Optics Development for LIGO

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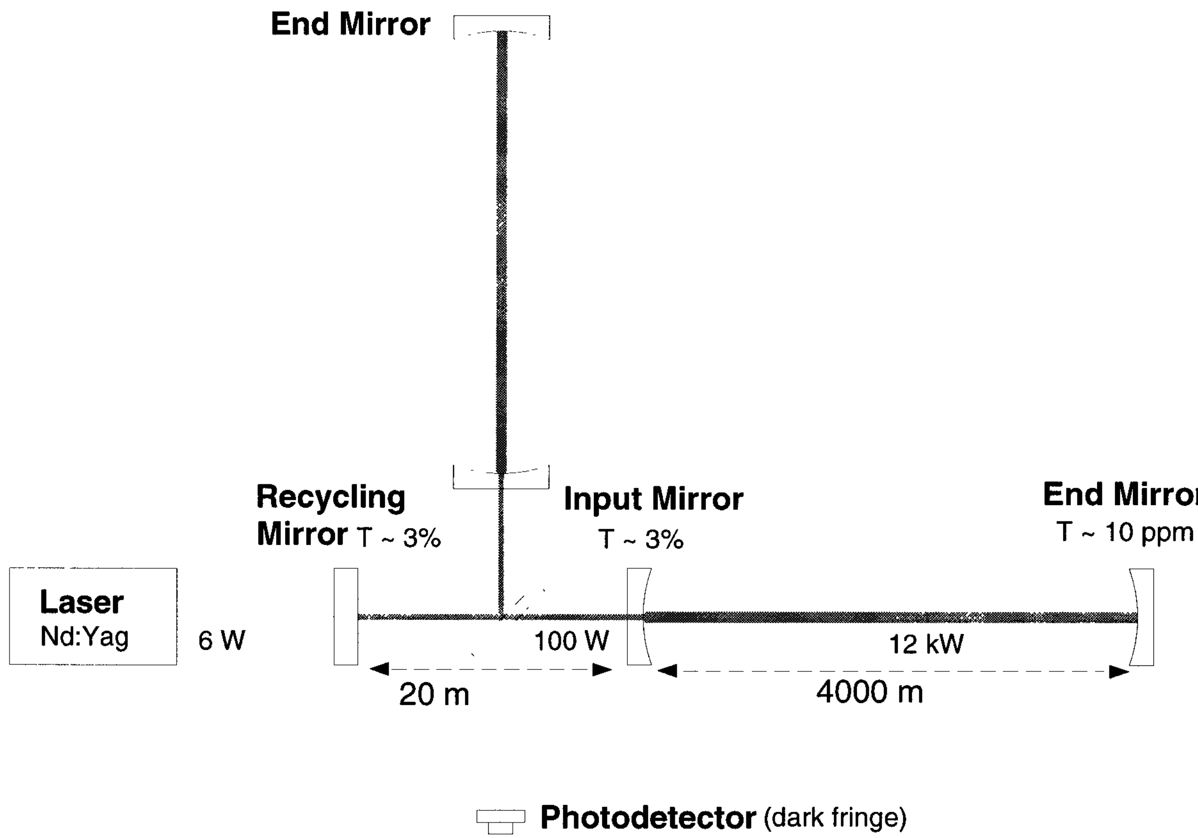
Large Optical Components ("Core Optics")

- Test Masses
  - ››End Mirror
  - ››Input Mirror
- Beamsplitter
- Recycling Mirror
- Total Number: 20
  - ››WA 4km: 6 Optics
  - ››WA 2km: 8 Optics
  - ››LA 4km: 6 Optics
  - + Spares



Core Optics

- High purity fused silica
  - 25 cm diameter x 10 cm thick (except beamsplitter: 4cm thick)
  - Beams fill some optics (to ~1ppm level)
  - 1064 nm HR mirrors and AR second surface coatings.
- Principal performance requirements:
  - $<$ 50 ppm loss per surface (limits resonant stored energy: shot noise)
  - Surface figure errors to scatter negligible power from TEM_{00} (best dark fringe)
    - Similar requirement for bulk inhomogeneity
  - High mechanical Q to "suppress" thermal noise ($Q \geq$ few x 10^6)
  - Low bulk (<~5ppm/cm) and coating (<2ppm) absorption (thermal lensing limit to beam power and dark fringe contrast).

