LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Core Optics Components
Preliminary Design

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LIGO Science Collaboration

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1 Overview

This document is to accompany the Core Optics Components (COC) Design Requirements document and COC development plan. This document specifies a design, fabrication and testing strategy to produce COC whose performance satisfies the COC DRD requirements. The conventions, acronyms, and assumptions used in the DRD document are also used here.

1.1 LIGO references

Advanced LIGO Systems Design LIGO-T010075

Optical Layout for Advanced LIGO LIGO-T010076

COC Design Requirements Document LIGO-T080026

COC Development Plan LIGO-T000128

Action Items from the COC Design Requirements Review L040025-00

Report of the Core Optics Components Design Requirements Review Committee T040009-00

1.1.1 Non-LIGO references

2 Preliminary Design Description

Table 1 summarizes the reference design for the Advanced LIGO cores optics components. The design will be discussed in general under the following headings:

- Substrate materials
- Substrate processing (including polishing and figuring).
- Coatings
- Mounting, interface and stay clear considerations.
- Spares.

Section 3 Supporting Design

- Metrology
- Storage, cleaning and contamination.

2.1 Substrate material

Fused silica is the baseline material for COC[1], with the exception of four recycling cavity optics, which are Borosilicate crown glass.

The different physical type substrates are specified in table 1. Fine ground blanks of high grade material are to be procured from suppliers according to the following considerations:

2.1.1 Material types

2.1.1.1 Low Absorption Fused silica (Input Test Mass, Beamsplitter and Compensation plates)

Low absorption fused silica is used for the Input Test Mass, Beamsplitter and Compensation plates. Recent advances in manufacturing have brought the very low OH Heraeus 3001 material into the realm of affordability. The level of OH content in the 3001 material should lead to absorption of less than 0.02ppm/cm. The slope of the Absorption/OH content line is roughly 62.5.

This material is specified with zero inclusions. Inclusions are defined to total ≤ 0.03 mm^2 /100cm^3 of Glass within the clear aperture. Inclusions with a diameter of 0.06 mm or less are disregarded. The maximum inclusion diameter is < 0.1 mm.

2.1.1.2 High quality fused silica (Recycling Mirrors)

The Transmissive Recycling Mirrors (power and signal) are 0AA Corning, 7980 fused silica or equivalent. The absorption properties are less important for these pieces. High bulk homogeneity material with no special absorption specification is adequate. This material is specified with zero inclusions. Inclusions are defined to total ≤ 0.03 mm^2 /100cm^3 of Glass within the clear aperture. Inclusions with a diameter of 0.06 mm or less are disregarded. The maximum inclusion diameter is < 0.1 mm.

Cost may be the most significant driver for this material.

2.1.1.3 Optical quality fused silica (End and Fold mirrors)

The End test mass and Fold mirror bulk are not part of any resonant cavity. The beam transmitted through the end test mass may be used on a quadrant detector, or by a Hartman sensor. The Hartman sensor would monitor only changes in the phase. The ETM therefore has no specific requirement for maintaining the fidelity of the arm cavity phase on transmission. Since cost is the main driver, a nominal optical grade material is planned for both the ETM and FM: Corning 5F or equivalent. Reference http://docuserv.ligo.caltech.edu/docs/internal/C/C070214-00.pdf for a discussion of ETM material choice. These materials are specified with no inclusions within 5mm of any flat surface.

2.1.1.4 Optical quality Borosilicate crown glass

The non-transmissive recycling cavity optics, PRM2, PRM3, SRM2 and SRM3 are chosen as BK7 or equivalent. This allows for efficient ring heater actuation in each arm of the recycling cavity.

2.1.2 Blank sizes

Common practice is to procure the glass blanks oversize from the baseline by 4mm in diameter and 4mm in thickness. The baseline sizes and relevant RODAs are summarized in Table 1.

2.2 Substrate processing

In this category, we consider all other fabrication to the COC exclusive of the coatings and suspension attachments. Two stages may be distinguished: Shaping and Final Polishing

2.2.1 Shaping to final size and rough polishing

After appropriate inspections, tests and selection steps, the blanks will be shaped to final substrate form by grinding and rough polishing over 100% of surface area. This polishing stage will be final for all surfaces except the surface #1 and #2 faces. At this stage the substrates will have the appropriate diameter, thickness, wedge and polished barrel and bevel. The test masses willl be shaped similarly and brought to the form described in figure 1. All non-optical surfaces are polished completely out of the grey with no scuffs or scratches visible to the naked eye when viewed in normal room light against a black background.

