Photon pressure calibrator in GEO600


Courtesy Planetary Society

A safe and reliable method ?

Stefan Hild, AEI Hannover, for the GEO-team

Photon pressure calibrator: independent check of absolute calibration

Absolute calibration of the ESDs:
ESDs ⇒ MMC2_feedback ⇒ Master laser piezo

Potential problems:
- Many steps involved (accumulating errors)
- Some measurements have low SNR
- Some measurements are only done at certain frequencies
- longterm stability of ESDs (unknown)

Independent check of calibration using:

$$F = 2\,\frac{P}{c}$$

Resulting displacement:

$$x(\omega_m) = \frac{2\,P_m \cos(\alpha)}{M c \omega_m^2},$$

A brief history of the efforts in GEO (1)

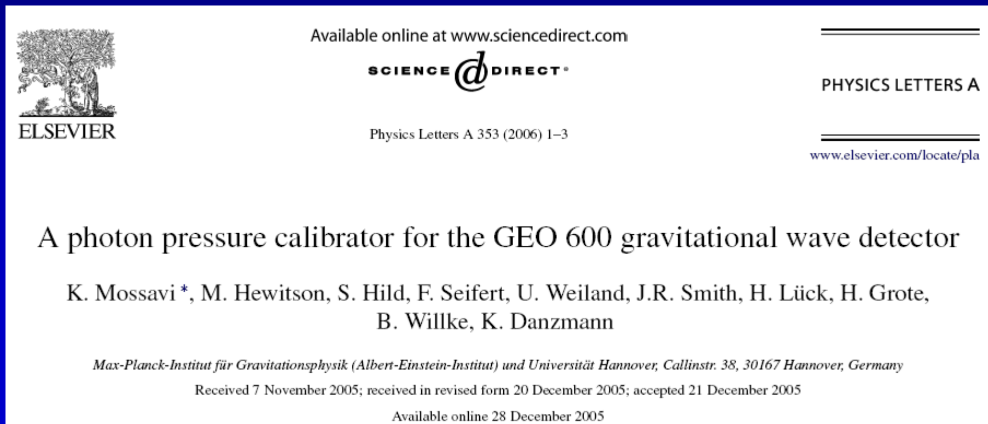
1st setup (Febuary 2004)

- Laser diode (976 nm)
- poor optical setup
- ‚proof of principle', but deviation from 1/f^2 was observed.

2nd setup (Spring 2005)

- Fibre coupled Laser diode (1035 nm)
- Improved optical setup
- Better measurements: SNR improved by 1 order of magnitude (due to improved sensitivity of GEO600).
- Between 100 and 1000 Hz good agreement to official calibration.

Measurements from spring 2005



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A photon pressure calibrator for the GEO 600 gravitational wave detector

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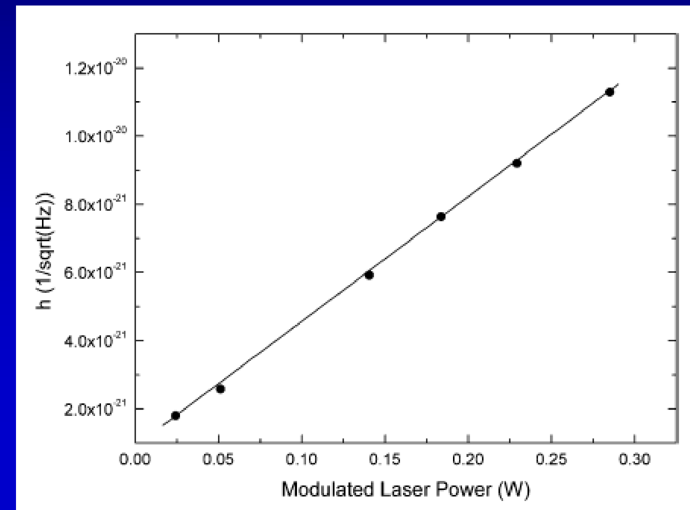
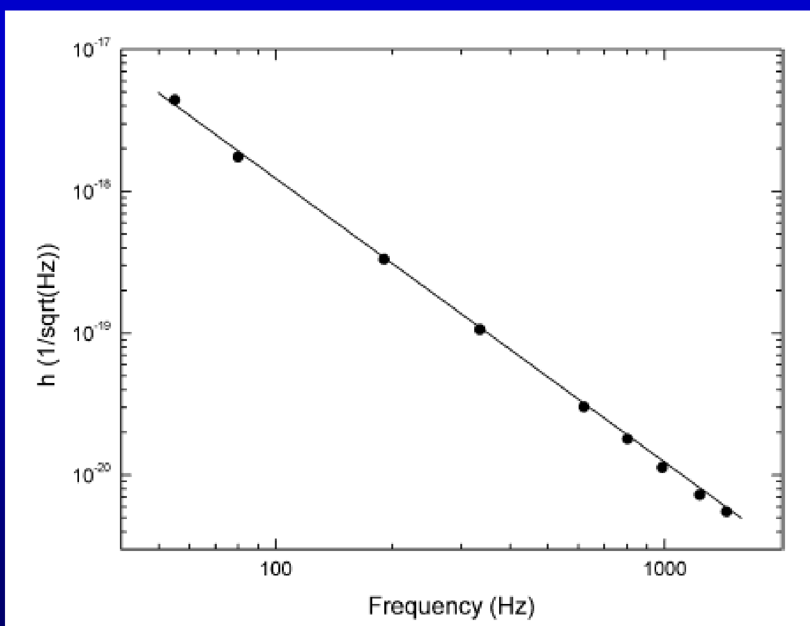
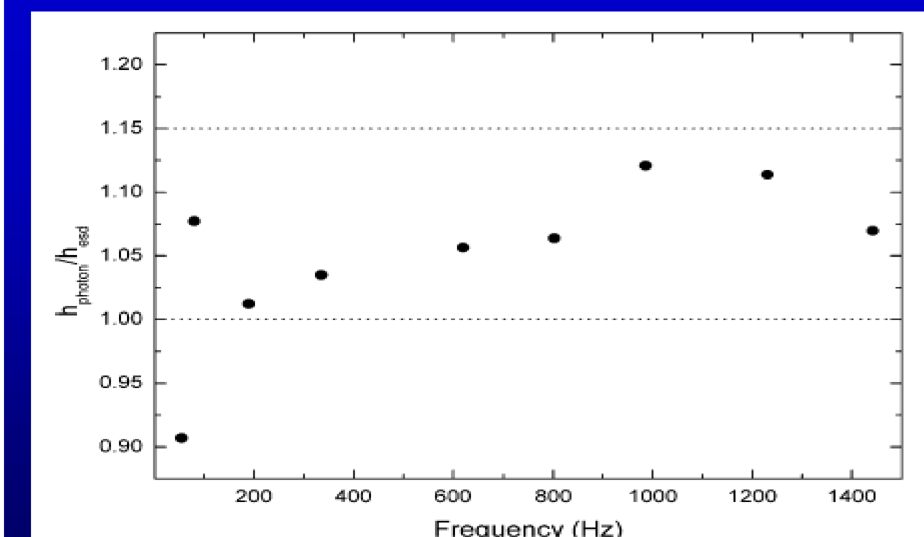






A brief history of the efforts in GEO (2)

Accuracy achieved with 2nd setup:

- Absolute: within 15% to the official calibration.
- Relative: within +/- 8%

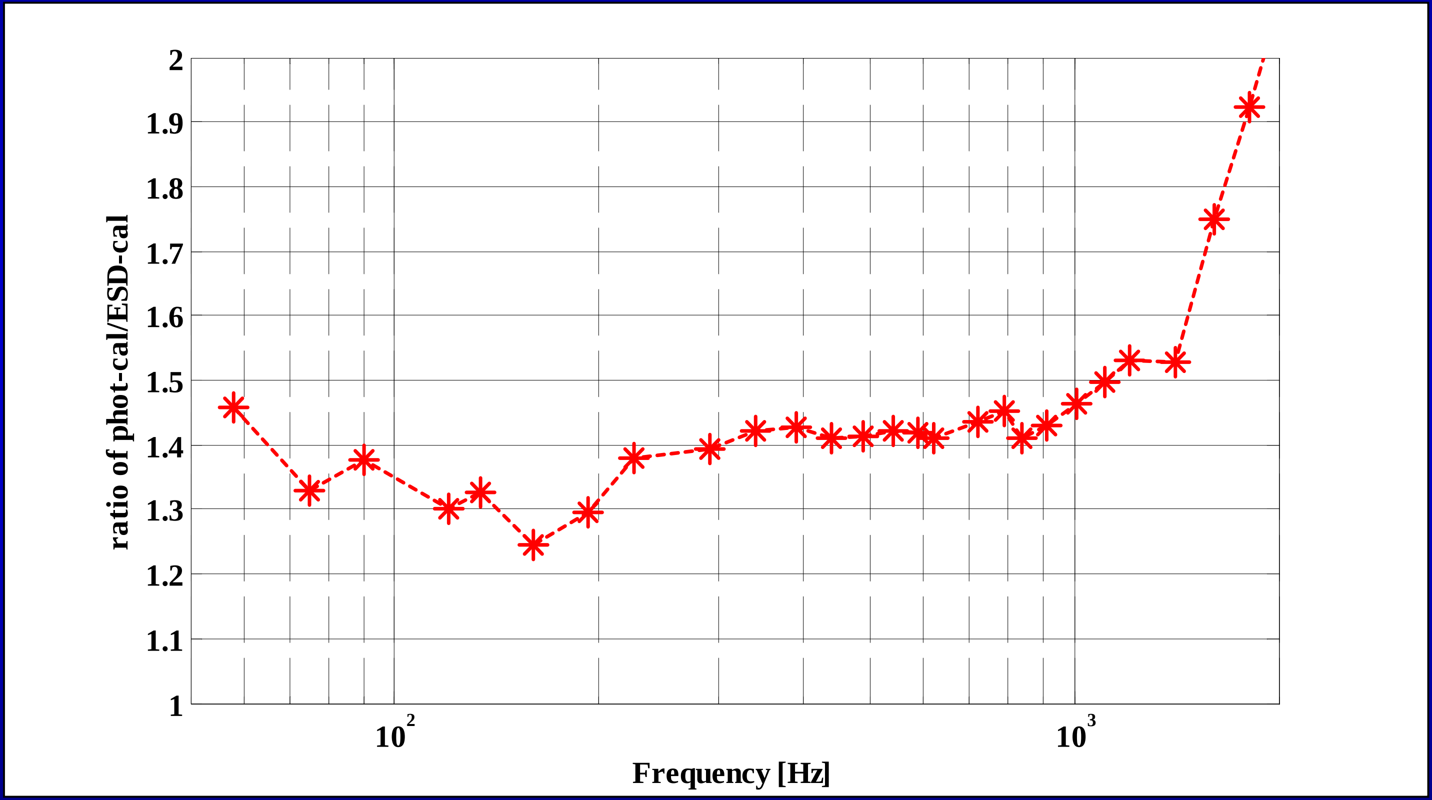
2nd setup improved (early 2006)

- Improved alignment and centering of the beam on testmass
- Improved accuracy of the power measurement.
- Measurements are done towards higher frequencies
- Continuous injecting of a calibration line for S5.

