# Advanced LIGO Input Optics Design Requirements Review

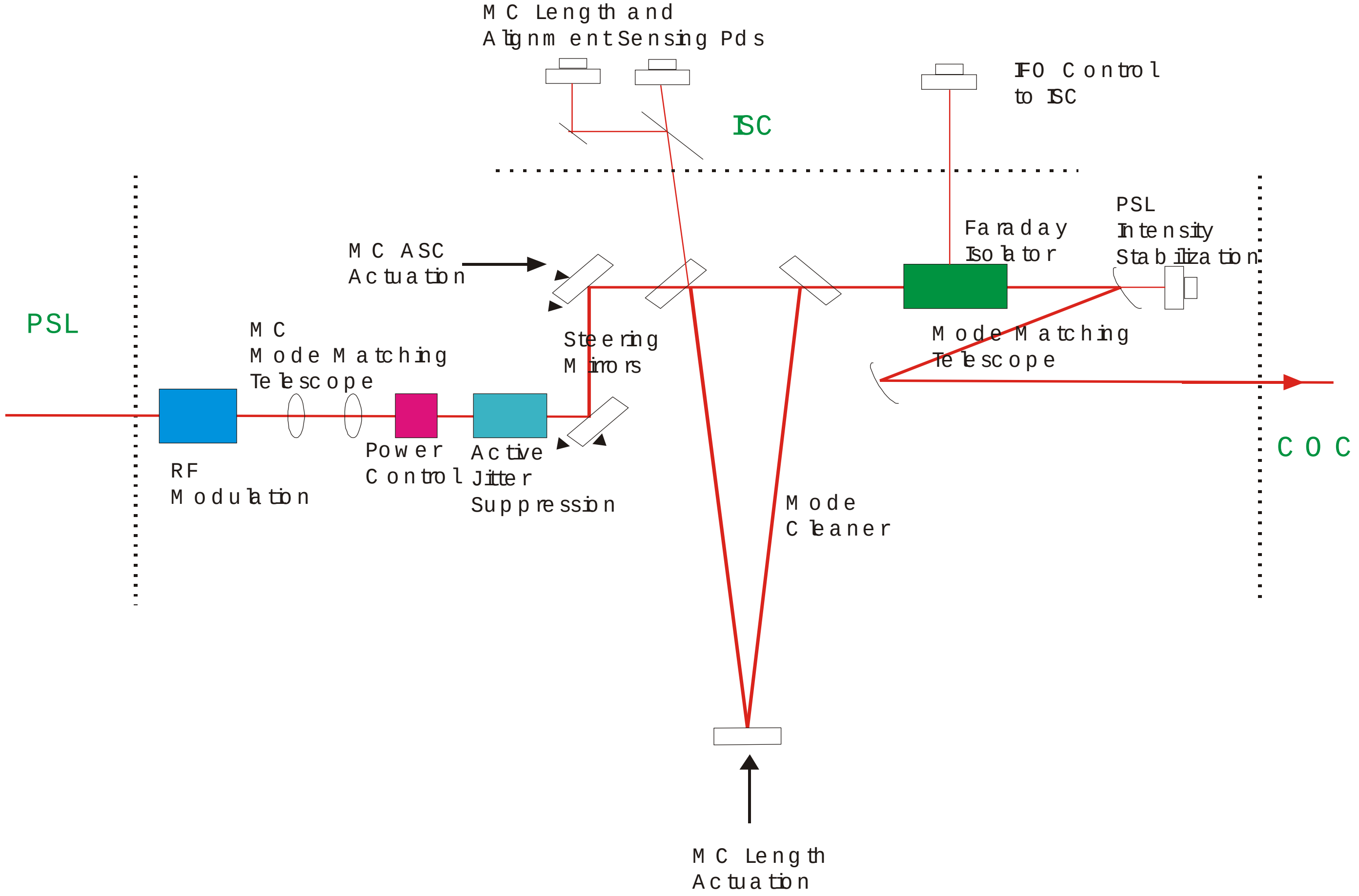
## Presentation Outline

- Design Requirements
  - Introduction, Production Functions (Dave R., 5 minutes)
  - Design Requirements (Guido*, 55 minutes)
- Conceptual Design
  - Introduction, Layout (David T., 10 minutes)
  - RF Modulation (Guido, 10 minutes)
  - Active Jitter Suppression (Guido, 10 minutes)
  - Mode Cleaner (David T., 10 minutes)
  - Faraday Isolation (Dave R., 10 minutes)
  - Mode Matching (Dave R., 10 minutes)

# Input Optics Product Functions

- RF modulation
- Input mode cleaning
- Additional active jitter suppression before interferometer
- Laser power control to the interferometer
- Mode matching (interferometer and mode cleaner)
- Optical isolation and distribution of sensing beams for other subsystems
- internal diagnostics

# IO Schematic



# Not Included in IO

- Output (AS port) mode cleaner (AOS)
- Modulation drive (ISC)
- Suspension design for IO mirrors (SUS)
  - » Suspension fabrication for large MMT
- MC length and alignment sensing and control (ISC)
  - » should be active participation in design by IO group member
- Electronics (CDS)
  - » MC
  - » active jitter suppression

# ADVANCED LIGO

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Primary Requirements from Adv. LIGO Systems Design:

- Frequency Noise at IFO, MC, and PSL
- Intensity Noise at IFO

Additional Primary Requirements calculated for

- P = 125W
- Sapphire mirrors
- 40ppm ± 50% losses on reflection
- 1% difference in Arm Cavity Intensities.
- DC- and RF-Sensing

Include always safety factor of 10!

# MODELLING BEAM JITTER

- **Input Field:** $\begin{pmatrix} 0 \\ 1 \end{pmatrix} \hat{=} \begin{matrix} TEM_{00} \\ TEM_{10} \end{matrix}$
- **Propagation:** $\begin{pmatrix} e^{i\varphi_0} & 0 \\ 0 & e^{i(\varphi_0+\varphi_G)} \end{pmatrix}, \qquad \varphi_0 = \omega 2\pi\frac{L}{c}, \qquad \varphi_G =$ **Gouy-phase**
- **Reflection:** $\begin{pmatrix} \sqrt{1-4\Gamma^2} & -2i\Gamma \\ -2i\Gamma & \sqrt{1-4\Gamma^2} \end{pmatrix}, \qquad \Gamma = \Theta\frac{2\pi w}{\lambda}$
- **Build full IFO with these matrices**
- **Output: Dark Port Field:** $E_{out} = \begin{pmatrix} a \\ b \end{pmatrix}$
- **Beat only** $TEM_{00}$**-component** $a$ **with LO (Output MC)**
- **Repeat for Jitter SB around RF-SB.**

**Compare with GW-Signal** $\Rightarrow$ **Requirements**

# BEAM JITTER

## Beam Jitter requirement depend on Mirror Tilt:

$$\Delta\Theta_{ITM} = \Theta_{ITM1} - \Theta_{ITM2}$$

## DC-Sensing:

$$a_{10}^{max}(f) = \sqrt{\left(\frac{2.5\cdot 10^{-5}}{f^2}\right)^2 + (5\cdot 10^{-10})}\frac{[2\cdot 10^{-8} rad]}{\Delta\Theta_{ITM}}\frac{1}{\sqrt{Hz}}$$

## RF-Sensing:

$$a_{10}^{max}(f) = \sqrt{\left(\frac{4.5\cdot 10^{-5}}{f^2}\right)^2 + (5.5\cdot 10^{-10})}\frac{[2\cdot 10^{-8} rad]}{\Delta\Theta_{ITM}}\frac{1}{\sqrt{Hz}}$$