Optics Development Program ("Pathfinder")

- Purchase and evaluate fused silica blanks (5/94)
  - ››Corning 7940 OAA Grade
- Best effort polishing of substrates (8/95-4/96)
  - ››Commonwealth Scientific and Industrial Research Organization (CSIRO)
  - ››General Optics (GO)
  - ››Hughes-Danbury Optical Systems (HDOS)
- Independent substrate metrology (4/96-8/96)
  - ››National Institute of Standards and Technology (NIST)
- Coating uniformity development (7/95-ongoing)
  - ››Research Electro Optics (REO)
- Coated optic metrology (NIST, early '97)
- Analysis of all data in LIGO computer model

Defining the Optics Requirements

- Primary tool is computer model of full recycled interferometer
  - FFT-based optical propagation code
  - Includes the surface figure of all optical components (either real or simulated)
  - Includes OPD of substrates
  - Solves for carrier and sidebands for modulation/demodulation
- Contributions from many people
  - Original code courtesy of Jean-Yves Vinet and Patrice Hello (VIRGO)
  - Extensive modification and enhancement by Partha Saha, Yaron Hefetz, and Brett Bochner
  - Used to establish LIGO requirements by Bill Kells

Core Optics Requirements

- Tight matching of all optical parameters arm to arm

Physical Quantity	*Test Mass* End	*Test Mass* Input	*Beam splitter*	*Recycling mirror*
Diameter of substrate, ϕ_s (cm)	**25**	**25**	**25**	**25**
Substrate Thickness, d_s (cm)	**10**	**10**	**4**	**10**
1 ppm intensity contour diameter (cm)	**24**	**19.1**	**30.2**[a]	**19.2**
Lowest internal mode frequency (kHz)	**6.79**	**6.79**	**3.58**	**6.79**
Mass of Suspended Component (kg)	**10.7**	**10.7**	**6.2**	**10.7**
Nominal surface 1 radius of curvature (m) and g_i factor	**7400** **g_2=.46**	**14540** **g_1=.725**	∞	**9890** **g=.9984**
Tolerance on radius of curvature (m)	**absolute: +220 matching: ±111**	**-1000, +145**	**>-720 km convex, >200 km concave**	**-100, +500**

a. For these 45° angle of incidence optics, this is the smallest diameter circle centered on the optic face which is everywhere outside of the 1 ppm intensity field.

Substrate Material Results

- Optical homogeneity measured and evaluated using FFT model
  - ››OPD maps of best grade fused silica indicate sufficient homogeneity
  - ››Bulk $\Delta n \leq 5\ 10^{-7}$ through 10cm.
- Mechanical Q's measured > 8 10^6 (lowest 5)
- High dn/dT coefficient for silica requires very low absorption.
  - ››VIRGO measurements correlate 1064 nm absorption with OH concentration.
  - ››Typical process: 500-1000 ppm OH (10-20 ppm/cm absorption): Heraeus process ~200 ppm OH (~5 ppm/cm absorption).
  - ››Only critical for input mirror and splitter.
- Orders for ~40 blanks have been placed
  - ››Heraeus selected for input mirrors and splitters and Corning for all others
  - ››Spares and allowance for in-process problems

