Thermal Compensation System Design Requirement and Conceptual Design Review Presentation

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Thermal Effects in the Interferometer

- ROC change of the TM HR surfaces→arm cavity mode structure change
- Thermal lensing in the PRC→RF sideband power and overlap reduction
- Thermal lensing in the PRC→reduced arm power coupling
- Thermal lensing in the SRC→reduced GW sideband extraction efficiency
- All of the above in differential mode→contrast defect and increased power at the dark port

Other Uses for TCS

- Thermal tuning of arm transverse mode structure to control acoustic parametric instability
- Correction of curvature errors in delivered optics

Arm Cavity Mode Structure

The requirement (3.1.2.1)

» *TCS shall be able to adjust the arm cavity spot size by adding up to 35 km thermal radius of curvature to all test masses' HR faces.*

Reviewers' comments:

We would like to see more backup information/calculations for the stated requirement. E.g., it appears to us that a factor of 2 margin has been applied to come up with the 35km number -- is this correct? Including information on the absorbed power and thermal distortion in the first paragraph of this section would be useful; also a reference to where the calculation of the thermo-elastic deformation can be found. We strongly suggest that the thermal effect not be expressed as ROC, but rather as diopters or saggita change.

Arm Cavity Mode Structure, cont.

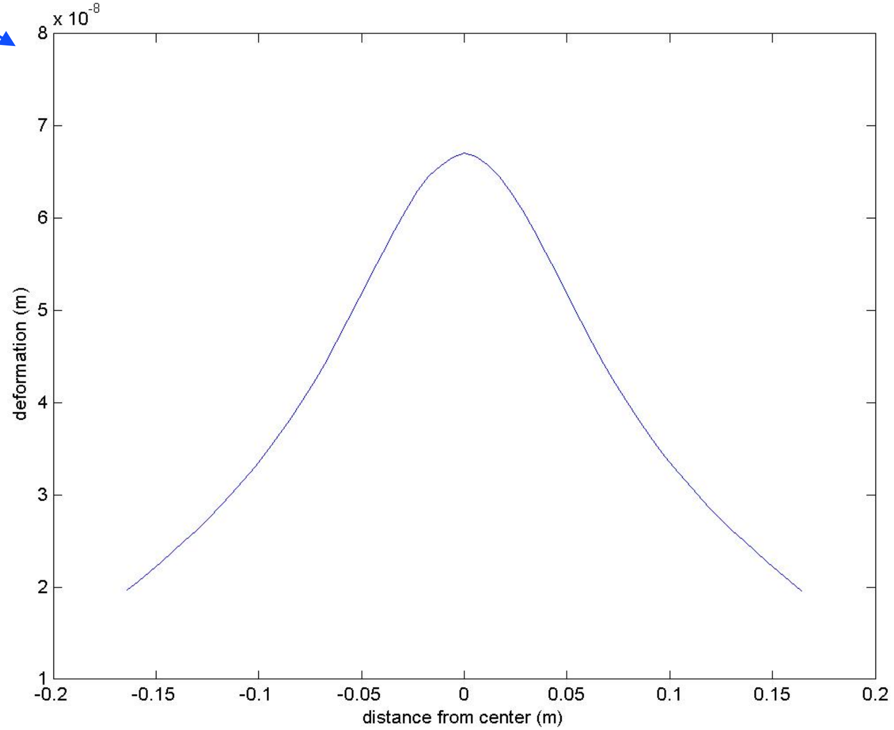
- The fundamental assumptions are:
  - » 6.0 cm cold spot size on the test masses
  - » .5 ppm absorption in the coating
  - » 2 ppm/cm absorption in the substrate
  - » 850 kW circulating arm power
  - » 2100 W traversing ITM substrate (counting both directions)
  - » Thus, .425 W absorbed in coating, .084 W in substrate

All these assumptions are specified in sections 2.5.1-3 (though the 850kW, 2100W figures are loosely calculated from numbers in 2.5.3.)

Arm Cavity Mode Structure, cont.

- The thermal distortion of the TM surface (basically the same for ETM and ITM) is shown in Figure 3 of the CDD, and here

Applying this distortion to both mirrors in a cavity leads to ~5.3 cm spot size, about the same as 70km (or 1.4e-5 diopter) curvature. Requiring TCS to provide down to 35km (or 2.9e-5 diopter) curvature provides a margin of ~2x.



Arm Cavity Mode Structure, cont.

- *Designing for a factor of 2 margin over the assumed absorption level is prudent, but we wonder if it is sufficient margin. Of course at some level the whole system relies on low-absorption optics, and we will have to clean or replace optics if they aren't good enough; but, we would like to know how feasible it is to design the TCS to handle up to 3x, or 4x, the assumed absorption.*
  - » TCS is already planned to provide a large degree of compensation compared to previously demonstrated values. If the absorption is 2x nominal, thermal lensing in a marginally stable SRC will be very difficult to correct, and the ring heaters will reach their limit (see later).
  - » This question is probably connected to the stable recycling cavity issue.

RF Sidebands in the Recycling Cavities

- The requirement (3.1.2.2):
  - » *TCS shall compensate the thermal aberrations in the recycling cavities sufficiently that the RF sideband power in the recycling cavities does not decrease as the input laser power is increased, up to an input laser power of 120W.*
- Reviewers' comment:
  - » *This requirement should specify that the RF sideband power remain (principally) in the carrier mode (ie, it's not enough that the SB power does not decrease, it must also overlap with the carrier).*
- Our response:
  - » The requirement flows down from ISC, the subsystem that uses the RF sidebands. Is ISC happy if the comment is incorporated?

Dark Port Power Coupling

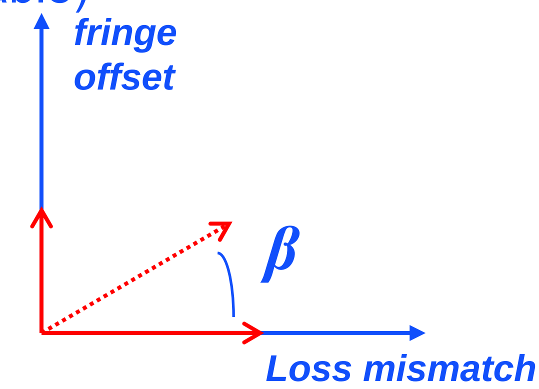
- The requirement (3.1.2.4):
  - » *TCS shall maintain the arm mismatch component of the homodyne dark port signal to within 1 mW of its nominal value.*
- Reviewers' comment:
  - » *We are not completely sure we are interpreting this requirement correctly, so please be prepared to clarify.*

Dark Port Power Coupling Clarified

- The DC readout scheme relies on weak carrier light to provide the homodyne LO for GW sideband detection. This reference light is partly from arm mismatch and partly from arm detuning. The ratio determines the homodyne phase angle.

