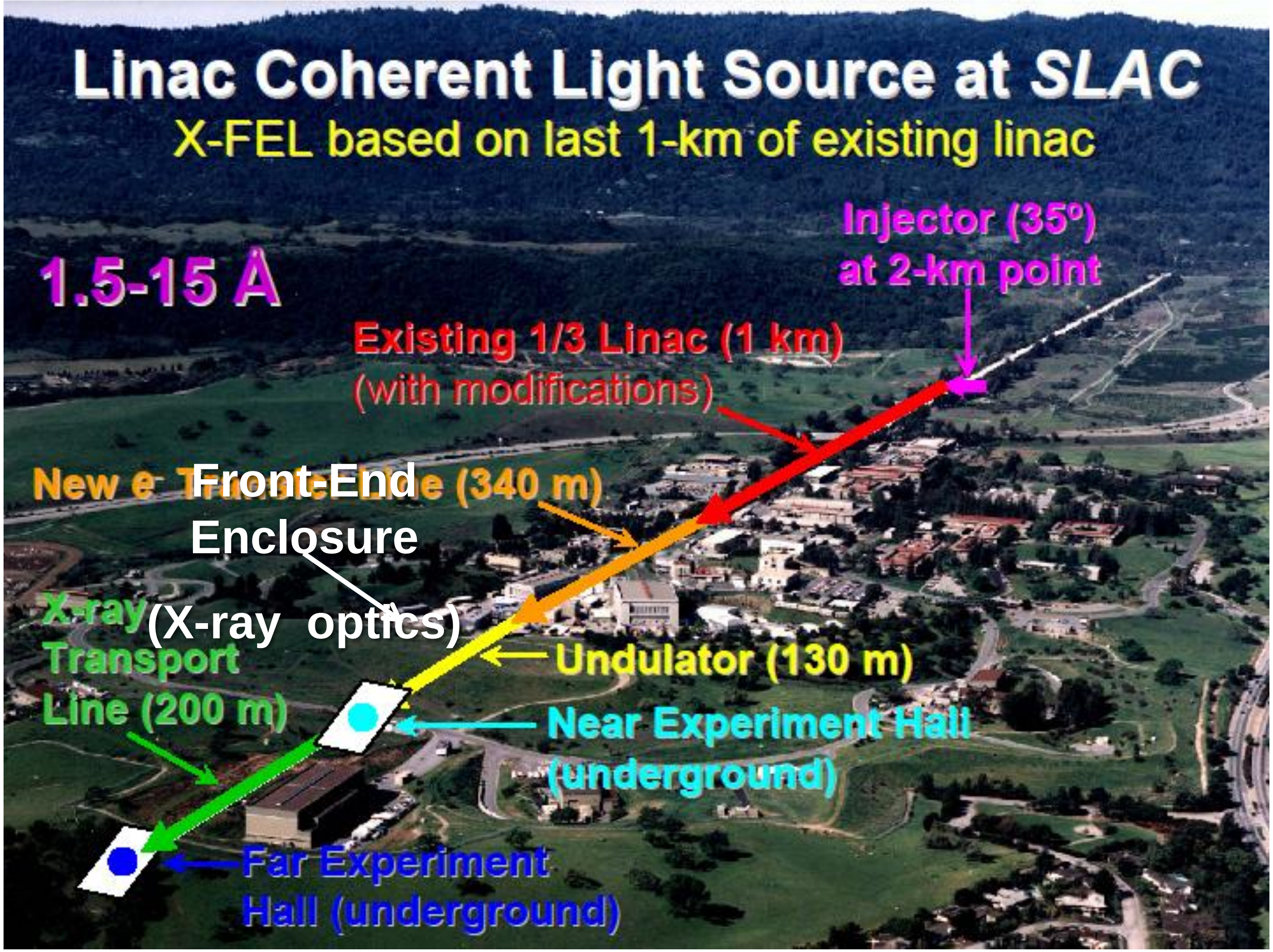






R.Soufli, et al, Proc. SPIE 4343, 51-59 (2001).
U. Dinger, et al, *Proc. SPIE* 5193, 18–28 (2004).
H. Meiling, et al, Proc. SPIE 5751 90-101 (2005).
R. Soufli, et al, Appl. Opt. 46, 3736–3746(2007).
M. Lowisch, et al, Proc. SPIE 7636, 763603 (2010).

The advance of x-ray Free Electron Laser (FEL) sources has pushed the limits of x-ray optics fabrication



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Si substrate specifications for the LCLS are driven by the need to preserve the coherence of the x-ray FEL beam

Error Category		Specification	Spatial Wavelength
Figure	Height Error	≤ 2.0 nm rms‡	1 mm to Clear Aperture†
	Slope Error	≤ 0.25 μrad rms	
Mid-Spatial Roughness		≤ 0.25 nm rms	2 μm to 1 mm
High-Spatial Roughness		≤ 0.4 nm rms	20 nm to 2 μm

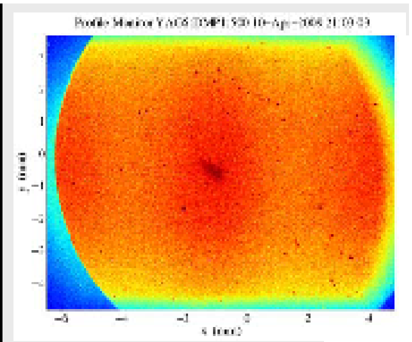
† SOMS mirrors: Flat, planar, 250×30×50 mm^3, Clear Aperture = 175×10 mm^2

† HOMS mirrors: Flat, planar, 450×30×50 mm^3, Clear Aperture = 385×15 mm^2

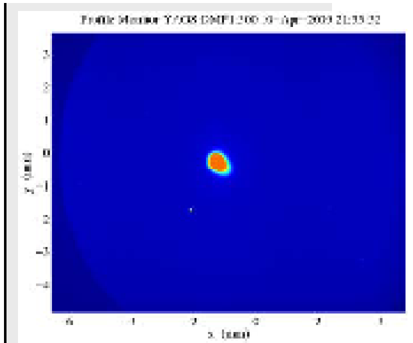
‡2 nm rms height error derived from Maréchal criterion: wavefront error < λ/14 rms

M. Pivovaroff, R. M. Bionta, T. J. Mccarville, R. Soufli, P. M. Stefan, "Soft X-ray mirrors for the Linac Coherent Light Source", Proc. SPIE 6705, 67050O (2007).

R. Soufli, M. J. Pivovaroff, S. L. Baker, J. C. Robinson, E. M. Gullikson, T. J. McCarville, P. M. Stefan, A. L. Aquila, J. Ayers, M. A. McKernan, R. M. Bionta, "Development, characterization and experimental performance of x-ray optics for the LCLS free-electron laser" Proc. SPIE 7077, 707716 (2008).

