Multilayer coatings for the first Micro-Exposure Tools with NA=0.5

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Technical contributors

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- Eric M. Gullikson, Patrick Naulleau (*CXRO/LBNL*)
- Luc Girard, Lou Marchetti, Mark Bremer, Jim Kennon, Bob Kestner, John Kincade (*Zygo Corp., Richmond, California*)
- Holger Glatzel (*formerly Zygo Corp.)*

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Overview

- This presentation will discuss highlights from the development of Mo/Si multilayer coatings for the first NA=0.5 micro-exposure tools for EUVL
- Low stress
- High reflectivity
- Multilayer-added figure errors < 80 picometers rms

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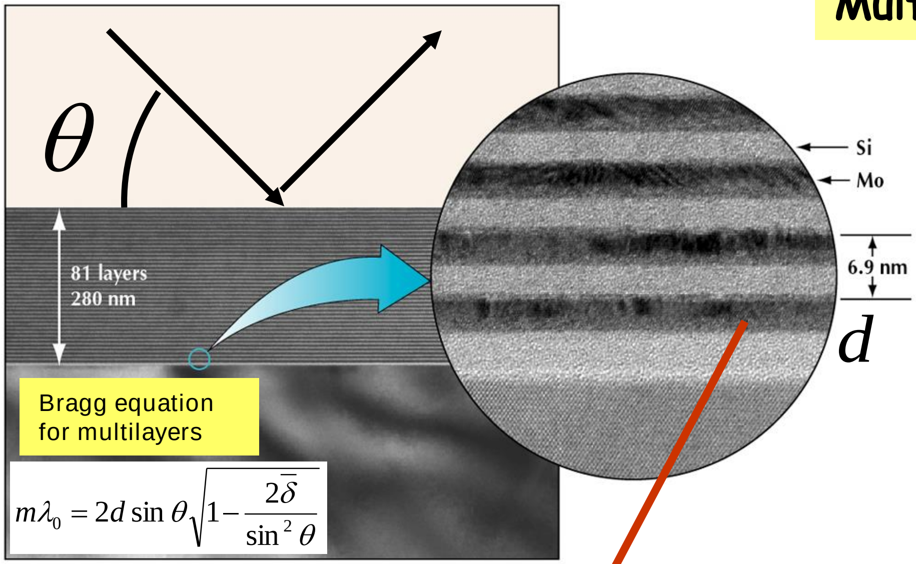
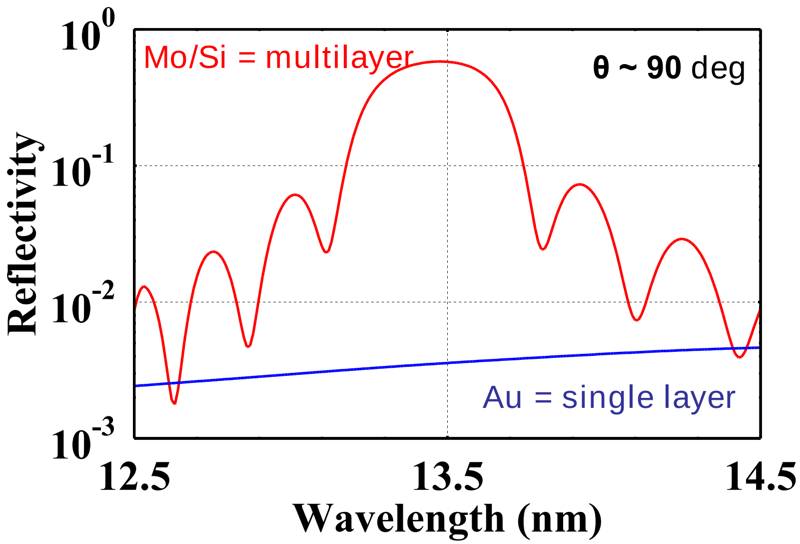
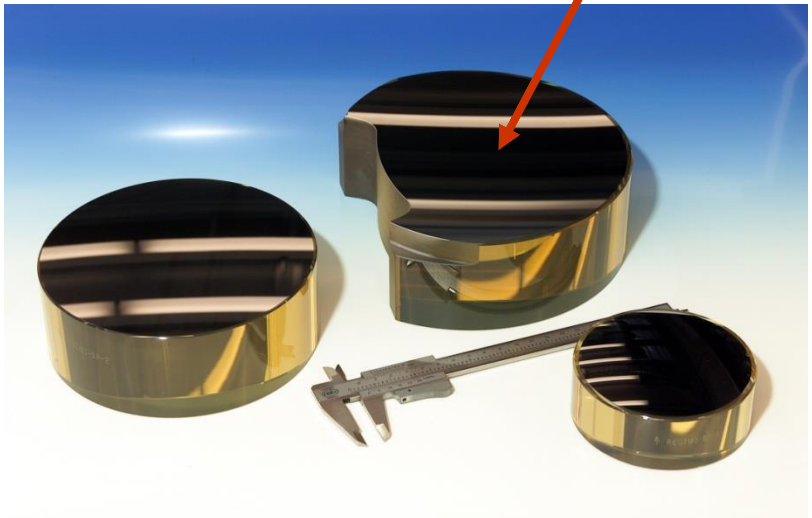
Multilayer interference coatings have particular properties and requirements. *Thin films ≠ bulk materials !*



$$m\lambda_0 = 2d\sin\theta\sqrt{1-\frac{2\bar{\delta}}{\sin^2\theta}}$$

Multilayers enable imaging at normal incidence





REQUIREMENTS FOR EFFICIENT MULTILAYERS:

- ✓ Nanometer-scale layers
- ✓ Layer-to-layer thickness control
- ✓ Thickness control across large, curved surfaces
- ✓ Wavefront preservation
- ✓ Smooth and sharp layer interfaces
- ✓ Low stress, long-term stability

