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TCS and IFO Properties

Dave Ottaway

For a lot of people !!!!!!

LIGO Lab

Kavli Institute for Astrophysics and Space Research,

Massachusetts Institute of Technology

LIGO-G050188-00-Z

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Outline of Talk

- The Questions
- Thermal Issues in LIGO 1 Optic
- The TCS system
- The static spatial offsets in the IFO
- The excess absorption in H1 Optics
- Conclusions

The Questions asked at the IFO Spatial Modeling Workshop

LLO

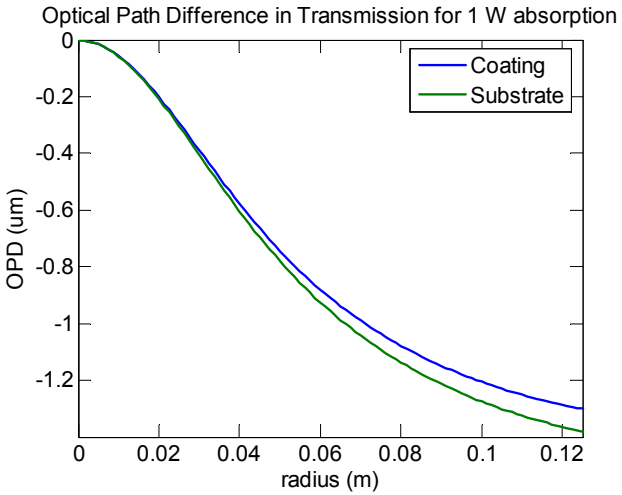
1. Why does SPOB depend on the sideband frequency ??
2. Why does phase noise sensitivity change with sideband frequency ??
3. Why does SPOB not reach its theoretical maximum ???

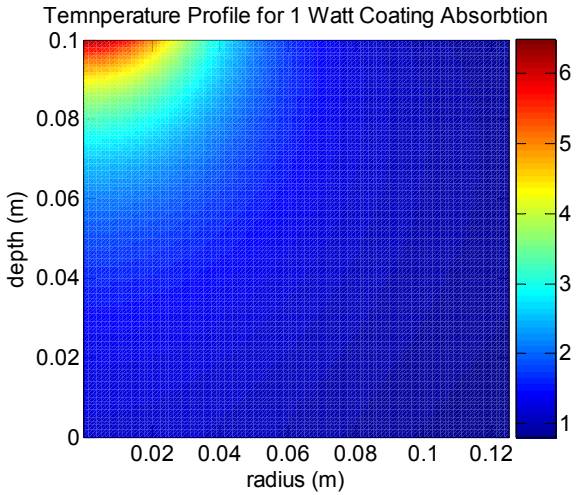
LHO

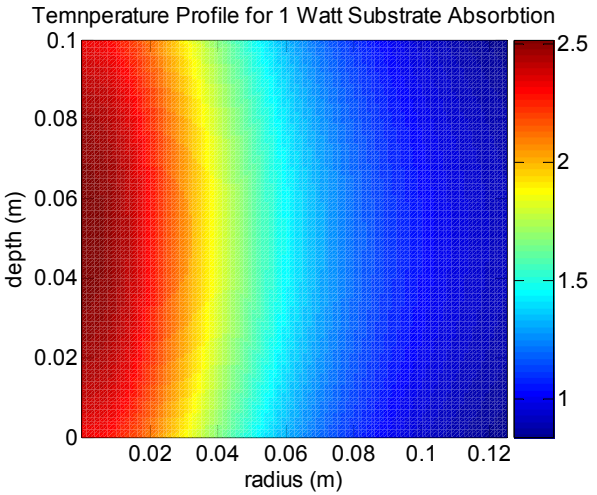
1. Why do we need 90 mW to reach optimum SPOB in PRM ??
2. Why is the 4K MC efficiency so low ???
3. What is the mechanism for coupling phase noise into the IFO ??
4. Why does the LHO 4K have such lousy thermal properties ??
5. Which optic in the PRM is the bad egg, how do we show it conclusively ??? What is wrong with it ??
6. What makes the 2K Optical properties so stellar ???

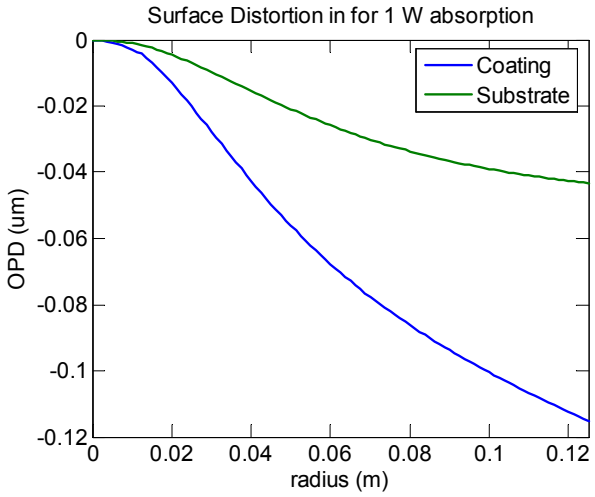
   ie High SPOB and low phase noise sensitivity

