Optical Development of Test Masses

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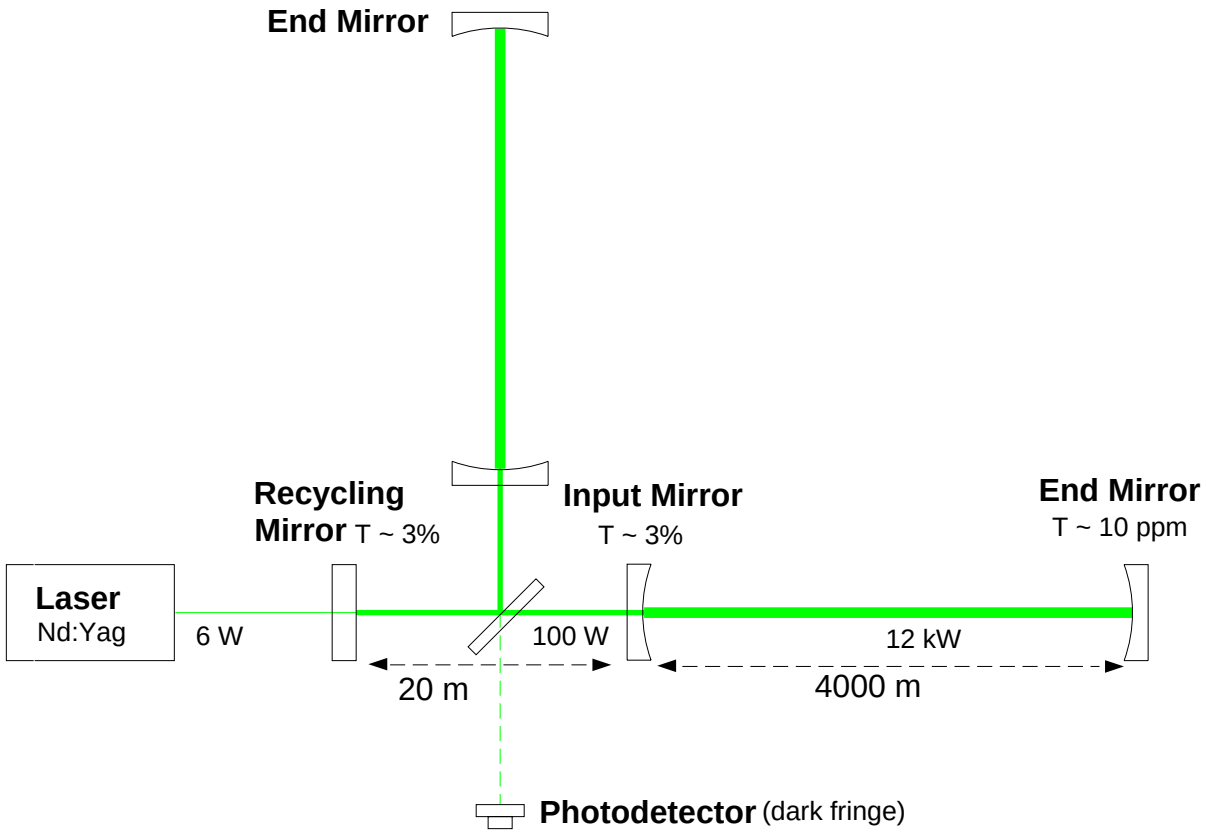
Large Optical Components ("Core Optics")