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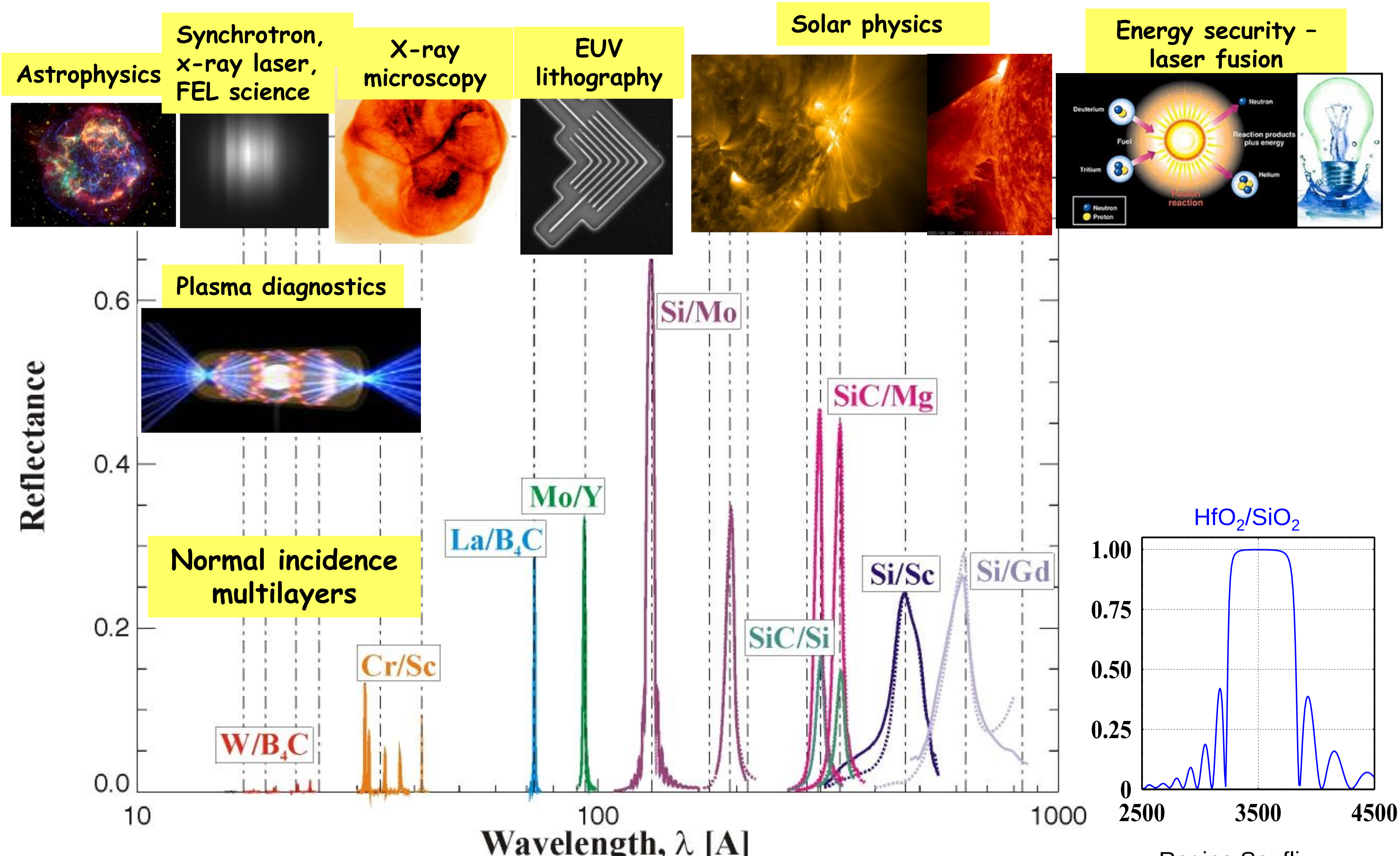
Multilayers enable many science applications



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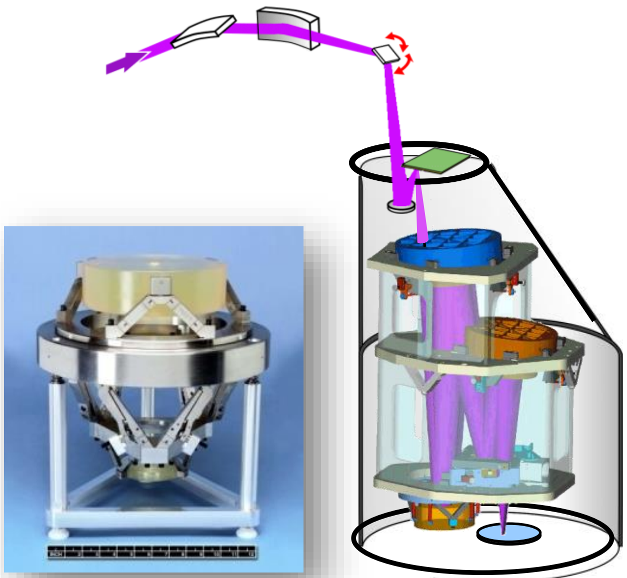
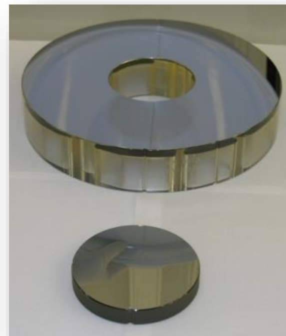
Our group at LLNL has participated in the development of EUV/x-ray optics for various applications

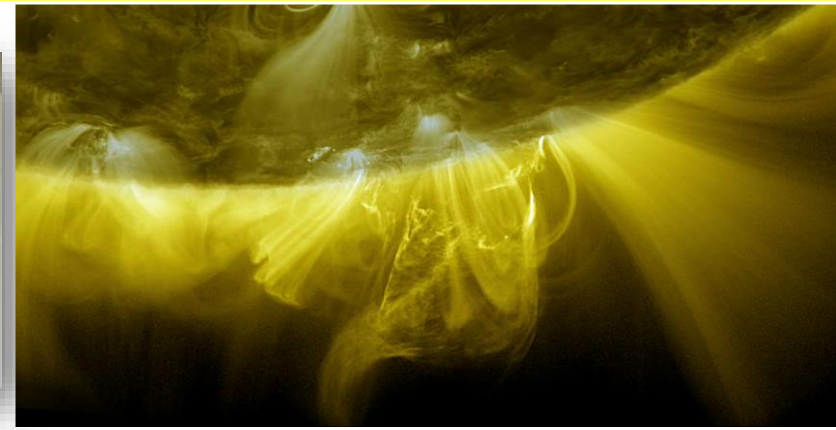
EUV Lithography



EUV solar missions (NASA's SDO and NASA/NOAA's GOES-R)



Solar Dynamics Observatory (SDO). Launched Feb.11, 2010.