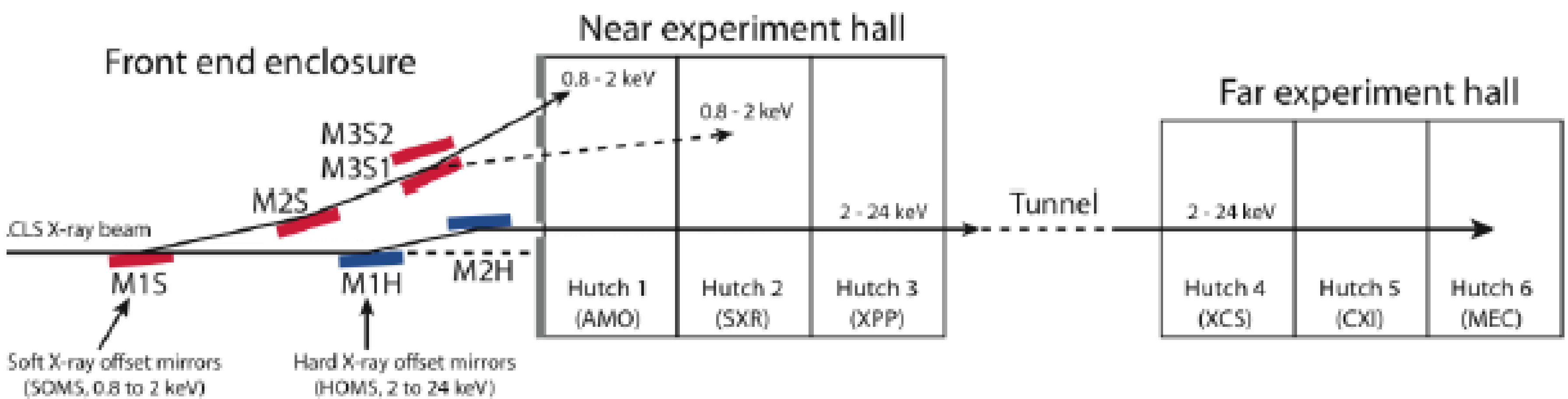


Spontaneous Beam



FEL beam

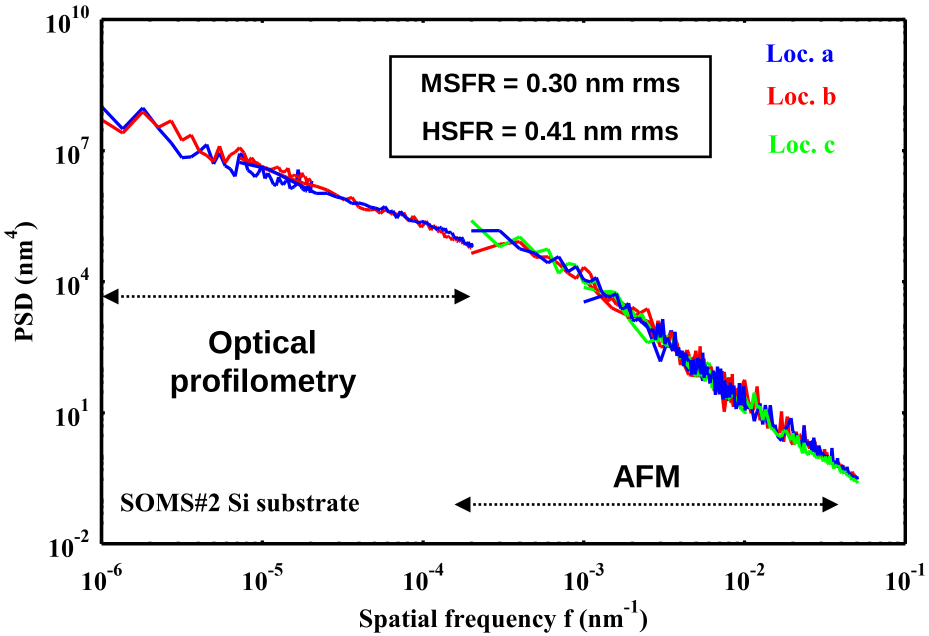
- LLNL led the construction of the LCLS front-end enclosure x-ray optics and diagnostics, and developed coatings and metrologies for x-ray mirrors and gratings for the AMO, SXR , CXI and MEC beamlines
- About 20 diffraction-limited, grazing incidence x-ray mirrors (consisting of a Si substrate coated with B_4C or SiC materials) will be ultimately installed at LCLS

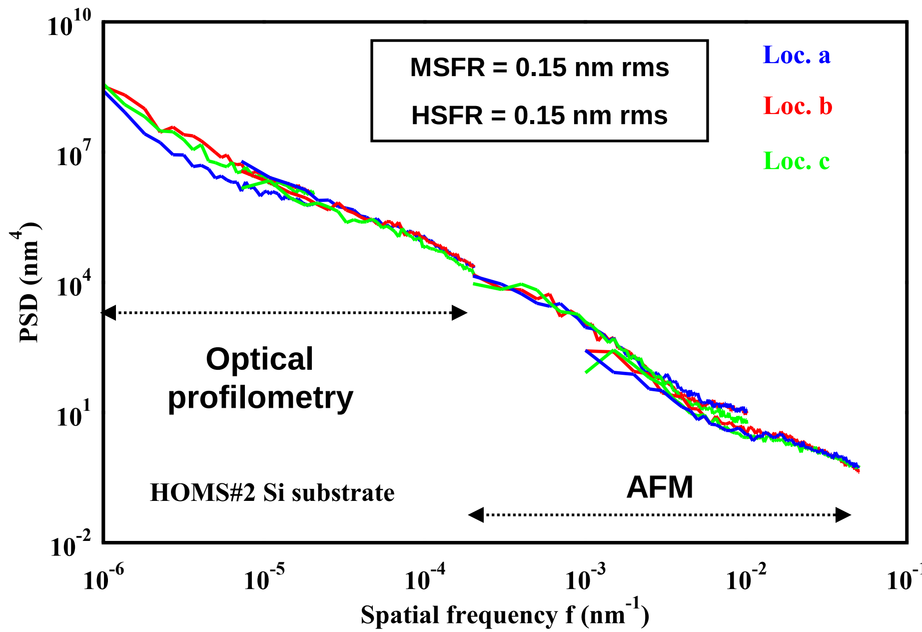


Unique requirements for LCLS x-ray mirrors:

- **Withstand instantaneous peak power of LCLS FEL (B_4C and SiC coating materials)**
- **Coherence/intensity preservation of LCLS wavefront (< 2 nm rms figure, 0.25 nm rms MSFR)**
- **Pointing stability and resolution (< 900 nrad for soft x-ray, < 90 nrad for hard x-ray mirrors)**

Diffraction-limited, grazing incidence Si substrates with EUVL-quality figure and finish have been manufactured for the LCLS x-ray FEL





Mirror #	Figure (nm RMS)	Slope error (μrad RMS)
SN1	1.8	0.19
SN2	1.3	0.2
SN3	1.2	0.37
SN4	0.64	0.14
SN5	1.4	0.37

Measured along central 200 mm

Mirror #	Figure (nm RMS)	Slope error (μrad RMS)
SN1	2.4	0.27
SN2	1.0	0.27
SN3	2.0	0.22
SN4	1.5	0.23

Measured along central 420 mm

SOMS Si substrates manufactured by InSync (Albuquerque, New Mexico)

HOMS Si substrates manufactured by Carl Zeiss Laser Optics (Oberkochen, Germany)

A. Barty, R. Soufli, T. McCarville, S. L. Baker, M. J. Pivovaroff, P. Stefan and R. Bionta, "Predicting the coherent X-ray wavefront focal properties at the Linac Coherence Light Source (LCLS) X-ray free electron laser", Optics Express 17, 15508-15519 (2009)

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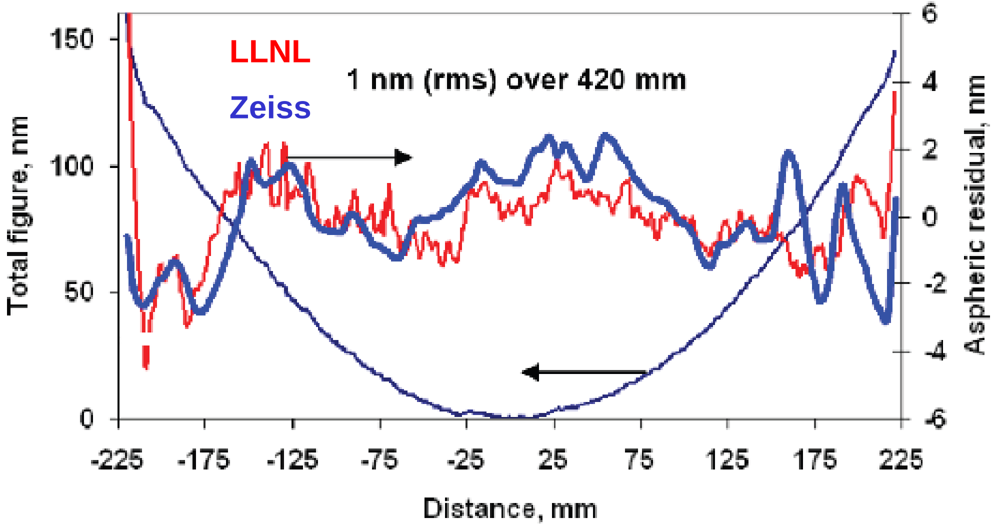
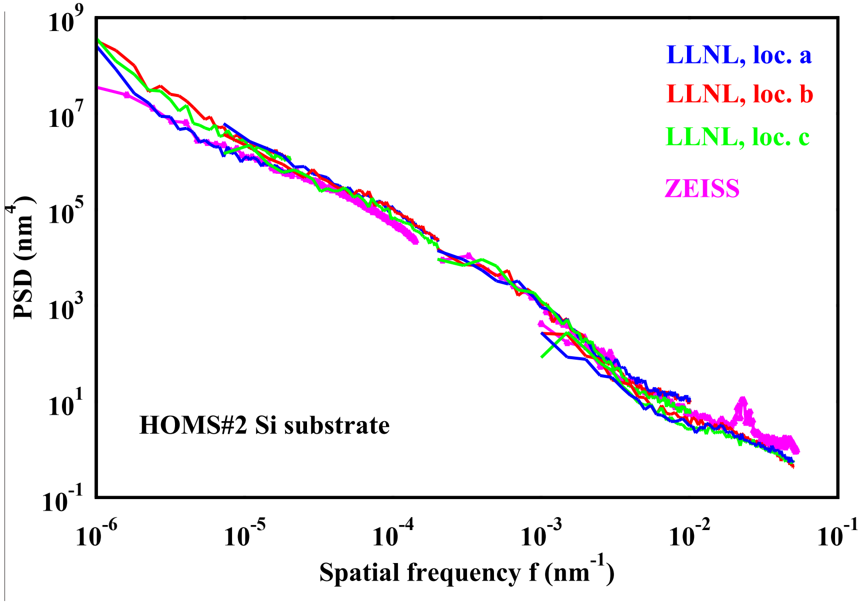
Recent cross-validation of LLNL and Zeiss metrology in the figure, MSFR and HSFR





