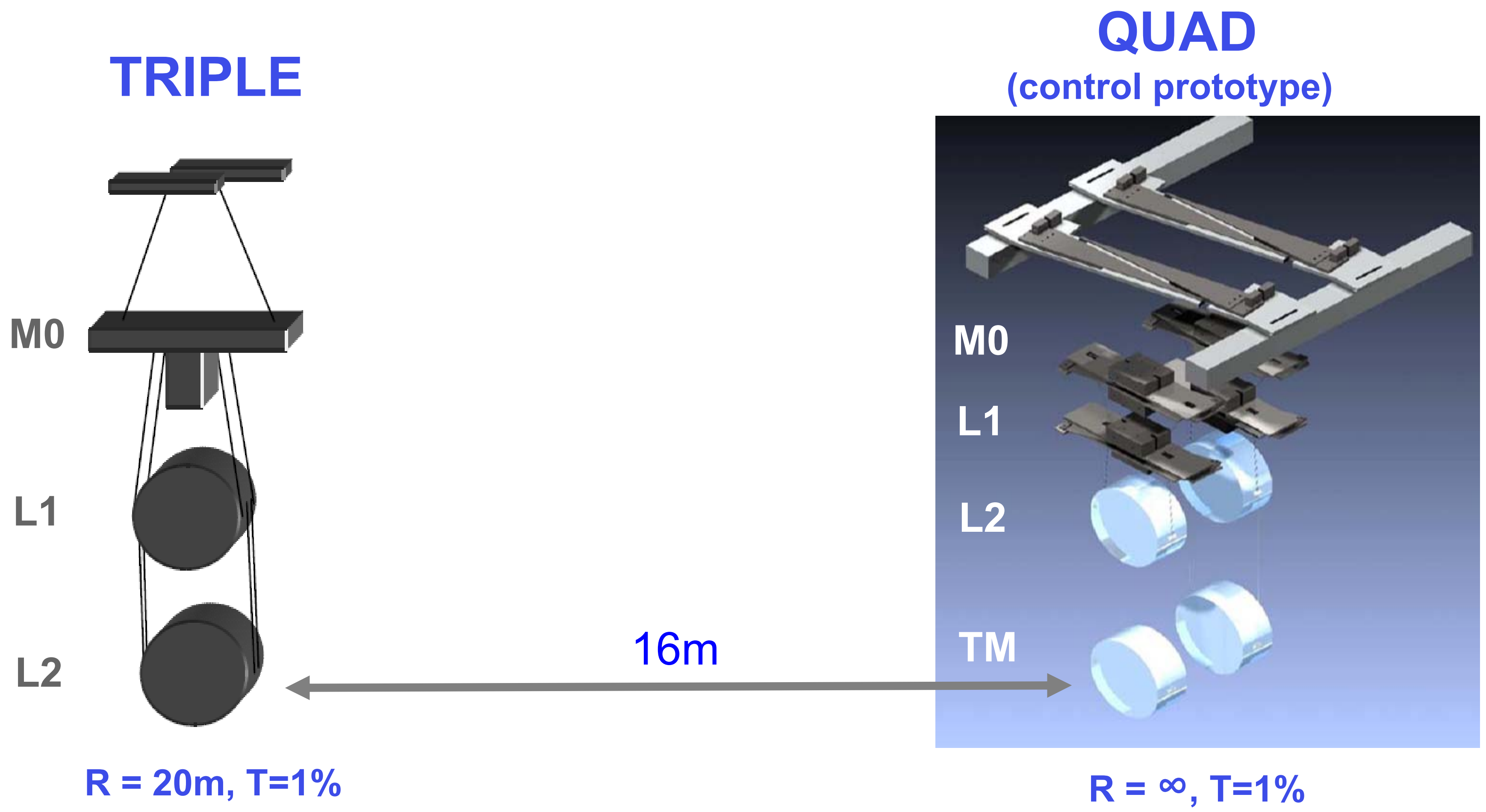
Cavity Work at LASTI

Lisa Barsotti and Matthew Evans for the LASTI group

LSC-VIRGO Meeting, *Hannover - 24th October 2007*

One Arm Cavity



- Optimally coupled cavity (no mode matched light reflected back)
- Finesse ~ 625

Goals

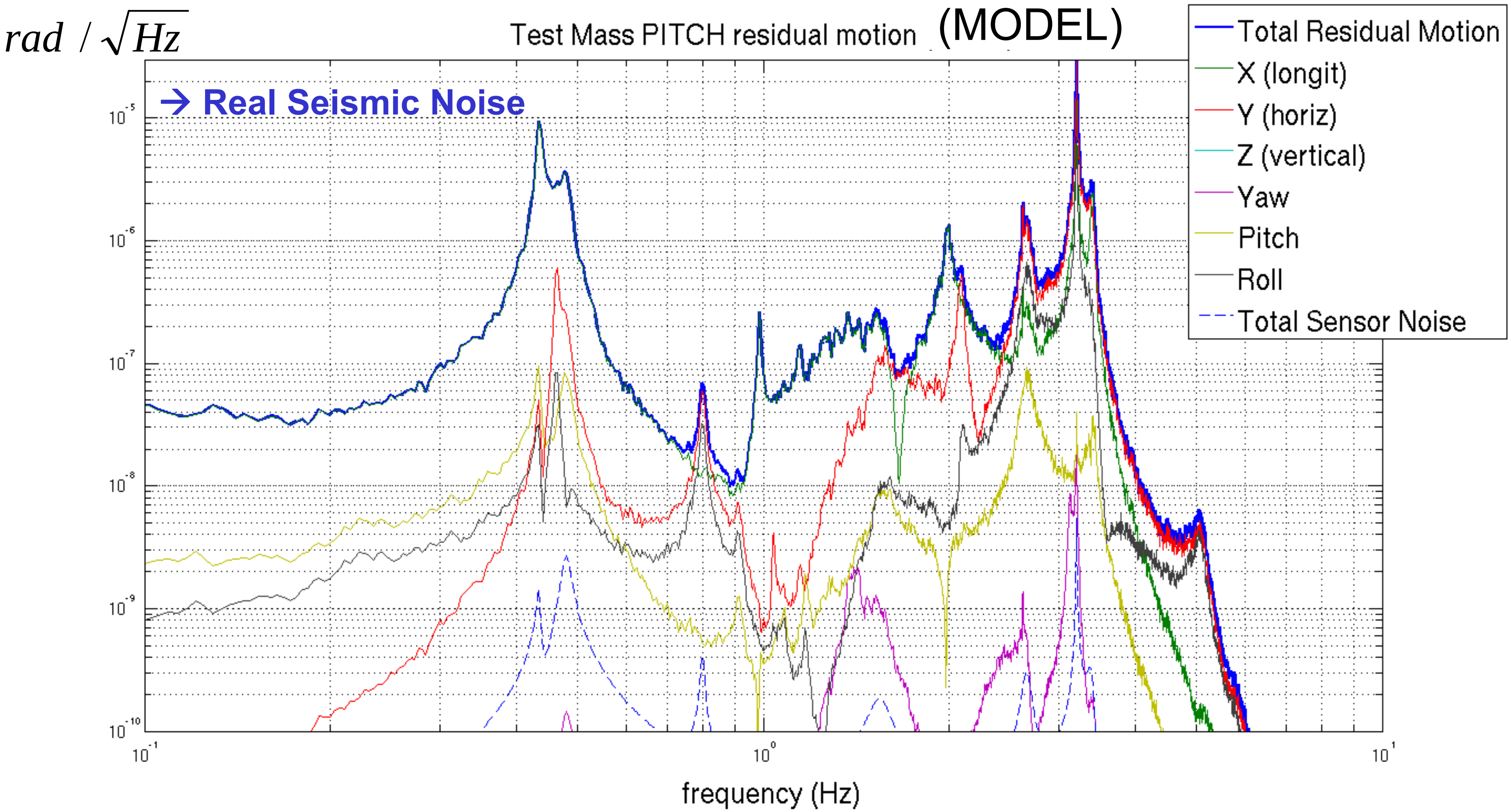
Test of the QUAD :

