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Input Optics (IO)

Technical Breakout Presentation

NSF Review of Advanced LIGO Project

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UF

May 31-June 2, 2006

LIGO-G060206-00-M

$3.35 M

Input Optics Major Functions

- The Input Optics conditions the light from the Pre-Stabilized Laser and sends it on to the main interferometer optical system

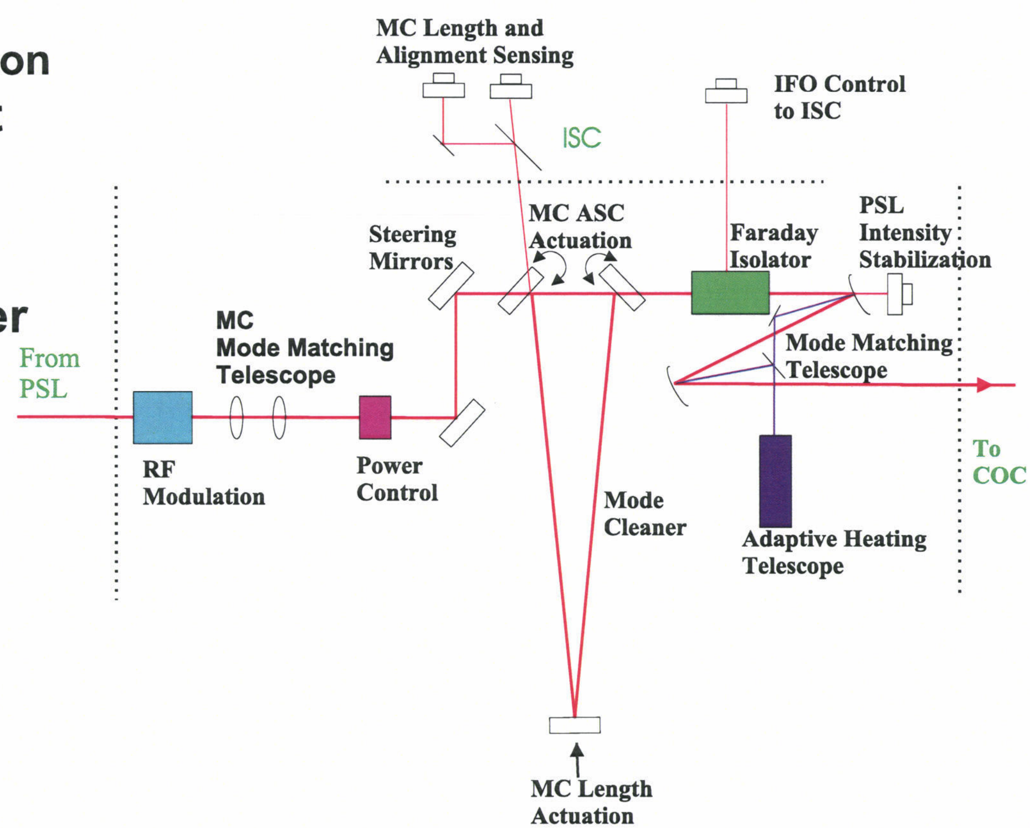
» **Interferometer power control**
  - **Continuous variable attenuation**

» **Phase modulation of the input light**
  - **Electro-optic modulation**

» **Spatially and temporally filter the light into the interferometer**
  - **mode cleaner**

