Modulators and Isolators for Advanced LIGO

UF LIGO group

28 April 2006

LIGO mid-life upgrade

- After S5 LIGO will undergo a mid-life upgrade
- Laser power will be increased to 30 W
  - Electro-optic modulators (EOMs) and the Faraday isolators (FIs) must be replaced.
  - $LiNbO_3$ modulators will suffer from severe thermal lensing
  - Absorption in the FI leads to thermal lensing, thermal birefringence, and beam steering

- Same devices as will be used in advanced LIGO

Overview

- EOMs
  - » RTP as EO material
  - » RTP has significantly lower absorption and therefore thermal lensing.
  - » Use "industry standard" housing, so can be replaced in existing hardware.

- FI
  - » Uses two TGG crystals/ quartz rotator to cancel thermally induced birefringence
  - » Uses DKDP, a -*dn/dT* material, to compensate thermal lensing.

- Performance data and implementation issues presented in “Upgrading the Input Optics for High Power Operation”
- This review tries to answer questions posed by the review panel

EOM materials

- Worked with Crystal Associates and Raicol Corp.
- Choose rubidium titanyl phosphate ($RbTiOPO_4$ or RTP) for the modulator material in advanced LIGO.
- Rubidium titanyl arsenate (RTA), also meets requirements.
- Lithium niobate ($LiNb0_3$), used in initial LIGO, not satisfactory
  - Thermal lensing
  - Damage
  - Residual absorption

High Frequency Modulation

- “The capability of modulating at 180 MHz, with a depth of 0.5 rad, clearly stresses the driver design, but it is very unlikely that such a modulation would be needed. We can discuss modifying the requirements to something more reasonable.”
- Response:
  - » iLIGO upgrade – highest frequency is 68.8 MHz, depth is m ~ 0.06
    - – Not an issue …
  - » AdvLIGO – Mach-Zehnder architecture requires 4x overdriving the index to achieve the effective index
    - – If $m_{effective} = 0.06$ is required → m ~ 0.24

Thermal properties

- Section 1.2.5 says that no thermal lensing was seen up to 60 W. What is the upper limit on alpha, or on the focal length, that can be established with this data?

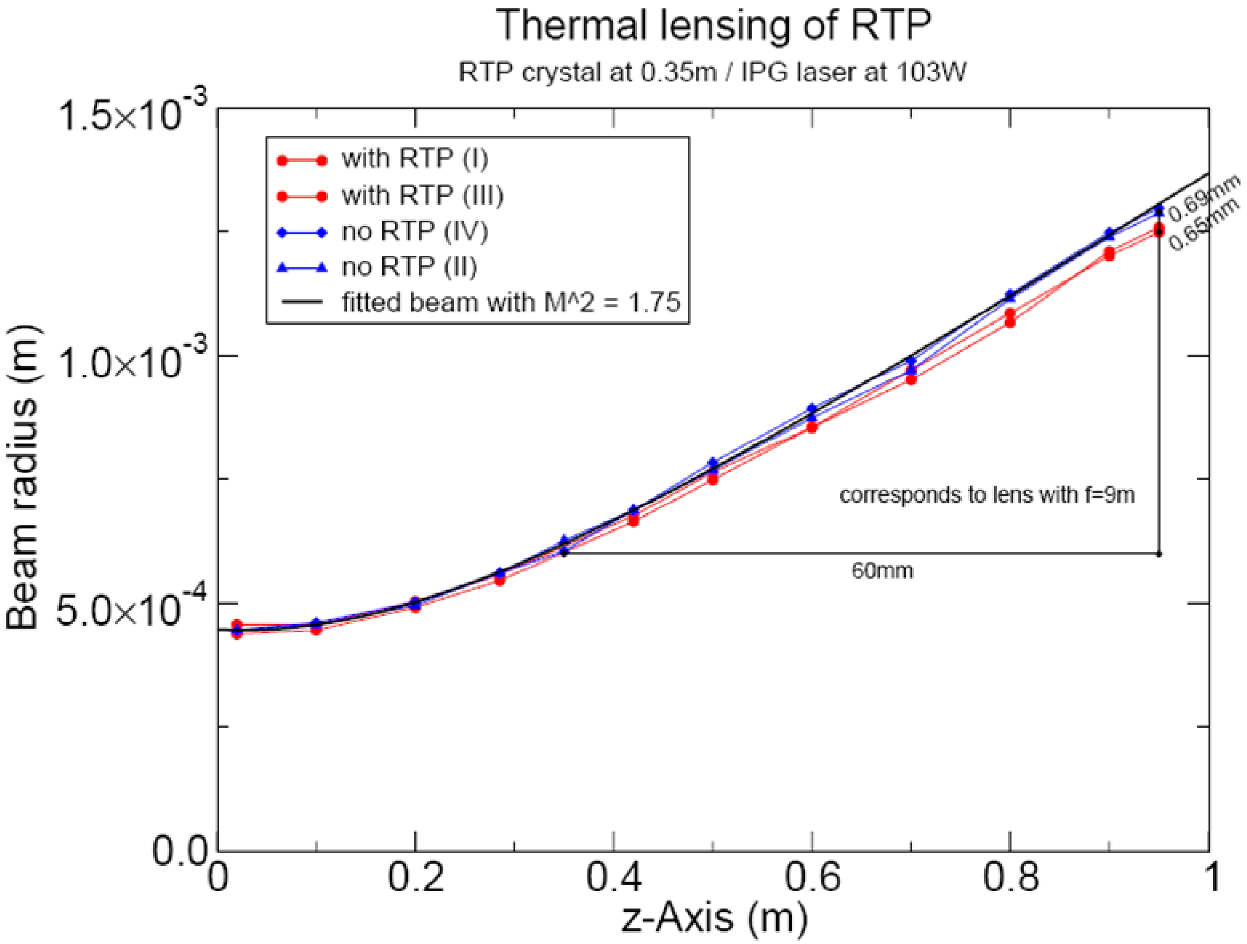
- Thermal lensing scales as the parameter *Q* $Q \equiv \frac{dn}{dT}\frac{\alpha}{\kappa}$

- RTP has *Q* 30—50 times smaller than $LiNbO_3$
- Can estimate thermal lens of *f* ~ 20 m
- Measured a *f* ~ 9 m thermal lens at 103 W power
- Corresponds to a ~ 5 m thermal focal length when scaled to 180 W.
  - » compare with LiNbO3 (20 mm long): $f_{thermal}$ ~ 3.3 m @ 10 W

Thermal lens measurement

Blue lines show beam divergence with no RTP crystal

Red lines => 15 mm long RTP crystal



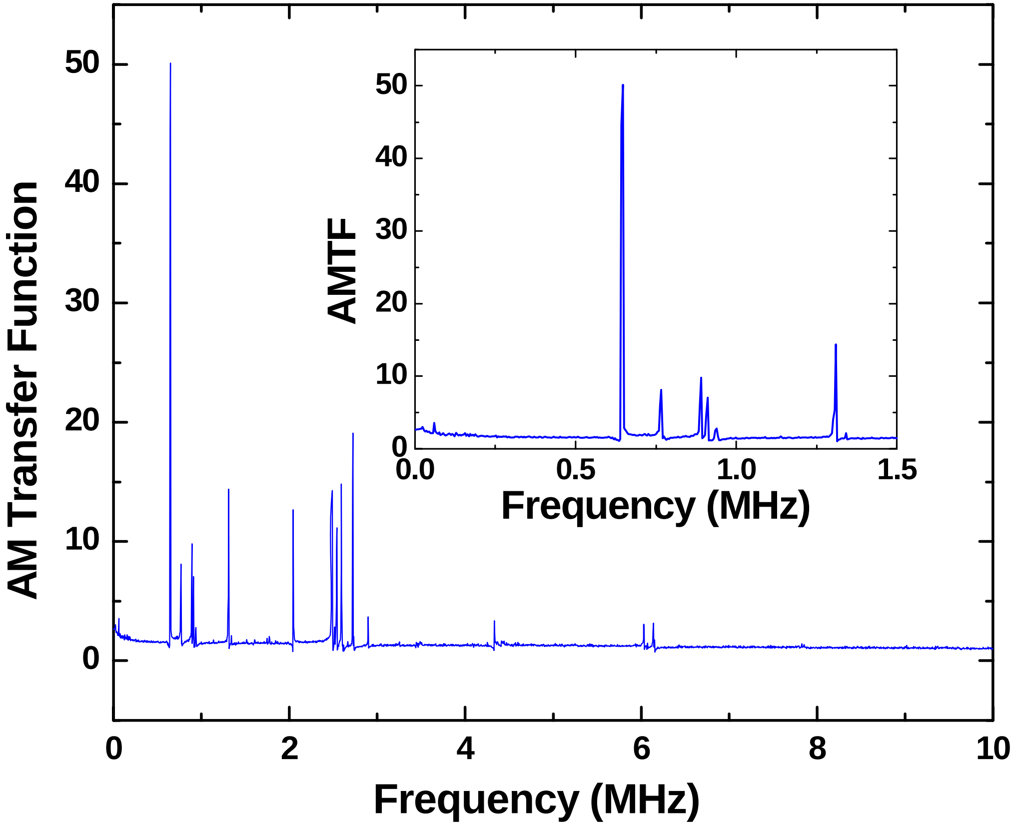
thermal lens will scale inversely with crystal length

Crystal Cross Section and Beam Size

- "How was the 4 mm x 4 mm size chosen? How large can the beam be made for this size? Section 1.3 mentions a 360 μm radius beam, but this seems very small for this size crystal."
- Crystal aperture constrained by trade-offs
  - » Damage threshold
  - » Ability to get high quality large aperture crystals
  - » Drive voltage considerations
- Chose 4 x 4 mm^2
  - » Largest aperture available when we started testing (now up to 8 x 8 mm^2)
  - » Drive voltages not extreme (U_z = 124 V; reduced by ~10x with tank circuit)
  - » 360 μm spot used for damage testing only (I_{beam} ~ 10x $I_{AdvLIGO}$)
  - » 900 μm gives a 50 ppm clip loss for 4 mm diameter aperture
- We choose 900 μm spot size in x-tal

Piezo-Resonances

- Swept sine measurement 0-50 MHz
- Detected resonances by spikes in AM component
- Highest resonance is at 6.8 MHz
- Typical FWHM ~ 10 kHz
  - » Q ~ 100
- No features between 10 MHz and 50 MHz