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

  + Spares



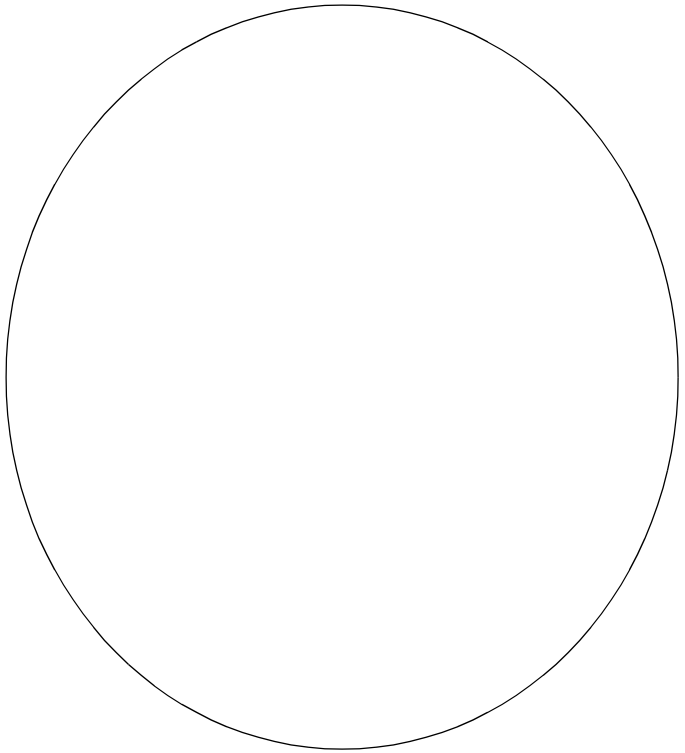
Core Optics Requirements

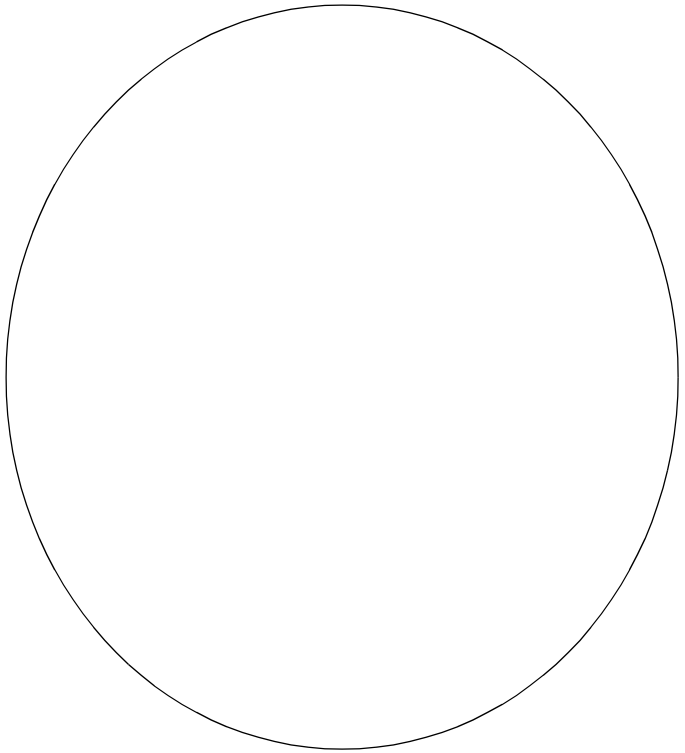
- High purity fused silica
  - 25 cm diameter x 10 cm thick (except beamsplitter: 4cm thick)
  - Beams fill some optics (to ~1ppm level)
  - 1064 nm HR mirrors and AR second surface coatings.
- Principal performance requirements:
  - < 50 ppm loss per surface (limits resonant stored energy: shot noise)
  - Surface figure errors to scatter negligible power from TEM_{oo} (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, ongoing)
- Analysis of all data in LIGO computer model

