Status Report: Adaptive Thermal Compensation & Sapphire Thermophysical Constants

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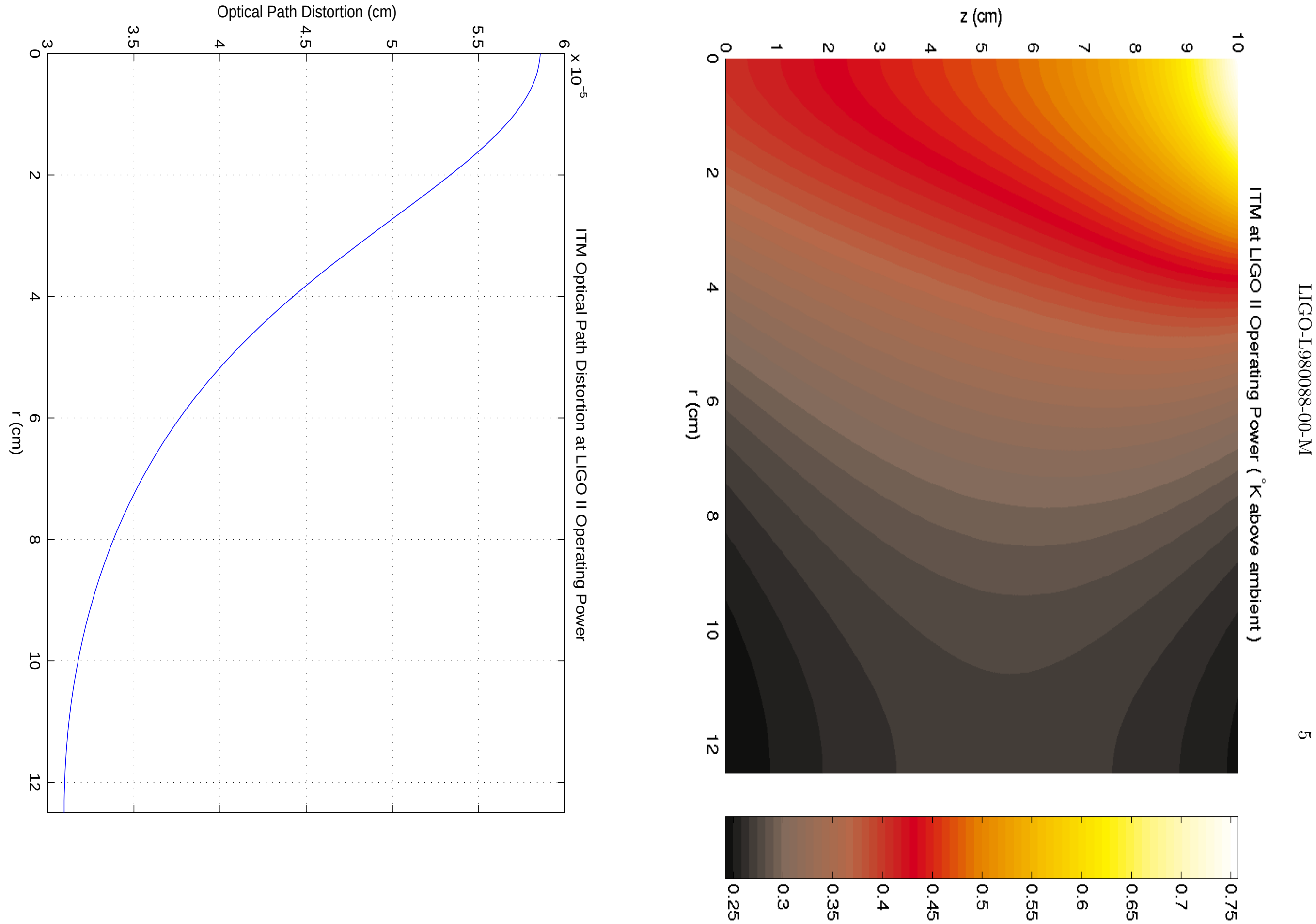
FEA model: uncorrected SiO_2 ITM



Adaptive Compensation of Thermal Lensing in LIGO II Core Optics

- Thermal lensing forces polished-in curvature bias on LIGO I core optics for cavity stability at operating temperature
- LIGO II will have ~20X greater laser power, ~3X tighter net figure requirements

  - higher order (nonspherical) distortions significant; prepolished bias, dynamic refocusing not adequate to recover performance

  - possible bootstrap problem on cold start

- Test mass & coating material changes may not be adequate

  - SiO_2 has low k_{th}, high dn/dT, but low bulk absorption

  - Al_2O_3 has higher k_{th}, moderate dn/dT, but high bulk absorption (so far...)

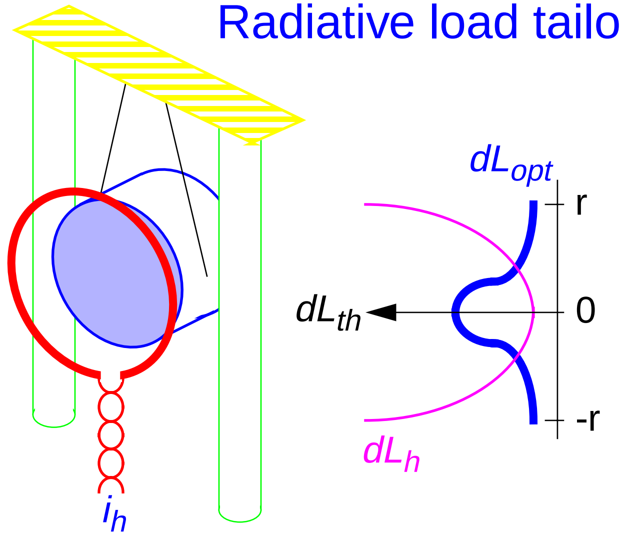
  - coating improvements still speculative

