Co-Design Ideas for the Post O5 Suspensions
Episode 1: Controlling the Top Mass

Thank you for coming to our Podcast

Jeff Kissel, Brian Lantz

G2102370

We’re here today to talk about the future.

- Bigger suspensions for Post O5 and as a stepping stone for Cosmic Explorer.
- We’re starting to think about the design these future detectors
- Hoping to take some lessons from the current suspensions and incorporate that into the design for these next generation machines.

Welcome to Episode 1 of our Podcast series on
Design Ideas for the Post O5 Suspensions:

Improving the controls on the top mass.

Why Controllability?

Suspension thermal noise ✓

Passive isolation is great. ✓

LIGO is limited by **control** noise

We've learned a lot of things in aLIGO about these quads, and there are things that we can do better in the design to improve the **controllability**.

We're going to talk about two **control system design** changes for the top mass to improve the angular noise of the optic.

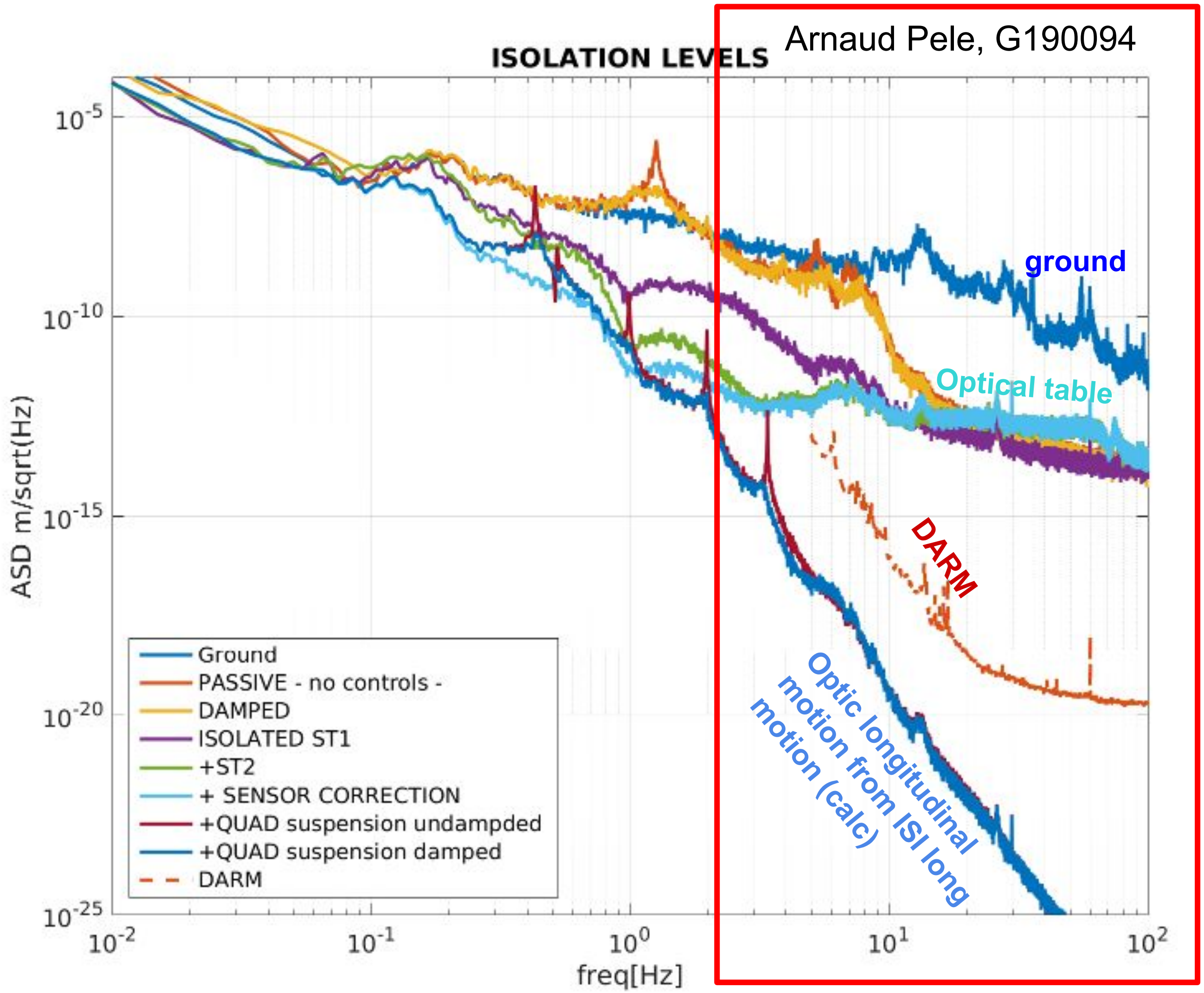
We're going to continue along the journey of **co-design**, marrying the mechanic design with the **controls design** to improve the performance

We've already started thinking about this in the SWG: eg. higher stress fibers, lower noise sensors, damping the UIM, optical levers from the ISI, etc.

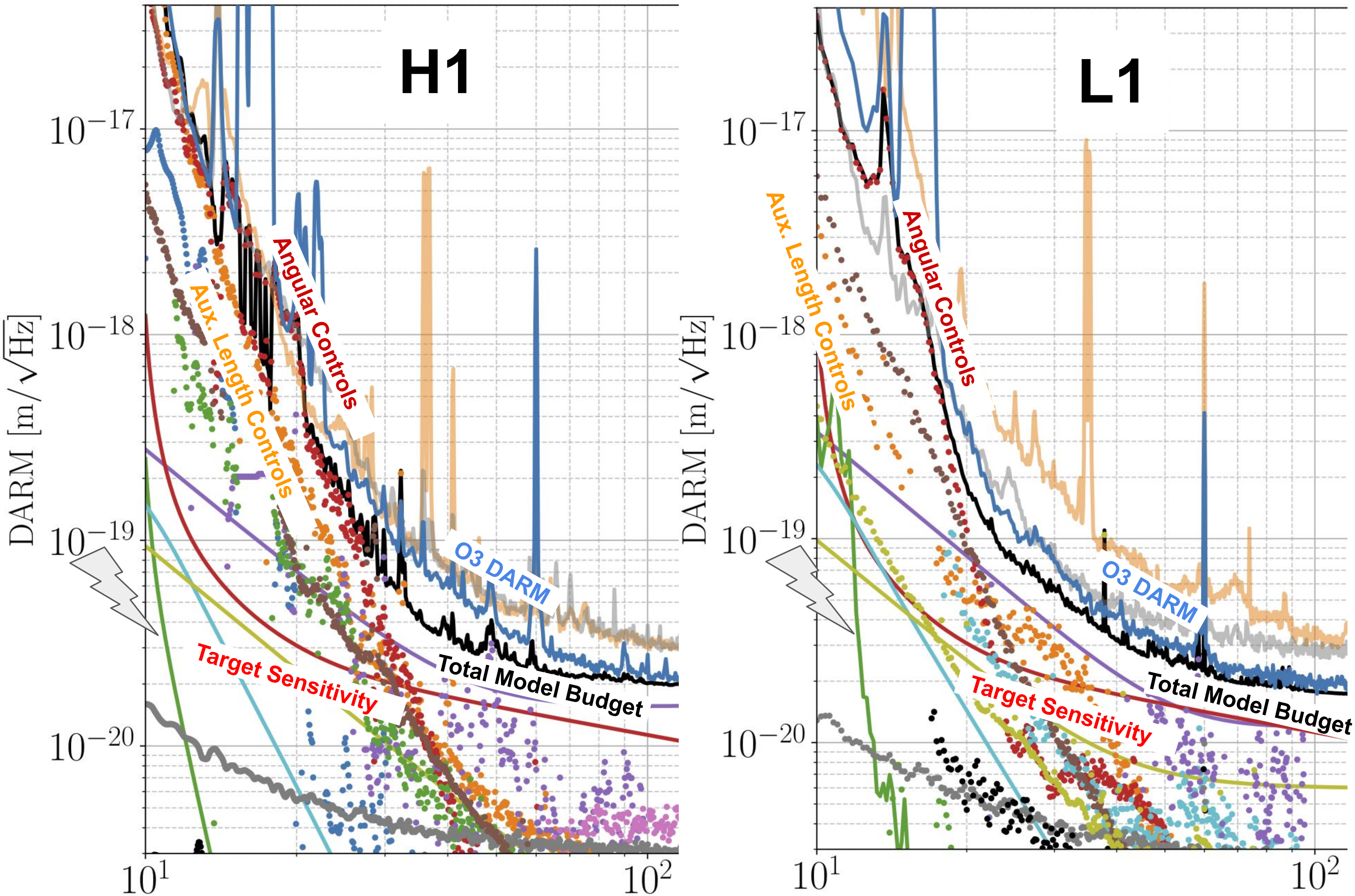
In this episode we're going to pick another component of the suspension where we can *co-design* the mechanics and the control system to improve the **controllability**.

