Thermal Compensation System – TCS
Technical Presentation

aLIGO NSF Review

LIGO Livingston Observatory

25-27 April 2010

TCS Functions

- Measures the thermal lens in the Input Test Mass substrate and Compensation Plate using a Hartmann Sensor
- Compensates thermal lensing in the Input Test Mass substrate and Compensation Plate using a CO_2 laser projector system
- Controls the radii of curvature in the Input Test Mass and End Test Mass using ring heaters
- Intermittently measures the End Test Mass with the Hartmann sensor to investigate thermal loading

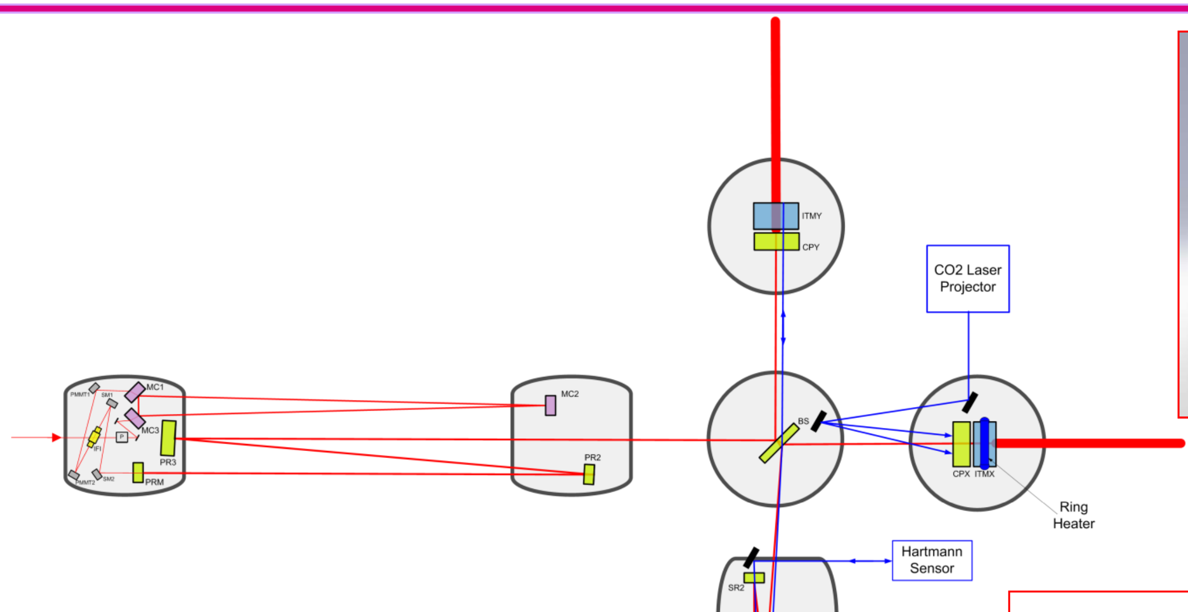
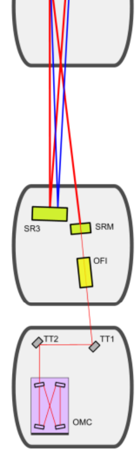
TCS Requirements

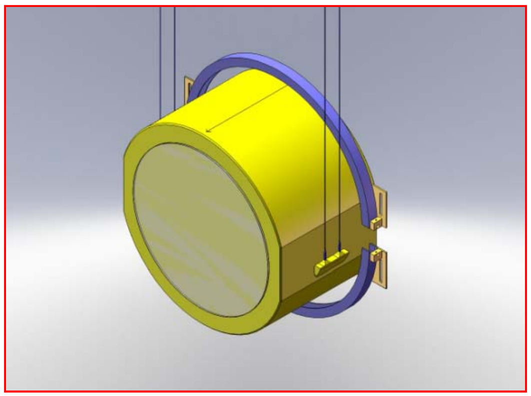
- Provide up to -5% radius of curvature change to test mass high-reflectance faces
- Maintain radiofrequency sideband gain in power recycling cavity up to 120W input power
- Maintain arm cavity power buildup to 95% of cold cavity value
- Maintain gravitational wave sideband extraction through signal recycling cavity to 95% of cold cavity value
- Maintain homodyne power at dark port to within 1mW
- Above requirements met by maintaining thermal aberrations to within $\lambda/47$ (Core Optics requirements are ~$\lambda/300$)
- Must meet these requirements without injecting noise above technical noise requirements (phase noise, magnetic noise, etc.)

