State of the Photon Calibrators

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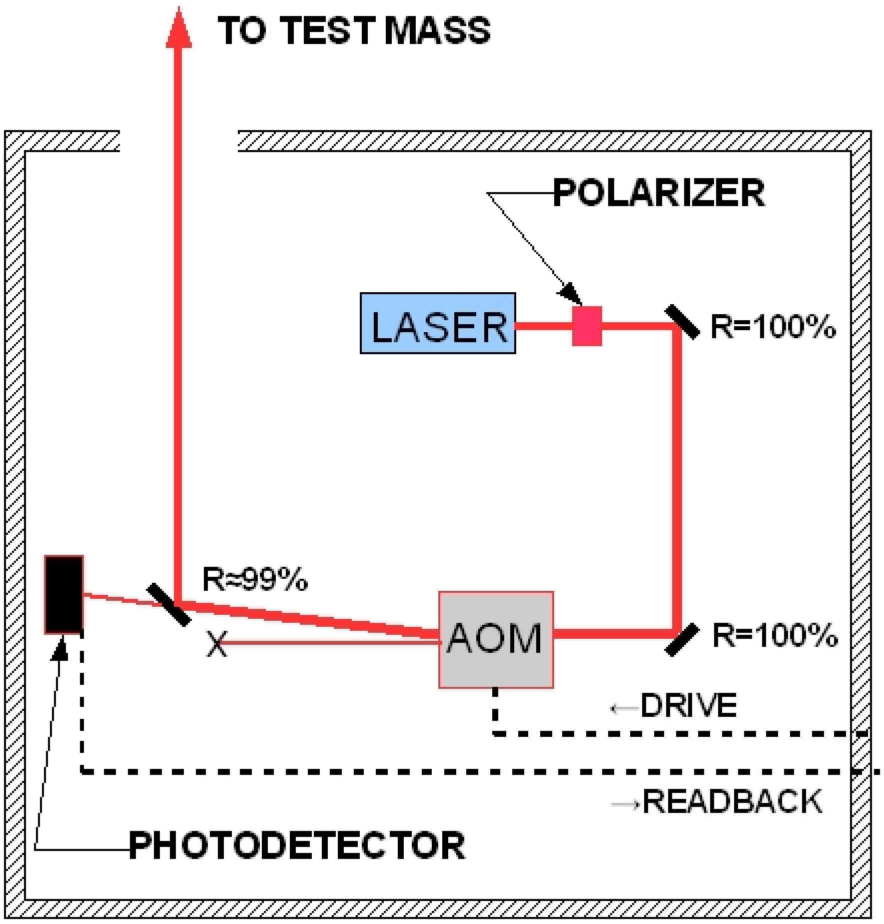


LSC Meeting August 2006

G060686-00-I

LIGO

Plan of the talk

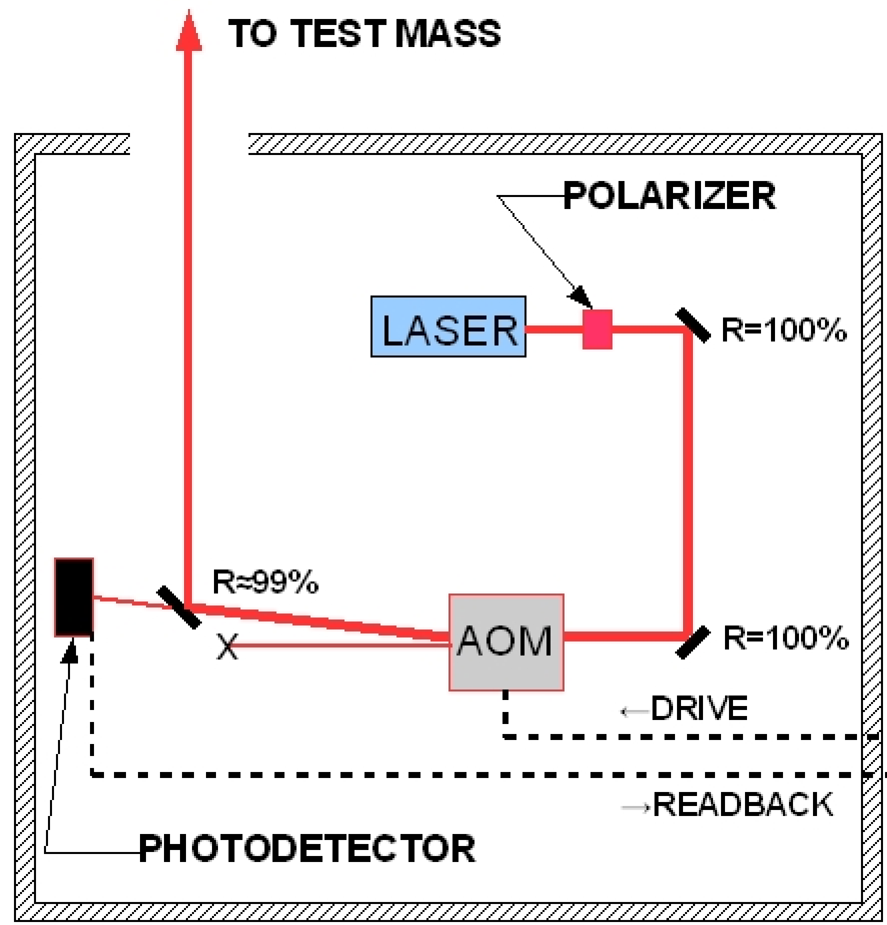
- Introductory
  - brief intro to the photon calibrator system
  - error sources
  - a DMT monitor to make the measurements
- Overview of discrepancy with coil calibration
- Things we have checked
- Things we are checking
- Things we plan to check

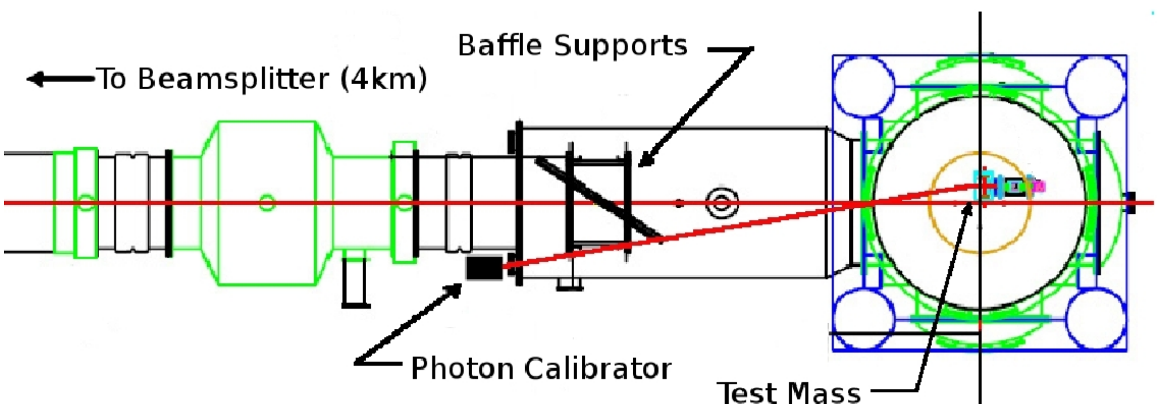
Photon Calibrator System

- Intensity modulated radiation pressure excites ETM, approximately sinusoidally, at f_{pcal}.
- Power deduced from photodetector looking at beam pickoff. Displacement (strain) calculated:

$$x_{exc}(\omega)=\frac{2P\cos\vartheta}{Mc\omega^2}$$

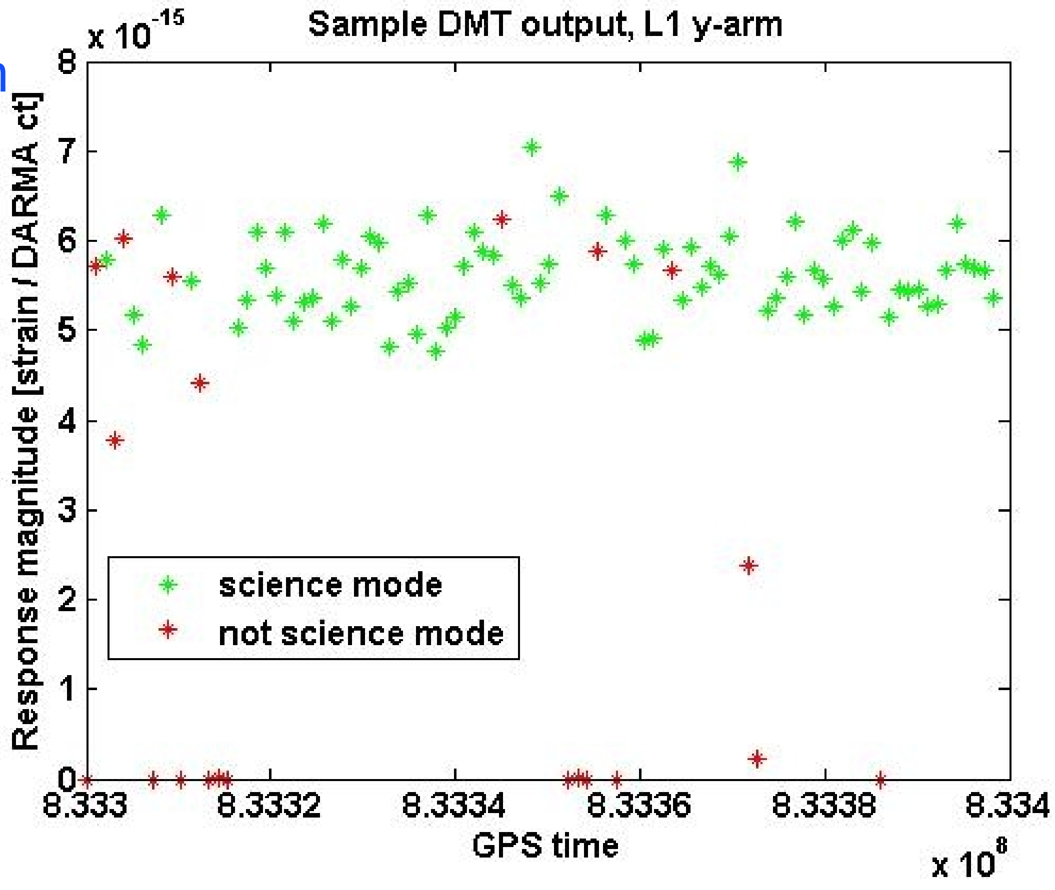
- Measure DARM_ERR to get $R(f_{pcal})$ in strain per counts.
- Errors:
  - DARM_ERR statistical (depends on SNR)
  - photodetector conversion (2%)
  - viewport reflectivity (1% or negligible)
  - power meter (3%)
  - off-centered spot (3%, H1 only)



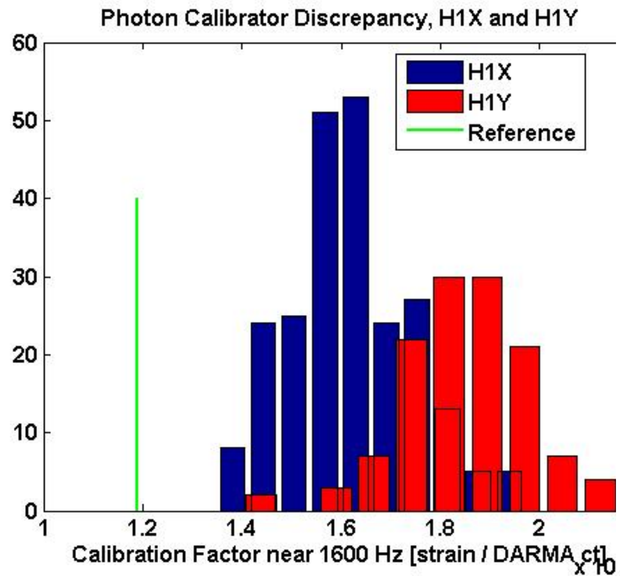


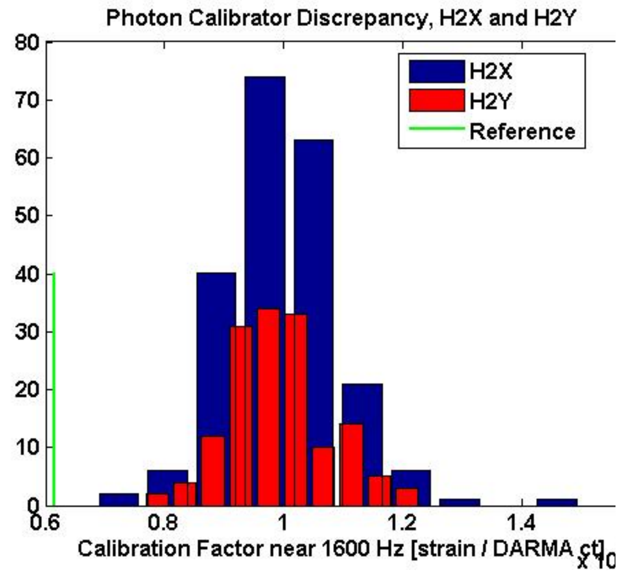
PhotonCal DMT Monitor

- Repeatedly measures $R(f_{pcal})$ in strain per DARM_ERR cts
- Uses config files constructed by Matlab scripts, which contain all the details of each of the 6 photon calibrators
- Propagates coil calibration for comparison purposes
- Monitors state vector
- Not yet admitted to DMT production environment



A problem: Measurements at running frequencies (near 1600 Hz)





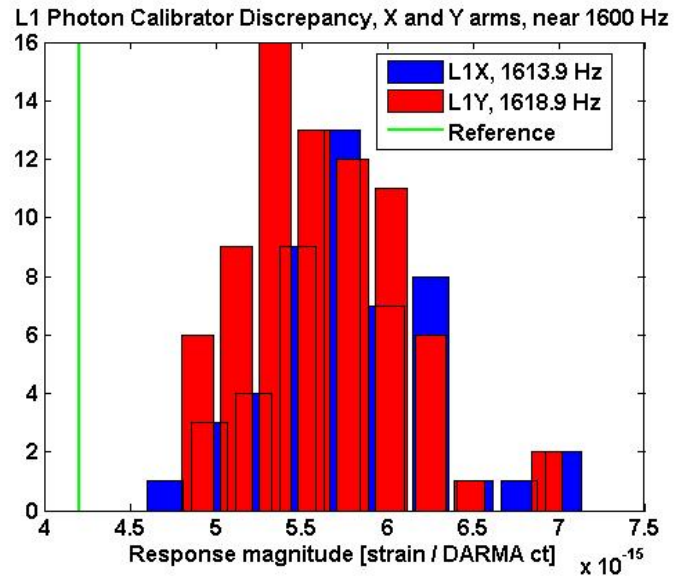


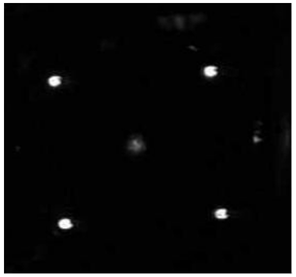
Table 1: Summary of photon calibrator discrepancies near 1600 Hz.

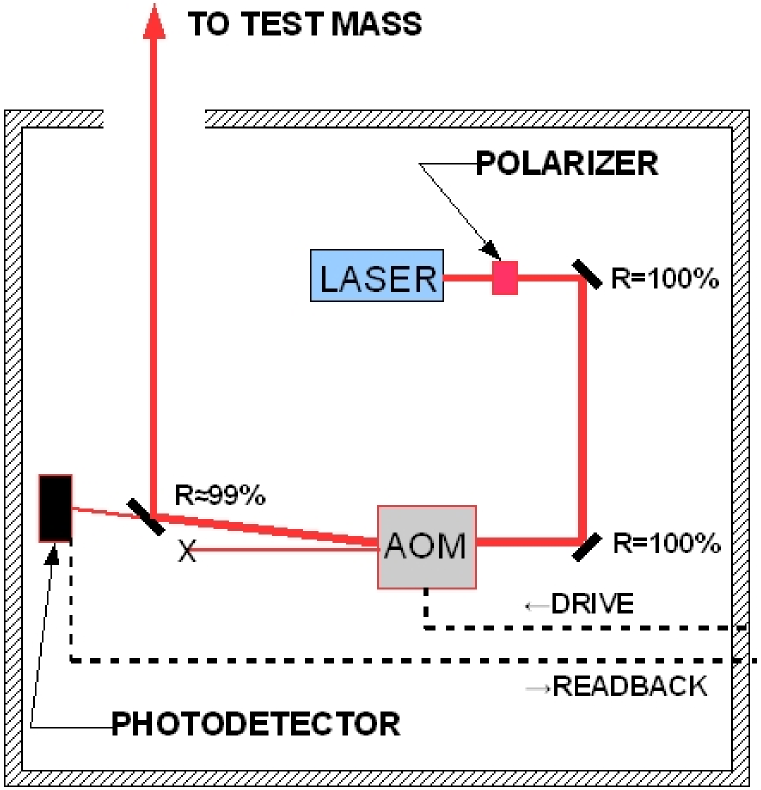
	H1X	H1Y	H2X	H2Y	L1X	L1Y
f [Hz]	1605.7	1609.7	1622.9	1626.7	1613.9	1618.9
$\left\|\overline{R}_{pcal}\right\|$	1.62e-14	1.85e-14	9.98e-15	9.92e-15	5.79e-15	5.62e-15
$\left\|\overline{R}_{pcal}\right\| / \left\|R_{ref}\right\|$	1.36	1.56	1.62	1.61	1.38	1.33
σ [%]	7.6	6.9	9.8	8.4	8.8	8.2
N	235	126	214	148	49	76

- ~1000 second integrations to get decent SNR
- green lines are unpropagated coil calibration

What can go this wrong with pCal?

