Motion spec for Comp. plate

Brian Lantz, Peter Fritschel, G2302228

- DARM is 6e-20 m/√Hz at 10 Hz
- use factor of 10 for safety, so contribution of CP <= 6e-21
- IFO noise for short Michelson is 285 times less sensitive than DARM, so
- CP length contribution should be < 6e-21 * 285 = 1.7e-18 m/√Hz
  (this should compare to the beamsplitter req.)
- CP is transparent, (*compare triple SUS to double with clear optic*)
  wedge of 1.2 mrad couples transverse motion to MICH length
- coupling is (1.45 - 1) * 1.2e-3 = 5.4e-4 m/m. Call it **1e-3 m/m** (PF)
- so transverse motion req is
  1.7e-15 m/√Hz = 1.7e-18 m/√Hz / 1e-3 m/m (includes margin of 18)
- (note - best ISI is about 2e-13 m/√Hz at 10 Hz)

Other DOFs

- We might set the vertical "target" to match,
  - is this just a requirement just for the sake of having a target?
  - cross coupling is always an issue
- beam-direction motion? probably a velocity to limit scattering?
- For now, set all 3 translations to 1.7e-15 m/√Hz,
  transverse is a requirement, call vertical and longitudinal "targets"
- What about the coupling of pitch and yaw to lateral motion?
- sensitivity to Roll seems really small,
  wedge * beam offset? birefringence? motion of dirt?

Risks:

- What about the wires for the ESD, PUM drive, and witness sensors?
- This all assumes a cold plate - what about when you heat it?

Reaction Chain

Brian Lantz, Nov 2023, G2300686-v4

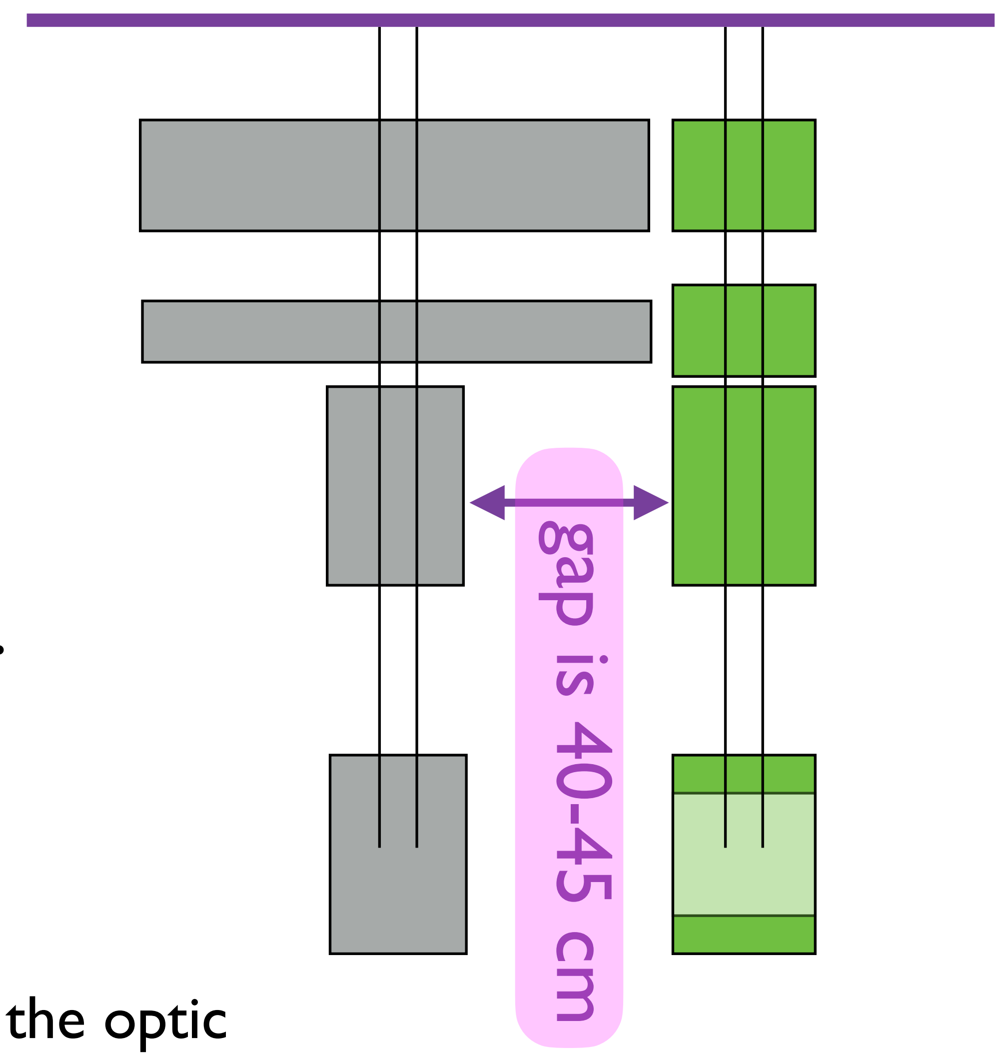
Update on the reaction chain - need to decide soon, and need to think carefully before deciding.

Because - If the TOP and UIM are wide,

then the aLIGO reaction chain doesn't work.

- What are the requirements for an updated reaction chain?
- Can we use a double?

These are roughly drawn from Stanford's A# calculations.
100 kg mirror is 27 cm thick.
TOP & UIM drawn 100 cm wide.
Vertical spacing is 34, 34, 34, 60 cm.



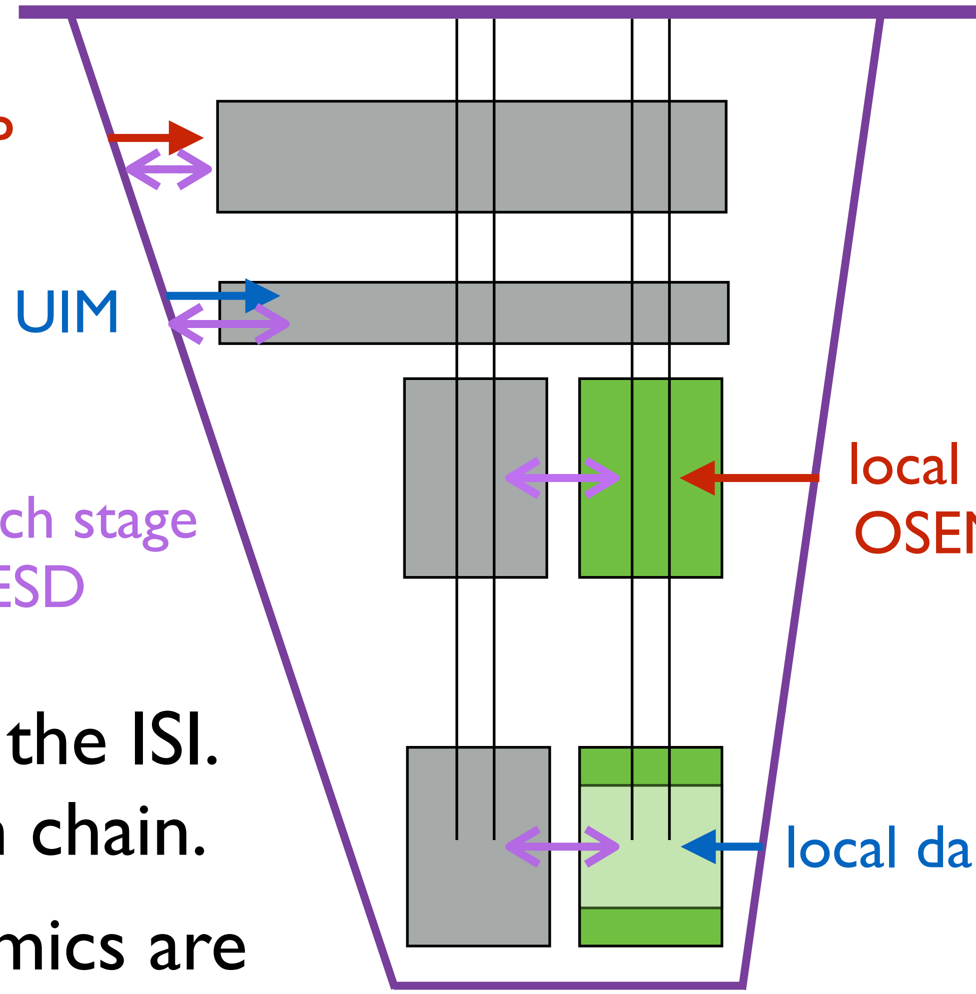
(100 cm - 27cm)/2 + 5 cm top gap = 41.5 cm at the optic

Requirements?

