zygo®

Strengthen | Expand | Grow

Metrology driven Optics Manufacturing

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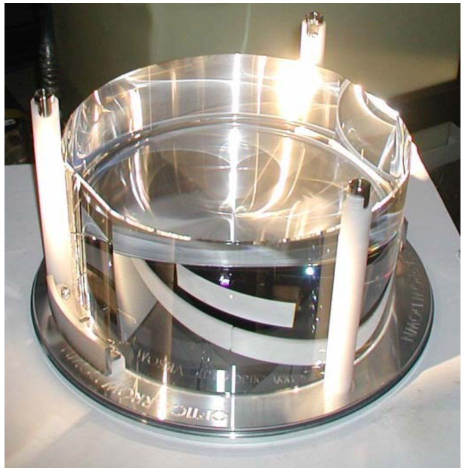
Acknowledgements:
- LLNL, CEA
- Advanced Ligo
- EUV Customers

Outline

- Introduction
- High Energy Laser Projects
- Advanced Ligo
- Extreme UV Lithography optics
- Conclusions



One Company – Two Operational Divisions

METROLOGY SOLUTIONS

Leading metrology systems for critical process control and advanced research

- Industrial/Precision Machining
- Optics/Photonics
- Semiconductor
- Data Storage
- Energy
- Academia/Research

- 3D Optical Profilers
  - Surface Roughness
  - Materials/Films Characterization
  - Critical Dimensions
- Laser Fizeau Interferometers
  - Surface Shape/Form
- Distance Measuring Interferometers
  - Lithography Stage Control
- OEM/Integrated Metrology
  - Semiconductor
  - Displays

OPTICAL SYSTEMS

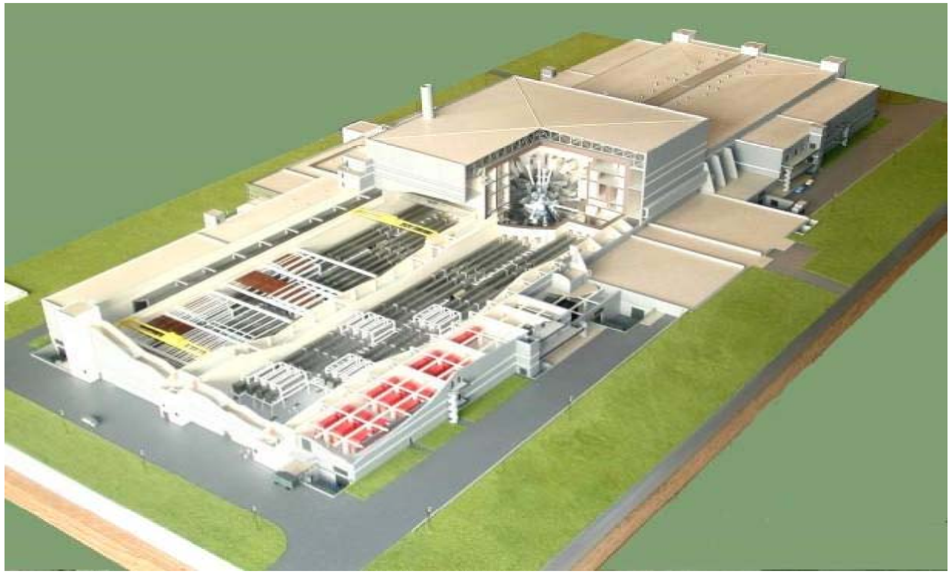
OEM supplier of high precision integrated optical systems and components

- Defense & Aerospace
- Industrial
- Life Sciences / Medical
- Semiconductor

- Optical components
  - Lenses, Mirrors, windows…
  - Flats, spheres, aspheres, free-form…
  - Glass, ceramics, metals…
- Electro-Optical systems
  - Design & analysis
  - Prototypes and production
  - Lens assemblies, sources, sensors…