Zeiss measurements courtesy of Helge Thiess, Carl Zeiss Laser Optics

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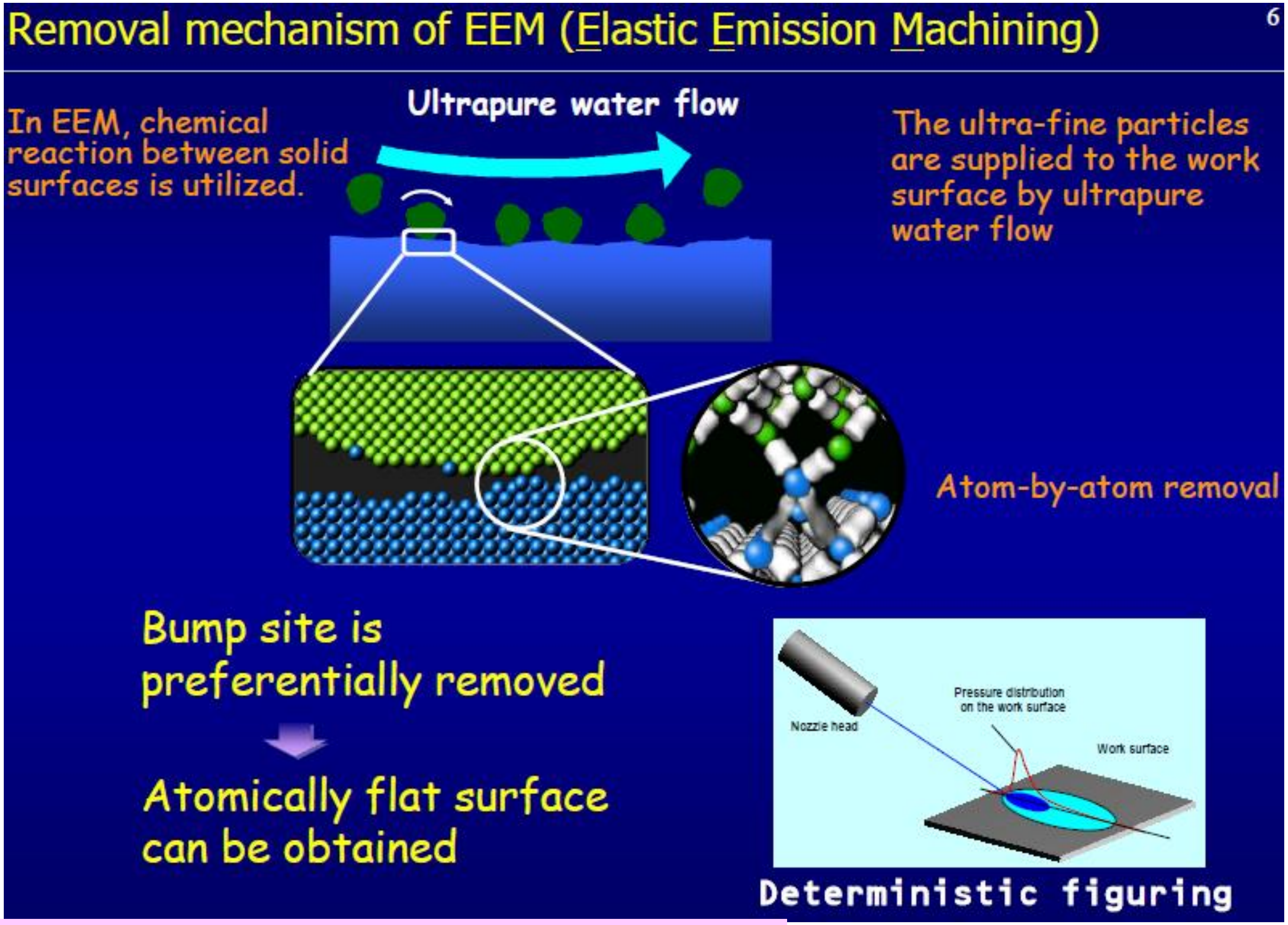
EUVL could also benefit from novel, advanced polishing techniques developed for synchrotron and FEL optics

Courtesy: Prof. Kazuto Yamauchi (Osaka University)



K.Yamauchi et al, Rev. Sci. Instrum. 73 2028 (2002).

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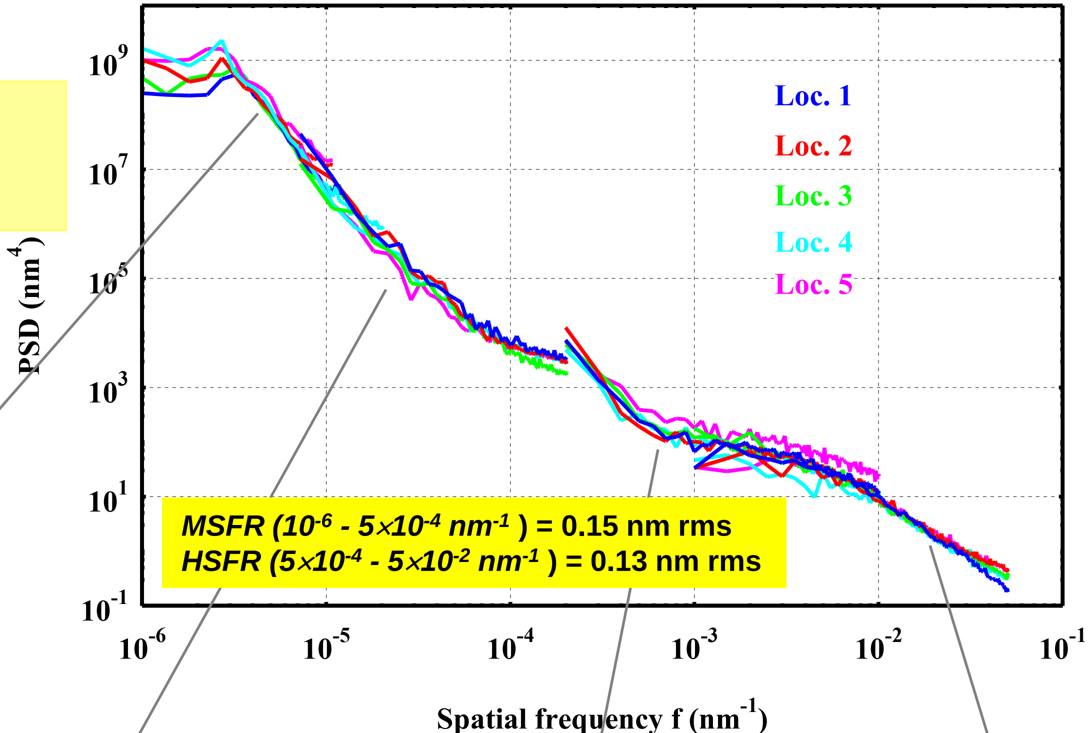
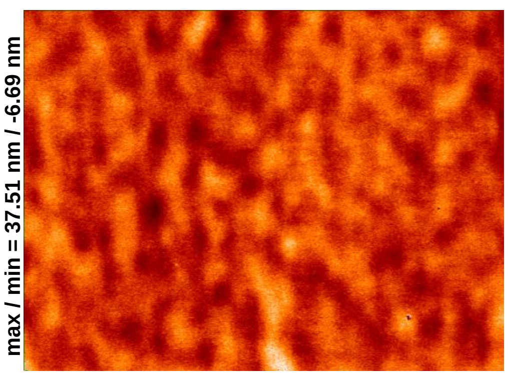
Si substrate for the LCLS FEL, polished by EEM

CXI KB1 Si substrate

Figure of ~ 1 nm rms along 350 mm was measured at BESSY (Frank Seiwert)