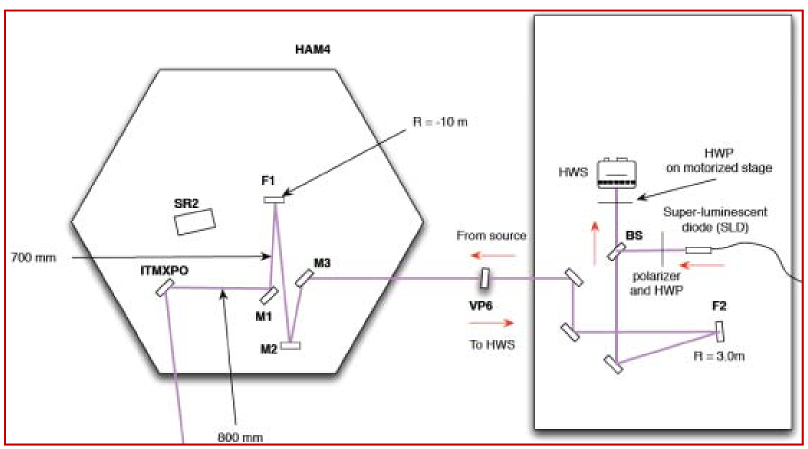
TCS Design Concept

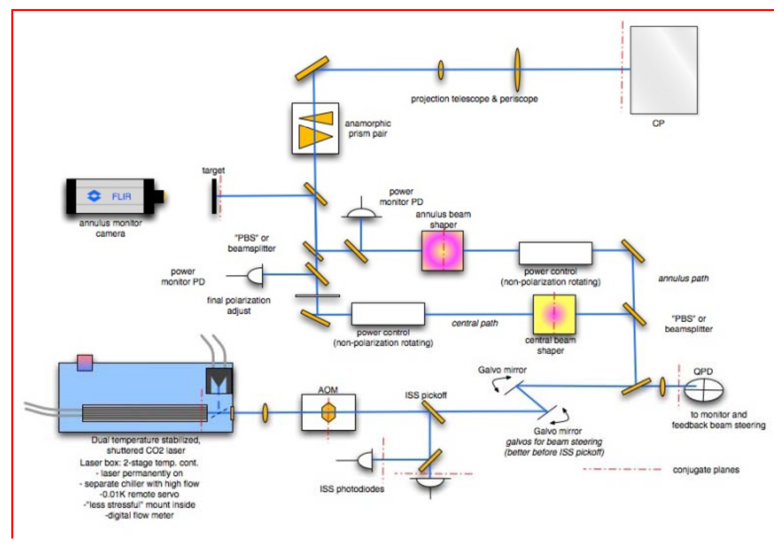
- TCS consists of *sensors* to detect thermal aberrations and *actuators* to correct thermal aberrations
  - » Sensors:
    - – Hartmann wavefront sensor to measure thermal phase profile in individual End Test Masses and Input Test Mass/Compensation Plate pairs
    - – Phase camera and bull's-eye sensor to measure interferometer beam profiles
  - » Actuators:
    - – Carbon dioxide laser projector acting upon compensation plate to correct thermal lens in recycling cavities
    - – Radiant ring heaters to correct test mass mirror surface radii of curvature

Thermal Compensation System (TCS)