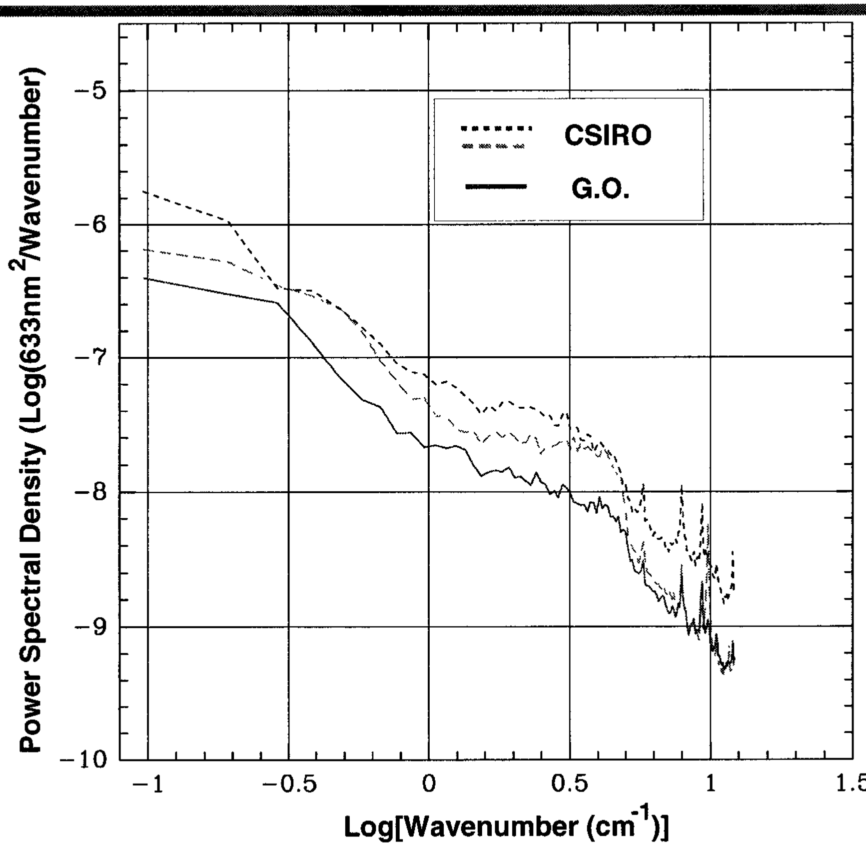
Core Optics-Polishing Demonstration

- Best Effort Polishing/Metrology of Substrates
  - ››HDOS, CSIRO, GO
  - ››Flat on one side; R= 6000 m on other side
  - ››Goal: “mid scale” surface figure errors <.8 nm rms (central 8 cm diameter)
  - ››Goal: < 0.4 nm rms microroughness
- Independent Substrate Metrology
  - ››NIST (C. Evans, R. Parks, et al.)
  - ››PMI absolute metrology, multiply redundant measurement approach
  - ››Surface scales ≥ 3mm using existing 633 nm equipment
- LIGO supervision, coordination, analysis
  - ››GariLynn Billingsley, Doug Jungwirth, Bill Kells, Cathy Kreath (consultant), Rick Savage, Rai Weiss

Core Optics-Polishing

- Conclusion: rms deviation from sphere < 1nm over 20cm diameter are achievable!
  - In some cases, apparent rms ~0.5 nm measured
- With care, measurements at ≤ 1 nm level possible
  - Reproducible features seen; Consistent intercomparisons demonstrated
  - Small, subtle systematic effects noticed
    - Flat reference vs. curved surface
    - Fizeau path differences
    - Focus effects
- GO and CSIRO selected to polish LIGO Core Optics

Pathfinder Polishing: Surface Figure



One dimensional power spectra from NIST metrology of curved surfaces. Z(0,0),Z(1,1) Z(2,0),Z(2,2),Z(3,1),Z(3,3),Z(4,0) removed

» NIST Measurements

» HDOS-polished optics comparable

Pathfinder Polishing: Microroughness

- Comparative surface roughness measurements made at REO

Polisher	Optic/Surface	Microroughness (Å rms)	
		Micromap SW (5 location ave.)	PSD area analysis (R. Weiss)
CSIRO	006/Curved	3.6	3.7
	006/Flat	2.8	2.7
	002/Curved	2.7	3
	002/Flat	3.1	3
GO	005/Curved	0.85	0.6 - 1.4
	005/Flat	0.88	0.7 - 1.2