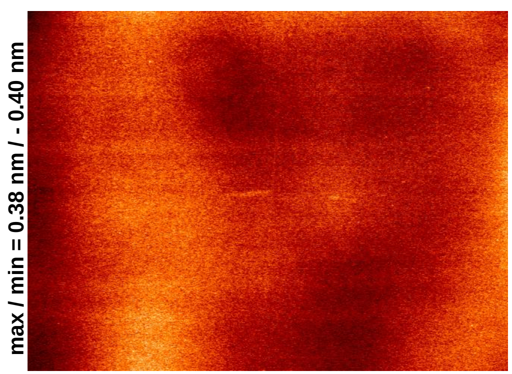
370 mm





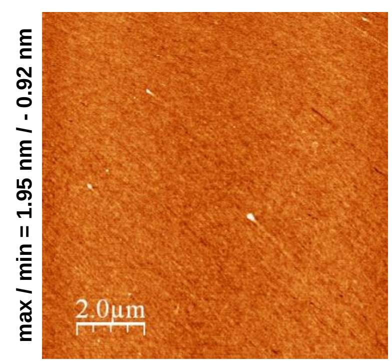
2.95 mm

Zygo 2x



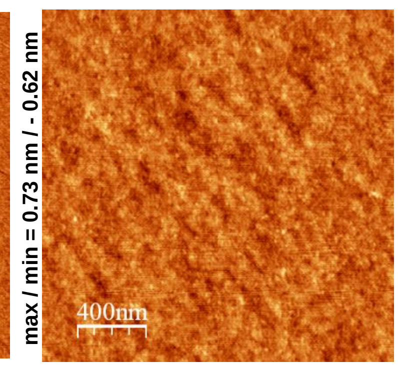
0.37 mm

Zygo 20x



10 µm

AFM



2 µm

AFM

Regina Soufli, 06/16/11

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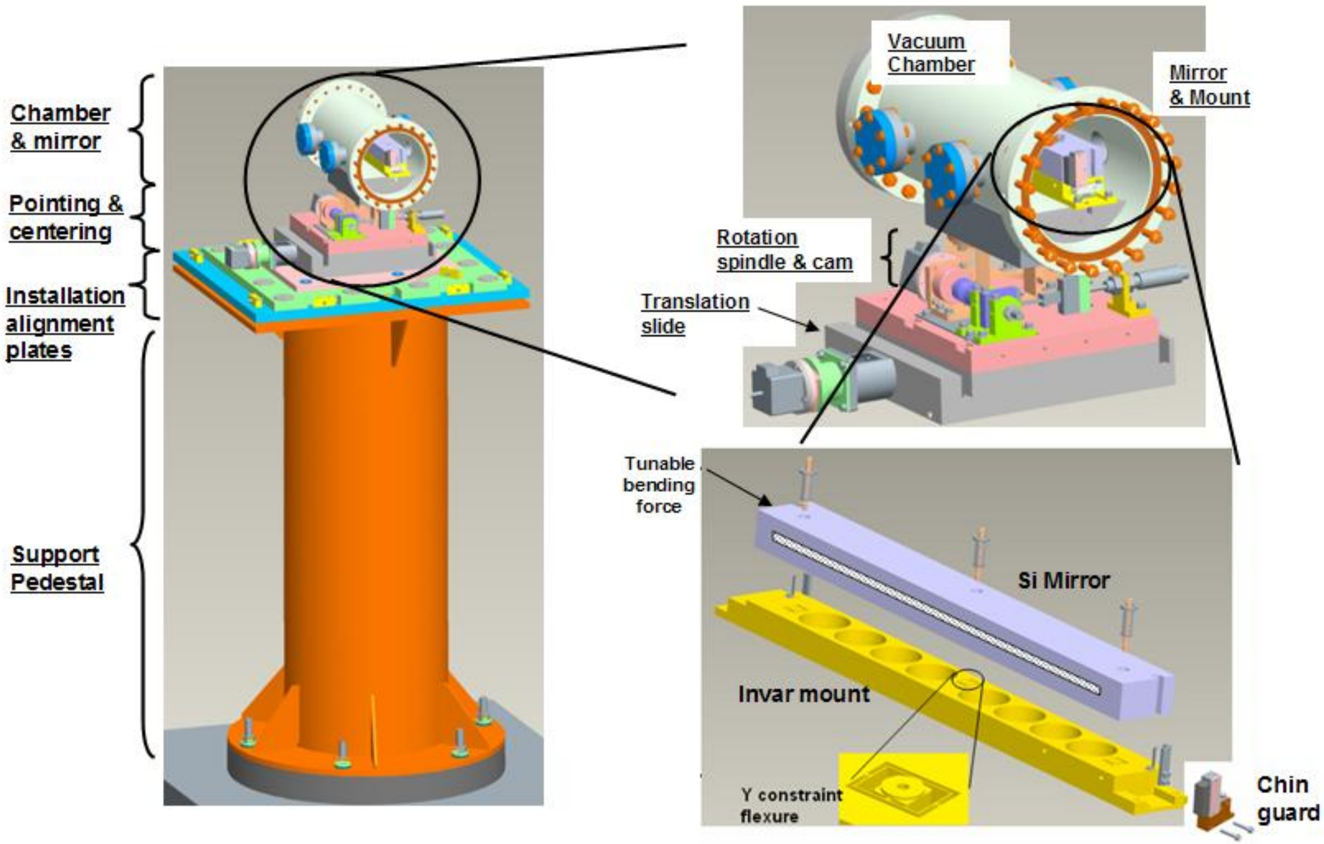
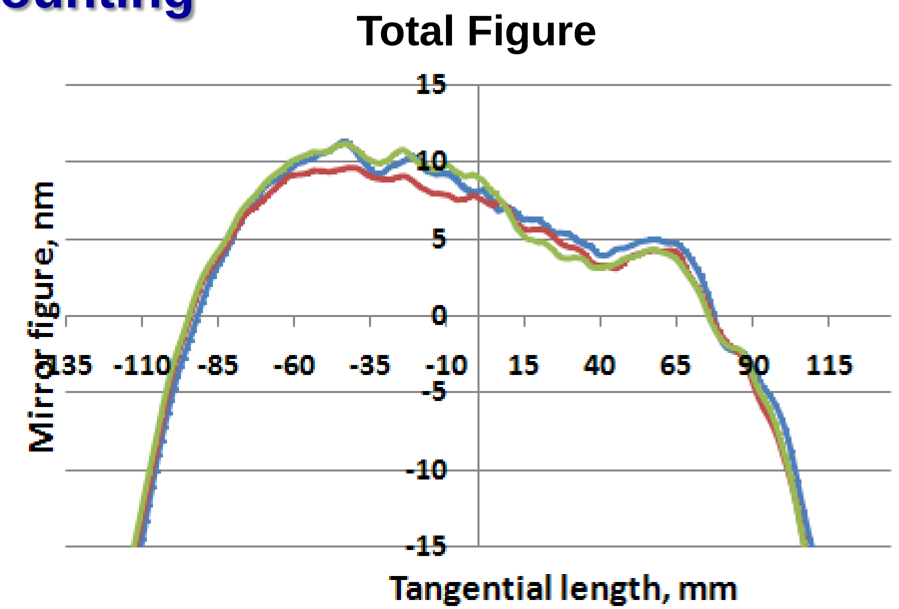
Novel concepts in x-ray mirror mounting, installation and alignment at LCLS



- T-controlled enclosure demonstrates ± 0.01 °C temperature and ± 30 nrad HOMS pointing stability
- Hard x-ray mirror figure can be remotely controlled

T. J. McCarville, P. M. Stefan, B. Woods, R. M. Bionta, R. Soufli, M. J. Pivovaroff, "Opto-mechanical design considerations for the Linac Coherent Light Source X-ray mirror system", Proc. SPIE 7077, 70770E (2008).

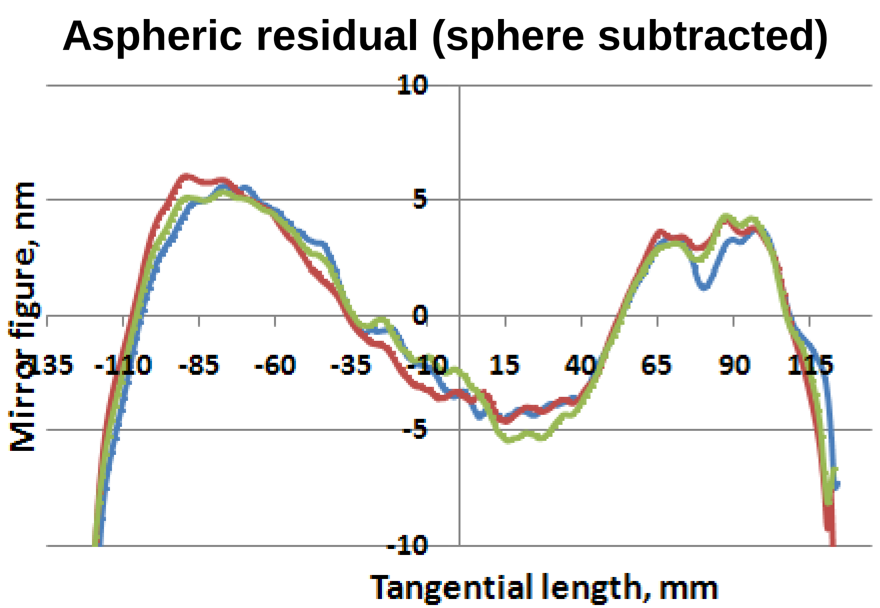
LCLS soft x-ray mirror figure is maintained after coating and mounting



Before coating

Coated, un-mounted

Coated & mounted



Before coating:1.81 nm & 0.19 μrad rms over central 200 mm

Coated, un-mounted:1.62 nm & 0.173 μrad rms

Coated & mounted:1.88 nm & 0.18 μrad rms

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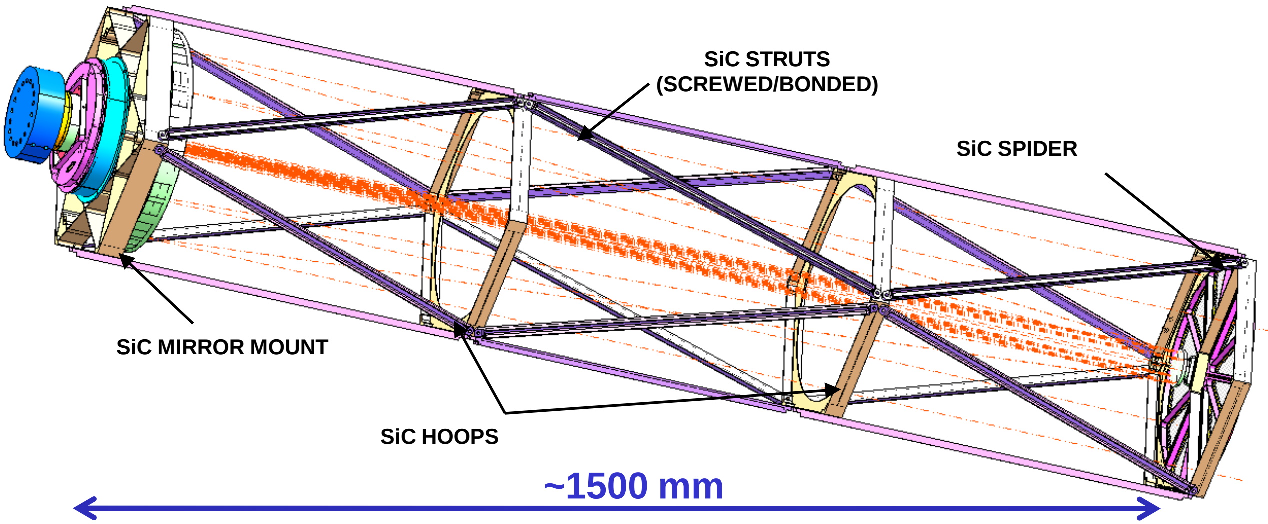
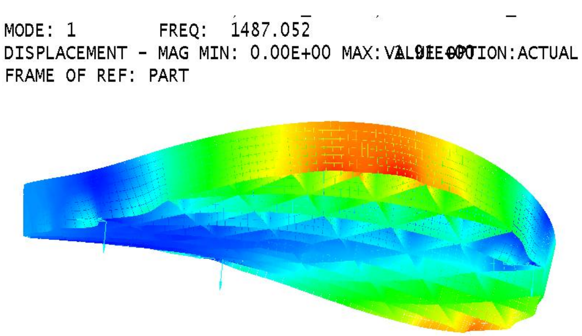
Silicon Carbide (SiC) has emerged as a viable material for EUV/x-ray space telescope and synchrotron optics