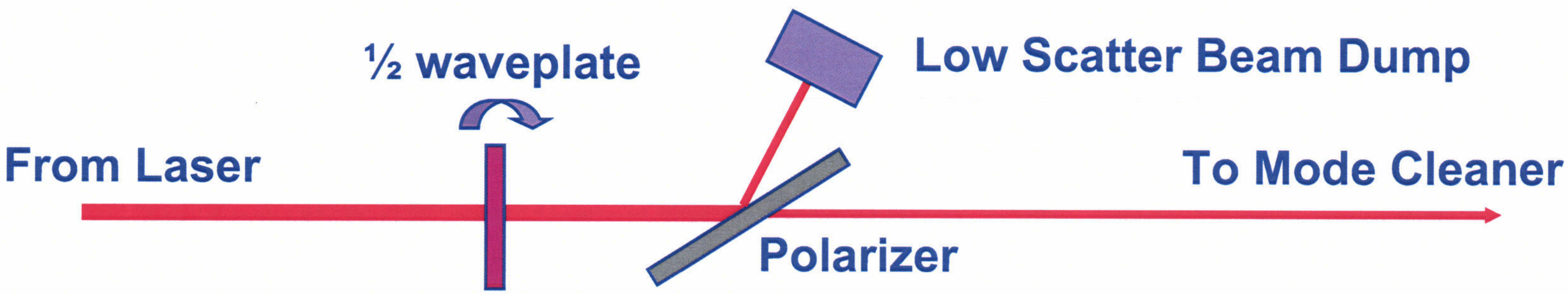
» **Optical isolation as well as distribution of interferometer diagnostic signals**
  - **Faraday isolation**

» **Mode match into the interferometer**
  - **beam-expanding telescope**
    - Adaptive for adjustable mode-matching



Power Control into the Interferometer

- Input Optics provides adjust power control into the interferometer
  - » Commissioning
  - » Low frequency (low power) operation
  - » High frequency (high power) operation
- Finely adjustable ½ waveplate and polarizer in combination



  - » Waveplate mounted on stepper stage
    - – 0.012⊕ accuracy → $\Delta = 6 \times 10^{-4}$ at ½ power point
      - ΔP ~ 75 mW into IFO for P = 90 W
      - ΔP_{armcav} ~ 350 W for P = 400 kW
    - – Software control to gently increase power
- High power, low scatter beam-dump
  - » 180 W → water-cooled dump

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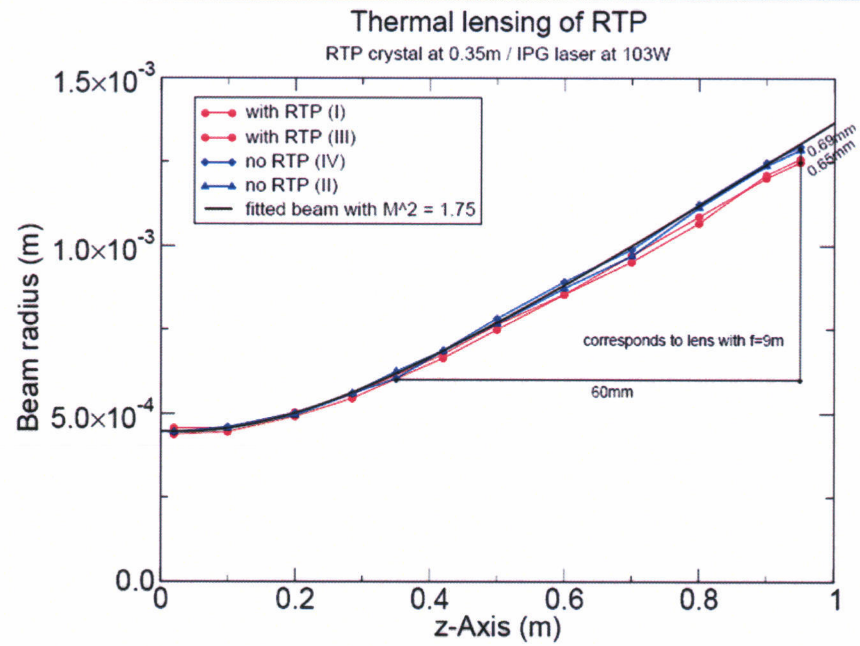
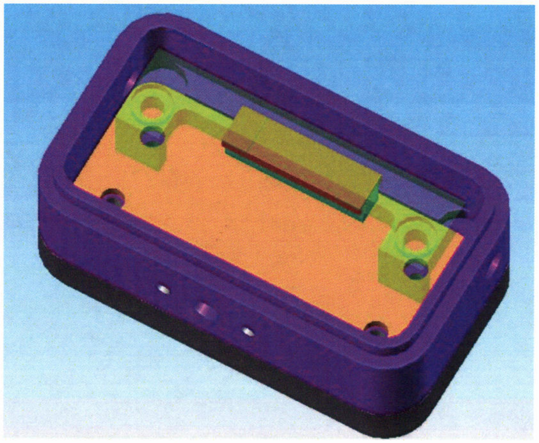
RF Modulation

