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Refer to:	L080029-00
Subject:	Response to Comments and Questions on the COC Design Requirements Document (DRD)
Authors:	Helena Armandula, GariLynn Billingsley, Bill Kells, Gregg Harry (COC PDR team) and the COC PDR review committee: Doug Cook, Dennis Coyne (chair), Peter Fritschel, Eric Gustafson, David Reitze, Norna Robertson, Ken Strain, Bill Tyler, Hiro Yamamoto

The review committee and the design team met Feb 14th, 15th, 21st, Mar 3rd and 5th to discuss the COC Design Requirements Document (DRD, T000127-02) and the COC Preliminary Design Document (PDD, E080033-00). This document covers the review of the Design Requirements Document (DRD) as part of the preliminary design review of the Core Optics Components (COC) subsystem of Advanced LIGO. There is a companion document covering the Preliminary Design Document (PDD), which is L080019-01. There is also a committee report on the COC PDR and Glass Procurement/Fabrication Readiness Review, which is L0800xx-00.

While there are many comments and questions, the documents are clearly well developed and nearly complete for the PD stage.

The comments/questions below are presented in sequential order by document section. This document captures the questions and comments of the review committee, as well as the subsequent initial responses to these questions by the design team and final resolution reached after discussion with the committee. The committee's original comments and questions are given below in un-highlighted text or with grey highlighting to signify potentially controversial or uncertain items.

Yellow highlighting signifies comments or explanation pertinent to committee questions, added by PDR team

Red text signifies direct answers (by PDR team) to questions posed by the committee.

Green highlighting signifies that the suggestions or corrections are acknowledged and will be adopted verbatim in a revision to the DRD.

Where needed to bring closure on an issue or discussion topic, magenta highlighting signifies the committee's resolution.

COC Design Requirements Document (DRD)

- 1) A. Use T000127-03 (new revision), not a new document number (i.e. T080026).
Otherwise we have two documents with the same title and unfortunate searchers who happen upon the old document don't realize that there is a newer one (which obsoletes the one they happened upon). Also note that the document & version number on body page headers are not consistent with that on front page.
B. Fix the table of contents.
- 2) Section 2:
 - a. "The original development plan for manufacture and test ... was the COC development plan, LIGO-T000128." Is this an obsolete plan? **Yes!**
The COC team has an action to evaluate whether there is merit in updating the development plan.
 - b. Mention that the scope of this document is limited to the COC optical elements themselves and not the metrology equipment used to verify their performance; The metrology instrument requirements will be covered in separate documentation.
- 3) Section 2.1:
 - a. Change "High reflectance coating applied to surface 1 of each optic." to "High reflectance coating applied to surface 1 of each optic, with the exception of the BS (50/50 coating) and the SRM and PRM (partially transmissive)." High reflectance (HR) was intended to distinguish the critical cavity defining reflective surfaces, not necessarily a "high" reflectance (in accord with industry nomenclature). Strictly each coating is different in its particular reflectance, e.g. the ITMs too would be partially transmissive.
OK, keep terminology as is.
 - b. Add a "TBD" to the gold plating on the CP. One comment on this gold barrel coating: its effect is to decrease (substantially) the emissivity on surfaces applied. This will tend (exact numbers TBC) to increase the mean ITM temperature beyond what is discussed in Q 36 (below).
- 4) Section 2.1.1.1 (and other sections through out the document): In conjunction with the very recent decision to employ stable recycling cavities, we propose that:
 - a. COC should define the requirements for the mode matching telescopes now set within the power and signal recycling cavities. The requirements for the power recycling mode matching telescope (MMT) in the IO DRD only addresses coupling efficiency, alignment and beam steering. IO team members should assist COC. The COC requirements should cover all optical elements of the power and signal recycling cavities.
 - b. IO should have the lead design responsibility for the mode-matching telescope (MMT) designs for the power and signal recycling cavities,

- c. AOS will have no scope in design or procurement of the signal recycling cavity MMT¹,
- d. COC will have procurement scope for the large MMT elements, i.e. PR3 and SR3, and
- e. IO will have the procurement scope for the small MMT elements (i.e. PRM, PR2, SRM, SR2).²

This division of responsibility is documented in a (pending approval) RODA M080038.

- 5) Section 2.2: some acronyms are missing, eg. ESD, FT, HR, CP, OPD, MTTR, CD. In most cases, it's obvious what the abbreviation stands for, but worth including. Some are inconsistent with the text, eg. IO vs IOO.
- 6) Section 2.3.1:
 - a. The title for M040405-00 is "Advanced LIGO Substrate Selection Recommendation"
 - b. E030647-01 has no title and is not in the DCC Will investigate.
 - c. Add P080004-00, Design of the Advanced LIGO Recycling Cavities In already.
 - d. Add T020103-04, Test Mass Material Down-Select Plan
 - e. Add T040199-00, Dimensions for Advanced LIGO Fused Silica Test Masses
 - f. Add T040232-00, Beamsplitter First Elastic Mode Frequency versus Dimensions
 - g. Add E070070, Specification: LASTI Test Mass Handling and Shipping Procedures
 - h. Add T070233-00, LASTI Test Mass Coating Characterization
 - i. Add T070247-00, AdvLIGO Interferometer Sensing and Control Conceptual Design
- 7) Section 3.2.4: Remove the last paragraph stating that there is a possible use of BK7 for some of the recycling cavity elements³.