From ‘DC Readout for Advanced LIGO,’ P. Fritschel (G030460-00)

- Two components
  - » Carrier field due to loss differences (not controllable?)
  - » Carrier field due to dark fringe offset (controllable)
- Loss mismatch component
  - » Average arm round trip loss: 75 ppm
  - » Difference between arms: 30 ppm
  - » Output power due to mismatch: 1.6 mW



- Detection angle, β
  - » Tuned by adjusting fringe offset
  - » Broadband (NS-NS) optmimum:
    - – Fringe offset power: approx. 0.3 mW
    - – Differential arm offset: approx. 1 pm
  - » Can tune from 0 to 80 deg with 0-100 mW of fringe offset power

TCS is required to maintain this value

GW Sideband Extraction Efficiency

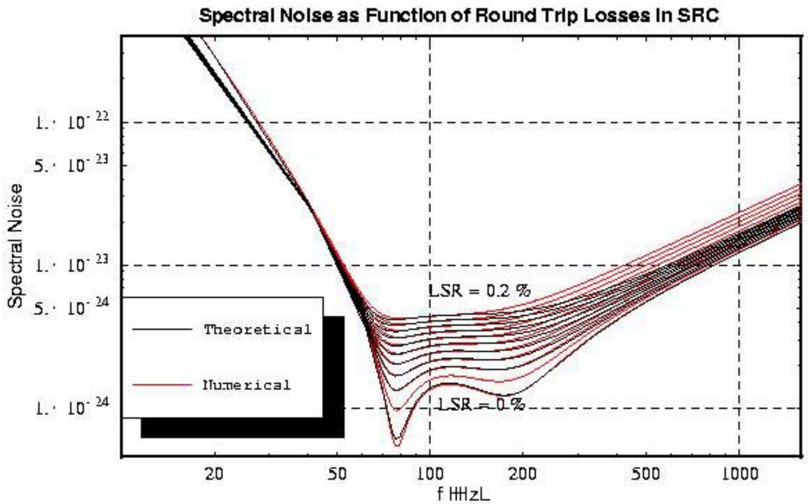
- The requirement (3.1.2.5):
  - » *TCS shall maintain the extraction efficiency of the gravitational wave sidebands through the signal recycling cavity to the dark port to at least 95% of its nominal value.*
  - » Plus from 3.1.2.6: *A 0.1% round trip loss from the signal recycling cavity causes 5% loss of gravitational wave sideband signal at the dark port.*
- Reviewers' comment:
  - » *What is the source of the statement: "A 0.1% round trip loss from the signal recycling cavity causes 5% loss of the gravitational wave sideband signal at the dark port" ? Check this against the result given here:*

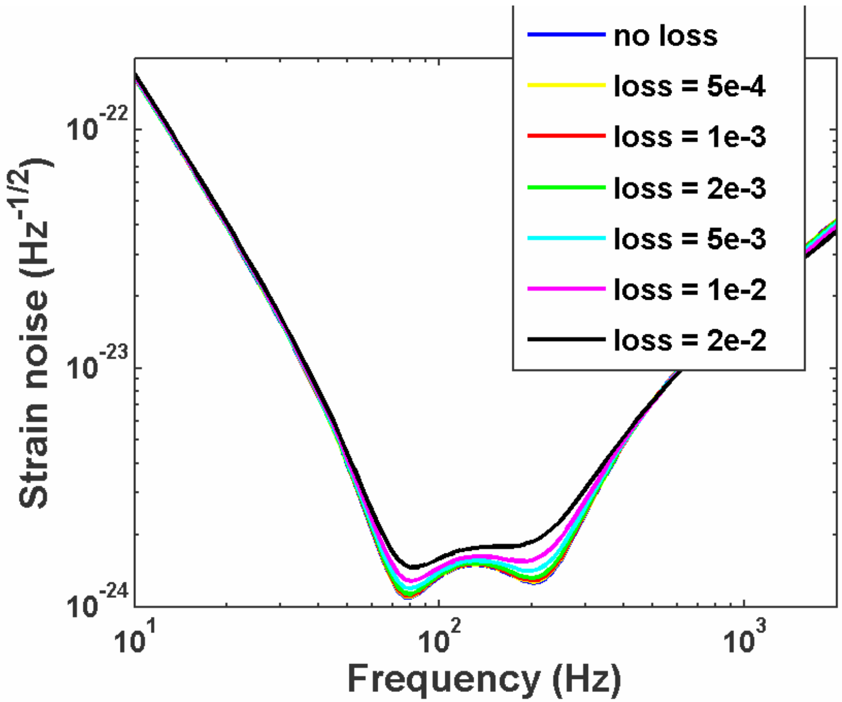
    http://ilog.ligo-wa.caltech.edu:7285/advligo/SignalRecyclingCavityLoss
    which suggests a much larger RT loss is allowable.
- Our first response:
  - » The basic requirement that 95% GW sideband extraction efficiency has escaped comment. Is it truly satisfactory?

GW Sideband Extraction Efficiency, Cont.

From *http://ilog.ligo-wa.caltech.edu:7285/advligo/SignalRecyclingCavityLoss*:

Both plots come from Tom Corbitt's code- the earlier one (below) was used in estimating acceptable loss, and was in rough (factor 2) agreement with estimates by James Mason and Yi Pan. Still, this needs better modeling.





