LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LIGO-E980061	-00-D	4/27/98
Doc Number	*Group-*	*Date*

Core Optics Components Final Design

G. Billingsley, B. Kells, H. Yamamoto,
J. Camp, D. Li, H. Armandula, S. Bell, S. Elieson

This is an internal working note
of the LIGO Project
Distribution:
COC-FDR review board

California Institute of Technology
LIGO Project - MS 18-34
Pasadena CA 91125
Phone (626) 395-2966
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu
WWW: http://www.ligo.caltech.edu

file /home/jordan/coc/fdr/cocfdr.fm - printed April 27, 1998

1 INTRODUCTION

The Core Optics final design document presents the results of the final design period in this subsytem relative to the requirements established in the Core Optics Design Requirements Document. Included is:

- Core Optics Design Requirements Summary
- Core Optics Final Design
- Core Optics Quality Assurance

1.1. Acronyms

BS	Beam Splitter
ETM	End Test Mass
FM	Folding Mirror
ITM	Input Test Mass
RM	Recycling Mirror

1.2. Applicable Documents

1.2.1. LIGO Documents

1.2.1.1 General

LIGO-E950099 Core Optics Components Requirements (1064)

LIGO-T950100 COC Conceptual Design Document

LIGO-E960027 Review Report, Design Requirements Review, Core Optics Components

LIGO-T970091 Determination of the Wedge Angles for Core Optics Component

LIGO-T980003 Current Progress in LIGO Optical Contamination Studies

1.2.1.2 Shipping Handling proceedure

E970034-00-D Core Optic Components Shipping and Handling Procedures

D961460-C Large Core Optic Component Carrier Assembly

D961461-C Beam Splitter Optic Carrier Assembly

1.2.1.3 Polishing Specifications

LIGO-E960092 Specification for Substrate, Recycling Mirror

LIGO-E960093 Specification for Substrate, Input Test Mass

LIGO-E960100 Specification for Substrate, Beam Splitter

LIGO-E960101 Specification for Substrate, Folding Mirror

LIGO-E960102 Specification for Substrate, End Test Mass

LIGO-E950104 Specification for Substrate, Super Polished End Test Mass

1.2.1.4 Polishing Drawings

LIGO-D960785 Recycling mirror Substrate

LIGO-D960787 Input Test Mass Substrate, 4K

LIGO-D960803 Input Test Mass Substrate, 2K

LIGO-D960789 Beam Splitter Substrate

LIGO-D960790 Folding Mirror Substrate

LIGO-D960791 End Test Mass Substrate, 4K

1.2.1.5 Material Specifications

LIGO-E960094 Specification for Mirror Blank Material, Beam Splitter

LIGO-E960095 Specification for Mirror Blank Material, Input Test Mass

LIGO-E960096 Specification for Mirror Blank Material, Recycling Mirror

LIGO-E960097 Specification for Mirror Blank Material, Folding Mirror, End Test Mass

1.2.1.6 Material Drawings

LIGO-D960793 Beam Splitter Blank

LIGO-D960794 Core Optic Blank

LIGO-D970504 Recycling Mirror Blank

1.2.1.7 Coating Specifications

LIGO-E980065 Specification for Coated Mirror Substrate, Foldling Mirror

LIGO-E980066 Specification for Coated Mirror Substrate, Input Test Mass 2K

LIGO-E980067 Specification for Coated Mirror Substrate, Input Test Mass 4K

LIGO-E980068 Specification for Coated Mirror Substrate, End Test Mass

LIGO-E980068 Specification for Coated Mirror Substrate, Beam Splitter

LIGO-E980068 Specification for Coated Mirror Substrate, Recycling Mirror

2 CORE OPTIC COMPONENT REQUIREMENTS

The requirements summarized in this section are taken from the Core Optics Design Requirments Document, LIGO-E950099-03D. They are grouped into the following categories:

- Physical Size and Shape
- Matching to LIGO IFO parameters
- Wavefront distortion
- Light scattering and absorption
- 2 km interferometer

2.1. Physical Size and Shape

The size and shape of the Core Optics must be such that the following requirments are satisified:

2.1.1. Clipping loss

The optic diameters and ROC must be large enough to limit the power loss from beam clipping at the optic edge to the following levels:

Table 1: Allowed Power Loss from Finite Optic Size

Optic	Loss
FM, RM, ITM, ETM	1 ppm
BS	100 ppm

2.1.2. Wedge angles

Wedge angles must be included to provide for pickoff beams and separation and control of ghost beams.

2.1.3. Mechanical Q’s, internal thermal noise contribution to IFO strain noise, and internal mode frequencies

The COC material must yield internal mechanical mode Q’s $> 5 \times 10^6$. The Optics internal thermal noise contribution to the interferometer noise budget must meet SYS requirements (roughly a factor of 3 below pendulum thermal noise for the initial detector.) The frequency of the lowest internal mode shall be > 6 kHz for the RM, ITM and ETM and > 3 kHz for the BS to minimize constraints on the length control system bandwidths.

