LIGO Laboratory / LIGO Scientific Collaboration

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Core Optics Components
Final Design

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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-v3.

Optical Layout for Advanced LIGO LIGO-T010076

COC Design Requirements Documents LIGO-T080026 and LIGO-T000127-v5

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

Review Committee's Report on the Preliminary Design Review (PDR) and Glass Procurement Readiness Review for the Advanced LIGO Core Optics Components (COC), L080031-02.

Action Items from the COC Preliminary Design Review 3-28-08, L080067-00,

*Design of the Advanced LIGO recycling cavitie*s, LIGO-P080004, Opt. Exp. **16**, 10018

Design of the Advanced LIGO ALS system, LIGO-T0900144-v4

Hartmann sensor requirements for core optics coatings for CSIRO, LIGO-E0900489-v4a

Hartmann sensor probe beam: coating specification for SR2, LIGO-T1000055-v1.

Decision to reduce ITM beam size to 5.30 cm, LIGO-M0900025-v1

Diffraction and Matching losses in the Recycling Cavities, LIGO-G0800129-v4.

Scattering Light Loss from LIGO Arm Cavity Mirrors, LIGO-T0900128-v3

Analysis of scattering loss in AdvLIGO arm, LIGO-T0900159-v1

Modal Diffraction Loss, LIGO-T080392-v1

Astigmatism by the stable Michelson cavity, LIGO-T0900384-v1

Effects of small size anomalies in a FP cavity, LIGO-T1000154-v5

Mode matching and diffraction loss of FP cavity with thermal deformations, LIGO-T0900306-v6

Abbreviated Pre-Coating test plan for first two ITMs and ETMs for Advanced LIGO,LIGO-T1000137-v1

AdLIGO COC Materials Design, LIGO-T1000382-v1.

AdLIGO COC Polish Specifications, LIGO-T1000383-v1,

AdLIGO COC Coatings Design, LIGO-T1000381-v1.

Advanced LIGO interferometer for Full Aperture Surface Figure Metrology, LIGO-E080503-v2

Final Design Document ETM/ITM Ears, LIGO-T0900447-v3

Protecting installed COC from Particulates, LIGO-T080067-v1

Thinner Compensation Plates for Reduced Squeeze Film Damping, LIGO-T1000175-v2.

First Contact™ Application and Removal Procedure, LIGO-E1000079-v2.

ALIGO Optic Container Shipping Procedure, LIGO-E0900394-v5.

Measurement of a low-absorption sample of OH reduced fused silica, Appl. Opt. **45**, 7269

Retro-reflection from the ITM and ETM Flats and Barrel in the Arm Cavities, T080120-02

IO Final Design Document, T0900386-v4

Abbreviated Pre-coating test plan for first two aLIGO ITMs and ETMs, T1000387-v1.

Advanced LIGO ERGO Arm Hazard Analysis, T080231-v6

Suprasil 3001 bulk absorption check at LMA, C1000257-v1.

First Contact™ Hazard Analysis, T1000425

aLIGO Coatings Specification Spreadsheet, E0900059-v7

aLIGO TM Coatings Specification Tracker, E1000018-v2

1.2 Terminology

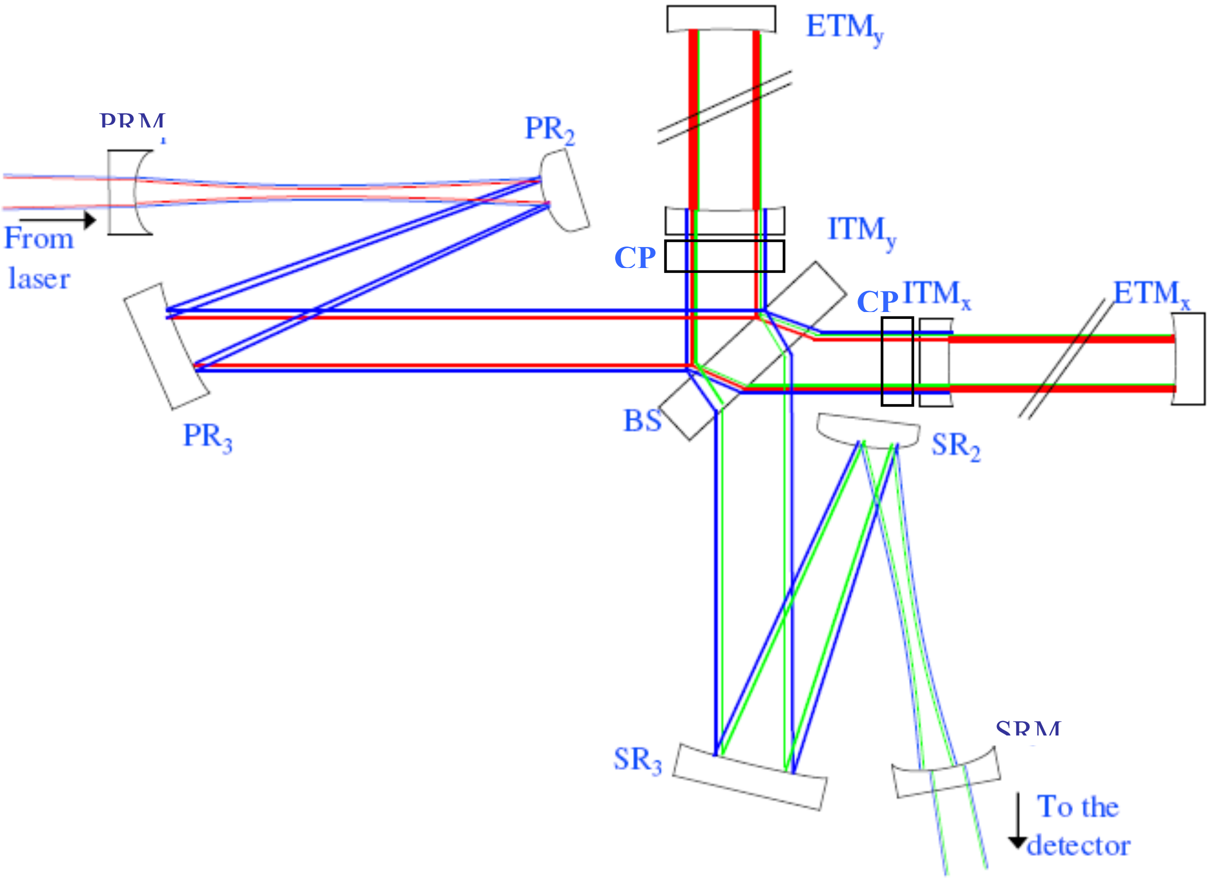

Figure 1. Elements of the COC subsystem covered in this document

For the purpose of this overview design document all 13 (or 15 for the folded, H2 interferometer) optical elements of each aLIGO interferometer (illustrated in Fig. 1 and identical to those described in the COC requirements document T0100127-v5) are included as a uniform COC subsystem design. Some of these COC elements (PRM, SRM, PR2, SR2, and their folded interferometer version) have design and procurement aspects designated as IO subsystem (see IO design document, T090386-v4) responsibilities. The division of responsibilities entailed has been detailed in the RODA memorandum M080038-v3.

