Thermal Compensation:
The GEO and LIGO experience and requirements for advanced detectors

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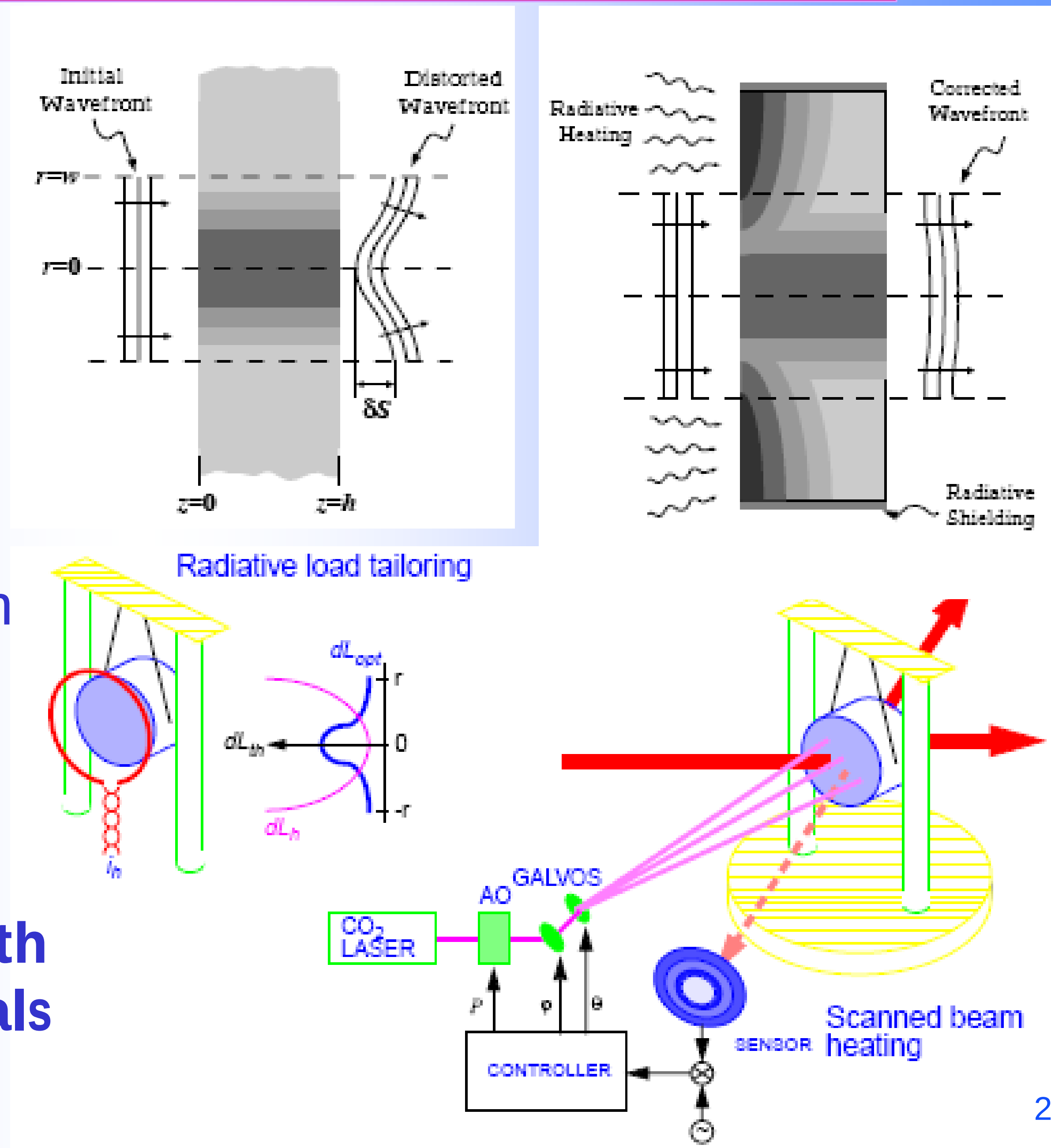
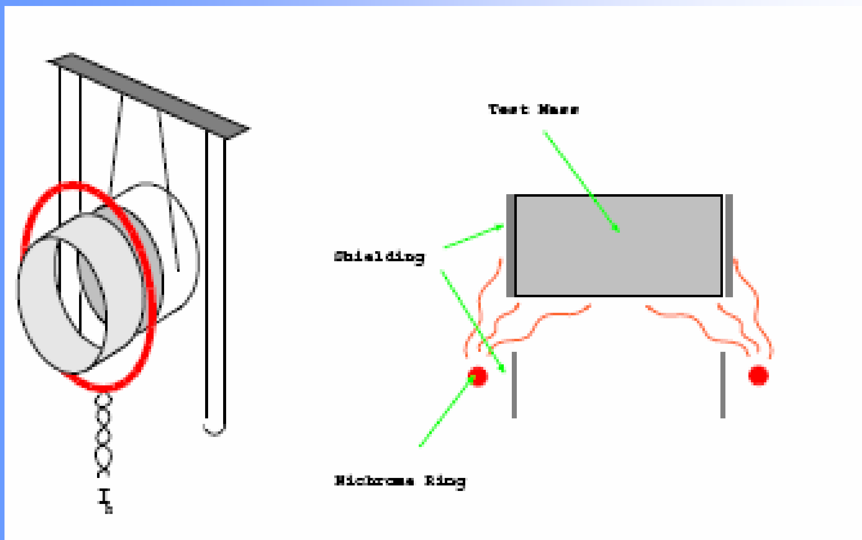
Ryan Lawrence's Thesis

- **Two heating techniques**
  - Ring heater
  - Scanning CO_2 laser
- **Ring heater for radially symmetric absorption**
- **Scanning laser for inhomogeneous absorption**
  - Point absorbers (dust)
  - Complicated absorption patterns (sapphire)
- **Two substrate materials**
  - Silica
  - Sapphire
- **Excellent results from both techniques on both materials**

