LIGO

MEMORANDUM

DATE: July 19, 2006

TO: Rana Adhikari, Doug Cook, Peter Fritschel, Dave Ottaway, Rick Savage, Sam Waldman
FROM: UF IO Group
SUBJECT: Response to EOM-FI Preliminary Design Action Items
Refer to: LIGO-T060081-00-D

The preliminary design for the electro-optic modulators (EOMs) and Faraday Isolator (FI) for the initial LIGO upgrade andAdvanced LIGO was presented in "Upgrading the Input Optics for High Power Operation" LIGO-E060003. This memo presents responses to action items called out by the review committee.

Electro-optic modulators
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o Reduction of modulation frequency & mod. depth requirements. 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: This is really a question for ISC, but we agree that a phase of 0.5 rad seems large, given the 180 W power from the laser. The modulation depth is driven by signal-to-noise issues in the ISC system, and the power on various photodetectors may not be that much different from initial LIGO. It is important to keep in mind that should a Mach-Zehnder modulation scheme be employed for Advanced LIGO, the effective modulation index is 1/4 of the modulation index imposed by the EOM. Therefore, if the Advanced requirement is relaxed to, say 0.05, than the driver electronics will still need to provide m = 0.2.

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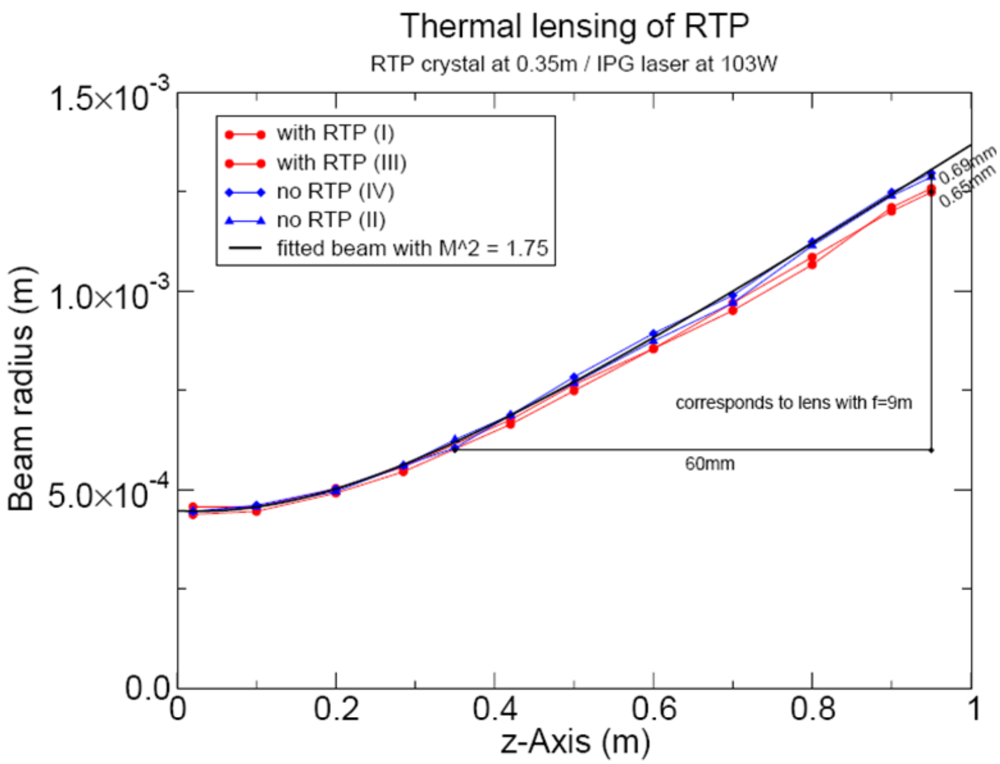
o RTP thermal lensing. Section 1.2.5 says that no thermal lensing was seen up to 60 W. What is the upper limit on alpha, or on the focal length, that can be established with this data?