X-ray optics for the LCLS free-electron laser

Hard x-ray /gamma-ray astrophysics and radiation detection up to 0.65 MeV

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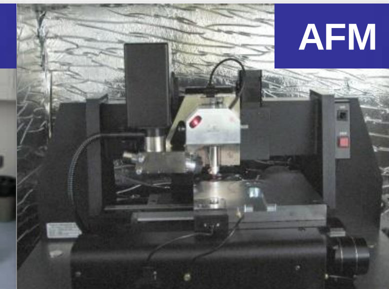
LLNL facilities for thin film deposition and characterization

DC- and RF-magnetron sputtering deposition systems

Precision surface metrology



Also (not pictured):
- Contact profilometers
- Thin film stress measurement apparatus
- Full-aperture interferometers

Custom cleaning facility for optical substrates

X-Ray Diffractometer

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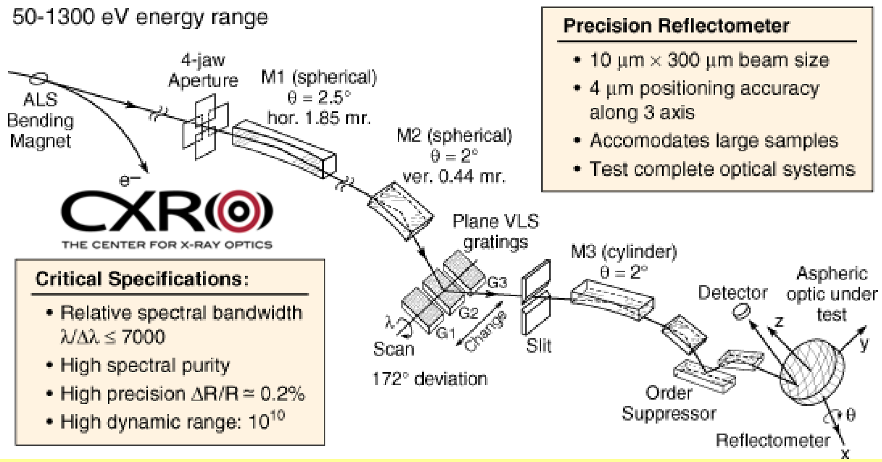
We use light sources from the UV to the gamma-ray for at-wavelength testing of multilayer optics

Advanced Light Source
An Office of Science User Facility



Calibration and standards beamline 6.3.2
λ = 1-50 nm

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INTERNATIONAL YEAR OF LIGHT 2015

GOBIERNO DE ESPAÑA — MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

CSIC

GOLD facility, λ = 50-200 nm

NSLS
NATIONAL SYNCHROTRON LIGHT SOURCE

Beamline X17B1, hv = 62, 186 keV

ESRF The European Synchrotron

Beamline ID15A, hv = 384, 511, 645 keV

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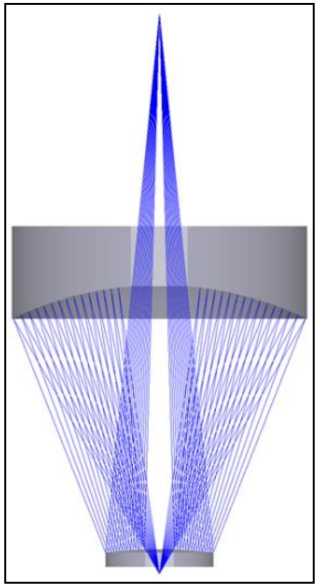
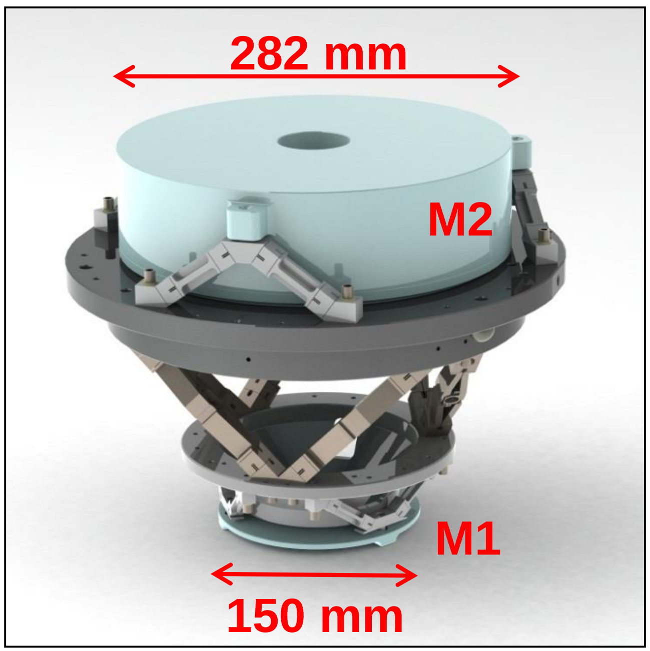
Micro-Exposure Tool MET5: the first NA=0.5 EUV lithography system



- R&D Tool for ~ 8 nm feature sizes
- Field size: 200 μm x 30 μm
- Modified Schwarzschild Design
- Wavelength λ : 13.5 nm
- Reduction ratio: 5x
- NA: 0.50
- Near diffraction limit:

  Total system transmitted wavefront error < 1.0 nm
- Mirrors = substrate + Mo/Si multilayer coating → stress-induced deformations, thickness errors



- H. Glatzel, *et al*, Proc. SPIE 9048, 90481K (2014).
- K. Kummings, *et al*, Proc. SPIE 9048 (2014).

SEMATECH zygo CXRO THE CENTER FOR X-RAY OPTICS HYPERION DEVELOPMENT SPILLER X-RAY OPTICS

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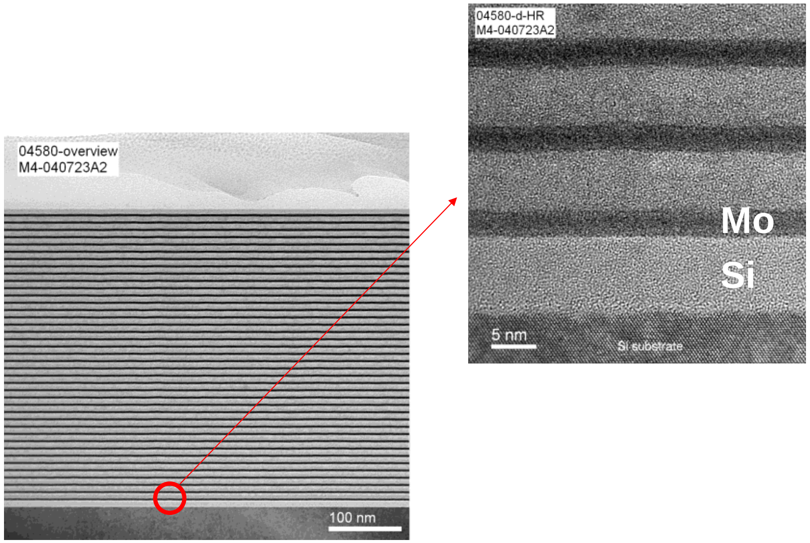
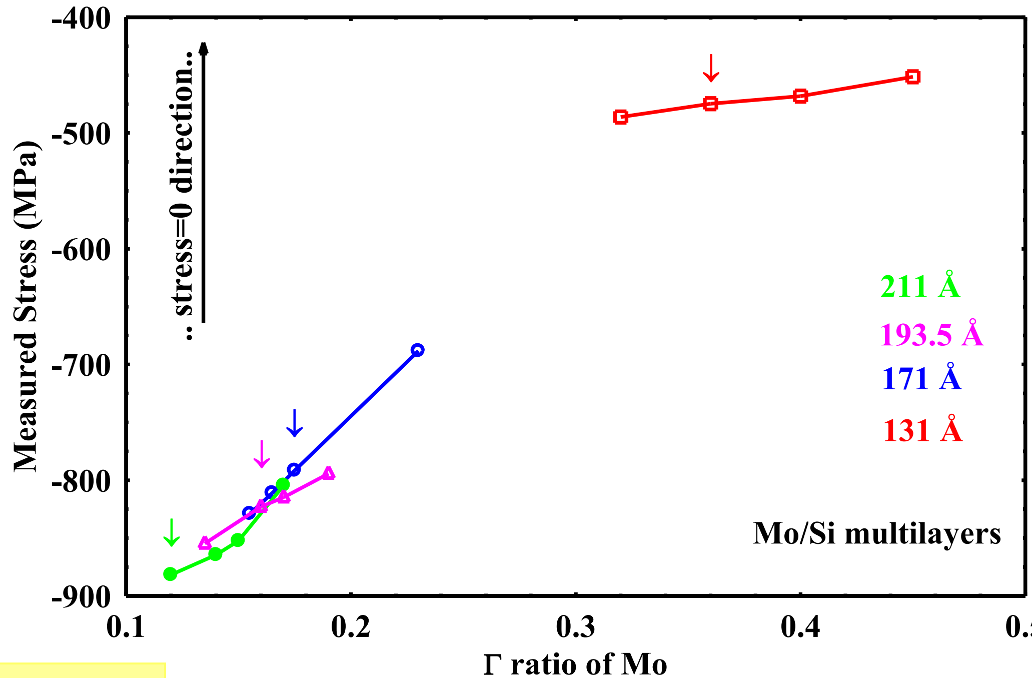
Mo/Si multilayers have compressive stress