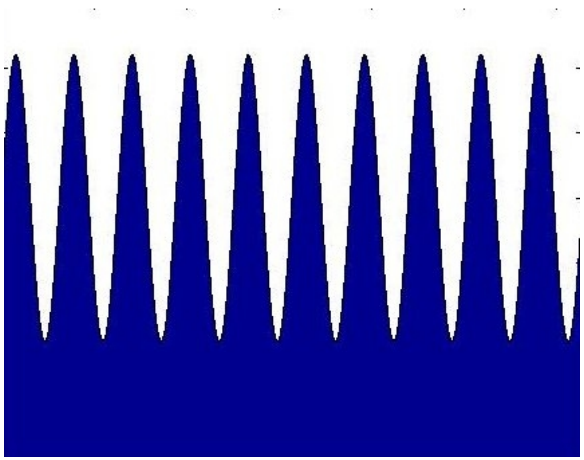
- Blunder in calculations?
- Beam drift on photodetector?
- Harmonics?
- Photodetector calibration (ADC cts to power out of enclosure) ?
- Power meter calibration?
- Clipping downstream of pickoff?
- Viewport issues, reflection, absorption?
- Beam shape – are all photons getting to ETM?
- Excitation of other pendulum modes?
- Thermal issues?
  - thermal expansion of HR coating
  - thermal expansion of substrate
  - other complex coating / optic physics

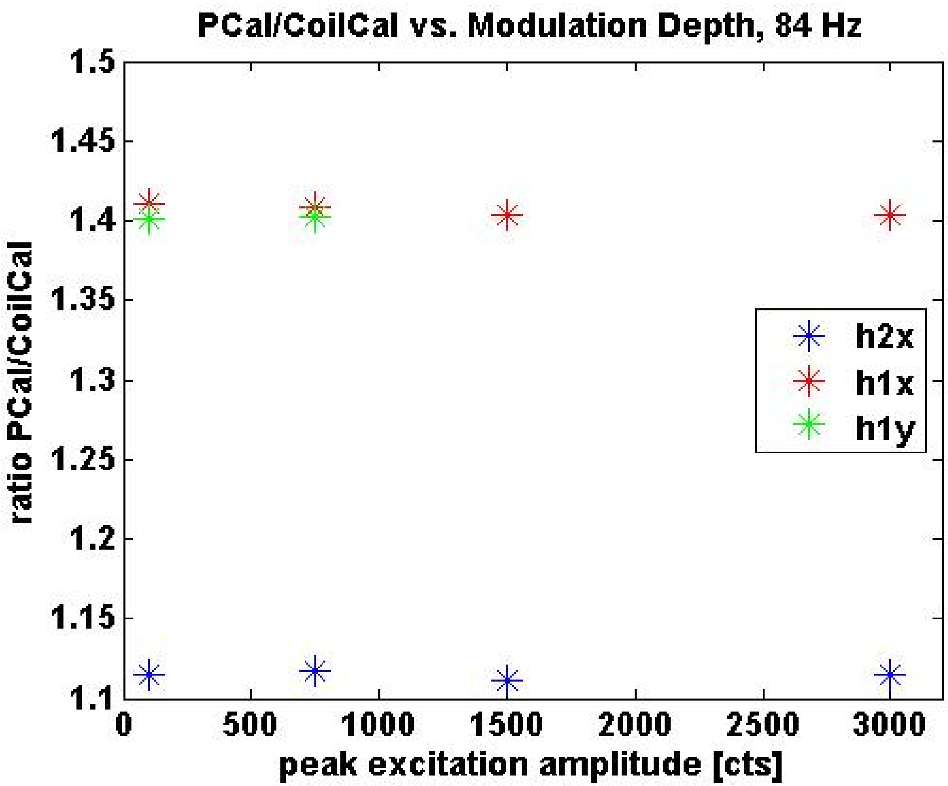


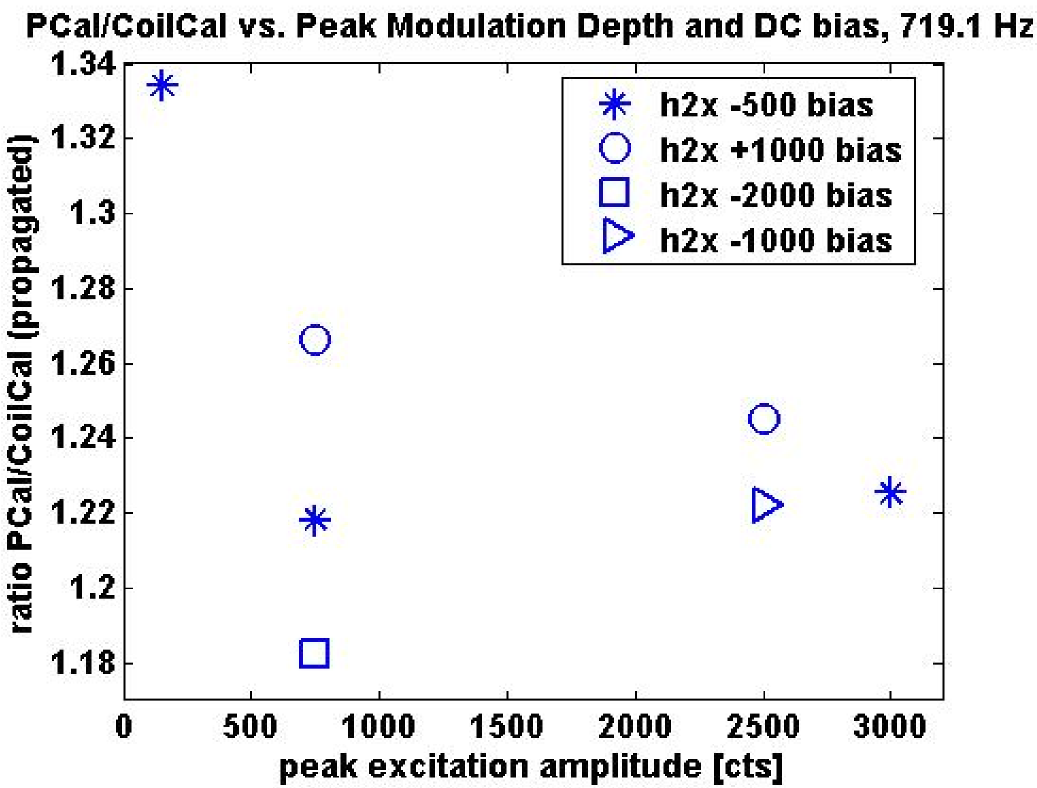


Dependence on pCal laser peak excitation amplitude

- Peak excitation amplitude measurements made at
  - 84 Hz
  - 719.1 Hz
  - ~1600 Hz
- No dependence observed







Dependence on pCal laser DC bias

AOM drive cts, laser power [mW]