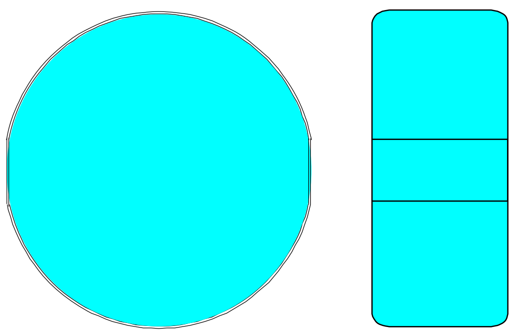

Figure 1 The basic shape of Test Masses

2.2.1.1 Shapes.

The basic shape of all COC elements is taken to be the right circular cylinder. The dimensions of the various optic types are summarized in Tables one and two. The exact right circular cylindrical shape will be modified in the following ways:

- Wedge, < 2° for all optics. The exact wedge angle will be determined by analysis of the entire IFO configuration and beams layout as described in LIGO-T010076. Preliminary results of this analysis indicate that each type of COC will likely require a different specific wedge angle. Transmissive optics (RM, BS, ITM) will be wedged symmetrically such that there are no 90 degree internal reflections. This minimizes the possibility of scatter back into the IFO resonant cavities. Wedges are specified by AOS, the magnitude and orientation in LIGO-T080007.
- Standard optic edge bevel, 45°, 2mm height on each leg to the virtual corner.

- All primary face surfaces except for CP, BS and FM will have spherical form, given by the values in Table 1
- Each optic will have a consecutive serial number by type, beginning with the optic designation. ITM01, ETM01, CP01, BS01, FM01, SRM101, SRM201, SRM301, PRM101, PRM201, PRM301

2.2.1.2 Suspensions interface

- All Test Masses will have flats polished on the OD perpendicular to gravity. These flats are used for attachment of the suspension prisms. The flat size, position and polish are specified by SUS to be 95mm long, the entire thickness of the optic, and $\lambda/10$ in the mounting area. There is not yet a formal definition of the mounting area.
- Each optic is marked with an arrow on the barrel, at the thinnest part of the optic, and pointing to the side that will have the HR coating. There are three additional reference lines marked at 90° intervals around the barrel for suspension reference. SUS has indicated, in supplying the drawing for the LASTI TM, that these marks should be located within 1°0' parallel and perpendicular to the wedge axis.
- Cylindricity, parallelism, and dimensional tolerances are specified by SUS. COC reserves a larger than optimal tolerance on thickness in case repolishing is required. COC will report final dimensions and/or mass to SUS after polishing.
- The compensation plate is fitted with grooves and collision stops as specified by SUS for similarity with the ETM reaction mass.
- Sizes

  Definition: the thickness of the optic is measured at the thickest point.

  http://www.ligo.caltech.edu/docs/M/M050397-02.pdf defines sizes for TMs, BS, RM

  http://www.ligo.caltech.edu/docs/M/M040006-00.pdf the FM and BS are the same size

  http://www.ligo.caltech.edu/~coyne/AL/project_management/RODA/M060305-01.pdf Compensation plate dimensions.

2.2.2 Final polishing

All COC faces will be polished to a figure whose deviation from the exact values of table 1 is determined by the requirements of the COC Design Requirements Document (DRD), as well as the final results of the Pathfinder process. In particular a final balance between specification of surface microroughness and figure errors awaits evaluation of actual process results.

2.3 Coatings.

All COC front surface optical coatings are to be of the hard oxide dielectric type. The coating process will be ion beam sputtering. This technique yields dense layers with optical absorption of less than 1 ppm.

The optical coatings will be of four types, Test Mass High Reflection (TMHR), High Reflection (HR), Anti Reflection (AR) and Beamsplitter (T/R 50/50)

All coatings are specified to have low scatter and low absorption, the current state of the art being 5ppm point defect scatter loss, and 0.5ppm absorption at 1064 nm. Coating uniformity is specified on optics where the incident beam will be greater than ~2cm. The state of the art uniformity only affects the radius of curvature of the optic.