2 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

Details of the individual COC element specifications are found in table 1 as follows:

Table 1 Compendium of aLIGO core optics detailed design

Type	material spec	material drawing	polish spec	polish drawing	coating spec	Gold Spec	Gold Drawing
ITM	E080031	D080039	E080511	D080657	E0900041		
ETM	E080047	D080055	E080512	D080658	E0900068		
CP *	E080037	D080051	E080513	D1000979	E0900074	E0900112 E0900113	D0900931
BS	E080035	D080050	E080514	D080660	E0900073		
PR3	E080041	D080053	E080516	D080662	E0900071		
SR3	E080041	D080053	E080518	D080664	E0900069		
PR2	E080039	D080052	E0900091	D0901176	E0900247		
SR2	E080039	D080052	E0900093	D0901179	E0900248		
PRM	E080028	D080038	E0900087	D0901172	E0900245		
SRM	E080028	D080038	E0900089	D0901174	E0900246		

*** The thickness of the CP optic was redesigned for gas damping mitigation (see T1000175-v2).**

2.1 Substrate material

Fused silica is the baseline material for COC[1], 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

Material specification for all the COC are detailed in the following spreadsheet:

materialsummary.xls (T1000382-v1)

Unless otherwise stated table material specifications pertain to the full optic substrate diameter. For more detail on the recycling cavity elements of the COC see T0900043-v10.

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[2] 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.

Homogeneity of ingot 70127600

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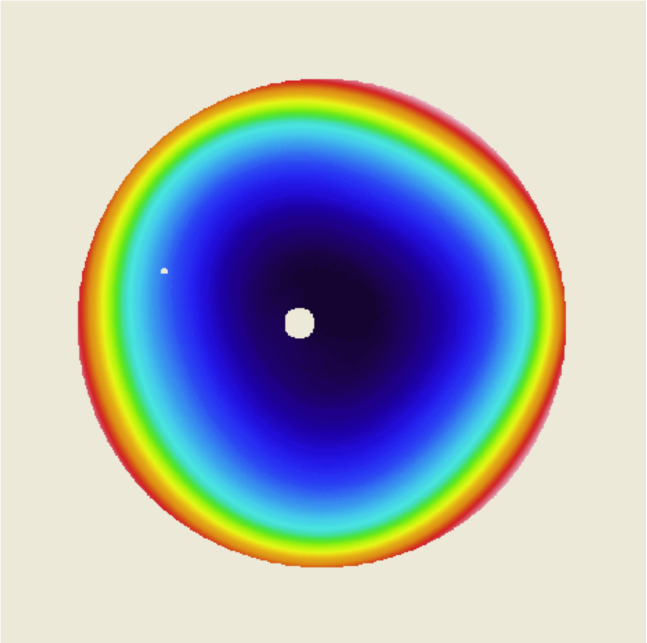
[1] **Advanced LIGO Substrate Selection Recommendation, 31 December 2004**

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

[2] LIGO-T070258-00



Aperture	LIGO Requirement	Measured value	P-V Optical path difference
80 mm	0,5 ppm	0,04 ppm	8 nm
200 mm	2,5 ppm	0,45 ppm	90 nm
275 mm	none	1,56 ppm	156 nm

The polishing specification of the ITM requires that the polisher compensate side two of the piece so that the surface curvature negates the material inhomogeneity. While we do not have a precise measurement over 120 mm diameter with power subtracted, we can see that the inhomogeneity of this material is largely in the spherical term. We note that this typical spherical inhomogeneity level is comparable (over the aLIGO) beam diameter to our required (see E0900041-v5, and analysis in T1000154-v5) limitation to TM mirror surface distortion sag.

We can also look to the pathfinder final reports for information on the problem of material inhomogeneity. There was none. This is a high quality material and requires little or no correction. We keep the polishing compensation specification because the nature of Heraeus material is that it has spherical aberration. This needs to be checked on the ITM and CP because they are relatively thick and on the BS because we use such a large area.

Section 3.7 of our system design document T010075-01 states: Advanced LIGO will use the ultra-low-absorption Heraeus Suprasil 3001 material for the ITMs, for which the absorption is < 0.5 ppm. The level of OH content in the 3001 material is less than 1 ppm as specified by the vendor, This low OH content may lead to absorption of less than 0.02ppm/cm based on an extrapolation of OH content vs. absorption as shown in Figure 2 (sufficiently low absorption after blank annealing has also been determined: C1000257-v1). The current best measurement of the absorption of this material[3] is 0.2ppm/cm (see also Appl. Opt. 45, 7269).

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[3] LIGO-C080019-00

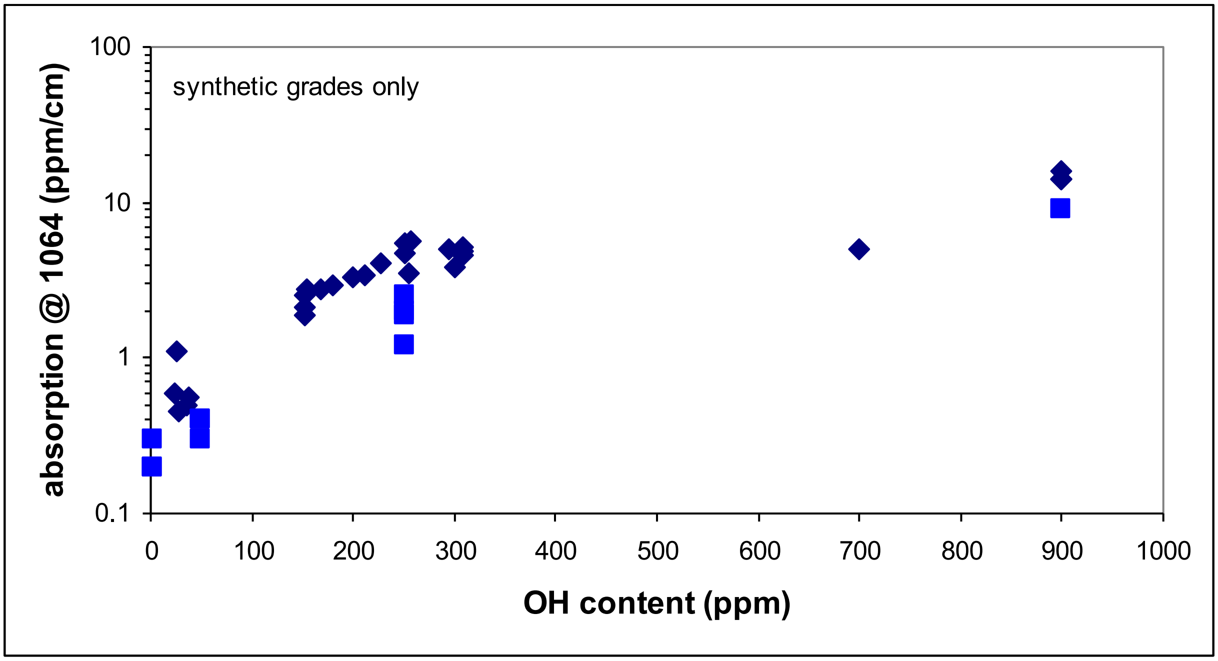

Figure 2 Measured absorption vs. OH content of high quality fused silica

This material is specified better than class zero inclusions. Inclusions are defined to total ≤ 0.01 mm^2 /100cm^3 of Glass within the clear aperture. Inclusions with a diameter of 10μm or less are disregarded.