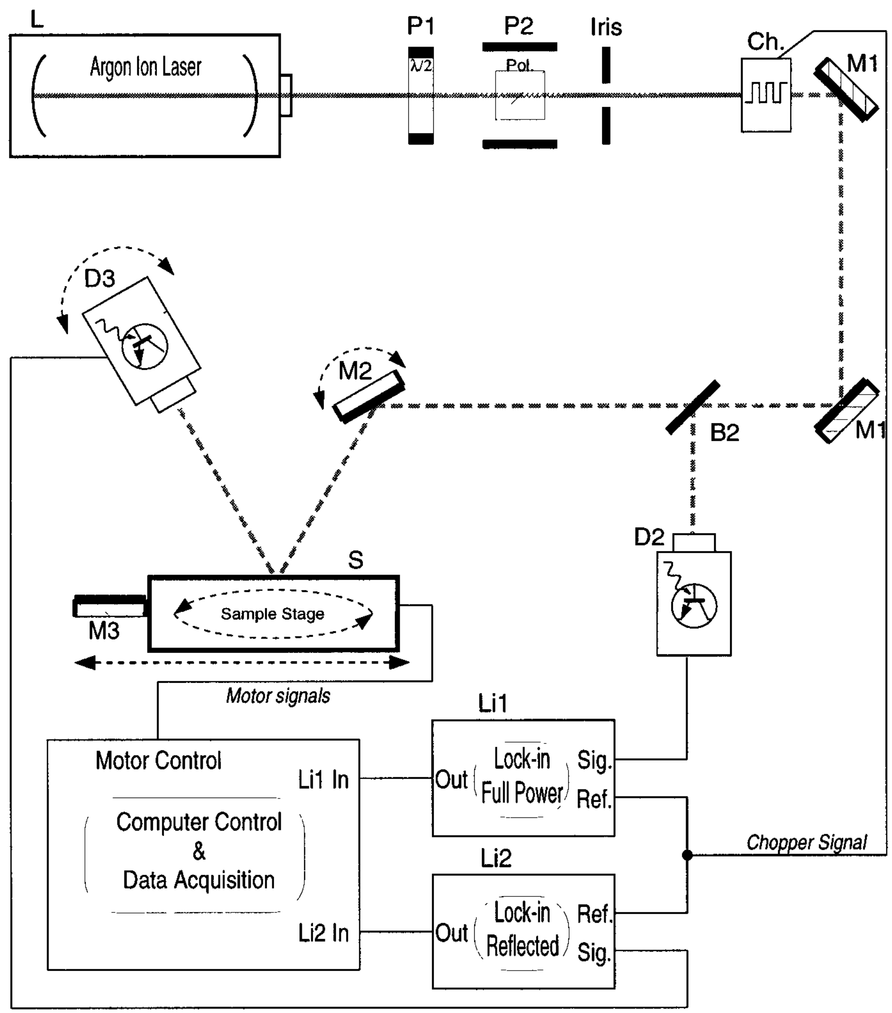
›› HDOS results comparable to CSIRO

›› CSIRO (and HDOS) improving microroughness

Coating Uniformity Development

- Coating Uniformity Development: REO
  - ››Goal: Scale up low loss ion beam sputtered coating technology to LIGO diameters
  - ››Preliminary test pieces show good uniformity to 15 cm diameter
  - ››Final verification: Coat Pathfinder optics for 633 nm and test
- Development of new test technique
  - ›› Measurements: Doug Jungwirth, Alex Golovitser
  - ›› Analysis: Hiro Yamamoto, Bill Kells
  - ›› Coatings: Research Electro Optics, Ramin Lalezari