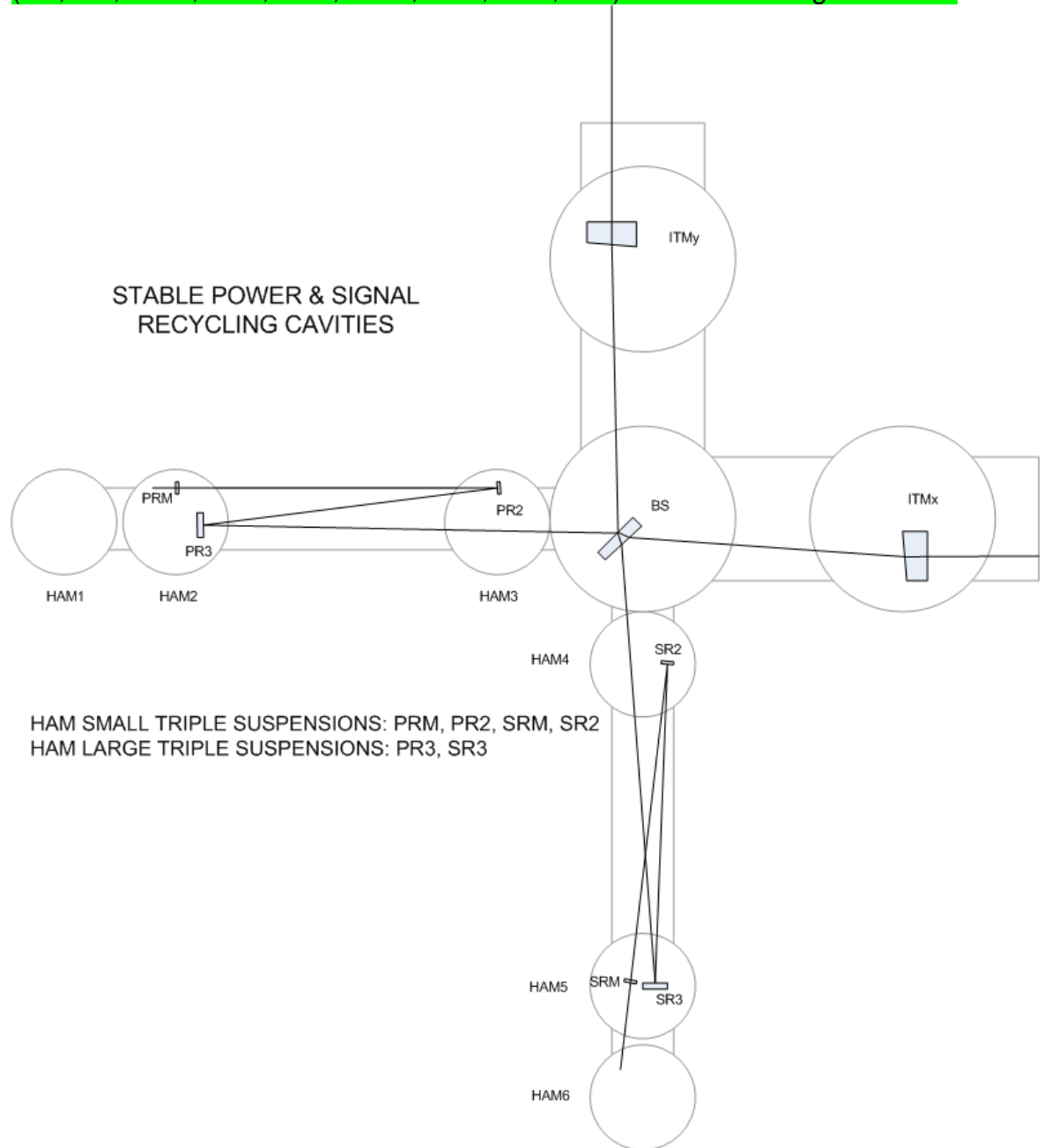
¹ Historically these were to be compact, off-axis parabolic, telescopes, but they are now identical in concept to the input MMT

² This will necessitate a transfer of project funds nominally from AOS to IO to cover the cost of the output MMT optical elements. This accounting transfer should be done in the context of the larger issue of setting budgets properly for the new stable recycling cavity choice.

³ BK7, while better for possible future thermal actuation in the MMT (not baselined), has too much thermally induced absorption for realistic coating absorption levels (~10 ppm) in the PRC. While one could use BK7 for SRM & SR2, this would require unique suspension variants. Since the TCS CP appears to have sufficient authority/range to compensate for residual mismatch, we will use FS everywhere.

8) Section 3.3:

a. Please include a simple diagram showing the COC and IO elements with labels (BS, CP, PRM, PR2, PR3, SRM, SR2, SR3, etc.) similar to the figure below.



b. Remove the parenthetic comment "(LIGO I Type)". The Advanced LIGO wire suspensions are considerably different than the Initial LIGO design.

