Adaptive Thermal Compensator Retrofit for Initial LIGO Interferometers

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Problem

- Currently achieve only 6% sideband coupling--> shot noise high by factor of ~ 3 in strain
- RM polished "too flat" by design; thermal lensing in ITM's relied on to stabilize recycling cavity for sidebands
- Designed for "exactly" 25 mW (±?) heat in each ITM
  - 15mW < bulk substrate absorption of 150W in RC (x2)
  - 10mW < surface absorption of 18 kW carrier in arm cavity
- Even at 'full power' we may fall short or overshoot
  - absorptions, circulating powers have substantial variation
  - MC transmission, laser output, contamination may vary over time
    - Even a lucky hit may not last
    - Unable to optimize shot noise given power we can get
- "Point Design" is *fragile*

What do we know now?

- H1: Probably too much lensing @ full power (?)
- H2: Can't really tell until bad ITM is replaced
- L1: Measurements not understood yet
- Bottom line: measurements need more work
  - Invasive methods (break lock) after S2
  - Use phase camera to look at SB field explicitly ?
  - Improved interpretation (explicit modeling?)

Possible Approach: New Tailored RM's

- Refine the point design:
  - Measure 'as-built' lensing vs. power in each IFO
    - Best technique & accuracy TBD
  - Model "full power" & back out best RM curvature
  - Grind, polish, coat, install, & retest
- Downsides:
  - Vulnerable to measurement and model errors
  - Minimum 6 months, $much to get new RM's
    - H2 can't be measured reliably until after ITM replacement
  - Much downtime for install, degassing
  - Vulnerable to a new set of mfg. tolerances
  - Even if it works, you still have a *POINT DESIGN*

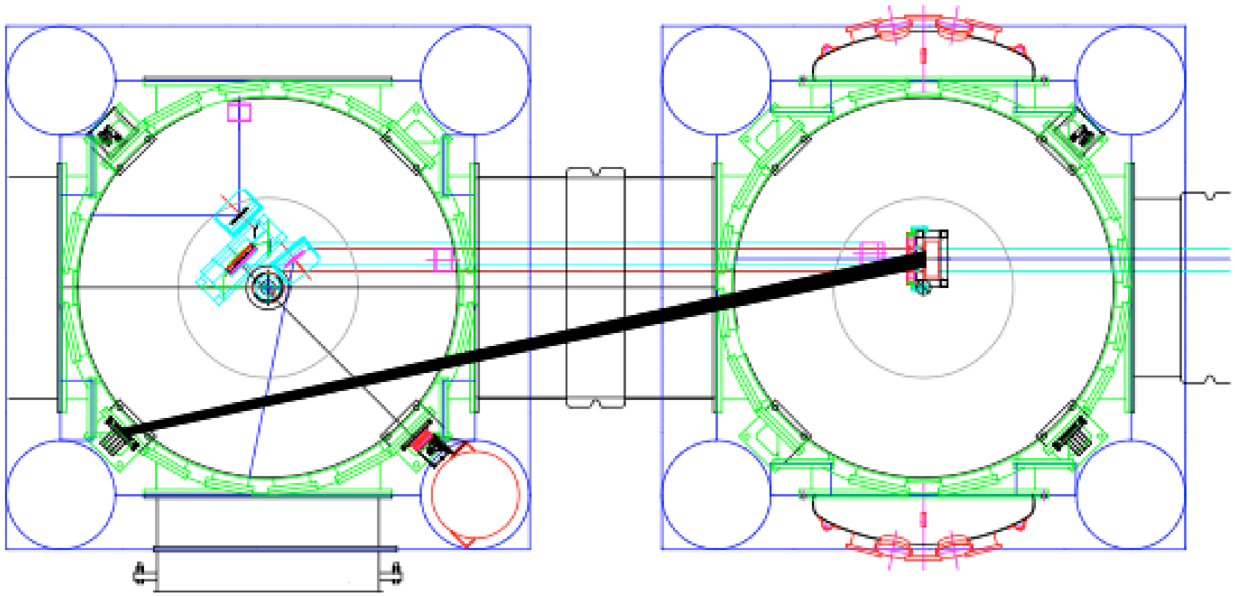
More Interesting: Adaptive Thermal Compensator