HiLiTE: a 300-mm aperture Cassegrain telescope design made entirely of SiC, including optical substrates and metering structure. Overall mass is <u>4X lighter</u> than the mass of an equivalent conventional telescope



	System
Effective Focal Length	10.313 m
Focal Ratio	f/34
Plate Scale	20 arcsec/mm
Field of View	> 4x4 arcmin*
	Primary Mirror
Clear Aperture	300 mm
Radius of Curvature	- 3564.2564 mm
Conic	- 1
	Secondary Mirror
Clear Aperture	40 mm
Radius of Curvature	- 680.89795 mm
Conic	- 2.0116

D. S. Martínez-Galarce, P. Boerner, R. Soufli, B. De Pontieu, N. Katz, A. Title, E. M. Gullikson, J. C. Robinson, S. L. Baker, "The high-resolution lightweight telescope for the EUV (HiLiTE)", Proc. SPIE 7011 , 70113K (2008).

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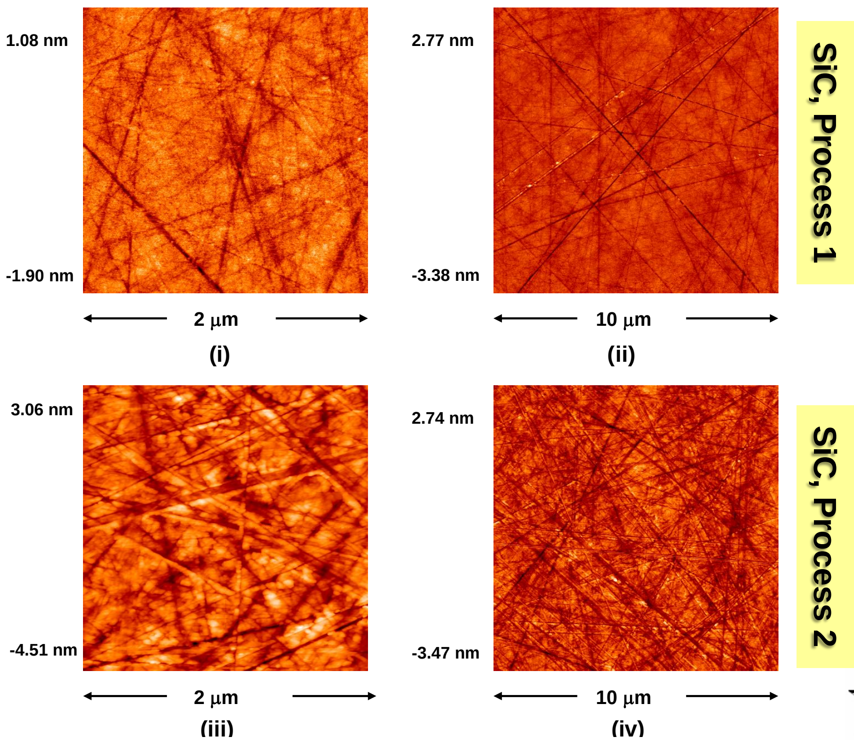
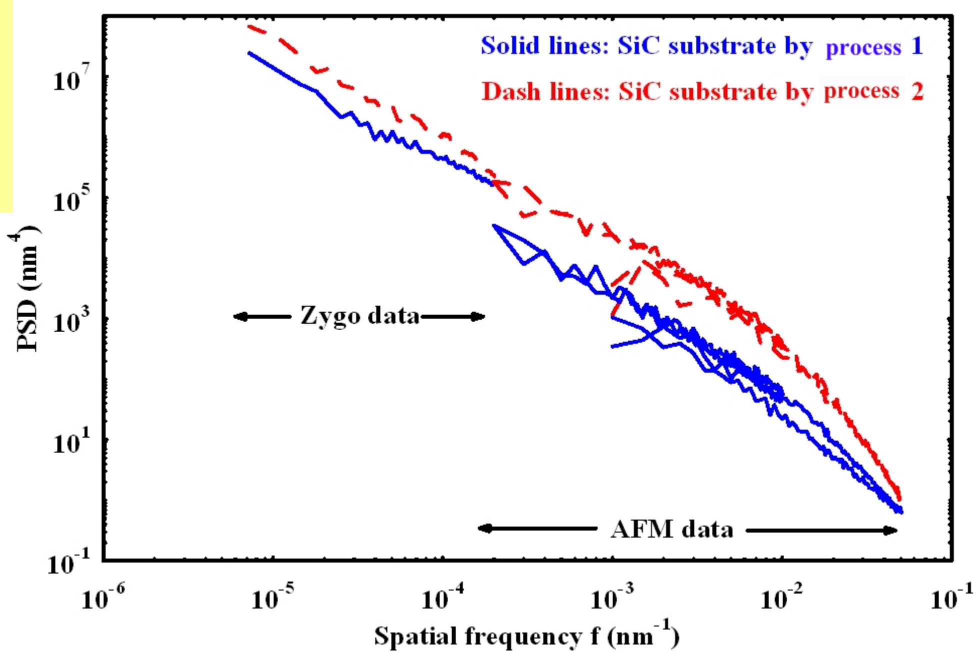
Fabrication and polishing techniques for SiC optical substrates



- Start with bulk SiC, deposit SiC "cladding" using using a CVD-type process
- Or: deposit SiC entirely using a CVD-type process
- Polish using mechanical grind/polish, reactive atom plasma etching, or other technique



	HSFR 0.05 μm < Λ < 2 μm
Process 1	0.30 nm rms
Process 2	0.84 nm rms

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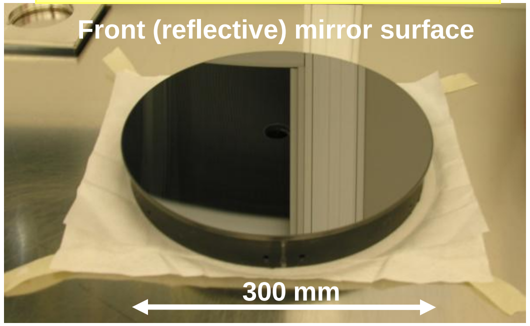
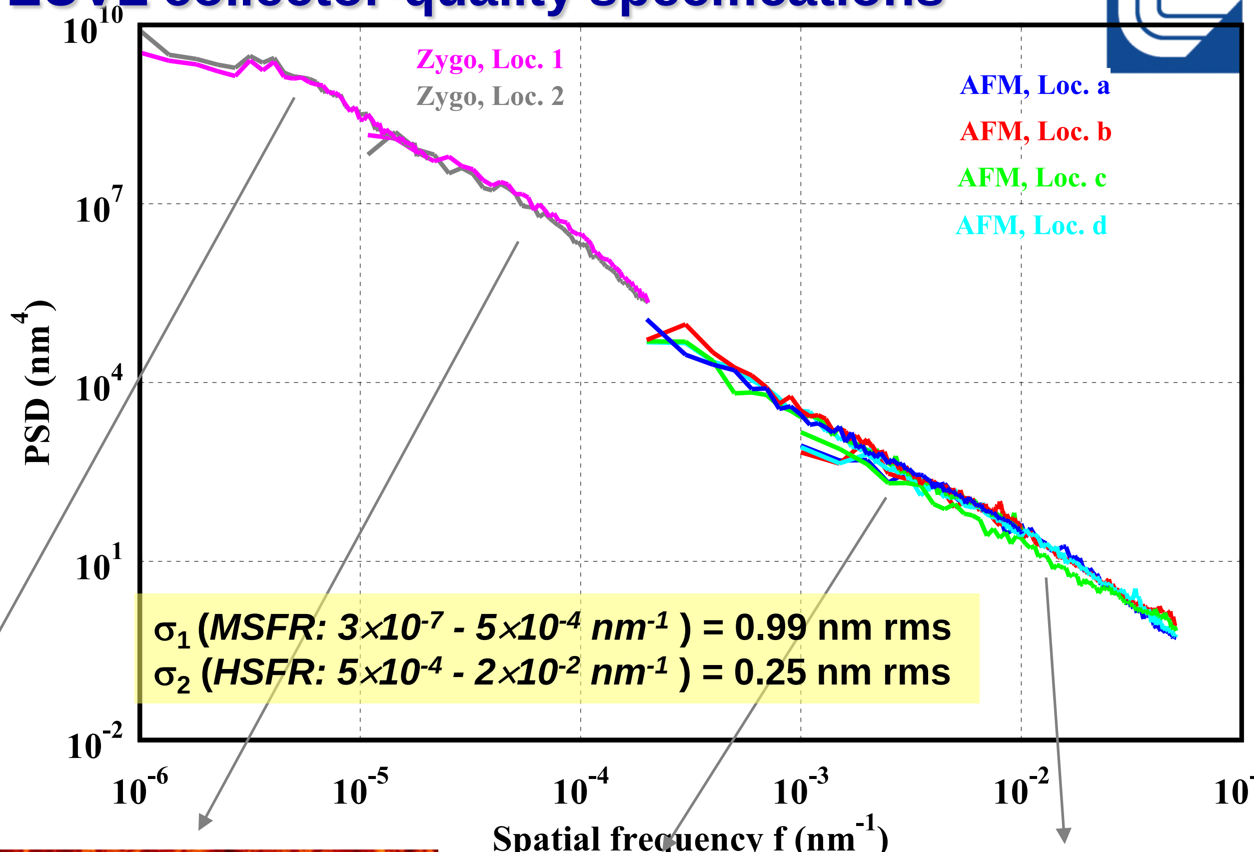
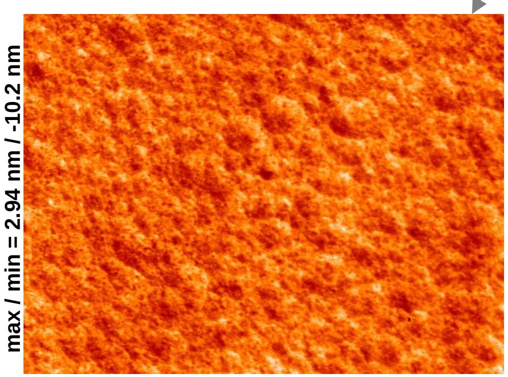
SiC could be polished to EUVL collector-quality specifications