$368 K

- **Requirements:**
  - » **Amplitude and phase stability:**
    - – **Amplitude: differential radiation pressure noise due to arm cavity carrier imbalance**
    - □ $\Delta m < (10^{-9}/m)(f/10\ \text{Hz})/\text{rHz}$
    - – **Phase: no direct coupling for DC readout, but possible couplings through auxiliary loops**
- **Modulators based on rubidium titanyl phosphate (RTP)**
  - » **Electro-optic response similar to $LiNbO_3$**
  - » **low absorption → low thermal lensing**
- **In-house design and build**
  - » **Matching circuit in separate housing**
- **Modified version will be implemented in initial LIGO upgrade**

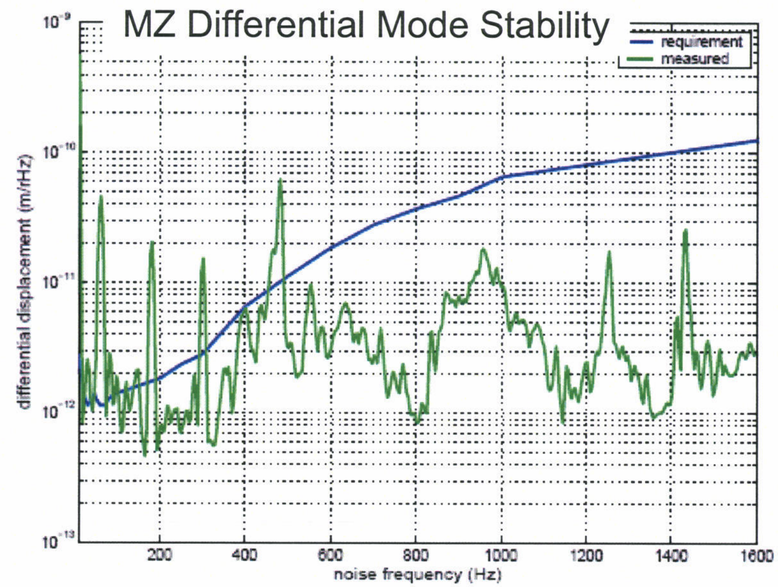


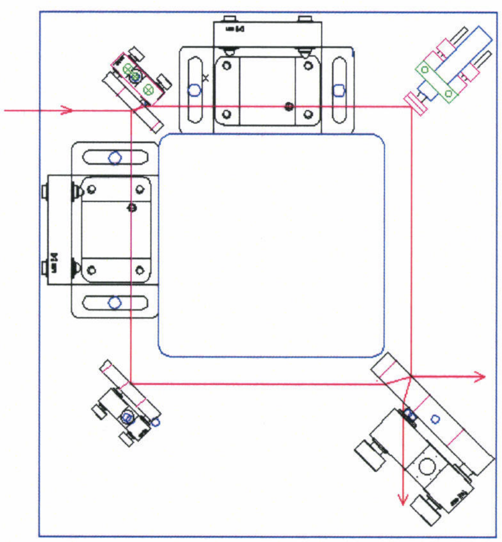


Mueller, LIGO T020022 (2002).
Mueller, et al., LIGO T020025 (2002).
UFGroup, LIGO E060003 (2006).

RF Modulation II

- **Modulation architecture needed to eliminate cross products**
  - » **Mach Zehnder architecture**
    - – **Requirement: differential arm motion → carrier-sideband phase noise → common mode frequency noise:**
    - □ **ΔL ~ 6 x 10^{-13} m/rHz in 20 – 80 Hz band**
  - » **Also looking at complex (AM/PM) modulation**





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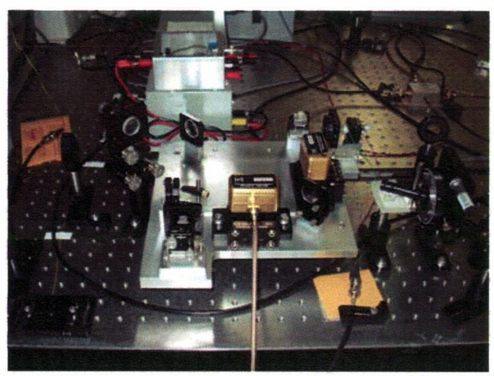