- Adds capabilities beyond "this problem"
  - Cold start @ full steady-state sensing matrix
    - Also "ride through" dropouts, perhaps better lock acquisition
    - No sign flips to dance through on REFL
  - Low-power diagnostics w/"lensed" sensing matrix
  - Soft failure on laser, COC, MC degradation
  - Future flexibility
- Proposed requirements:
  - Added noise < SRD/10
  - Noninvasive/minimally invasive installation
  - "Bipolar" lensing range
    - Optimize SB coupling down to ZERO main beam heating
    - Opposite (- lens) sign for excess beam heating (range TBD)

Compensator Approaches

- Initially favored "ring heater" concept
  - Simple & cheap (one already in GEO!), *but:*
    - "+" lensing variant needed; possible with shielding, but needs work (both "+" and "-" in same setup?)
    - Requires bolting something onto LOS
    - Human ingress, misalignment & damage potential, water degassing time...
    - No offline test facility: iterations require more ingress etc.
- Can we do it all from outside the VE?
  - Beam heater might involve only adding a viewport
  - Can do "+" and "-" lensing (at least in principle)
  - Can develop & iterate non-invasively

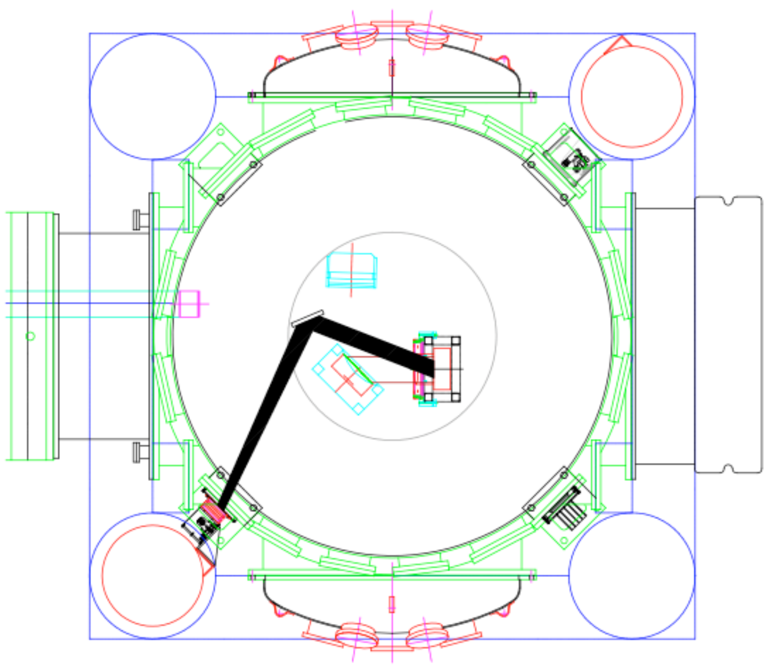
4k Beam Path



Aperture limited by elliptical baffle behind ITM

2" ZnSe viewport added (no entry planned)

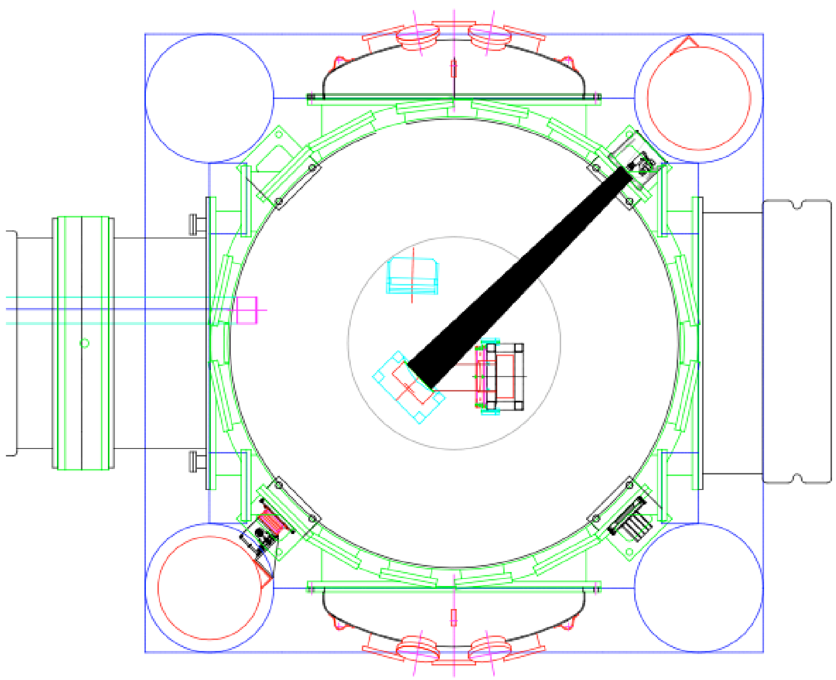
2k Beam Path (internal relay)