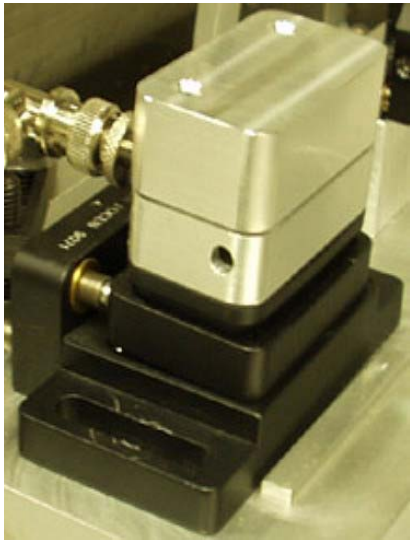


RTP Crystal Ends

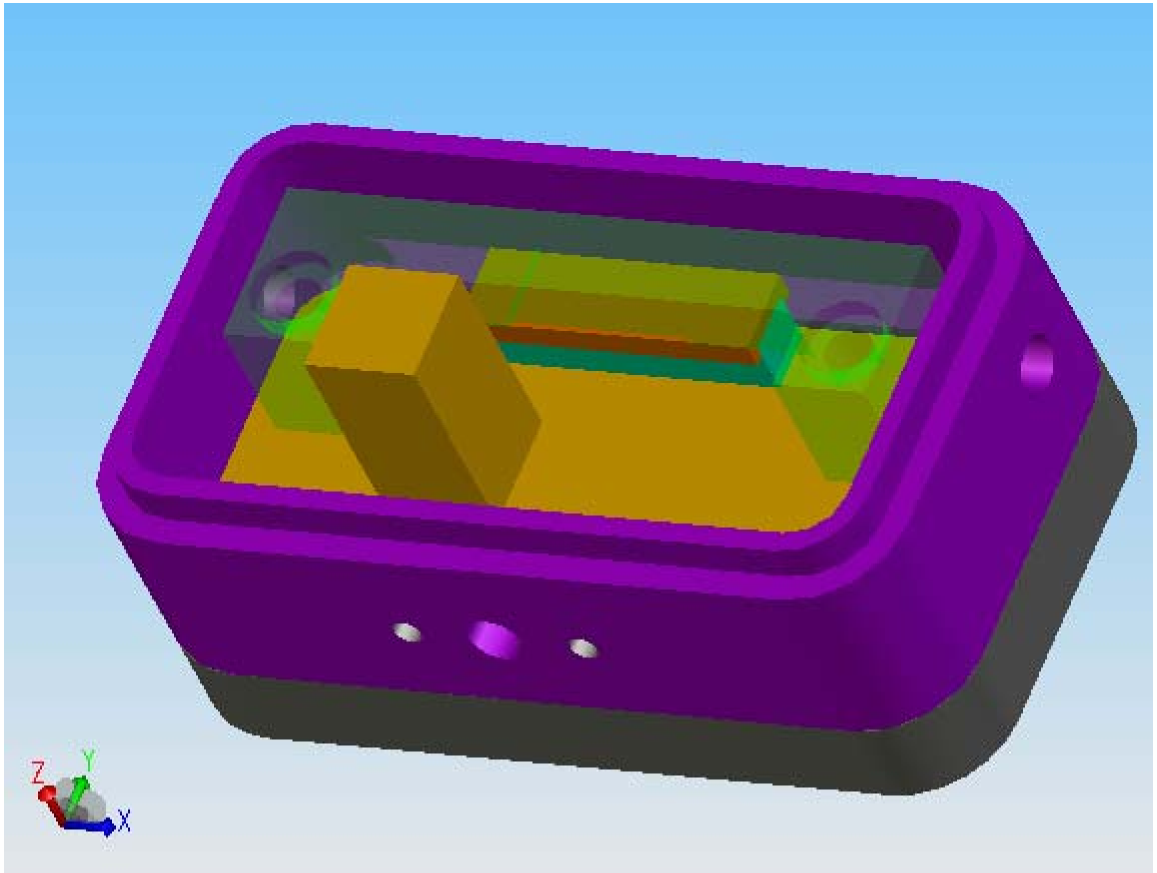
- “Who does the AR coatings, and what is the spec? Are the ends wedged? should they be?”
- For prototypes, AR < 0.1% were provided by Raicol
- Can spec as low as 300 ppm
  - » Will require REO or Advanced Thin Films (ATF) to do batch job
- Original crystals were not wedged, but can (and probably should) wedge at ~ 2 deg
  - » RFAM measurements: $\Delta I/I \sim 10^{-5}$ at Ω_{mod}

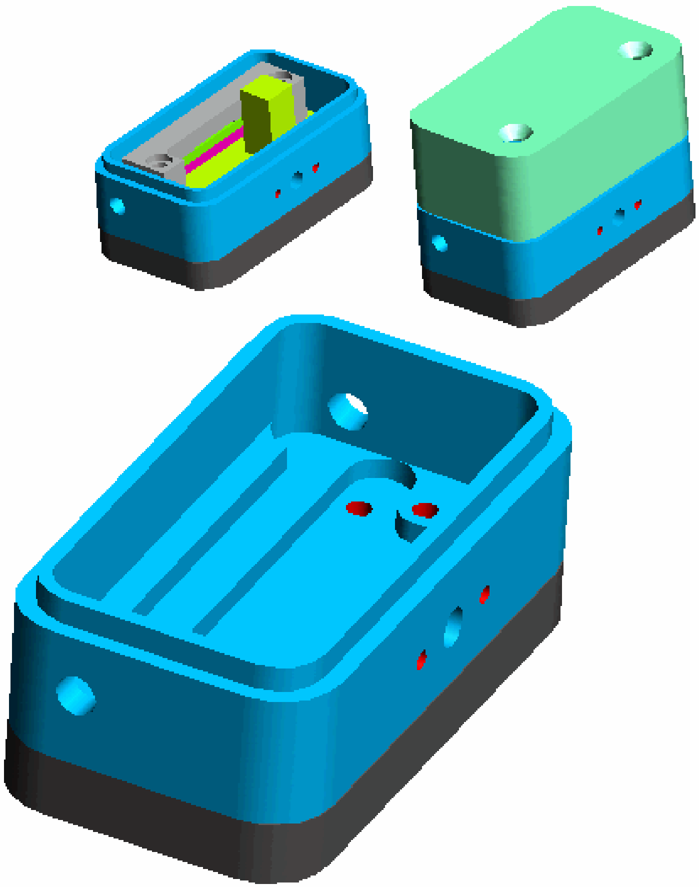
EOM Housing

- “How is the crystal mounted in the box? How big is the aperture in the housing? What thought went into choosing the (Al) housing material?”
- 1.5 cm x 0.4 cm x 0.4 cm crystal
- Electrodes: gold over titanium
- Industry-standard housing
  - » New Focus reverse-engineered
- Cover and can made of aluminum
  - » durable and easy to machine.
  - » Other materials are possible.
- The base is made of delrin.



Modulator Design

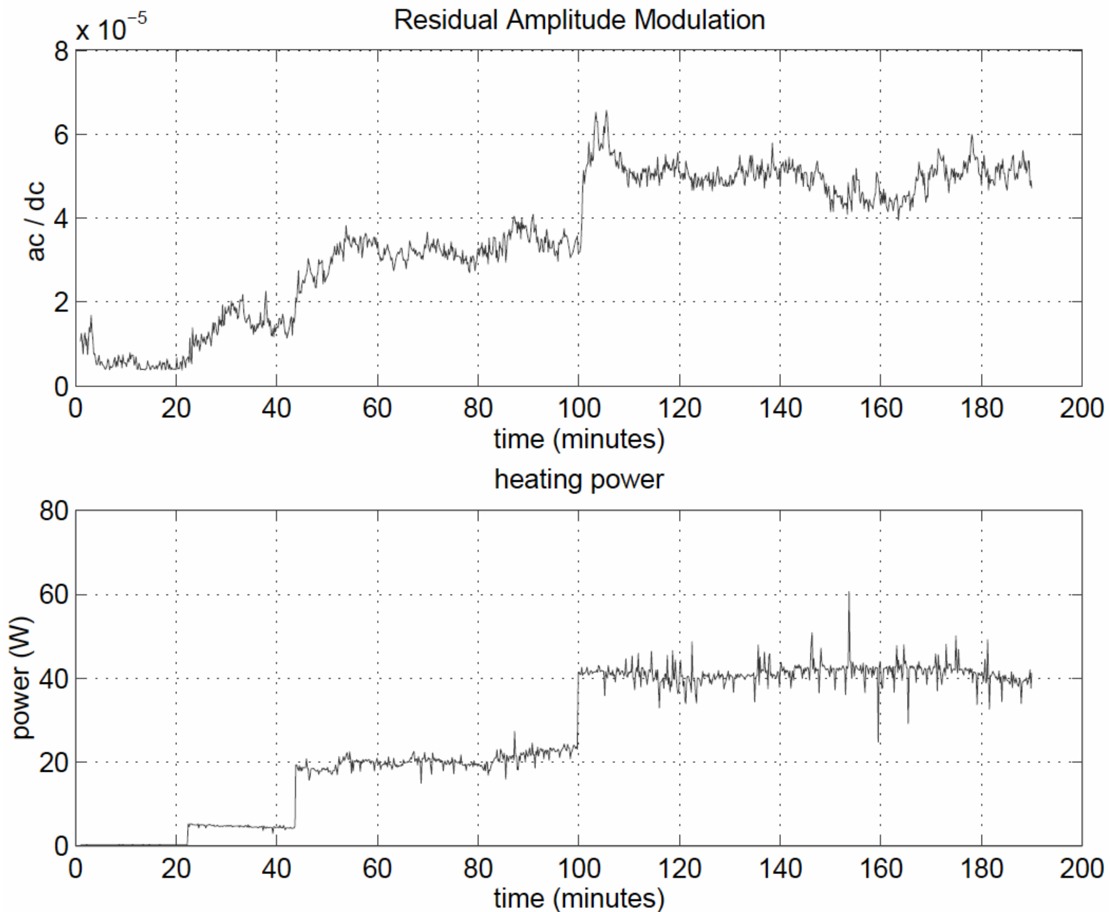




eom_assembly.easm

Dynamic RFAM

- “Would like to see a measurement of the dynamic RFAM, with comparison to the current LiNbO3 modulators.”



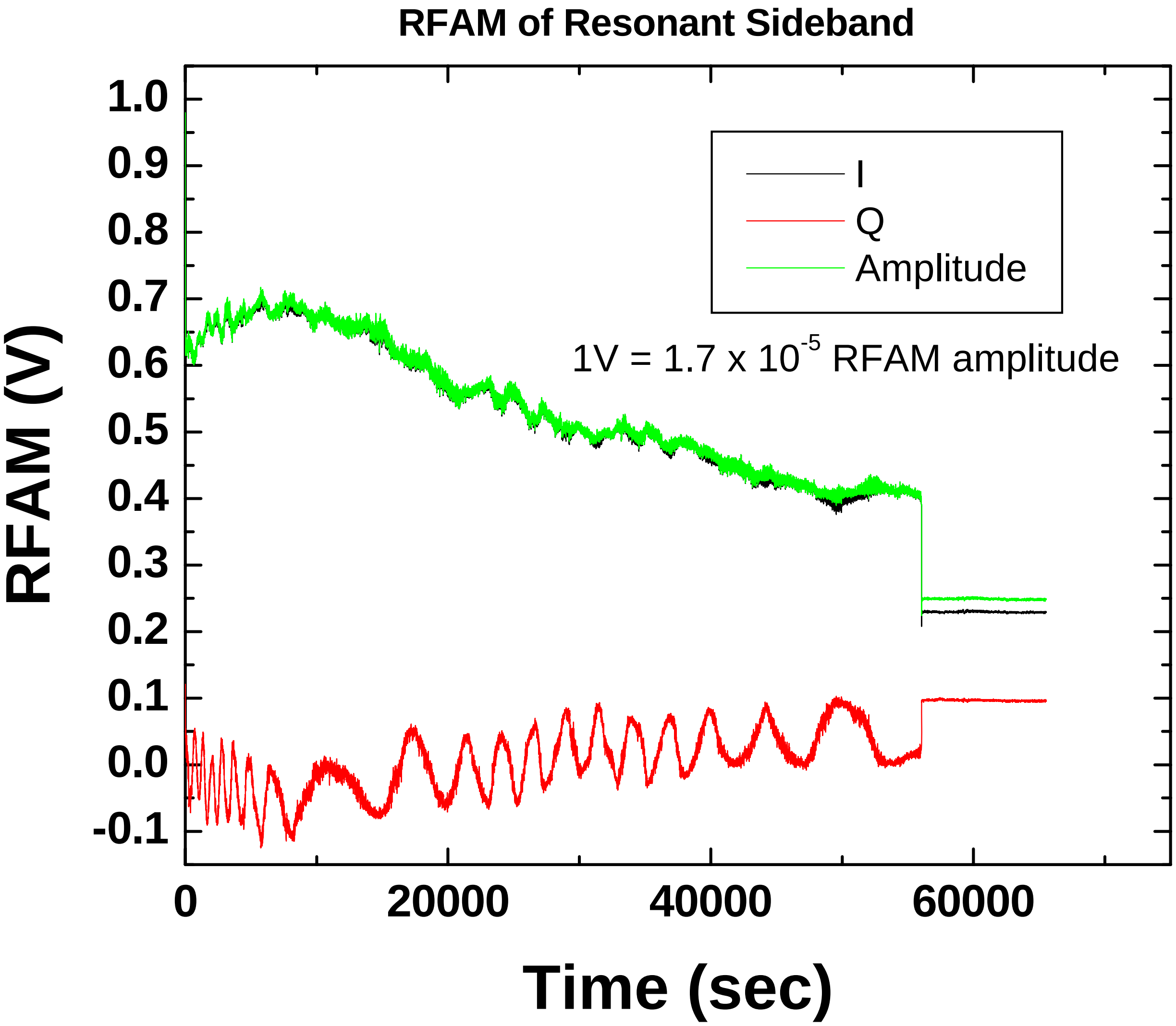
- Measured RFAM in RTP EOMs vs laser heating power
- ‘Static RFAM’ measured over 20 min period
  - $\Delta I_{\Omega mod} / I_{DC} \sim 10^{-5}$ @ $\Omega_{mod} = 19.7$ MHz

(No attempt to correct and re-establish baseline upon heating)

RFAM in νFocus $LiNbO_3$ EOMs

- data from LLO PSL enclosure, Oct. 2000
- $\Delta I_{\Omega_{mod}}/I_{DC}$ ¤ 7 x 10^{-6}

  (Better now?)
- Comparison:
  - LIGO1 EOMs somewhat better
  - Possibly due to the lack of wedges on the crystal on RTP
  - or temperature conditions
- could investigate temperature-stabilized EOMs



One or three EOMs?