RESPONSE: Recently, we have remeasured the thermal lens in a 15 mm long RTP crystal at 103 W power levels, finding an upper limit for the thermal focal length of 9 m, corresponding to a ~ 5 m thermal focal length when scaled to 180 W. This value can be compared with a 3.3 m thermal focal length induced in $LiNbO_3$ at 10 W for initial LIGO for 20 mm long crystals. The poor beam quality (M^2 ~ 1.75) comes from upstream optics in the experiment (ie, it's not induced by the RTP).



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o 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.

RESPONSE: The 4 mm x 4 mm crystal was selected with the following considerations in mind:
- Availability of large RTP/RTA crystals at the time we were purchasing them. It is now possible to get larger aperture crystals (up to 8 x 8 mm).
- Reasonable RF power. The drive voltage scales linearly with crystal thickness and inversely with crystal length. In addition, the length should reasonably short so as to minimize the propagation length and associated thermal effects.
- The aperture should be large enough to keep the power density comparable to LIGO 1 operation.

The 360 μm beam waist was selected for power density testing purposes. We are **not** recommending that it be used for iLIGO enhanced operation or Advanced LIGO. A 900 μm waist size will experience a clip loss of ~ 50 ppm on a 4 mm diameter aperture and, for AdvLIGO, have a power density roughly 2.5 times that in iLIGO (assuming 10 W operation). We therefore recommend a beam waist of approximately 900 μm be used. If larger crystals are used, we could go with a larger beam, but based on damage testing there is no compelling reason to do so.

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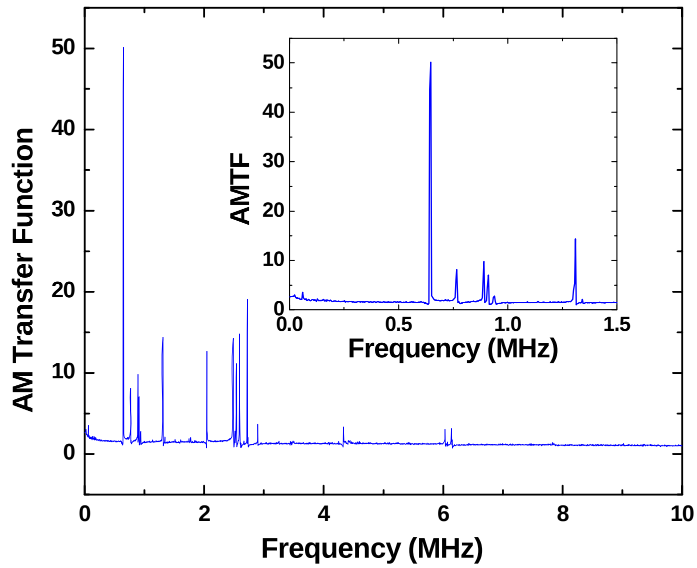
o We would like to see a test for piezo-resonances, with a frequency sweep up to at least 50 MHz. Are there piezo-resonances that need to be damped?



RESPONSE: The amplitude modulation produced by a swept sine measurement of a 4 x 4 x 20 mm^3 RTP crystal is shown below from 0 to 10 MHz.

The highest lying resonance is at 6.8 MHz; typical FWHM are ~ 10 kHz. There are no features above 10 MHz up to 50 MHz.

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o Crystal ends. Who does the AR coatings, and what is the spec? Are the ends wedged? should they be?

RESPONSE: For the first set of crystals, Raicol provided the AR coating (< 0.1%). We could ask them for the bare crystals and send them to REO or Advanced Thin Films and get better AR coating if necessary.

The ends are currently not wedged. It is probably a good idea to introduce a slight wedge to eliminate the possibility of spurious AM.

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o Crystal 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?

RESPONSE: The PCB board carries one electrode, which has the dimensions of the crystal. The crystal sits on this electrode. A copper plate on top of the crystal, clamping it to the PCB board. A Teflon clamp presses the copper plate to the crystal and the crystal to the PCB board. The Teflon clamp is screwed to the PCB board.

The aperture in the housing is 4 mm in diameter. We may reduce this to 3.5 mm to protect the crystal from catastrophic damage due to misalignment of the laser beam (touching one edge of the crystal face, which would cause serious and rapid heating of the electrode).