9) Table 1.

a. Add a row with "surface reflectivity at wavelength(s) other than the carrier", "AOS", "For use in initial alignment", and "Specific mirror reflectivity at specific wavelengths".

Since this is subordinate to other coating requirements, there is no need to

state required reflectance at specific wavelengths as this can be handled in the preliminary design document (PDD).

- b. In the row for "Element mass and aspect ratio", add under the column "Requirement Category", "Thermal Noise". See T040199-00 for the trade-off between thermal noise and diffraction loss.
- c. In the row "Element surface contamination control", by "Lowering of Qs" do you mean "Lowering of optical Qs" (i.e. Finesse) **Yes!** If lowering of mechanical Qs is meant, what is the evidence that contamination (at realistic levels) can degrade mechanical Q?
- d. Add a row for consideration of factors effecting loss in the Michelson cavity and mode matching to the arms. (see next item)
- e. Add a row to address the effect of BS wedge and ROC on astigmatism and resulting CD. Ok, but are such specific items appropriate here? Original intention of such a [cryptic] table was to just outline categories. The committee thinks that these two factors (d & e) are significant that they merit inclusion in Table 1. Either add a row(s) or incorporate into the last column where appropriate.

- 10) Section 4.2.2.1, 4th item: The PRM and SRM can be either concave or convex. In the stable power recycling cavity design presented in the IO preliminary design document (T060269-02) the PRM is convex. The primary reference used for this writing, P080004-00 describes concave only. Change the reference from PRM and SRM to PR3 and SR3 (which are both concave).

11) Section 4.2.2.1.1.1:

- a. not exceed 20ppm : where does this come from? This is the simple single pass clipping/diffractive loss expected from a $w=5.55\text{cm}$ beam at 45° incident on the given BS clear aperture (364mm dia face), then allowing ~factor 2 increase margin. This assessment of the expected diffractive loss of the BS should be given in the PDD (to show that it meets a loss budget established in the DRD) and it should be based on, or reference, the FFT study performed by Hiro rather than just clipping loss.
- b. Are you sure that the total loss in RC is dominated by the AR reflectivity and internal telescope diffractive loss and not the BS size? This is crudely based on RC loss (RT) budget of $2(50\text{ppm} + 50\text{ppm})$ AR; $2(2.5\text{ppm/cm})$ 26cm internal; $2(20\text{ppm})$ 3 scatter; and 37ppm S/PR3 clipping/diffractive amounting to ~490 ppm. This compares then with a similarly estimated BS clipping/diffractive loss of 1-2 (15ppm per two faces) <60ppm. COC should set the allowable RC loss for minimal impact on the interferometer performance. The DRD should then establish loss budgets for the power and signal recycling cavities to achieve the allowable loss. The diffractive loss should be stated as the loss due to the combined geometry of the RC optics (not for example PR3 or SR3 separate from the BS) The DRD should then show that the proposed design meets these loss budgets.

c. BS wedge angle introduces large astigmatic error; 4% when going through (Y-arm to SRM) and 8% when bent (X-arm to SRM). This can introduce increased contrast defect. What are the tolerable limits? This large astigmatic effect due to the proposed BS wedge (0.8°) was recognized just prior to this review. The DRD was not formulated taking this into account. I do not believe that a full analysis of its consequences has gelled yet, nor have possible options to address it (can the wedge be eliminated/reduced?) been appreciated. Certainly the asymmetry of this distortion will contribute to CD. However, at least one estimate of its contribution to an optimally balanced CD would be $\sim(4\%)^2$ possible TBD?

Need to resolve tolerable astigmatism and BS wedge in the final design phase. The loss due to this effect should be discussed and compared to the budget in the design document.

d. BS surface curvature can also introduce astigmatism. What is an acceptable ROC lower limit? A reasonable polished surface flatness specification could be Power or astigmatism < 3 nm (Zernike amplitude) over $\phi=3w$. This would limit BS reflected wavefront astigmatism to < 0.1 times that produced by the proposed BS wedge (in transmission) 4% astigmatism.

Need to resolve tolerable BS ROC based on tolerable astigmatism in the final design phase. The loss due to this effect should be discussed and compared to the budget in the design document.

12) Section 4.2.2.1.1.4: states "AOS design requires that IFO control signals are derived from leakage through several of these FT HR mirrors." Please revise the statement to read "IFO control and alignment signals are required through PR2 (for input MMT alignment, PSL intensity stabilization and the BS pickoff beam) and SR2 (for output MMT alignment and an entry port for the ITMy Hartmann sensor beam)."

13) Section 4.2.2.1.1.5, Fold Mirrors: FM surface curvature can also introduce astigmatism. What is an acceptable ROC lower limit? Same comment as above for BS.

14) Section 4.2.2.1.1.5 Compensation Plates should actually be 4.2.2.1.1.6. Yes: changed

15) Table 2:

a. Since phase map metrology only needs to be done to verify the transmission map, we do not need a wedge angle. This would in turn simplify AOS's job of dumping the associated ghost beams.

b. Recycling cavity mirror dimensions are not correct (75mmx25mm). They should be 150 mm dia. x 75 mm thick (per IO PDD, T060269-02).

c. The mass of the RM (i.e. PRM and SRM) is ~ 3 kg, not 15.6 kg.

d. Note that the thickness is measured at the thick end for wedged optics.

e. The ITM wedge (0.32 deg) is incorrect. What then (had this)? More generally, it may not be necessary and/or appropriate to list parameters which are defined by other considerations outside of COC, such as wedge angles and ROC. For wedge angles one could state the requirement is to be consistent with optical layout requirements defined by SYS. (If one does choose to cite specific values, they will need to be updated to stay consistent with the COC PDD and other

source documents.) On the other hand there is some COC consideration since astigmatism is induced (insignificant in this case.... depending on angles).