What are the requirements for the reaction chain for the Quad?

1. Quiet place for ISC actuators to push against
   See this doc for length calc's. Evan did calc for UIM, 2e-11 is OK
2. Angle is TBD.
3. Dynamics OK for ISC reaction (see 3.3 Hz issues)
4. Isolates the ISI from ISC kicks (see Beamsplitter)
5. Low relative velocity to manage scattered light (see R0 tracking)
6. Less than 200 kg and fits into space
   - less mass is better, see Calum
   - see the back sides of all the aLIGO Quad masses are in-plane
7. Suspends compensation plate with Transverse & Z < 1.7e-15 m/√Hz
8. Holds wires for ESD & PUM actuator (OSEM)
9. **Q: What else?**

2 stage Reaction Chain



Top 2 stages of the Quad react against the ISI. PUM and optic react again the reaction chain.

Advantages: RC is more compact. Dynamics are much simpler. Allows R0 tracking. High freq. drives don't act on ISI.

Disadvantages: motion of reaction points is larger than now at UIM, PUM, & optic.
UIM reaction pushes ISI.
Compensation plate isolation worse.

Both stages of RC need z isolation

what else?

How about a double?

1. Quiet place: Calc's for BOSEMs on triple indicate ISC noise OK even for HAM isolation and no reaction chain
2. Dynamics: dynamics of damped double are much simpler than quad damped only from the top.
3. Kicks to ISI at UIM during lock acquisition: need to check, but should be fine if high freq. drives sent to bottom 2 stages of quad.
4. Tracking for scatter: should be fine, R0 tracking for double should be simpler than a quad because dynamics are simpler.
5. Size and Weight: Fits.
   Modeled with 40 and 80 kg mass (easily fits 200 kg budget).
   Wires routed through the TOP & UIM (requires 4 holes).
6. Compensation plate meets requirement if both stages have springs.
7. **Q: What else?**

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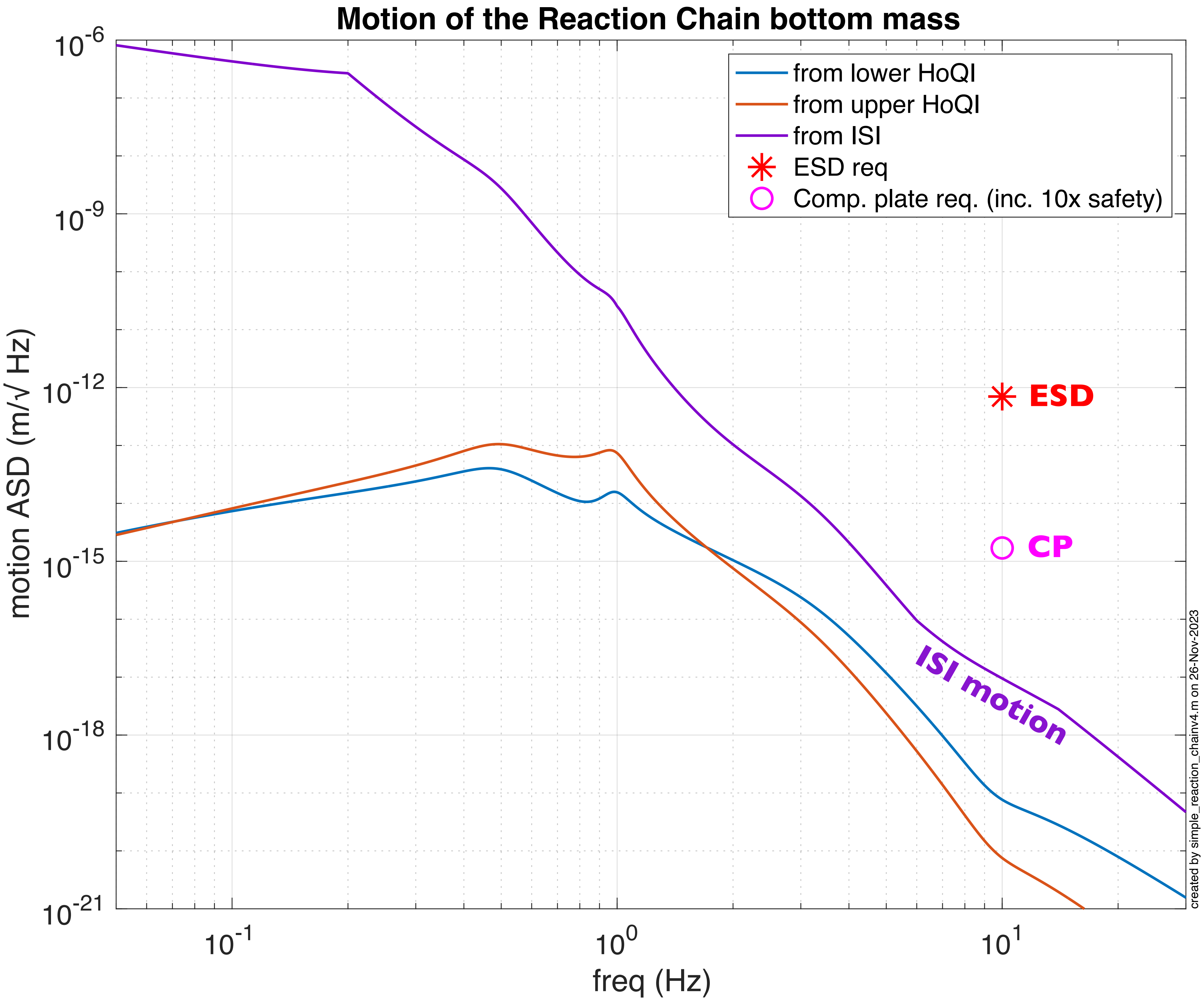
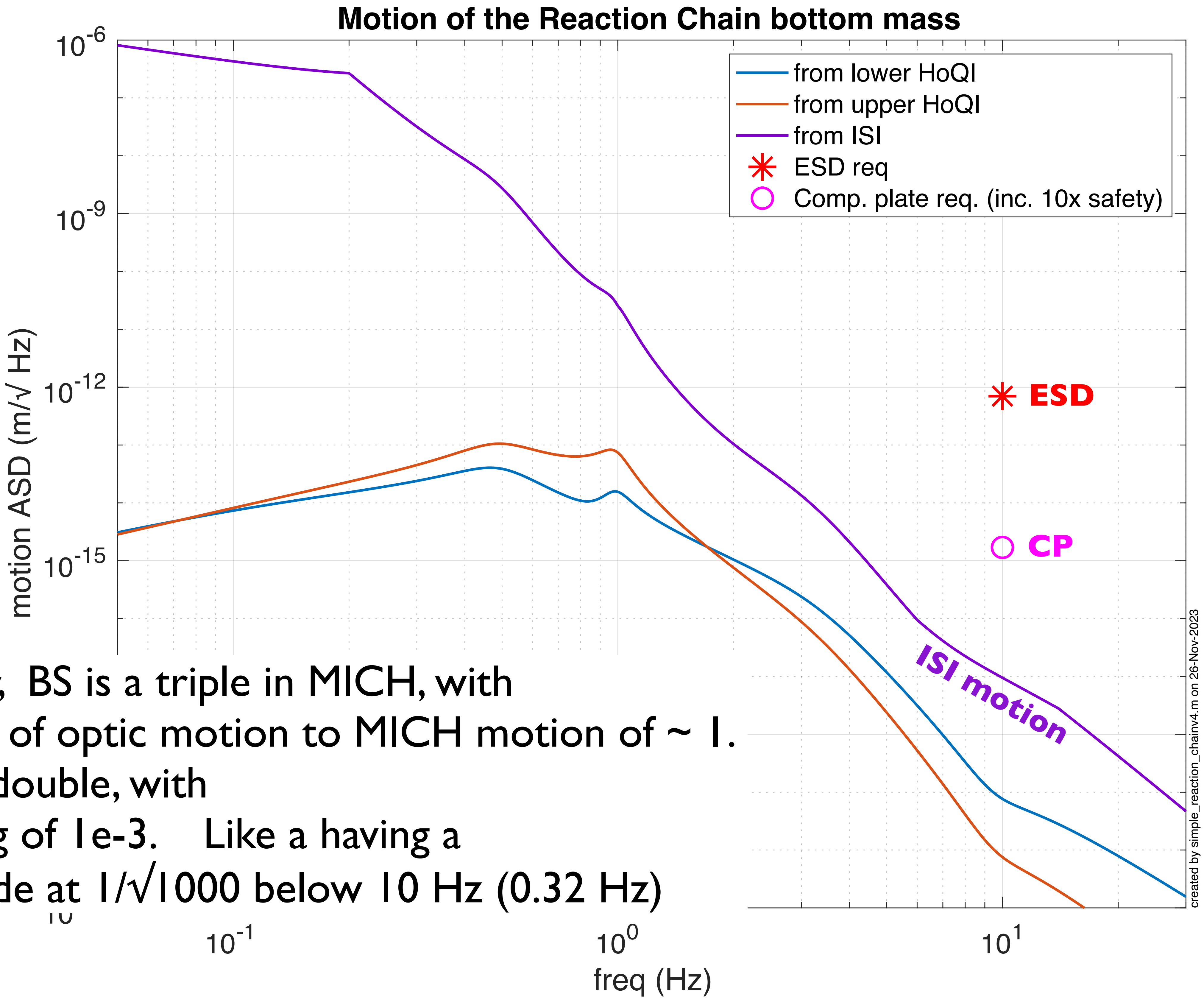
7. **Q: What else?**