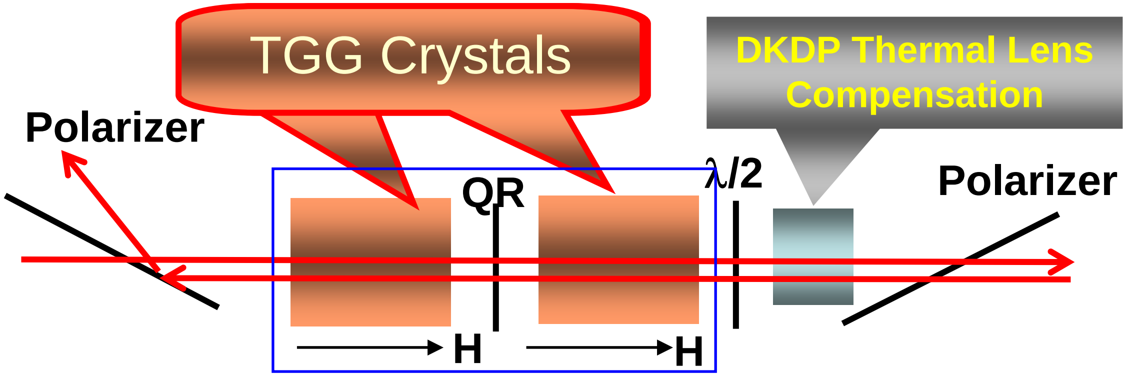
- “Need to discuss the different options of driving & impedance matching to the crystal:
  - » - single electrode vs multi-electrodes on the crystal
  - » matching circuit components: inside vs outside the crystal housing”
- - some progress toward a multiple frequency driver circuit, but more simulations and testing are needed before we feel confident that it will work.
- Matching circuits: for higher frequencies, better to put the matching circuit in the crystal housing
  - » Driving the cable at high frequencies is difficult
- possible to get crystals as long as 40 mm
  - » could put three electrodes (one for each frequency) on a single crystal.
  - » Some thought would need to be put into defining the gap spacing and estimating the effects of fringing fields between the gaps.

EOMs in vacuum

- “if we are tempted to mount a EO modulator in the vacuum system, after the MC, to be able to tune the signal recycling cavity, how would the design need to change for an in-vacuum unit?”
- Two issues
  - » Vacuum compatibility
    - – Replace teflon clamp with boron nitride
    - – Design EOM can for vacuum compatibility
    - – Matching circuit outside the vacuum
    - – Alternatively, put the EOM in its own vacuum container in the main vacuum
      - Similar to AdvLIGO PSL intensity stabilization PD?
  - » Beam size
    - – MC beam waist is 2.1 mm in Advanced LIGO
    - – Requires large diameter aperture…
      - 8 mm → 70 ppm clipping
    - – … or alternatively modify the layout to accommodate a 1 mm focus for the EOM after the MC
      - Not obvious how to do this

Faraday isolator

- Faraday rotator (FR)
  - » Two 22.5° TGG-based rotators with a reciprocal 67.5° quartz rotator between
  - » Polarization distortions from the first rotator compensated in the second.
  - » ½ waveplate to set output polarization.
  - » Thermal lens compensation *via* negative *dn/dT* material: deuterated potassium dihydrogen phosphate, KD_2PO_4, or 'DKDP').
- Most likely TFPs
- Mounted on breadboard as single component

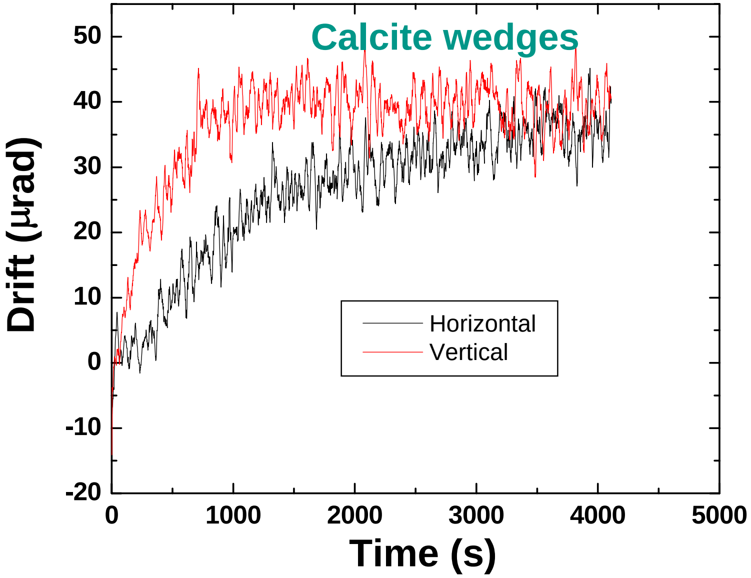


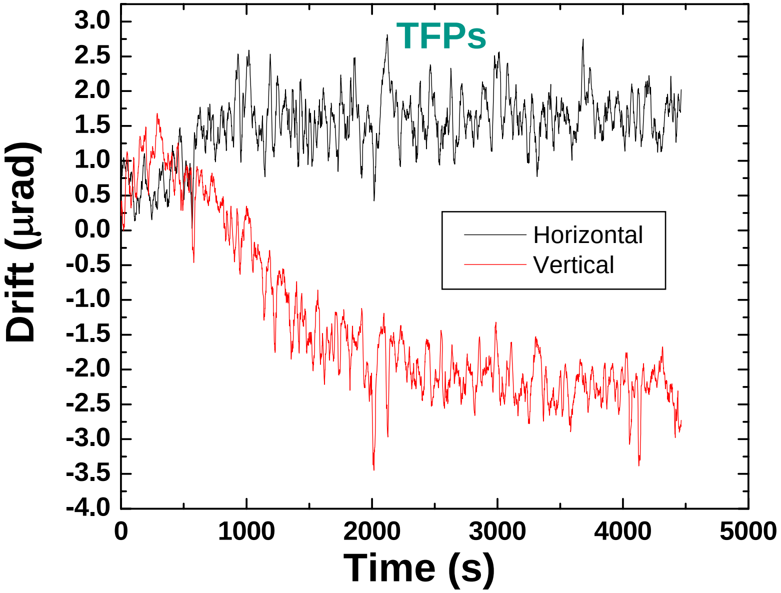
Isolation Requirement

- “What is the basis of the isolation requirement?”
- Somewhat ill-defined
  - » iLIGO FI’s provide ~ 30 dB isolation
  - » parasitic interferometers seen at power levels of a few watts into IFO in iLIGO
  - » Scale to AdvLIGO powers (125W/4W):
    - – 15 dB of additional isolation at least is needed to achieve the same performance
    - – Hard to get to 45 dB, but not impossible

Thermal Drift/Steering

- “Thermal beam drift/steering: the limit of 100 μrad seems too high, it's a large fraction of the beam divergence angle -- and we'd prefer not to have to use the RBS to compensate for it. Can we make it more like <10% of the beam divergence angle, which would be around 20 μrad?”
- iLIGO upgrade (upper limit of 30 W through the FI)

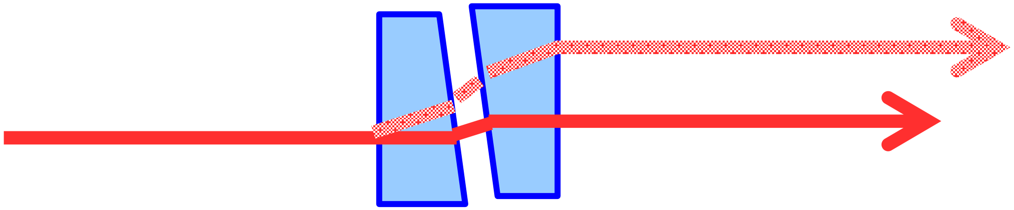




- Calcite: 40 μrad @ 30 W; TFPs: 3 μrad @ 30W

Thermal Drift/Steering II

- Scaling to AdvLIGO (~ 150 W)
  - Calcite: 200 μrad
  - TFPs: 15 μrad
- Calcite potentially problematic for AdvLIGO
  - Could think about using double wedges for compensation, but beam separation may be a problem