- f. The "flat" surface 1 ROC for the BS and FM should be a minimum absolute (unsigned) value.

- 16) Section 4.2.2.2.2.1. Please provide motivation for the $1e-7$ loss limit -- where does this put the substrate Brownian noise in comparison to the coating noise and the science requirements?

Theory predicts $4e-10$ at 100 Hz. There has been skepticism that the theory still holds in this frequency and loss regime. $1e-7$ is a legacy. The best lower limit based on actual Q measuring is about $2e-9$ at room temperature. This is probably a better estimate to include here.

Include this explanation in the DRD.

where does this put the substrate Brownian noise in comparison to the coating noise and the science requirements?

At $2e-9$, the substrate thermal noise is rises to about $8e-25$ strain/rtHz at 100 Hz, a factor of 5 below the combined coating thermal noises. Since this represents an upper limit to the substrate thermal noise, this is felt to be adequate to treat substrate thermal noise as a technical noise source. There is an ongoing effort to measure silica Q in the frequency, surface to volume ratio, and mechanical loss regime closer to the Advanced LIGO case.

Include this explanation in the DRD.

- 17) Section 4.2.2.2.2.2:

- a. Based on current coating values and the Bench code, we think that the per mirror thermo-optic noise is expected to be $7e-21$ m/rtHz @ 100 Hz and not $3e-21$ as stated; Please check. Agreed, the $3e-21$ number is a legacy.
- b. It should be emphasized in this section that the requirement is for the coatings to be designed for low thermal noise, in addition to low absorption and low scatter; A specific numerical target gives context and motivation, but isn't the requirement per se.

- 18) Section 4.2.2.2.2.4: Change "The loss angle and Young's modulus of any contacting material must not cause an increase in thermal noise." to "The contribution to thermal noise, due to the loss angle and Young's modulus of any contacting material, must not exceed $1/10^{\text{th}}$ of the thermal noise of a pristine optic."

- 19) Section 4.2.2.3.1: Arm finesse is 450. Where did the T matching of $\pm 2\%$ come from? This tolerance was more an absolute tolerance meant to indicate a tolerable variation of mean arm finesse.

Our target is to balance the arm power to 1% to limit technical radiation pressure (per section 5.5 of the System Design Document, T010075-00). Ok, will change what is wanted here to a differential, matching tolerance to $\pm 0.5\%$ to assure this SYS criterion. Careful investigation (with coaters) is still needed to determine how realistic this is, especially since it has not been decided whether ITMs should be coated in pairs.

- 20) Section 4.2.2.3.2: PRM transmission will be close to 3% (per Table 5 of the ISC draft CDD, T070247-00).

How did you determine the tolerance? The tolerance is indicated as “TBD”, however the number ($\pm 10\%$) seems reasonable in view of the results of T070303-01 (specifically Fig. 1, with respect to fine tuning the PRM transmission). Should give the basis for the tolerance requirement in the text.

21) Section 4.2.2.3.3. SRM transmission will be close to 20%. (per Table 5 of the ISC draft CDD, T070247-00)

22) Section 4.2.2.3.4. ETM transmission should be specified as 5 ± 1 ppm (an ISC design choice).

23) Section 4.2.2.3.5 – The AR coating reflectivity requirement should explicitly state that the AR coatings will provide adequate light levels when the interferometer is operated in low power mode.

24) Section 4.2.2.3.7:

- a. Replace the reference for the limit of TM diameter to 34 cm from “fabrication exigencies” to “Dimensions for Advanced LIGO Fused Silica Test Masses”, T040199-00. Given fixed TM mass and beam spot radius certainly T040199 specifies. On the other hand there was some compelling sense that ~34 cm dia was at the limit at which fabricators could easily hold surface tolerances, and then given this a 6 cm beam radius was tailored.
- b. We get different ROCs to give spot radii on the mirrors of 5.55 cm and 6.2 cm; namely, ITM ROC 1970 m, ETM ROC 2192 m ($L = 3995$ m). Please check. I used $L=3994.75$ m (section 3.3, realizing now this is given for the folded ifo !) which calculates to ITM ROC=1970.70m, ETM ROC = 2191.18m. For the $L=3996$ m given for the non-folded ifos, ITM ROC= 1971.20, ETM ROC= 2192.04 m. The correct lengths are 3994.75 for the folded interferometer and 3996.00 for the non-folded interferometer. Please base test mass ROCs on these lengths.
- c. The TM ROC tolerance of ± 10 m is relative, not absolute. The absolute tolerances are much higher ($\sim \pm 36$ m). The ± 10 m tolerance discussed in this section is meant to be absolute. Even smaller relative tolerance (hoped for: ± 3 m) can certainly be compensated for by TCS ring heat adjustment. The fact that ± 10 m absolute in the polish fabrication is stringent suggests that the TCS take up at least part of that as required. The criterion assumed is that thermal noise not increase by $> 1\%$ by absolute ROC (cavity mode size) uncertainty, per Fig. 1. This section explicitly states that “a tight but reasonable fabrication tolerance on R_{eff} would be ± 10 m”; This assertion contradicts the PDD. The clarification above indicates that the ROC tolerance is based on a criterion of not increasing the thermal noise by more than 1%. However, the trapezoidal box in Figure 1 (corresponding to ± 10 m) spans more $\sim \pm 3\%$.
- d. The TCS barrel ring heater decreases the ROC of the TM. The proposed polished ROC bias is in the wrong direction. (See f. below): Yes, the direction of ring heater action was appreciated. The concept of the bias was that when entirely cold the ROCs would be slightly non-optimal (by a maximum of < 20 m) but that by the level of cavity power necessary for significantly shot noise (\sim cavity loss) limited science operation, the cavities would self heat to form near

