# Input Optics

Technical Status
NSF Review of Advanced LIGO Project

David Reitze
David Tanner
University of Florida

# IO Functions

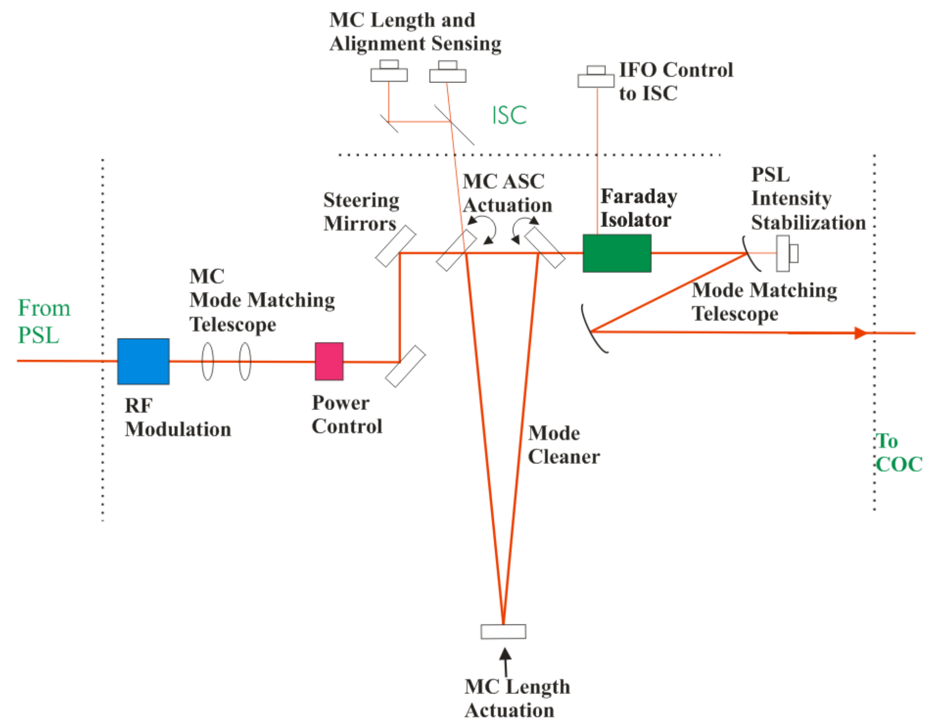
Project cost for IO is $4.37M

The Input Optics (IO) conditions the PSL laser light and delivers it to the interferometer.

It provides:

- RF modulation for length and alignment control functions
- Power control
- Laser mode cleaning and frequency stabilization
- Isolation of laser from interferometer reflected light
- Optical signal distribution to length and alignment control
- Mode matching to recycling and arm cavities
- Design and fabrication of small PRMs and SRMs

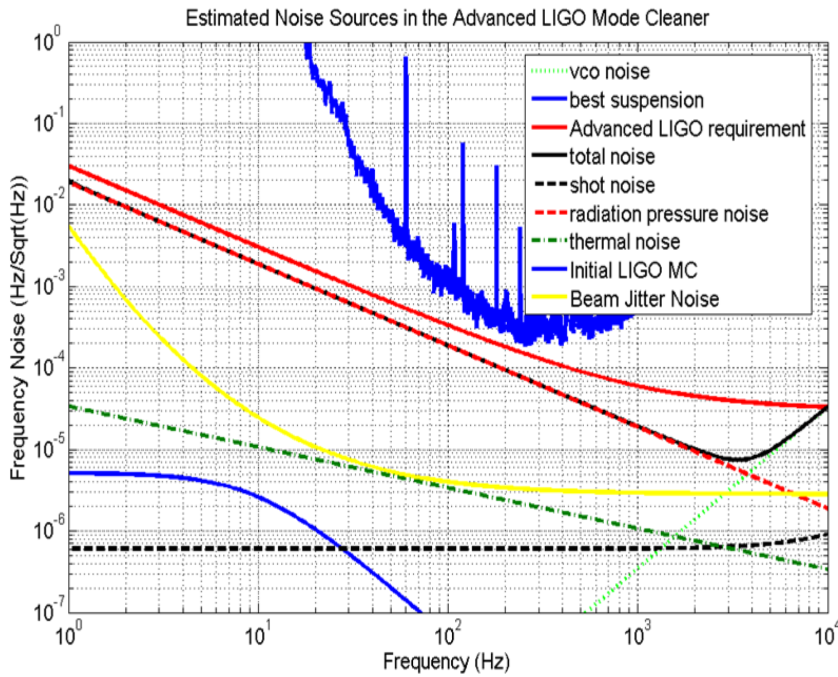
The IO has interfaces with many aLIGO other subsystems




PSL = pre-stabilized laser
COC = core optical components
IMC = input mode cleaner
ISC = interferometer sensing and control
PRM = power recycling mirror
SRM = signal recycling mirror

# IO Requirements I

- Phase modulated light:
  - » Straight interferometer $f_1$ ~9.1; $f_2$ ~45.5 MHz, $f_{IMC}$ ~24.1 MHz
  - » Folded interferometer $f_1$ ~8.7; $f_2$ ~43.4 MHz $f_{IMC}$ ~23.0 MHz
  - » Modulation index range for $f_{1,2}$ $\Gamma$ = 0.1-0.8
  - » RF amplitude modulation: $\Delta\Gamma < 10^{-9}/\Gamma$ (10 Hz)
- Power control:
  - » Operate from 1 to 165 W
- Mode cleaning:
  - » Suppress laser beam jitter by 250x
  - » Provide intermediate length standard for laser frequency stabilization for ISC

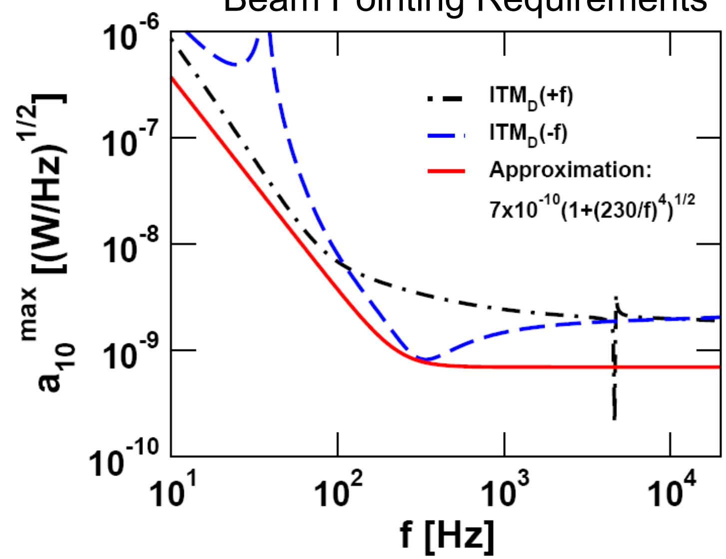



Modeled noise sources in the input mode cleaner. Solid red line is the requirement. The solid black line is calculated noise, dominated by radiation pressure noise.
(The upper blue line is the initial LIGO IMC measured frequency noise)

# IO Requirements II

- Optical isolation and beam routing via Faraday isolator:
  - » >30 dB isolation
  - » Deliver diagnostic beams to interferometer sensing and control system
- Mode matching:
  - » PSL → modulator
  - » modulator → input mode cleaner
  - » Input mode cleaner → power recycling cavity
  - » *Minimal thermal modal distortions*
- High overall optical throughput
  - » > 75%
- Stable power and signal recycling cavities:
  - » Incorporates beam expanding/reducing telescope size to match arm cavities
  - » IO designed telescope, specifies radii of curvature, purchases small RMs