Reminder: L->L, P->P Isolation of the SUS is good at 10 Hz & doesn't limit DARM

Horiz. motion for an LLO test mass during O3



From P2000122 Fig 2



DARM at 10 Hz is from control noise, ASC is an important contributor (but not the only one) and needs to be improved if we are going to reach the fundamental limits

Big Picture: Today's

Clearly control noise and controllability continues to be a challenge.

What do we do about the angular controls?

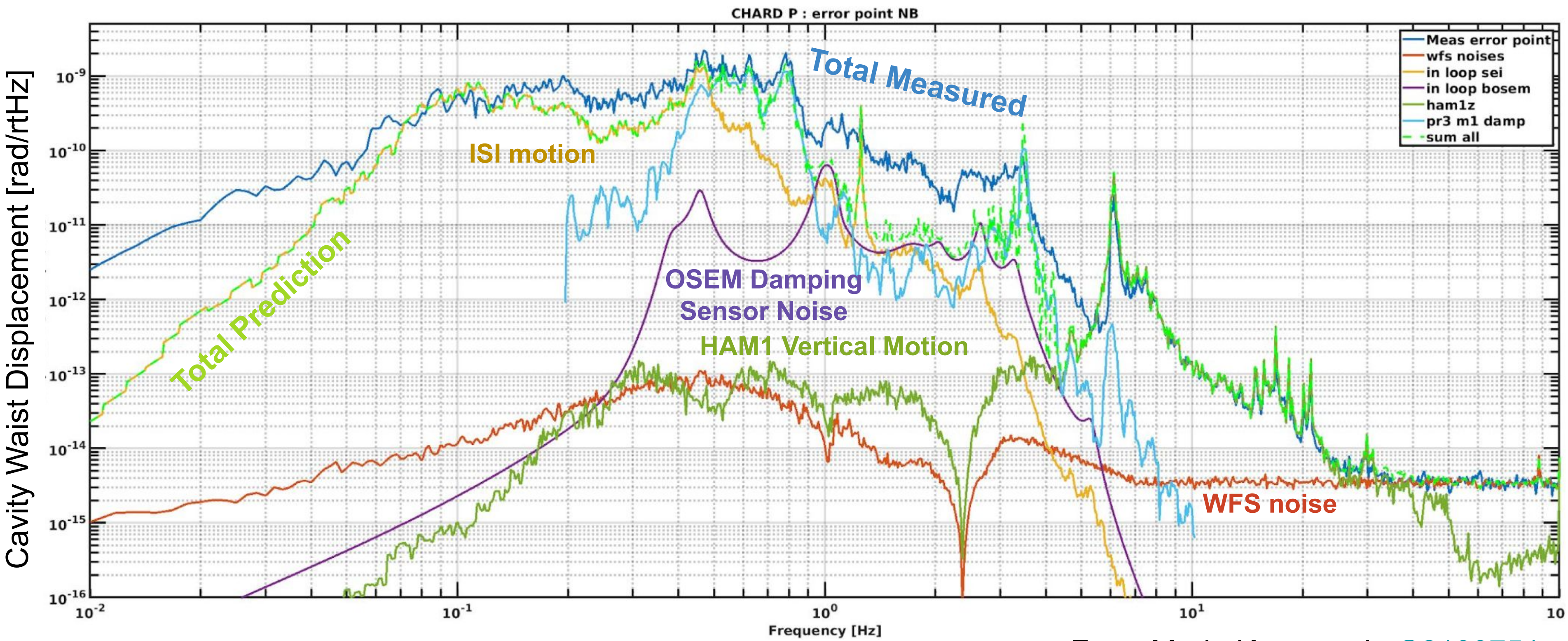
We present a couple of ideas that help accomplish the following:

- Reduce the angular drive/ excitation of the optic
- Reduce the bandwidth of the global angular control loops
  (because the WFS have noise)

What causes the pitch motion of the mirrors?

Angular noise budget (there’s a lot going on…)

Why do we need to do both?



From Marie Kasprzack, G2100751

Reduce the excitation

OSEM Damping Sensor Noise

ISI motion

Reduce the bandwidth

WFS noise

HAM1 Vertical Motion

There are many ways to **Pitch** an Optic...

Pitch motion of the optic comes from

1. Local damping OSEM sensor noise causes **Pitch**
2. Imbalance in OSEM actuation creates **Pitch**
3. ISI SUSPOINT Pitch transmits to **Pitch**
    a. Via mechanical transfer function
    b. Via local Damping (because the sensor/actuator is attached to the cage)
4. ISI SUSPOINT Longitudinal cross-couples to **Pitch**
5. LSC control (to any stage) mechanically creates **Pitch**
    a. (actuator plane is out of zero moment planes)
6. Pitch ASC sensors are noisy creating **Pitch**
    a. Global sensor (WFS/QPD) noise
    b. “Shenanigans” mechanical noise locally, underneath the angular sensor
7. Local longitudinal damping loops cross-couple to **Pitch**
8. DAC Noise through actuators cause **Pitch**