DC-magnetron sputtered , normal-incidence Mo/Si multilayer coating with Γ=0.16 at 19.35 nm for NASA's Solar Dynamics Observatory

R. Soufli, D. L. Windt, J. C. Robinson, et al, "Development and testing of EUV multilayer coatings for the atmospheric imaging assembly instrument aboard the Solar Dynamics Observatory", Proc. SPIE 5901, 59010M (2005).

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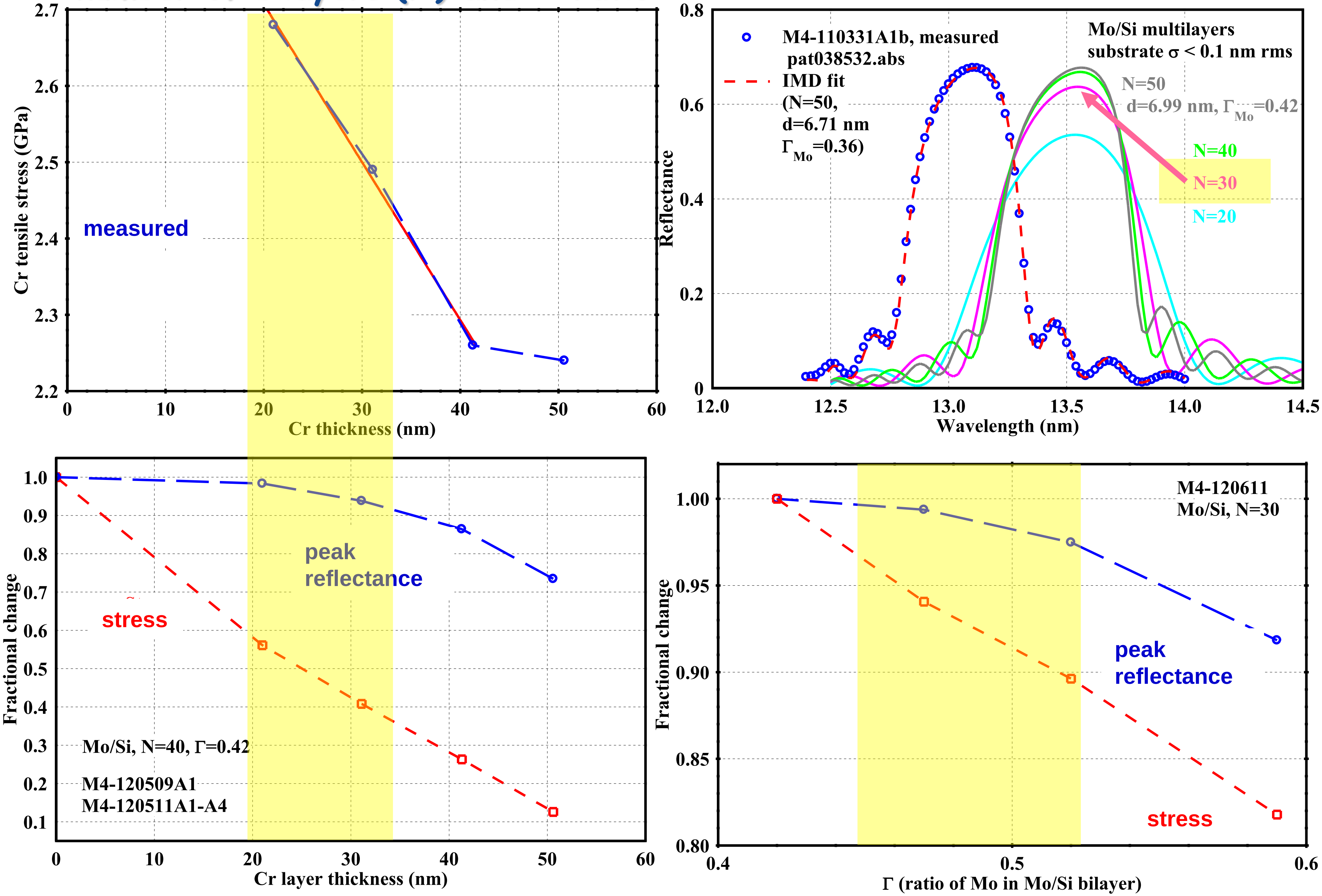
Mo/Si stress and reflectance vs. Cr under-layer thickness, number of bilayers (N) and Γ-ratio