The cover and can are made of aluminum because it is durable and easy to machine. Other materials are possible. The base is made of delrin.

An e-Drawing of the assembly and pdf component drawings can be viewed in:
http://www.phys.ufl.edu/~reitze/AdL/EOM-FI/

(Note: You may need to save the SolidWorks e-Drawing onto disk and run the e-Drawing viewer from your machine

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

RESPONSE: We have made RFAM measurements using an NPRO probe laser, simulating the heating of the AdvLIGO laser with a multi-longitudinal mode-pump. Those data were shown on page 9 in the original document. The instrinsic RFAM (for the temperature fluctuations in our laboratory) can be inferred from a segment of the constant data, i.e., the first 20 minutes. The absolute level was 10^{-5}, larger than that in the iLIGO $LiNbO_3$ EOMs (~ 10^{-6}), possibly due to the lack of wedges on the crystal. It is constant to the few 10^{-6} level over short times. Longer times are probably more reflective of the laboratory environment (which we made little attempt to control).

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o 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

RESPONSE: We have made 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, it is better to put the matching circuit in the crystal housing so we don't have to drive the cable at high frequencies.

It is possible to get crystals as long as 40 mm, and we could put three electrodes (one for each frequency) on one such crystal. Some thought would need to be put into defining the gap spacing and estimating the effects of fringing fields between the gaps.

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o Topic for open discussion: 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?

RESPONSE: The Teflon crystal clamp would need to replaced with a suitable vacuum compatible material, perhaps boron nitride (LIGO-E960050-B-E "LIGO Vacuum Compatible Materials List"), and the matching circuit would need to be removed from the housing and placed outside the vacuum. Alternatively, a vacuum can could be used to seal the EOM from main vacuum.

The beam behind the mode cleaner is larger than it is on the PSL table (the mode cleaner waist in advanced LIGO is 2.1 mm) so should the current AdvLIGO IO layout be maintained, the crystal would need to be 8 x 8 mm^2. (At 4 x 4 mm^2, the clipping would be at the 15% level. At 8 x 8 mm^2, clipping is 700 ppm, with no allowance for misalignment.) Alternatively, a focus could be introduced on the beam after it leaves the MC to allow for a smaller crystal aperture, although it is not immediately obvious that this is easily achievable.

<u>Faraday Isolator:</u>

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o What is the basis of the isolation requirement?

RESPONSE: The somewhat ill-defined requirement comes from crudely scaling up what is known from initial LIGO about spurious interferometers in the IO. There is evidence that parasitic interferometers have been seen at power levels of a few watts in initial LIGO (from back-scattered MC light?). The iLIGO FI's provide ~ 30 dB isolation. Scaling to AdvLIGO powers (125W/4W), 15 dB of additional isolation at least is needed to achieve the same noise performance. In absolute terms, we don't know what the acceptable level of isolation for Advanced LIGO, so we chose a strong but doable value.

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o Thermal beam drift/steering: the limit of 100 urad 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 urad?

RESPONSE: This number was derived from the dynamic range of the LLO RBS system (but allowing for little headroom). At 30 W powers, both TFP and calcite polarizers demonstrate drifts below 100 μrad (40 μrad in the case of calcite and ~ 3 μrad in the case of TFPs). Assuming ~ 15-20 W out of the MC for the iLIGO upgrade, we can safely adopt the lower value of 20 μrad.

Scaling the drift measurement to 150 W operation for AdvLIGO, the calcite polarizers have ~ 200 μrad drift, and TFPs have < 15 μrad drifts, so only TFPs will meet the requirement. As noted above, we are in discussions with Advanced Thin Films about development of TFPs with higher extinction ratios. We hope to have them for AdvLIGO.

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o We are unclear on the design/strategy for dealing with the different beam heights in initial and advanced LIGO; please explain.