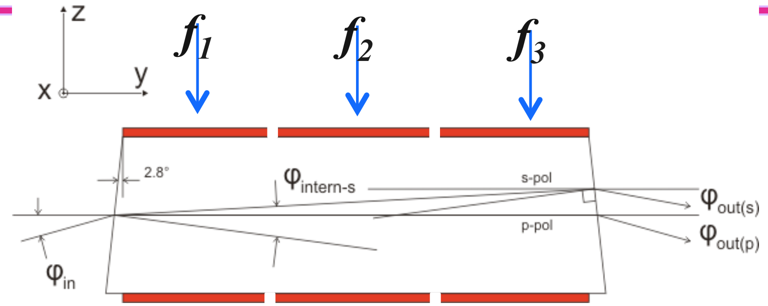
Beam Pointing Requirements

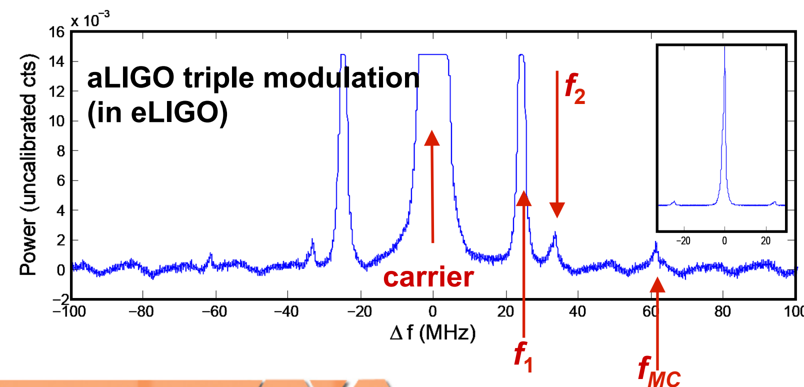


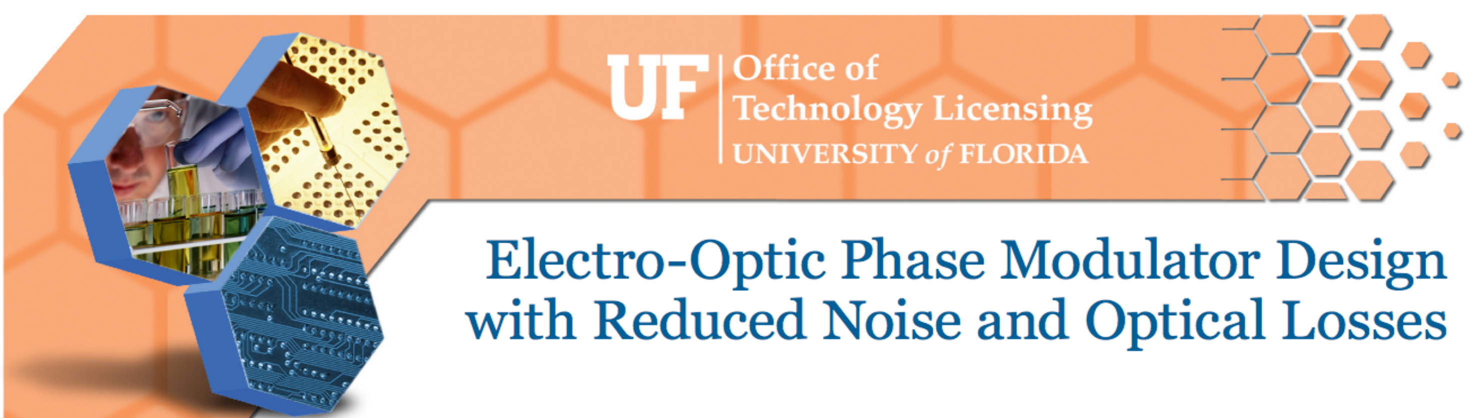

REFL = interferometer reflected beam
ISC = interferometer sensing and control
PSL = pre-stabilized laser
EOM = electro-optic modulator
IMC = input mode cleaner
PRC = power recycling cavity
SRC = signal recycling cavity

# Modulator: eLIGO certified

- Three electrodes – one crystal
- Wedged cut to suppress amplitude modulation
- RF matching circuit in separate housing
- Rubidium titanyl phosphate
  - » High damage threshold
  - » Low absorption (~50 ppm/cm)
- *Operated in eLIGO for 2 years; no problems*
  - » Also tested at 100 W levels for 300+ hours
- Patented by UF

