LSC Meeting, LIGO Hanford Obs.
August 15-17, 2000
LIGO-G000240-00-D

Reference Design for the LIGO II Input Optics

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Input Optics Functions

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

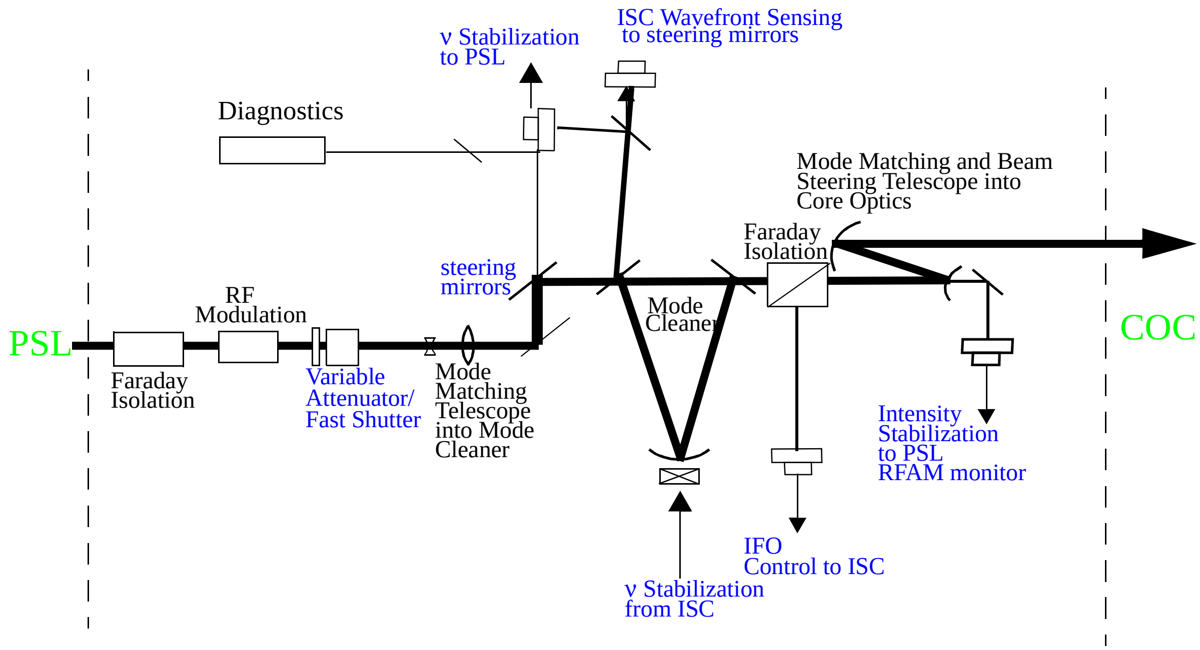


Figure 1: Conceptual layout of IO optical components

Design Considerations

Philosophy

- LIGO I Input Optics works! (to level of testing to date)
- Keep it simple; if it isn't broken, don't fix it.
- Contingency plans and fall back positions to manage technical risk.
- Examine trade-offs.
- Where ever possible, leave comfortable margins for meeting requirements

Issues

- Increased power --> modal degradation, performance impact
- Increased sensitivity --> increased performance
- finite $$ --> limitations on changes of vacuum envelope

Electro-optic Modulation in LIGO 2

- Function: EOMs are used to phase modulate carrier to provide resonant and non-resonant sidebands for interferometer length and alignment locking; also mode cleaner length and alignment on controls
- LIGO sensitivity and availability place requirements on EOMs

