THERMALLY ADAPTIVE OPTICS: RECENT RESULTS
LIGO-G000139-00-R

RYAN LAWRENCE
MIT LIGO LAB

COLLABORATORS: MIKE ZUCKER AND PETER FRITSCHEL, MIT

1. The Detrimental Effects of Power Absorption

1.1. Thermal Lensing.

1.2. Thermoelastic Deformation.

2. Thermal Effects in LIGO II

2.1. Fused Silica.

2.2. Sapphire.

3. The Modeling Effort

3.1. Static Axisymmetric Thermal Compensation.

3.2. Dynamic Thermal Compensation.

4. The Experimental Effort

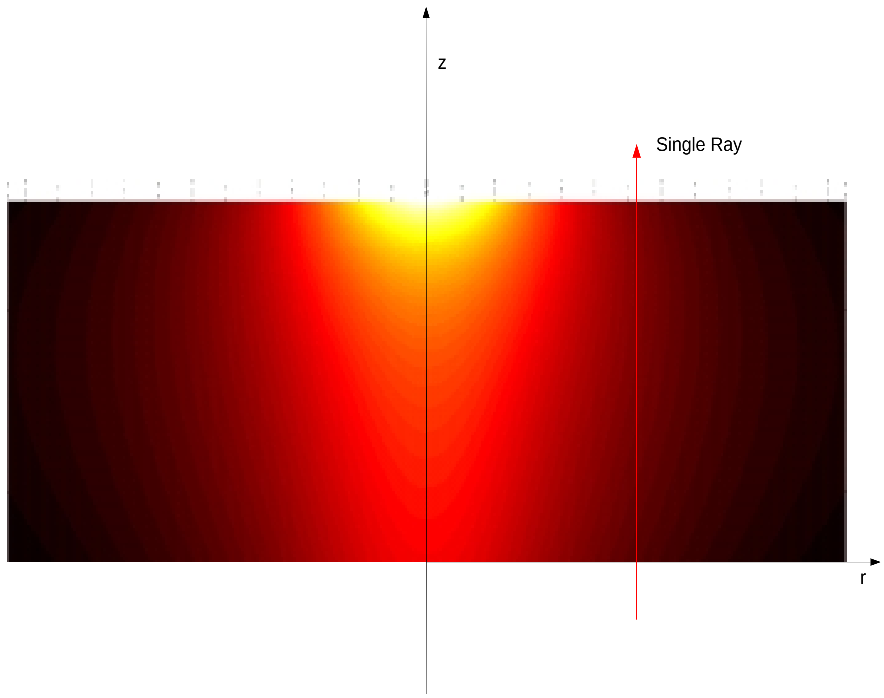
4.1. The Setup.

4.2. Progress to Date.

5. Conclusions and Future Directions

Date: May 30, 2000.

Thermal Lensing



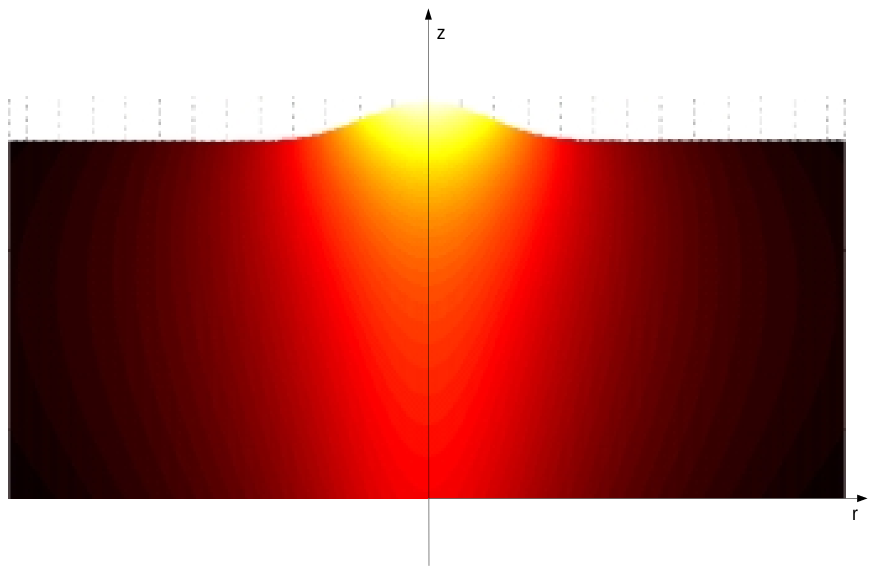
The total optical path $\Phi(r)$ for a single ray at radius r is:

$$\begin{aligned}\Phi(r) &= \int_0^H n\left(T(z,r)\right)\,dz \\ &\simeq n(T_0)H + \frac{dn}{dT}\int_0^H \left(T(r,z) - T_0\right)\,dz \\ &= n(T_0)H + \phi(r)\end{aligned}$$

where T_0 is the external temperature, $\frac{T(r,z)-T_0}{T_0} \ll 1$, and $\phi(r)$ is the optical path distortion at radius r:

$$\phi(r) \equiv \frac{dn}{dT}\int_0^H \left(T(r,z) - T_0\right)\,dz$$

Thermoelastic Deformation



Upper bound for expansion of the optic's surface:

$$\delta s \lesssim \int_0^H \alpha \ (T(z,r) - T_0) \ dz$$
$$= \beta\phi(r)$$

where α is the thermal expansion coefficient and $\beta \equiv \alpha / \frac{dn}{dT}$ is the relative strength of the deformation $\delta s(r)$ with respect to the corresponding thermal lens $\phi(r)$.

For Sapphire: $\beta \sim 1$
For Fused Silica: $\beta \sim 0.05$

Mathematical Preliminaries

Our goal is to calculate $\int_0^H (T(z,r) - T_0)\, dz$ for abritrary heating. We can do so numerically in 2-D by solving the Steady-state Heat Equation:

$$-k\nabla^2 T(\vec{r})) = H_b(\vec{r}) \qquad \text{in the optic}$$

Boundary Conditions:

$$-k\frac{\partial T(\vec{r})}{\partial n} = \sigma(T^4(\vec{r}) - T_0^4) + H_s(\vec{r}) \qquad \text{on the boundaries}$$

where:

T_0	ambient temperature
n	unit normal on the surface
$H_b(\vec{r})$	power absorbed per unit volume in the bulk
$H_s(\vec{r})$	power absorbed per unit area on the surface
k	thermal conductivity

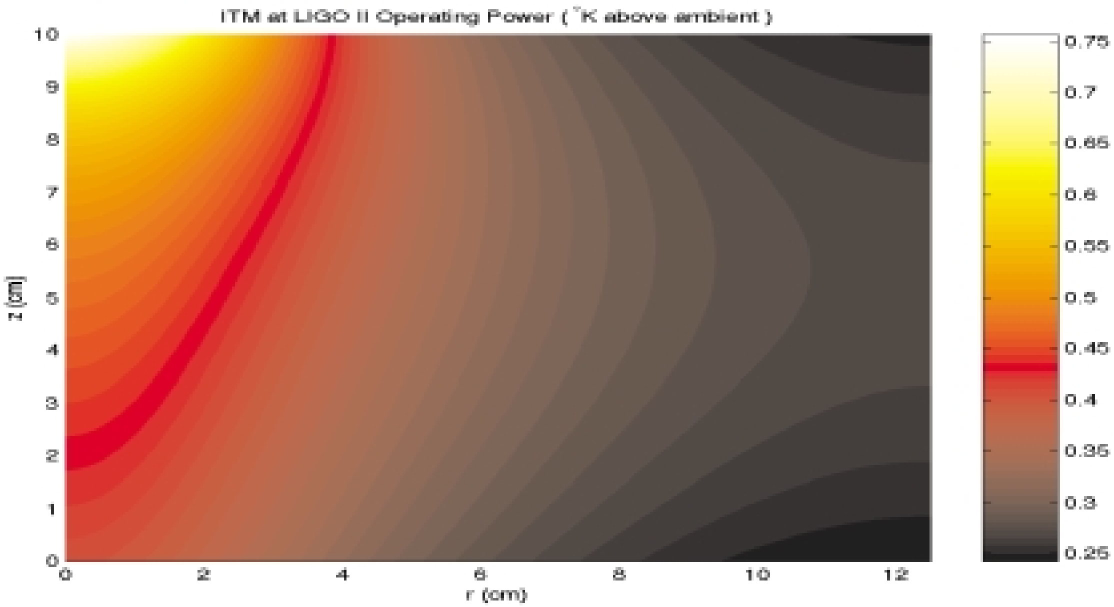
- If:

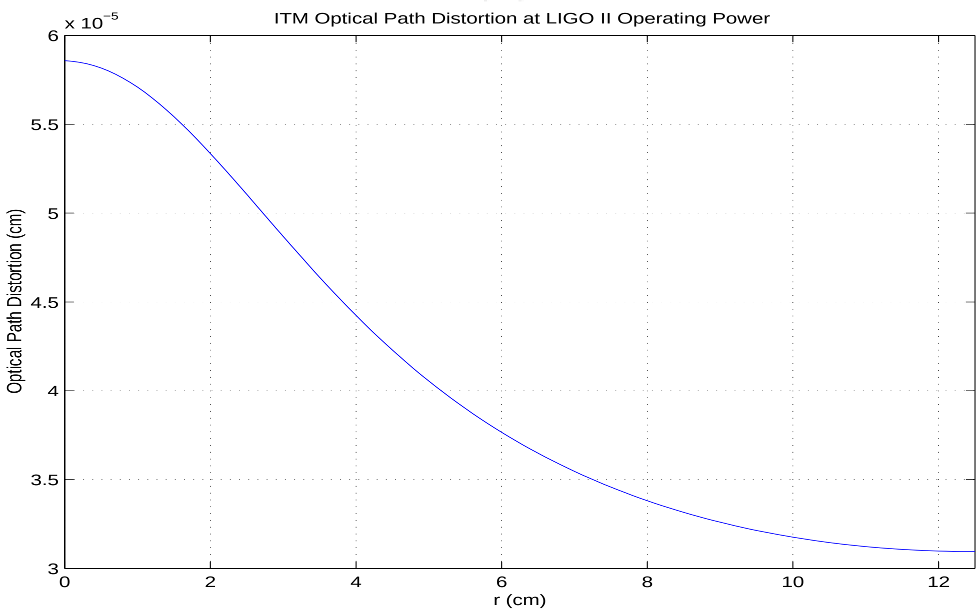
$$\frac{T_{max} - T_0}{T_0} \ll 1$$

$$\Rightarrow (T^4 - T_0^4) = 4T_0^3(T - T_0) + 6T_0^2(T - T_0)^2 + 4T_0(T - T_0)^3 + (T - T_0)^4$$
$$\simeq 4T_0^3(T - T_0)$$

Fused Silica

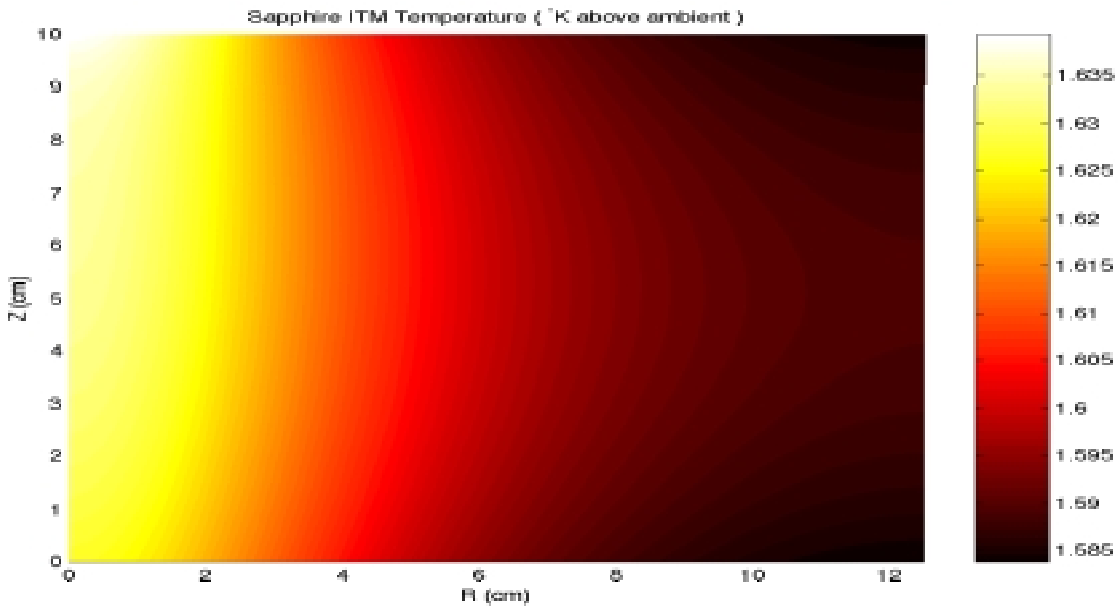
$\alpha_b = 0.5ppm/cm$	$\alpha_s = 0.6ppm$
$\kappa = 1.38W/m/^\circ K$	$\frac{dn}{dT} = 11.8 \times 10^{-6}/^\circ K$

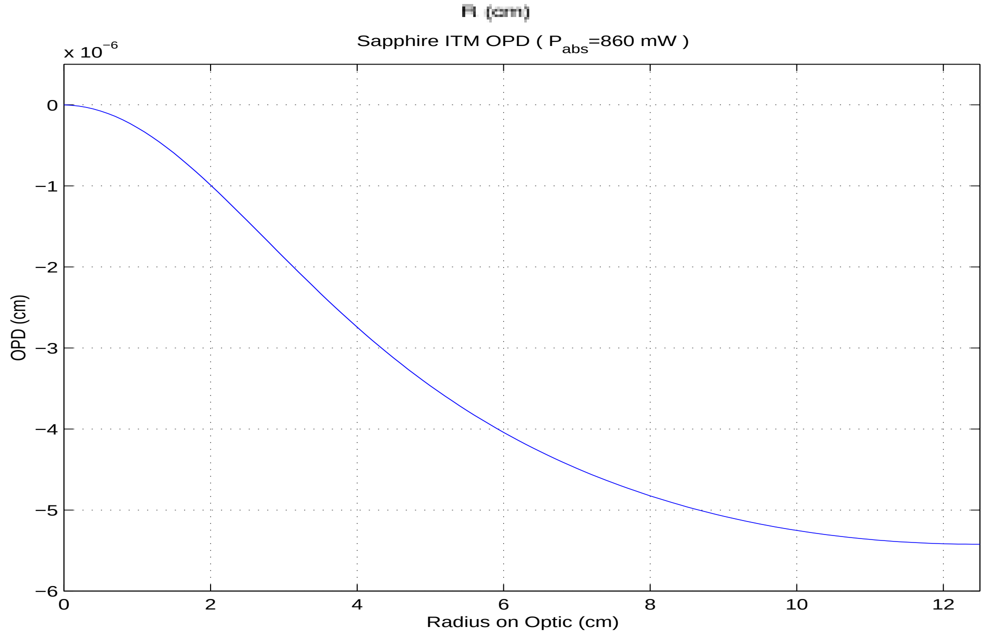




Sapphire

$\alpha_b = 40ppm/cm$	$\alpha_s = 0.6ppm$
$\kappa = 41.4W/m/^\circ K$	$\frac{dn}{dT} = 12 \times 10^{-6}/^\circ K$