LIGO has one ITM blank on hand, obtained from Heraeus as a proof of concept during development

2.1.1.2 High quality fused silica (Recycling Mirrors)

The Transmissive Recycling Mirrors (power and signal) are 0C Corning, 7980 fused silica or equivalent, with special inclusion specifications. The absorption properties are less important for these pieces. Due to the small beam size in this location, reasonable homogeneity material with no special absorption specification is adequate. This material is specified with zero inclusions. Inclusions are defined to total ≤ 0.01 mm^2 /100cm^3 of Glass within the clear aperture. Inclusions with a diameter of 10μm or less are disregarded. For the comprehensive analysis of requirements for optics quality in the recycling cavities including thermal lensing see P080004-00 (Opt. Exp. **16**, 10018). An unreasonably large 7980 absorption of 20ppm/cm would cause a PRM absorption of 10 mW, leading to an additional 400m fl lensing (the dominant effect for FS) for this optic. Even this distortion would be insignificant from the perspective of IOO optical matching design.

Cost may be the most significant driver for this material.

2.1.1.3 Optical quality fused silica (PR3, SR3, End and Fold mirrors)

The End test mass and R3 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 a relaxed requirement for maintaining the fidelity of the arm cavity phase on transmission[4]. These materials are specified with no inclusions of diameter 100μm or more within 5mm of any flat surface.

LIGO has four ETM blanks on hand, these are Suprasil 311, supplied by the University of Glasgow as Advanced LIGO test masses. It has been shown that Corning 7980 fused silica grade 3D has poor figure stability at annealing temperatures required for ion beam coatings. Heraeus 311 and 312 have proven to be quite stable (E1000440, C1002008) and are required for End Test Mass substrates

LIGO has five PR3/SR3 blanks on hand, these were procured as test pieces and spares for LASTI.

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 (for relevant RODAs see 2.2.1.2 below) are summarized in T1000382-v1 (see also 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 will be shaped similarly and brought to the form described in Figure . 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. Cylindircal smoothness of the barrel will be monitored for compatibility with possible attachments (acoustic dampers), per specific specifications in table 1.

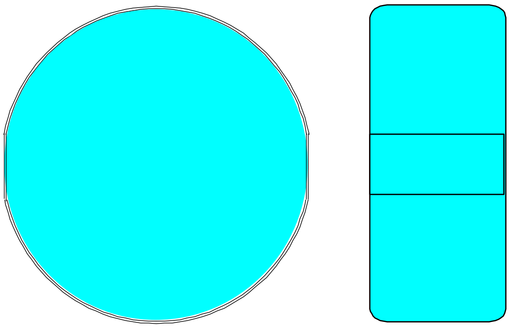

Figure 3 The basic shape of Test Masses

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[4] LIGO-M080042-00

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 the following spreadsheet:

polishsummary.xls (T1000383-v1)

. 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-T080078-05, "Optic Coordinates and Cavity Lengths (for Stable Recycling Cavities." Current results of this analysis indicate that each type of COC will require a different specific wedge angle. Similarity has been sought wherever possible to minimize fixtures. In the past LIGO has carried symmetric wedges for the transmissive optics. This was to minimize the possibility that a glint from a right angle could cause a problem on reflection. SUS prefers a right angle on one side of the optic (see individual COC final fabrication shape drawings in table 1 as specified by SUS). The glint problem has been analyzed (T080120-02) and found to be negligible. Tolerances to all wedge angles have been developed in close accord with design requirements of the AOS, SYS, and SUS subsystems. The BS wedge is 0.04 deg. To maintain the PO beam position within 20%, we need to specify +/- 0.5 minute tolerance on the wedge. The CP/ERM and ITM wedge angles tolerances should be specified to +/- 1 minute tolerance for to accommodate AOS baffles/dumps.

	horizontal	vertical
ITM/ETM	0.08A	0
CP	0.04A?	0
BS	0.04S	0
PR3/SR3	0.00	0.60
PR2/SR2	0.00	1.00
PRM/SRM	0.00	1.00
FM	0.04S	0.00

- Standard optic edge bevel, 45^{o}, 2mm height on each leg to the virtual corner.
- All primary face surfaces except for CP, BS and FM will have spherical form, as given in the values in the spreadsheets.
- Each optic will have a consecutive serial number by type, beginning with the optic designation. ITM01, ETM01, CP01, BS01, FM01, SRM01, SR201, SR301, F-SRM01, F-SR201, F-SR301, PRM01, PR201, PR301, F-PRM01, F-PR201, F-PR301

2.2.1.2 Suspensions interface

- The suspension drawings for the End Reaction Mass, and Penultimate mass will be the basis for the Compensation Plate and Test Mass drawings. See SUS final design documentation (E080512-v4)
- ll Test Masses will have two opposing flats polished into the barrel. 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 λ/10 in the mounting area. The SUS ear bond mounting area (TM barrel) has been specified in detail to be identical to that defined by SUS for the penultimate mass bonding (see D080658-v4, and E080512).
- 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.
- Cylindricity, parallelism, and dimensional tolerances are specified by SUS. COC reserves a larger than optimal tolerance on thickness in case re-polishing is required: a budget of .25mm per side per repolish. COC will report final mass to SUS after polishing (to +/- 10 gr).