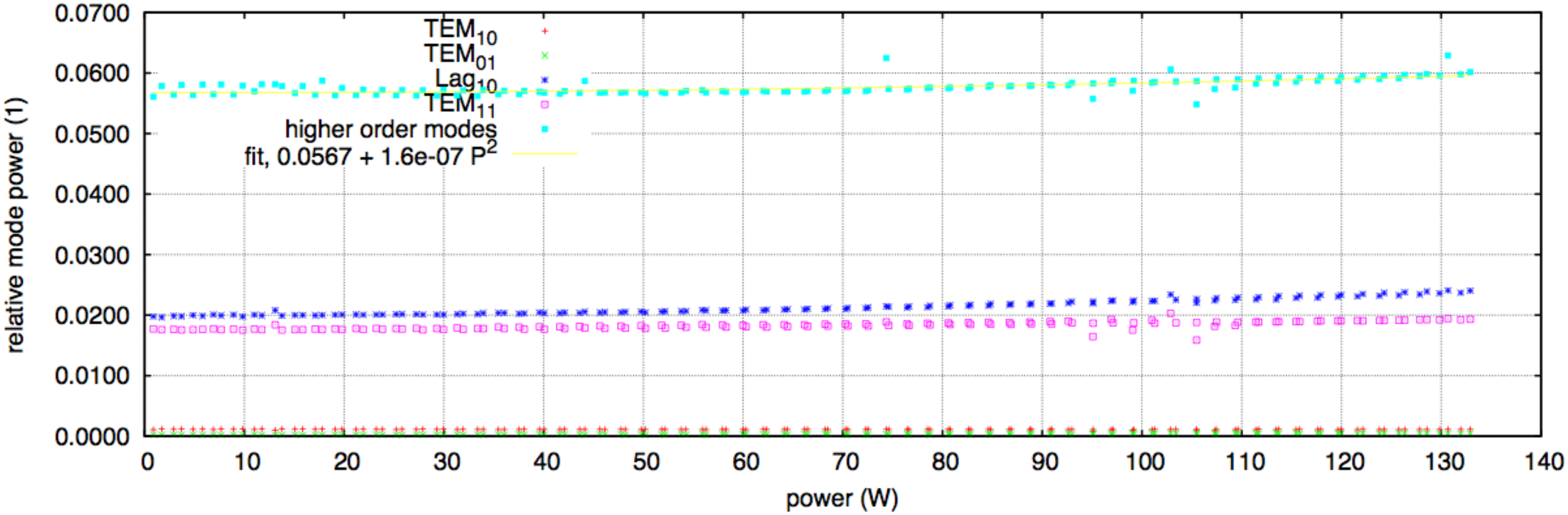


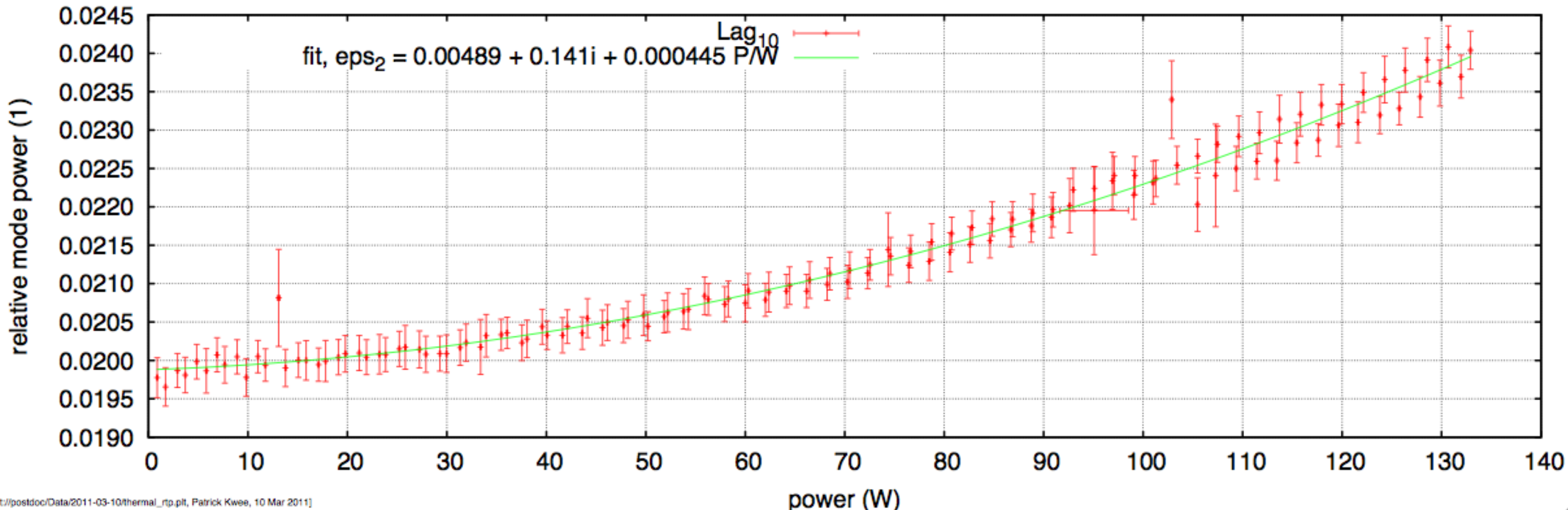



# Thermal modal distortions at aLIGO laser power

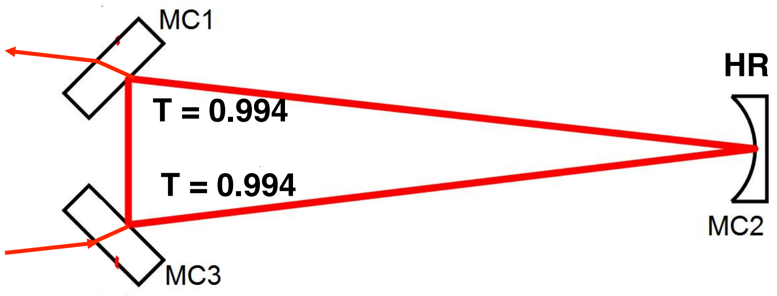
**Data from Patrick Kwee, AEI**



# Input Mode Cleaner Design Concept

- Triangular ring cavity design
- Length, *L/2* = 16.5 m (straight); 17.3 m (folded)
- FSR = 9.1 MHz (straight); 8.7 MHz (folded)
- Finesse ~ 520
  - » $P_{store}$ = 23,200 W (@ 165 W input)
- All three mirrors on "HAM small triple suspensions"
- Low coating absorption – minimize thermally-induced modal distortions
  - » 0.5 ppm (goal); 1.0 ppm (required)
- Low scatter loss: < 30 ppm/mirror




FSR = free spectral range
SUS = suspensions subsystem
HAM = horizontal access module chamber

# IMC mirror phase maps

**Measurement Parameters**

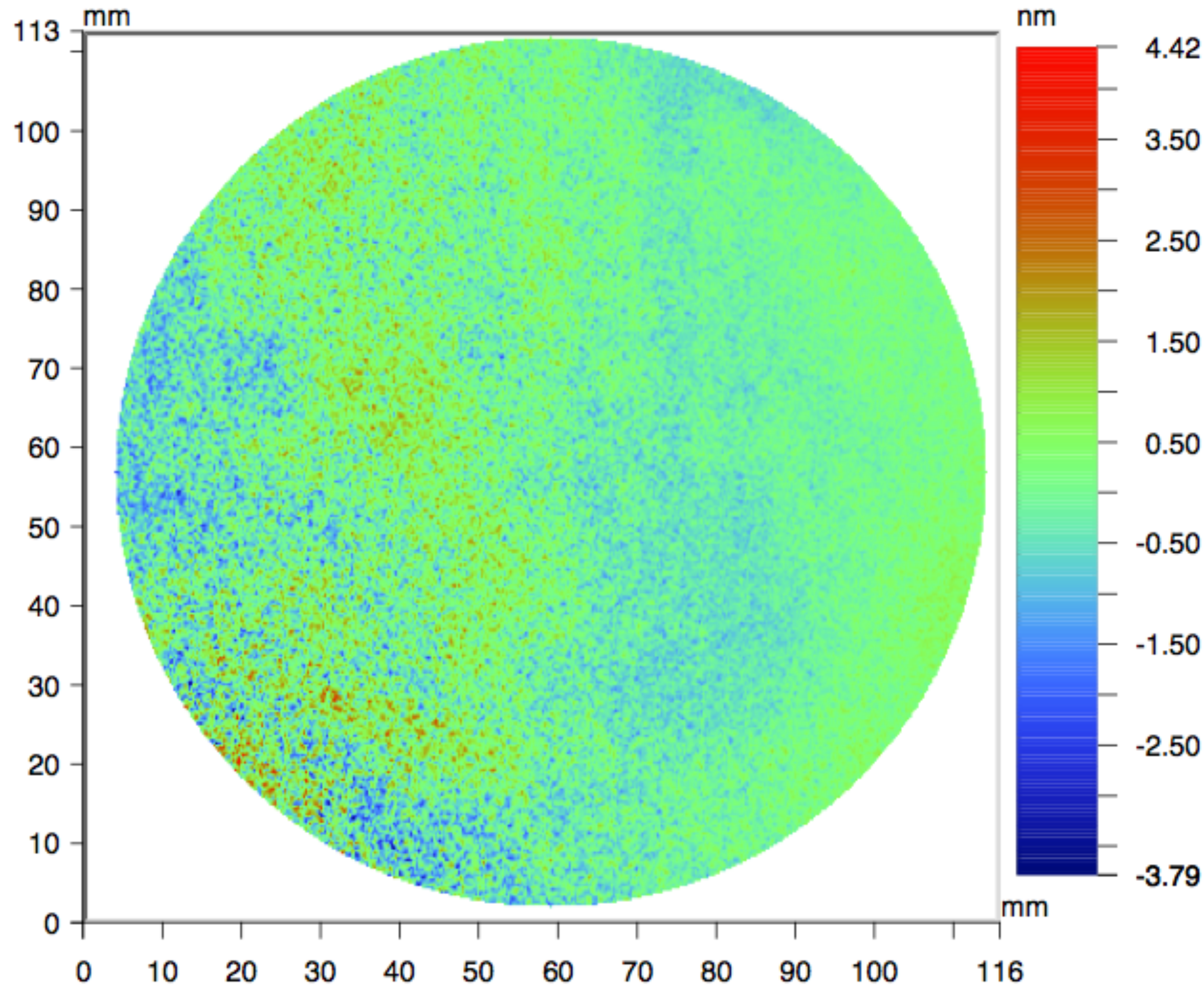
| | |
|---|---|
| File: | WYK9A |
| Wavelength | 1.06 um |
| Wedge | 0.50 |
| X/YSize | 438 X 365 |
| Pixel size | 265.05 um |
| Date | 09/22/2010 |
| Time | 13:36:40 |
| Averages | 16 |

**Analysis Results**

| | |
|---|---|
| Ra | 0.428 nm |
| Rms | 0.579 nm |
| 20 Pt. PV | 7.090 nm |
| 2 Pt. PV | 8.20 nm |

**Analysis Parameters**

| | |
|---|---|
| Terms | Tilt Power Astig |
| Masks: | Detector Mask |
| Filtering | None |
| Data Restore | Yes |
| Valid Points | 116281 |



LIGO

UNIVERSITY of FLORIDA

# IMC mirror phase maps

### Measurement Parameters

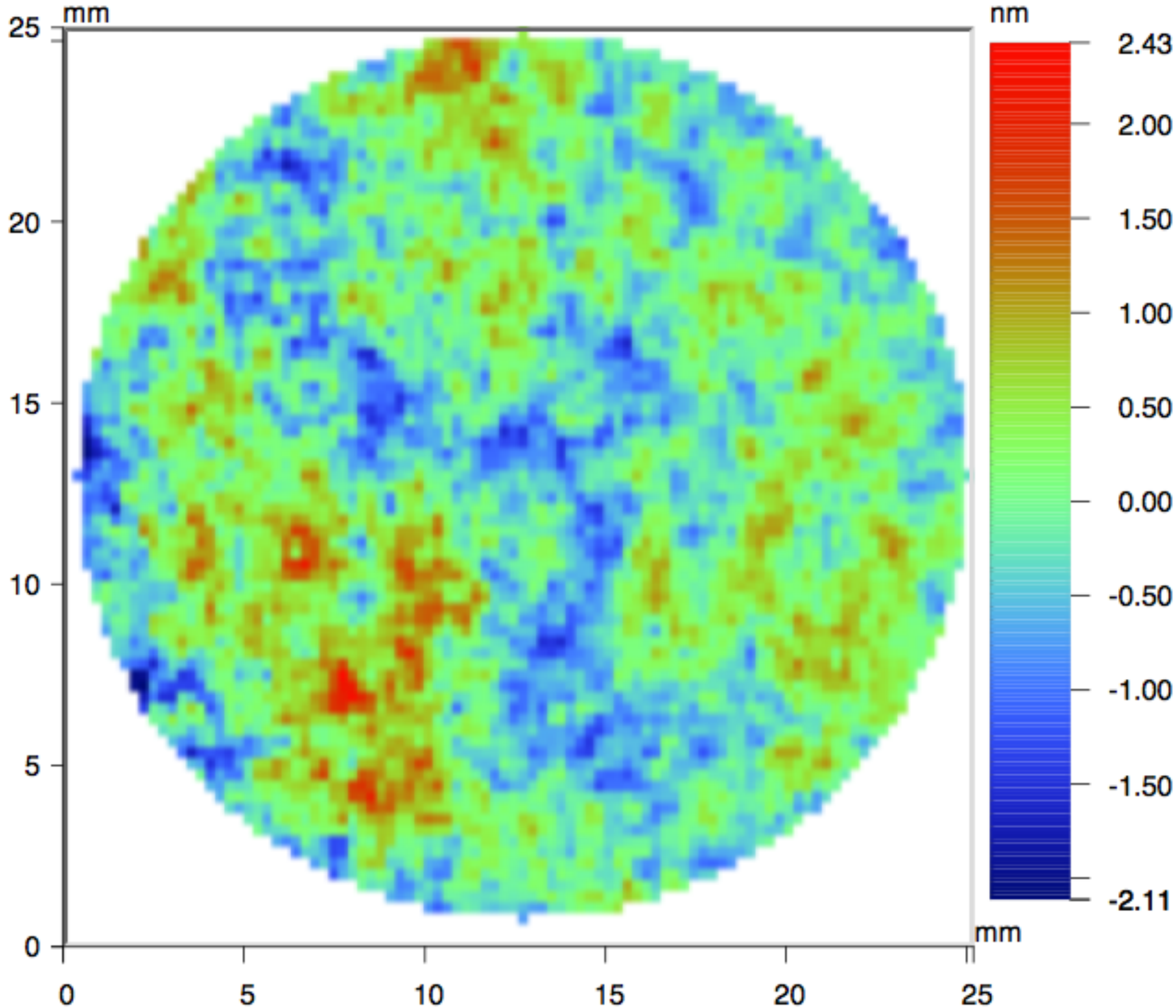
| | |
|---|---|
| File: | WYK36 |
| Wavelength | 1.06 um |
| Wedge | 0.50 |
| X/YSize | 96 X 83 |
| Pixel size | 265.05 um |
| Date | 09/22/2010 |
| Time | 13:40:08 |
| Averages | 16 |