updated performance plot



updated performance plot

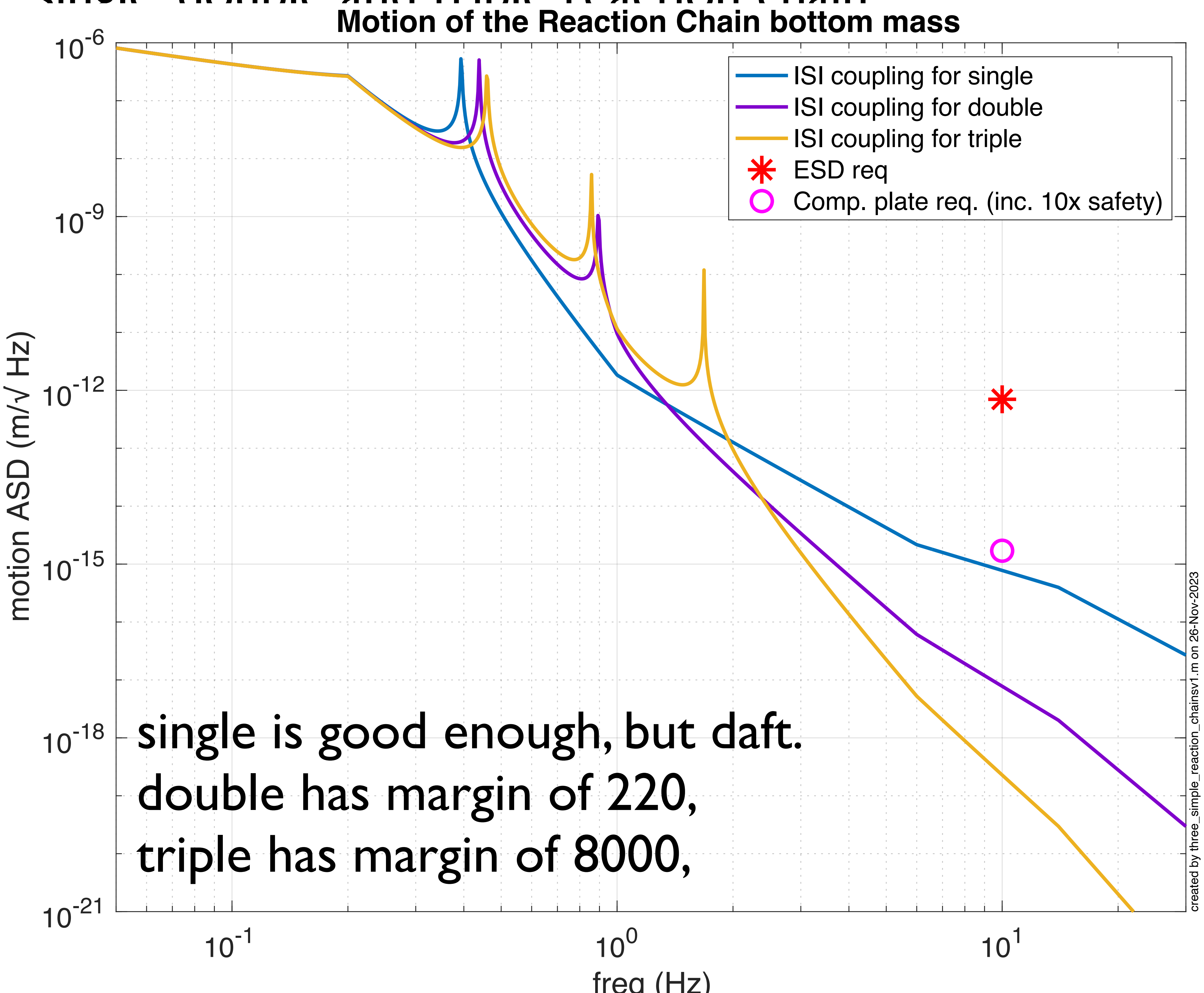


consider, BS is a triple in MICH, with
coupling of optic motion to MICH motion of ~ 1.
RC is a double, with
Coupling of 1e-3. Like a having a
SUS mode at 1/√1000 below 10 Hz (0.32 Hz)

just for fun

consider the performance of a

single, double and triple reaction chain



single is good enough, but daft.
double has margin of 220,
triple has margin of 8000,

triple is
M = 80, 60, 40 kg
L = 68, 32, 60 cm

1, 2, 3, 4

Single - no margin, daft
Quad - Too much. Similar performance to main chain, but we're 285 *1000 times less sensitive to the motion of the CP.

Double

- Good fit, good weight
- Meets all motion req's w/ large margin (220 and 10x SF)
- Direct sensing on UIM enables more info about where the stages are, and makes things like modal damping more more plausible
- With sensors and actuators at bottom mass you get very well damped performance (see 3.3 Hz mode)
- Need vertical springs on both stages
- No reaction mass for UIM driver. Lock acq. pushes on ISI. This calc is complicated and necessary. BTL expects it will be OK.
- Maybe drive local reaction masses?

