Thermal Compensation Update

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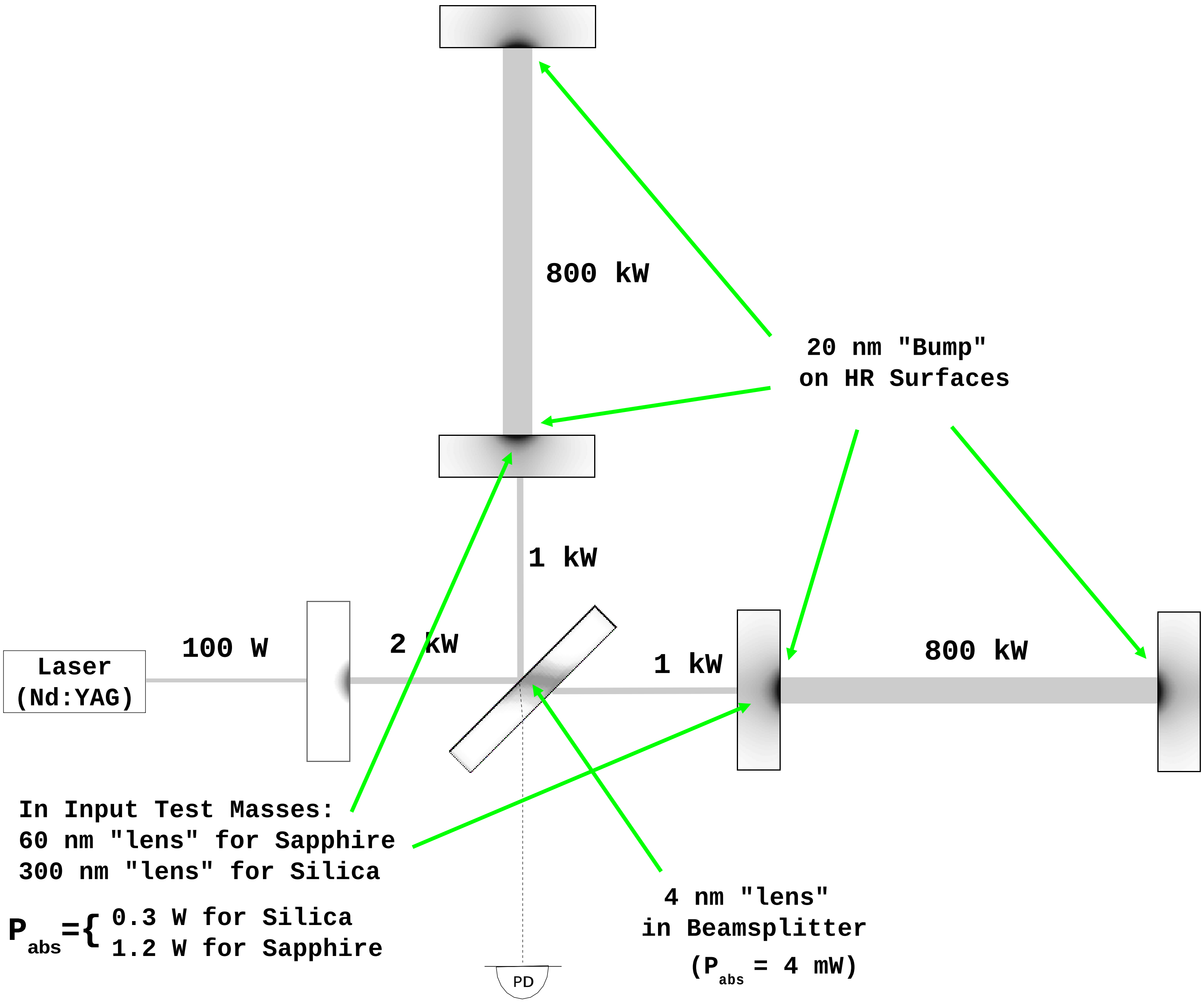
Ryan’s Portion

- Power Handling Problems in Advanced LIGO
- Heating Ring Thermal Compensation
- Scanning Laser Thermal Compensation
- Thermal Compensation Experiment
- Conclusions to Date

LIGO II

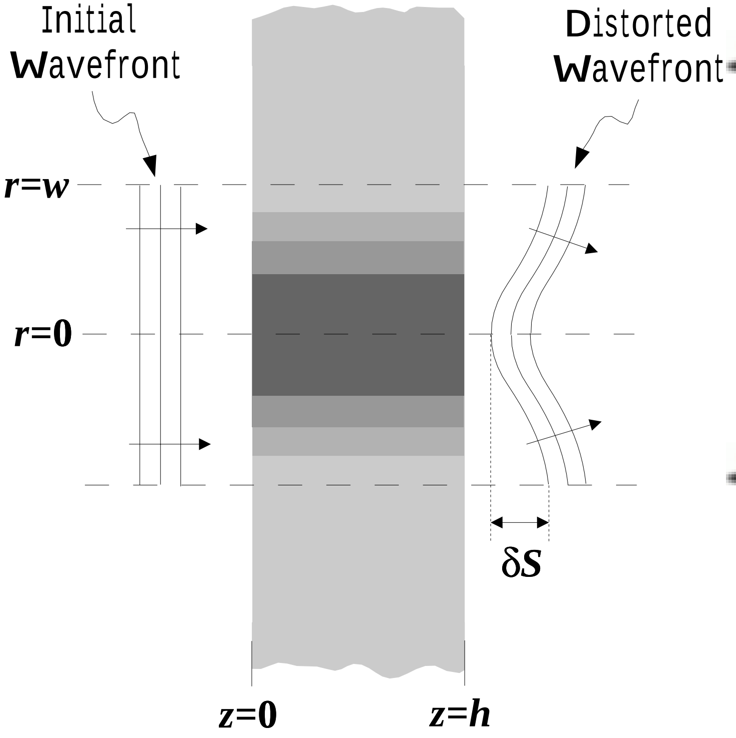


In Input Test Masses:
60 nm "lens" for Sapphire
300 nm "lens" for Silica

$$P_{abs} = \begin{cases} 0.3\ \text{W for Silica} \\ 1.2\ \text{W for Sapphire} \end{cases}$$

4 nm "lens"
in Beamsplitter
(P_{abs} = 4 mW)

Wavefront Distortions via Optical Absorption



Total power P_a absorbed causes local temperature increase ΔT:

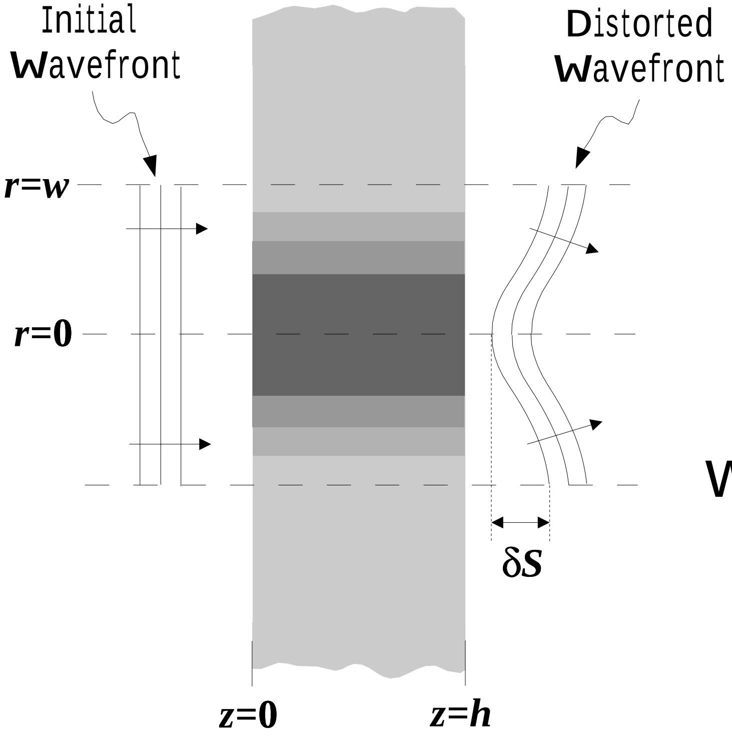
- **Thermal Lensing**: Change in local index of refraction

$$n \rightarrow n_0 + \frac{dn}{dT}\Delta T$$

- **Thermal Expansion**: Optical surfaces expand

$$h \rightarrow h_0 + \alpha h_0 \Delta T$$

Wavefront Distortions via Optical Absorption



Resulting optical path distortion over the beam waist:

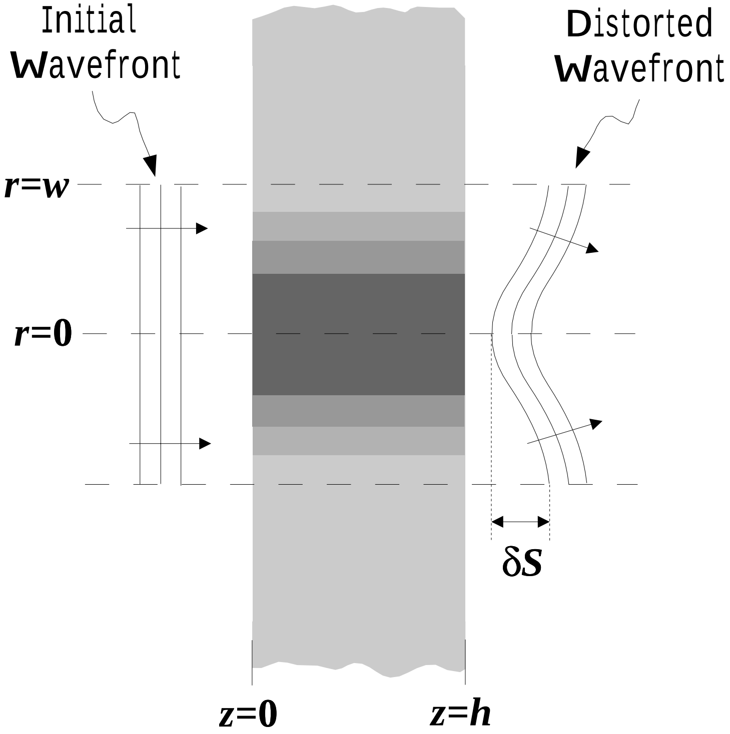
$$\delta S \approx \beta \int \delta T\, dz \approx \beta \frac{P_a}{2\pi k}$$

$$\approx 1\,\frac{\mu\text{m}}{\text{W}} \left(\frac{1.4\,\text{W/m/°K}}{k}\right)\left(\frac{\beta}{10\,\text{ppm/°K}}\right)$$

where:

$$\beta \equiv \begin{cases} \dfrac{dn}{dT} + \alpha, & \text{in transmission} \\ -\alpha, & \text{on reflection} \end{cases}$$

Wavefront Distortions via Optical Absorption

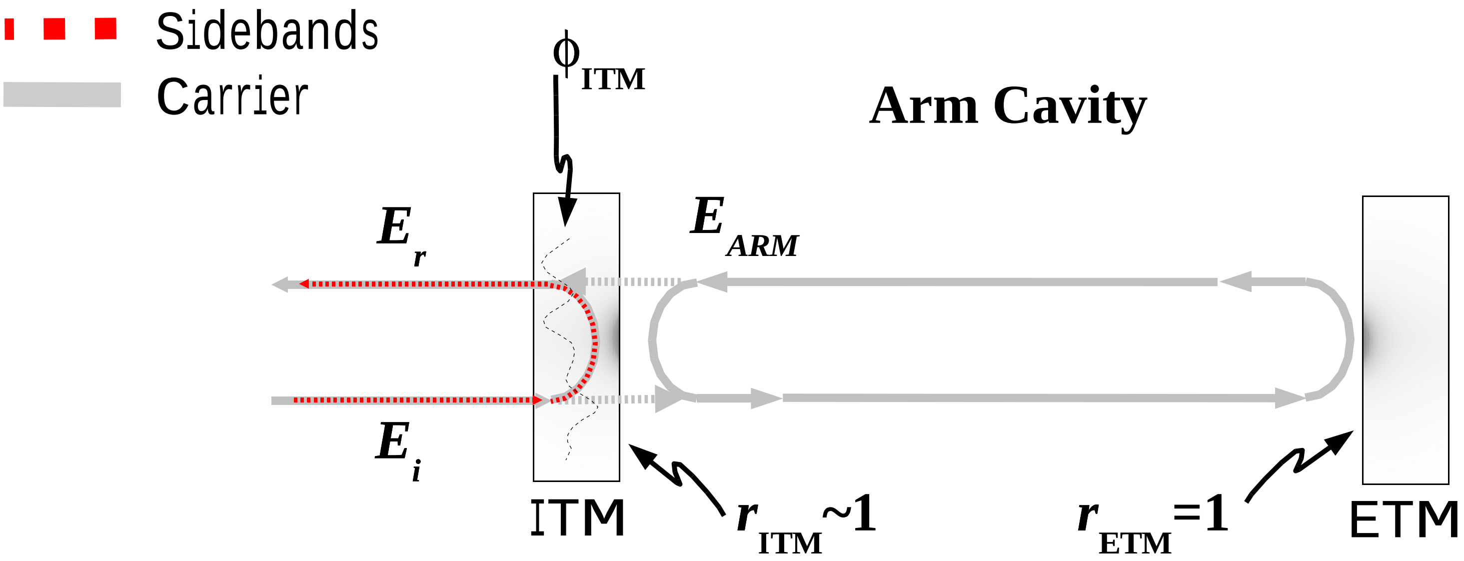


In terms of TEM$_{00}$ scatter (assume a a spherical distortion):

$$\mathcal{S} \approx \left(\frac{\beta P_a}{2\lambda k}\right)^2$$

$$\approx 10\,\frac{\text{ppm}}{\text{mW}^2}\left(\frac{1.4\,\frac{\text{W}}{\text{m}\,{}^\circ\text{K}}}{k}\right)^2\left(\frac{\beta}{10\,\frac{\text{ppm}}{{}^\circ\text{K}}}\right)^2$$

Effects of ITM Distortion



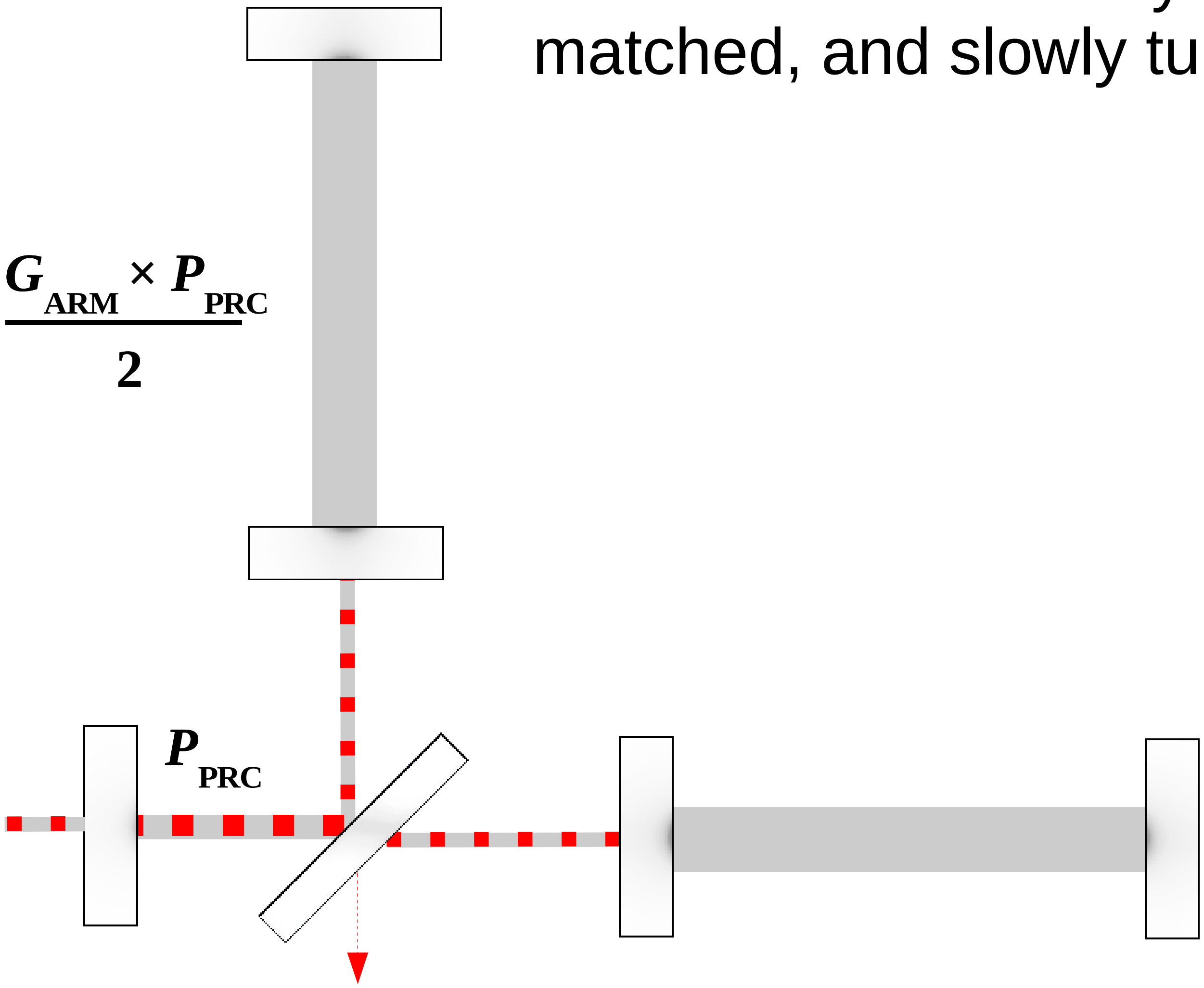
- For the carrier:

$$E_r^{(c)} \approx \underbrace{r E_i^{(c)} e^{2i\phi}}_{\text{Reflected Field}} + \underbrace{it\frac{it}{1-r}E_i^{(c)}e^{i\phi}}_{\text{Cavity Leakage Field}} \approx -E_i^{(c)}$$

- For the sidebands:

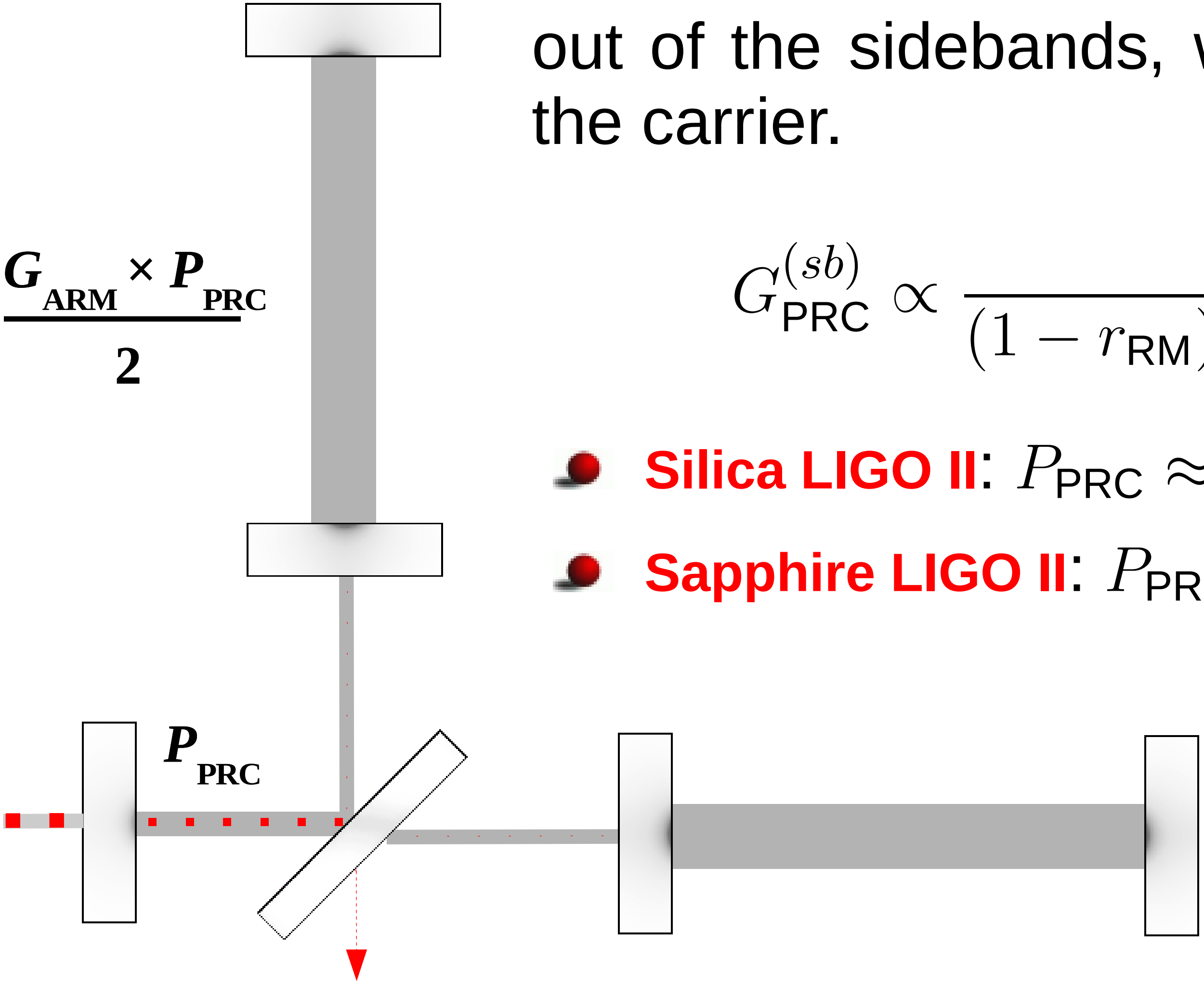
$$E_r^{(sb)} \approx E_i^{(sb)} e^{2i\phi}$$

Effects in LIGO II



Start off with everything cold mode-matched, and slowly turn up the power.