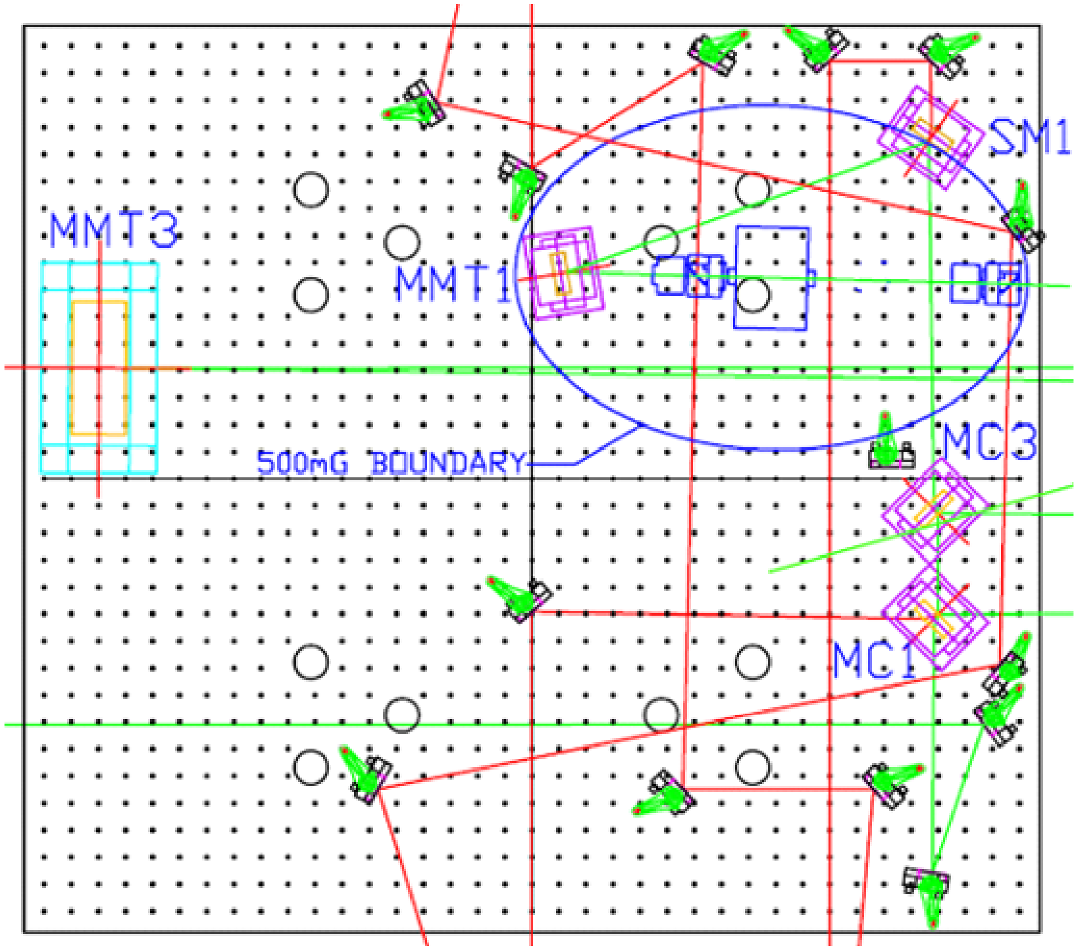
RESPONSE: We're not sure exactly what specifically is being asked for, but here is the general idea. The layouts in the iLIGO upgrade and in AdvLIGO are quite different. Thus the strategy for the use of the AdvLIGO Faraday isolator in the iLIGO upgrade and its reuse in AdvLIGO will involve remanufacturing of the breadboard, of the structure that holds the Faraday rotator, and of the stands for the polarizers, waveplate, and steering mirrors.

iLIGO - For H1,L1, the FI is moved from its current position between steering mirror (SM1) and MMT1 to in between MMT1 and MMT2. The beam rises at an angle of {2.48 mrad (H1), 2.79 mrad (L1)} from MMT1 (on HAM1) to MMT2 (on HAM2). To accommodate this, the base plate will be angled such that the optical axis of the FI corresponds to center to center MMT1,2 axis. The REFL beam will propagate slightly downward (at the same angle) back toward MMT1 and out toward the first routing mirror. That mirror will direct the beam to the proper height on the second routing mirror.