National Ignition Facility (NIF) USA
Laser Megajoule CEA France

NIF building:
- **Located at Lawrence Livermore National Laboratory (LLNL)**
- **Size of about 3 football fields**
- **Requiring thousands of meter class size optics**



EUROPE
- **AWE/UK Orion Laser Project**
- **CEA /F Laser Megajoule**

Credit: Lawrence Livermore National Laboratory, CEA France

Laser Fusion Optic
Products and requirements

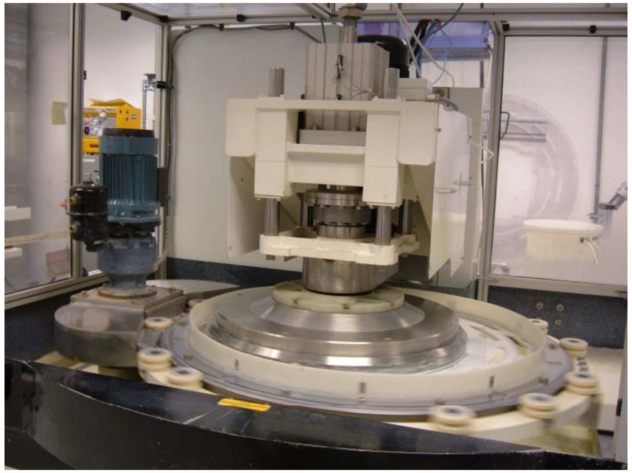
- Over 7,000 Laser Fusion Optics produced to date (& counting…)
- That is 4,200 m² polished or:
  - ~0.6 Soccer Field
  - ~1 American Football Field

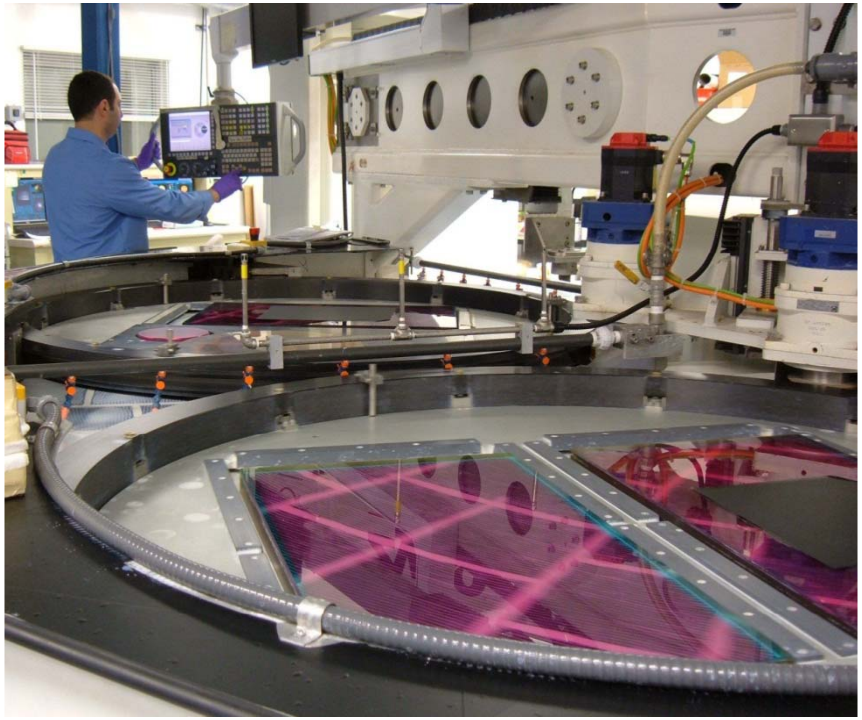
Requirements:

- Optical Material Quality
  - High homogeneity
  - No bubbles / inclusions
- Optical Performance
  - Global wavefront performance
  - Minimal slope gradients
  - Micro-roughness
- Surface and Optic Quality
  - 30/10 or less scratch/dig & max scratch lengths
  - No sub-surface damage
- Low breakage and damage occurrences
  - Optic material costs exceed finishing costs