=> Observed suprisingly large discrepancy to official calibration.

Results with present setup

What we would like to get is: **phot-cal/ESD-cal =1**

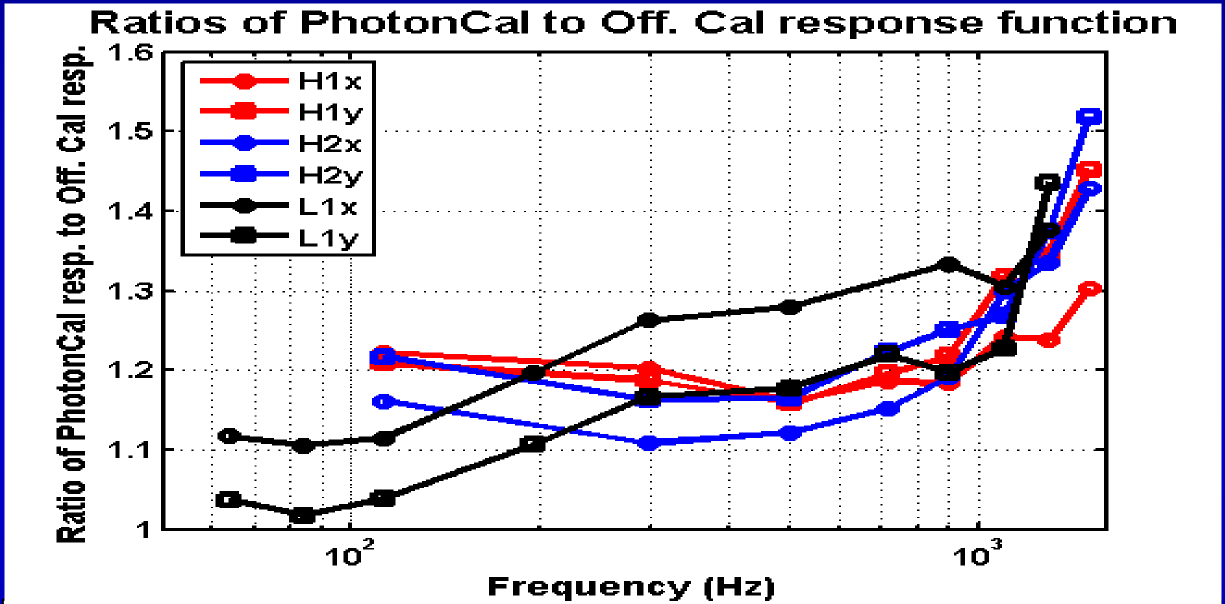


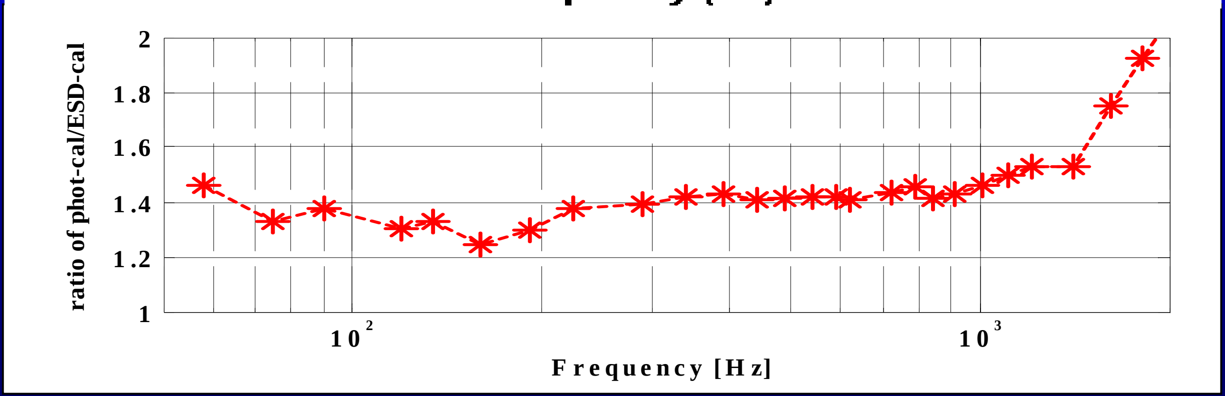
This does not work out in reality. ☹
We observe a remarkably large discrepancy, but ...

The GEO results vs the LIGO results

Credits for the LIGO measurements:
Peter Kalmus, Evan Goetz, Rick Savage, Brian O`Reilly, Mike Landry

..., but we seem to be in good company:





Official calibration

It is important to state here:

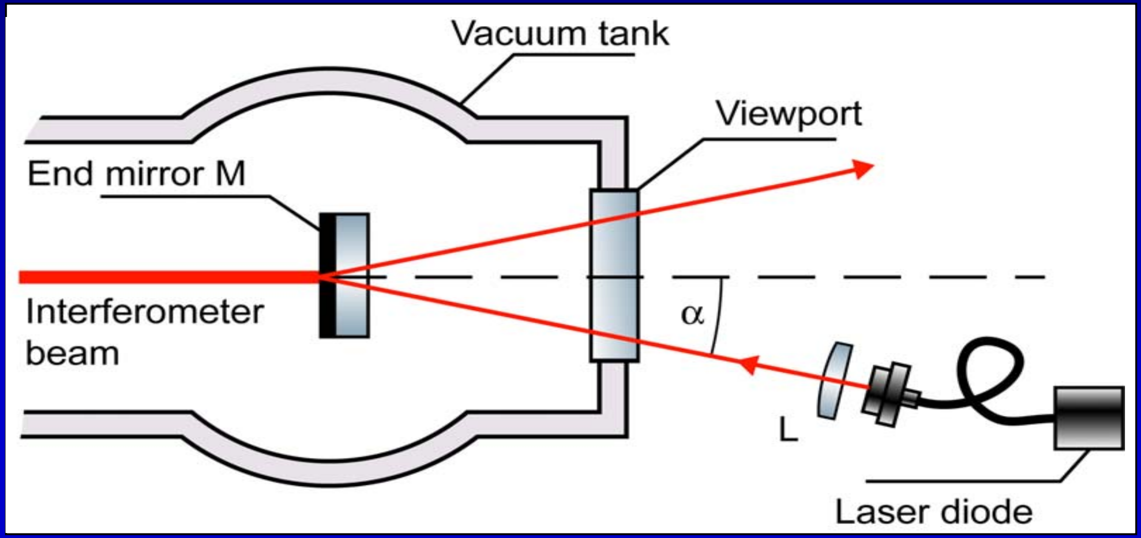
WITHIN BOTH PROJECTS (LIGO and GEO) MANY CROSSCHECKS OF THE OFFICIAL CALIBRATIONS HAD BEEN PERFORMED.

• There is a high confidence level for the official calibrations.

•There are believed to be correct to within 10%.

• Both projects believe that the discrepancy originates from the photon pressure actuators being imperfect.

The GEO setup

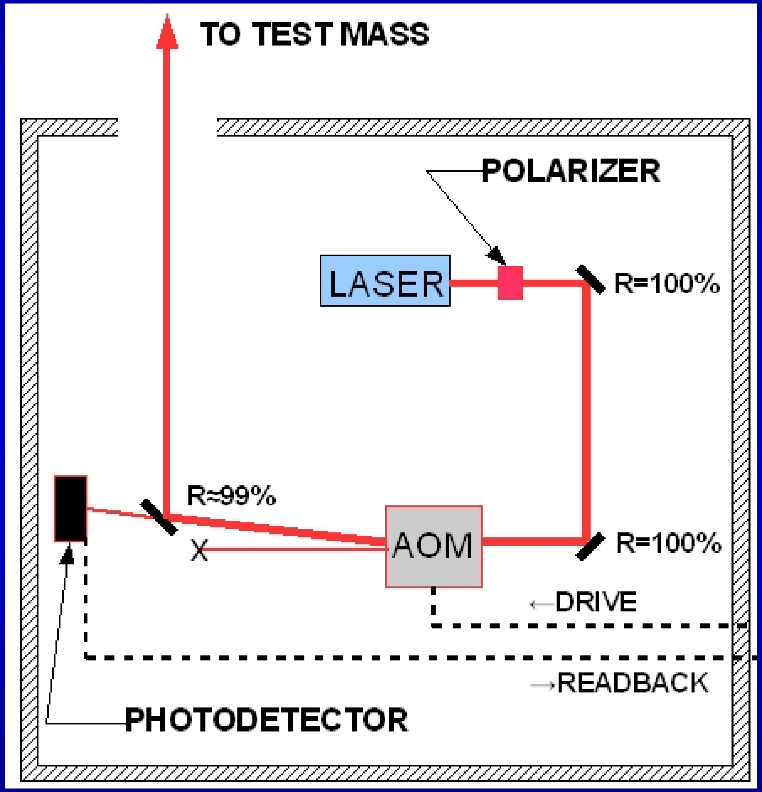


- Source: modulated Laser diode.
- Wavelength =1035 nm, DC power = 1 W, modulated power up to 800 mW.
- Power is monitored by an photodiode inside the Laser diode.
- Shining from back (through the substrate)
- Restricted geometrical setup: the reflected beam is clipped on the way out of the vacuum.
- PPD beam diameter at MFN = 5mm (main IFO beam = 50 mm)

