LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
-LIGO-
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Technical Note	**LIGO-T040009- 00- D**	1/28/04

Report of the Core Optics Components Design Requirements Review Committee

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This is an internal working note
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INTRODUCTION AND CHARGE

This document is the report of the committee charged with reviewing the Advanced LIGO Core Optics Components (COC) Design Requirements, Conceptual Design, Development Plan, and plans for the sapphire/fused silica test mass downselect planned for May 2004. These materials were presented to the committee on January 6, 2003, by the team of Garilynn Billingsley, Bill Kells, Gregg Harry and Helena Armandula. The charge to the committee is:

1) With regard to requirements:
    a. determine whether the requirements identified in the Design Requirements Document (DRD) are complete (including functional, performance and interface requirements),
    b. advise whether proposed requirement values are appropriate,
    c. if needed, recommend additional requirements to be specified, and
    d. recommend other appropriate actions.
2) With regard to the conceptual design:
    a. evaluate the conceptual design of the COC to determine if it is consistent with the DRD for both the baseline sapphire test mass material design and for the fall-back, fused silica test mass material design,
    b. advise on whether the test mass material down-selection plan is appropriate and complete,
    c. advise whether the design is sufficiently developed to proceed with the Preliminary Design phase, and
    d. advise whether the criteria and plan for test mass material selection is appropriate and complete.

RESPONSE OF THE COMMITTEE

The committee unanimously declares that the team presented the COC Design Requirements and Conceptual Design very well. With the recommendations listed below, we declare the requirements in the DRD to be complete and the COC subsystem team to be ready to proceed to the Preliminary Design phase. We list our comments to the team in rough order of decreasing significance.

(1) Thermal compensation. It is critical to Advanced LIGO, yet the interface between AOS and COC in the area of thermal compensation is sketchy, and some on the committee suggest that thermal compensation be included within the scope of COC. At the very least, the requirements and designs relating to thermal compensation should be reviewed side-by-side with the rest of Core Optics, even if it is formally in a different subsystem. The requirements that flow down from SYS to COC and AOS collectively regarding carrier and RF sideband power buildup in the power recycling cavity, contrast defect, and

operation at high and low input laser powers should be clearly stated in the DRD.[1] The downselect document contains almost no mention of thermal compensation issues. The degree of thermal lensing vs. absorption, along with sources and compensation possible for silica and sapphire should be tabulated in the downselect document and the CDD. In particular, a research plan to measure coating absorption nonuniformity and model its effect in the interferometer, for both silica and sapphire, should precede the downselect, as it could strongly disfavor fused silica.[2] Likewise, the homogeneity of absorption in sapphire should be measured in more large samples before the downselect, and the acceptable rms and peak-to-valley level and spatial scale of inhomogeneity should be modeled by AOS and given as requirements to COC.[3] Is the 20ppm/cm absorption value for sapphire a requirement or a goal? A different value of 100ppm/cm with a different justification is given in the CDD. Our knowledge of the suitability of large sapphires is based upon only a few commercial demonstrations, and sapphire growth is not very reproducible. COC should contract Crystal Systems to continue to grow and evaluate large sapphire boules so to amass better statistics on optical quality, and continued studies of sapphire absorption mitigation in the Development Plan are encouraged.[4]

(2) As it stands, the compensator plates themselves are within the scope of COC, yet their requirements are nearly unspecified. The size (and possibly material if negative dn/dT materials are considered[5]) should be input to COC from AOS, and its suspension will differ from the other core optics- it will certainly not be suspended from fibers, but from wires or possibly in a composite structure that mimics the weight of an ITM.[6] Either way the compensator plate will not have flats for silicate bonds.[7]

(3) The deformation of the HR surface of the ITM at high arm power, if not directly compensated on the ITM itself, could require an unstable or nearly unstable cold arm cavity to provide a large spot size during high power operation. This would appear to mandate thermal compensation directly on the ITM. This needs to be carefully studied before the downselect, to understand what compensation is needed and possible, how much the ITM would be heated to provide this compensation, and what requirement on coating absorption is needed to make thermal compensation practical. The inhomogeneity of coating absorption could contribute to the arm scatter loss, and this should be analyzed as well before the downselect.