Effects in LIGO II

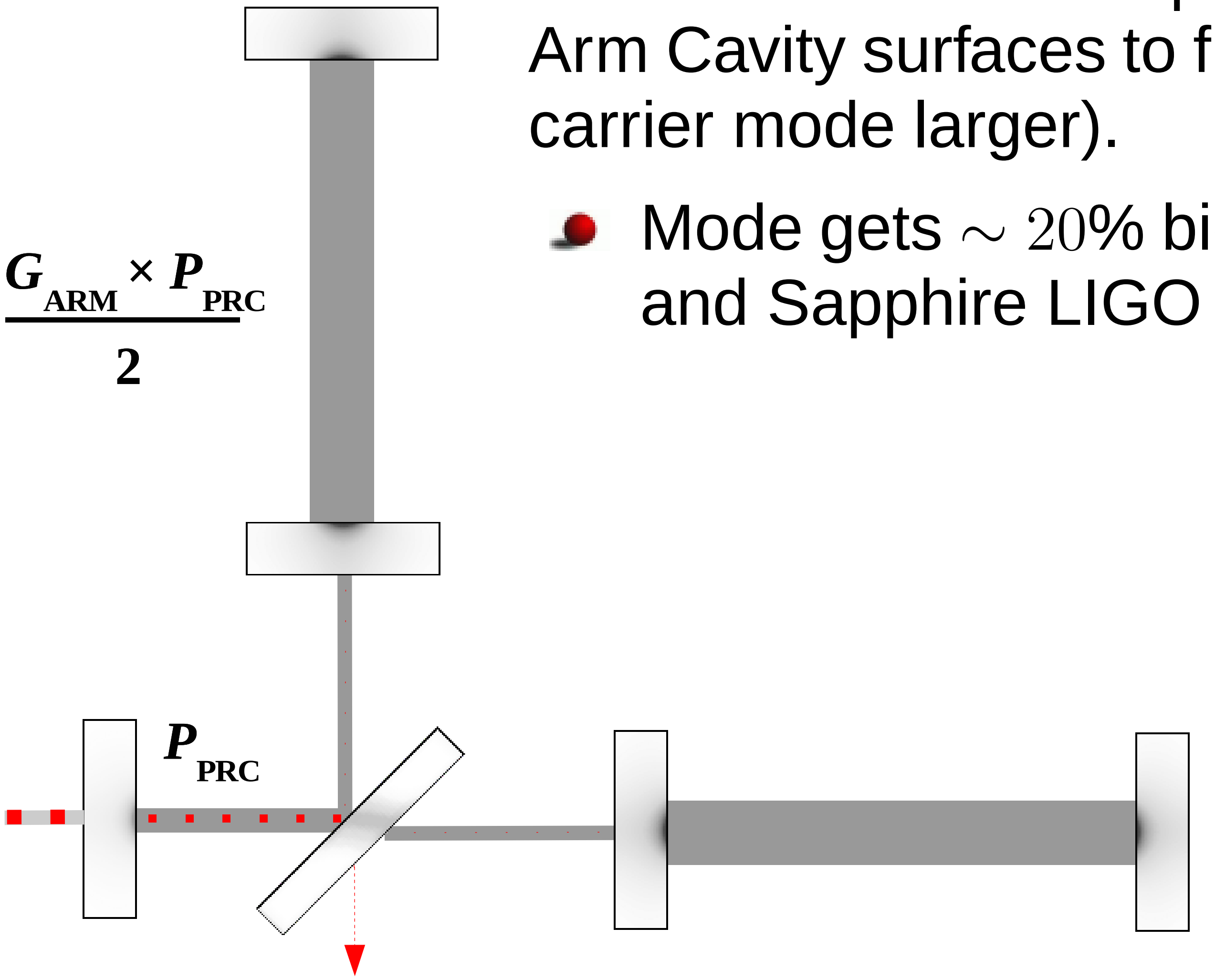


ITM thermal lens scatters TEM_{00} power out of the sidebands, with little effect on the carrier.

$$G^{(sb)}_{\text{PRC}} \propto \frac{t^2_{\text{RM}}}{(1 - r_{\text{RM}})^2 + r_{\text{RM}}\mathcal{S}_{\text{ITM}}}$$

- **Silica LIGO II**: $P_{\text{PRC}} \approx 50$ Watts
- **Sapphire LIGO II**: $P_{\text{PRC}} \approx 280$ Watts

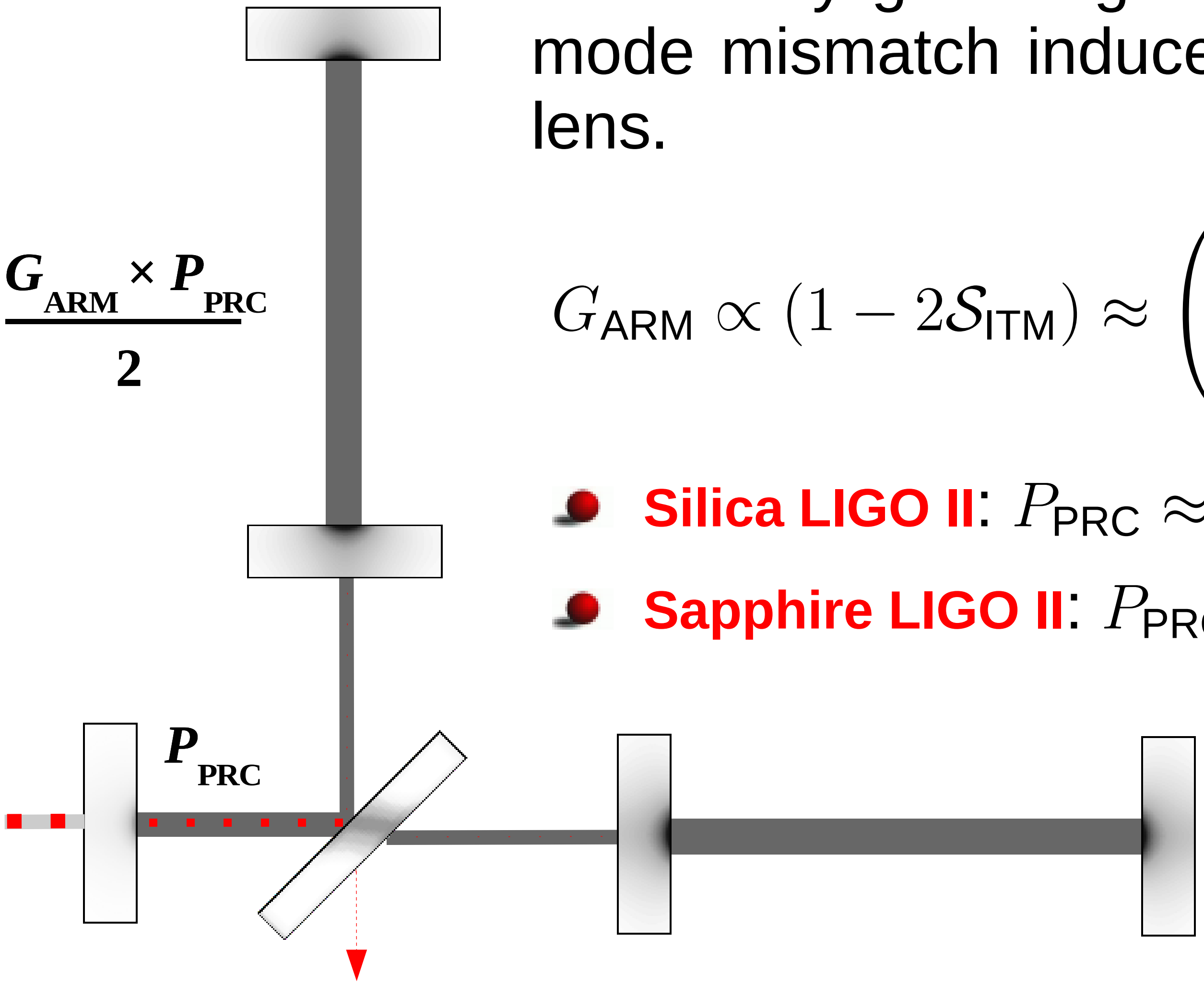
Effects in LIGO II



ITM & ETM thermal expansion causes the Arm Cavity surfaces to flatten (making the carrier mode larger).

- Mode gets $\sim 20\%$ bigger in *both* Silica and Sapphire LIGO II.

Effects in LIGO II

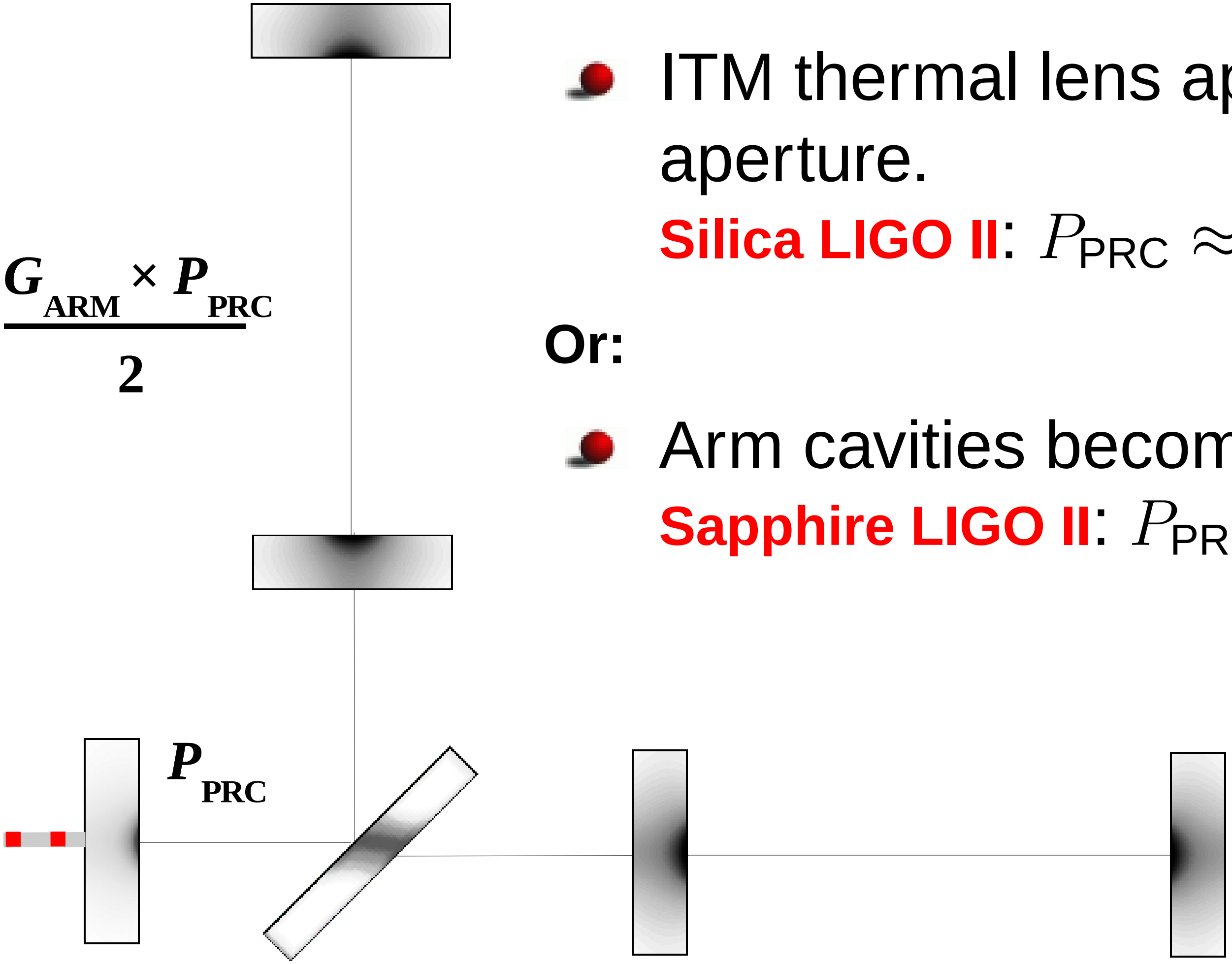


Arm cavity gain begins to fall off, due to mode mismatch induced by ITM thermal lens.

$$G_{\mathrm{ARM}} \propto (1 - 2\mathcal{S}_{\mathrm{ITM}}) \approx \left(1 - 2\left(\frac{\beta P_a^{\mathrm{ITM}}}{2\lambda k}\right)^2\right)$$

- **Silica LIGO II**: $P_{\mathrm{PRC}} \approx 350$ Watts
- **Sapphire LIGO II**: $P_{\mathrm{PRC}} \approx 2200$ Watts

Effects in LIGO II



Total instrument failure when:

- ITM thermal lens approaches $\frac{\lambda}{4}$ in the aperture.

  Silica LIGO II: $P_{\text{PRC}} \approx 1200$ Watts

Or:

- Arm cavities become unstable.

  Sapphire LIGO II: $P_{\text{PRC}} \approx 3300$ Watts

Effects in LIGO II

Summary of Thermal Nastiness

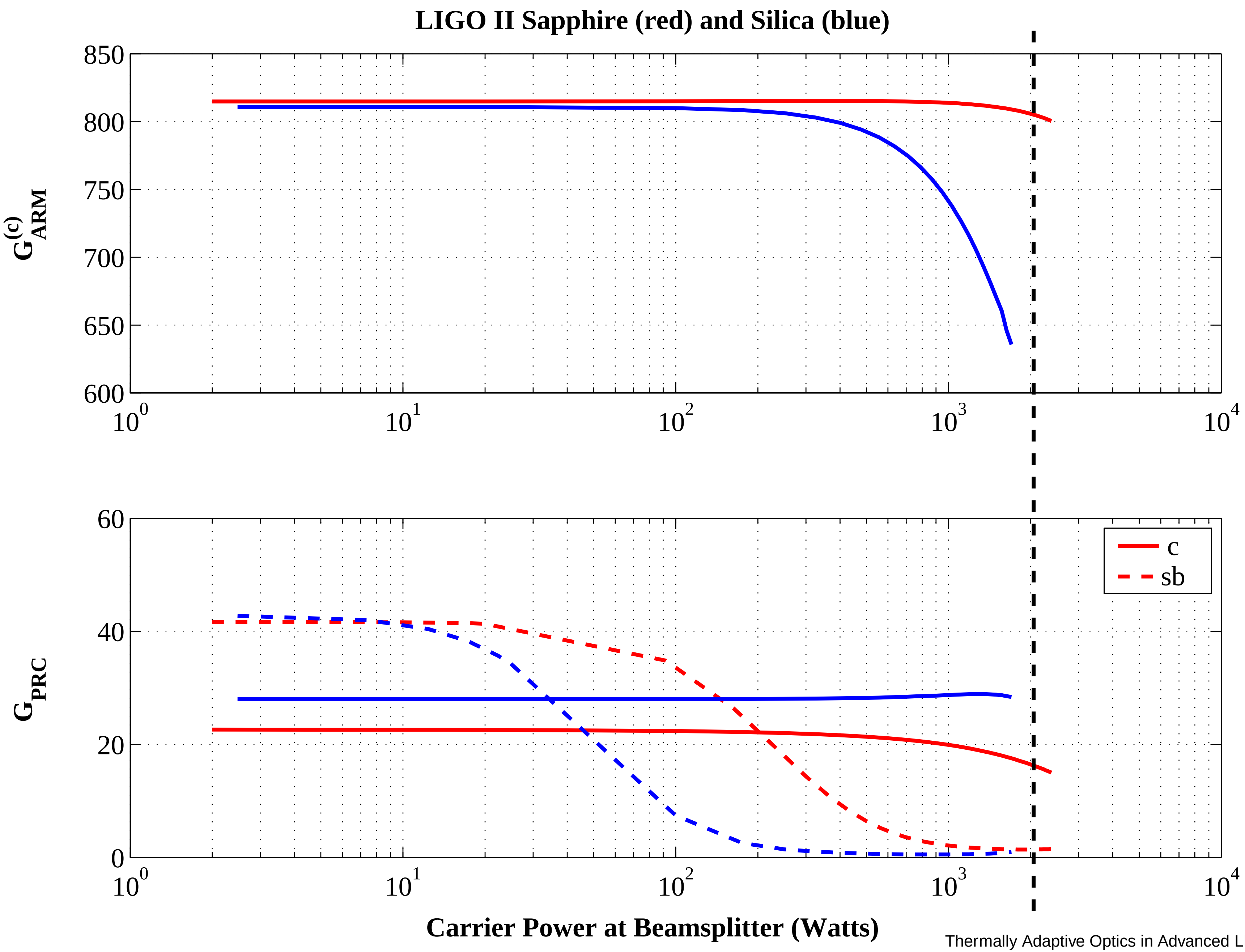
	LIGO II Sapphire		LIGO II Silica	
(Watts)	P_a^{ITM}	$P_{\text{PRC}}^{(c)}$	P_a^{ITM}	$P_{\text{PRC}}^{(c)}$
Nominal Operation	**1.20**	**2100**	**0.270**	**1300**
Sideband Failure	0.17	280	0.010	50
Arm Cavity Gain Falloff	1.3	2200	0.070	350
Carrier Failure	2.0	3300	0.24	1200