- Electrostatic Drive (ESD)
- Hierarchical Control
- Lock Acquisition

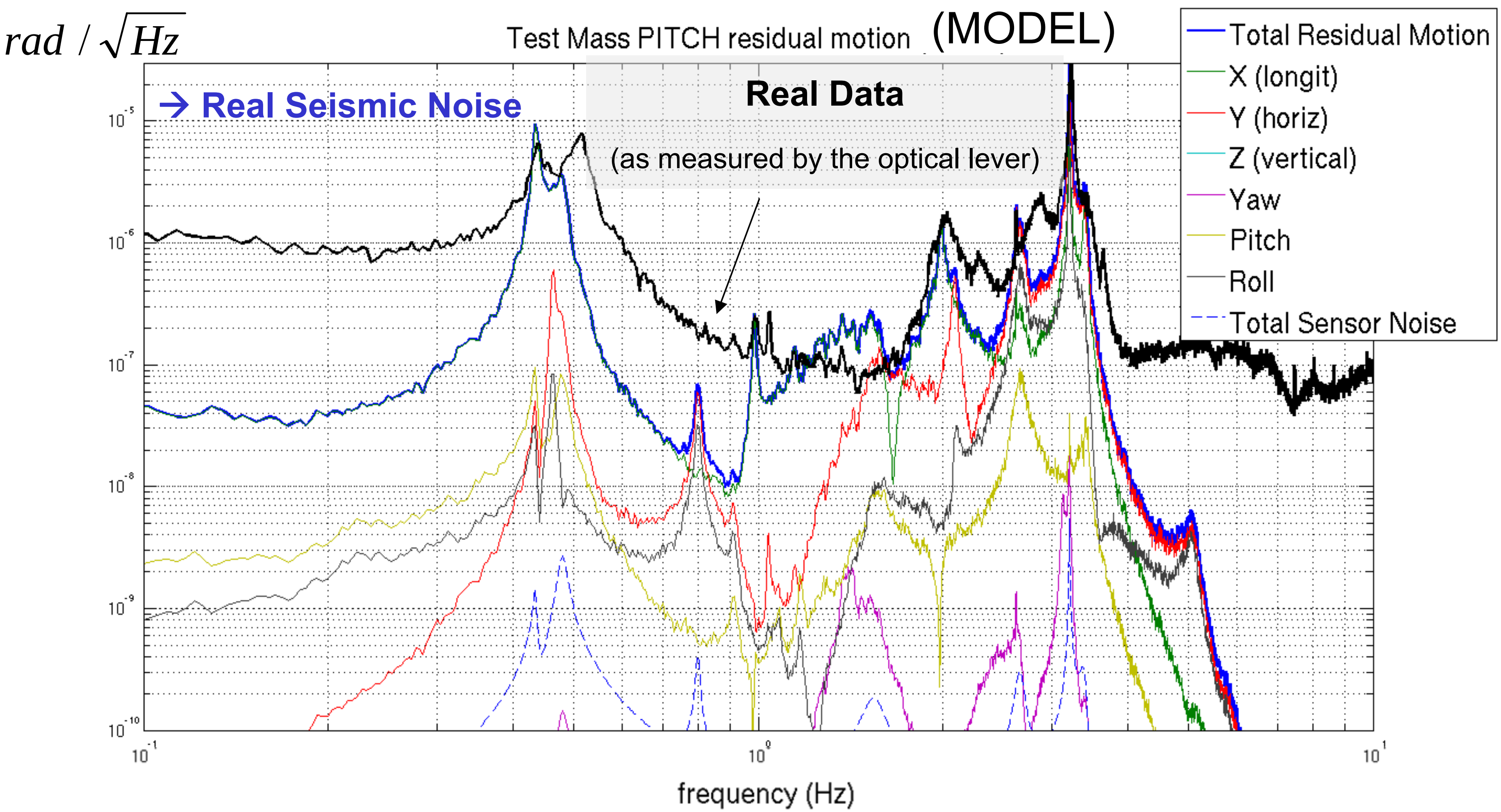
 TF and resonance frequencies:

T07009-00, by Brett and Richard

QUAD performance

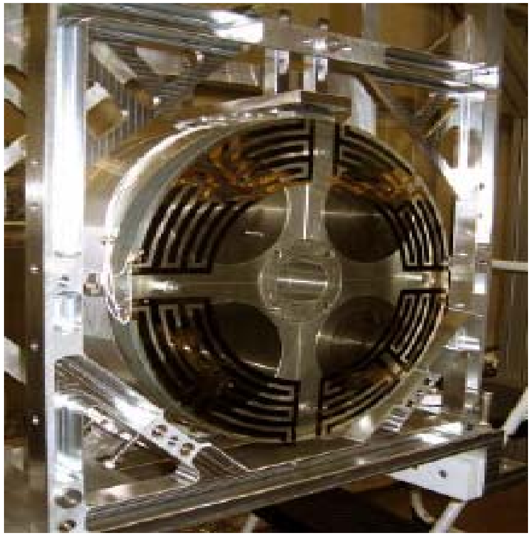


QUAD performance



ESD: Principle

- Goal: get rid of coil-magnet actuators (reduce noise coupling due to magnets)
- 4 pairs of electrodes, coated onto the reaction mass
- Each pair of electrodes forms a capacitor, whose fringe field attracts the mirror surface (dielectric) placed in front of it



- The attractive force F is proportional to the square of the difference in the applied voltage ΔV to the electrodes:

Coupling coefficient [N/V²]

$$F = \alpha(\varepsilon, \varepsilon_r, d, a)(\Delta V)^2$$

Constant geometry factor depending on the electrode pattern design

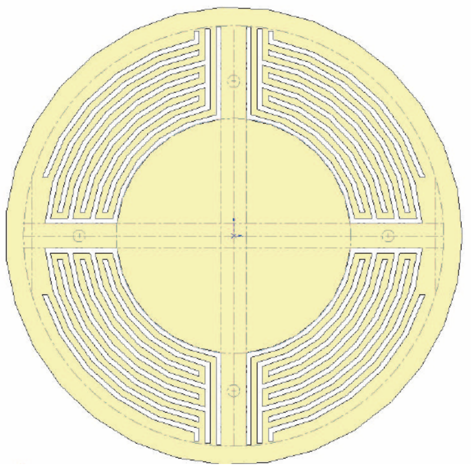
distance between test mass and reaction mass

Design for Advanced LIGO

Electrostatic drive (ESD) results from GEO and application in Advanced LIGO
T060015-00-K, K. Strain (Feb 2006)

- Optimized electrode pattern for AdvLIGO
- Coupling coefficient *expected** to be:

$$\alpha = 7e\text{-}10 \ \mathrm{N/V^2}$$



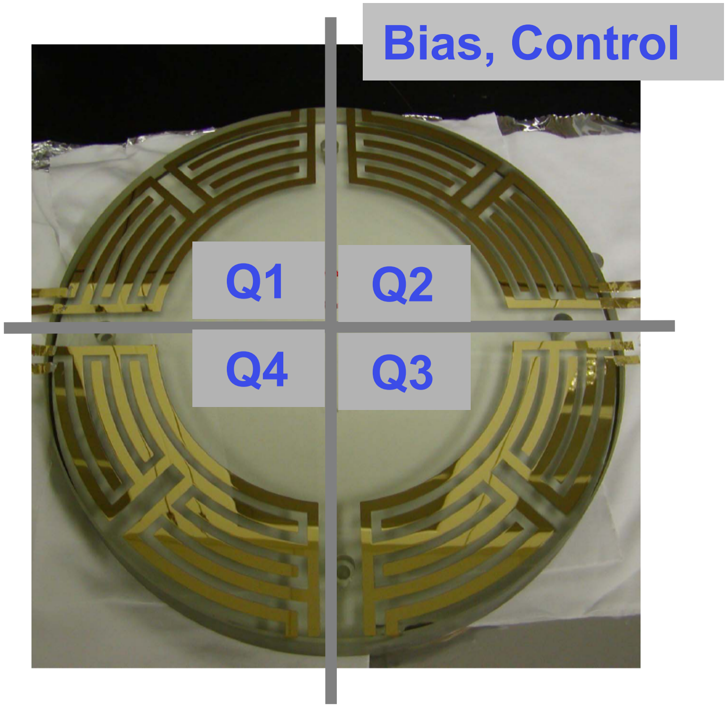
* Based on the GEO measurement (**4.9e-10 N/V²**); for Advanced LIGO estimate of 35% more force produced for a given voltage

- Maximum force available for lock acquisition (with a difference of **800** V between the two channels):

$$F_{MAX} = 7e\text{-}10 * (800)^2 = \mathbf{450\ \mu N}$$

ESD at LASTI *(QUAD Controls Prototype)*

- Coupling coefficient expected to be as in GEO: **α = 4.9e-10 N/V²**
  (not optimized electrode pattern yet)
- Maximum difference voltage currently available at LASTI: **600 V**
- Maximum force expected:



$$F_{MAX} = 4.9e\text{-}10 * (600)^2 \sim \mathbf{180}\ \mu N$$

LASTI Measurement - I

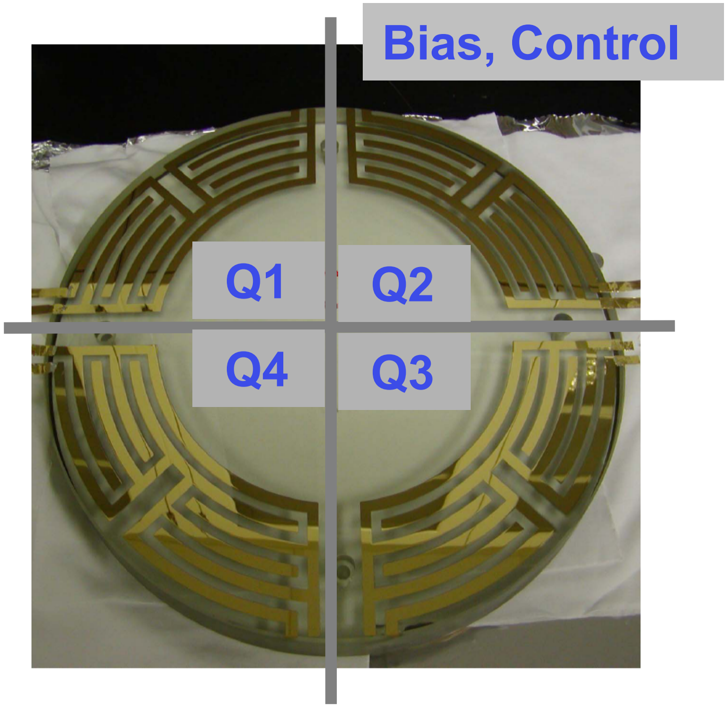
- Cavity locked by acting on the triple (OSEM)
- ESD Drive:

$$F = \alpha\ (V_{bias} - V_{con})^2$$

$$V_{bias} = V \qquad V_{con} = V\sin(\omega t)$$

$$F = \alpha\ V^2 + \alpha\ V^2 \sin^2(\omega t) - 2\ \alpha\ V^2 \sin(\omega t)$$