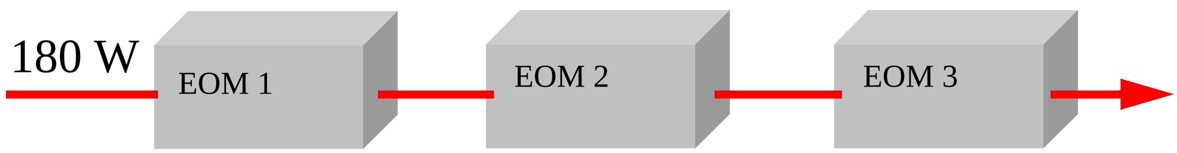
REQUIREMENTS FOR LIGO MODULATORS

Requirement	*LIGO I*	*LIGO II*	*Issues*
Power	**10 W**	**180 W**	**Thermal Lensing, Damage, Depolarization, Nonlinear Processes**
Modulation Frequency	**< 100 MHz**	**< 100 MHz ?**	**Piezoelectric Resonances, Loss tangents**
Modulation Depth	**$0 < \Gamma < 1$**	**$0 < \Gamma < 1$***	**Higher order sidebands**
MTBF	**10000 Hours**	**10000 Hours**	**PR Damage**
RF Amplitude Modulation	**$< 10^{-3}$**	**$< 10^{-3}$???**	**Alignment, Depolarization**

Electro-optic Modulation in LIGO 2

Two approaches

- Serial modulation --> materials problem

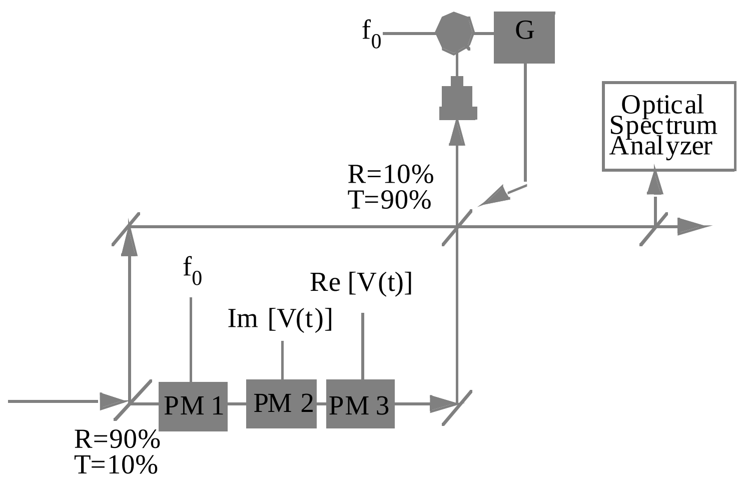


›› Find an EO material that can handle 180 W and modulate to required specs

– *$LiNbO_3$* may not work (Hagop Injeyan, TRW); photorefractive darkening at 100 W powers for 24 hour exposures (7 x 7 mm aperture)

– *KTP* does work; no problems using 300 W of 1064 nm light

- MZ modulation --> architecture problem



LIGO 2 Mode Cleaner

- Major Requirements (as we know them now)

›› Jitter suppression - beam jitters couples to interferometer mirror angular misalignments and leads to in-band signals.

– $\varepsilon_1 < 3.5 \times 10^{-10}$ / $Hz^{1/2}$, similar for higher order modes

›› Frequency stabilization - light entering interferometer must be stabilized to the level required by L_+ loop gains

– $\delta\nu(f) < 10^{-5}$ Hz / $Hz^{1/2}$ at f = 100 Hz; 1×10^{-6} Hz / $Hz^{1/2}$ at f = 10 kHz

›› Intensity stabilization - maybe very important in L2 since only side band reached dark port in current L2 control schemes