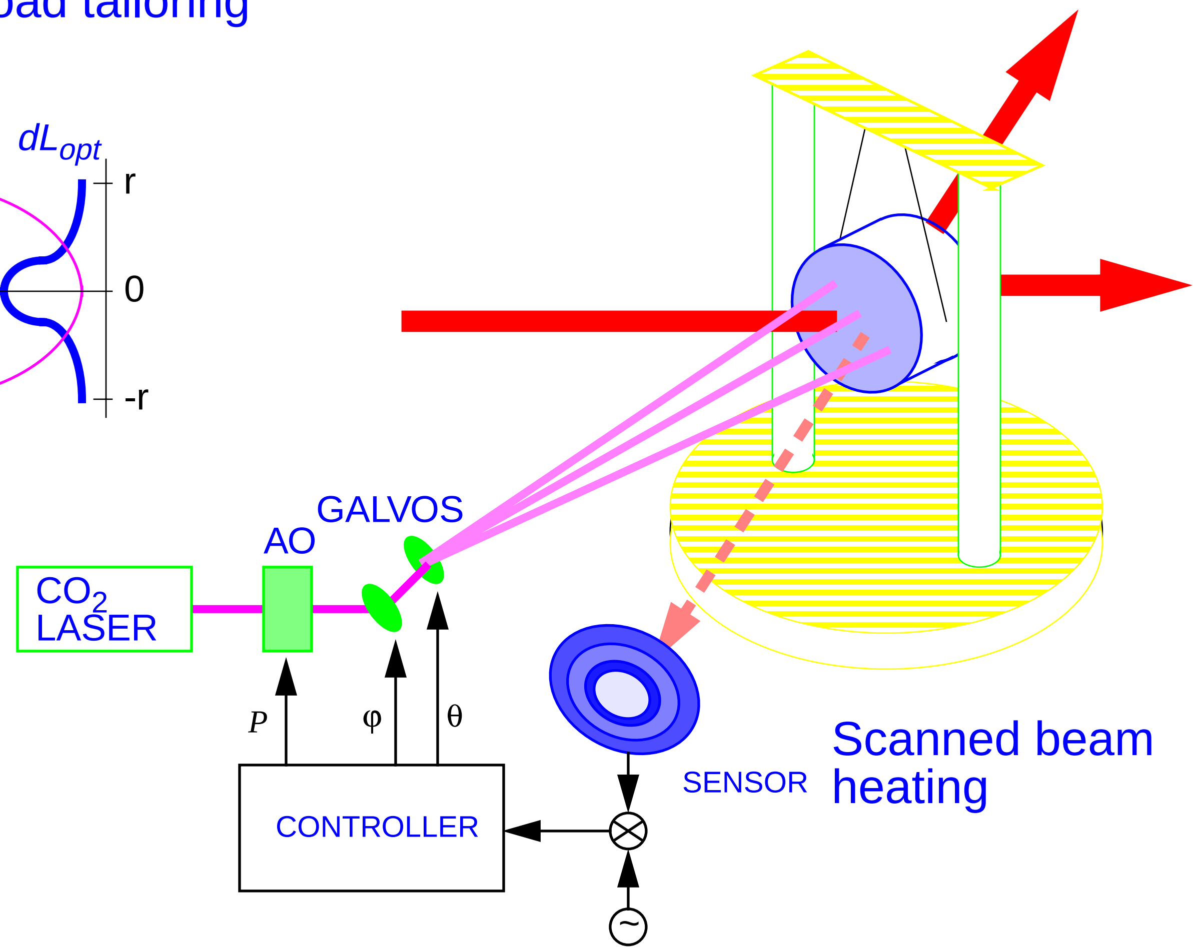
Sensing & Actuation

- Extend LIGO I “WFS” to spatially resolve phase/OPD errors
  - scanning “Phase Camera” (Adhikari, MIT)
  - staring “Bullseye WFS” (Mueller, UF)
- Thermal actuation on core optics (Lawrence, MIT)
  - Noncontact actuator with minimal spurious phase noise
  - Time constants matched to disturbance timescales
- Two actuators in development
  - Passive radiative ring heater and low-emissivity shields
    - Only copes w/axisymmetric errors, but minimal potential for spurious noise
  - Scanned directed beam
    - Arbitrary spatial correction, but induced thermoelastic noise is a concern