Steady state effect of absorption on the optics









- $OPD_{coating}/OPD_{substrate}$ = 2.9 for surface reflection
- $OPD_{coating}/OPD_{substrate}$ = 0.95 for optics transmission
- Model does not include deformative effects of the coatings

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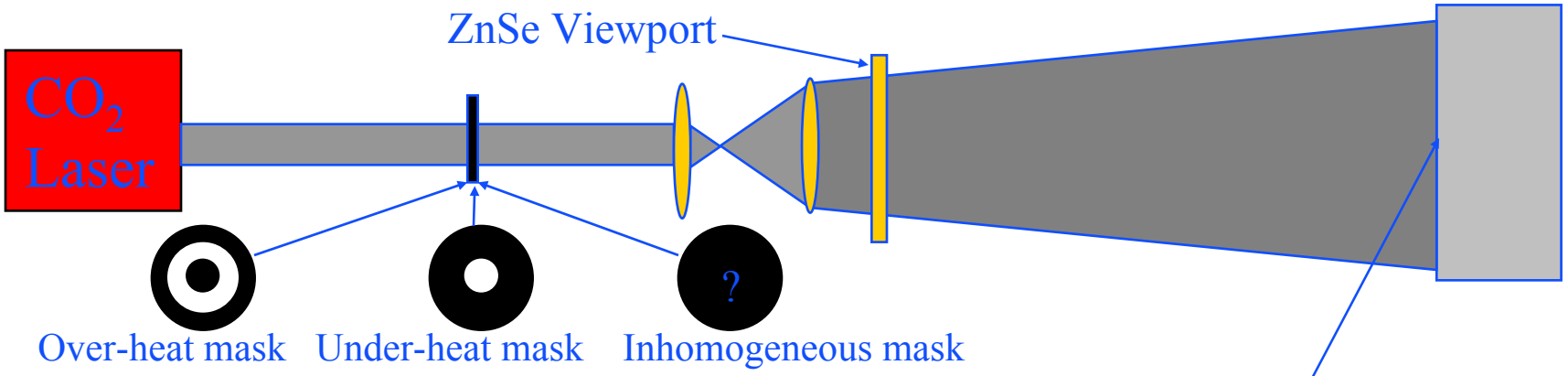
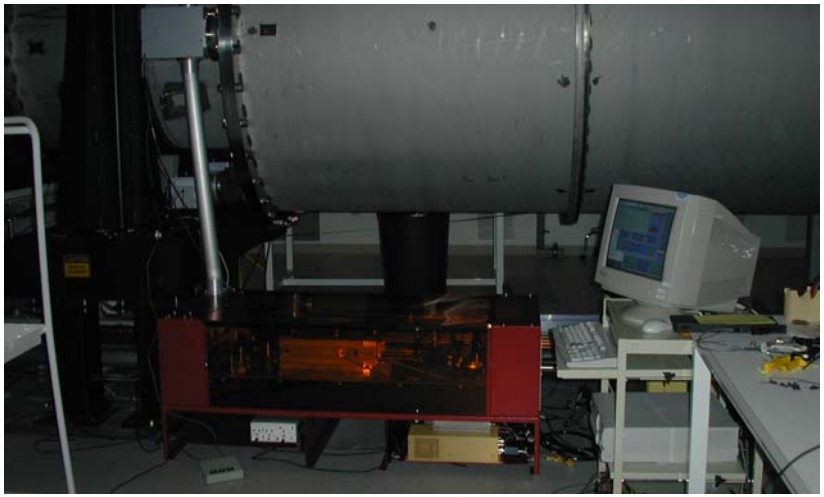
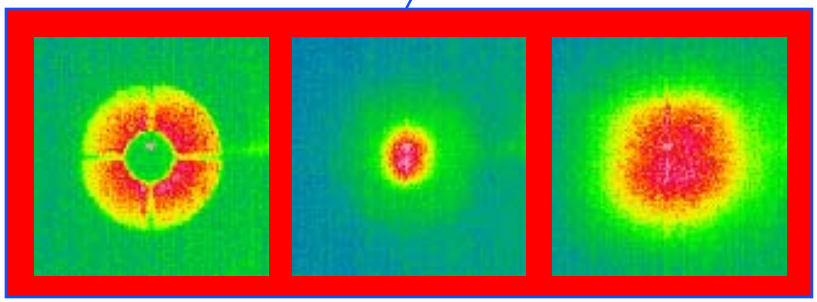
Effect of Heating Optics

- Effects are biggest when inner optics are heated ie Beamsplitter and Input Test Masses
- Has minimal effect on Carrier power (stabilized by the arms)
- Common heating (equal heating of the ITMs effects) sideband build-up and mode shape in the power recycling cavity
- Differential heating effects AS_I level and phase noise coupling