The LIGO setup

Credits: Peter Kalmus, Evan Goetz, Rick Savage, Brian O`Reilly, Mike Landry

- Source: Laser + AOM.
- Wavelength =1036, DC power = 300mW, modulated power up to 150 mW.
- Power is monitored by an photodiode in front of the vacuum.
- Shining onto the front surface of the testmass.
- Restricted geometrical setup: the reflected beam is not accessable.
- PPD beam diameter at Testmass = 10-20 mm, main IFO (H1) beam = 90 mm (ETM) *(values from pc with Keita)*

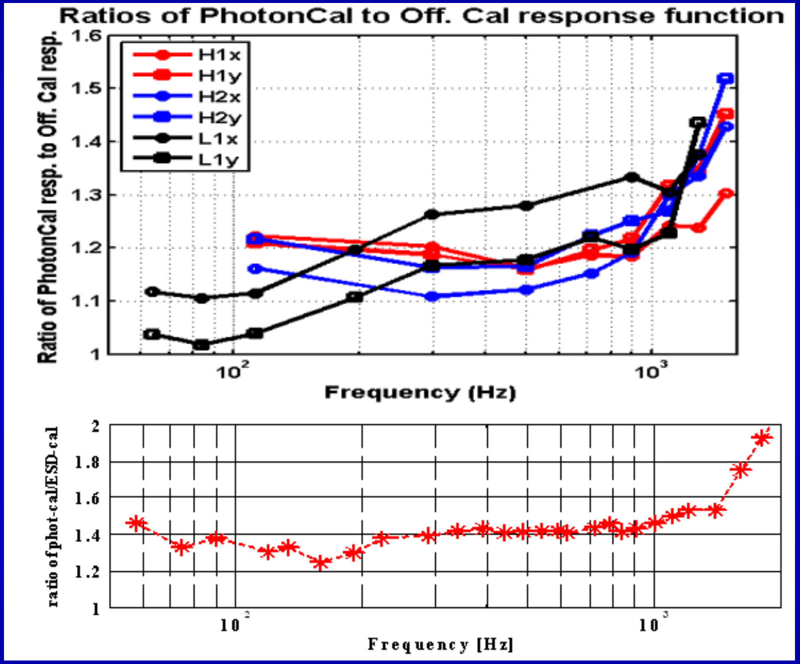


GEO vs LIGO

Hypothesis: If the discrepancies in GEO and LIGO have the same origin we can rule out several points.

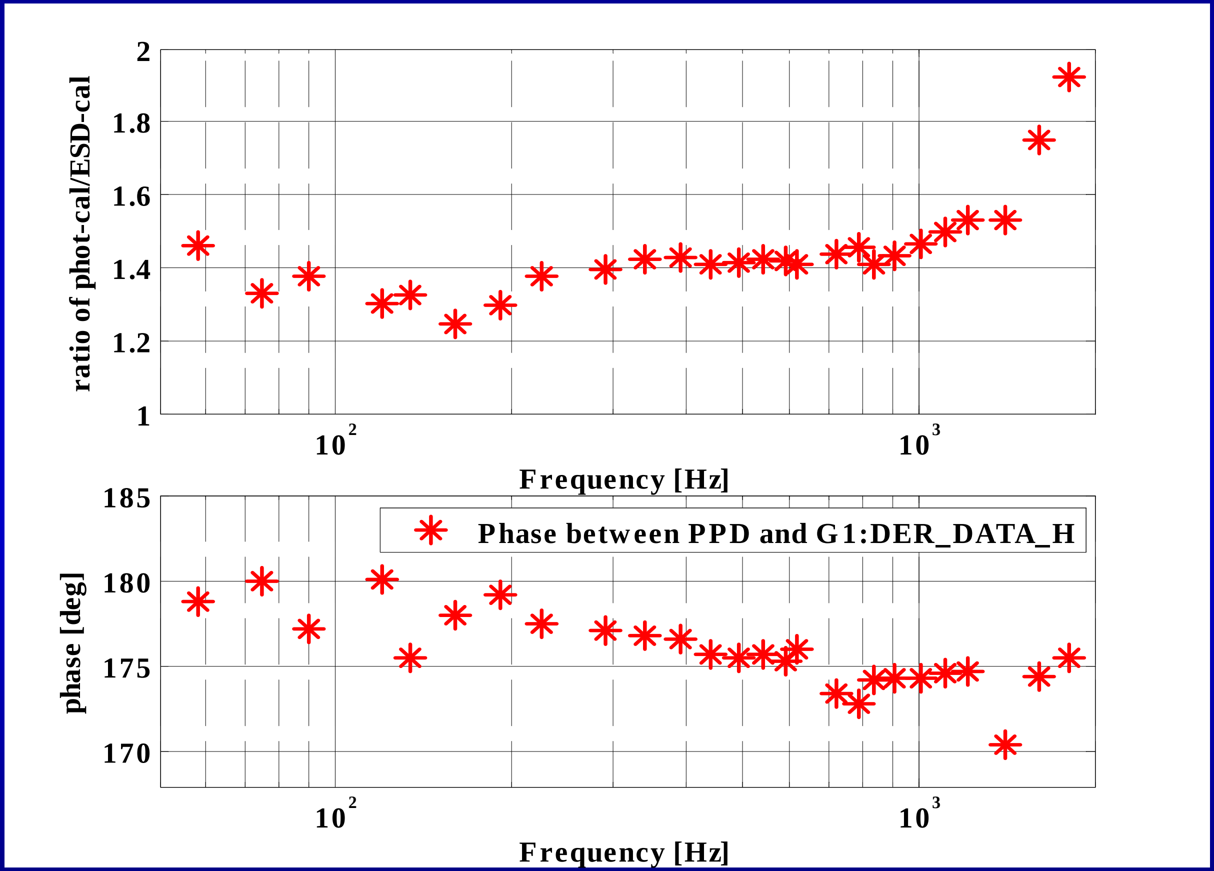
• Official calibration is different (ESD vs coil magnet, Signal-Recycling vs arm cavities, etc)
=> Ruling out any effects from official calibration procedures

• LIGO shines on the front surfaces, while GEO is coming from the back through the substrate.
=> Ruling out any thermal effects from the mirror substrate



Discrepancy + Phase

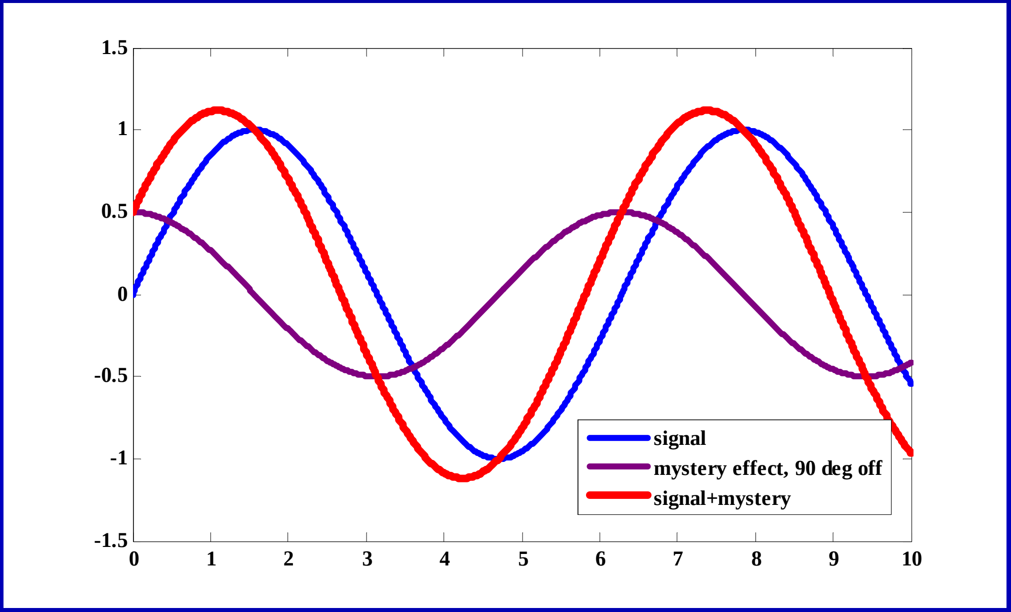
The phase contains a lot of information we should include !!!!



Due to the pendulum response the mirror is 180° out of phase with the applied light modulation (quite unintuitive).