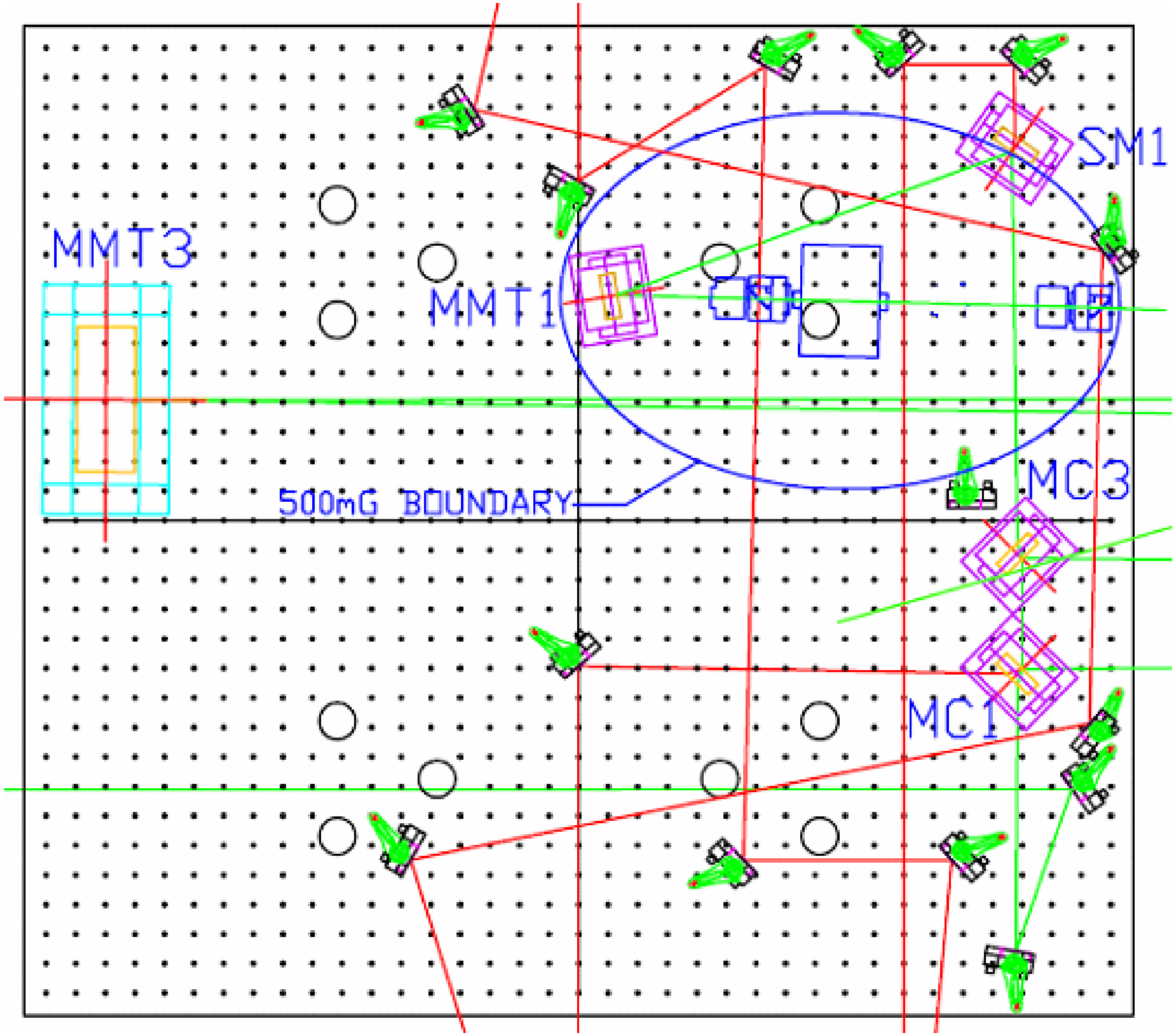


- We recommend TFPs, and are working with ATF to develop special high extinction ratio coatings (10000:1)

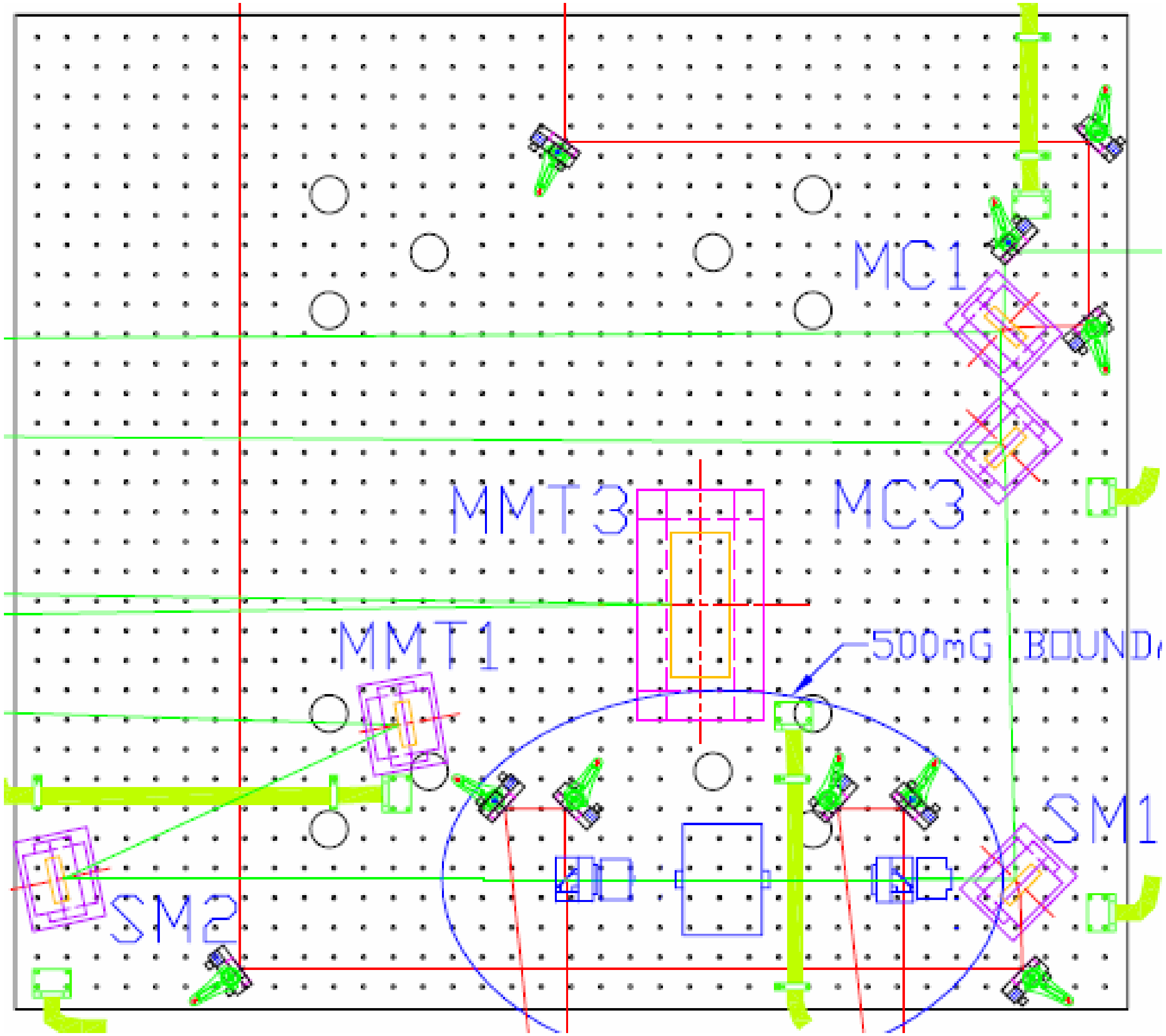
Beam Heights in iLIGO, AdvLIGO

- H1, L1
  - » FI moved downstream of MMT1
  - » Need to account for rising beam from MMT1 – MMT2
    - – H1: 2.48 mrad; L1: 2.79 mrad
    - – Breadboard will be angled to align FI axis with beam axis
      - Need to establish level REFL beam height HAM 1, since it will have same downward angle → mm downward shift on first mirror
      - Need to establish level diagnostic beam heights → same idea
- H2
  - » FI maintains position between SM1 and SM2
- AdvLIGO
  - » FI located between SM1 and MMTs where beam is level
    - – Beam height is 8.46” off table

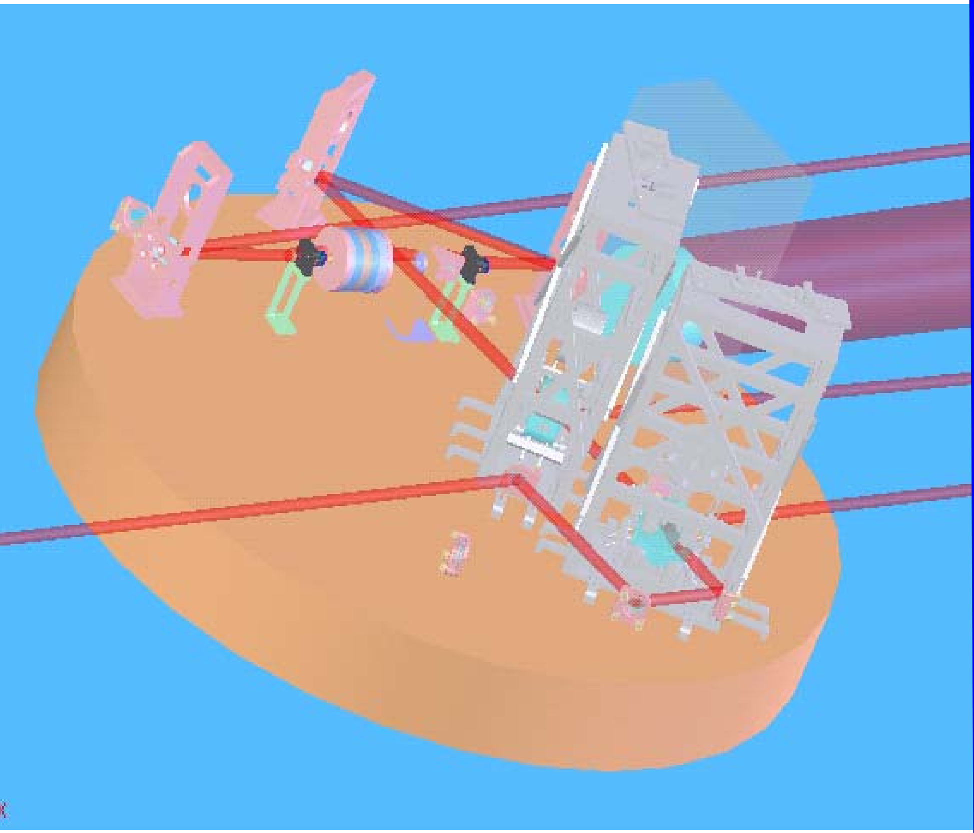
H1, L1 layout (preliminary)

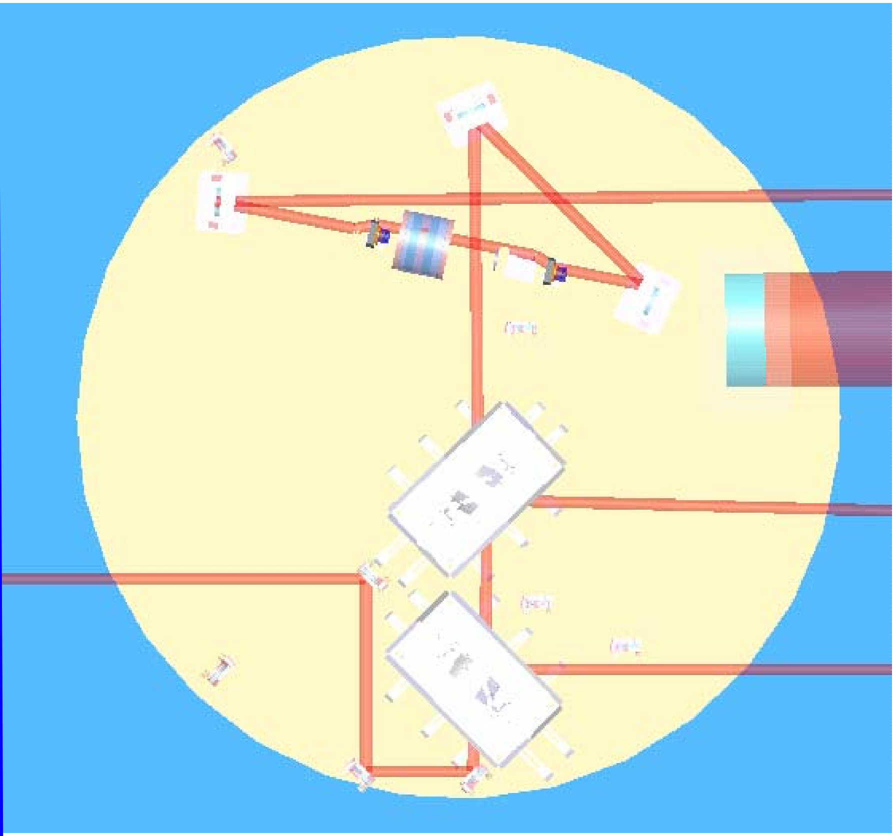


H2 layout (preliminary)



AdvLIGO layout (preliminary)