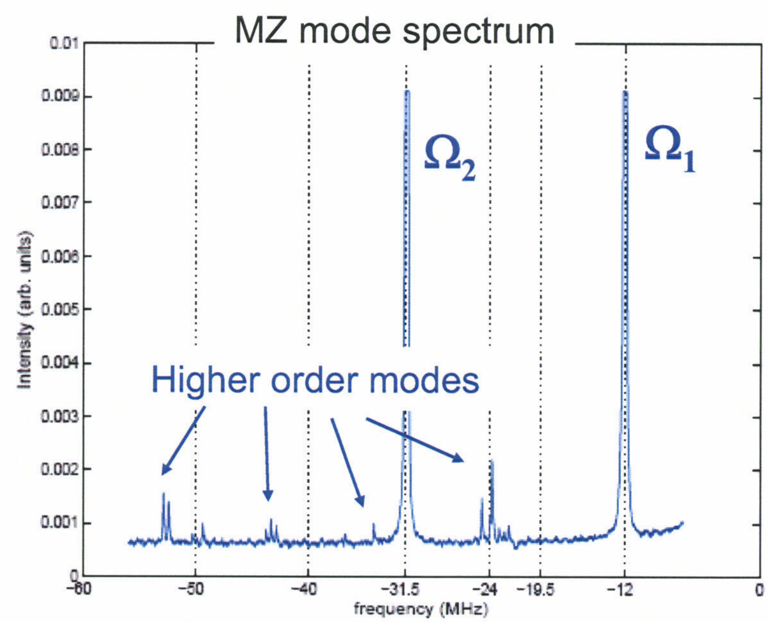

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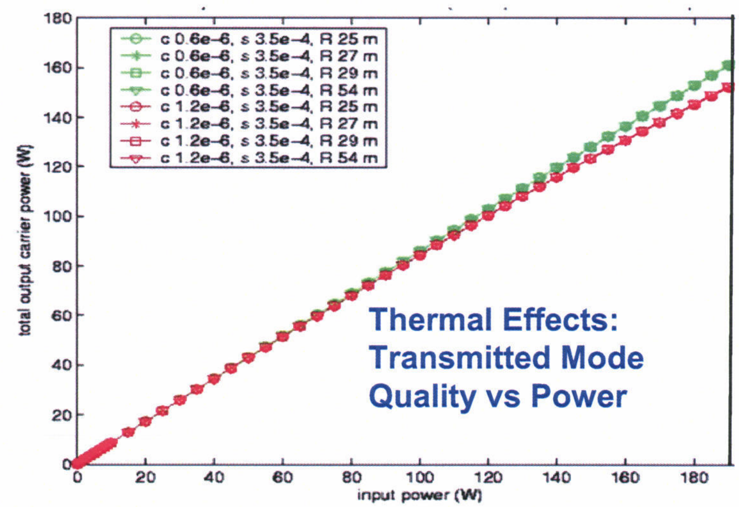
Mode Cleaner

