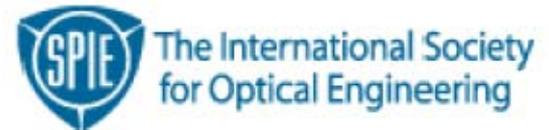


Optical Characterization of Very Low Loss Optical Components for HEL Applications

Ric P. Shimshock
MLD Technologies, L.L.C.
Mountain View, CA USA

Mirror Technology Days 2008

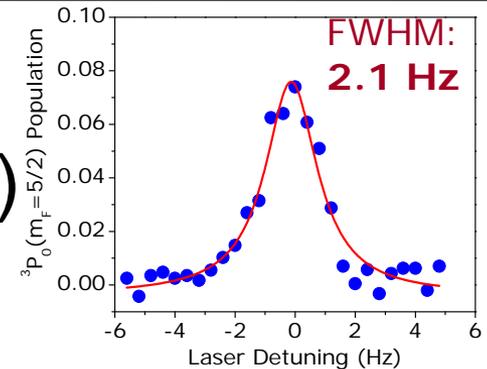
nmOptics



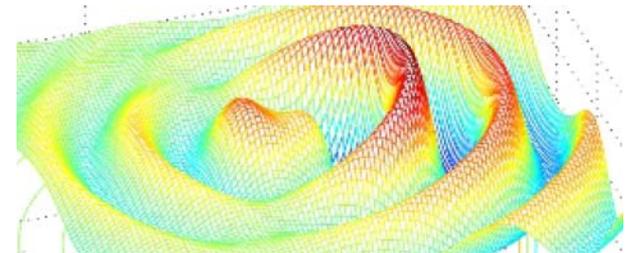
[MLD Technologies, LLC](http://www.mldtechnologies.com)

Optical Coatings currently limit achievable performance of critical optical instruments and applications

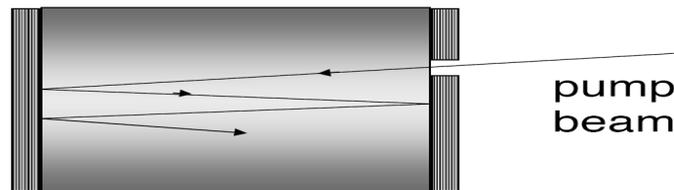
- Optical atomic clocks (spectroscopy)



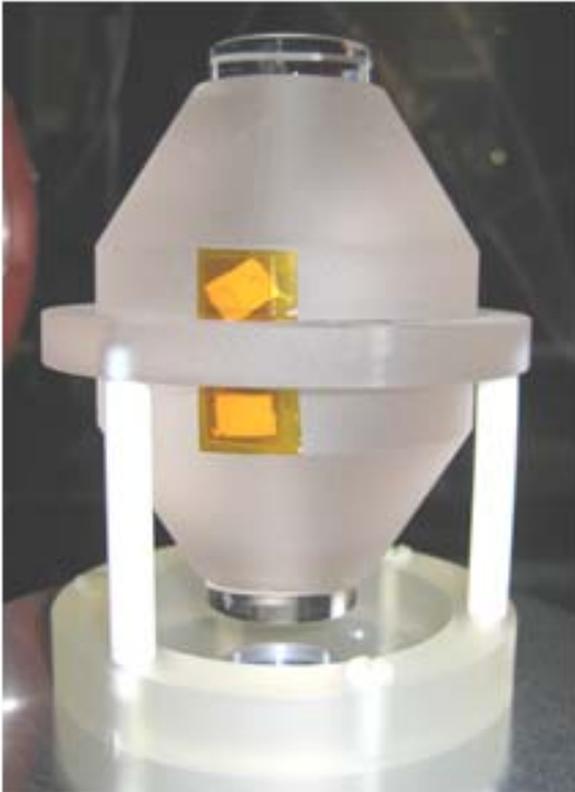
- Gravity wave detection.



- Laser Cooling



The JILA Sr clock laser



-Mirror technology:

- 40 layers of Ta_2O_5 and SiO_2 $\frac{1}{4}$ wave dielectric stacks ($\phi \simeq 4 \times 10^{-4}$)*.

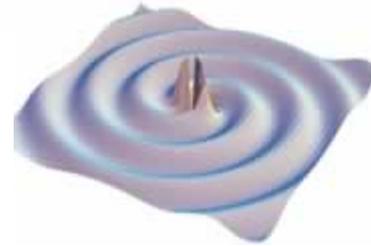
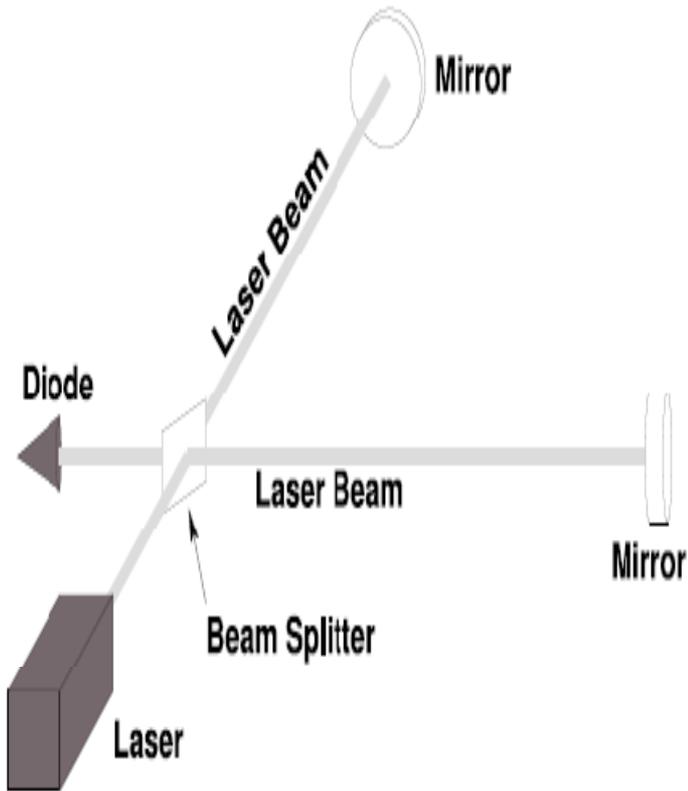
-Deposited via ion beam sputtering.

-Surface flatness and reflectivity support finesse of 250,000.

-Substrate and coating thermal noise limited.

*Numata et. al. *PRL* 93, 2004.

Gravity Wave Observatories (GWO) are online



Two North American LIGO Observatories

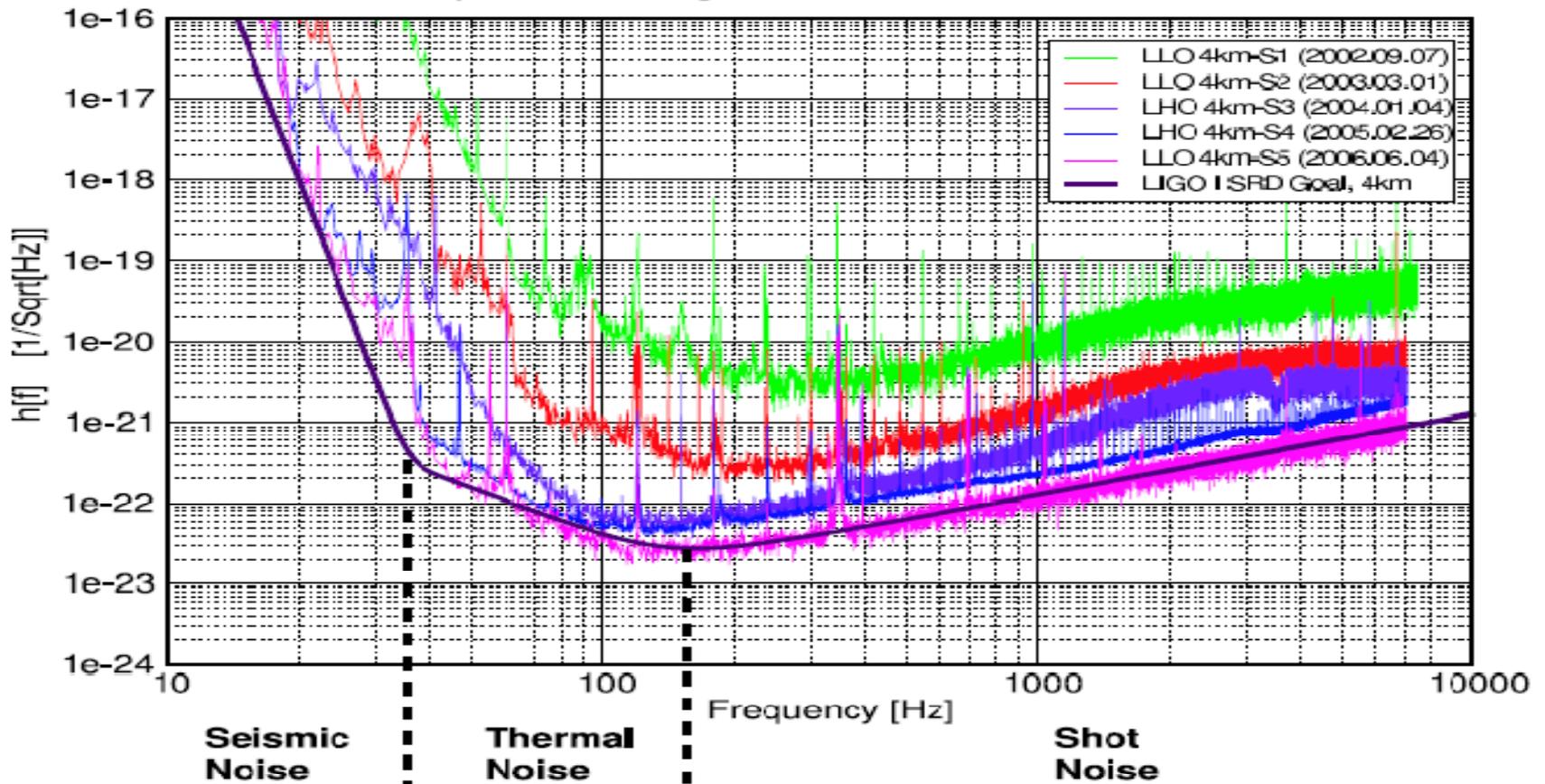
Laser Interferometric Gravity Observatory (LIGO)

- Einstein predicted Gravity Waves in 1918.
- 1980's Taylor and Hulse win Nobel Prize for observing binary pulsars - providing strong evidence for gravity waves
- Gravity Waves are extremely weakly coupled
- Gravity Wave Observatories (GWO) are not based on Electro-Magnetic (EM) Observation per se - but based use of an extremely sensitive interferometers with long arms (i.e are being detected using EM) to sense motion
- GWO have been in operation for nearly 40 years
- GWO must operate in extreme seismic isolation
- GWO search for four types of signals (bursts – quasiperiodic)
- “Noise Floor” limits GW detection
- LISA is a future GWO planned for Space Deployment

Current LIGO Sensitivities

(published Spring 2007)

Best Strain Sensitivities for the LIGO Interferometers
Comparisons among S1 - S5 Runs LIGO-G060009-02-Z



LIGO Noise Issues in Mid-Frequency Range

Shot noise limit :

- directly by laser power
- indirectly by optical imperfections

$$\tilde{h}_{shot}(f) = 1.08 \times 10^{-24} \cdot f_{pole} \cdot \sqrt{1 + \left(\frac{f}{f_{pole}}\right)^2} \cdot \sqrt{\frac{1}{\eta \cdot S_{rec} \cdot P_{BS}}}$$

Mirror thermal noise limit :

- Q of test-mass (substrate, coatings)
- T of test-mass, M of test-mass

$$h_{th} \propto \sqrt{\frac{k_B T}{M \cdot Q}}$$

→ Increase laser power but increase also thermal effects

(radiation pressure problem : larger masses)

$$\tilde{h}_{rad,press} = \frac{1}{M \cdot L_{arm} \cdot f^2} \sqrt{\frac{\bar{h} \cdot P}{2\pi^3 c \lambda}}$$

→ New materials for mirrors, high Q even at low T, large size, optical quality

GWO Mirror components

- Substrates
 - Super polished low absorbing Fused Silica
- Coatings
 - low absorption, low loss 1064 nm High Reflectance Mirror Coatings
 - Metal oxide coating materials ($\text{Ta}_2\text{O}_5/\text{SiO}_2$)
 - Doped High Index Materials being studied

A LIGO Mirror

Substrates: SiO_2

25 cm Diameter, 10 cm thick

Homogeneity $< 5 \times 10^{-7}$

Internal mode Q's $> 2 \times 10^6$

Polishing

Surface uniformity $< 1 \text{ nm rms}$

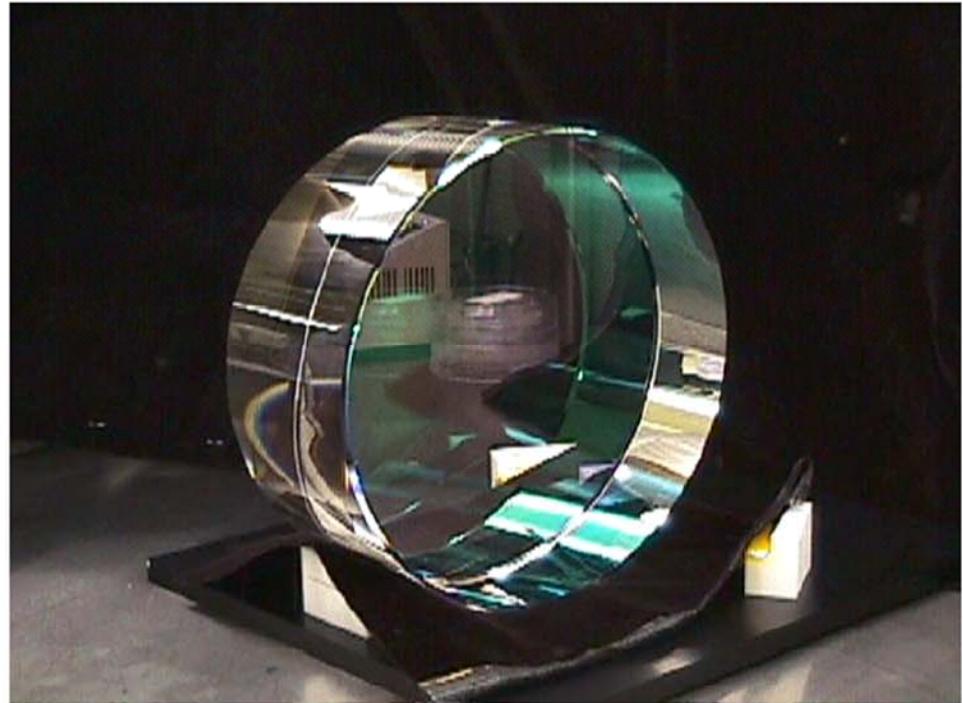
Radii of curvature matched $< 3\%$

Coating

Scatter $< 50 \text{ ppm}$

Absorption $< 2 \text{ ppm}$

Uniformity $< 10^{-3}$



Coatings: optical performances

Optical performances achieved in Virgo-SMA (LMA):

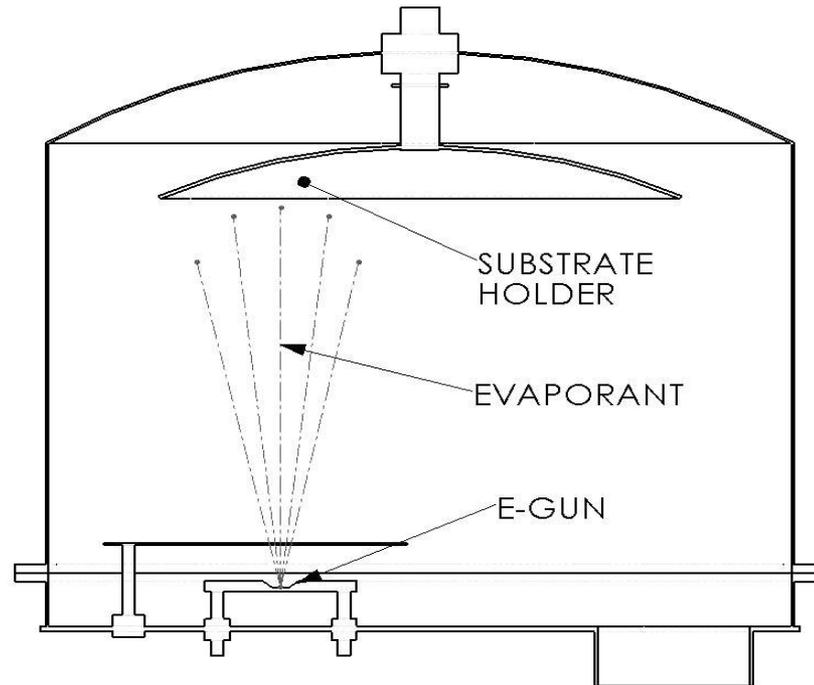
	1992	1994	2000 to Virgo	
Absorption at 633 nm	20 ppm	10 ppm	< 5 ppm	4 ppm
Absorption at 1064 nm	-	2 - 3 ppm	0,5 ppm	0.6 ppm
Scattering at 633 nm	50 ppm	5 ppm	1,2 ppm	4 ppm
Scattering at 1064 nm	-	2 ppm	0,6 ppm	4 ppm over Φ 150 mm
Wavefront	-	-	-	3.8 nm rms over Φ 150 mm
Components diameter	25 mm	50 mm	25 mm	350 mm