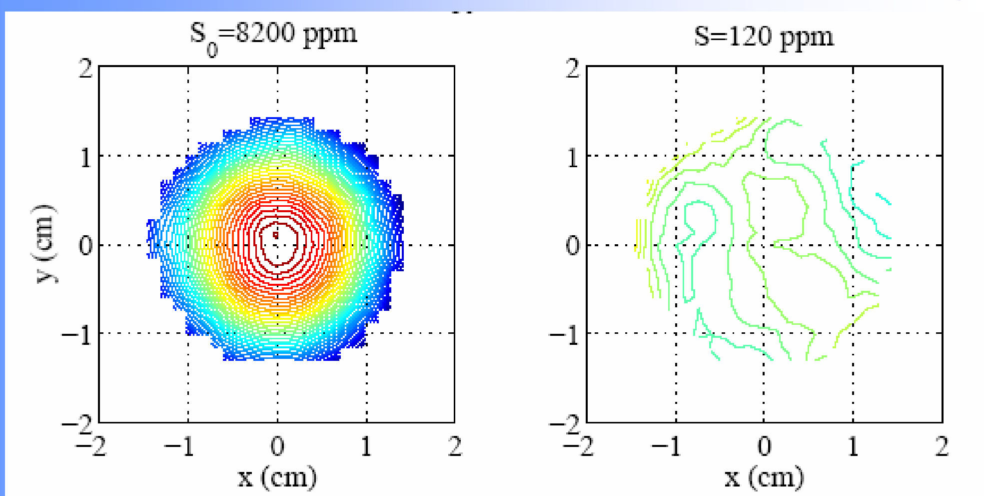


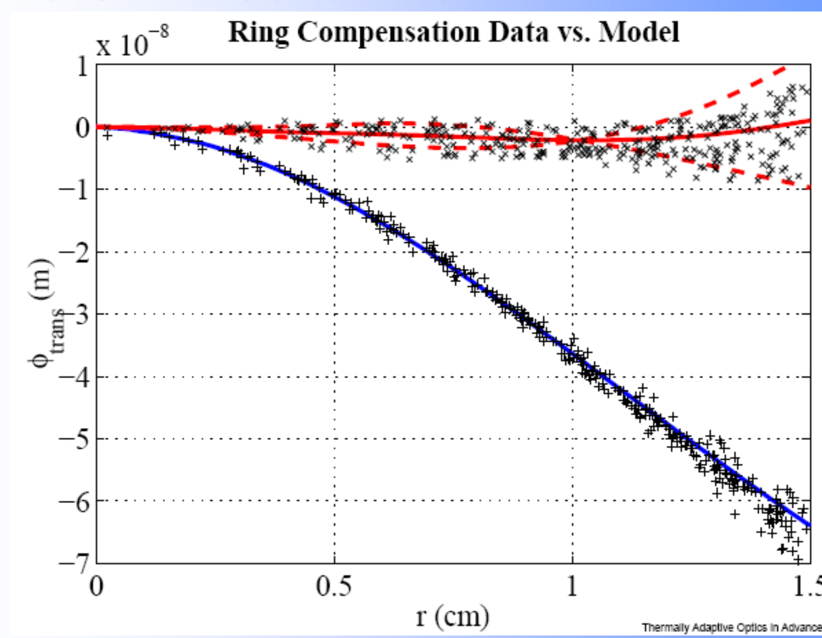
Ryan Lawrence's Thesis: Ring Heater



Ring heater system

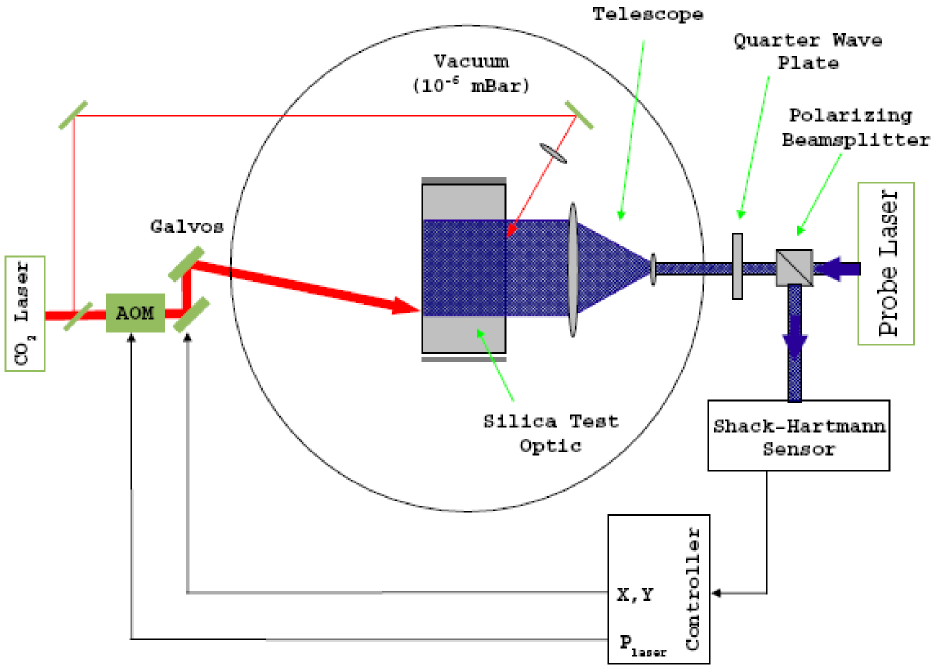
- Heat from incandescent source
- Shield keeps heat at edge of optic to avoid radial gradients
- Excellent correction of radially symmetric thermal lens
- Less efficient use of heat than laser

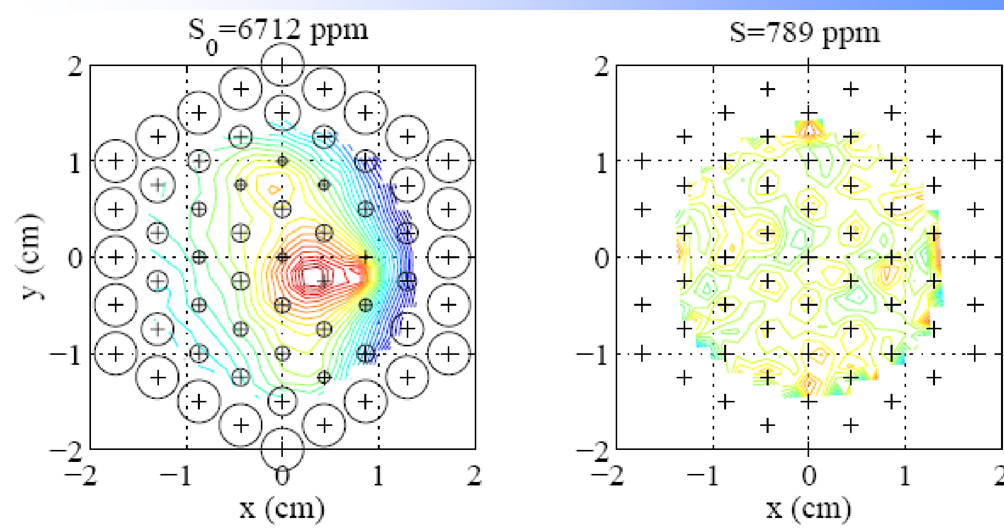




Ring Heater on Silica Optic

Ryan Lawrence's Thesis: Scanning CO_2 Laser





Reduction in thermal lens from point absorber

Scanning CO_2 laser system

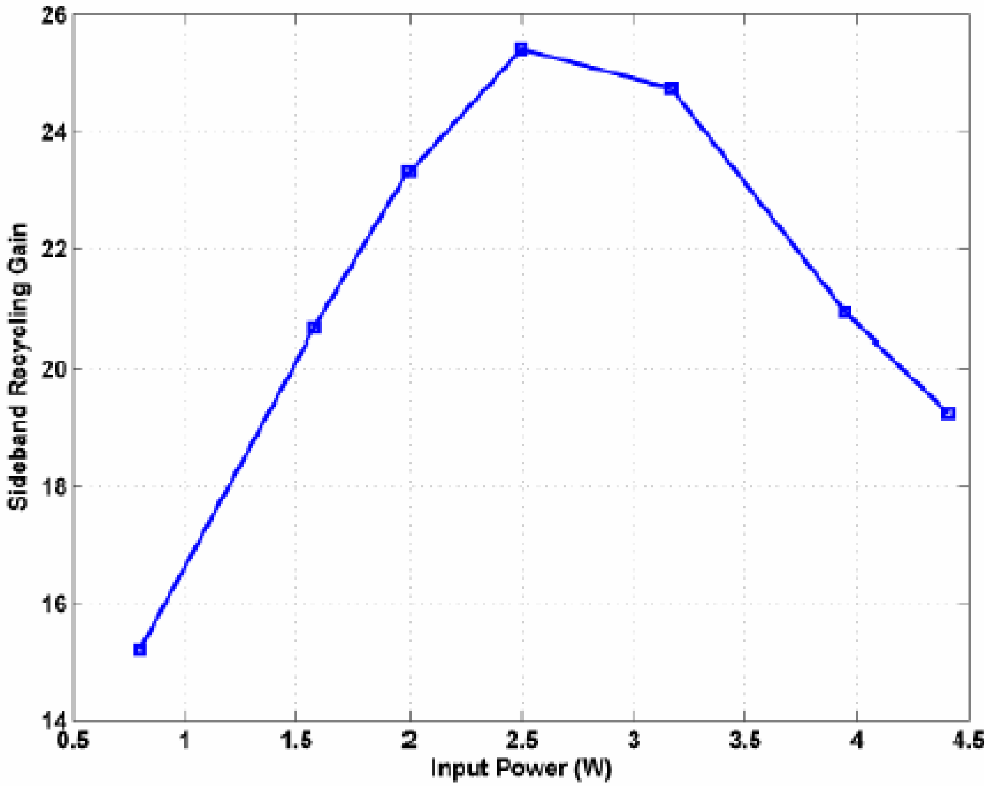
- Galvos used to control beam
- Shack-Hartmann sensor used to readout transmitted wave
- Feedback from sensor to galvos to minimize thermal lens