2.2. Matching to IFO Parameters

2.2.1. Reflectivity and AR coating of Optics

The reflectivity of the optics must satisfy the following reflectivity and AR coating parameters as determined by SYS.

Table 2: Reflectivity of Optics Coatings

Optic	High Reflector	AR coat
Folding Mirror	Max	Min
Recycling Mirror	97%	Min
Beam Splitter	50%	Min
Input Test Mass	97%	600 ppm
End Test Mass	Max	Min

2.2.2. Arm cavity g-factor

The arm cavity g-factor has been specified by SYS to be 1/3 for the 4 km and ~2/3 for the 2 km.

2.2.3. Arm cavity reflectivity

The variation in arm-to-arm cavity reflectivity must not exceed 1% to provide interferometer common mode rejection of frequency noise.

2.3. Wavefront Distortion

The surface figure of the optics must be sufficiently uniform to limit the distortion of the reflected wavefront to the following levels. (Wavefront distortion couples to increased shot noise.)

Table 3: Required Limits on Wavefront Distortion

Requirement	**ITM, ETM**	**BS, FM**	**RM**
Arm-arm match of ROC	1.5 %	-	-
rms figure error[a] out to 2 w_0	λ / 1200	λ / 200	λ / 200
rms figure error past 2 w_0	λ / 600	λ / 100	λ / 100
μ-roughness[b]	0.6 nm	0.6 nm	1 nm

a. $w_0 > \lambda_{spatial} > 2.3$ mm
b. 2.3 mm $> \lambda_{spatial} > 1.3\ \mu$m

2.4. Scattering and Absorption

Scattering and absorption from the Core Optics must be held to the following levels to limit cavity losses and to prevent excessive thermal lensing.

Table 4: Required Limits on Scattering and Absorption (ppm)

Requirement	ITM	ETM	BS, FM	RM
Bulk scattering of transmitted beam	50	-	50	50
Surface Absorption	0.6	2	50	50
Surface scattering from μ-roughness	50	50	100	200
Bulk absorption within substrate	40		20	40

2.5. 2 km interferometer

The response to COC DRR Action Item #11 addressed the Core Optics parameter choices for the 2 km interferometer. The accepted recommendation was to use the same reflectivities and optics sizes for the 2 km as for the 4 km. Thus all the other requirements listed above apply to the 2 km optics.

3 CORE OPTICS FINAL DESIGN

3.1. Design Perspective

The design of the core optics has incorporated a balance between lowest loss and reasonably available technology.

3.2. Physical Size and Shape

In an effort to minimize spares, all components but Input Test Masses are interchangeable between the 2 and 4K interferometers. The COC subsystem consists of the following items.

3.2.1. Fused Silica cylindrical substrates

Table 5: Substrate Dimensions

	Diameter	Thickness	Wedge
2K Input TM	250mm +1, -0	At thickest point 100mm +0, -0.5	0˚ 34´ symmetric
4K Input TM			1˚ 10´ symmetric
End TM			2˚ 0´ right angle
Folding mirrors (FM)			2˚ 0´ right angle
Recycling mirror (RM)		At thickest point 97.5 +0, -0.5	2˚ 24´ symmetric
Beam splitter (BS)		At thinnest point 40 mm +0, -0.5	1˚ 0´ symmetric

3.2.2. Radius of Curvature (ROC)

The following radii of curvature have been determined for the Core Optics.

Table 6: Core Optics Radii of Curvature

Optic	ROC (km)	comment
RM	14.9	compensates thermal lensing of ITM $G_{rc} = 50$ at $P_{inc} = 6$ W
FM	flat	-
BS	flat	-
ITM	14.2	compensates thermal expansion of ITM, sets g = 1/3
ETM	7.4	sets g = 1/3, keeps spot size so that clipping < 1ppm

3.3. Polishing Results

The following tables list the polishing results for the ETM and the FM. The ETM were polished at General Optics and measured at NIST. The FM were polished and measured at CSIRO.

End Test Mass	DRR Requirements	Specified Requirements	Results to date
Arm-arm match of R_{eff} (fractional)	0.015	Match to .015	0.015
rms surface errors for $w > \lambda_s > 2.3$ mm out to ~2w diameter	$\lambda/1200$ (0.89 nm)	0.8 nm	0.5 max
rms surface errors for $2w > \lambda_s > 2.3$ mm past 2w diameter	$\lambda/600$ (1.77 nm)	0.8 nm	0.5-0.8
rms surface error for $2.3\text{mm} > \lambda_s > 1.3\mu\text{m}$ out to ~ 3w diameter	<0.4 nm	0.2 nm	.05-0.2
rms surface errors for $\lambda_s > 3\text{-}4w$	$\lambda/160$ (6.65 nm)	1.6 nm	0.9 nm
rms transmission OPD for $2w > \lambda_s > 2.3$ mm out to ~ 2w diameter	$\lambda/50$ (21.3 nm)	50 nm P-V	33 nm PV max
Birefringence (transmission) δ (mrad)	20	.03	<.03