Initial LIGO TCS Concept





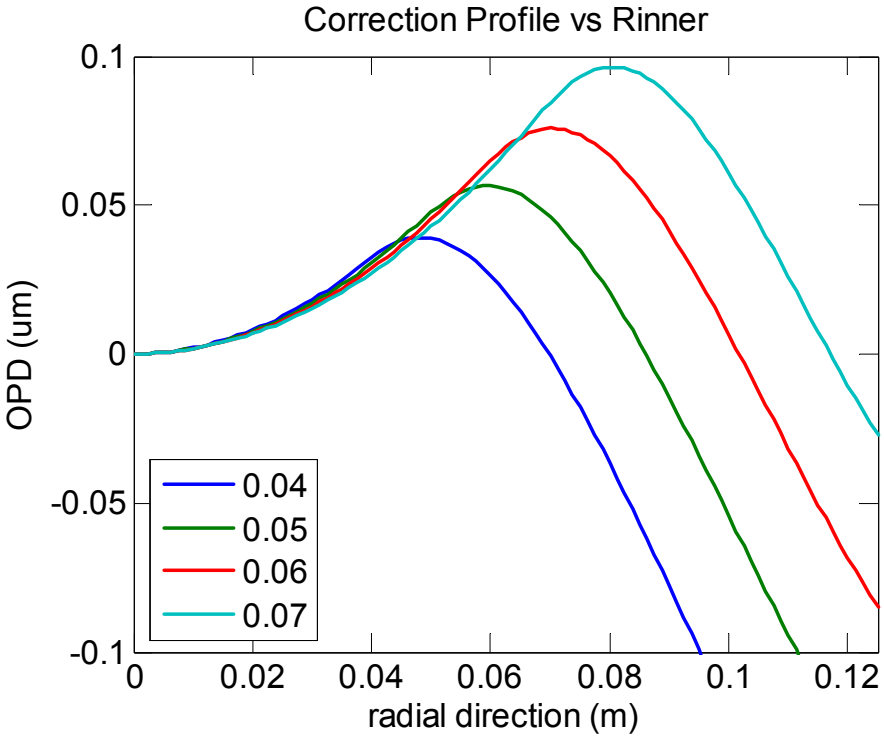


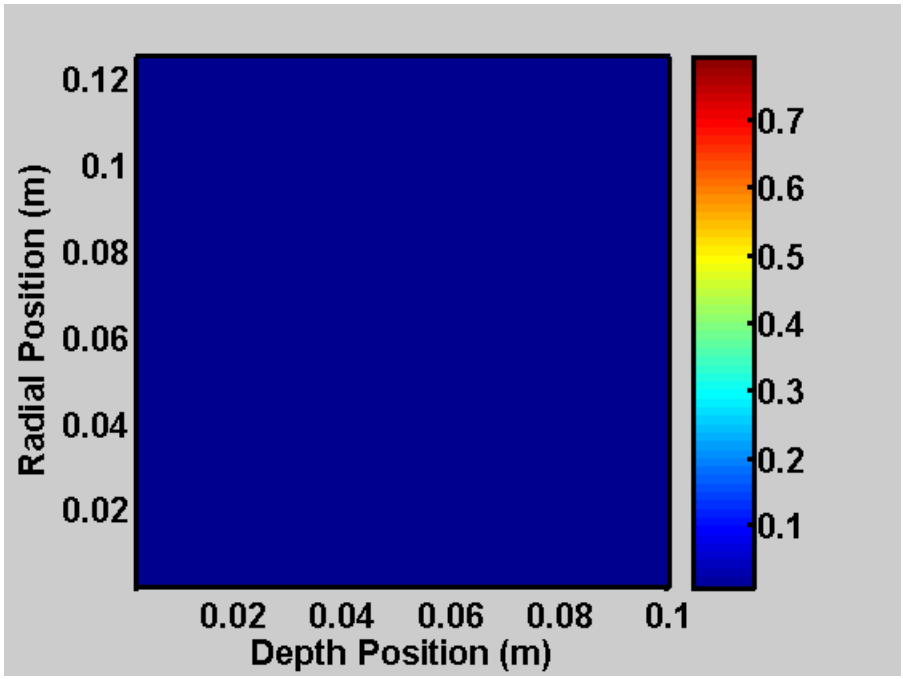
Over-heat pattern

Under-heat pattern

Raw Heating pattern

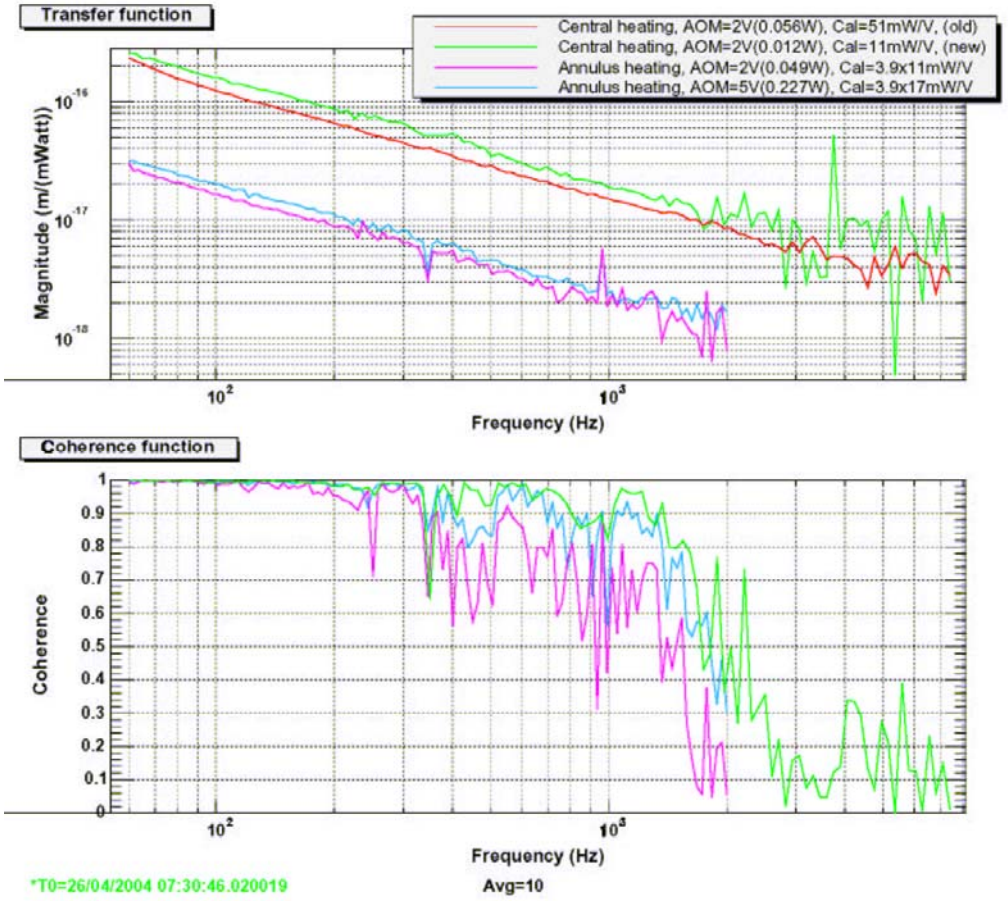
Effect of TCS on Optics

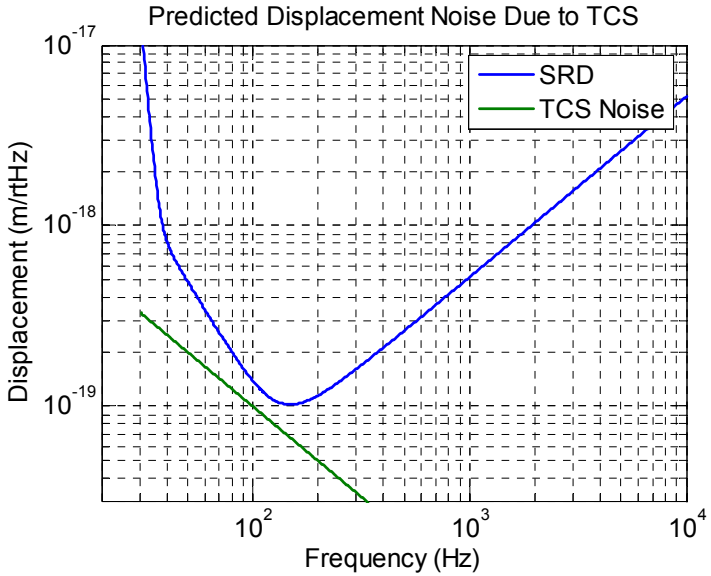




- All initial modeling for TCS was done assuming the static case