– $\delta I(f) / I \sim 3 \times 10^{-9}$ / $Hz^{1/2}$, 40 Hz $< f <$ 10 kHz

›› Optical efficiency

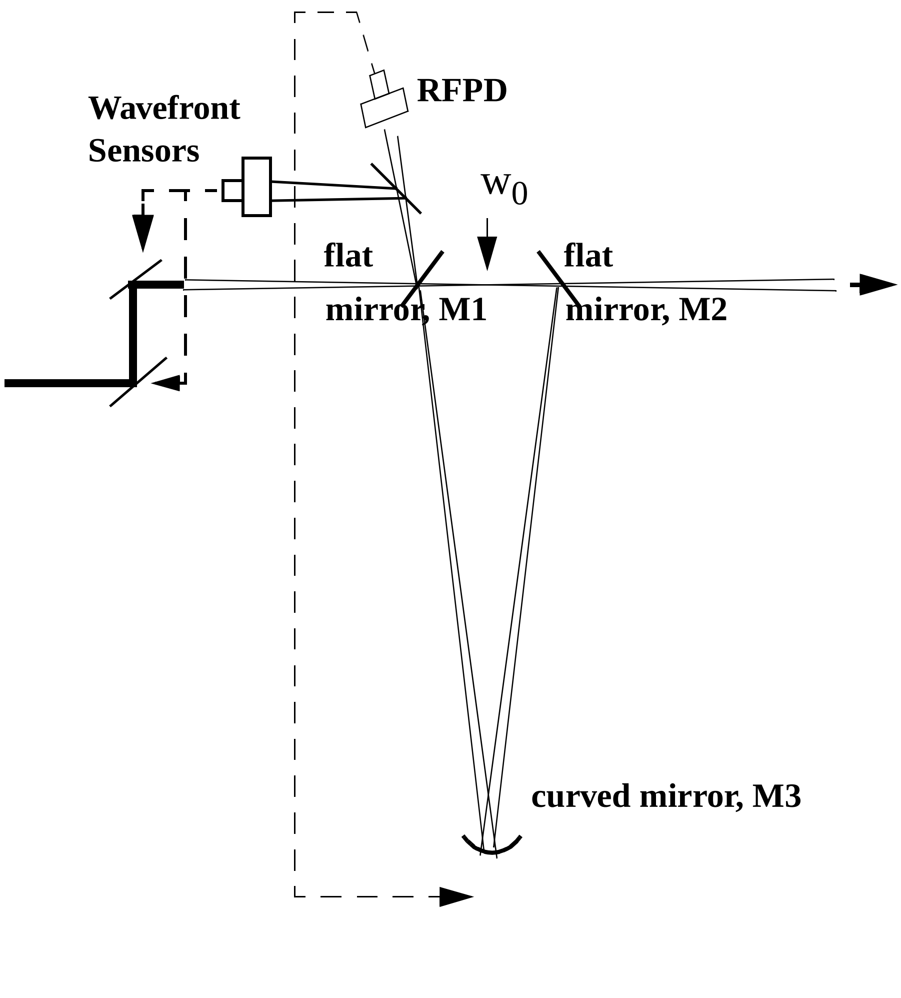
– throughput > 0.83

›› Modal quality - non-Gaussian modes do not couple into interferometer, end up as junk light on RFPDs

– $TEM_{00} > 0.95$

LIGO 2 Mode Cleaner

- 3 mirror, triangular cavity
- triple pendulum suspensions
- fused silica substrates (sapphire not ruled out, though)



LIGO 2 Mode Cleaner

- Design Parameters

Parameter	***'Short' Design***	***'Long' Design***
Mode Cleaner Length	**25 m**	**100 m**
Free spectral range	**6 MHz**	**1.5 MHz**
Mirror Dimensions	**25 cm diameter 10 cm thick**	**25 cm diameter 10 cm thick**
MC Flat mirror reflectivity (intensity)	**0.9985**	**0.9980**
Assumed mirror losses	**15 ppm**	**15 ppm**
Finesse	**2090**	**1570**
MC curved mirror RC	**43.2 m**	**254.0 m**
Cavity *g* factor	**0.421**	**0.606**
Jitter suppression	**1/3000**	**1/2500**
Max TEM_{mn} Transmission	**1.5 ppm**	**3.5 ppm**
Waist size	**2.7 mm**	**6.5 mm**
Stored Power	**93 kW**	**70 kW**
Intensity at flat mirrors	**410 kw/cm^2**	**53 kw/cm^2**
Transmittance	**97%**	**98%**

LIGO 2 Mode Cleaner

Technical Noise

- Radiation Pressure Noise

$$S_R(\omega) = \frac{1}{4}\frac{1}{\pi^4}\frac{(\cos\varphi)^2}{c^2m^2}\frac{1}{f^4}S_P(\omega)$$