Polishing Process (Full Aperture)

- Large size pitch and high-speed synthetic lap polishing machines:
  - Custom made
  - From 1.2 meter to 4.26 meter (14')
- Single side and double side processes





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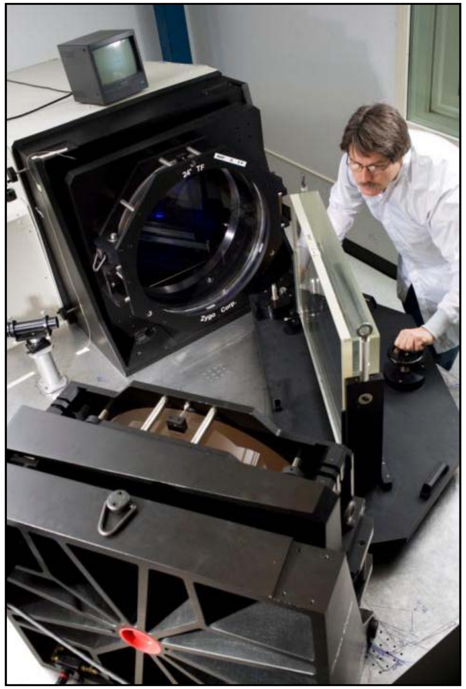
Polishing Technologies (Sub-aperture)

- **Computer Controlled Polishing (CCP)**
  - Custom made tools
- **Magneto Rheological Finishing (MRF®)**
  - Large number of different size machines for flats, continuous phase plates CCP, substrates, polarizer's, windows, but also for very precision spheres
- **Ion Beam Figuring (IBF)**
  - Flat, spheres, aspheres, free-form etc.
  - Surface figure < 0.25nm rms (λ/2500 @ 633nm)
  - Works on delicate and/or easily deformed surfaces, e.g. ultra-lightweight substrates (no print-through)
  - Can be applied to surface geometries that are not accessible to conventional polishing tools
  - No scratching

High Precision Metrology



In process and final metrology

- 24” and 32” interferometers enabling full aperture measurements
- NewView Microscopes, optical profilers
- Phase measuring interferometers
- Wavelength shifting interferometers

Dedicated environment

- **Temperature controlled**
- **Vibration controlled**
- **Remotely operated**

Advanced LIGO
Input and End Test Mass (ITM/ETM)

- Ø 340mm x 200mm thick
  - Weight ~40 kg / 88 lbs
- Demanding polishing requirements
  - Very tight surface quality tolerance.
  - Concave Radius 2km
    - Corresponds to 5.6μm Sag over Ø300mm
  - Radius measurement uncertainty ±5m
    - Fabrication tolerance ±15m.
    - 5m radius error corresponds to 14nm Sag over Ø300mm
    - All 12 ITM/ETM parts matched to ±1m fabrication goal
  - Figure requirement < 0.3nm RMS
- Approx 50 pcs of LIGO optics were manufactured in our Richmond (ex ASML Optics) facility

Advanced LIGO optics metrology

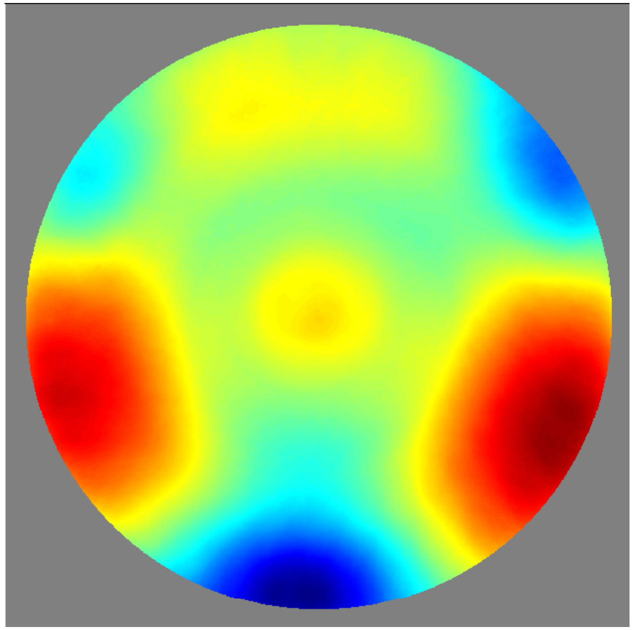
GOAL: Measure figure and radius of parts with a 2km radius to the required precision