Triple

- Heavier, fit is complicated (see JD's talk in a few minutes)
- Likely compromises performance of the main chain - probably going to compromise the UIM design (interfering springs, size to achieve large moments on RC hard, structure of the Main chain UIM gets cut up, or lower masses are sausage shaped)
- Meets all motion req's w/ very large margin (8000 and 10x SF)
- Maybe sense vs. ISI and drive vs. reaction masses?
- 3 stages have more modes to control
- Need vertical springs on 2 stages
- No UIM drive on the ISI

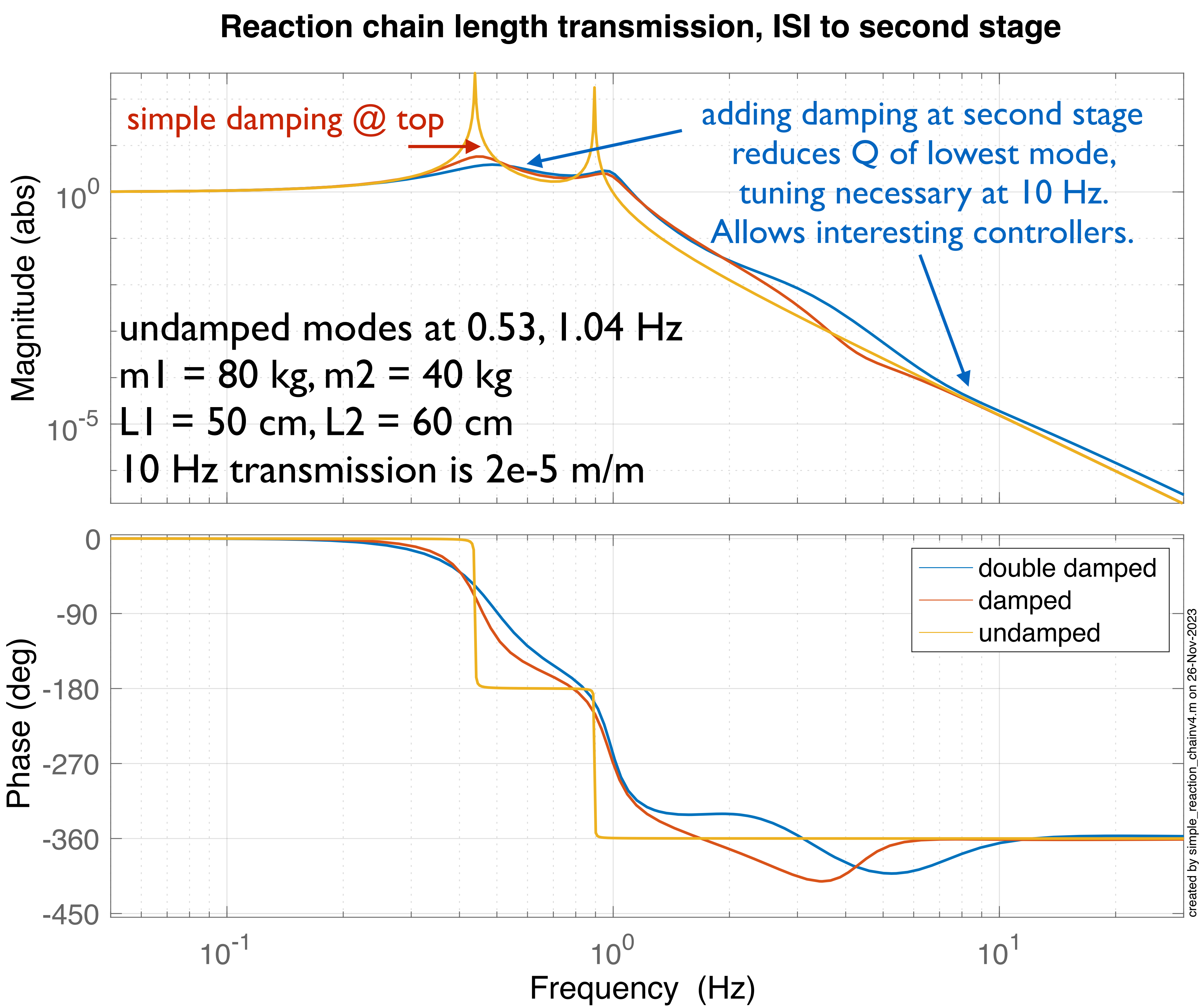
Moving forward…

- I think the double is the right way to move forward
- The extra performance margin of the triple is not worth the "cost" of interfering with the main chain

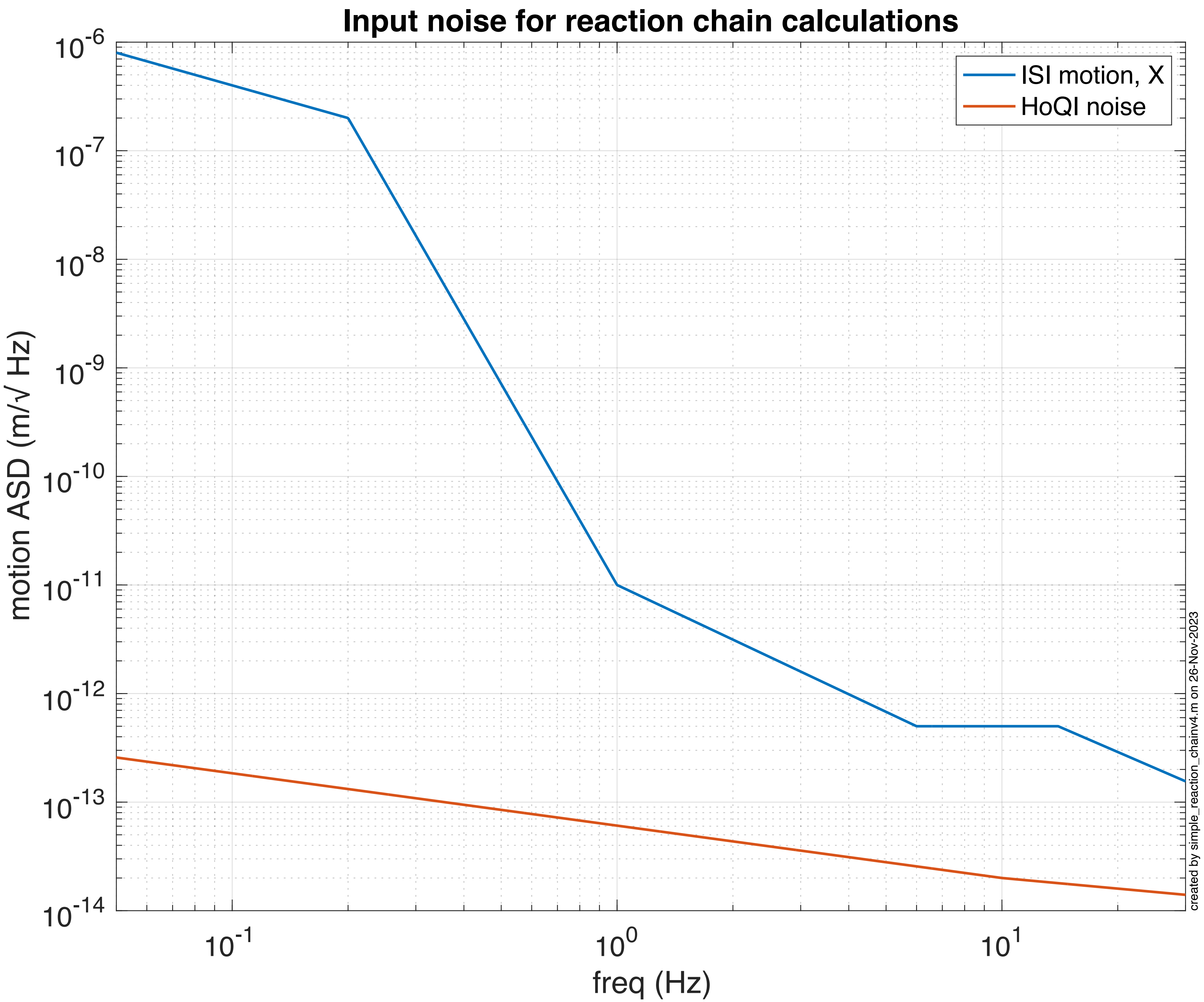
Next steps

- The ISI reaction to locking needs to be done, check that no UIM reaction mass is OK
- Are there other calculations/ measurements we should do before we pick 2 vs. 3?
- Start getting "workshop parameters" for masses, springs, angular modes, etc.

updated transmission



input noise



Input noise for reaction chain calculations
ISI motion, X
HoQI noise
motion ASD (m/√ Hz)
freq (Hz)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-1}
10^{0}
10^{1}
created by simple_reaction_chainv4.m on 26-Nov-2023

The rest of these slides are unchanged from the first workshop

Coupling via ESD spring

TL;DR - scaling from aLIGO @ 400 V, ESD requires reaction mass motion < 7e-13 m/rtHz

From aLIGO:
Effective spring rate of the ESD is proportional to the slope
da/dx = -2.38 * 9.54*10^{-16} * $x^{-3.38}$ N/(m*V^2)
at 5 mm, 400 V, (LLO only uses 100 V now)
k = dF/dx = -0.022 N/m (400 V) or -0.0014 N/m (100 V).