2.3.1 Test Mass High Reflection (TMHR)

These coatings are still being developed. They are designed for low mechanical loss, in addition to all other stringent LIGO requirements. Development and optimization can continue until we are ready to coat the AdLIGO test masses. Pairs of ITM of equal radii of curvature should be identified for coating in the same coating run, or provisions made with the coating vendor to assure sufficient matching.

2.3.2 High Reflection (HR) coatings.

These coatings are standard Si/Ta ion beam coatings. They will provide front surface mirrors for the recycling cavities. The bottom layers of the coating are to be tuned in thickness such that there is zero electric field at the surface of the coating. There is an additional double layer of SiO2 for protection.

There may be a need to change the value of the reflectivity for both PRM1 and SRM1 after the initial characterization runs of the interferometer. Three spares of each type are to be left uncoated to allow for this.

2.3.2.1 Beamsplitter coatings

Beamsplitter coatings are designed to provide 50% reflection for an incoming angle of incidence of 45°. Due to the large aspect ratio of the Beamsplitters, they will increase in curvature after coating. There are two solutions; prepolish an offset into sides one and two, or put an equivalent stress coating on side2.

2.3.3 Anti Reflection (AR) coatings

These coatings will be on all secondary (wedged) surfaces, and on the primary surface of the compensation plate. They serve to limit the beam power diverted to ghost reflections, as well as to provide pick off beams for sensing and control systems. The minimum AR at 1064nm demonstrated to date is ~15ppm

2.3.4 Coating Interfaces

2.3.4.1 Alignment

In cases where pick off or alignment beams are needed, COC will be advised by ISC of the desired reflectivity. This should not compromise the operation of the COC in any way. The RODA M050175-01 notes that COC will supply coatings on all core optics for Advanced LIGO with a reflectivity of 5% or greater at 670 nm wavelength, from zero to 22 degrees incident angle. These are preferred to be on the front surface of all optics, but may be on the AR side if the wedge angle is also supplied. COC will supply graphs of reflectance over a range of 600 to 1100 nm for each optic surface. It is assumed that this requirement does not apply to the compensation plate.

2.3.4.2 Suspension coating

A Suspension coating is a low optical quality metallic coating. The thickness and pattern are determined by SUS. This coating is applied to the first surface of the compensation plate, nearest the ITM. Table 1 explicitly states which optics have this coating.

2.4 Mounting and Stay-clear

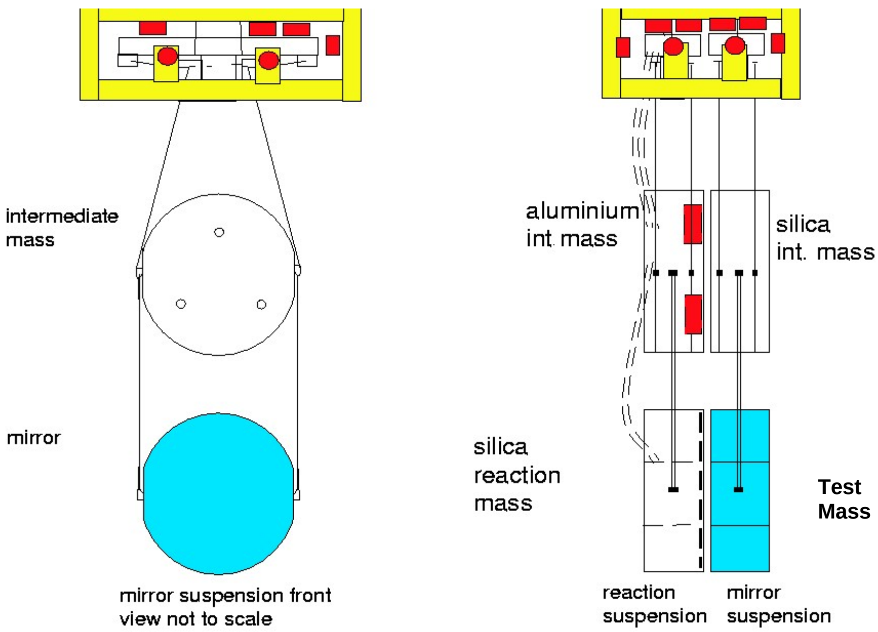

Figure 2 COC (blue) shown in suspension (graphic courtesy of GEO)

COC test masses will finally be used in the mounted configuration illustrated in figure 2. Strictly, most of the components shown, other than the coated COC substrate itself, are excluded from COC. However, a crucial account of this mounting must be taken in the following respects:

2.4.1 Effect of appendages on Q.

The expected degradation of substrate mechanical Q must be carefully monitored. The LASTI test mass will be used for verification.