  - ›› Need heavy mirrors
  - ›› Total MC displacement noise from radiation pressure

$$dx_{rad}(f) = 6.75\times10^{-14}\frac{\mathrm{m}}{\sqrt{Hz}}\left(\frac{\mathrm{kg}}{m}\right)\left(\frac{dP}{P\times10^{-9}}\right)\left(\frac{P}{100\mathrm{kW}}\right)\left(\frac{\mathrm{Hz}}{f}\right)^2$$

- Thermodynamic Fluctuation Noise

$$S_{TDF}(\omega) = \frac{8}{\sqrt{2\pi}}\alpha^2(1+\sigma)^2\frac{kT^2}{\rho C}\frac{a^2}{r^3}\frac{1}{4\pi^2f^2}$$

  - ››for fused silica (worse for sapphire)

$$dx_{TDF}(f) = 1.8\times10^{-18}\left(\frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}\right)\left(\frac{2\mathrm{mm}}{ro}\right)^{3/2}\left(\frac{\mathrm{Hz}}{f}\right)$$

LIGO 2 Mode Cleaner

- Photothermal Noise

$$S_{PT}(\omega) = 2\alpha^2(1+\sigma)^2\frac{h\upsilon Po}{(\rho C\pi ro^2)^2}\frac{1}{4\pi^2 f^2}$$

  - ››fused silica

$$dx_{PT}(f) = 1.1\times10^{-18}\left(\frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}\right)\left(\frac{Po}{100\mathrm{mW}}\right)^{1/2}\left(\frac{2\mathrm{mm}}{ro}\right)^2\left(\frac{\mathrm{Hz}}{f}\right)$$

- Brownian motion (structural damping)

$$S_{SD}(f) = \frac{4kT}{2\pi}\frac{(1-\sigma^2)}{Ero\sqrt{2\pi}}\Phi\frac{1}{f}$$