(4) Arm loss. The committee feels that the 75ppm total loss budget for a single arm cavity is stringent and cannot be met given the large surface scatter in the initial LIGO optics. We recommend study to identify the source of point scatter in initial LIGO LHO optics, and

[1] In a private communication, Peter Fritschel has stated the requirement that the core optics be sufficiently compensated against thermal aberration that the RF sideband power in the power recycling cavity not saturate for any operating power of the interferometer.
[2] Any requirements on coating absorption nonuniformity should be added to the DRD, section 4.2.2.5.2.
[3] To be put added to the DRD, section 4.2.2.5.1
[4] in addition, continued sapphire absorption tests should be included in section 5.1.2.1 of the DRD.
[5] DRD, section 3.2.4 and CDD, section 2.1.
[6] DRD, section 3.
[7] DRD, section 4.2.2.1 and CDD, section 2.2.1.1.

that LLO optics be checked in a similar way.[8] We also recommend a program to measure scatter of new coatings comparing vendors, substrate type, and preparation. Is this scatter somehow specific to LIGO? During the review was mentioned the idea to incorporate such a program into the coating mechanical Q study, which seems a good idea, but there are yet no concrete plans to do this. Another part the arm cavity loss budget is aperture diffraction losses, for which there are differing estimates. This is a significant part of a tight arm cavity loss budget and should be calculated precisely. The mid-scale scattering losses due to likely thermal lens inhomogeneities should also be estimated. Given these difficulties, we ask whether the 75ppm arm loss requirement could be relaxed by SYS.

(5) A separate scattering issue that needs clarification is Rayleigh scattering in sapphire; section 2.4 of the CDD claims it is 10x smaller than in fused silica, yet measurements by the UWA group show scatter 10x larger.[9]

(6) Contamination is strongly suggested by the large surface scatter mentioned above. The possible contribution of cleaning to scatter and to the anomalous AR reflectivity of the Hanford 2k ITM needs to be understood. In addition, the cleaning procedure will need to be specified and incorporated into the requirements and conceptual design to the extent that they can debase COC performance. For example, if cleaning can induce scatter, then scatter should be measured after applying the COC cleaning procedure. Each different type of coating should be tested. COC should do its own tests of cleaning vs. DI water temperature and detergent type, in order to estimate our confidence in REO's finding that hot cleaning etches coatings. Solvent drag wiping should also be re-evaluated with respect to scatter.

(7) We suggest analysis of the LIGO I mode cleaners for scattering/absorption changes due to accumulated contamination in order to test the <1ppm contamination estimate for Advanced LIGO. Better requirements on contamination are needed.[10] For example, section 4.2.5 of the DRD states, "the only form of maintenance will be in cleaning the optical surfaces. There is no inherent contamination mode so that a MTTR for cleaning will not be a requirement imposed on the COC." Yet the same section later asserts, "contamination equivalent to that in table 5[11] [shall] not accrue in less than 2 months operating time. This estimate is based on the assumption that replacing or cleaning the contaminated mirrors will cost an effective observation down time of one month." This implies that 36ppm arm cavity loss due to contamination per year is acceptable. Better phrasing and better intent would be, "there is no specific contamination mode that we have identified," and "should one be determined, we will establish a requirement."