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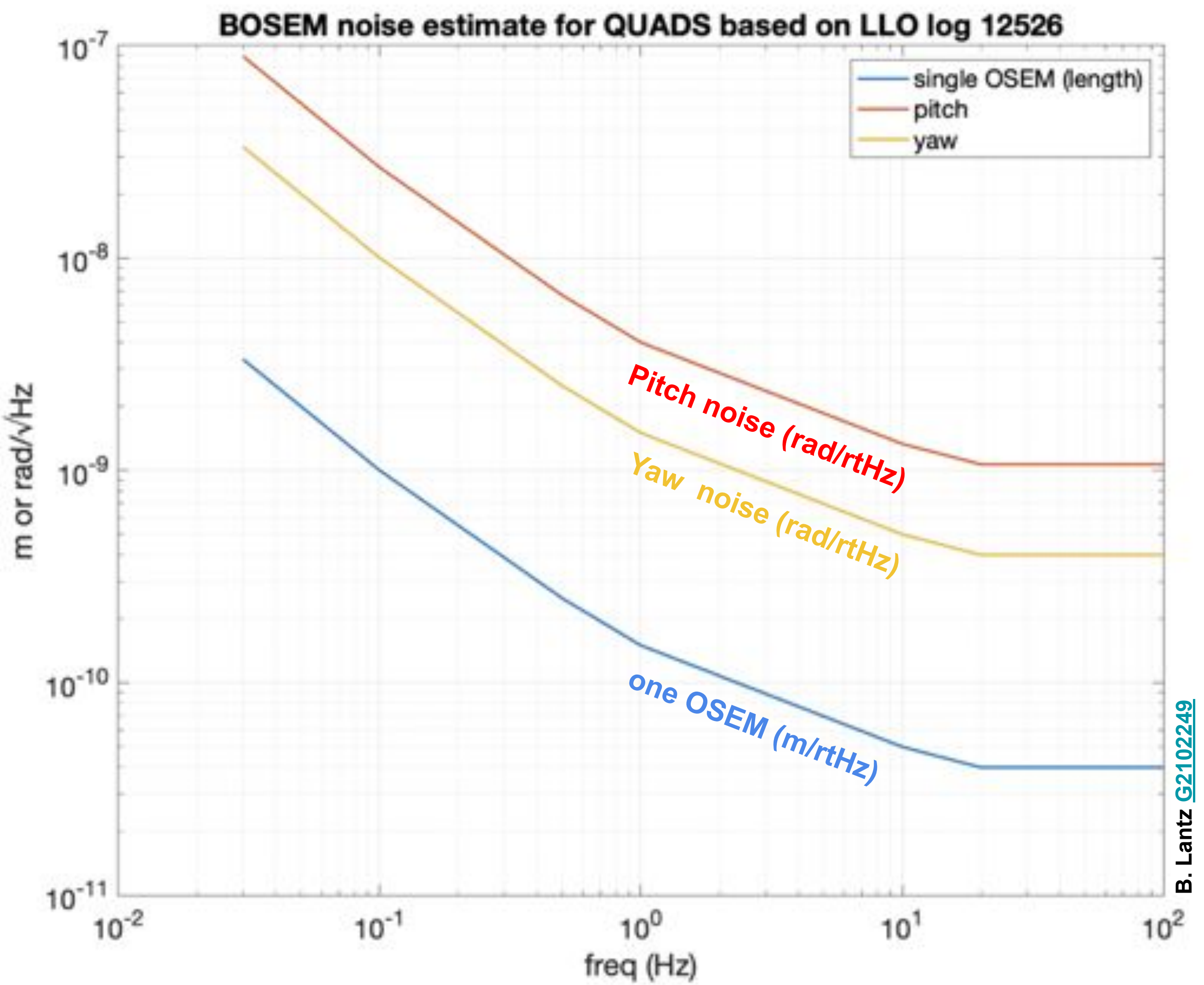
Today, in episode one, we’re going to talk about how to improve the first 5...

1. Let's improve the Pitch noise of the OSEMs by moving them farther apart



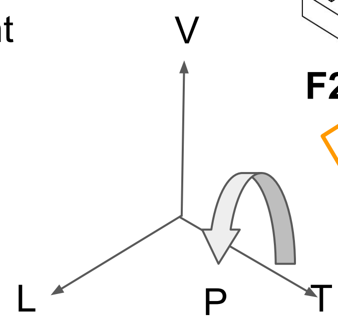
The Current QUAD Top Mass

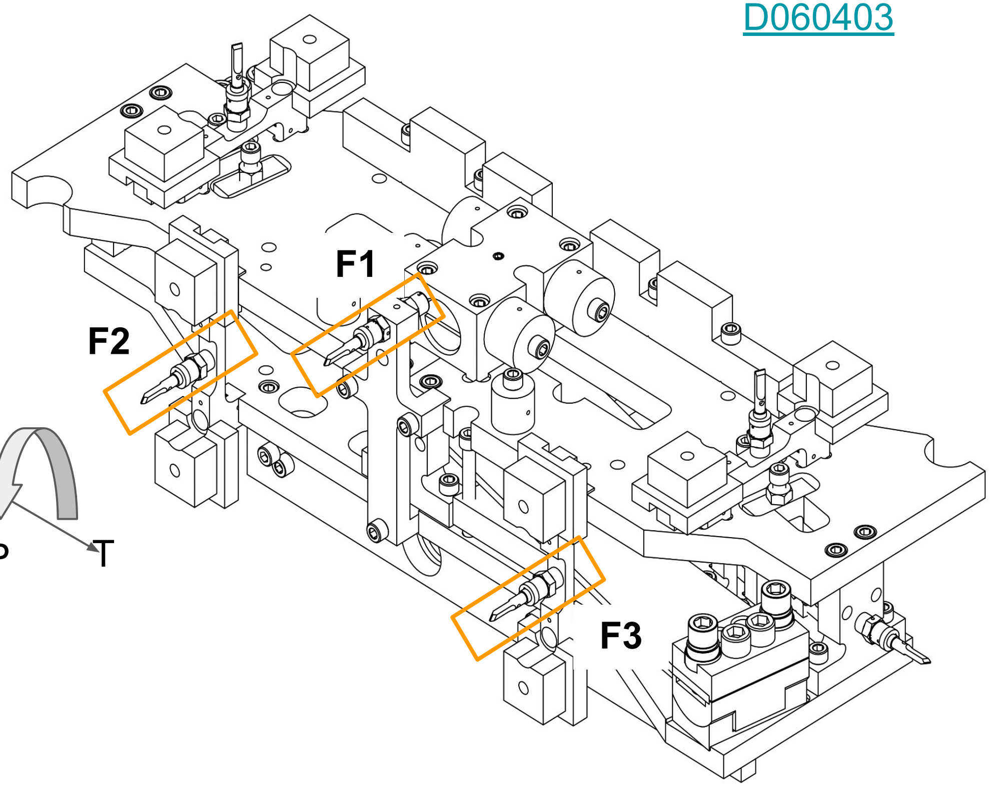
D060403

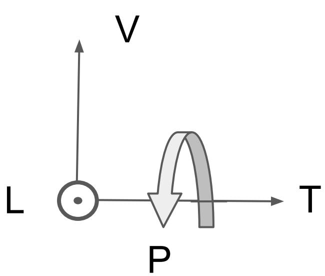
Longitudinal is a common measurement of (**F2** + **F3**)/2

Pitch is a differential measurement between (**F2** + **F3**)/2 and **F1**

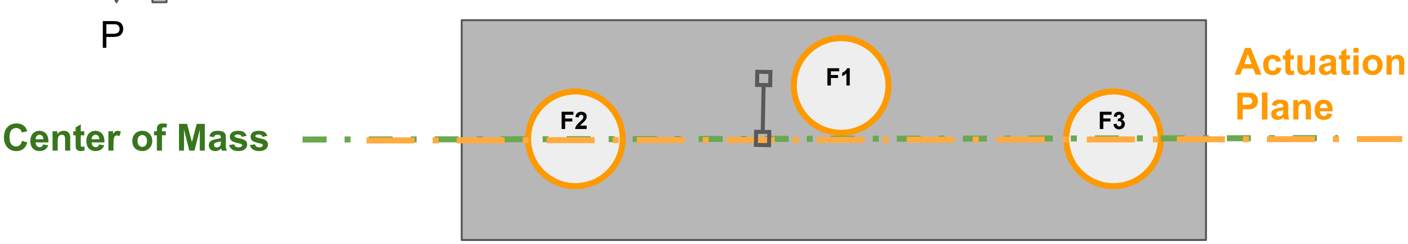
The lever arm is really short.