Thermal OPD Actuators

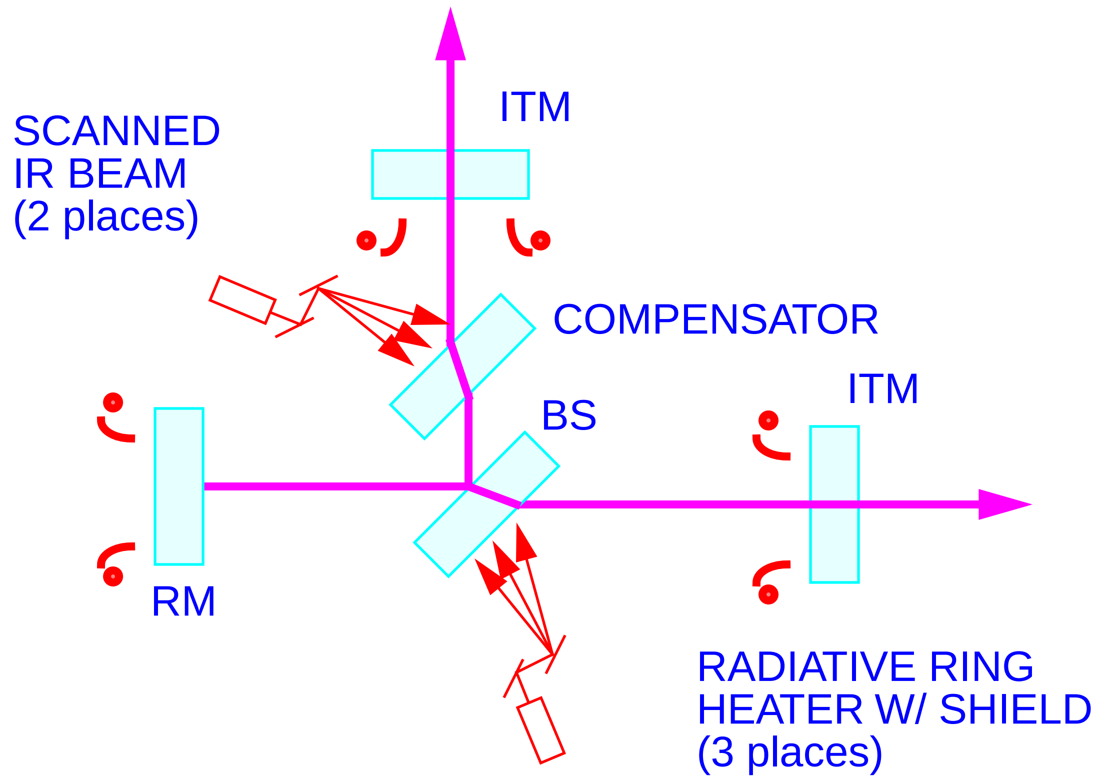
Radiative load tailoring



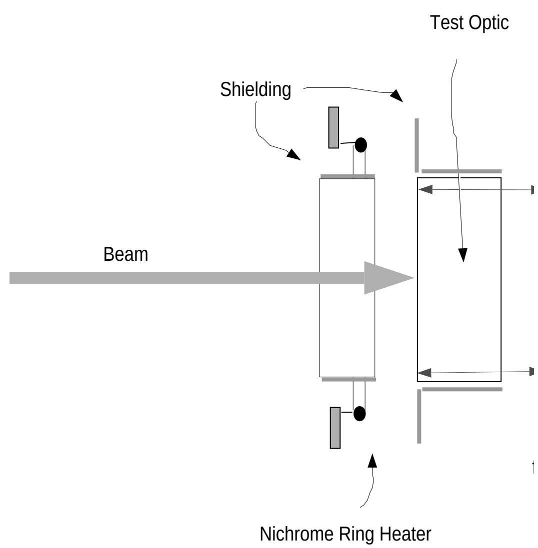


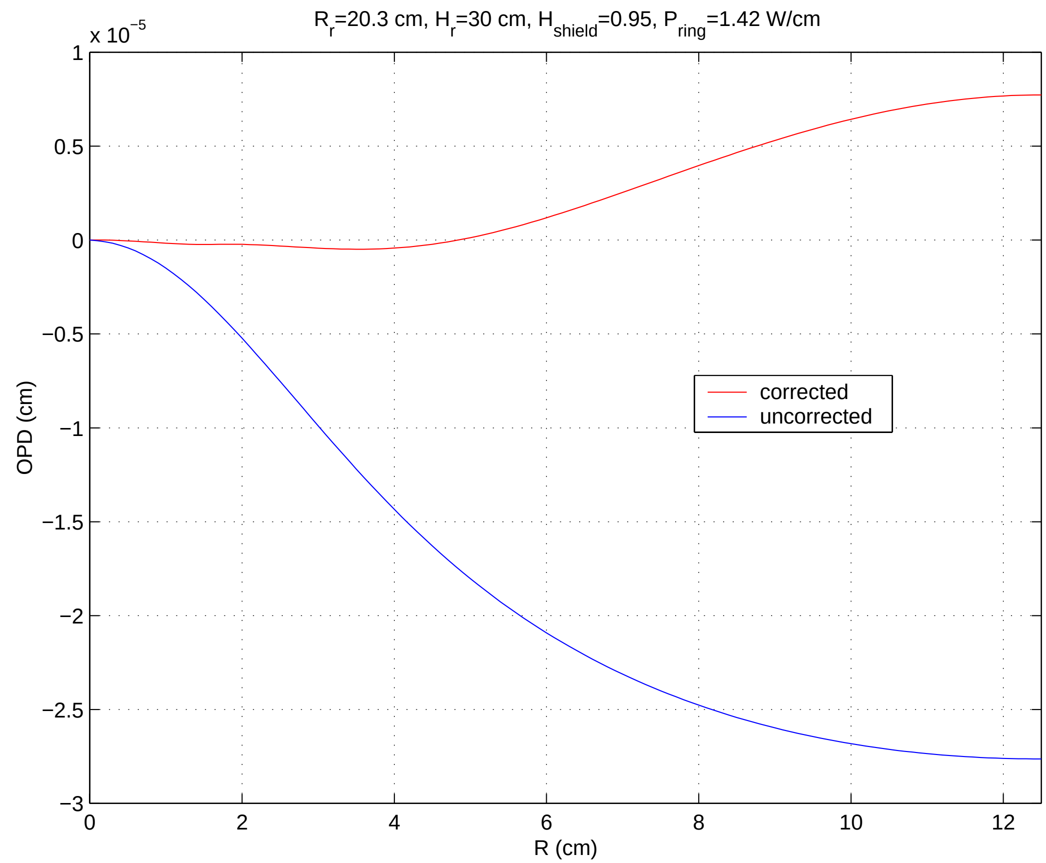
Scanned beam heating

Implementation (SRM and ETM's not shown)