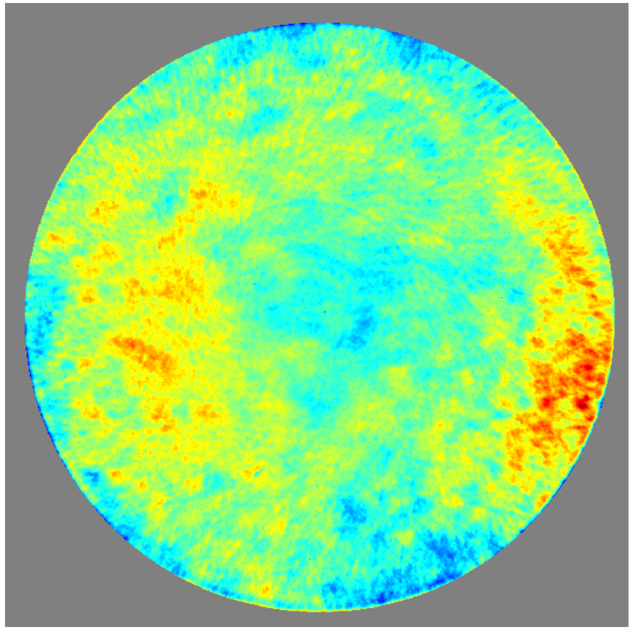
- Using a custom 12-inch convex transmission sphere (TS)

Zero-expansion ceramic glass transmission sphere for LIGO 2km radius parts

- **A TS with such a radius of curvature and this low level of uncertainty is a unique metrology solution because of the challenge in qualifying and fabricating it.**
  - Radius uncertainty of ±2m
    - A qualified test plan and error budget allocation is used to manage the sources of error.
    - The radius of the TS is qualified against a flat, that has been calibrated by an absolute measurement method.
  - Radius stability of < 1m
    - Zero expansion ceramic glass qualified for internal homogeneity for very good transmission quality.
  - Support fabrication to <0.3nm RMS
    - The TS figure is calibrated to <0.15nm RMS by absolute, self-referencing methods.