Melody Model of LIGO II

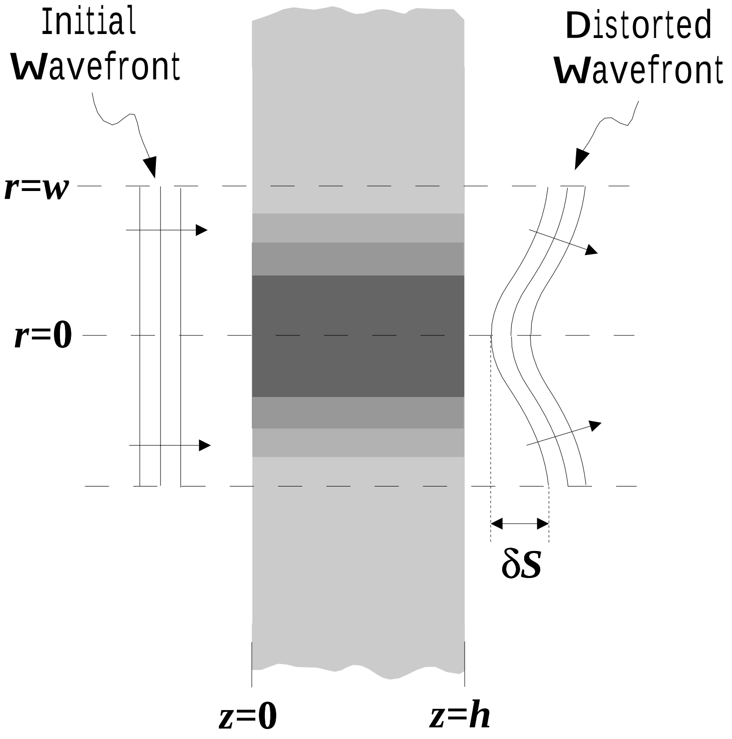
Sapphire LIGO II			
ITM Radius	15.7 cm	$\frac{dn}{dT}$	7.2 ppm/K
ITM Thickness	13.0 cm	Thermal Expansion	5.5 ppm/K
Arm Cavity Waist	6.1 cm	Thermal Conductivity	37 W/m/K
Coating Absorption	0.5 ppm	Substrate Absorption	30 ppm/cm

Silica LIGO II			
ITM Radius	19.0 cm	$\frac{dn}{dT}$	8.7 ppm/K
ITM Thickness	15.4 cm	Thermal Expansion	0.55 ppm/K
Arm Cavity Waist	6.1 cm	Thermal Conductivity	1.4 W/m/K
Coating Absorption	0.5 ppm	Substrate Absorption	0.5 ppm/cm

Melody Model of LIGO II

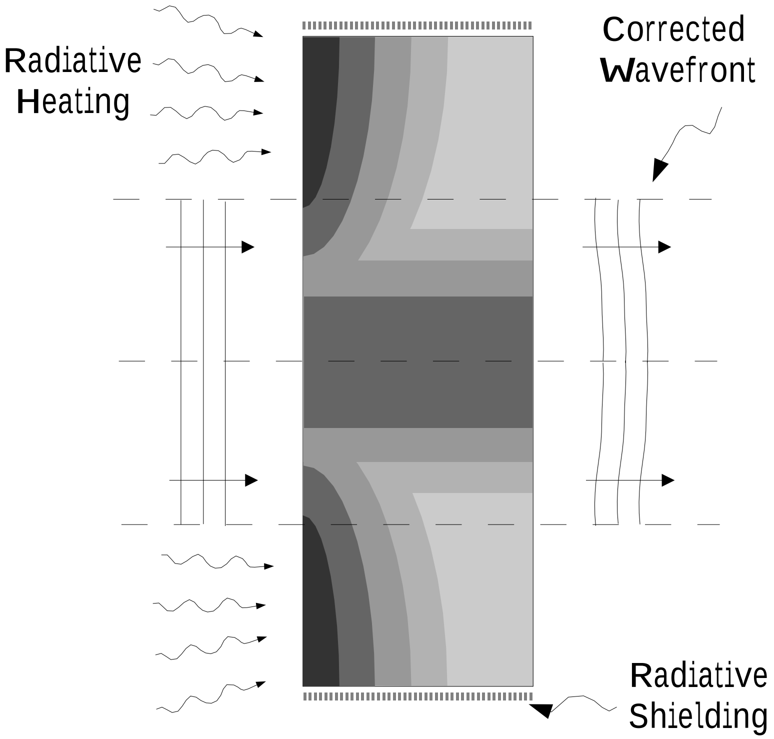


Thermal Compensation



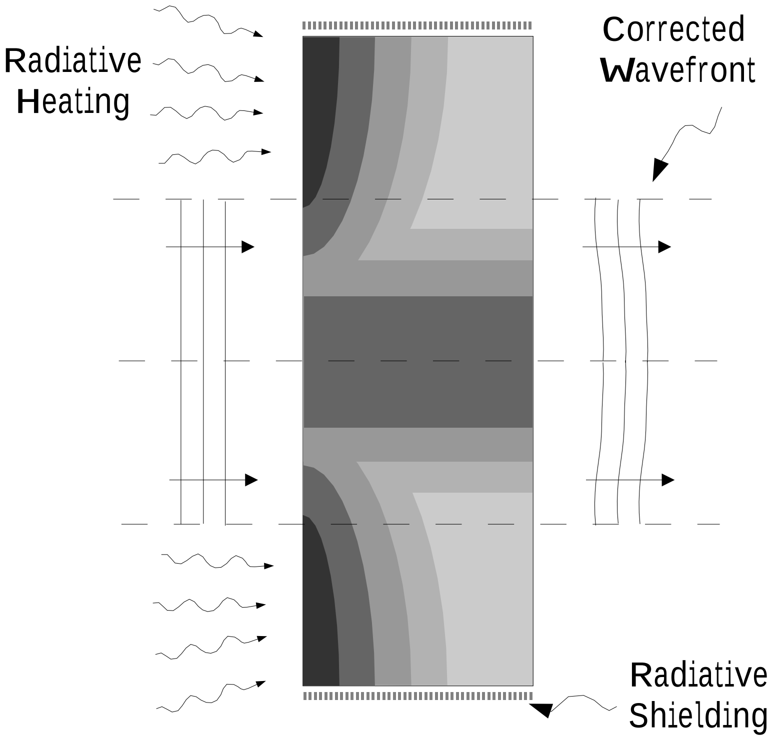
- Intensity pattern of absorption: $I_a(x, y)$

Thermal Compensation



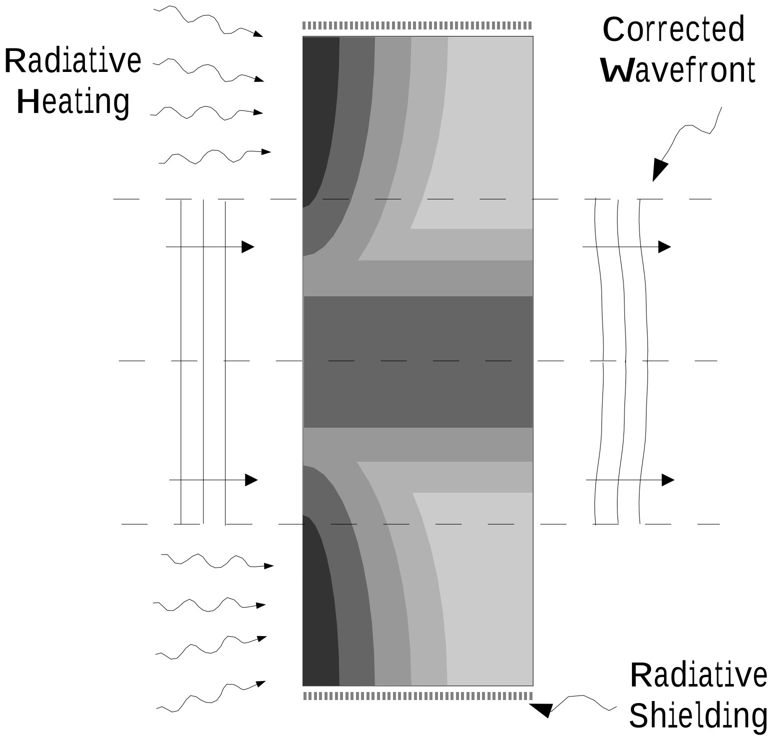
- Intensity pattern of absorption: $I_a(x, y)$
- Apply radiative compensation: $I_c(x, y) = \max I_a - I_a(x, y)$

Thermal Compensation



- Intensity pattern of absorption: $I_a(x, y)$
- Apply radiative compensation: $I_c(x, y) = \max I_a - I_a(x, y)$
- Resulting temperature increase: $\overline{\Delta T} \approx \frac{\max I_a}{8\epsilon\sigma T_\infty^3}$

Thermal Compensation



- Intensity pattern of absorption: $I_a(x,y)$
- Apply radiative compensation: $I_c(x,y) = \max I_a - I_a(x,y)$
- Resulting temperature increase: $\overline{\Delta T} \approx \frac{\max I_a}{8\epsilon\sigma T_\infty^3}$
- **For a Gaussian beam**:

$$\overline{\Delta T}_{ideal} = \frac{P_a}{4w^2\epsilon\sigma T_\infty^3}$$

$$\approx 20\,\frac{^\circ\mathrm{K}}{\mathrm{W}}\left(\frac{5\ \mathrm{cm}}{w}\right)^2$$

Thermal Compensation

Figures of Merit

- **Quality**: Reduction in scatter out of cavity mode, for compensating 1 Watt of absorbed optical power.

$$\mathbb{C} \equiv \frac{\mathcal{S}_c}{\mathcal{S}_0} \equiv \frac{\text{TEM}_{00}\text{ scatter through corrected distortion}}{\text{TEM}_{00}\text{ scatter through initial distortion}}$$

Thermal Compensation

Figures of Merit

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$$\mathbb{C} \equiv \frac{\mathcal{S}_c}{\mathcal{S}_0} \equiv \frac{\text{TEM}_{00}\text{ scatter through corrected distortion}}{\text{TEM}_{00}\text{ scatter through initial distortion}}$$

- **Efficiency**: Resulting mean temperature increase, as compared to the “ideal”:

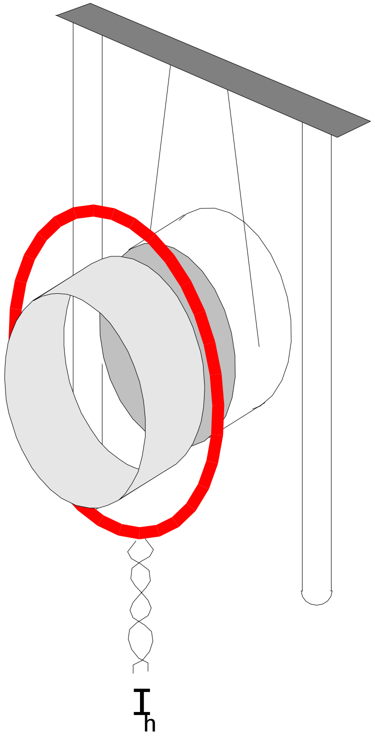
$$\mathbb{T} \equiv \frac{\overline{\Delta T}_c}{\overline{\Delta T}_{ideal}}$$

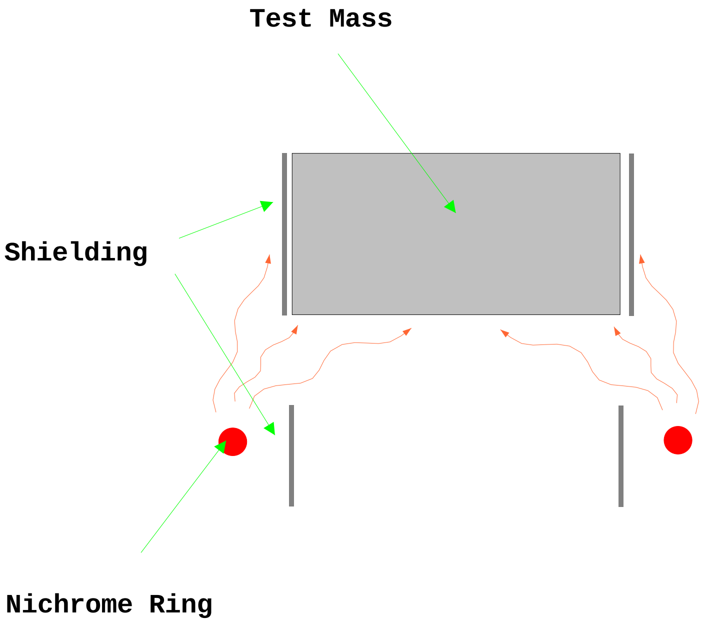
PART II: Heating Ring Thermal Compensation

Heating Ring Thermal Compensation

Design an “optic toaster” to fix anticipated distortions.

(e.g., a nichrome ring with some strategically placed shielding)





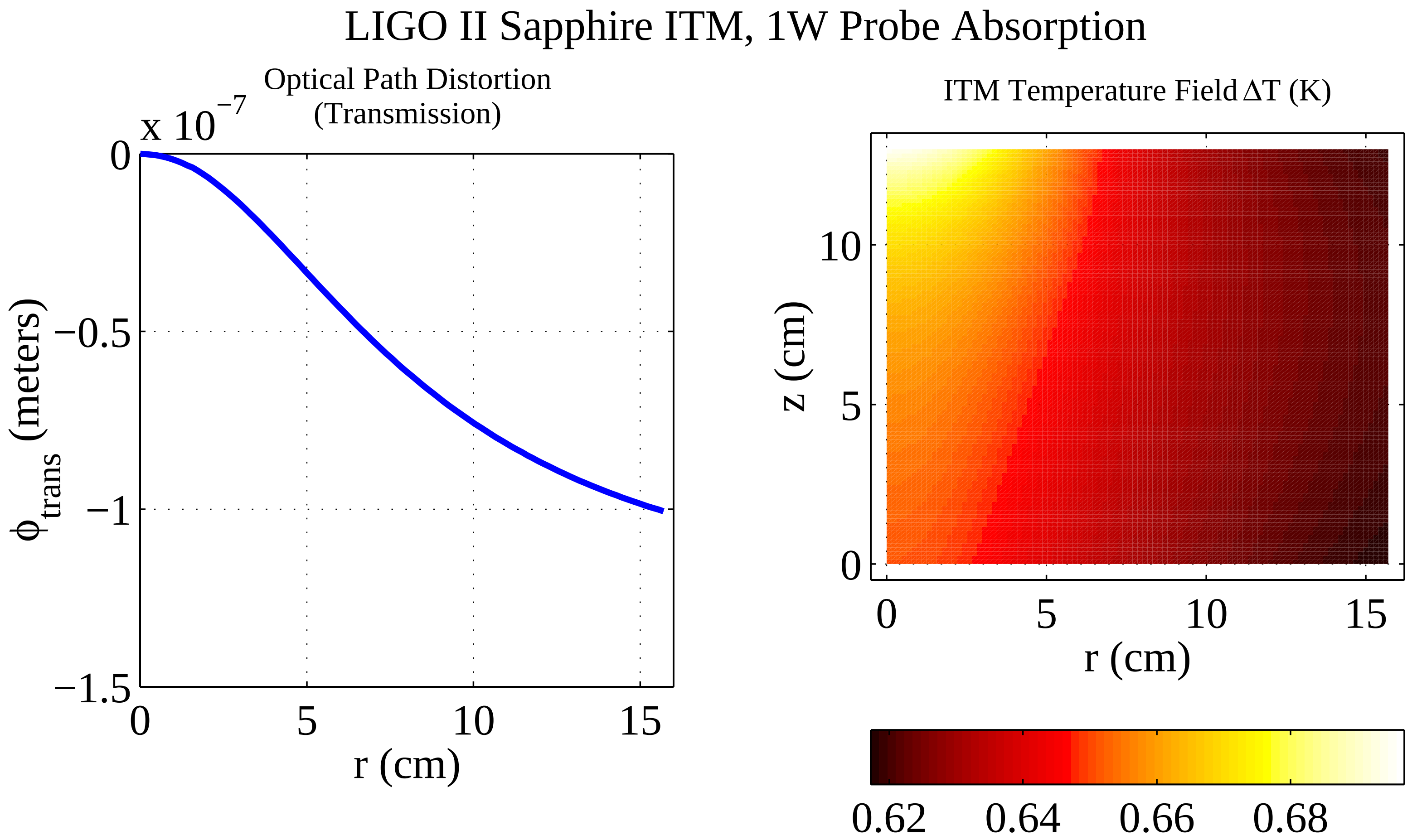
Heating Ring Thermal Compensation

The Procedure

1. Via generic 2D FEM, compute the distortion to compensate (at unit power absorbed)
   $\Rightarrow$ Transmission through ITM
2. Devise method of compensation (e.g., simple ring)
3. Calculate the compensator’s effect on boundary conditions vs. relevant degrees of freedom (e.g., radiation pattern vs. ring radius, height, and power).
4. Apply to 2D FEM, and minimize $\mathbb{C}$ over relevant degrees of freedom.
5. Examine results and devise improvements (adding shielding, insulation, etc.) and return to item 3.