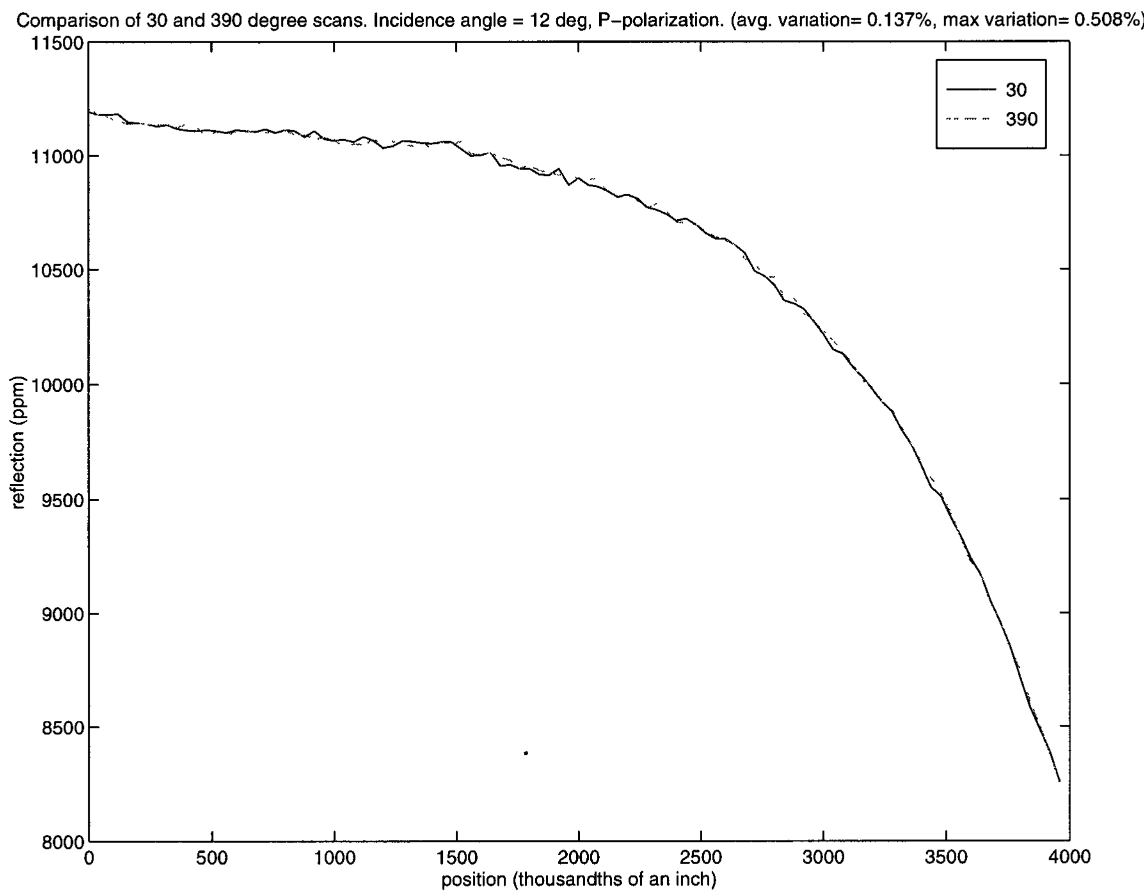
Coating Uniformity Measurements



- Map reflectivity of specially designed AR coating
  - Insensitive to surface figure of underlying substrate
  - Can investigate uniformity of individual coating layers
- Make measurements at:
  - 2 Polarizations
  - 3 Angles

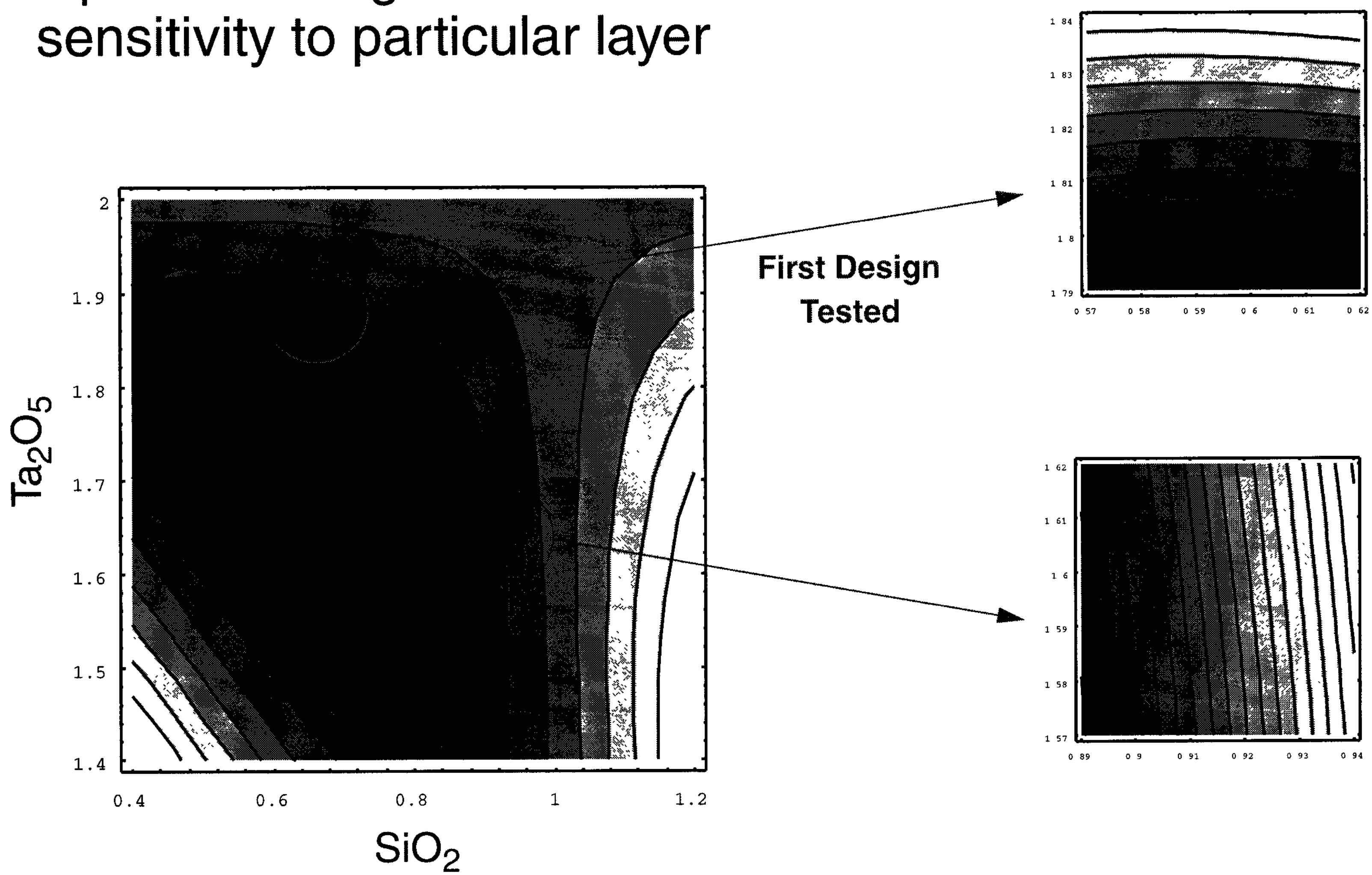
Coating Reflectivity Data

- Typical radial scan shows good reproducibility (~0.2%)