- Stefan B showed that TCS effectiveness decreased with time
- Finite element model by Stefan accurately predicted the behavior

Effect on TCS Laser Noise on IFO performance

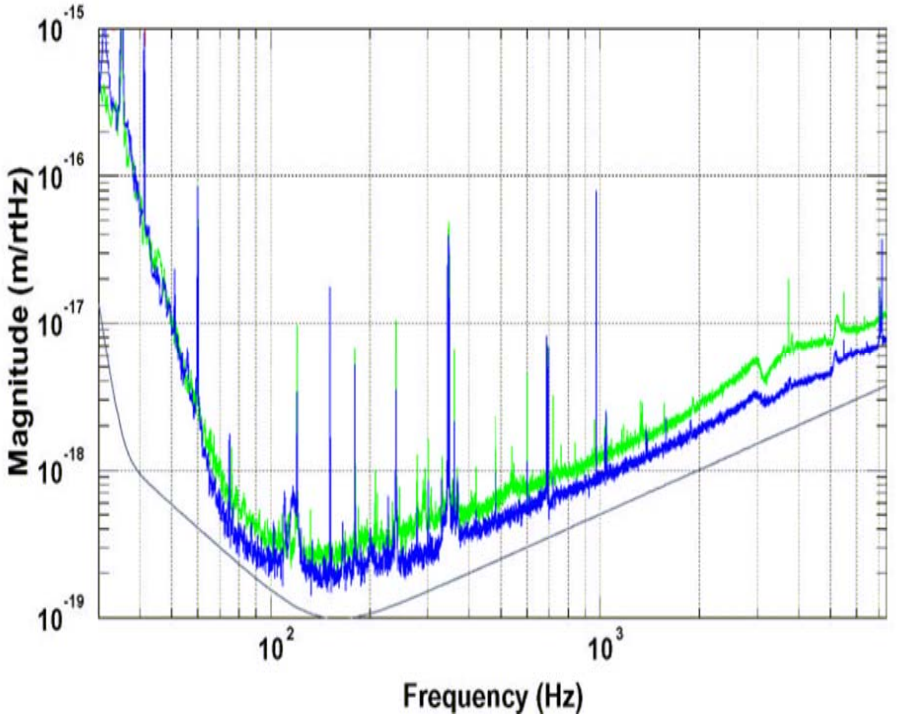




- Predicted actuation agrees within 10% (ie experimental error)
- Noise for 3nV circuit and 10 Watts Annulus heating
- Thermal expansion of HR surface is the dominant noise term