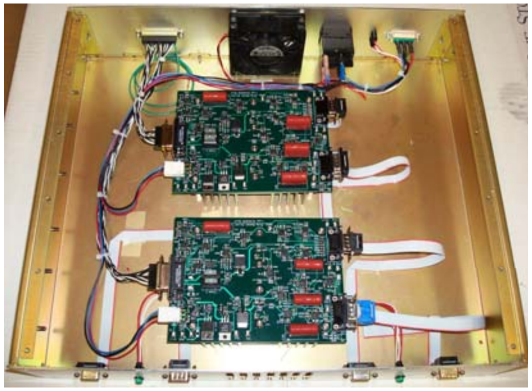



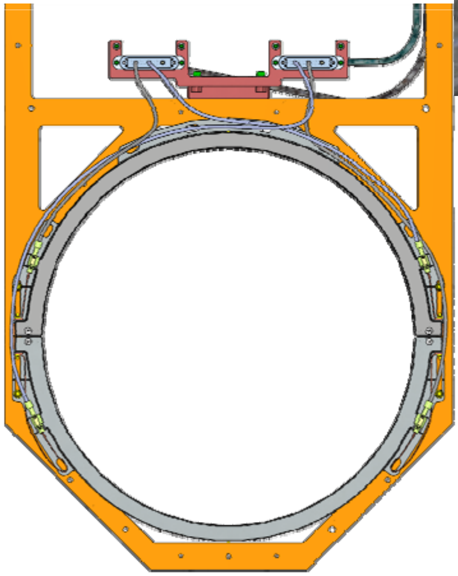




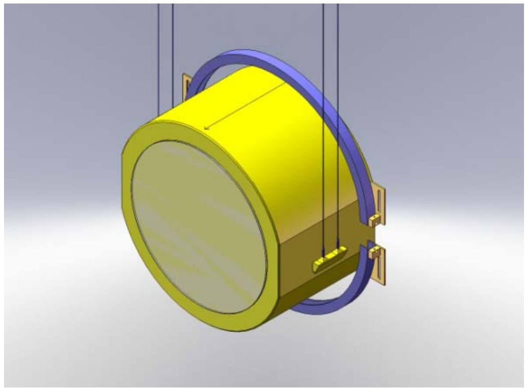


TCS Production Units
Ring Heater





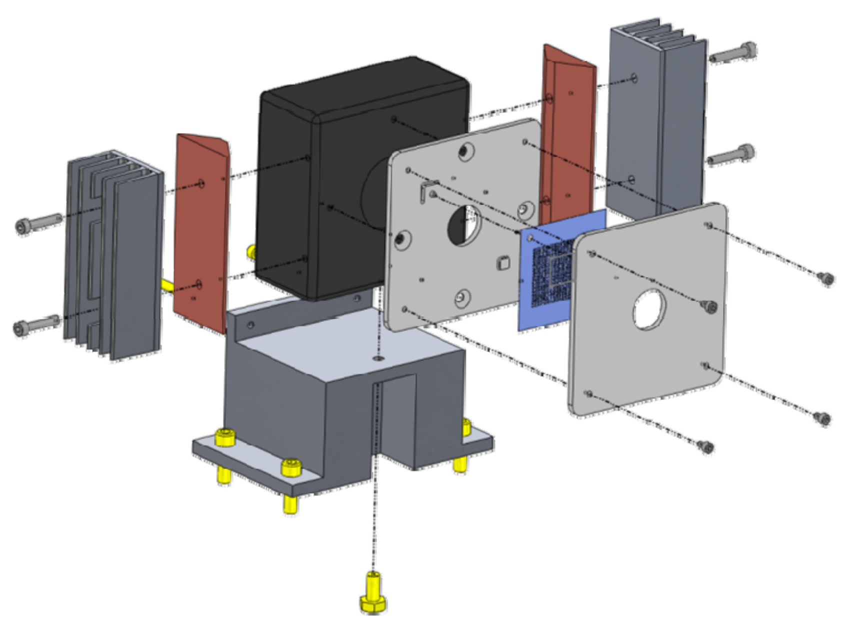
- The ring heater has passed final design and is now on project.
  - » PDR completed July 2010
  - » FDR completed December 2010
- University of Florida group is verifying heating pattern in vacuum of delivered heaters and developing alternative risk-reduction ring heater design