Requires ingress & adding (small) mass moment to stack

Relay mirror is well above IFO plane

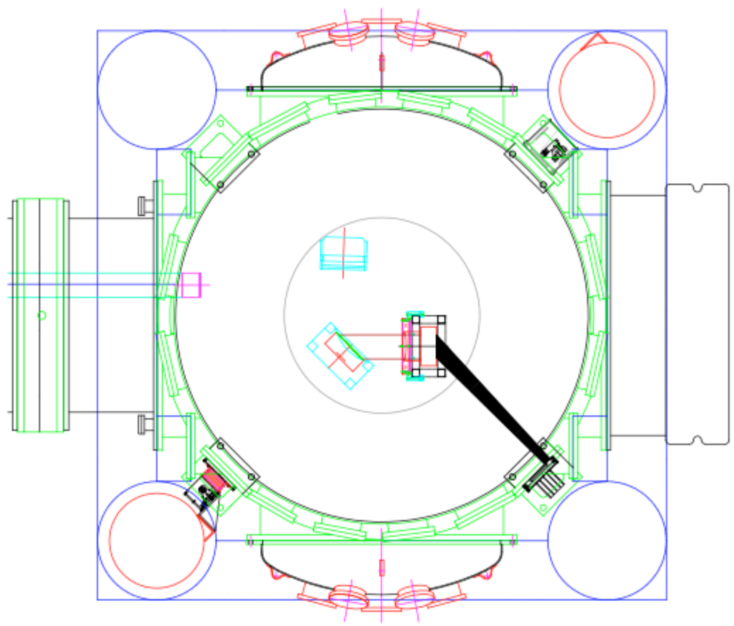
2k Beam Path (FM face)



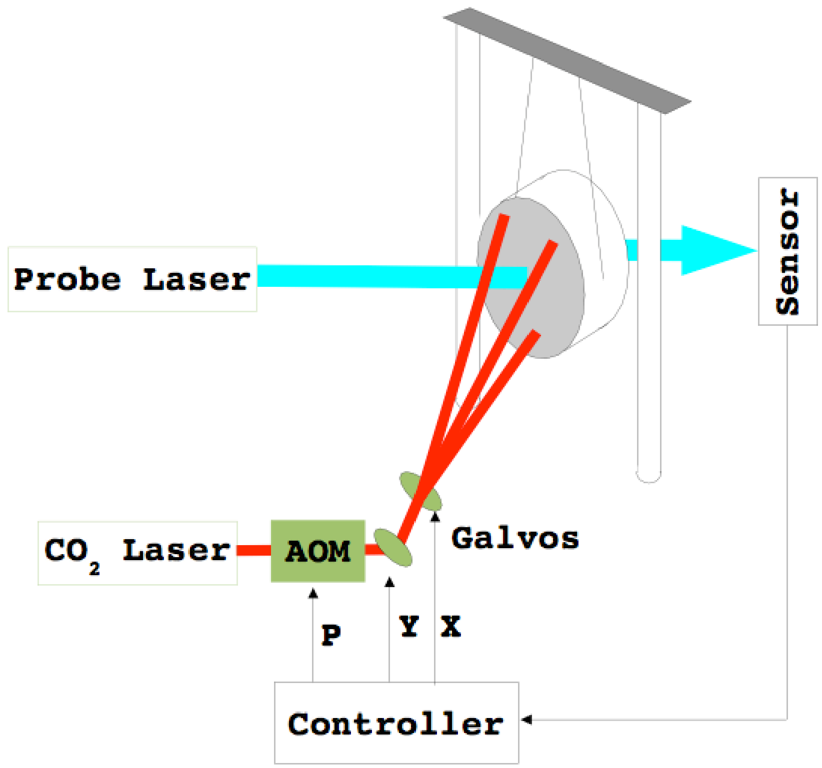
Requires ~20x power for comparable effect