optimal mode shapes. A clear statement of the intent and derivation of the proposed ROC bias should be made, including a derivation of the acceptability of a maximum 20 m non-optimal ROC for the cold case. In addition this choice of biasing the ROC should appear in the PDD not the DRD (this is not a requirement but rather a design choice).

- e. However, we are unsure about the proposal to rely on TCS to achieve the desired ROCs at all power levels. If it's feasible to get the TMs delivered to sufficient accuracy, which it looks like it is, then we shouldn't take this approach. Please interpret Figure 1 for us: what are the ROC tolerances that we should specify to the vendors if we don't rely on TCS for tuning at all powers? In the DRD specify the ROC tolerance needed to achieve the criterion of $< 1\%$ thermal noise increase. In the PDD state the absolute ROC tolerance to be achieved by polishing and the amount to be achieved by use of the TCS. Indicate the expected performance as a function of input power with and without the TCS functional.
- f. Similarly, we're not convinced it's a good idea to polish the ROCs at 10 m under the desired values (which could be 20 m under with the proposed tolerance). The concept here was that at least some such offset would be advantageous. For example if the HR surface distortion is $\Delta R \sim 60\text{m}$ at 0.83 MW (T060214-01) in the arms then for low power science (20% full arm power) this offset should be significantly compensated. Then as full arm power is approached minimal TCS ring heating need be applied to bring the ROC back down. See the comment above under 24.d
- g. My reading of the TCS documentation is that the TM ring heater gives $\Delta R = 70\text{ m}$ at 20 W input (which I think is max power), not 116 m ... how do you get your number? Re-checked this with Phil who quotes (equivalent to TCS PDR ?) design requirement max. ring heater bending of $R=35\text{km}$, or ΔR to 1971m ROC surface of 116m OK. Reference G060498-00, pg. 6, for the maximum range of the TCS system as 35 km (at 22 W) or -105 m change in ROC from 1971 m nominal ROC.

25) Section 4.2.2.3.8.

- a. We assume that the length adjustment of the telescope is an initial static adjustment for the cold (low power) case and that there is no proposed requirement to dynamically adjust the telescope length. Please make this explicit in the text.
- b. Don't understand the bottom line of this section; We would expect to read the proposed ROC tolerances for all (6) recycling cavity optics.
- c. The beam heating ROC change of 0.16% relative for the RM doesn't look right (I get a much smaller number, even for 10 ppm absorption). This number (0.16%) is found by scaling the arm HR surface residual "dimple" ($\sim 60\text{nm}$ height over beam spot) due to beam heating down to RC power and PRM HR spot size (per the PRM design in LIGO- P080004-00). With the COC transmission values in the ISC CDD (T070247-00, Table 2), the power recycling cavity factor is 45.8. With 125 W maximum input, the power on

the PRM is 5730 W. The PR telescope design given in G080113-00 has a beam size at the PRM of 1.75 mm and a PRM ROC of 8.22 m. Using Winkler's formulation for the sagitta change due to surface heating, and assuming a 10 ppm absorption, the sagitta change is 1.8 nm or ~1%. Please check this calculation.

- 26) Section 4.2.2.4.1. The $\sigma < 0.7$ nm spec was based (we think) in large part on FFT simulations of arm cavities. Please show in this document the simulation results that led to this requirement (or cite a document where the derivation is given). This section is not intended as an independent derivation of a ~ 0.7 nm rms Spec. Instead it takes 0.7 nm total distortion rms as a good upper limit candidate estimate (based on much previous, e.g. FFT analysis), and substantiates that this leads to reasonable bounds on performance degradation directly associated with cavity mode distortion: modal mismatch/contrast defect; and possible distorted arm cavity mode incremental edge loss. This section does not address the (probably more significant) prompt loss contribution (for this see 4.2.2.5.1.3) of this regime of distortions (contained in the 0.7 nm total) which cannot [also] contribute to cavity mode change.