2.4.2 Stay-clear

For all COC the suspension components must be designed to stay adequately clear of the beam envelopes so as not to occlude the 1ppm beam envelope in the Fabray Perot arms, or the limiting aperture in the recycling cavity.

2.4.2.1 Beamsplitter

This element requires critical stay clear on both faces, the situation is complicated by the 45^{o} incident beams. In the recycling cavity, beamsplitter defines the limiting aperture in the horizontal direction, 260mm.

2.5 Spares

The spares requirements are detailed in Table 1. This spares approach is based on an early enough manufacture to re-polish and re-coat in the event an optic does not meet final specification.

Test masses require 100% spares because the radii of curvature must be matched more closely in the interferometer than even exceptional manufacturing tolerances will allow.

Recycling mirror spares are based on one spare for the initial installation, plus one replacement for each interferometer should the final configuration require a different recycling mirror transmission.

Beamsplitters have two spares due to the complexity of the coating.

Table 1: Summary of COC specifications

	PRM1	PRM2	PRM3	SRM1	SRM2	SRM3	BS	FM	CP	ITM	ETM
Optic size (mm) M050397-02	150 x 75	150 x 75	265 x 100	150 x 75	150 x 75	265 x 100	370 x 60 M070120-02	370 x 60 M040006	340 x 130 M040005 M060305-01	340 x 200	340 x 200
Number in IFOs 41	3	3	3	3	3	3	3	2	6	6	6
Total Spares 31	4	2	2	4	2	2	3	1	3	4	4
Total optics 72	7	5	5	7	5	5	6	3	9	10	10
Equivalent Material*	0C	BK7	BK7	0C	BK7	BK7	3001	5F	3001	3001	5F
Mounting Flats Roda M060315	No	No	No	No	No	No	No	No	No	Yes	Yes
SUS coating	No	No	No	No	No	No	No	No	Yes	No	No
TCS coating	No	No	No	No	No	No	No	No	TBD	TBD	TBD
Clear Aperture mm **	30	30	275	30	30	275	315	315	275	275	275
Radius of curvature m	8.95	-2.335	35.048	107.29	-2.155	35.048	Flat	Flat	Flat	1973+TCS	2195+TCS
Roc tolerance	1%	1%	0.10	1%	1%	0.10	1nm?	1nm?	2nm?	± 10 matching +36,-22 absolute	± 10 matching +36,-22 absolute
Surface error - TPA (nm rms) over clear aperture	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 3	< 0.7	< 0.7
Microroughness in clear aperture (nm rms)	< 0.4	< 0.4	< 0.4	< 0.4	< 0.4	< 0.4	< 0.4	< 0.4	< 0.4	~ 0.16	~ 0.16

	PRM1	PRM2	PRM3	SRM1	SRM2	SRM3	BS	FM	CP	ITM	ETM
Bulk Absorption (ppm/cm)	< 20	NA	NA	< 20	NA	NA	< 1	NA	< 1	< 1	NA
Homogeneity P-V in central 110mm		NA	NA		NA	NA	$<5\text{x}10^{-7}$	NA	$<5\text{x}10^{-7}$	$<5\text{x}10^{-7}$	NA
Homogeneity P-V in clear aperture	$<2.5\text{x}10^{-6}$	NA	NA	$<2.5\text{x}10^{-6}$	NA	NA	$<2.5\text{x}10^{-6}$	NA	$<2.5\text{x}10^{-6}$	$<2.5\text{x}10^{-6}$	NA
Coating Absorption (ppm)	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Coating Uniformity (%)	NA	NA	0.1	NA	NA	0.1	0.1	0.1	0.1	0.1	0.1
Side 1 (HR) Transmission	~6±0.5%			5.0 ±0.5%			50 ±.05 %	< 20 ppm	AR <20ppm	0.01±0.002 %	5 ± 1 ppm
AR Coating Reflection (ppm)	<100			<100			200	< 300	< 20	< 20	<300
Scatter (ppm)	<15			<15			<15	<15	<15	<15	<15

*Terminology does not imply vendor selection is final. These materials, or equivalent, are specified.