  Size, and shaping for all COC are specified in the T0900043-v10 and:

  Tolerances specified in table 1 are in accord with best reasonable manufacturability. Deviations from an ideal cylindrical barrel surface on ITM and ETM are to be evaluated and controlled for compatibility with any devices attached (in the future, e.g. acoustic mode dampers) to them.

  with the definition: the thickness of the optic is measured at the thickest point.
- Certain specifications have has been altered in the development of the COC outside of review of this design document:

  LIGO-M040006: Record of Decision/Agreement (RODA) - Same Size FM and BS Optics

  - LIGO-M040020: Record of Decision/Agreement (RODA) - Sapphire/fused silica downselect date
  - LIGO-M040135: Record of Decision/Agreement (RODA) - Detailed Scope of Work on Advanced LIGO by the UK AdL Team
  - LIGO-M040387: Record of Decision/Agreement (RODA) - Recycling Mirror size for Advanced LIGO
  - LIGO-M050175: Initial Alignment Requirements for COC
  - LIGO-M050397: Record of Decision/Agreement (RODA) - Core Optic sizes, including TMs, BS, FM and RM
  - LIGO-M060032: Elimination of the Photon Drive from the AL baseline
  - LIGO-M060305: Record of Decision/Agreement (RODA) - Compensation Plate dimensions
  - LIGO-M060315: Record of Decision/Agreement (RODA) - No Flats on Input Mode Cleaner Optic & Recycling Mirror for Advanced LIGO
  - LIGO-M070055: Dimensions of the Large MMT Mirror (MMT3) and the Recycling Mirrors (PRM & SRM) for the Marginally Stable Recycling Cavities

- LIGO-M070120: Record of Decision/Agreement (RODA) - Beamplitter Optic Size, Geometry, Wedge Orientation and Suspension Wire Material
- LIGO-M080022: Record of Decision/Agreement (RODA) - ETM reaction mass has same mass as Thermal Compensator Plate
- LIGO-M080042: Record of Decision/Agreement (RODA) - Transmission Requirements for ETM and ERM
- LIGO-M080041: Thickness of PR3 and SR3 and wedge information
- LIGO-M080371: RODA: Arm Length Stabilization system to use end-station injection of a 532 nm beam, and PDH cavity sensing.
- LIGO-M0900025: RODA: Decision to reduce the beam size on the ITMs to 5.3 cm
- LIGO-T1000175: Thinner Compensation Plates for reduced Squeeze film damping

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 results of the Pathfinder process. Our plan is to specify an overall loss budget to the polish quality (including any coating imperfections) with a goals of:

RT fundamental mode loss in each arm of 75 ppm.

RT fundamental mode loss (including mismatch to arm mode) in PRC of 1000 ppm.

RT fundamental mode loss (including mismatch to arm mode) in SRC of 2000 ppm.

with limiting tolerable loss set by the SYS requirements document T010075-v3. How these net losses can be budgeted over various polish imperfection categories is described in the COC requirements document (T000127-v5). Vendors will be required to submit sufficient polished surface measurement data for us (via ongoing simulation) to calculate expected net cavity loss (see for example T0900128-v3, T0900159-v1, T080392-v1, T0900384-v1, T1000154-v5, and T0900306-v6). The highest quality polish with regard to scatter diffraction loss will be specified given constraints of current manufacturability.

Results are available from two of the three pathfinder vendors, with final results available from only one vendor. The final results from Vendor 1 are documented in C070179-01. Intermediate results from Vendor 2 can be found in C070216-00. The phase map supplied by this vendor has been used in an approximate FFT simulation and found to produce a loss from surface figure errors of 28ppm with an uncertainty of a few percent.

A comparison of critical parameters according to vendor data:

	ROC (m)	Figure (nm rms)	Microroughness (nm rms)
Vendor 1	2174 ± 13 (absolute)	0.8	0.19
Vendor 2	2105 ± 2 (relative)	*3.1 (0.45)	*6.8 (0.26)

Vendor 3 (preliminary)	Goal ± 5 (absolute)	Goal 0.3-0.5	0.08
Specification	2098 +36, -22	< 0.7	< 0.16

* Vendor 2 was able to demonstrate the properties in parenthesis on a 3" part supplied by LIGO Pages 109 – 127 of C070216-00. Their initial run on the full size piece was spoiled by a vibration that could not be repaired by their equipment. They are in the process of another attempt on the full size piece as of this writing.

We will bias the Radius of curvature target by the appropriate uncertainty once we determine the Test mass polishing vendor. See DRD section 4.2.2.3.7 Effective TM curvature radii[5]. The primary requirement on the effective TM ROCs is that the Gaussian beam half width be constrained to 5.30cm (ITM per M0900025-v1 and G0810029-v4)) and 6.20 cm (ETM).

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) . A summary of all coating specifications is in the following spreadsheet:

coatingsummary.xls (T1000381-v1).

All coatings are specified to have low scatter and low absorption, the current state of the art being 5ppm point defect scatter loss (part of the net loss budget described in 2.2.2), and 0.5ppm absorption at 1064 nm. Coating uniformity is specified to be <0.1% in a 21.5 cm diameter on optics where the incident beam will be greater than ~2cm. With state of the art coatings deviations in layer thickness is of lowest spatial order, axisymmetry dominated, so that only the effective radius of curvature of the optic is appreciably effected. Our finished TM mirror specifications (table 1) require vendor coatings to negligibly alter design ROCs.

One full size optic has been coated HR/AR, this is the LASTI test mass. A report on this coating can be found in T070233-00. The vendor data are found in E070150-00. The most notable and worrisome feature of these coating runs are that there were bubbles in the HR coating and that these were found by inspection at CIT rather than at the vendor (subsequent coating work for VIRGO with this same vendor has identified the process problem and eliminated these bubbles. Scatter, absorption, and transmission of the HR coating and reflection of the AR coating of the LASTI optic were measured at Caltech.

Scatter was found to have a background value of about 9 ppm with notable spikes of well above 50 ppm. This results in a total scatter of about 11 ppm. Because the coating was cleaned using First Contact^{TM}, these spikes are not believed be to be due to surface contamination, but rather are part of the coating.

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[5] COC DRD LIGO-T000127-05-D

Absorption was found to have a background value of 0.2 ppm, with a very few spikes between 1 and 25 ppm, resulting in an average value of 0.3 +/- 0.1 ppm.

Transmission was found to have most points between 9 and 10 ppm with good uniformity. There were, however, 9 points found in a 160 mm X 160 mm area that had transmissions between 2000 and 7000 ppm, which is an average density of 0.04 per square centimeter. These high transmission defects appear circular under a dark field microscope.

The AR reflection showed higher variation than the HR transmission, varying between 160 ppm and 230 ppm, with an average value of 180 ppm, in a 160 mm X 160 mm area.

The TNI direct measurements of coating thermal noise show reasonably good agreement with what is expected from Q measurements and the Brownian thermal noise theory. The un-optimized tantala/silica coating gives an equivalent homogeneous coating loss angle of 3.2 X 10^{-4}, compared to 3.0 +/- 0.2 X 10^{-4} from Q measuring; the titania-doped tantala/silica coating gives 2.3 X 10^{-4}, compared to 1.9 +/- 0.3 10^{-4} from Q measuring; the optimized tantala/silica coating gives 2.7 10^{-4}. There are plans to measure direct thermal noise on an optimized titania-doped tantala/silica coating, which should give lower thermal noise than all three previous cases measured.