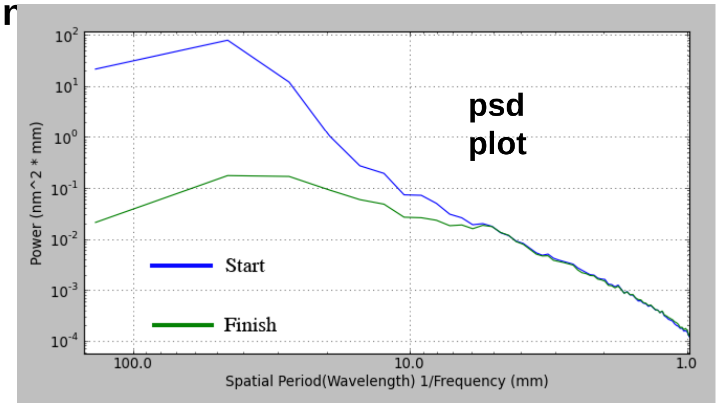
Figure Convergence





Following traditional polishin

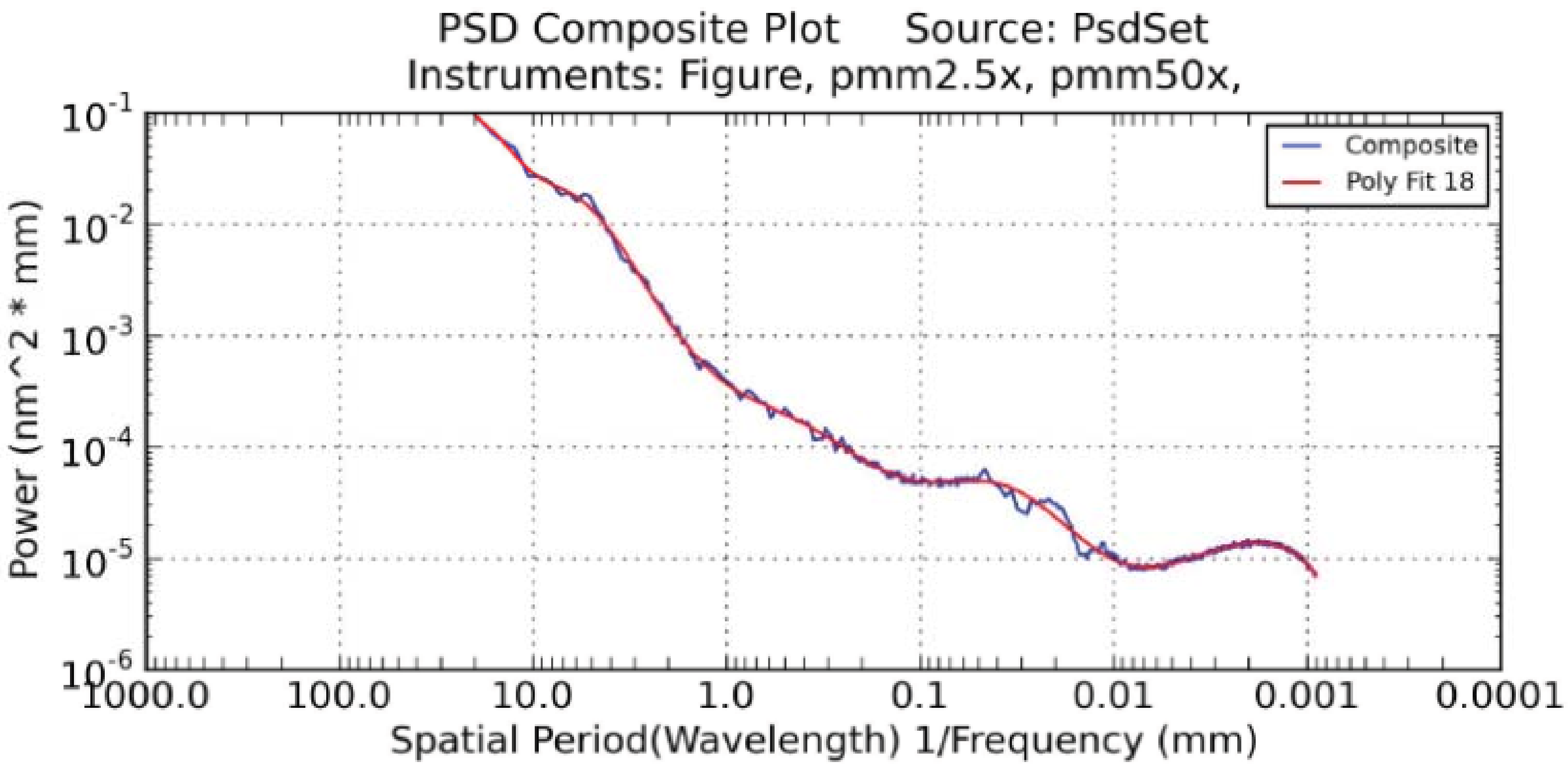
- **8.37nm RMS**
- **46.8nm PV**
- **300mm aperture**



After Fine Figuring

- 0.18nm RMS
- 1.96nm PV

Maintaining Low Micro-roughness



Range (mm)	Specification (nm rms)	Actual (nm rms)	Poly-Fit (nm rms)
1.0000-0.0013	0.16	0.105	0.105