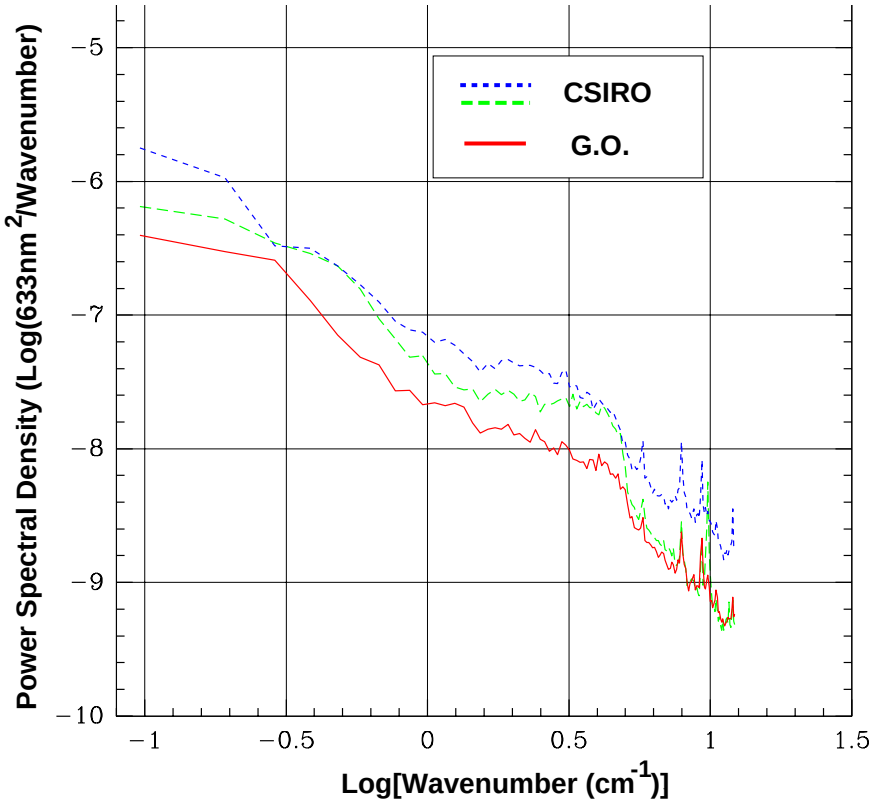
Pathfinder Metrology
Comparison of NIST and HDOS Results





Pathfinder Polishing Surface Figure Results

- NIST measurements of CSIRO and GO parts



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

Coating Uniformity Development

- Stans viewgraph of coating uniformity comparison

Coating Uniformity - Change in Radius Stress?

›› Initial saggita after polishmeasured at NIST (over 15 cm)	501.0 nm
›› Expected sag due to coating uniformity	512 nm
›› Initial sag after coating measured at NIST we assume that the coating stress is roughly compensating for the coating uniformity	500 nm
›› Expected sag after annealing Stress no longer compensating for uniformity	512
›› Measured sag after annealing	525.3 nm