-2000 cts ~ 80 mW

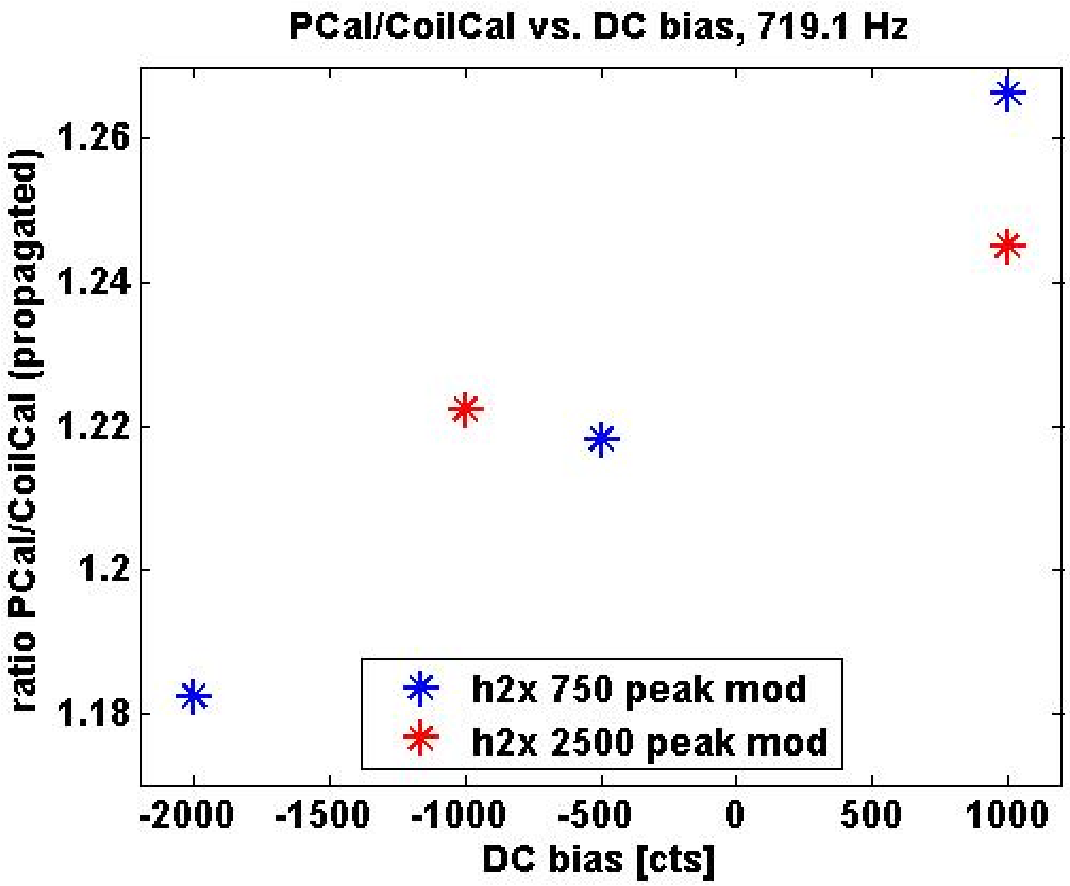
-1000 cts ~150 mW

-500 cts ~190 mW

1000 cts ~320 mW

What would this look like at 1064nm instead of 1047nm?

What would this look like across all frequencies?



Spot size

- We are eager to change the beam spot size on the ETM and take some measurements...

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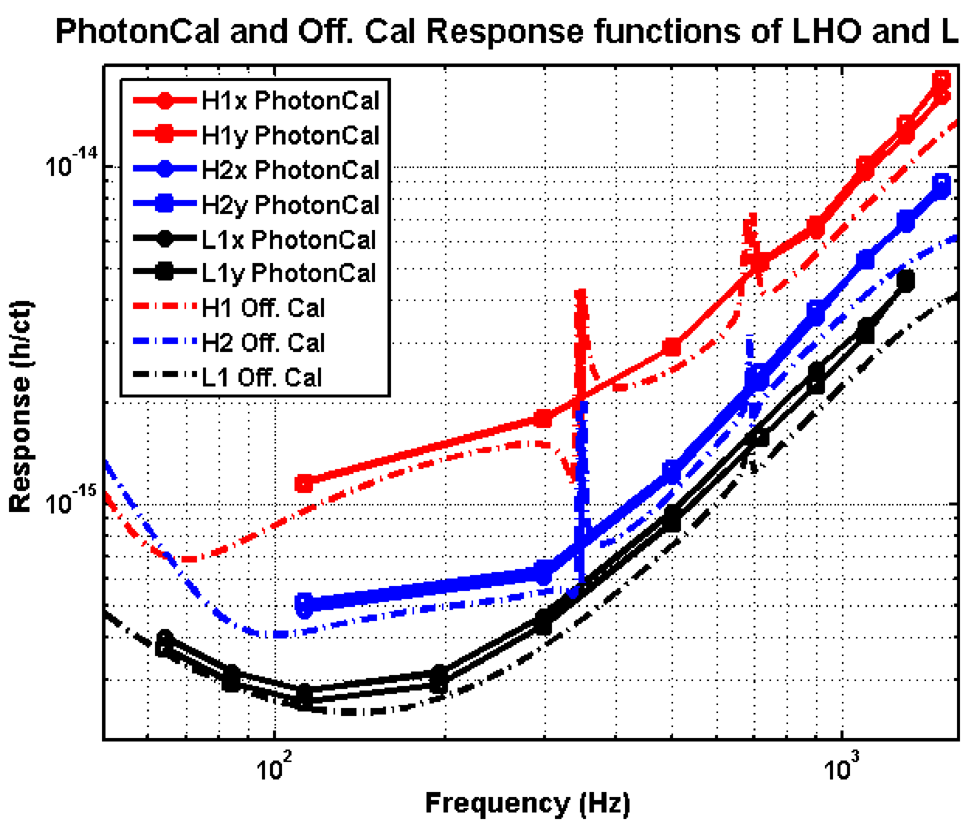
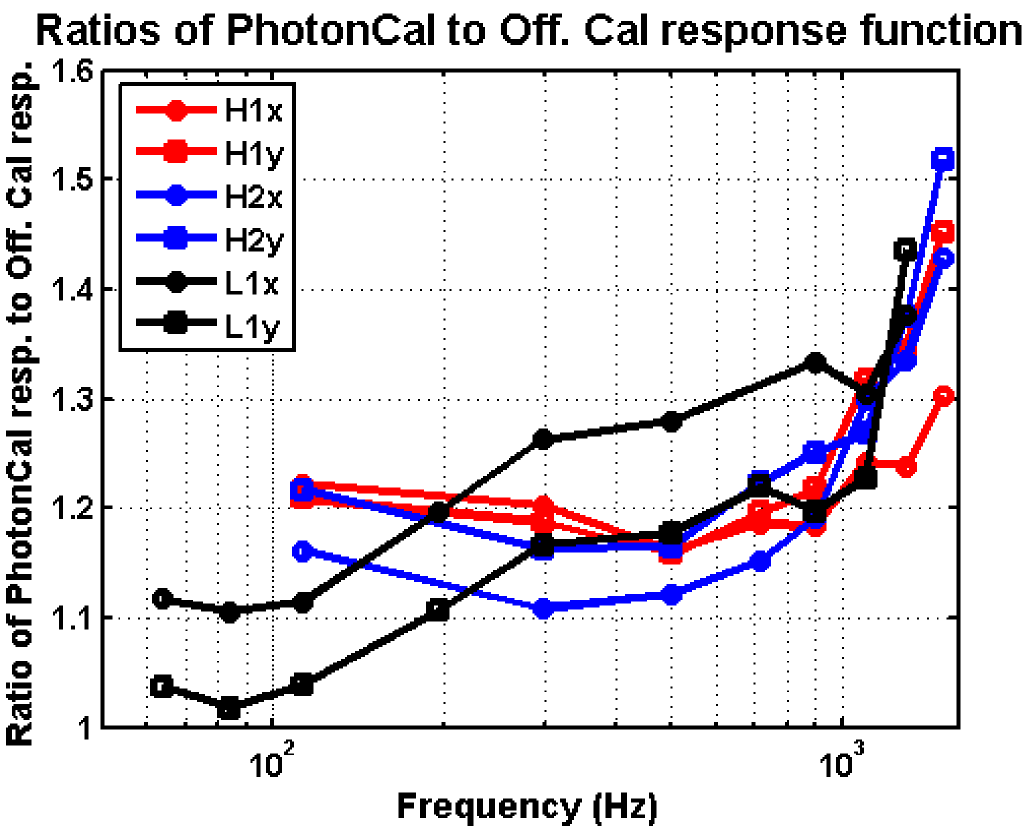
Frequency Dependence