2ω component ω component

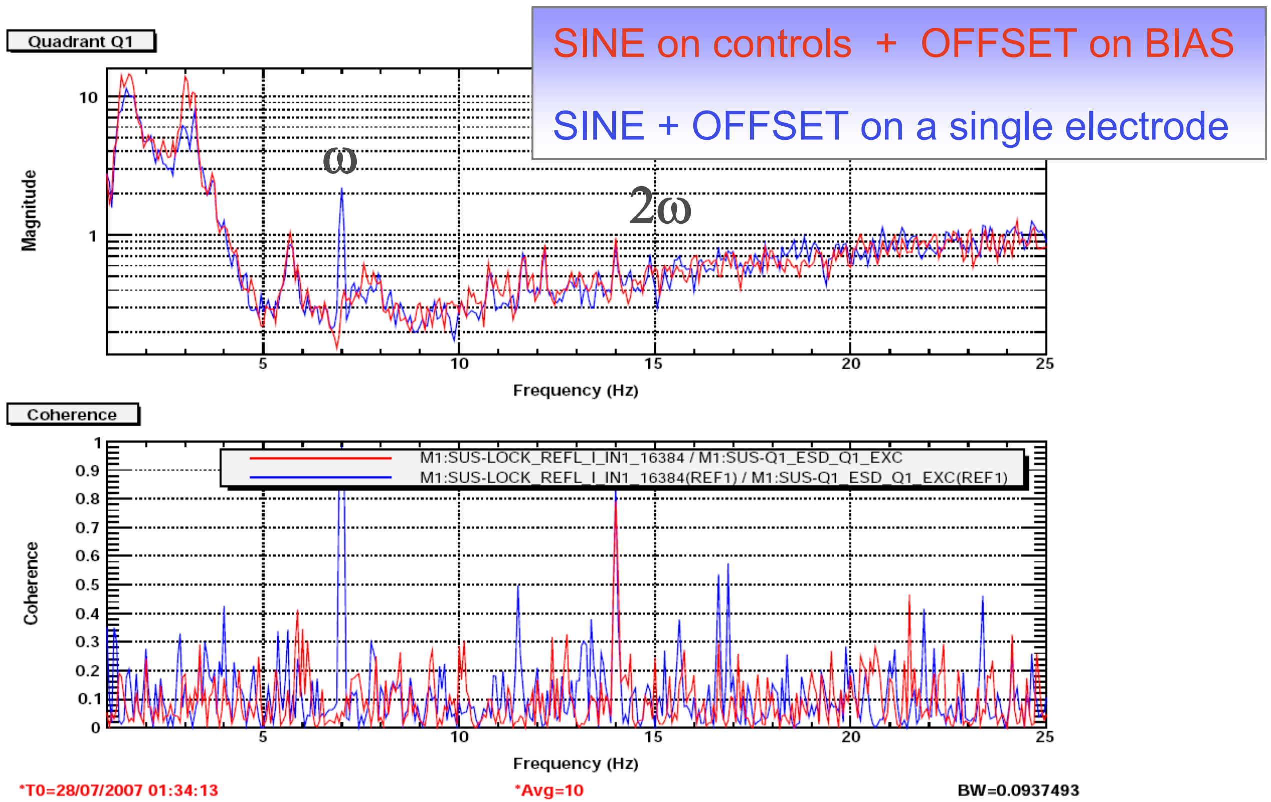


With a 7Hz line we expect **the ω component (2π*7Hz)** to be **twice as big as the 2ω (2π*14 Hz)….**

…but ω component **not measured at all..**

LASTI Measurement - II

- By driving a single electrode with an OFFSET plus a SINE, we get the fundamental (similar results for all of the 8 electrodes):



- By driving the 8 electrodes with an OFFSET plus a SINE: **No significant difference** measured in the amplitude of the ω component by inverting the sign of the drive on the BIAS relative to CONTROL!

LASTI Numbers

- Cavity error signal calibration: 2e6 counts/ mm → 610 V/mm
- Coupling coefficient a measured by driving ALL the electrodes with V = 110 + 110*sin(wt):

$$2\alpha V^2 = 52\mu N \rightarrow \alpha = 2.15e\text{-}9\ N/V^2$$

- Maximum force available for lock acquisition

$$F_{MAX} = 2.15e\text{-}9 * (300)^2 \sim \mathbf{180}\ \mu N$$

The same as if the ESD behaved correctly,

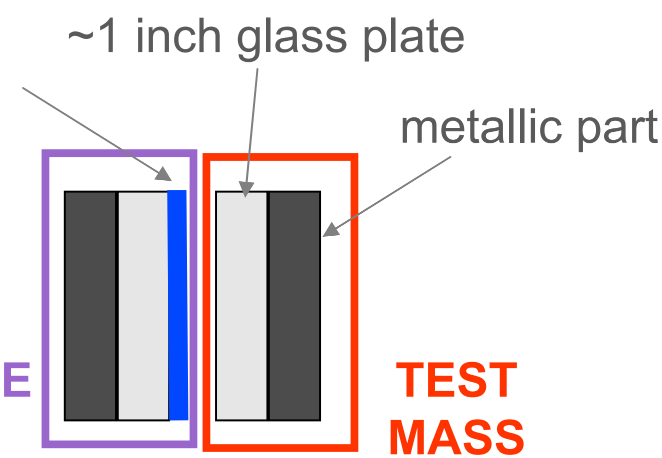
about 2.5 times less than the Advanced LIGO design

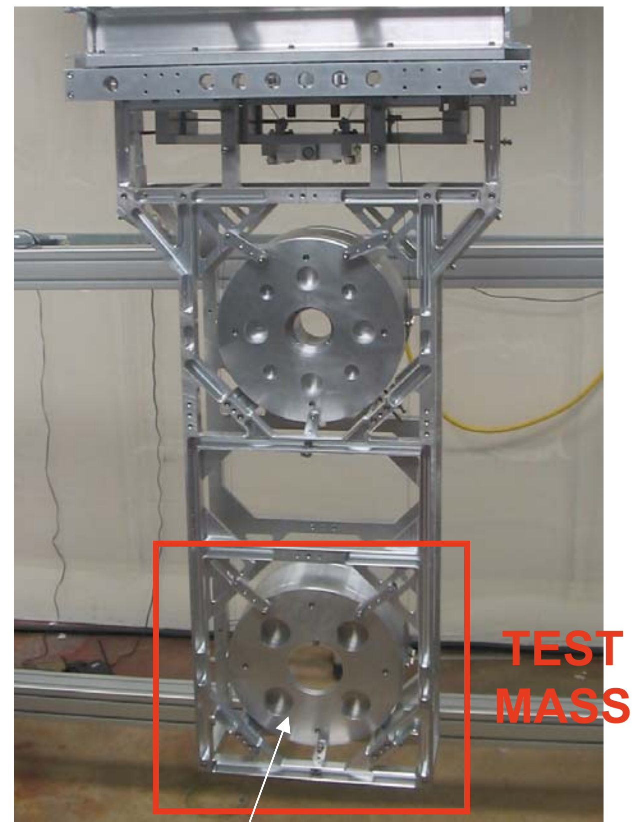
What's the problem?