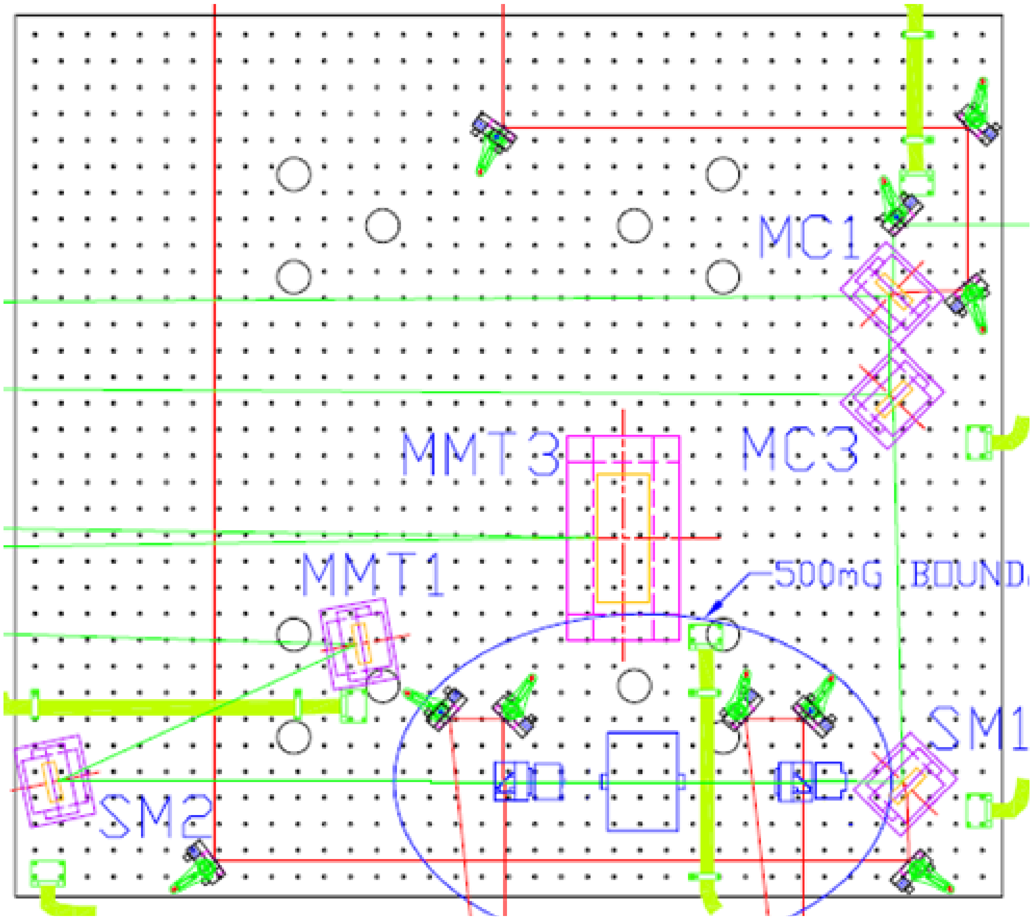
For H2, the FI will sit in the same position as it currently sits between SM1 and SM2, thus there are no changes in the beam heights from their current positions.

AdvLIGO – The AdvLIGO layout is at a sufficiently preliminary state that it is difficult to know at this stage exactly how the FI will be placed. What we can say at this point is that the beam height in AdvLIGO is approximately 8" (~ 2" taller iLIGO) and that the FI will be located such that all entrance and exit beams are parallel to the HAM table.

Layouts for the iLIGO are shown below. A preliminary SolidWorks layout for the AdvLIGO IO is located at: http://www.phys.ufl.edu/~reitze/AdL/EOM-FI/aligo_IO_LHO4k_layout3.easm.



Plan view of HAM1 for the initial LIGO upgrade. The breadboard for the FI is not shown. Also, the TFPs are drawn with exit angles of 90° based on polarizers obtained from LZH. We will most likely use ATF polarizers which have 112° exit angles; this will change the routing of the diagnostic beams.