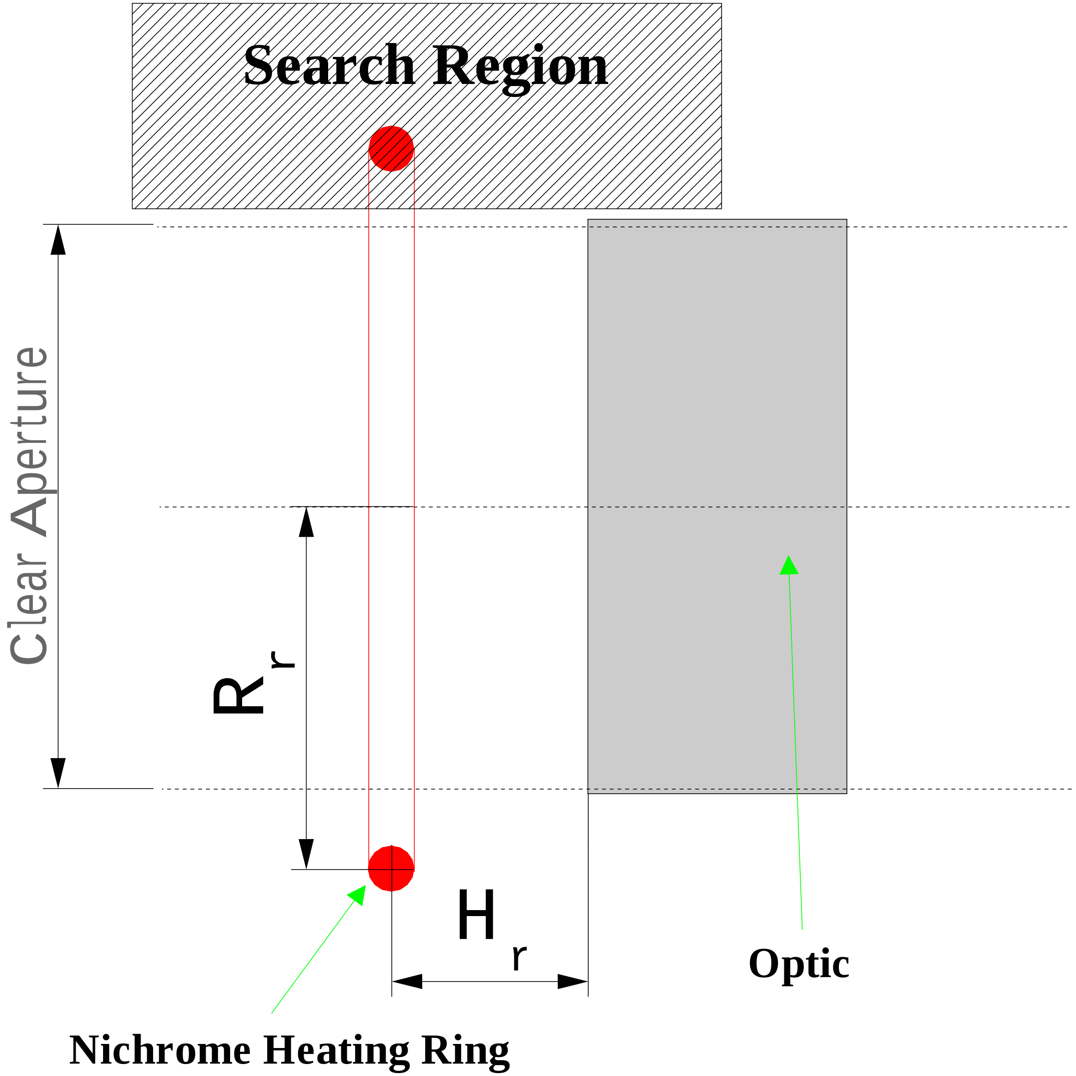
Heating Ring Thermal Compensation

The anticipated distortion ($w = 6$ cm):



TEM$_{00}$ scatter $\mathcal{S}_0 \approx 0.01$.

Simple Heating Ring



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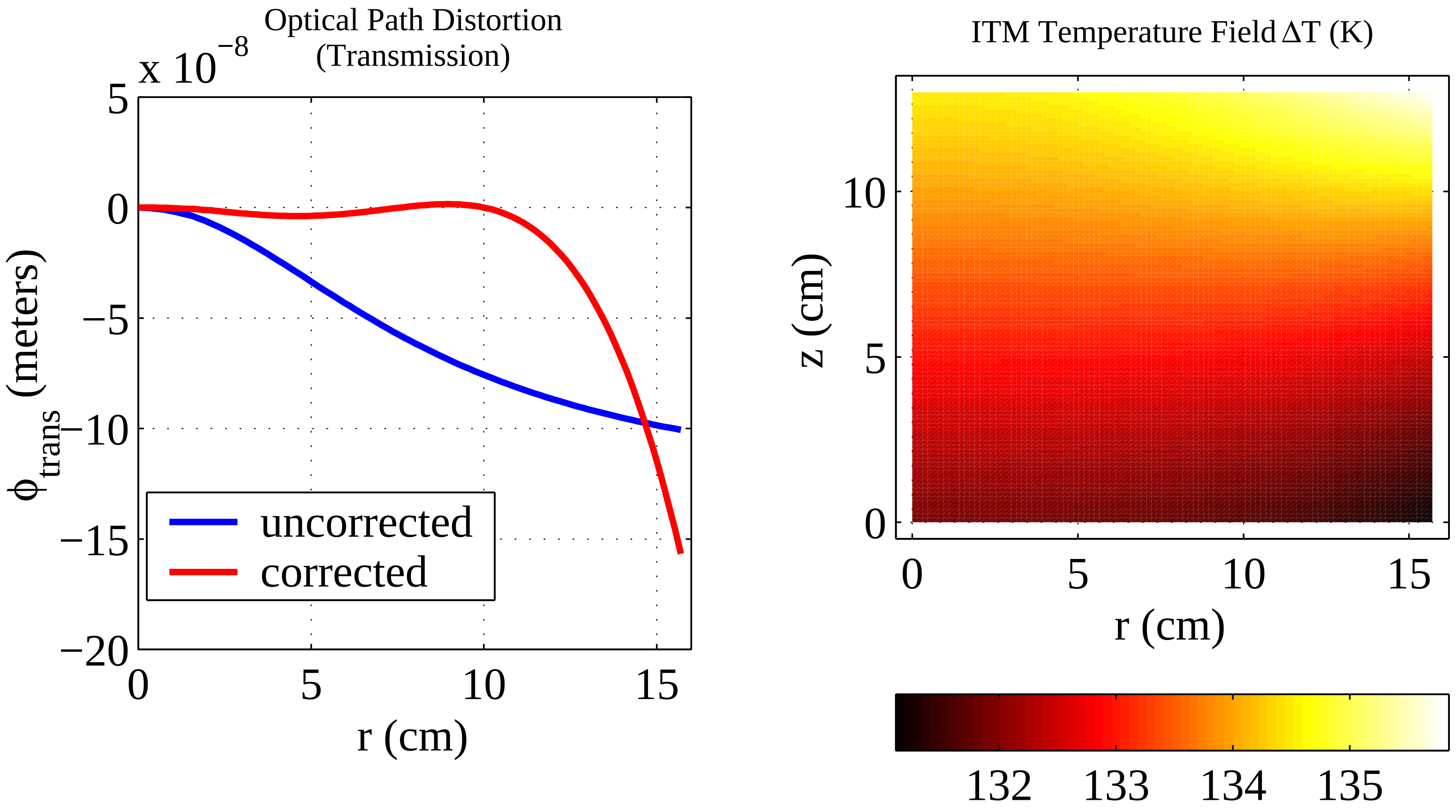


LIGO II Sapphire ITM, 1W Probe Absorption, Ring Compensated

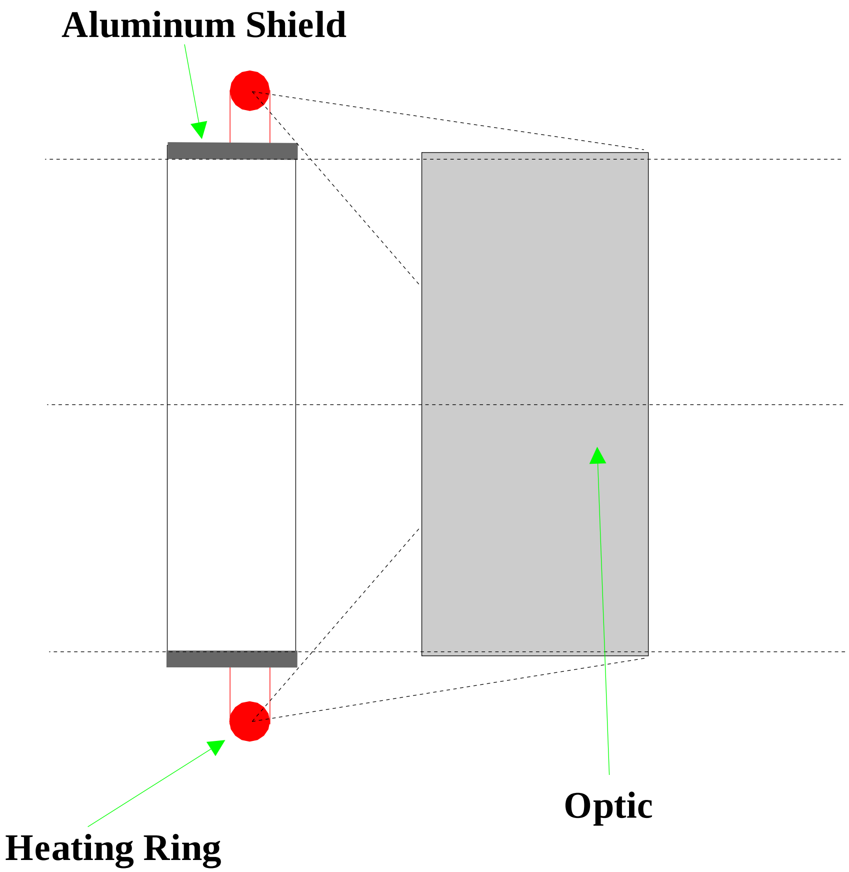
Optical Path Distortion (Transmission)

ITM Temperature Field ΔT (K)

$$\mathbb{C} \approx 10^{-2.1} \qquad \mathbb{T} \approx 6$$

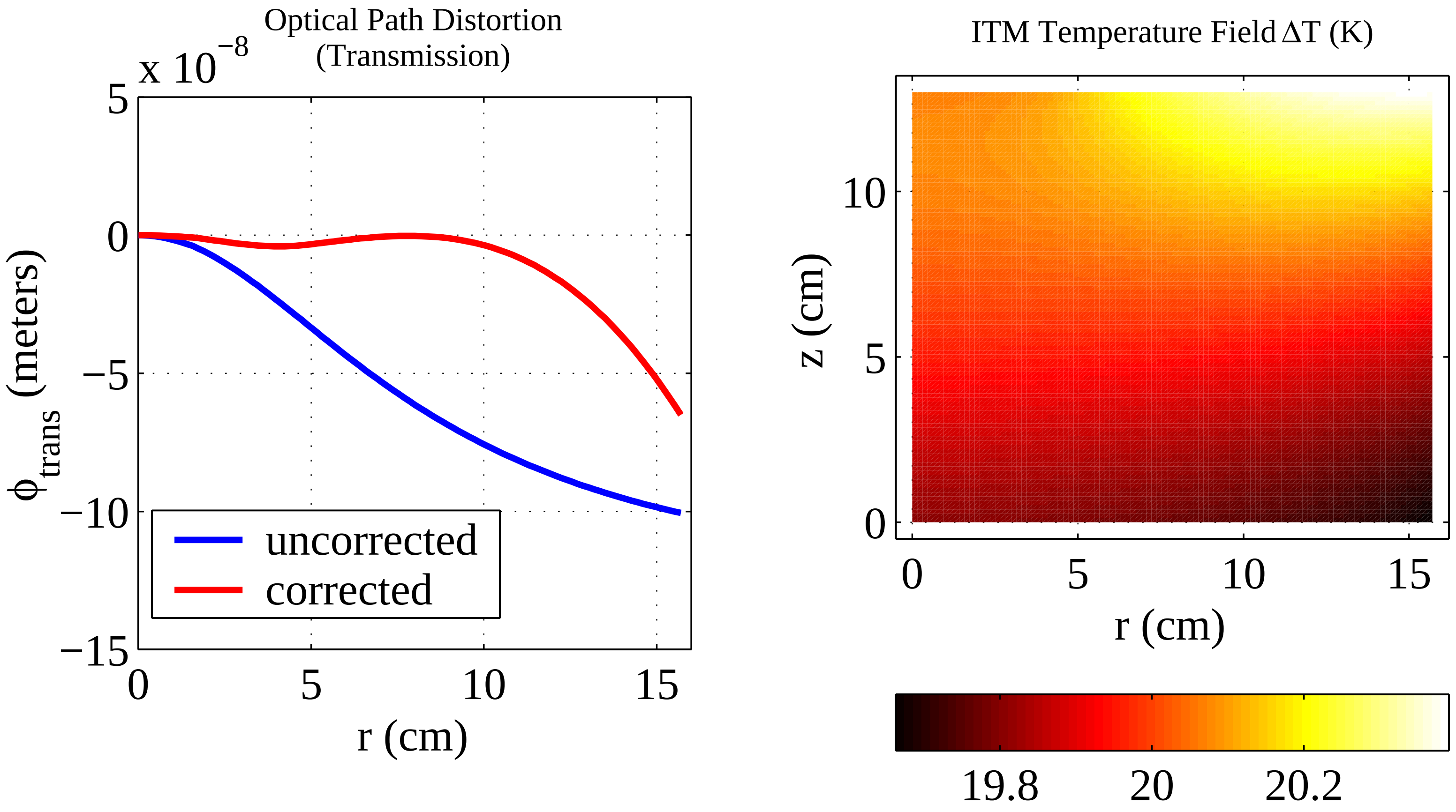
$$R_r = 21.7\,\text{cm} \quad H_r = 7.6\,\text{cm} \quad \frac{P_r}{2\pi R_r} = 14.0\,\text{W/cm}$$

Shielded Heating Ring



- Improve efficiency by hiding the center of the optic from the ring’s radiation.

Shielded Heating Ring



LIGO II Sapphire ITM, 1W Probe Absorption, Shielded Ring Compensated

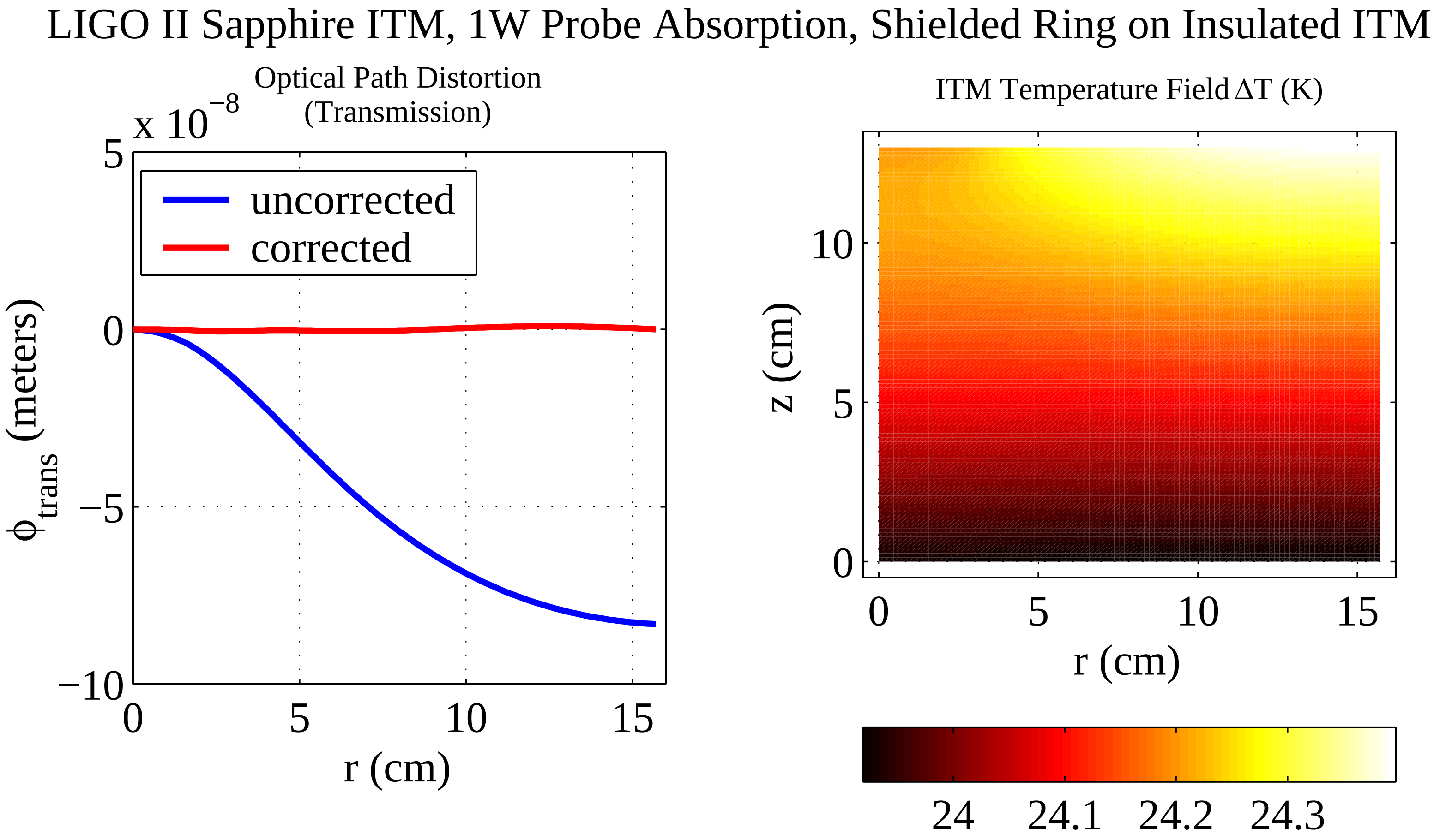
Optical Path Distortion (Transmission)

ITM Temperature Field ΔT (K)

$$\mathbb{C} \approx 10^{-2.2} \qquad \mathbb{T} \approx 1$$

$$R_r = 22.3\,\text{cm} \quad H_r = 16.0\,\text{cm} \quad h_s = 0.89 \quad \frac{P_r}{2\pi R_r} = 4.1\,\text{W/cm}$$

Shielded Heating Ring on Insulated Optic



LIGO II Sapphire ITM, 1W Probe Absorption, Shielded Ring on Insulated ITM

Optical Path Distortion (Transmission)

ITM Temperature Field ΔT (K)

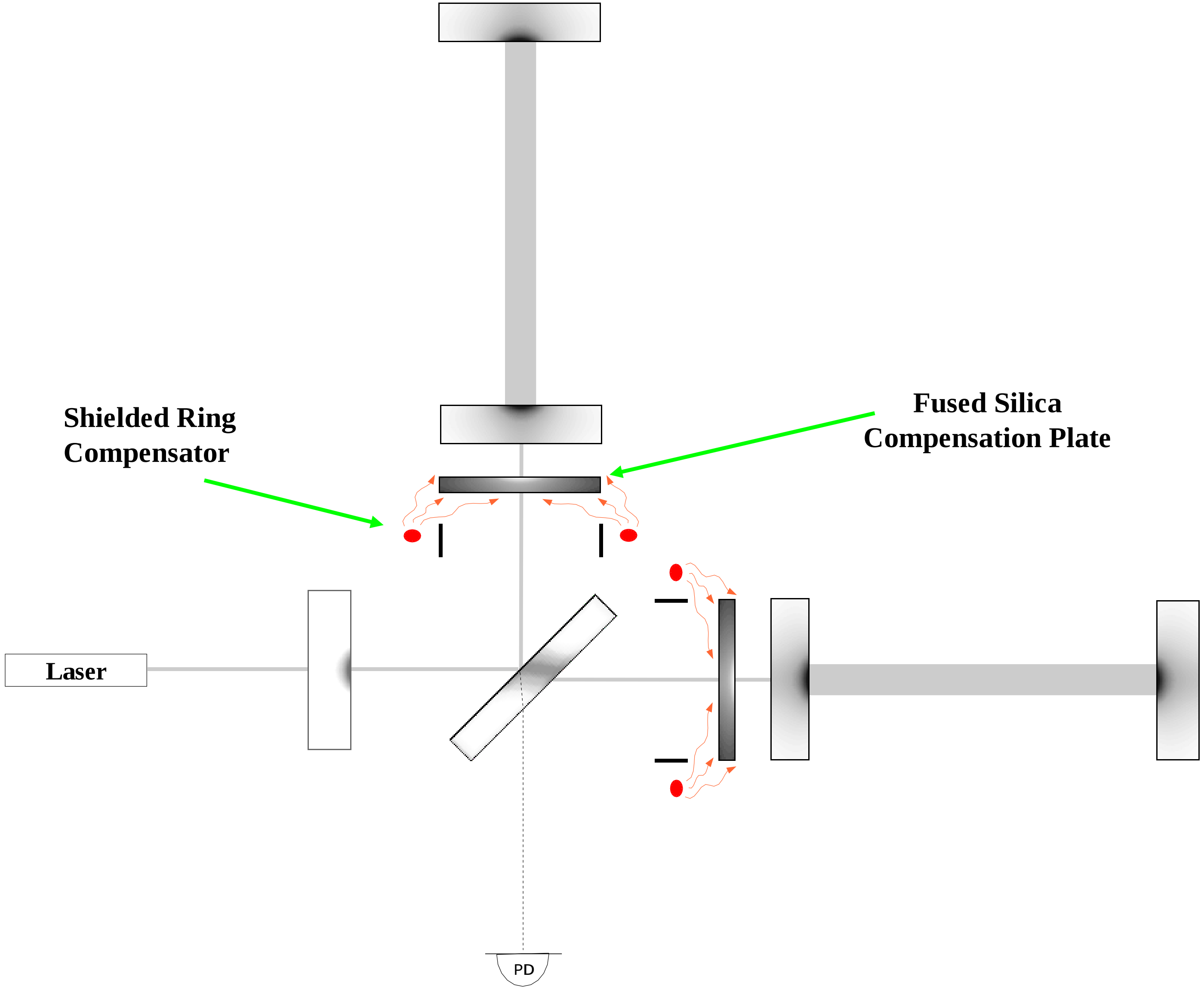
$$\mathbb{C} \approx 10^{-4.0} \qquad \mathbb{T} \approx 1.3$$

$$R_r = 16.3\ \text{cm} \quad H_r = 20.5\ \text{cm} \quad h_s = 0.99 \quad \frac{P_r}{2\pi R_r} = 3.9\ \text{W/cm}$$

So Far...