The good: Correct trend

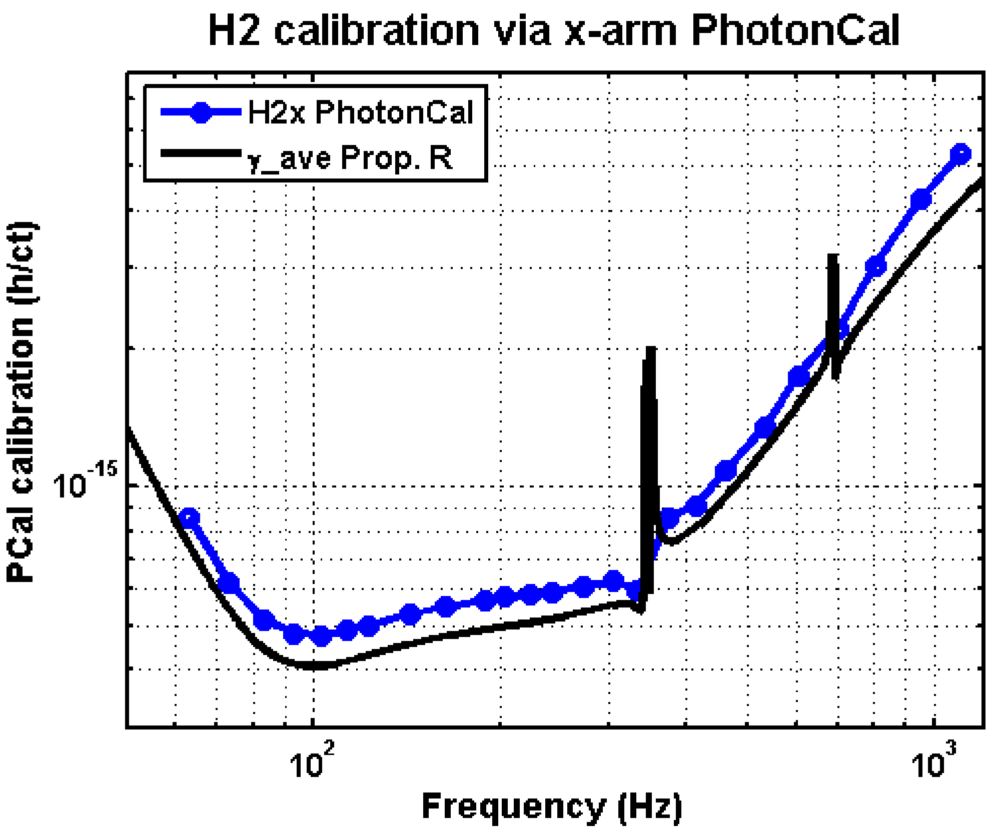


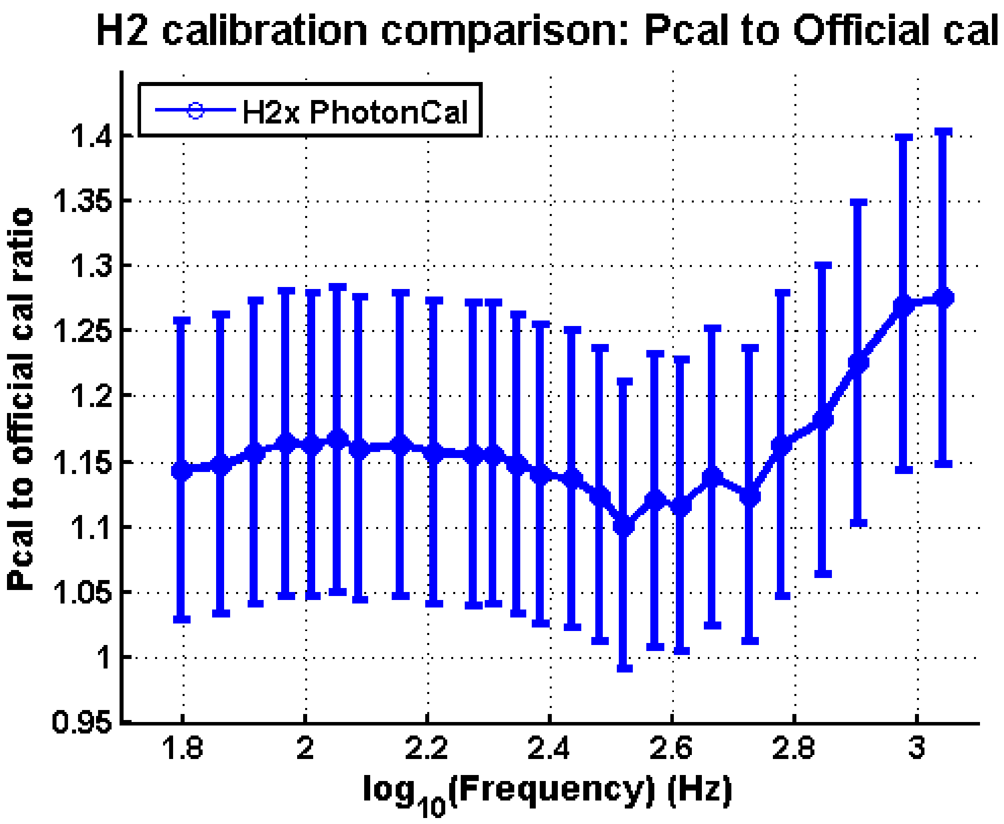
The bad: Ratio doesn't agree



LHO measurements: 21 June 2006
LLO measurements: 26 July 2006

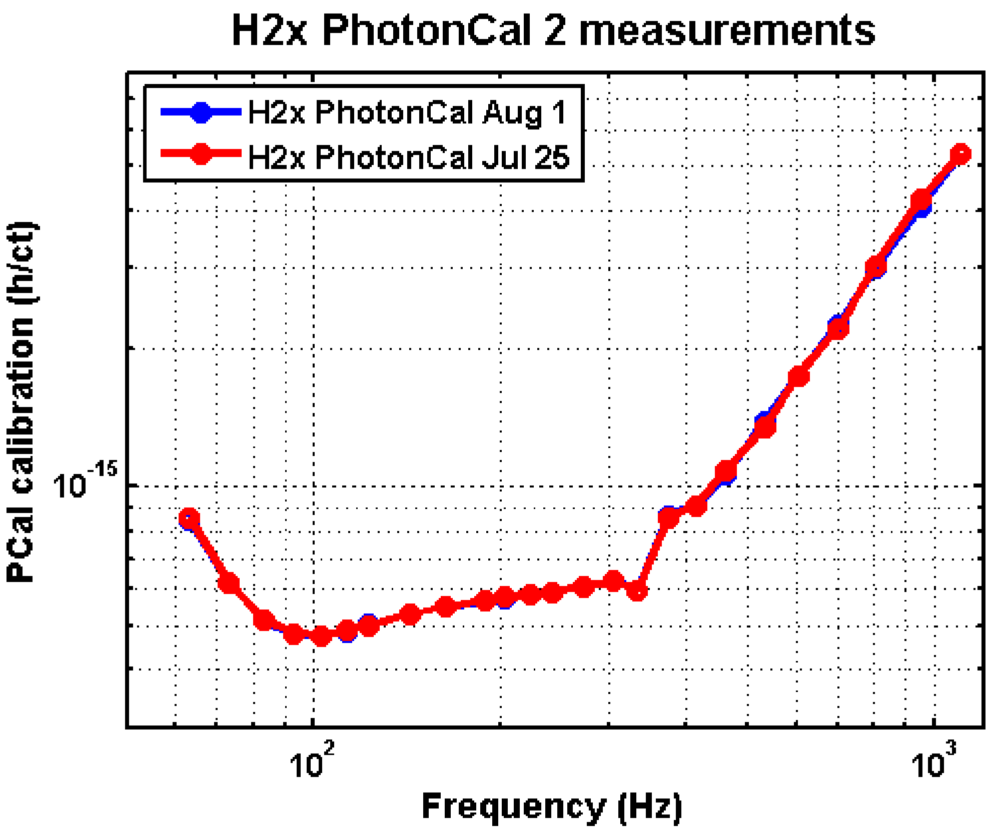
Frequency Dependence (H2)