Folding Mirrors	DRR Requirements	Specified Requirements	Results to date
Arm-arm match of R_{eff} (fractional)	0.015	+25 nm, -7 nm	13 nm
rms surface errors for $w > \lambda_s > 2.3$ mm out to ~2w diameter	$\lambda/200$ (5.32 nm)	1.6 nm	0.5 max
rms surface errors for $2w > \lambda_s > 2.3$ mm past 2w diameter	$\lambda/100$ (10.6 nm)	1.6 nm	0.5-0.8
rms surface error for $2.3\text{mm} > \lambda_s > 1.3\mu\text{m}$ out to ~ 3w diameter	<0.8 nm	0.4 nm	.05-0.2
rms surface errors for $\lambda_s > 3\text{-}4w$	$\lambda/320$ (3.3 nm)	3.2 nm	0.9 nm
rms transmission OPD for $2w > \lambda_s > 2.3$ mm out to ~ 2w diameter	$\lambda/100$ (10.6 nm)	100 nm P-V	33 nm PV max
Birefringence (transmission) δ (mrad)	< 10	.03	<.03

Shown below are the power spectra, rms and p-p of the FM surface variations.

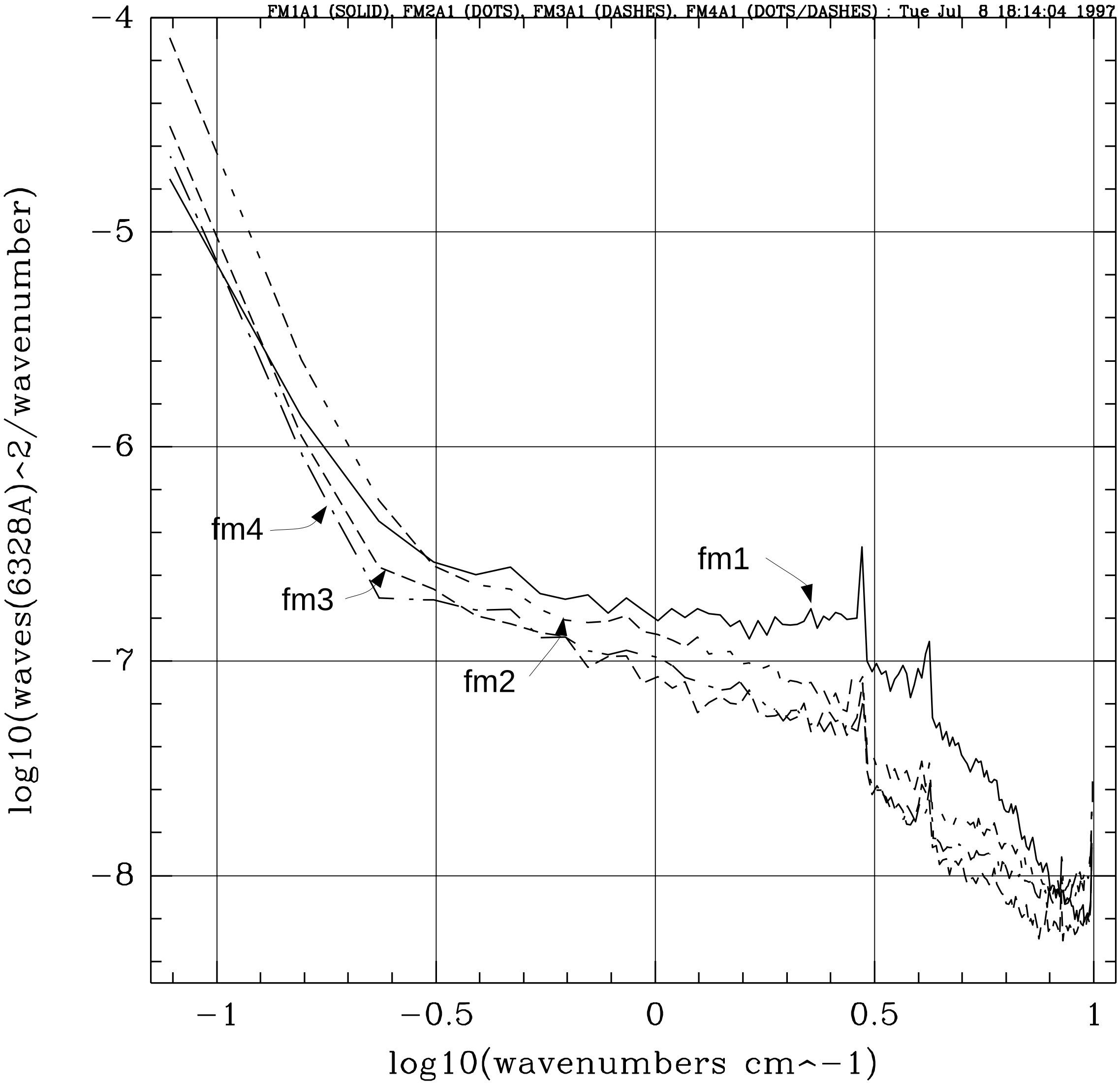
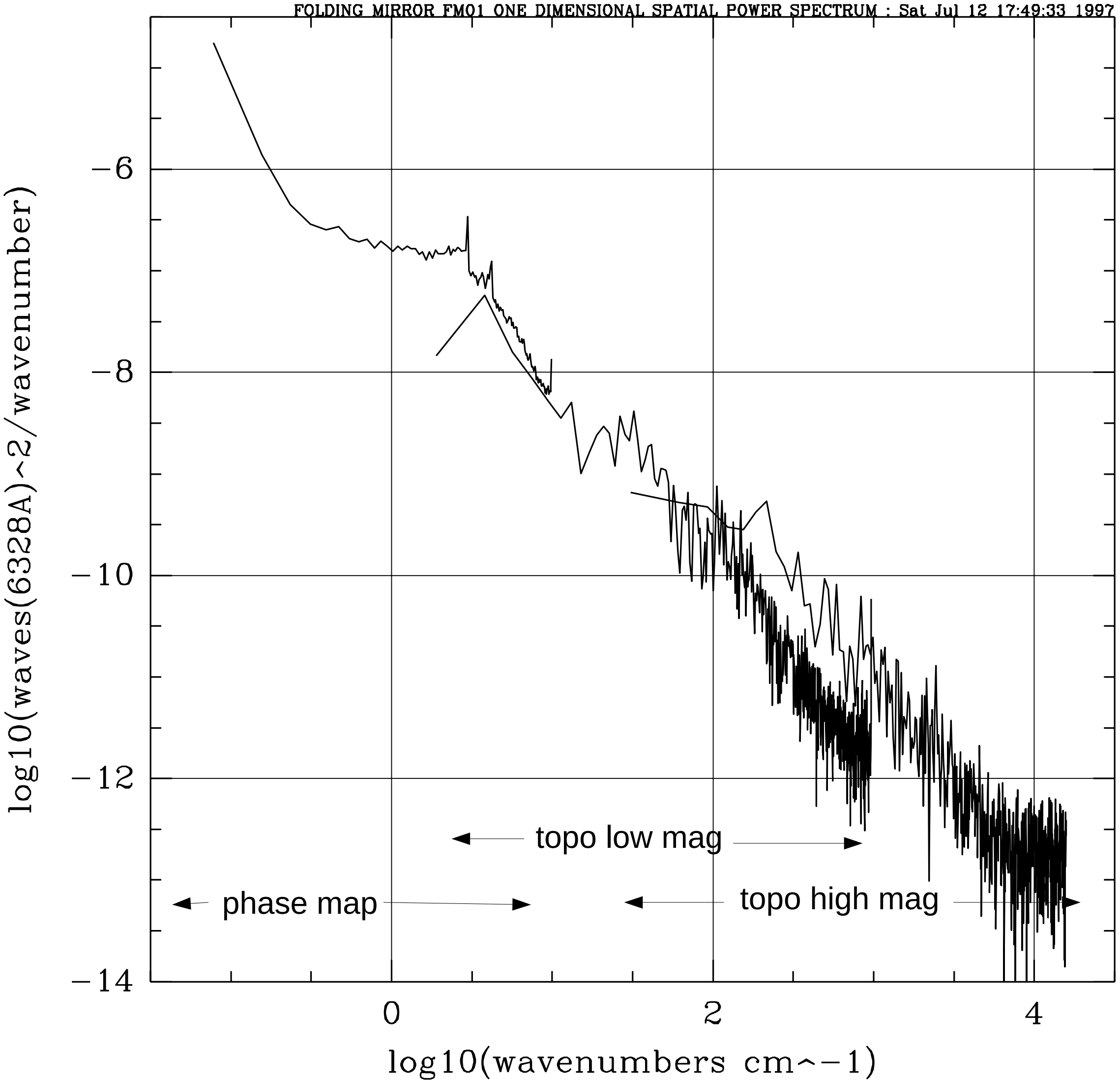


Table 7: Statistics over 23.4 cm aperture

surface	sigma	p-p	sigma Z removed[a]
	waves 6328A	waves 6328A	waves 6328A
fm1a1	0.00216	0.020	0.0019
fm2a1	0.00276	0.017	0.00239
fm3a1	0.00624	0.051	0,00526
fm4a1	0.00461	0.022	0.00162

[a] Z(1,1), Z(2,0) and Z(2,2) removed from the phase map

The following power spectrum shows data taken from 3 separate measurements at CSIRO: the Fizeau interferometer, and the Topo roughness map at low and high magnification. The data are seen to be mutually consistent, adding confidence to the measurements.