The TNI results are primarily a check on the expected coating thermal noise as predicted by Q measuring. The four TNI results (un-doped tantala plus un-optimized, doped tantala plus un-optimized, un-doped tantala plus optimized, and doped tantala plus optimized) show the expected relationship between themselves, and the overall thermal noise level is roughly what is expected from the Q results. The TNI results are most consistent with a higher phi for titania doped tantala than seen in most Q measurements and used for designing the Advanced LIGO mirrors. However, since the practical specification for coating thermal noise is that it be as low as possible and there being no way known to reduce thermal noise beyond an optimized titania doped tantala based coating, it is not possible to improve our design based on this result. Therefore final TM coating thermal noise may be slightly higher than hoped but, other than impacting astrophysical reach, it won't cause problems for any other aspect of Advanced LIGO.

2.3.1 Test Mass High Reflection (TMHR) Coatings.

These coatings 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, with little impact on actual coating process cost or schedule impact. TM Pairs (5 planned each for ITM and ETM) with closely matched radii of curvature and homogeneity compensation are to be identified for coating in the same coating run, or provisions made with the coating vendor to assure sufficient matching.

The Advanced LIGO core optic HR coating will be made from a series of doublets consisting of one layer of high index titania-doped tantala and one layer low index silica, with the concentration of titania in the tantala of roughly 20 %. The thickness ratio between the high index and low index materials in each doublet as well as the total number of doublets on the ETM HR coating will be chosen so that the transmission is less than 6 ppm at 1064nm, the transmission at 532nm is 0.01 to 0.04 with 0.03 as a goal, and the total thermal noise from all sources, including Brownian and thermo-optic, is minimized within these transmission limitations. The exact design suited to these constraints will be done by the vendor in close consultation with LIGO laboratory and LSC scientists. This will likely result in a ratio between high index and low index of about 1:3, with the high index being about λ/8 in thickness, and about 25 doublets. The top and bottom layers of the coating will have their thickness adjusted to minimize absorption and scatter, so long as it has a minimal impact on thermal noise performance. The ITM HR coating will be constructed similarly, so that it has a transmission of 1.4 % at 1064nm and a maximum transmission of 1% at 532nm and with minimum thermal noise otherwise. At 100 Hz, the expected noise from all coating thermal noises is 2.44 x e-24 /rtHz.

2.3.2 High Reflection (HR) coatings.

These coatings are standard Si/Ta ion beam coatings since thermal noise is not an issue in the recycling cavity. 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 Min: 45.029 Max: 45.156 with respect to P polarization incident (T1100128). Due to the large aspect ratio of the Beamsplitters, they will increase in curvature after coating. In initial LIGO we found a 20-25 nm change in radius of curvature due to coating stress. The Advanced LIGO Beamsplitter has a similar aspect ratio, so we should anticipate a similar change. We have a low quality BS blank on hand that will be polished and coated by the selected vendor to establish a definite curvature change for that process. The vendor will attempt an AR coating to correct, or oppose the HR stress. If this does not bring the BS within tolerance, we will specify a concave ROC on the BS polish to balance the coating stress. Specific test coating runs will be performed to determine the best strategy to maintain the finished TM mirror within required ROC tolerance (8nm full aperture sag, per table 1 specifications).

The DRD specifies that the (P polarized) beams coming out of the BS should match to within 1%. If we assume a 50ppm AR coating loss and 60 ppm (~10ppm/cm) bulk loss, the single pass loss totals to 110 ppm.. Allocating the 1% amongst transmitted and reflected beams implies 0.5% tolerance, a factor of 50 higher than the transmission loss. The specification will be 50% ± 0.5% , which will push the limits of manufacturability.

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. For both test masses, we specify <50ppm with a best effort to achieve <20ppm at 1064nm. The ETM has an additional requirement of reflectivity between 1 and 4% at 532nm.

2.3.4 Coating Interfaces

The COC coatings act as interfaces with other wavelength sub-systems than the primary 1064nm interferometer ASC control. With coating designs optimized for the primary 1064nm functionality (as described in preceding sections) specific designs will then be chosen compatible with ALS operation (section 2.3.3 and 2.2.9 per T0900144-v4) at 532nm (see also E0900041-v5 and E0900068-v3).

Similar secondary compatibility of the COC surface coating designs must chosen for operation of the AOS/TCS Hartmann sensor system near 670nm (see T1000055-v1 and E0900489-v4a). The ITMs have a requirement that either surface 1 or 2 must have a reflectivity at 670nm >0.05, as required from T000127-v5 (section 2.3.4.1).

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. Any coating spec for performance at a wavelength other than 1064 and 532 nm is at a "best effort" level. A decision was made by SYS that the coatings should be designed as it makes sense for 1064 and 532nm, then AOS can chose a laser wavelength based on that coating design (the choice of the alignment beam wavelength remains under study). 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 Electro-Static Drive (ESD) coating

The ESD coating is a (low optical quality) suspension metallic coating. The ESD pattern is segmented (in quadrants) in an annular region between the edge of the optic and an inner clear aperture. (See D060189-A1 for a drawing of the evaporative mask for the ETM reaction mask for the suspension noise prototype, which is representative of the intended design.) The minimum inner aperture diameter is defined by COC in the DRD based on optical considerations. The ESD pattern, thickness and material (nominally gold) is defined by SUS. COC has the responsibility to implement the coating. This coating is applied to the first surface of the Compensation Plate and End Reaction Mass, nearest the respective Test Mass. Table 1 explicitly states which optics have this coating.

The Systems layout (D0901920 and D0902216) have determined that the Compensation Plate wedge be oriented 180 degrees different when hung in an X arm or Y arm of the interferometer. Therefore, the Compensation Plate ESD connection will accommodate this dual configuration (L1200291-v4.) A transformation process is found at E1300745. Compensation plates treated in this way may be hung in either the X or Y position. Those not treated for transformation may only be hung in an X arm position.

2.4 Mounting and Stay-clear

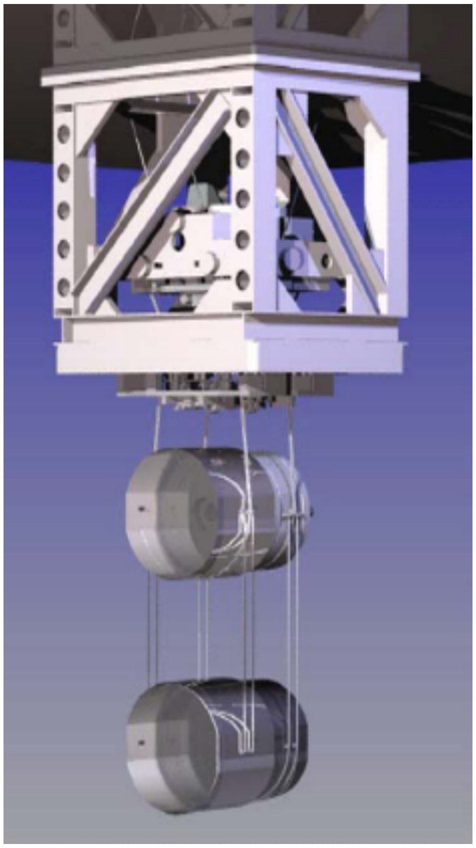

Figure 4: Test Mass Suspension

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 thermal noise.

