Thermal Headaches in Advanced LIGO Input Optics

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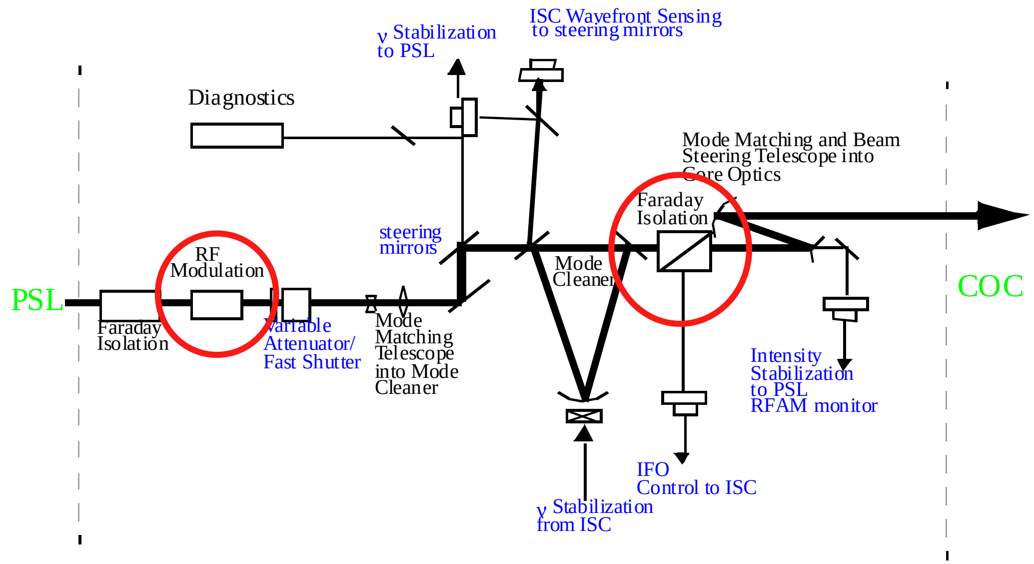
Input Optics Functions

- **RF Modulation**
- **Mode Cleaning**
- **Mode Matching**
- **Optical Isolation**
- **Distribution of Control Beams**
- **Self Diagnostics**



Parameter	*LIGO I*	*Advanced LIGO*
Laser Power	**8.5 W**	**180 W (150 W)**
Overall IO Efficiency (TEM_{00})	**75%**	**66%**
Optical Isolation	**70 dB**	**(> 85 dB)**

The Challenge

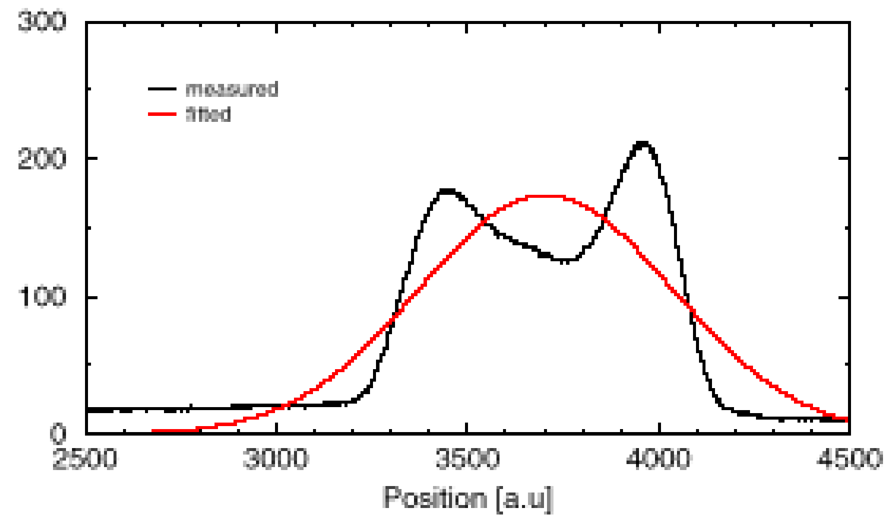
Advanced LIGO will operate at 180W CW powers - “presents some challenges”:

•Thermal Lensing --> Modal Degradation

$$\zeta = \alpha L \frac{dn}{dT} P / 2 K \lambda \qquad z = 1 + i \zeta$$

$$\tilde{\vec{E}} = \vec{M}(\zeta, z) \bullet \vec{E}$$

LiNbO$_3$ at 30W:



5 x 5 x 40 mm LiNbO$_3$ EOM - thermal lensing is:
i) severe
ii) position dependent

•Thermally induced birefringence

-FI- loss of isolation

-EOM - spurious amplitude modulation

•Damage

•Other (nonlinear) effects (SHG, PR)

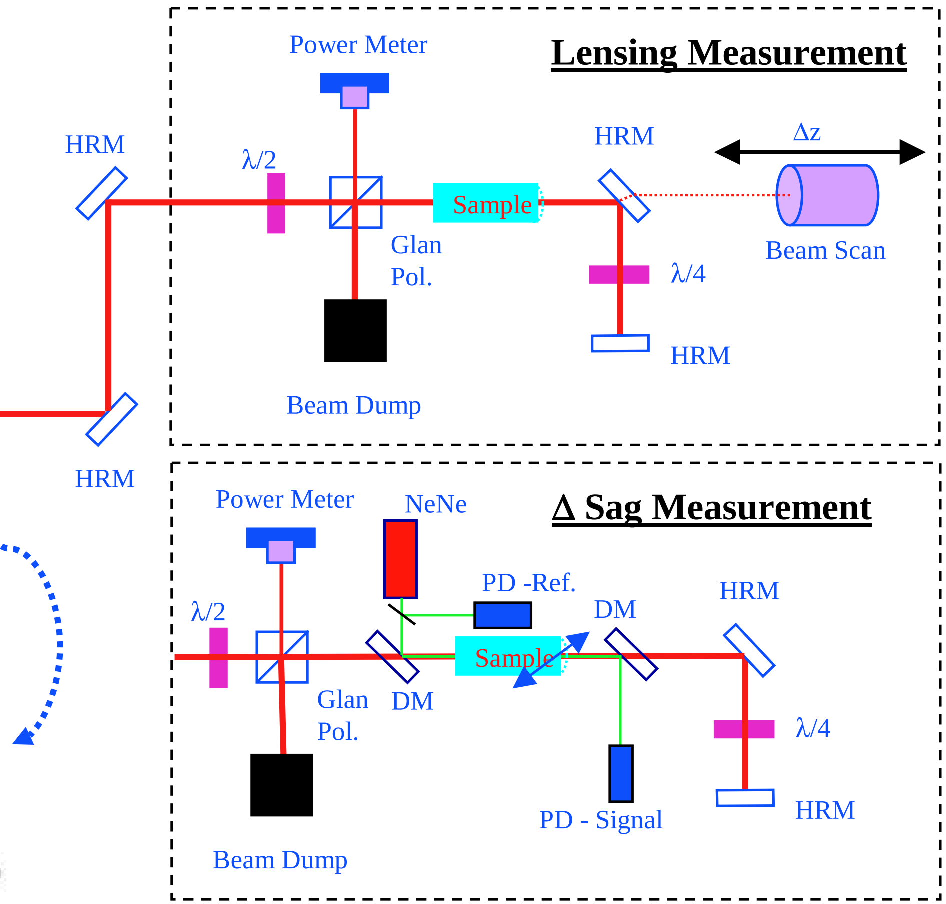
LIGO

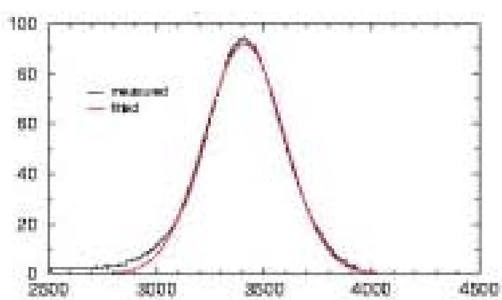
Characterization of thermal lensing

Samples:

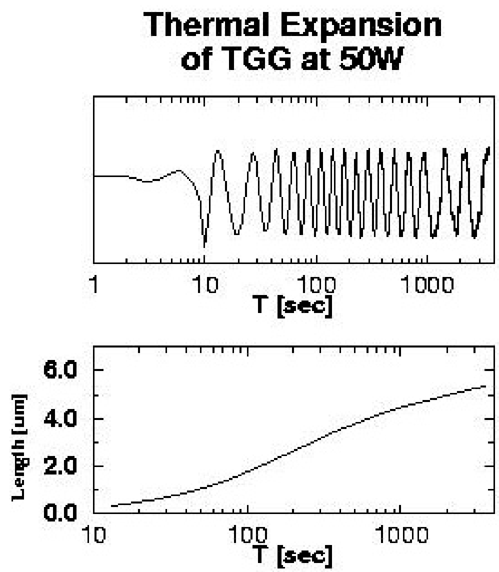
TGG: Litton [111]
10 mm diameter,
20 mm length

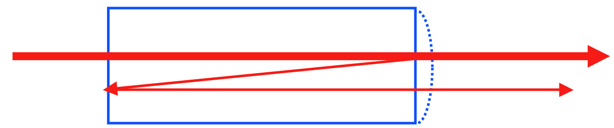
$LiNbO_3$: Leysop,
5 x 5 x 40 mm

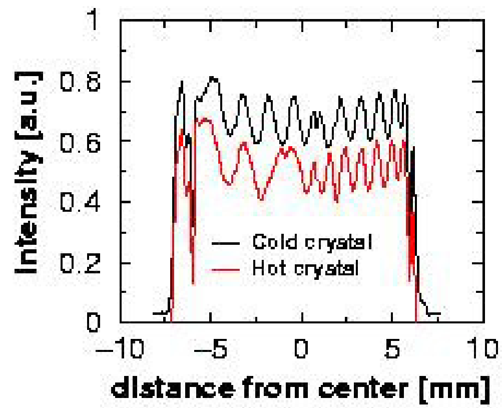


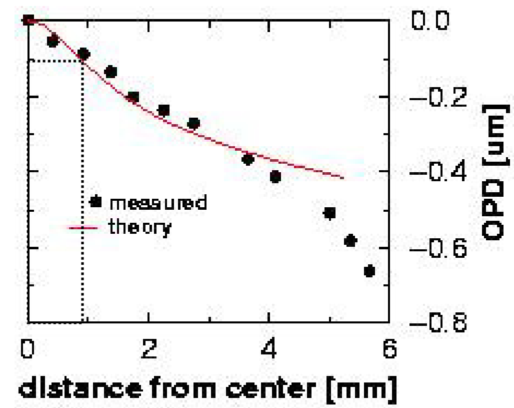


Optical Path Difference Measurements









Theory: Hello-Vinet

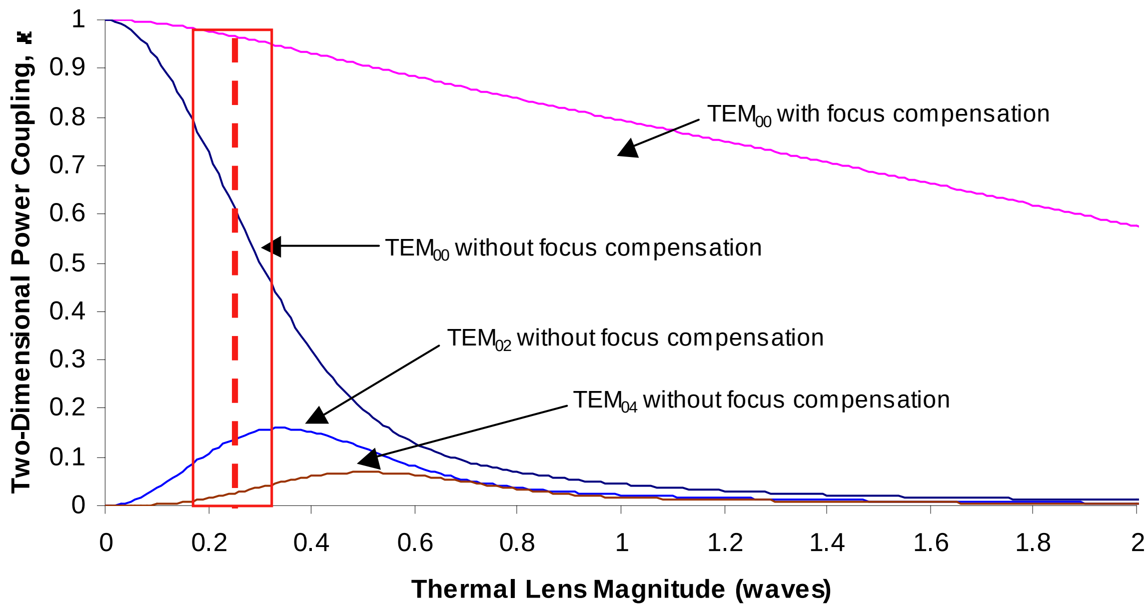
P=50 W
Absolute ΔL (hot - cold): 10 μm
ΔOPD (1/e intensity): ~ 100 nm → 250 nm @ 125W