Phase picture

Considering a second effect (‚mystery') coming into the game (thermal absorbtion + thermal expansion) with 90 deg different phase:

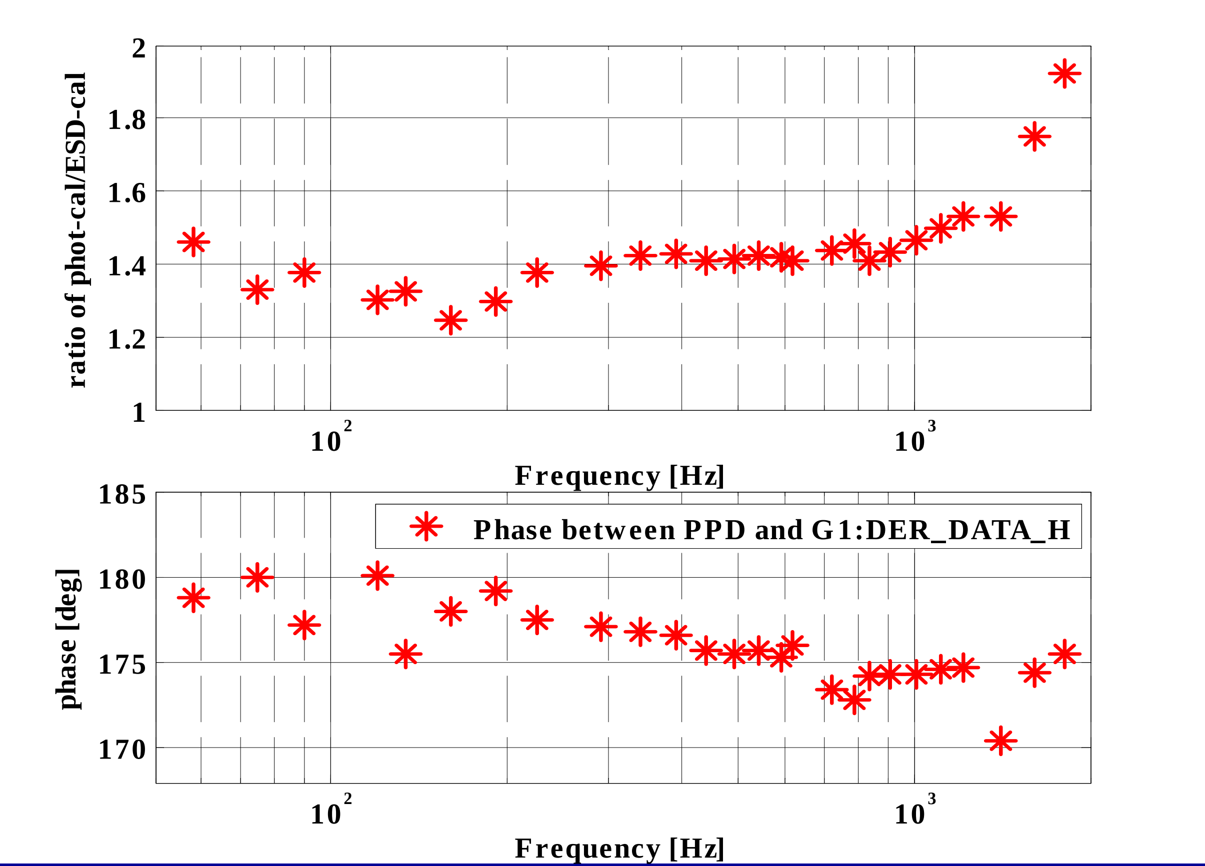


The resulting amplitude gets larger. In contrast we observe in the experiments a smaller amplitude than expected.

⇒ **The mystery effect needs to have a phase between 0 and 90 deg.**

⇒ **There is also a phase shift due to the mystery effect.**

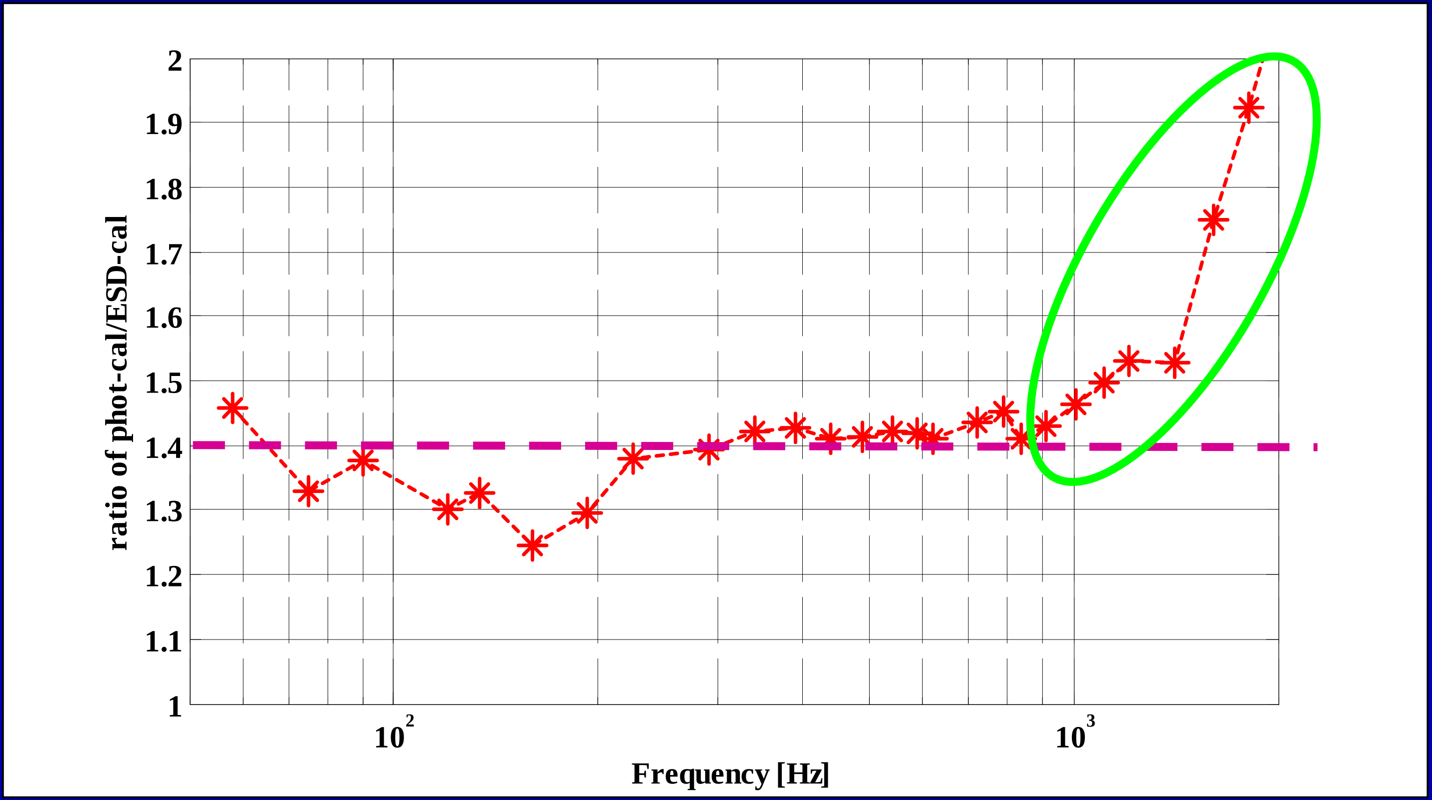
Discrepancy + Phase



The observed phase stays at 180 deg.

=> The mystery effect needs to have a phase near 0 deg. (if you add a 0 deg and a 180 deg effect phase stays constant, while amp changes)

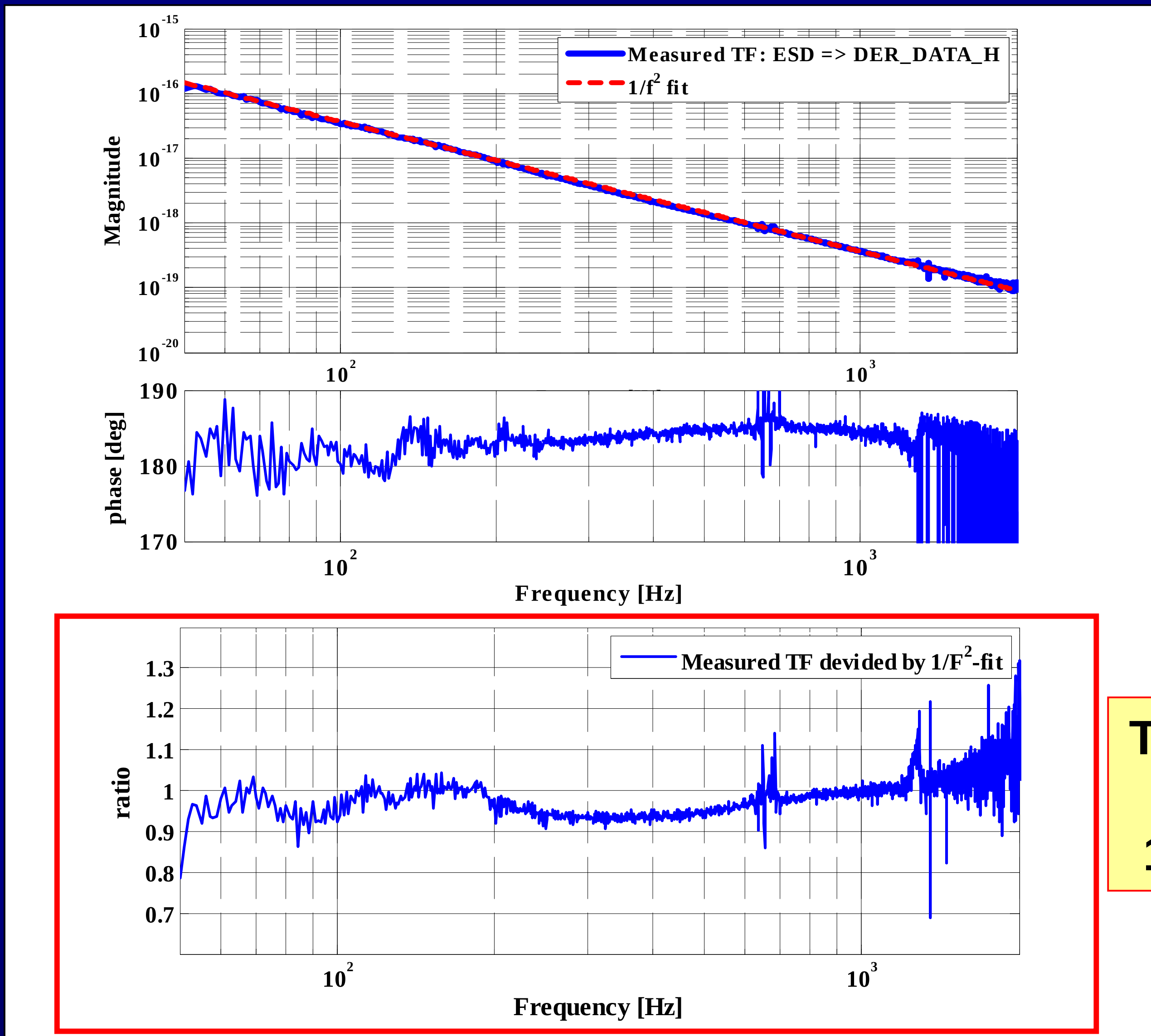
Two main problems



1. Absolute deviation of 40 % (amp in DER_DATA_H is smaller than expected)

2. Step roll off above 1kHz

Ruling out any artefacts from calibration process: Checking the 1/f^2 of ESD vs official calibration.