Plan view layout for HAM 7. The breadboard for the FI is not shown. Again, the TFPs are drawn with exit angles of 90° based on polarizers obtained from LZH. We will most likely use ATF polarizers which have 112° exit angles; this will change the routing of the diagnostic beams.

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o What is the assumed and/or optimum spot size in the Faraday?

RESPONSE: The characterization measurements were performed with a beam size of ~ 1.9 mm. For comparison, the beam size in the FI in initial LIGO is 1.6 mm (H2) and 1.8 mm (H1,L1), and the beam size in FI in Advanced LIGO is planned to be 2.1 mm.

From the standpoint of thermal effects, the beam size does not matter to first order. The isolation ratio will in general be better for a smaller beam since it samples a more homogeneous region of magnetic field (as long as the beam stays in the center of the crystal).

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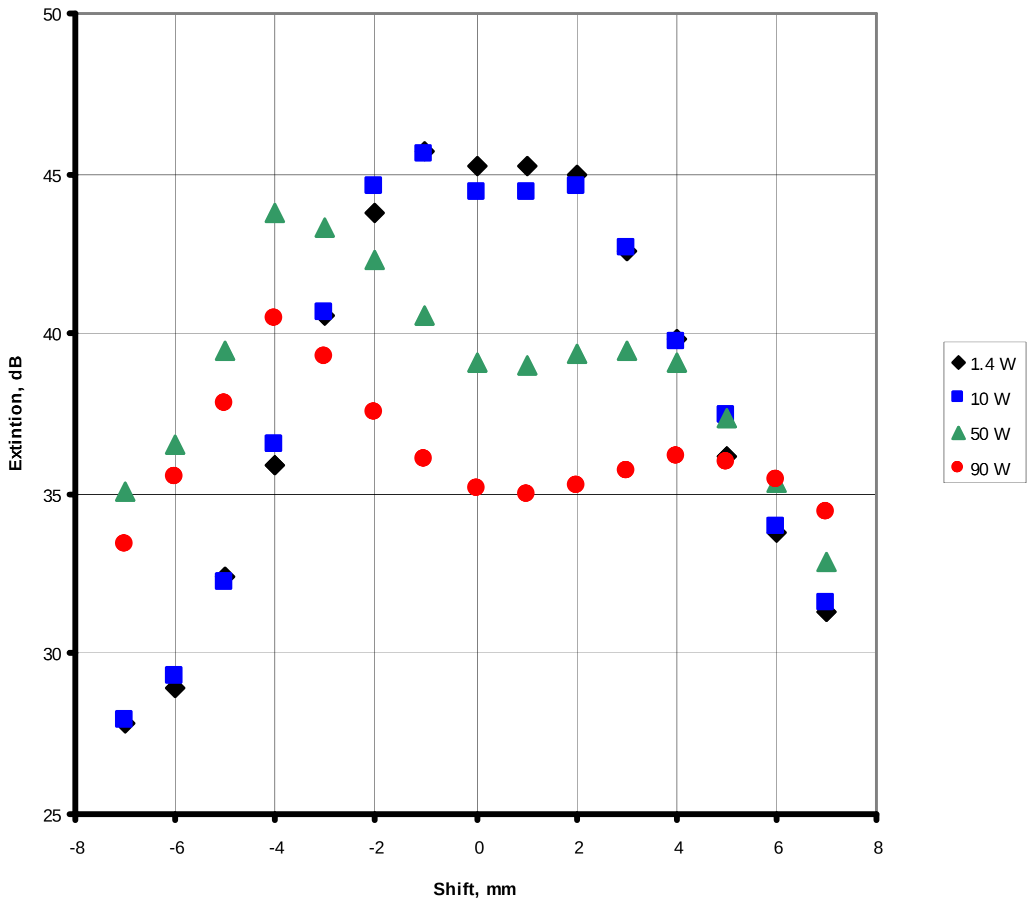
o How sensitive is the isolation to the transverse beam position?

RESPONSE: We expect that there is some sensitivity to transverse position since the magnetic field is not completely homogeneous. We find that within a 6 mm radius aperture, the isolation is between 35 and 45dB at any power between 1.3 and 90W. Measured isolation values as a function of lateral shift are shown in the figure below.