Advanced LIGO Test Mass Coatings: Requirements

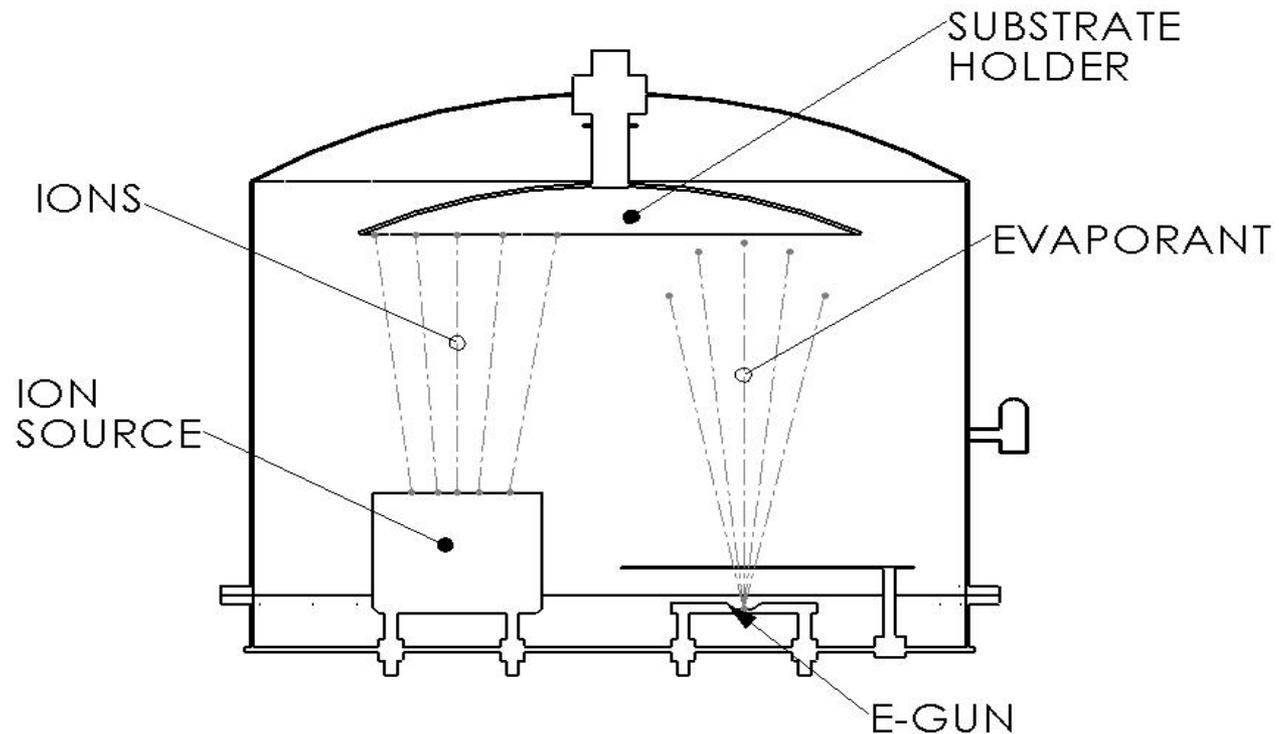
G. Harry, et al.,
LIGO-C030187-00-R

Parameter	Sapphire goal	Sapphire requirement	Fused Silica goal	Fused Silica requirement
Mechanical loss ¹	2×10^{-5} *	6×10^{-5} *	1×10^{-5} **	3×10^{-5} **
Optical Absorption ²	0.5 ppm	1 ppm	0.2 ppm	0.5 ppm
Thermal expansion ³	$5 \times 10^{-6}/K$ *	$< 2 \times 10^{-5}/K$ * $> 1 \times 10^{-6}/K$ *	$5 \times 10^{-7}/K$ **	$< 2 \times 10^{-6}/K$ ** $> 1 \times 10^{-7}/K$ **
Birefringence ⁴	1×10^{-4} rad	2×10^{-4} rad	-	-
Scatter ⁵	1 ppm	2 ppm	1 ppm	2 ppm
Thickness uniformity ⁵	10^{-3} (over 21.5 cm diameter) 10^{-2} (over 33.0 cm diameter)	10^{-3} (over 21.5 cm diameter) 10^{-2} (over 30.0 cm diameter)	10^{-3} (over 21.5 cm diameter) 10^{-2} (over 33.0 cm diameter)	10^{-3} (over 21.5 cm diameter) 10^{-2} (over 30.0 cm diameter)
ITM HR transmission	-	5×10^{-3} $\pm 2.5 \times 10^{-4}$	-	5×10^{-3} $\pm 2.5 \times 10^{-4}$
ETM HR transmission	5 ppm	10 ppm	5 ppm	10 ppm
Test Mass HR matching $2(T_1 - T_2)/(T_1 + T_2)$ ⁶	5×10^{-3}	1×10^{-2}	5×10^{-3}	1×10^{-2}
AR reflectivity	-	200 \pm 20 ppm	-	200 \pm 20 ppm

Schematic Diagram of E-Beam Deposition System



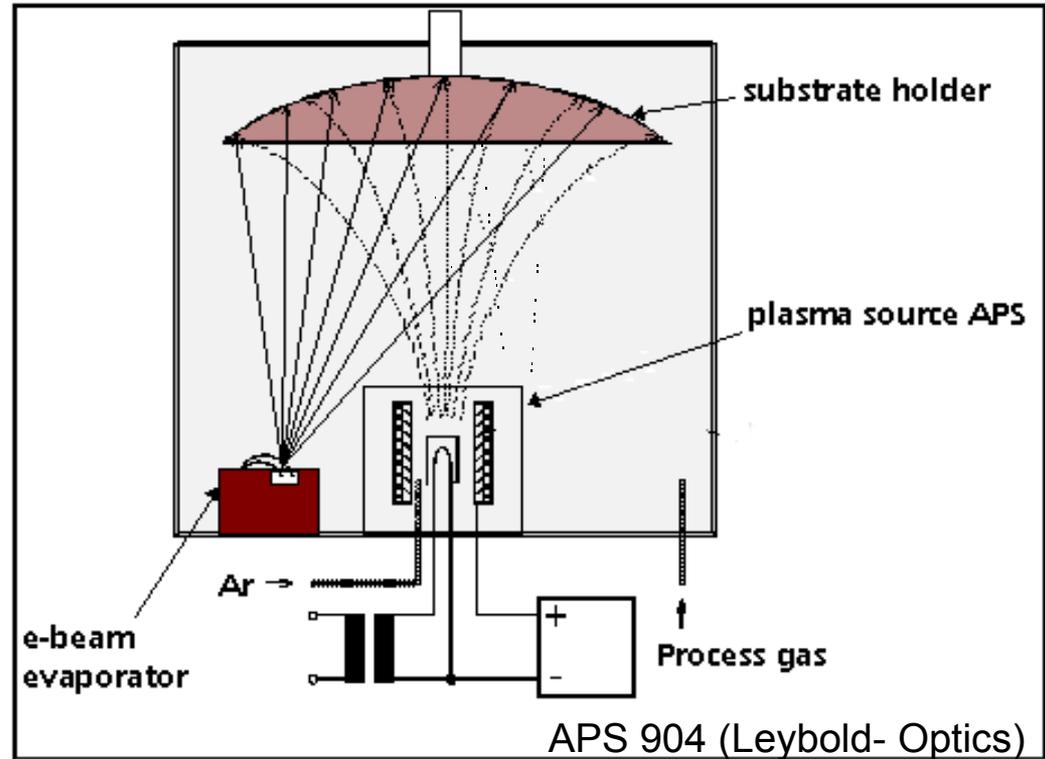
Schematic of Ion Assisted E-Beam Deposition System



Plasma/Ion Assist Coating Technology

Plasma - Ion Assisted Deposition

- low process temperature critical
- e-beam evaporation
- boat- evaporation
- ion source APS
- Ar- ion assistance :
60eV – 160eV



Microstructure of IBS Films

IBS: coating quality



← **Thermal deposition**
particle energy: **0.1-0.3 eV**
low mobility, shading
columnar structure
packing density 0.7-0.9
tensile coating stress

IBS →
particle energy: **5-20 eV**
high mobility
amorphous structure
packing density: 0.95->1
compressive stress
high quality, reproducibility



Advantages of IBS Process

..

IBS-coatings offer best optical quality achievable today

application of IBS-processes

production of laser coatings with

- highest quality
- complicated designs
- on sensitive substrates
- in low quantities or with
- small coating area

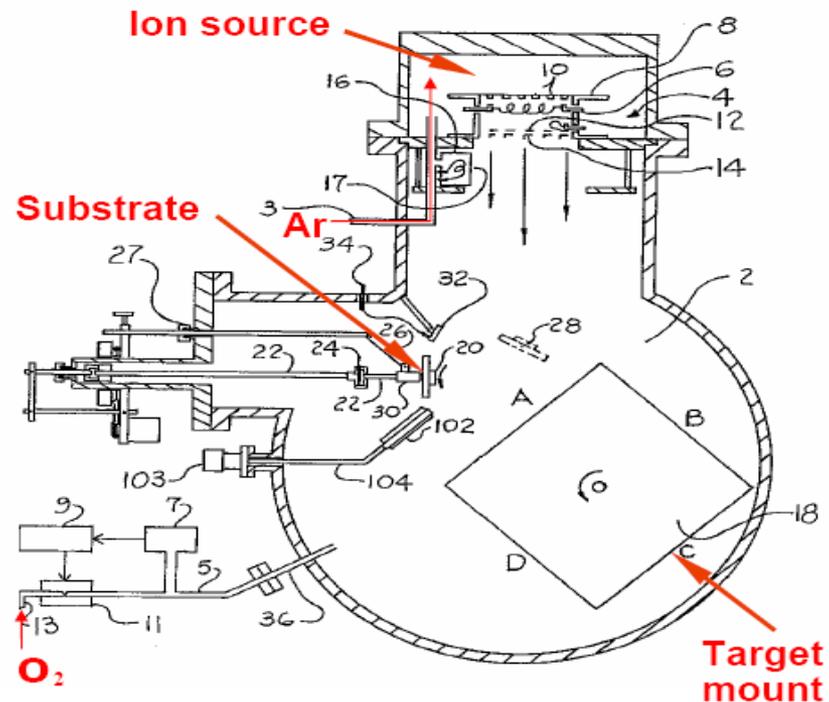
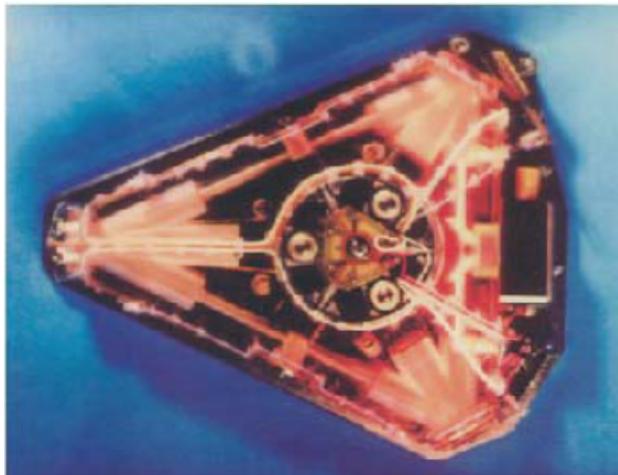


Critical Laser Application (Laser Gyro) Initially Limited by Performance of the Optical Coatings

Ion beam sputtering: historical aspects

Low loss mirrors for lasergyro systems

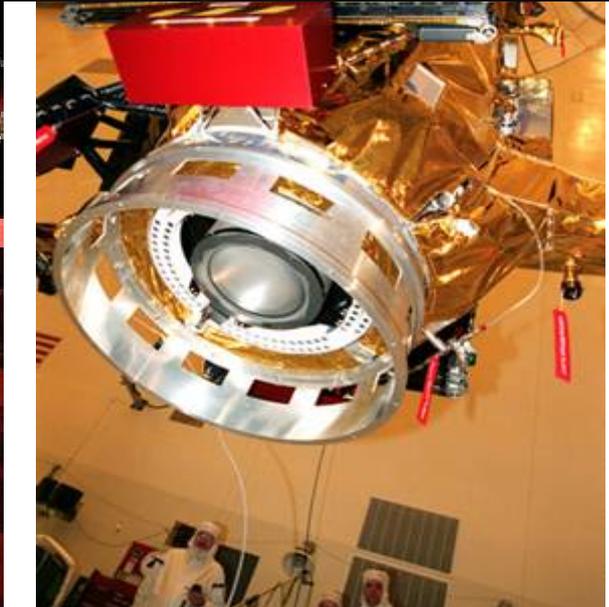
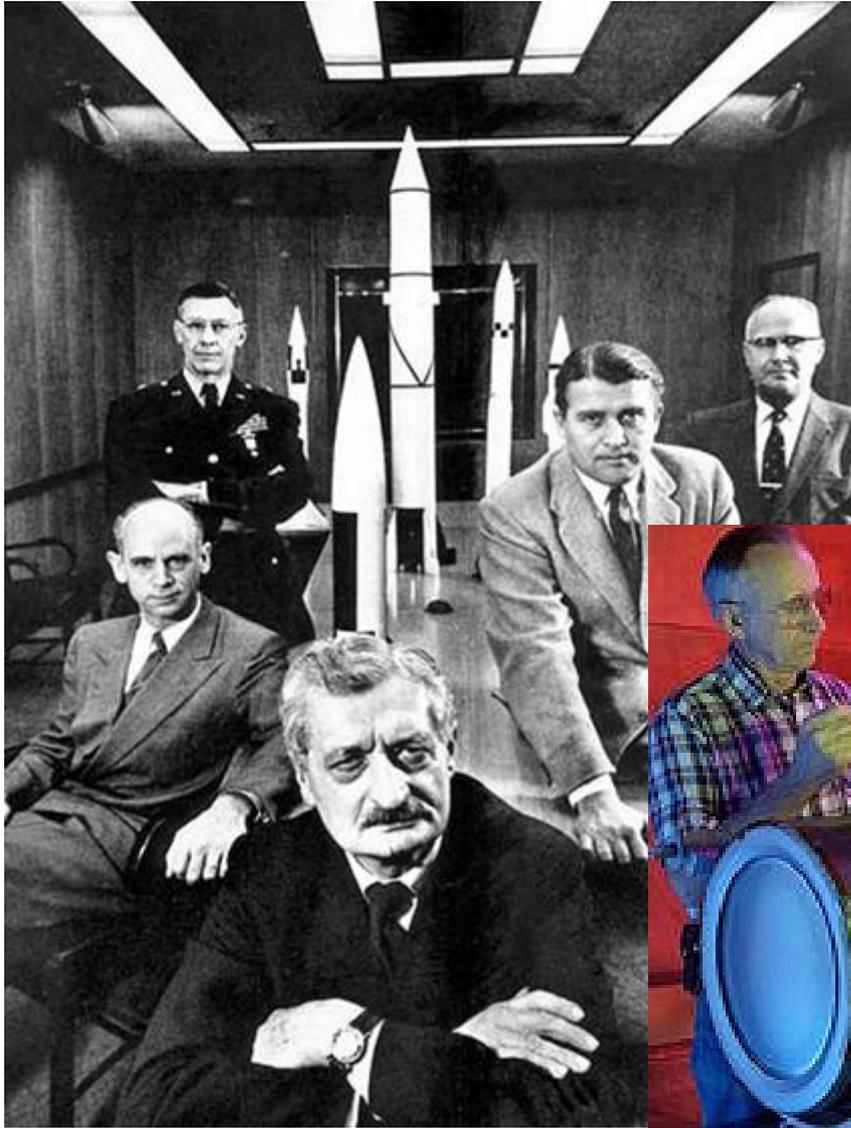
- stability in HeNe-discharge
- back scattering <20ppm



Patent US 4,142,958

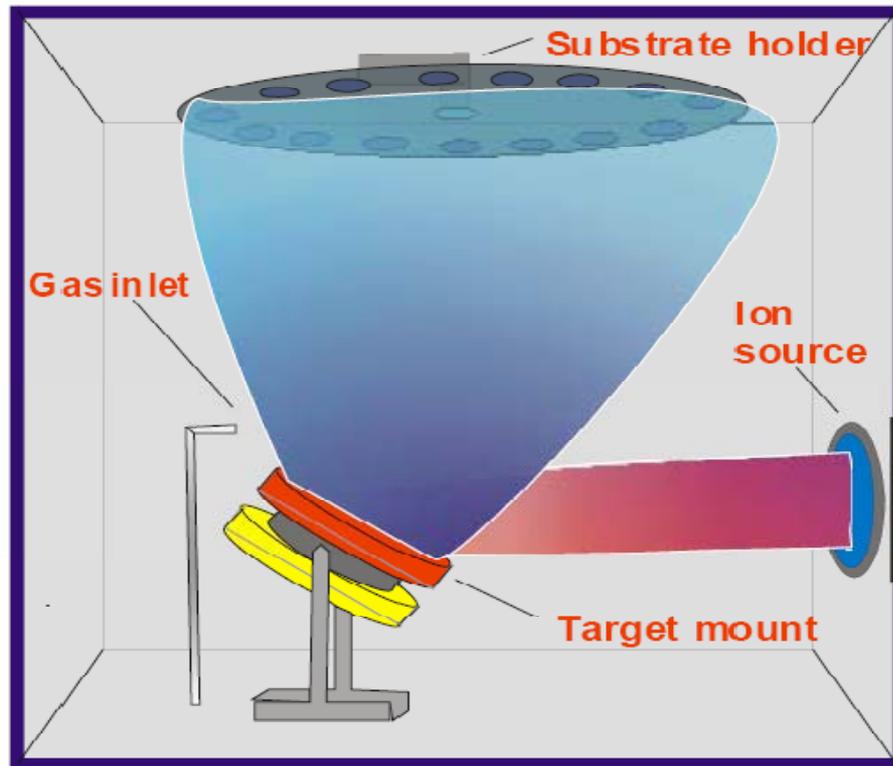
1978 Litton D.T. Wei, A.W. Louderback

Herman Oberth and the ABMA rocket team (Early 1950s)



Schematic of Ion Beam Sputtering (IBS) Process

Ion beam sputtering: fundamental principle

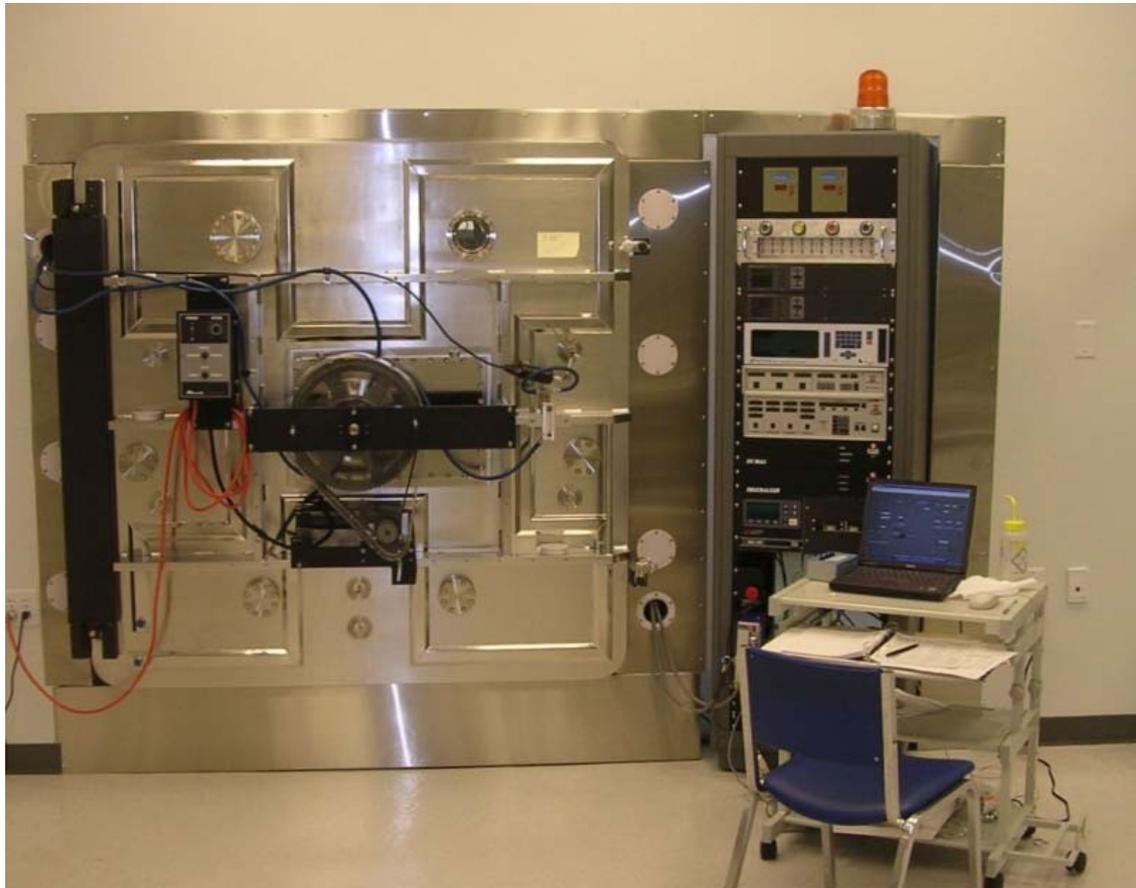


Ion Beam Sputtering (IBS)