# RF-MODULATION

**Two possible noise sources:**

- **Changes in the SB-amplitude**

  ⇒ **Change Carrier Intensity**

  ⇒ **Creates Radiation Pressure Noise**

- **Oscillator Phase Noise**

  ⇒ **changes phase of LO at dark port**

  ⇒ **scales with carrier amplitude**

# RF-MODULATION

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## Changes in SB-Amplitude

### DC-Sensing:

$$\delta m(f) < \frac{10^{-9}}{m_0\sqrt{Hz}}\frac{f}{[10Hz]}$$

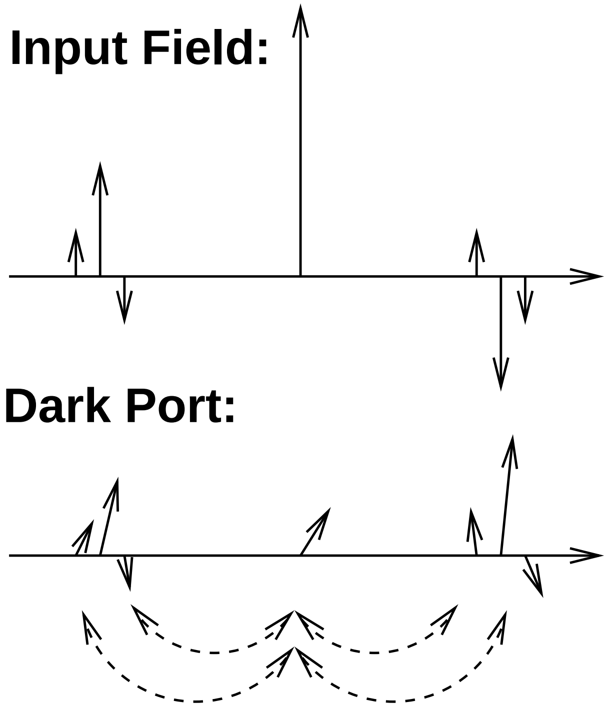
### RF-locking:

$$\delta m(f) < \frac{10^{-9}}{m_0\sqrt{Hz}}\frac{f}{[10Hz]} \qquad f < 100Hz$$

$$\delta m(f) < \frac{10^{-8}}{m_0\sqrt{Hz}} \qquad f > 100Hz$$

# OSCILLATOR PHASE NOISE

$$E = E_0 e^{i\omega_c t} exp\left(im\cos\left[\Omega t + \frac{\delta\nu}{2\pi f}\sin(2\pi f t)\right]\right)$$



**Detuned Interferometer:**

- **both RF-sidebands different amplitude and phase**
- **all noise sidebands different amplitude and phase**

**Two contributions:**

- **OPN-Sidebands beat with Carrier on PD.**
- **Oscillator Phase Noise in LO at mixer.**

**No Noise Cancellation anymore !**

# RF-MODULATION

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## Requirements for 180 MHz:

- $\mathbf{l}_{SSB}(10Hz) < -92$ **dBc/Hz**
- $\mathbf{l}_{SSB}(100Hz) < -140$ **dBc/Hz**
- $\mathbf{l}_{SSB}(1\,kHz) < -163$ **dBc/Hz**

## Critical Parameters:

- **Detuning in arm cavities and MI**

$$\Phi_- < 10^{-7}\mathbf{rad} \qquad \phi_- < 10^{-4}\mathbf{rad}$$

- **Differential Losses in arm cavities**

$$\Delta L < 15\ ppm$$

**Reason: Scales with Amplitude of Carrier at DP.**

# SECONDARY REQUIREMENTS

**Beam Jitter:**

- **passive suppression: mode cleaner ( 1000)**
- **active suppression necessary**

**Puts Requirements on Mode Cleaner:**

- **Angular Alignment (below GW-band):**
  **Beam Jitter creates frequency noise:**

$$\Theta_{MC} < 10^{-7}\textbf{rad}$$

- **Angular Stability (in GW-band):**
  **MC mirror motion creates Beam Jitter:**

$$\Theta_i(f) < \sqrt{\left(\frac{2.5\cdot 10^{-12}}{f^2}\right)^2 + (5\cdot 10^{-15})^2}\,\frac{[2\cdot 10^{-8}]}{\Delta\Theta_{ITM}}\,\frac{1}{\sqrt{Hz}}$$

# ADDITIONAL REQUIREMENTS

- **Frequency Noise Requirement behind MC limited by radiation pressure noise**

$$\Rightarrow 3 \cdot 10^{-2} \frac{Hz}{\sqrt{Hz}} \frac{Hz}{f} \qquad f < 1\ kHz$$

$$\Rightarrow 3 \cdot 10^{-5} \frac{Hz}{\sqrt{Hz}} \qquad f > 1\ kHz$$

- **Oscillator Phase Noise and SB-Amplitude couple if FSR $\neq$ RF-frequency**

$\Rightarrow$ **Difference between FSR & RF-frequency $<$ 14Hz**

$\Rightarrow$ **Otherwise Requirements start to change**

# MODE MATCHING

## Mode Matching Telescope:

- **Two Mirrors**
- **Required Efficiency 95%**
- **Adjustable to accomodate small core optics deviations**

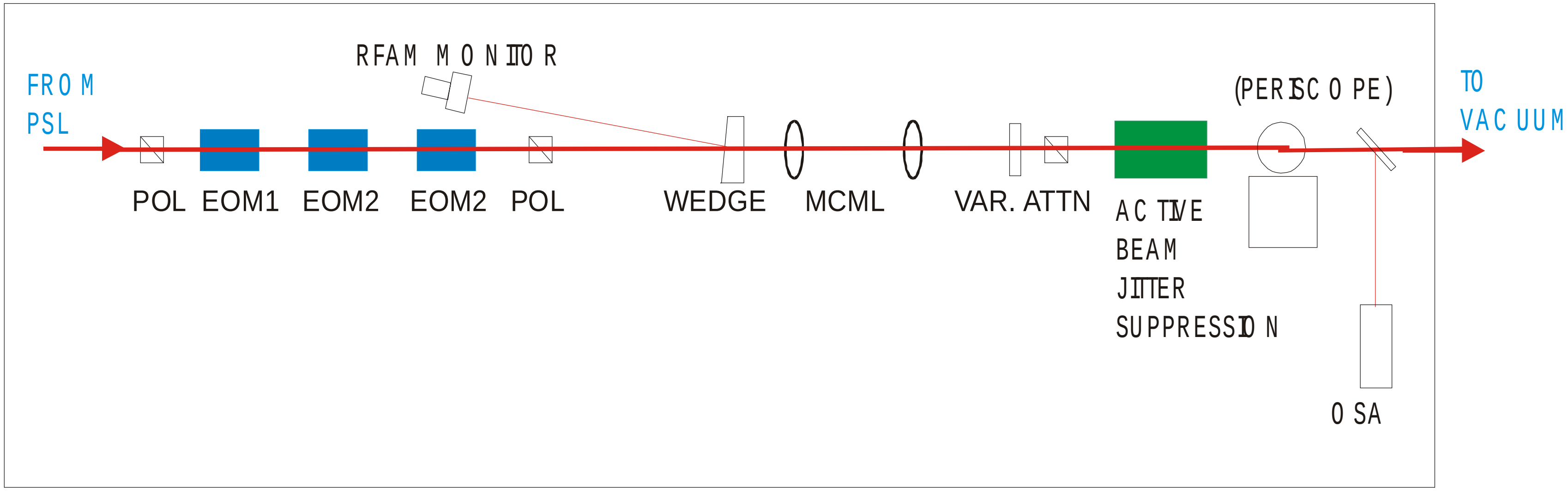
## Angular Requirements:

- $\Delta\Theta_{MMT} < 6 \cdot 10^{-9}$ **rad (rms)**
- $\delta\Theta_{MMT} < 10^{-12}/\sqrt{\mathbf{Hz}}$

# General Design

IO System Layout

- Optics not in vacuum are mounted on the same table as the PSL in a clean, enclosed, and acoustically/seismically stable environment.
- Conceptual Layout of IO Components on the PSL Table:



# Possible Methods for Minimizing Frequency Noise from Acoustic Coupling to Mirror Mounts and Periscopes

- LIGO 1 suffered from coupling of acoustic noise in the PSL/IOO table environment to mirror mounts.