### Analysis Results

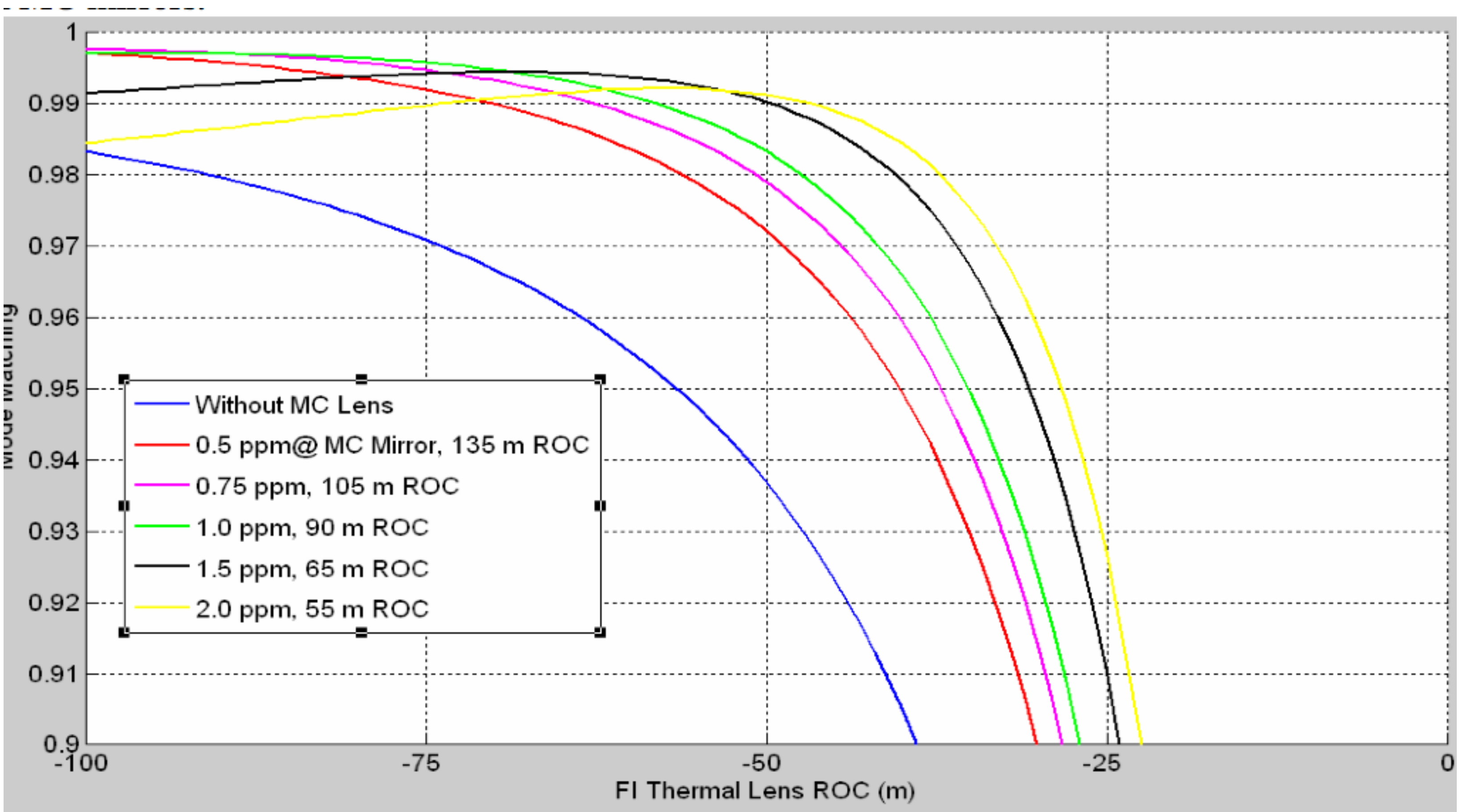
| | |
|---|---|
| Ra | 0.457 nm |
| Rms | 0.574 nm |
| 20 Pt. PV | 3.431 nm |
| 2 Pt. PV | 4.54 nm |

### Analysis Parameters

| | |
|---|---|
| Terms | Tilt Power Astig |
| Masks: | Det Anl Trm Masks |
| Filtering | DBP (0.04/2/mm) |
| Data Restore | Yes |
| Valid Points | 5895 |