Overall TCS Performance

- H1 achieves sideband build-up at ~ 2 watts
- Cannot lock reliably without TCS at ~ 4 Watts input
- Reduces oscillator phase noise sensitivity, which is dominant at higher frequencies
- Increases sideband to maximum
- Does not have enough power to correct H1 at 4 Watts input
- H1 show significant 1.064 um absorption
- A nice servo for TCS (See Stefan's commissioning talk)



- Green curve (Without differential TCS)
- Blue curve (With differential TCS)

Livingston TCS Performance

- Is not plagued by the same thermal issues as H1.
- No sign of 1.064 um heating
- NSPOB level increased from 150 – 330
- Sideband power to dark port increase as NSPOB
- Optical Gains Increase (Not quite what you would expect)
  - » Darm ~ $NSPOB^{0.8}$
  - » POB_I , POB_Q ~ $NSPOB^{2}$
  - » Refl gain increases
- Reduces phase noise sensitivity by 10
- DC AS_I Level Reduced by a factor of 3
- System becomes unstable when TCS reduces AS_I to zero
  - » This is not understood
- TCS runs open loop, no servo used
- Summary provided by Valery Frolov

Optimum power to correct static curvature errors

IFO	ITMX	ITMY
LHO 4K	35 52 27	60 82 60
LHO 2K	0 57	17 110
LLO 4K	22 53	39 83

- Experimental Data (Blue), Simple Curvature Model (Black) and Full FFT (Green)
- Model results by Hiro, additional power required for BS ROC
- Measurements assume a 15% loss from the calibration point to the power

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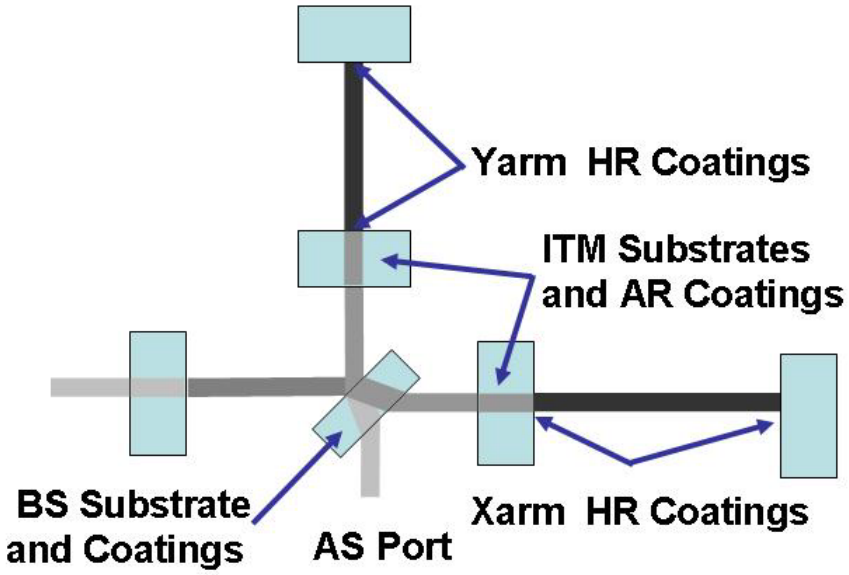
Optical Absorption in the IFOs

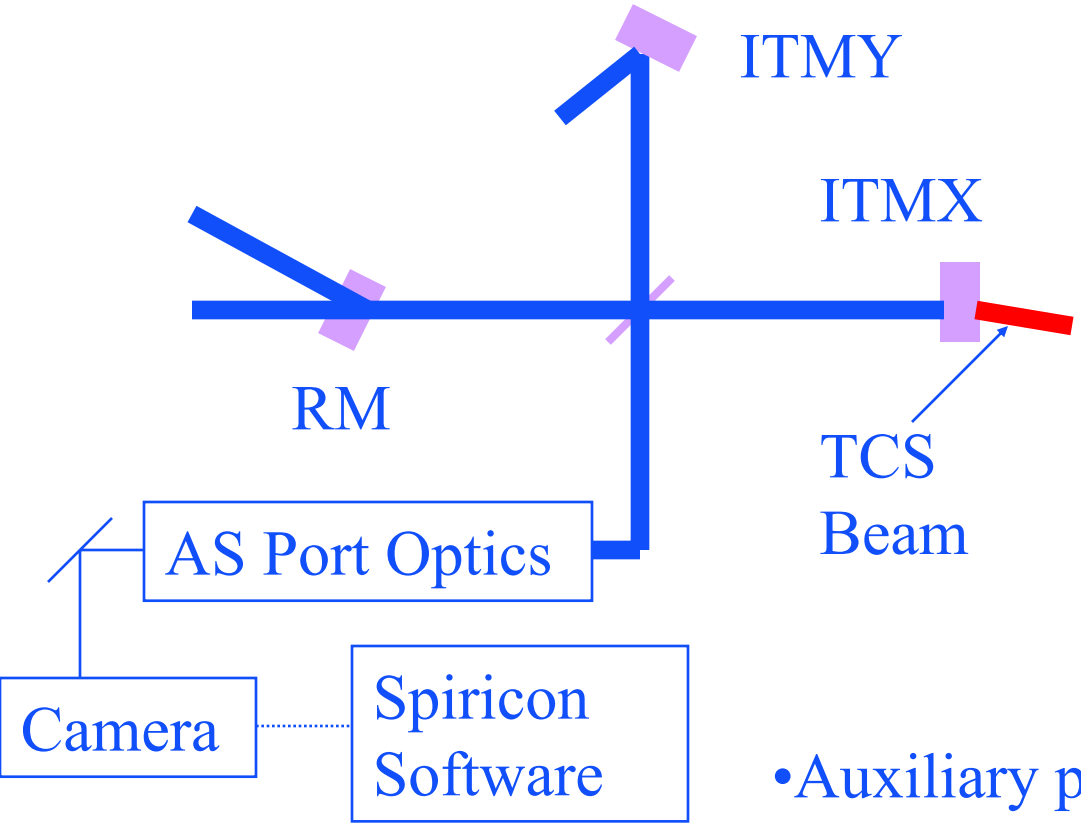
- IFOs are originally designed as a point designed with 1.06um absorption needed to get to optimum operating point
  - » 12mW in coating and 16 mW in substrate for 6 Watt input
  - » Substrate absorption ~ 4 ppm/cm, Coating absorption ~ 0.5 ppm
  - » Numbers from Ryan Lawrence's PhD Thesis
- H1 gets to the optimum operating point with ~ 2 Watts of power
- L1, H2 show negligible 1.064 um heating