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o Polarizer choice: 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.

RESPONSE: Custom made TFPs from AT Films should have losses <0.5% and still provide an extinction ratio close to 10000. We are currently waiting on a firm quote to produce them. One potential design change could be to coat **both** sides of a fused substrate as a TFP with a coating with R_p < 0.25% and an extinction ~1000. That would give losses <0.5% and an extinction of 10^6. We are exploring this.

We are not sure that the hybrid solution will improve the situation. The input polarizer sets the isolation and reflects the REFL beam. We might even take out the second polarizer. Or is the proposal to use the calcite polarizer at the input and use only the 0.5% reflected off the TFP (output polarizer) as the REFL port. Thus we would have to dump the 99.5% of the reflected field.

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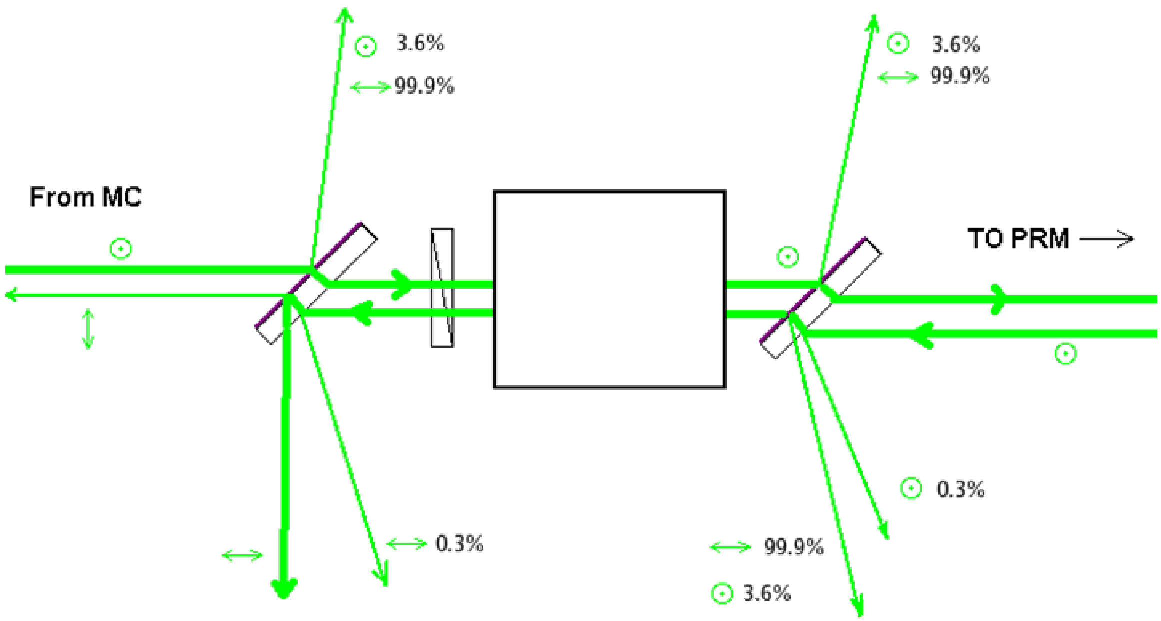
o Power budgets (section 2.2.4). Where is the power going (for both the transmitted and rejected cases)? Are all the beams being sufficiently dumped?

The drawing below shows the losses for the FI using TFPs. As is currently done in H2, we intend to capture most (or all) of the dumped beams and direct them out of the vacuum system to be available for diagnostic purposes (measure depolarization vs input power, e.g.).



Measured % losses as a function of polarization for an FI with TFPs. The MC is located to the left of the drawing; the PRM to the right.

Not shown are reflections from optical surfaces at near-normal incidence. Assuming 300 ppm AR coatings, beams with ~ 50 mW power levels will proliferate. Our experience from table-top investigations is that these will need to be identified and dumped during the alignment of the FI.

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o Thermal performance in vacuum. Has there been any analysis of this? Any problems foreseen?