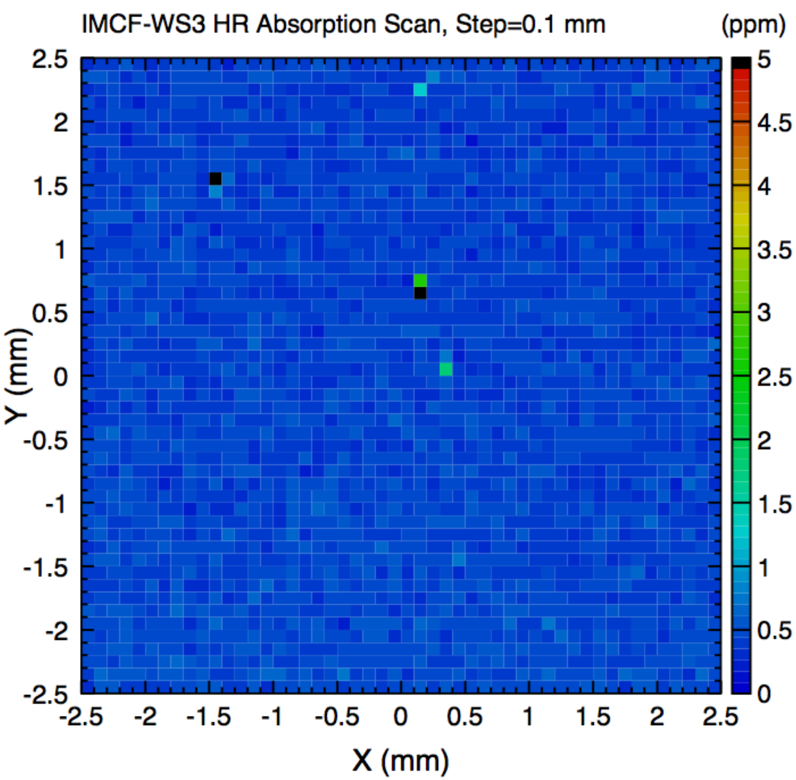
# Thermal effects in the IMC

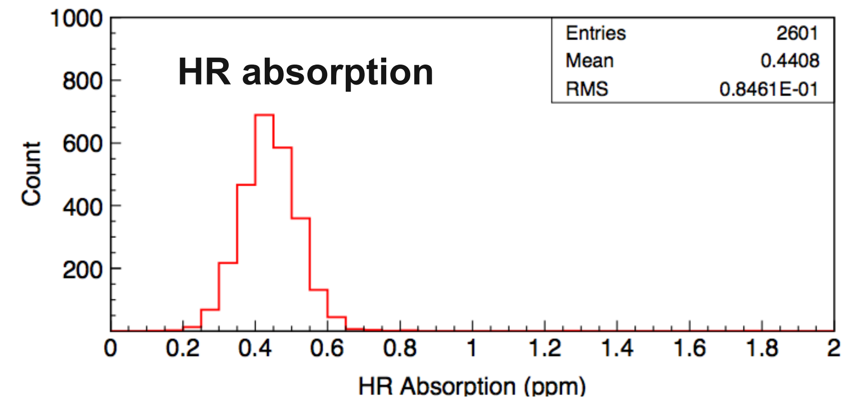


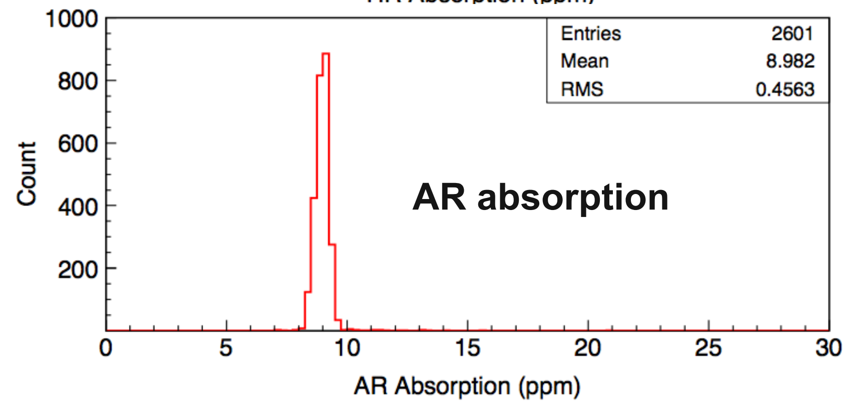

**Substrate Thermal Lensing in Mode Cleaner, LIGO- T070095-00-E**

# IMC Mirror Absorption

## MCF-WS3 witness sample absorption scan

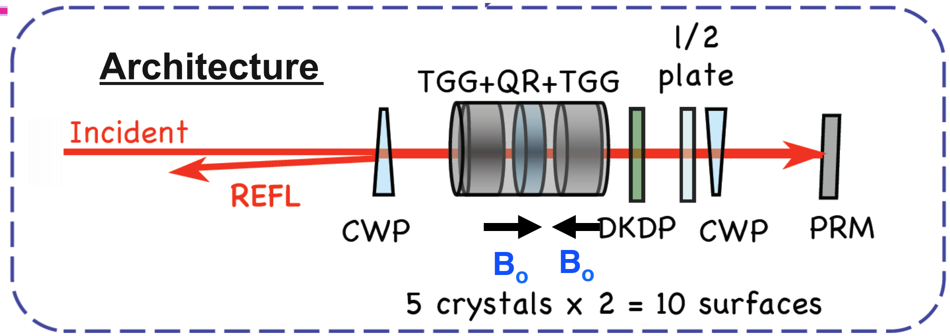


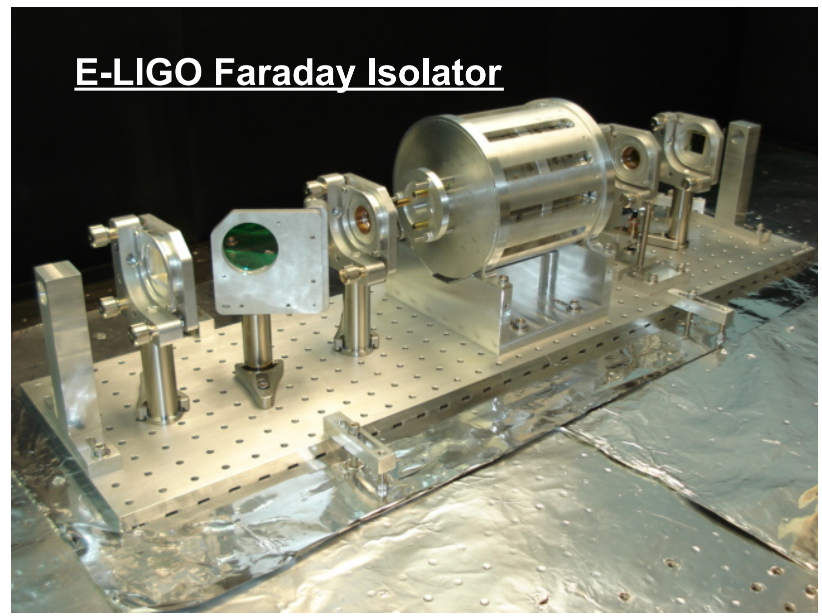



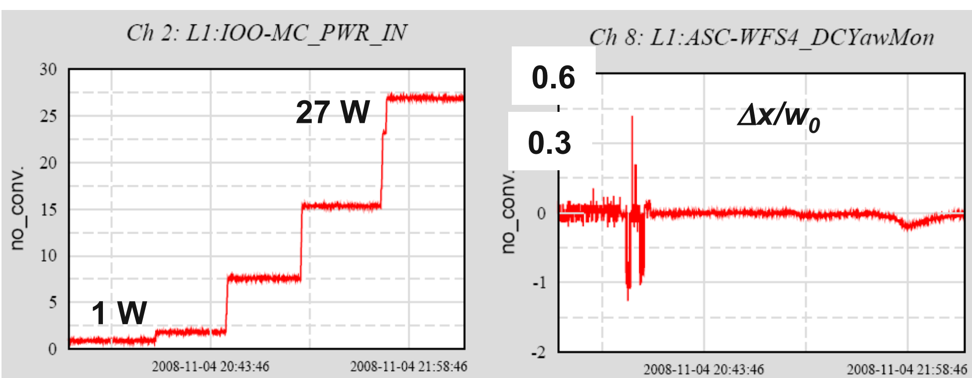
# Input Faraday Isolator

- Another battle-tested eLIGO component
  - Operating at ~ 10 - 20 W power levels over two years with no problems
  - Prototype tested to 100 W (100 hours)
  - Adjustable ½ waveplate for in-vacuum tuning of isolation ratio




**Thermal angular drift of back-rejected beam**

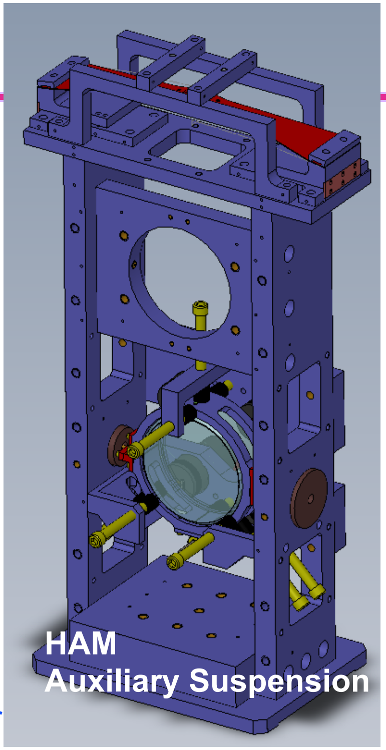


# HAM Auxiliary Suspensions: Requirements and Design

- The HAM Auxiliary suspensions are single stage suspensions that route the beam from the IMC to the PRM

- Requirements:
  - 10 mrad pitch, yaw range
  - Resonant frequencies < 10 Hz
  - Passive damping
  - Displacement noise $10^{-11}$,$10^{-14}$ m/Hz$^{1/2}$ (10 Hz, 100 Hz)
  - RMS pointing to < 1 urad
  - In-band pointing < $6 \times 10^{-13}$ rad/Hz$^{1/2}$ (100 Hz)