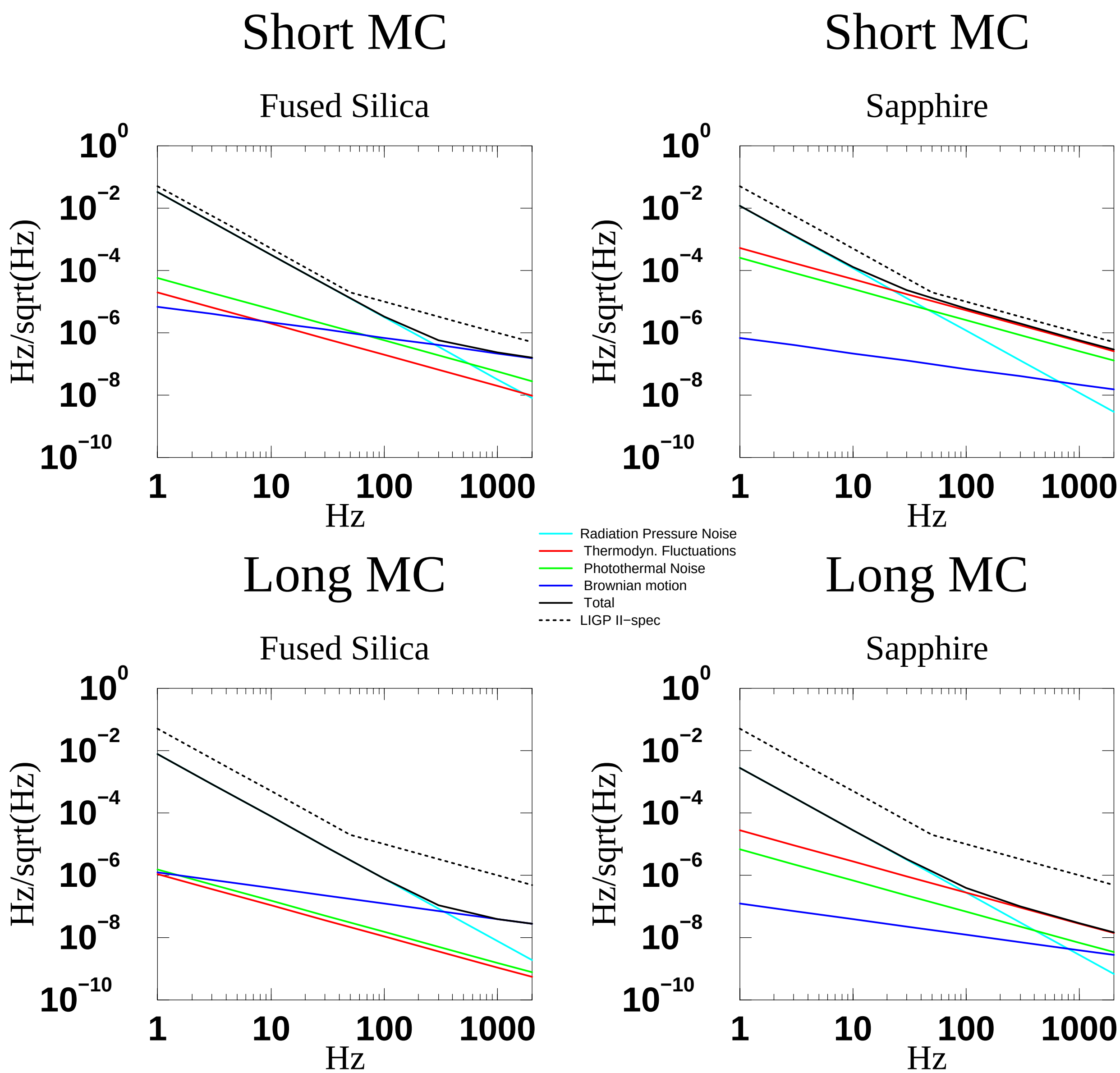
  - ›› fused silica

$$dx_{SD}(f) = 5.9\times10^{-19}\left(\frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}\right)\left(\frac{2\mathrm{mm}}{ro}\right)^{1/2}\left(\frac{\mathrm{Hz}}{f}\right)^{1/2}$$

- Sensor/Actuator Noise

$$dx_{OSEM} = 1.0\times10^{-11}L_{SUS}\sim 1\times10^{-16}\frac{m}{\sqrt{Hz}}$$

LIGO 2 Mode Cleaner



LIGO 2 Mode Cleaner

Design Trade-offs

- Jitter suppression vs. radiation pressure

›› beam de-wiggling increases with increasing cavity finesse...

$$S_{mn} = \frac{1}{\left[1 + \left\{\frac{2\Im}{\pi}\sin[(m+n)\operatorname{acos}(\sqrt{g})]\right\}^2\right]^{\frac{1}{2}}}$$

›› ...as does radiation pressure

$$F = 2\cos\varphi\frac{\Im P_{in}}{\pi c}$$

›› Possible solution: active pre-stabilization of the PSL beam before entering the mode cleaner

- Increasing mode cleaner is an easy way to decrease frequency noise...