  1) enclose PSL components in separate vacuum (with suitable vibration isolation).

  2) provide low-acoustic (anechoic) enclosure around PSL with all noise producing devices (fans, etc) outside this enclosure.

- PSL/IOO table of L1 was not stiff enough to constrain the (heavy) periscope frame first employed; eventually a lighter design was used.

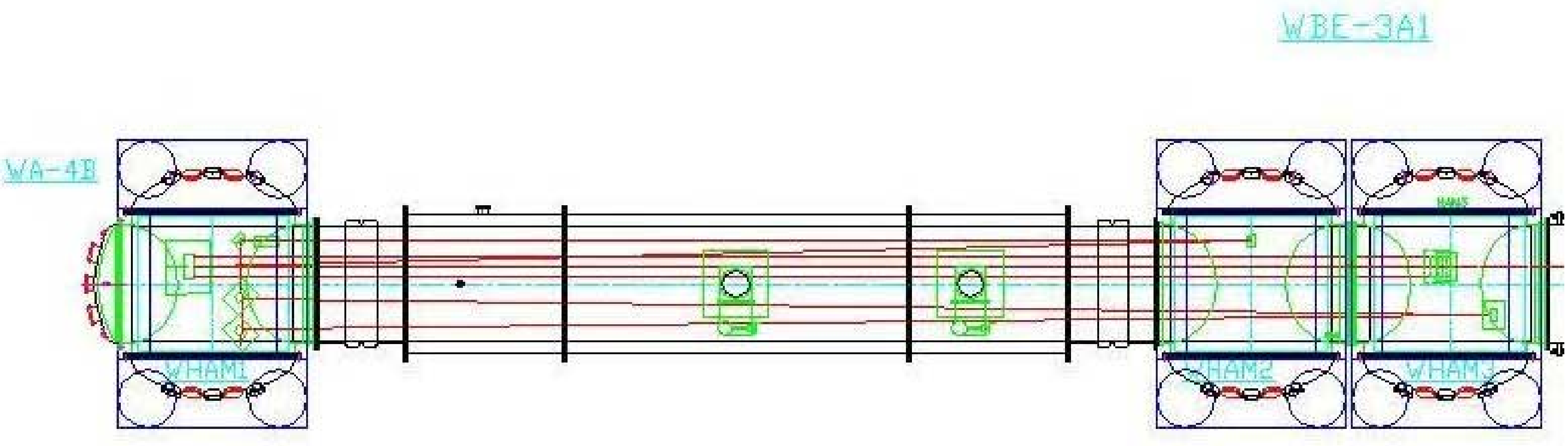
  1) move periscope into vacuum system (requires a HAM viewport at table level).

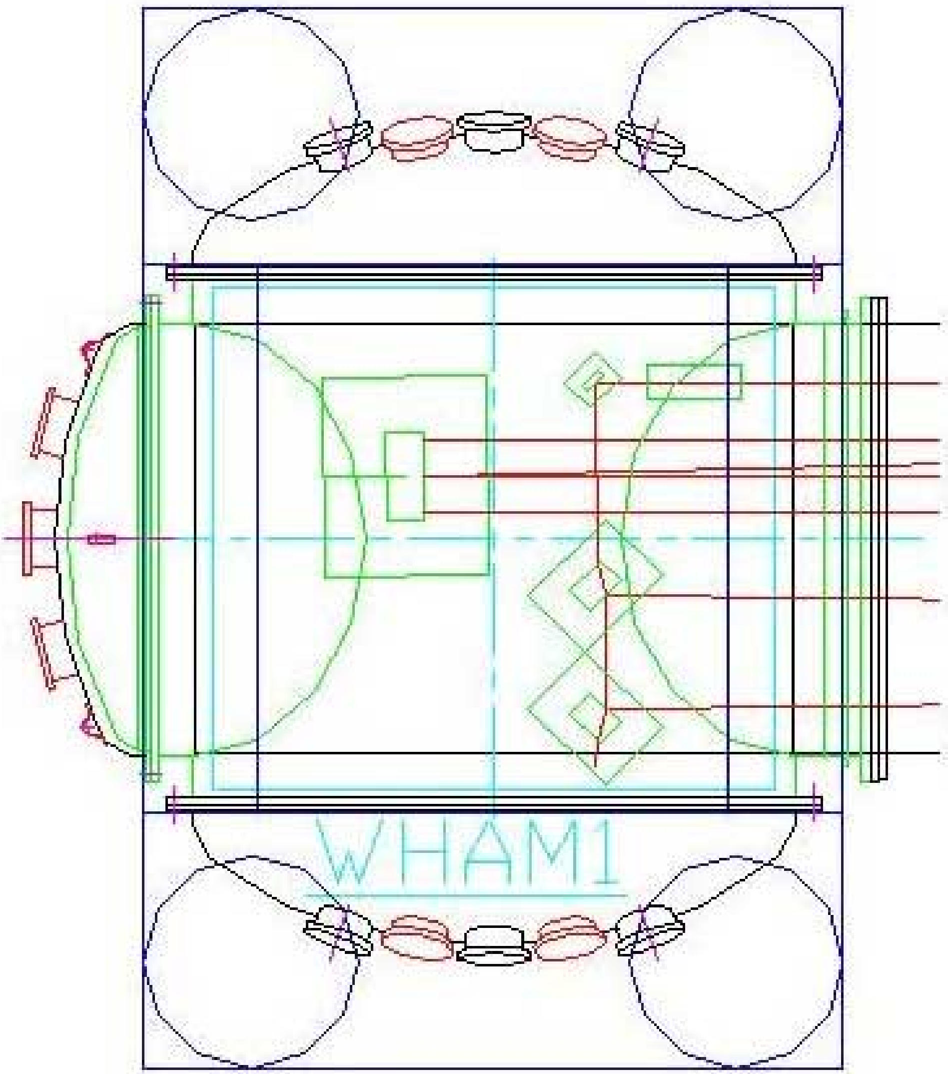
  2) raise table to eliminate periscope.

- Both treatments are outside the scope of the IOO subsystem alone.