- The simple ring works, but is very inefficient ($\mathbb{C} \approx 10^{-2.1}$, $\mathbb{T} \approx 6$).
- Shielding the center of the optic greatly improves efficiency ($\mathbb{C} \approx 10^{-2.2}$, $\mathbb{T} \approx 1$).
- Insulating the radial edge of the optic further improves correction quality ($\mathbb{C} \approx 10^{-4.0}$, $\mathbb{T} \approx 1.3$).
- Can we do even better?

Shielded Heating Ring on Silica Compensation Plates



Shielded Ring Compensator

Fused Silica Compensation Plate

Shielded Heating Ring on Silica Compensation Plates

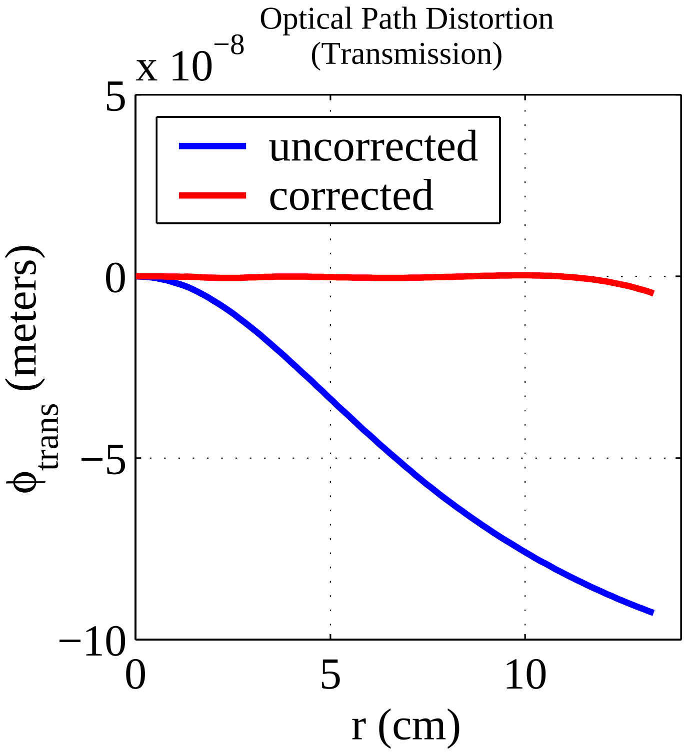
Benefits:

- Input Test Masses remain untouched.
- For sapphire LIGO II: gain in efficiency due to lower thermal conductivity of silica CP's (i.e., more OPD per watt of input).
- Make the CP thin ⇒ edge insulation unnecessary.

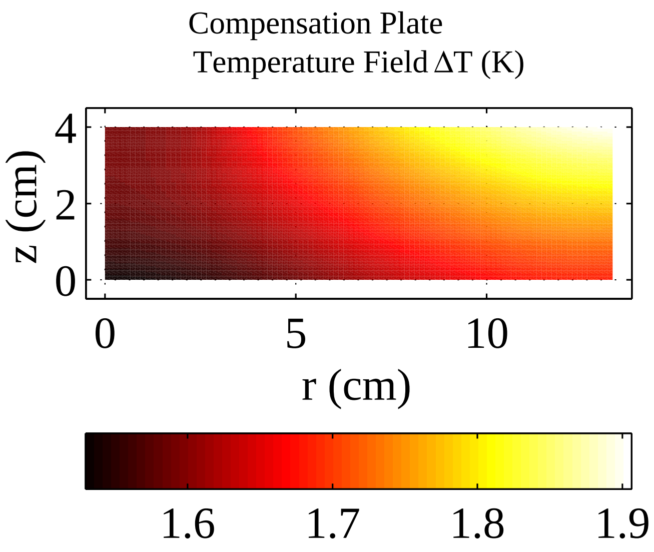
Drawbacks:

- Does not help stabilize arm cavity mode.
- Increases system complexity (more optics).

Shielded Heating Ring on Silica Compensation Plates



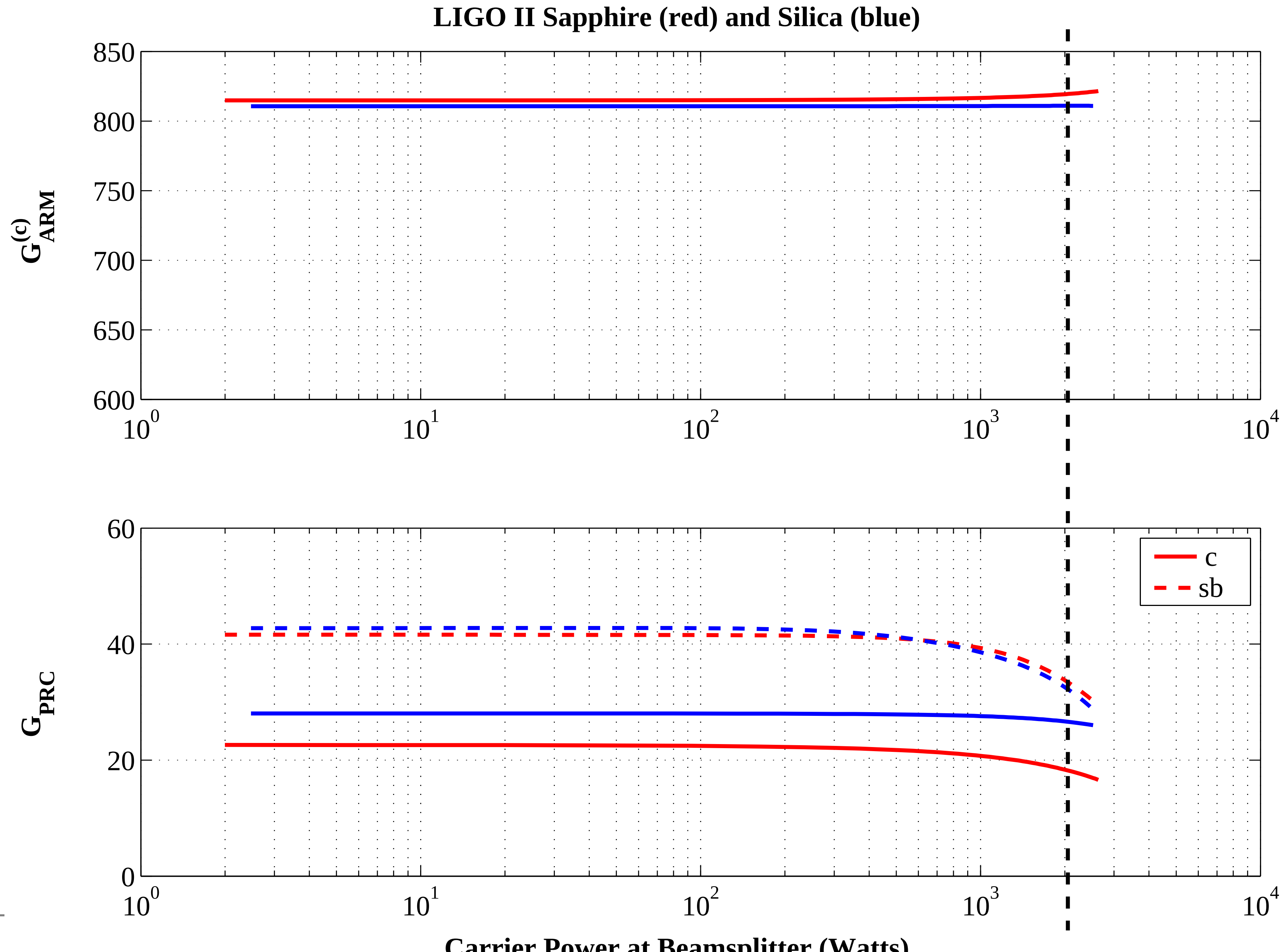
LIGO II Sapphire ITM, 1W Probe Absorption
Shielded Ring on Compensation Plate



$$\mathbb{C} \approx 10^{-4.1} \qquad \mathbb{T} \approx 0.2$$

$$R_r = 24.5\,\text{cm} \quad H_r = 14.0\,\text{cm} \quad h_s = 0.90 \quad \frac{P_r}{2\pi R_r} = 0.2\,\text{W/cm}$$

Melody Model of CP Compensated LIGO II



Heating Ring Noise Considerations

- Consider 20 Watts of ring power delivered (P_d) to compensate 1 Watt optical absorption (P_a).
- Relative power fluctuation $\mathcal{R}_d$ on delivered power $\Rightarrow$ optical path fluctuations δx:

$$\delta x(\omega) \approx \frac{\beta}{\rho c \omega} \frac{P_a}{\pi w^2} \mathcal{R}_d(\omega)$$

$$\approx 5 \times 10^{-12}\,\text{m} \left(\frac{100\,\text{Hz}}{\omega} \right) \left(\frac{\beta}{10\,\text{ppm}/^\circ\text{K}} \right) \mathcal{R}_d(\omega)$$

Heating Ring Noise Considerations

- Consider 20 Watts of ring power delivered (P_d) to compensate 1 Watt optical absorption (P_a).
- Relative power fluctuation for delivered ring power:

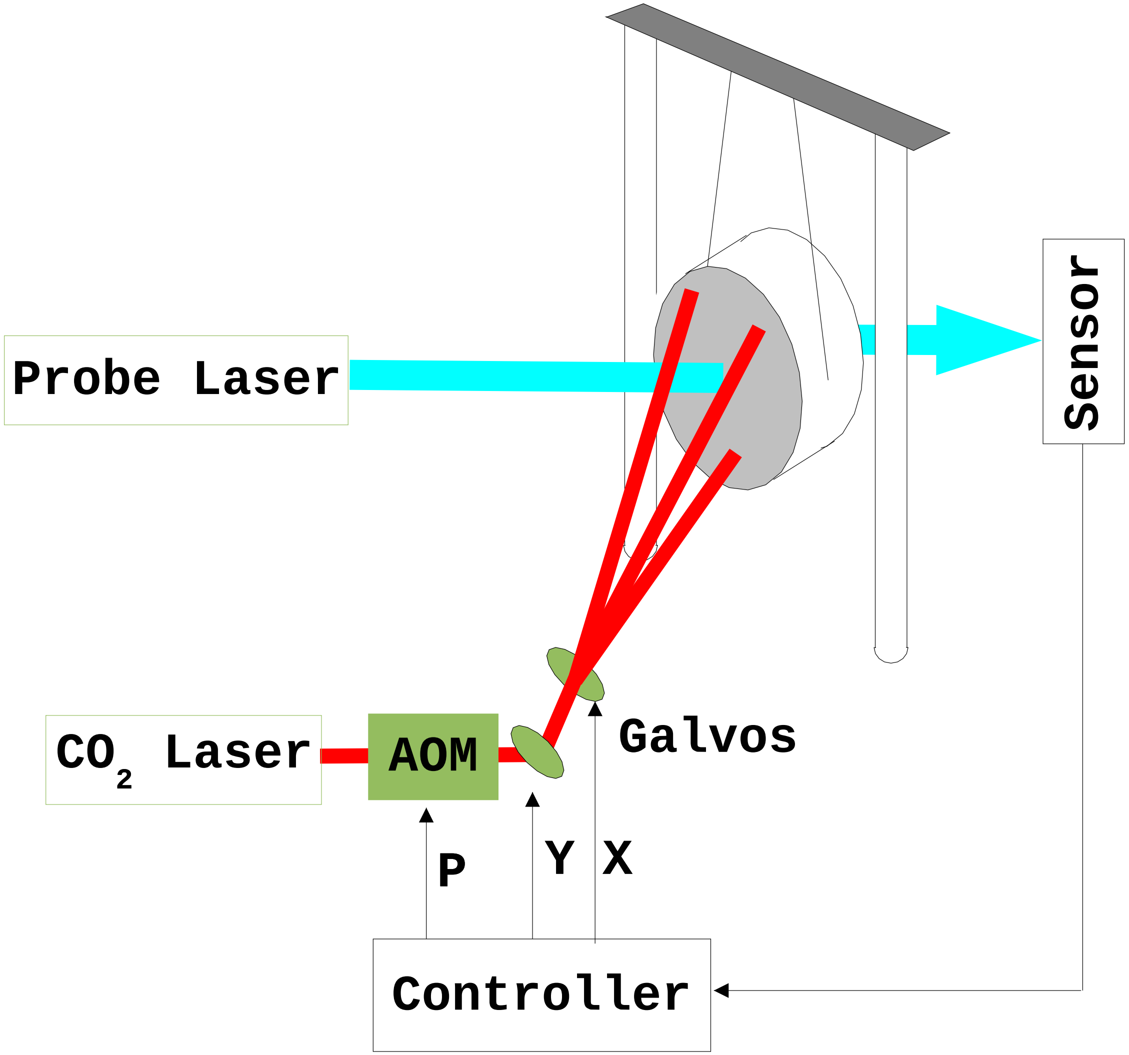
$$\mathcal{R}_d(\omega) \approx \underbrace{\frac{\mathcal{R}_{ps}(\omega)}{\tau_r \omega}}_{\text{Power Supply Fluctuation}} + \underbrace{\sqrt{\frac{8k_B T_r}{P_d}}}_{\text{Blackbody Shot Noise}}$$

$$\approx 3 \times 10^{-5}\, \mathcal{R}_{ps}(\omega) \left(\frac{100\ \text{Hz}}{\omega} \right) + 6 \times 10^{-11}/\sqrt{\text{Hz}}$$

- To work ***everywhere***, need power supply relative fluctuation $\mathcal{R}_{ps}(\omega) \lesssim 2 \times 10^{-6}/\sqrt{\text{Hz}}$ at 100 Hz.

PART III: Scanning Laser Thermal Compensation

Scanning Laser Thermal Compensation



Scanning Laser Thermal Compensation

- Assume fixed scan pattern and actuator beam waist.

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- Given any actuator powers $\{P_m\}$, the resulting phase distortion is easily calculated:

$$\phi(x, y) = \sum_{m=1}^{M} P_m \mathcal{A}_m(x, y)$$

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- Given any actuator powers $\{P_m\}$, the resulting phase distortion is easily calculated:

$$\phi(x, y) = \sum_{m=1}^{M} P_m \mathcal{A}_m(x, y)$$

- Now, how do we go *backwards*? (i.e., get $\{P_m\}$ given ϕ)

Scanning Laser Thermal Compensation

- **Decompose $\phi(x, y)$ in the nonorthogonal basis $\{\mathcal{A}_m(x, y)\}$**, and apply the transformation (matrix) which orthogonalizes this space.

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Scanning Laser Thermal Compensation

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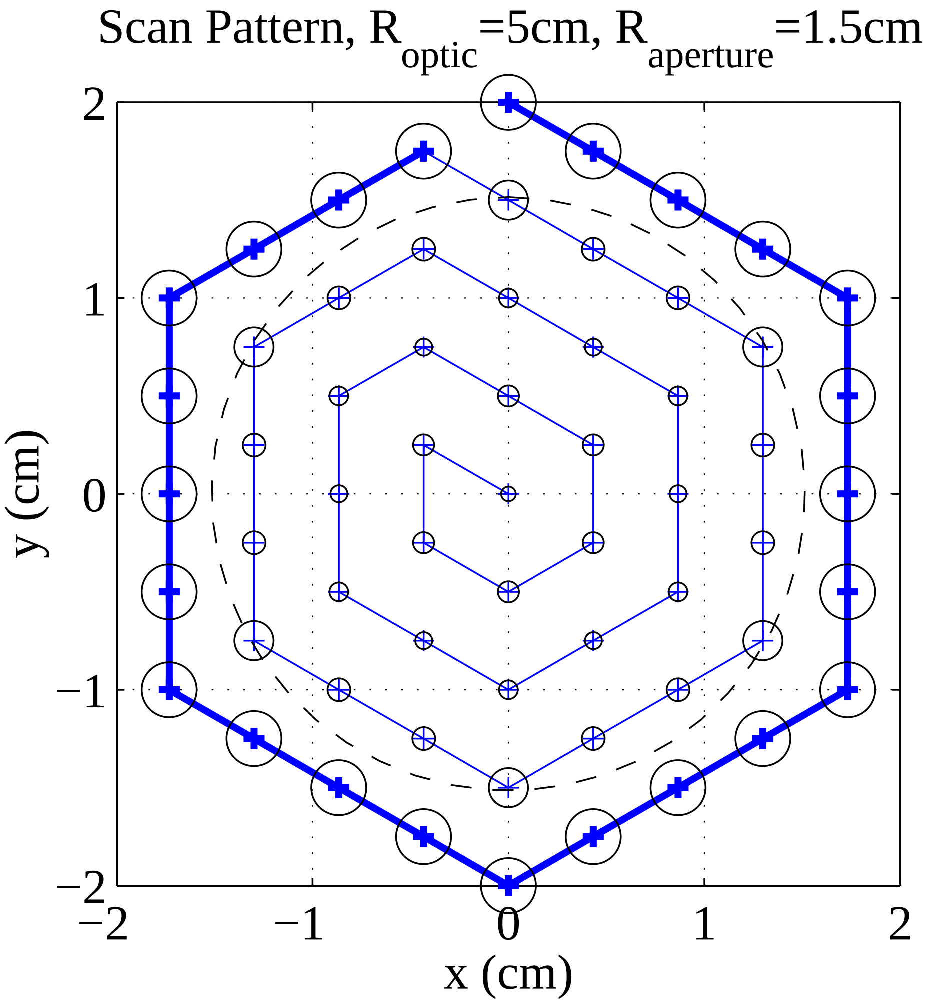
- Resulting $\{P_m\}$'s are not all necessarily positive.
  $\Rightarrow$ Add a DC offset to ϕ (i.e., piston) until all $P_m > 0$
- Must be able to cleanly generate piston.
  $\Rightarrow$ actuator beam can't be too small
- Also, actuation functions must look sufficiently different.
  $\Rightarrow$ actuator beam can't be too big

Implementation

1. Choose pattern and beam waist.
   $\Rightarrow$ driven by distortion and attainable pattern frequency.
2. Via 3D FEM, compute actuation functions $\{A_n(x,y)\}$.
3. Compute the orthogonalization matrix and make sure piston is clean. If not, tie together degenerate points or make the beam size smaller and start over.
4. Compensate distortions $\phi(x,y)$ by integrating $-\phi$ against $\{A_n\}$ and applying the orthogonalization matrix.
5. Add piston until all powers are positive.