Pitch lever arm = 78 mm



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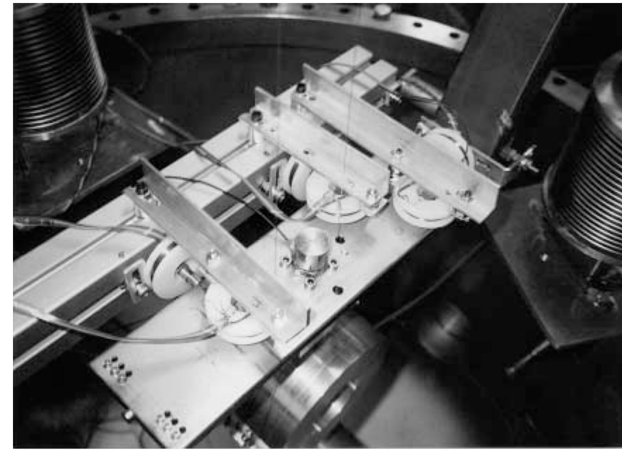
The story about the OSEMs' pitch lever arm.

Why is the lever arm small?

Calum's thesis: P000040



Calum's thesis says: "The channel gains should then all be within a few dB of each other."

Brian interprets this "this is ***the*** reason" the pitch lever arm is so small:
"decrease the lever arm of pitch, so the analog controllers can be the same for the various DOFs."

This design intent was informed by the fact that *it was an entirely analog control system.*

This doesn't matter at any more with our digital control system.

BUT. There is another merit to this design choice...

Because - for widely separated angle OSEMs -- that also drive longitudinal -- don't want DAC drive for long and pitch to be wildly different, or else "differential" drive is swamped by "common" drive, and makes you sensitive to coil imbalance.

Perhaps it's time to rethink the sensor-actuator arrangement.

Here’re some proposed OSEM arrangements and why.

Increase Controllability IDEA 1.

- **Make the mass physically large.**

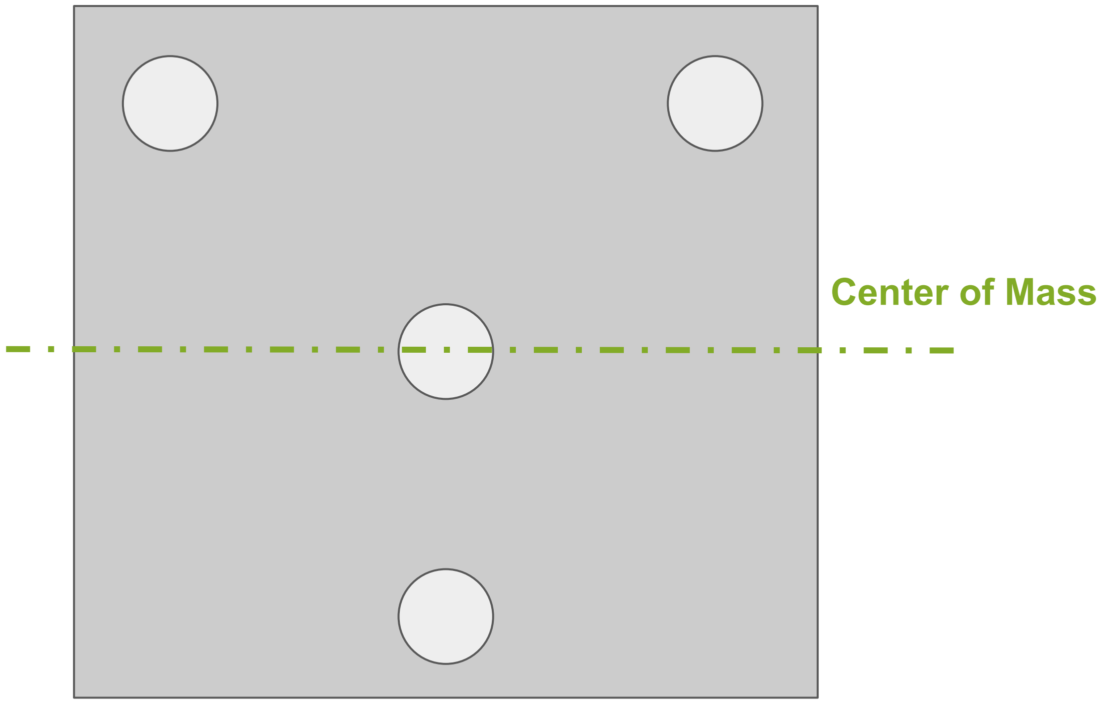
Problem there, is that it doesn’t fit. >> Another discussion for another day as to how to make it fit.

- **Spread out the angular sensing.**
- **Increase OSEM count by 1.**
- **Separate longitudinal and pitch actuation**

Now, 4 sensor/actuator pairs for 3 degrees of freedom.

If we do that, though, we balancing the electronics / actuation may still be a challenge.

Go to next slide!



One actuator in the middle that does the majority of longitudinal actuation.
Three pitch sensors with big lever arms.

Why not make it easy?

Increase Controllability IDEA 2.

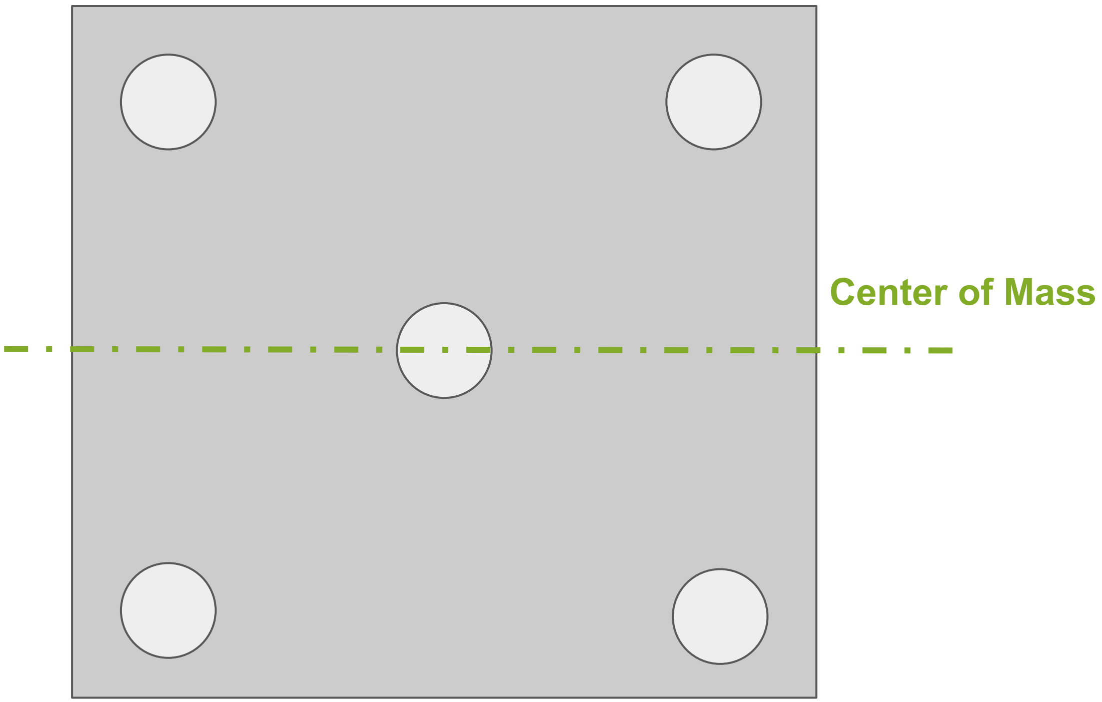
Remember: we're redesigning this thing for better controllability.