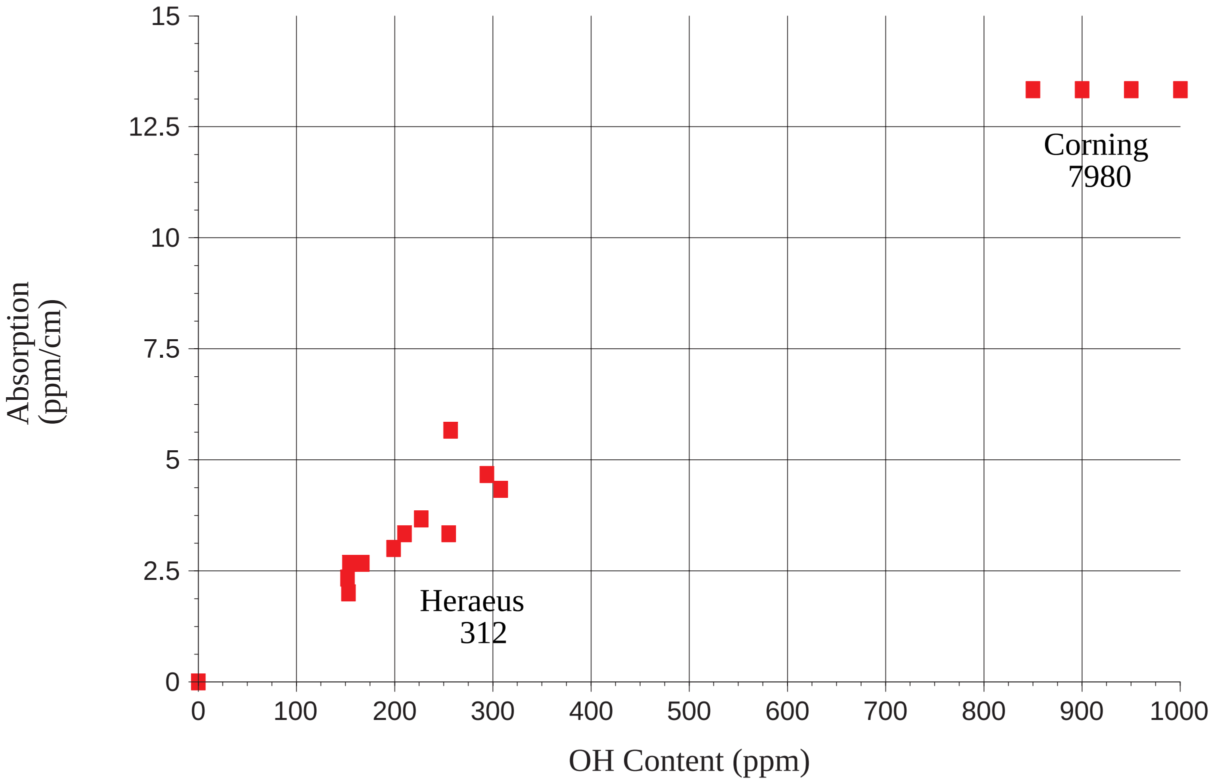


Analysis of the data at the following spatial frequency bands shows:

- low (λ<10/cm): surface phase map sufficiently uniform for LIGO shot noise requirements
- mid (10/cm<λ<100/cm): BRDF from optic low enough to control scattered light in beam tube
- high (λ>100/cm): arm cavity microroughness loss < 20 ppm
- entire range: total arm cavity loss < 120 ppm

3.4. Substrate Absorption

Substrate absorption leads to heat deposit and thermal lensing and expansion in the optics, a significant concern. To limit this problem, two types of substrates are used in the Core Optics. The RM, FM, and ETM are Corning 7980. The BS and ITM, which transmit the higher power recycling cavity light, are made from Heraeus 312, special low OH content glass. The following plot show the absorption of 7980 and 312 witness samples.



The absorption is seen to be well correlated with the OH content of the glass. These numbers satisfy the substrate absorption requirements for the various Core Optics.

3.5. Coating Results

The following plot compares the surface variations of a polished Pathfinder optic before (p05ca) and after (p05cac) the application of an HR coating at 633 nm. This was done as a check on coating uniformity. The rms and p-p variations indicate sufficient surface uniformity to proceed with the actual Core Optics coatings. A comparison of p05cac and p06cac, optics coated during the same run, shows that the loss per optic is sufficiently small so that the 1.5% arm cavity reflectivity match requirment is met (cavity scatter loss ~120 ppm, cavity total loss = 3%)