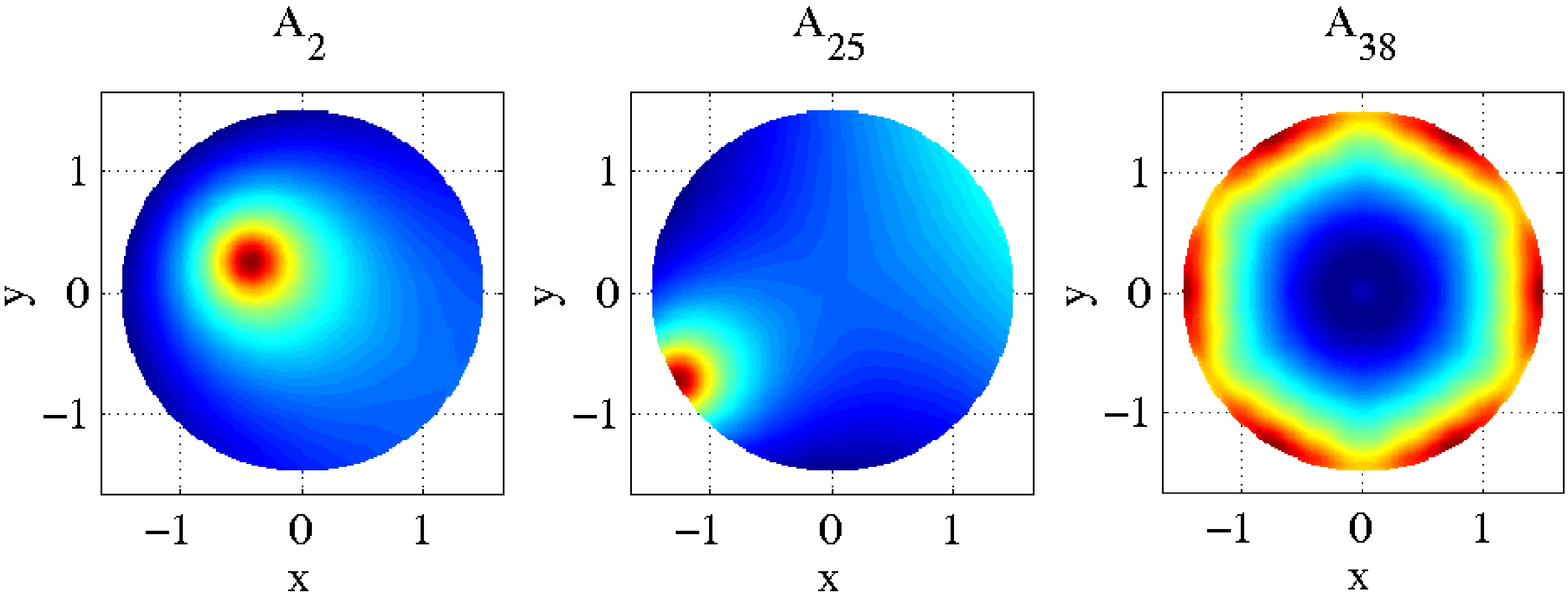
Scanning Laser Example



- 3 cm aperture on 10 cm silica optic
- 0.5 cm spacing on 61 pattern points
  $\Rightarrow$ 0.2 cm actuator beam
- Outer 25 points “linked” to skirt degeneracy
- Circles denote piston powers

Scanning Laser Example

A few actuation functions...



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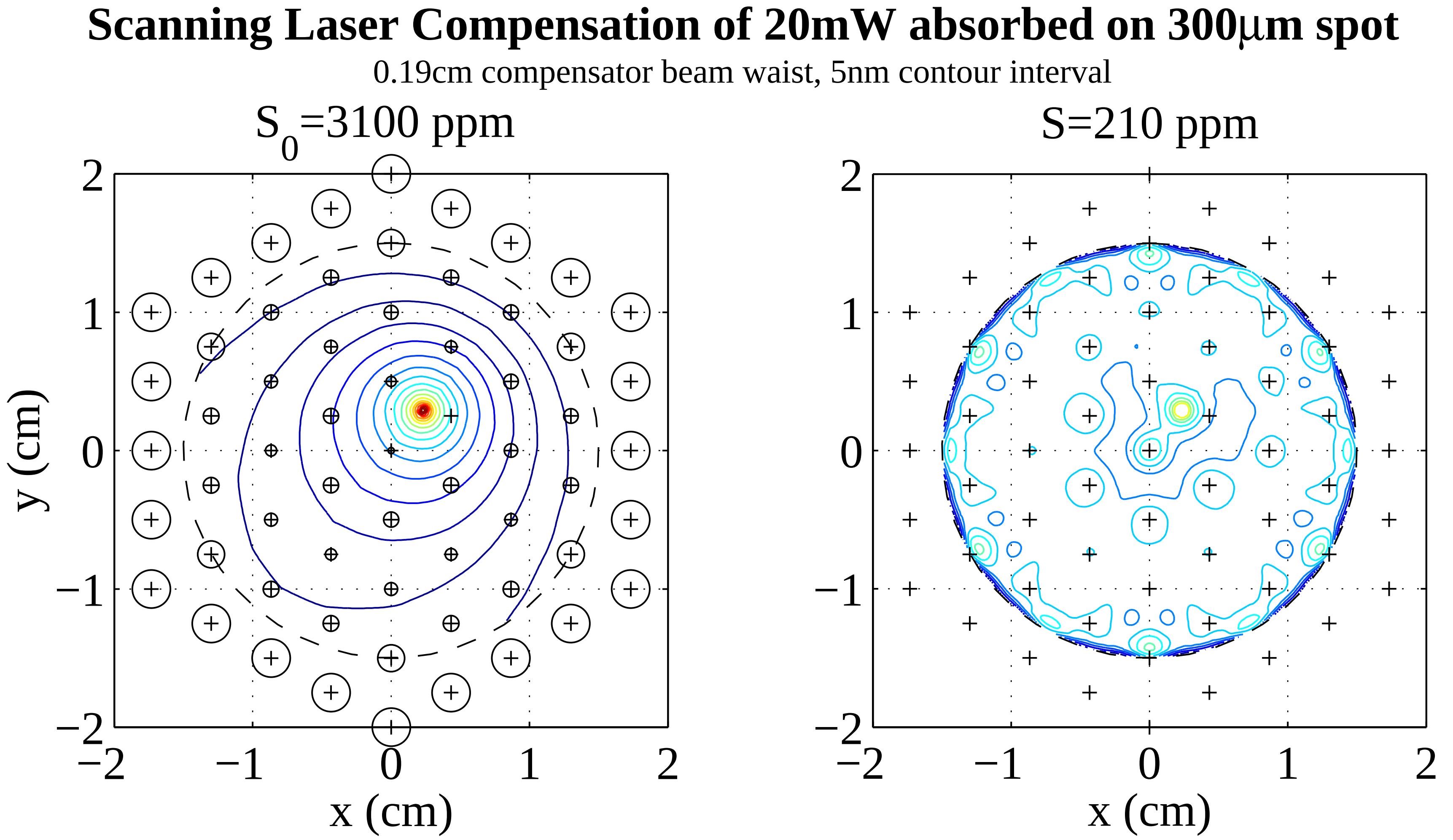


“Measured” Wavefront→Actuator Powers→Corrected Wavefront

Scanning Laser Noise Considerations

Sources of optical path fluctuations:

1. Pattern Repetition. Pattern of N points repeated at:

$$f_p \gg \underbrace{\frac{k}{\pi w_a^2 \rho c}}_{\text{Local thermal time constant}} \approx 10\,\text{mHz} \left(\frac{1\,\text{cm}}{w_a}\right)^2$$

2. Actuator Modulation. Beam switches on-and-off at

$$f_m = f_p \times N$$

3. Broadband intensity noise on the laser.

Scanning Laser Noise Considerations

Fluctuations due to Pattern Repetition:

- OPD decays over whole aperture $2w$, while laser actuator (waist w_a) shines on-and-off depositing mean power P_m..
- Occurs at pattern frequency f_p (use 0.1 Hz for 1 cm beam).
- Maximal *sensed* fluctuation:

$$\begin{aligned} \|\delta x\|_{pat} &\lesssim \frac{\beta P_m}{\rho c f_p w_a^2} \\ &\approx 60\,\text{nm} \left(\frac{P_m}{0.1\,\text{W}}\right) \left(\frac{0.1\,\text{Hz}}{f_p}\right) \left(\frac{5\,\text{cm}}{w}\right)^2 \end{aligned}$$

Scanning Laser Noise Considerations

Fluctuations due to Actuator Modulation:

- OPD regularly rises abruptly at each actuation point.
- Occurs at modulation frequency $f_m = f_p \times N$ (about 6 Hz for 61 points).
- Maximal *sensed* fluctuation:

$$\|\delta x\|_{mod} \lesssim \frac{w_a^2}{w^2}\|\delta x\|_{pat} \lesssim \frac{\beta P_m}{f_p w^2 \rho c}$$

$$\approx 2\,\text{nm}\left(\frac{P_m}{0.1\,\text{W}}\right)\left(\frac{0.1\,\text{Hz}}{f_p}\right)\left(\frac{5\,\text{cm}}{w}\right)^2$$

Scanning Laser Noise Considerations

Broadband Fluctuations due to Intensity Noise:

- Intensity noise $\Delta P(\omega)$ on the actuator shining at radius r_m induces optical path fluctuations:

$$\|\delta x(\omega)\| \approx \frac{\beta}{\rho c \omega} \frac{2\Delta P(\omega)}{\pi w^2} e^{-2\frac{r_m^2}{w^2}} < 3 \times 10^{-18} \mathrm{m}/\sqrt{\mathrm{Hz}}$$

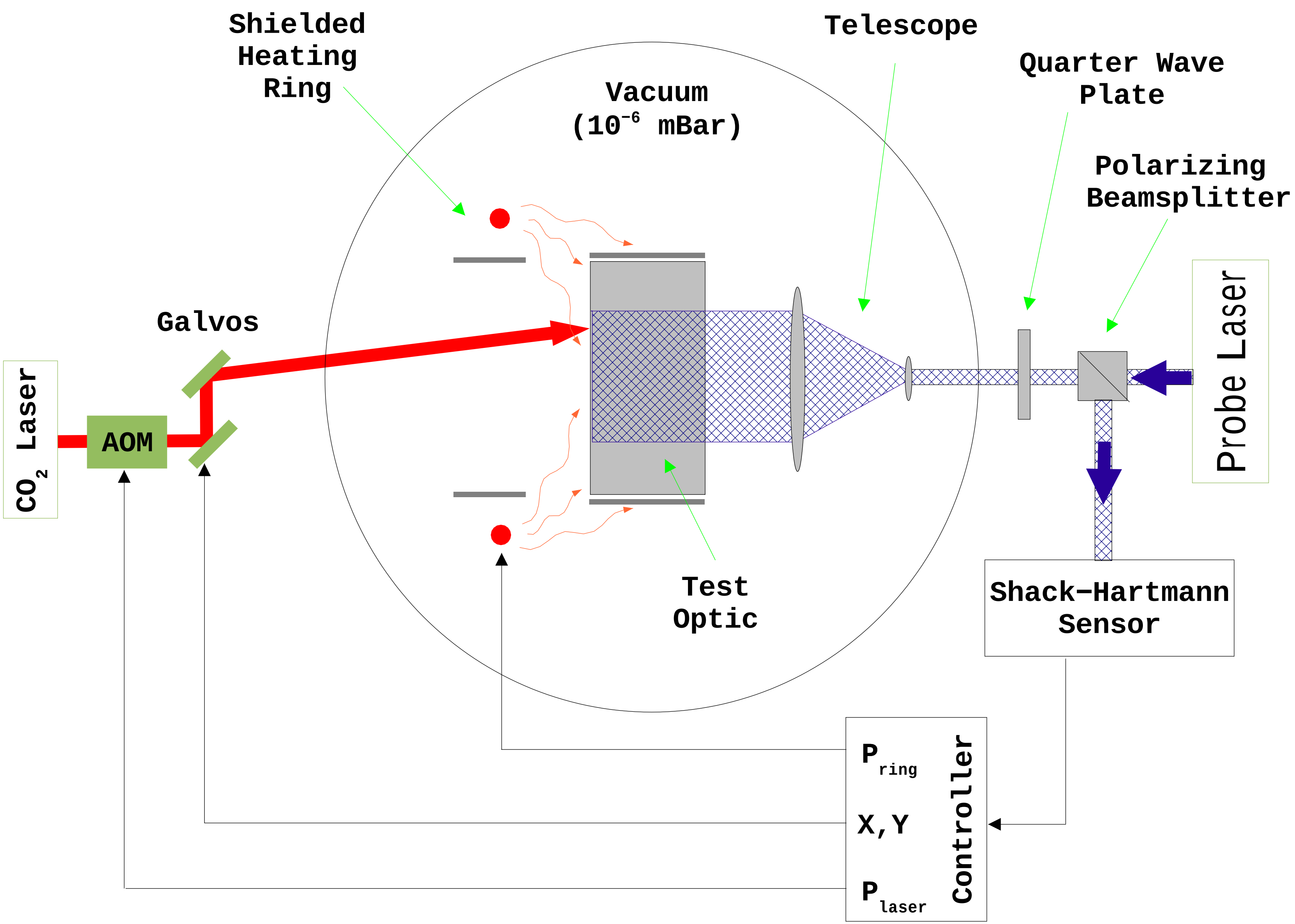
$$\Rightarrow \Delta P(\omega) < 2 \times 10^{-7} \frac{\mathrm{W}}{\sqrt{\mathrm{Hz}}} e^{2\frac{r_m^2}{w^2}} \left(\frac{\omega}{100\,\mathrm{Hz}}\right) \left(\frac{w}{5\,\mathrm{cm}}\right)^2$$

- Shot noise limit on 10 Watt CO2 beam:

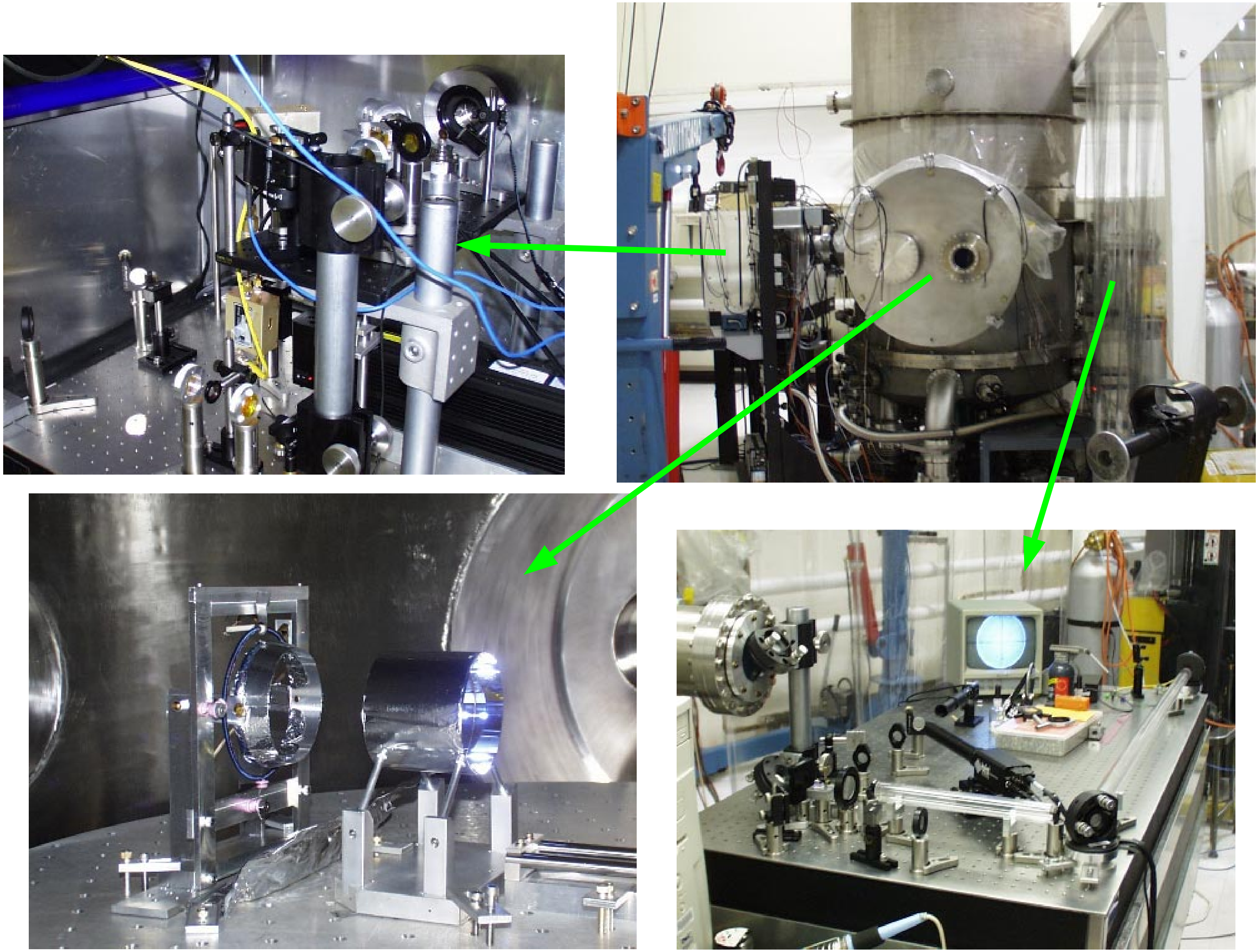
$$\Delta P_{shot} = 6 \times 10^{-10} \frac{\mathrm{W}}{\sqrt{\mathrm{Hz}}} \left(\frac{P}{10\,\mathrm{W}}\right)^{\frac{1}{2}}$$