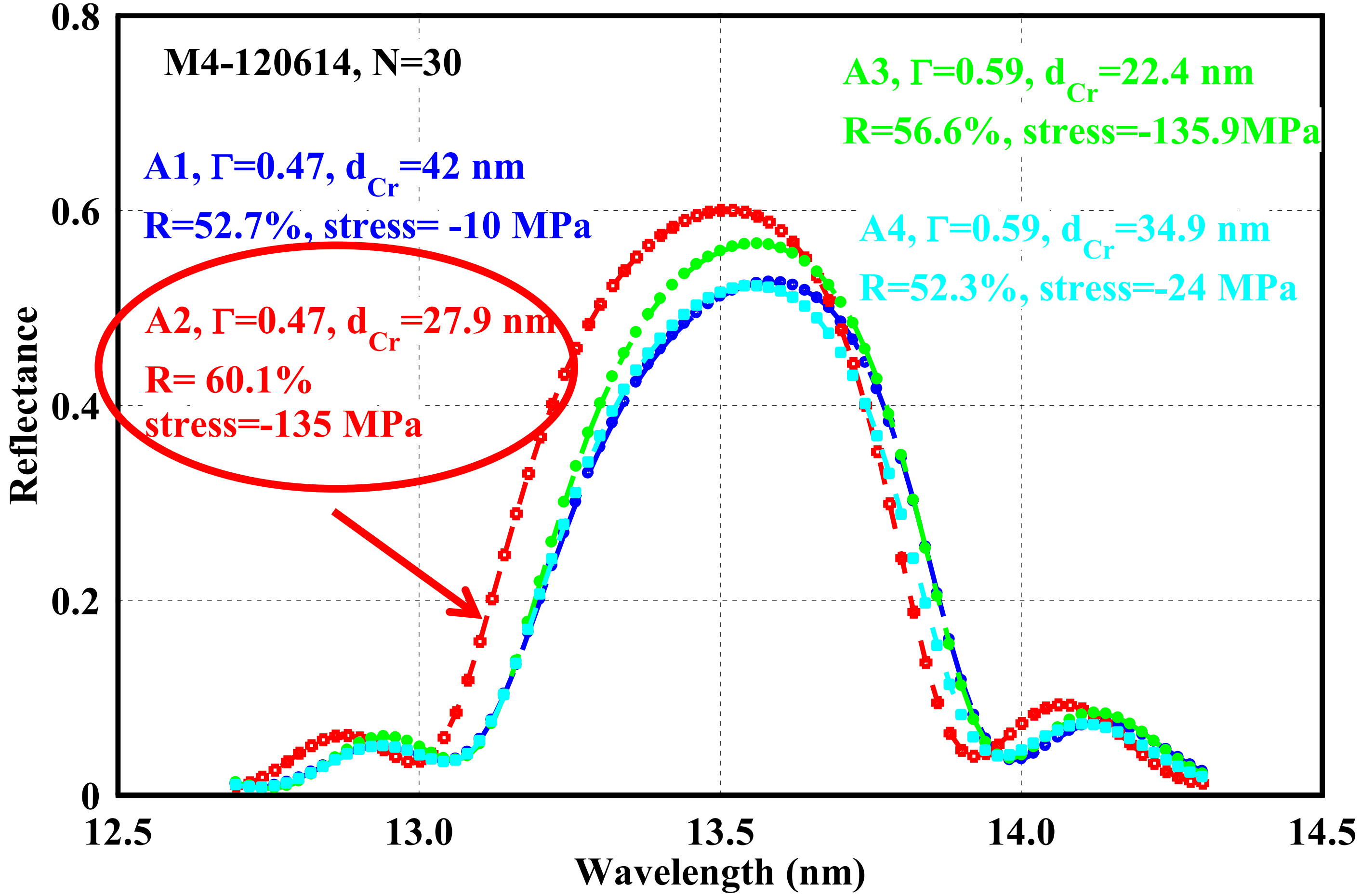


Optimization of stress and reflectivity for Mo/Si with Cr underlayers

Required Cr underlayer thickness d_{Cr} to achieve a total stress value σ:

$$\sigma \times d \approx \sigma_{Cr} \times d_{Cr} + \sigma_{Mo/Si} \times d_{Mo/Si}$$

Measured at beamline 6.3.2. of the ALS



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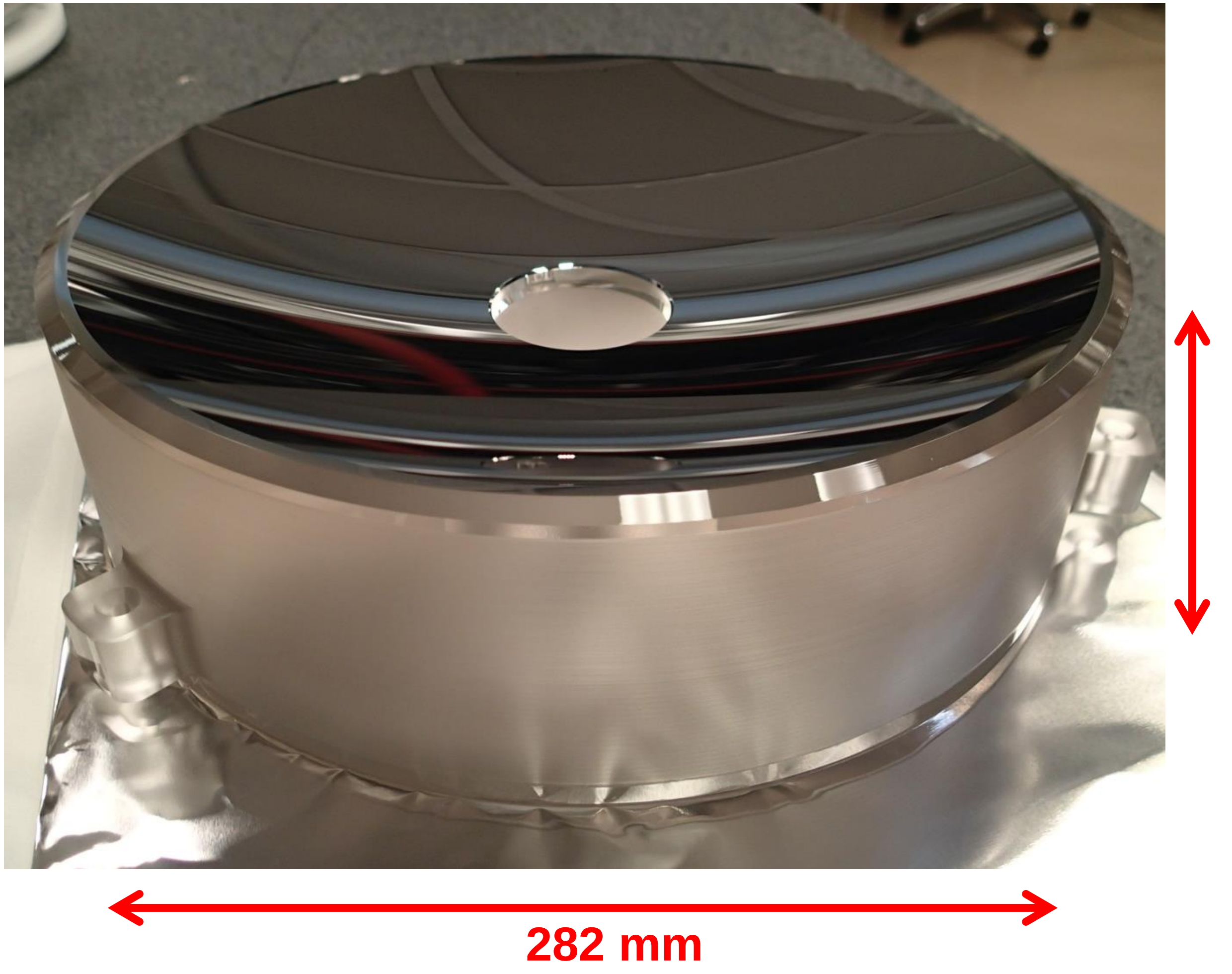
Coating results on MET5 secondary mirror (M2)

Photo courtesy Zygo Corp.