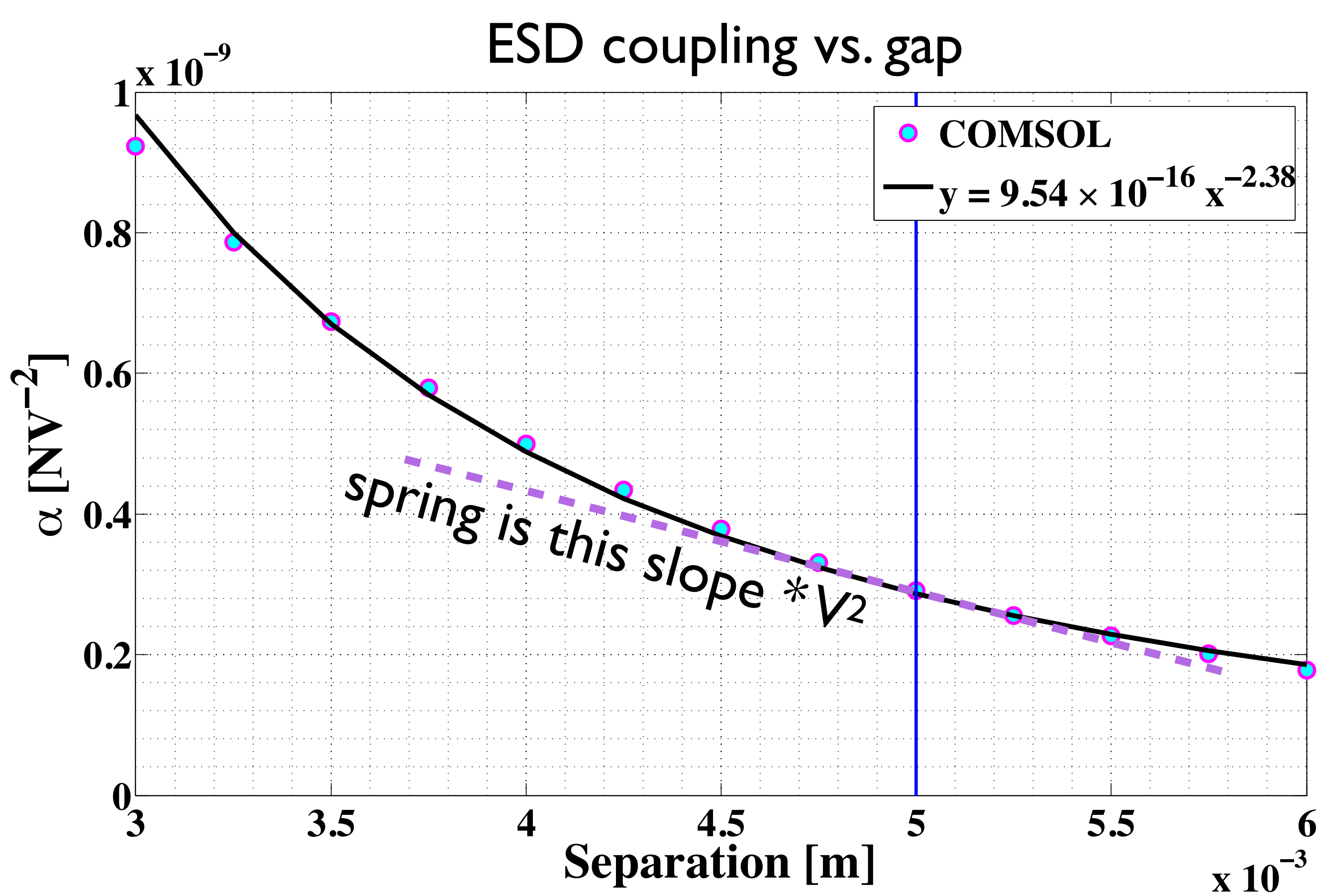


Figure 5.17: The ESD coupling coefficient α as a function of separation between the reaction mass and the test mass. Vertical line shows nominal separation corresponding to 2.9×10^{-10} NV^{-2}. Least squares fitting reveals that dependence is stronger than quadratic.

pg 233, John Miller's thesis P1000032

Scale to A# by guessing similar geometry and gap,
Use 2.5 more authority for the 100 kg mass.
Gives a conservative estimate of
k = 0.055 N/m for A# ESD (likely 10x smaller)

$m*w^2 * X_{TM} = k * X_{RC}$
at 10 Hz, 100 kg, k of 0.055, we get
X_{RC} = 7e-13 m/rtHz
(ISI is about 1e-12 m/rtHz at 10 Hz)

Coupling calc

T2300112, based on pg 233 of P1000032

What is the spring rate for the Advanced LIGO ESD, and what might we expect for A#?

For aLIGO From John Miller's thesis P1000032, pg 233, we get

$$\alpha = 9.54 * 10^{-16} * x^{-2.38} N/V^2 \tag{1}$$

so the slope is

$$\frac{d\alpha}{dx} = -2.38 * 9.54 * 10^{-16} * x^{-3.38} N/(m * V^2) \tag{2}$$

at $x = 5 * 10^{-3}$ meters, this becomes

$$\frac{d\alpha}{dx} = -1.36 * 10^{-7} N/(m * V^2) \tag{3}$$

The Advanced LIGO bias can go as high as 400 V, although for O4 it is expected to be 100 V at LLO, and LHO is also considering working at 100 V bias. We make the conservative choice of 400 V for this calculation. This results in a spring rate, k_{aLIGO}, of

$$k_{\text{aLIGO}} = \frac{dF}{dx} = -1.36 * 10^{-7} * V^2 \text{ N/m} = -0.0218 \text{ N/m at 400 V for aLIGO} \tag{4}$$

At 100 V bias, this drops to $k = -1.36 * 10^{-3}$ N/m.

No real work has been done on the ESD for A#, so we assume the same basic electrode geometry, bias, and 5 mm gap. Because the mass is 2.5 times larger, we scale the electrode size up by 2.5, and estimate the spring rate $k_{\text{A\#}}$ for A# ESD to be

$$k_{\text{A\#}} = -0.0544 \text{ N/m at 400 V for A\#} \tag{5}$$

Now, we can estimate the allowed motion of the reaction mass at 10 Hz. When the reaction mass moves, this spring produces a force on the optic.

$$m * \omega^2 * x_{optic} = k * x_{RM} \tag{6}$$

If we set the motion requirement of the optic to be less than 10^{-19} m/rtHz at 10 Hz, then the allowed motion of the reaction mass is

$$100kg * (2\pi * 10)^2 * 10^{-19}\text{m/rtHz}/(-0.0545 \text{ N/m}) > x_{RM} \tag{7}$$

$$x_{RM} < 7.26 * 10^{-13}\text{m/rtHz at 10 Hz} \tag{8}$$

Triples - no reaction chain

In 2002, Phil Willems showed the triples don't need a reaction chain (T020059)
Updated in 2008 by J. Kissel, N. Roberston, M. Barton, P. Willems
Coupling via ISC drive at least 100x below coupling via SUS transmission

Now - ISC drives react directly against the SUS cage (and ISI)
Q: Do HAM triples have any issues with no reaction chain?

Triples includes the Beamsplitter.
Beamsplitter **does** have an issue - there are no drives for the bottom stage (the beamsplitter optic) so high frequency lock acquisition is driven from the middle mass. (no reaction chain, no direct drive. HF drives are very large)
The back reaction from this drive creates so much disturbance on the ISI that the loops saturate. Thus, ISIs engage full isolation after MICH is locked.
Beamsplitter Drive issue would be resolved with OSEMs at bottom stage (True/ False?)

Quad reaction chain isolates the ISI from lower stage ISC drives.