Why not make measuring the coil imbalance easy?

- **Increase OSEM count by another 1 (total 5)**

5 sensors for 3 DOFs, characterizing imbalance is much easier.

You also get slightly better noise performance too.



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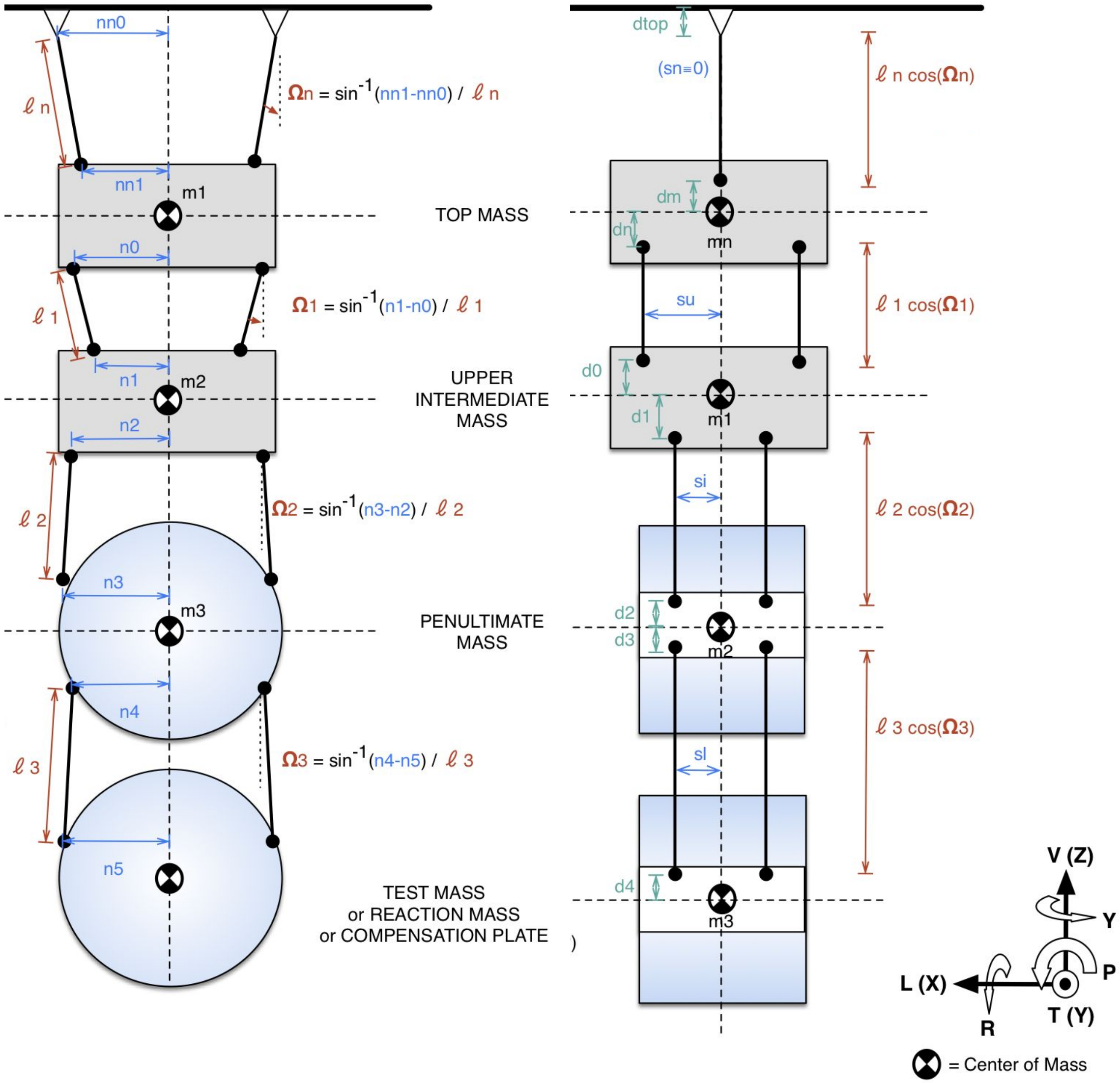
Quick look at the suspension



From T1400447, J. Kissel, M. Barton

Just ***two wires*** suspending the whole suspension

Two wires on the top mean that there is nominally no mechanical coupling to pitch about the “suspension point” (ie the top of the wires)

This relies on gravity and the dm, dn offsets to make the top mass stable (not tip over)

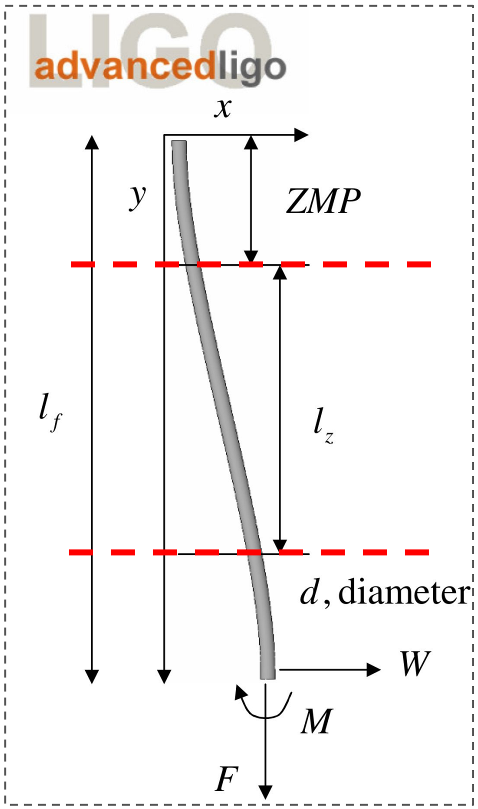
but...

Reduce the length/ pitch cross coupling

Separation of suspension point from center of mass means:

1) It generates lots of pitch motion for the optic

2) It makes the SUS control very complicated - typical loops have at least 8 modes instead of 4, so clever control work is much harder. Dan DeBra says “make my life as simple as possible”