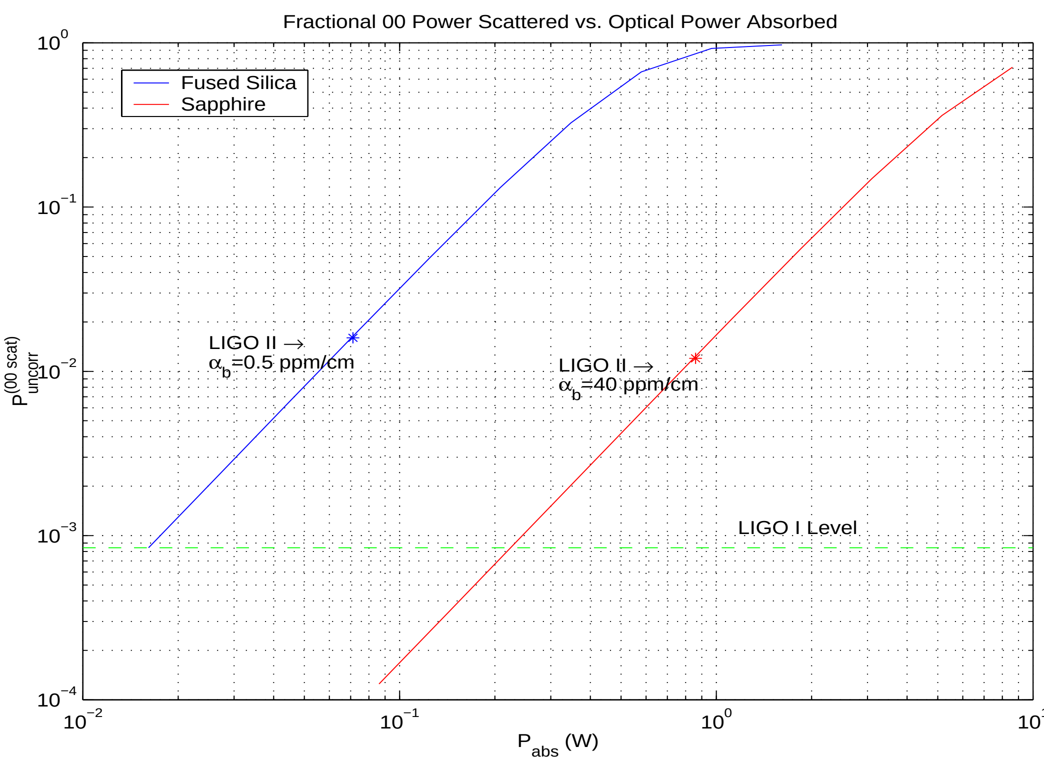




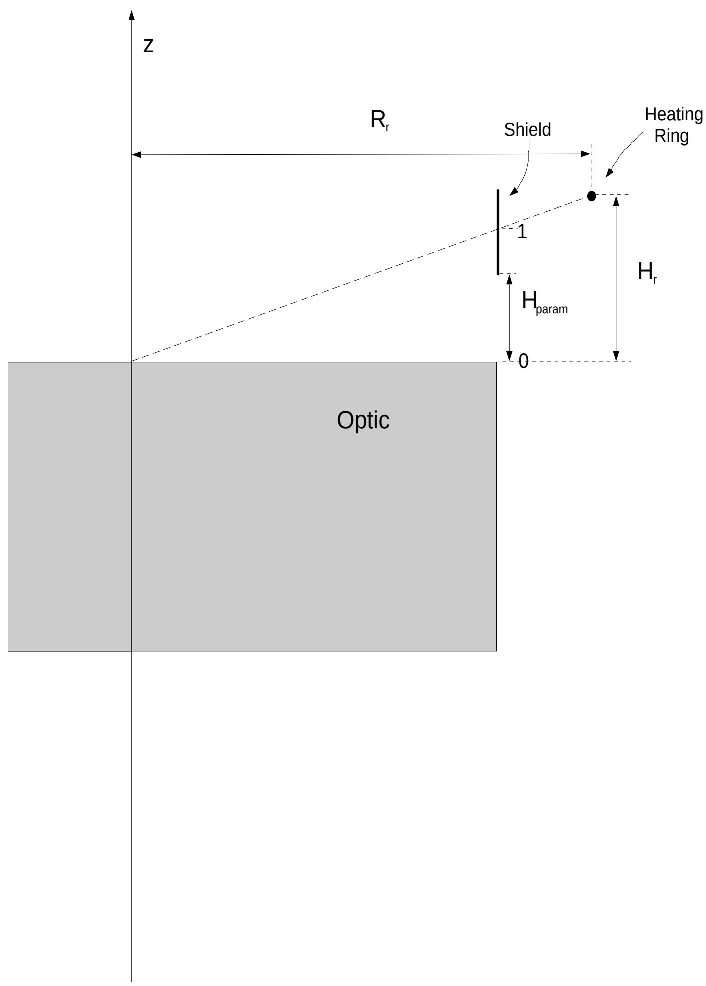
The Figure of Merit

The fractional power lost out of the TEM 00 mode (for a single pass through the optic) is given by:

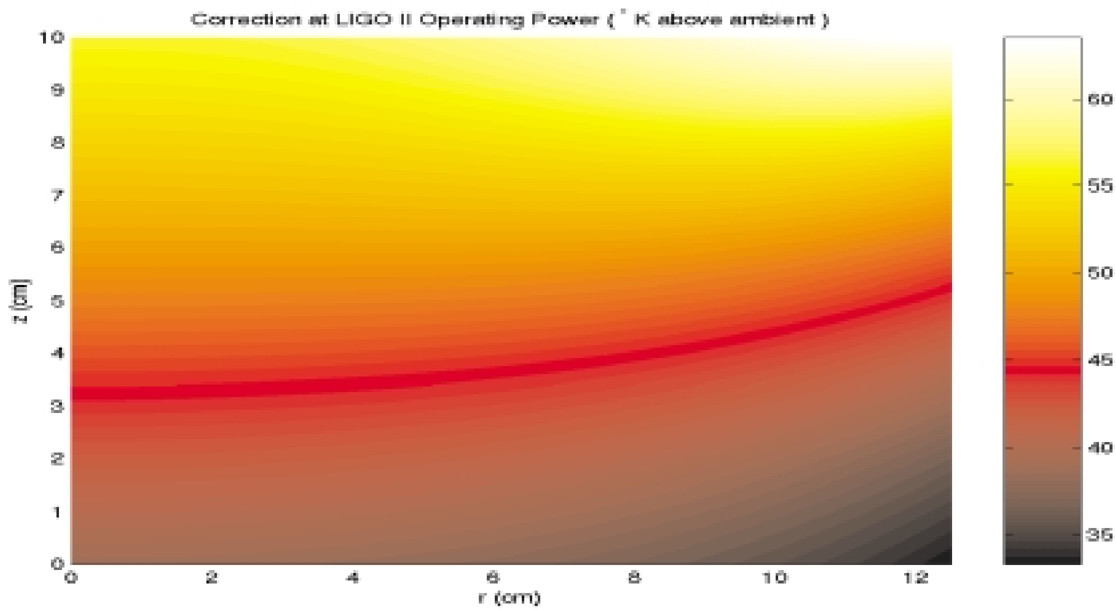
$$P_{loss} = 1 - \left| < 00 | e^{i\frac{2\pi}{\lambda}\phi(r)} | 00 > \right|^2$$
$$= 1 - \frac{16}{w^4} \left| \int_0^\infty e^{i\frac{2\pi}{\lambda}\phi(r)} \, e^{-2\frac{r^2}{w^2}} \, 2\pi r \, dr \right|^2$$