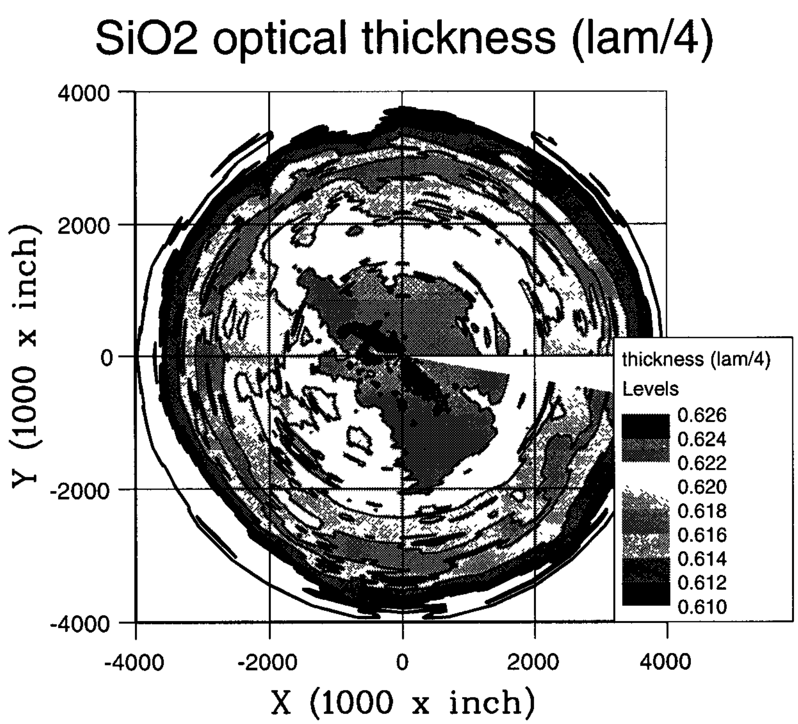
Test AR Coating Design

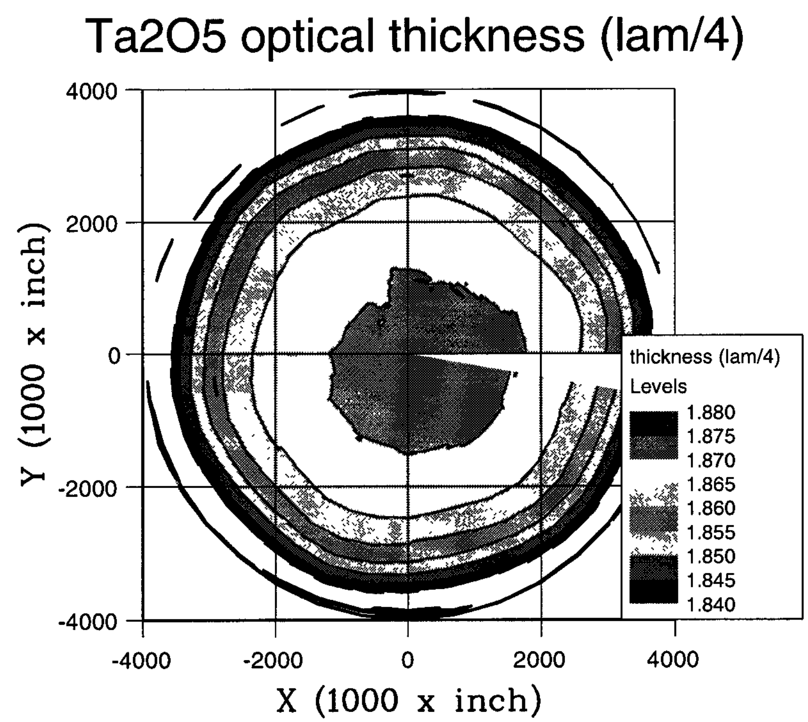
- Optimize design for maximum sensitivity to particular layer