From 'Detailed Report on Thermal Compensation Effects in Advanced LIGO'

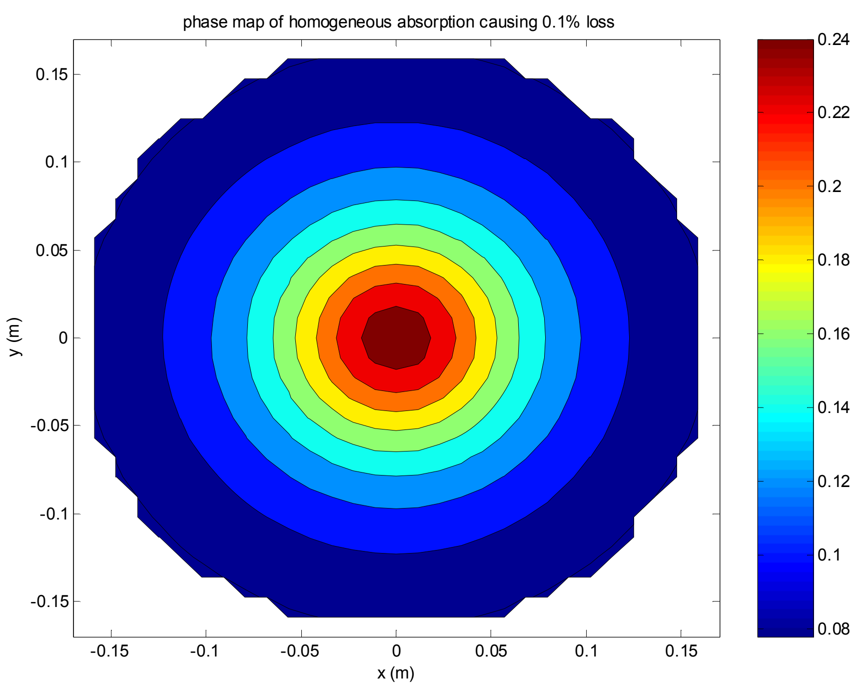
Section 3.1.2.6: Quantitative estimates of the thermal compensation requirements

- From the DRD:
  - » *Based upon the thermal modeling reported in document LIGO-T-060068-00-R, the level of optical path variation that causes 5% loss of the gravitational wave sideband extraction efficiency in a marginally stable signal recycling cavity is approximately .08 radians for either homogeneous absorption or a single point absorber.*
- Reviewers’ comment:
  - » *Also, please amplify the argument that point absorbers have about the same effect as homogenous absorption; there must be some stipulation that the ‘point' be near the beam center.*
- Our response:
  - » Yes, a central point absorber is the worst case.

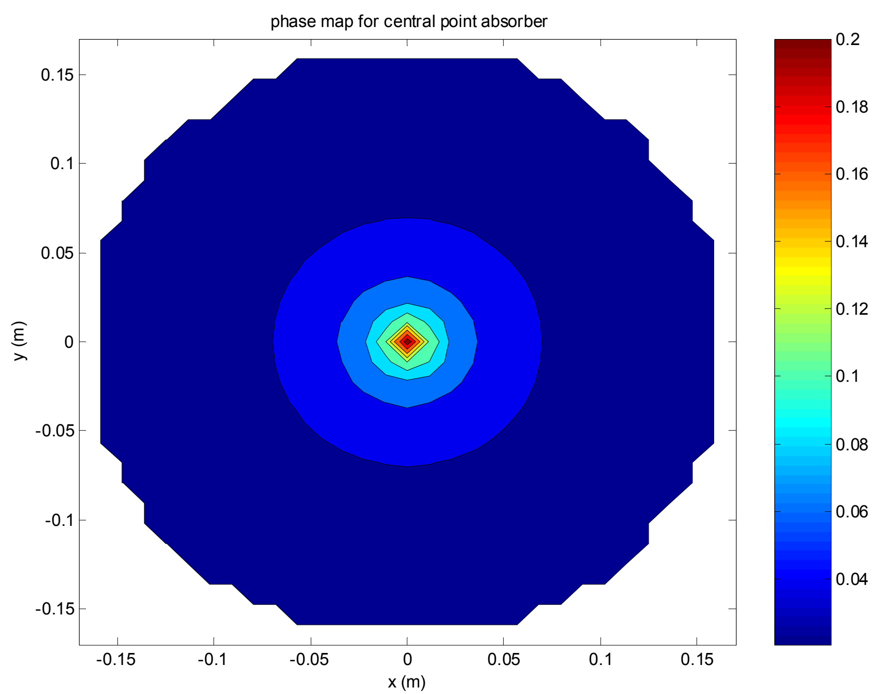
Homogeneous Vs. Point Absorption

Both phase maps scatter the same 0.1% power from the carrier mode-

Homogeneous absorption



Central point absorption



TCS Noise Requirements

- **From Section 3.1.3.1 Compensation Plate Noise Motion**
  - » *The noise injected by an individual CP is injected only into a single arm of the recycling cavities. Therefore, its injected noise has a similar effect as Folding Mirror noise, and must meet the same requirements. For reference, the longitudinal displacement noise requirement for the Folding Mirrors is 2x10-17 m/√Hz at 10 Hz, falling to 6x10-19 m/√Hz at 100 Hz.*
- **Reviewers' Comments:**
  - » *Suggest this heading is changed to 'Compensation Plate Motion', or 'Compensation Plate Noise' (we weren't sure what 'noise motion' was supposed to mean).*
  - » *The statement that the CP noise has a similar effect as folding mirror noise is puzzling, as the coupling from optic motion to path length change is very different for the two.*

TCS Noise Requirements, cont.

- Our Response:
  - » We'll change the title.
  - » The comparison of CP and FM noise is for phase noise- in both cases, only in the recycling cavities, and only in one arm. The sensitivity to CP <u>displacement</u> noise is much lower.

TCS Noise Requirements, cont.

- Reviewers' Comment:
  - » *The displacement noise slope, 1/f^4 or faster, is for seismic noise only, but the suspension thermal displacement noise does not fall so fast. Has the 1/f^4 slope been used to constrain any noise contributions? If so it may be overcontraining the design.*
- Our response:
  - » The 1/f^4 slope is mentioned in the assumptions section of the DRD. The suspension noise budget for the test masses does not rely on the 1/f^4 slope to constrain the noise for ring heaters acting directly on the test masses. In the CDD, the requirement is derived based upon the suspension longitudinal thermal noise. This will be made more explicit in the CDD and the requirement corrected in the DRD.

TCS Noise Requirements, cont.

- Requirement, from 3.1.3.3:
  - » *The TCS sensors shall not inject more than 0.3 mW of DC optical power to the dark port detector. Within the Advanced LIGO band, the TCS sensors are required to not scatter more than 1/10 the SRD light power.*
- Reviewers' comment:
  - » *What is '1/10 the SRD light power' ? Why should there be any TCS sensor light at the dark port?*
- Our response:
  - » The phrase '1/10 the SRD light power' is incorrect. What should be written is "Within the Advanced LIGO band, stray light scattering from the TCS sensors must be consistent with the overall Stray Light Control requirement that phase noise resulting from light scattered back into the IFO from moving surfaces not exceed 1/10th the Advanced LIGO sensitivity."
  - » The dedicated sensor probe beams are on-axis, and therefore mix with the main IFO beam, although they are well separated in wavelength. They must therefore be present at the signal port at some level.