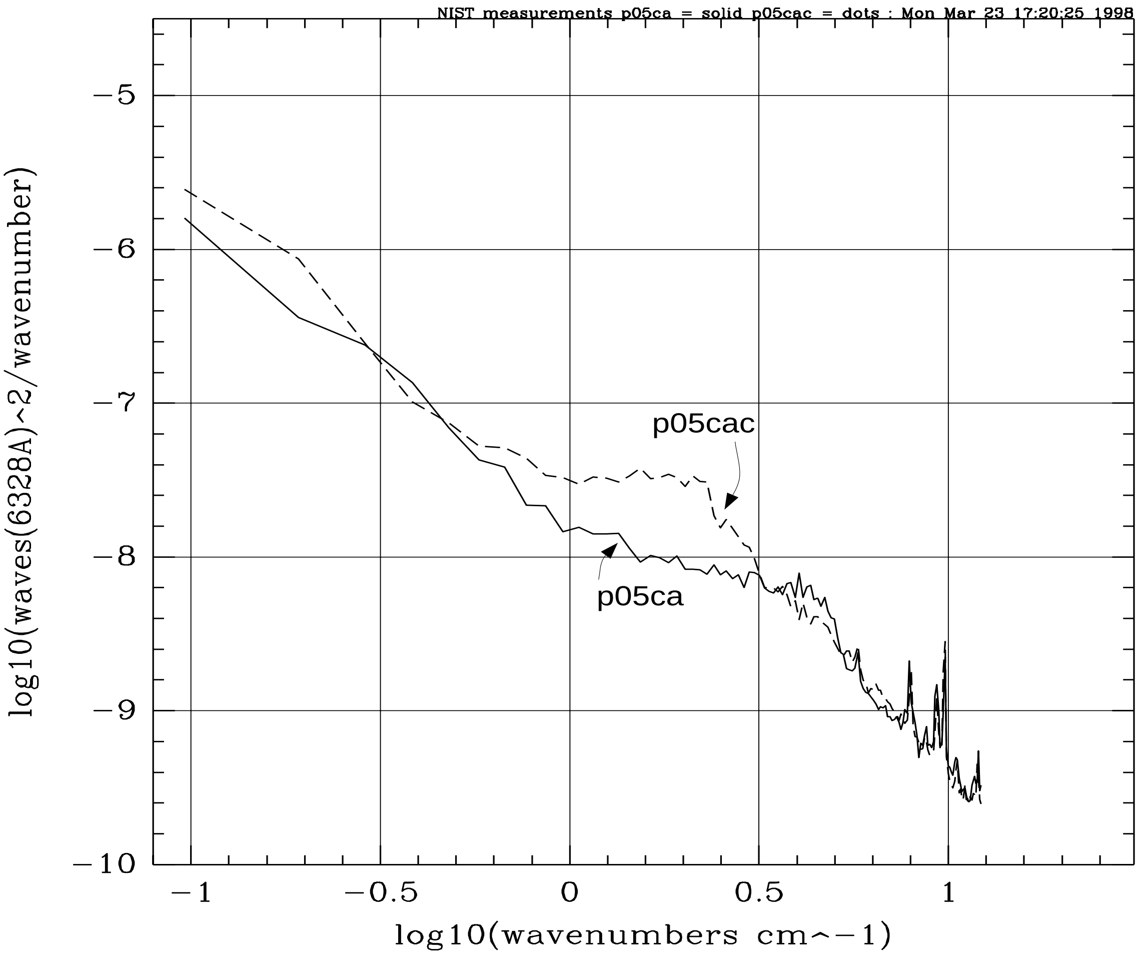


Table 8: Surface statistics over 14.6 cm aperture in microns

surface	rms	p-p
p05ca	3.81×10^{-4}	7.32×10^{-3}
p05cac	5.08×10^{-4}	4.00×10^{-3}
p06ca	3.74×10^{-4}	3.87×10^{-3}
p06cac	6.69×10^{-4}	4.62×10^{-3}

3.5.1. Effect of coating on ROC

The following data was obtained from NIST metrology of pre and post annealed Pathfinder pieces, coated for HR at 633 nm, with a nominal ROC of 6 km. The change in ROC occurs through application and then relief of coating compressive strain. The sign flip is due to the presence of 2 components: a long-range coating nonuniformity of ~ 6 nm, and the compressive strain of the HR coating of ~12 nm. Annealing will be done for the Core Optics.

Table 9: Effect of Coating on ROC

Optic	Change in ROC after coating (%)	
	Pre Anneal	Post Anneal
A005	-	- 2.5
A006	2.5	(waiting for data)
A008	2.3	(waiting for data)

3.6. Coating Loss Data

Coating losses contribute < 0.5 ppm absorption on 1” mirrors. This data was obtained through the cavity mode frequency spacing technique and was found to be repeatable over 4 sets of mirrors.

Scatter losses for 1” mirrors have been measured to be < 5 ppm, consistent with loss from substrate surface microroughness. Thus we have no evidence for an effect of the coating on microroughness.