Sapphire thermo-elastic properties

Thermo-Optic Coeff:	$dn/dT = 7.2$ ppm/K
Thermal Expansion:	$\alpha_o = 5.6$ ppm/K
	$\alpha_e = 5.1$ ppm/K
Thermal Conductivity:	$\kappa_o = 39$ W/m/K
	$\kappa_e = 36$ W/m/K
Emissivity:	$\varepsilon = 0.89$

Initial LIGO: Excess Absorption at Hanford

- **Input optics curved to match recycling mirror curvature at 8 W**
    - Point design assumes a value for absorption
- **Found best matching at 2.5 W**
    - Additional absorption causes excess thermal lensing
- **Excess absorption has to be in recycling cavity optic**
    - Input mirrors or beamsplitter

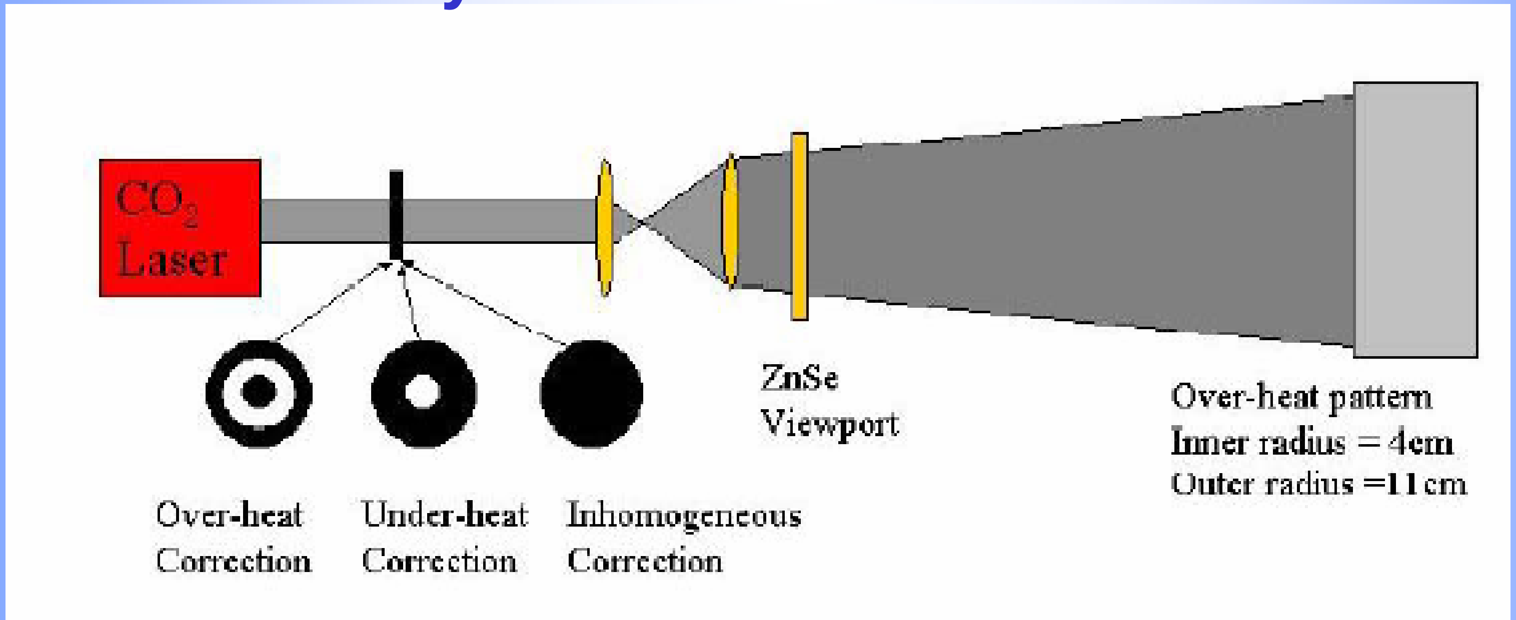


Other interferometers (2 K at Hanford and 4 K at Livingston) found to have much less absorption than expected

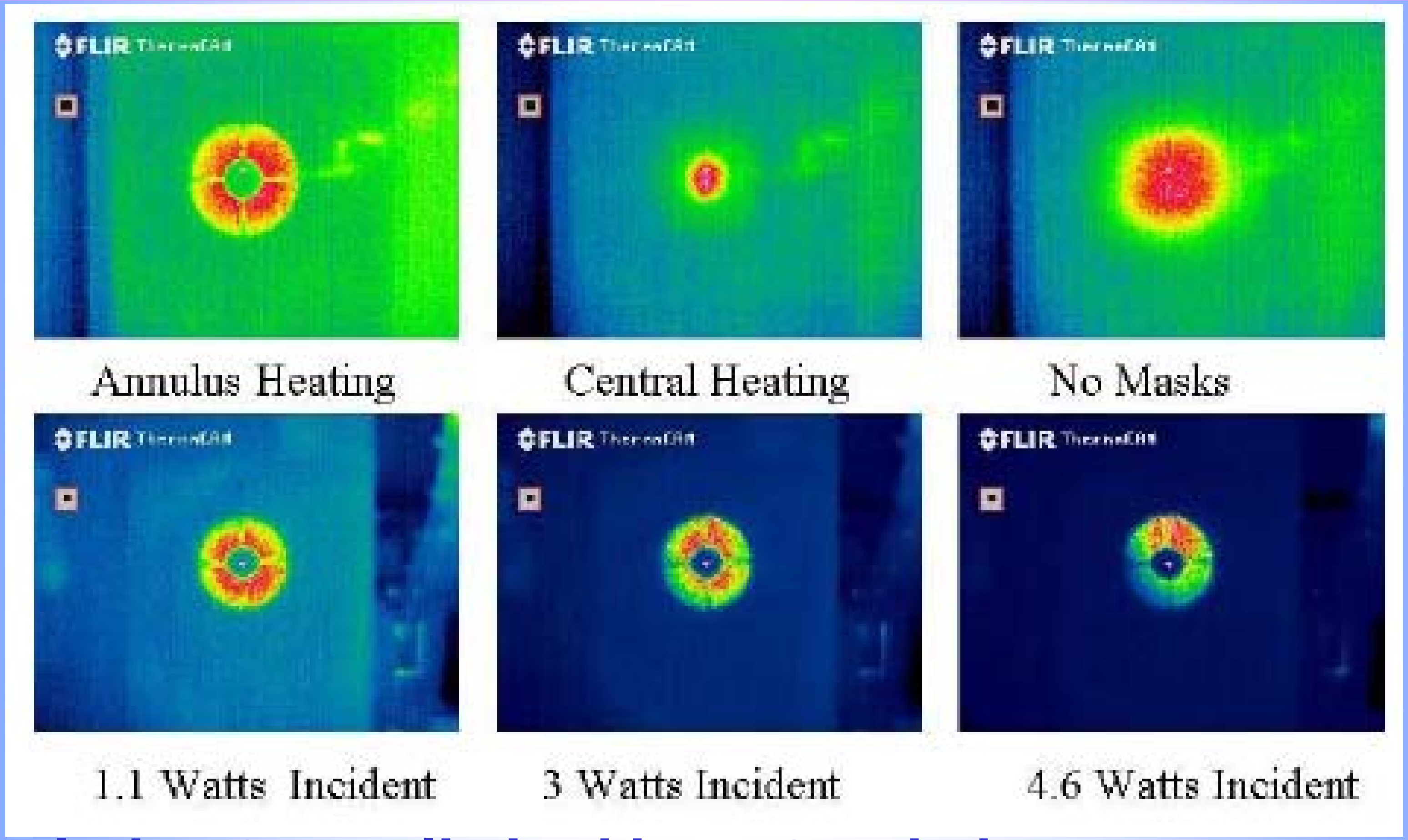
Sideband Recycling Gain LIGO 4K Hanford IFO