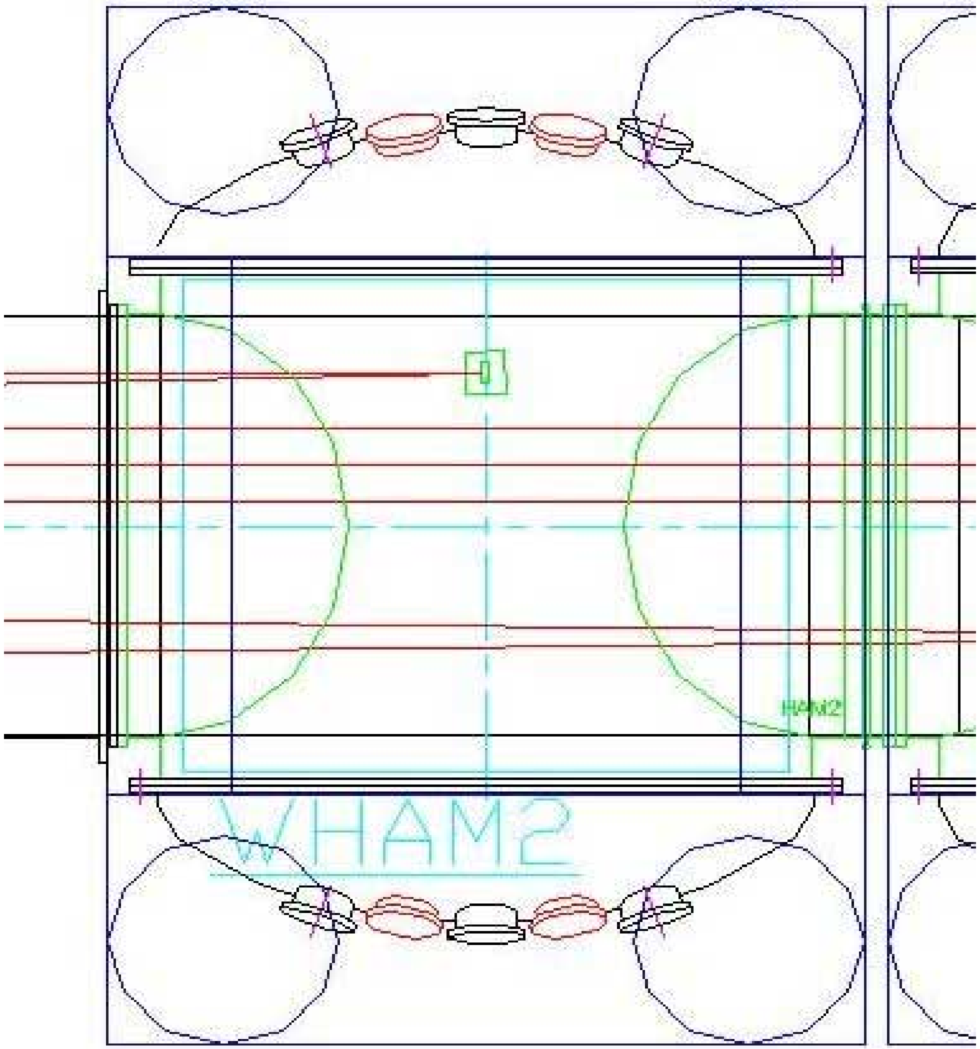
# In-vacuum optics

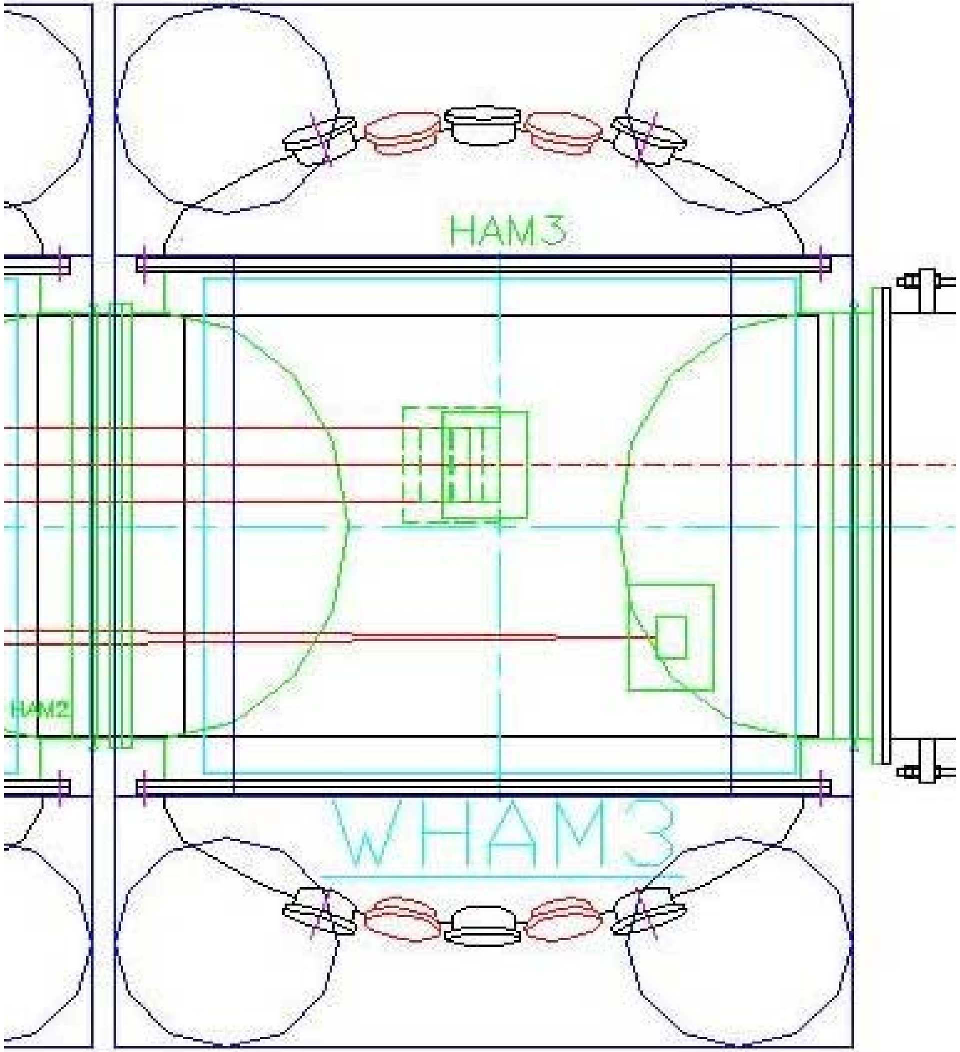
- With the exception of the Faraday isolator, all main IFO beam optics including and following the mode cleaner will be suspended.
- Diagnostic beam optics for IFO and MC control will be located on fixed mounts.
- Output ports in the HAMs used as optical feedthroughs for sensing beams.





LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY


WHAM2
HAM2


HAM3
WHAM3
HAM2

# Dimensional Constraints

- IO system located on PSL table. HAMs 1, 2, and 3. HAM 3 also holds the power recycling mirror.
- Dimensions:

| *Item* | *Unit* | *Value* |
|---|---|---|
| PSL table area dimensions | ft x ft | 16 x 5 |
| HAM1(7) - HAM2(8) spacing (center-center) | m | 13.72 |
| HAM2(8) - HAM3(9) spacing (center-center) | m | 2.63 |
| HAM1(7) stack area dimensions (L x W) | m x m | 1.90 *x* 1.70 (TBR) |
| HAM2(8) stack area dimensions (L x W) | m x m | 1.90 *x* 1.70 (TBR) |
| HAM3(9) stack area dimensions (L x W) | m x m | 1.90 *x* 1.70 (TBR) |
| HAM1,2 (7,8) Connecting Beam Tube Diameter | m | 1.2* |

* HAM1,2 and HAM 7,8 beam tube to be replaced

# Dimensional Constraints, cont.

| | | |
|---|---|---|
| $\Delta z$ (HAM1-HAM2, local coordinates, LHO) | mm | 8.49[†] |
| $\Delta z$ (HAM2-HAM3, local coordinates, LHO) | mm | 1.59[†] |
| $\Delta z$ (HAM7-HAM8, local coordinates, LHO) | mm | -8.49[†] |
| $\Delta z$ (HAM8-HAM9, local coordinates, LHO) | mm | -1.59[†] |
| $\Delta z$ (HAM1-HAM2, local coordinates, LLO) | mm | 4.28[†] |
| $\Delta z$ (HAM2-HAM3, local coordinates, LLO) | mm | 0.80[†] |

[†] The LHO *x*-axis slopes downward by 0.619 mrad; the *y*-axis slopes upward by 0.012 mrad. WHAM1 (7) is 8.5 mm higher (lower) than WHAM2 (8). At LLO the *x*-axis slopes downward by 0.312 mrad and the *y*-axis slopes downward by 0.612 mrad. LHAM1 is 4.3 mm higher than LHAM2.

- Suspensions must either be raised on platform or have adjustment capability so that the plane of the MC beam is level
- Capability for optical levers on all suspended mirrors required.