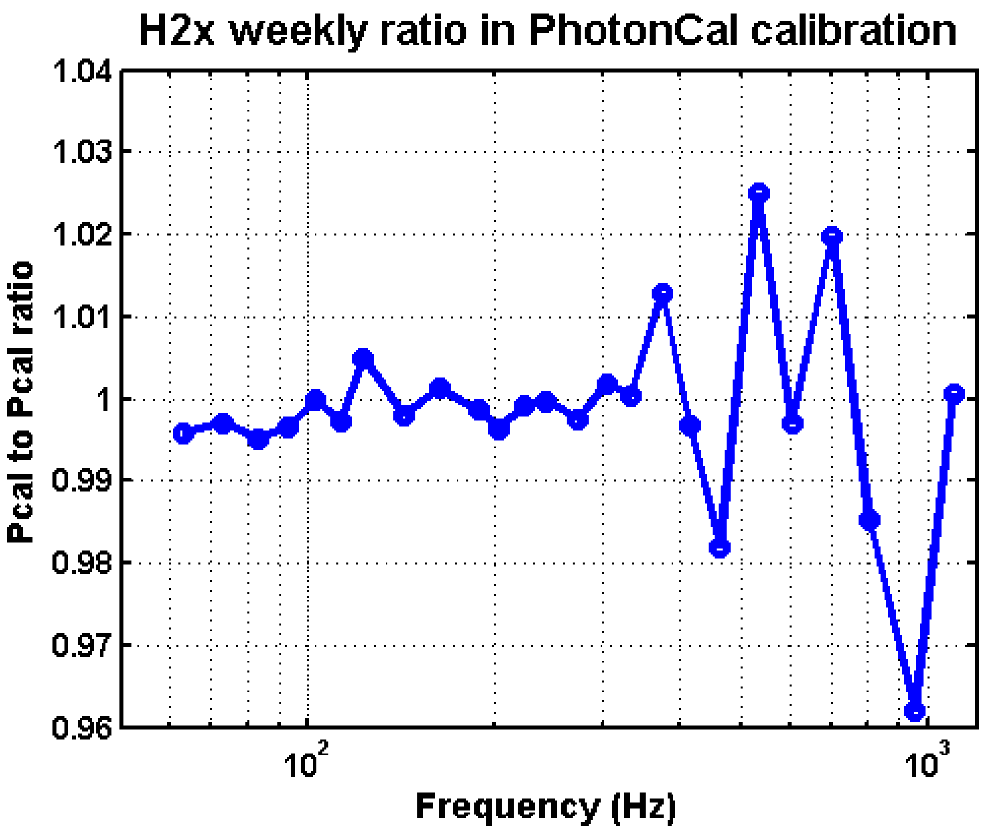




Measurement: 25 July 2006

Frequency Dependence (H2)

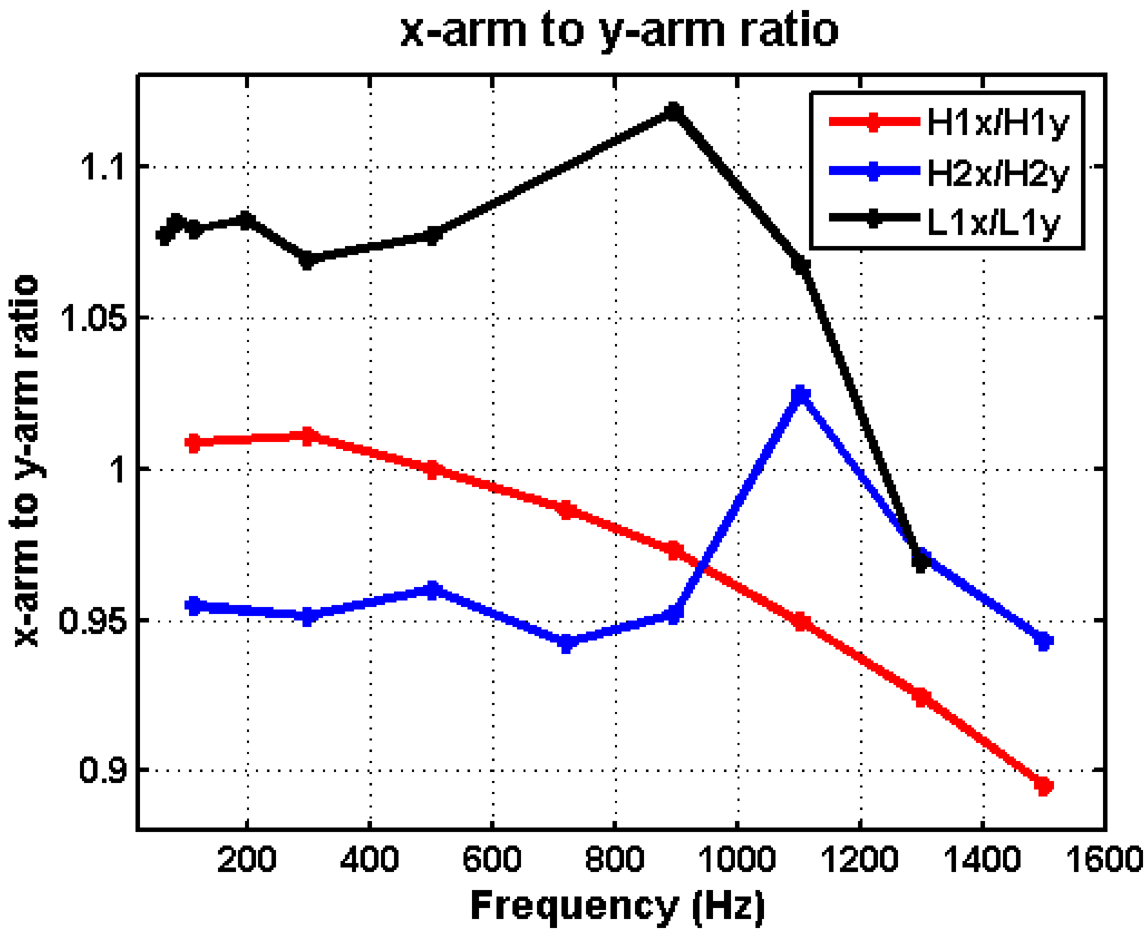




25 July to 1 August 2006

Change in γ from measurement to measurement is <1%

Arm v Arm measurements



- Within potential error of photon calibrator?
- Potential causes: DC laser power different on each ETM, viewport absorption,spot location on ETM, other?

Pendulum response

- Can we assume simple pendulum ==> free mass response?
- ETMs are more than just a simple pendulum
  - Pendular, pitch, yaw motions
  - Pendulum and pitch modes are coupled
  - Yaw mode not coupled to length changes (pendulum motion)
- Off-center beam alignment can drive other modes besides pendular
- Do we lose pendular motion due to excitation of other modes?
- If we do, this would help the situation
- Currently studying theoretically and will perform future experiments