- ions generated (1-2KeV) in separate ion gun
- ion beam focused on target (deposition material)
- sputtering of target material, flight zone

➤ formation of layer, energy regime 5-20 eV

Low Loss IBS Process has been scaled to a 1.5 Meter Class IBS Chamber



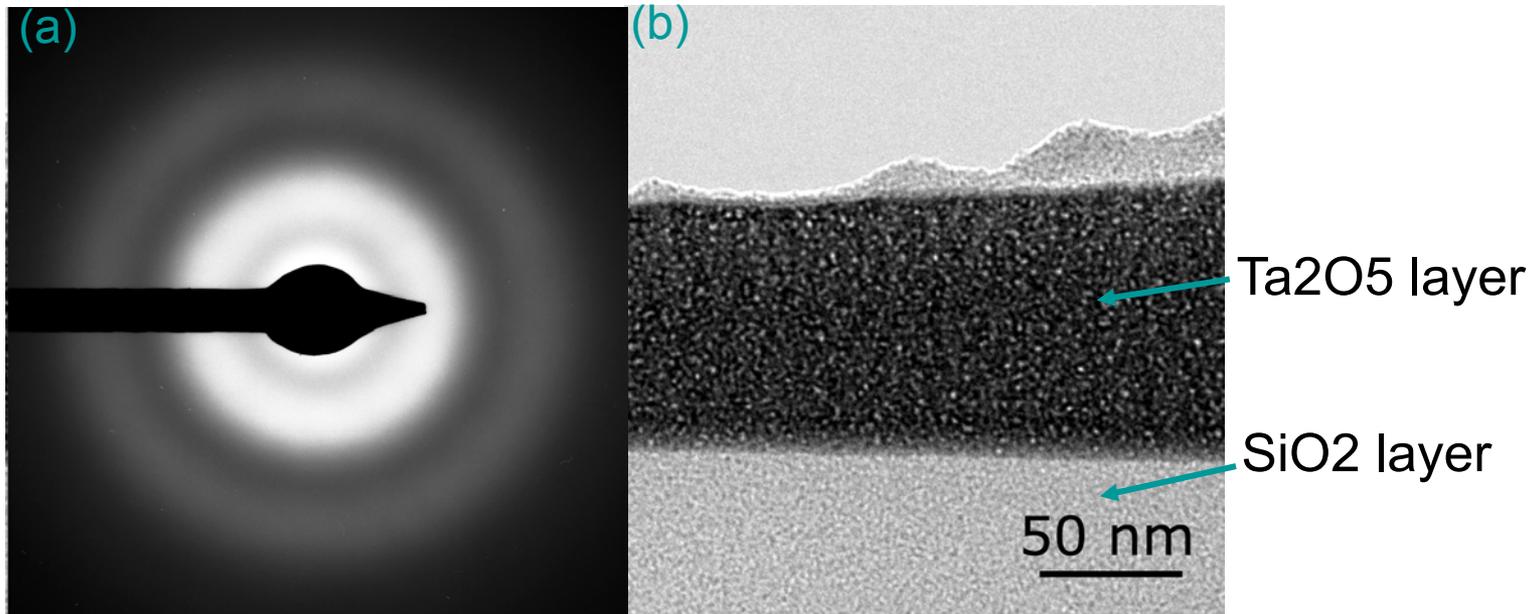
Key mechanical properties of metal oxide films deposited by IBS

IBS films are typically:

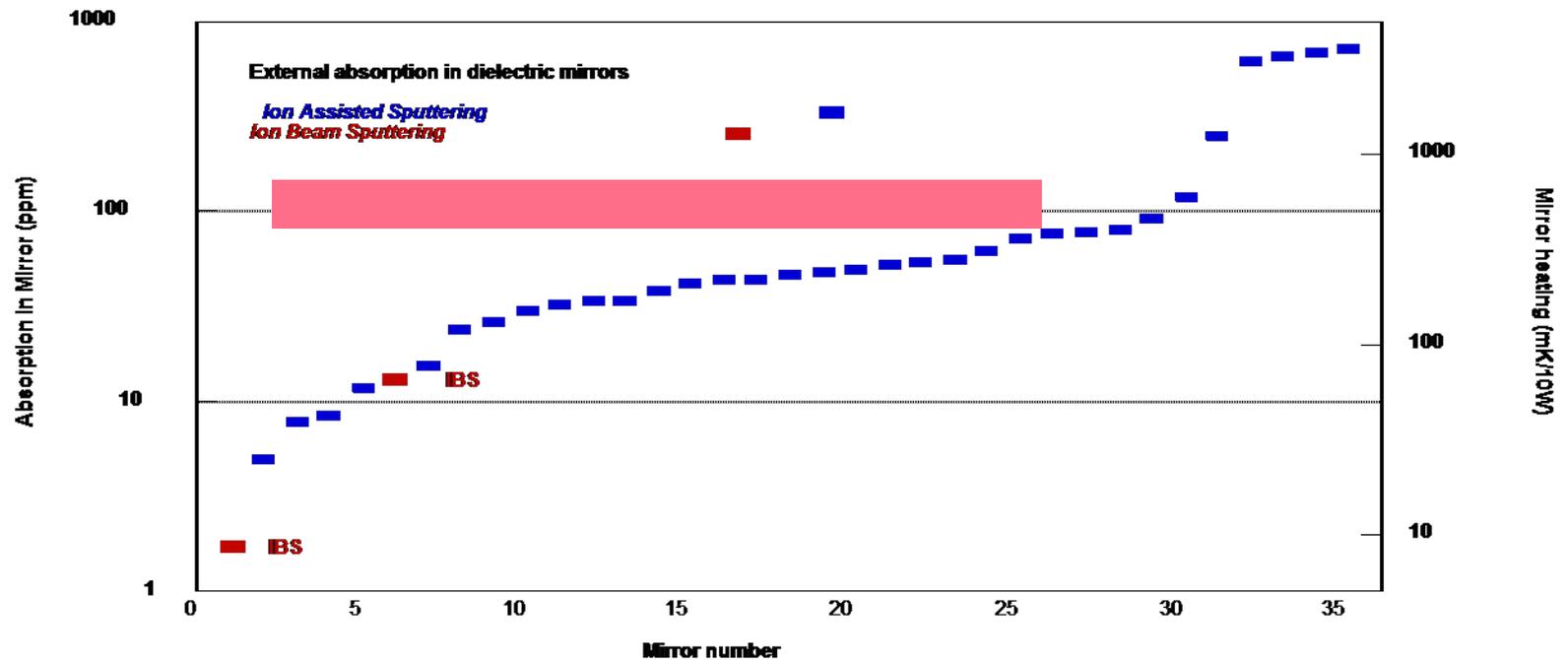
- very low scatter, exhibiting few voids and defects from the deposition process (one or two orders of magnitude less than e-beam films)
- amorphous or quasi amorphous (very small crystalline domains) microstructure – low bulk scatter
- have high compressive stress, in the range of 300 MPa
- exhibit high packing density and do not absorb water, do not exhibit spectral shift or surface figure changes with changes in humidity, temperature or vacuum to air transitions
- have better thermal conductivity than films deposited by thermal, e-beam or IAD techniques

TEM studies of coating structure

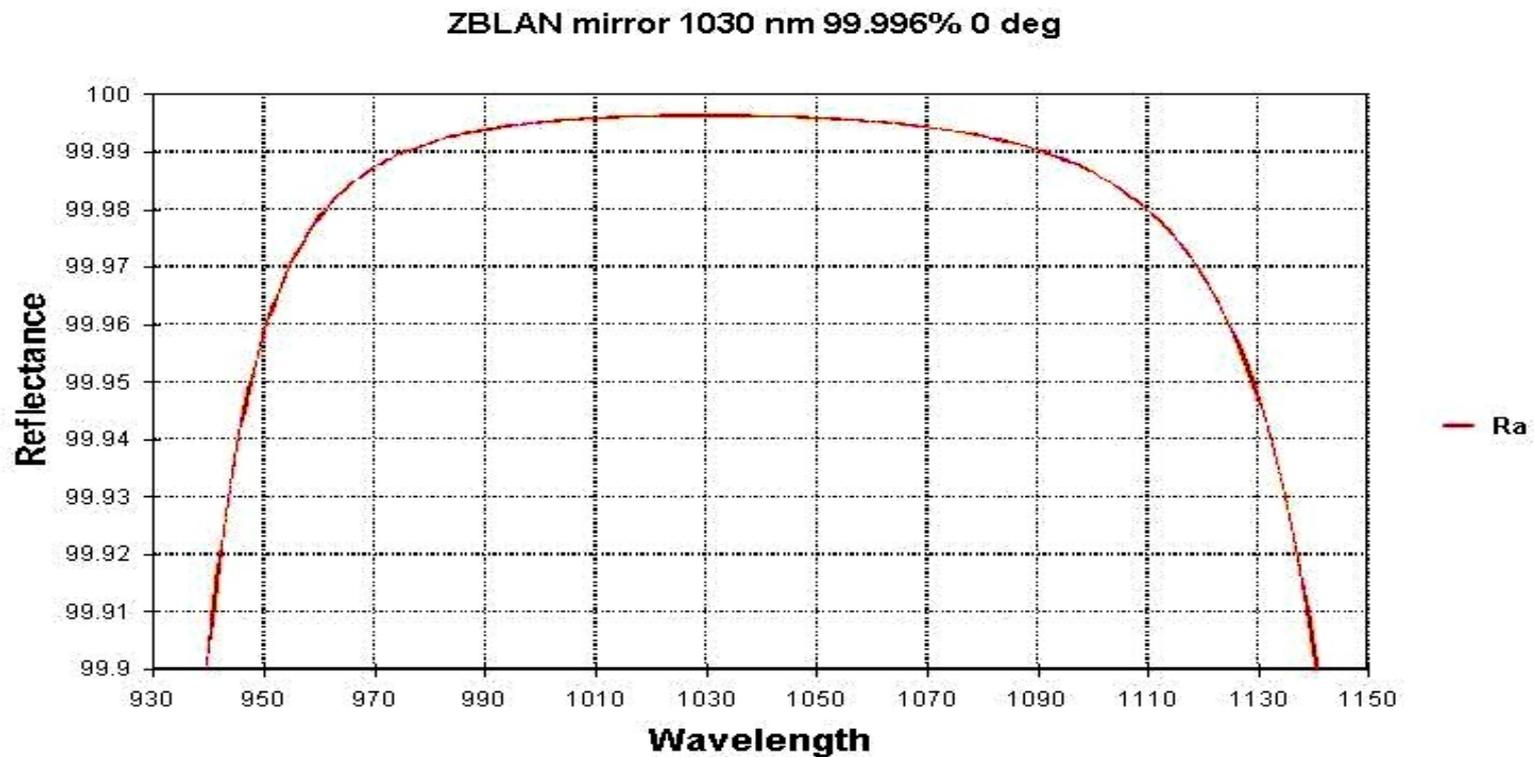
- Convergent beam **electron diffraction** measurements (a) of a doped ion-beam sputtered Ta_2O_5 layer (see TEM image, (b)) showing only diffuse rings of intensity, confirming that the layer is **amorphous**.



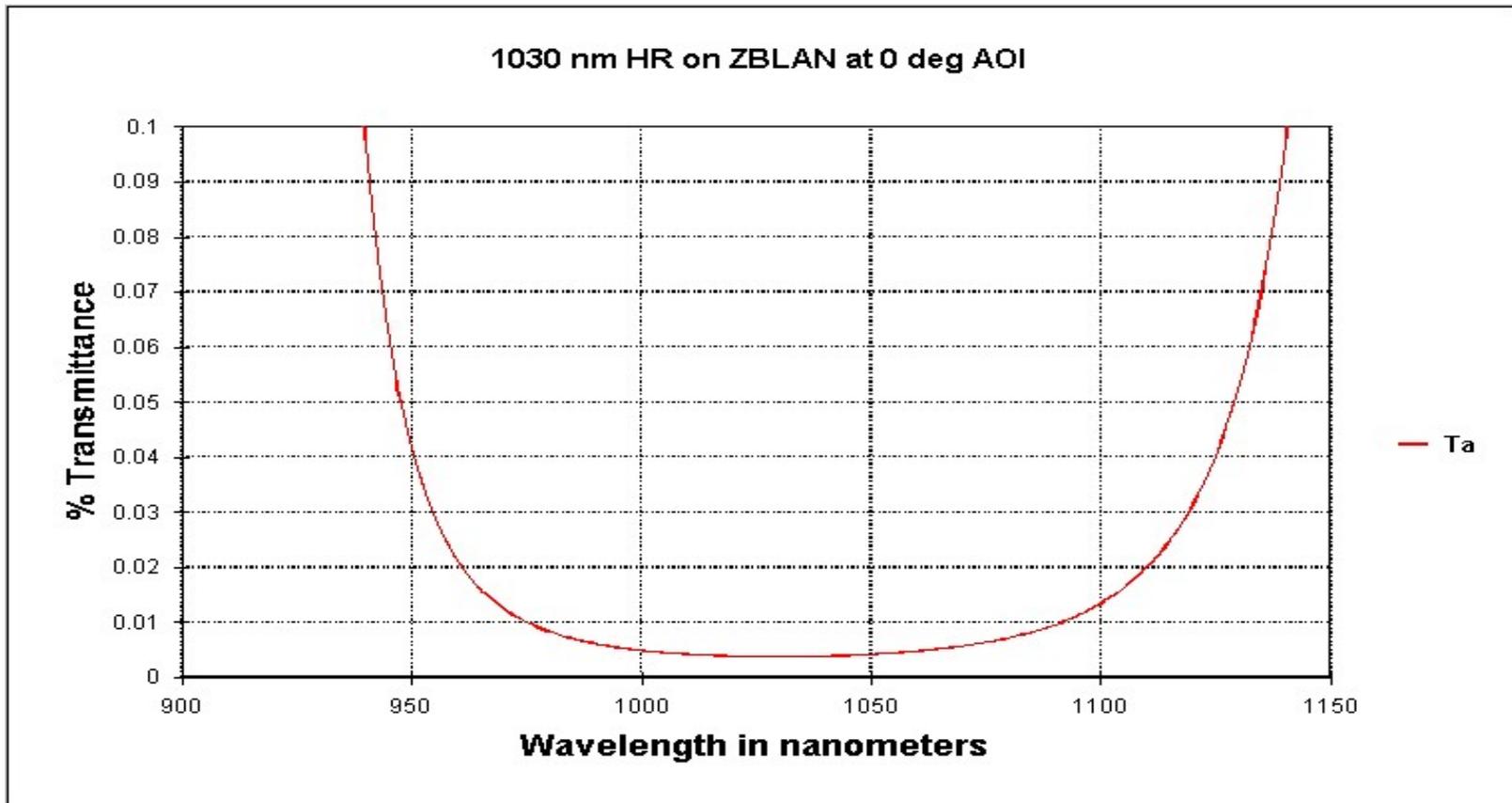
LANL Measured External Heating in Dielectric Mirrors (after Greenfield)



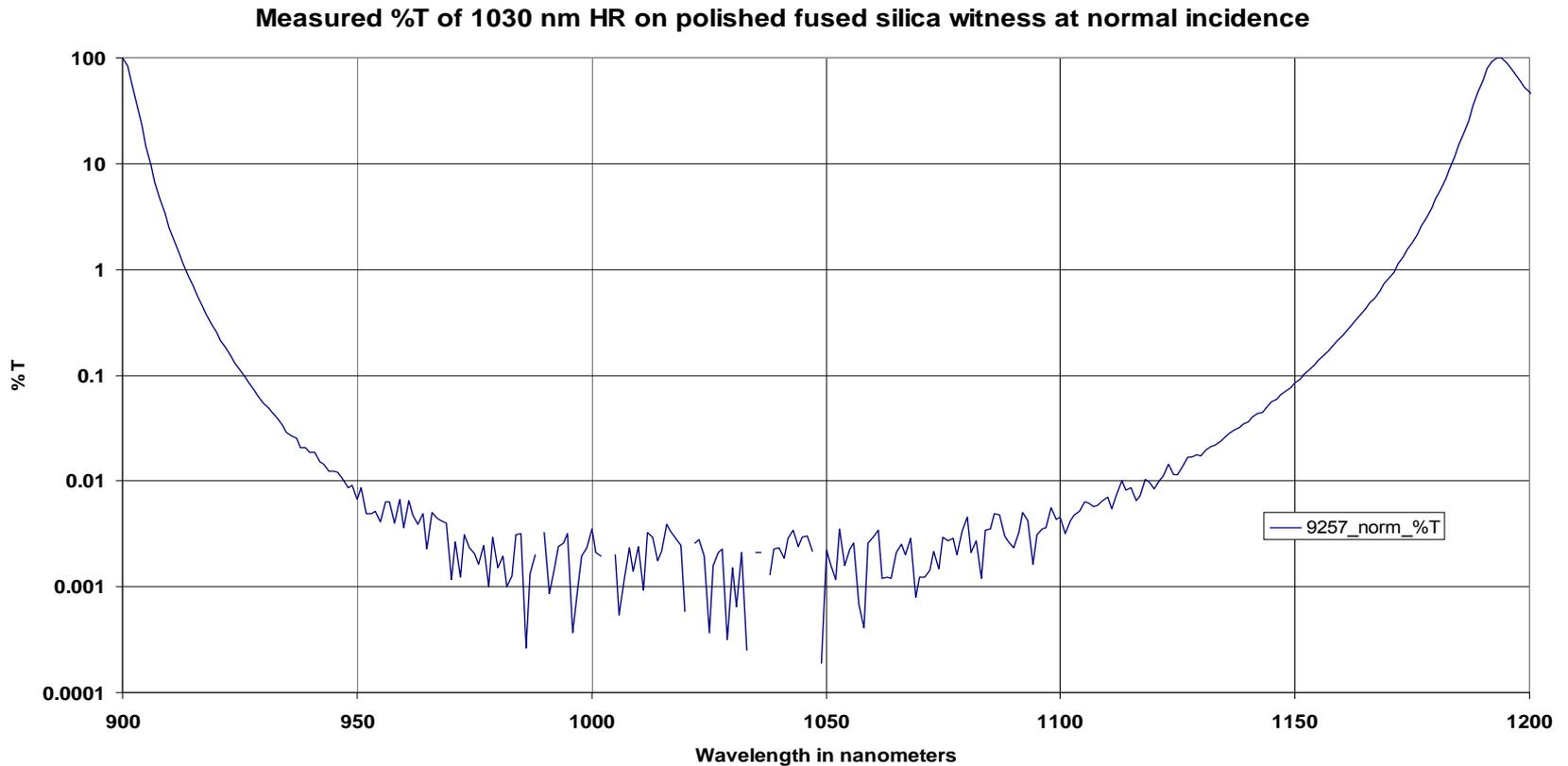
Calculated 1030 nm Reflectance on ZBLAN (expanded scale)