The SUS group will add appendages to the optics for the purpose of suspending them. The most sensitive optics, the test masses, have ‘ears’ that are bonded to the flats on the sides of the optic (as specified in details of table 1). Analysis was used to set the maximum bond area so that the resulting increase to the thermal noise was less than 10% of the overall intrinsic thermal noise of the interferometer (T050216-00), as required. Our per mass mirror thermal noise value is 5.7 10^{-21} m/rtHz, per the FDD. According to P0900053, the expected thermal noise level from the new ear design, using the new bond loss angle from this publication, gives 5.4 x 10-22 m/√Hz. This is just under th1s 10% limit. This bond angle and new ear design ear design is described in T0900447-v3.

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 cavity mode power in the Fabry Perot arms SUS elements should also insignificantly (<100 ppm power occlusion) degrade the recycling cavity modes in comparison with known modeled losses (BS aperture, baffles, in/out of line asymmetries).

2.4.2.1 Beamsplitter

This element requires critical stay clear on both faces, the situation is complicated by the 45° 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 2. This spares approach is informed by and based on the initial LIGO experience. Test masses require more spares because the radii of curvature must be matched more closely in the interferometer than even exceptional manufacturing tolerances will allow. Fabrication in pairs (5 each for ITM/ETM) in particular allows for coating twins.

Recycling mirror spares are based on one spare for the initial installation, plus two replacement for each interferometer should the final configuration require a different recycling mirror transmission. This is complicated by the possibility of different radii of curvature optics needed for the different length of the Recycling cavities for the folded and non-folded interferometers.

PRM: 4 spares: 3 coated (one for each IFO; 2 with ROC= -11.00m, and1 with ROC= -8.87m) + 1 uncoated (and unpolished)

SRM: 9 spares= 3 polished (2 with ROC=-5.69m and 1 with ROC= -11.40m) and coated with the same transmission as the ones first used in aLIGO + 6 uncoated, but polished with the right ROC for each IFO (4 with -5.69m, 2 with -11.40m). The uncoated spares will be coated later with a different transmission than the ones first installed in aLIGO

PR2: 3 spares; two with ROC=-4.56m + one with ROC=-4.41m. All coated.

SR2: 3 spares; two with ROC=-6.43m + one with ROC=-4.89m. All coated.

Beamsplitters have 1 spare per interferometer due to the complexity of the coating. Compensation Plates have one spare pre interferometer since they go through the extra step of applying an ESD coating.

Table 2: COC spares

	PRM	**F-PRM**	**SRM**	**F-SRM**	**PR2**	**F-PR2**	**SR2**	**F-SR2**	**PR3**	**F-PR3**	**SR3**	**BS**	**FM**	**CP**	**ITM**	**ETM**
Number in IFOs	2	1	2	1	2	1	2	1	2	1	3	3	2	6	6	6
Uncoated Spares	1, also un-polished		4	2	0	0	0	0								
Coated Spares	2	1	2	1	2	1	2	1	1	1	1	3	1	3	4	4
Total optics	7		8	4	4	2	4	2	3	2	4	6	3	9	10	10

3 Supporting Design

3.1 Characterization Metrology

There are two purposes for metrology in LIGO; verification and characterization. The purpose of verification is to confirm conformance of the product to specification. Verification processes are covered under the section on Quality Assurance.

The purpose of characterization is to provide absolute data to the user community for purposes of analyzing the performance of the interferometers and predicting the benefit of future enhancements. The qualities of the data are limited by current technology, reasonable cost and physical reality.

3.1.1 Automated mirror parameter measurement

Some COC properties are characterized by automated scan measurements. These include bulk absorption, coating absorption, coating reflectivity, transmission and surface and bulk scatter. This program has been developed for 1064 nm and has been used extensively in LIGO development. For an example of the data obtained by this instrument, see the report characterizing the LASTI optic, LIGO-T070233-00 A description of the instrument can be found in LIGO-G080162-00.

3.1.2 Coating Characterization

Many coating characteristics are verified in the development phase. During production, process control is used to ensure replication of the desired qualities. The reflectivity is monitored during and after coating, and the vendor has a lot of experience satisfying these types of requirements. For other optical properties (scatter, absorption) and mechanical properties (phi, Young's modulus) we are relying on the material values being fairly reproducible. Defect count and absorption will be measured at the vendor, tests will be made at Caltech on witness samples, both can be measured and tracked in situ once installed. Maintaining vendor values of scatter and absorption throughout handling and installation will primarily be through the use of First Contact^{TM} to keep the surfaces covered. Degradation in these values during the inevitable uncovering will be controlled by keeping an extremely clean environment (see section 3.3).

The process certified specifications include:

- Mechanical loss – proven in development
- Thermal expansion
- Birefringence
- Thickness Uniformity

Properties requiring 100% inspection in the production phase are:

- Reflectivity/Transmission
- Absorption
- Scatter

3.1.3 1064 nm phase front interferometry.

Full aperture surface maps will be generated for each coated 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 by using a “fixed zoom” approach. This enables the user to zoom in at one or more different magnifications in order to characterize the extended spectrum of the surface. There may be several higher spatial frequency data ranges, these are required to overlap in order to provide suitable context for each measurement.

LIGO will acquire a full aperture interferometer, install and characterize it in time to perform final surface characterization of the optics (see E080508-v2). The accuracy of these measurements depends substantially on the thermal, vibrational and acoustical stability of the environment and the quality of the calibration. LIGO has acquired space in the sub-basement of Caltech’s Lauritsen laboratory, north wall, for the final measurements. This should provide accuracy comparable to or better than that of initial LIGO.

The instrument used for initial LIGO characterization, in combination with calibration and environment, was able to provide repeatable measurements to 0.2 nm rms, which was the noise floor of the instrument. Measurement of radius of curvature agreed with those made by HDOS and CSIRO to within 1.5 nm in saggita on the same optic. At this time we have abandoned a plan to have absolute pattern surface test plates fabricated for metrology calibration.

We will use the same instrument that characterized the LIGO1 optics for our verification metrology of the small COC (xRM, xR2). For a description of verification metrology, see the section on Quality Assurance.

3.1.4 Mass

SUS has requested that the mass of the optic be reported after polishing to within +/- 10g (not including any protective coating). COC will weigh each piece after receipt from polishing and include this in the individual optic’s characterization data. The nominal specification masses (table 1) are in compliance with SUS design tolerances.