IMC = input mode cleaner
PRM = power recycling mirror

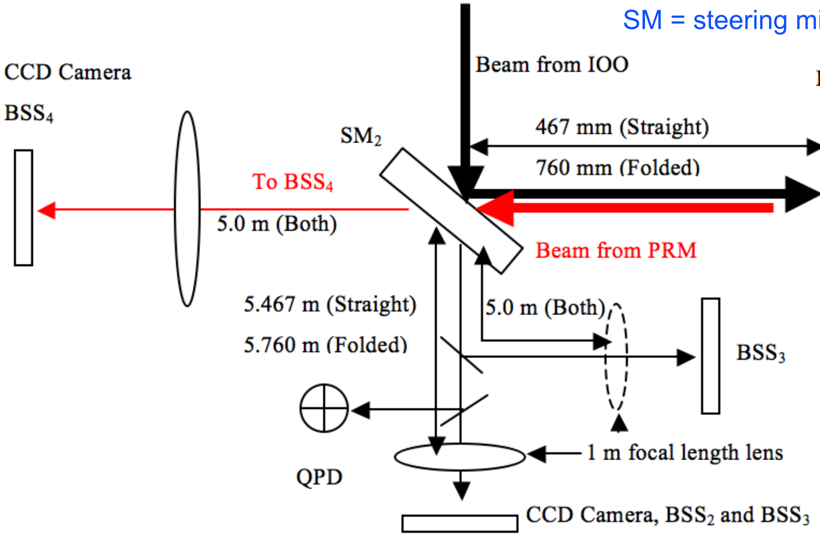



| Name | Description | Model | Measured Value |
|---|---|---|---|
| fPitch1 | Frequency of first pitch/x normal mode | 0.98 Hz | 0.95 Hz |
| fPitch2 | Frequency of second pitch/x normal mode | 1.12 Hz | 1.04 Hz |
| fYaw | Frequency of yaw mode | 0.76 Hz | 0.80 Hz |
| fBounce | Frequency of vertical motion | 7.19 Hz | 6.14 Hz |
| fRoll1 | Frequency of first roll/y normal mode | 1.00 Hz | 1.00 Hz |
| fRoll2 | Frequency of second roll/y normal mode | 10.63 Hz | 8.97 Hz |

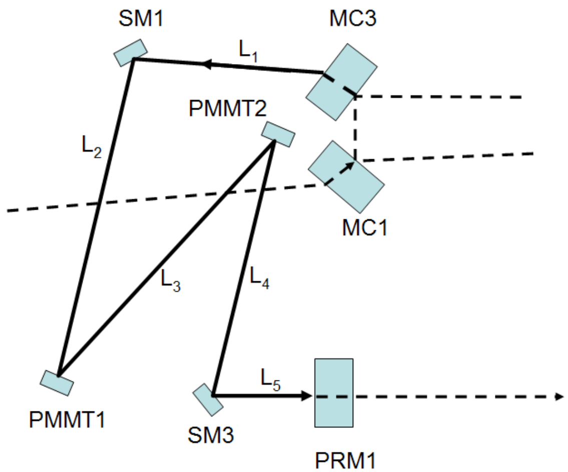
# Mode Matching Design Concept

- IO mode-matching allocated in two phases:
  - » PMMTs mirrors mode-match from IMC to power recycling mirror
  - » PRM, PR2, PR3 mode-match into arm cavities
- PMMT telescope designed to be very insensitive to position
- Mode-matching sensors (CCDs) provide online sensing of mode size

BSS = Beam Size Sensor
PRM = power recycling mirror
SM = steering mirror




Optical layout for the BSS sensors for monitoring mode matching into the interferometer



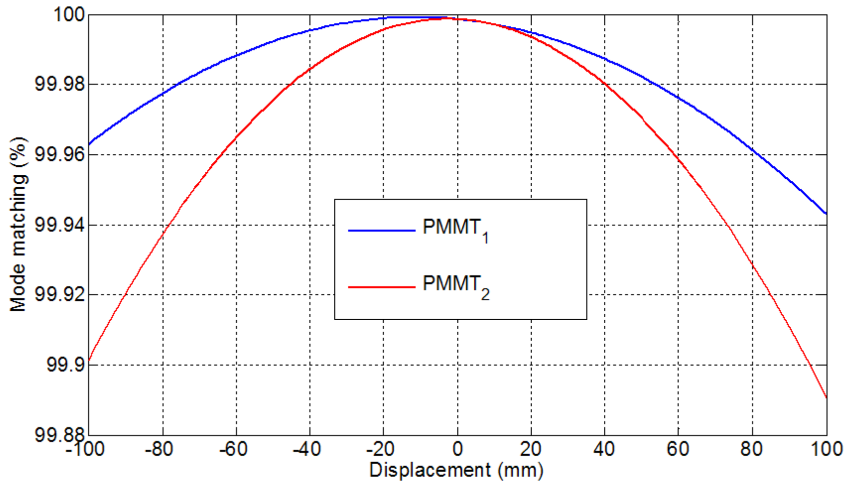
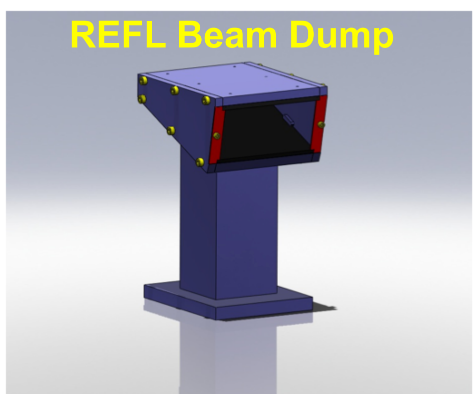



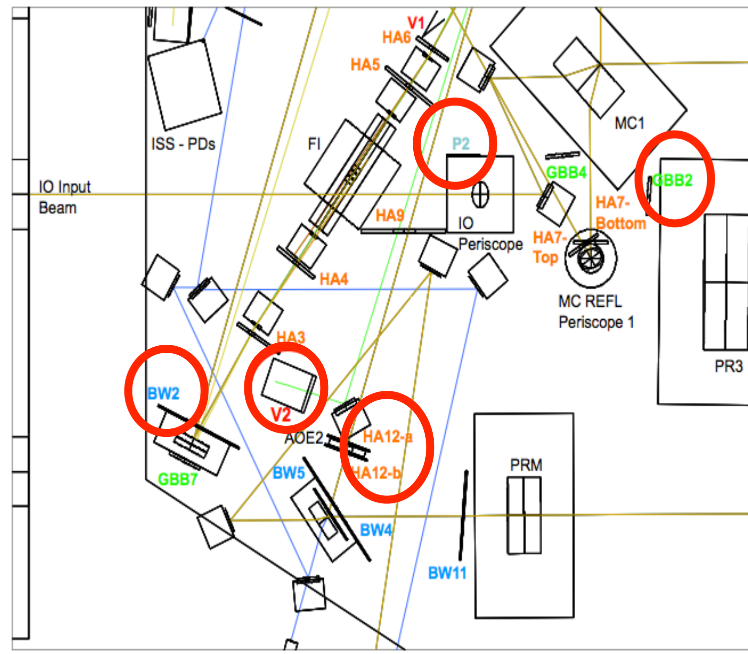

Fig. 4: Mode matching as a function of positioning error for $PMMT_1$ and $PMMT_2$ mirror for the straight interferometer shown as displacement from the designed value.

# IO Baffles

- The IO has a high density of high power lasers beams in a very confined space.
- The IO baffles serve two purposes:
  - » To prevent scattered light from entering sensing the interferometer and sensing photodiodes
  - » To protect the in-vacuum components from laser damage
- A variety of IO baffles: parking beam dumps, suspensions, hard apertures, scrapers, ghost beams
- Layout in Zemax