Individual Layer Maps

- Individual layer thicknesses determined by least squares minimization process

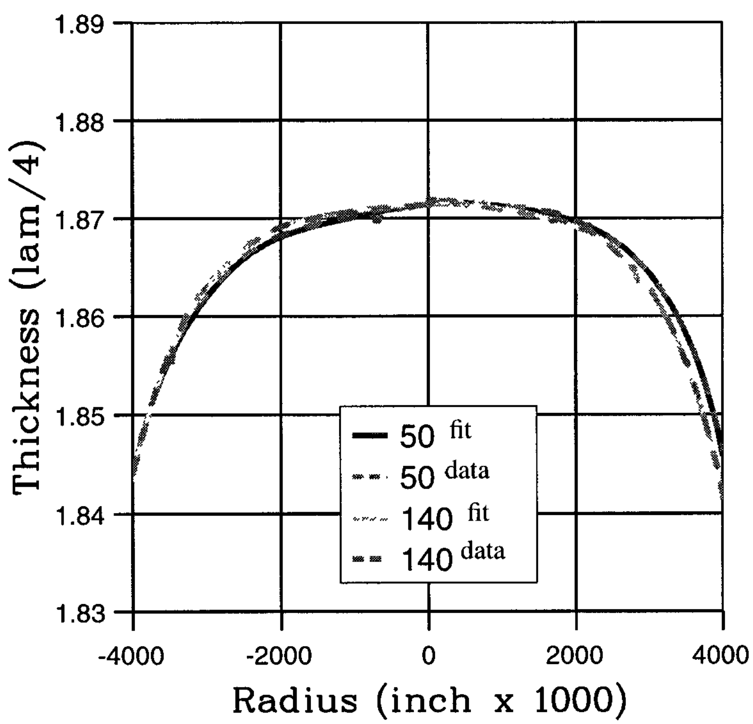




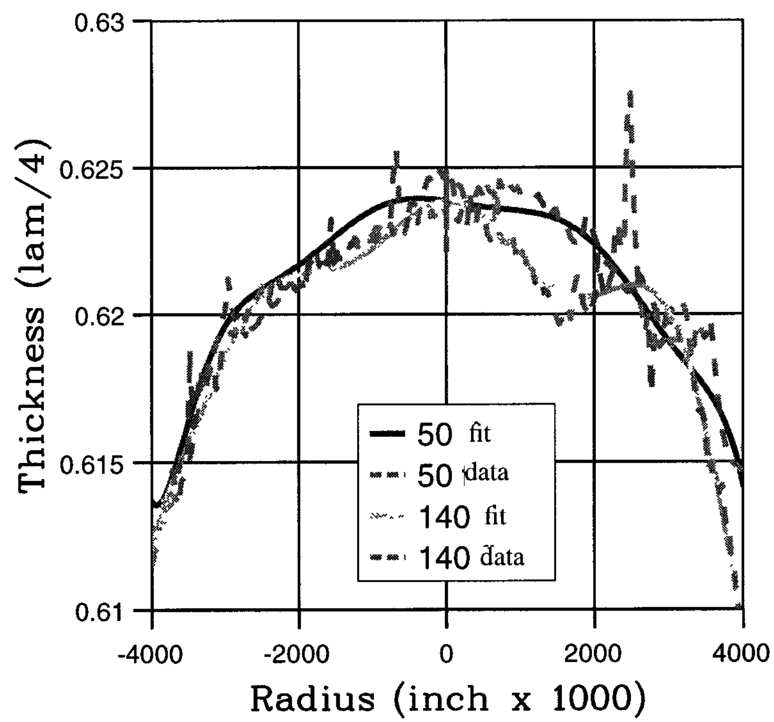
Sample Scans and Fits

- Fit Data to Zernike polynomials up to tenth order
- Deviations from fits consistent with measurement errors