TCS Noise Couplings

- *Reviewers:*
  - » *We're not sure that we follow the estimate of heater noise injection on the test mass, so we'd like that gone over for us. We would like to see a 'noise budget spectrum', for both the test masses and CP, showing the various expected TCS noise terms vs frequency.*

TCS Optical Characteristics

- Requirement, from 3.1.5:
  - » *The total surface reflection loss from the compensation plates shall not exceed 100 ppm. Ghost beams from these surfaces shall be captured on baffles.*
- Reviewers' comment:
  - » *Total CP reflection loss < 100 ppm. Is this round trip? If so, each surface would need an AR < 25 ppm, which sounds un-feasible. Point to discuss.*
- Our response:
  - » Given the 0.1% loss requirement in the SRC- which is under review- it seems prudent to limit the loss at AR faces to much less (1/10th) than this value. This is a round-trip loss.

System Interface Requirements

- From section 3.1.6.1.1:
  - » *Due to severe space limitations, the compensator plates will be suspended from the recoil pendulums of the ITM suspensions by metal wire loops.*
- Reviewers' comments:
  - » *Should also include here the requirement: CP cabling must not short circuit the isolation provided by the quad suspension.*
  - » *A drawing/sketch of this interface would be quite useful.*
- Our response:
  - » We expect the cabling to be to the ring heater, and will specify that it not short circuit the TM isolation
  - » The precise layout of the CP and ring heater is quite difficult and is now being undertaken in concert with SUS.

Stay Clear Zones

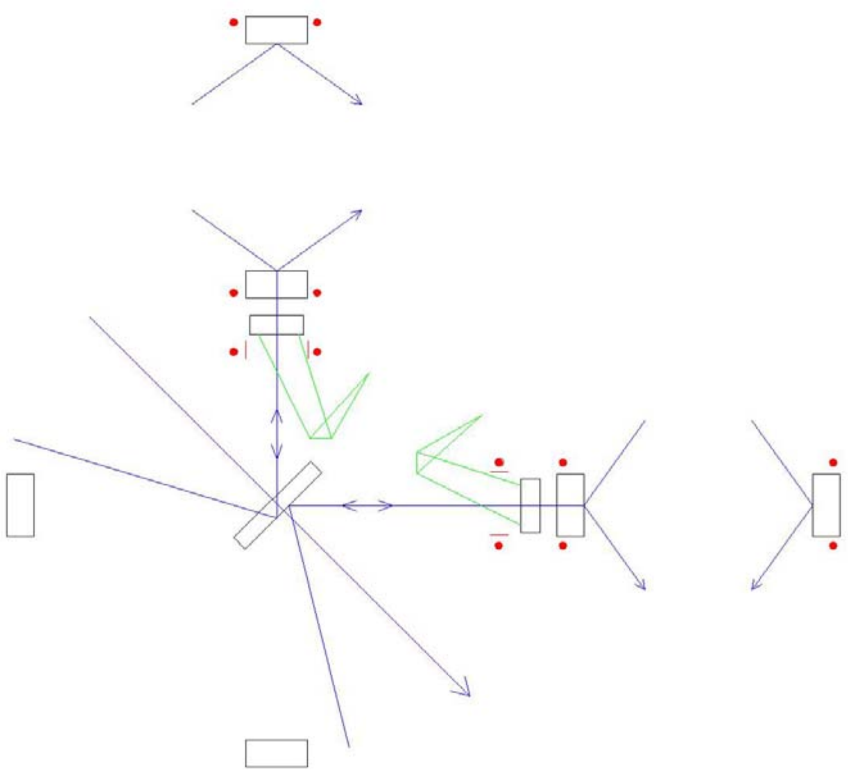
- Requirement, from 3.1.6.1.4:
  - » *The ring heater and shielding for the compensator plates will stay outside the scatter zone for the power recycling cavity beam.*
- Reviewers' comment:
  - » *What is the 'scatter zone for the power recycling cavity beam' ?*
- Our response*:*
  - » This is the region within the shielding provided by the elliptical baffle at the ITM.

Conceptual Design: Overall TCS Strategy

Layout of thermal compensators and thermal compensation sensors. Red dots and lines: ring heaters and shields. Blue arrows: optical path sensors (Hartmann sensors or Fizeau interferometers). Green projections: carbon dioxide laser heaters.

Reviewers' comment:

The idea of providing thermal abberation sensors for all (6) important beam paths or surfaces is a very nice one, in principle. However, the committee looks at the complexity of the hardware required to implement these sensors and wonders whether it is worth it. Point to discuss.



Overall TCS Strategy

- Reviewers' comment:
  - » *Here's a comment on this issue from Guido: Most important quantity is sensitivity. Phil seems to believe that the most important diagnostic information for the TCS to improve the sensitivity is likely the mode profile of the interferometer beam. Thermal deformation sensors for individual optical components are then used to guide the TCS while it tries to improve the mode profile until the phase camera signals are making sense. Then they will be used to improve the sensitivity. If this staged or hierarchical system is the idea, it should be described in greater detail because it also sets how sensitive each sensor stage has to be. What is generally missing is an analysis/estimation which sensing stage can reach which level of thermal compensation.*

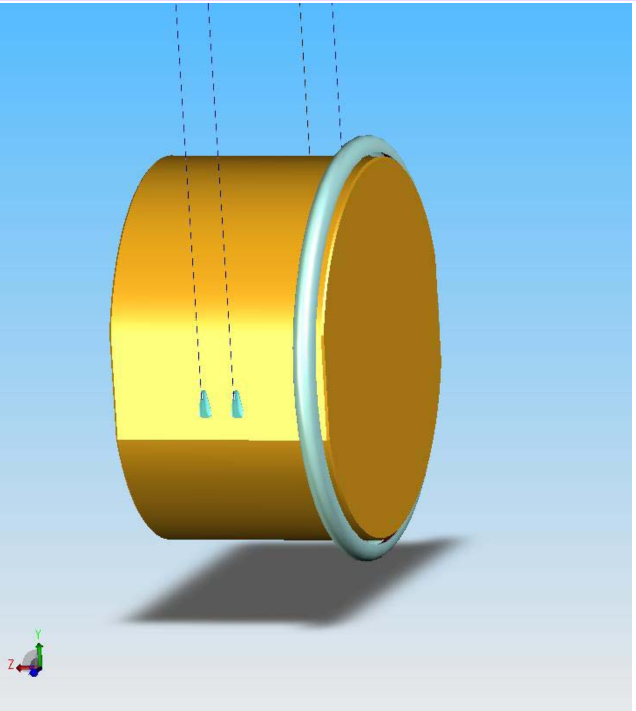
Overall TCS Strategy

- Reviewer comment:
  - *Basic idea: Phase Cameras for the mode profile of the main IFO beam, dedicated sensors for subsets of optics. Dedicated sensors can further be separated in on-axis sensors and off-axis sensors. Makes sense but performance in terms of sensitivity and dynamic range for these sensors is missing.*
- Response:
  - Sensitivity: λ/1000 for on-axis sensors, λ/64 for off-axis
  - Dynamic range: not specified in documents but can be set by uncompensated aberrations to 800 nm for on-axis sensor, 50 nm for off-axis
  - Phase camera sensitivity and dynamic range yet unspecified.