BOSEM estimate

T020059-V3

In T020059-v1, the noise coupling from the third stage's OSEMs (mounted to the cage) to the bottom mass, $F_B^{O\to B}(f)$, is modeled to be **at worst**

$$F_B^{O\to B}(f) \;=\; F_{max}^{O_B} \times \frac{(dF/dx)}{F} \times x_p(f) \qquad (2)$$

with $F_{max}^{O_B} = N_{O_B} I_{O_B}^{req} A_{O_B}$, the maximum possible force exerted by the bottom OSEMs in $[N]$ (N_{O_B} is the number of OSEMs acting on the optic, $I_{O_B}^{req}$ is the dynamic range requirements of the coil drivers in $[A]$, and A_{O_B} is the actuation strength of the coils on the magnets in $[N/A]$ all for the bottom OSEMs), $(dF/dx)/F$ is the gradient of the applied force with displacement in $[1/m]$, and $x_p(f)$ is motion of the platform to which the suspension is mounted (assumed to be the same motion as the cage, and therefore the OSEMs) in $[m/\sqrt{Hz}]$. As with the requirements, this force is converted to displacement assuming a simple equation of motion,

T020059-V1

with distance. A Mathematica model of the LIGO OSEM supplied by Mark Barton shows that, so long as the magnet is positioned within 1mm of the 'sweet spot' of the coil, then the gradient of the force with displacement in any direction is about (dF/dx)/F=.1/mm, or 100/m.

T020059-V3, for HLTS (pg 9)

Magnet Type, Size	$mm \times mm$	$T: NdFeB, 1.905 \times 3.175$ $M: NdFeB, 1.905 \times 3.175$ $B: NdFeB, 1.905 \times 3.175$	$T: NdFeB, 10 \times 10$ $M: SmCo, 1.905 \times 3.175$ $B: SmCo, 2 \times 0.5$	M0900034, Tbl. 1
$F_{max}^{O} = N_O\ I_O^{req}\ A_O$	N	$T: --$ $M: 80$ $B: --$	$T: 1.156 \times 10^{-1}$ $M: 1.896 \times 10^{-4}$ $B: 1.686 \times 10^{-6}$	Calculated
$(dF/dx)/F = C_O^{F\to x}/A_O$	$1/m$	100	$T: 90.97$ $M: 101.9$ $B: 102.5$	Calculated
f	Hz	1.0	2.899	T080310

AOSEM coupling for Quad

pg 3 of T1100595

Suspension Stage	OSEM Type	Magnet Type	Magnet Size diameter x thickness	Coil Magnet Actuation Strength	Coil Magnet Actuation Strength
Units	[ ]	[ ]	[mm]	[N/A]	[N/mA]
Main and Reaction Chain Top (TOP)	BOSEM	NdFeB	10 x 10	1.694	0.001694
Upper-Intermediate Mass (UIM)	BOSEM	SmCo	10 x 10	1.694	0.001694
PenUltimate Mass (PUM)	AOSEM	SmCo	2 x 6	0.0309	0.0000309

Coil Driver	DC Transconducance	DC Max Current Output	DC Current Range	DC Current Range Requirement	Frequency Range
Units	[mA/V]	[mA_p]	[mA_pp]	[(mA_pp) or (mA_rms)]	[Hz]
TOP (D0902747-v4)	9.943	99.43	198.86	200 (pp)	continuous
UIM (D070481-v4)	0.1535	1.535	3.07	2 (rms)	< 1
MODUIM (T1400223-v1)	0.6154	6.154	12.308	2 (rms)	< 1
PUM (D070483-v5)	0.2685	2.685	5.37	16 (rms)	200 - 5000

F_{max} = 3.09e-5 N/mA * 2.685 mA-pk max * 4 actuators = 3.3e-4 N_{max}

k = F_{max} * (df/dx)/F_{max}= 3.3e-4 N_{max} * 100 1/m = 3.3e-2 N/m for aLIGO

k = 8.3e-2 N/m for A# (2.5x larger)

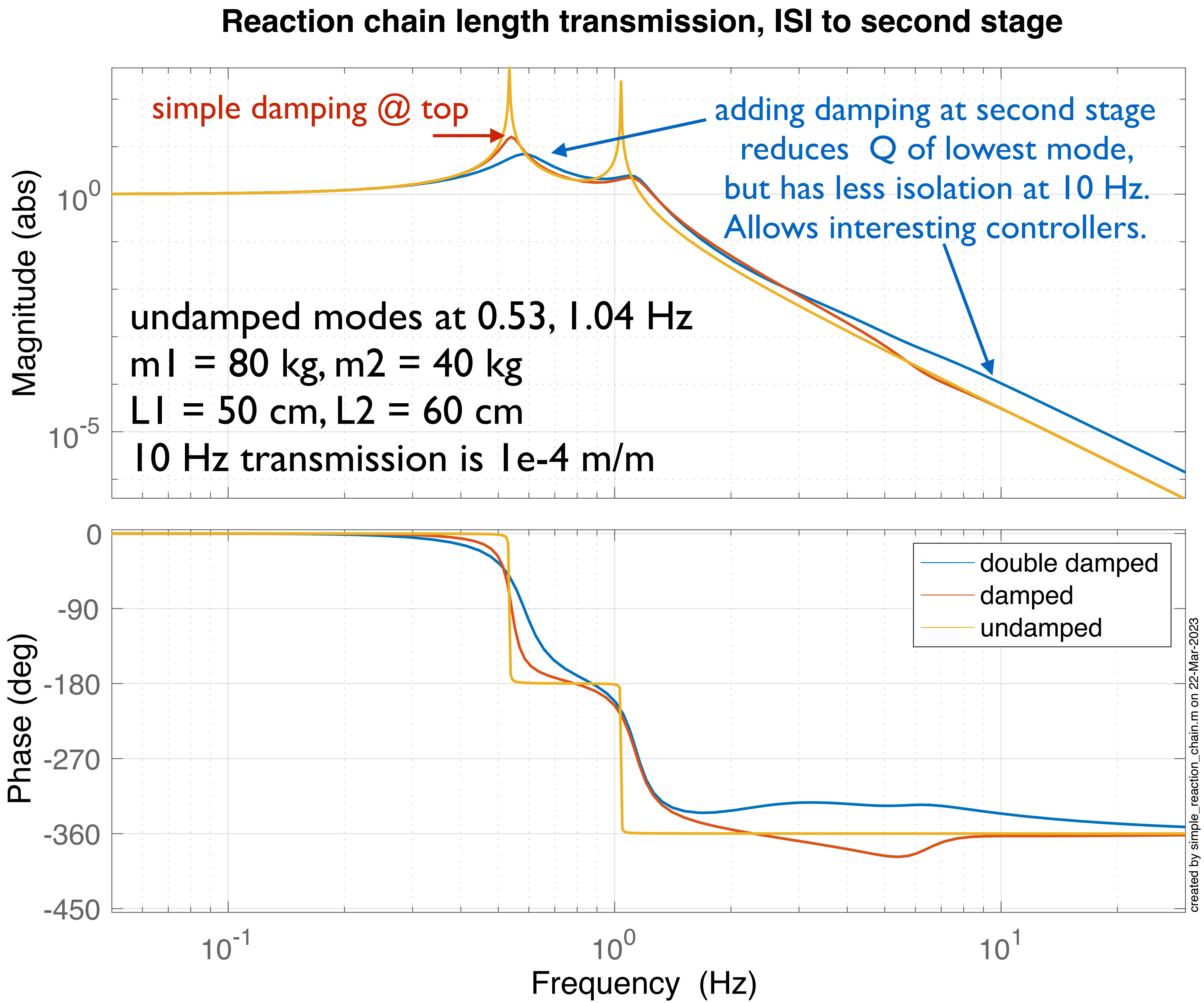
X_{optic} = $TF_{PUM2optic}$ (m/N) * k (N/m) * $X_{PUMreaction}$

X_{optic} = 1e-8 m/N * 8.3e-2 N/m * $X_{PUMreaction}$ @10 Hz (from Edgard)