Initial LIGO: Thermal Compensation Design

- **8 W CO_2 laser directly projected onto mirrors**
  - Ring heater not used to minimize installation time in vacuum
  - Scanning laser not used to avoid Shack-Hartmann sensors and radiation pressure issues
- **Different masks used to compensate for high or low absorption**
- **Laser power controlled by acousto-optic modulator (H2) and rotating polarization plate (H1, L1)**
- **Power controlled by feedback from IFO channels**



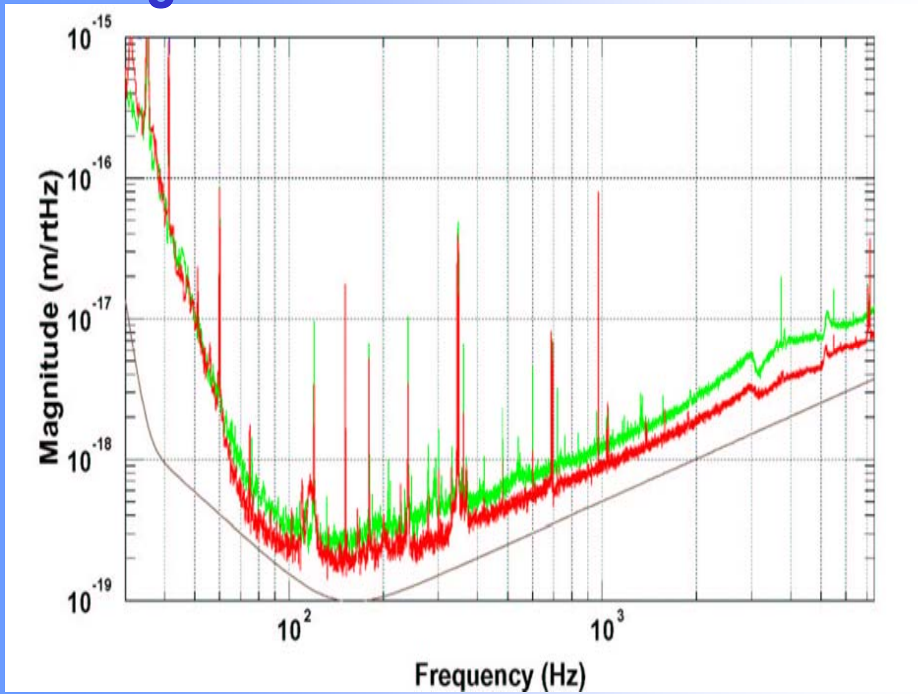
Initial LIGO: Effects of Thermal Compensation



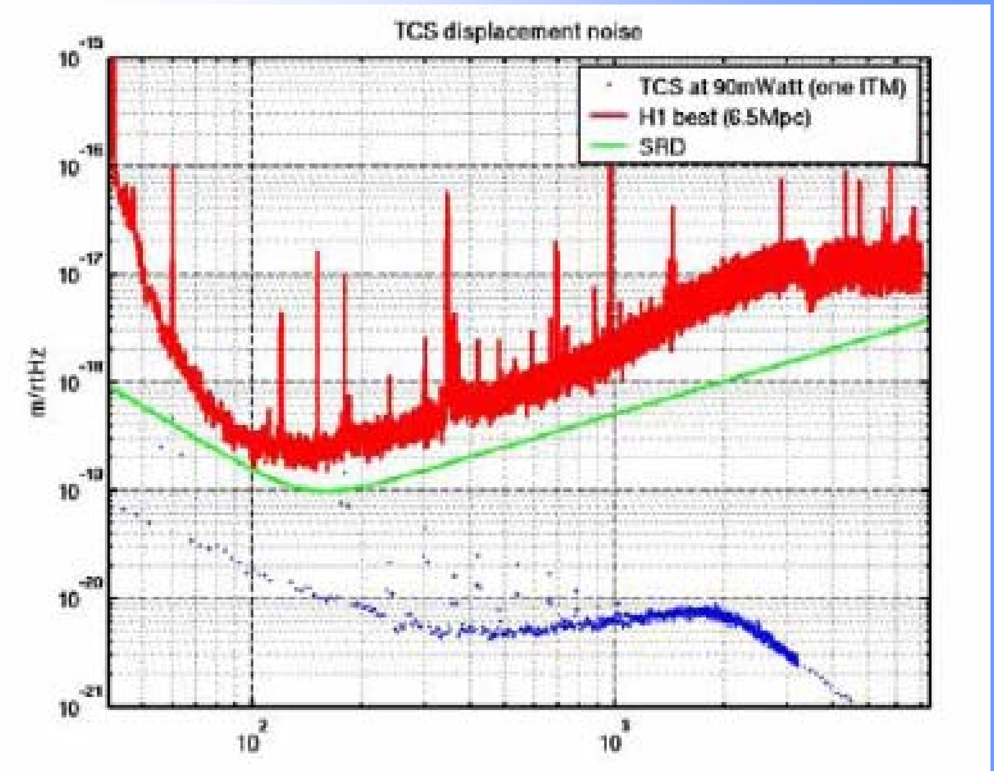
- **Resolution 6 mm, limited by ZnSe window aperture**
- **Underheat mask - Gaussian profile same as main beam**
- **Overheat mask - Annulus with radii optimized**
- **Poor illumination at 3 - 4.6 W from high RF power in AOM**
  - Switch to polarizer as control mechanism

Initial LIGO: Noise from Thermal Compensation

- **Improvement in sideband balance reduces sensitivity to sideband phase noise**
  - Uncovers shot noise
- **High frequency noise now at design level of shot noise**