Overall TCS Strategy

- Reviewers' comment:
  - » *We wonder if it wise not to provide compensation for thermal lensing in the beamsplitter. Another point to discuss.*
- Our responses:
  - » Ryan Lawrence found that the BS thermal lens was smaller than the likely differential thermal lens between the arms, and his models gave good IFO performance without acting on the BS itself.
  - » The BS has an asymmetric thermal profile and needs a very large clear zone around it for the 45°-incidence beams from both faces, making a shielded ring heater approach seem very unpromising.

Test Mass Ring Heaters



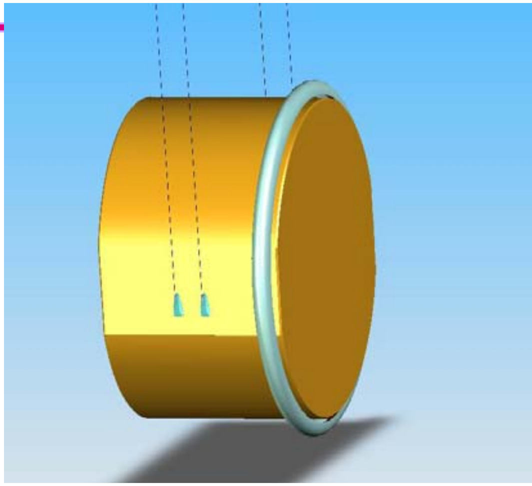
- Any compensation inside the arm cavities must be applied directly on the test masses:
  - » Arm cavity mode shape
  - » Transverse mode tuning for acoustic parametric instability suppression
- Noise requirements on these actuators are severe and unlikely to be satisfied by CO_2 lasers. Ring heaters essential.

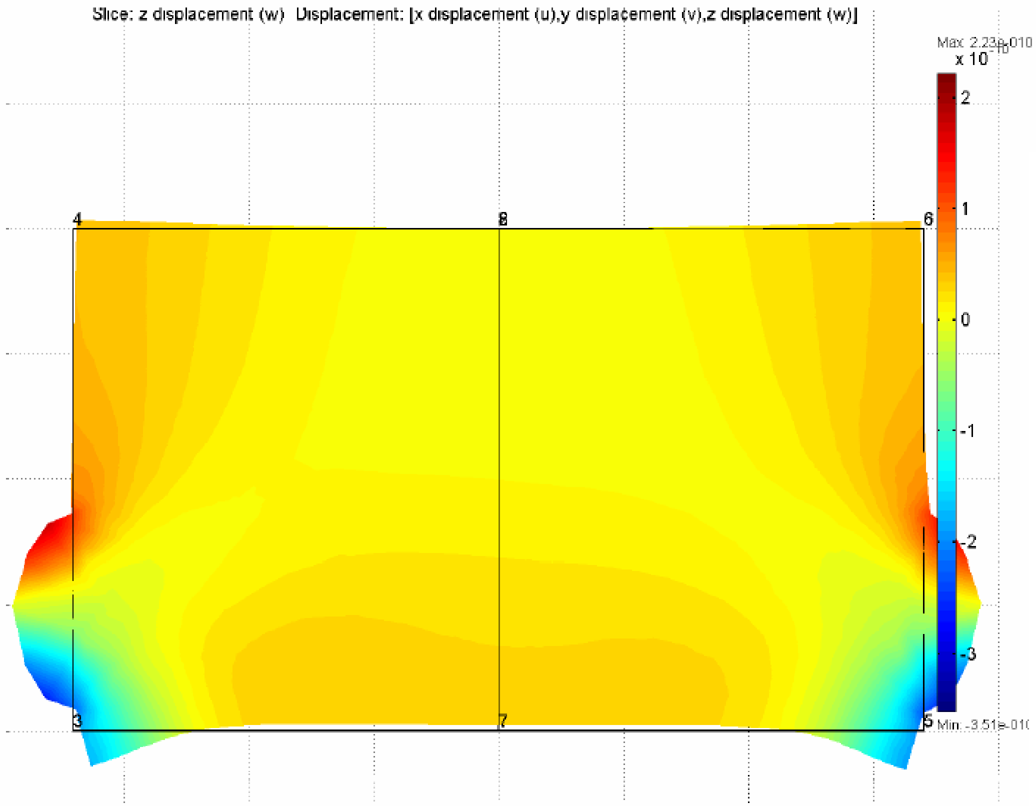
Test Mass Ring Heaters

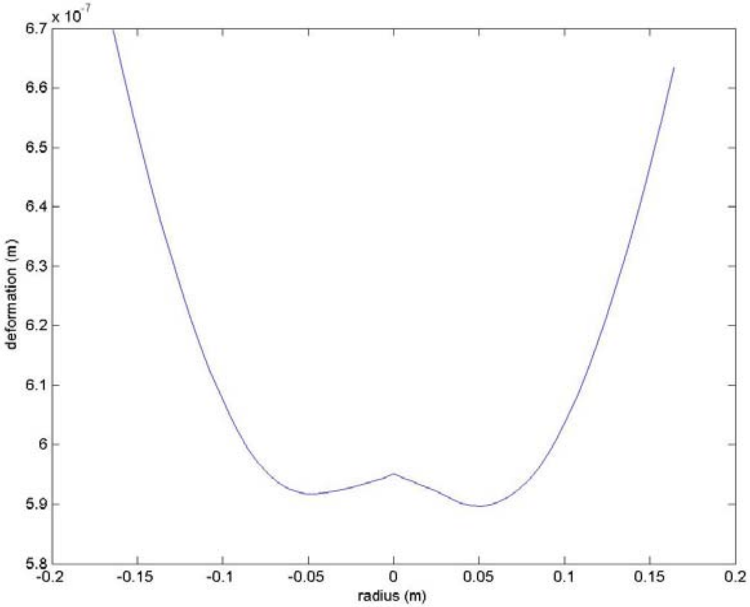
- Reviewers' comment:
  - » *We would like to see details of the origin of the 11 W ring heater number. M Arain's understanding from Ryan's thesis is that it would be much higher, so please lead us through your ring heater calculations. And regarding the location of the ring, we would like to see the calculation of the HR surface distortion versus the axial position of the ring, to verify the claim that heating near the AR surface is just as effective as heating near the HR surface. Also, please discuss the temperature rise that would be expected in the ITM with the ring heater in operation. We would also like to see more details of the construction of the ring (a drawing), and the expected/modeled radiation patter from the heater.*