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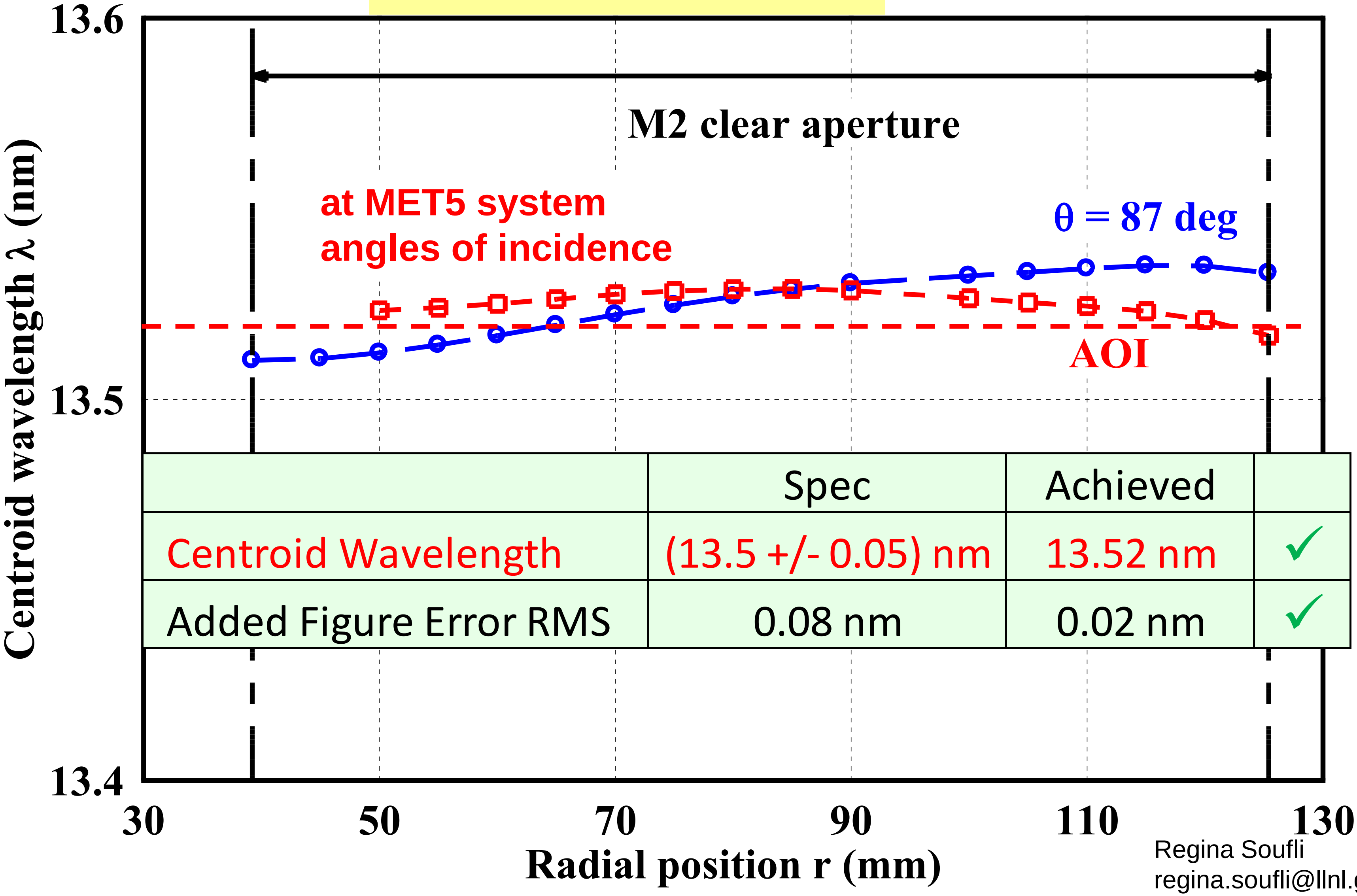
Multilayer-added figure error < 80 picometer rms is achieved across 250 mm diameter on M2 mirror

Measured at ALS beamline 6.3.2.



	Spec	Achieved	
Centroid Wavelength	(13.5 +/- 0.05) nm	13.52 nm	✓
Added Figure Error RMS	0.08 nm	0.02 nm	✓