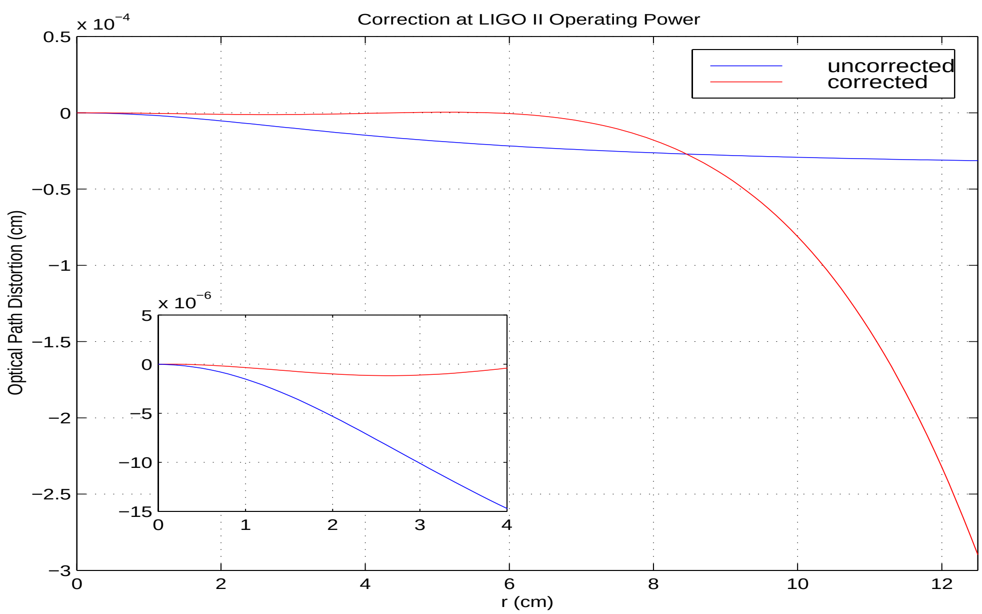


Static, Axisymmetric Thermal Compensation

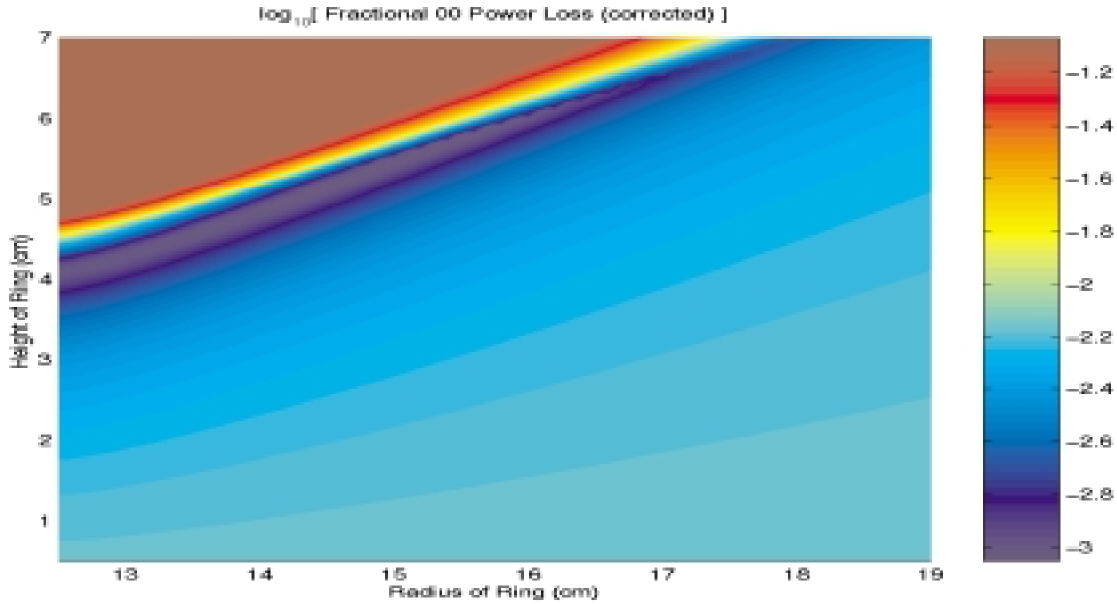


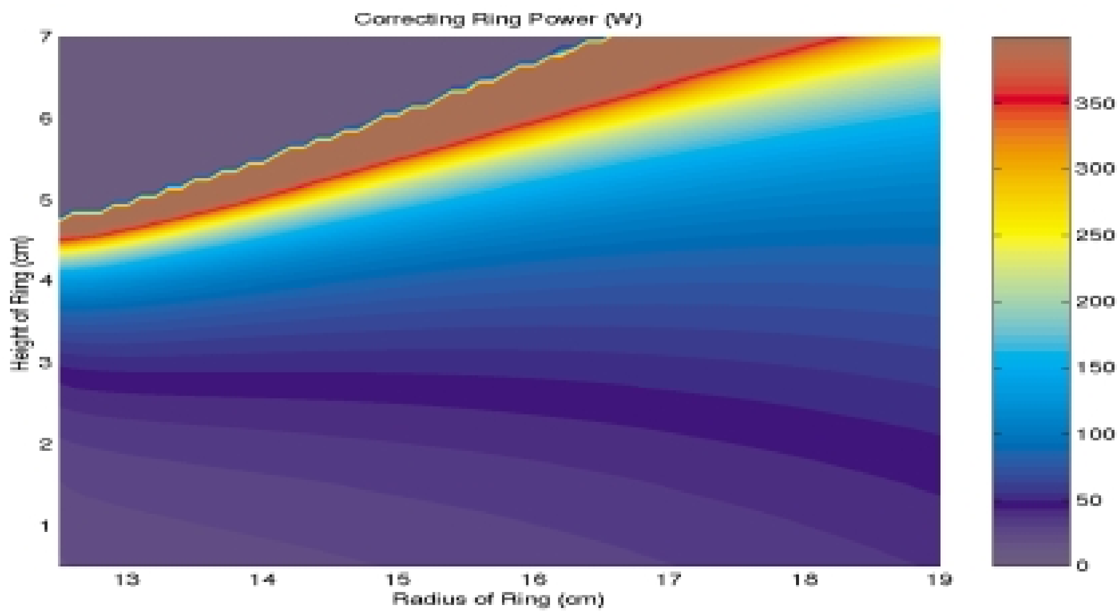
Bare Nichrome Ring
(Fused Silica ITM)





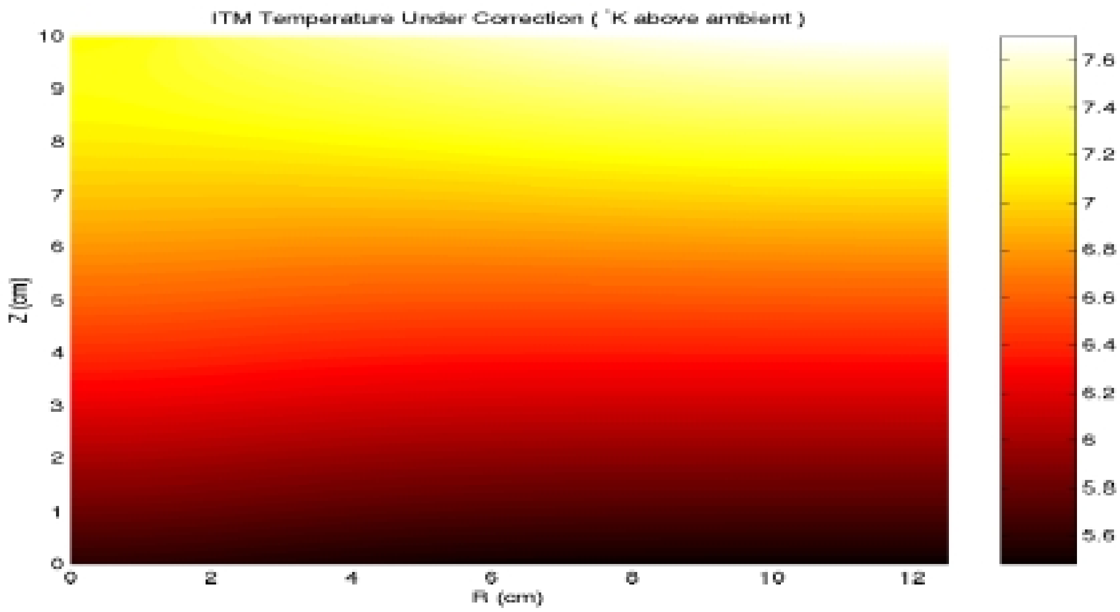
Bare Nichrome Ring
(Fused Silica ITM)

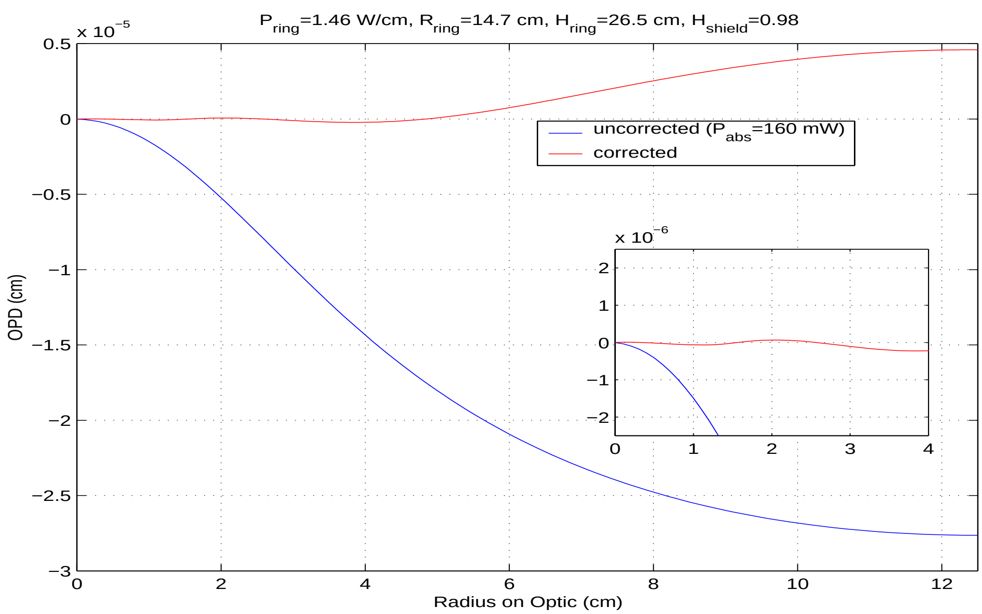




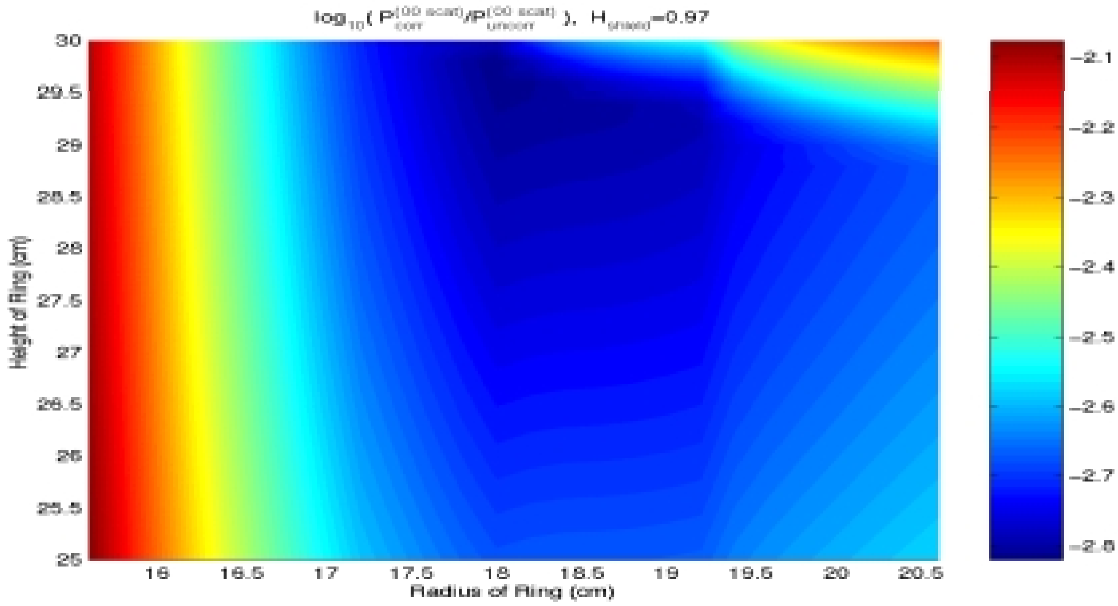
Shielded Ring, Insulated Optic

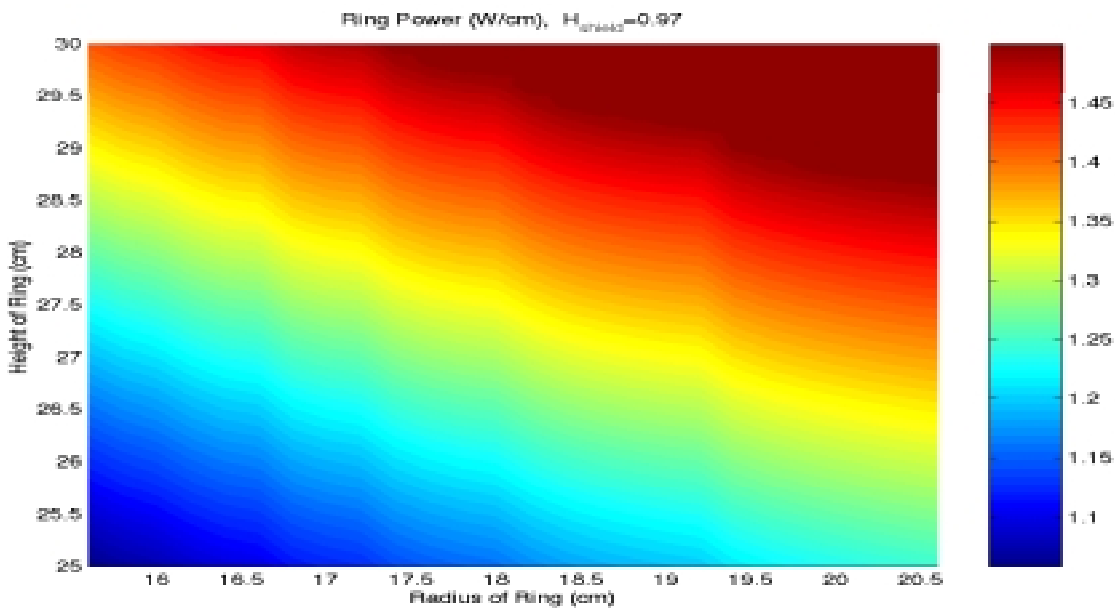
(Fused Silica ITM)