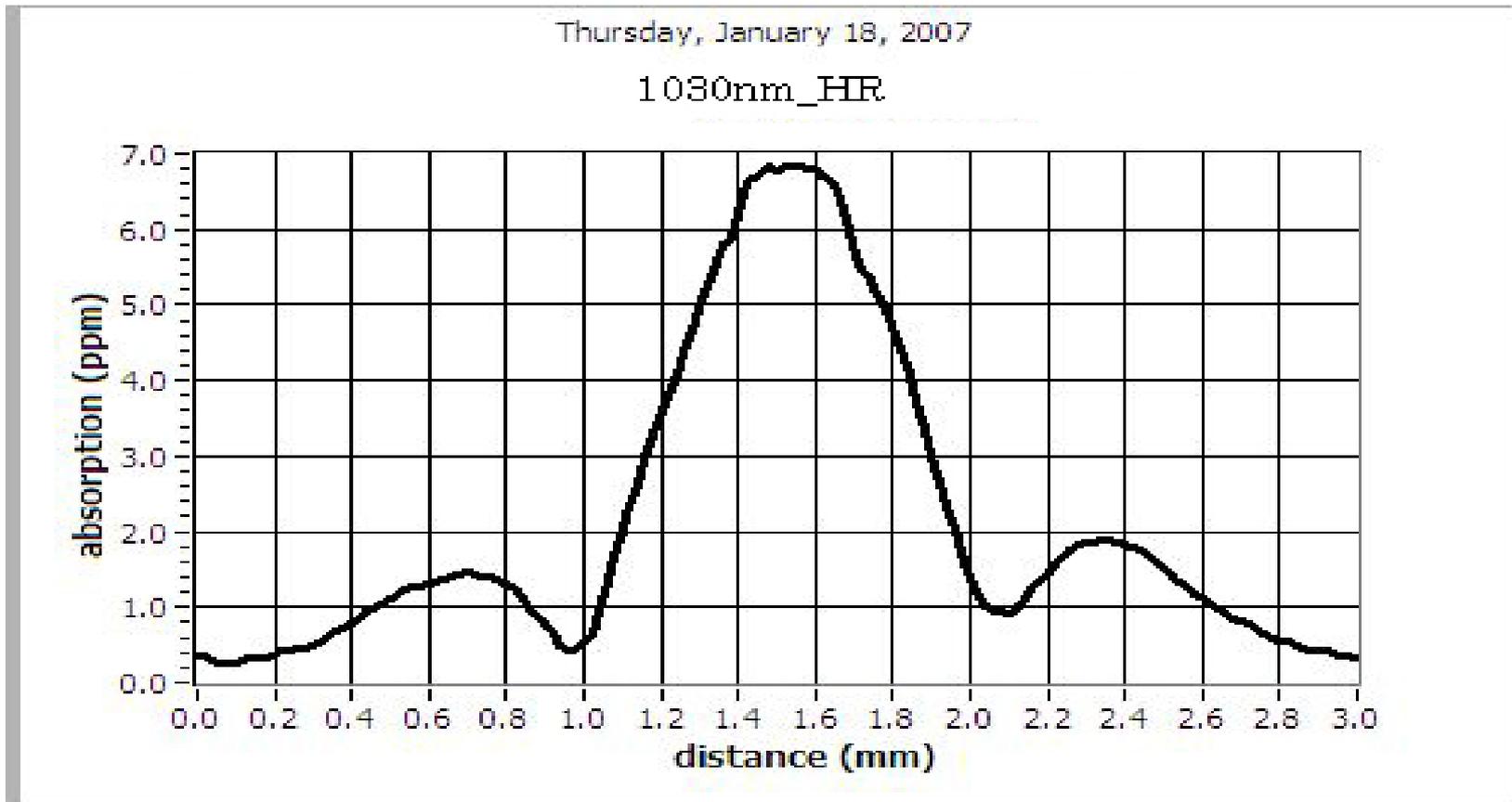
Calculated Transmission of 1030 nm HR coating (expanded scale)



Measured % T of 1030 nm HR on commercial spectrophotometer



Measured IBS deposited 1030 nm HR film absorption on fused silica witness @ 1064 nm using Photothermal Technique (PCI-03)

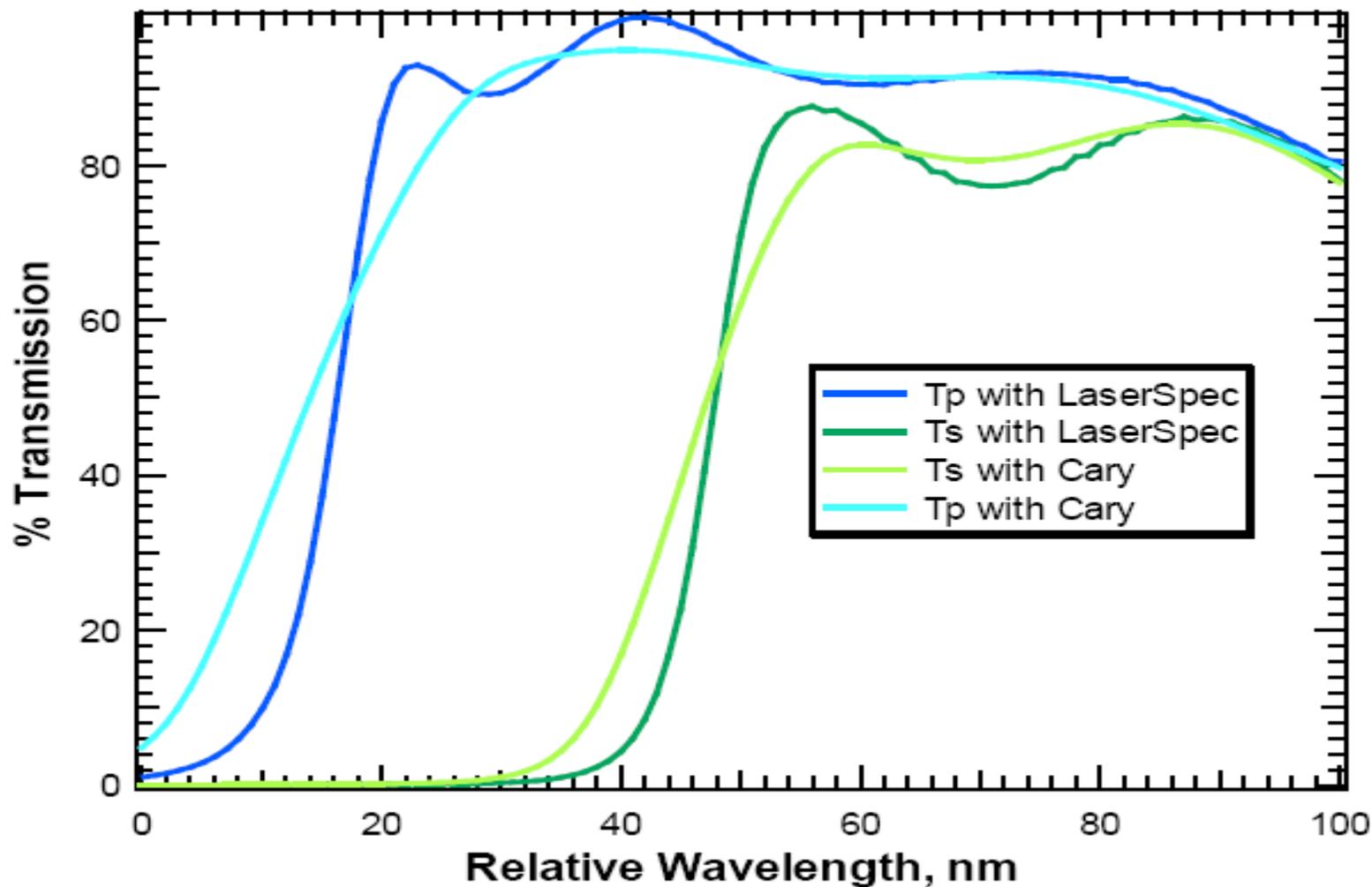


Ultra low loss 1030 nm HR has been successfully applied to polished ZBLAN samples

- Non-optimized ZBLAN glass material supplied by LANL
- “Laser Polish” applied by fabrication vendor to ZBLAN surfaces
- Coating Process variations investigated to establish performance and adhesion of HR coating stack to ZBLAN
- 20 ppm Total Loss — 7 ppm Absorption- 9 ppm Transmission — 4 ppm scatter



Characterization of thin film polarizer coating using a commercial spectrophotometer compared to tunable Laser Spectrophotometer

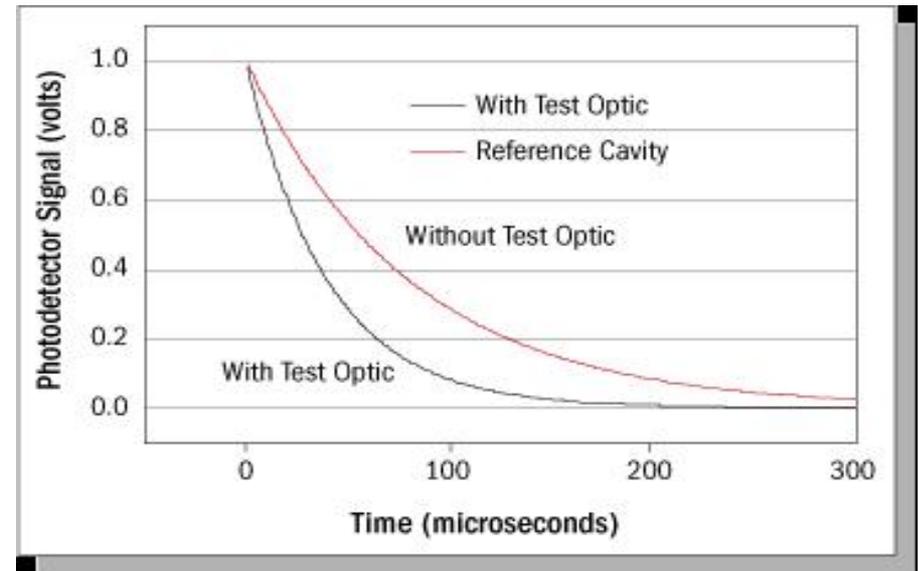


Optical Metrology of low loss films based on Energy Balance $\{1=T+R+A+S\}$

- **Cavity Ringdown Lossmeter (CRD) – measures total loss [Absorption (A)+Scatter (S)+Transmission (T)]**
 - Measures decay of a light pulse in a resonant cavity as a function of time. Knowing cavity length and speed of light determine cavity loss per round trip from decay curve. Compare loss in 2 & 3 mirror cavity.
- **Photothermal Common-path Interferometer (PCI) – measures (A) @ laser wavelength**
 - Detects the weak phase distortion of a probe beam (633nm) caused by the absorption of a focused “pump” beam (at the wavelength of interest - .e. 1064 nm). Detection occurs in the volume defined by the intersection of the two beams. Calibrated against a “known” reference.
- **Thermal Camera (A) – Measure temperature rise of absorbing region. Calibration of standard and understanding of system characteristics.**
- **Calorimeter – measures (A) (ISO 11551)**
 - Measures the temperature rise for a known mass when illuminated by a light beam of known intensity.
- **Scatterometer – ARS, OHP, BRDF and TIS to measure (S)**
- **Photometer – measures (T) & (R) using a Laser based approach or commercial spectrophotometer**

Cavity Ringdown Lossmeter

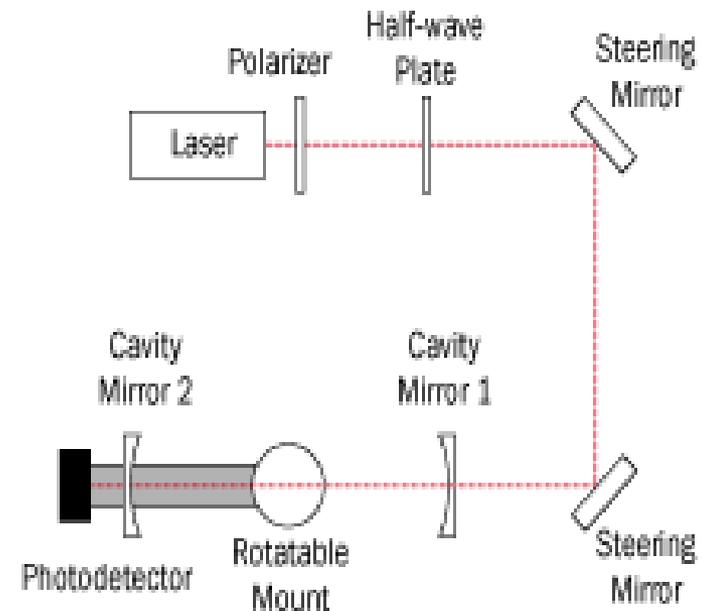
- **Example cavity-transmission traces illustrate the variation with cavity loss after the laser is turned off.**
- **Measured time values determine total loss**
- **Optimized performance for low loss (1-10 ppm) operation with custom mirrors**
- **Measurements can be performed at angle and for a given polarization**



$$\frac{1}{\tau} = \left(1 - R_{cavity} + \sigma_{air} L\right) \frac{c}{L}$$

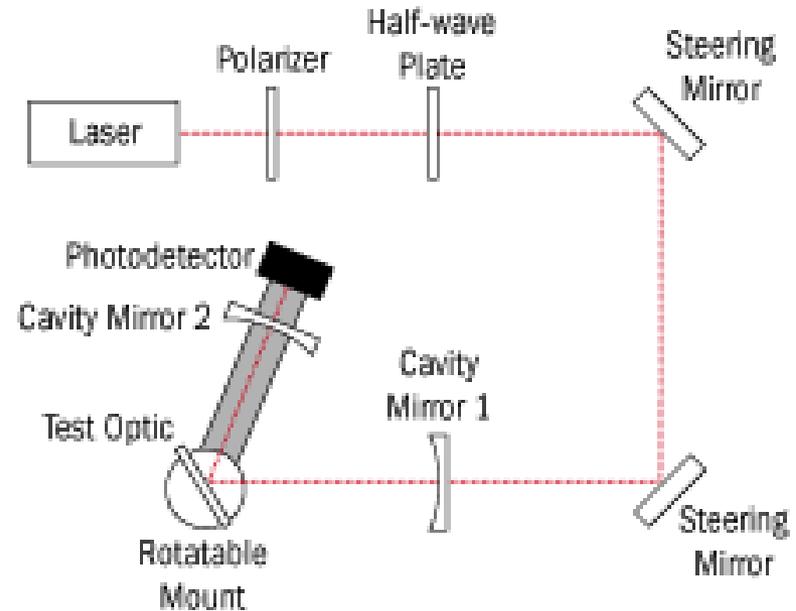
Reference-Cavity Measurements

- In this setup for reference-cavity measurements (without test optic), transmitted light through Cavity Mirror 2 is collected by a photodetector.
- The voltages are digitized and analyzed by an on-board computer.
- This data is stored as the reference.



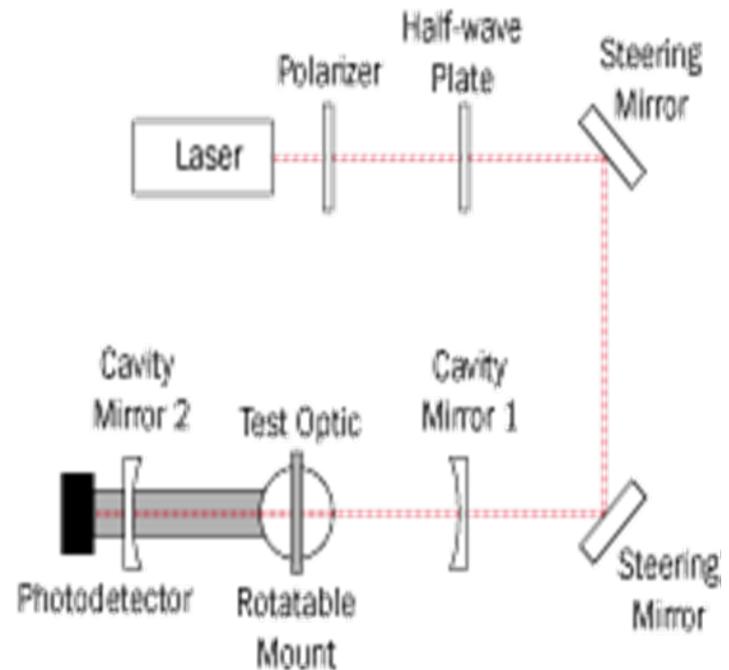
Reflectivity Measurements

- For characterizing losses in HR's – the sample under test is introduced into the cavity.
- A second measurement is made and compared to the cavity



Characterization of intracavity losses can also be made

- For characterizing losses in bulk materials and absorptance – the sample under test is introduced into the cavity.
- A second measurement is made and compared to the reference cavity results

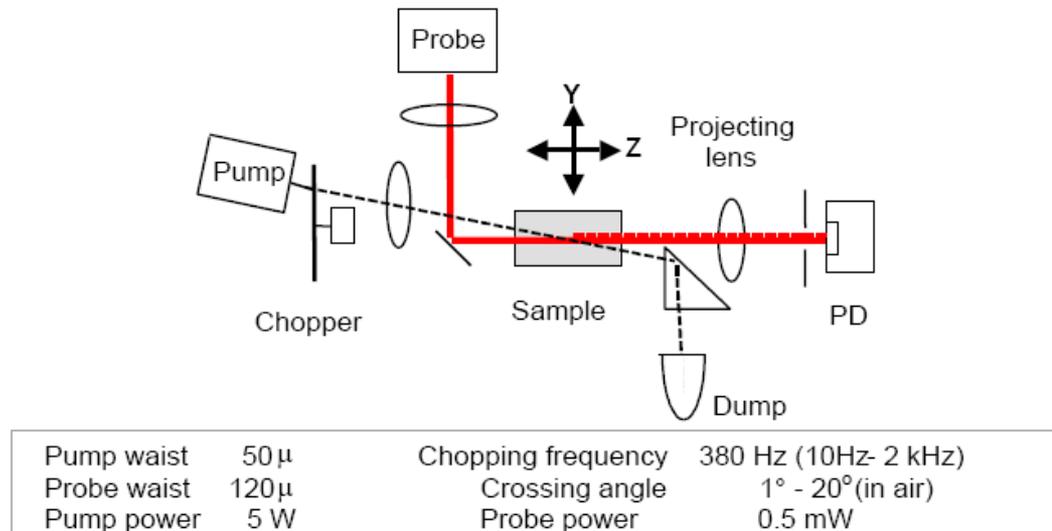


Photothermal characterizations are also made

- Rapid characterization of sample performance
- X,Y and Z Scans of uncoated and coated sample can be made
- Measurements made under relatively high power levels
- Surface and bulk evaluations can be made
- Cleaning, bulk materials and process evaluations can be made