Part to Part Repeatability

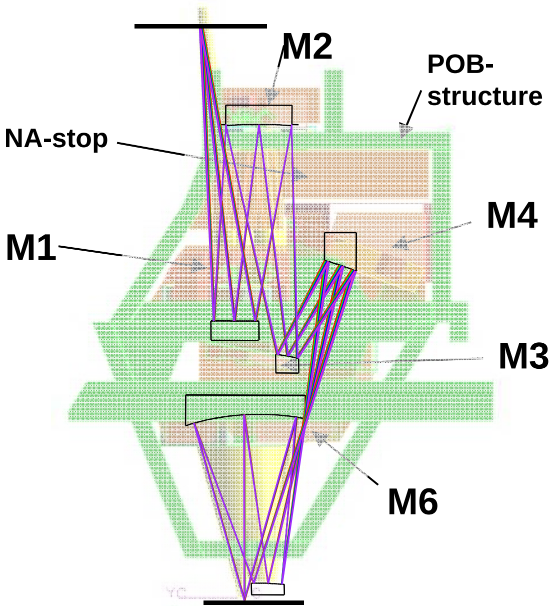
	Radius (m)	Figure (nm RMS)
ETM 01	2249.8	0.09
ETM 02	2250.3	0.15
ETM 03	2250.1	0.23
ETM 04	2250.4	0.17
ETM 05	2250.0	0.11
ETM 06	2248.6	0.15
ETM 07	2250.8	0.17
ETM 08	2249.3	0.13
ETM 09	2250.8	0.08
ETM 10	2250.1	0.08
Target	2250.0	
STDev	0.6	

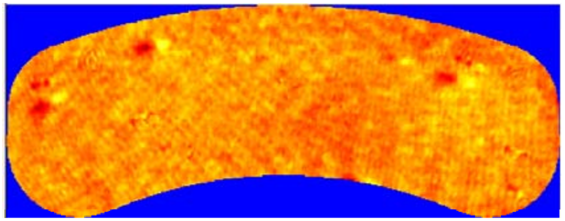
	Radius (m)	Figure (nm RMS)
ITM 01	1938.3	0.10
ITM 03	1938.5	0.08
ITM 04	1938.6	0.15
ITM 05	1939.2	0.10
ITM 06	1937.7	0.09
ITM 07	1938.5	0.10
ITM 08	1938.4	0.16
ITM 09	1938.1	0.11
ITM 10	1939.7	0.14
ITM 11	1939.4	0.18
Target	1939.0	
STDev	0.6	

- Final Measurements at ø160mm
- Figure With $Z_{0,0}$ $Z_{1,1}$ $Z_{1,-1}$ $Z_{2,0}$ $Z_{2,2}$ & $Z_{2,-2}$ Removed per Born and Wolf pp. 523-525

EUV Mirror

- Mirror for EUV lithographic projection system.
  - 13.5nm wavelength, 0.25NA, 4x reduction, less than 30nm printing resolution.
- Off-axis aspheric mirror
  - 500+ mm concave surface with a few um of aspheric departure
    - Kidney shape clear aperture
  - Off-axis: The optical axis is completely off the mirror substrate.
- Testing to support manufacture.
  - < 0.1nm RMS Figure requirement