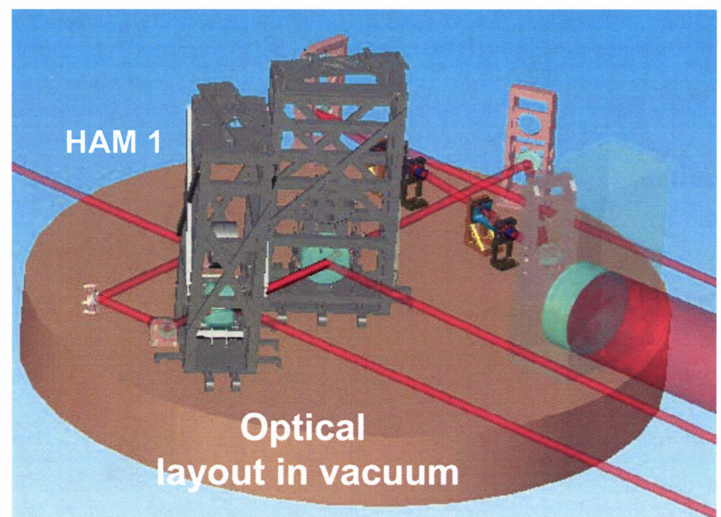
$970 K

- **Requirements:**
  - » **Frequency: noise allocated to Input Optics.**
    - – **$\delta\nu(f) < 3 \times 10^{-2}$ Hz/rHz (Hz/ f)**
  - » **Intensity: passive suppression above $f_p \sim 8$ KHz**
  - » **Jitter: couples with arm cavity mirror misalignments→ output mode cleaner → carrier intensity fluctuations**

$$\varepsilon_1(f) < \sqrt{\left(\frac{2.5\times10^{-5}}{f^2}\right)^2 + \left(5\times10^{-10}\right)^2}\,\frac{[2\times10^{-8}]}{\Delta\Theta_{ITM}}\,\frac{1}{\sqrt{Hz}}$$

- **Suspended triangular cavity in vacuum**
  - » Similar to current LIGO, but larger mirrors
- **Mode cleaner mirror specifications substantially complete**
- **Thermal effects in MC**
  - » Thermal modeling with Melody
  - » Compare with initial LIGO MC:
    - – **Current intracavity intensity: ~ 45 kW/cm^2**
    - – **AdvLIGO intracavity intensity: ~ 200 kW/cm^2**
  - » active jitter suppression before MC if required