3.7. Coating Specifications

3.7.1. Reflectivities

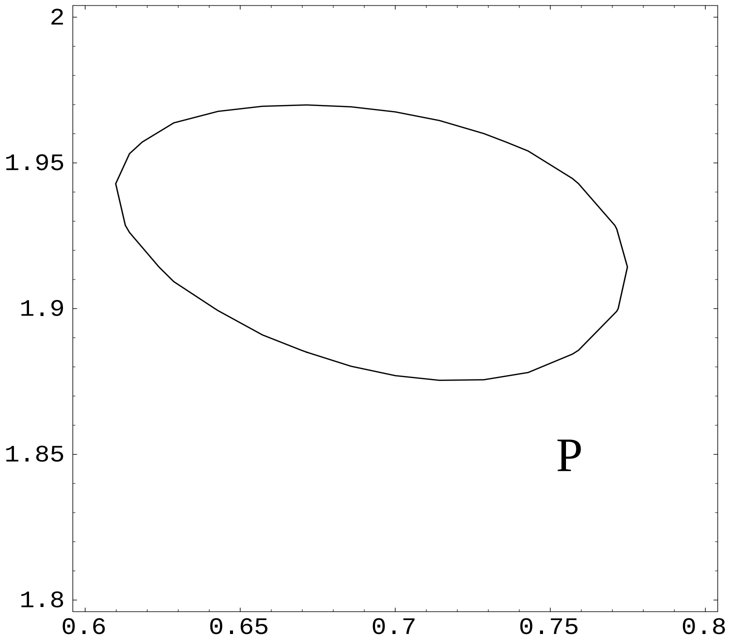
The following coating specifications are consistent with SYS requirements listed above and have been agreed to by the coating vendor, Research Electro Optics (REO).

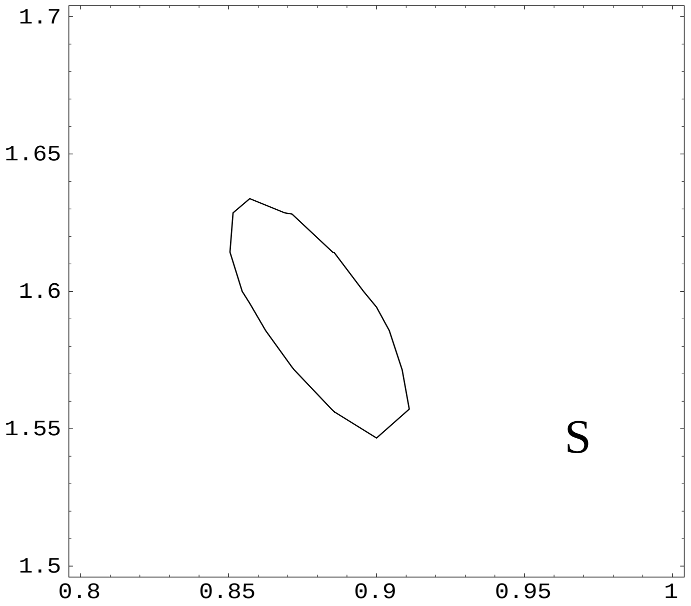
Table 10: Specified COC Reflectivities

Optic	HR coating	AR Coating
Folding Mirror	< 500 ppm	< 300 ppm
Input Test Mass	3 +/- 0.3 %	600 +/- 100 ppm
End Test Mass	< 20 ppm	< 300 ppm
Beam Splitter	50 +/- 1 %	< 100 ppm
Recycling Mirror	3 +/- 0.3 %	< 100 ppm

3.7.2. Polarization

The following simulations show the tolerance of high performance AR coatings to thickness variations. The plots are 300 ppm AR contours, with axes in units of λ / 4 thickness of Ta_2O_5 (y) and SiO_2 (x).The desire to produce the best possible AR coating for the beamsplitter led to the choice of P polarization in the interferometer.





4 CORE OPTICS QA PROGRAM

The Core Optics QA program addresses the need to assure the performance of the Optics, from receipt from the vendor to installation in the interferometer, and through its illumination for long periods of time under vacuum. This section covers the following topics:

- IR interferometer
- Core Optics Loss Scanner
- Contamination studies
- Cleaning and shipping procedures

4.1. IR interferometer

The Wyko IR interferometer is a Fizeau design which uses a set of highly polished reference flats in an interferometric comparison to the Core Optics. It will produce phase maps of the final coated optics so that the combined surface polish and coated figure can be examined. The IR interferometer has the following specifications:

- 150 mm aperture
- P-V surface accuracy for focus and astigmatism ~ 10 nm
- ROC accuracy for Core Optics < 3%
- rms accuracy for residual surface variations < 1 nm

Delivery of the IR interferometer is expected in late June 98.

4.2. Core Optics Loss Scanner

The Core Optics Loss scanner is an apparatus which forms an in-air resonant cavity with a Core Optic and a separate 1” diameter mirror. It will be used to map out substrate and surface losses of the final Optics by mounting them on a translation stage which scans the cavity optical axis across the Optics surface. The scanner beam parameters are:

- Input power: 100 mw
- Spot size: 1 mm
- Loss in air of 1.06 μm beam: 20 ppm / meter

The scanner will provide the following functions.

- Transmission map of optics surface
- Ringdown measurements of total surface loss
- Cavity mode frequency spacing measurements of surface and substrate absorption loss
- Scatterometer to examine surface inclusions

The following table lists the estimated accuracy of the loss measurements of the Optic scan. The values differ amongst the various Optics because of the different fringe width and stored power.