3.2 Storage and handling

All optics carriers, optic documentations (e.g. travelers), and optic process specification (to all vendors) are to specifically warn against any exposure of the COC (as well as witness samples) to UV or X-ray exposure. There is significant evidence that optics such as these (their coatings in particular) may be degraded (especially with respect to optical absorption at 1064nm) by such exposure.

3.2.1 Storage

The test mass carriers for use in Advanced LIGO are shown in D0902146. They are cylindrical containers with 2 spring loaded alignment stops to hold the optic in place radially while the optic sits on a PFA-440HP Teflon O-ring as a cushion. The lid is designed to accommodate the wedge of each optic, so the carriers for different optics differ slightly from one another. The handling and shipping procedures is documented in E0900394. Storage of these carriers will be on large sheet metal storage shelves.

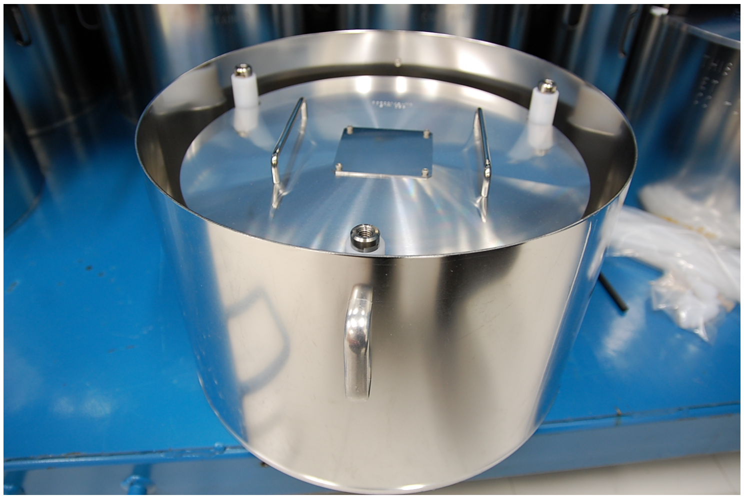

Figure 5: Test Mass container

3.2.2 Handling

A small crane will be used for lifting the optic containers out of the transit case and onto a clean working surface. A prototype mirror handling device (Ergo Arm) has been designed and fabricated for lifting, moving and cleaning 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.

The design of the ergo arm is based upon the idea of a vacuum chuck. The device has a vacuum tank, which moves around with the lifting arm. The vacuum chuck has a gauge attached to the small vacuum volume used for mounting the optic. This gauge is used to monitor the quality of the vacuum. The hazard analysis plan for using this equipment is LIGO-T080231-00. For instance alarms for adequate vacuum pressure will sound.

The Ergo arm is the preferred method for handling the optics. Contractors are to be offered the use of an Ergo arm. They may use their own lifting equipment as long as the equipment is reviewed and approved by the Core Optics design team.

3.3 Cleaning and contamination

3.3.1 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. All aspects of COC cleaning are now subordinate to our use of First Contact^{TM} as a primary assurance. Therefore all cleaning procedures must support this primacy (see E1000079-v2 and T1000137-v2). For instance ionized gas blowing behind First Contact^{TM} removal will suppress static dust attraction.

3.3.2 Contamination

Our experience in LIGO (initial) and eLIGO has shown that contamination of in vacuum optics (and especially the TM surface 1) is a critical issue for successful operation. Programs for maintaining these optics contamination free both in preparation and assembly, as well as during ongoing operation will be an integral part of aLIGO. Fortunately the evidence from the long duration of LIGO operation also is that in the absence of any distinct events (e.g. ventings, failed cleanings) the optics remain operationally clean long term.

3.3.2.1 Contamination control guidelines

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.

3.3.2.2 Contamination control plan

The optics will be cleaned at the coater before coating, and will remain in clean room environments immediately after coating and during measurements made by the vendor. They will be placed in the test mass container, and then shipped to Caltech.

At Caltech, the containers will be opened and the optics placed in a clean room environment. There the necessary metrology will be performed per section 5.1.3. After measurements, the optics will be cleaned and First Contact^{TM} reapplied according to E1000079-v2 and placed back in the test mass container. The optics will then be shipped to the sites. Outside of controlled clean environments our primary reliance is to be on First Contact^{TM} protection. It remains under planning and study what precautions for environment cleanliness need be adopted during test and handling exposure (see T080067-v1 for systematic planning, with ongoing studies underway).

At the sites, the shipping containers will be opened and the optics installed. First Contact^{TM} will remain on the optics as long as possible during handling. Re application procedures allow for a final cleaning just before closing the doors for pump down.

3.3.2.3 Contamination studies

Optical loss, primarily scatter and absorption, has been studied on the initial LIGO test masses, both in situ and in the lab. G060040 and T050074 give summaries of absorption studies of the H1 ITMs, which found elevated values of 10-15 ppm compared to the 1 ppm level expected. The H1 ITMx (4kITM07) was taken to Caltech for further studies, where it originally was found to have an absorption of 13 ppm. After cleaning, this value dropped to about 1 ppm. H1 ITMy was cleaned in situ and the absorption dropped to less than 2 ppm.

T070051 gives a summary of both scatter and absorption measurements on these optics. H1 ITMx in the lab at Caltech had 10X higher scatter before cleaning, when individual scatter points showed correlation with absorption points. The surface was studied before cleaning for chemical or particulate impurities but did not find any suspicious results. Scatter measurements in situ give roughly 80 ppm per HR surface, but there are difficulties making and interpreting these measurements. This scatter value is consistent across all installed optics, regardless of their microroughness or cleaning history. Individual point scatters seem to dominate this value, and can be clearly seen in images of the optics (see G060586). The position and intensity of these scatter points has remained roughly constant over years of observation.

3.3.3 In Situ Cleaning

In the event that "in situ" cleaning is required on optics suspended by wire, the surfaces should be cleaned using First Contact™. First Contact™ is planned for all core optics, independent of what material is used in its suspension. Virgo has used First Contact™ on a vertically hanging optic (see http://wwwcascina.virgo.infn.it/commissioning/weekly/2008/Mar2008/ILIAS_WG1_03-2008-Punturo.ppt as well as http://lma.in2p3.fr/NI-Cleaning-compressed.avi) First Contact™ has often been used on vertical mirrors by the astronomy community and techniques have been developed to deliver it with a high volume low pressure sprayer to get the needed thickness. Virgo applied First Contact™ with a brush (our adopted method).

There is concern about charging of the optics from removal of First Contact™. Tests are underway at Moscow Statue University and at Trinity University to study what charge is left on Advanced LIGO-like optics after removal. These tests will be done with both standard First Contact™ and with the new First Contact™ that contains [conductive] carbon nanotubes, which was specifically developed to reduce charge transfer. The Virgo experience with First Contact™ also noted the charging problem, and a discharging method using ionized nitrogen was developed and used (we tentatively intend something similar). Continued R&D here is subsumed as part of the larger critical issue of COC charging (and its mitigation). This is very much and area of ongoing development.