TF from ESD-FB to DER_DATA_H is 1/f^2 within +/-5%

Brainstorming: discrepancy @ high freqs.

Assuming the monitor diode gives a correct measure of the power leaving the PPD then:

- We don‘t believe that the power hitting the mirror is wrong by 50%.

- Secondary effects like for instance absorbtion+thermal_expansion would do with much less power-loss. (photothermal absorbtion)

Photothermal absorbtion in the game?

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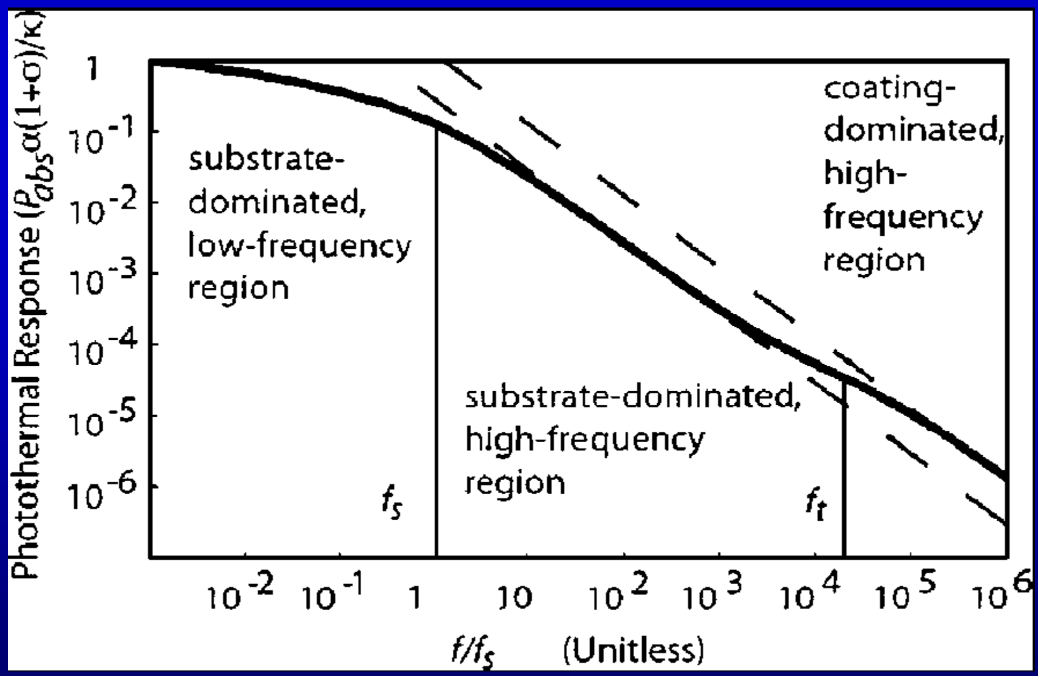
Enhanced photothermal displacement spectroscopy for thin-film characterization using a Fabry-Perot resonator

Eric D. Black, Ivan S. Grudinin, Shanti R. Rao, and Kenneth G. Libbrecht
LIGO Project, California Institute of Technology, Mail Code 264-33, Pasadena, California 91125

(Received 23 October 2003; accepted 5 March 2004)



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- We don‘t believe that the power hitting the mirror is wrong by 50%.

- Secondary effects like for instance absorbtion+thermal_expansion would do with much less power-loss. (phototermal absorbtion)

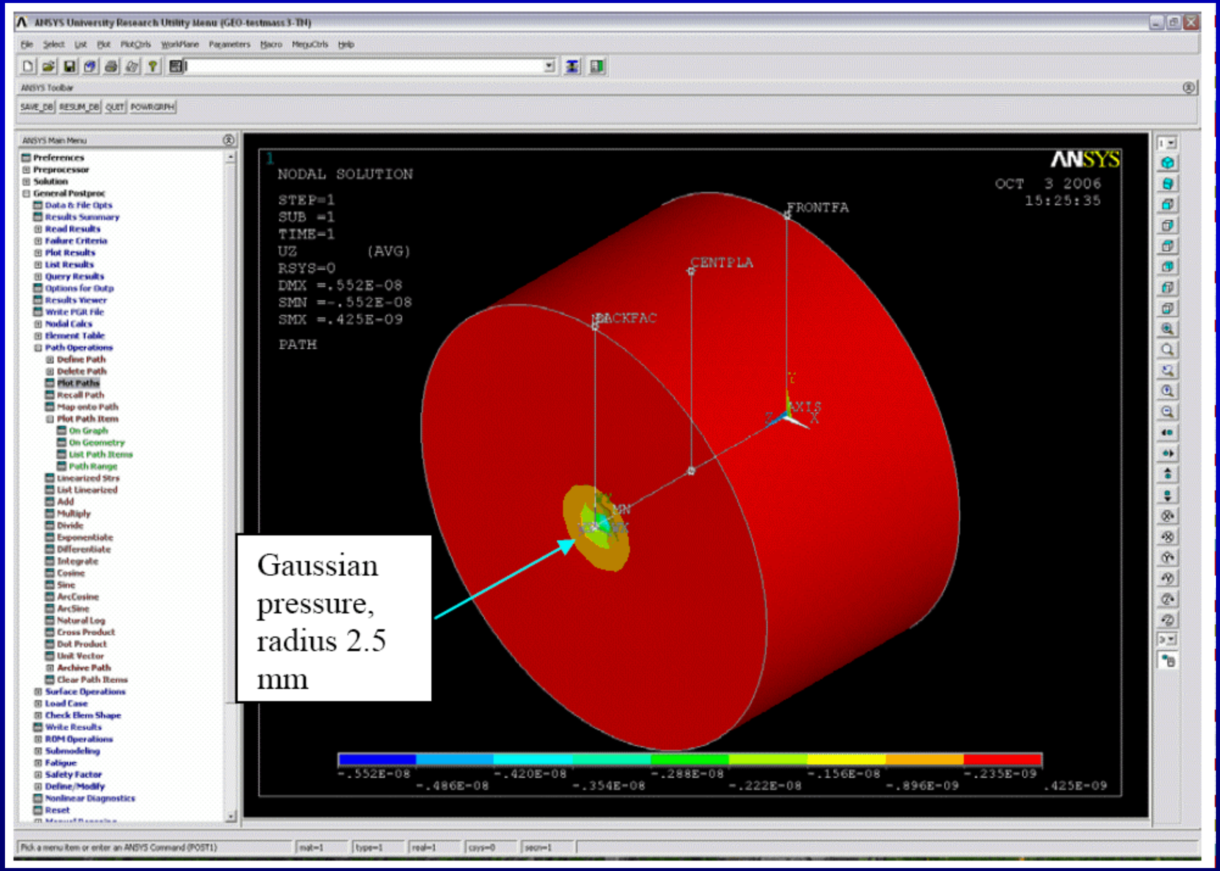
- Are our mirrors really rigid bodies?

Finite Element Simulation

Credits to Iain Martin, Stuard Reid, Jim Hough (IGR, Glasgow)