(8) There are many requirements which should appear in the DRD and CDD, but do not. Table 1 of the CDD should include CP parameters, and wedge angles for all optics. Once

[8] Ken Strain knows a laser gyro manufacturer who tested REO coatings made at the same time as the LIGO coatings and found significant point scatter.
[9] This would appear to answer the question in section 3.4.4 of the Downselect document, though measurements in large pathfinder samples are still valuable.
[10] In this spirit, in section 3.4.2 of the CDD 'silicon' should be 'silicone.'
[11] Table 3 is meant. The text should be corrected.

the diffractive losses and SUS requirements are known, the flat sizes should be finalized. The clocking requirement against polarization losses should be finalized. Folding mirror requirements and design are frequently absent, for example reflectivity and aperture diffraction loss requirements.

(9) Wedges and radii of curvature. The requirements for the pickoff beams and ghost beams need specification. While the CDD specifies symmetric wedges, these are not needed, and the wedges could be smaller than in initial LIGO. VIRGO is gaining experience on unwedged optics which may indicate that not all core optics require wedges. This may save Advanced LIGO in cost or design complexity, and should be investigated. The committee has no firm consensus on whether radius of curvature (ROC) or sagitta should be specified in the requirements, but, whichever is used, we advise COC to recheck the tolerances in the DRD and CDD. The differential arm ROC tolerance should be consistent with the common-mode tolerance. If sagitta becomes the specified requirement, errors in transverse dimension of the measurement should be accounted for. The influence of coatings on ROC should be accounted for in the requirements and design.

(10) Coatings are equally important to Advanced LIGO as the substrates and equally extensively researched, but are de-emphasized in the documents, for example section 3.2 of the CDD. Yet here COC needs to be especially flexible. We may find the pleasant surprise the coating loss can be made ten times lower. Would we change our conceptual design if this happened, and how? Conversely, we may find that coating loss can be improved only at the price of increased absorption or scatter. If so, how do we make the tradeoff? All coating characterization and design philosophy should be discussed in the documents.[12]

(11) Diving into details, there are many specific coating requirements that need amendment. First, the documents should never specify reflectivities or transmissivities in percents, but rather as a number between 0 and 1. This will make the error specification less ambiguous, as in Table 1 of the CDD. Also, please define 'ER' for the sake of the greenhorns.[13] Generally, the ITM reflectivities and transmissivities are stated as having to match within 1%. More precisely, the arm cavity storage times need to match to 1%. This may explain the ambiguity in Table 1 of the CDD. There is mention of coatings required by SUS on the RM's, ITM's, and ETM's, but these coating are never specified, nor are requirements set on them.[14] There is some inconsistency in the ETM transmissivity requirements: as low as possible, 1-10ppm, and less than 20ppm are variously mentioned.[15] There are additional requirements that need to be set: for example, if red-light autocollimators are used for initial alignment then the COC HR surfaces must reflect a useful amount of autocollimator light; the AR coatings for the CP

[12] E.g., the coating requirements in slides 29-30 of the presentation.
[13] DRD, section 4.2.2.3.1 and henceforth.
[14] DRD, table 2 and CDD, table 1.
[15] CDD, section 2.3.1.1; DRD, section 4.2.2.3.4; and CDD, table 1, respectively.

and ITM must be consistent with the pickoff beam being taken from the CP[16]; and the coating should be insensitive to small errors in the top layer thickness.

(12) Charging of optics is a serious issue and a research plan must be rapidly developed. Requirements should be set by SYS (for noise forces) and SUS (for control issues) and mitigation of effects should be studied.

(13) These actions we have proposed, if all adopted, would comprise a significant addition to the development plan, which already bears no strong resemblance to the research being done in COC today.[17] One example: the sapphire pathfinder program refers to two separate phases, the first with half-sized, and the second with full-size optics, yet the rest of the document ignores this distinction, and the cost for special half-size tooling may obviate the advantages these smaller pieces would have for us, though we cannot judge this from the materials at hand. The development document would be more useful if it had some sort of schedule attached to it; what dates it does contain are now obsolete. We are skeptical that there is sufficient manpower, facilities, and money available to do all we would like before a June downselect. Therefore COC should attempt to set some priorities in the development plan; for example, the modeling of gravitational loading strain in sapphire could be seen as not essential prior to the downselect.