- It looks like each electrode driven by itself gives some response, but it doesn't "see" the one next to it
- Possible explanation:

→ the metallic part standing in for the QUAD mirror changes the behavior of the electric field between the ESD electrodes and the test mass

ESD



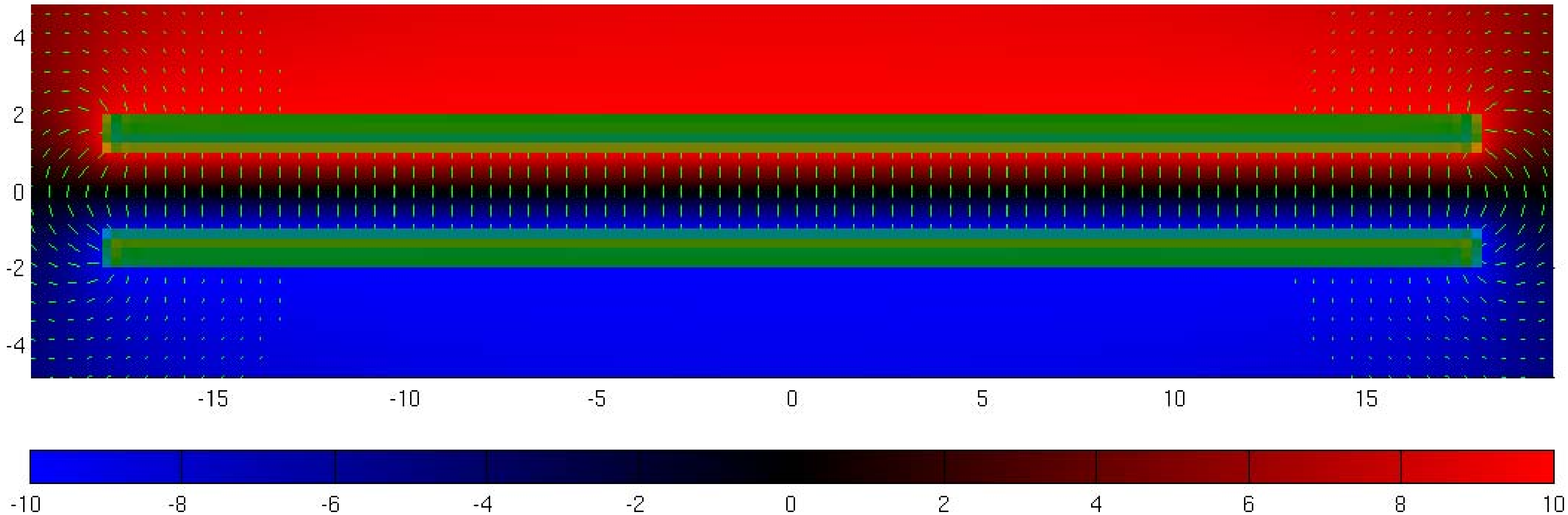


Metallic structure

Finite Element Model (by Matt)

- Matlab model which solves electrostatic problems
- Given the potential on the conductors, it deduces the charge distribution on the conductors, the electric field and the potential everywhere in the space

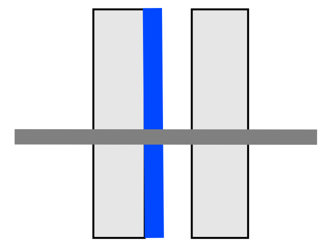
Example: Simple Capacitor

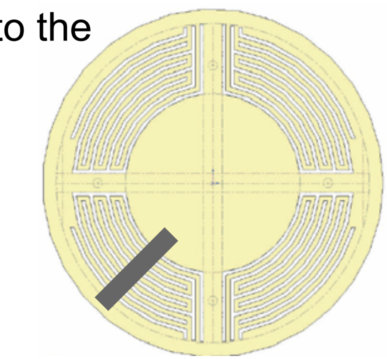


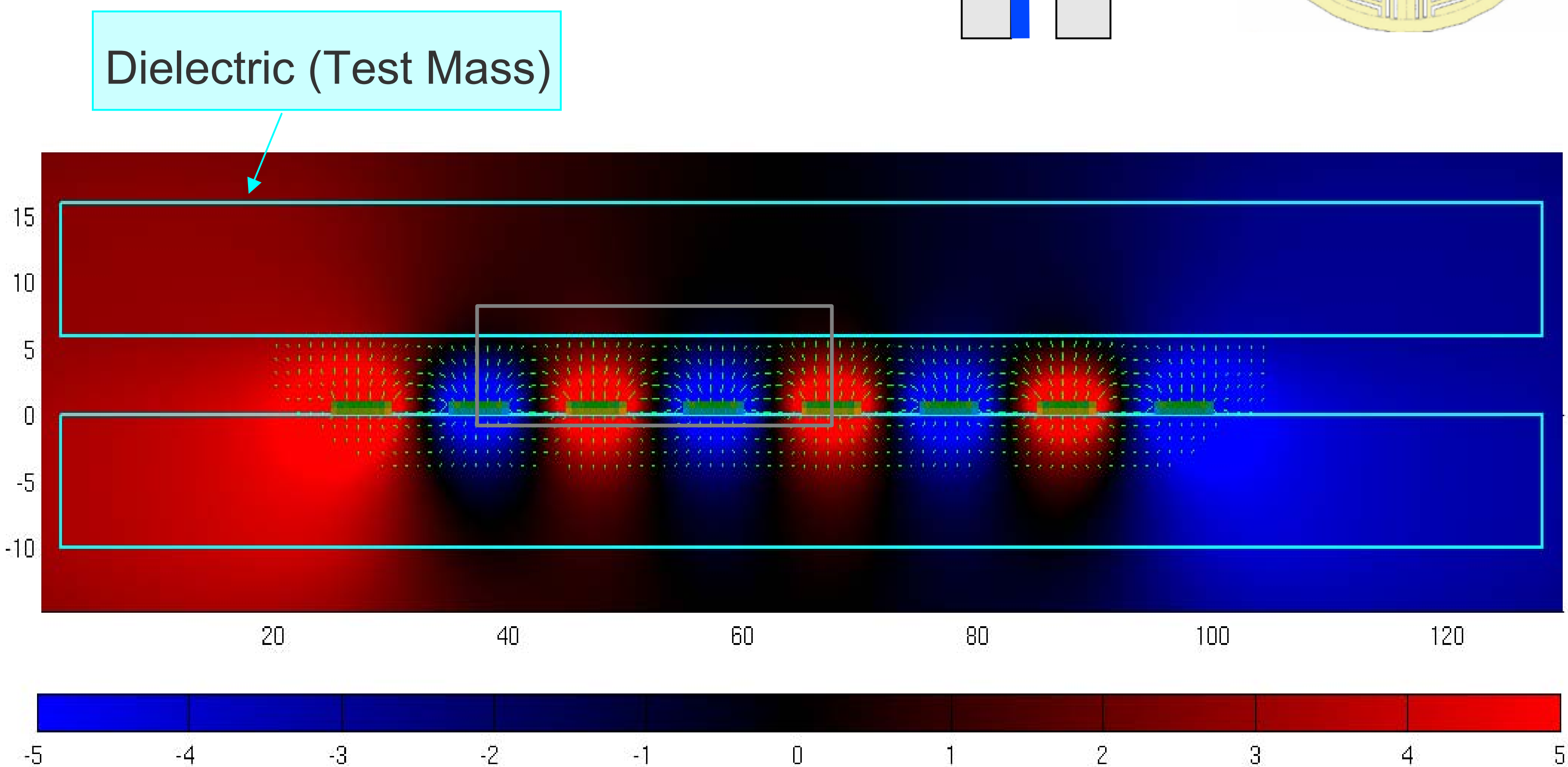
ESD Model for AdvLIGO

- Electrodes driven with +V, -V

Section perpendicular to the ESD plane



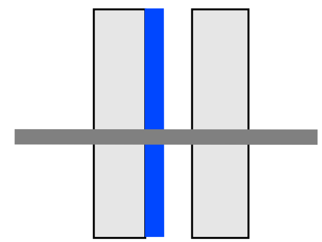


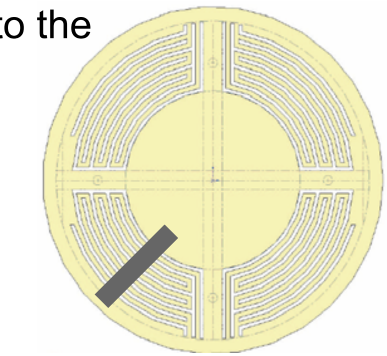


ESD Model for AdvLIGO

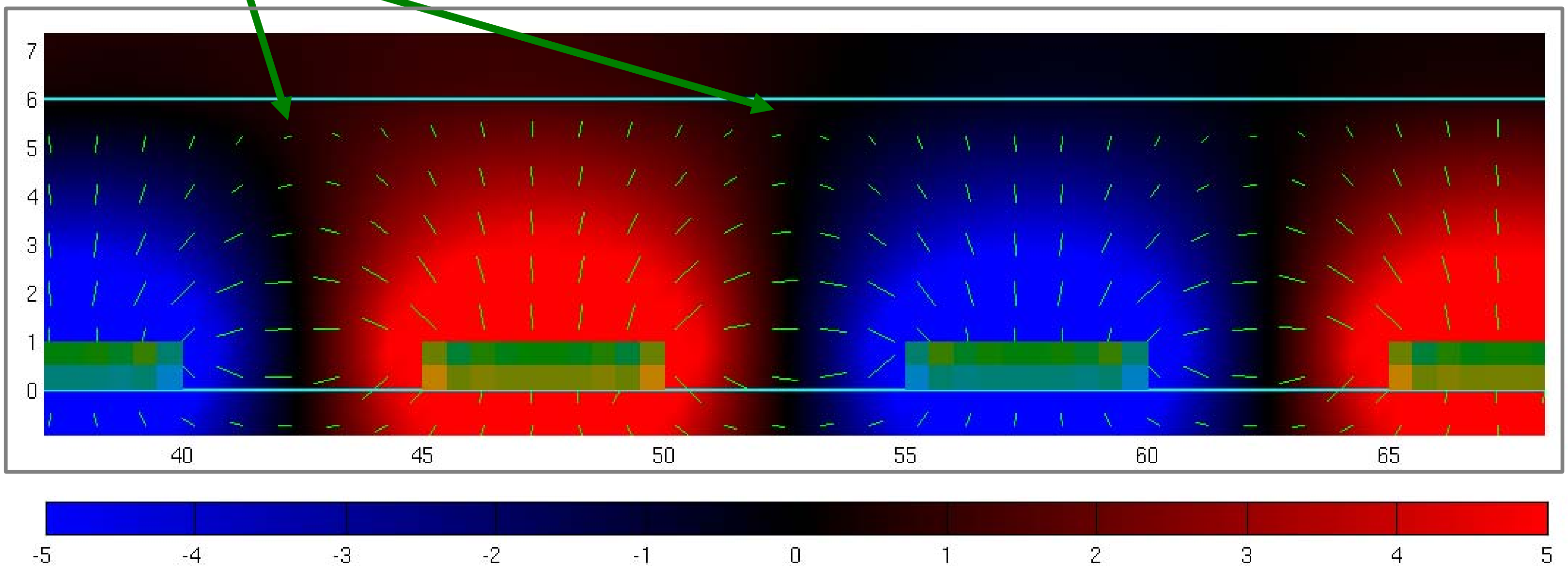
Coupling coefficient in agreement with the expected one (within 50%)