Shielded Ring, Insulated Optic
(Fused Silica ITM)





Static, Axisymmetric Compensation in Sapphire

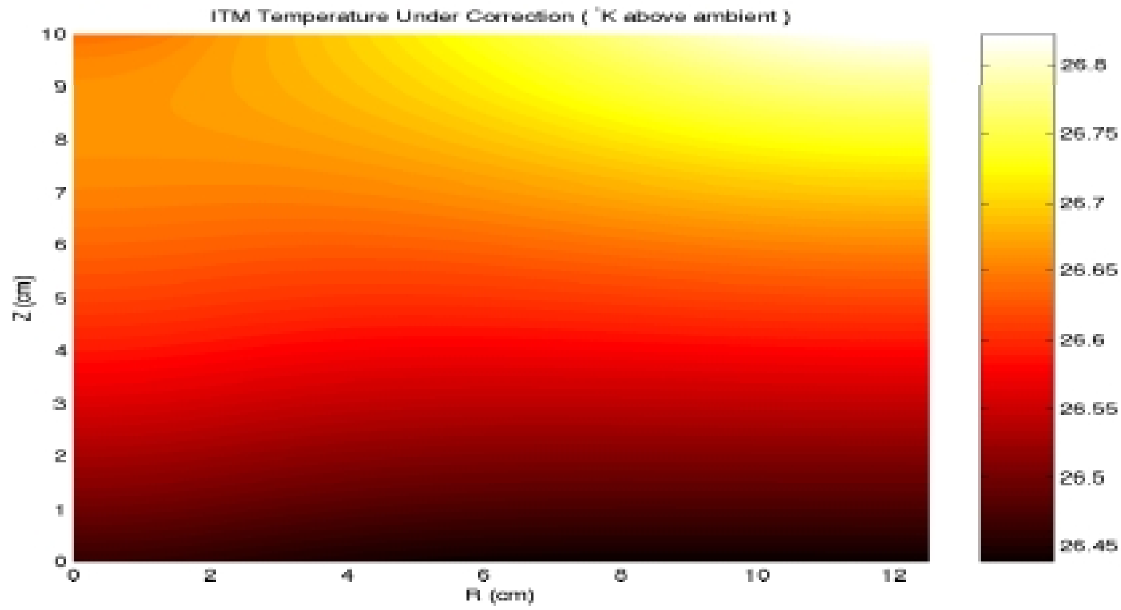
• Thermal Conductivity is $\sim 30\times$ that of Fused Silica.
$\Rightarrow$ A correspondingly larger heater power is required to maintain a similar wavefront correction.

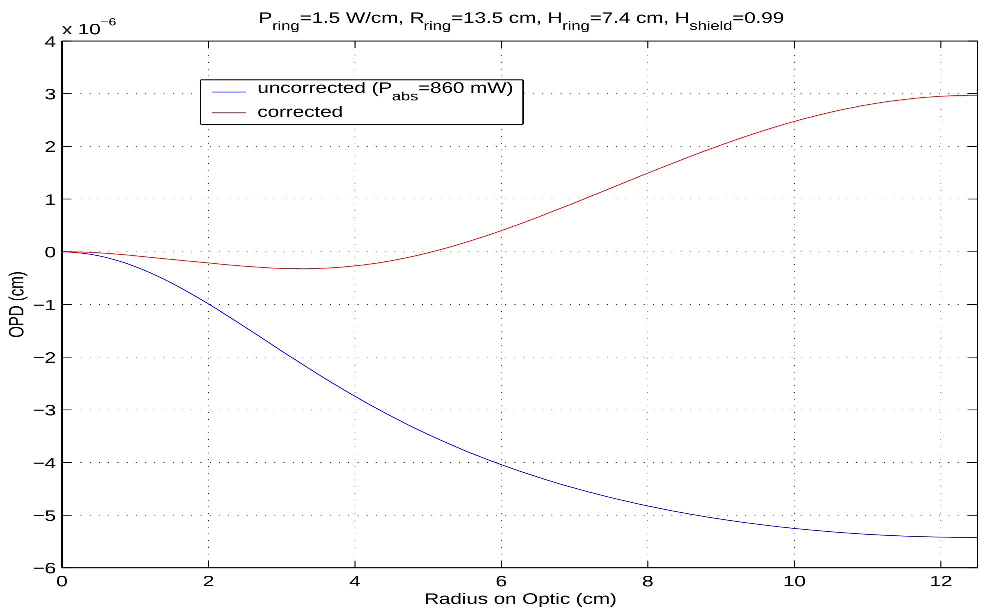
• At the same time, Sapphire is highly transmissive for $\lambda \leq 5\mu m$
$\Rightarrow$ Must keep the heater temperature low ($\sim 500°K$).

For the bare ring, with Sapphire's current absorbptivity, one needs $\sim 1kW$ (!) to remove the thermal lens. It is thus impractical.

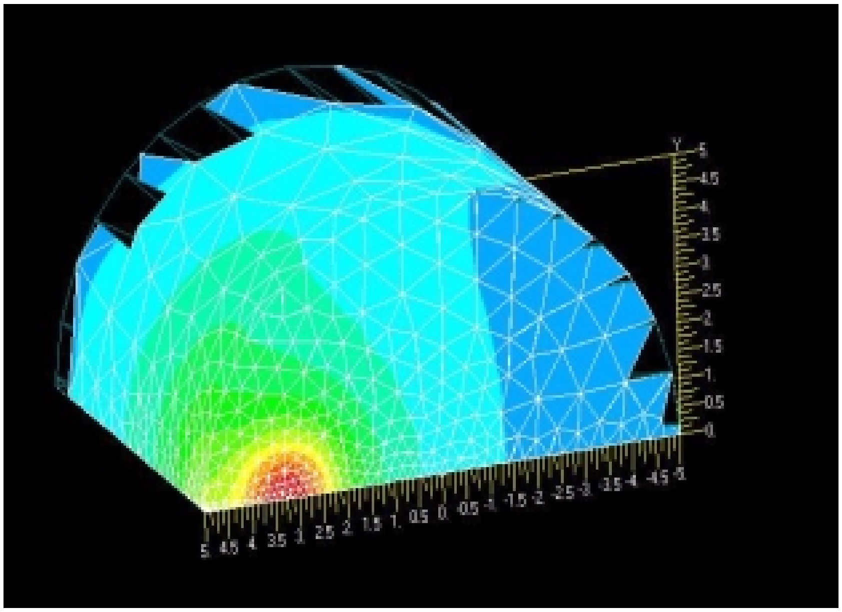
For the shielded ring, we are saved by the broad parameter space. We can simply move the ring closer to the optic, at the price of a poorer (but still acceptable) correction.

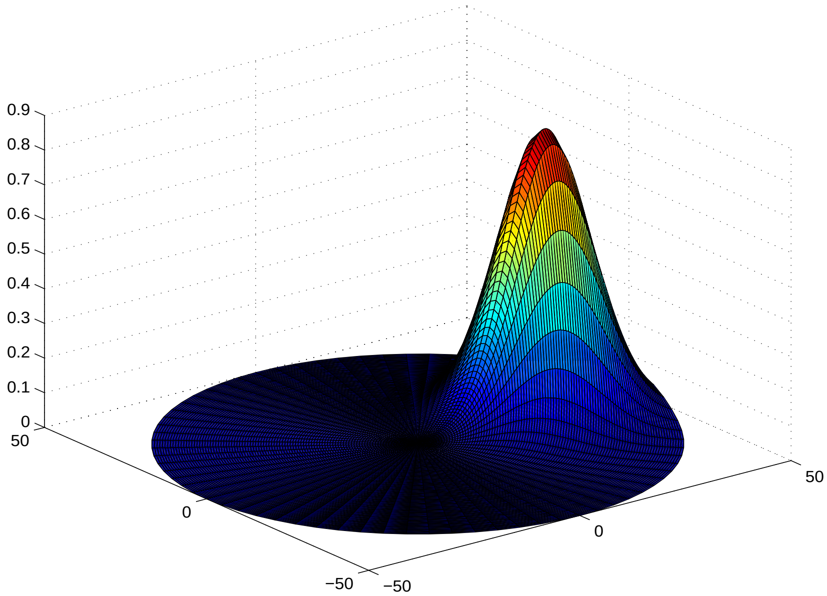
Shielded Ring, Insulated Optic (Sapphire ITM)





Heating by Scanning CO2 Laser
(Rob Bennett, MIT undergrad)