Each low order HTM (TEM_{00} basis) was studied, excited by a matched surface distortion of amplitude saturating the 0.7 nm Spec. In all cases resulting contrast defect was acceptable, and the distorted cavity mode had clipping approximation loss < 6 ppm. These are worst case assumptions. An idea of actual contribution of these very lowest order modes to total surface distortion rms can be had by studying actual LIGO size/polish surfaces. For example the CSIRO pathfinder optic has a WYKO central $\sim 3w$ Dia. surface rms = 0.886 nm (tilt, power subtracted). Of this the lowest order surface distortion terms (astigmatism, coma, and Z8 spherical) contribute 0.624 nm (70%). This is a typical situation found from maps of our best mirrors.

From Hiro Yamamoto:

Regarding the diffractive loss vs roughness requirement, my FFT study differs from Bill's modal analysis to some extent. By generating surface with spatial spectrum f^{-2} , the rate that the diffractive loss per arm > 40 ppm is 5% for $\sigma = 0.5$ nm, while it is 50% for $\sigma = 0.7$ nm. This is the result keeping Zernike term ≥ 5 . If Zernike terms ≥ 6 are kept, i.e., roughness is more from shorter wavelength, the rate to have diffractive loss ≥ 40 ppm becomes 10% for $\sigma = 0.5$ nm and 75% for $\sigma = 0.7$ nm. So, the requirement of 0.7 nm is not stringent, but rather a compromise.

The text of the DRD should cite (or include a synopsis of) the FFT and/or measurement results which lead to an rms specification. (Much of the text above could serve as a start on this missing discussion.)

The committee suggests that during the final design phase, the COC team strongly consider re-stating requirements in terms of a limiting PSD for the surface error (or a family of PSDs) as an alternative to the current approach of specifying rms levels in spatial frequency bands (e.g. figure error and microroughness).

- 27) Section 4.2.2.4.2. How bad could the transmission distortion be for the ETM trans beam? Without some test specification stipulated for the blanks (and/or AR polish) this is hard to certainly predict. Nominal supplier specification is only in terms of normal path OPD, which leaves large irregular distortion ($> 1\lambda$ PV between any surface points) a possibility. Typically (LIGO I BS, ITM and Adv. Samples) any large amplitude distortion is substantially as power, therefore not an "imaging" problem.

Action: A calculation will be done (jointly by COC & SYS) to establish the tolerable level of low spatial order errors in transmission through the ETM and the ETM reaction mass. In addition the OPD errors in the initial LIGO optics will be examined by COC to see what should be expected. If needed a specification will be established for the ETM transmitted wavefront error. The requirement for acceptable OPD error will be evaluated for the ETM centering quadrant detector, the Hartmann probe beam and an injected Seismic Platform Interferometer (SPI) beam.

28) Table 3:

- a. If we interpret the first line correctly, the arm-arm match of ITM/ETM ROC is 3 m (+/- or total?) --- if so, this seems inconsistent with the ± 10 m given in 4.2.2.3.7. The ± 10 m discussed in 4.2.2.3.7 was intended as an absolute tolerance. Relative matching was not explicitly called out, under the assumption that it would be even tighter and subsumed under TCS (ring heating) authority. Clarify whether the arm-arm match (1st line in Table 3) is by fabrication or by use of the TCS or both.
- b. What does .00x wrt flat mean? Yes, not so clear. Meant fractional wrt wavefront R_{eff} at the specified optic. $R_{\text{eff}} = 1971$ m. Clarify in the text.
- c. What's the definition of micro-roughness? (spatial wavelength range) Define micro-roughness in the text.
- d. Please compare these specs (for the TMs) to the pathfinder polisher specs -- some of these are different, I think; why? The pathfinder serves as the experimental basis for achievable optics performance. Cite the pathfinder specification and include a explanation/reason for any differences (either in the DRD or in the PDD). See also the note under item 26 regarding exploring a PSD specification as an alternative to specifying rms levels in spatial frequency bands (e.g. figure error and microroughness).
- e. In general the basis for these requirements is not documented. Cite other documents, include results (e.g. FFT analyses) or supporting rationale.

29) Section 4.2.2.4.3: It is stated that thermally induced birefringence effects have been studied, found to dominate over intrinsic material birefringence but to be small relative to beam heating OPD phase distortions. Has thermal stress birefringence in both the substrate and the coating been considered? No! (except that the coatings are carefully annealed at temperatures far higher than seen in LIGO service) In the final design phase re-look at the birefringence effects and include the results of these studies, or cite appropriate references (in either the DRD or FDD as appropriate).

30) Section 4.2.2.4.4: The astigmatism due to the BS wedge can introduce ROC change by 4% (X-arm to SRM 8%, Y-arm to SRM 4%) and a beam size change of 2% (each direction). Rough mode coupling gives 10^{-2} to 10^{-4} mode mismatch. So the CD may need to be revisited. See question 11c above: this was not considered in the first DRD version. See action cited under 11c above.

31) Section 4.2.2.4.6

- a. Include FFT results or cite reference. The same peripheral break point diameter problem was faced for LIGO I. At that time extensive FFT runs were performed

specifically to address this question. Standard simulated mirror surface maps (essentially the same as used in Bochner's thesis work) were rescaled or replaced with "noise" in this peripheral region. At least as much tolerance relaxation as required here was adopted from that work for the LIGO I DRD. These specific modelings can be presented on request.