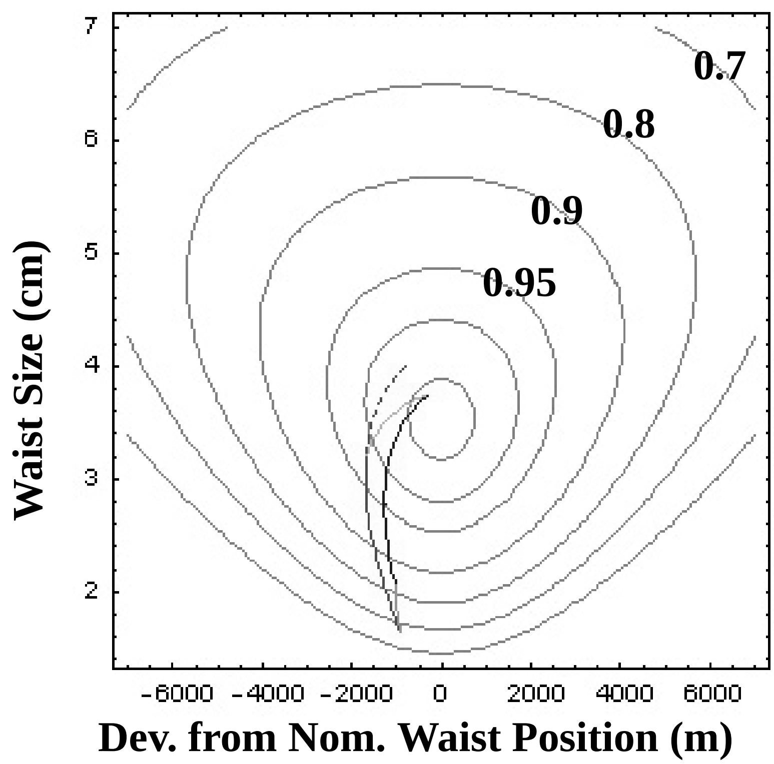
$$\delta f = \frac{c\,dx}{\lambda L_{MC}}$$

›› ... and cost $$ to modify the LIGO vacuum envelope

›› Possible solution: 25 m length requires moving one HAM/ interferometer and manufacturing a longer connection tube

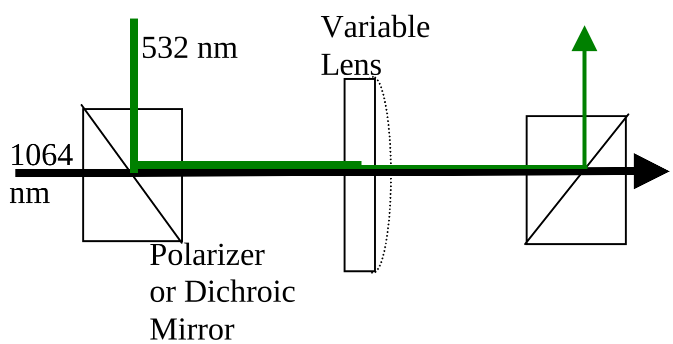
Mode Matching Telescope

- Very similar to current LIGO Telescope
  - 3 mirror design (will investigate 2 mirrors, also)
  - Accommodates wide range of mode matching parameters
  - All large optics
  - Telescope-induced beam jitter



Mode Matching Telescope

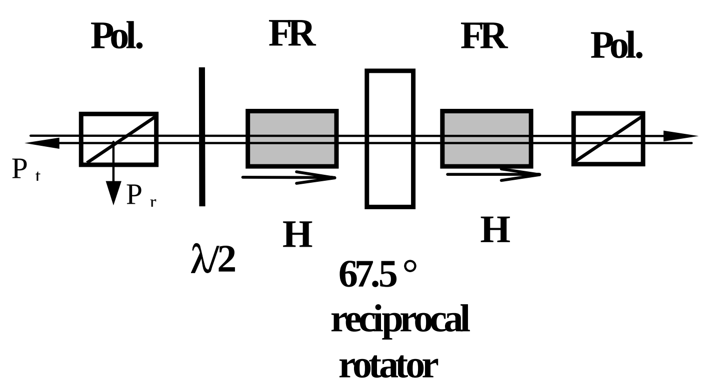
- Active mode matching - using thermal lensing to our advantage
  - ›› Feedback control
  - ›› Bullseye monitoring of mode matching (both carrier and res. side band)



LIGO 2 Optical Isolation

Technical Issues

- Increased power
  - ›› thermal lensing
    - –measurements estimate ~ 3-5% modal degradation after beam passes through Faraday isolator
  - ›› isolation ratio: novel dual crystal isolator
    - – at 100 W, provides 45 dB isolation



- Issues to be addressed
  - ›› location of FI in L2
  - ›› suspended?

Conclusions

- LIGO 2 Input Optics will look a lot like current Input Optics

- No real worries (yet)
  - ›› modulation technique TBD
  - ›› isolator location TBD