'Bowing' effect makes net concave hard to achieve

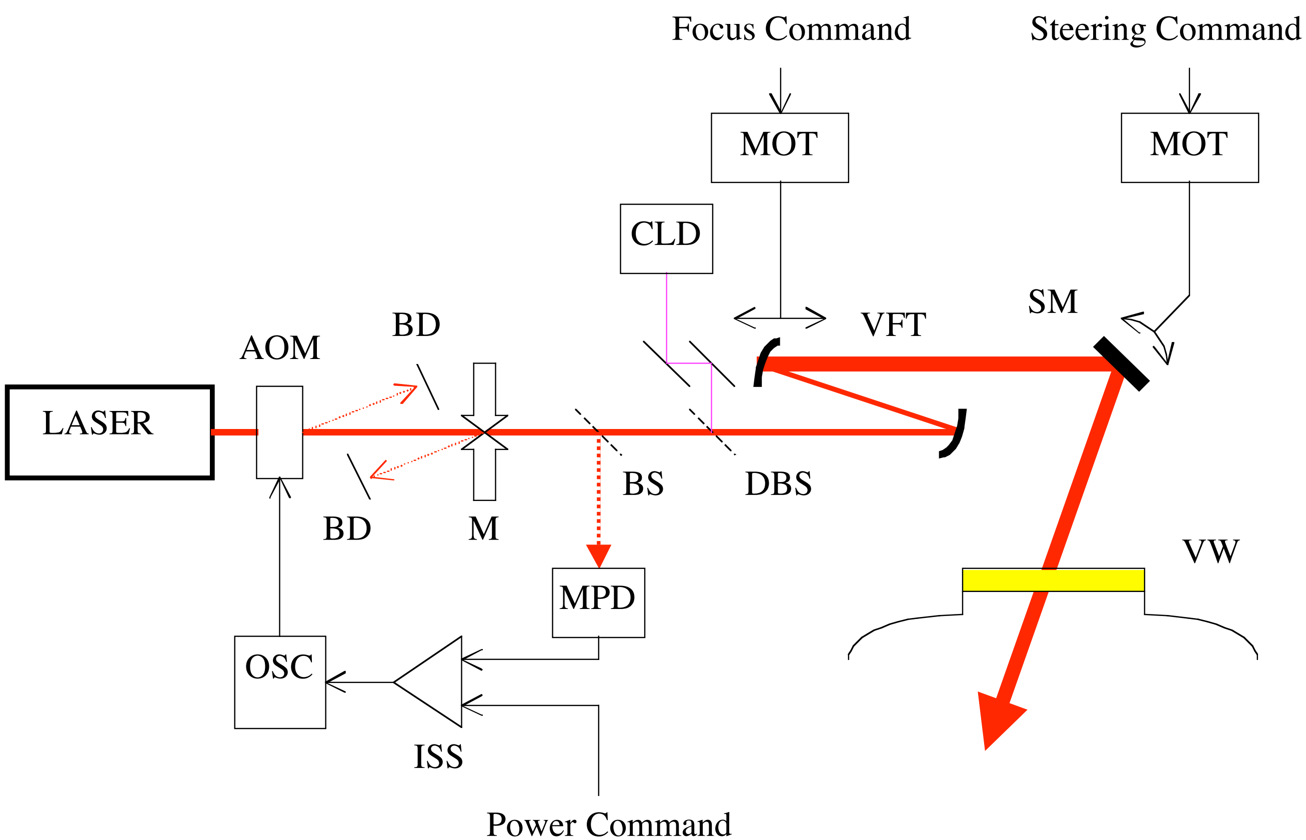
ITM face path



"Scanning" beam actuator



"Staring" beam heater concept



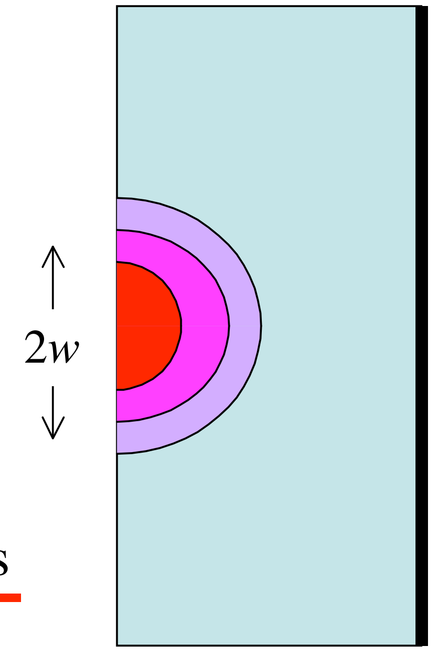
Main Features

- Laser: 10-30W CW TEM_{00} CO_2 (10.6 μm)
- Ge AOM: intensity stab., power selection
- Reflective mask: intensity profile & astigmatism compensation (power to burn)
- Relay optics (adj. focus/pattern size, pos'n)
- Pilot laser: visible LD w/pattern generator

Issues/Challenges

- Feasible limit of "negative" compensation?
  - 10 cm clear aperture limits "edge" heating
- Can you really do anything with the FM?
- Intensity stabilization of CO_2 laser
  - Direct actuation on ITM couples heat to Δx
    - Radiation pressure
    - Thermal expansion (if cavity surface is heated)
    - Index variation

Laser AM for SRD/10 (crude estimate)



- External radiative time constant ~ 2h, so behavior ~ infinite silica half space; local transport dominated by conduction
- Thermal volume of radius *w* equilibrates to center-edge temp. rise ΔT_w , with time constant τ_w
- Laser power variation => OPD fluctuation over this volume, filtered by τ_w (also surface deformation; 5x worse effect if actuating HR face, negligible for AR face)