- b. Last sentence: "...(<2.1 nm rms requirement, Table 3)". There is no 2.1 nm rms values called out in Table 3. Should this be <3.0 nm rms? Will reconcile: hard to be numerically precise on this, however the more conservative ~2.1 nm ought to be reasonably achievable by polishers as well.

- 32) Section 4.2.2.5: We suggest just providing overall loss limit requirements in the DRD and then the breakout into instrument ranges in the PDD. See also the comment on re-stating requirements in terms of a PSD above under (26).
- 33) Section 4.2.2.5.1. The claim is made that 5 ppm of scattering on an AdL coating has been demonstrated (last sentence). The LASTI optic coated at LMA shows ~15 ppm of scattering. CSIRO data indicated ~25 ppm loss for the middle range roughness (~1 mm wavelength). Please cite the data supporting 5 ppm scatter loss. Indeed this example (spare LIGO MC mirror #MCCM4K01) of 5ppm achieved is not typical, but represents a feasible goal demonstrated by vendors LIGO already uses. This loss is in the micro-roughness regime so there is no reason to believe we cannot successfully specify it to the large mirrors. Include this explanation (caveat) on the demonstrated scatter loss in the DRD.
- 34) Section 4.2.2.5.2. Mean scatter of < 5 ppm ... again, please show the data. OTF measurements, including T070233 show most of the large scale optics have large angle losses > 10 ppm. See 33, above.
- 35) Section 4.2.2.5.3: In several of these questions pertaining to the dominant [scatter] loss in the advanced LIGO arms it can help to appreciate what the incremental IFO performance loss would be for ~1-10s ppm arm cavity loss variations. One illustration of this is (Figure 2.... inserted here): We agree that a discussion of the (in)sensitivity of various sources to arm cavity loss should be included in the DRD in order to put the loss budget goal of 75 ppm into proper context. The motivation for the 75 ppm loss budget is that this is the best that we might reasonably expect to achieve.

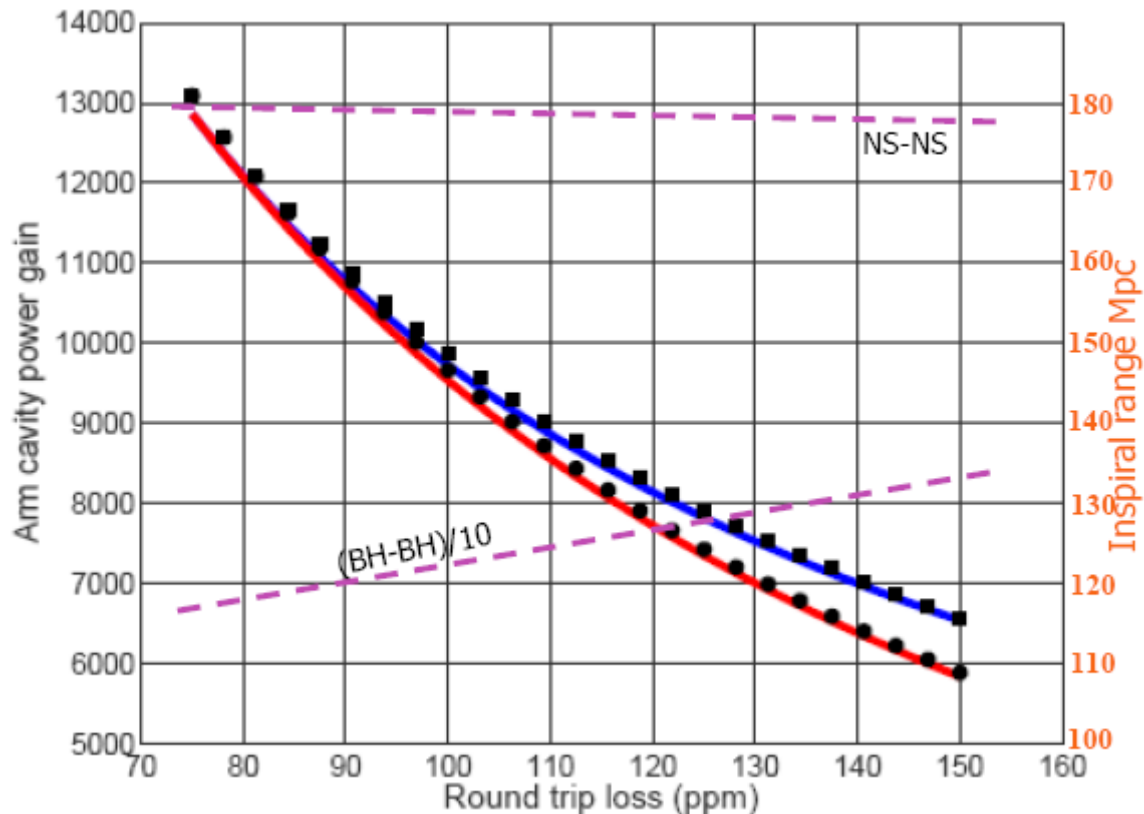


Figure 2. All points are for fixed (125 W) IFO input power. Points and solid curves (from LIGO T070303-00) show the sensitivity of arm power to loss. However actual detection (NS, or BH binary) sensitivity is hardly dependent (dashed curves from full Bench62 model of with current advanced LIGO parameters). Of course, highly shot noise limited detection modes (e.g. SRC optimized narrow band ~1 KHz) depend more sensitively on loss (1 KHz narrow band tuned SRC strain degrades ~0.5%/ppm).