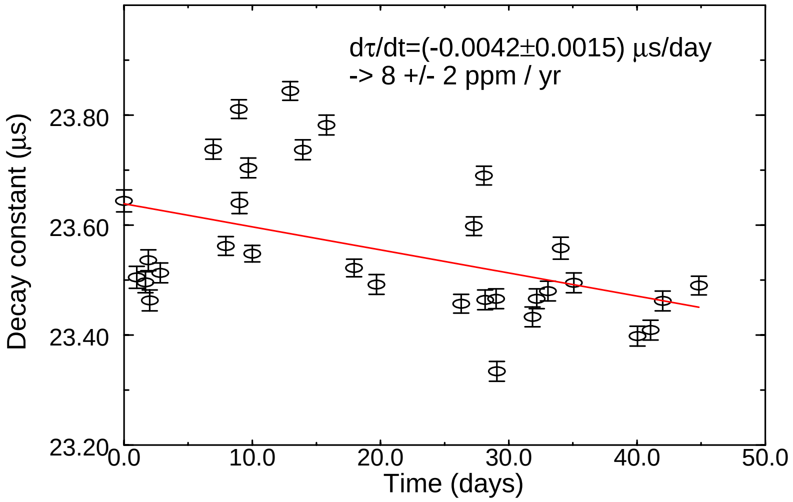
Table 11: Core Optics Loss Scanner Estimated Accuracy

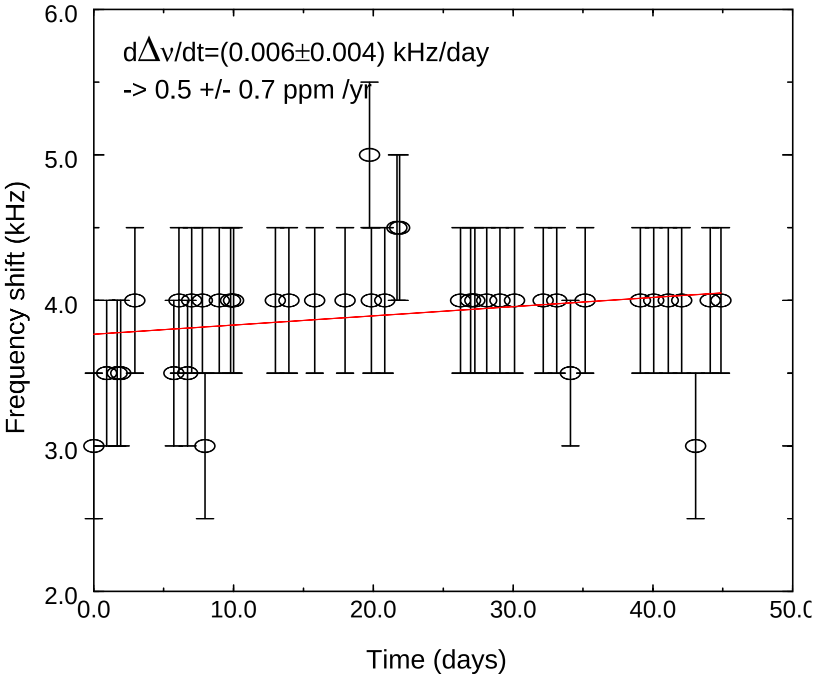
Optic	Transmission	Accuracy of Loss Measurement (ppm)		
		Surface Total Loss Variation	Surface Absorption	Substrate Absorption (cm^{-1})
ETM	20 ppm	10	1	0.1
ITM	3 %	-	< 5	1
RM	3 %	-	< 5	1
BS	50 %	-	-	?

The loss scanner will be used to qualify the Core Optics coatings, substrates, and cleaning procedures.

4.3. Contamination Studies

To ensure the performance of the Core Optics under irradiation in vacuum while being exposed to material outgassing, a program of contamination tests has been undertaken in the OTF. This involves running high finesse cavities with suspect materials, and taking ringdowns and cavity mode frequency shifts. The following plots show the results of a 2 month run with 5 suspension LED's and photodiodes.





The extrapolated losses were deemed small enough to qualify the LEDs and PDs as acceptable for use in LIGO. The data were obtained in a vacuum chamber with pump speed ~ 10 liter / sec.

The following materials are now under test:

- kapton
- teflon wire

The following materials will be tested, in rough order of priority:

- viton
- air baked steel
- conductive teflon
- vacseal epoxy
- sintered magnet
- optical components: Faraday Isolator, etc.
- solder
- other materials

4.4. Cleaning Procedures

A number of options are under consideration for cleaning the Core Optics, with and without magnet assemblies. They include the identification of possible surface contaminants:

- adsorbed materials from the environment
- particulate contaminants
- adsorbed materials from process steps

The following cleaning approaches are under consideration:

- DI water rinse, warm detergent wipe, DI water rinse, alcohol flush
- warm detergent immersion
- spin cleaning

Key items in these procedures will be the development of

- handling fixtures to protect attachments
- sound rinsing and drying process

These procedures are expected to begin test and development in a clean enclosure in the OTF in late May.