# Overall IO Efficiency

- Requirement: IO must deliver 76% of the PSL $TEM_{00}$ light to the IFO
- Includes all losses from reflection, transmission, and absorption in the IO optical components, as well as light lost into uncompensated higher order modes through thermal lensing.
- Transmission of the components of the IO components:
  - Suspended components assumed to have coatings similar those achieved in the LIGO I (~$50$ ppm loss)
  - Other optics assumed to have antireflection coatings that match the standard commercial narrowband multilayer coatings ($0.1\%$).
  - Out-of-vacuum optics assumed to have $200$ ppm scatter.
  - Loss of $TEM_{00}$ mode in the RF modulators and Faraday isolator are based on conservative estimates of passive thermal lensing compensation using $-dn/dT$ values for FK51 Schott glass.

o

| *Item* | *Loss* | *$TEM_{00}$ Mode Loss* | *$TEM_{00}$ Transmittance* | *Integrated Transmittance* |
|---|---|---|---|---|
| RF mod./lenses | 0.035 | 0.04[1] | 0.925 | **0.925** |
| PSL mirrors (2) | 0.002 | 0 | 0.998 | **0.923** |
| MC mml (3) | 0.002 | 0.0001 | 0.9979 | **0.921** |
| HAM viewport | 0.006 | 0.001 | 0.993 | **0.915** |
| MC injection mirrors (3) | 0.0006 | 0 | 0.9994 | **0.914** |
| Mode cleaner | 0.05[2] | 0.001 | 0.949 | **0.868** |
| Faraday isolator | 0.05 | 0.025[3] | 0.925 | **0.805** |
| Steering mirror | 0.033[4] | 0 | 0.967 | **0.778** |
| MMT 1 | 0.0002 | 0 | 0.9998 | **0.778** |
| MMT 2 | 0.0002 | 0 | 0.9998 | **0.778** |
| Mode Matching | 0 | 0.015 | 0.985 | **0.763** |

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[1] Based on preliminary measurements of thermal lensing in rubidium titanyl arsenate.

[2] Losses include mode mismatch and cavity visibility.

[3] G. Mueller et al., *Classical and Quantum Gravity*, to appear, 05/2002.

[4] Assumes 5 W needed for PSL intensity stabilization; TBD.

# MODULATION

## Material: RTP (back up RTA)

| Properties | RTA | RTP | LiNbO3 |
|---|---|---|---|
| Laser Damage Threshold [MW/cmˆ2, 10ns 1064nm] | 400 | 600 coated | 280[b] |
| $n_x$ @ 1064nm | 1.8 | 1.9[a] | 2.23 |
| $n_y$ @ 1064nm | 1.8 | 1.9[a] | 2.23 |
| $n_z$ @ 1064nm | 1.9 | 1.9[a] | 2.16 |
| $\alpha^c$ @ 1064 nm [1/cm] | 50ppm | 50ppm | $\leq$0.5% |
| $r_{33}n_z^3$ | 273 | 272 | 306 |

- Half Wave Voltage within 10% of $\text{LiNbO}_3$
- Thermal Lensing very small

**Temperature Changes change Modulation Index:**

$$\delta T \approx \frac{33\mu\text{K}}{\sqrt{\text{Hz}}}\frac{1}{m^2}\frac{f}{[10\text{Hz}]}$$

# MODULATOR

## Modulator Design:

- Material: RTP
- Temperatur stabilized
- Alignment very critical
  (active stabilized if necessary)
- Thermal Lensing very small
  (if needs compensation ⇒ FK51)

## Oscillator Phase Noise:

At the edge of state of the art Oscillators

Very Critical !!

# POINTING

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## Requirements:

- MC reduces pointing by factor 1000
- need active suppression (at least by 10..100)

## Actuators:

- PZT-mounted mirrors
- RTP-prisms (will be studied)

## Detection (under study):

- wave front sensing at MC or IFO
- Quad-Detector on HAM
- fixed spacer cavity on HAM

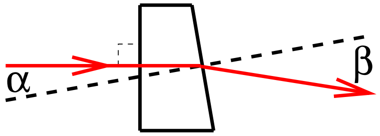
# POINTING-ACTUATOR

**Assume Laser Pointing of**

$a_{10}(f) \approx 2 \cdot 10^{-6}/\sqrt{Hz}$ $\quad f =$ **10 Hz..10 kHz**

**Requirements:**
- **Actuator Range:** $\delta\beta \approx 7 \cdot 10^{-10}$ **rad**
- **Frequency Range: 10Hz..10kHz**

**Two Possible actuators:**
- **PZT-mounted mirrors:**
  - **a PZT on each side of the mirror**
  - **required length change** $\approx 10pm$
- **RTP-prism:** $\delta n \approx 10^{-8} \Rightarrow \delta V = 1V$



# POINTING-DETECTION

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## Reference for Pointing:

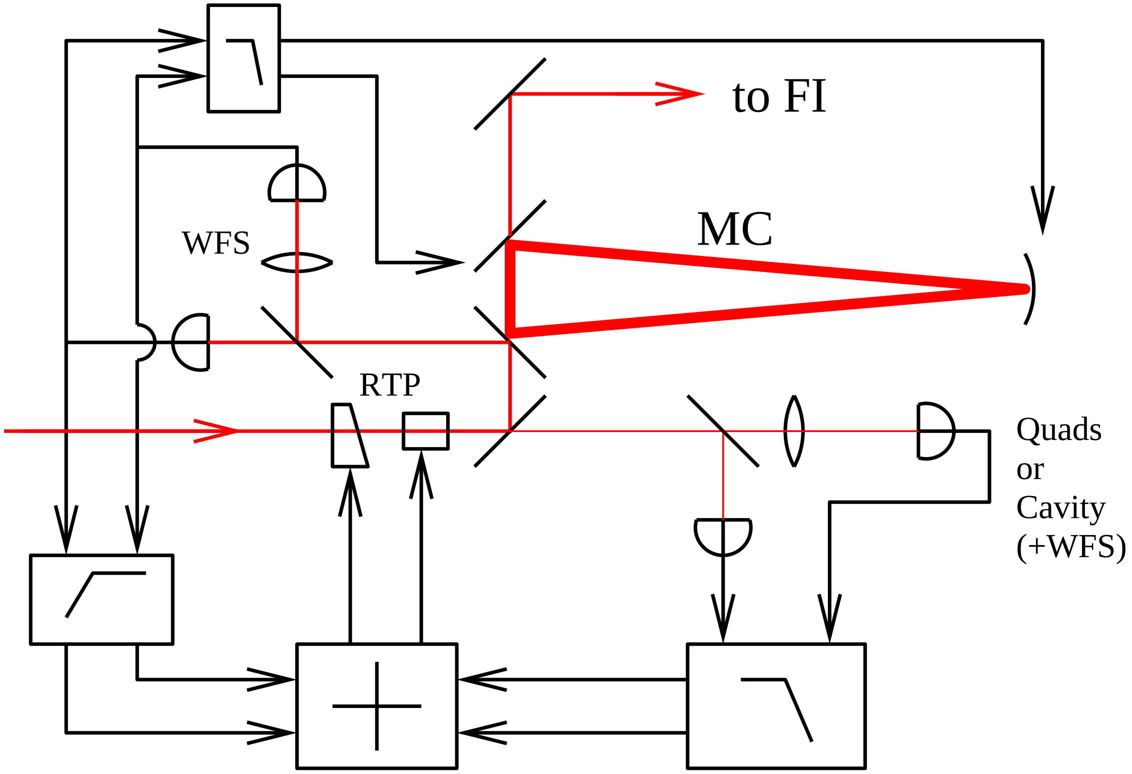
- below GW-band: HAM-table is reference
- in GW-band: Mode Cleaner is reference

## Detection of Pointing:

- below GW-band: Quad-Detector or fixed spacer cavity in front of MC
- in GW-band: Wave front sensing
  - below GW-band: aligns mode cleaner
  - above GW-band: suppresses pointing

# POINTING-DETECTION

## Concept:



- **WFS @ MC**
  - **DC-10 Hz: align MC**
  - **$>$ 10 Hz: align beam using RTP**
- **WFS @ Fixed Spacer Cavity or Quad. Det.**
  - **DC-10 Hz: align beam using PZT**

# Mode Cleaner

The suspended mode cleaner of the IO subsystem serves the following functions in stabilizing the laser light.

- In-band active frequency stabilization.
- Rejection of laser output not in the $TEM_{00}$ mode. (Beam Jitter suppression.)
- Passive intensity and frequency stabilization above the cavity pole frequency.