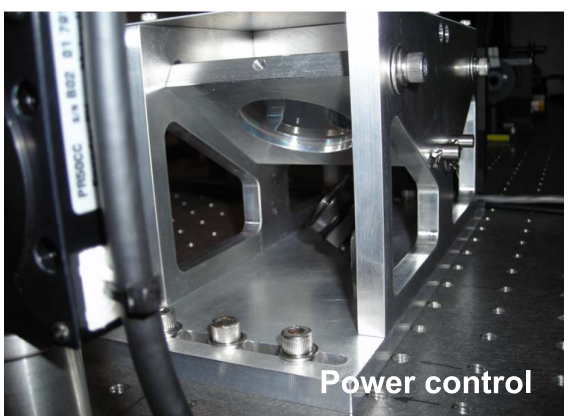




**Baffles in HAM2**

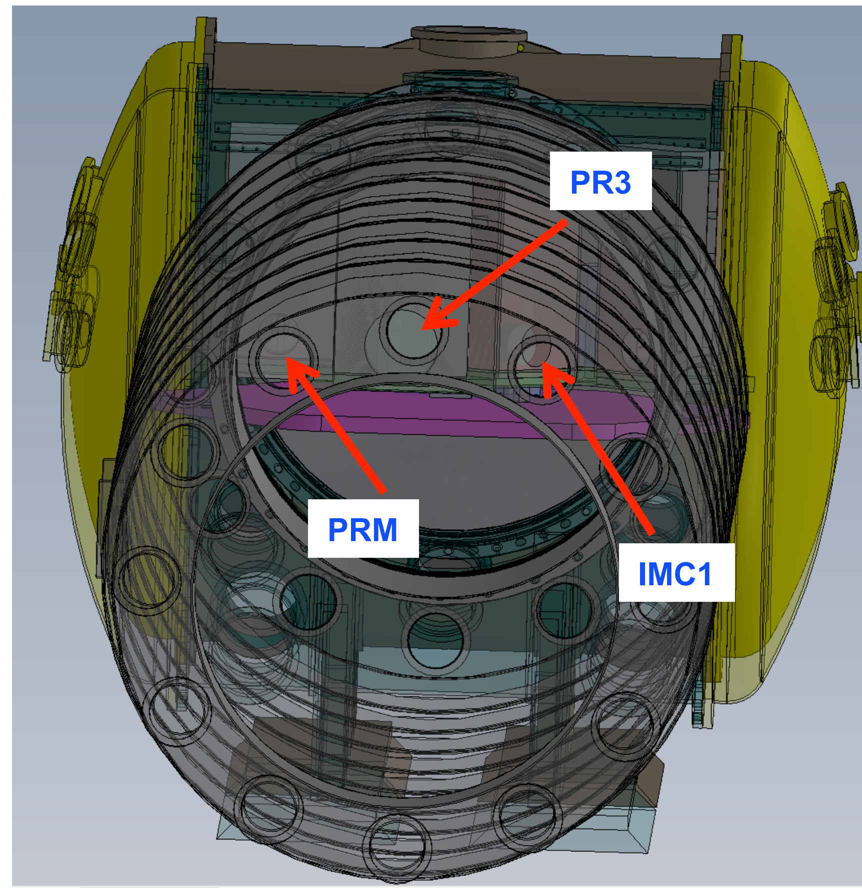


# Other Items: Design Concepts

- All main beam line optical components super-polished (except for a few FI components)
- Power control: motorized waveplate and 2x thin-film polarizers on PSL table, behind EOMs.
  - Custom thin film polarizers with 99% throughput
- Mode-matching to IMC: 2 lens telescope on PSL table
- Cameras for viewing all IO components in vacuum
- Double window viewport for safety on all high power beam entry and exit points

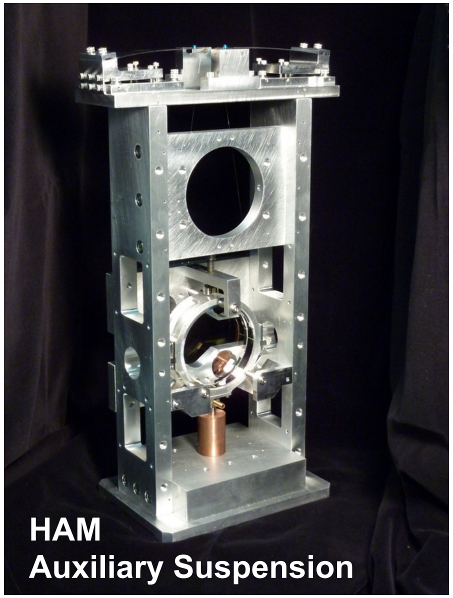


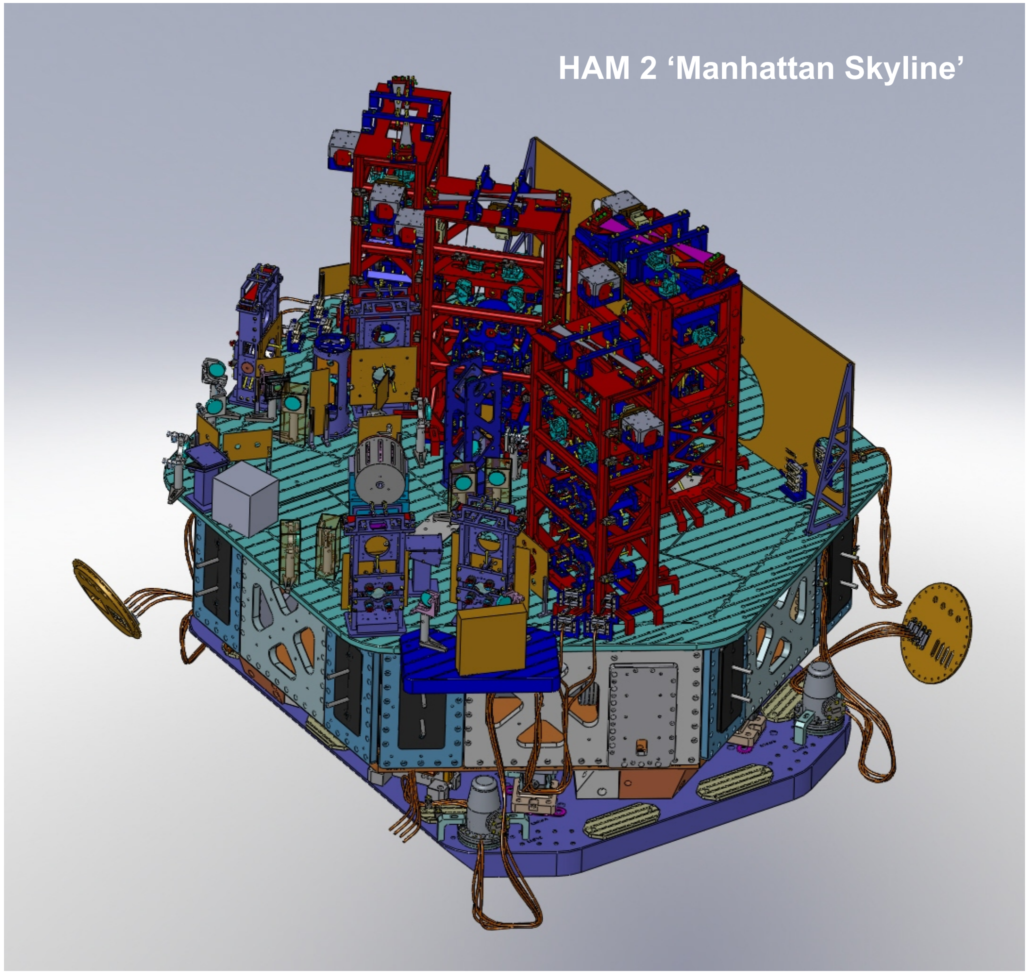

PSL = pre-stabilized laser
IMC = input mode cleaner
EOM = electro-optic modulator



# Selected IO Design Accomplishments

- IO optical layout for straight interferometers complete
  - Folded interferometer almost complete
- PSL and auxiliary IO sensing table layouts complete
- HAM Auxiliary Suspension prototyped and tested




HAM = horizontal access module chamber

LIGO

UNIVERSITY of FLORIDA

# IO Development Status

- The IO has completed all designs and design review documentation; final approval from project management pending
- Awaiting reports from review committees on
  - » IO baffles in final phase of design review (awaiting committee report)
  - » IO installation plan

- Control and Data System interface with IO currently under review.

# IO Subsystem Project Organization

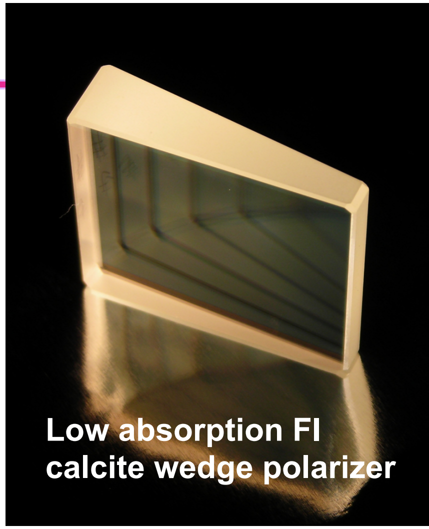
- University of Florida has primary responsibility for IO design and project phase
  - » UF did the IO for initial LIGO
- Design, procurement, fabrication efforts centered at University of Florida
- Project Team:
  - » Leads: David Reitze, David Tanner
  - » Optical: Rodica Martin
  - » Mechanical Engineers: Luke Williams, Joe Gleason, Deepak Kumar
  - » Site liaisons: David Feldbaum, Matt Heintze
- Design Team:
  - » Project Team + Guido Mueller, Giacomo Ciano