Optical Path Difference Measurements

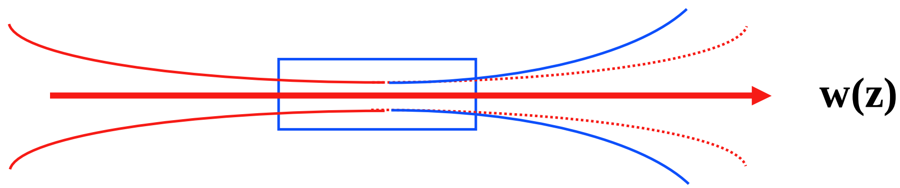
$$c_x(\psi_{aberrated},\psi_m)=\int_{-\infty}^{+\infty}\psi_m(x)\cdot\psi^*_{aberrated}(x)dx$$

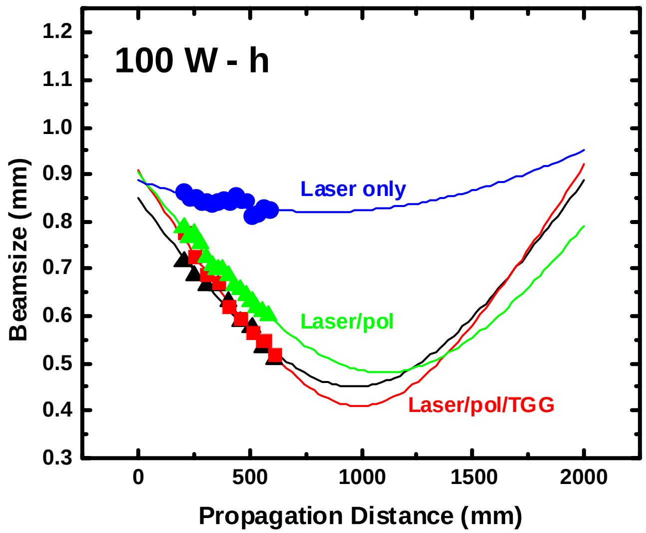
Mansell, et al., Appl. Opt., 2001

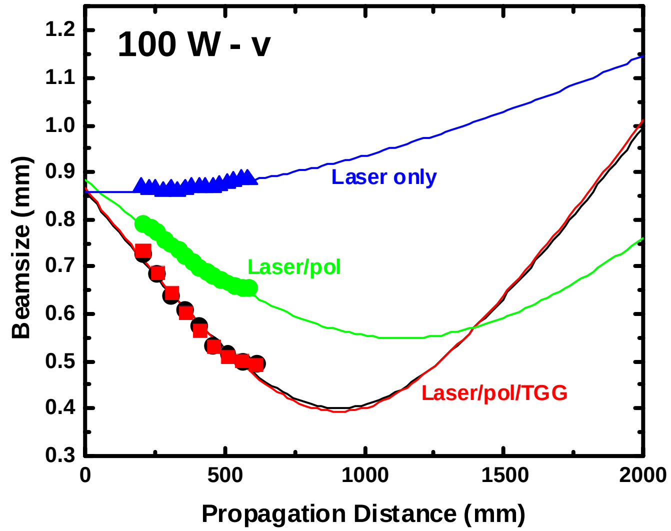
$$\kappa=\left[c_x(\psi_{aberrated},\psi_m)\cdot c_x^*(\psi_{aberrated},\psi_m)\right]\cdot\left[c_y(\psi_{aberrated},\psi_n)\cdot c_y^*(\psi_{aberrated},\psi_n)\right]=\kappa_x\cdot\kappa_y$$