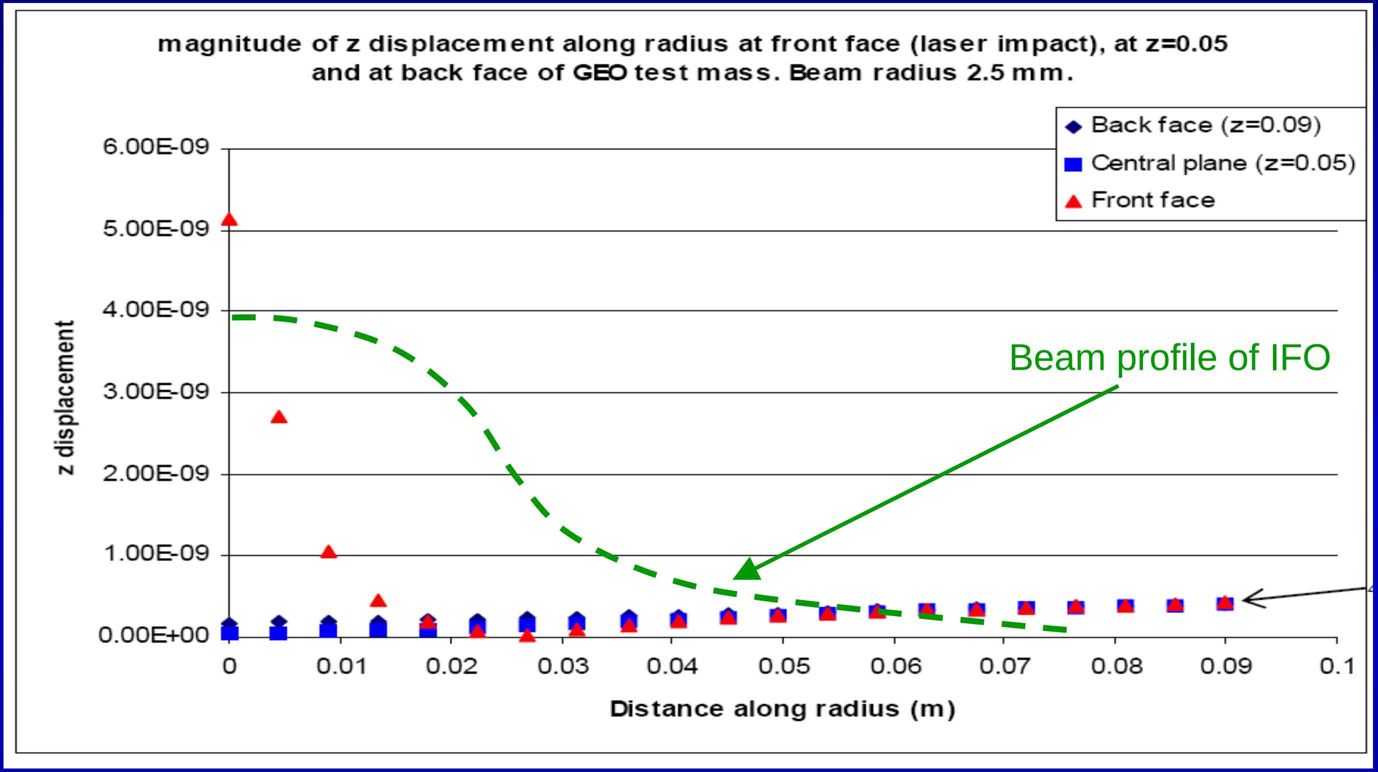
Applying a gauss shape force (2.5mm radius) of 2.77 N to the center of a GEO-mirror.

The test mass is held in place using the inertial relief function in Ansys



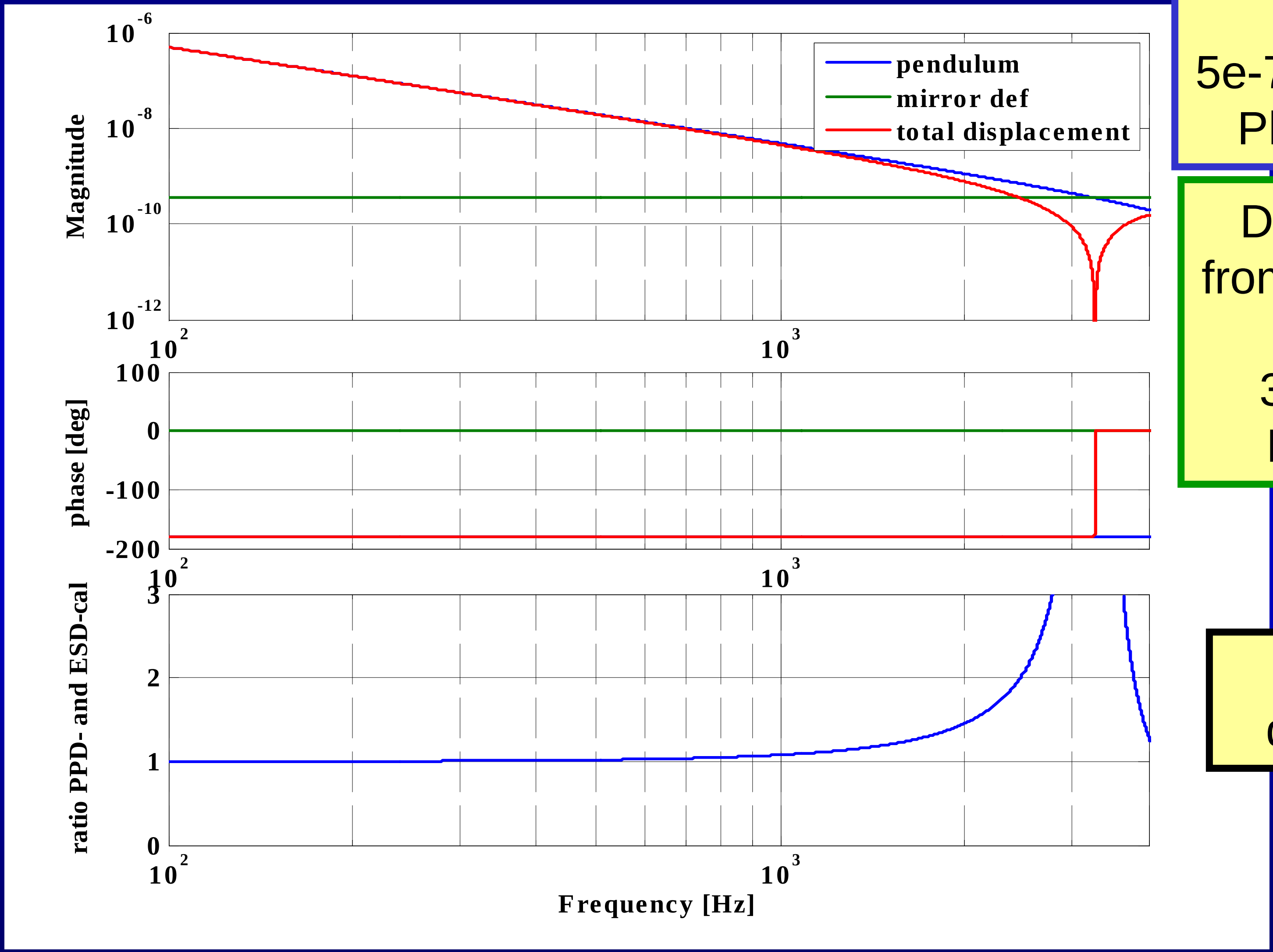
Finite Element Simulation (2)

Credits to Iain Martin, Stuard Reid, Jim Hough (IGR, Glasgow)



- The displacement needs to be weighted by the overlap of the main IFO beam. For now I will use 1e-9 m/2.77N.
- I assume the displacement to being flat in frequency (below the resonance) and in phase with the applied light.

Simple model (including mirror deformation)