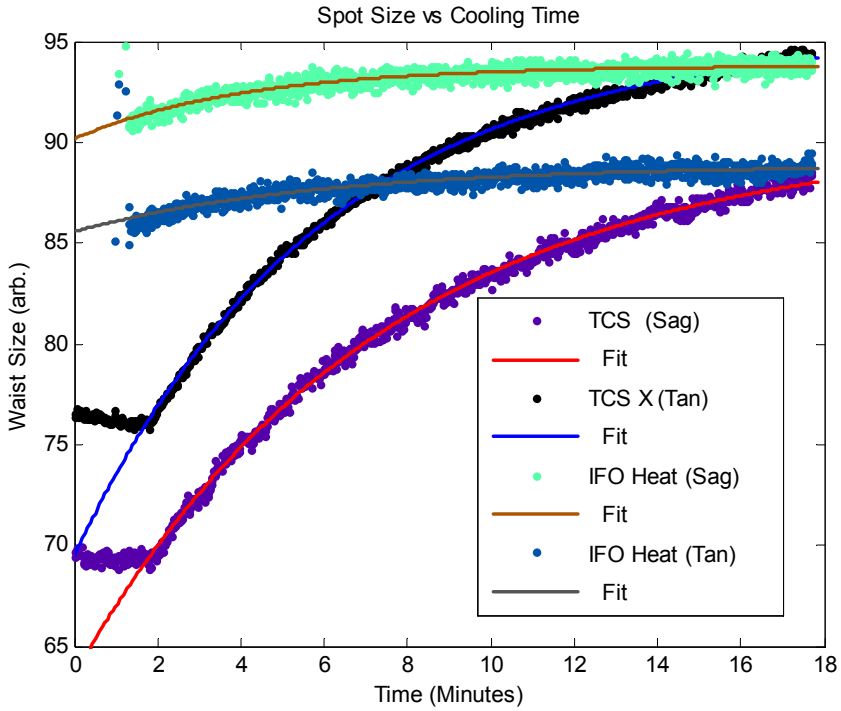
Measurements to quantify absorption in H1

- Significant power potentially absorbed in various optics
- TCS servo to optimize heating power (Stefan B)
  - » Determine reduction in central heating required at each power level
  - » Sensitive to power absorbed in BS, ITM coatings and substrate
  - » Measures optimal absorption
- G factor measurements (Rick S, Malik, Bill K and Keita)
  - » See talk by Rick Savage
- Spot size measurements (Dave O and Joe B)



Spot Size Measurement





- Auxiliary ports have not been done yet
- Calibrated using TCS

What are these measurements sensitive to ???

Mirror	ITMX		ITMY		ETMX	ETMY	BS	Done
Coating/Substrate	C	S	C	S	C	C	S,C	
Xarm TCS	0.95	1					1	√
Yarm TCS			0.95	1				√
Xarm G factor	2.9	1			2.9			√
Yarm G factor			2.9	1		2.9		√
POB Spot Size							1*	
POX Spot Size	1	1					0.25	
POY Spot Size			1	1				
AS Spot Size (X)	1	1					1*	√
AS Spot Size (Y)	1	1					0.5*	√