Modeled Test Mass Heat Profile

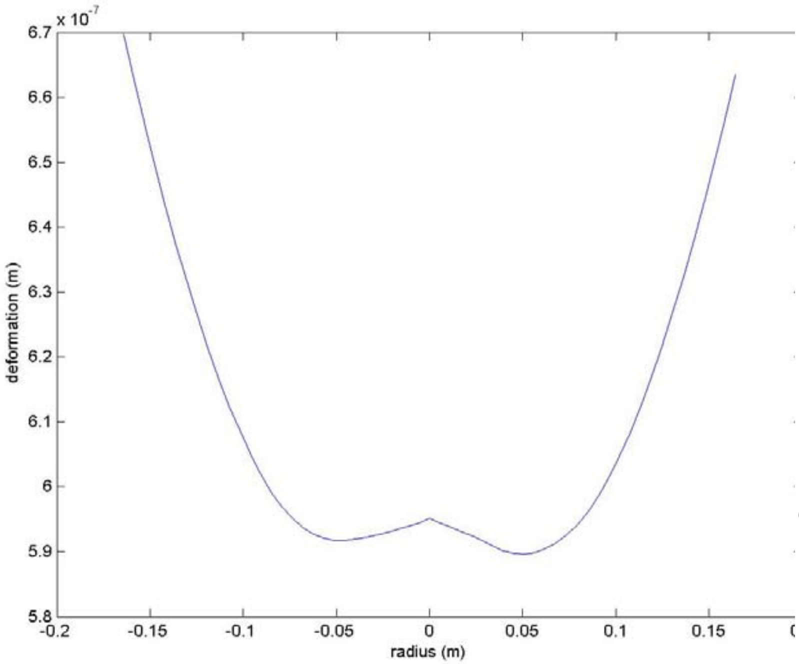
$$587 * \exp\left(-(z-.05)^2/.01^2\right)\frac{W}{m^2}$$

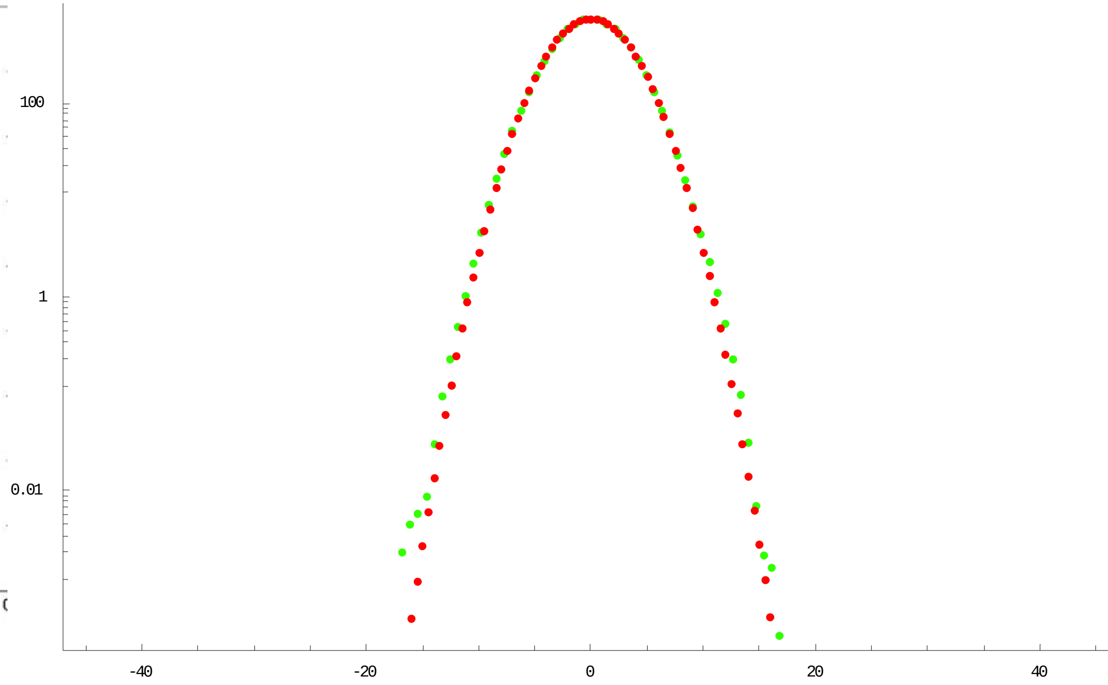






Compensated Arm Cavity Mode





- Reviewers' comment:
  - » *Fig. 5. Looks Gaussian, but can you tell us how much power is in higher order modes? Does it meet the requirement?*

Test Mass Ring Heaters

- Reviewers' comment:
  - » *Would it help to incorporate a heat shield around the Test Masses?*

Power Margin Revisited

- Reviewers' comment:
  - *Has the reduction of the efficiency of the ring heater versus heater power (pgs 212-214 of Ryan's thesis) been incorporated into the design?*
- Our response:
  - TM ring heater power: 0.1 W/cm, (4% of max power)- the CDD value is incorrect.
  - CP ring heater power: 1.3 W/cm, (50% of max power)- this effectively sets our power margin to 2x.