# Project Phase Status

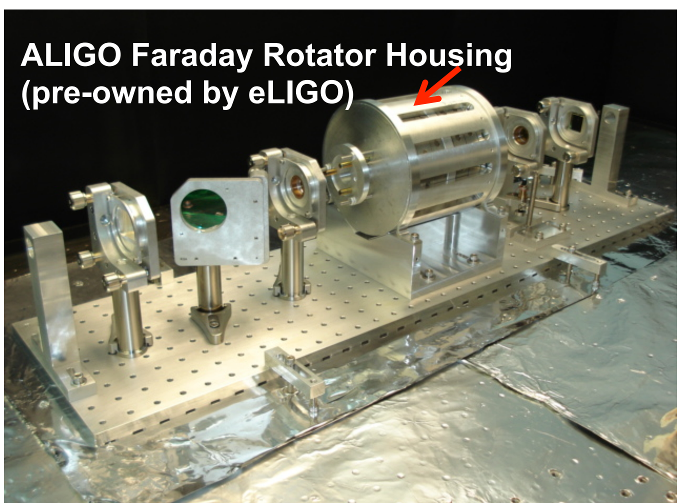
- Procurements/Fabrication:
  - » Major optics fabrication for all custom IO and recycling mirror optics completed
  - » Custom optical crystals and components for EOMS, Faraday completed
    - – Awaiting delivery on final FI components
  - » HAM Auxiliary Suspensions components fabricated
  - » EOM and FI mechanical components in fabrication: 50% complete
  - » Ancillary in-vacuum optics mounts procurement/fabrication: 40% complete
  - » Commercial opto-mechanical components for out-of-vacuum optical procurement/fabrication: 35% complete
  - » Custom optics transport containers, alignment and installation fixtures: 60% complete
- Metrology for mirrors (phase maps & radii of curvature, absorption): 25% complete
  - » IMC flat mirrors complete, awaiting reference spheres for other mirrors
- De-installation and recovery of IO components from Livingston and Hanford 2 km interferometer complete
  - » Will re-use Livingston EOM and FI housings (but not optics and crystals)

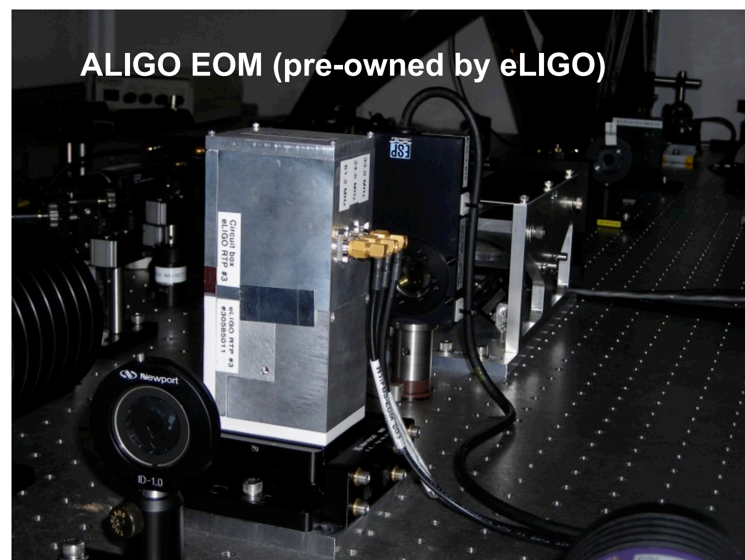
FI = Faraday isolator
IMC = input mode cleaner
EOM = electro-optic modulator
HAM = horizontal access module chamber

# Project Phase

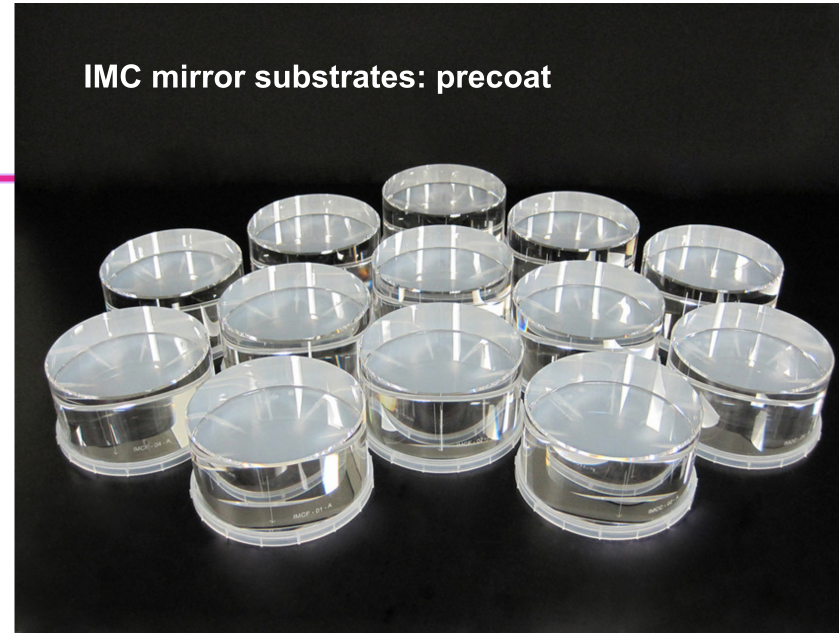




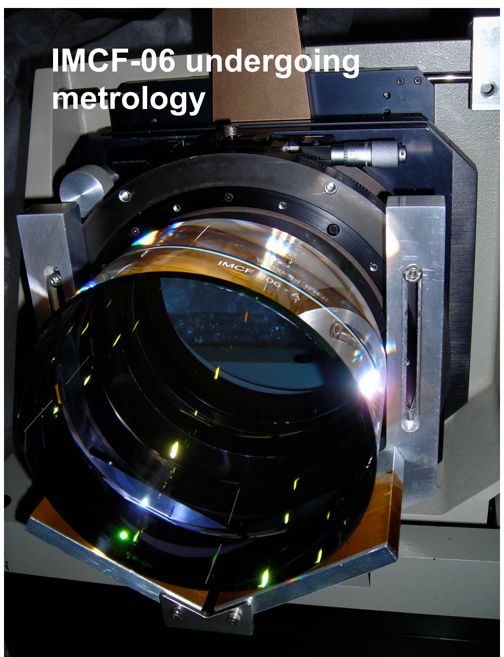



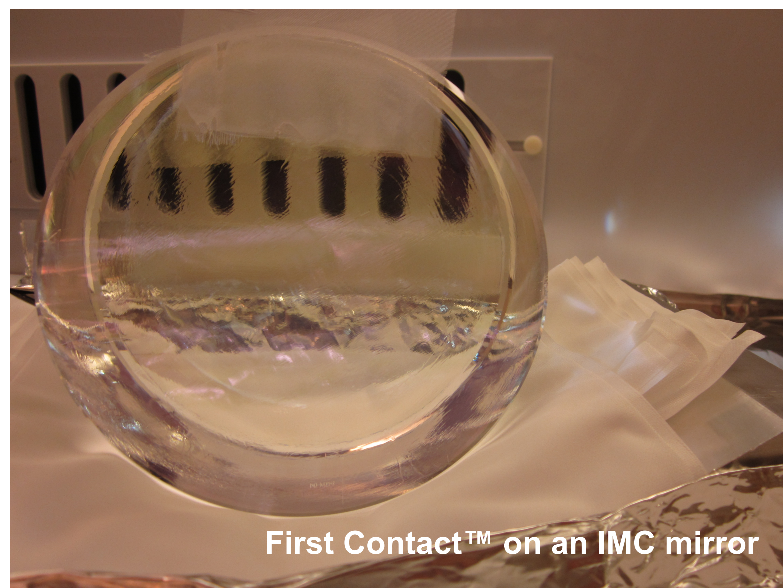
HAM Auxiliary Suspension components



IMC mirror substrates: precoat



IMCF-06 undergoing metrology



First Contact™ on an IMC mirror

# Challenges, Risks, and Mitigations

- Concern: The IO group (like everyone) has a significant amount of assembly, test, and installation work in the coming 6 month period – installation of much of the of LIGO Livingston Input Optics, and assembly of Hanford H2 IO components. Schedules and delays in the IO internally (procurements, assembly, test) or in other parts of the project will push out the schedule and present logistical challenges
- Mitigation:
  - » close coordination with Installation subsystem to maintain awareness of schedule
  - » Re-prioritize activities as needed to optimize installation

# Challenges, Risks, and Mitigations

- Concern: Delay in procurement of reference spheres for recycling mirror metrology may delay of measurements of radii of curvature needed for installation in L1
- Mitigation: fall back plan is to use LIGO1 methods (2f imaging) to get 1% accuracy

- Concern: Delays in HAM small triple suspension fabrication (welding) and test may delay HSTS assembly and installation
- Mitigation:
  - » Structure welding difficulties resolved, HSTS frames now in production.
  - » Build second test stand. Enlist additional staff to help with assembly.

# Input Optics: Next 6 months

- Complete procurements for all three interferometers
- Complete fabrication of L1 custom components
- Complete metrology of small recycling mirrors
- L1 interferometer assembly and installation
  - » Assemble/Test electro-optic modulator
  - » Assemble/Test HAM auxiliary suspensions
  - » Assemble/Test Faraday isolator
  - » Assemble/Test HAM Small Triple Suspensions (with SUS group)
  - » Install IO optics on PSL table
  - » Begin installation in HAM vacuum chambers