* Depends on exact location of heating

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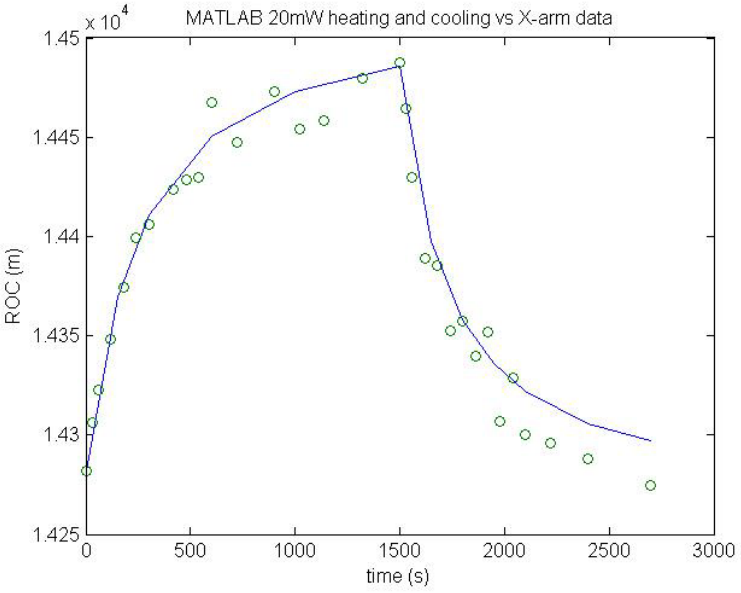
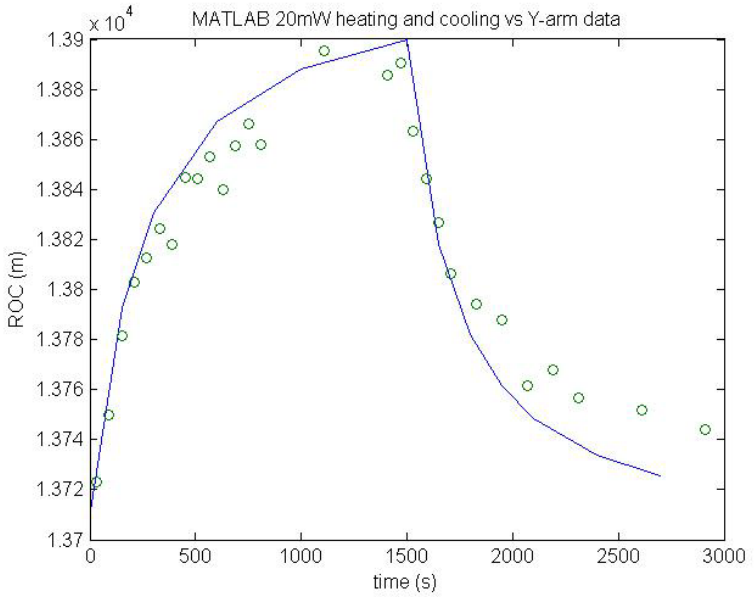
The Results so far

- TCS optimal heating
  - » 19 +/- 5 mW per W (Ypath), 50 +/-10 mW per W (Xpath)
- G factor changes
  - » 21 mW per W (Yarm), 25 mW per W (Yarm)
- Spot size changes (Preliminary)
  - » 20 +/- 4mW per W (Ypath), 35mW +/- 7mW per W (Xpath2) Horizontal Direction
  - » 4.5 +/- ? mW per W(Ypath), 31mW +/- 7mW per W (Xpath2) Vertical Direction
- All these results use TCS as calibration source, is this a good idea ???

How good is the TCS Calibration ??

- Within experimental error for the 4K IFO static offset correction. Model depends on K, w, dn/dT, power
- Within experimental error for intensity noise transfer models. Models depend on K, w, sigma, power
- But … 50 % off regards to the ROC g factor measurements. Model depends on K, w, sigma, power





•Models use Hello-Vinet, method , static PDE models also agree with the dynamic models !! Dynamic models by Phil Willems.

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Comments and Further Experiments

- Either the BS or the ITMX is absorbing a considerable amount of 1.064 um light
- If H2 and L1 coatings were absorbing the same power in the coatings, optimal power would have been reached at 6 Watts without TCS.
  - » What is different about H1 coatings ????
- Follow Up
  - » Repeat g factor measurements
  - » Use spot size measurement on POB, POY and POX
  - » Look at the ITMs with a thermal imaging camera through TCS view port
- There appears to be a problem in the models
  - » Do coating properties need to be considered in modeling ??

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Conclusions

- A considerable amount of progress has on determining the spatial properties of the IFO and compensating errors using the TCS system
- Significant amount of power is absorbed in either the ITMX or BS.
- If this is not corrected ~ 10 Watts of TCS correction will be required to reach the SRD

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Modeling and Comments

Melody (Amber Bullington)

- Need to add a module to generate real error signals

- New Adv LIGO model – models mirror off-axis

FFT (Erika d'Ambrosia)

- LSC locking allows generation of real error signals

E2E (Hiro Yamamoto)

Erikonal Model (Bill Kells)

-Simple parallel ray approach that enables the physics of the PRM to be explored

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Experiments and Comments

- Observed astigmatism on AS port (Mike Smith and Hiro Yamamoto)
  - Cannot be explained by mis-alignment of the AOS telescopes or curvature of the BS
- Phase camera images (Joe Betzweiser and Biplab Bhawal)
  - Fitted the mode structure of the phase camera images using hermite gauss expansion
  - Readout speed of 1S enough to capture accurately the detail
  - It is difficult to get the physics out of the phase camera pictures
  - Connection between the IFO states and the images needs to be established