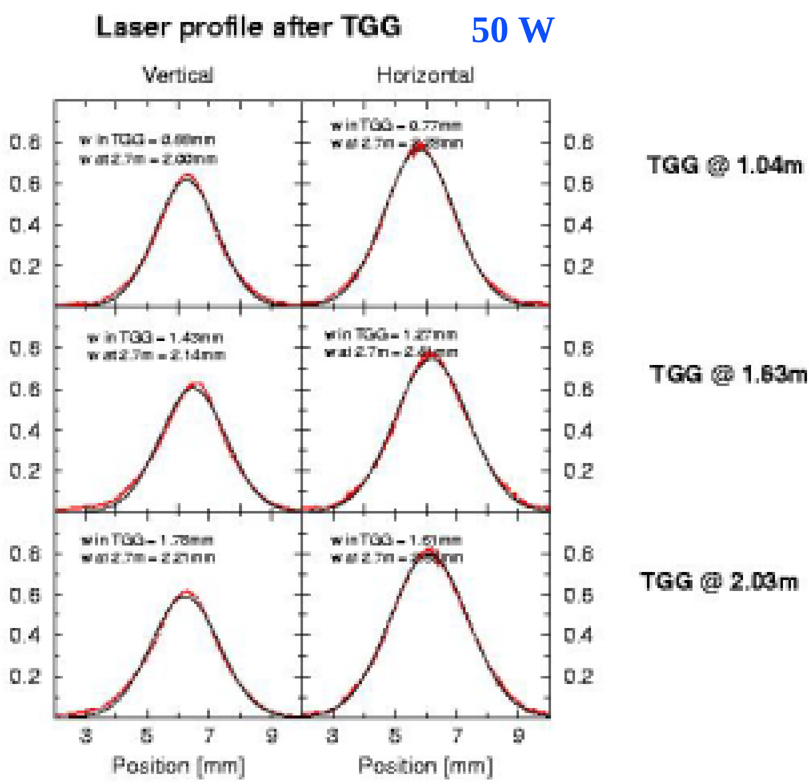
Propagation Measurements I

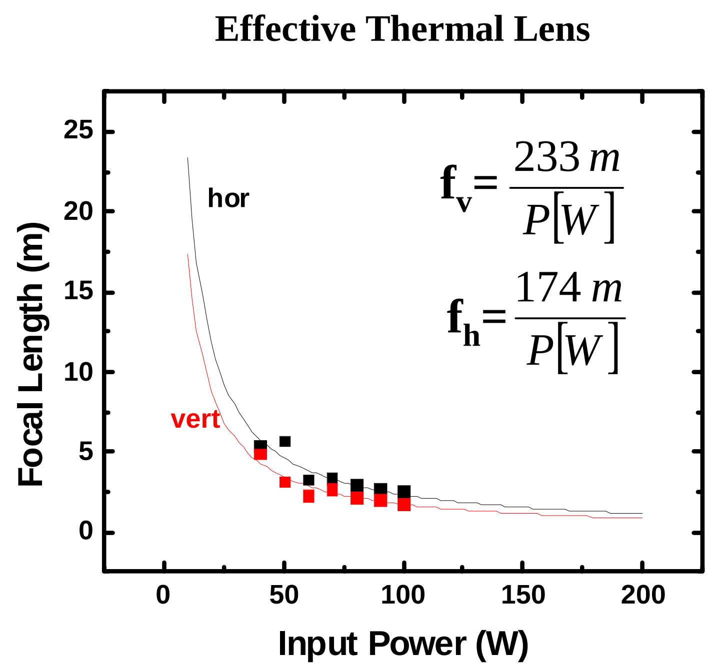




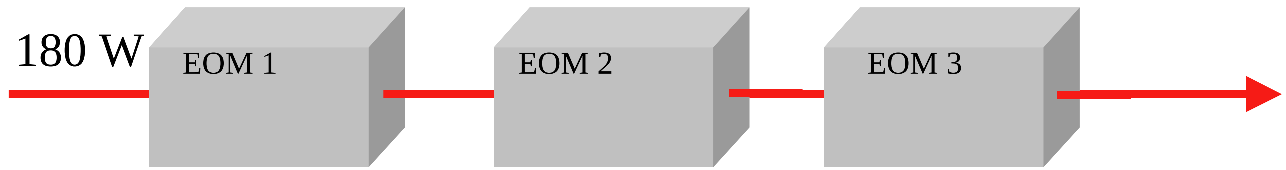


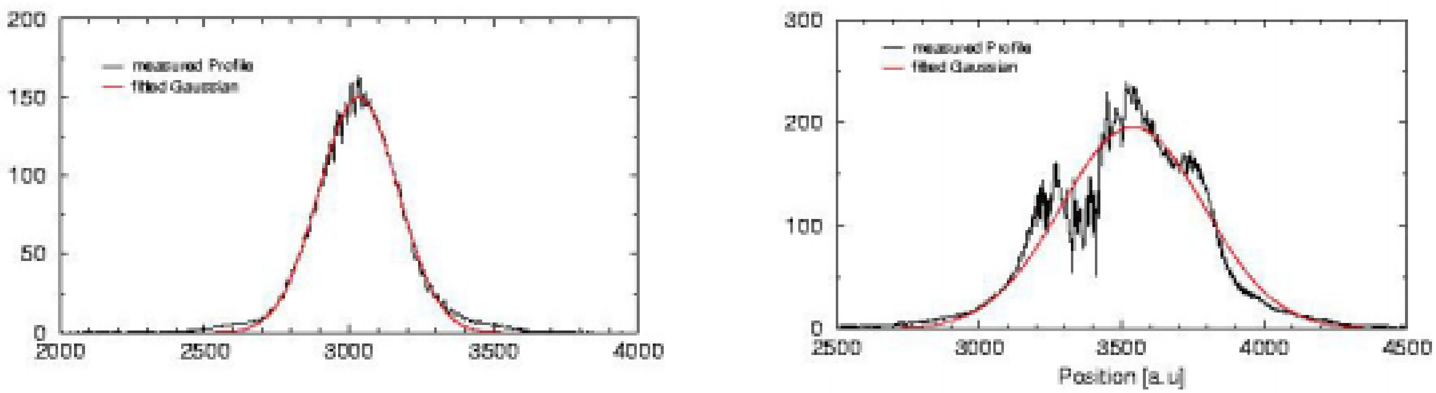