RESPONSE: Based on thermal lensing measurements, we estimate an absorption loss of 0.3% for each of the TGG crystals and the DKDP compensator. An upper limit on the absorption of the TGG crystals has been measured to 0.7% per crystal, but the error bars are large.

Assuming Advanced LIGO operating conditions (the worst cast) for the Faraday and 0.3% loss for each of the absorbing elements, the total absorption is roughly 1.0%, or ~ 1.5W. Because the TGG is in physical contract with the rotator body, the majority of the heat is conducted away through contact with the HAM stack.

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o Presumably all the elements have AR coatings ... are they high quality? what are their specs?

RESPONSE: The quoted AR coatings in the prototype Faraday isolator (calcite) were < 0.2%. This includes 2 TGG crystals, 1 quartz rotator, 1 DKDP compensator, and two calcite polarizers. This gives a total of 12 surfaces. The measured transmission is ~ 98%, and includes ~1% absorption losses from the TGG and DKDP. Subtracting off the absorption losses, we find that the AR coating is ~ 0.1%.

As noted above, this could be improved by a factor of 3X to 300 ppm with specialized coatings.

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o 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?

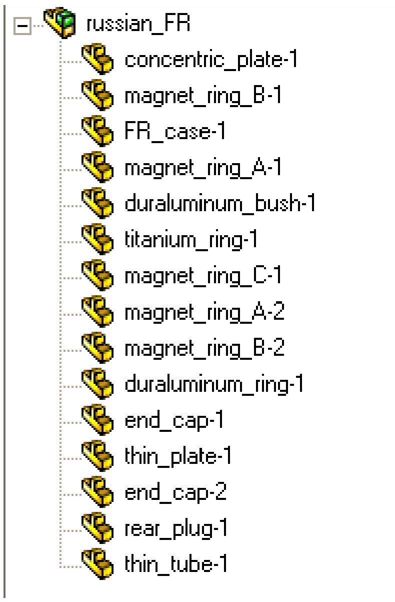
RESPONSE: The prototype FI was not designed with vacuum compatibility as a primary consideration, thus we did not expect to pass an out-gassing test (and it didn't). It was not assembled to LIGO cleanliness standards; there were blind holes as well as places for trapped air in the rotator housing. We are undergoing a redesign which should correct theses problems. In addition, the individual components will be clean and baked before assembly of the rotator, and then assembled in a clean environment at one of the sites.

We are also looking into a possible redesign of the rotator housing. In the current design, both TGG crystals and the quartz rotator sit in one housing for a compact footprint. We are exploring the possibility of having each TGG and the rotator mounted separately

We note the first generation iLIGO FI experienced similar problems, so we feel confident that this FI can be made to work.

The list of components is as follows:

<u>Rotator components</u>



-The magnet is made of sintered NiFeB
- The housing is made of aluminum with one titanium part
- Terbium gallium garnet (TGG) is the magneto-optic material
- the polarization rotator is made of quartz

An e-drawing is located at http://www.phys.ufl.edu/~reitze/AdL/EOM-FI/russian_FR.easm

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o 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.

RESPONSE: Looking at the drawings above, we believe mirrors can be placed on HAM1 and 7 that will provide a view to the FR entrance and exit from the two upper viewports which currently house illuminators and cameras. It may be difficult to get a clean view of the FR entrance on HAM1, but the polarizer can be placed significantly close such that a beam going through the center of the polarizer will be well aligned in the FI.

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o The layout of the HAM1 table is not completely clear to us. This will have to be carefully reviewed eventually; for now we can just go over what you are thinking.

RESPONSE: Hopefully, some answers have been provided above. Probably best to deal with this question interactively.

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o 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?

The static B-field will cause a DC force and torque on the mirror. This static force and torque should not hurt the interferometer and will be taken out during the initial mechanical alignment. We are not aware of any requirements on the static forces or torques.

Here are estimations of the rotation of the MC mirror caused by the magnetic field and the magnetic field gradient:
Rotation:
$\Phi < 3x10^{-8}$ rad x grad B/[G/m]
$\Phi < 4x10^{-7}$ rad x B/[G]

assuming:
$\mu = 0.0107$Nm/T
m = 3.89kg

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