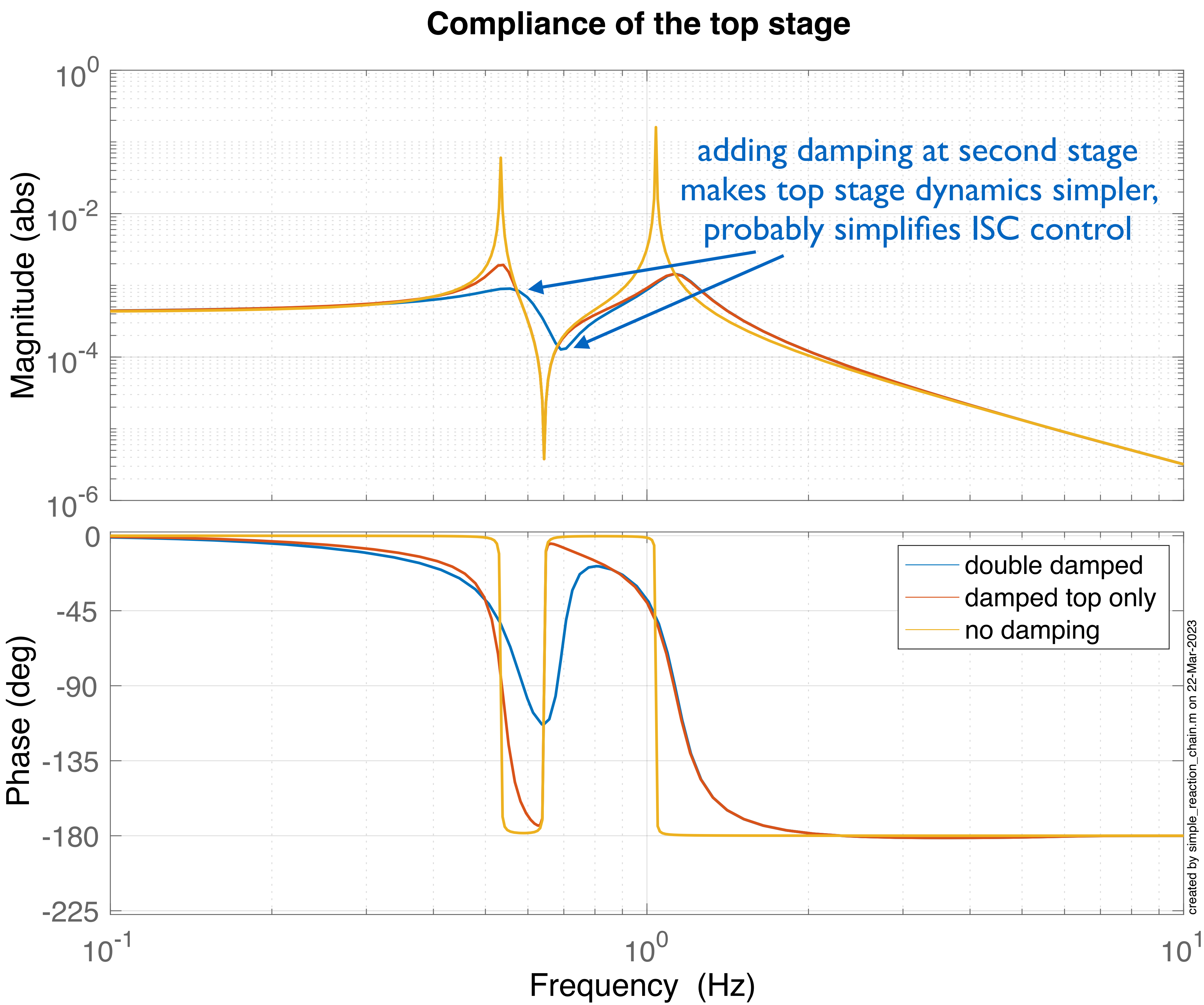
X_{optic} = 8.3e-10 * $X_{PUMreaction}$ for aLIGO

$X_{PUMreaction}$ < 7.5e-11 m/rtHz at 10 Hz, for optic motion to be < 6e-20 m/rtHz