Propagation Measurements II





Thermal Lensing in $LiNbO_3$

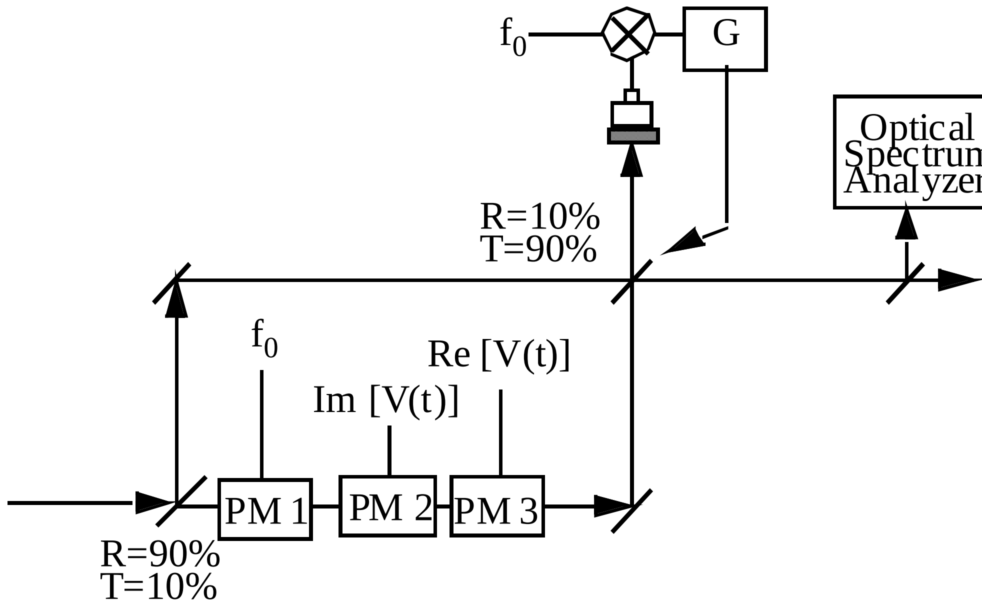




•**KTP does work; 300 W CW power, 1064 nm (H. Injeyan, TRW);**
RTA should also work (lower loss tangent)