Test mirror for space telescope

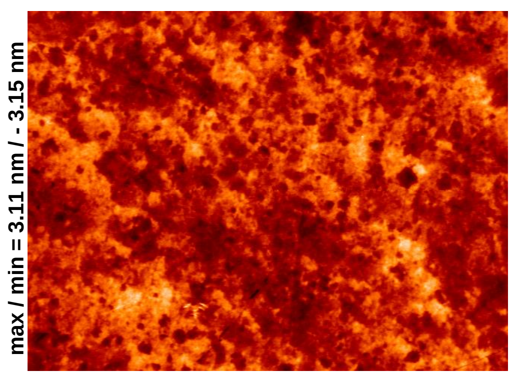






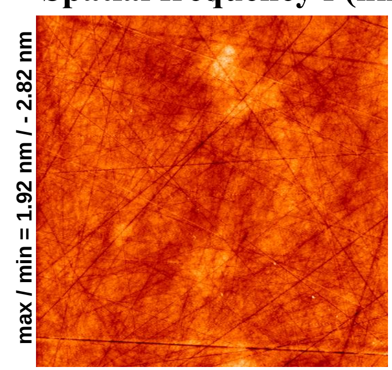
2.95 mm

Zygo 2x



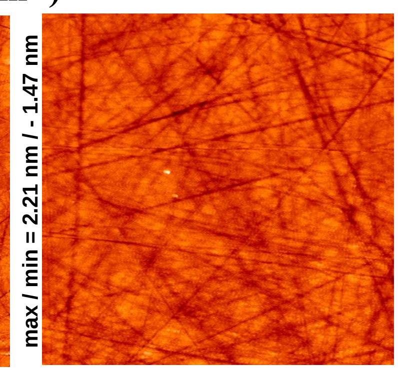
0.37 mm

Zygo 20x



10 μm

AFM



2 μm

AFM

Other SiC-based ceramic composite materials could be considered for EUVL collector substrates

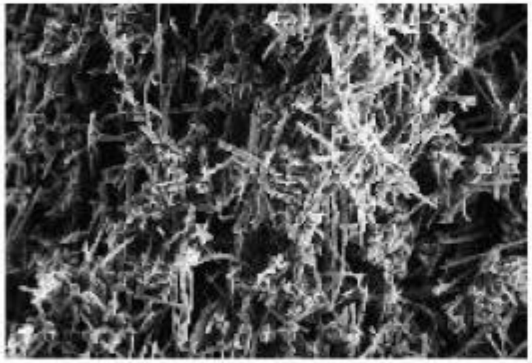
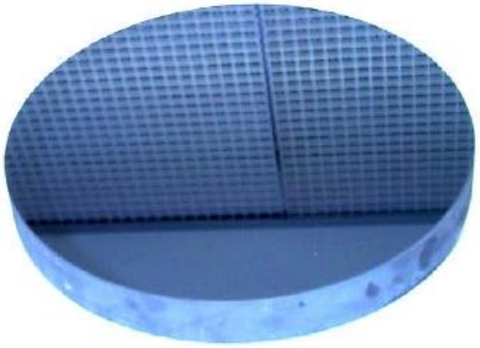


Fig. 2 REM microphotograph of the greenbody chopped C/C fiber material

- Infiltration with liquid Si at high temperature
- Coating with CVD SiC and figuring/polishing



300 mm

➢ Novel SiC-based ceramic composite materials have been developed for space optical substrates and structures

➢ Materials are lightweight, with high stiffness, high conductivity and low CTE

➢ Feasibility of achieving figure/finish quality to EUVL collector specifications would have to be verified

M. R. Kroedel, "Cesic®-Engineering material for optics and structures" Proc. SPIE 5868, 58680A (2005).
M. R. Kroedel and T. Ozaki, "HB-Cesic Composite for Space Optics and Structures", Proc. SPIE 6666, 66660E (2007).
M. Strahan *et al*, "Novel technologies for large deformable mirrors", Proc. SPIE 7736, 773664 (2010).

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EUVL collector optics have more relaxed figure and MSFR specs compared to projection optics and can be fabricated using low-cost techniques

- Aspherical mirrors made by conventional figuring / finishing are very expensive
- Diamond-turned (metal) or ground (ceramic) mirrors are much cheaper and meet EUVL collector figure specs but have insufficient high-spatial frequency roughness (HSFR)

Proposed solution:

- Fabricate diamond-turned metal (e.g. Al, Cu) or ground ceramic (e.g. SiC) mirrors
- Reduce HSFR with smoothing film
- Follow with appropriate coating (single-layer or multilayer) for EUV reflectance

J. A. Folta, C. Montcalm, J. S. Taylor, E. A. Spiller, "Low-cost method for producing extreme ultraviolet lithography optics", U.S. Patent No. 6,634,760.

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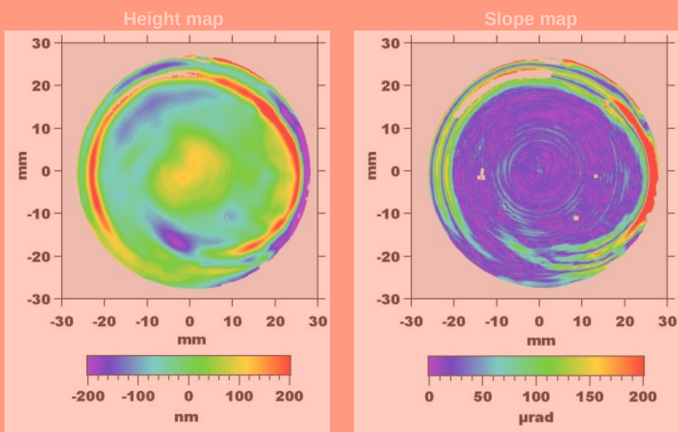
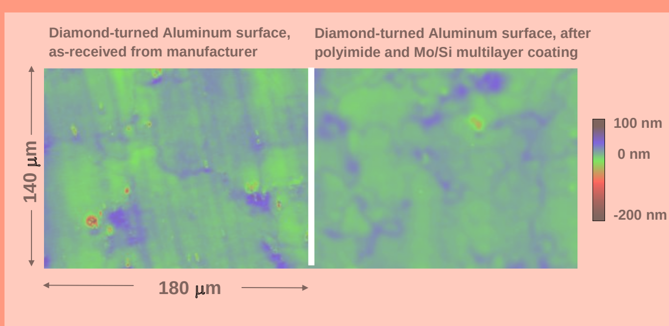
Polyimide-smoothing of diamond-turned Al EUVL collector substrates dramatically improves HSFR while maintaining figure within specs

Visible light interferometry results from multilayer-coated, diamond-turned condenser mirror