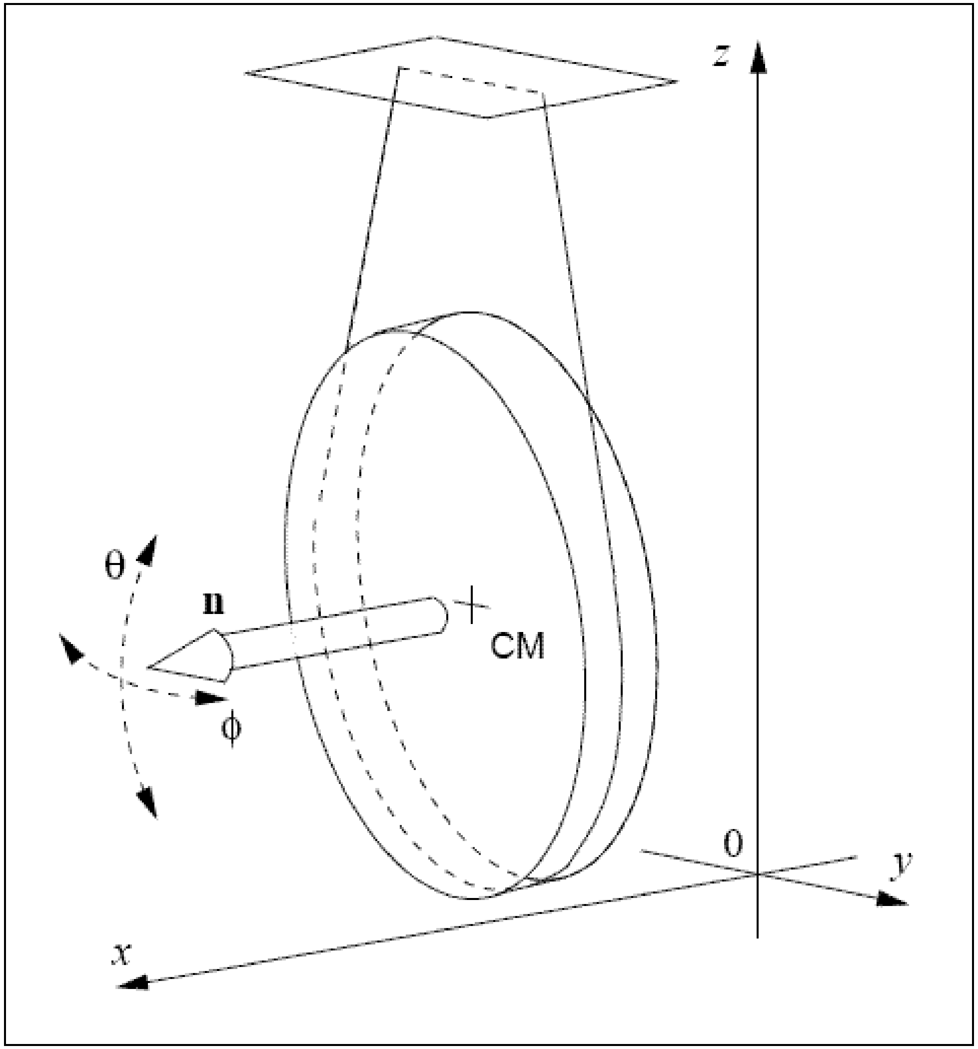


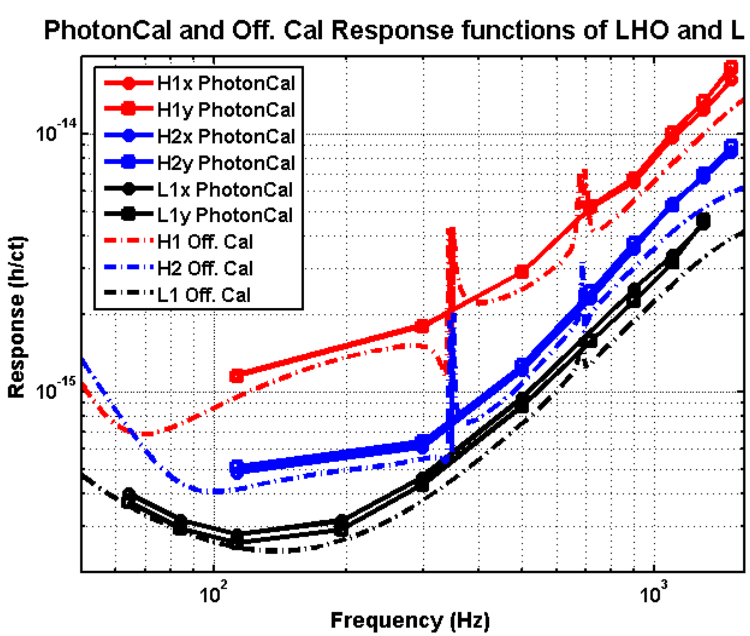
Diagram by Malik R.

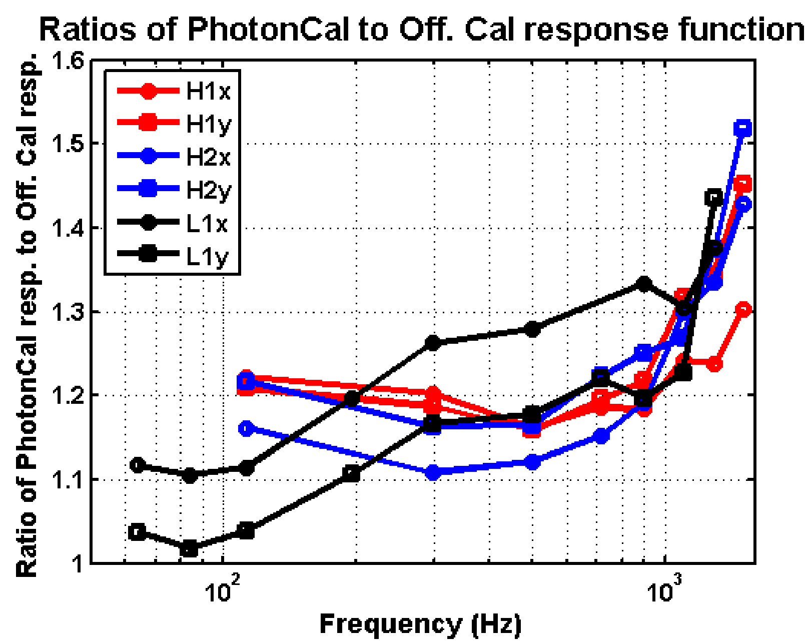
Future experiments

- More DC power level tests (Thermal)
- Photon calibrator laser spot size on ETM (Thermal)
- Move the spot around to verify theoretical pendulum response (Mechanics)
- Understand whether the photon calibrator transfer-function falls as 1/f^2 even past 1 kHz (Thermal and Mechanics)
- Viewport absorption has not been measured but predicted to be negligible. Is this true? (Optical)
- Reviewing details in the official calibration (Comparisons)
  - Working with the official calibration committee

Summary

- Close to official calibration, but interesting differences
- Photon calibrators on all LIGO IFOs show similar discrepancy with the current official calibration
  - Bias component (systematics?): ~10-15%
  - Frequency dependent component growing with increasing frequency >1 kHz
  - All photon calibrators on all IFOs show discrepancy in the same direction
- Continuing to explore possible causes with a variety of experiments of the photon calibrator.



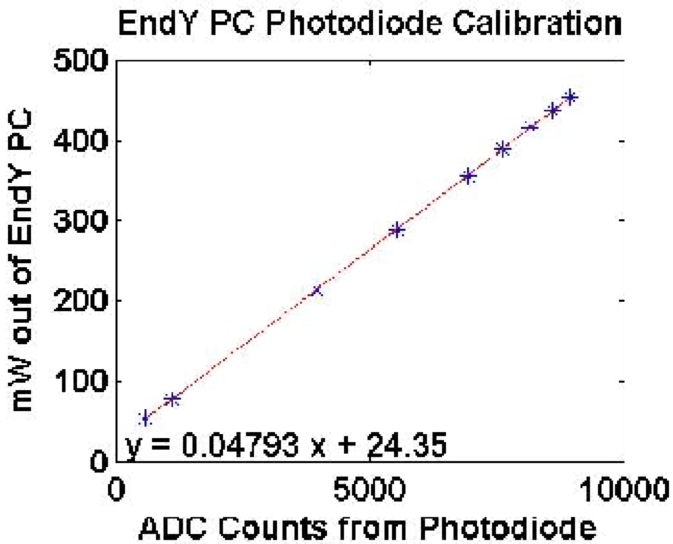


Checks

- Things we think we understand pretty well
  - we are doing the measurements & calculations correctly
  - power meter calibration
  - photodetector calibration
  - clipping
  - spots on optics moving or changing
  - reflection from viewports
  - transmission through optics
  - vary pcal laser modulation depth and observe discrepancy
  - optic pendulum transfer function
- Things we might like to look at more
  - Additional characterization of discrepancy – more frequency resolution
  - vary pcal laser DC bias and observe discrepancy
  - review official calibration procedure
  - off-centered beam and angular motion
- Things we have not yet explored
  - vary spot size and observe behavior of discrepancy
  - modeling of thermal properties of optic coating and substrate
  - photon calibrator phase

3. Converting Photodetector Ouput to TM Incident Power

- 1. Convert photodetector counts to Watts out of pcal box
  - This measurement was done at DC.
    - AOM and Photodetector both should have flat transfer functions to MHz and higher (according to manufacturers
    - In fact, I have measured a mysterious ~2% attenuation (a ~1600Hz) from DC.
    - If this attenuation is due to AOM, it would have no effect (AOM is upstream from photodetector readback).
    - If this attenuation is due to readback, it would result **underestimate** of power in beam, causing us to **underestimate** cal factor.
  - The measurement may need to be updated.
    - **Two experiments: 1. examine data near beginning of and see if discrepancy is not as bad there; 2. re-measure.**
  - Power meter used in measurement may read high by ~10%. This is currently under investigation. If it does read high by ~10%, this would cause cal factor to be overestimated by ~10%.



Experiment: Remeasure Photodetector Calibration Factor

- 6/6/06: Evan and Corey went out to EX and measured a PD calibration (adjusted for their 4% high Unit4 power meter) of 0.04384 mW/PDcts.
- Measurements from 8/12/05 and 9/16/05 at EX yielded 0.0432 and 0.04435 mw/PDcts, respectively (again, adjusted for the 4%). The average of these values, 0.04378, agrees with Evan and Corey's value to much better than 1% and it appears the PD calibration is reasonably stable.
- It is therefore very unlikely that this calibration plays a significant role in the photon calibrator discrepancy.

Experiment: Power Meter Systematic Error

- a Scientech power meter at Hanford consistently read ~10% lower than the Ophir power meters (which were used to calibrate the photodetectors for the photon calibrator)
- Sent to Scientech for comparison to a NIST standard meter. An e-mail from Dennis Froman at Scientech:

On 5/22/06 we received this system again. The AC25HD was found to be 6.70% low in power (out of tolerance) and 4.33% low in energy (out of tolerance). After calibration the percentage difference from the standard was 0.15% high in power and 0.17% high in energy both of these are in tolerance.