(14) The Downselect Document itself needs a clearer plan of what we need to know and are likely to know by the downselect, tabulated, with each factor influencing the sapphire/fused silica decision weighted for importance and likelihood that either material will satisfy requirements, and it should contain the date of the downselect itself. Instrument sensitivity is obviously the primary factor. Figures 1-3 in the Downselect document are useful,[18] but limited. We suggest tracking thermal noise in three frequency bands: low frequency (to compare to SUS thermal and low laser power radiation pressure noises), 100-200 (to roughly estimate NBI sensitivity), and high frequency (to compare to high laser power shot noise). This will allow us to estimate the influence of material choice on other GW searches.

(15) Operations and handling issues should be more fully specified. Cleaning and contamination, referred to above, are a part of this requirement. Though not in the COC scope, the sites should be tested to verify that Class 100 clean room conditions hold, and the two sites should have similar operating conditions. PFA-440 Teflon rather than TFE should be used in the ergonomic arm. Other issues needing more specification include handling, transport, equipment (e.g. carriers) and static control. Most of these requirements should be found in sections 4-7 of the DRD, but much of the information already there cannot be practically applied to core optics. A sample: welding glass fibers to attachments produces UV light, which might damage coatings, and the welding will

[16] If the pickoff is to be taken instead from the ITM, the effect of the index inhomogeneity compensating polish on the diagnostic beam must be analyzed.

[17] For example, reference to 30kg test masses persists in section 3, and sapphire absorption is still assumed to be homogeneous in section 2.2.2.

[18] Incidentally, in figure 2 the nominal fused silica Q should be changed to 100 million. There is enough evidence now to justify this.

not be the tungsten-inert-gas process specified.[19] COC should establish a 'travelers' procedure, each core optic having its own traveler, which defines inspection stops, equipment and instructions needed, and allowing for measurement comparisons between LIGO and vendors. Do we need a plan to verify the birefringence of the sapphires? There should be separate witness polish and coating samples with large side 2 wedge angles. The ergonomic arm should also be better described in the conceptual design, and a set of testable requirements should be specified. Guards against optic damage due to either accidental slippage or normal use are needed.

(16) Finally, we present a shopping list of typos, glitches, and inclarities found in the documents:

1) The thickness of silica in the downselect Document, section 3.2.1, should be 20cm.
2) Section 2.3.3 of the CDD is tautological.
3) Repair the section numbers in table 3 of the DRD.
4) The DRD has the stay clear area at 1ppm diffraction loss, but the CDD has it as TBD.
5) The last section reference in 4.2.2.3.7 should be 4.2.2.3.2.
6) In table 1 of the DRD, does 'restarted' mean 'scattered?'
7) There are lots of weird symbols in the PDF Downselect Document.
8) Change 'lead' to 'led' in section 2.3 of the Development Plan, and remove the empty section 3.1.3.
9) Section 2.1 of the DRD specifies the TM's as fused silica. Not just yet.
10) Section 2.1 of the DRD refers to table 4 for wavefront distortions, but table 3 is meant.
11) In section 2.2 of the Development Plan, by 'Southern,' is Southern Louisiana University meant?
12) In section 3.3.5.1, 'SOS' should now be 'AOS.'
13) The lowest mode frequencies in table 2 of the DRD are not correct, and the g-factor for the power recycling cavity seems far too stable.
14) In section 4.2.2.5.2 of the DRD, the ROC of the ITM is increased, not decreased, by thermal lensing.
15) In section 4.2.2.2.2.1 of the DRD, the sapphire loss is required to be less than 10^{-7}. How is this consistent with the 200 million Q requirement for sapphire?
16) In section 2.3 of the CDD, is it meant that if silica is the TM material then vendors will also verify homogeneity of TMs?

[19] In the first subsection of section 4.3.1.3 of the DRR, which is labeled 2.1.1.1.1 by mistake.