Simultaneous TM and CP Thermal Compensation

- Reviewers' comment:
  - » *Fundamental question about the actuator approach: When the ITM ring heater is applied to correct the ITM HR surface, Fig 6 shows that a negative lens is formed in the ITM bulk. Thus we need to apply a compensating positive lens, but this cannot be done with the silica compensation plate and its ring heater. As mentioned in 3.1.5, the ITM/CP compensation combination needs to be further modeled, but it appears to us that either: the CP correction would have to be done entirely with the CO_2 laser; or, a negative dn/dT material would need to used for the CP.*
  - » *We are quite interested in the idea of using a negative dn/dT material for the CP, and would like to discuss this (even aside from the above point).*

Compensation Plate/Ring Heater Design

- Reviewers' comment:
  - » *What parameters of the ring heater have been optimized for in this design? Again, the ring heater power (6 W) looks small comparing to Ryan's results, so we'd like to see the details of the calculation to convince us this is correct. Also, what's the CP temperature rise? Is the ring heater design for the CP the same as that for the TM? If not, what are the differences, and why?*
- Our response:
  - » The ring heater power is 170 W, of which only 6 W reaches the CP.
  - » The CP temperature rise is ~6K.
  - » The ring radius and distance from the CP were optimized for optimum heating profile. The CP was chosen small enough that the folded IFO ring does not block the unfolded IFO.
  - » The TM ring heater was optimized to fit into the SUS structure.

In-Vacuum Optics

- Reviewers' comment:
  - » *Could the CO_2 beams be projected into the vacuum system through one of the viewports in the (new) mode cleaner tubes? If so, this could avoid many of the in-vacuum optics needed in the proposed design. Please look into this possibility.*
- We did, but it doesn't help.

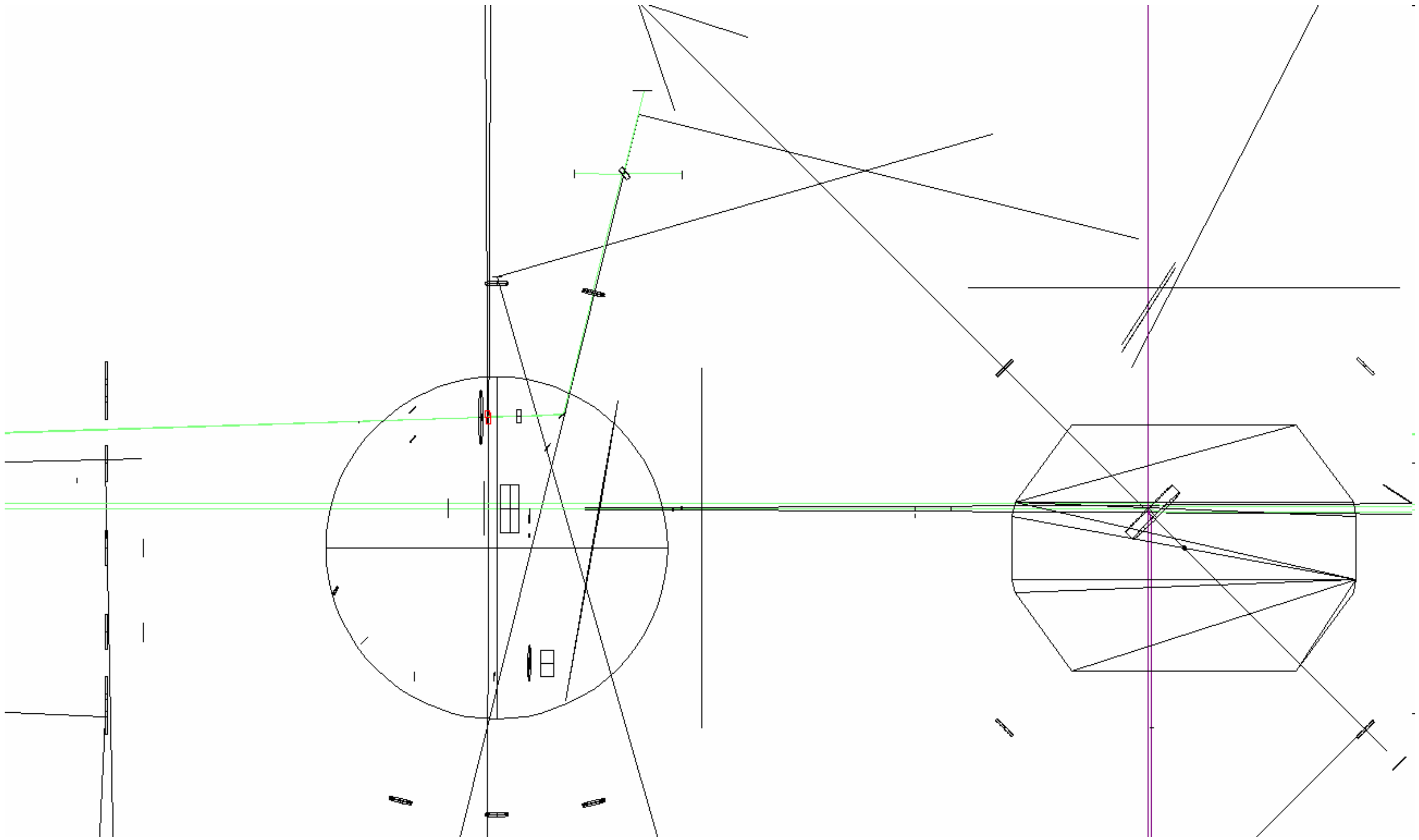
Sensor Design

- Reviewer comment:
  - » *It is noted that the ITM/CP probe beams sense the BS abberations differently than the interferometer beams, which could give sensing errors of 10-20%. Thus a separate BS sensor is proposed. But how accurate does the BS sensor need to be, to be able to extract the desired accuracy for the ITM/CP abberation of each arm?*
- The BS sensor needs to have comparable accuracy to the ITM/CP sensors.