Defining the Optics Requirements

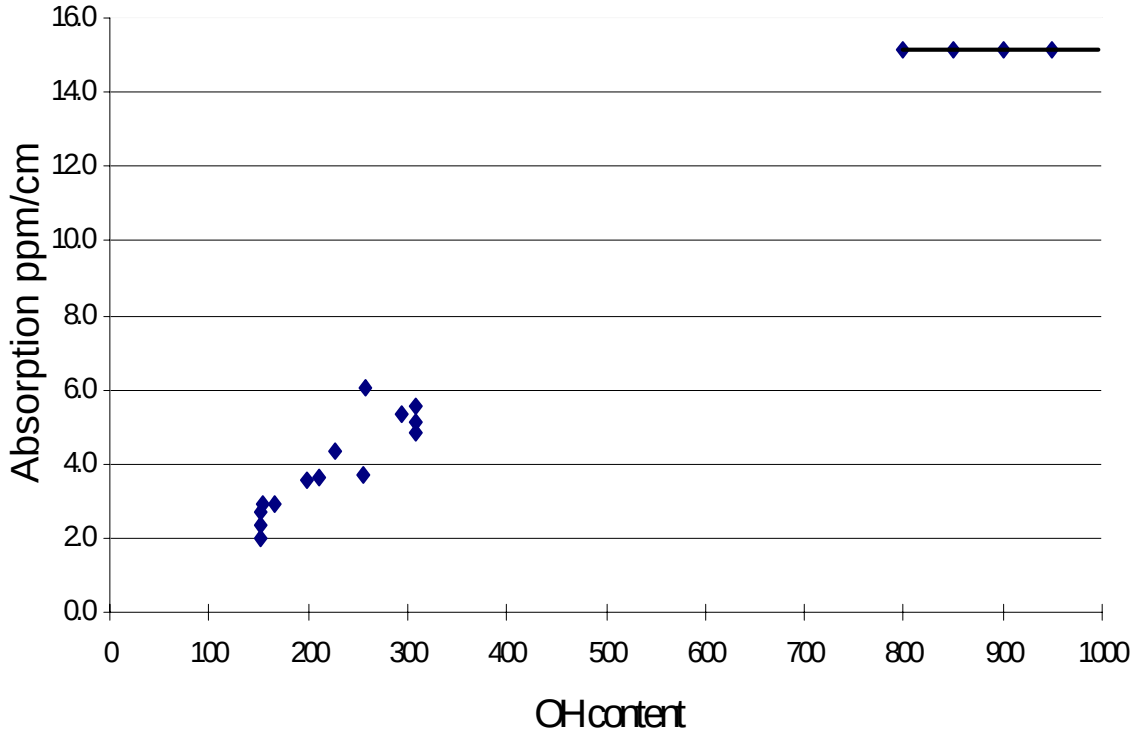
- Primary tool is computer model of full recycled interferometer
  - ››FFT-based optical propagation code
  - ››Includes the surface figure of all optical components (either real or simulated)
  - ››Includes OPD of substrates
  - ››Solves for carrier and sidebands for modulation/demodulation
- Contributions 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*	*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)	**7400**	**14570**	**∞**	**14900**
Tolerance on radius of curvature (m)	**absolute: +220 matching: ±111**	**-1000, +145**	**>-720 km convex, >200 km concave**	**-150, +750**

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.

Absorption in Input Test Masses



››Measured in collaboration with VIRGO

Polishing Results to date
CSIRO

	Surface Errors < 4.3 cm $^{-1}$ over 80mm	Surface Errors 4.3-7,500 cm $^{-1}$ over 200mm
FM Reqts. CSIRO	σ_{rms} <1.6 nm	σ_{rms} <0.4 nm
FM01	0.5 nm	0.37 nm
FM02	0.4 nm	0.33 nm
FM03	0.4 nm	0.3 nm
FM04	0.4 nm	0.31 nm
ETM Reqts. CSIRO	σ_{rms} <0.8 nm	σ_{rms} <0.2 nm
ETM01	0.46 nm	0.17 nm
ETM02	0.46 nm	0.17 nm
ETM03	0.47 nm	0.20 nm
ETM04	0.45 nm	0.20 nm

- Similar results for recycling mirror
- Input Test Masses and Beamsplitters are in work now

End Test Masses
Polished at General Optics

ETM Goals (GO)	σ_{rms} < 0.8 nm	σ_{rms} <0.1 nm
ETM01	0.35 nm at NIST	0.042 nm at GO
ETM02	0.31 nm at NIST	0.046 nm at GO
ETM03	0.35 nm at NIST	0.049 nm at GO
ETM04	0.36 nm at NIST	0.041 nm at GO
ETM05	0.39 nm at NIST	0.034 nm at GO
ETM06	0.72 nm at NIST	
ETM07	1.23 nm at NIST	0.029

Future Test Development

- General Optics has agreed to polish 2 C axis pieces
  - 150 mm diameter sapphire test piece grown by Crystal Systems
    Radius: 6000 m, +/- 170m, best effort
    Surface Figure: lambda/800 at 632.8 best effort
  - 100 mm diameter piece grown by Shanghai Institute of Fine Mechanics