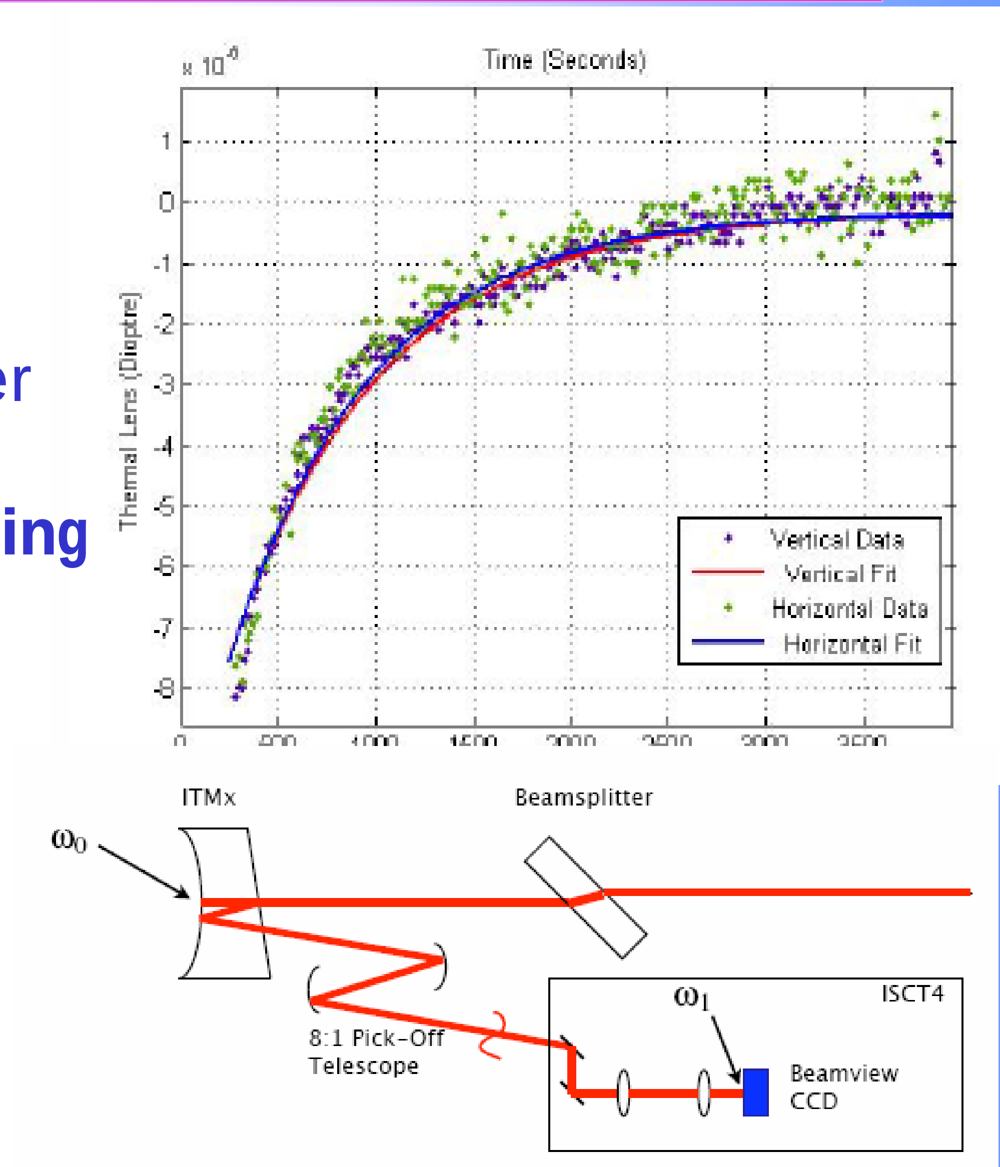
Green: without thermal compensation
Red: with thermal compensation



- **Direct noise from thermal deformation of high reflecting surface**
  - Annulus heating lower by factor of 10

Initial LIGO: Excess Absorption at Hanford

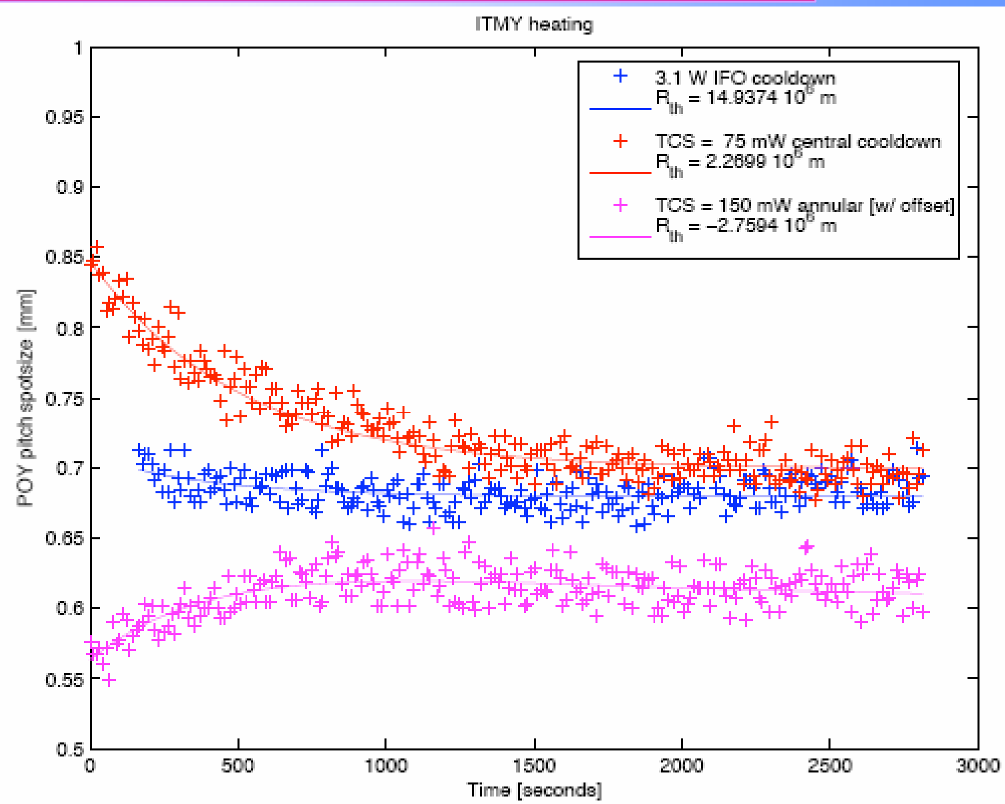
- **Three techniques used to determine source of excess absorption**
  - Change in g factor
  - Thermal compensation power
  - Change in spot size
- **Fairly consistent result (assuming absorption in HR coating)**
  - ITMx 26 ppm
  - IMTy 14 ppm
  - Design 1 ppm
- **Resulting changes**
  - ITMx replaced
  - ITMy drag wiped *in situ*