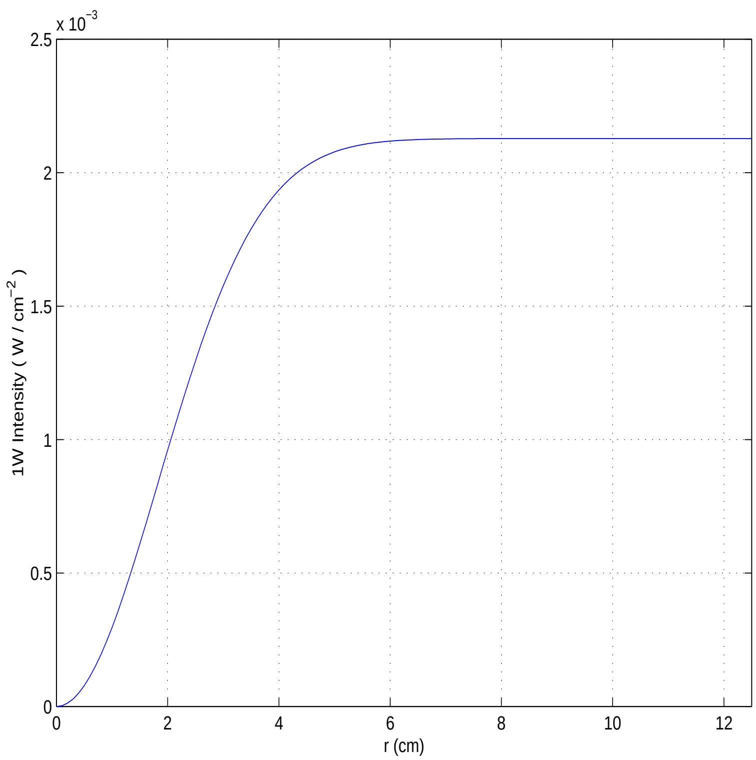
Heating by Scanning CO2 Laser

• Preliminary calculations show it to be potentially impractical in a Sapphire ITM due to CO2 laser intensity noise coupling into displacement noise via Sapphire's high thermal expansion coefficient and high thermal conductivity (i.e. shorter thermal time constant).

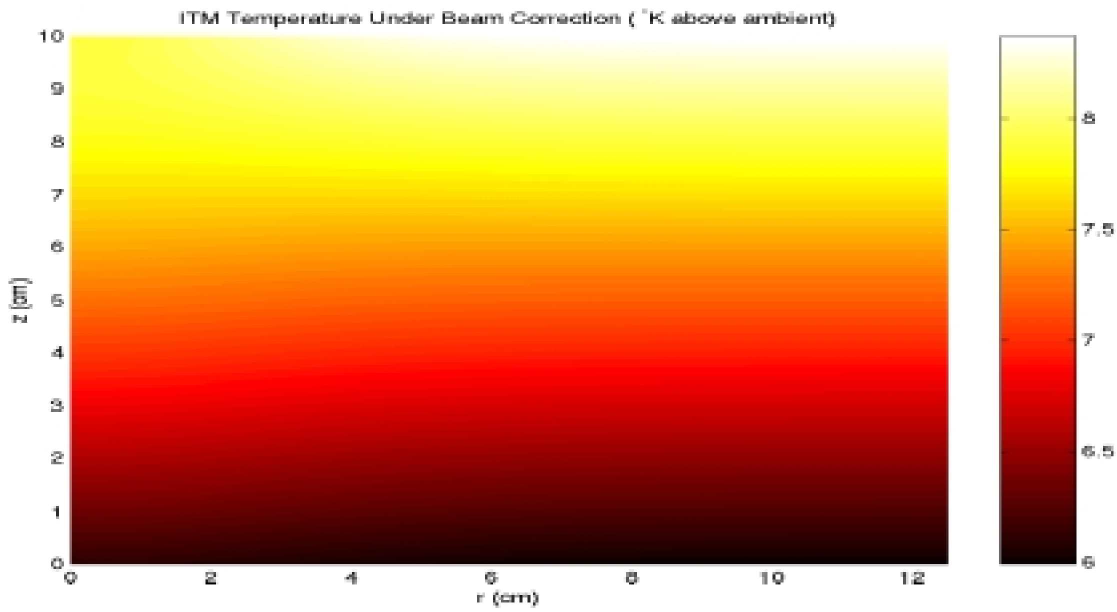
• Same calculation shows it to be potentially feasible in Fused Silica.

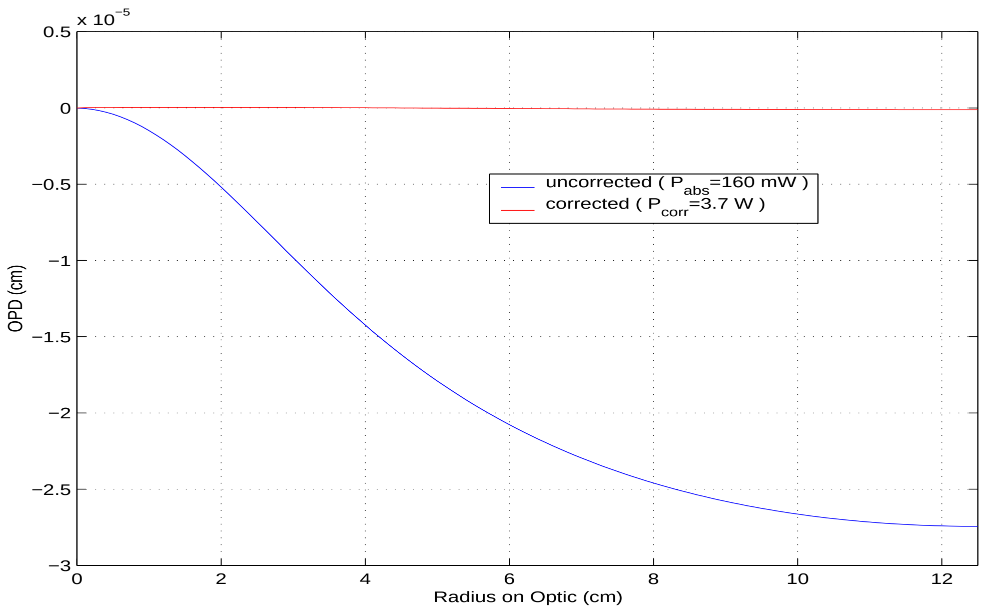
• Detailed numerical model underway to solve the eigenvalue problem in Fused Silica.

In the meantime, use an axisymmetric model of an "antigaussian beam" heating the surface of an insulated optic.



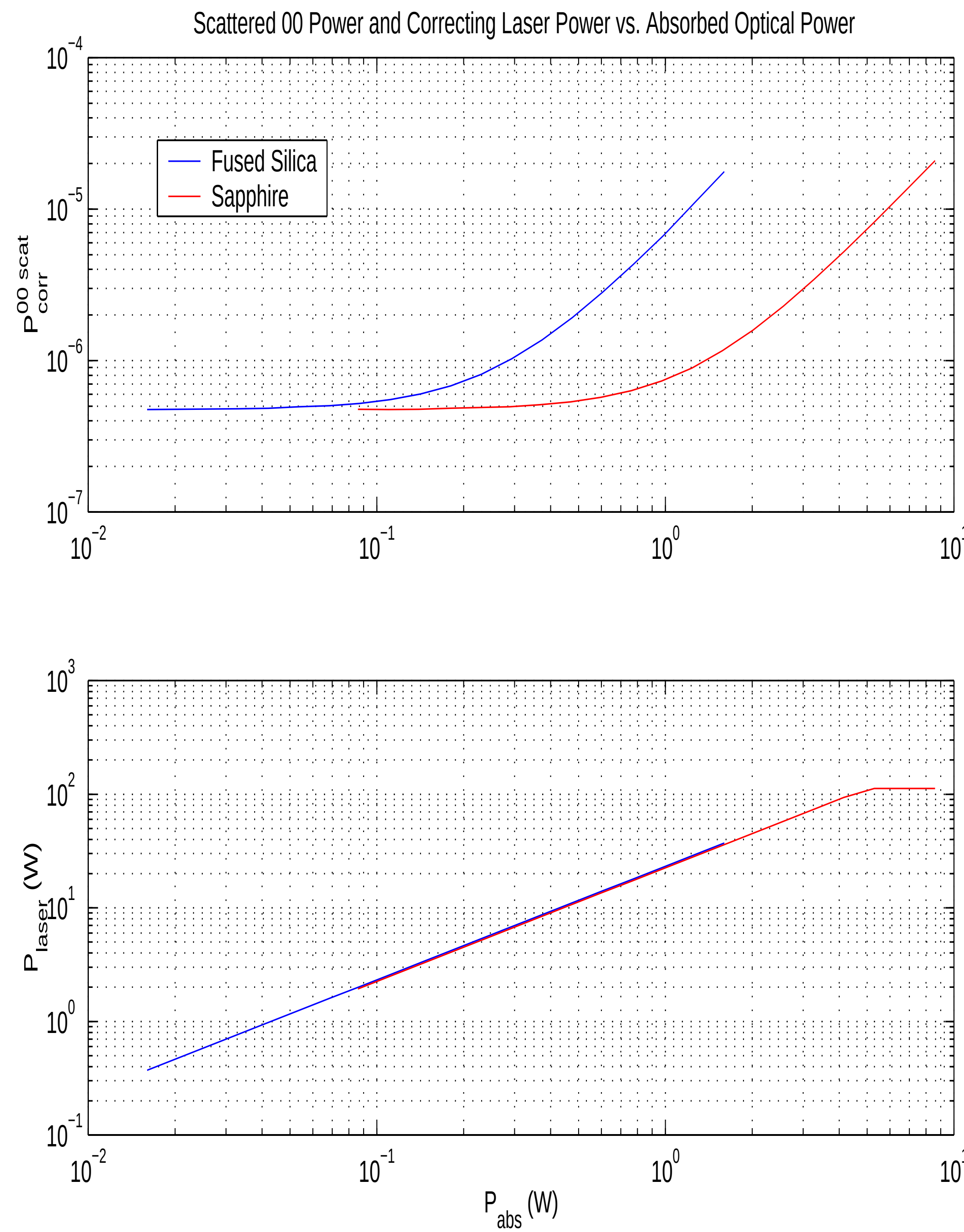
Heating by "Anti-Gaussian Beam"
(Fused Silica)