** Clear aperture is specified for purposes of inspection and is distantly related to useful optical area. It is roughly 2x the beam diameter at the optic location.

3 Supporting Design

3.1 Verification metrology

Technical development through the Pathfinder mechanism should allow all production COC to be specified and measured to a level satisfying the optical performance requirements of the DRD.

3.1.1 Automated mirror parameter measurement

COC are characterized by automated scan measurements. This includes coating absorption mapping, reflectivity, transmission and surface scatter. This program has been developed for 1064 nm.

3.1.2 1064 nm phase front interferometry.

Full aperture surface maps will be generated for each COC. The full aperture maps will include surface frequencies up to ~1 mm^{-1}. Statistical data at higher frequency will be acquired in the center zone of each optic. The higher spatial frequency data ranges will overlap in order to provide suitable context for each measurement. The low and high spatial frequency characteristics of optical surfaces will be measured using a LIGO approved process at the polishing vendor. The purpose of the vendor measurements is to qualify the optic for delivery. The purpose of the LIGO measurements is to provide accurate knowledge of the surfaces, within the limits of existing technology.

3.1.3 Homogeneity

Homogeneity, where required, will be measured and certified by the vendor. Transmission measurements will be required at the vendor for polishing of ITM, BS and CP.

3.1.4 Birefringence

Birefringence, where required, will be measured and certified by the vendor.

3.1.5 Bulk Absorption/OH content

The ITM, BS and CP absorption and correlation with OH content will be verified on a statistical sample of the 35 low absorption elements. OH content certification provided by the vendors will then be sufficient to qualify these pieces.

3.1.6 Inclusions

Incoming blank material will be inspected visually for bulk inclusions.

3.1.7 Dimensions

Mechanical dimensions will be certified by the responsible vendor. There is no plan to verify these within LIGO.

3.2 Coating Characterization

Many coating characteristics are verified in the development phase. During production, process control is used to ensure replication of the desired qualities. These process certified specifications include:

- Mechanical loss
- Thermal expansion
- Birefringence
- Thickness Uniformity

Properties requiring 100% inspection in the production phase are:

- Reflectivity/Transmission
- Absorption
- Scatter

3.3 Storage and handling

3.3.1 Storage

Optics are stored in protective containers. These containers protect the optical surfaces during conditions of storage and standard commercial shipping. They are also designed to interface with lifting and handling fixtures.

The containers prevent the optics from coming into physical or vapor contact with any non-vacuum qualified material. The containers support the optic without contacting any surface within the outer 1cm of the optical surfaces and the entire outer diameter.

E070070-00-D LASTI Test Mass Handling and Shipping Procedures

3.3.2 Handling

A prototype mirror handling device has been designed and fabricated for lifting, moving, cleaning and testing of the core optics. The purpose of this mechanical arm is to ensure the safety of the operator as well as the optic. There will be one full size "Ergo arm" at each observatory, one full size unit at MIT for the duration of LASTI, and one small unit at CIT for use in the tight confines of the optical test labs.

There are high friction bands that may be used on the optics before they are sent to coating (final high quality cleaning). Use of these bands require a 2 man lift.

3.4 Cleaning and contamination

3.4.1 Cleaning

The addition of ionizing bars close to the optics during cleaning and assembly procedures will prevent electrostatic charges on the mirror surfaces that attract particle contamination.

3.4.2 Contamination

Optics should not be in contact with silicon based materials. There is evidence that contact with tape adhesives has caused trouble with bonds in LIGO1. Silicon migrates easily and so should not be used around the optics.

Optics should be kept under clean flow benches at all times and not be left uncovered for any length of time after final cleaning. Hydrocarbons and dust particles in the air will cling to the surface and contaminate the optic.

3.4.3 In Situ Cleaning

In the event that "in situ" cleaning is required on optics suspended by wire, the surfaces could be cleaned by drag wipe. First contactis also an option. An initial assessment of this cleaning method has been done by inspecting mirrors cleaned with First Contact on the up-graded scattering measuring system. This cleaning method was used during the coating characterization of the LASTI test mass.