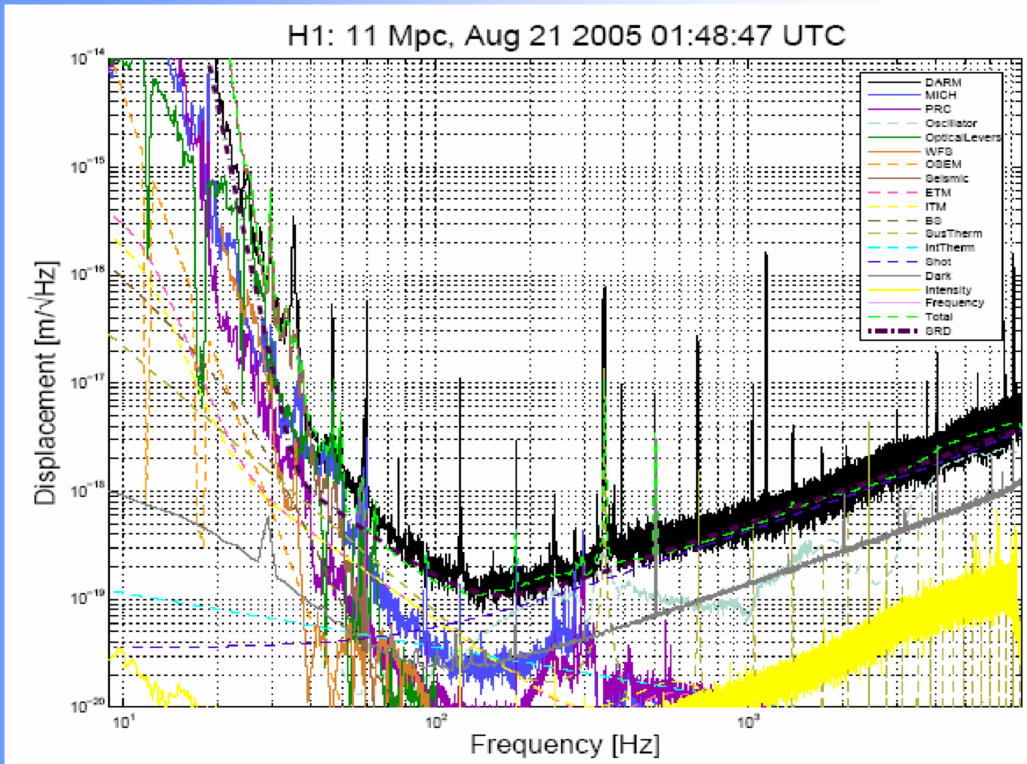


Spot size measurements: Data and technique

Initial LIGO: Absorption improvement at Hanford

- **ITMx replaced with spare optic**
- **ITMy drag wiped in place**
- **Both optics (ITMx and ITMy) show improved absorption**
    - Both < 3 ppm

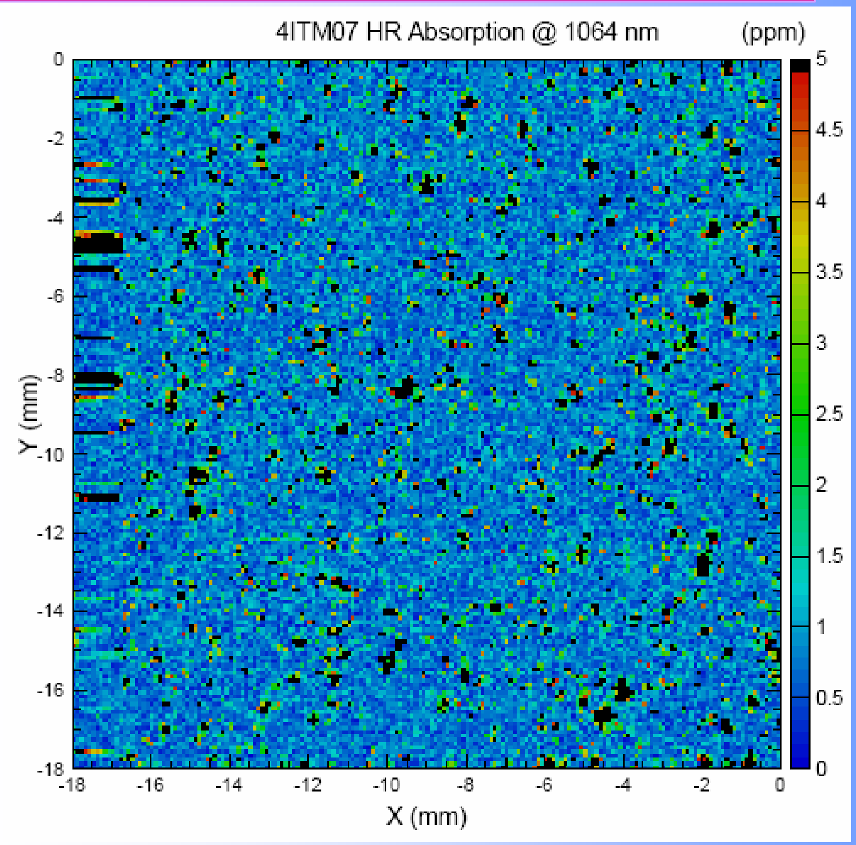




- **Power 6.8 W - mode cleaner**
- **Shot noise at design level**
- **11 Mpc binary neutron star inspiral range**

Initial LIGO: Bench Tests of H1:ITMx

- H1:ITMx shipped to Caltech immediately after removal
- Absorption measured using photothermal common-path interferometry
- Background < 1 ppm
- Significant outliers with absorption > 40 ppm

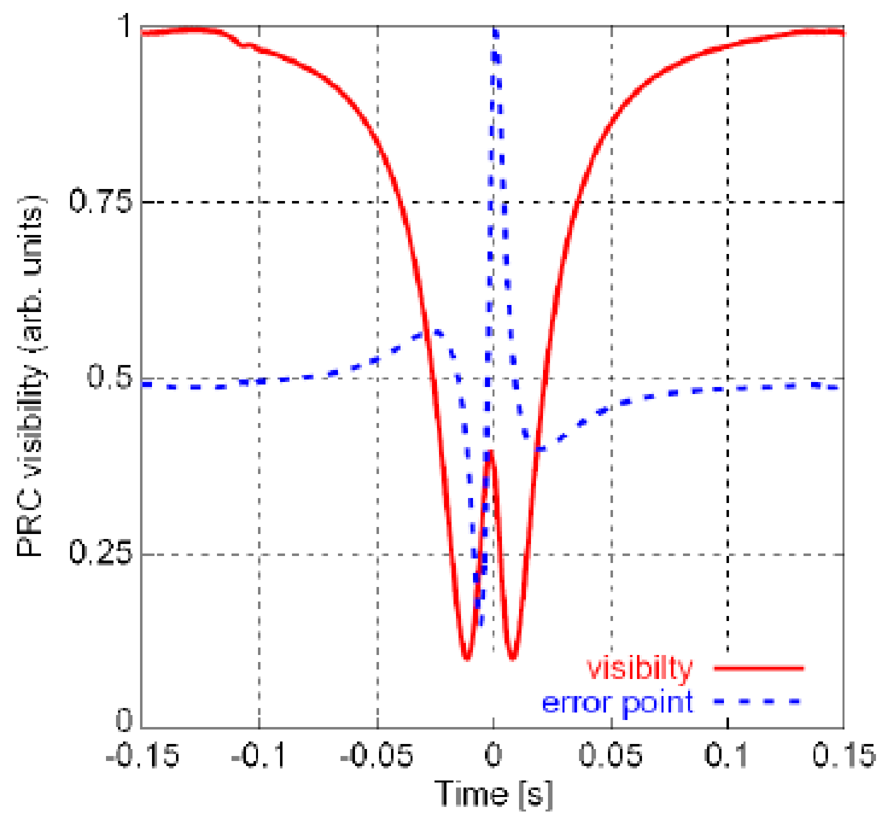


Dust source of absorption?