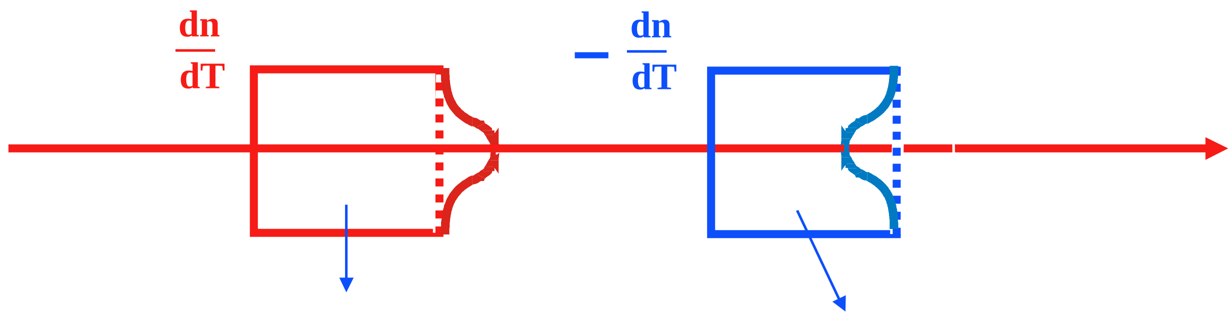
E-O Modulation in Advanced LIGO

<u>Alternative Method:</u> Mach-Zehnder modulation --> architecture problem



Prototype developed for initial LIGO detectors, but not well characterized
>> R&D effort

Power Independent Compensation of Thermal Lensing



$$\begin{bmatrix} TEM_{\tilde{0}} \\ TEM_{\tilde{2}} \\ \cdots \end{bmatrix} = \begin{bmatrix} & M(\zeta, z) & \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ \cdots \end{bmatrix} \qquad \begin{bmatrix} 1 \\ 0 \\ \cdots \end{bmatrix} = \begin{bmatrix} & M^{-1}(\zeta, z) & \end{bmatrix} \begin{bmatrix} TEM_{\tilde{0}} \\ TEM_{\tilde{2}} \\ \cdots \end{bmatrix}$$