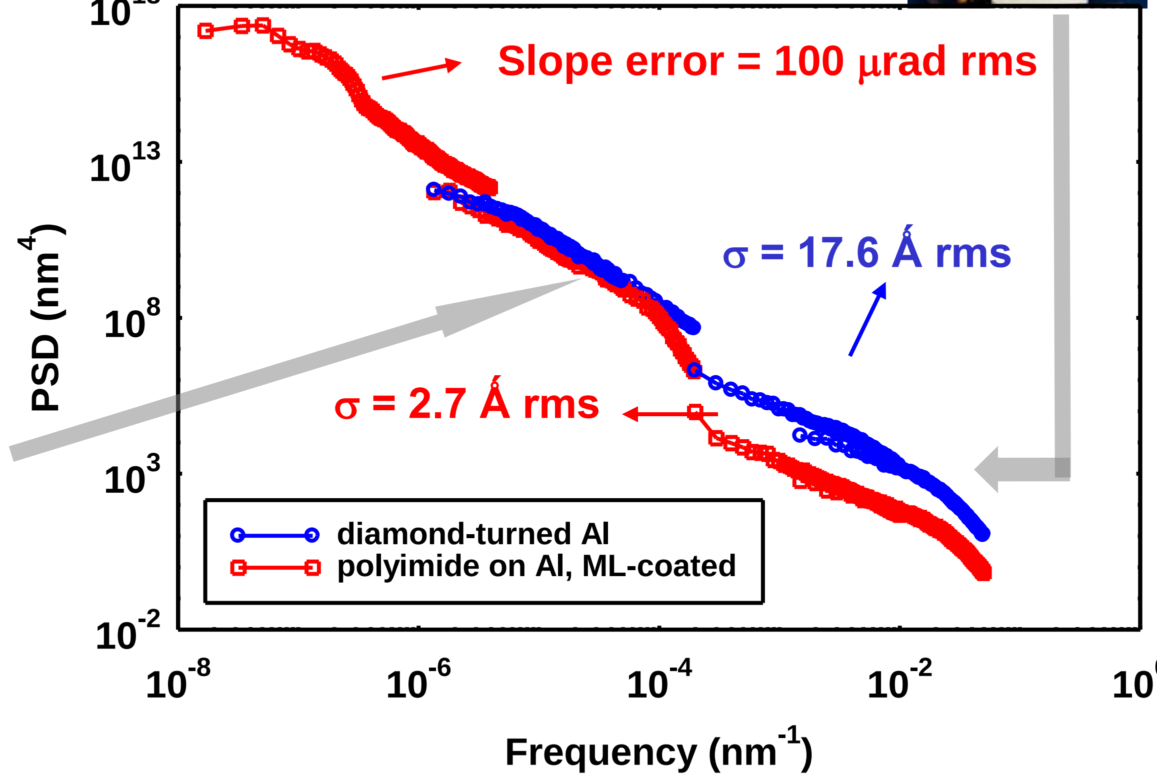


Polyimide smoothes high spatial frequency roughness, including 10 µm-range diamond turning marks



Measurements obtained with a Zygo New View™ optical profiling microscope operated at 40× objective lens magnification

R. Soufli, E. Spiller, M. A. Schmidt, J. C. Robinson, S. L. Baker, S. Ratti, M. A. Johnson, E. M. Gullikson, Opt. Eng. 43(12), 3089-3095 (2004).



Regina Soufli, 06/16/11

Acknowledgement: TOPO software by D. L. Windt

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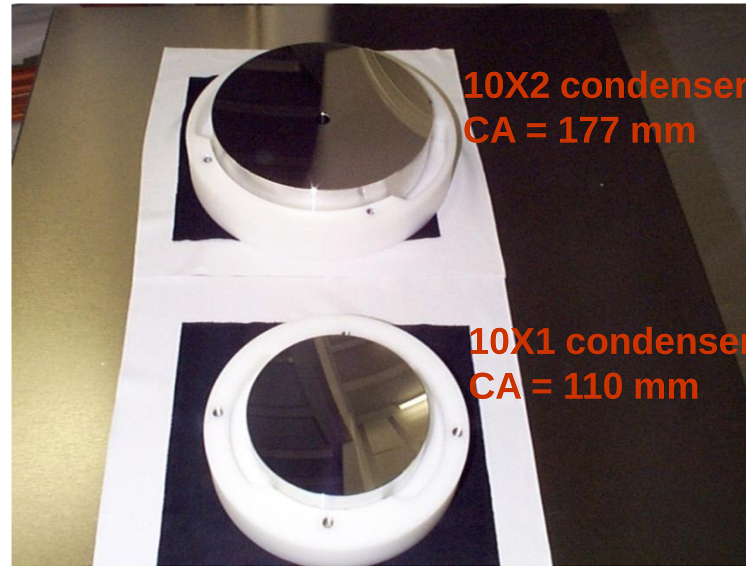
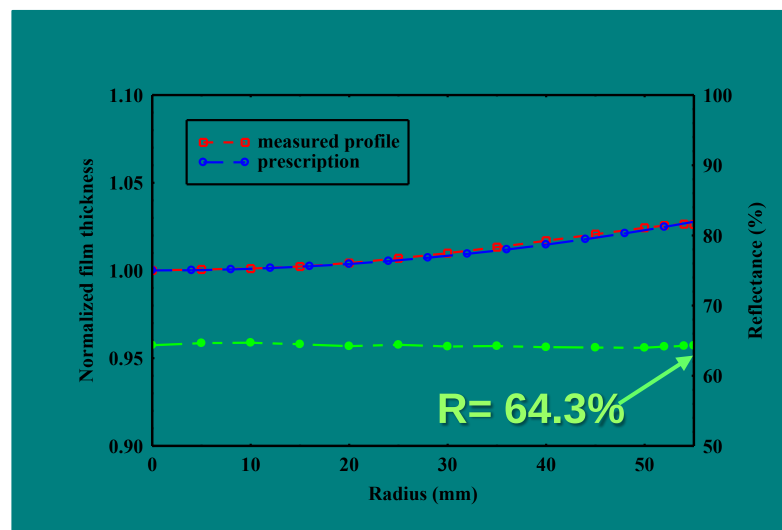
Diamond-turned, polyimide-smoothed EUVL condenser optics developed at LLNL

C1 collector optic for the ETS

Illuminator optics for SNL microstepper



- HSFR is reduced from ~3 nm to ~0.3 nm, and 64.3 % reflectance is achieved at 13.35 nm and 8 deg off-normal, after Mo/Si multilayer coating
- No accelerated degradation or outgassing were observed, when exposed to 11.5M shots of EUVL laser-plasma source environment (Xe liquid jet source at SNL)



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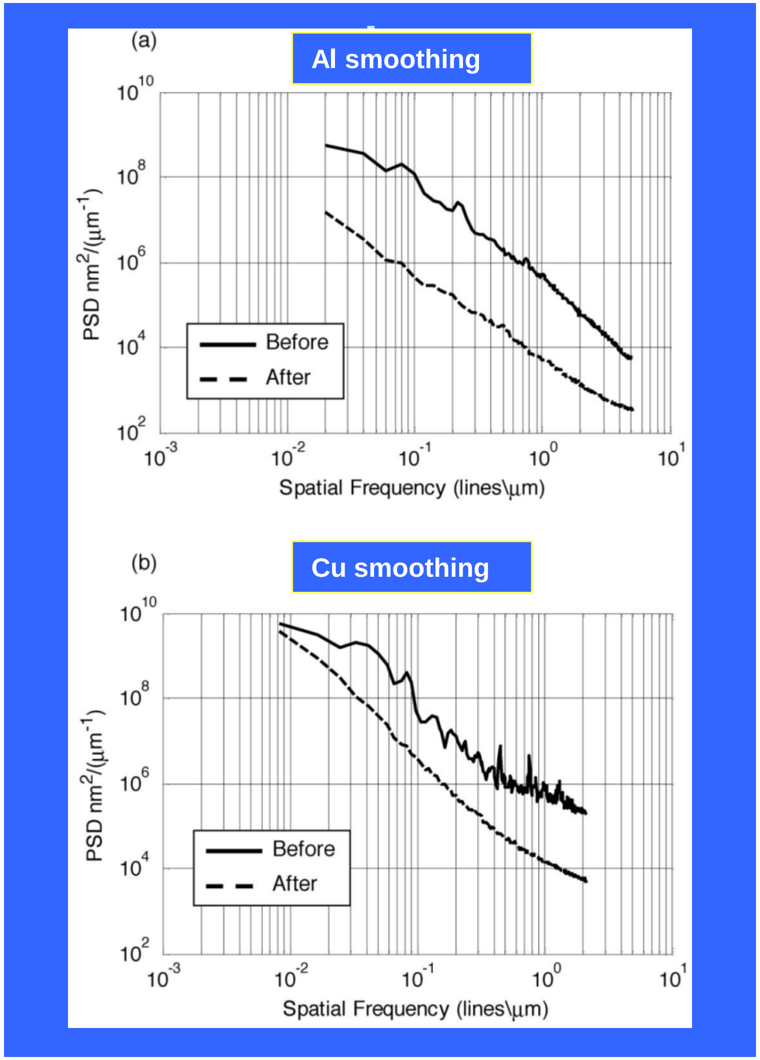
Smoothing of diamond-turned Cu and Al condenser optics with spin-on-glass resist was also demonstrated at CXRO/LBNL



- HSFR is reduced from ~3.3 – 3.7 nm to ~0.4 -0.6 nm, and 64-65 % reflectance is achieved at 13.50 nm and 28 deg off-normal, after Mo/Si multilayer coating
- Mo/Si-coated, smoothed optics are used as illuminator mirrors for MET beamline at LBNL

CXRO THE CENTER FOR X-RAY OPTICS

BERKELEY LAB

F. Salmassi, P. P. Naulleau, and E. M. Gullikson, “Spin-on-glass coatings for the generation of superpolished substrates for use in the extreme-ultraviolet region”, Appl.Opt. 45, 2404-2408 (2006).