T070233-00 – LASTI Test Mass Coating Characterization

E070304-00 - Updated LIGO Optics Cleaning Specifications Used in iLIGO and eLIGO

E070292-00 - Optics Cleaning Specifications – First Contact

4 Documentation

4.1.1 Specifications

Material:

Each optic type will have a specification and drawing

Polish:

Each optic type will have a specification and drawing

Coating:

Each optic type will have a specification and reference the Polish drawing.

4.1.2 Design Documents

Conceptual Design

T000127-01 COC Design Requirements Document

T000128-02 COC Development Plan

T020103-08 TM Material Downselect Document

M040405-00 Advanced LIGO Substrate Selection Recommendation

C030187-01 Coating Development Plan

T000098-02 Conceptual Design Document

T030233 Coating Test Plan

T040070 Research Plan on Noise Effects of Electric Charge on Advanced LIGO

E000487 Advanced LIGO Coating Development and Preliminary Production Specifications

Preliminary Design

T080026 Core Optics Components Design Requirements Document

E080033 Core Optics Components Preliminary design

E060268-A Advanced LIGO Pathfinder Polish - anticipated for AdLIGO ITM

E070002 LASTI ETM Coating Specifications

E050190 Final Polish, LASTI End Test Mass

D040431 Silica Test Mass – LASTI, mechanical prototype for all AdLIGO TMs, except for wedge.

T070174-01 LASTI Test Mass characterization and test plan

E060274 Fused Silica Substrate, LASTI Compensation Plate

D060534 Thermal Compensation plate

D080097-00-D - Adv. LIGO - Test Mass Carrier

4.1.3 Engineering Drawings and Associated Lists

Material Specifications and Drawings for Final Design

Optic	Specification	Drawing	DCN
ITM	E080031-A.pdf	D080039-A.pdf	E080032-A.pdf
BS	E080035-A.pdf	D080050-A.pdf	E080036-A.pdf
CP	E080037-A.pdf	D080051-A.pdf	E080038-A.pdf
RM1	E080028-A.pdf	D080038-A.pdf	E080029-A.pdf
RM2	E080039-A.pdf	D080052-A.pdf	E080040-A.pdf
RM3	E080041-A.pdf	D080053-A.pdf	E080042-A.pdf
FM	E080045-A.pdf	D080054-A.pdf	E080046-A.pdf
ETM	E080047-A.pdf	D080055-A.pdf	E080048-A.pdf

4.1.4 Technical Manuals and Procedures

4.1.4.1 Procedures

E070292-00 - Optics Cleaning Specifications - First Contact

E070070-00 - LASTI Test Mass Handling and Shipping Procedure

E070293-00 - Pathfinder Substrates- Handling and Shipping Procedures

E070304-00 - Updated LIGO Optics Cleaning Specifications Used in iLIGO and eLIGO

4.1.4.2 Data

Vendor reports, in house measurements and history of each optic will be recorded and filed in the DCC. A traveler with specific history will accompany each optic.

4.2 Logistics

1.) Raw material is purchased by LIGO, inspected at LIGO then shipped to shaping.

2.) After shaping the blank comes back to LIGO for inspection, then is shipped to polishing.

3.) After polishing the blank comes back to LIGO for inspection, then is shipped to coating.

4.) After coating the mirror is shipped back to LIGO for final characterization.

5.) The optic is then shipped to the observatory.

TM pairs are determined at step three. The TMs are then coated together and will ultimately be installed together. Appropriate spares will be identified for each TM Pair at step three, these will be coated as similarly as possible, final determination of proper spares will be determined after step four. Spares are covered explicitly in section 2.5.

4.3 Precedence

The following lists the principle COC requirements in descending order of importance

- Primary optical surface quality requirement (both substrate polish and coatings)
- Cleanliness requirements
- Substrate material homogeneity for primary beam transmitting elements
- Mechanical Q requirements
- Physical dimension tolerance requirements.

4.4 Qualification

Acceptance of the COC elements from the optical fabricator and the thin film coating provider will be subject to a full array of tests which will assure that the requirements of section 4.2.1 above have been met. These tests will be partially accomplished by approved tests conducted by the vendors and subsequently completed and supplemented by LIGO “in house” tests.

Each vendor will submit data or certifications as required by the item specification.