TCS Development Plan
Hartmann Sensor

- Hartmann sensor camera FDR completed August 2010
- Remaining Hartmann sensor PDR completed April 2011
- Remaining FDR: October 2011

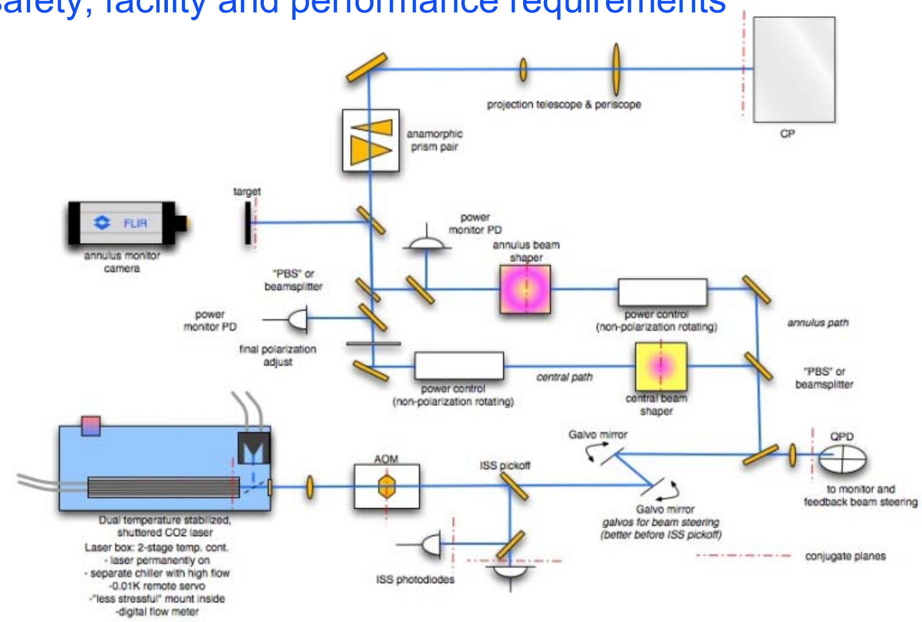
- University of Adelaide is making significant contributions to aLIGO TCS: now purchasing cameras for aLIGO as per MOU with LIGO and writing Hartmann Wavefront Sensor software.
- Hartmann sensor probe beam wavelengths have been chosen, layout is being finalized. Beamsplitter antireflection coating design optimization for Hartmann Wavefront Sensor is still being considered.



TCS Development Plan

CO_2 Laser Projector

- CO_2 projector design operated on Enhanced LIGO with high power − most noise couplings were identified and mitigated
- A search is ongoing for a stable, higher-power laser to handle aLIGO thermal lens with desired power margin
- PDR: July 2011
  - » Optical path layouts to be optimized for safety, facility and performance requirements
- FDR: November 2011



CO_2 Laser Procurement

- The initial vendor for the CO_2 laser failed to deliver a laser that met requirements
- The CO_2 laser choice presents no <u>technical</u> risk to the CO_2 laser projector design, only cost or schedule risk.
- We can adopt an off-the-shelf 30W laser presenting:
  - » No budgetary risk
  - » No schedule risk
  - » Low to moderate technical risk to initial realization of adequate power margin, to be met with higher power development if deemed necessary
- We can adopt an upgraded off-the-shelf 50W laser:
  - » High budgetary risk (+50%)
  - » Moderate schedule risk
  - » Low technical risk to realization of adequate power margin
- Other vendors also under consideration