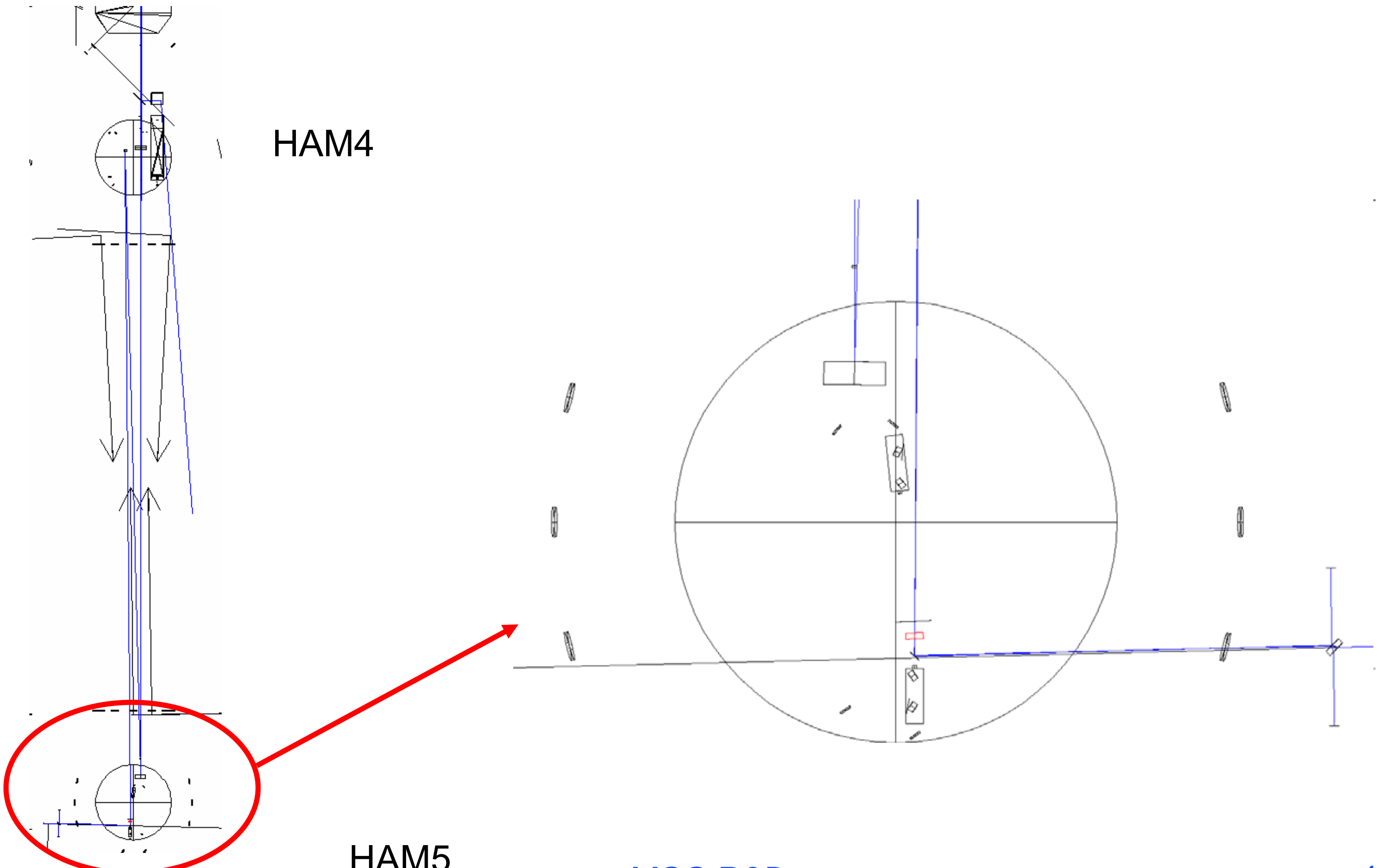
Sensor Design

- Reviewers’ comment:
  - » *An alternative design for the probe beams would be to inject them through the mode-matching telescopes (MMT2), let them be expanded by the MMTs, and point them to be nearly colinear with the interferometer beams. This could be done from both the symmetric and anti-symmetric ports, to probe each arm. The coating reflectivities of the BS, MMTs, and RMs, would need to be specified appropriately for this to work, but the advantages would be that the probe beams sample the right paths, and lots of in-vacuum components currently needed for the probe beams could be eliminated. We'd like to discuss this alternative.*

ITMx Hartmann Probe Beam



ITMy Hartmann Probe Beam



Sensor Design

- Reviewers’ comment:
  - » *Hartmann sensor: The Adelaide detector seems to meet the requirements, appears to be flexible, and should be straight forward to use.*
- Response:
  - » One drawback of the Hartmann sensor not realized when we wrote the CDD was that, because it compares distorted wavefronts to reference wavefronts collected in the past, it is susceptible to drift errors. This requires investigation.

Sensor Design

- Reviewers' comments:
  - » *The WLISMI is a great technique which might have better performance than the Hartman sensor but it seems to be rather complex to operate and it's not clear how this can be implemented for anything other than the ETM. It is a great idea but probably not applicable for LIGO.*
- Response:
  - » To use the WLISMI on the ITM/CP, the ITM HR face and front face of the CP must be coplanar to within a few mrad, which is feasible.
  - » To use the WLISMI on the BS, either separate regions of one BS face must be compared, or a reference optic must be positioned coplanar with the BS face in the probe path
  - » The WLISMI can only compare regions of the TM HR surfaces.
  - » Unlike the Hartmann sensor, each WLISMI measurement is absolute.

Sensor Design

- Reviewers:
  - » *- do you have any test data for either type of sensor that shows their sensitivity/performance?*
- Response:
  - » See following talk for data on Hartmann sensors.
  - » WLISMI data is in the CDD and presented in LSC meetings past

Sensor Selection

- Reviewers' comments:
  - » *- how will the choice between the two sensors be made? what further tests will be done?*
  - » *- how will LIGO get experience with the sensors? are there any plans to test them in an experiment that somehow mocks up their intended application on LIGO interferometers?*

Phase Camera

- Reviewers' comments:
  - » *Phase camera: The committee is most interested by the possibility of an image sensor (CCD, e.g.) type sensor. This could be coupled with the idea of a fiber-delivered, frequency shiftable (via AOM) reference field, which would beat with the probed field to pick out a particular frequency component, and heterodyned to a convient IF signal. Question: what are the plans for developing the phase camera? i.e., who is going to do it?*
- Response:
  - » We mention this possibility in the CDD mainly on the authority of who suggested it- Rana. No plans currently exist to develop this camera.

- From the CDD:
  - » It is our judgment that a significant amount of distortion can be tolerated in the TCS sensors.
- Reviewers’ comment:
  - » *Agree with the contention that significant fixed aberrations can be accounted for. However does the argument hold for the CO2 trains? Will the CO2 beams cause any of their own thermal aberrations? These would change with ifo power increase and thus not be 'fixed' aberrations. Is this of any concern?*
- Response:
  - » This concern is valid, and most likely seen in transmissive ZnSe optics. This will require more specific study of the projector.

Thermal Depolarization

- Reviewers' comment:
  - » *This will need revisiting if a crystalline negative dn/dT material is considered for the CP.*
- While the initial estimates indicate the thermal depolarization is small, this deserves revisiting as soon as suitable models are available.