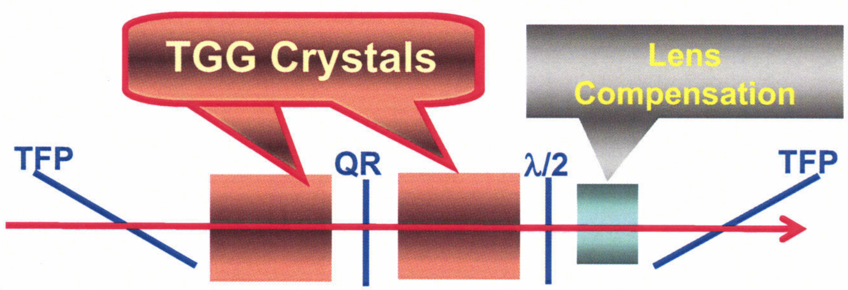


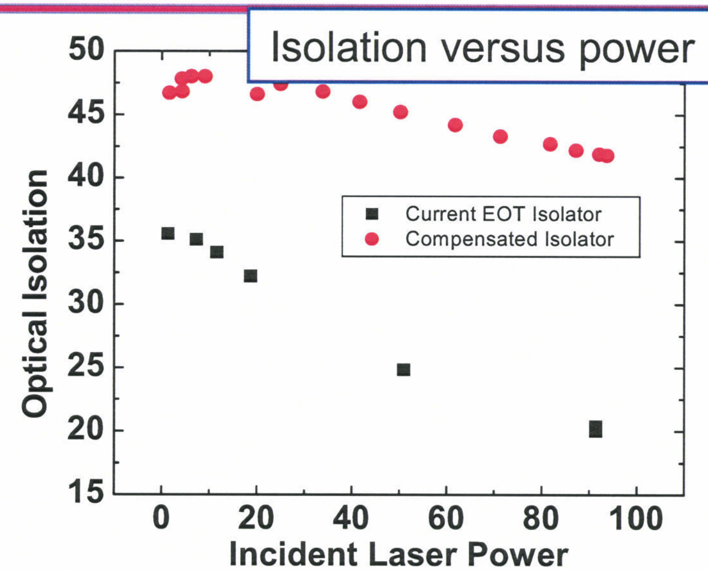
Faraday Isolator

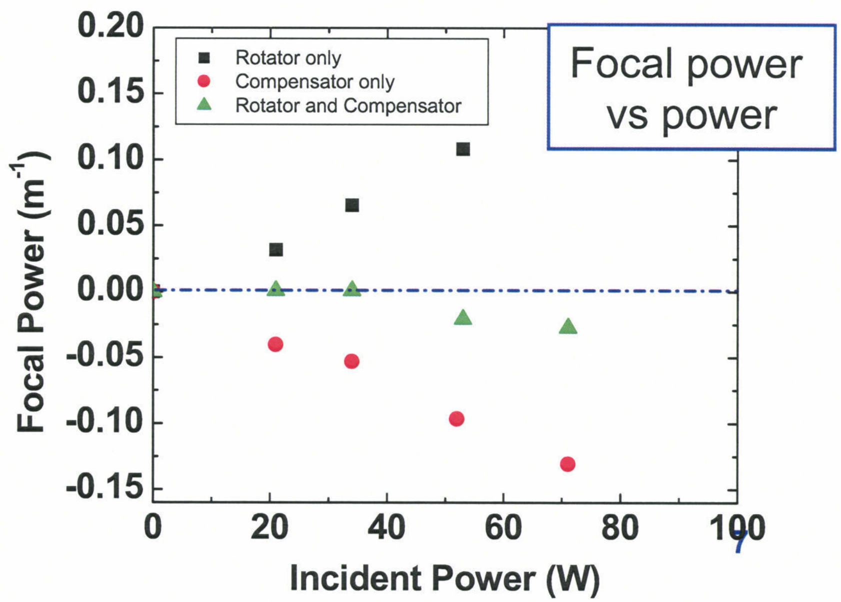
$847 K

- **Faraday Isolator designed to handle high average power**
  - » Increased immunity from thermal birefringence
    - – In excess of 40 dB at 100 W loading
  - » thermal lensing
    - λ/10 thermal distortions demonstrated
    - < λ/20 possible
- **Will be implemented in initial LIGO upgrade**

Khazanov, et al., J. Opt. Soc. Am B. 17, 99-102 (2000).
Mueller, et al., Class. Quantum Grav. 19 1793–1801 (2002).
Khazanov, et. al., IEEE J. Quant. Electron. 40, 1500-1510 (2004).