Section perpendicular to the ESD plane





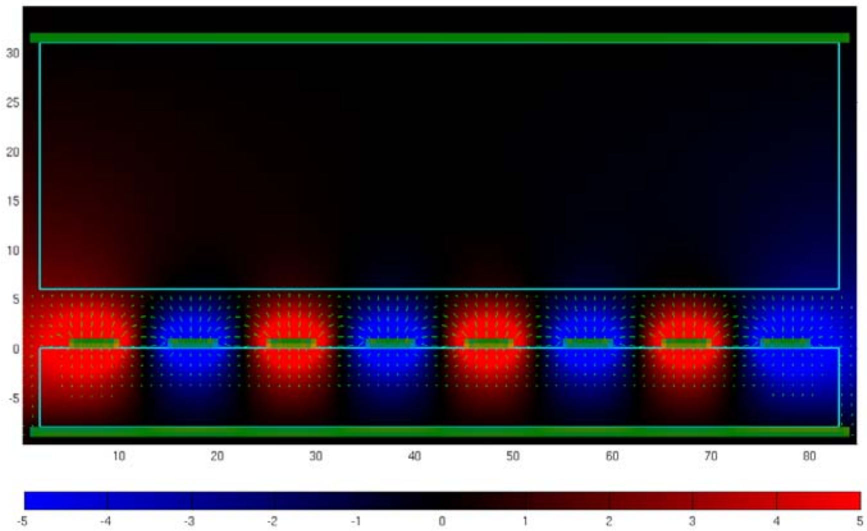
Fringe field

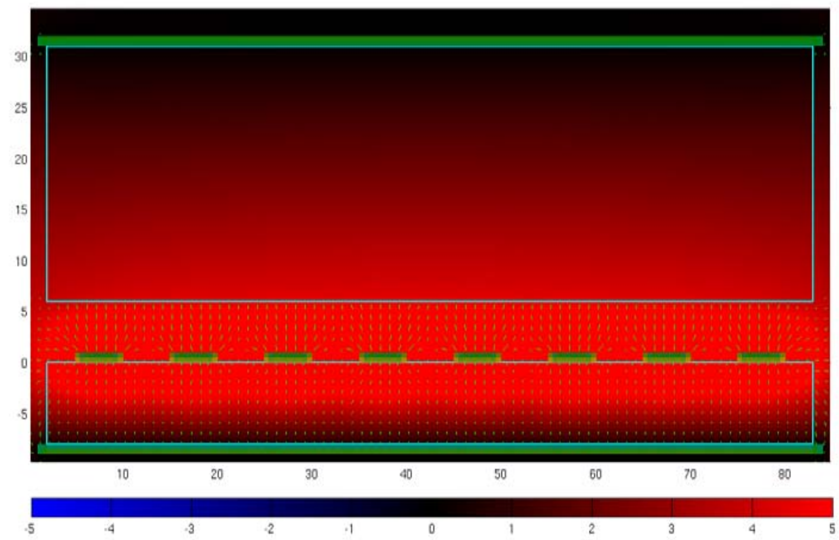


ESD Model for LASTI - I

- Electrodes driven by +V, -V
- Negligible force on the ground plane
- Force on the dielectric due to the ESD fringe field, coupling coefficient α_{diff}

- Electrodes driven by +V, +V
- Negligible force on the dielectric (no fringe field)
- Force on the ground due to the gradient of the potential, coupling coefficient α_{comm}





According to the model, α_{diff} and α_{comm}, are the same (bad luck??) and their value is compatible with the measured value (within 50%)

ESD Model for LASTI - II

- **Ground plane** which modifies the behaviour of the ESD

$$F = \alpha_{diff} (V_{bias} - V_{con})^2 + \alpha_{comm} (V_{bias} + V_{con})^2$$

- $V_{bias} = V$, $V_{con} = V\sin(\omega t)$:

  $F \sim 2V^2 (\alpha_{comm} - \alpha_{diff}) \sin(\omega t)$ ⇨ No fundamental if $\alpha_{comm} = \alpha_{diff}$

- $V_{bias} = V + V\sin(\omega t)$

  $V_{con} = V_{bias} \rightarrow F \sim 8V^2 \alpha_{comm} \sin(\omega t)$

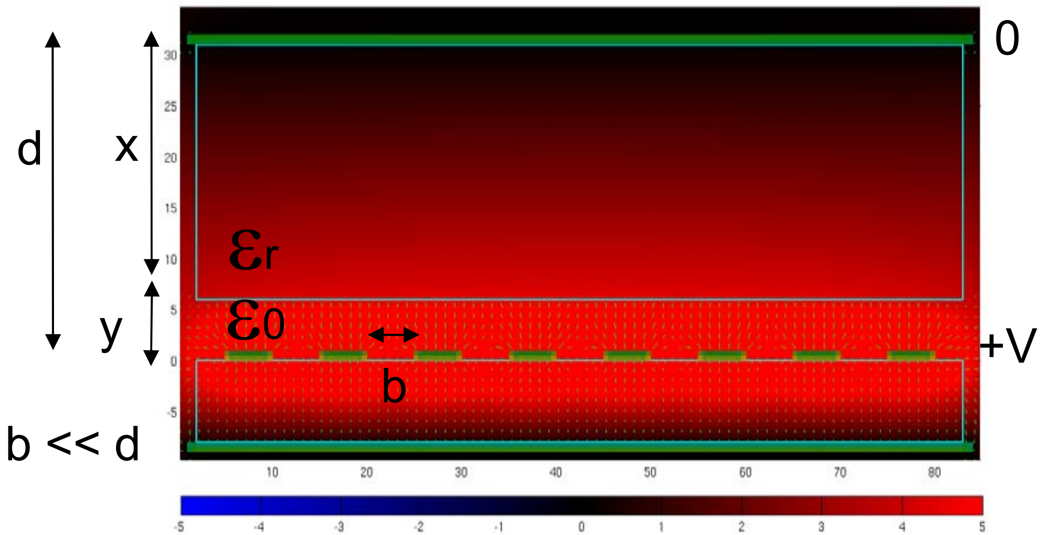
  $V_{con} = -V_{bias} \rightarrow F \sim 8V^2 \alpha_{diff} \sin(\omega t)$

  ⇨ Same result if $\alpha_{comm} = \alpha_{diff}$

Model explains the experimental results

ESD Model for LASTI - III

- Further cross check by analytically computing the coupling coefficient assuming the electrodes as a plane at the potential V



$$U = \frac{1}{2}\varepsilon_0\varepsilon_r \frac{AV^2}{(\varepsilon_r y + x)}$$

$$\alpha = \frac{1}{2}\varepsilon_0\varepsilon_r^{\,2} \frac{A}{(\varepsilon_r y + x)^2}$$

Computed coupling coefficient in agreement with the measured one (within 50%) and the one derived from the model