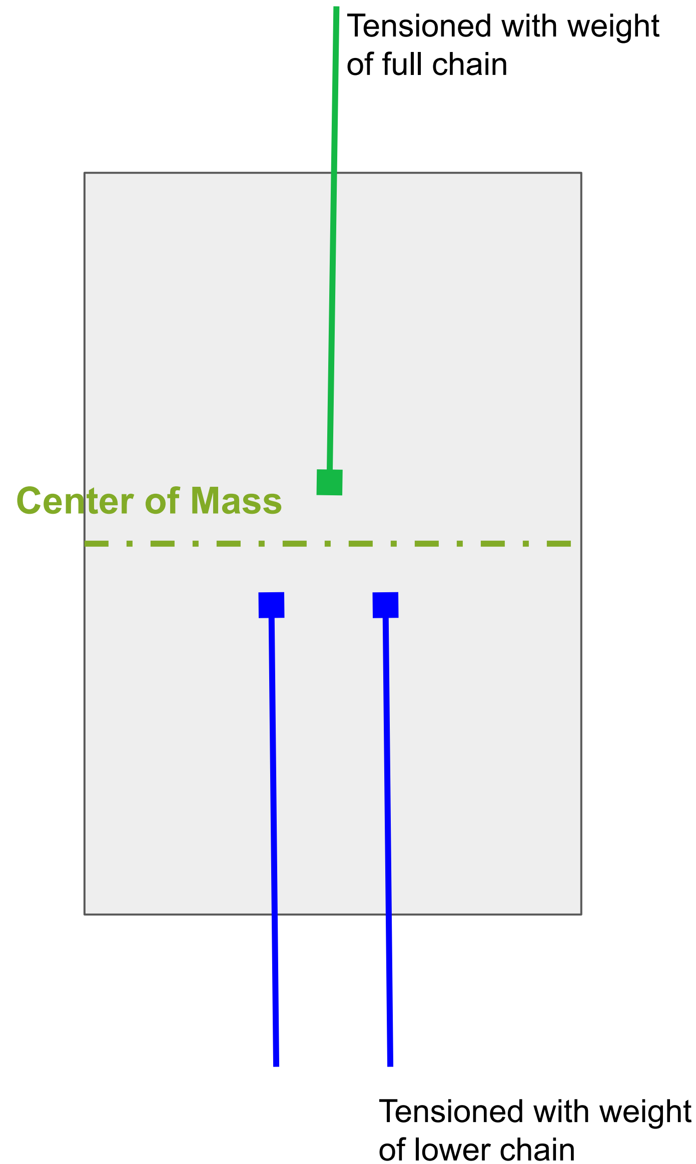
One way to do this:
Align the bending points (**d** parameters, **z**ero-**m**oment **p**oints) of the SUS wires with the actuators and the center-of-mass for each stage of the suspension.

Discussed in the SWG call in March 2021, SWG log 11833.

But - 2 wires are not stable - you need 4.
(Mark Barton and Edgard Bonilla have built a “12 wire” quad model we can play with)

Quick illustration

Quick view of how LSC drive and ISI motion generate torques on the mass by angling the wires



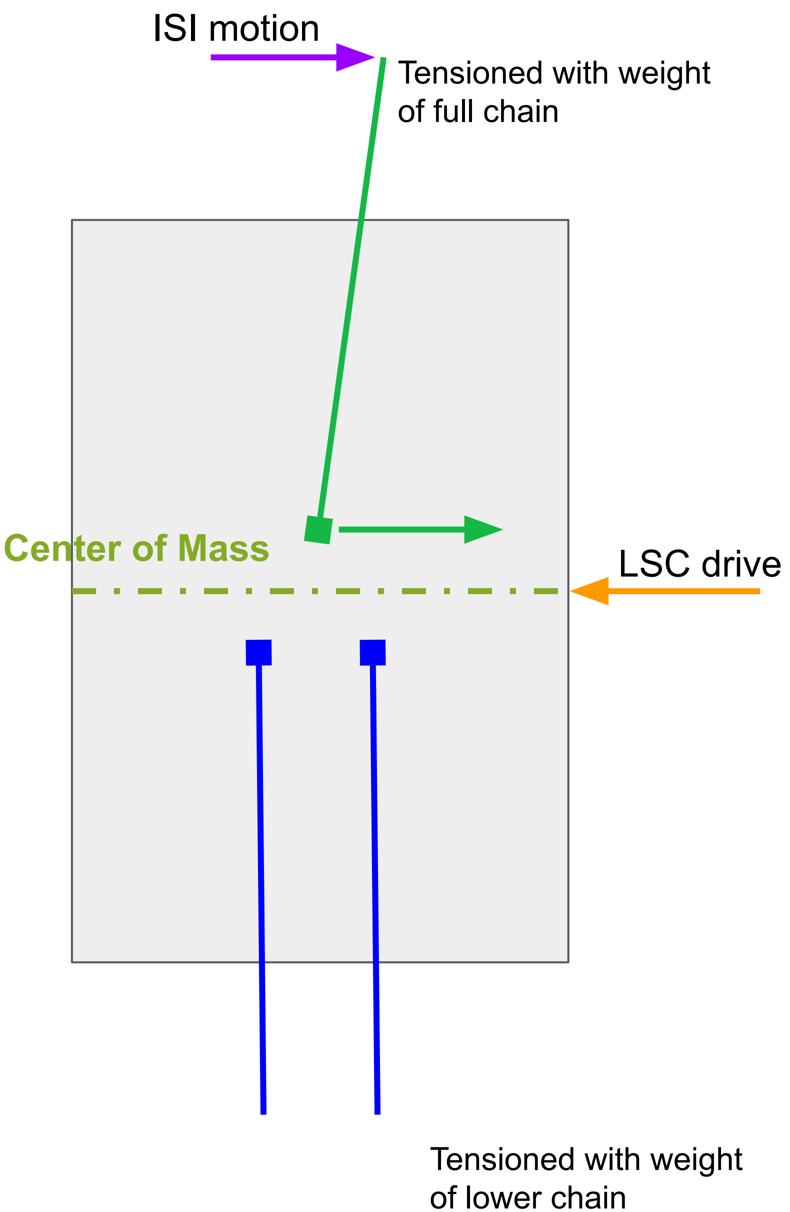
Quick illustration

Quick view of how LSC drive and ISI motion generate torques on the mass by angling the wires

The longitudinal force from the wire is not aligned with the cg or the LSC drive, so this makes a torque on the top mass

If the **ZMP**s of the wires are offset from the Center of mass,
displacement of the mass -> torque, and
rotation of the mass -> lateral forces

This couples Length & Pitch



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Quick view of how LSC drive and ISI motion generate torques on the mass by angling the wires

The longitudinal force from the wire is not aligned with the center of mass or the LSC drive, so this makes a torque on the top mass

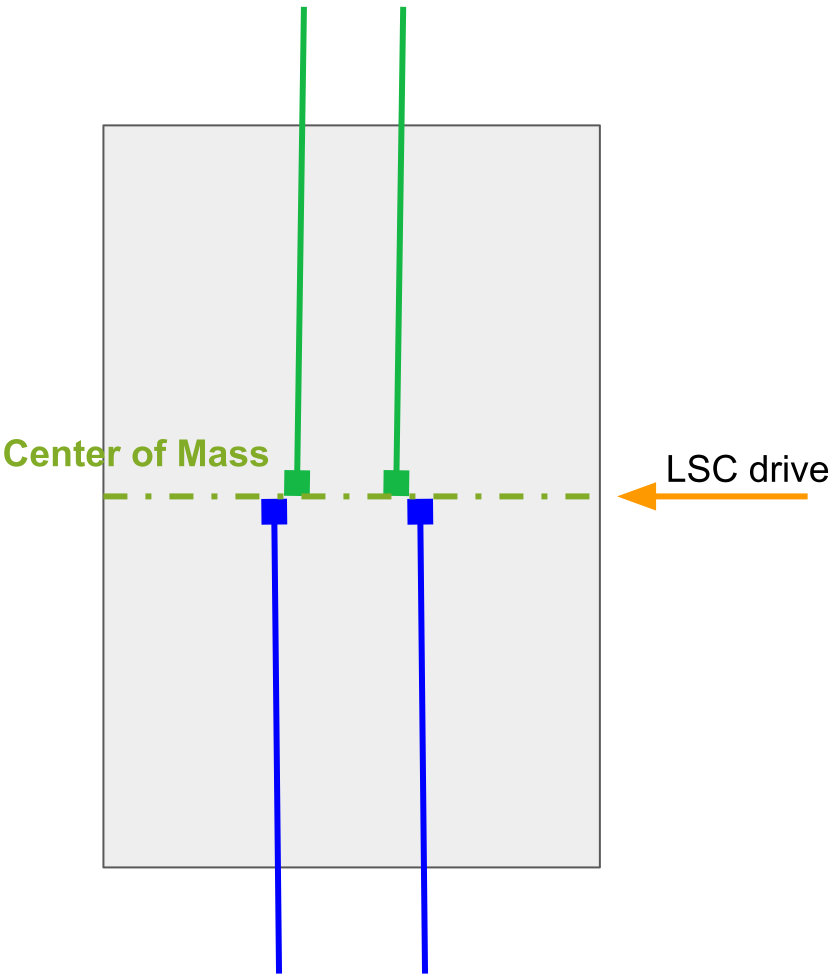
If the ZMPs of the wires are offset from the cg, displacement of the mass -> torque, and rotation of the mass -> lateral forces

This couples Length & Pitch

Solution - align the **ZMP**s, actuation plane, and center of gravity as well as possible.