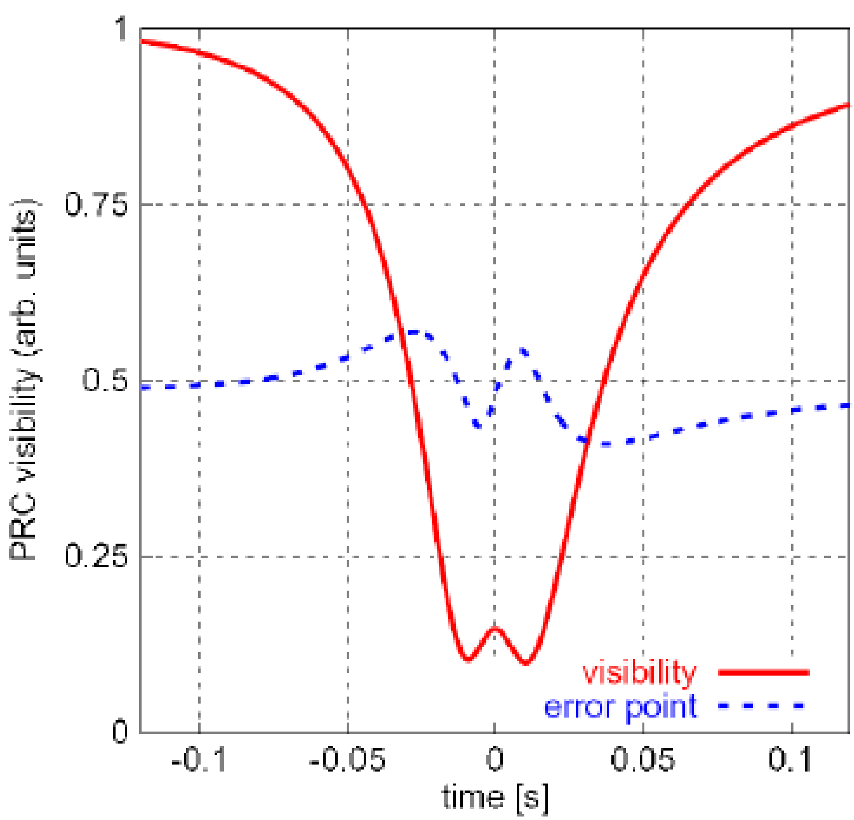
- Soot from brush fire in 2000?
- Attracted by charged surface?
- Insufficient cleaning and handling procedures?

GEO: Power and locking problem

- Poor contrast at dark port
- Mismatch in radii of curvature of end folding mirrors



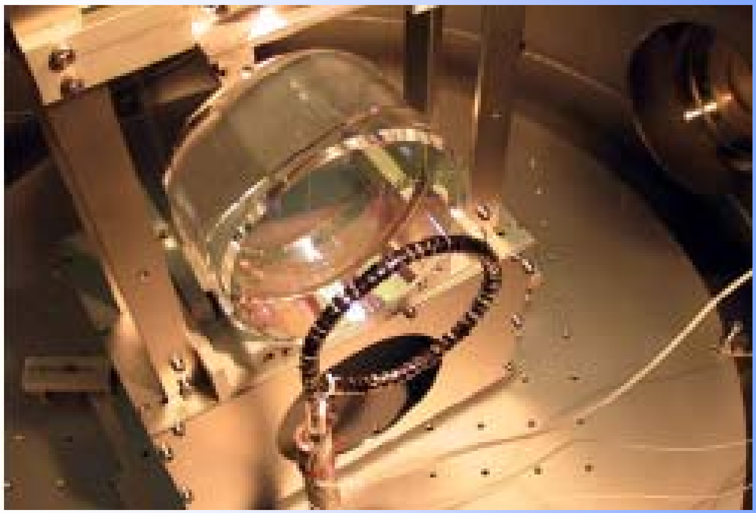
Error signal for locking and power level near design radius

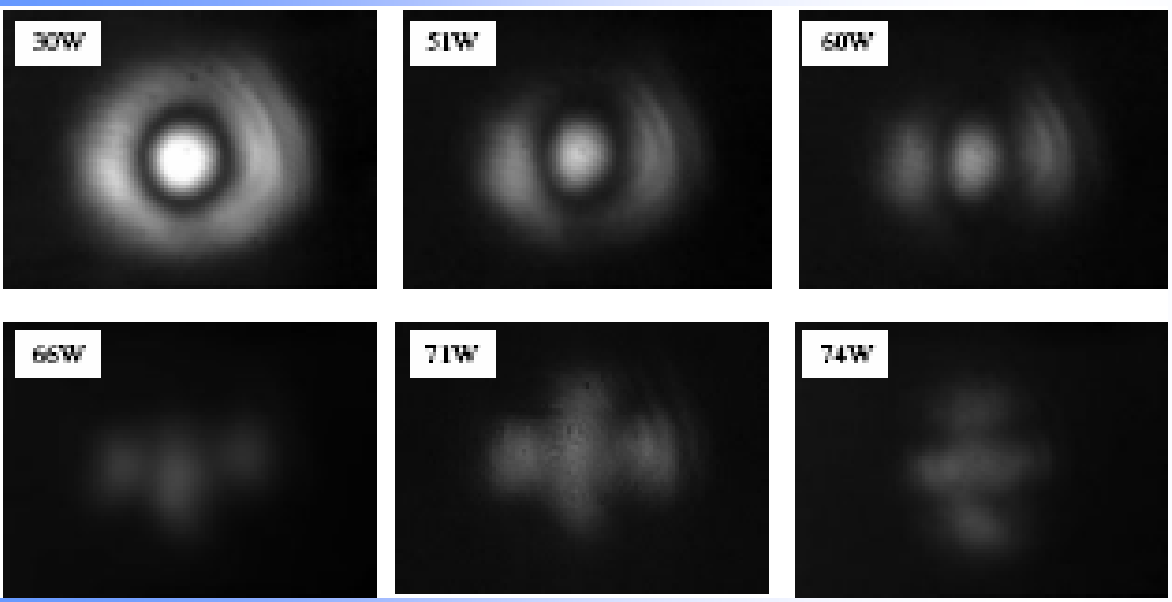


Error signal for locking and power level with observed radii

GEO: Control of optic with ring heater

- **Ring heater installed behind east end folding mirror**
- **Thermal expansion changes radius of curvature**
- **Radius**
  - East 687 m -> 666 m
  - North 660 m

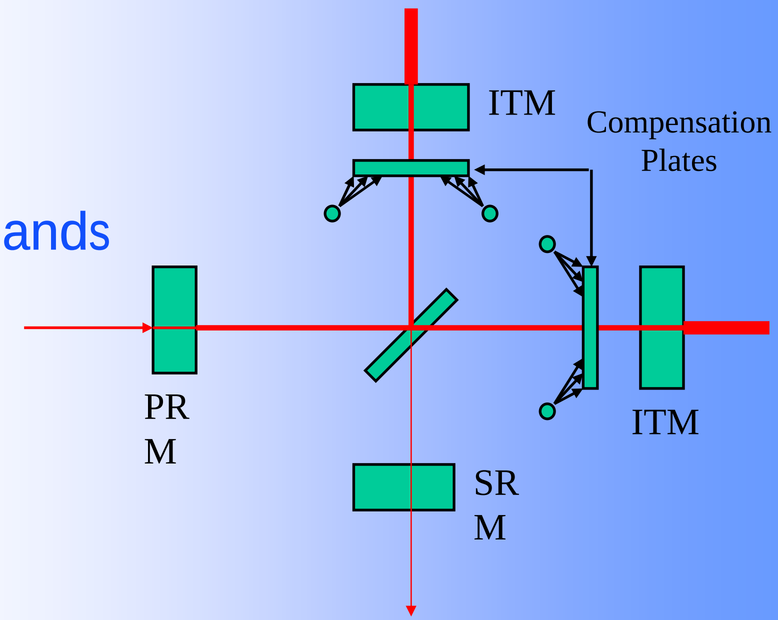




- **Increase in heater power changes contrast defect**
- **Slight astigmatism causes horizontal and vertical curvature match to be at different powers**
- **71 W best compromise**