LIGO data will complete the qualification.

Vendor and LIGO data are compiled in one report for each optic.

5 Quality Assurance Provisions

5.1 General

5.1.1 Responsibility for Tests, frequency and method

See Appendix A.

5.1.2 Special Tests

- Bulk absorption at 1064 nm
- Absorption test of HR coated surfaces at 1064 nm.
- Scattering test of AR and HR coated surfaces to determine net normal incident 1.06 micron scattered light.
- Q measurement of characteristic internal substrate resonance modes. This test is not performed on fabrication optics.
- Interferometric mapping of the optical surfaces.
- Dark field inspection to determine the state of optical surface contamination.

6 Preparation for Delivery

Packaging and marking of equipment for delivery shall be in accordance with the Packaging and Marking procedures specified herein.

6.1 Preparation

All optics are cleaned at LIGO and coated with first contact before delivery to the observatories.

6.2 Packaging

The containers prevent the optics from coming into physical or vapor contact with any non-vacuum qualified material. The containers support the optic without contacting any surface within the outer 1cm of the optical surfaces and the entire outer diameter.

E070070-00-D LASTI Test Mass Handling and Shipping Procedures

6.3 Marking

All optics are marked with the optic type and serial number as follows:

ITMxx

ETMxx

CPxx

FMxx

BSxx

PRM1xx

PRM2xx

PRM3xx

SRM1xx

SRM2xx

SRM3xx

Where xx represents a two digit number starting at 01 for each optic type.

Optics are also marked with an arrow at the thinnest point and indicating the HR side of the optic. There are also four fiducials as used and specified by SUS, see for example D040431-C. All markings are etched or ground, and of minimum useful size.

7 Notes

Low absorption fused silica is used for the Input Test Mass, Beamsplitter and Compensation plates. The bulk material present inside the recycling cavity must have low inhomogeneity and scatter. Absorption must also be low. Recent advances in manufacturing have brought the very low OH Heraeus 3001 material into the realm of affordability. Homogeneity has been a question for the very low OH material. This question was put to rest in the development phase by purchasing one TM of Heraeus 3001, and asking Heraeus to characterize the homogeneity. The results from Heraeus for the 3001 material homogeneity can be found at LIGO-C070187-00. This is comparable to the 311 material (Higher OH) that was provided by the University of Glasgow. The various material certifications can be found at:

Vendor sn	Certification	OH content ppm	Homogeneity in 80mm clear aperture
7008870001	http://www.ligo.caltech.edu/docs/E/E060006-00.pdf	197	0.03
700888000	http://www.ligo.caltech.edu/docs/E/E060007-00.pdf	205	0.03 ppm
700889000	http://www.ligo.caltech.edu/docs/E/E060009-00.pdf	180	0.06 ppm
7009120001	http://www.ligo.caltech.edu/docs/E/E060005-00.pdf	218	0.07 ppm
70127600 "new" 3001 material	http://docuserv.ligo.caltech.edu/docs/internal/C/C070187-00	< 1	0.04 ppm

The level of OH content in the 3001 material should lead to absorption of less than 0.02ppm/cm. The slope of the Absorption/OH content line is roughly 62.5.

Material Summary	ITM	BS	CP	RM1	RM2	RM3	FM	ETM
Spec number								
Drawing number								
Blank Size (4mm over in each dim)	344 x 204	374 x 64	344 x 134	154 x 79	154 x 71.5	269 x 94	374 x 64	344 x 204
Clear Aperture	275	315	275	30	30	275	315	275
Material	Fused Silica				BK7		Fused Silica	
Final Shaping	…progression of grit size ending with a 320 or smaller grit tool							
Defect Depth	≤ 0.5 mm							
Index homogeneity in central 110	≤ 5 x 10^{-7} P-V	≤ 5 x 10^{-7} P-V	≤ 5 x 10^{-7} P-V	na	na	na	na	na
index homogeneity in clear Aperture	≤ 2.5 x 10^{-6} P-V	≤ 2.5 x 10^{-6} P-V	≤ 2.5 x 10^{-6} P-V	≤ 2 x 10^{-6} P-V	na	na	na	na
Birefringence	≤1 nm/cm within the clear aperture, ≤ 5 nm/cm outside the clear aperture				≤ 10 nm/cm		≤ 5 nm/cm	
Bubble and inclusion cross section	Total ≤ 0.03 mm^2 /100cm^3				No bubbles or inclusions within 5mm of a flat surface			
Maximum inclusion diameter	≤ 0.1 mm				na	na	na	na
Striae	Class 1, Grade A				na	na	na	na
OH content	≤ 1 ppm	≤ 1 ppm	≤ 1 ppm	≤ 1000 ppm	na	na	na	na
For my own reference….								
Reflective or transmissive	T	T	T	T	R	R	R	R
Beam waist at optic mm	55.5	55.5	55.5	1.85	3.4	56.5	55.5	62
2x beam diameter mm	222	313.908	222	7.4	13.6	226	313.908	248
		45 ° optic					45 ° optic	
Material nickname	3001	3001	3001	0C	BK7	BK7	5F	5F