Answering the unsolved questions – Thermal heating

- Experiments
  - High power PRM to eliminate ITM coatings
  - Spot size measurements using PO signals
  - ITMs and BS are passed 4 times on these signals
  - Power up on H2 and L1 to determine absorption
- Modeling
  - More time domain modeling of optics
  - Additional modeling of the effect of heat in various locations on the BS.
- Review procedures
  - Cleaning procedures differences between the sites
  - Particularly the use of liquinox

Answering the unsolved questions: SPOB/Phase noise sensitivity to sideband frequency

- Possibility of additional $2f_{mod}$ coupling
  - Finesse or twiddle modelling
- Additional spatial mode modeling using FFT, E2E or Melody modeling

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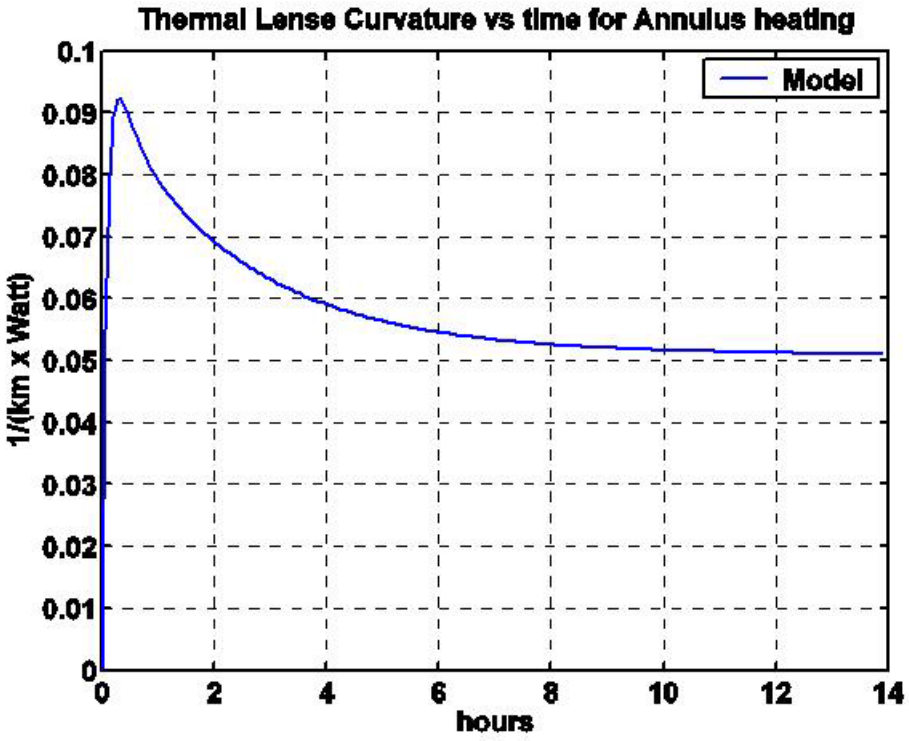
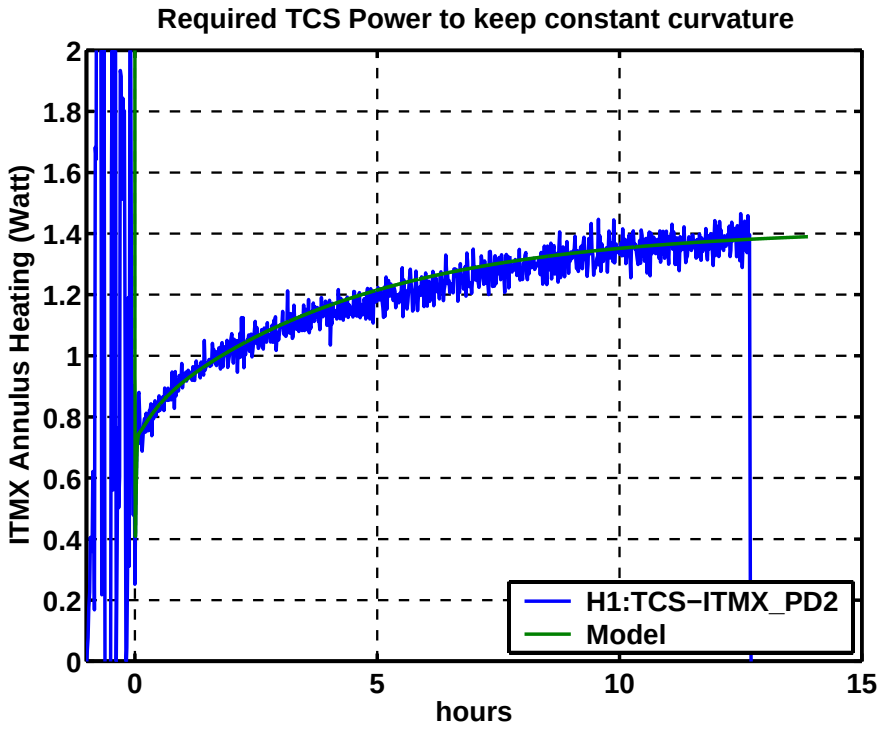
More …

- Talks are at http://www.ligo.caltech.edu/~willems/IFOModes
- Summary written report is being compiled
- Follow up session at the March LSC Meeting

Time Constant in Annulus Heating





- Reduction of TCS Power with time is due to heat flowing into the center of the optic which reduces TCS efficiency
- See talk by Stefan