Heating by "Anti-Gaussian Beam"

(Fused Silica and Sapphire)



The Bottom Line:

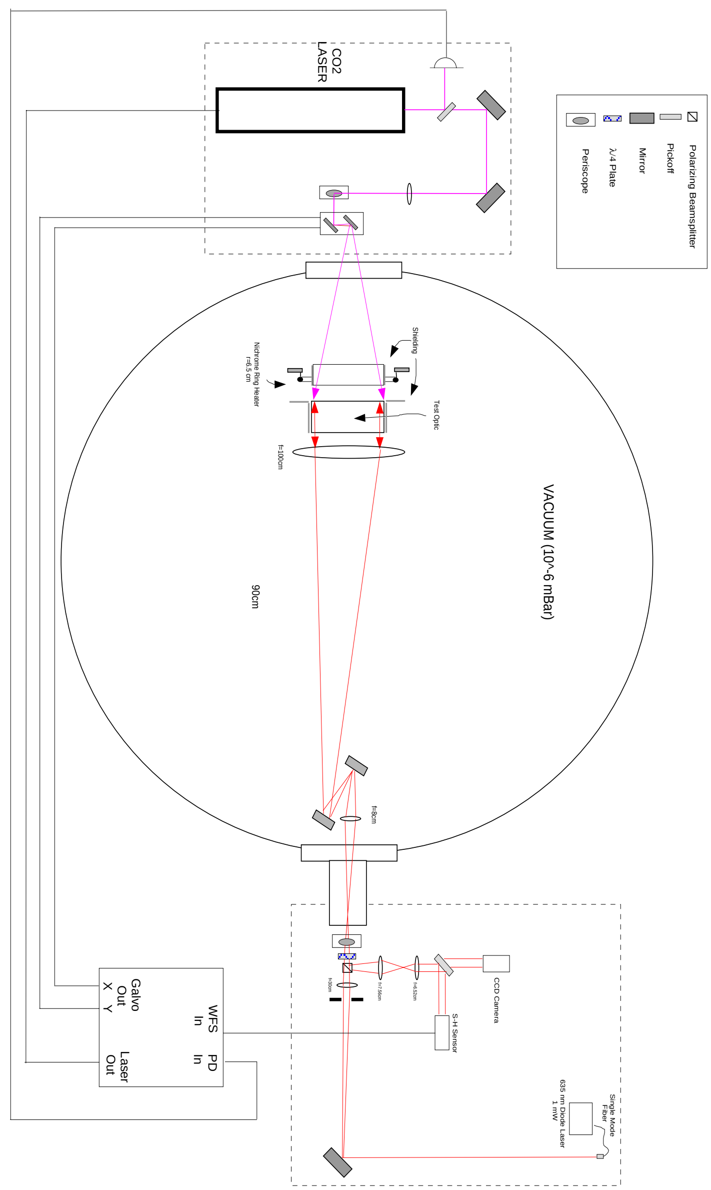
- For Fused Silica:

	$P_{uncorr}^{(00scat)}/P_{corr}^{(00scat)}$	max(P_{abs})	Notes
Bare Ring	100	80 mW	Steep Parameter Space
Shielded Ring, Insulated Optic	1600	400 mW	Broad, Flat Parameter Space
Scanning Beam (Antigaussian)	100000	800 mW	More Detailed Modeling Required

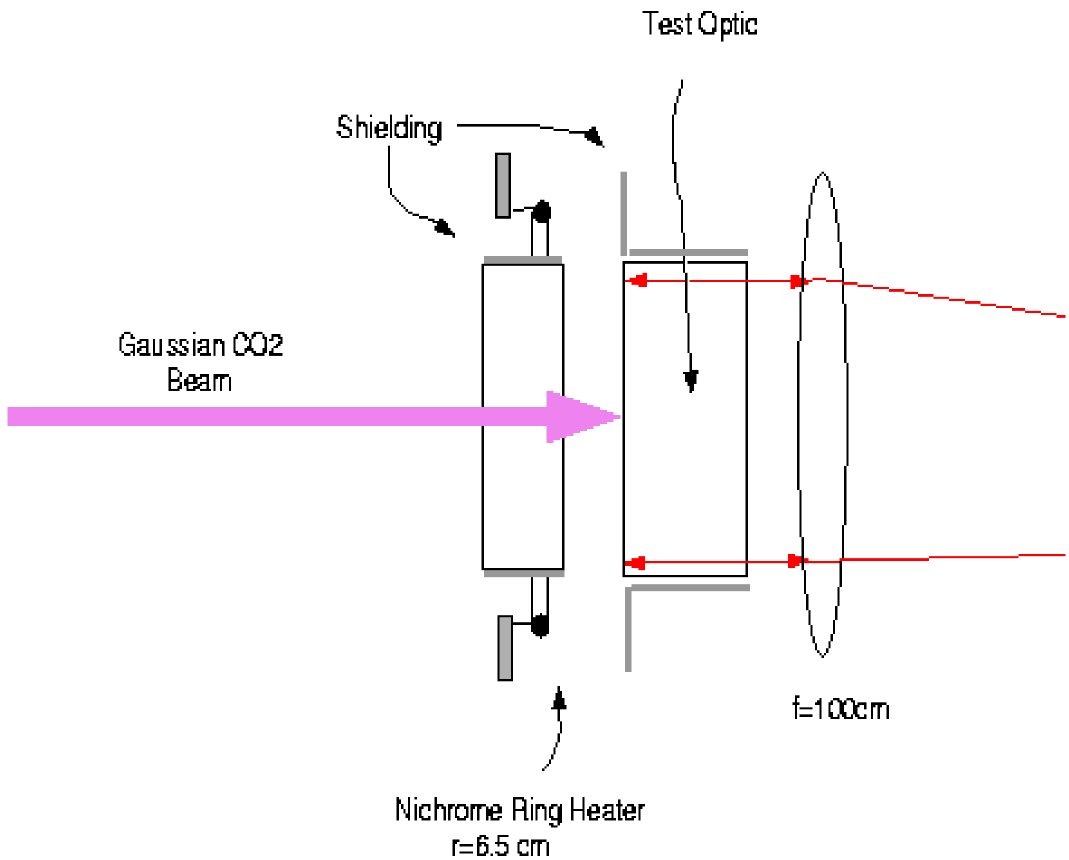
- For Sapphire:

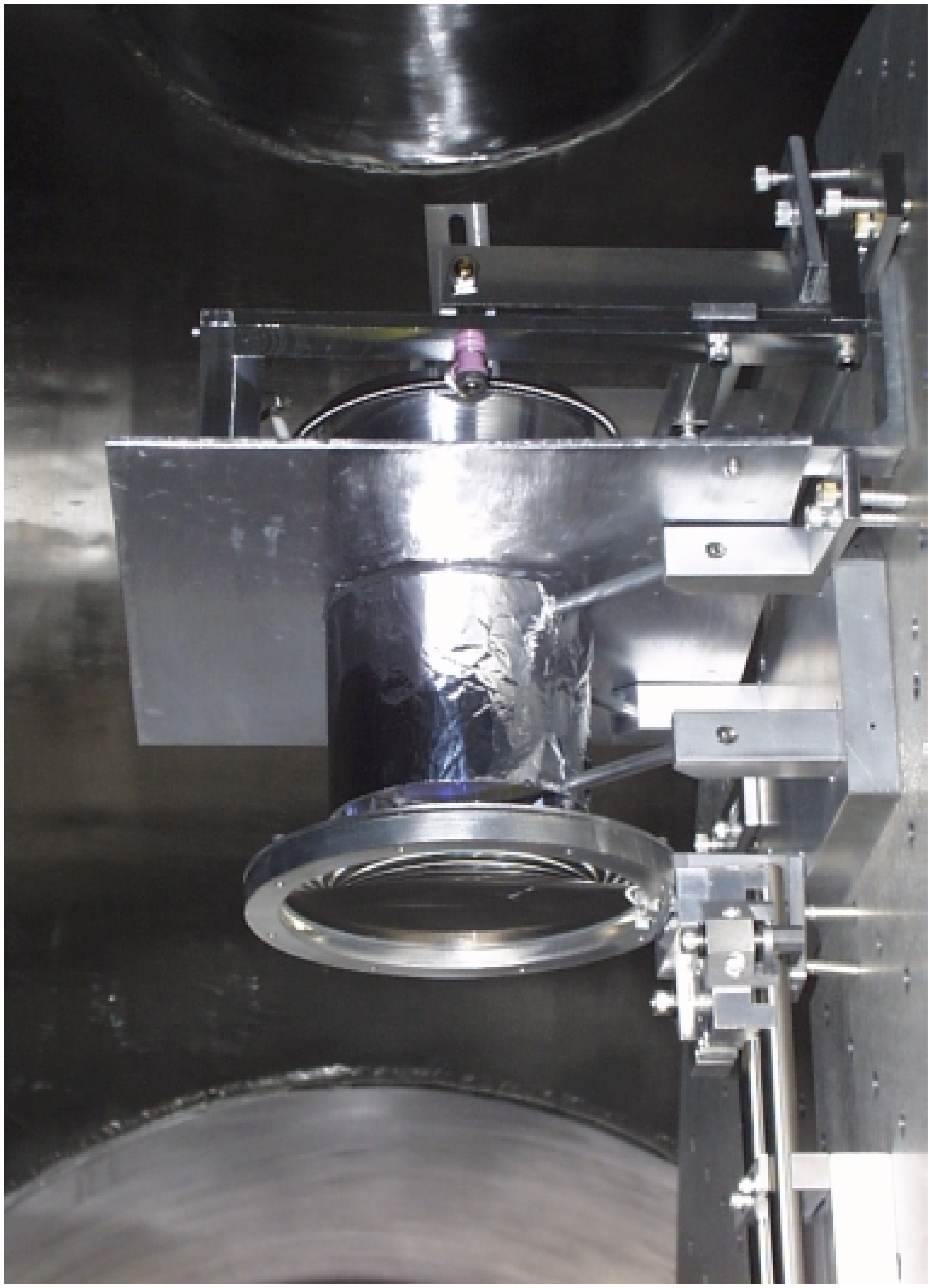
	$P_{uncorr}^{(00scat)}/P_{corr}^{(00scat)}$	max(P_{abs})	Notes
Bare Ring	-	-	Impractical Due to Ring Power Required
Shielded Ring, Insulated Optic	60	1 W	Limited By Ring Power Required
Scanning Beam (Antigaussian)	-	-	Impractical Due to Laser Intensity Noise (?)

The Experimental Effort

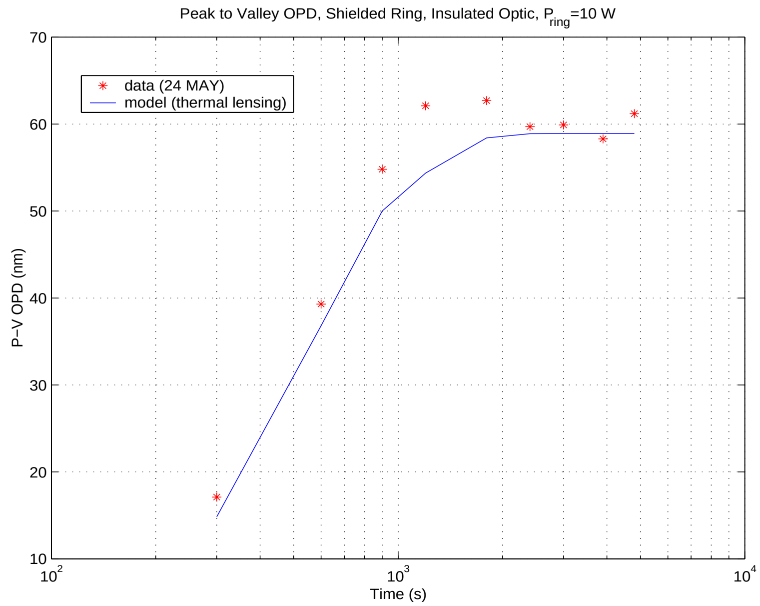


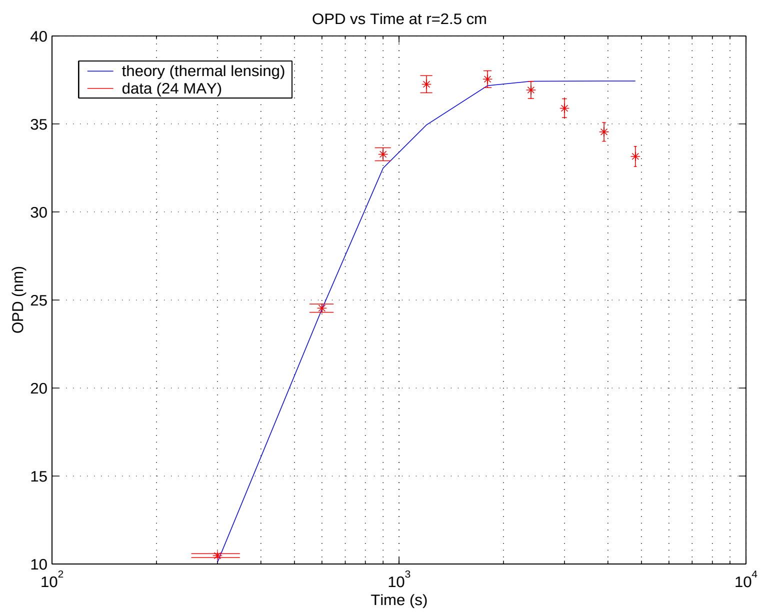
Experiment #1
Static Removal of LIGO-like distortion



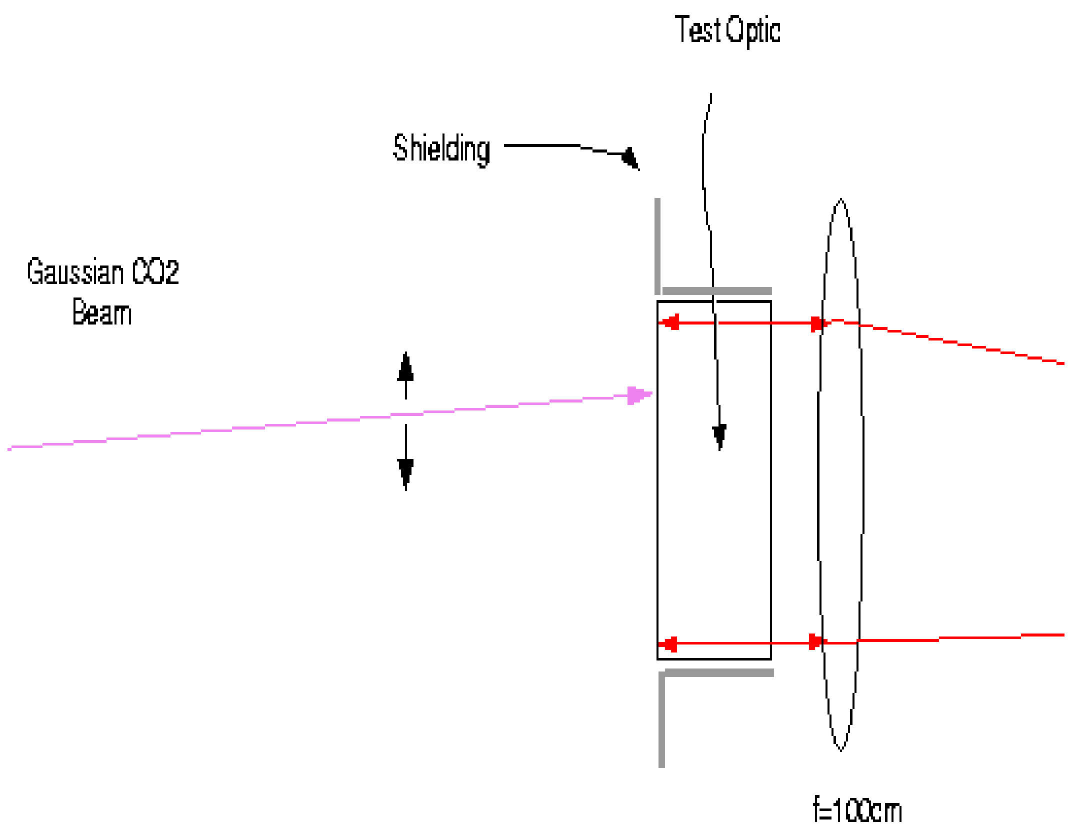


The Data (So Far)
Shielded Ring, Insulated Optic





Experiment #2
Generation of Arbitrary Curvature with Scanning CO2 Beam



Conclusions

From the modeling effort:

• In fused silica, axisymmetric thermal compensation can correct axisymmetric thermal lensing (and, presumably, thermoelastic deformations) to better than LIGO I levels of wavefront distortion.

• In Sapphire, one can correct axisymmetric wavefront distortions to better than LIGO I levels (using the shielded ring, insulated optic), although it is more difficult due to sapphire's high thermal conductivity and transparency at wavelengths $\lambda \leq 6\mu m$.

• The shielded heating ring shining on an insulated optic is the most efficient static solution found, so far.

• Solution of the scanning laser (dynamic thermal compensation) eigenvalue problem is nearing completion.

From the experimental effort:

• We have constructed an apparatus at MIT to test the various methods of thermal compensation on a 10cm Optic (care of the Caltech 40m).

• Tests of the shielded ring, insulated optic are underway.

• Tests of the scanning CO2 laser method will commence in July/August '00.