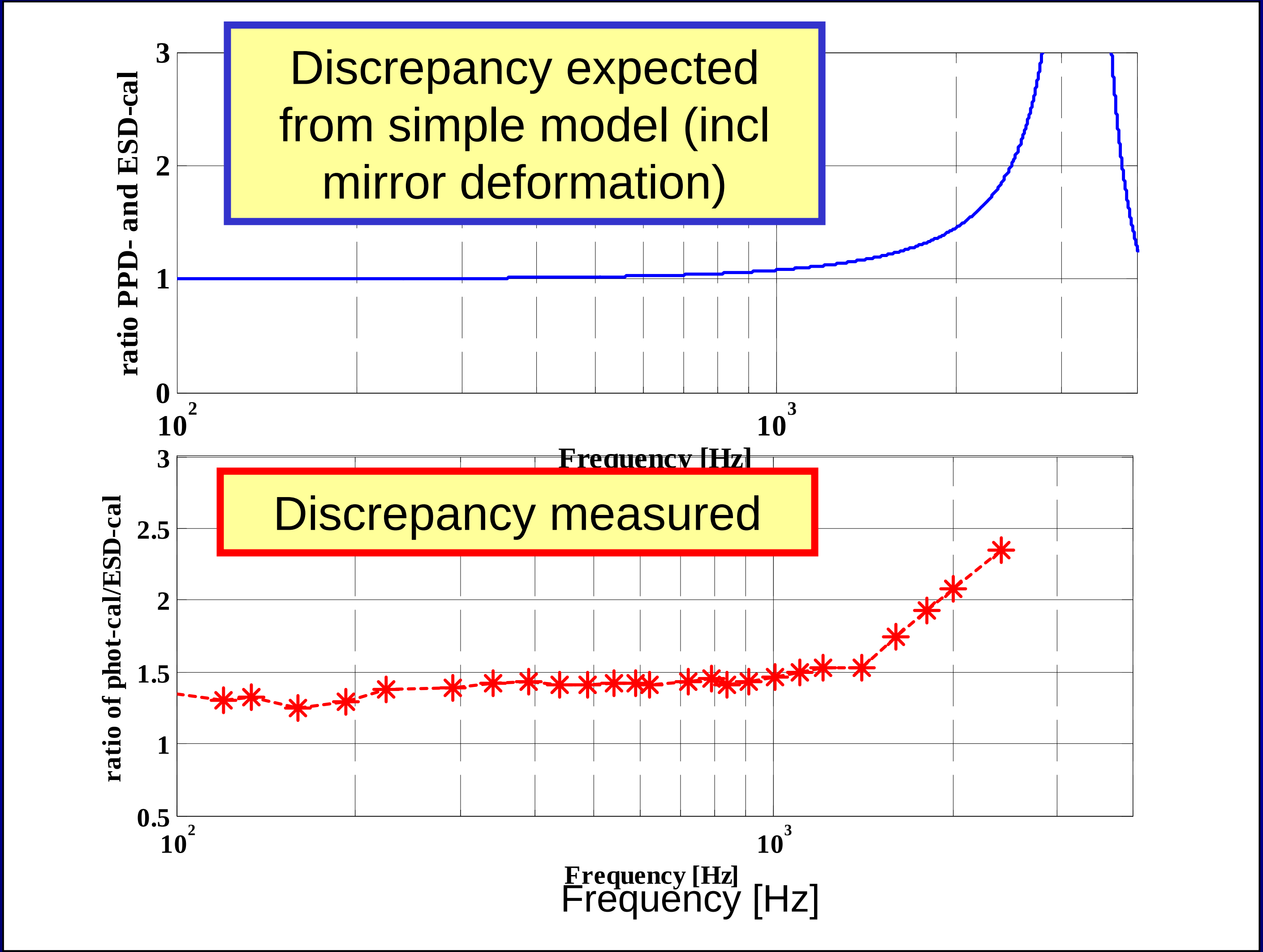


Pendulum resp:
1/f^2
5e-7m/N at 100Hz
Phase = 180°

Displacement from mirror defor.: flat
3.6e-10m/N
Phase = 0°

Resulting discrepancy

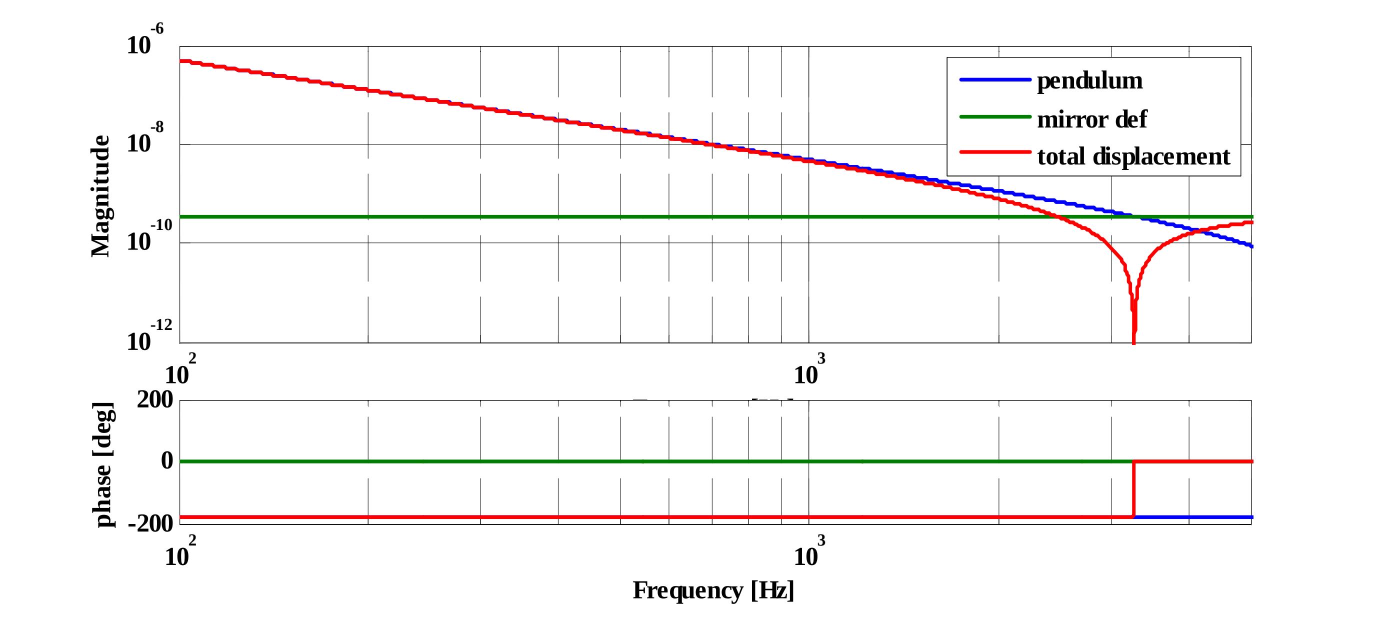
Comparison of model and measurement



To-Do: check simple model vs experiment

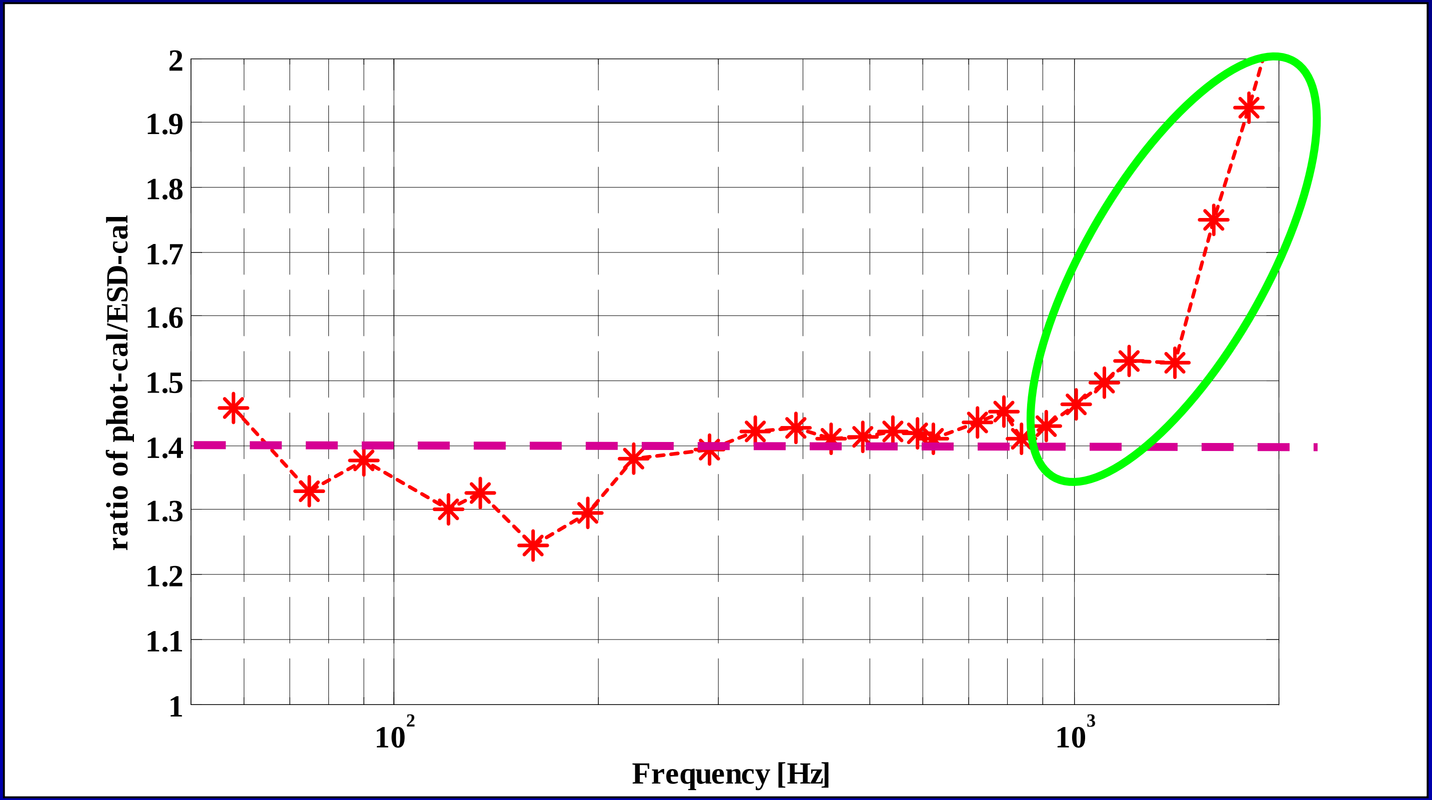
• Easiest to do by injecting a high frequency line and checking the phase (at the crossover it will jump from 180 to 0 deg).

• Amplitude response should become flat in frequency above the crossover (hard to check because of very small signal)



To get rid of the problem: Increase PPD beam radius @ testmass.

Two main problems

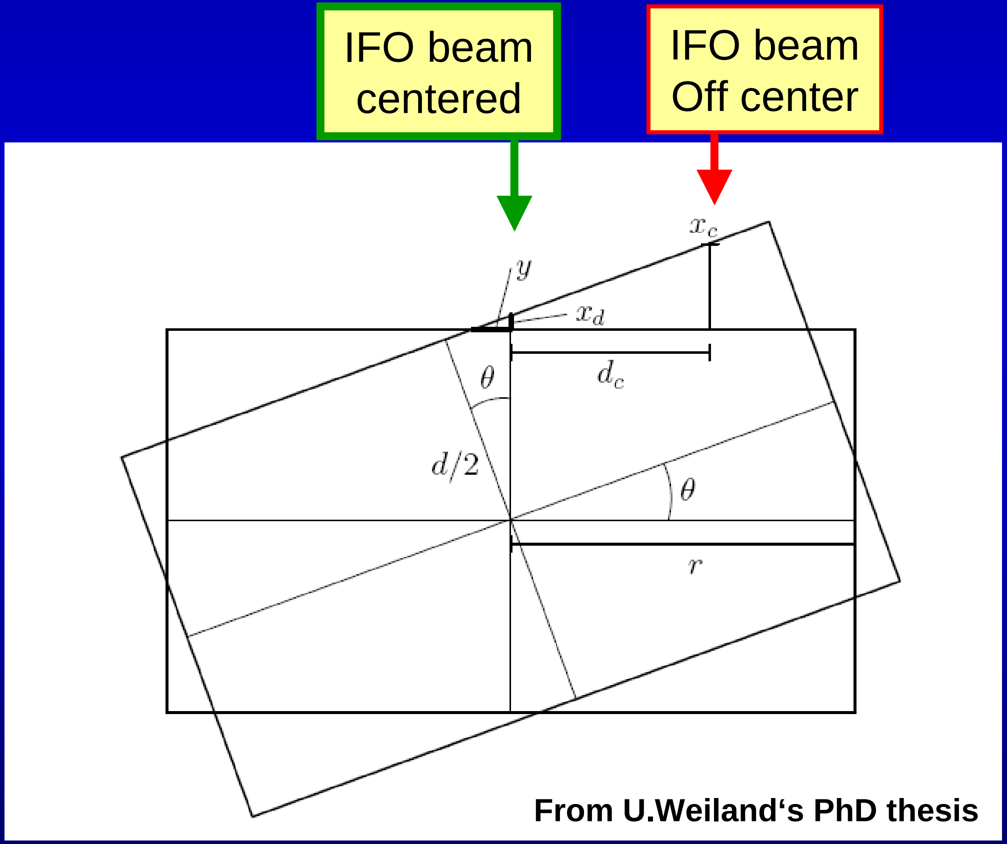


1. Absolute deviation of 40 % (amp in DER_DATA_H is smaller than expected)

2. Step roll off above 1kHz

Effects from mirror rotation/tilt (yaw/pitch)

The photon pressure actuator can cause rotation (and or tilt) when hitting the mirror off center.