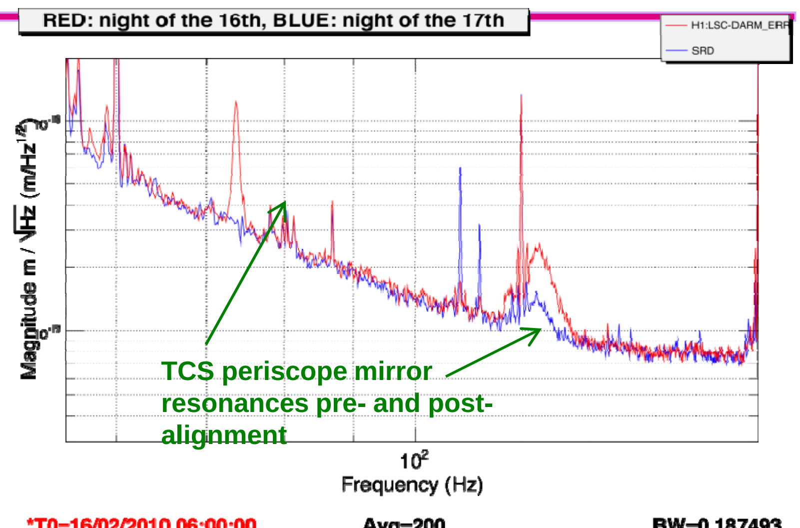
TCS Project Organization

- TCS Team Leader/Mechanical Engineer - Mindy Jacobson - Caltech
- Cognizant Scientist - Phil Willems - Caltech
- Electronics Engineer - Steve O'Connor - Caltech
- Staff scientist - Aidan Brooks - Caltech
- Operator/Technical support - Cheryl Vorvick – Hanford Observatory; Chris Guido – Livingston Observatory
- Mechanical Engineer/Draftsperson - Caltech
- Ring heater design support - Guido Mueller, Giacomo Ciani, Deepak Kumar, Chris Mueller- University of Florida group
- Hartmann sensor design and material support - Jesper Munch, Peter Veitch, David Ottaway, Won Kim - University of Adelaide

People/positions in red are new or unfilled

TCS Development Accomplishments

- CO_2 laser projector operated successfully on Enhanced LIGO; projector in-vacuum steering mirror for H2 reviewed and in fabrication, with one to be installed during H2 single-arm test; power control waveplate mount designed
- HWS probe beam wavelengths chosen and optical layout nearly finalized; HWS cameras on project and currently in procurement. Beta version of core HWS software complete.



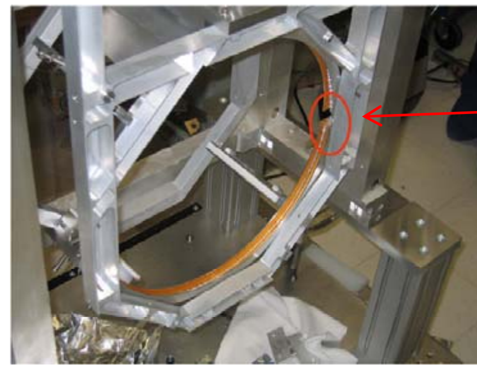
Power control waveplate mount

Hartmann sensor mounting plate with thermal sensor

CO2 projector in-vacuum steering mirror

TCS Development Accomplishments

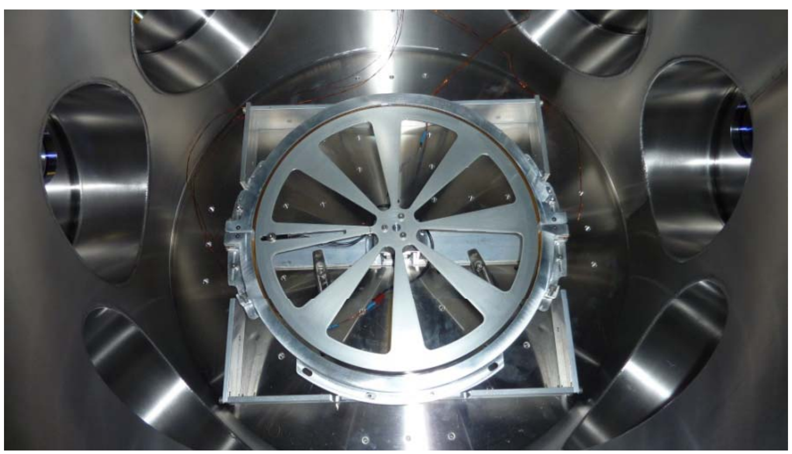
- Ring heater through design phase and in fabrication for installation during H2 single-arm test- heater pattern uniformity meets requirements, current driver meets magnetic noise requirements
- TCS/SYS integration: laboratory floor layout, vacuum compatibility of fabrication, interfaces with CDS,SUS,COC,ISC