Mechanically decouples longitudinal and pitch!

New graduate student, Regina Lee is working on this with Kevin K. and Brian L.



Episode Summary

Right now, in 10-20 Hz region, IFO control noise is up to 100x ‘fundamental’ noises, and far above seismic (or thermal) noise.

But we’ve learned some things for aLIGO and we think improvements are possible with updated suspension designs

Rethinking the OSEM sensor/ actuator placements

> improve sensing and **separate longitudinal and Pitch** control and

Aligning the ZMP to the Center of Mass

> **minimize mechanical Length to Pitch** cross-coupling

Coming up this season on
Designing the Post-O5 Suspensions:

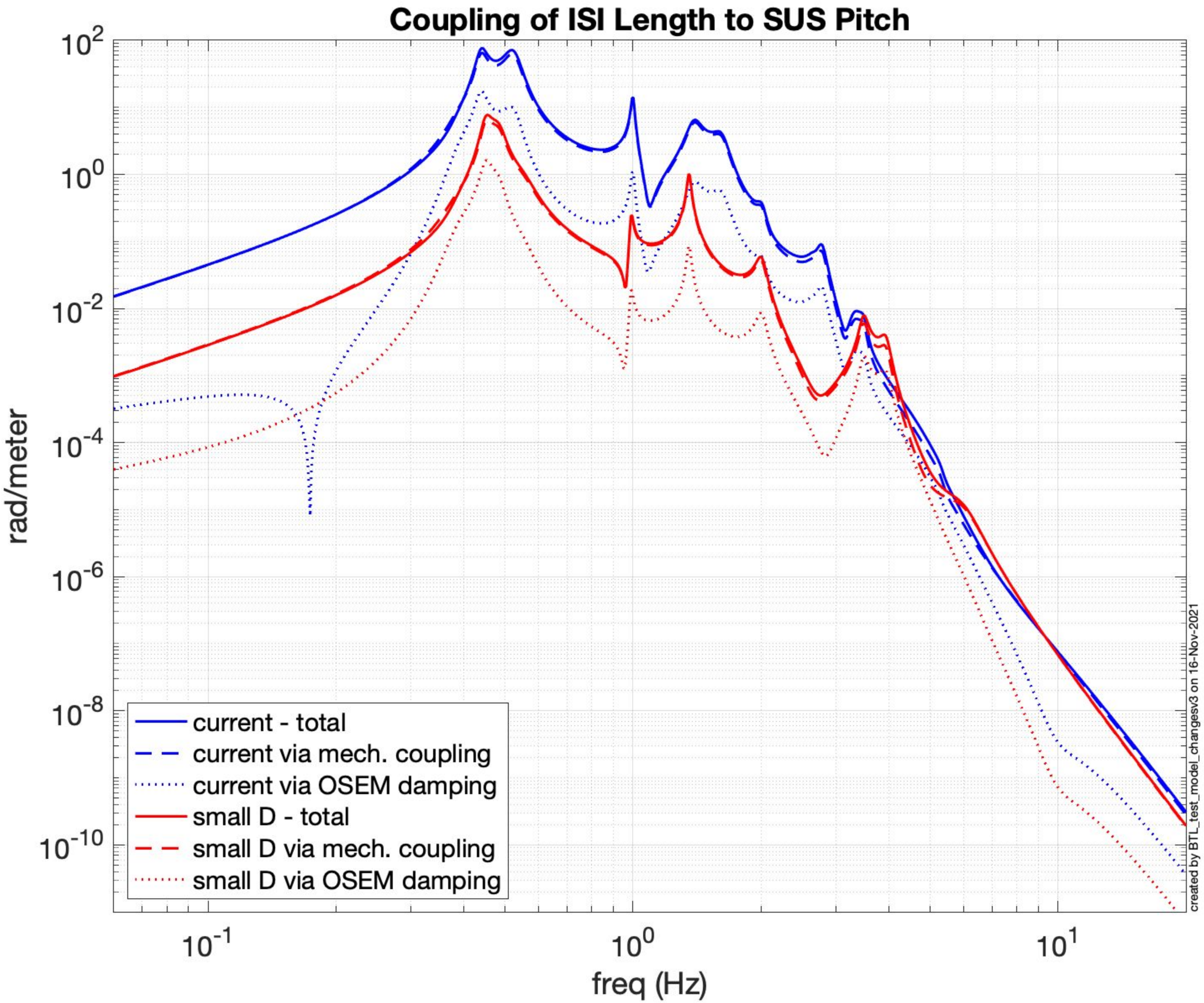
100 kg test mass, higher stress fibers, heavier intermediate masses with bigger moments of inertia, longer suspensions, HoQIs, damping at the UIM, make the reaction chain a triple, fused silica springs for the test mass, optical lever from the ISI to the test mass, ...