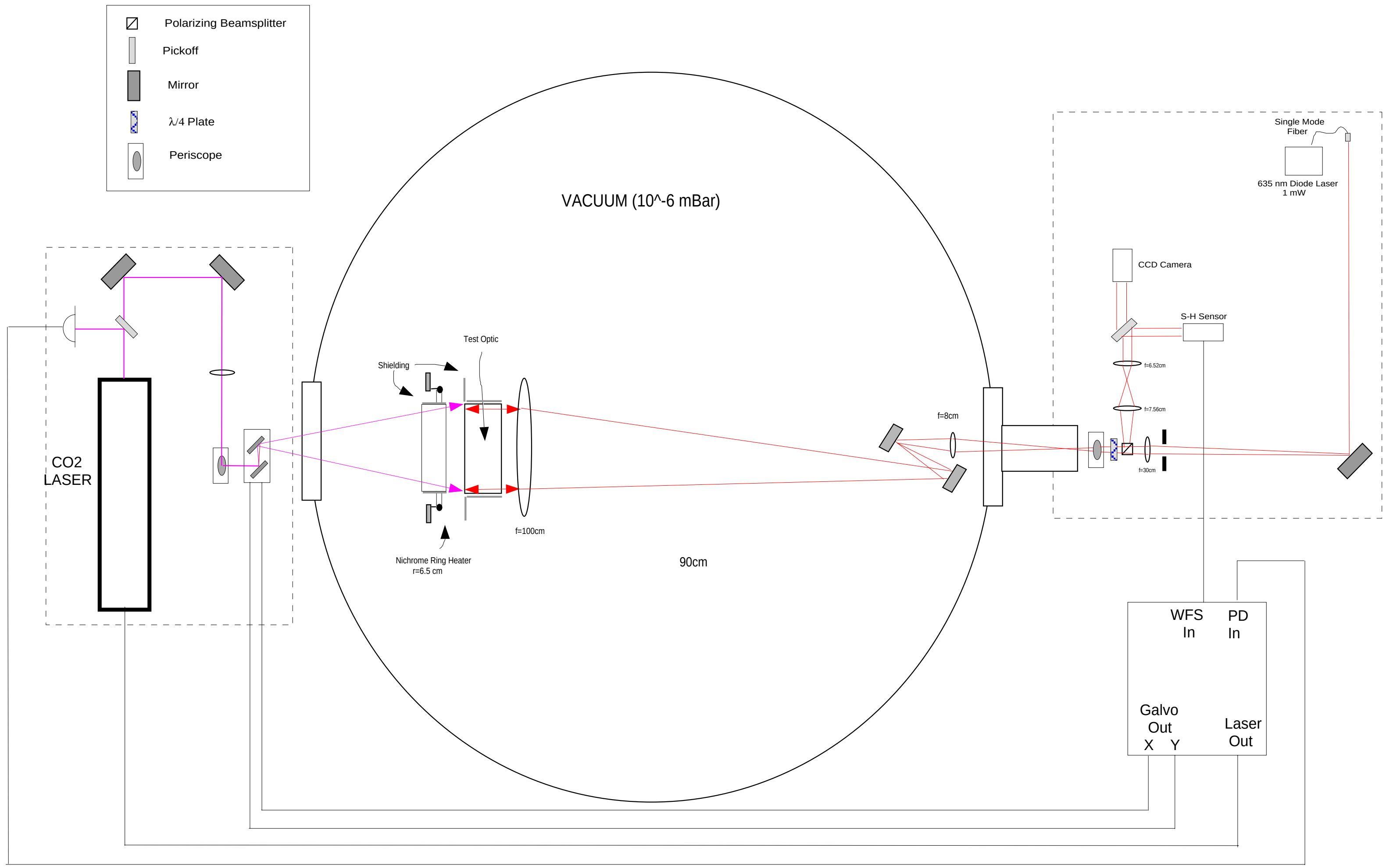


FEA model w/correction: ring heater + cylindrical radiation shield

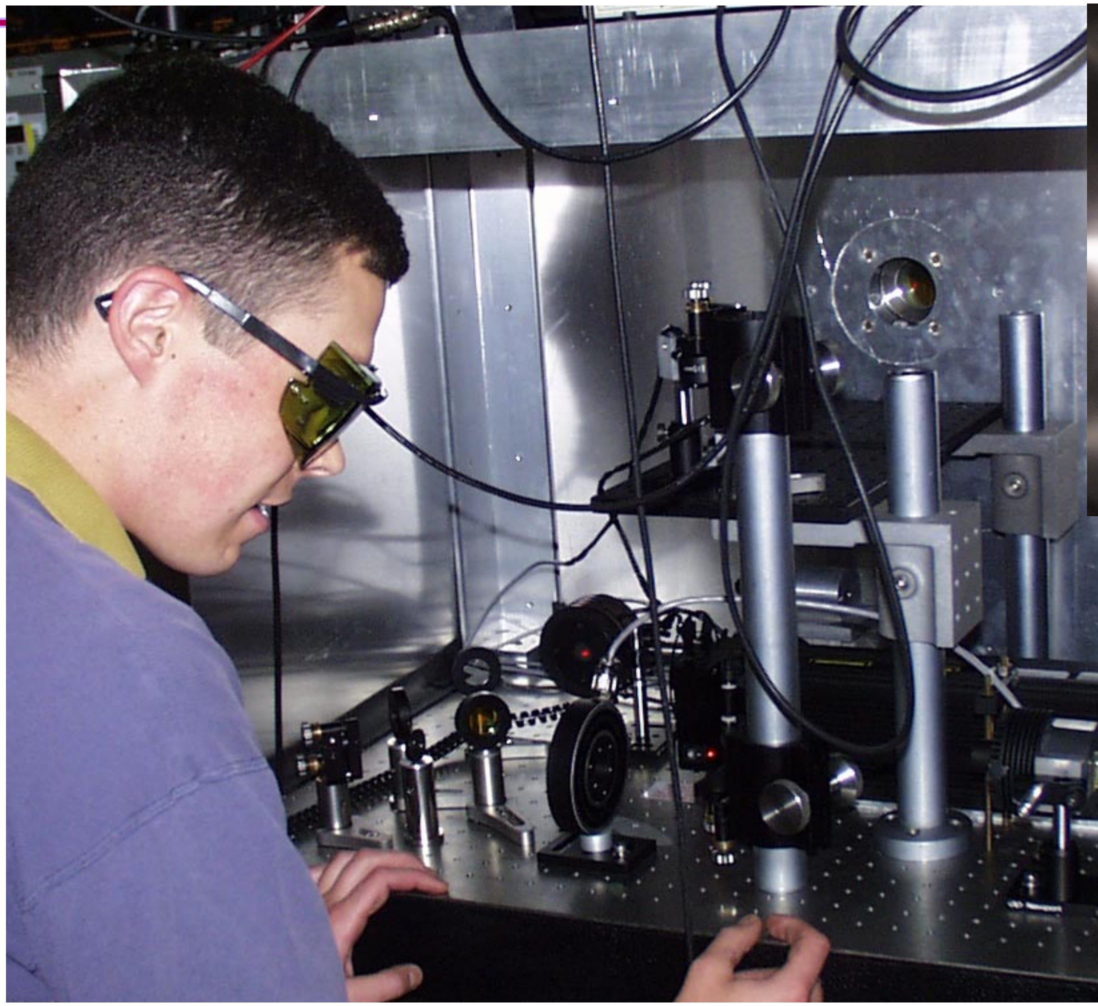


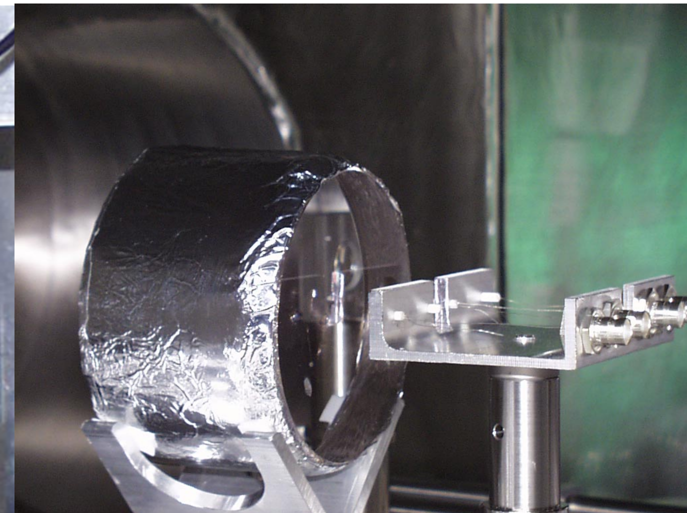


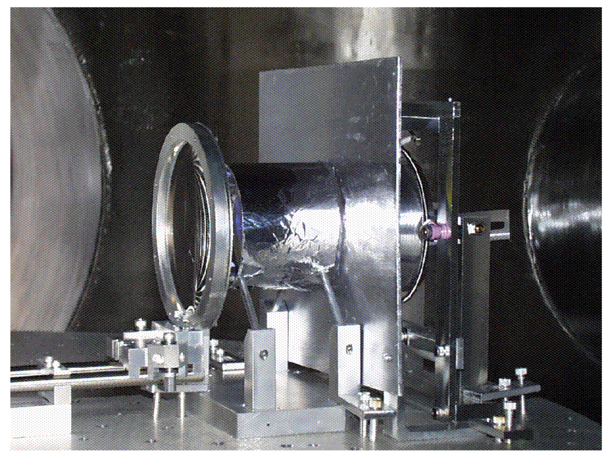
ATC Experiment



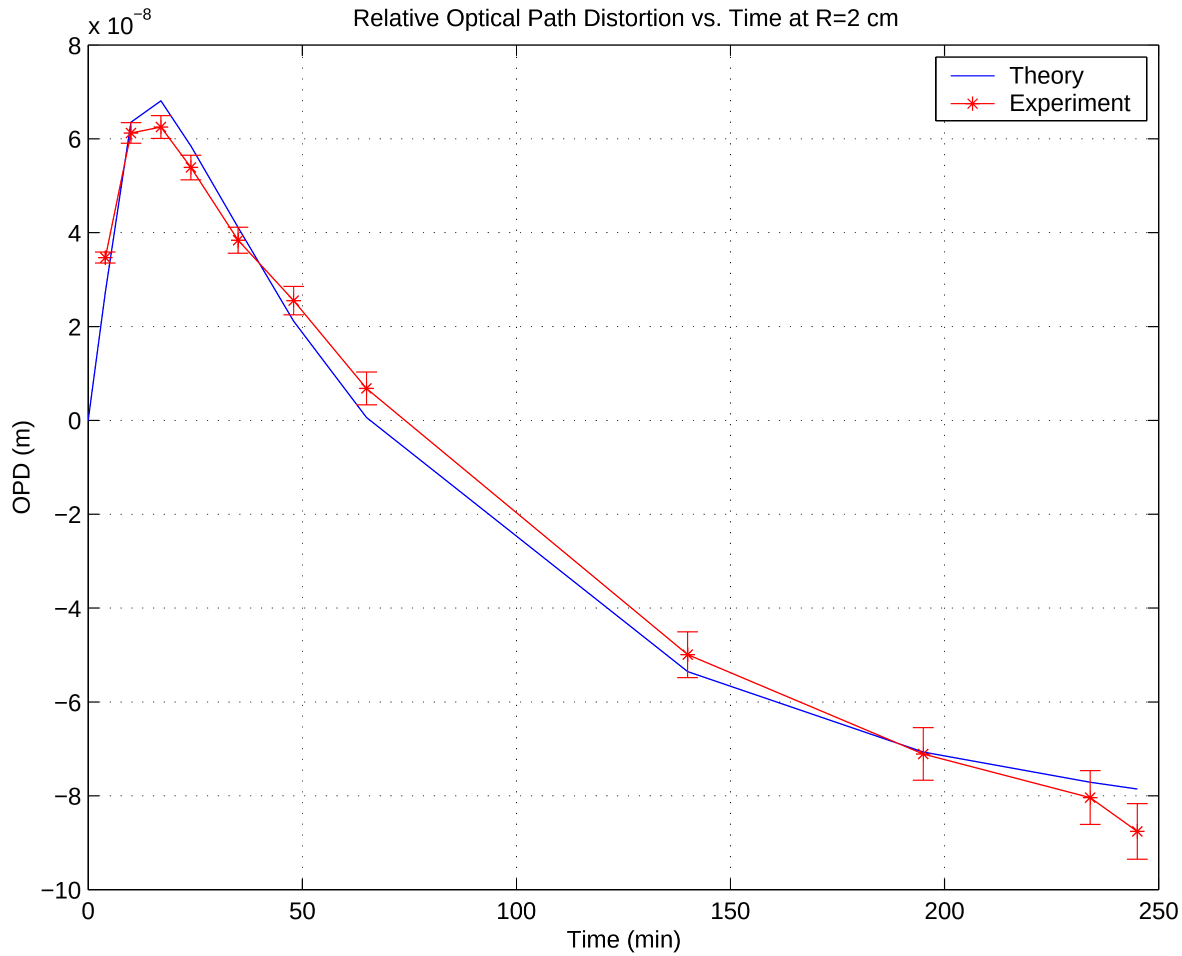
ATC Experiment



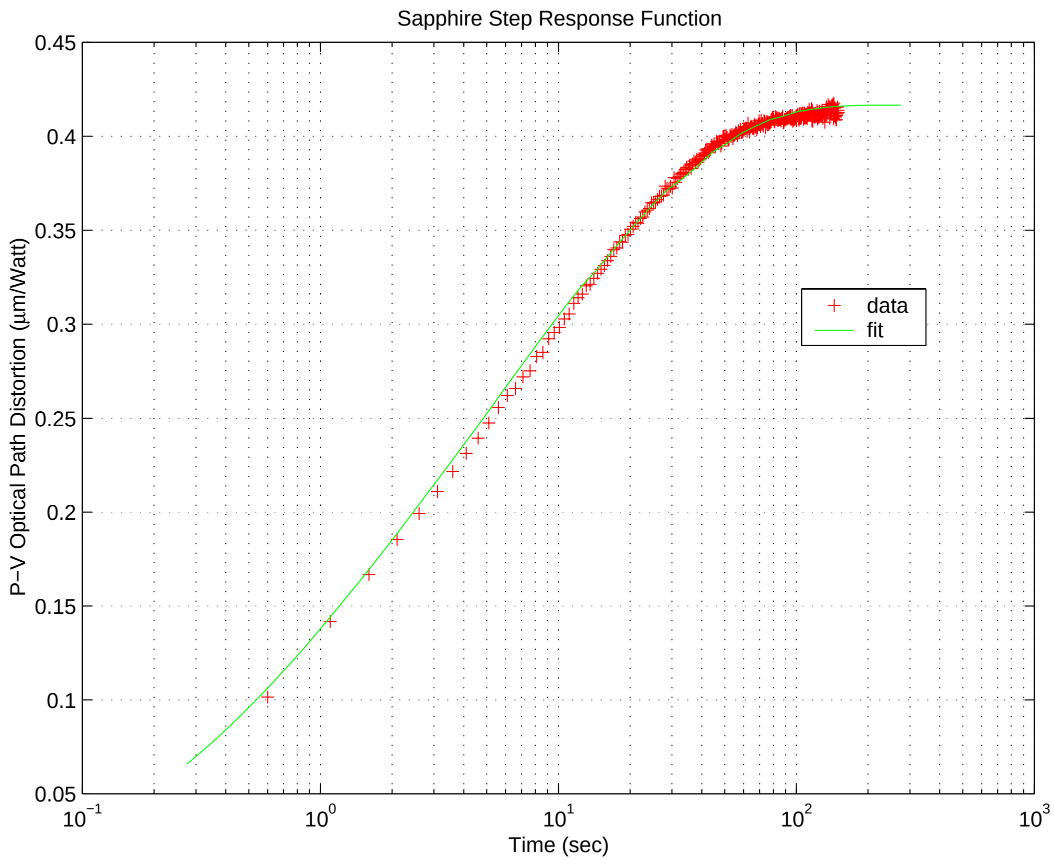




OPD vs. t, ring heater w/SiO2 test optic



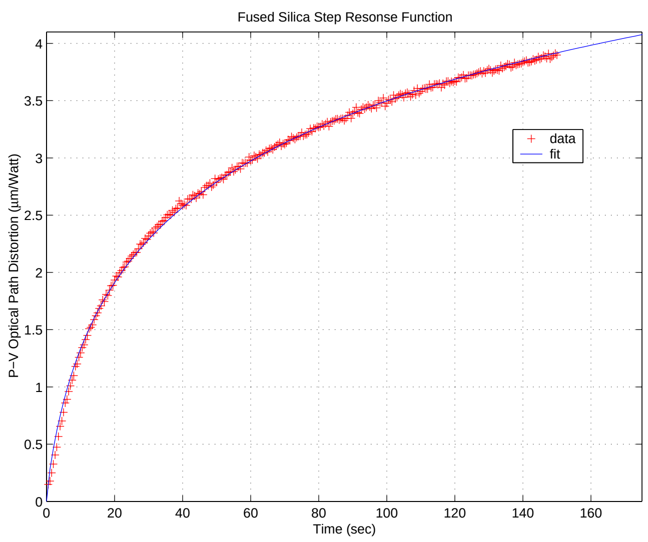
Directed Beam Compensation



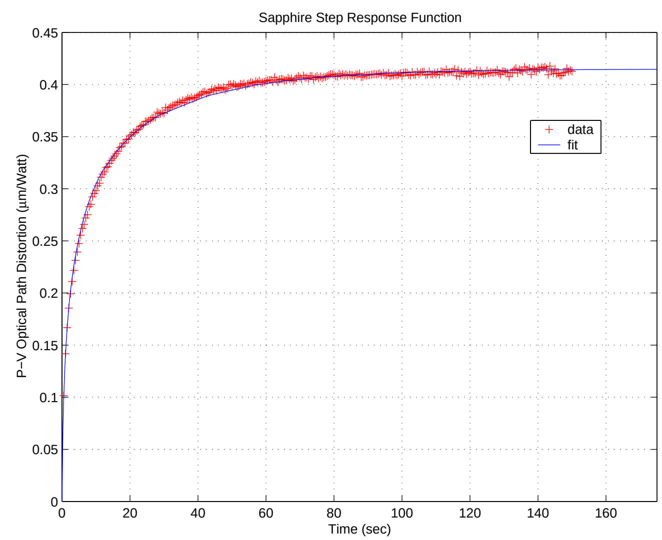