# Mode Cleaner Physical Parameters

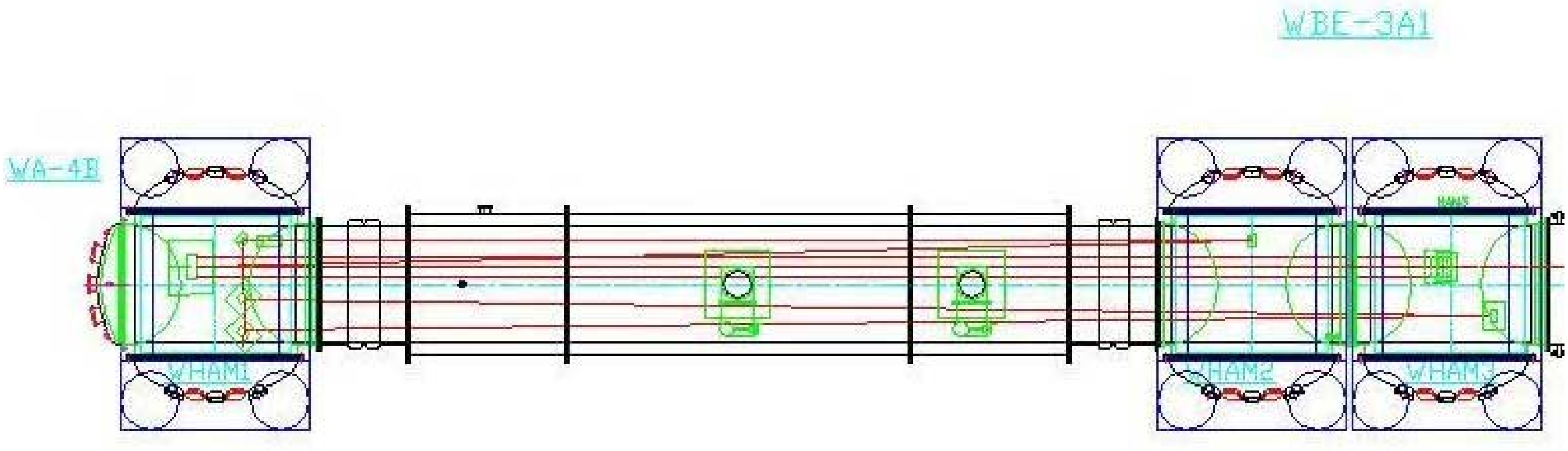
- For cold cavity (0 W) and hot cavity (165 W).

| ***Definition*** | ***Unit*** | ***Cold*** | ***Hot*** |
|---|---|---|---|
| Mode Cleaner Length | m | 16.681 | |
| MC1 radius of curvature | m | >10000 | -733 |
| MC2 radius of curvature | m | 26.900 | 27.92 |
| MC3 radius of curvature | m | >10000 | -733 |
| MC1+MC3 Intensity Reflectivity | | 0.9985 | |
| MC2 Intensity Reflectivity | | 0.99999 | |
| *g*-factor MC1 | | 1.0 | 1.023 |
| *g*-factor MC2 | | 0.3799 | 0.4025 |
| *g*-factor MC3 | | 1.0 | 1.023 |
| Cavity *g* factor | | 0.3799 | 0.4212 |
| Mirror absorption/scatter loss | ppm | 50 | |

| | | | |
|---|---|---|---|
| MC free spectral range | Hz | 8986045 | |
| MC finesse | | 2074 | |
| MC waist | mm | 2.102 | 2.114 |
| Cavity Pole Frequency | Hz | 4544 | |
| Rayleigh range | m | 13.06 | 13.99 |
| Input Power | W | 165 | |
| Stored MC Power | kW | 100 | |
| MC mirror mass | kg | 2.92 | |
| MC mirror diameter | cm | 15 | |
| MC mirror thickness | cm | 7.5 | |
| Static Radiation pressure | N/m^2 | 0.00035 | |

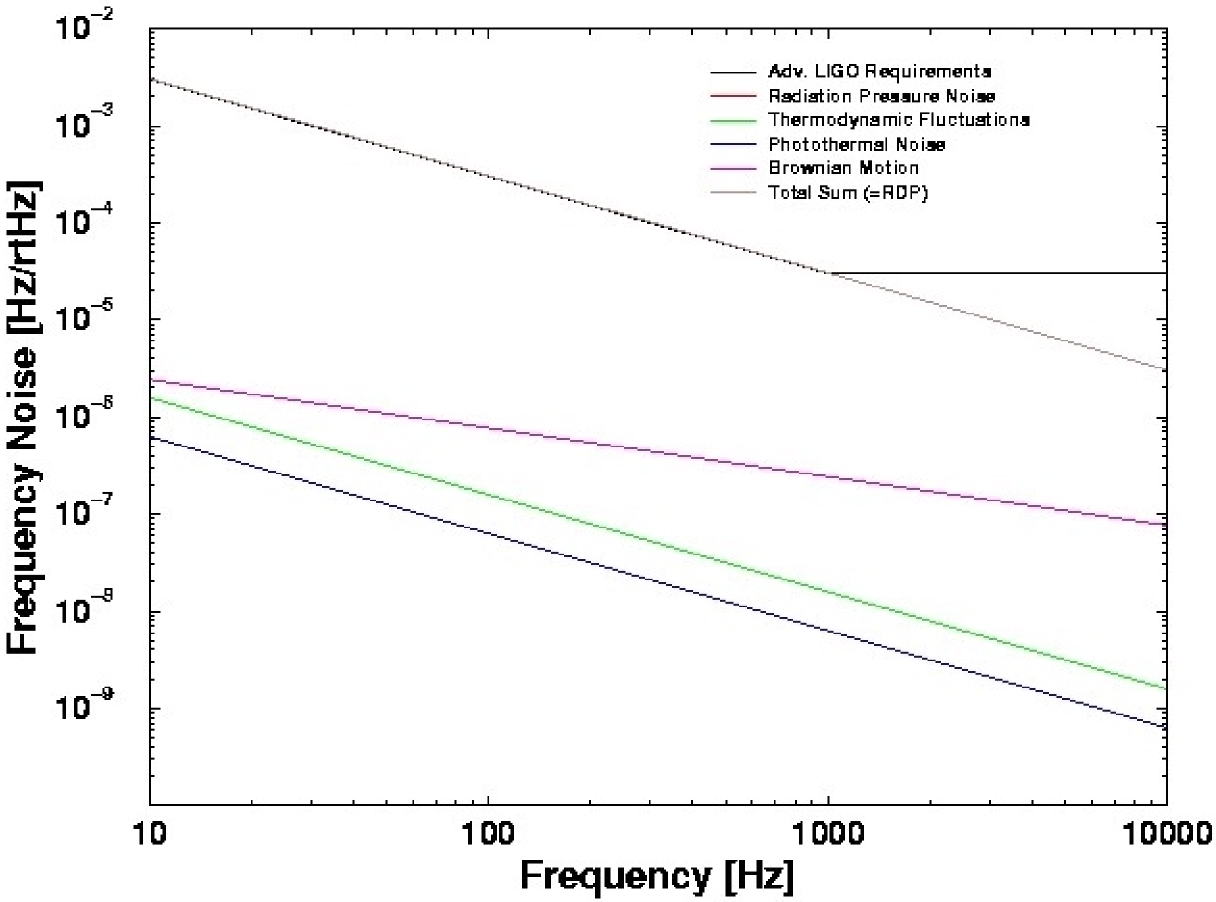
# Physical Layout

- Triangular cavity
- Triple-pendulum suspensions
- Fused silica mirrors
- Changes from the LIGO I mode cleaner:
  - o slightly increased length (Mirrors occupy HAMs 1 and 3)
  - o larger mass mirrors (Mirrors have 12-fold increase in mass)



# Frequency Noise

- Frequency stability is limited by technical radiation pressure noise over the entire frequency range.
- This stability and the allowed frequency noise of the field going into the main interferometer set the requirements on the frequency stabilization loop gains.
- Expected frequency noise (+ individual contributions to the MC frequency noise)



LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

# Beam Jitter Stabilization

- The mode cleaner acts as a spatial filter, providing passive stabilization of time-dependent higher-order spatial modes.
- Attenuation of higher-order modes (amplitude) for cold/hot cavity, assuming PSL jitter spec of $2 \times 10^{-6} /\mathrm{Hz}^{1/2}$

| ***Index (n+m)*** | ***Amplitude transmission*** | | ***Suppression Factor*** | | ***Output Jitter*** | |
|---|---|---|---|---|---|---|
| | **Cold** | **Hot** | **Cold** | **Hot** | **Cold** | **Hot** |
| 1 | 0.00096 | 0.00100 | 1040 | 1004 | 1.92E-09 | 1.99E-09 |
| 2 | 0.00078 | 0.00077 | 1281 | 1304 | 1.56E-09 | 1.53E-09 |
| 3 | 0.00185 | 0.00146 | 540 | 687 | 3.70E-09 | 2.91E-09 |
| 4 | 0.00162 | 0.00243 | 616 | 412 | 3.25E-09 | 4.86E-09 |
| 5 | 0.00077 | 0.00082 | 1299 | 1222 | 1.54E-09 | 1.64E-09 |
| 6 | 0.00101 | 0.00085 | 986 | 1174 | 2.03E-09 | 1.70E-09 |
| 7 | 0.01190 | 0.00332 | 84 | 302 | 2.38E-08 | 6.63E-09 |
| 8 | 0.00092 | 0.00128 | 1089 | 782 | 1.84E-09 | 2.56E-09 |
| 9 | 0.00079 | 0.00076 | 1259 | 1317 | 1.59E-09 | 1.52E-09 |
| 10 | 0.00216 | 0.00108 | 462 | 927 | 4.33E-09 | 2.16E-09 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 11 | 0.00145 | 0.00875 | 689 | 114 | 2.90E-09 | 1.75E-08 |
| 12 | 0.00076 | 0.00093 | 1311 | 1075 | 1.53E-09 | 1.86E-09 |
| 13 | 0.00108 | 0.00078 | 928 | 1281 | 2.16E-09 | 1.56E-09 |
| 14 | 0.00596 | 0.00170 | 168 | 587 | 1.19E-08 | 3.41E-09 |
| 15 | 0.00088 | 0.00193 | 1135 | 519 | 1.76E-09 | 3.86E-09 |

# Thermal Distortion

- Absorption → changes in effective radii of curvatures. Change of sagitta $\delta s$:

$$\delta s = \frac{\alpha}{4\pi\kappa} P_a$$

- $\alpha$, thermal expansion coefficient; $\kappa$ heat conductivity; and $P_a$ absorbed power.
- Based on coating absorption coefficient of 1 ppm, fused silica mirror:

$$\delta s \approx 3nm$$

- Radii of flats -> -733 m; $R$ of curved mirror changes from 26.9 m to 27.9 m
- Substrate acts as thermal lens for input and output beams:

$$\delta s = \frac{\partial n}{\partial T} \frac{P_a}{4\pi\kappa}$$

- Using (fused silica) 1 ppm/cm, effective sagitta change of transmitted beam is:

$$\delta s \approx 1nm$$

- The induced focal length of about 1 km neither changes the beam quality nor affects the mode matching.

# Alignment Procedure

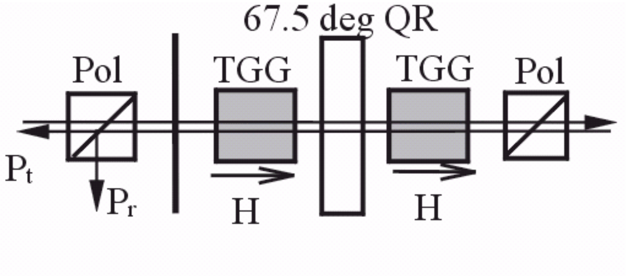
- Use fixtures for installation of the suspended mirrors
- Fixed targets for initial beam alignment using the PSL laser (suspensions need to accommodate these).
- In-air and in-vacuum resonance measurements for fine beam alignment
- Measure free spectral range for final length adjustment.
- Will be tested at LASTI.

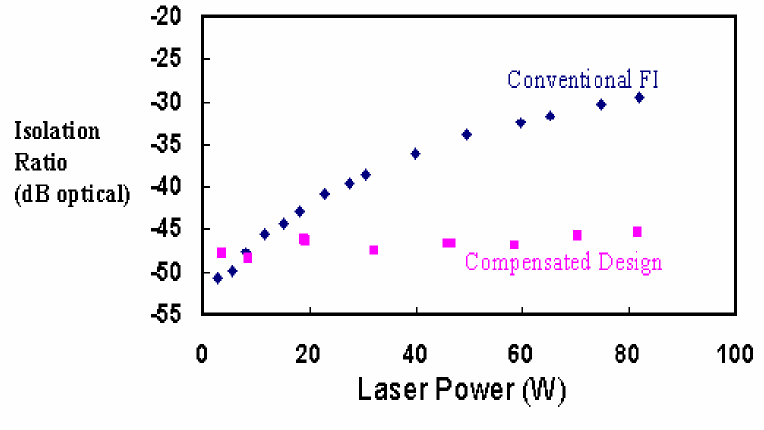
# Mode Cleaner Mode Matching

- Baseline system resembles closely LIGO I three-lens configuration.

# Faraday Isolator I

- Conventional FIs limited to ~20-30 dB isolation at high powers
  - » depolarization from thermo-elastic deformation
- Compensated crystal design approaches 45 dB isolation

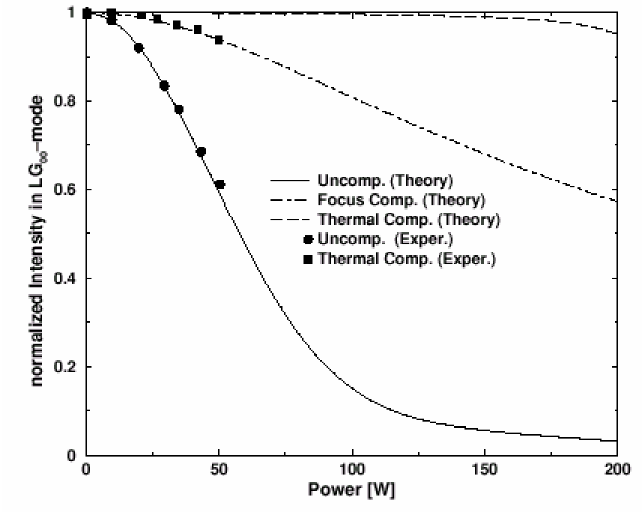


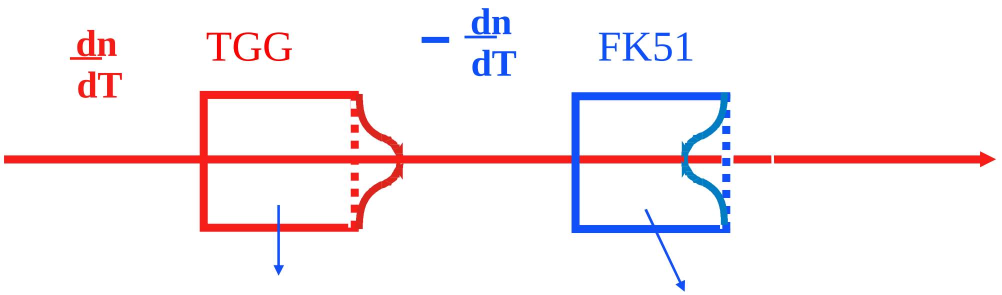


  - » limited by polarizers

# Faraday Isolator II

- Location of FI between MC and PRM
  - » isolates MC from IFO loss lock (rad pressure ‘kick’ to MC mirrors)
  - » no need to suspend: $\delta f = 1.5x10^{-12}\frac{Hz}{\sqrt{Hz}}\left(\frac{10Hz}{f}\right)^2\left(\frac{\delta x_{seismic}}{2x10^{-13}}\right)$
  - » thermal lensing in TGG a problem; but can be compensated