$$\zeta = \alpha\, L \frac{dn}{dT} P / 2 K \lambda$$

$$z = 1 + i\zeta$$

α = absorption coefficient

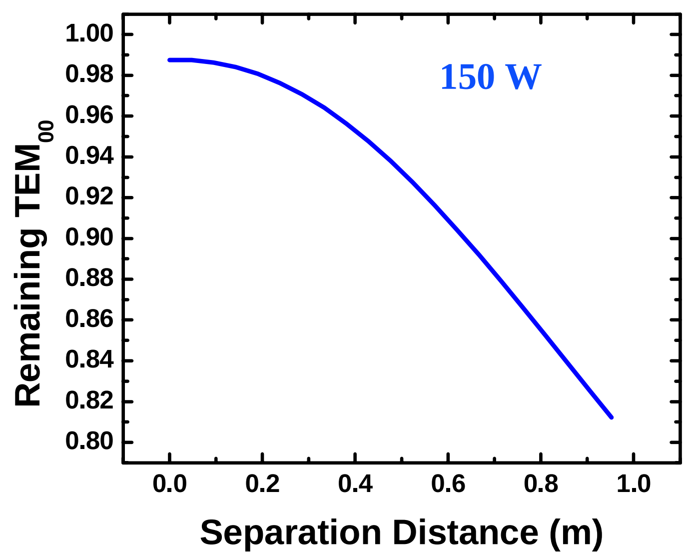
K = thermal conductivity

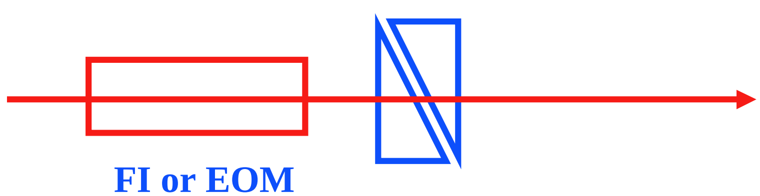
$$\begin{bmatrix} & M(\zeta, z) & \end{bmatrix} = \begin{bmatrix} \frac{1}{\sqrt{z}} & \frac{-i\zeta}{\sqrt{2}z^{3/2}} & \cdots \\ \frac{-i\zeta}{\sqrt{2}z^{3/2}} & \frac{2-\zeta^2}{2z^{5/2}} & \cdots \\ \cdots & \cdots & \cdots \end{bmatrix}$$

Thermal Lensing Compensation

Modeled using Melody

Parameter	*TGG*	*FK51*
α (m^{-1})	**2 x 10^{-1}**	**1 x 10^{-1}**
K (W/m K)	**7.4**	**0.9**
dn/dT (C^{-1})	**+ 2 x 10^{-5}**	**-6 x 10^{-6}**
Length (mm)	**20**	**15.9**

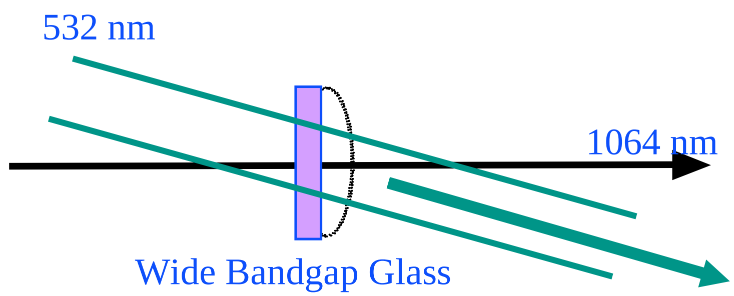


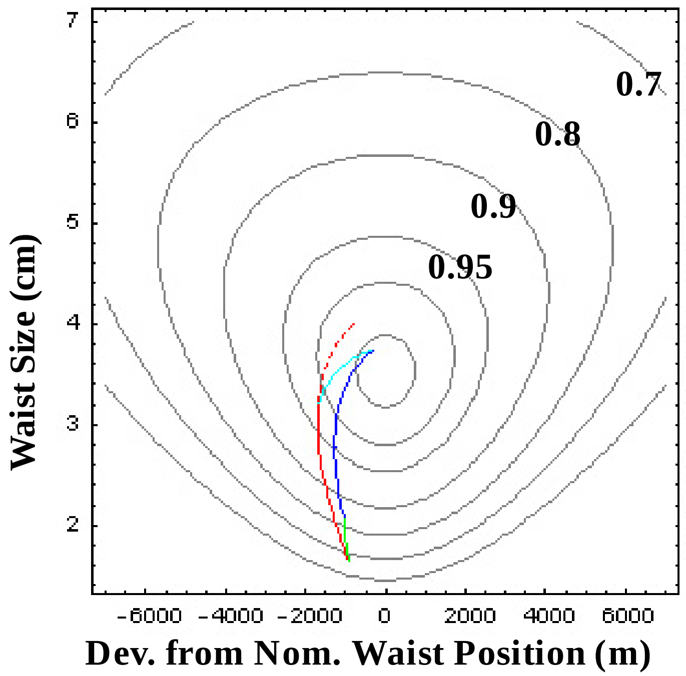


Thermal Lensing Telescope

Similar to current LIGO Telescope
- **2 mirror design (vacuum envelope constraints)**
- **Accommodates wide range of mode matching parameters**
- **All large (20 cm) optics**

- **in-situ adjustment with feedback**





R&D Issues Still to be Faced

- Modulator Development:
  - RTA performance
  - MZ modulation
- Isolator Development:
  - Full FI system test (TCFI, EOT)
  - Possible thermal compensation (-dn/dT materials)
- Telescope Development:
  - in-situ mode matching adjustment