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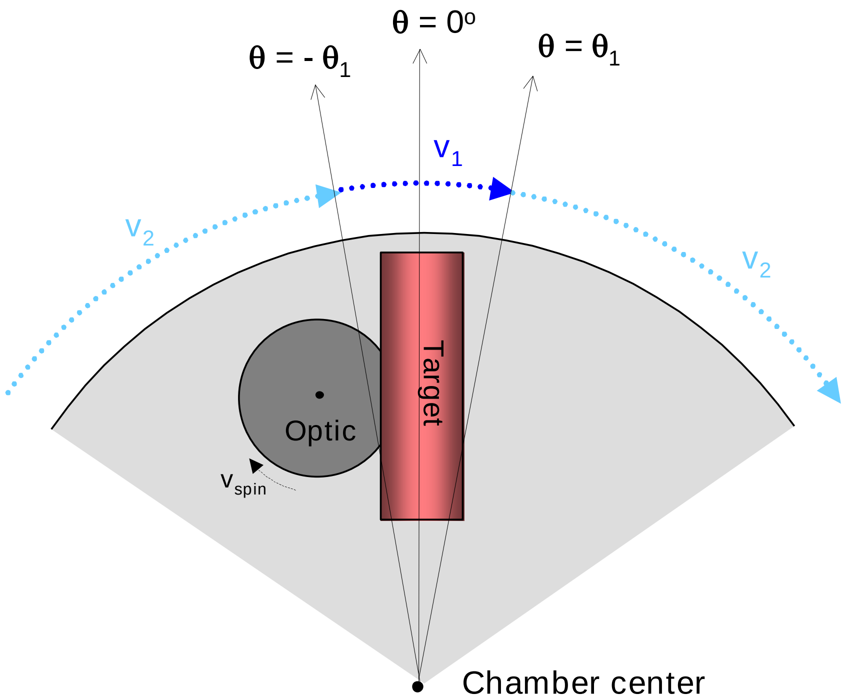
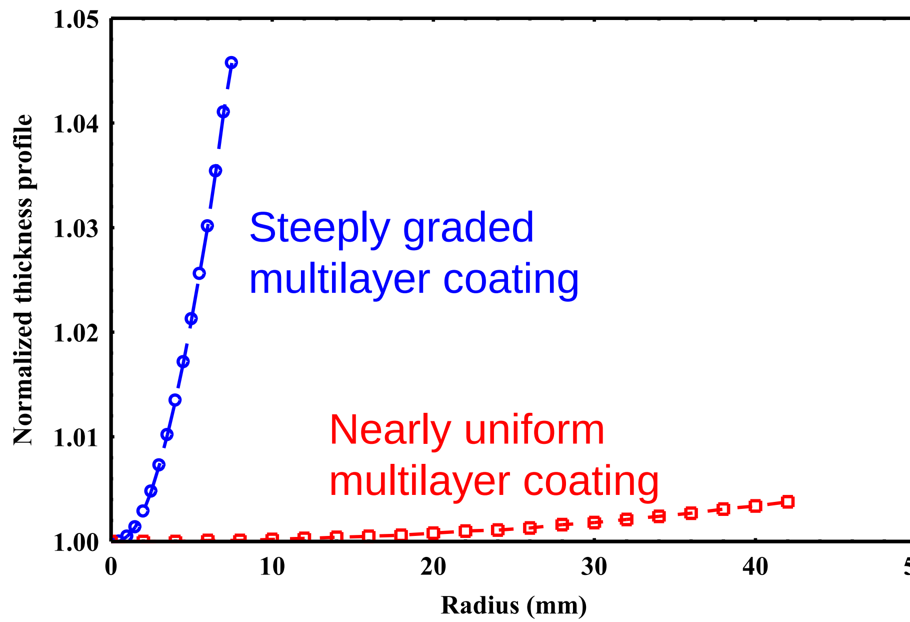
Velocity modulation is used during deposition to produce multilayer coatings with precise thickness control



1. **Simulate deposition process**
2. **Select optimum (v_2/v_1, θ_1), to achieve desired thickness profile**
3. **Measure results on test optic and iterate**



R. Soufli, R. M. Hudyma, E. Spiller, E. M. Gullikson, M. A. Schmidt, J. C. Robinson, S. L. Baker, C. C. Walton, and J. S. Taylor , Appl. Opt. 46, 3736-3746 (2007).

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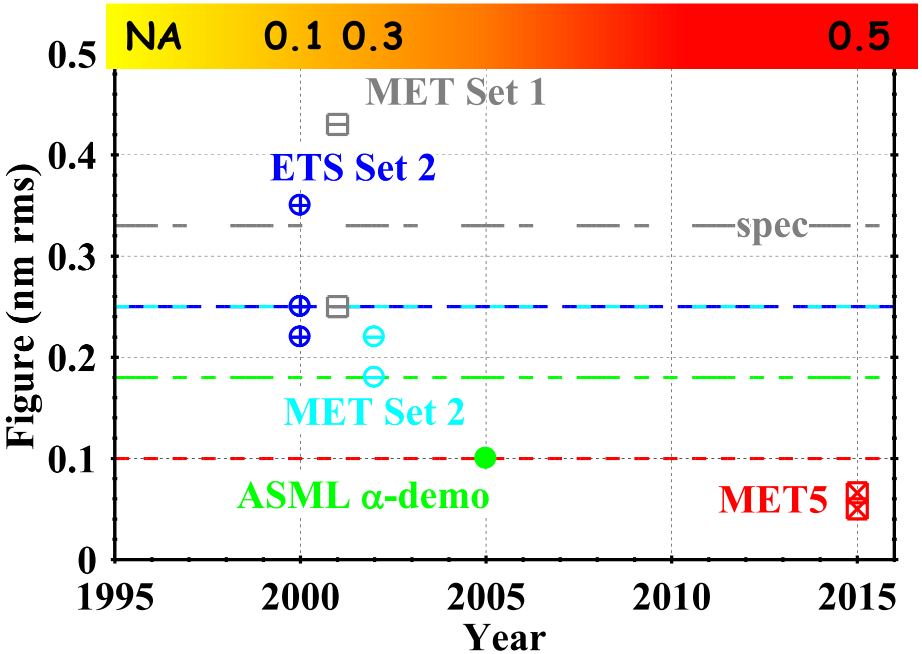
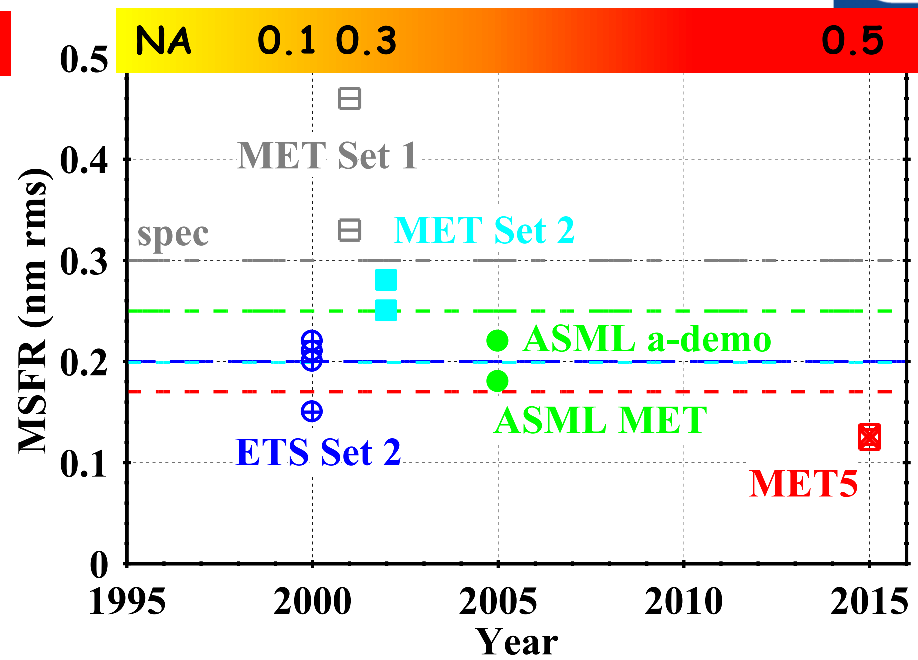
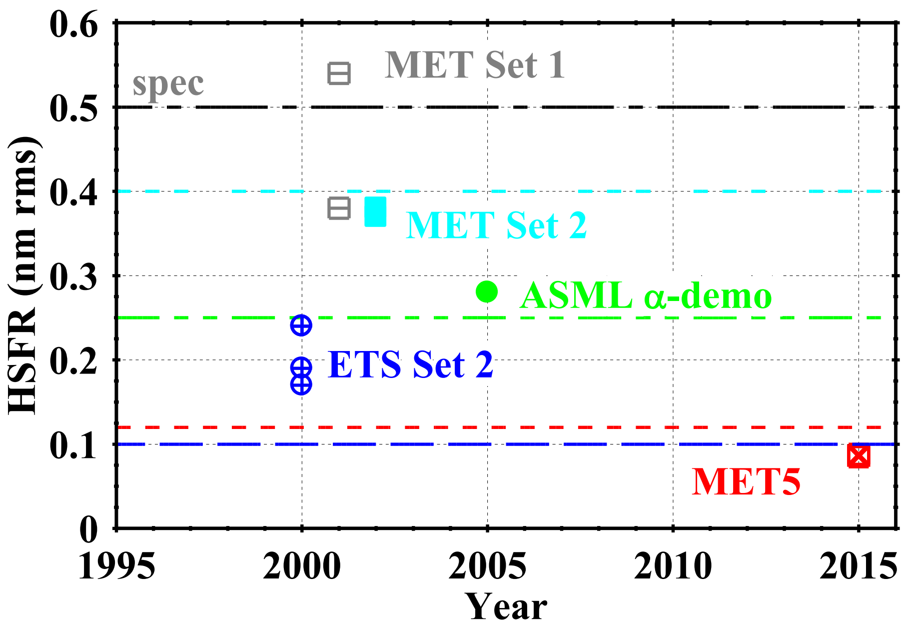
Historical evolution of figure, MSFR and HSFR of EUVL projection optical substrates