PART IV: The Experiment

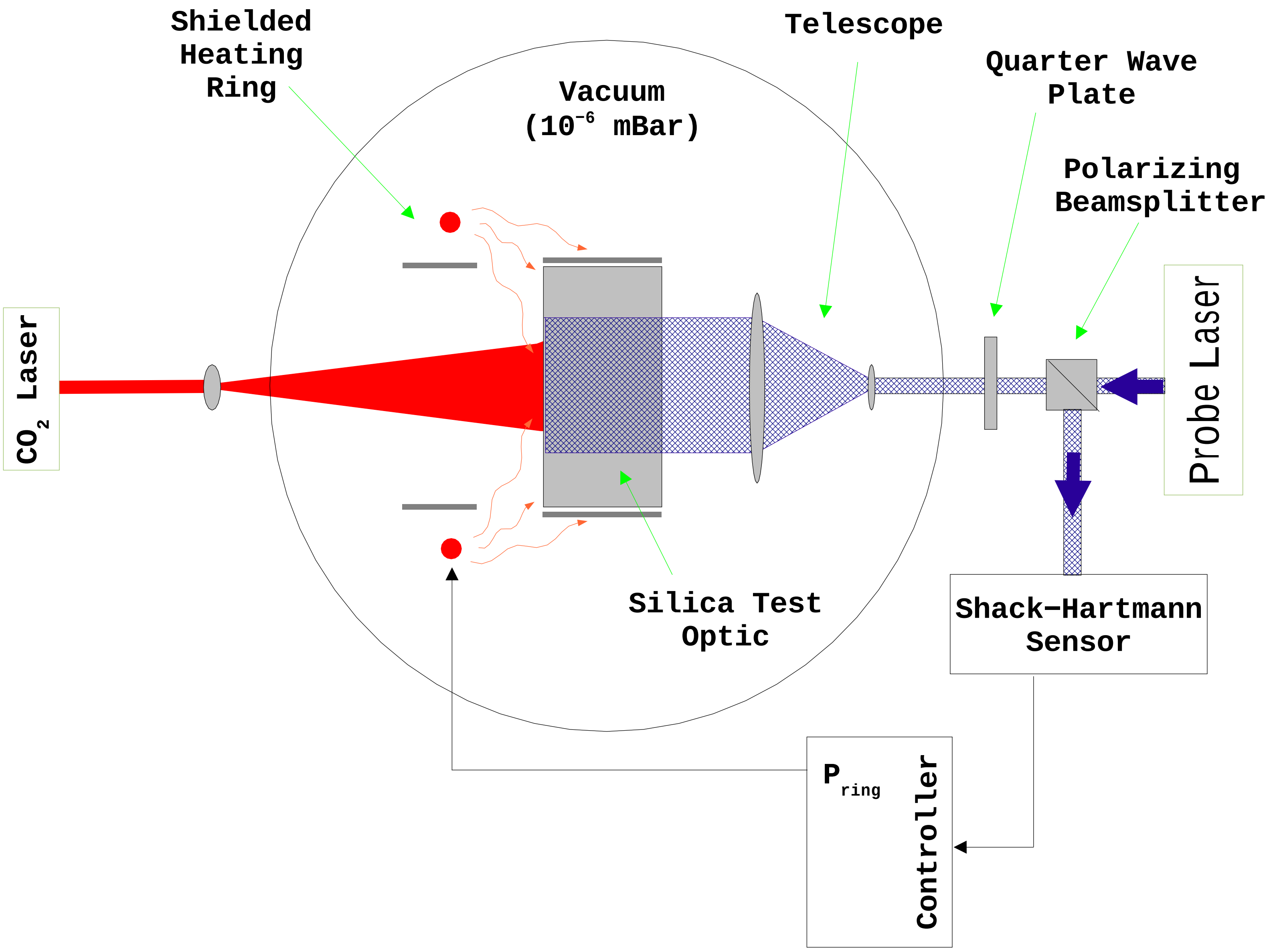
Thermal Compensation Experiment



Thermal Compensation Experiment



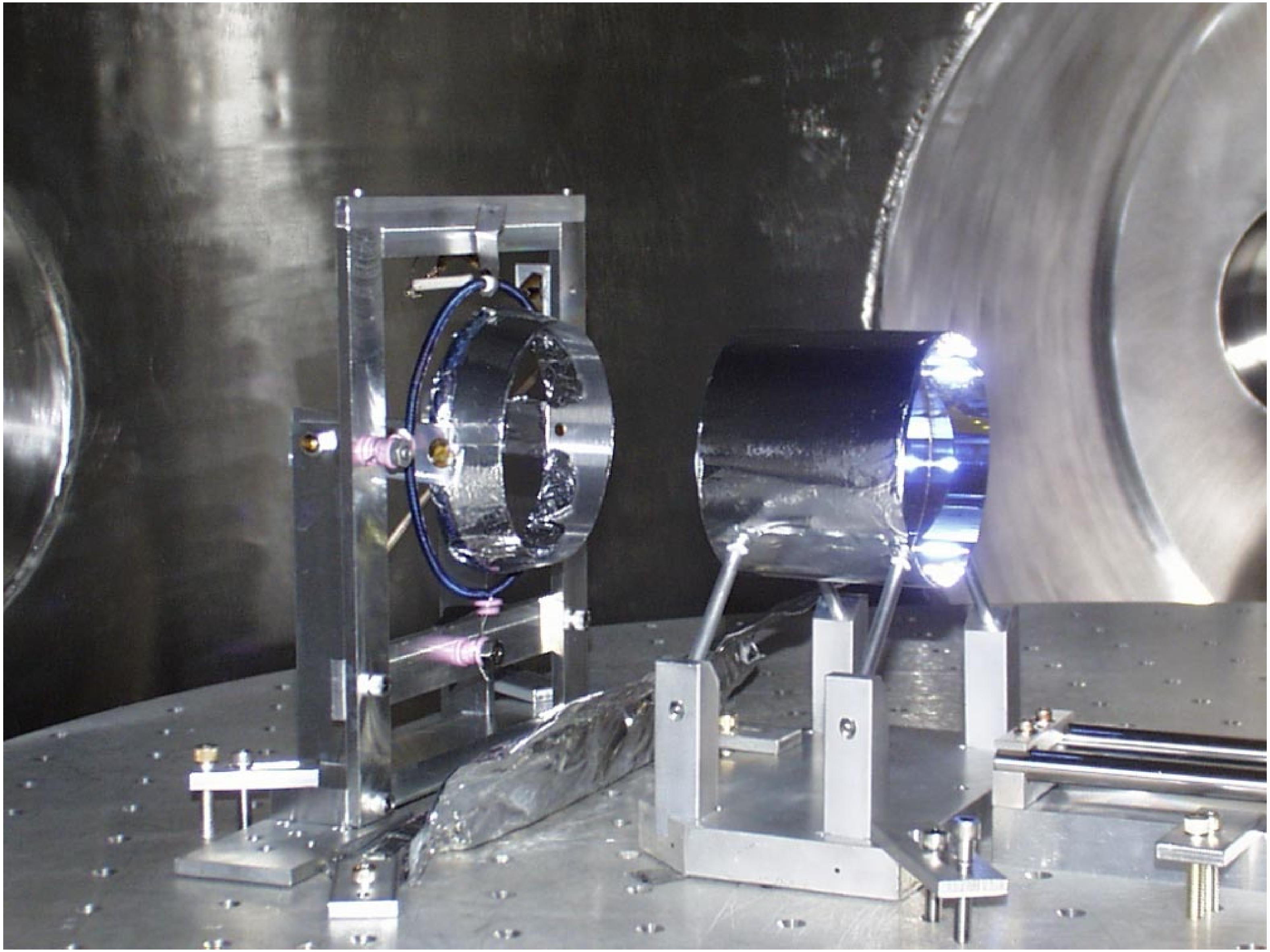
Ring Experiment



Ring Experiment

- Fused Silica Optic (10 cm diameter, 8 cm height) probed in transmission over 3 cm aperture.
- CO2 laser expanded to 1,5 cm waist radius, 50 mW absorbed in optic.
- Ring compensator 13.4 cm in diameter, 0.5 cm thick, held 11.9 cm off the optic's face. 100 Watts maximum input power.

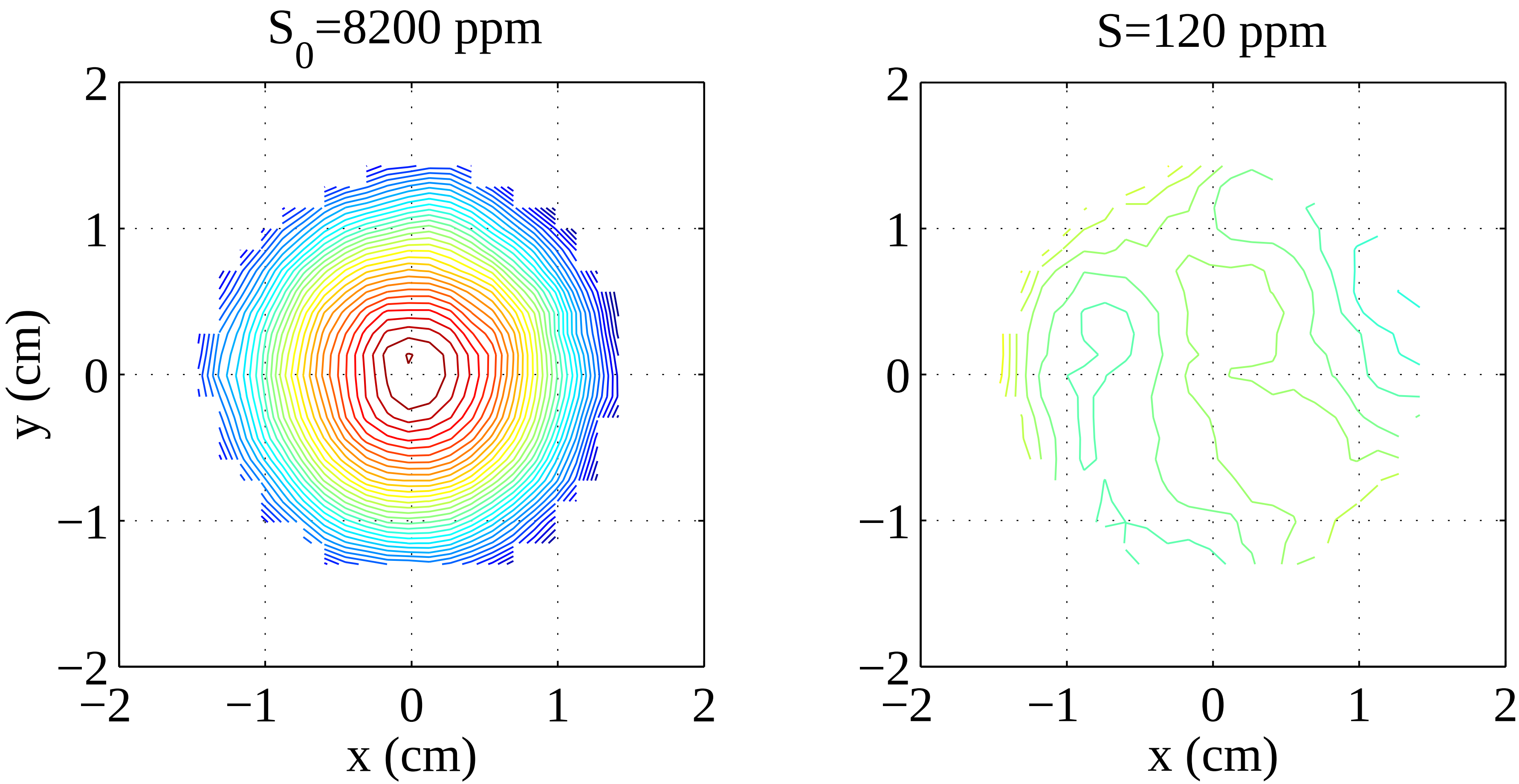
Ring Experiment



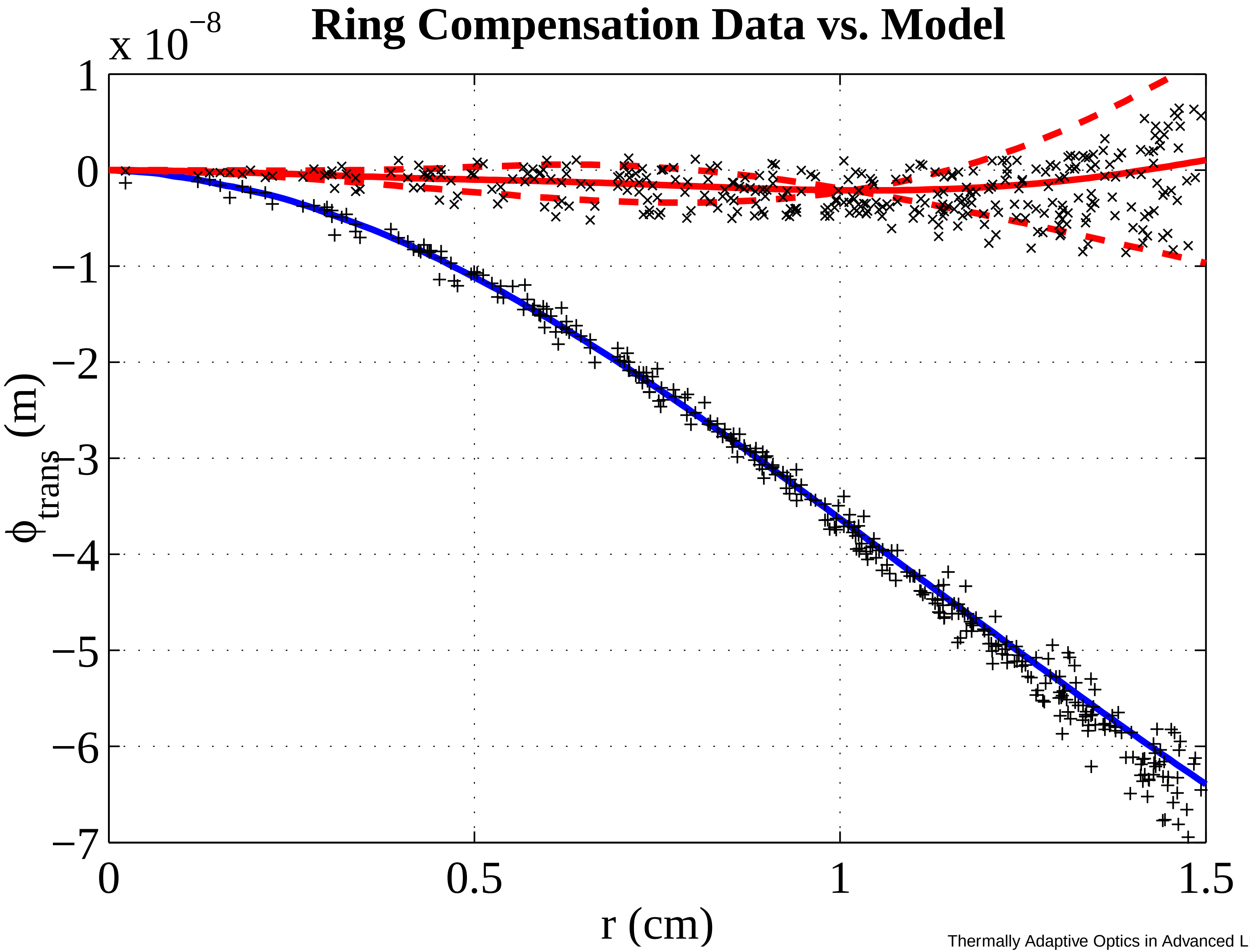
Ring Results

Heating Ring Compensation of 50 mW from w=1.5 cm beam

70 W effective ring power, 2nm contour interval



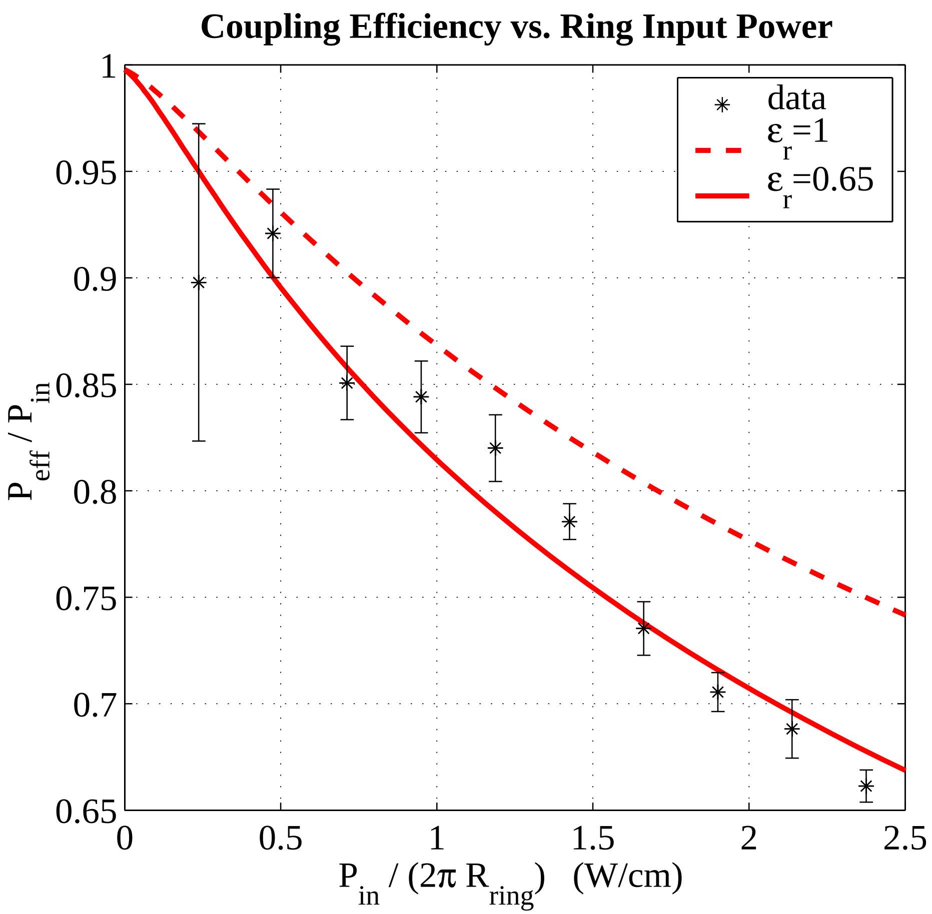
Ring Results vs. Model



Ring Coupling Efficiency

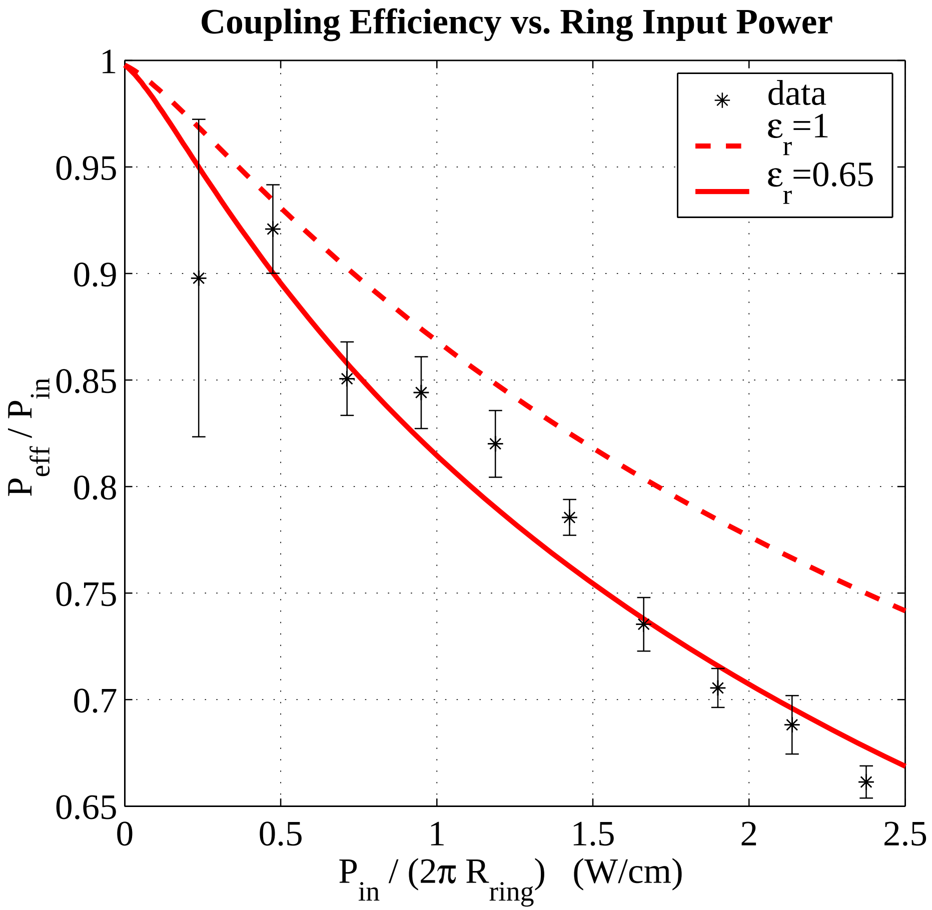
- Model fits well, *but* only 70 Watts should be necessary, while 100 Watts are provided. (Transmission?)