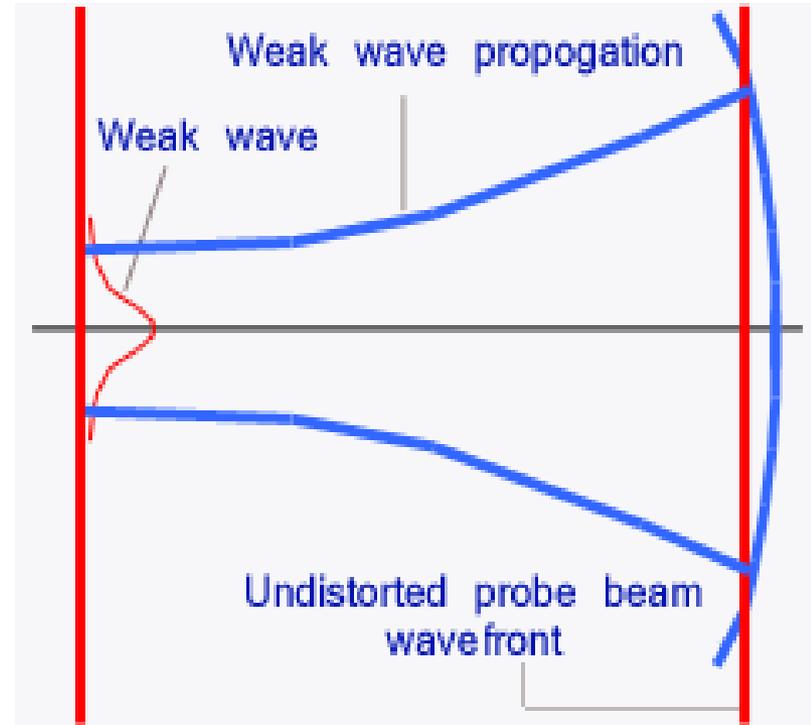
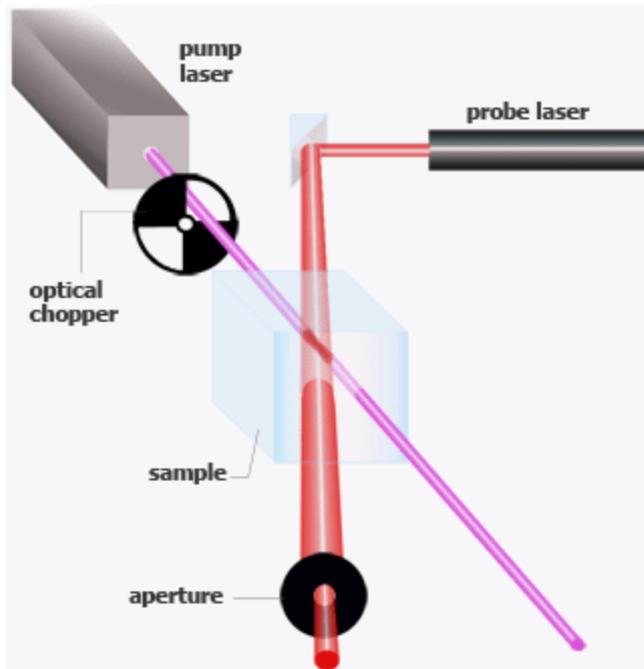
Schematic of Optical Layout

Photothermal Common-Path Interferometry - diffraction regime of cross-beam cw thermal lensing -



- ac-component of probe distortion is detected by photodiode + lock-in
- absorption coefficient $<10^{-7} \text{ cm}^{-1}$ (~10 ppb coating) can be detected with 5 W pump power
- crossed beams help to avoid false signals from optics and surfaces of the sample

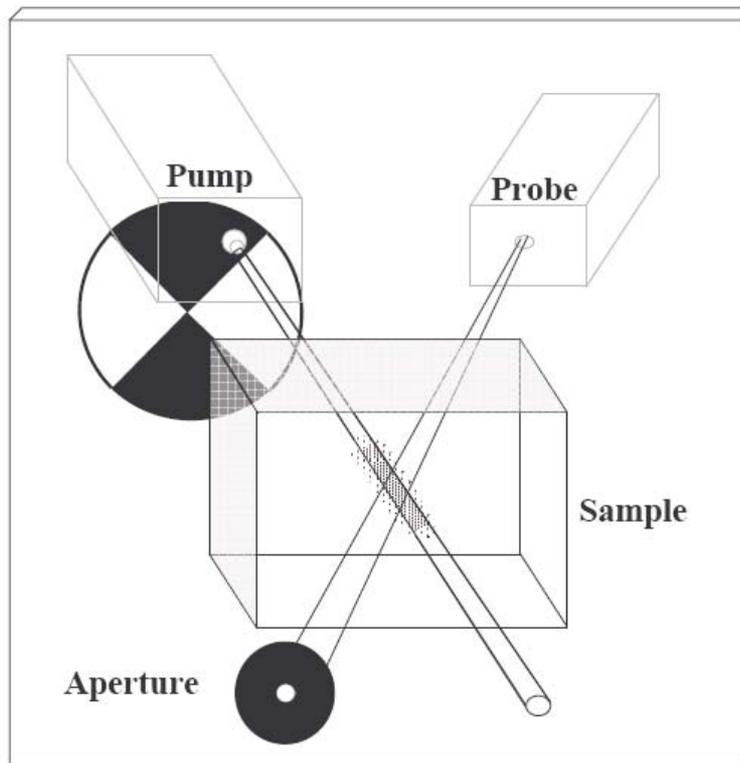
Weakly absorbing films are characterized



$$\exp(i\Delta\phi) \sim 1 - i\Delta\phi$$

Measurement Approach

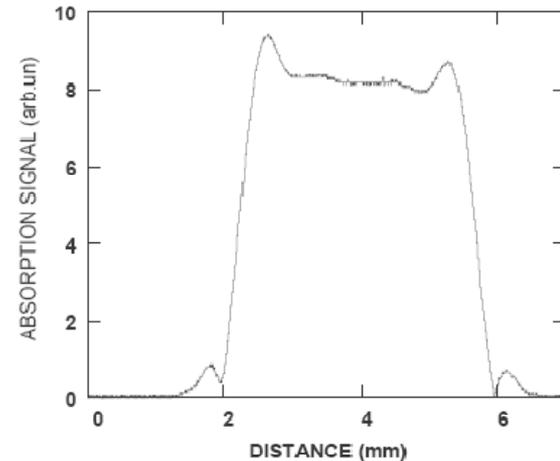
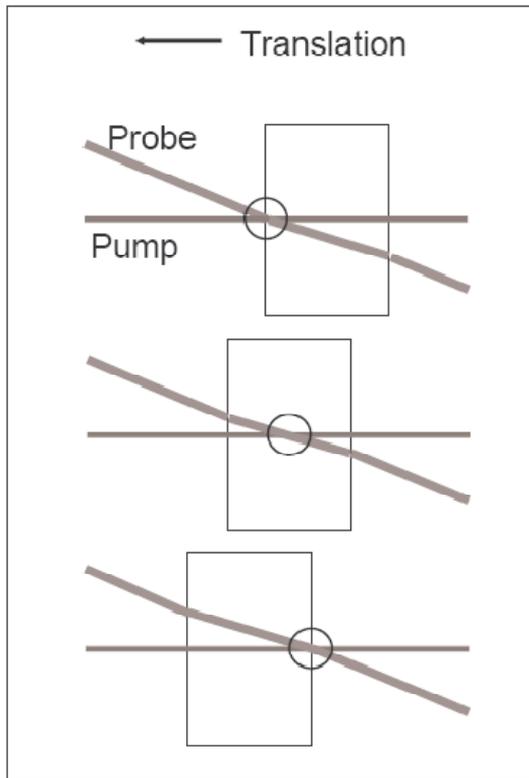
PCI basics



- ❖ CW, chopped pump provides periodic heating
- ❖ CW probe beam experiences periodic phase distortion
- ❖ Beams are crossed to allow some spatial resolution, i.e. crossed inside the sample to measure the bulk absorption
- ❖ Periodic distortion of the probe is detected after an aperture
- ❖ Lock-in is used to measure the detected AC-signal with a shot-noise-limited sensitivity

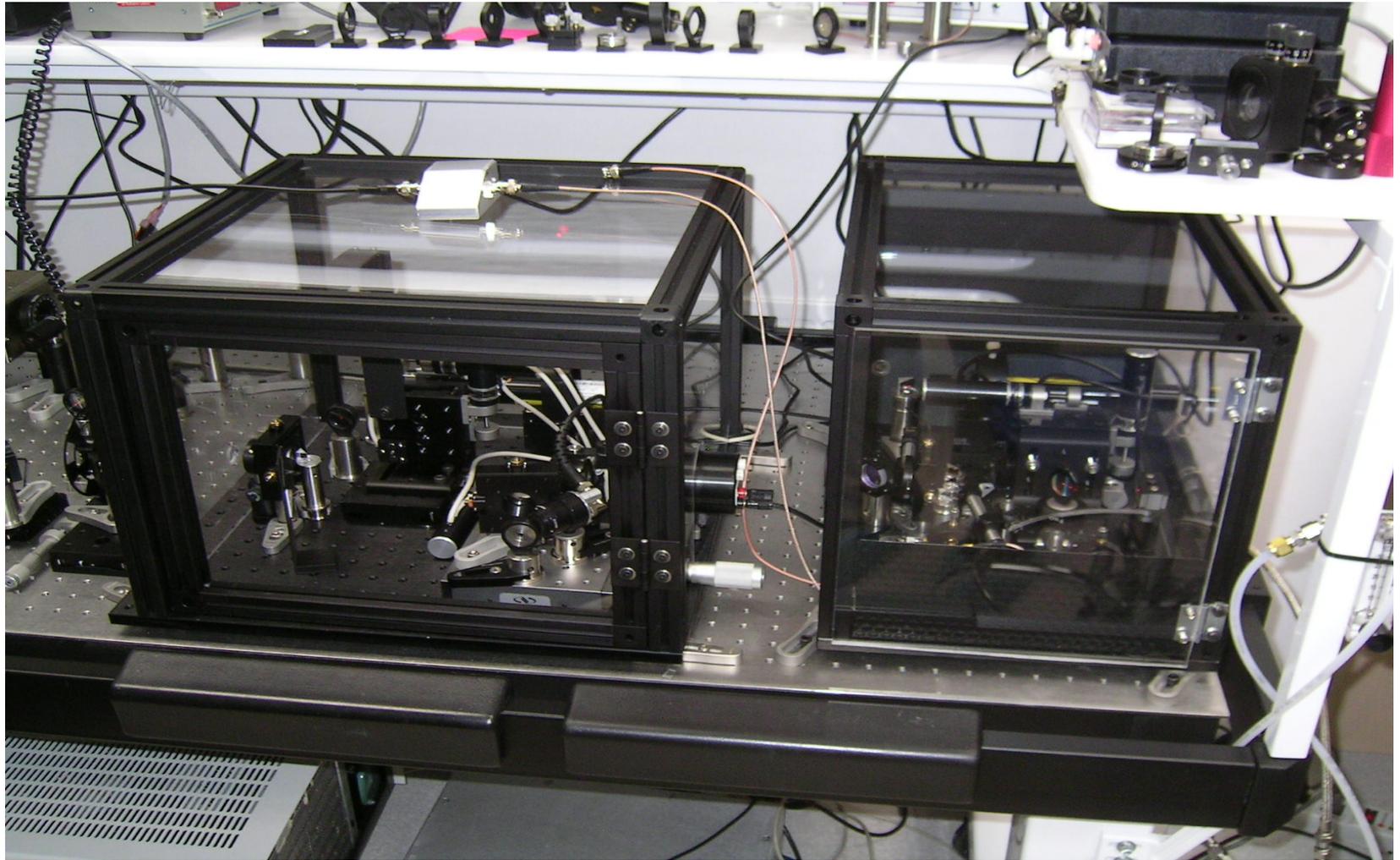
Samples are translated and Surfaces and bulk characterized

Space resolution: example (surface-to-surface scan)

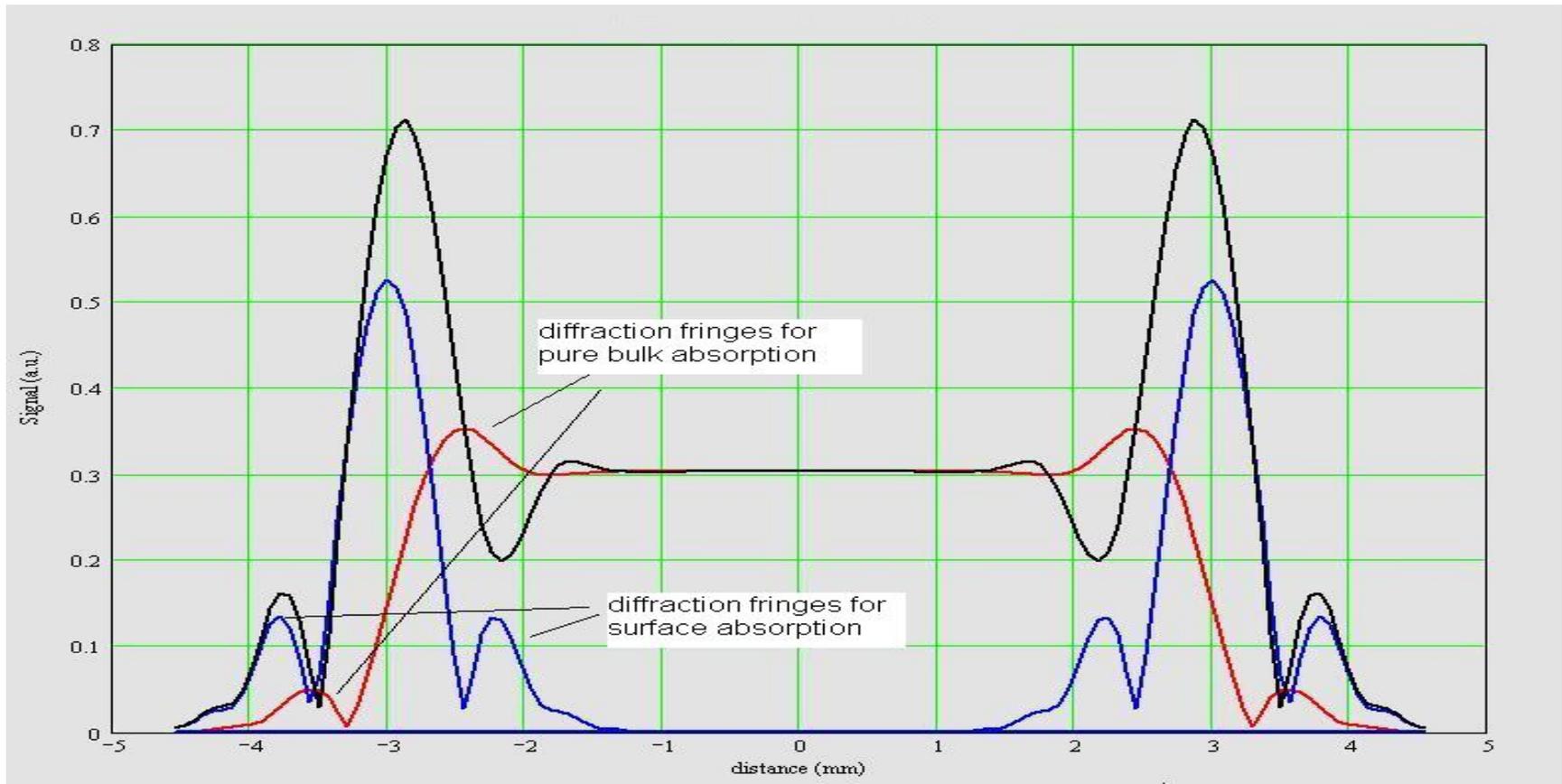


Example: PCI signal for a 3 mm-thick
neutral filter, 15%-absorbing
 $L_{eff} = 0.25$ mm

PCI -03 Installation



Measured Response of beam translating into sample has been modeled

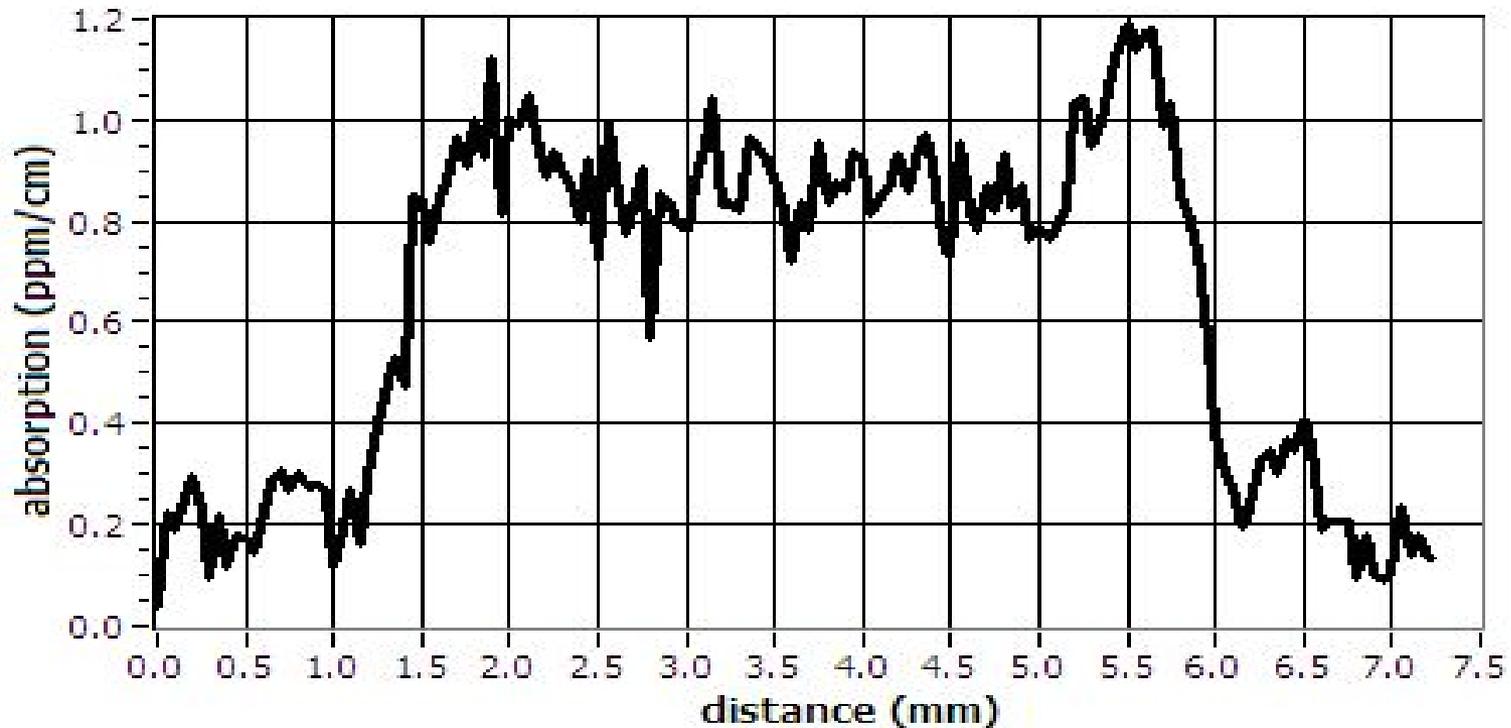


Z-scan simulation for 6 mm-thick fused silica substrate: red line - bulk absorption only, no surface anomalies of responsivity; blue peaks - surface responses; black curve - combined effect.