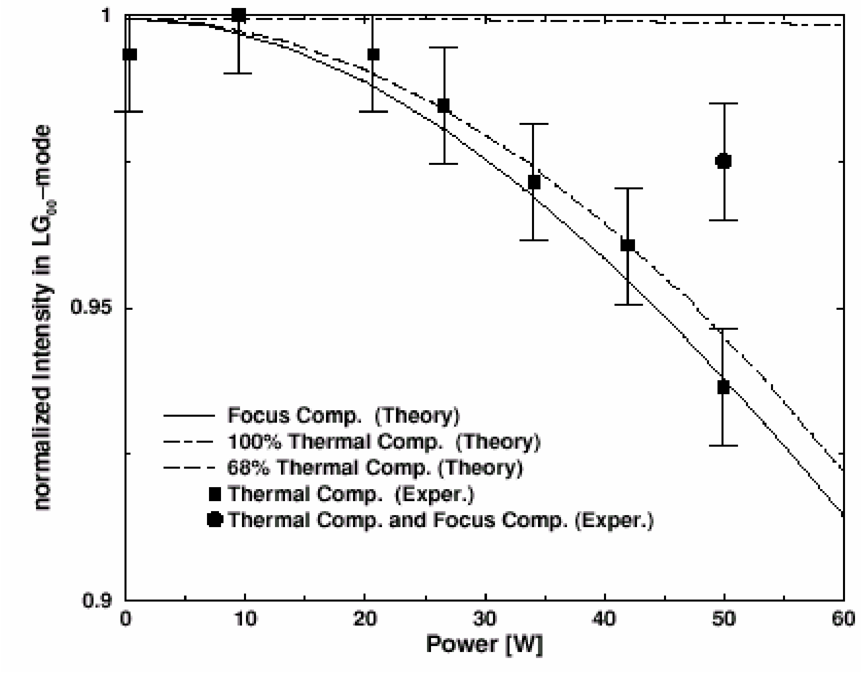




$$\begin{bmatrix} TEM_{\tilde{0}} \\ TEM_{\tilde{2}} \\ \dots \end{bmatrix} = \begin{bmatrix} M(\zeta, z) \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ \dots \end{bmatrix} \qquad \begin{bmatrix} 1 \\ 0 \\ \dots \end{bmatrix} = \begin{bmatrix} M^{-1}(\zeta, z) \end{bmatrix} \begin{bmatrix} TEM_{\tilde{0}} \\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

# Faraday Isolator III

- Experiment:
  - » highly absorbing TGG
  - » 97.5% TEM$_{00}$ mode at power levels of **150 W**
- FI Design Process
  - » screen for low $\alpha$ TGG
  - » build, test isolation unit
  - » determine optimal FK51 length for best compensation
  - » build, test integrated compensated FI



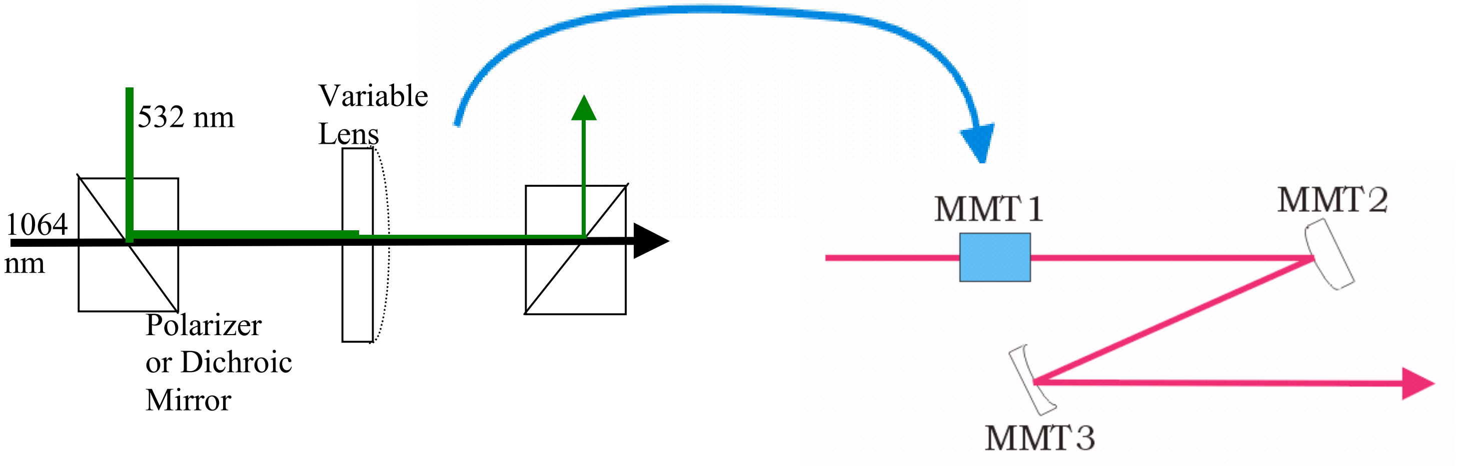
# Mode Matching Telescope

- Two mirror design
  - » LIGO I uses three mirrors
    - – can compensate for waist size, position mismatch
    - – requires (multiple) vacuum excursions
  - » MMT1 is small 3” optic (SOS)
    - – could be MC sized optic if stack resonances are a problem
  - » MMT2 is PRM-sized optic (both size and suspension)
- Third element is adaptive
  - » no vacuum excursions
- Detailed design needs final core optics configuration
- Pointing and alignment stability
  - » stacks,suspensions very quiet[1]; meets requirements

[1] LIGO-T000053-01-D “Cavity Optics Suspension Subsystem Design Requirements Document, P. Willems, et al.

# Adaptive Mode-Matching I

- Thermal effects in Advanced LIGO IFOs
  - sapphire core optics; 800 KW arm cavity powers; 2 operating points
- Measuring higher order LG modes possible
  - Bullseye design for LIGO I
- ➡ Adaptive MMT (no moving parts!)



# Adaptive Mode-Matching II

- variable lens material: OG590 Schott glass
  - transmittance @ 1064 nm: >0.9999 $P_{incident,}$ 532 nm: <0.00001 $P_{incident}$
  - scatter: 0.03 – 0.10 $mm^2$ of cross sectional area for 100 $mm^3$ volume
  - mounted directly to table
- heating laser: DPSS Nd:$VO_4$, 532 nm (could use different $\lambda$)
  - 10 W
  - amplitude and pointing stability TBD
  - waist: 6 mm at glass
- ·lensing
  - ·1064 waist: 2-3 mm
  - · ΔOPD @ 532 nm: ~$10^{-6}$ m/W; ΔOPD @ 1064 nm: ~ 0.2-0.3 x $10^{-6}$ m/W
  - · effective focal length range for 1064 nm: + 9.4 m to infinity

# Adaptive Mode-Matching III

- Preliminary Design Plan
  - detailed MMT design using 2 mirrors + variable lens
  - thermal modal modeling
    - optimal ratio of waist sizes
  - prototype table top demonstration
    - characterization of effective mode matching range
    - characterization of modal distortions

## Cost estimate (based on T. Frey work of summer 2001)

| | | |
|---|---|---|
| IO Subsystem Management | | 225,150 |
| IO Design | | 1,360,977 |
| IO Fabrication | | 3,170,122 |
| Modulation/jitter suppression | 3 x 195,426 | |
| Mirror blanks | 3 x 182,615 | |
| Mirror polishing | 3 x 212,200 | |
| Mirror coatings | 3 x 116,290 | |
| Metrology | 3 x 14,700 | |
| Isolator | 3 x 296,640 | |
| Tooling and installation | 116,500 | |
| Total | | 4,756,250 |

This is for 4 subsystems (i.e., includes IO components for LASTI)