$$\frac{\Delta T_w}{\langle P_A \rangle} = \frac{1}{2\pi\kappa w} \approx 3.2\,\frac{°\mathrm{K}}{\mathrm{W}} \qquad \tau_w = \frac{\rho w^2 C}{3\kappa} = \frac{\rho w^3 C}{6\kappa}\,\frac{\Delta T_w}{\langle P_A \rangle} \approx 500\ \mathrm{s}$$

$$\tilde{x}_w^{AR}(f) \approx \sqrt{N}\cdot \mathrm{RIN} \cdot \frac{\Delta T_w}{2\pi f \tau_w} \cdot w \cdot \left(\frac{\pi}{2\boldsymbol{F}}\beta\right)$$

$$\approx 1.0\cdot 10^{-20}\,\frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}} \cdot \left(\frac{150\ \mathrm{Hz}}{f}\right) \cdot \left(\frac{\langle P_A \rangle}{25\ \mathrm{mW}}\right) \cdot \left(\frac{\mathrm{RIN}}{2\cdot 10^{-5}\ \mathrm{Hz}^{-1/2}}\right)$$

ROM Cost Estimate

- Approx. $60k/IFO ($30k/ITM)
  - (Includes 15% hardware contingency)
- Add'l $20k/site for IR diagnostics equip.
- Est. 0.25 PY sci, 0.1 PY eng, 0.1 PY tech for development & fab.
- Main cost risk: unforeseen technical obstacles in pursuit of low RIN (e.g., single-mode laser could add $30k/IFO)

Tentative Plan (if approved)

- Set up intensity stabilizer exp't & establish RIN, imaging feasibility this summer
- Build & field test first article end of summer; install 6 ZnSe viewports at vent opportunities summer & fall
- Finalize design and build 5 more for phased installation & test in fall & winter