(neat sideshow: accurate constraint of sapphire material properties)

Measure waist, power; fit thermal OPD vs. time by adjusting α/k_{th}, $(dn/dT)/k_{th}$, k_{th}/C_v

SiO_2:
$dn/dT = (8.9 \pm 0.1) \times 10^{-6}\ K^{-1}$
$k_{th} = (1.25 \pm 0.07)\ W\ m^{-1}\ K^{-1}$



Al_2O_3(c-axis):
$\alpha* = (3.65 \pm 0.55) \times 10^{-6}\ K^{-1}$
$k_{th}* = (33.1 \pm 2.5)\ W\ m^{-1}\ K^{-1}$



** Depends strongly on assumed dn/dT*

Interesting sapphire results so far (preliminary)

- Due to test geometry α and k_{th} degenerate with dn/dT (sense beam transmitted through bulk)
- Taking dn/dT = 10^{-5} K^{-1} gives "accepted" value k_{th} = (33.1± 2.5) $Wm^{-1}K^{-1}$ but comparatively low α = (3.65±0.55) x 10^{-6} K^{-1} (test lab: $\alpha \sim$ 5.5 x 10^{-6} K^{-1})
- Sample may be peculiar (large fissure, internal stress, and many inclusions)
- More tests:
  - Several other sapphire samples on the way
  - Measure face distortion w/o transmission to sidestep dn/dT (rework SH optics)

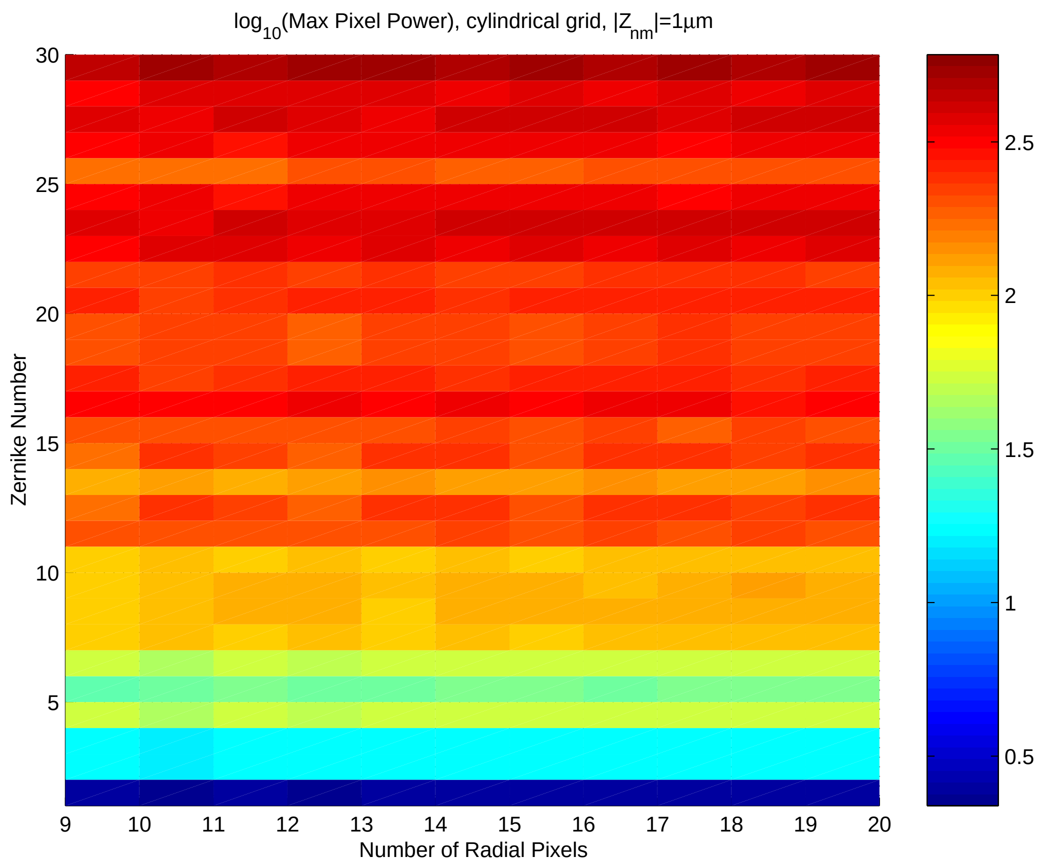
Current ATC Work

- FEA model of spatial "impulse response" for heating beam
  - ◊ Senior thesis of R. Bennett
  - ◊ Showed edge effects unimportant over req'd actuation area; translation of generic influence kernel to each corrector location gives negligible errors
- Developing 'optimized' correction algorithm
  - ◊ Best patch size as function of highest-order 'significant' Zernike aberration
  - ◊ Scan pattern for minimum power to correct a given aberration
- Interferometer modeling
  - ◊ RCL now learning MELODY, R. Beausoleil to visit MIT in May
  - ◊ Build rigorous "goodness/badness" figure of merit to measure performance