Perspectives on 6.x nm lithography

- A PO system with near-zero as-designed wavefront error will be required
- Phase change through multilayer stack vs. angle of incidence is expected to be more severe at 6.x nm than 13 nm, therefore:
  - Differences between actinic and non-actinic inspection will be larger
  - Actinic qualification of PO boxes may be required
- Flare requirements lead to MSFR specifications beyond the state-of-the-art in polishing technologies
- Reflectance and bandwidth of 6.x nm multilayers will need to be greatly improved. Recently determined, experimental optical constants for B and B_4C are available to model the performance of B- and B_4C-based multilayers. See next 2 slides and also presentations by V. Banine, E. Louis and Y. Platonov
- Source, resist - see also presentation by V. Banine
- Extensive and coordinated synergy between industry, universities and research institutes would be required to successfully address the above issues

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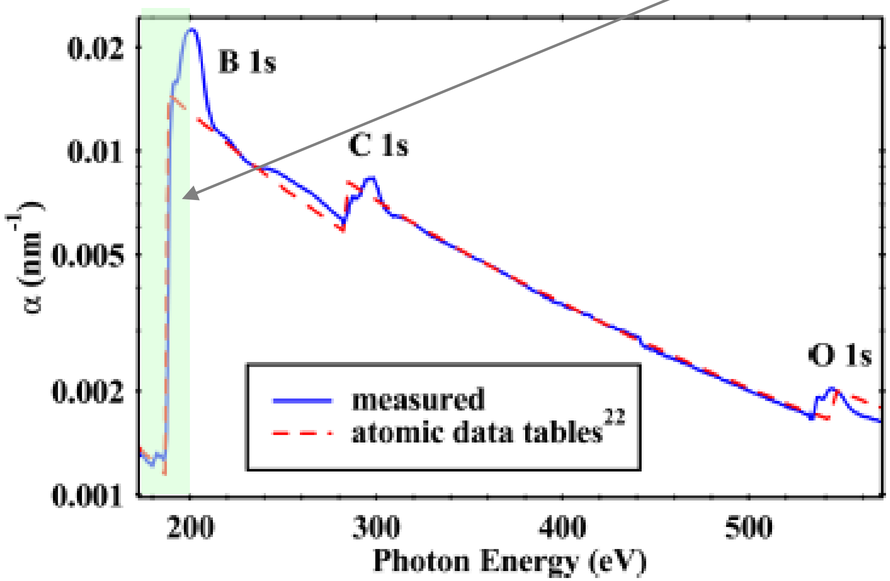
Photoabsorption measurements yield updated values for the EUV/x-ray refractive index of B_4C films, including NEXAFS

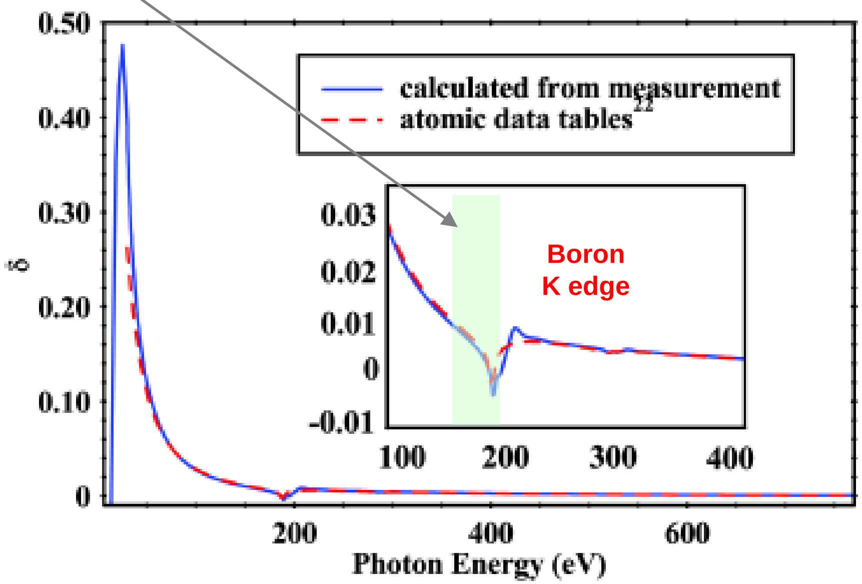
Accurate values of the refractive index (optical constants) enable accurate modeling of multilayer performance

$$n(\lambda) = 1 - \delta(\lambda) + ik(\lambda)$$

$$k(\lambda) = \lambda\alpha / 4\pi$$

Energy region of interest for 6.x nm, B_4C-based multilayers



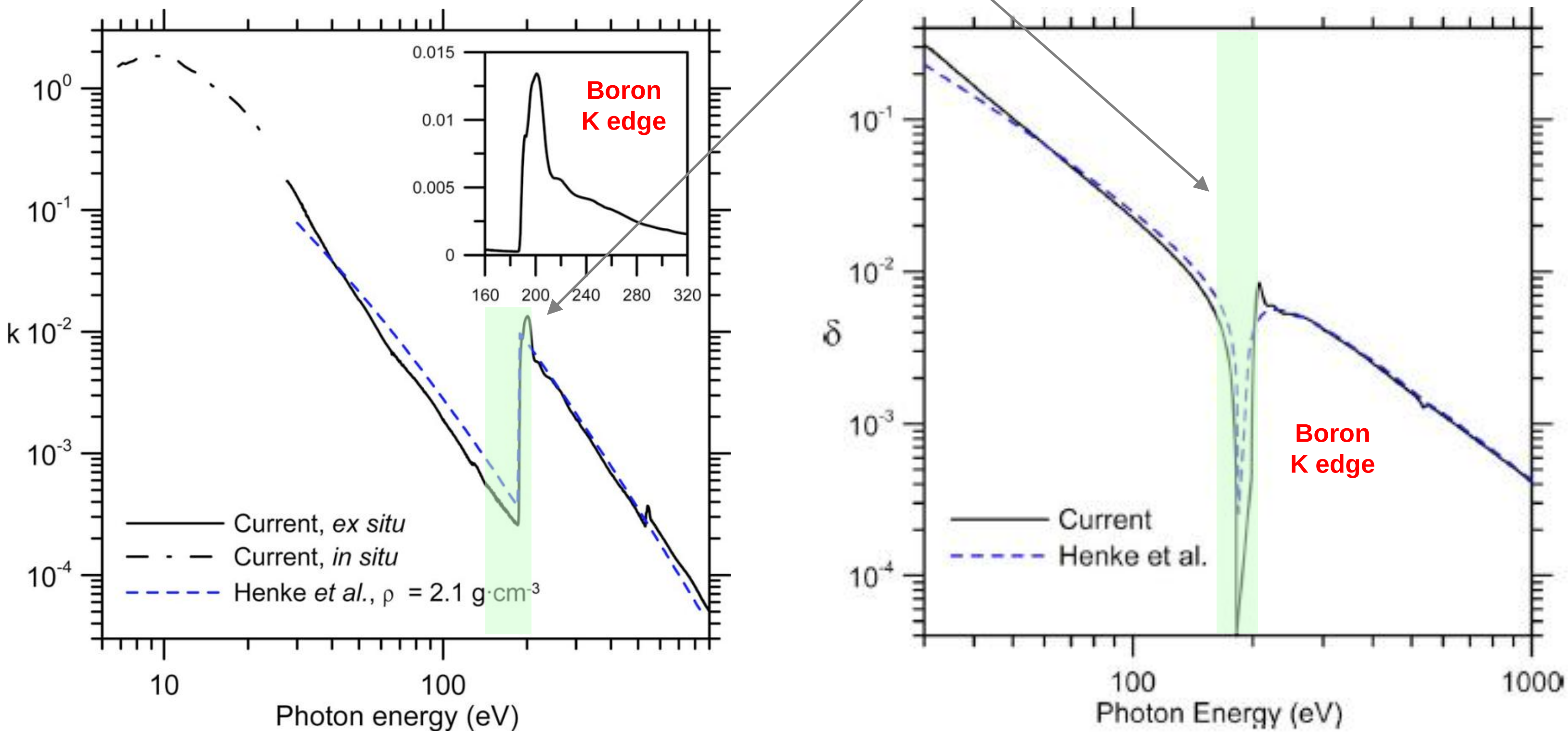


R. Soufli, A. L. Aquila, F. Salmassi, M. Fernández-Perea, E. M. Gullikson, "Optical constants of magnetron sputtered boron carbide thin films from photoabsorption data in the range 30 to 770 eV", Appl. Opt. 47, 4633-4639 (2008).

We have also determined experimentally the Boron optical constants

$$n(\lambda)=1-\delta(\lambda)+ik(\lambda)$$

Energy region of interest for 6.x nm, B-based multilayers



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Summary and conclusions

- One of EUVL's most significant technology accomplishments has been the fabrication and metrology of the world's most accurate normal-incidence optics
- Needs for higher throughput, lower flare and the ever increasing size and complexity of projection optical surfaces in advanced EUVL systems continues to push the limits of fabrication and metrology to picometer (pm) levels
- Overcoming manufacturing challenges may enable ULE to be used for EUVL projection optics substrates and achieve pm-level figure and roughness
- EUVL collector substrate technologies could benefit from recent advances in polishing/metrology/mounting of Si, SiC and other ceramic materials for FEL and space optics

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