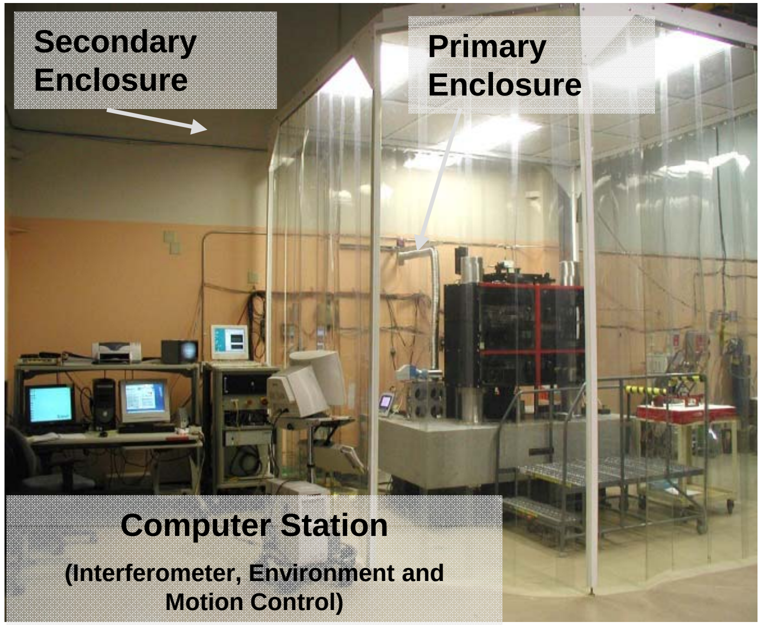


Example of test reproducibility:

difference between an individual test and average of multiple tests

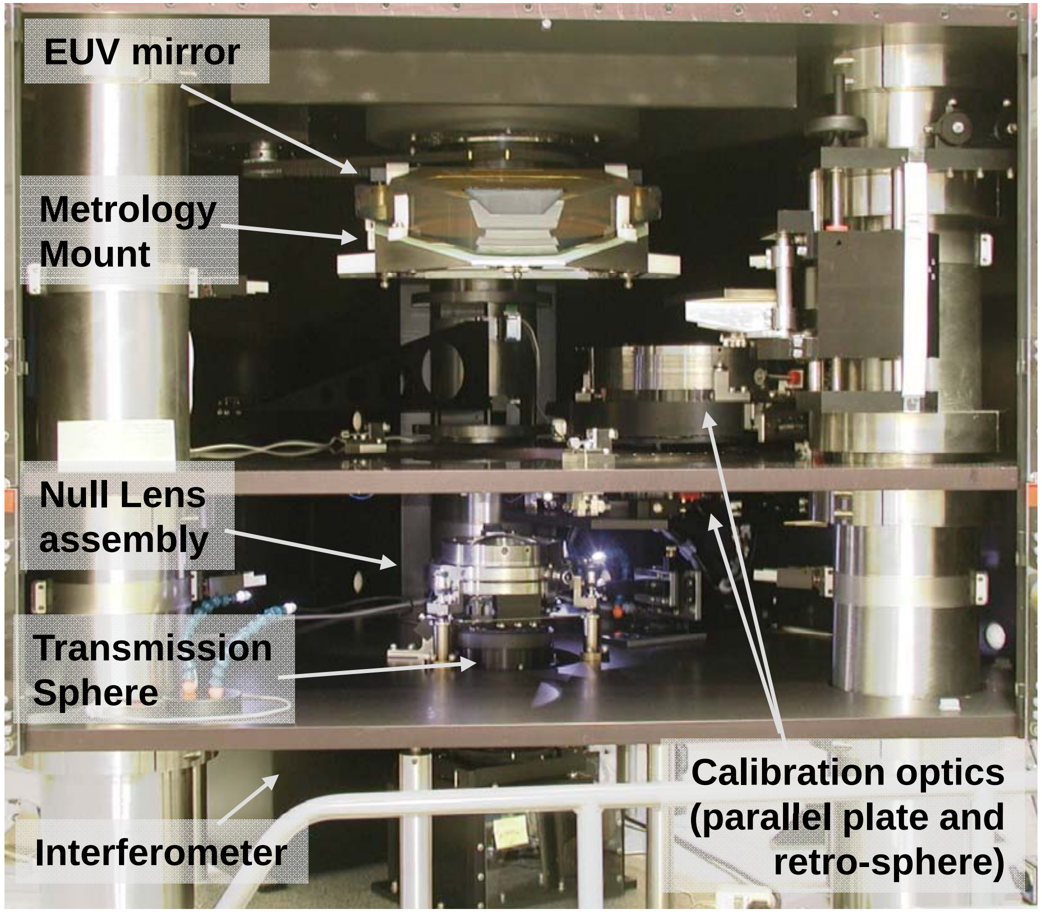
0.042nm RMS,
0.496nm P-V

Mirror Figure Metrology



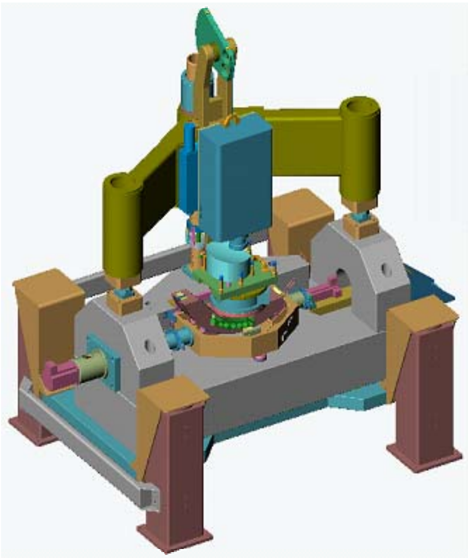
- Temperature controlled room
- Multiple enclosures

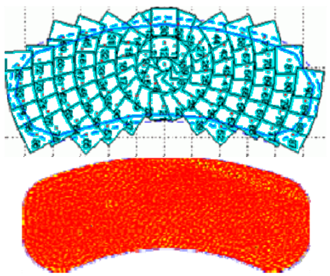
The Primary Enclosure contains all the critical optical components.



SASHIMI and PSD

- Interferometer to measure high resolution, full aperture Mid-Spatial Frequency surface error by combining small aperture maps
  - Bridge the gap between figure interferometer and Phase-Measuring Microscope (PMM)
  - Provide full aperture data to support manufacturing processes.





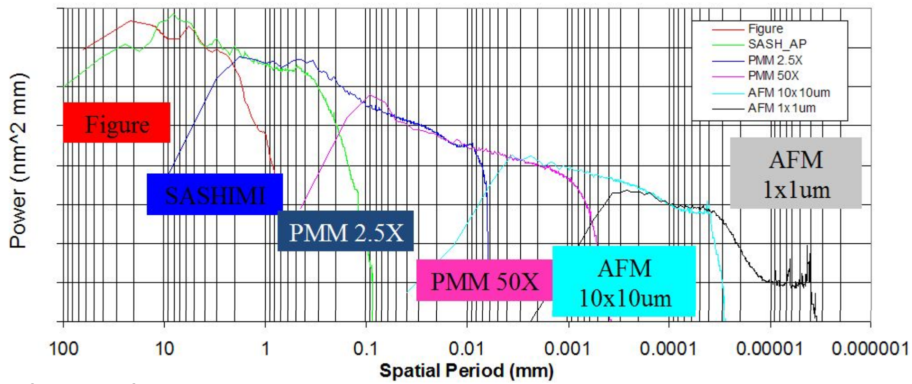
EUV M4 Mirror

SASHIMI Data [5-0.5mm]

RMS 0.10nm

- Full spectrum surface characterization constructed with multi-instrument PSD plot.
  - Each Instrument has a limit to its spatial resolution. A power spectral density (PSD) process is used to characterize each instrument's response.
- The Figure, SASHIMI, PMM and AFM PSD's are combined to create a composite with a much larger range than can be acquired by a single instrument.

EUV M4 mirror –Sample PSD plot



SASHIMI: Sub-Aperture Surface Height Interferometric Measuring Instrument

Conclusions

- From making thousands of laser fusion optics…
- … to long RC spheres with very tight requirements…
- …to probably some of the best optics ever made (EUV-L)…
- … a common theme:
- Metrology is key to success!