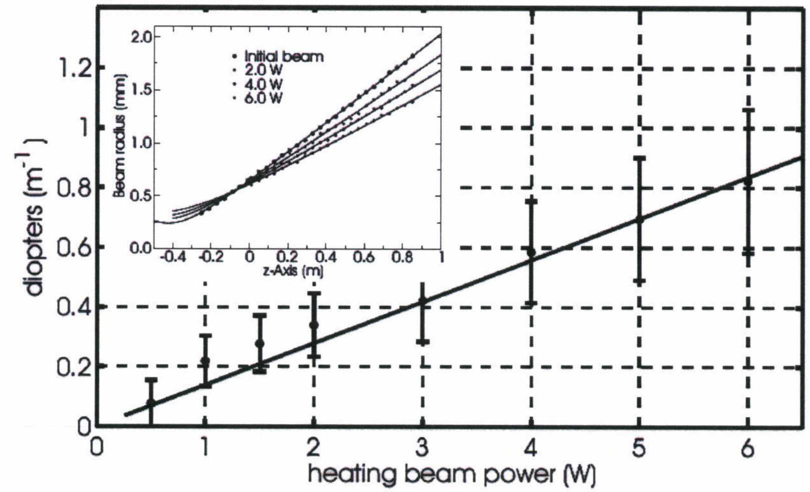


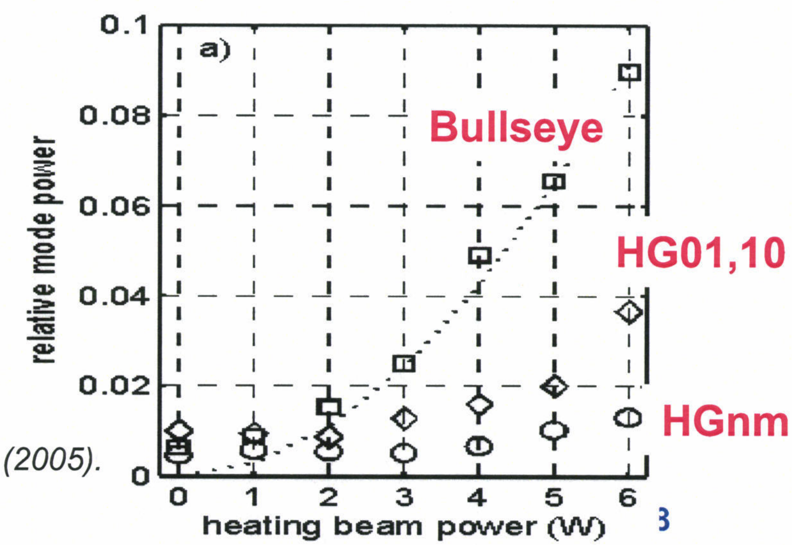


Adaptive Input Mode Matching Telescope (iMMT)

$1.01 M

- **Input Mode Matching Telescope – reflective three mirror design**
  - » Suspended optics
  - » Provide steering into IFO
  - » Almost identical to current design
- **Adaptive for added flexibility**
  - » Controlled thermal lens using auxiliary laser of two mirrors
  - » High dynamic range
    - – 1.6 m < $f_{thermal}$ < ◎
  - » Focal length and cavity mode analysis of table-top experiments





Delker, et. al., LIGO T970143-00 (1997)
Mueller, et al., LIGO T020026 (2002).
Quetschke, et al., Proc. SPIE Vol. 5876, p. 251-260 (2005).
Quetschke, et al., Opt. Lett. 31, 217-219 (2006).

Response to 2003 NSF Review of Advanced LIGO

From the report: "There appears to be no particular risk in either the Faraday isolators or the modulators. The investigators are encouraged to continue efforts to obtain improved quality of both TGG and RTP."

Response:

- modulators are ready for Advanced LIGO as is
  - •RTP robust against damage at power densities well in excess of Advanced LIGO.
  - •Thermal effects measured to 100W; scaling indicates performance superior to the $LiNbO_3$ modulators at current LIGO 1 conditions.

-FI tested to 200 W powers (double pass).
  - -reduced absorption in TGG (now 0.3% in a 9 mm long crystal),
  - -investigating methods for improving thermal drifts of the beams.

- Both modulators and FIs will be implemented in initial LIGO upgrade.
  - provide confidence for AdvLIGO design

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How we know we can build the AdvLIGO Input Optics

- AdvLIGO IO similar to initial LIGO
  - » UF designed and built the current LIGO Input Optics
  - » modifications for
    - Higher laser powers, more complex modulation method, adaptive mode matching
- Modulation
  - » RTP EOMs extensively tested for high power operation (initial LIGO upgrade)
  - » MZ prototype
    - Requirements not too difficult to meet; prototype working
  - » Complex modulation (AM/PM) also under development
- Mode Cleaner
  - » Experience from initial LIGO
    - MCs have been operating for 10000s hrs at high powers
  - » Larger (heavier) mirrors
  - » Thermal modeling
- Faraday Isolator (initial LIGO upgrade)
  - » Novel compensated design tested to 100 W (200 W in double pass)
- Mode Matching telescope
  - » Three mirror design same as initial LIGO
  - » Laser adaptive telescope based on bullseye sensing and CO_2 laser heating
    - TCS experience + UF table-top prototype CO_2 laser adaptive telescope

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Input Optics Major Tasks Remaining

- IO partially through preliminary design
- Electro-optic modulation
  - » Implementation of RTP modulators in initial LIGO upgrade (2008)
  - » Finish development of Mach-Zehnder modulation (Aug 2006)
  - » Finish development of complex modulation (Sept 2006)
    - – Choose between the two (Sept 2006)
- Mode Cleaner
  - » Very long term damage testing of mirror coatings (May 2007)
    - – If warranted, implement finesse reduction
  - » Scattered light calculation (July 2006)
- Faraday Isolator
  - » Implementation of compensated isolator in initial LIGO upgrade (2008)
    - – Choice of polarizers
    - – Vacuum compatibility
- Adaptive Input Mode Matching Telescope
  - » Layout in the vacuum system (March 2008)
    - – Depends on specifics of recycling cavity design
  - » Servo design (Nov 2008)
    - – Similar to TCS
- IO Final Design Review (Dec 2008)