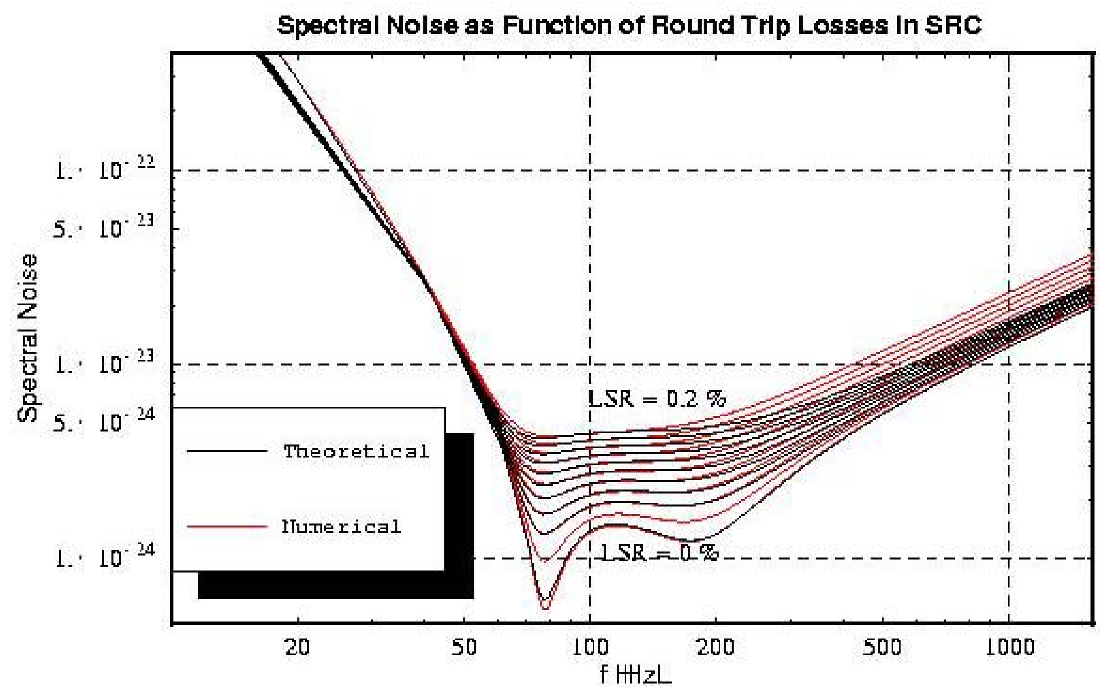
Advanced: Upgrades and challenges

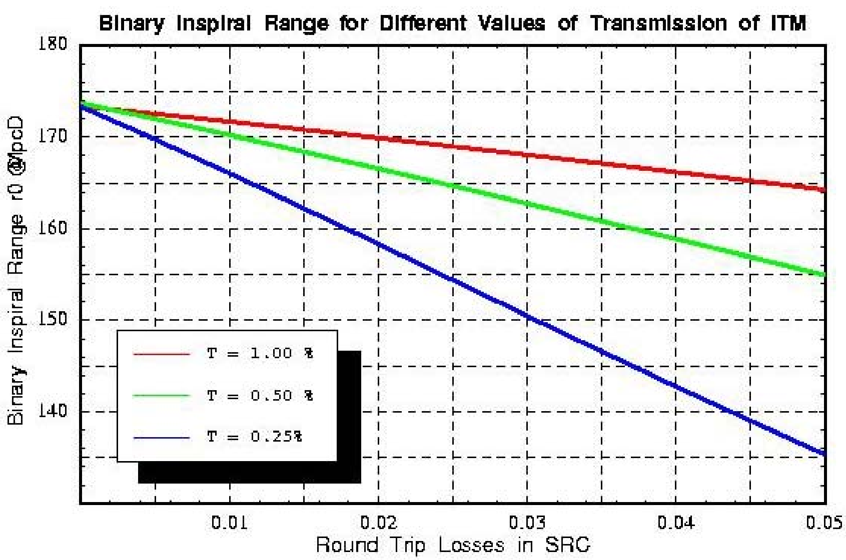
- Initial LIGO compensation effective at 100 mW absorbed
- Advanced LIGO expected to have 350 mW absorbed
- Cleanliness and handling will be crucial
  - Need to keep absorption down
- Potential improvements for advanced detectors
  - Graded absorption masks
  - Scanning laser system
  - Compensation plate in recycling cavity
  - Graded absorbing AR coating
  - DC readout, reducing requirements on RF sidebands
- Challenges
  - Greater sensitivity
  - New materials – sapphire ~ 20 ppm/cm absorption
  - Compensation of arm cavities
  - Inhomogeneous absorption
  - Noise from CO_2 laser



Advanced: Losses in signal recycling cavity

- Scatter in signal recycling cavity up convert gravity-wave sidebands
- Sets the most severe limit on thermal aberrations
  - ~ 0.1 % loss from TEM00 mode
  - ~ 5% loss in sensitivity

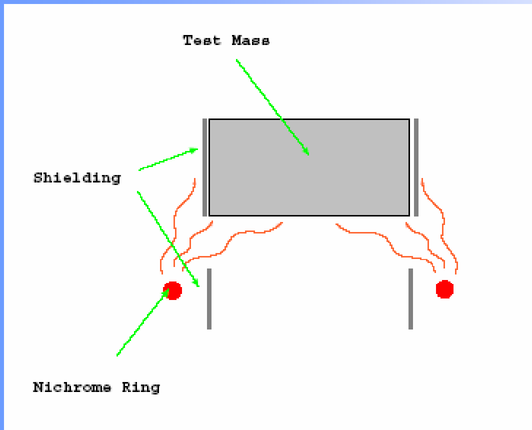


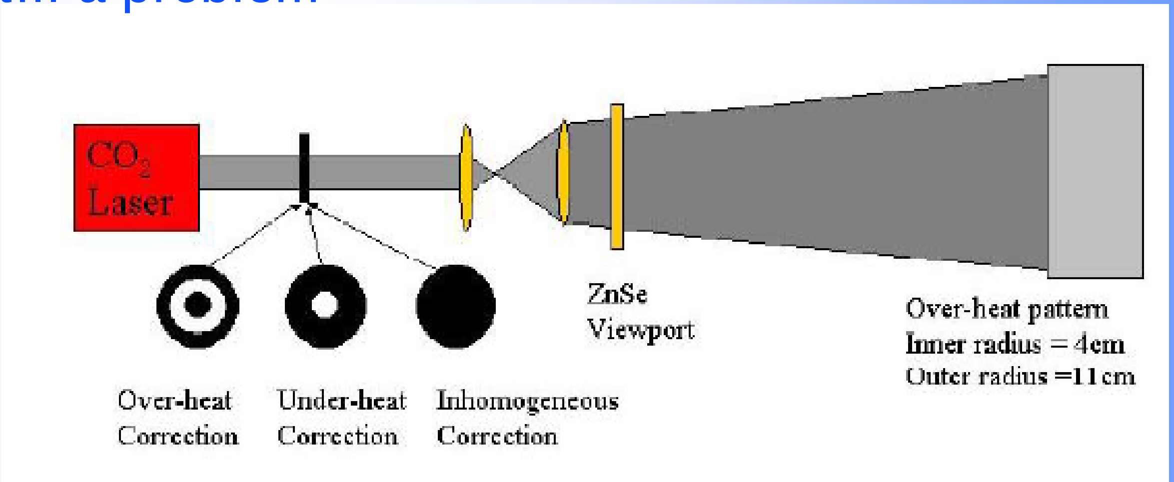


- Low frequency sensitivity set more by thermal noise
- Less effect from thermal aberrations

Advanced: Lasers and ring heaters

- Ring heaters simplest compensation system
  - Adds a lot of unnecessary heat
  - Could cause thermal expansion of other parts
- Scanning laser system causes noise
  - Jumps in location cause step function changes in thermal expansion
  - Harmonics of jump frequency could be in-band
  - Could require feedback with Hartmann sensors or similar
- Staring laser system works on initial LIGO
  - Could require unique masks for each optic
  - Unique masks could be inappropriate as system is heating up
  - CO_2 laser noise still a problem





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