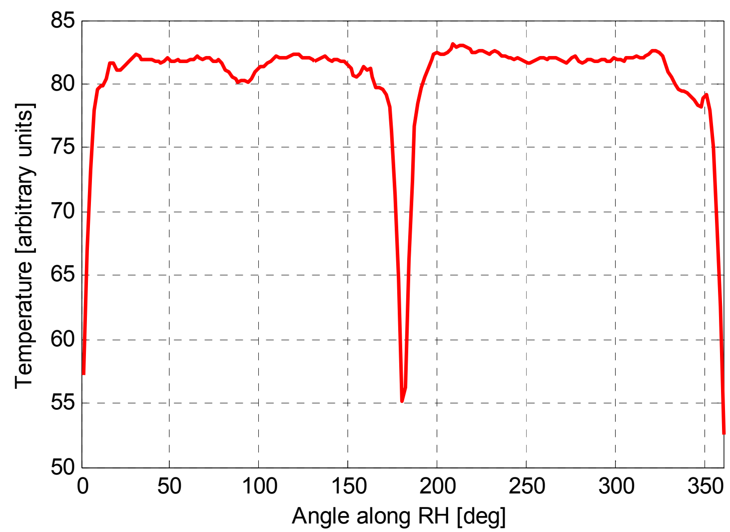


red circle shows gap between ring heater segments for SUS fiber welding

Ring heater seen during prototype quad SUS assembly

Vacuum ring heater tester at University of Florida





Sample ring heater temperature profile

TCS Fabrication Plan

- Much of the TCS optical and mechanical components are off-the-shelf
- Remaining components (e.g. ring heaters, in-vacuum mirrors, installation tooling) are being designed in-house and manufactured by local machine shops using established processes
- The University of Adelaide is procuring and delivering part of the TCS hardware (Hartmann sensor cameras) and has delivered a prototype baseline camera assembly.
  - » Procurement contribution is on the order of US$750k

TCS Project Phase Plans

- TCS entered the Project Phase in October 2010 to meet early need-by dates for in-vacuum TCS components integration
  - » Ring heater
  - » H2 in-vacuum steering mirror
  - » ZnSe viewports
- TCS will fully transition to Project Phase in December 2011 in order for remaining TCS components to meet later integration need-by dates.

TCS Challenges, Risks, and Mitigations

- Moderate TCS risks
  - » Noise due to TCS power instability, which are being mitigated by prototype study (projector noise reduction on eLIGO), and by optimizing ring heater components [AOS RR-003]
  - » Initial vendor for CO_2 laser proved unable to deliver suitable high power laser; we are currently investigating alternative vendors, and possibly installing lower power laser initially while pursuing higher power laser development [AOS RR-009]
- Major TCS risks
  - » Main risk is excessive or inhomogeneous absorption in ITM coatings. As-built coating prototypes meet (even exceed) spec; in-vacuo contamination is the remaining threat. In-situ cleaning procedures are currently under study to reduce contamination. [AOS COC RR-010]

TCS Near Term Activities

- Fabrication and installation of ring heaters and initial testing of Hartmann sensor on H2 single arm test
- CO_2 laser requirements and vendor re-evaluation
- CO_2 laser projector component design:
  - » Upper periscope mirror/ZnSe viewport design
  - » Beam shaping optics
  - » Intensity/beam drift stabilization
  - » In-vacuum steering optics for H1/L1
- Hartmann sensor PDR closeout and begin of Final Design phase
  - » Alignment optics for sensor installation
  - » Prototype electronics for Hartmann sensor at H2 single-arm integration