Ring Coupling Efficiency



- Model fits well, *but* only 70 Watts should be necessary, while 100 Watts are provided. (Transmission?)
- Examine ring OPD vs. electrical input power and compare with model.

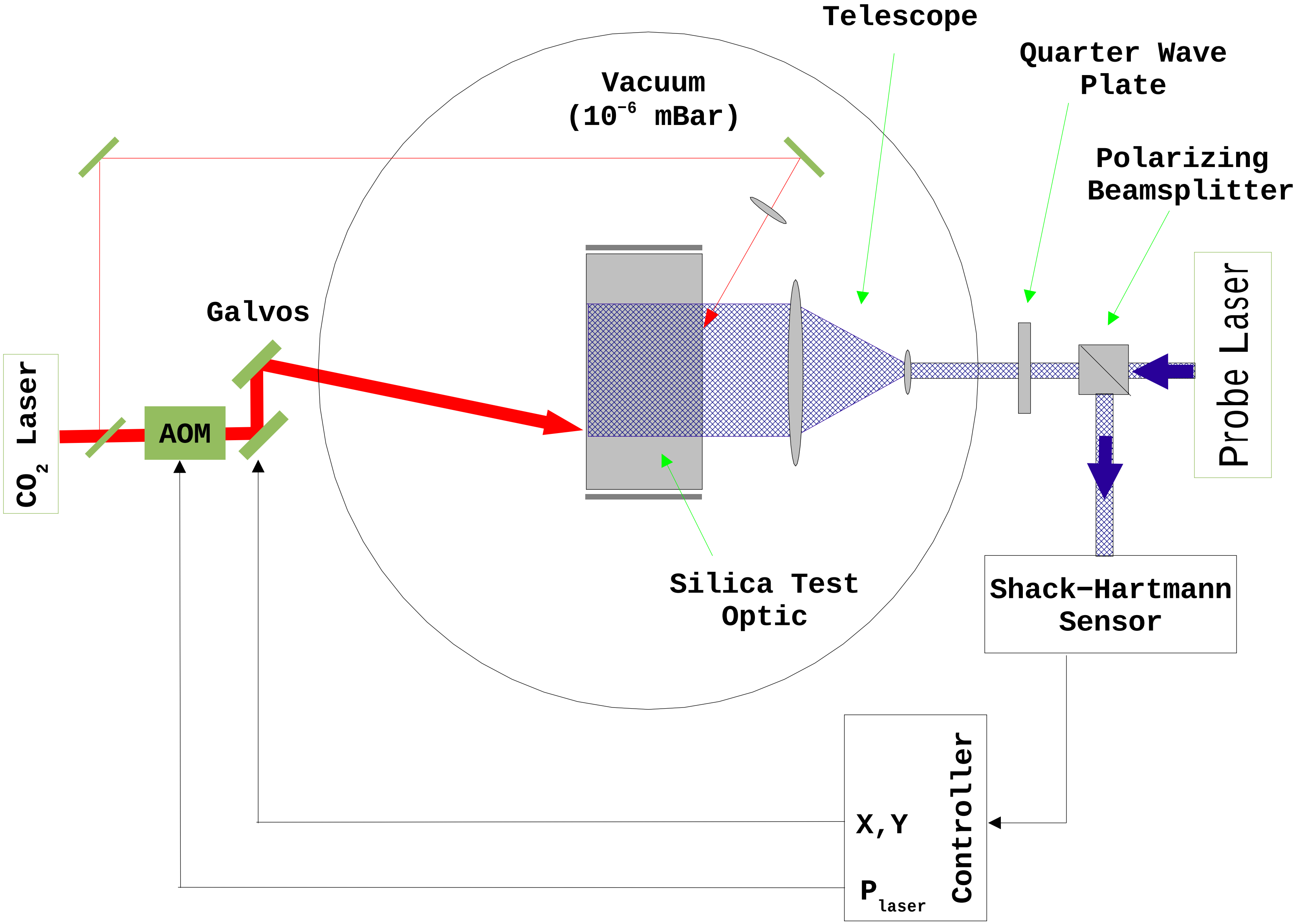
Ring Coupling Efficiency



- Model fits well, *but* only 70 Watts should be necessary, while 100 Watts are provided. (Transmission?)
- Examine ring OPD vs. electrical input power and compare with model.
- Roughly consistent with $\epsilon_r = 0.65$.

$\Rightarrow \frac{P_r}{2\pi R_r} \geq 2.5$ **W/cm is difficult to generate.**

Scanned Laser Experiment



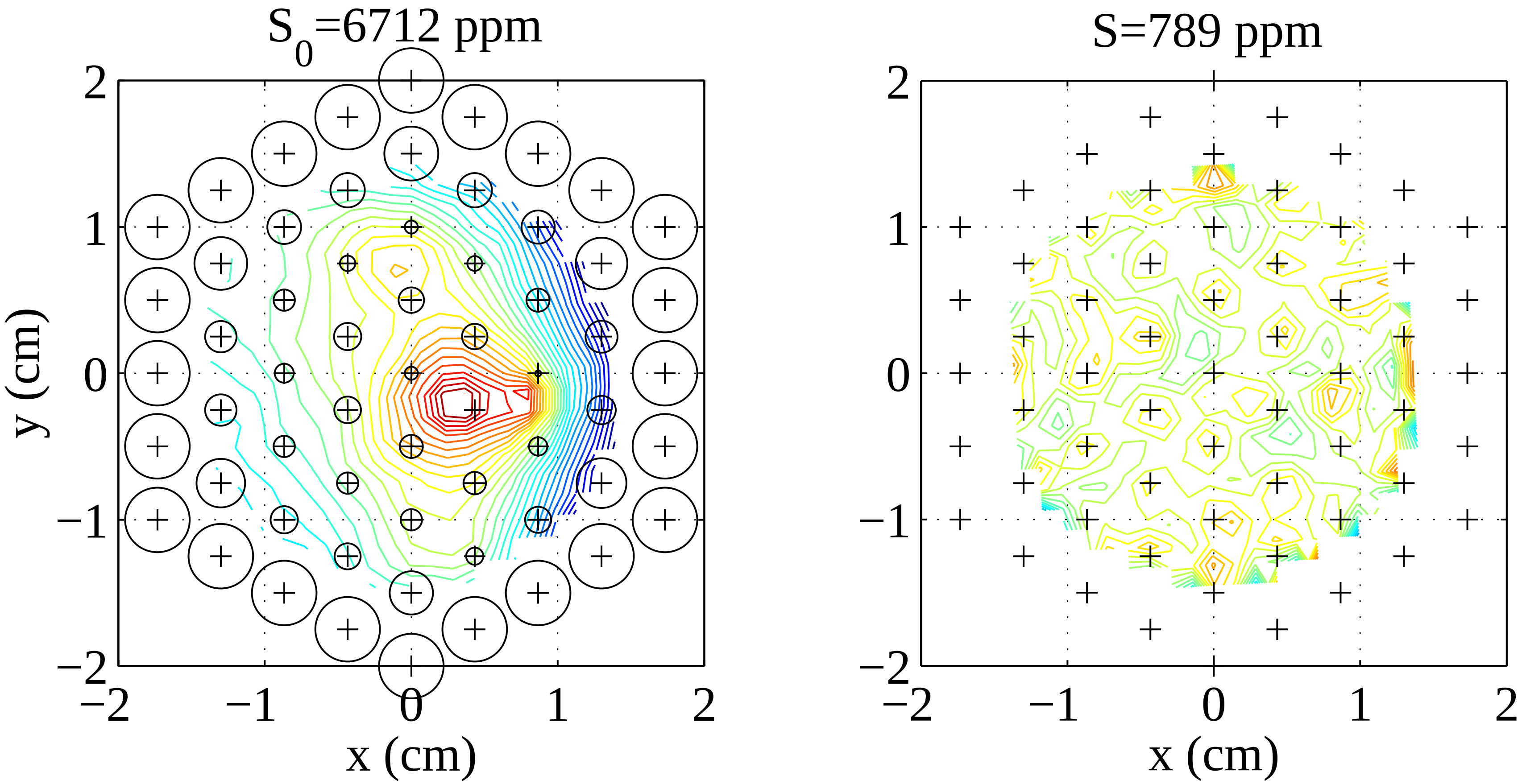
Scanned Laser Experiment

- Fused Silica Optic (10 cm diameter, 8 cm height) probed in transmission over 3 cm aperture.
- CO2 beam waist radius $w = 0.2$ cm with hexagonal pattern spacing 0.5 cm
  (same as example previously discussed).
- Distortion generated by ~ 20 mW focused to 300 μm spot.
- Control system:
  1. Acquires wavefront data
  2. Calculates necessary powers from model
  3. Updates pattern powers
  4. Waits 20 minutes and returns to step 1.

Scanned Laser Data

Scanning Laser Compensation of ~20 mW absorbed on 300µm spot

0.19cm compensator beam waist, 1nm contour interval



Conclusions to Date

Thermal Effects in LIGO II

- ITM distortion readily knee-caps sideband gain in PRC (GW sidebands in SRC too?) with little effect on carrier gain.
- Large ITM distortion hinders carrier coupling into arm cavity.
- Massive ITM distortion ($\lambda/4$) prevents instrument from working at all.
- Arm cavity surface distortions make carrier mode $\sim 20\%$ larger (which increases exponentially with absorbed power).

Conclusions to Date

Thermal Effects in LIGO II (cont.)

	LIGO II Sapphire		LIGO II Silica	
(Watts)	P_a^{ITM}	$P_{\text{PRC}}^{(c)}$	P_a^{ITM}	$P_{\text{PRC}}^{(c)}$
Nominal Operation	**1.20**	**2100**	**0.270**	**1300**
Sideband Failure	0.17	280	0.010	50
Arm Cavity Gain Falloff	1.3	2200	0.070	350
Carrier Failure	2.0	3300	0.24	1200

Conclusions to Date

Generic Thermal Compensation

- For "ideal" thermal compensation, have to live with a temperature increase:

$$\overline{\Delta T}_{ideal} = \frac{P_a}{4w^2\epsilon\sigma T_\infty^3} \approx 20\,\frac{{}^\circ\mathrm{K}}{\mathrm{W}}\left(\frac{5\ \mathrm{cm}}{w}\right)^2$$

- ⇒ compensation more difficult on smaller scales.
- ⇒ compensation impossible (?) at cryogenic temperatures.

Conclusions to Date

Heating Ring Thermal Compensation

- Engineered solution for anticipated azimuthally symmetric distortions.
- Heating ring works ($\mathbb{C} \approx 10^{-2.1}$, $\mathbb{T} \approx 6$), but shielded ring is more efficient ($\mathbb{C} \approx 10^{-2.2}$, $\mathbb{T} \approx 1$).
- Can actuate *anywhere* in the instrument with the shielded ring.
- Reducing heat flow out the radial edge (e.g., insulation) improves the quality of correction ($\mathbb{C} \approx 10^{-4.0}$, $\mathbb{T} \approx 1.3$).
- Actuating on a compensation plate appears to work the best, at the cost of losing control over the arm cavity mode ($\mathbb{C} \approx 10^{-4.1}$, $\mathbb{T} \approx 0.2$).

Conclusions to Date

Heating Ring Thermal Compensation (cont.)

- Model agrees well with experiment, which demonstrated $\mathbb{C} = 10^{-2}$ for 50 mW absorbed from 1.5 cm beam on a fused silica optic.
- Ring powers greater than 2.5 W/cm difficult to achieve (emission enters optic’s transmissive band).

Conclusions to Date

Scanning Laser Thermal Compensation

- Contingency plan to deal with nonuniform optical absorption.
- Can safely (?) actuate on Compensation Plates in PRC (*not* on arm cavity faces!).
- Factor of 10 or more correction, even for absorption on spatial scales smaller than the actuation pattern spacing.
- Means of design and control well understood.
- Model agrees well with experiment, which demonstrated $\mathbb{C} = 10^{-1}$ for 20 mW absorbed over a 300 μm spot on a fused silica optic.

Schedule for Thermal Compensation

Active optics compensation	**993d**	**29 Oct ‘02**	**17 Aug '06**
DRR	0d	29 Oct ‘02	29 Oct '02
Prelim design	6mo	29 Oct ‘02	14 Apr '03
Prototype fabrication	3mo	15 Apr ‘03	07 Jul '03
Ship to Gingin	0d	07 Jul ‘03	07 Jul '03
Prototype test	2mo	08 Jul ‘03	01 Sep '03
Data back from Gingin	0d	01 Sep ‘03	01 Sep '03
Final design	3mo	02 Sep ‘03	24 Nov '03
Clearance and fit test			
Prototype fab	3mo	25 Nov '03	16 Feb '04
Ship to LASTI	0d	16 Feb '04	16 Feb '04
Fabrication	12mo	Apr '05	02 Mar '06
Assembly	6mo	03 Mar '06	17 Aug '06

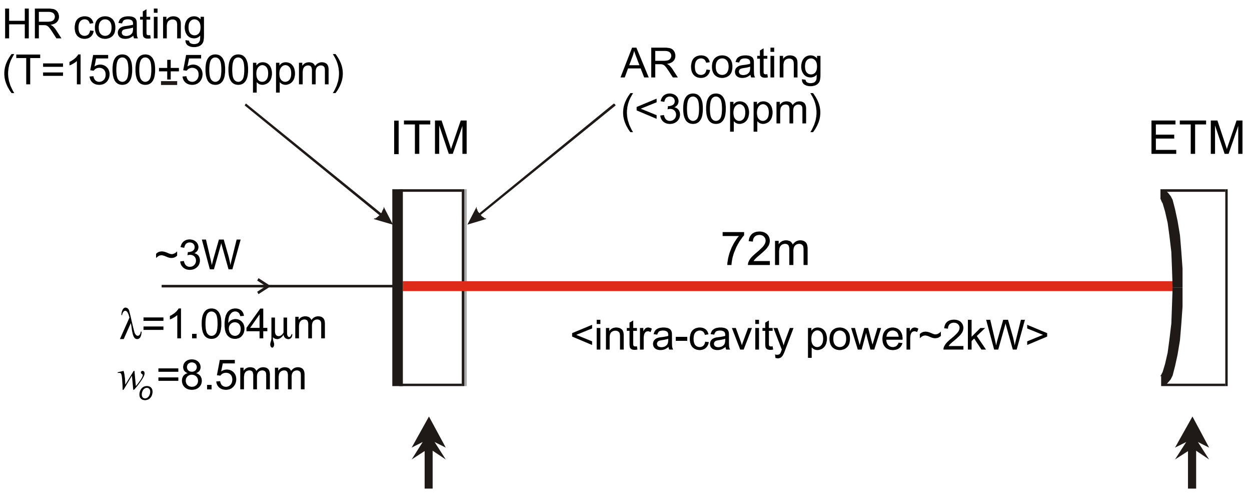
Preliminary Design Knowledge Gaps

- Gravitational wave sideband distortion and its effect on sensitivity. Generated within the cavity so no distortion nulling due to prompt reflection. Greater understanding through incorporation in Melody (Ray Beausoleil ~ End of November 02). (Modeling)
- Re-optimization of the thermal compensation scheme to minimize the HR surfaces changes. (Modeling)
- Accurate 2D absorption maps of Sapphire to aid in actuator selection (negative or positive dN/dT actuator plates). (Measurements required)
- Completer treatment of the displacement noise associated with scanning CO_2 laser (Modelling and measurements)

Gingin High Power Test Facility (HPTF), Western Australia

Gingin HPTF Test No. 1

- Measure distortion of input test mass (ITM) due to absorption of substrate material.



HR coating
(T=1500±500ppm)

AR coating
(<300ppm)

ITM

ETM

~3W

λ=1.064μm
w_o=8.5mm

72m

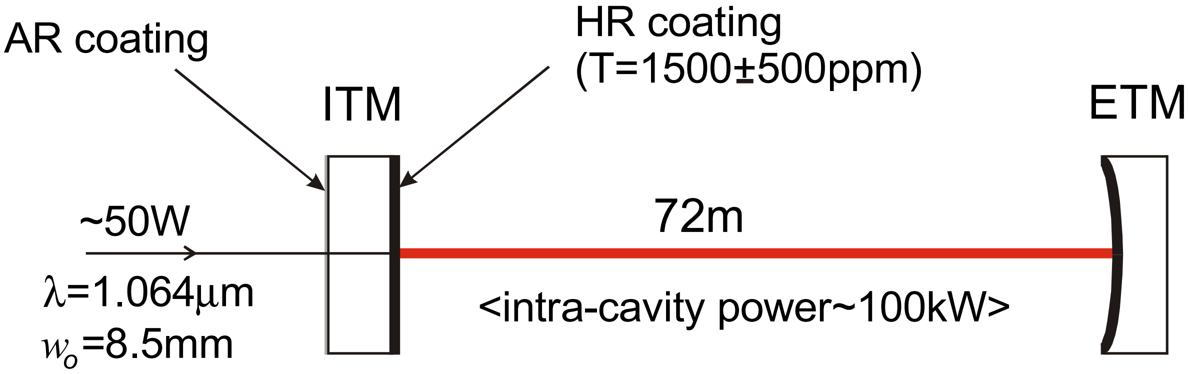
<intra-cavity power~2kW>

Input Test Mass (ITM)
Diameter: 100mm
Thickness: 50mm
Material: Sapphire (*a*-axis)
flat

End Test Mass (ETM)
Diameter: 150mm
Thickness: 80mm
Material: Sapphire (*m*-axis)
Radius of Curvature: 750±100m
HR coating: T<50ppm

Gingin HPTF Test No. 2

- Characterize distortion of HR coating due to heating, by reversing ITM.



- Use same optics, reversing ITM.
- Higher input power (~50W).
- Higher intra-cavity power (~100kW).

Summary

- More modeling required to fully set design requirements (Particularly SRM modes)
- Greater knowledge of the inhomogeneous spatial nature of the absorption of Sapphire (Finalize Design)
- Gingin is set up to explore the effects on Sapphire of high average circulating power
- It is not clear from a thermal compensation prospective, what LIGO will learn from the current Gingin plan unless larger spot sizes can be used somehow.