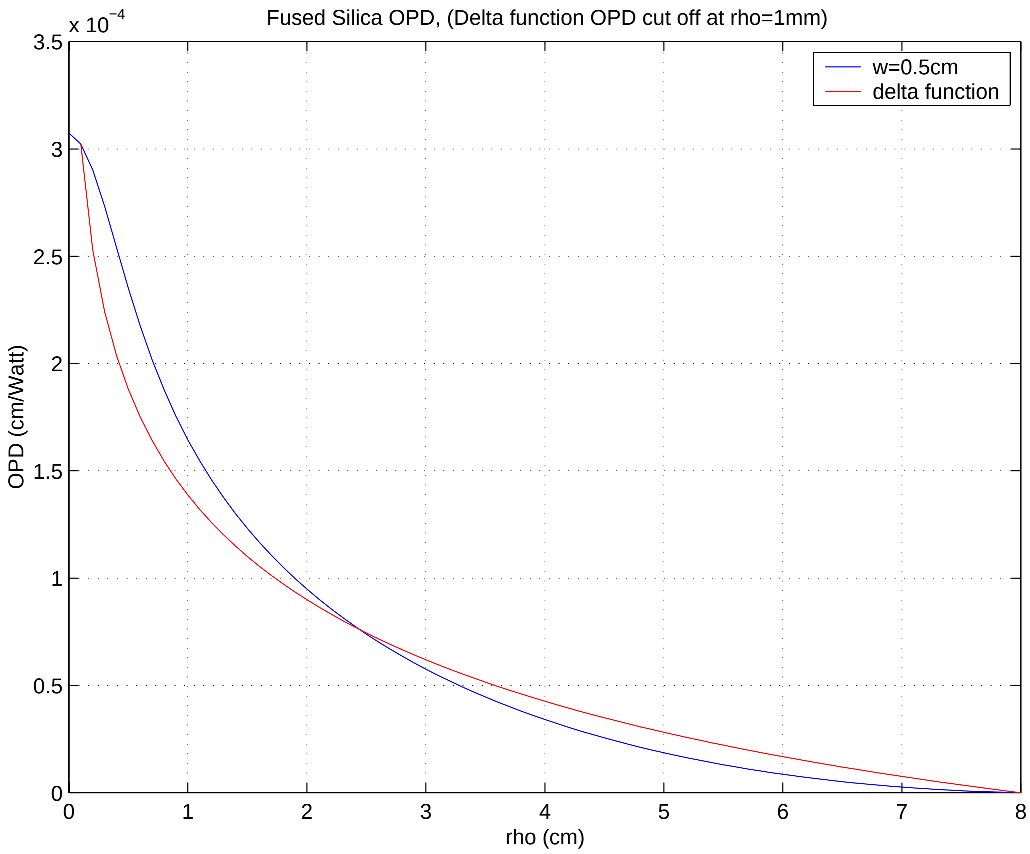
Correction Kernel Findings

- In steady state, corrector beam size doesn't drive maximum spatial frequency much
  - ◊ confined Gaussian heat distribution is transient, quickly relaxes to an inverted cone; spatial phase gradient (i.e., "contrast") depends mostly on pump power
  - ◊ (fortunately, this also applies to heat generated by small or pointlike losses!)
  - ◊ Power required starts to take off rapidly above order $(l + m) > 20$ or so
- "Spiral" scan pattern basis looks most efficient
  - ◊ Radial and azimuthal zone decomposition (looks much like Zernike basis)
  - ◊ Minimal acceleration for scanner; also expect lower thermoelastic "pinging" than raster

Power vs. Zernike Order



Spot Size: δ Function vs. 1 cm



Thermal Compensation: Issues

- Total heat deposited & net temperature rise
  - ◊ "Efficient" compensation will ~ double net ΔT w.r.t. ambient
  - ◊ 30K total rise plausible, would increase kT noise 5%
- Noise
  - ◊ Thermoelastic response to varying beam intensity/position (for sapphire)
  - ◊ Developing time-dependent thermal FEA to model better
- Absorption spatial inhomogeneity
  - ◊ Determines pixellation, complexity/depth of compensation required
- Net efficacy & trade with optics/material improvements
  - ◊ Depends on sensitivity of IFO sensing to figure errors & their spatial scales

Near term

- Now running with computer-controlled galvo scanner
  - ◊ Evaluating performance & efficiency on some toy problems, e.g., fix SH readout's spherical aberration, make specific Zernikes & measure residuals
  - ◊ verify FEA predictions on influence kernel near edges, power & spatial frequency optimizations
  - ◊ Phil Marfuta senior thesis
- Second round of sapphire material tests (April-June)
- Thermoelastic noise model (feed E2E model?)
- Possible test in small IFO (TBD based on MELODY results)
  - ◊ Near-unstable FP cavity?
  - ◊ Integration with RF phase map readout

Big picture

- 2Q'01: Proof-of-concept experiment & IFO model results
  - ◊ Improved requirements definition
  - ◊ Performance figure of merit vs. COC losses, power, etc.
  - ◊ Enables conceptual design for Advanced LIGO
- 3Q'02: Full scale radiative compensator demonstration
  - ◊ Engineering prototype at full mechanical scale (time constants, etc.)
  - ◊ Also demo main parts of wavefront error sensing technology
- 4Q'04: Full scale directed beam actuation demonstration