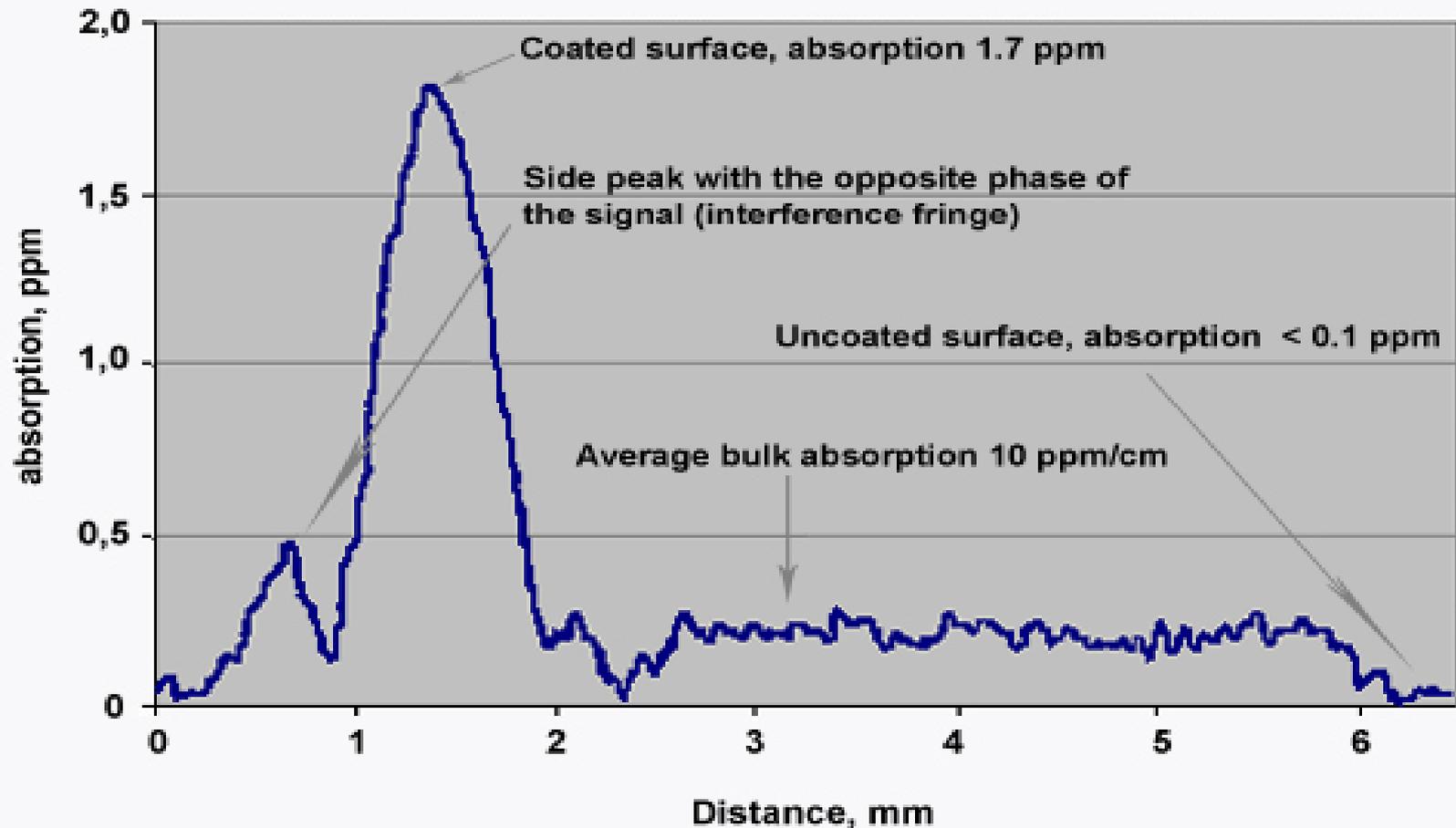
Measured Performance of Polished Suprasil 3001

Thursday, May 31, 2007

Suprasil_3001_Bulk_Absorption_@_1064nm_SN1_2nd_spot.txt

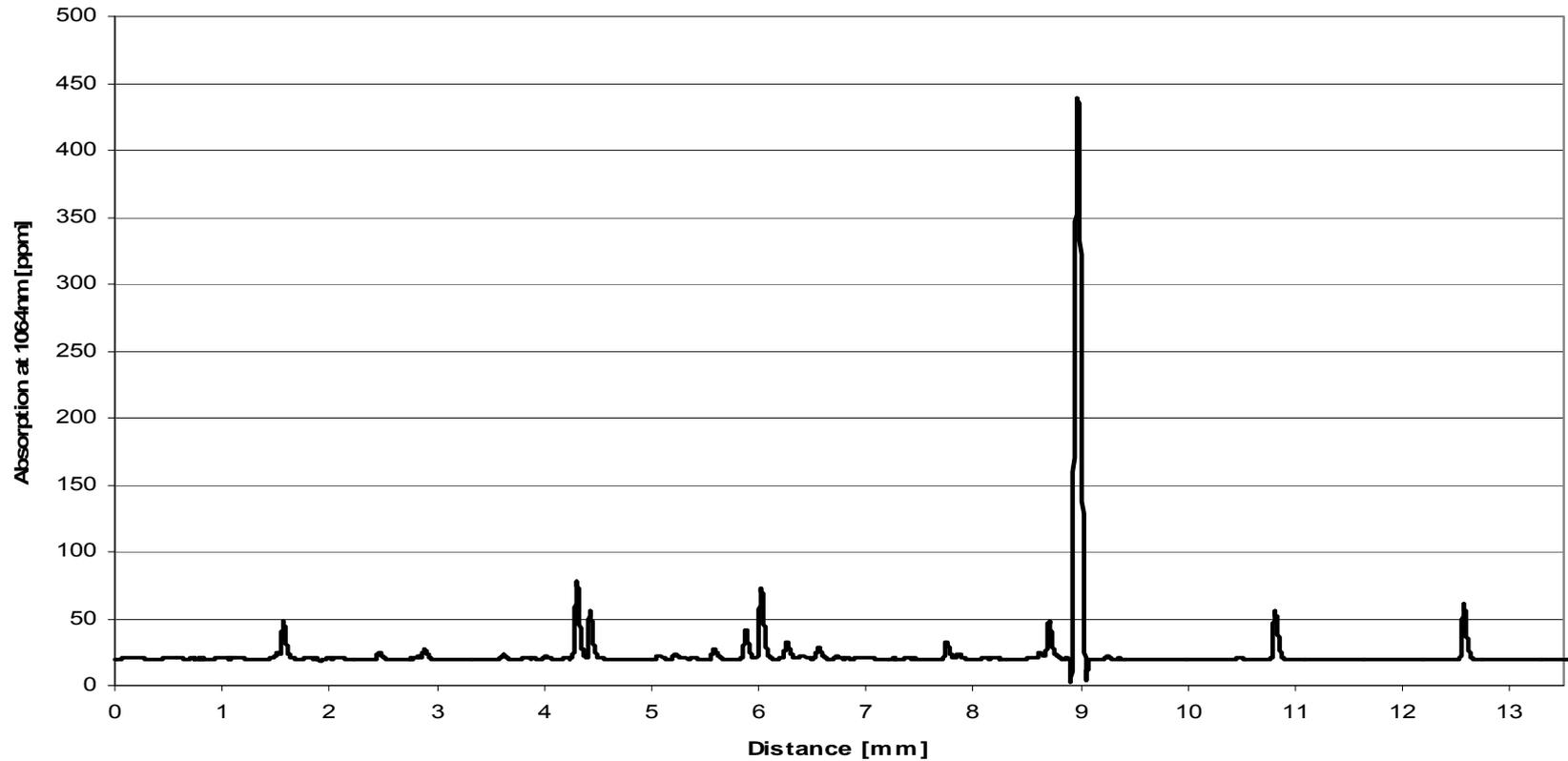


1064 nm Characterization Scan of HR coating on fused silica

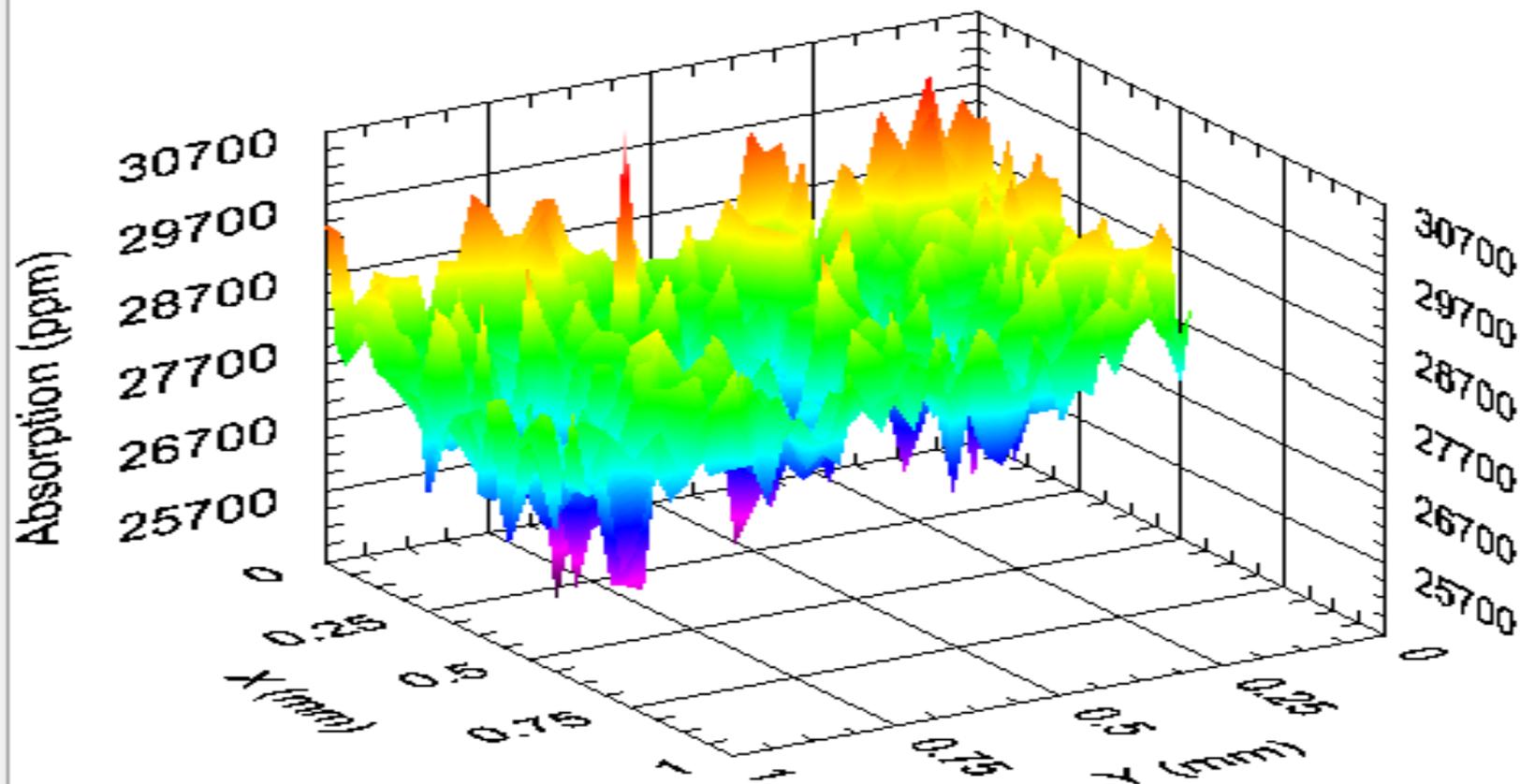


PCI Transverse Scan across 1064 nm HR

Transverse scan #1 of HR

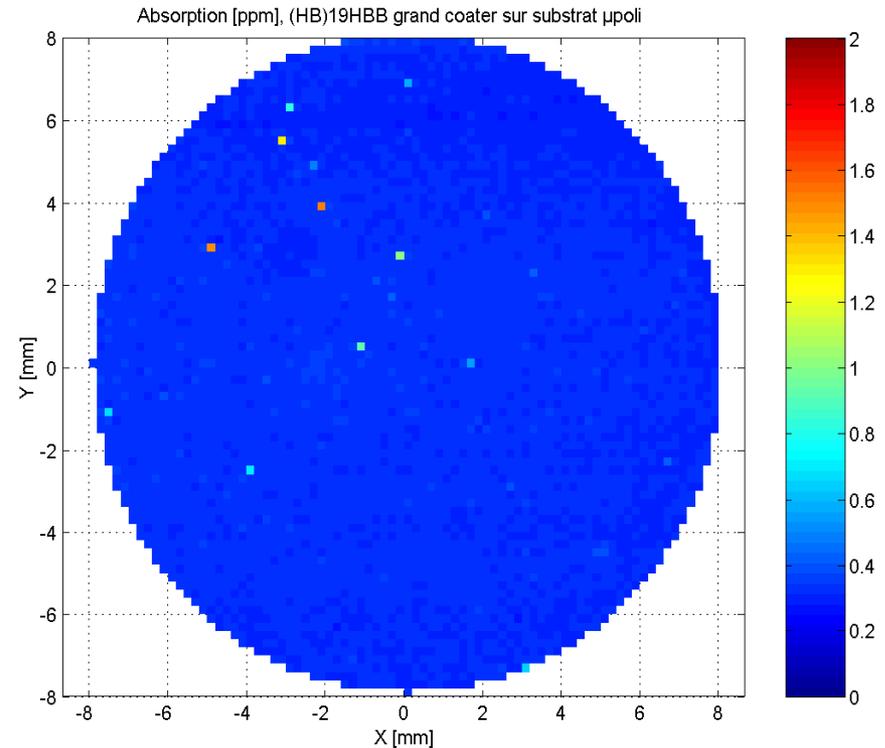


2D scan of 1064 nm Absorption of Overcoated Opaque Gold on Polished Silicon Substrate

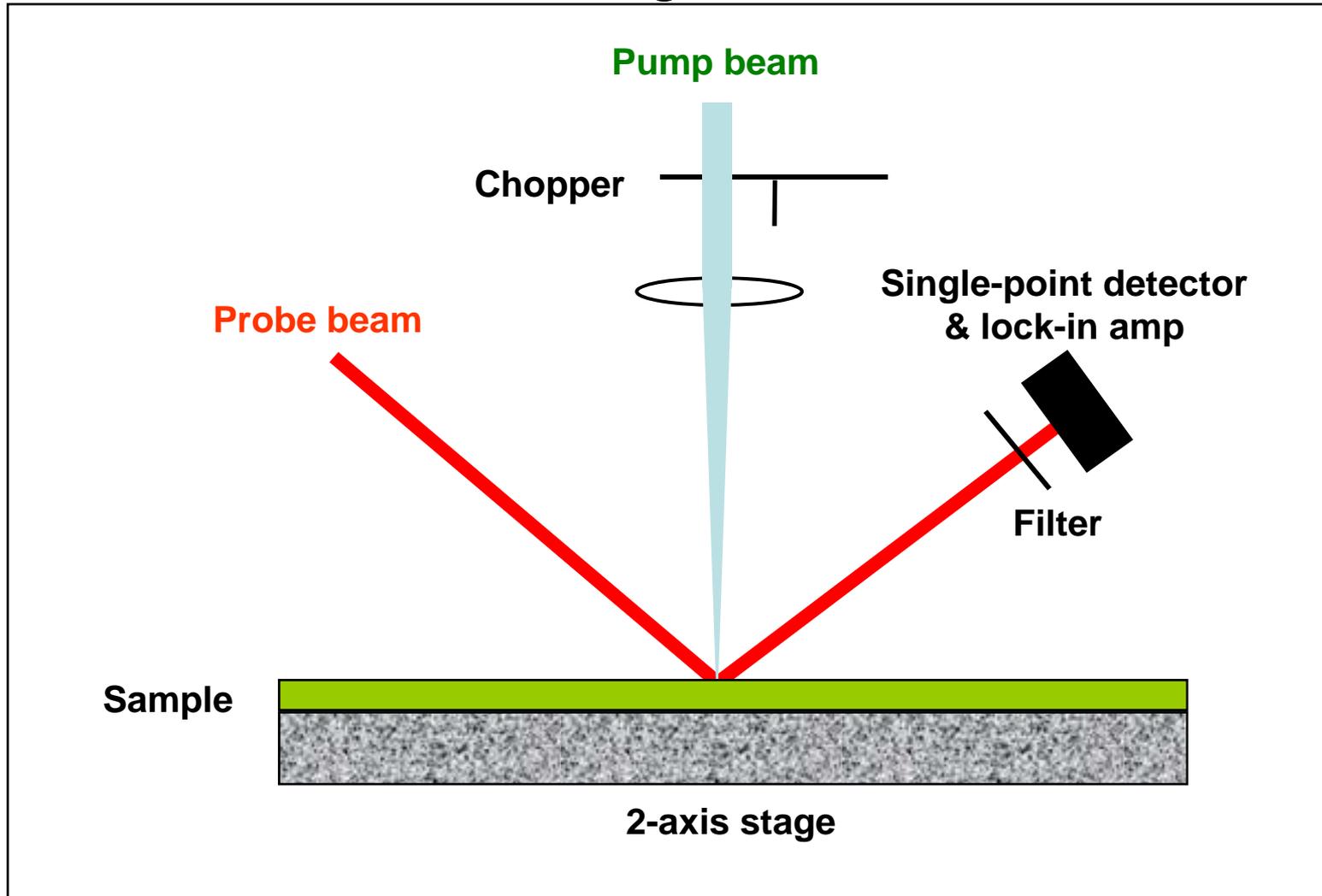


Test mass coatings: Optical properties

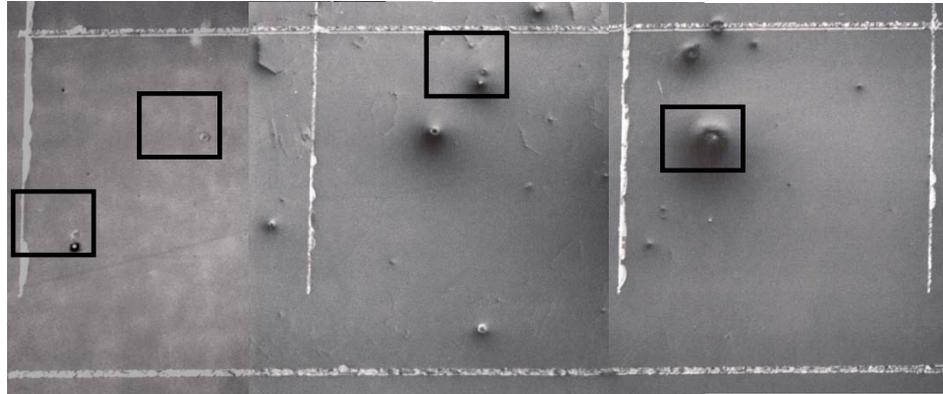
- Require low average absorption (0.5 ppm) to limit gaussian-shape thermal distortion
- Also require freedom from point absorbers to limit inhomogeneous distortion
- **2004: Maps of low-absorption coatings measured** in same class-10 room as coating machine (LMA)
- Best results: Average absorption 0.32 ppm
- Only 10 points greater than 0.5 ppm