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).
L. Girard, et al, Proc. SPIE/APOMA 9633 (2015).

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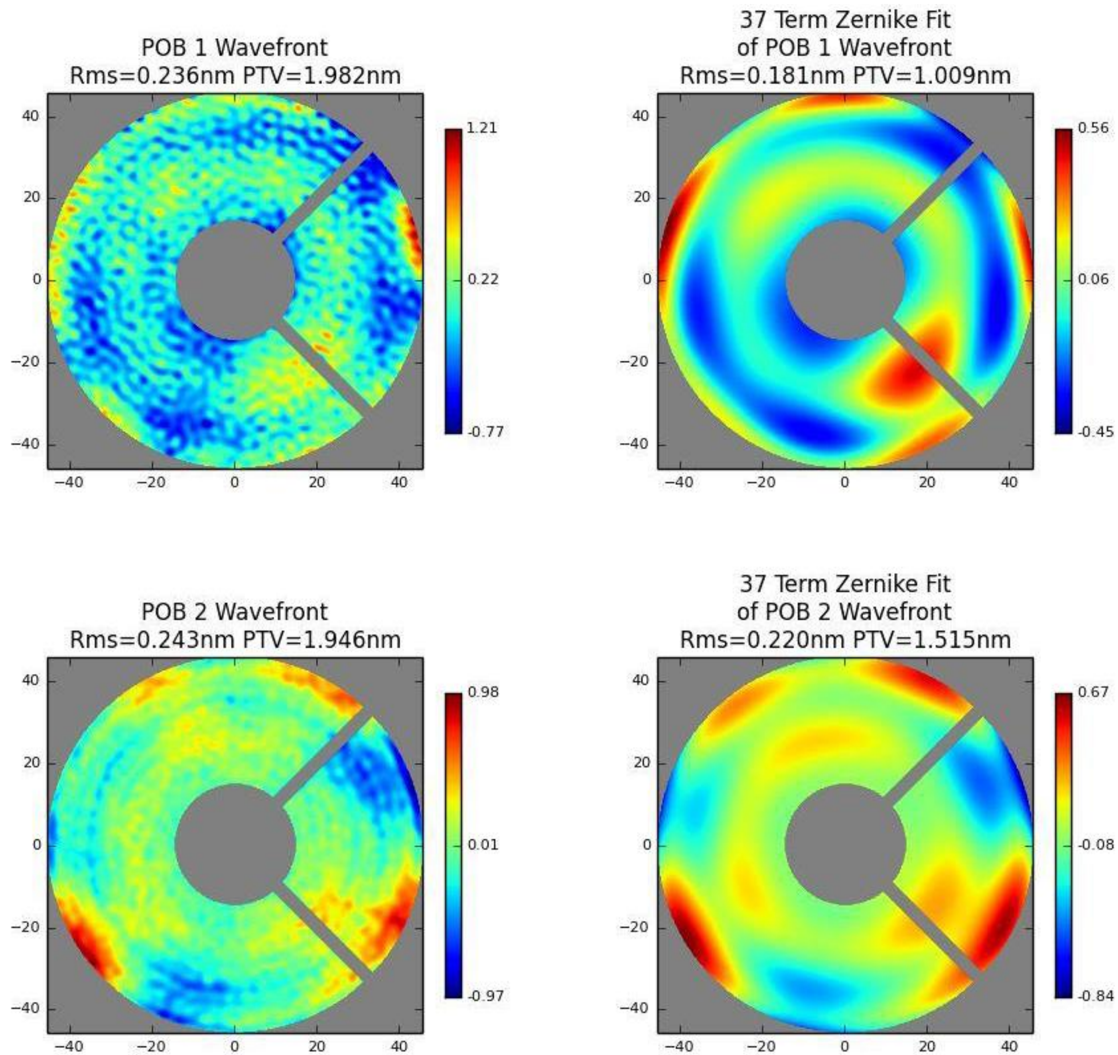
Total wavefront errors < 0.25 nm rms were measured by Zygo Corp. on the first 2 MET5 systems

Wavefront measured at center of field - See talk P68 by Luc Girard



L. Girard, L. Marchetti, M. Bremer, J. Kennon, B. Kestner, S. Hardy , Proc. SPIE/APOMA 9633, 96330V-1 (2015).

Also achieved:

- Flare (mid-frequencies) = 2.75% (*spec = 5%*)
- Maximum wavefront error (at edge of field) = 0.48 nm rms (*spec = 1 nm rms*)

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Summary

- The first EUVL MET tools with NA = 0.5 require a total wavefront error < 1 nm rms, posing extraordinary challenges for the multilayer coating stress, reflectivity and thickness control of the projection optics.

- Developed Mo/Si multilayer coatings with -100 MPa stress and 60% reflectivity.

- Achieved multilayer-added figure errors < 80 picometers rms over 250 mm clear apertures.

- Achieved < 0.1 nm rms contribution to total system wavefront from multilayer coatings of both M1 and M2 mirrors.

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