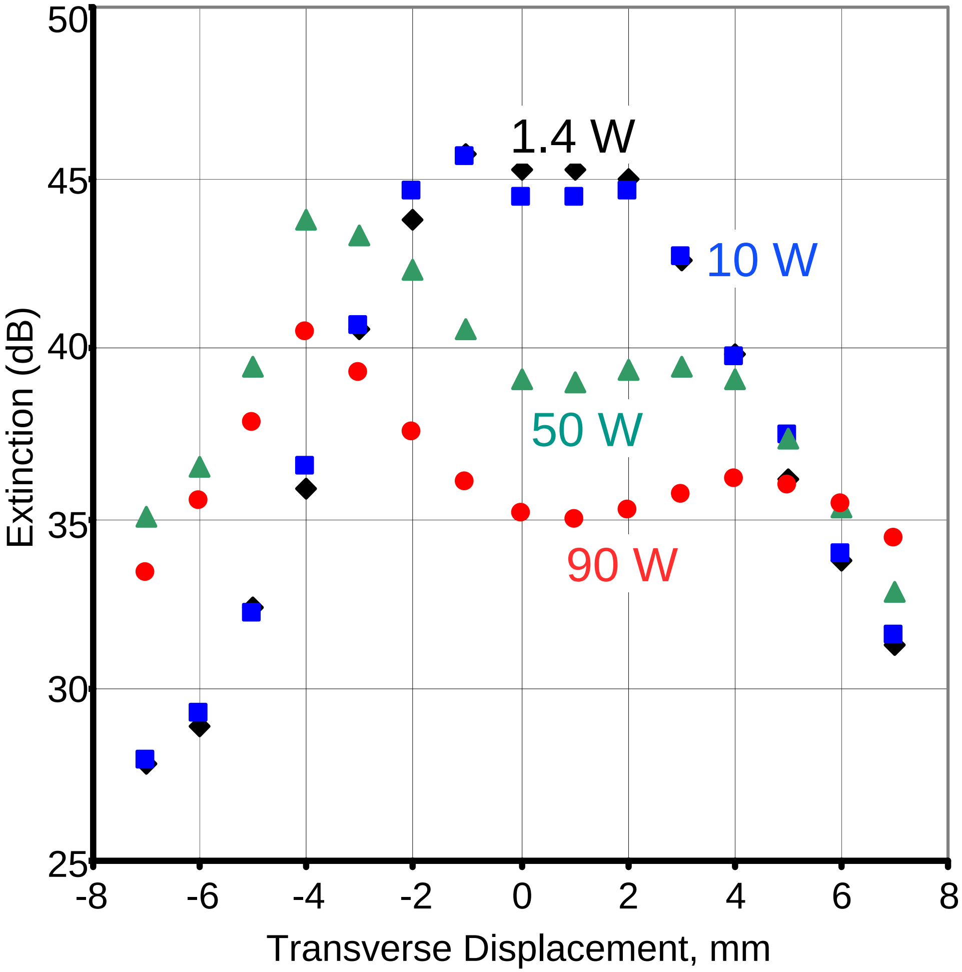


Spot Size in FI

- “What is the assumed and/or optimum spot size in the Faraday?”
- characterization measurements were performed with a beam size of ~ 1.9 mm
  - » Beam in iLIGO is 1.6 mm – 1.8 mm
  - » Beam in AdvLIGO is 2.1 mm
- Thermal effects are first order insensitive to beam size
- In general, smaller is better to sample homogeneous magnetic field

FI Sensitivity to Beam Displacement

- “How sensitive is the isolation to the transverse beam position?”



Choice of Polarizers

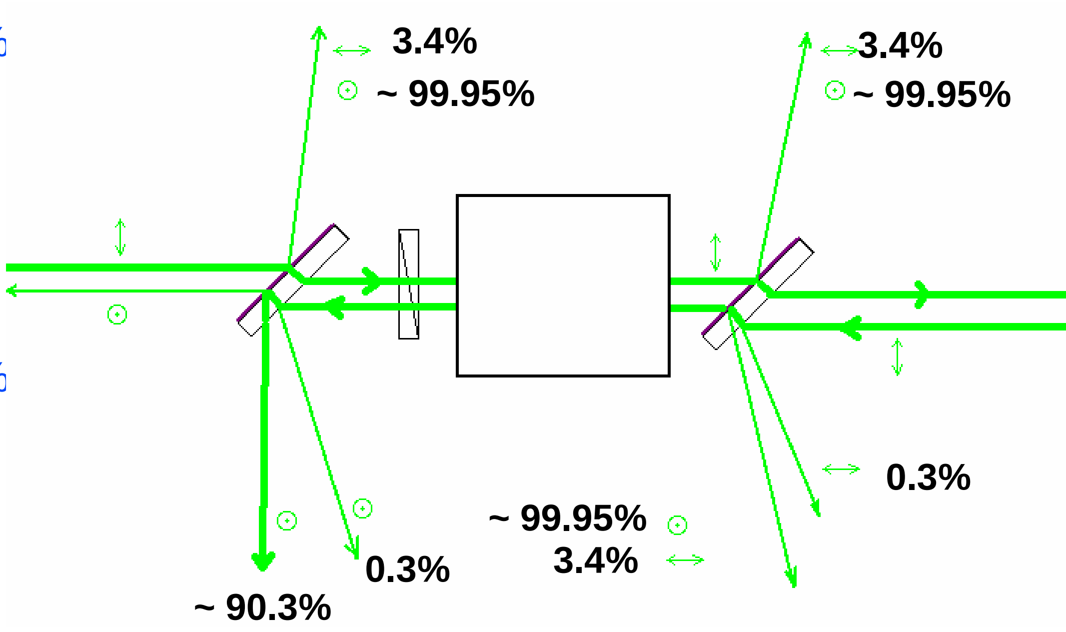
- “How about a hybrid approach, using the combination of a TFP + calcite polarizer. The REFL beam would come off the TFP, for low thermal drift, and the calcite would give high isolation. The TFP could even be just a piece of fused silica at Brewster's angle.”
- Hybrid approach probably doesn’t help much
  - » Input polarizers sets isolation; REFL reflects off of it
- Working to develop high extinction ratio TFPs from ATF
  - » All experiments on isolation ratio to date performed with calcite wedges
    - – Need to characterize sensitivity of extinction ratio to angle since beam will be steered in IO optics chain

Power budgets

- “Where is the power going (for both the transmitted and rejected cases)? Are all the beams being sufficiently dumped?”

- FI with TFPs:
  - » Percent transmitted: 93.3% +/- 0.3%
  - » Percent rejected: 90.3% +/- 0.3%
- FI with calcite wedge polarizers:
  - » Percent transmitted: 98.3% +/- 0.3%
  - » Percent rejected: 94.6% +/- 1.0%
- Most or all of the beams from polarizers will be picked off and sent through viewports for diagnostic purposes

Power Budget: TFP FI



Thermal Performance in Vacuum

- Thermal performance in vacuum: Has there been any analysis of this? Any problems foreseen?
- Maximum absorbed power is P ~ 1.5 W in TGG for AdvLIGO
  - » Concern about long term heating of magnet
  - » Assuming all heat is radiated, the temperature is:

$$T = (P/\varepsilon\sigma A)^{1/4} = 30\ C$$

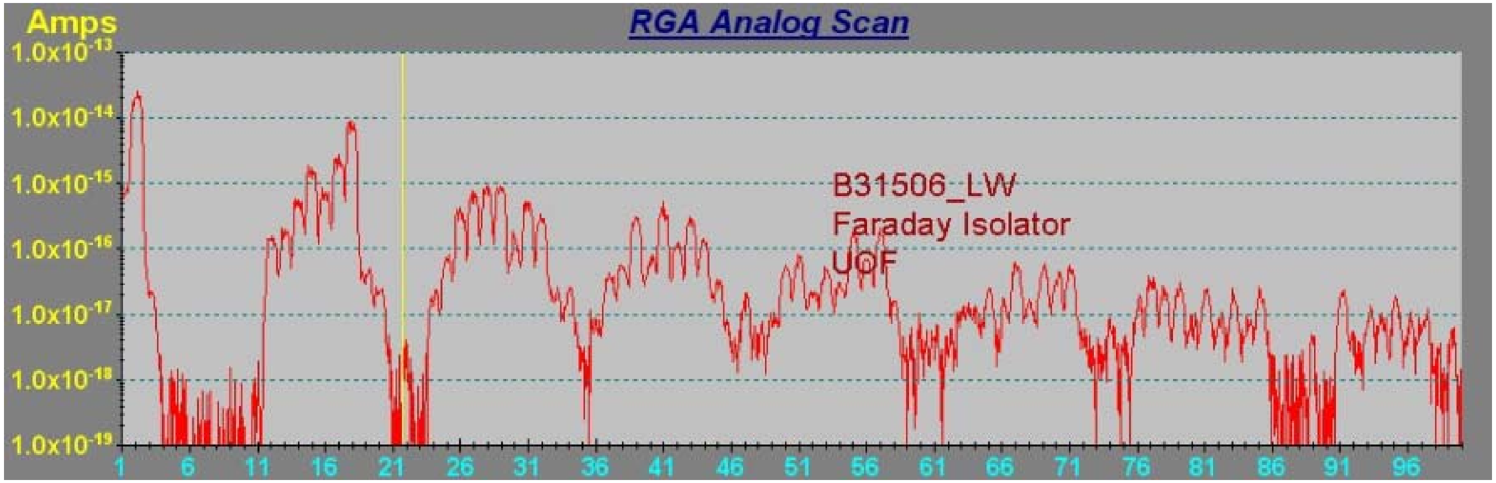
    - – Assume $\varepsilon \sim 0.9$, σ = Wien’s constant, A=TGG surface area
    - – This is somewhat conservative
      - TGG is thermal contact with rotator housing which is in good thermal contact with HAM tables

AR Coatings on Transmissive Optics

- “Presumably all the elements have AR coatings ... are they high quality? what are their specs?”
- For the FI:
  - » AR coatings were ~ 0.1% on all surfaces (14!)
    - – Calcite wedges
  - » Could be reduced to 300 ppm
    - – FI through put limited by TGG and quartz rotator absorption:
      - For calcite wedges: limit is ~ 99%
      - For TFPs, limited by intrinsic polarizer losses

FI Vacuum Compatibility

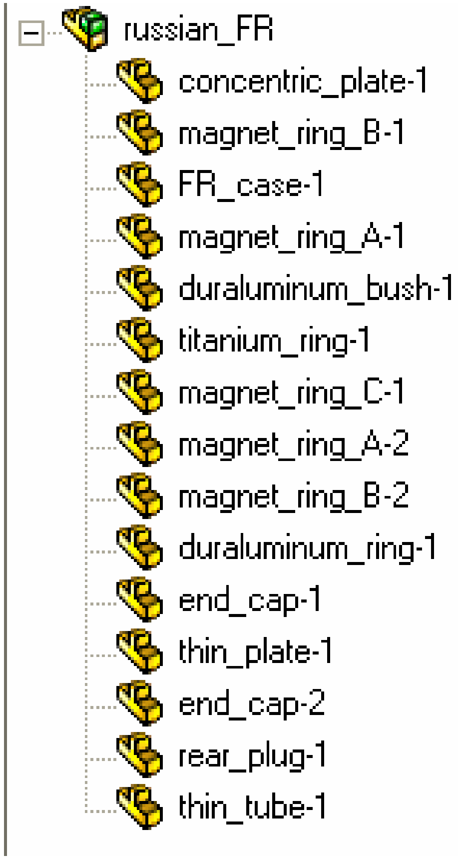
- “Would like to address vacuum compatibility. This seems to be not very mature at this time, and will need to be thoroughly reviewed before finalizing the design. Can we see a list of all components being used?”
- Prototype FR underwent bake out in March 2006
  - » All parts but optics baked at 60 C for 48 hours
    - – Magnet: sintered NiFeB
    - – Housing: aluminum with one titanium part
  - » Failed miserably…