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™.

E1000079-v2- Procedure for Applying and Removing First Contact™

T1000137-v2 – Drag Wiping and First Contact™

4 Requirements

4.1 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 Hazard Analysis

The COC represent highly critical, special process components of aLIGO. As such they represent substantial risk hazard for the project's timely completion. An over abundance of spares is not possible due to their time and expense for complete processing. This aspect has been addressed as a substantial risk element in aLIGO planning (see COC in the aLIGO risk registry). The COC themselves present no inherent personnel hazard. However several aspects of their care and handling do. For proper handling for metrology, assembly, shipping/receiving, cleaning, etc. within the LIGO laboratory dedicated "ERO-arm" fixtures have been designed, with specific hazard analysis (see T080231-v6). Specially designed shipping/storage containers will be used (T0900394-v5), which have been engineered with regard to both personnel and contents safety.

At all times that the COC are not being used, or during critical acceptance testing their optical surfaces are to be protected by First Contact^{TM}. This is a flammable material applied in a [highly flammable] solvent carrier. This has been well characterized and tested per personnel hazard T1000425-x0.

4.1.3 Design Documents (see also section **1.1**)

Conceptual Design

T000127-05 COC Design Requirements Document

T000128-02 COC Development Plan

T020103-08 TM Material Down-select 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

T0900386-v4 IOO Final Design Document

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

4.1.4 Engineering Drawings and Associated Lists

Material Specifications and Drawings for Final Design have been prepared in detail for preliminary release (the material blanks being the most critical lead item, see T000128 and L080031-02). Final specifications and drawings for the complete set of COC are presented in table 1.

4.1.5 Technical Manuals and Procedures

4.1.5.1 Procedures

E070292-00 and E1000079-v2 Optics Cleaning Specifications - First Contact^{TM}

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

4.1.5.2 Data

4.1.5.2.1 Vendor 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.

4.1.5.2.2 LIGO Data

A traveler and data package are developed and maintained by COC for every optic up to the point of delivery of the optics to SUS (for assembly) or INS (for spares). It becomes the responsibility of those teams to maintain the travelers and data packages.

4.2 Logistics

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

2.) After shaping the blank is either source inspected or shipped back to LIGO for inspection, then is shipped to polishing.

3.) After polishing the blank is either source inspected or shipped 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 requirements which take precedence in the event of a conflict with this document where this document implies a looser requirement.

- System Requirements
- DRD requirements (see T0100127-v5)
- RODAs (see section 2.2.12 above)

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 Table 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. See sections 5.1.1,2.3 below.

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 Blanks, Responsibility for Tests, frequency and method

Developed through vendor negotiations are the responsibilities outlined in T1000137-v1 for vendor screening and testing of quality. General guidelines we follow are (see also T1000387-v1):

Test Mass Blanks		
	Vendor	LIGO
Property	Certification	
OH content Bulk Absorption (ITM)	OH content as proxy for absorption 100%	
Homogeneity (ITM)	Fizeau Measurement 100%	
Bulk, Scatter (ppm) , ITM	Defect inspection 100 %	

Recycling Cavity Blanks		
	Vendor	LIGO
Property	Certification	
OH content Bulk Absorption (CP, BS)	OH content as proxy for absorption 100%	
Homogeneity (CP, BS)	Fizeau Measurement 100%	
Bulk scatter (ppm)	Defect inspection 100 %	

5.1.2 Substrates, Responsibility for Tests, frequency and method

Test Mass Substrates (polished, uncoated)		
	Vendor	LIGO
Optic size and fiducial location (mm)	Measurement 100%	Report Mass to SUS 100%
Mounting Flats	Measurement 100%	0
Radius of curvature m	Fizeau Measurement 100%	Fizeau Measurement 100%
Surface error less T,P,A (rms with full maps, PSDs) over clear aperture	Fizeau Measurement 100% and ITMs measured in transmission	Fizeau Measurement 100%
Microroughness in clear aperture (nm rms)	Measurement 100%	0
Surface scatter (ppm)	Defect inspection 100%	Dark field characterization 100%
Absorption	0	30%
Homogeneity (ITM)	Measurement 100%	0

Recycling Cavity Substrates		
	Vendor	LIGO
Optic size and fiducial location (mm)	Measurement 100%	
Radius of curvature m	Fizeau Measurement 100%	Fizeau Measurement 100%
Surface error less T,P,A (rms with full maps, PSDs) over clear aperture	Fizeau Measurement 100%	Fizeau Measurement 100%
Microroughness in clear aperture (nm rms)	Measurement 100%	0
Surface scatter (ppm)	Defect inspection 100 %	Dark Field Characterization 100%
Absorption	0	30%
Homogeneity (CP, BS)	Measurement 100%	0

*** Fizeau measurement by Tinsley at ASML is likely to be much more accurate than the small aperture WYKO at Caltech. The WYKO does not have a matching transmission sphere for these parts, allowing noisier, multi-fringe imaging.**

For the Recycling cavity optics the smaller curvatures are most difficult to measure. Accuracy and tolerance in this will be vendor guided as to best procedures. To insure this we will obtain sufficiently accurate reference spheres of 34 and 36m ROC for use with PR3 and SR3 metrology.

5.1.3 Finished, Coated Optics, Responsibility for Tests, frequency and method

Test Mass Optics		
	Vendor	LIGO
Coating Absorption (ppm)	Certification 100%	Absorption Measurement 100%
Figure	Measurement 100%	Measurement 100% of optics
Homogeneity (ITM)	0	Measurement 100% of optics
Side 1 (HR) Transmission	Measurement 100%	Measurement 100%
AR Coating Reflection (ppm)	Measurement 100%	Measurement 100%
Scatter (ppm)	Defect inspection 100 %	Measurement 100%

Recycling Cavity Optics		
	Vendor	LIGO
Coating Absorption (ppm)	Certification 100%	Absorption Measurement 100%
Figure	Certification 100%	Measurement 100% of optics
Homogeneity (CP, BS)	0	Measurement 100% of optics
Side 1 (HR) Transmission	Measurement 100%	Measurement 100%
AR Coating Reflection (ppm)	Measurement 100%	Measurement 100%
Scatter (ppm)	Defect inspection 100 %	Measurement 100%

*** If possible, depending on coating design.**

Vendor acceptance test plans for the coated optics are in final phases of being negotiated and planned with vendors. Strict adherence to the specifications(Table 1) will be continuously monitored. Detailed provisions are formulated in E0900059-v7 and E1000018-v2.

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^{TM} before delivery to the observatories. aLIGO TM shipping procedure is described in E0900394-v5.

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. No special provision is planned for back filling these containers with purified/inert gas.

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

PRMxx

PR2xx

PR3xx

SRMxx

SR2xx

SR3xx

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. It will be the vendor's responsibility to insure proper markings. These will be spot checked during the Caltech in house metrology phase.