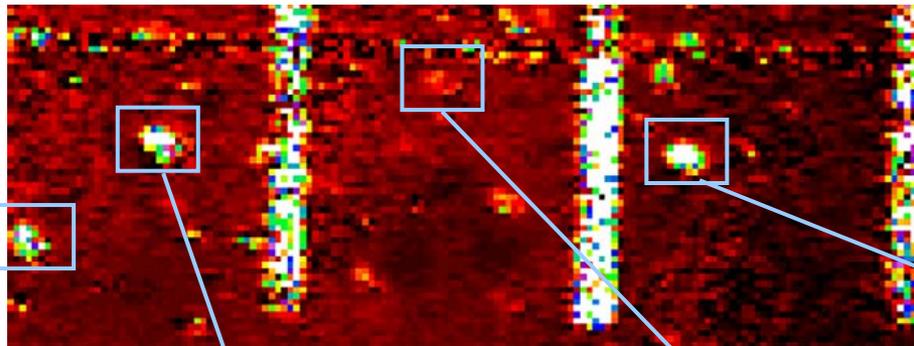
Photothermal microscopy is a powerful tool for examining fluence limiting defects



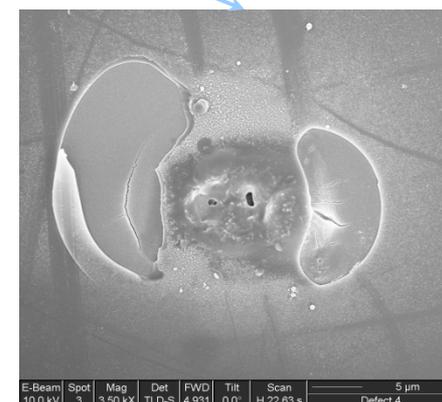
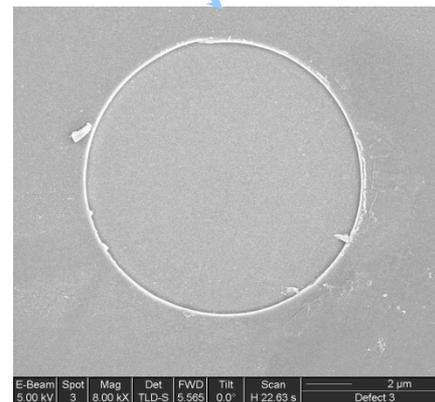
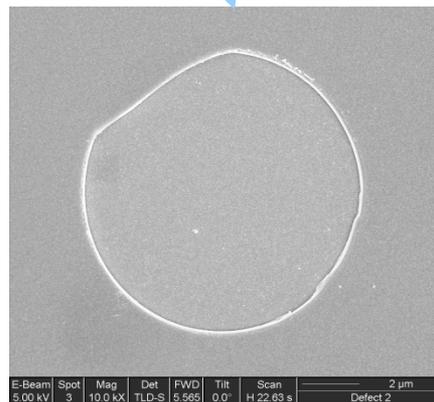
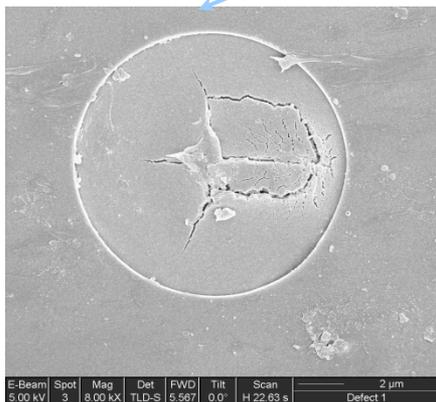
LLNL Photothermal images indicate that not all highly absorbing defects are nodules



SEM image after photothermal microscope induced damage

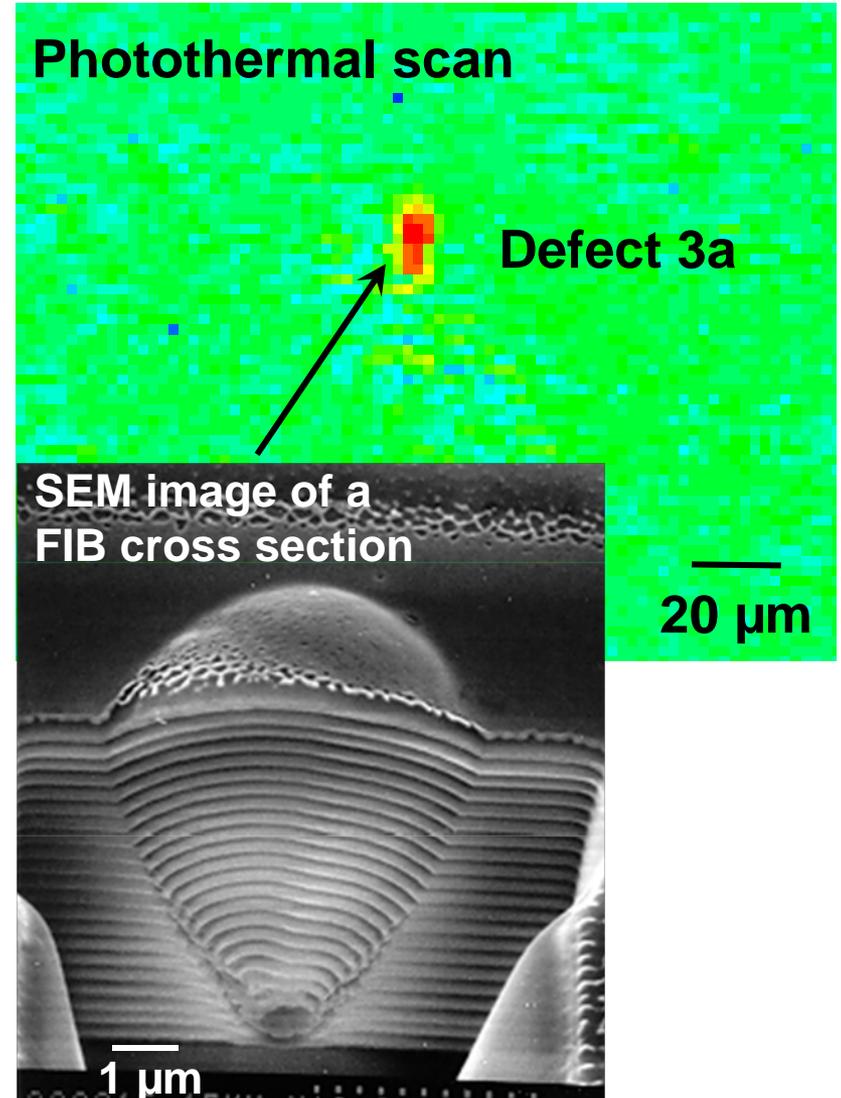
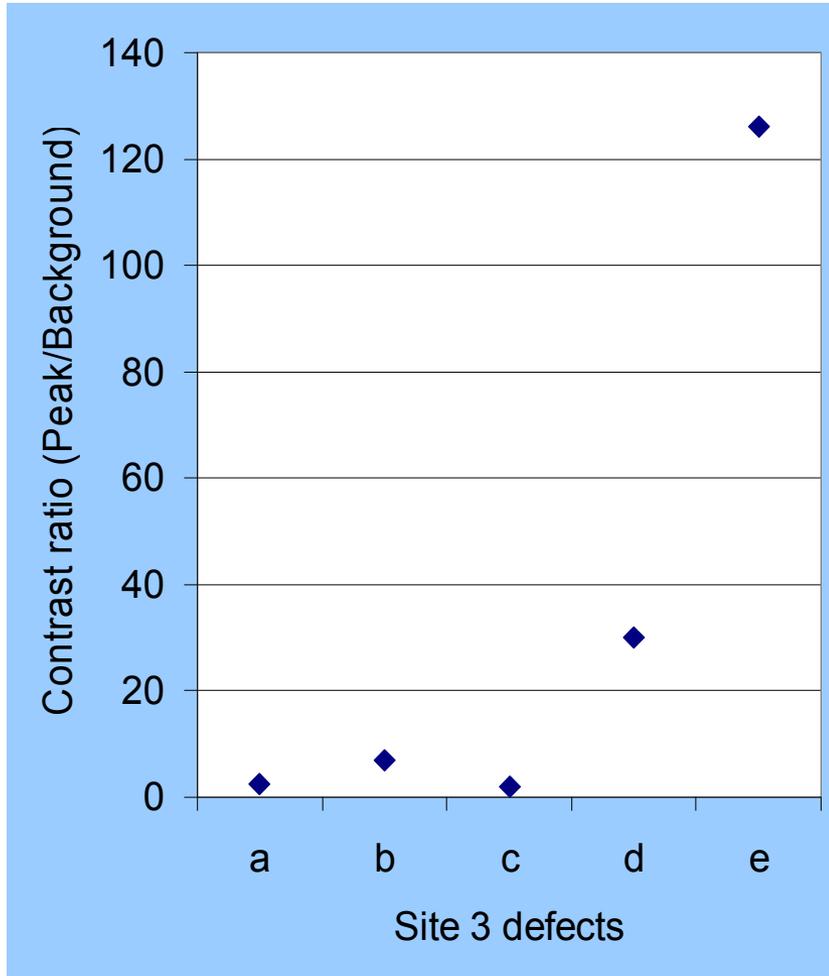


Photothermal image



Photothermal microscopy non-destructively identifies defects to enable further defect characterization

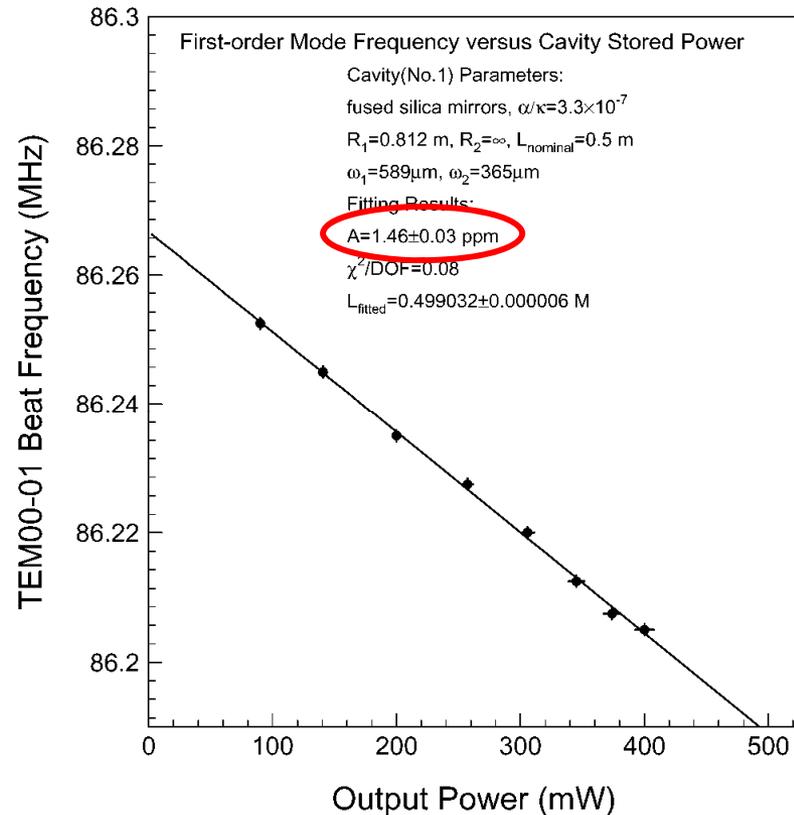
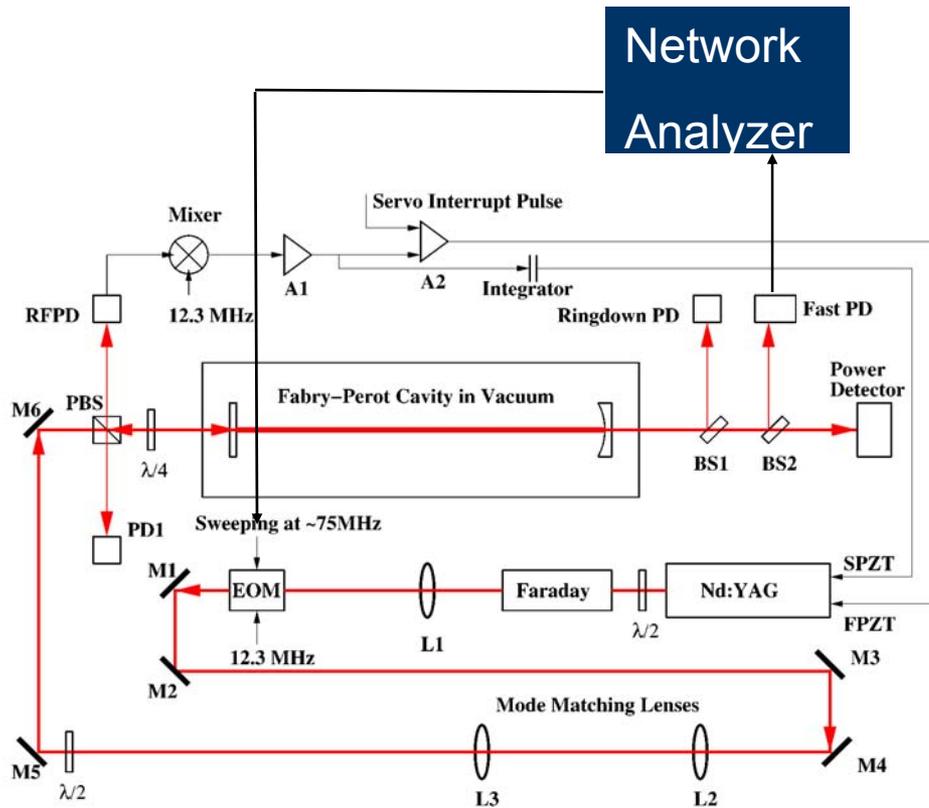
Photothermal signal for site 3 defects



Absorption measurement

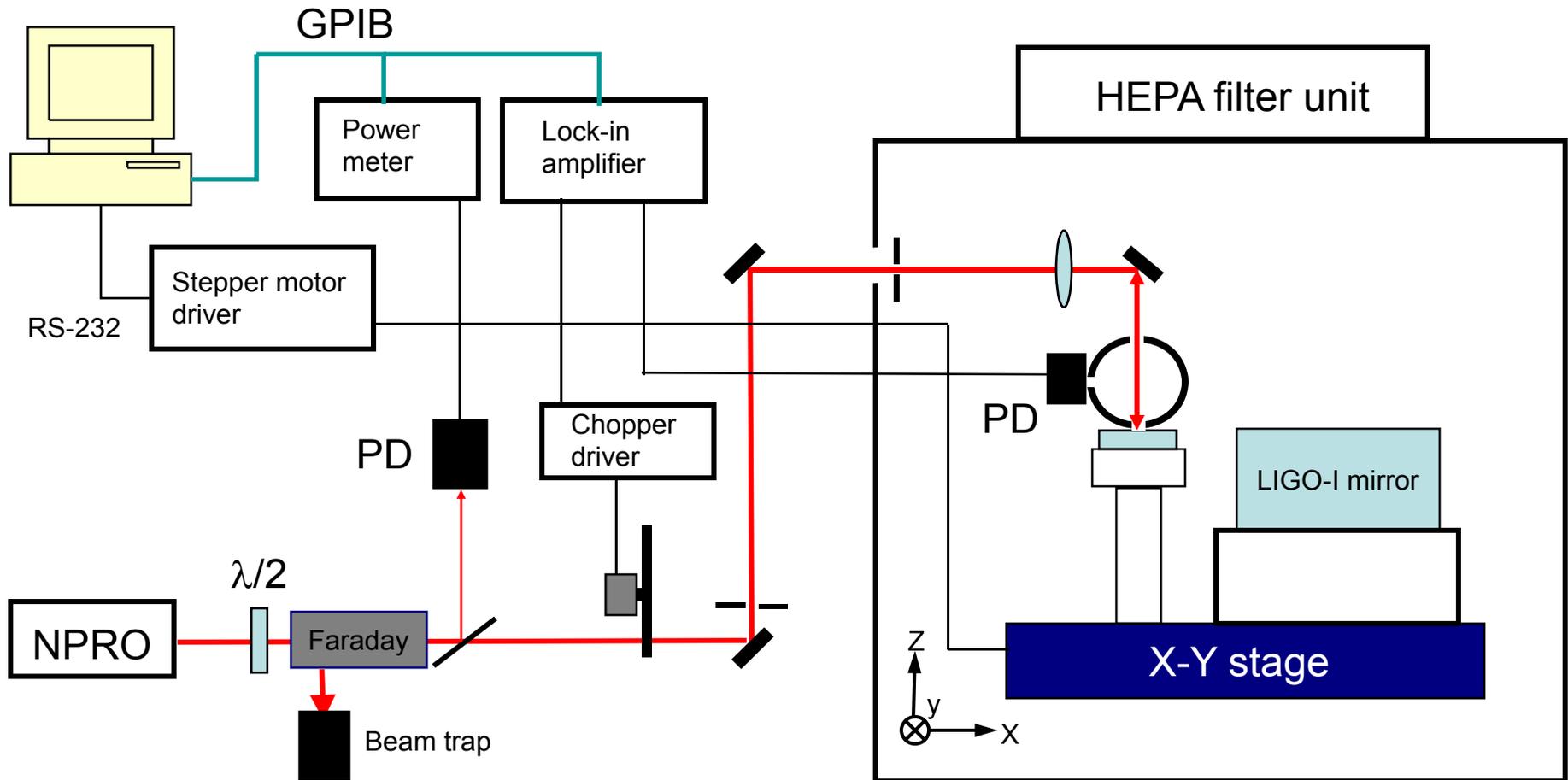
- Thanks to a visit to Ginzton Laboratory, Stanford University, we implemented the photothermal common-path interferometer (PCI, see A. Marksoyan's talk) in our RTS bench, using a 30W cw Nd:YAG and 5mW He-Ne.
- The calibration is based on the 1" (dia.) reference mirror which is measured in the contamination cavity, and cross checked with the mirror measured at Ginzton Laboratory.