ESD Linearization Code

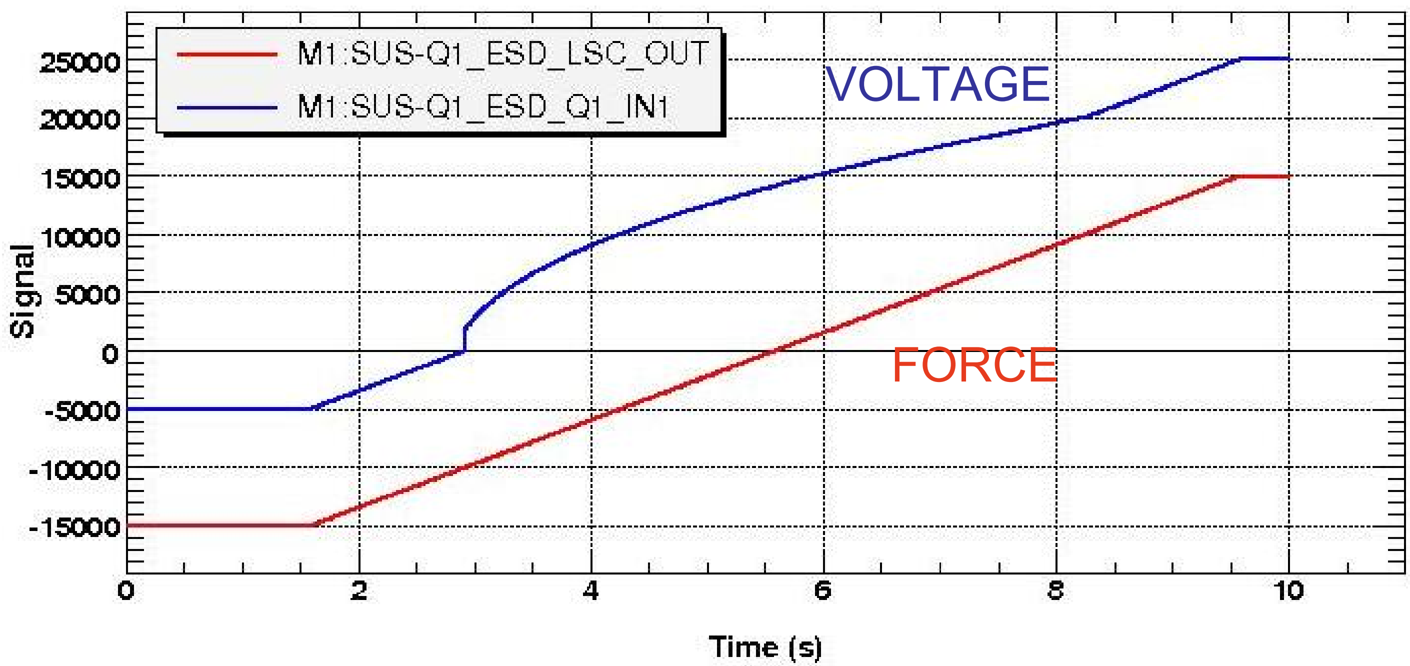
The voltage that I need to apply to produce the required F force is :

$$V = \sqrt{\frac{1}{\alpha}(F + F_{OFF})}, \text{ where I choose } F_{OFF} \text{ so to be in the middle of the force range :}$$

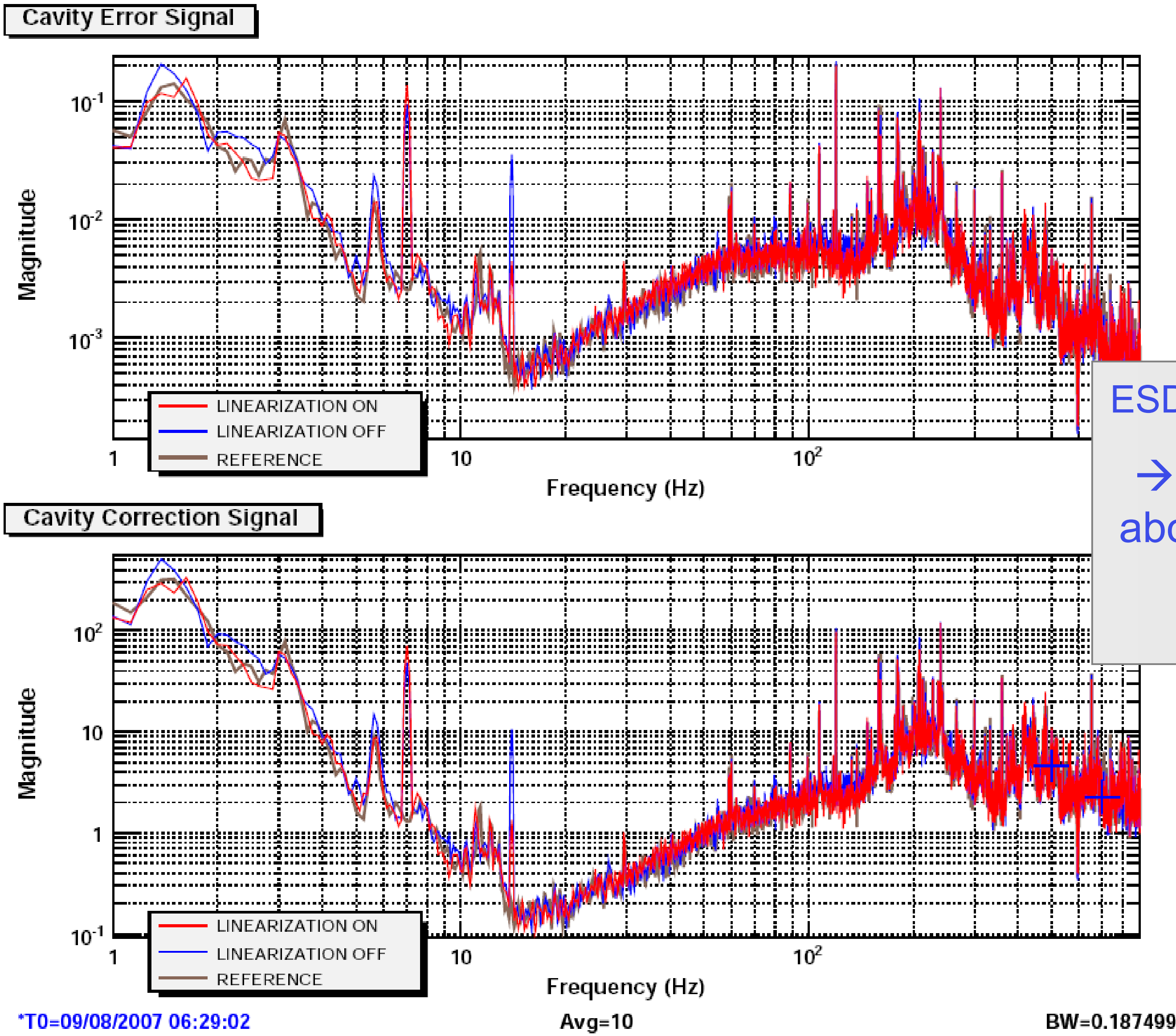
$$F_{OFF} = F_{MAX}/2 = \alpha V^2_{MAX}/2$$

In particular : for $F = 0$, $V = V_{MAX}/\sqrt{2}$

In our case : $V_{MAX} = 300V$, so that $F_{OFF} = 90\mu N$



ESD Linearization - Efficiency



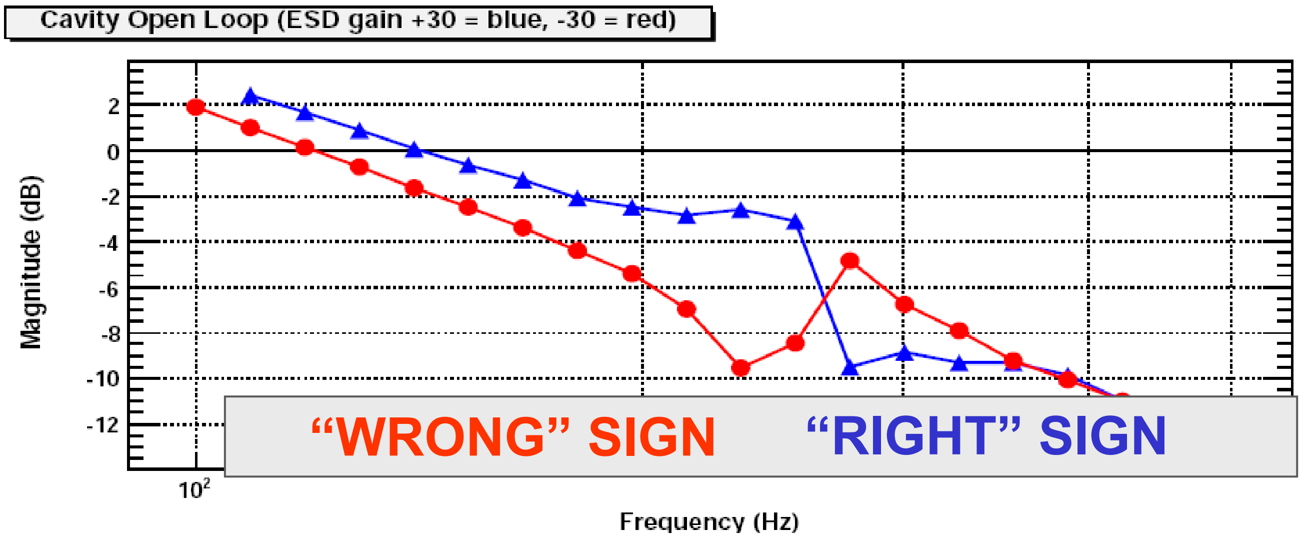
ESD driven @ 7 Hz

→ Reduction by about a **factor 10** of the first harmonic

ESD Drive

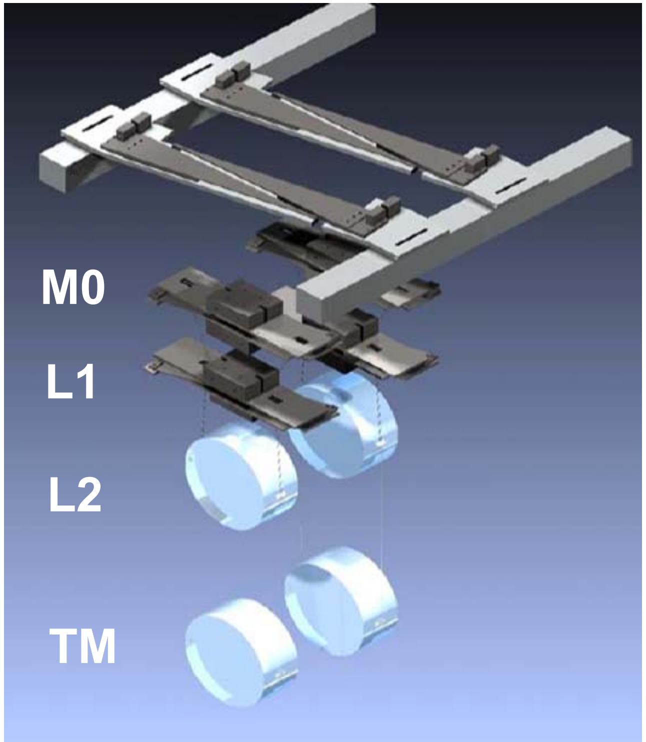
- Cavity locked by acting on the triple (OSEM)
- Correction signals moved from the triple to the quad ESD: saturation due to **frequency noise (~100 Hz/sqrt(Hz) @ 100 Hz)**
- Phase lock loop: down to **~10 Hz/sqrt(Hz) @ 100 Hz**
- **Frequency noise still too high!**