FI Vacuum Compatibility II

- … But this was not an unexpected result
  - » Prototype designed and assembled by IAP not for vacuum testing but for optical testing
    - – Blind holes in design
    - – Not assembled in LIGO ‘clean’ environment
- Housing undergoing redesign by UF to address vacuum issues
- Vacuum compatible version will be first baked and then assembled in clean conditions
  - » in optics labs at one of the sites (during an S5 break)
  - » Ready by late summer

russian_FR.easm



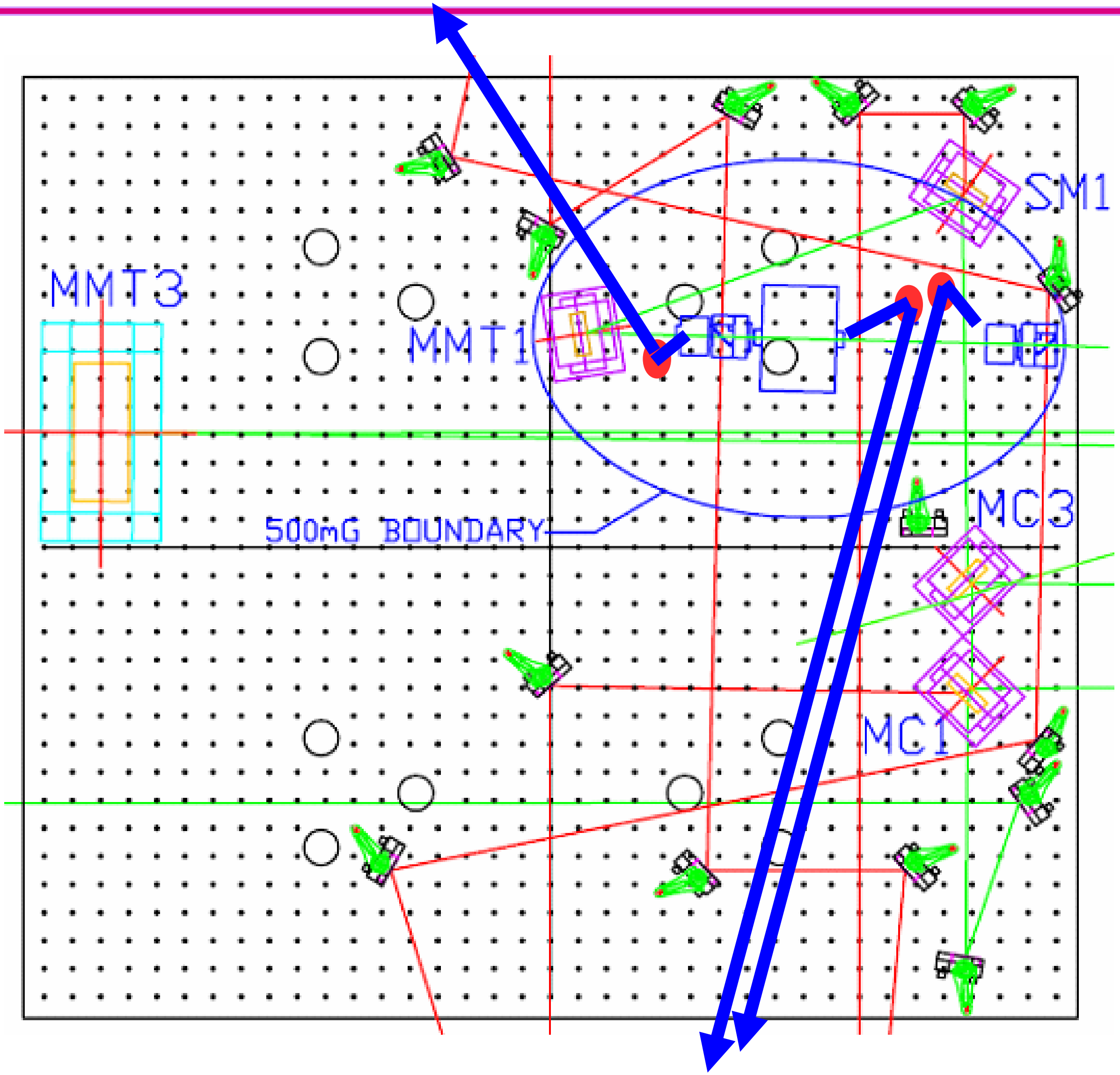
- russian_FR
  - concentric_plate-1
  - magnet_ring_B-1
  - FR_case-1
  - magnet_ring_A-1
  - duraluminum_bush-1
  - titanium_ring-1
  - magnet_ring_C-1
  - magnet_ring_A-2
  - magnet_ring_B-2
  - duraluminum_ring-1
  - end_cap-1
  - thin_plate-1
  - end_cap-2
  - rear_plug-1
  - thin_tube-1

Views to the FI

- "Need to think about being able to view important points of the assembly from outside the vacuum system; mirrors may need to be included to provide views."

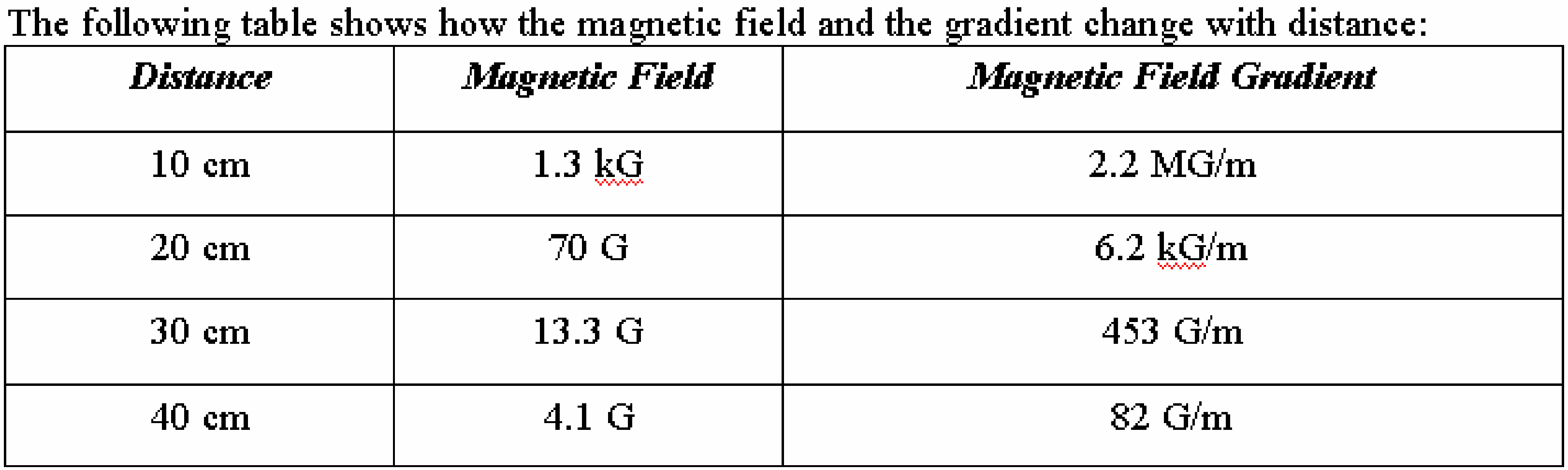
- For iLIGO upgrade, it will be possible to place mirrors on the HAM that will provide views from cameras mounted in the upper HAM door viewports
  - Access to the entrance aperture of the FR on HAM1 may be difficult, because component positions are constrained by beams
    - Should be able to get a look at the polarizer
- For AdvLIGO, layout is still sufficiently preliminary
  - HAM 1 is relatively clear where FI is located, so FI components can be separated

Views to the FI: HAM1



Low Frequency B-Field Coupling

- "You've analyzed the effects in the GW band (100 Hz). What about the static B-field, or the fluctuations at the stack modes for iLIGO -- could these be large enough to torque around any of the suspended optics?"
- B-fields exerts torques and forces on the mirrors
  - » $F = \nabla(\mu \cdot \mathbf{B})$, torque: $\tau = \mu \text{ x } \mathbf{B}$
  - » Static forces and torques can be compensated by initial alignment
  - » Rotation:
  - ≈ $\Phi < 3\text{x}10^{-8}$ rad x ∇ B/[G/m]
  - ≈ $\Phi < 4\text{x}10^{-7}$ rad x B/[G]



The following table shows how the magnetic field and the gradient change with distance:

Distance	***Magnetic Field***	***Magnetic Field Gradient***
10 cm	1.3 kG	2.2 MG/m
20 cm	70 G	6.2 kG/m
30 cm	13.3 G	453 G/m
40 cm	4.1 G	82 G/m

Low Frequency B-Field Coupling

Supplementary Material

RTP Thermal properties

Properties	Units	RTP	RTA	KTP	$\mathrm{LiNb0}_3$
dn_x/dT	10^{-6}/K	-	-	11	5.4
dn_y/dT	10^{-6}/K	2.79	5.66	13	5.4
dn_z/dT	10^{-6}/K	9.24	11.0	16	37.9
κ_x	W/Km	3		2	5.6
κ_y	W/Km	3		3	5.6
κ_z	W/Km	3		3	5.6
α	cm^{-1}	< 0.0005	< 0.005	< 0.005	< 0.05
Q_x	1/W	-	-	2.2	4.8
Q_y	1/W	0.047	0.94	2.2	4.8
Q_z	1/W	0.15	1.83	2.7	34

Optical and electrical properties

Properties	Units/conditions	RTP	RTA	$LiNbO_3$
Damage Threshold	MW/cm^2,	>600	400	280
n_x	1064nm	1.742	1.811	2.23
n_y	1064nm	1.751	1.815	2.23
n_z	1064nm	1.820	1.890	2.16
Absorption coeff. α	cm^{-1} (1064 nm)	< 0.0005	< 0.005	< 0.005
r_{33}	pm/V	39.6	40.5	30.8
r_{23}	pm/V	17.1	17.5	8.6
r_{13}	pm/V	12.5	13.5	8.6
r_{42}	pm/V	?	?	28
r_{51}	pm/V	?	?	28
r_{22}	pm/V			3.4
$n_z^3 r_{33}$	pm/V	239	273	306
Dielectric const., ε_z	500 kHz, 22 °C	30	19	
Conductivity, σ_z	$\Omega^{-1}cm^{-1}$, 10 MHz	$\sim 10^{-9}$	$3x10^{-7}$	
Loss Tangent, d_z	500 kHz, 22 °C	1.18	-	

Modulator parameters

- The largest EO-coefficient is r_{33}.
- Modulation depth (L = crystal length, U_z = voltage, d = thickness)

$$\Delta\Phi = m = \frac{\pi L}{\lambda} r_{33} n_z^3 \frac{U_z}{d}$$

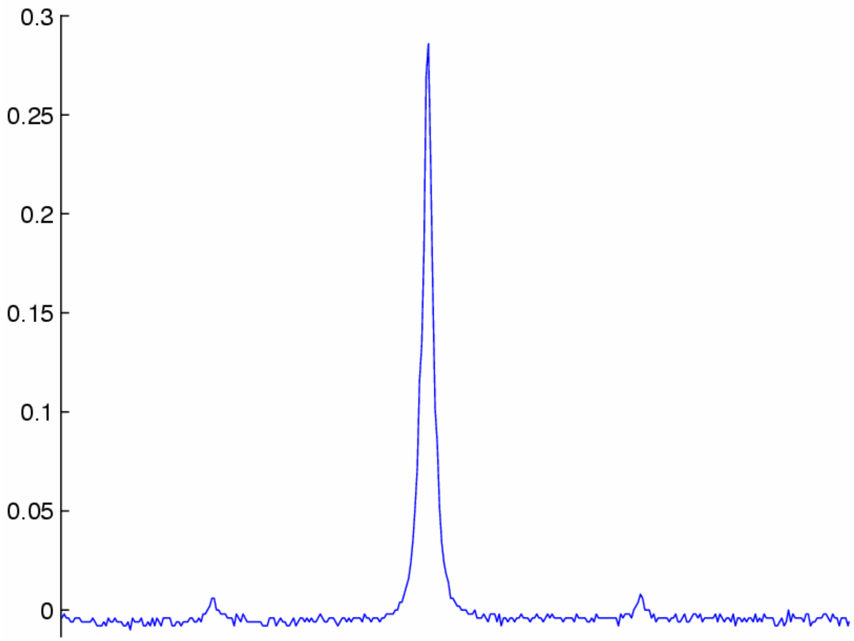
- For a modulation depth of $m = 0.5$:

$$U_z \frac{L}{d} = 708V$$

- For $L = 2.0$ cm and $d = 0.4$ cm, $U_z = 124$ V.
- Resonant circuit reduces voltage by Q~5-20.
- RF power loss in the microwatt range