From U.Weiland's PhD thesis

IFO beam centered:

$$x_d \approx \frac{d}{4}\,\theta^2$$

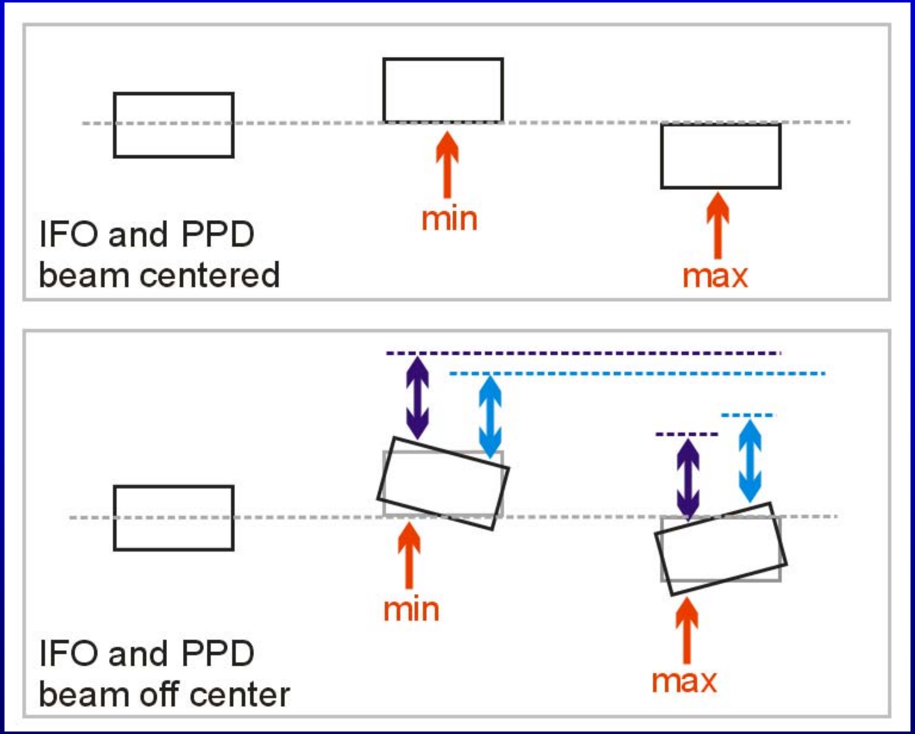
IFO beam off center:

$$x_c \approx d_c\theta + \frac{d}{4}\theta^2$$

Effects from mirror rotation in phase picture

In principle there is no difference between longitudinal and rotaional pendulum response:

- resonances are far below the frequencies of interest
- both give an 1/f^2
- both are 180° out of phase to the light.

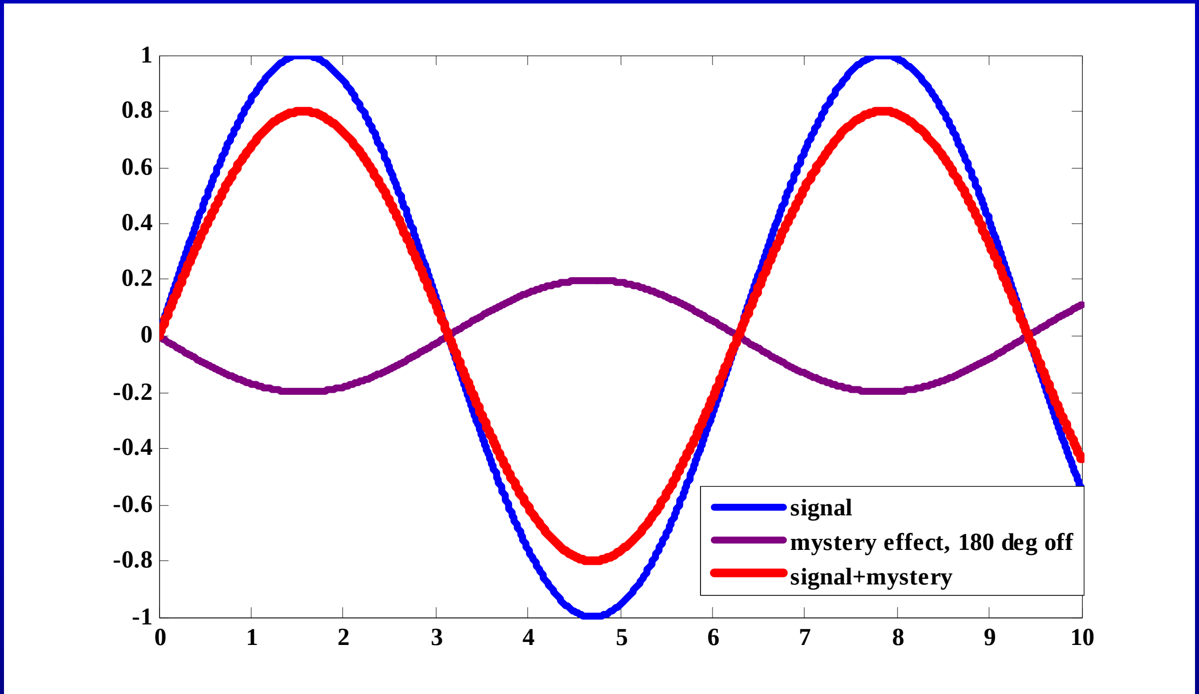


When IFO and PPD are off center to the same side: Rotation gives **180 deg.**

When IFO and PPD are off center to opposite directions: Rotation gives **0 deg.**

Effects from mirror rotation in phase picture (2)

When IFO and PPD are off center to opposite directions:
Rotation gives **0 deg (in respect to the light)**
Rotation gives 18**0 deg (in respect to longitiudinal)**



This effect would reduce the signal for the same amount over all frequencies !!

Can this effect explain 40% error ?

How far would we have to off the center to explain 40% ?

Displacement from rotation $$x_c(\omega) \approx \frac{2Pd_c d_{PPD}}{Ic\omega^2}$$

Displacement from longitudinal $$x(\omega) = \frac{2P}{Mc\omega^2}$$

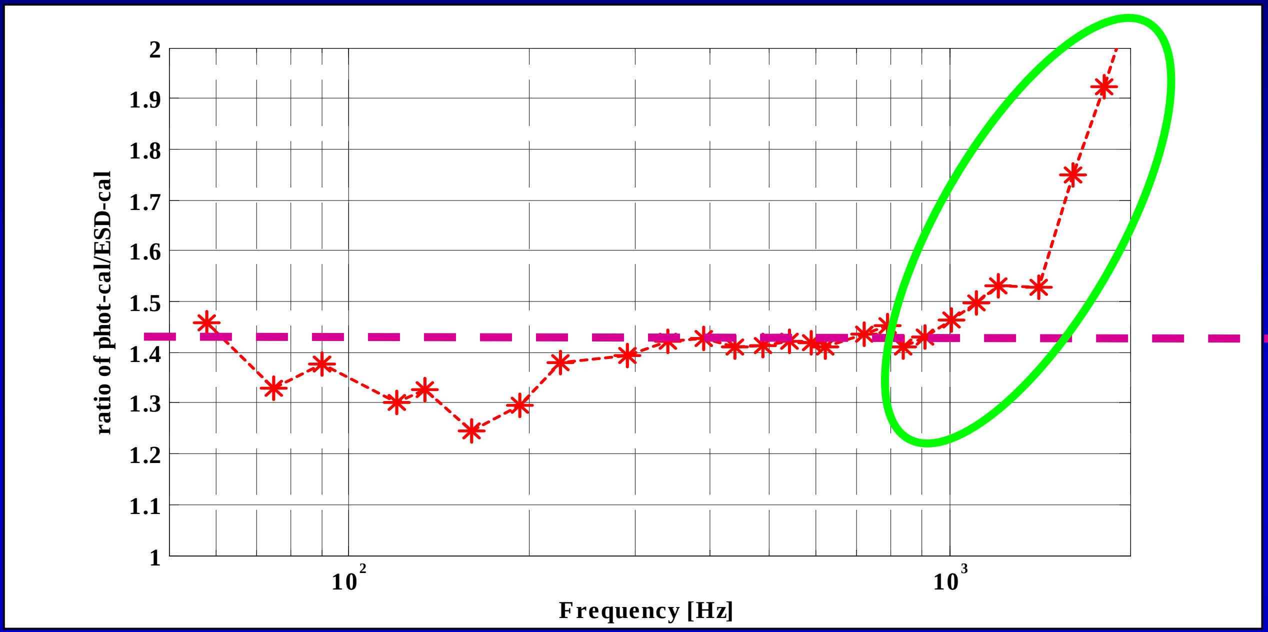
$$\frac{x_c(\omega)}{x(\omega)} = \frac{Md_c d_{PPD}}{I}$$

$$d_c d_{PPD} = 0.4\frac{I}{M} = 1.21 \cdot 10^{-3}\mathrm{m}^2 \qquad d_c = d_{PPD} = 3.4\mathrm{cm}$$

Error of 40% corresponds to being 3.4 cm of center.

To get better 1% beams need to becentered within 0.5 cm.

Two main problems + candidates



1. Absolute deviation of 40 % (amp in DER_DATA_H is smaller than expected)
Candidate: PPD and IFO not hitting center of testmass.

2. Step roll off above 1kHz
Candidate: (non) ridgity of the testmass