- What is 'mid-large scale' ? These are all scattering scales not explicitly counted already as contributing to prompt, "micro-roughness" loss of 4.2.2.4.1-2. The important point (for consistency) is that the low end of this scale be clearly within the total prompt loss regime and that there be no double counting (of total surface rms distortion already included in 4.2.2..4.1-2). If the scattering loss requirements are still presented in discrete bands (see comment under (26) above), then include this definition of "mid-large scale" into the text.
- What 30 ppm entry on Table 3 -- I think you mean Table 4, but I don't see the 30 ppm entry. Please clarify. **Yes: 36 ppm in Table 4.** Note that FFT simulations, under various assumptions, indicate that roughness with $\sigma = 0.7$ does contribute substantial (several 10s of ppm) loss. Yes, this specification and conclusion as an upper limit is in agreement with that. Keep in mind that this 0.7nm includes all distortions (other than power) so that a large portion contributes mainly to modal distortion (section 4.2.2.4.1) and not prompt loss. Typical LIGO mirror surface maps decompose (example in comment on Q 26 above) into a few low order aberrations contributing $<1/2$ the rms. Assuming

the remainder bounds the prompt loss of this section, we just reach the limit of table 4. Though this only demonstrates "0.7nm" as being marginally sufficient, additional appeal to Figure 2 (above) indicates weak consequence.

OK. Just correct reference to value in Table 4.

- 36) Section 4.2.2.6: It is stated that the absorption goal values given will result in ~11 K increase above [radiative] ambient. Does this include the heat deposited by the TCS? **Yes!** How much excess absorption caused by contamination on the coating can we compensate with the TCS? **I believe the max ring heater deliverable power can compensate ~3x that anticipated by full design cavity power (0.83 MW) x 0.5ppm surface/coating absorption.** If the excess absorption were at the maximum the TCS could compensate at what temperature would the mirror then be? **I estimate: 3x (1.5°K beam heating + 5.4°K ring comp. heating) =21°K (see T060214-01).** Do we run out of authority on the TCS before the properties of the substrate and the coating begin to change outside of our design limits? Is the "accumulated absorption surface 1" in table 4 the excess absorption due to contamination? **Yes, that is its meaning.** Over what time frame? **1 or 2 years.**

Include a synopsis of the above into the text in this section, with the conclusion that the TCS system as planned should be able to accommodate accumulated absorption while not causing the COC to exceed it's requirements.

- 37) Section 4.2.2.6.1. All bulk material in the RCs are to have ultra low absorption, <0.2 ppm/cm, not just the BS. **We only specify this special FS for CP,BS and ITM not P/SM elements.** OK, no change.

- 38) Section 4.2.2.6.4 The AR reflectivity for the BS, which is used to deliver the ITMx pick-off beam, should be marked as TBD. **Revise accordingly.**

- 39) Section 4.2.5

a. Change

"Given the COC operational environment (UHV) it is anticipated that the only mechanism for dealing with contaminated elements will be to change them out. However every effort will be made to investigate and develop possible in situ cleaning procedures."

to

"Given the COC operational environment (UHV) it is anticipated necessitating removal for the purpose of cleaning is impractical on a routine operational basis. Therefore every effort will be made to investigate and develop in situ cleaning procedures."

Revise accordingly.

- b. The down time goal of 1 month/year for cleaning COC optics = 8% does not seem to be good enough. Unless we have proof or convincing evidence that we can't do better within reasonable cost limitations, I'd set this level to at least 2 times better as a goal. **OK, some such tighter revision will be adopted.** **Revise accordingly.**

- 40) Section 4.2.6.1.1 surely operating conditions are tighter than stated in Table 5. It would be useful to put expected in-vacuum temperature range based on TCS and main beam heating. ~~Also state expected conditions for metrology based on available facilities.~~ Admittedly this table was some typical industry "safety" (against damage) Spec. It was not meant to critically limit actual IFO operating conditions. In fact though the COC elements alone are probably the least environmentally (heat, humidity) sensitive components. For instance, as soon as fiber suspension blocks are attached there will be a far more stringent limit.
Revise with realistic operating environmental conditions for the COC optics.
- 41) Section 4.2.7: The reference E070293-00 is incorrect – please revise with the correct reference. Yes, should be T070293-00
- 42) Blank sub-sections under 4.2 and 4.3, such as "Atmospheric Pressure", "Interchangeability", "Human Engineering", etc. should be marked as "Not applicable".
Revise accordingly.
- 43) Section 4.3.4, the LIGO System safety plan title and revision are not correct, "LIGO System Safety Plan" M950046-D.
Revise accordingly.
- 44) COC has elected to cover the last sections of the requirements guidelines (defined in [T950065-A](#)) in the PDD rather than the DRD (specifically the sections starting with "Documentation"). This is acceptable. The Table of Contents should be fixed to reflect this change (and to delete section 4.4 Assembly and Maintenance).