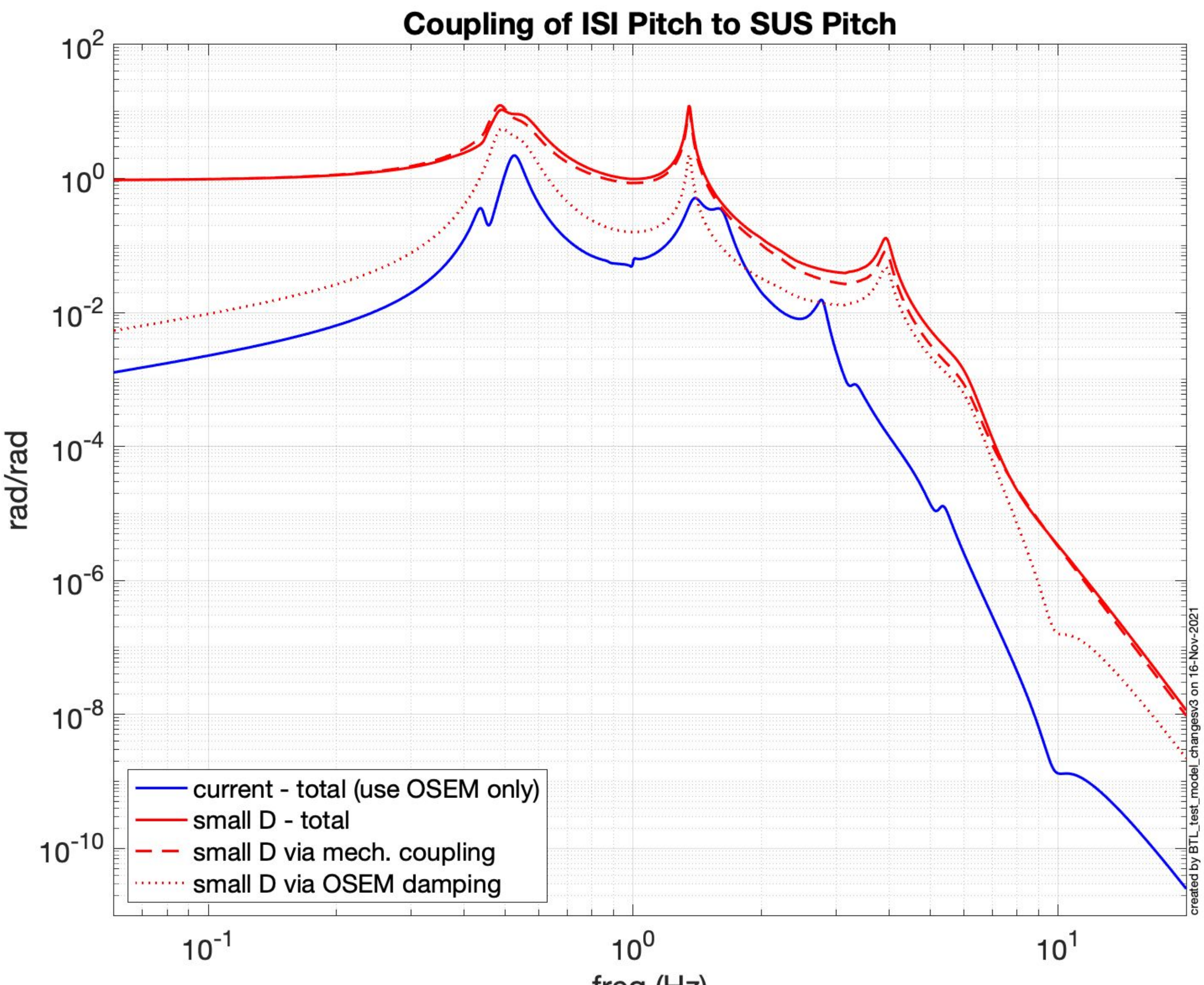
In the next Episode...

What happens as we make the ‘d’ offsets (ZMP) small?

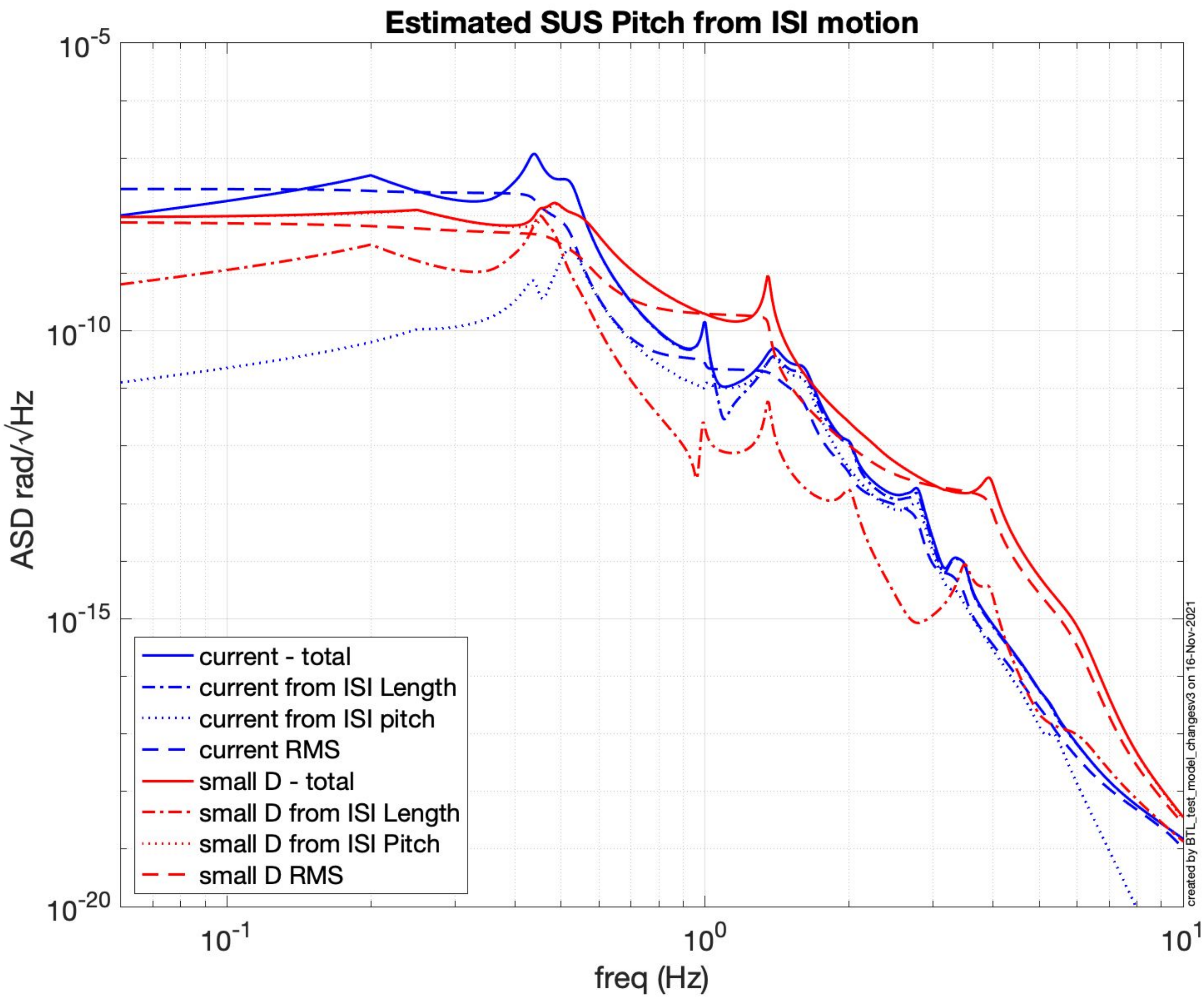
Start with the SUS model, and then Mark Barton and Edgard Bonilla made a special “12 spring” version.

By increasing to four wires, and decreasing ds





Coupling of ISI Pitch to SUS Pitch
rad/rad
freq (Hz)
current - total (use OSEM only)
small D - total
small D via mech. coupling
small D via OSEM damping
created by BTL_test_model_changesv3 on 16-Nov-2021



Estimated SUS Pitch from ISI motion
10^{-5}
10^{-10}
10^{-15}
10^{-20}
ASD rad/√Hz
10^{-1}
10^{0}
10^{1}
freq (Hz)
current - total
current from ISI Length
current from ISI pitch
current RMS
small D - total
small D from ISI Length
small D from ISI Pitch
small D RMS
created by BTL_test_model_changesv3 on 16-Nov-2021

Coming up this season on Design Ideas for the Post O5 Suspensions...

Design Ideas Solutions

- Have to make 2 wires in to 4 wires at the top mass.
- New arrangement of OSEMs at the top mass.
- Consider a bit more actuator / sensors than you “fundamentally need” for coil balancing (i.e. more than just n Sensor/Actuators for n DOFs)
- Align center of mass with ZMP and actuation plane
- Increase the ratio between moment of inertia and mass
- Play around with relationship between optic mass and the rest of the stages.
- Consider only a triple SUS for reaction mass (allowing for main chain top mass to be larger / high moment of inertia, if wires supporting reaction chain pass through the top mass)