  Cavity locked using the quad ESD above 20Hz and the triple OSEM below: only **25%** change in the open loop TF of the longitudinal loop measured with the "right" (**blue**) and "wrong" (red) sign of the ESD loop



Hierarchical Control

- Reallocation of the low frequency component of the mirror locking force to higher stages of the chain
- Less dynamic range needed for the mirror actuators → low noise state
- Sort of Hierarchical Control present in LIGO I (tidal control)
- More complex for multi-stage suspensions (VIRGO, ..)

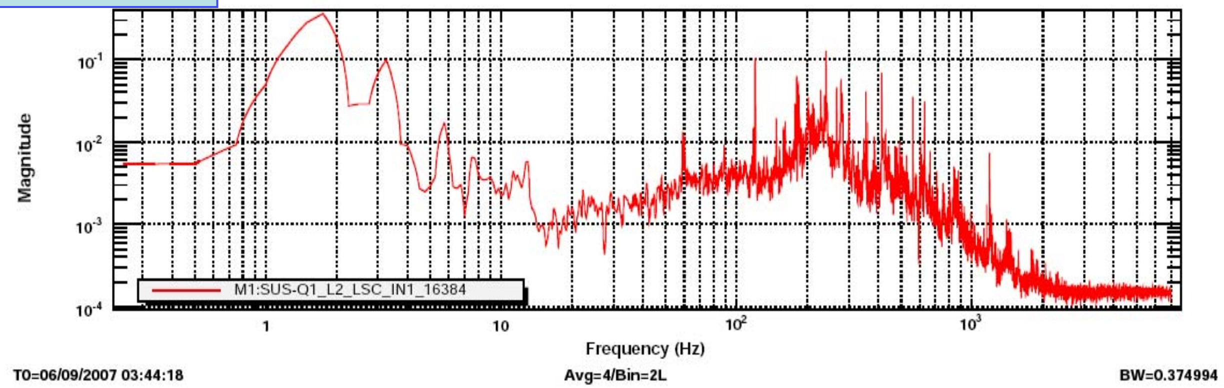


- Main concern: couplings between the dofs of the different stages
- Never tested on the QUAD before

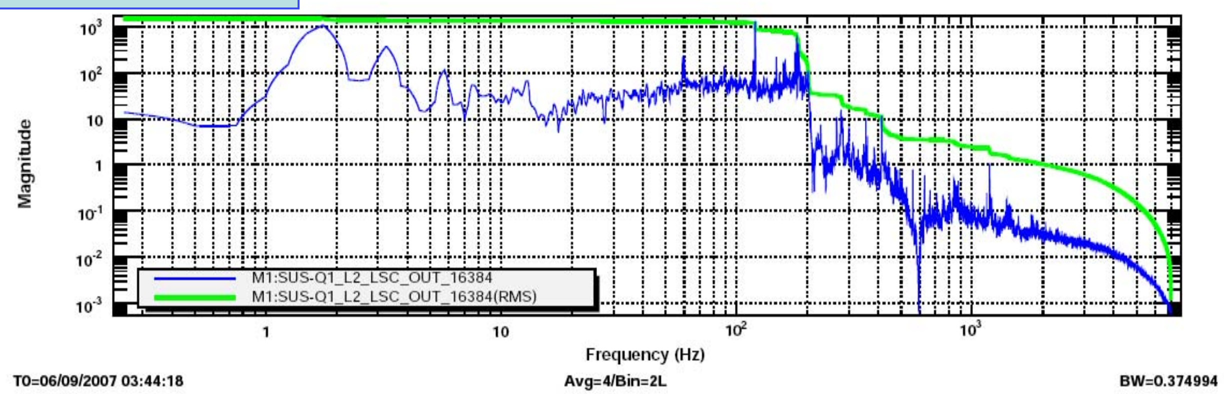
QUAD “Hierachical Control”

- ESD not able to be used to keep the lock (saturated by frequency noise)
- Test done by splitting the locking force between the **TRIPLE (above 10 Hz)** and the penultimate mass (L2) on the **QUAD (below 10 Hz)**

Error Signal



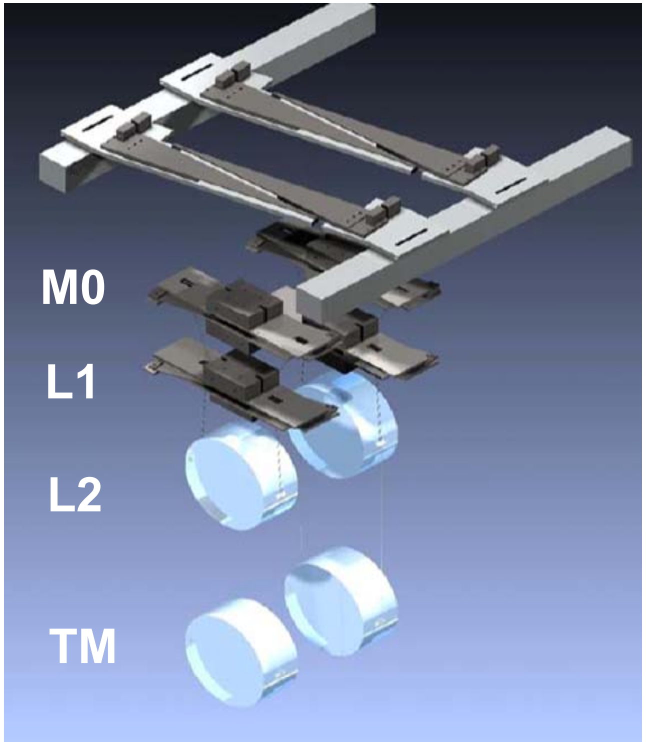
Correction Signal



Test Mass Charge: ESD as Sensor

- Top Mass (M0) driven at 2.5 Hz
- 4 electrodes of the ESD used as sensors, connected as input signal to an SR560
- BSC ground connected to the SR560 ground

If the charge on the TM is not null, you expect to get a signal on the ESD at the driving frequency



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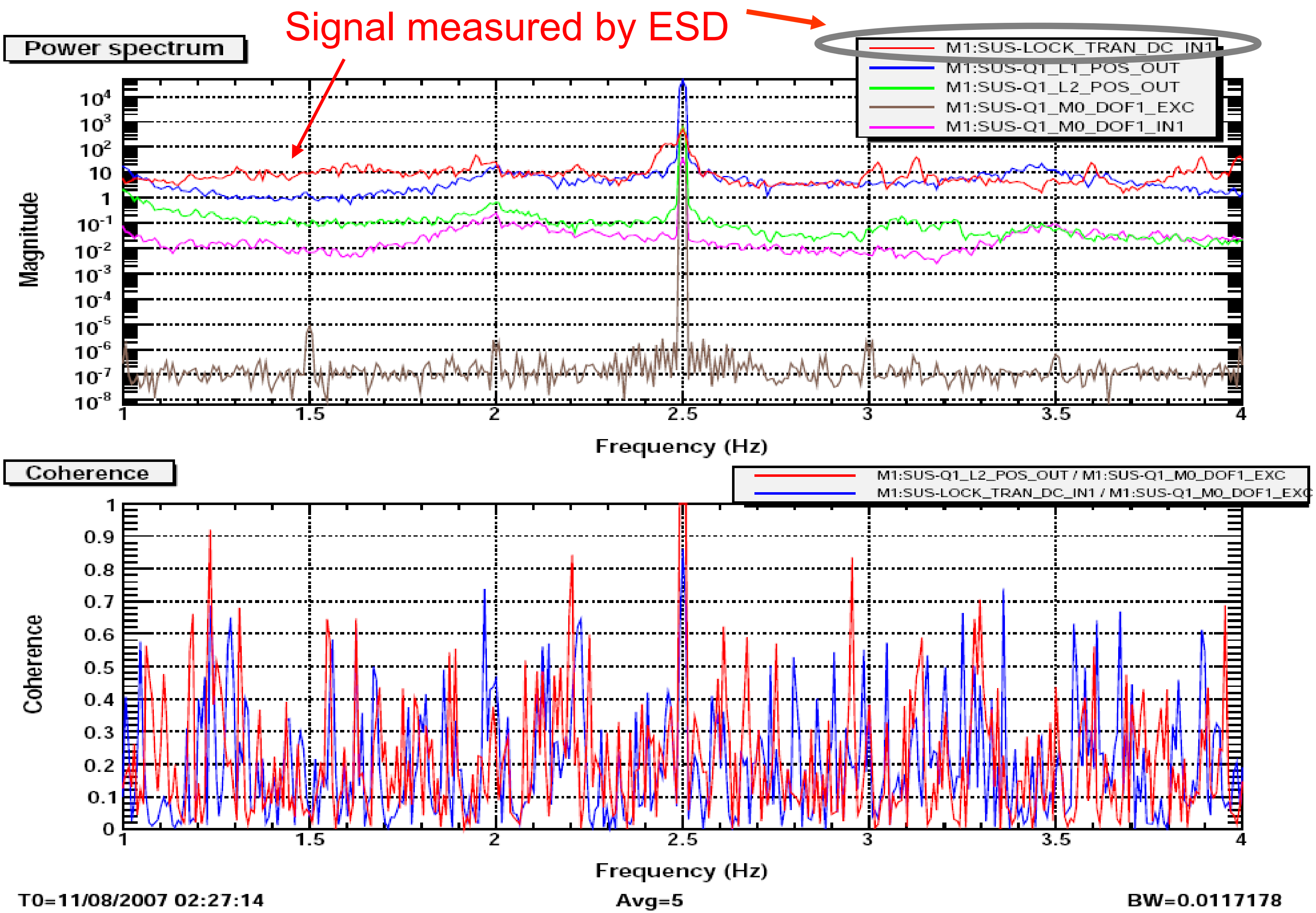