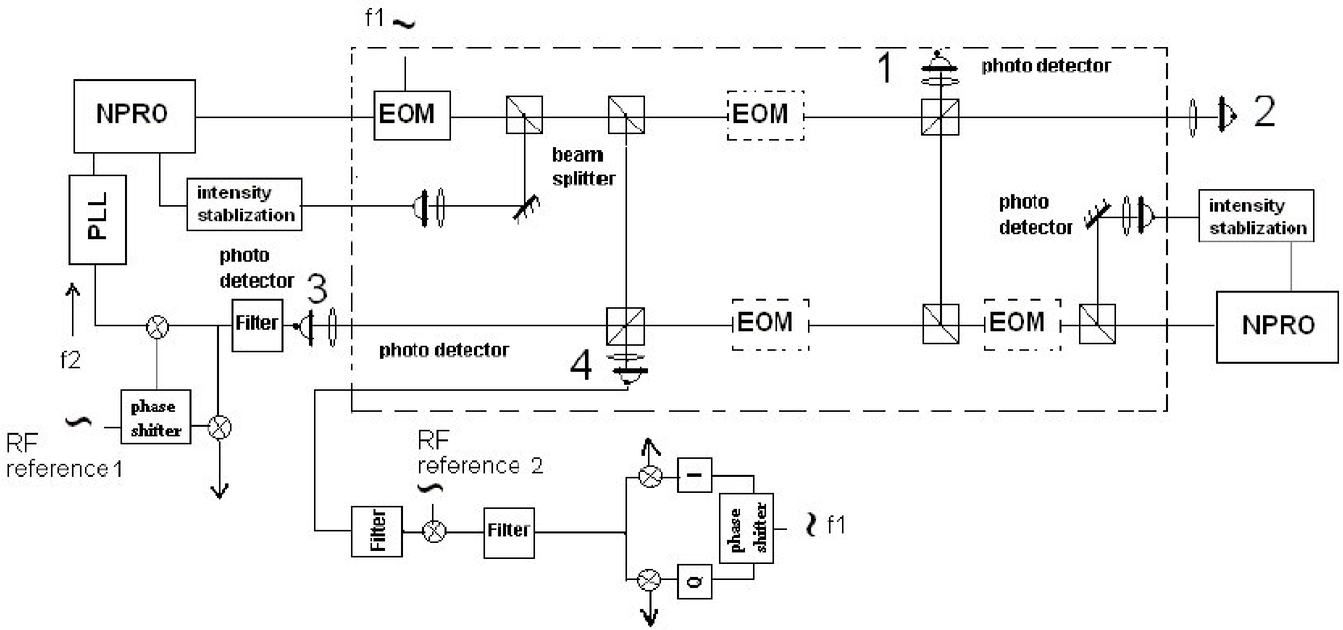
Performance

- 19.7 MHz matching circuit had Q = 20; 180 MHz, Q = 3
- 19.7 MHz modulator gave m = 0.2 with 5 V rms RF in
  - » 12 V rms -> m = 0.5.
  - » 4 W RF into 50 Ω.
- 180 MHz modulator gave m = 0.2 with 30 V rms RF in
  - » 75 V -> m = 0.5.
  - » 120 W into 50 Ω



Ongoing noise measurements

- Characterize excess phase and amplitude noise
- Modulated, intensity-stabilized NPRO beats against 2nd-locked, intensity-stabilized NPRO
  - » intensity stabilization ~10^{-8}/rHz at 100 Hz
  - » Components to go into vacuum



Damage

- In advanced LIGO, the central intensity in the EOM is:

  $$P(r=0) \approx 100\,\frac{\text{kW}}{\text{cm}^2}$$

  approximately 6000 times below the damage threshold quoted for 10 ns pulses
- We subjected an RTP crystal to 90 W of 1064 nm light for 300 hours, with no damage or other changes in properties.

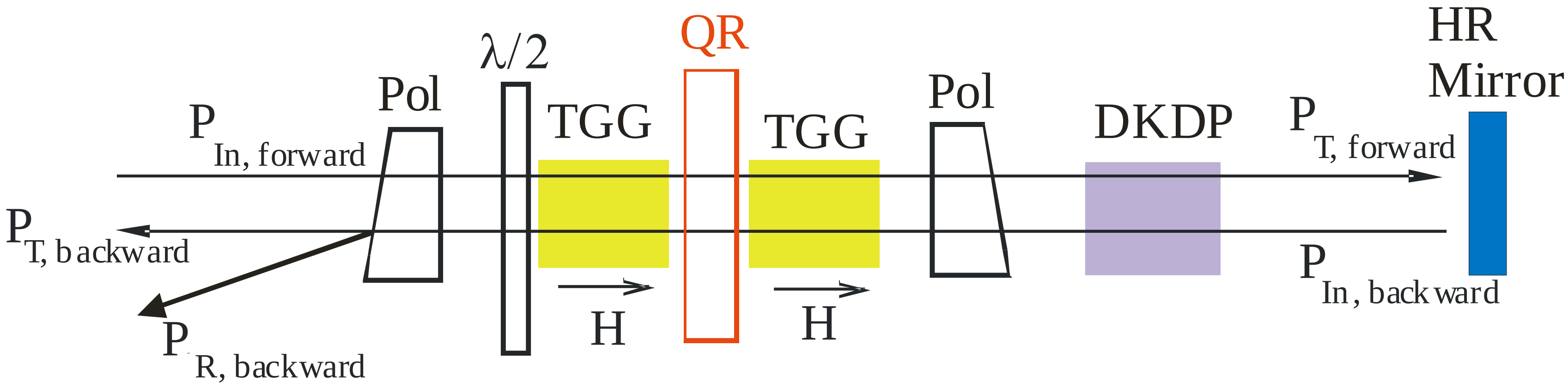
FI performance specifications

Parameter	***Goal***	***Comment***
Optical throughput (%)	> 95%	Limited by absorption in TGG and DKDP, surface reflections in the FI components (total of 16 surfaces)
Isolation ratio (dB)	> 30 dB	Limited entirely by extinction ratio of thin film polarizers[1]
Thermal lens power (m^{-1})	< 0.02	Leads to <2% reduction in mode-matching
Thermal beam drift (μrad)	< 100	Based on dynamic range of RBS actuators

[1] It may be possible to use calcite wedge polarizers (which have extinction ratios in excess of 10^5), which would improve the isolation specification to > 40 dB.

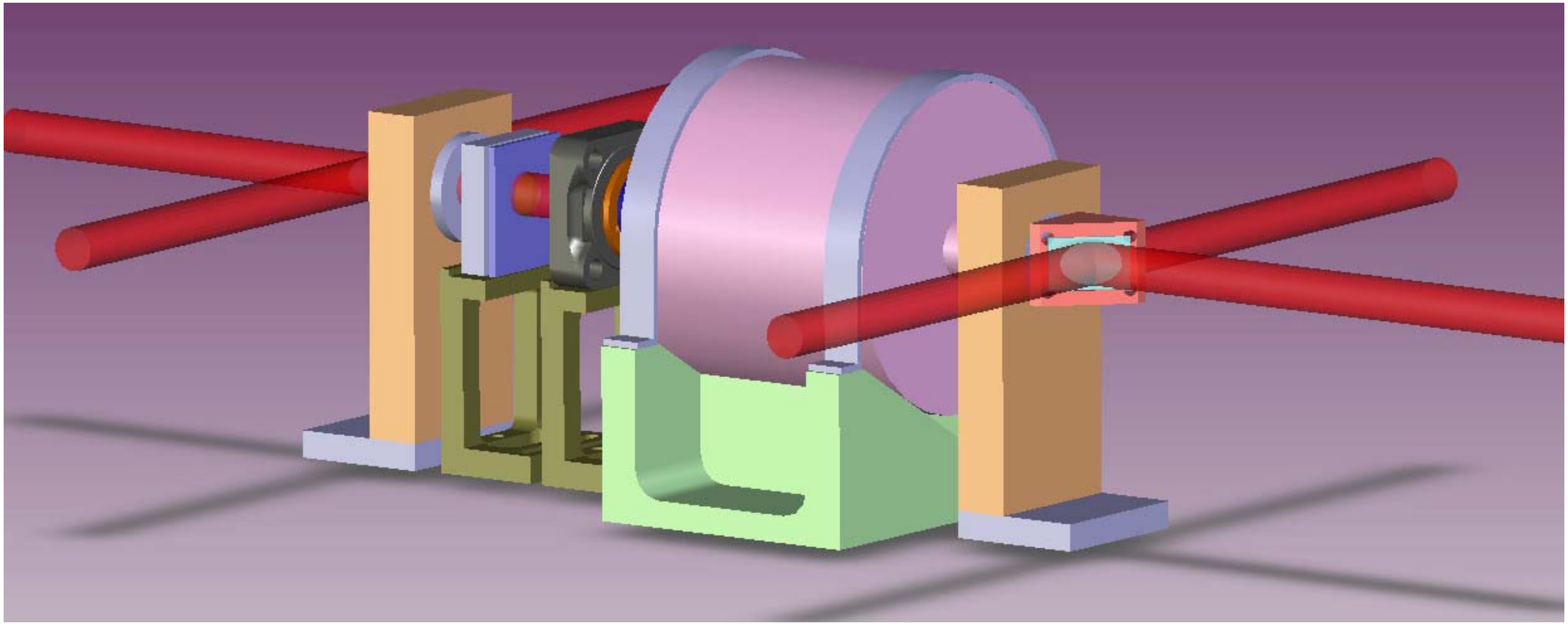
Faraday performance

- Optical isolation measured with beam reflected from the HR mirror
- High quality calcite wedge polarizers used (extinction ratio > 10^5)
- Not limited by the extinction ratio of the polarizers.