HR absorption measurement in the contamination cavity

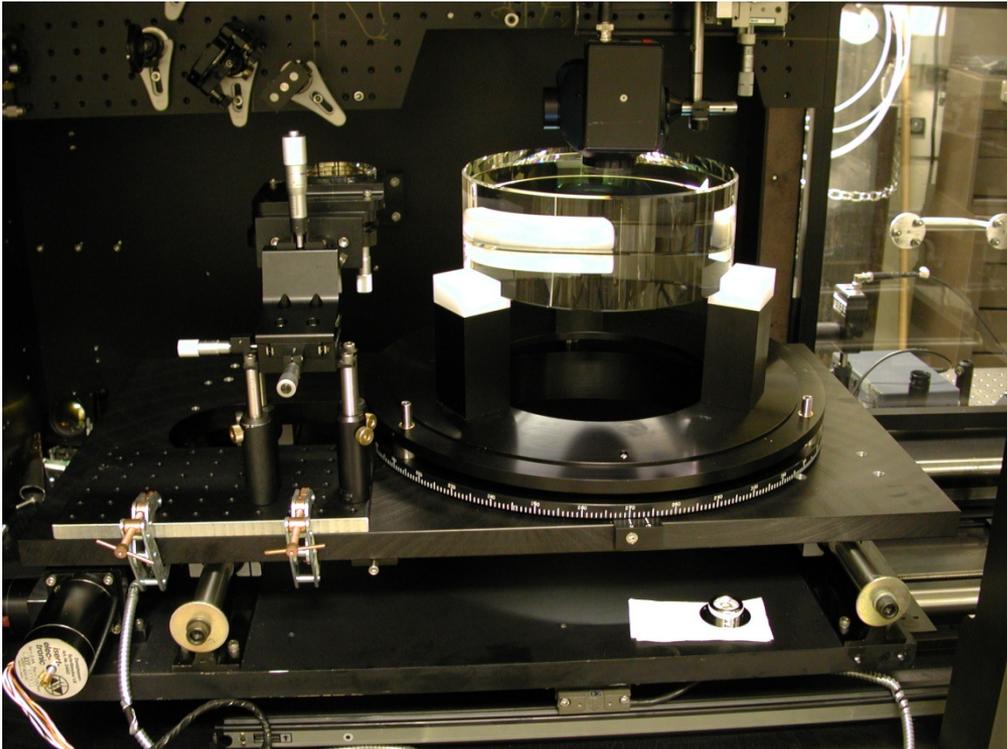


Daqun Li, Dennis Coyne, and Jordan Camp, Applied Optics, Vol.38, p5378, 1999

Schematic of the 'TIS' measurement



RTS system, an optical characterization bench



It was established at Caltech OTF lab in 1997 :

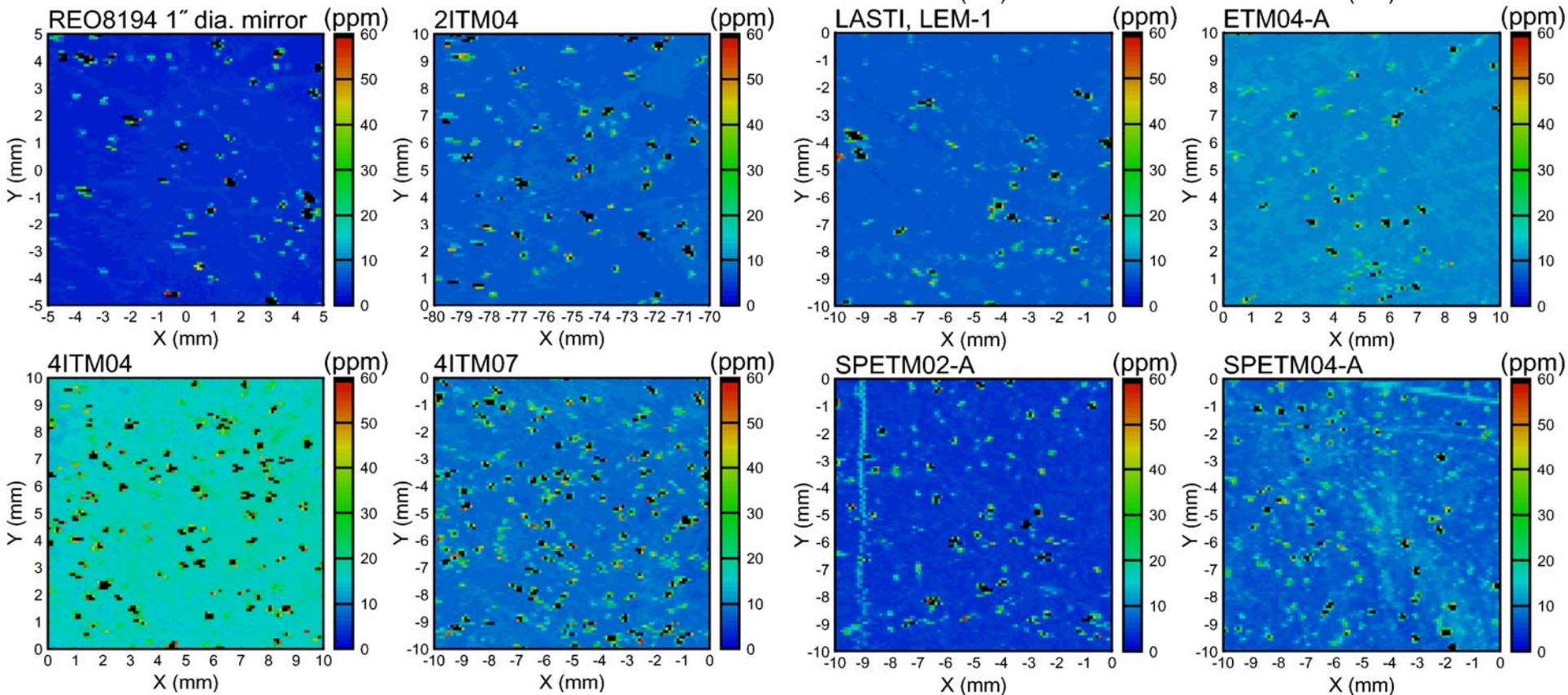
(Jordan Camp, Bill Kells et. al.)

- AR Reflection,
- HR Transmission,
- HR Scattering at 45° .

Since 2001 :

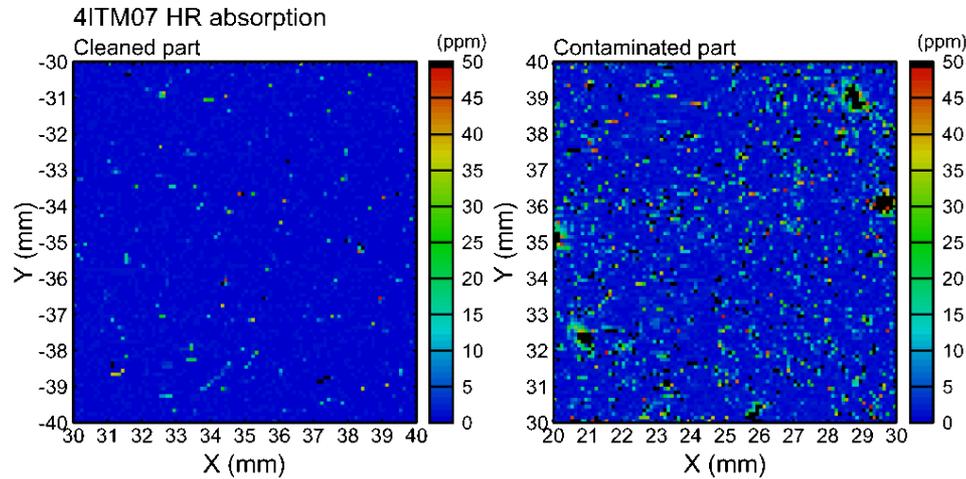
- Substrate birefringence homogeneity,
- HR 'Total Integrated Scattering' ($1.5^\circ < \theta < 78^\circ$),
- Substrate bulk absorption,
- HR Coating absorption.

TIS results of the LIGO I mirrors



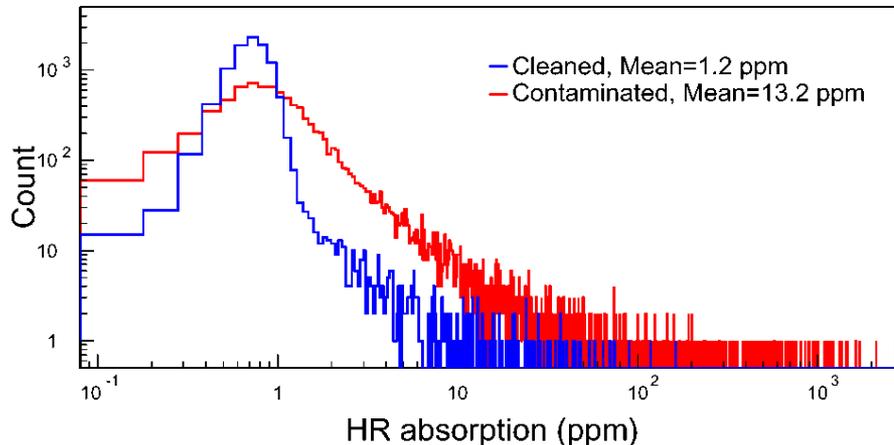
HR absorption of 4ITM07,

which was swapped out from LHO in 2005



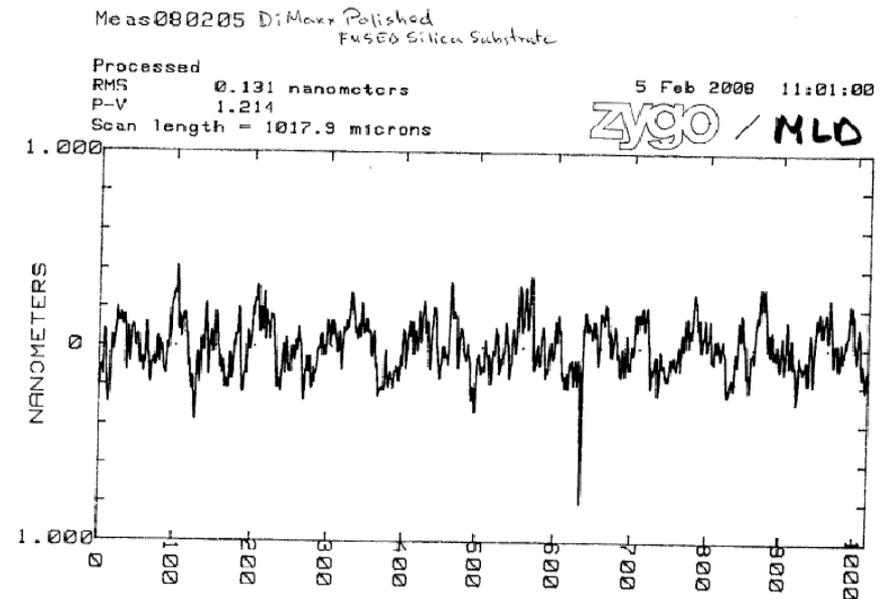
- No uniform contamination layer is observed.

- Contamination are some high absorption points.

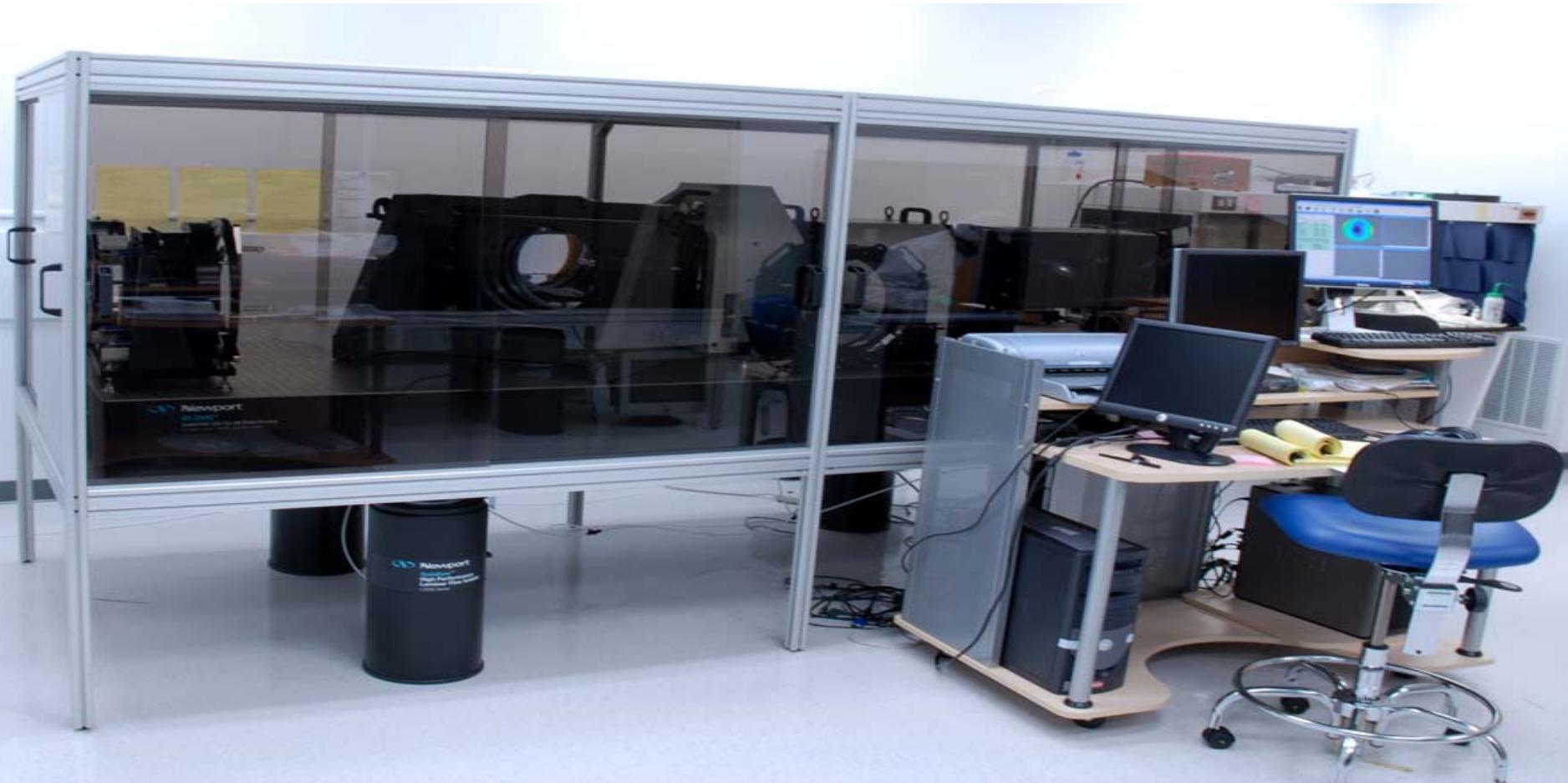


- The point contamination can easily be cleaned by drag wiping.

Zygo OHP Instrumentation supports optical surface evaluation of superpolished optical surfaces



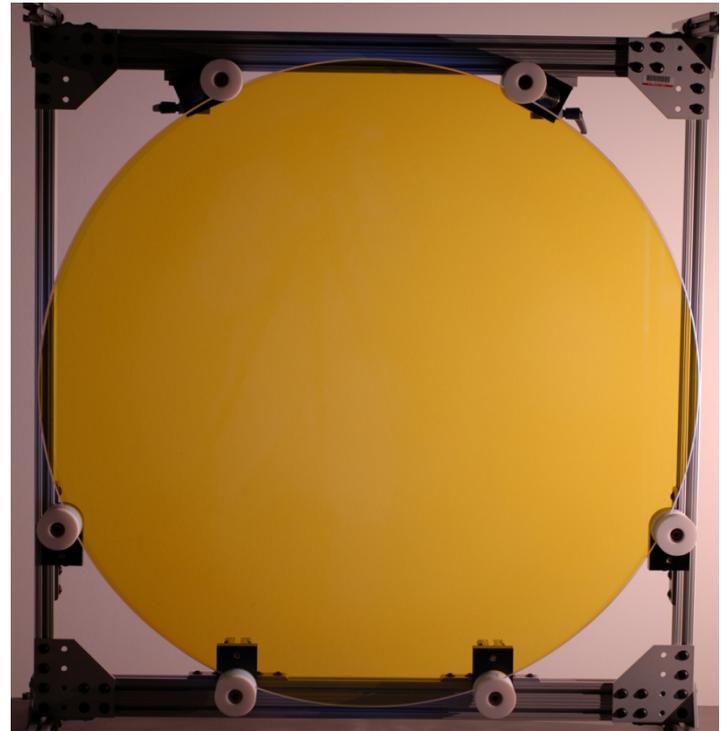
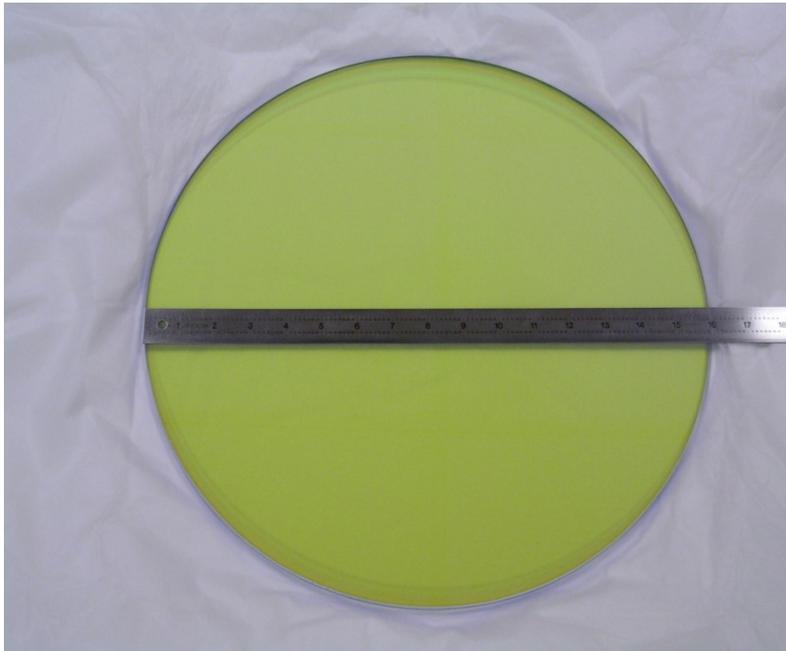
12" diameter Phase Measuring Interferometer supports measurement of coated optics at the wavelength of operation



Large Coated Optics can be inspected per Mil-Spec Conditions- but this is not sufficient for critical applications



Large Area Atomic Layer Deposition (ALD) Process provides Loss Low Optical Coatings that are conformal and pinhole free



Conclusions

- Optical Coatings currently limit the performance of some critical laser based optical systems
- Identification of source of point defects such as nano-precursors and specific defect mechanisms in high performance vapor deposited mirror coatings is a challenge
- Large Mechanical Losses due to Thermal Noise – i.e. Internal Friction of high index optical coating materials remains a challenge for GWO
- Cleaning is critical to achieving and maintaining low loss optical performance