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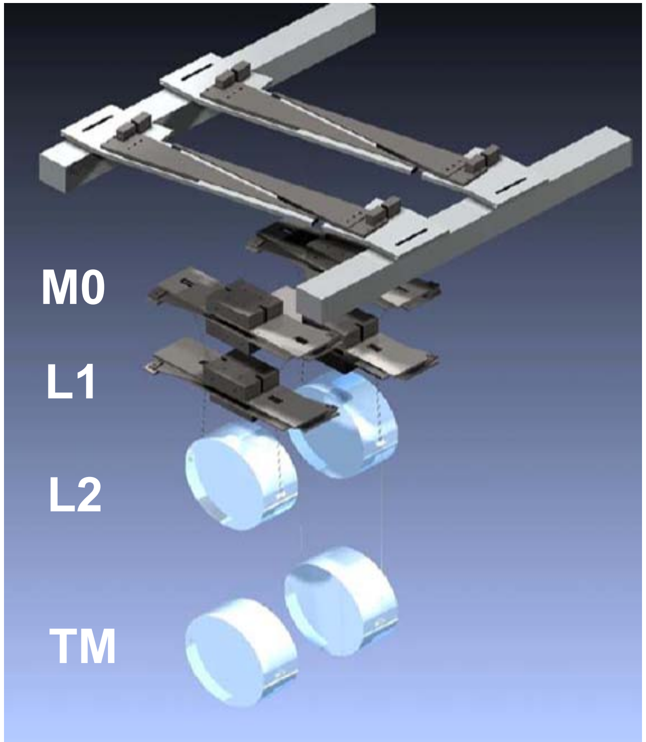


If the charge on the TM is not null,
you expect to get a signal on the ESD
at the driving frequency

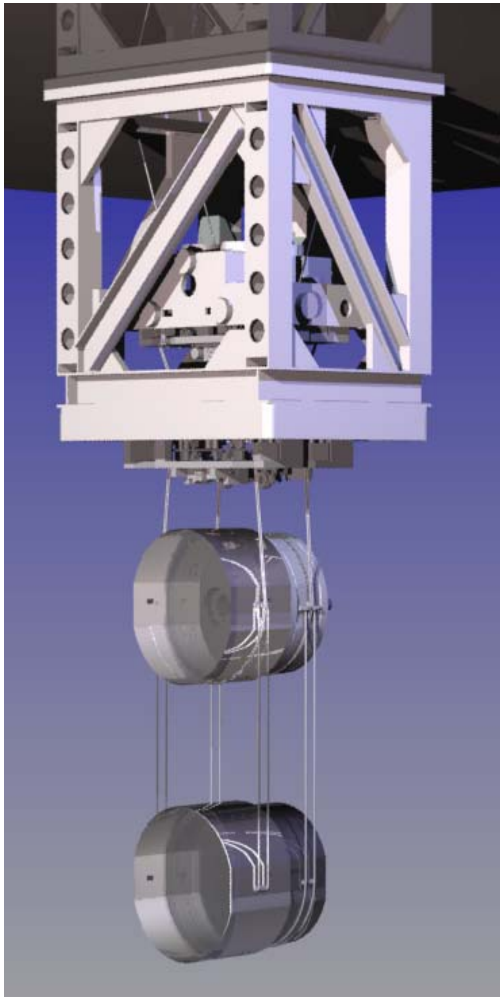
- Work function difference between Aluminium and Gold might be the cause for the signal that we measure
- The principle may still be valid without the metallic part

Summary

- ESD not behaving as designed, reasons understood
- Frequency noise in the present set-up too high
- Linearization code works properly
- *Hierarchical Control:* Cavity controlled below 10Hz acting on the penultimate mass of the QUAD

Plans

- Improve frequency stabilization (new input bench needed)
- Repeat tests *(ESD, Lock Acquisition, Hierarchical Control)* on **QUAD Noise Prototype** (test mass in glass)

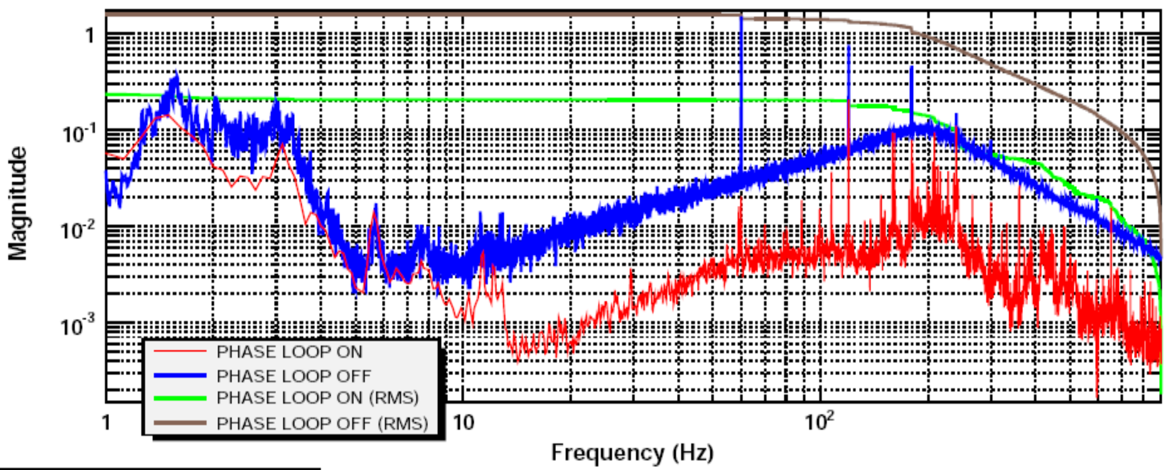


The End

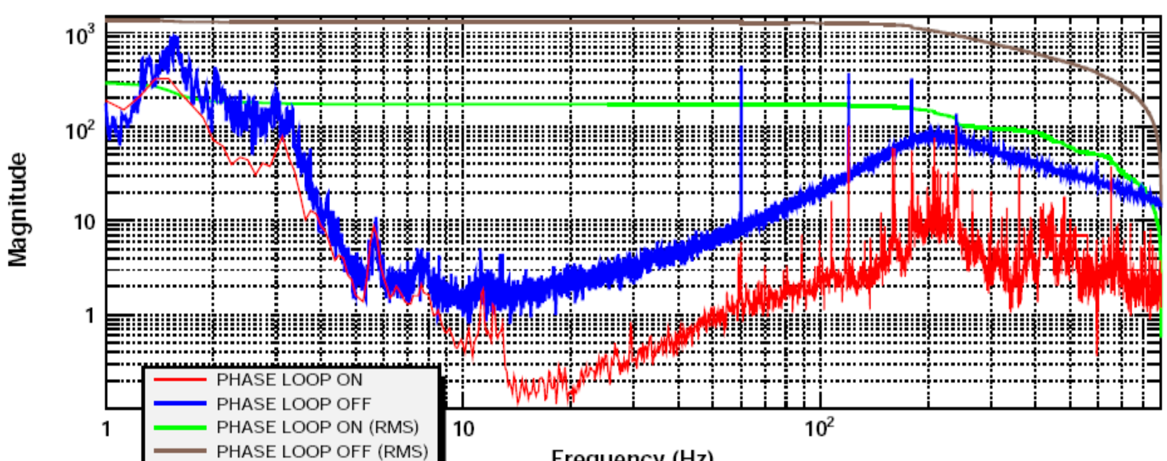
Frequency Noise Reduction

- Phase-lock loop: frequency noise reduced by about a factor 10

Cavity Error Signal



Cavity Correction Signal



*T0=09/08/2007 06:19:04 *Avg=10 *BW=0.187499

QUAD “Hierachical Control”