Ta2O5 Thickness at 50 and 140 degree



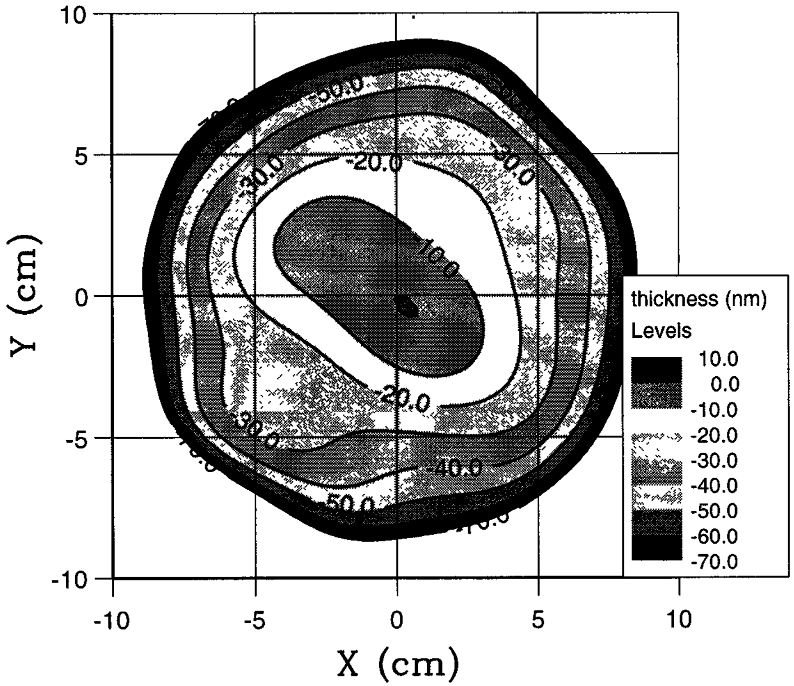
SiO2 Thickness at 50 and 140 degree



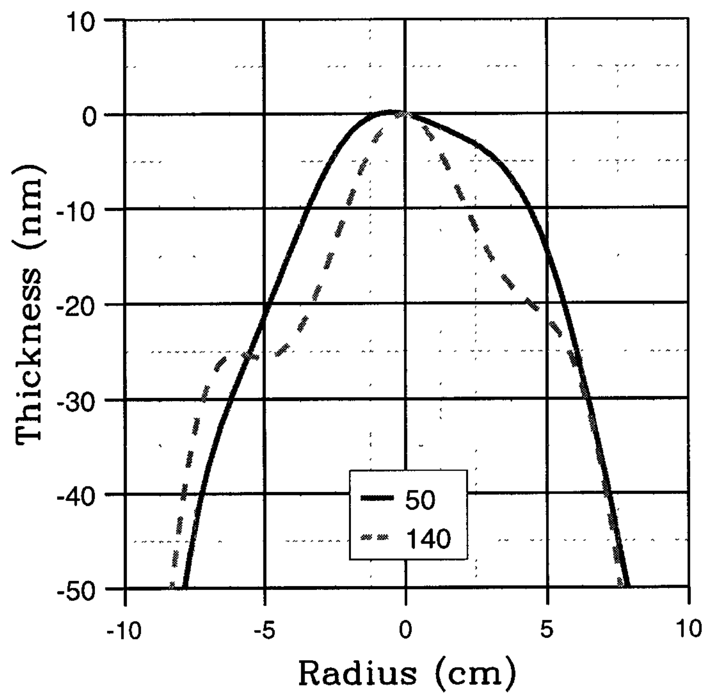
Extrapolate to Full HR Coatings

- Use fits to individual layers to synthesize predicted phase map for HR coatings

40 layer HR coating phase map



40 layer HR coating phase map



Preliminary Coating Assessment

- Have used FFT-model to assess performance in LIGO interferometer

Run Conditions	*Surface Figure (Å rms)*	*Recycling Factor*	*h(100 Hz) ($x10^{-23}$ $Hz^{-1/2}$)*
Standard Configuration: **Measured Substrate OPD's** **Surface Phase Maps Based on** **Polished Substrates**	**0.8**	**52**	**1.39**
Standard Configuration, except 40 Layer HR substituted on End Test Mass	**3.8 (ETM)**	**17**	**2.14**
Standard Configuration, except 16 Layer HR substituted on Input Test Mass	**1.9 (ITM)**	**33**	**1.73**
Standard Configuration, except 40 Layer HR substituted on End Test Mass and 16 Layer HR substituted on Input Test Mass	**3.8 (ETM)** **1.9 (ITM)**	**15**	**2.52**

- Some loss in sensitivity but within a factor of 2 of required uniformity

Coating Uniformity: Next Steps

- Make coating adjustments to reduce curvature (REO)
- Two new test AR coating runs
  - ››Separately test SiO_2 and Ta_2O_5
- Coat Pathfinder optics with HR coatings
- Measure reflected phase at NIST to confirm scaling from single layers to HR coatings

Summary

- Tools and techniques (both experimental and analytical) in place to evaluate LIGO optics against requirements
- Substrate material and polishing appear to be adequate for initial LIGO interferometers
- Preliminary coating uniformity data promising; further improvements and testing expected within the next few months