The Ophir system was found to be high 4.04% in power and 3.79% high in energy.

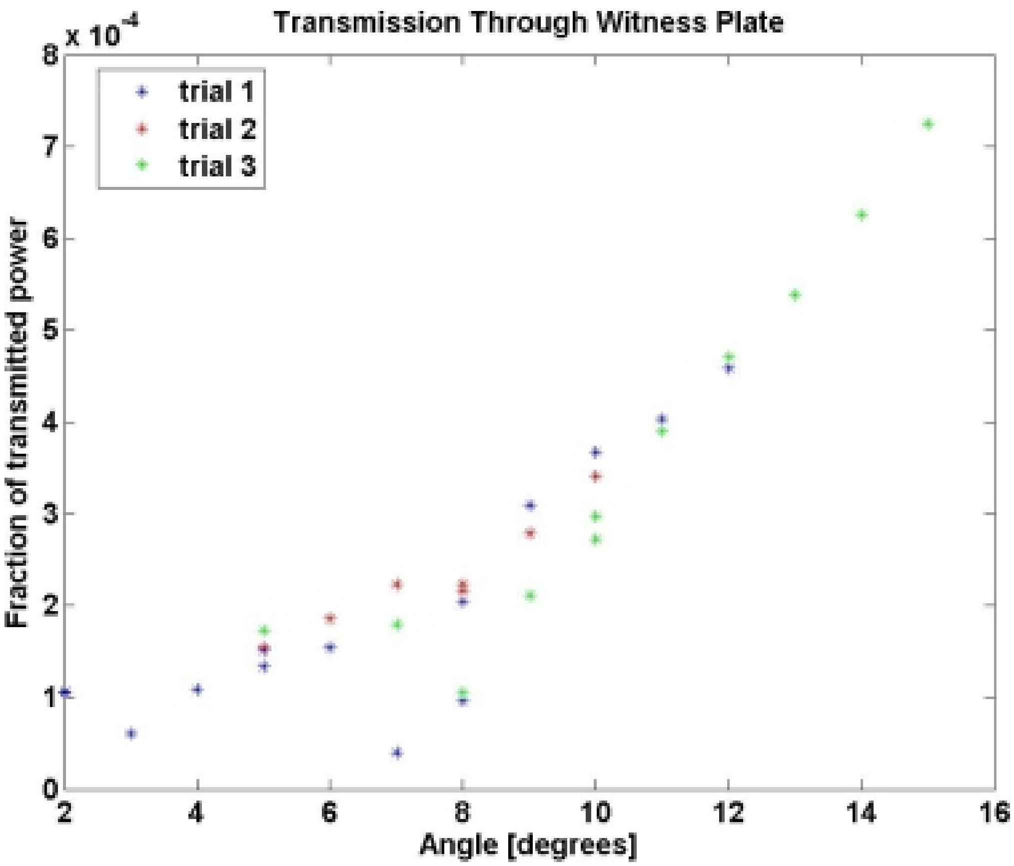
- This accounts for 4% of the Hanford discrepancy.
- We would like to compare LLO power meter to this one.

3. Converting Photodetector Ouput to TM Incident Power: Clipping

- 2. If the beam is clipping anywhere downstream of the readback, this would result in **overestimate** of power onto TM, and **overestimate** of cal factor.
  - beam could clip on something inside pcal box, or on something in beam tube (such as the baffle supports in H1).
  - it is very easy to check for clipping: beam is dithered back and forth, and a measurement made in DARM_ERR.
  - *I just realized that I never checked for clipping on the pitch axis*. The reason: we were mainly concerned with vertical baffle supports (in H1). It is unlikely that this is the problem (no visible deformation of spot; no likely candidates for clipping; beam reasonably centered through apertures; we would need systematic clipping on all units, including LLO which was set up independently) but it *should be checked*.
  - Experiment: move spots by ~1/2 cm and take more measurements.
  - Experiment: basic clipping check in vertical direction.

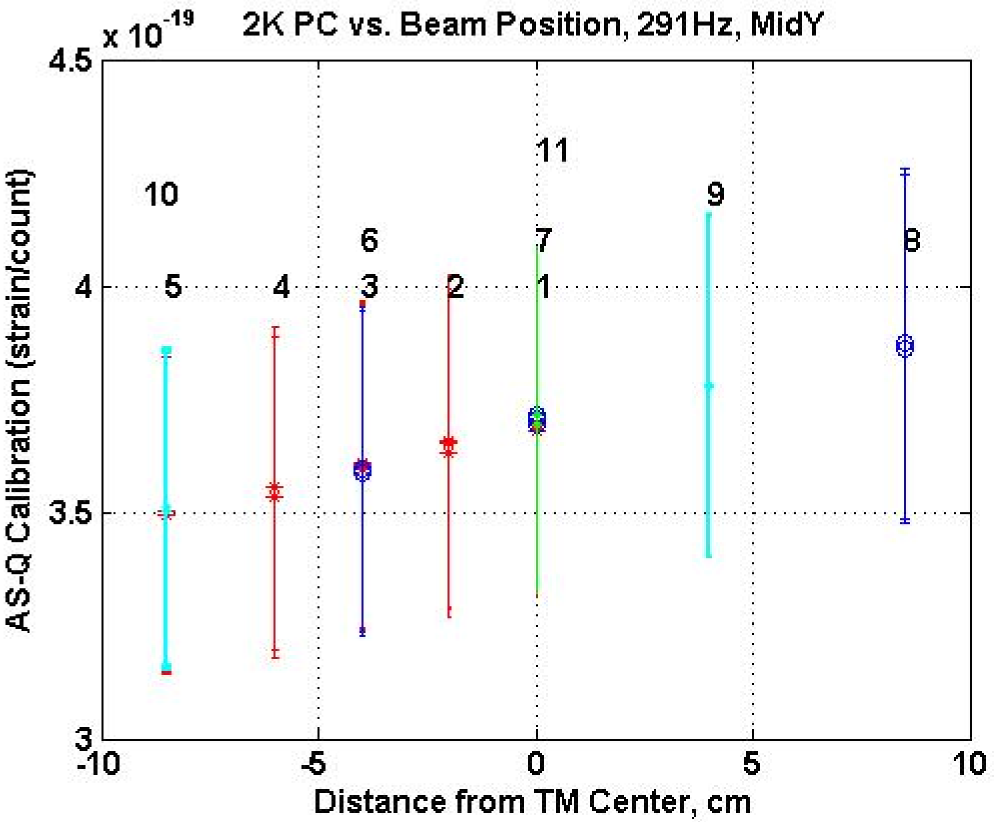
3. Converting Photodetector Ouput to TM Incident Power

- 6. Transmission through HR surface of TM
  - Very small effect
  - Corey has remeasured at Hanforc
  - Fairly difficult measurement, but e a very poor measurement would h little significance
  - Underestimating this would cause **overestimate** of cal factor. (It is m likely this is underestimated than overestimated.)
  - Experiment: model this mathematically (just a 1064nm coating on a surface) for a 1047nı laser as function of angle of incide
  - Experiment: ask someone to measure a real optic at CalTech



4. Other Ideas

- Harmonics?
  - They contain less than 1% of power; also, they will “factor out” of the result
- Angular Coupling?
  - any couplings other than on-axis will cause us to **overestimate** pcal factor.
  - effect of this was measured in H2 (in order to characterize effect of avoiding baffle supports in H1). 3% at 2cm.
  - An outstanding mystery....
  - Experiment: move beam on TM, remeasure.
- Calibration phase?
  - Why have we never bothered to check this? Could it provide information to help us with the magnitude discrepancy?
- Mass? Angle?



Experiment: Pendulum TF

- Does ignoring the pendulum eigenfrequency have any effect?
- No.
- Q = 10, wp = 2*pi*0.767
- tf = 1/s^2 vs. tf = 1/(s^2 + wp s / Q + wp^2)
- Plotted in matlab. Identical to at least 0.01% from 100 Hz on up.

Thermal Effects

- A. Bullington, P. Kalmus, D. Ottaway, M. Rakhmanov
- Substrate bulge modeled with formalism in Winkler et al. (1991)
  - model predicts substrate bulging to be negligible
- Formalism in Shanti Rao's thesis to estimate bulge in HR coating
    - coating with slow substrate (e.g. fused silica)
    - coating with fast substrate (e.g. sapphire)

- effect from HR coating bulge not ruled out by model
  - grey range in plot due to uncertainty in thermal params
  - plot shows effects if 180° phase relative to TM
- If phase not 180°, effect will be less or even contrary
- Experimental tests:
  - High frequency measurements
  - aim spot away from IFO beam