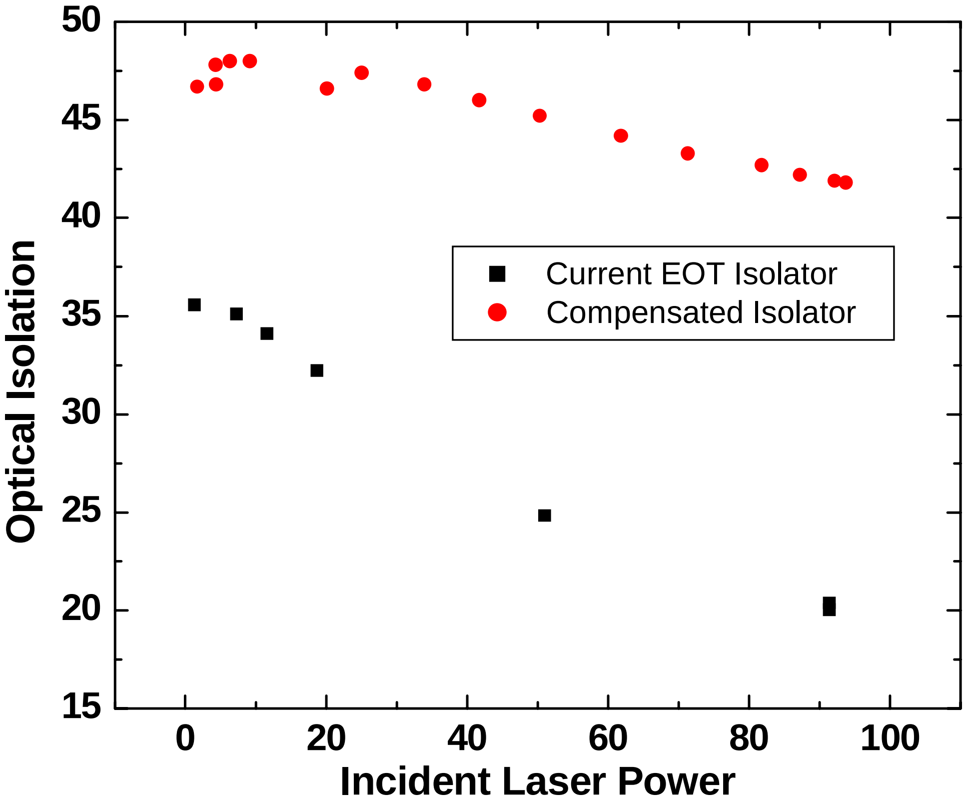
Mechanical design

- TGG and quartz crystals all in large magnet housing
- TFP’s on stands, orientation controlled by mechanical design
- DKDP compensator on fixed stand
- ½ wave plate on CVI vacuum-compatible rotator



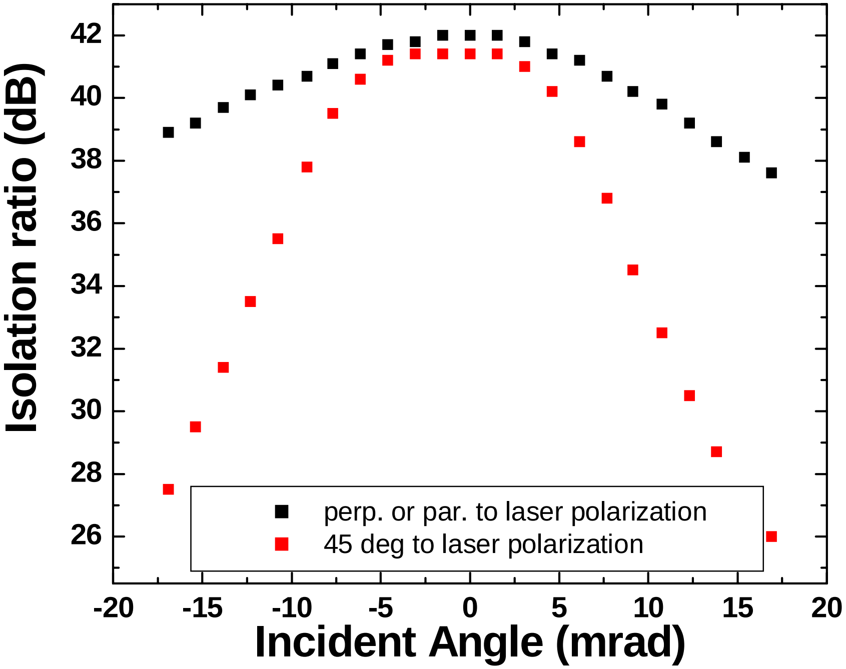
Isolation

- Isolation as function of incident laser power
  - » Red circles: Advanced LIGO design
  - » Black squares: LIGO 1 FI
- At 30 W, ~ 46 dB isolation
- If TFPs are used, isolation ~ 30 dB



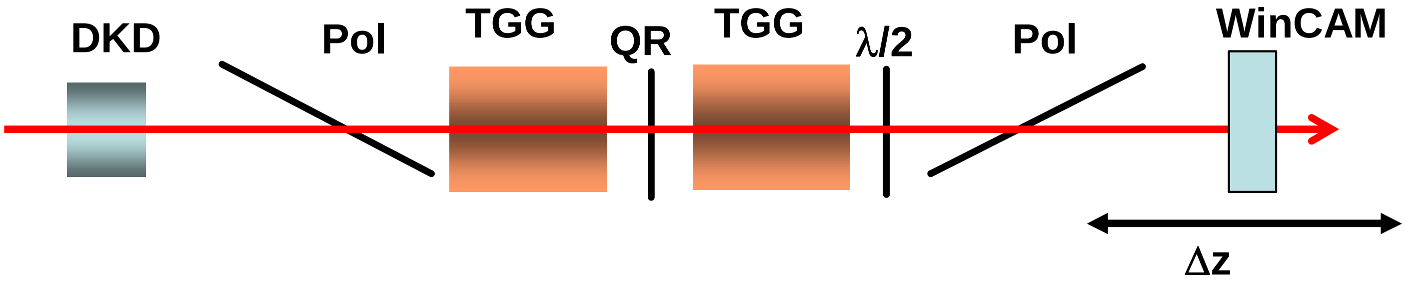
Incident angle variations

- Isolation ratio vs angle of incidence
  - Black points correspond to angular deviations parallel or perpendicular to the laser polarization axis and represent the minimum depolarization.
  - Red points correspond to angular deviations at 45^{o} to the polarization axis (worst case)



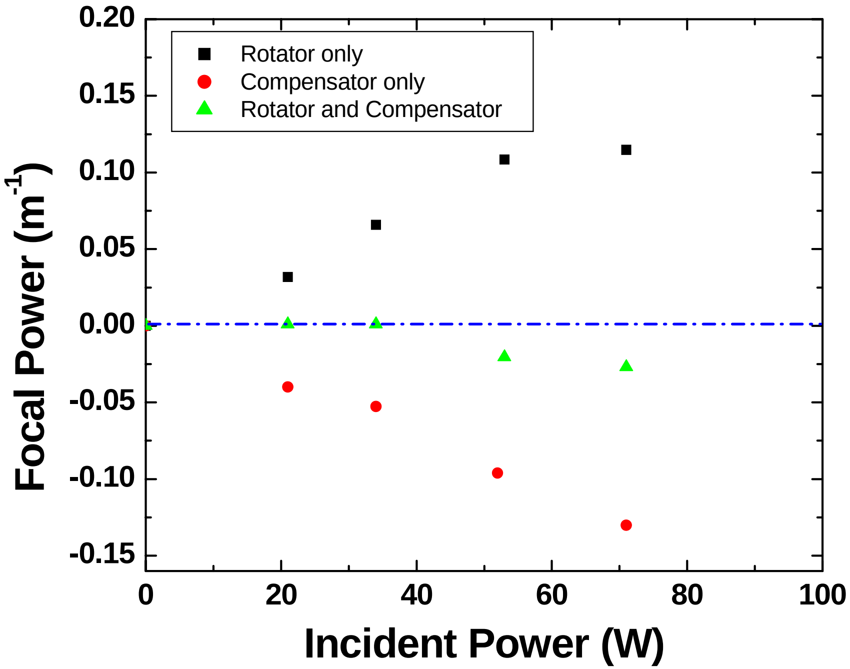
Thermal lensing

- DKPD was placed before the FI as lens compensator
- Only single-pass lensing measured
  - » Location of the DKPD in the upgrade will either be between the polarizer and wave plate or between the FI and the PRM



Thermal lens results

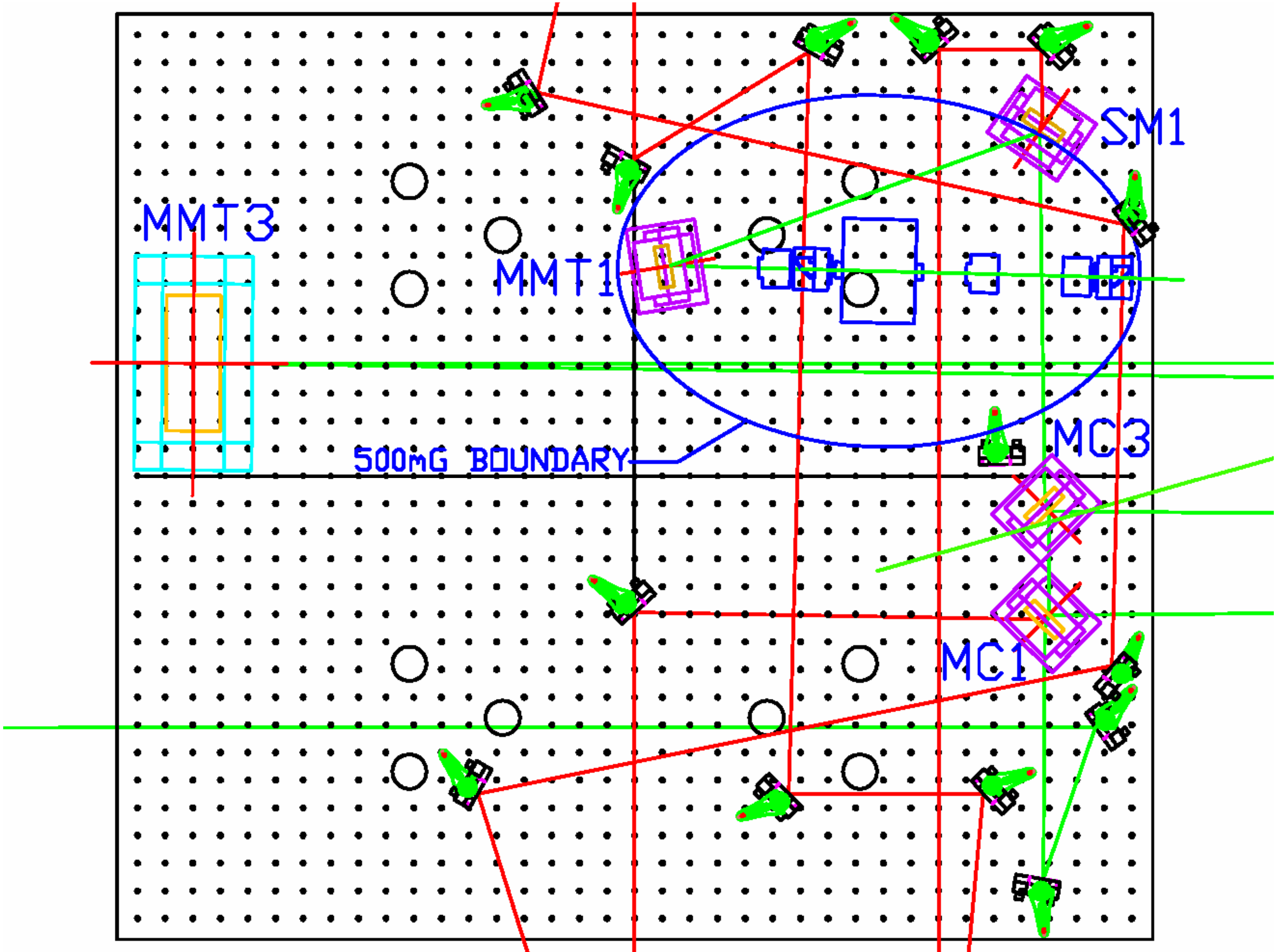
- Thermal lens (in m^{-1}) in the FI as a function of incident laser power.
  - » Black squares show focal power of the FI (no thermal compensation)
  - » Red circles show DKDP focal power
  - » Green triangles show focal power for the fully compensated FI.
- At 70 W, $f = 40$ m



HAM layouts for MLU

- Drawings of advanced LIGO FI in HAMS 1 and 7 in next two slides
- Main beam is green; aux beams are red
- Beam dumps
  - There are ghost beams from most surfaces
  - Will have to be identified and dumped
- 0.5 Gauss boundary is shown
- See docs for magnetic field couplings. They are manageable.
- Vacuum compatible design is underway

New Faraday in HAM 1



New Faraday in HAM 7