Appendix A Quality Conformance Inspections

Table 2 Quality Conformance Inspections

	Vendor	LIGO
Optic size (mm)	Measurement 100%	Inspection 100%
Material	Certification	Certification
Mounting Flats	Measurement 100%	Inspection 100%
SUS coating		
Radius of curvature m	Fizeau Measurement 100%	Fizeau Measurement 100%
Surface error - TPA (nm rms) over clear aperture	Fizeau Measurement 100%	Fizeau Measurement 100%
Microroughness in clear aperture (nm rms)	Measurement 100%	
OH content Bulk Absorption (ppm/cm)	OH measurement 100%	Absorption Measurement 30% Certification inspection 70%
Homogeneity	Fizeau Measurement 100%	Fizeau Measurement 100%
Coating Absorption (ppm)	Certification 100%	Absorption Measurement 100%
Coating Uniformity (%)	Certification 100%	Measurement 30%
Side 1 (HR) Transmission	Measurement 100%	Measurement 100%
AR Coating Reflection (ppm)	Measurement 100%	Measurement 100%
Scatter (ppm)	Defect inspection 100 %	Measurement 100%

8 Preliminary Design Review Checklist-M050220-02

System Design Requirements, especially any changes or refinements from DRR	T080026
Subsystem and hardware requirements, and design approach	T080026
Justification that the design can satisfy the functional and performance requirements	T080026
▪Subsystem block and functional diagrams	**NA**
▪Equipment layouts	**NA**
▪Document tree and preliminary drawings (information issued)	**4.1.3**
▪Modeling, test, and simulation data	T080026
▪Thermal and/or mechanical stress aspects	T080026
▪Vacuum aspects	T080026
▪Material considerations and selection	**M040405**
▪Environmental controls and thermal design aspects	**NA**
▪Software and computational design aspects	**NA**
▪Power distribution and grounding	**NA**
▪Electromagnetic compatibility considerations	**NA**
▪Fault Detection, Isolation, & Recovery strategy	**NA**
Resolution to action items from DRR	Closed via e-mail August 2004
Interface control documents	2.2.1.2, 2.3.4
Instrumentation, control, diagnostics design approach	NA
Fabrication and manufacturing considerations	2.2.2
Preliminary reliability/availability issues	Spares 2.5
Installation and integration plan	NA
Environment, safety, and health issues	NA
▪Mitigation of personnel and equipment safety hazards Reflected in equipment design and procedures for use	**3.3.2**
Human resource needs, cost and schedule	http://www.ligo.caltech.edu/~advligo/coc_table.html

Any long-lead procurements	M070011-02, Adv LIGO Proj. Procurement Plan
Technical, cost & schedule risks and planned mitigation	Advanced LIGO Risk Register
Test plan overview	Section 3
Planned tests or identification of data to be analyzed to verify performance	Section 3
▪In prototyping phase	**Section 3**
▪In production/installation/integration phase	**Appendix A**
Identification of testing resources	
▪The test equipment required for each test adequately identified	**Section 3**
▪Organizations/individuals to perform each test identified	http://www.ligo.caltech.edu/~advligo/coc_table.html
▪QA involvement	
Test and evaluation schedule, prototype and production	
Lessons learned documented, circulated	
Problems and concerns	

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1 **Advanced LIGO Substrate Selection Recommendation, 31 December 2004**

LIGO M040405-00-R http://www.ligo.caltech.edu/docs/M/M040405-00