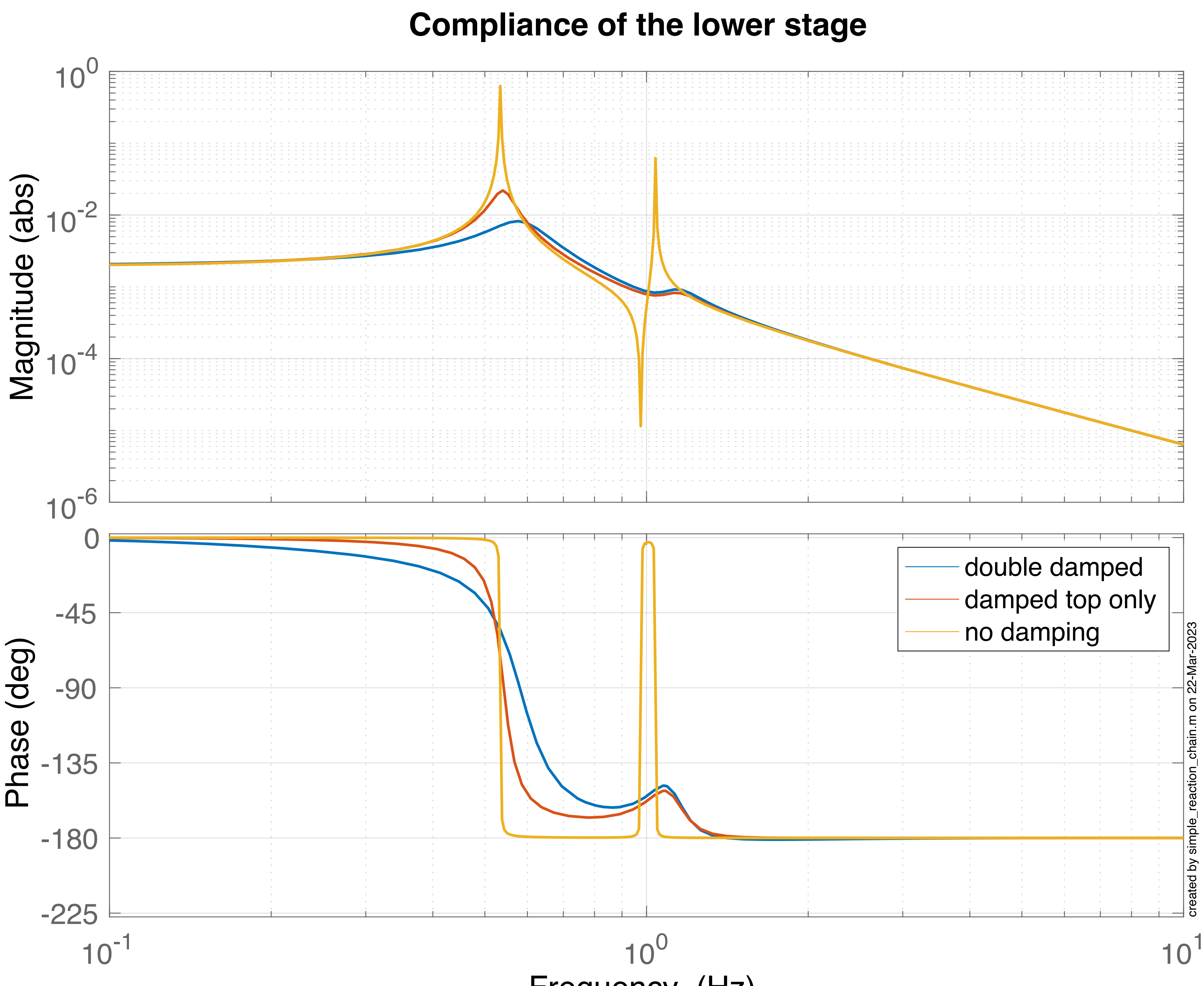
Double RC transmission



Dynamics of top stage

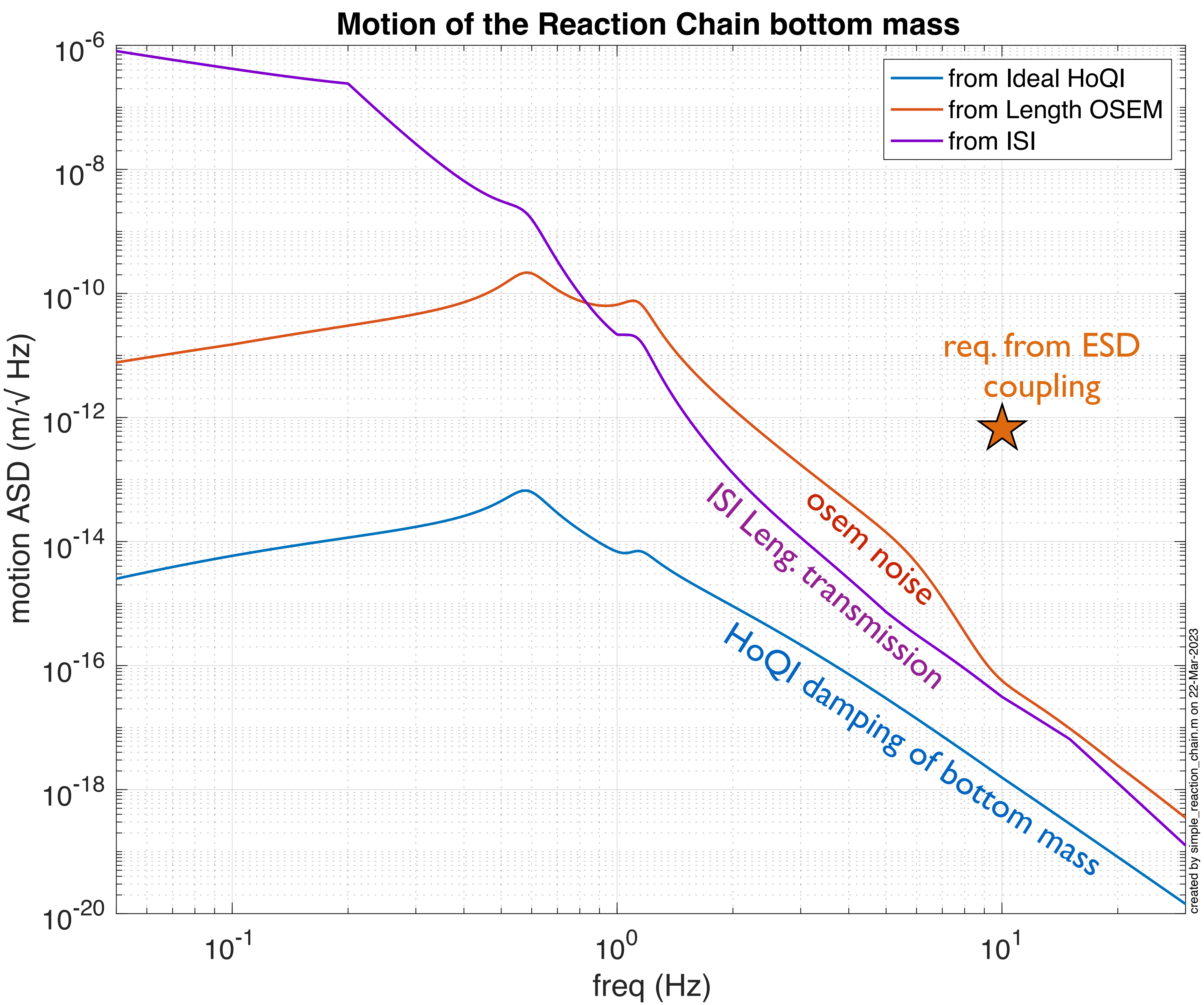


control on lower mass



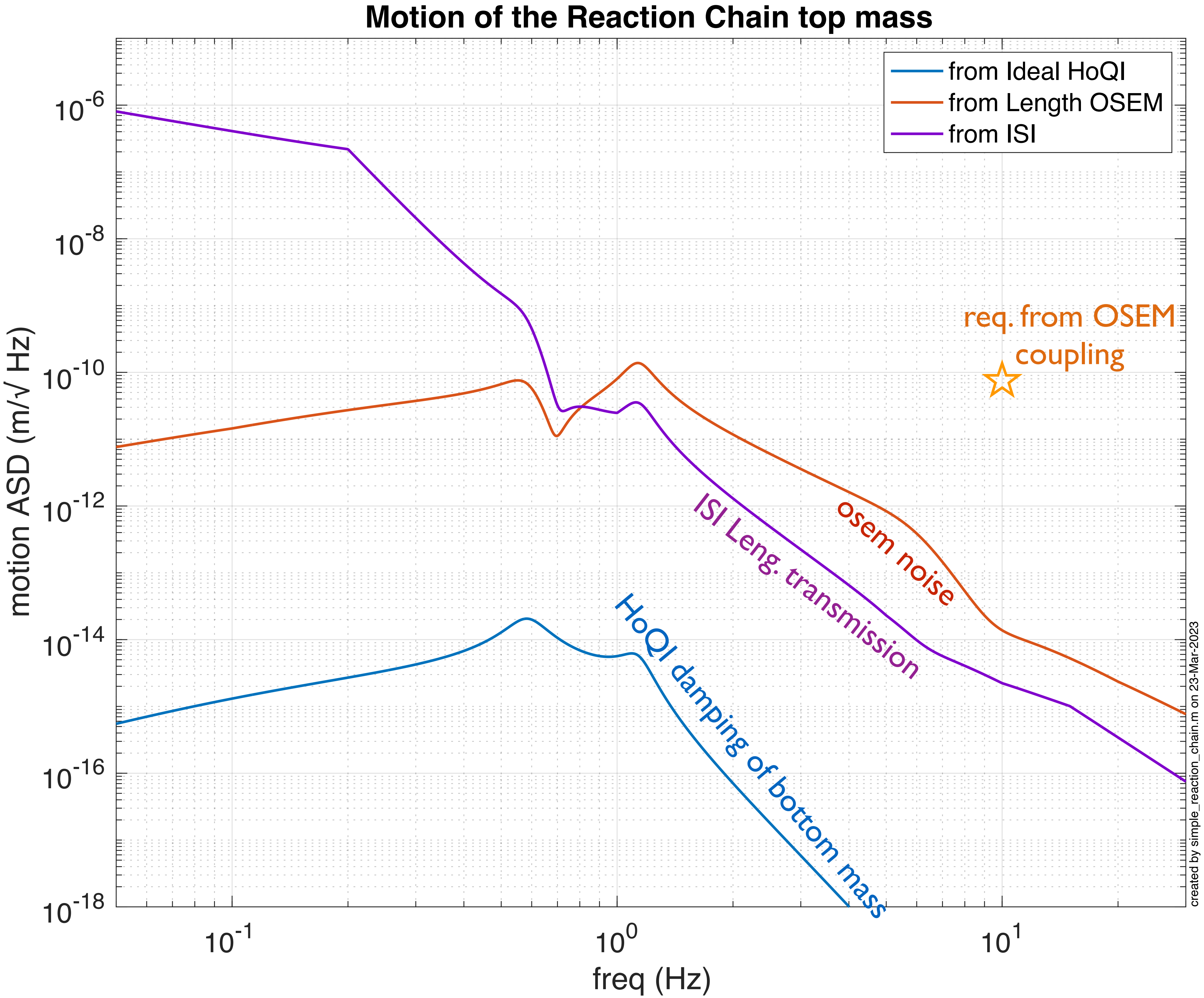
Reaction chain motion

The double reaction chain easily meets the 10 Hz ESD spec.
what about the compensation plate?



Reaction chain motion

Top mass motion and AOSEM spec



Conclusions

1. We need a reaction chain (ISC drive noise, scatter, ISI kicks)
2. A double seems to give large margin for isolation performance
3. but we haven't calculated angles,
4. or the vertical isolation requirements,
5. or the compensation plate.
6. The dynamics look really nice (no funny 3.3 Hz modes lurking)
7. It fits with the space and weight,
8. but probably requires a hole in the UIM structure.
9. Overall, it's probably easier to install than a quad
10. Please tell me what else we need to consider.

compensation plate?

Advanced LIGO System Design, Fritschel, Coyne, T010075-v3, pg 14 (2015)

Component	*Number of suspension stages*	*Fiber type*	*Noise req. @10 Hz* $m/\sqrt{Hz}$
Test masses	4	fused silica	1×10^{-19}
Reaction masses (CP, ERM)	4	steel wire	
Beamsplitter	3	steel wire	6.4×10^{-18}
Recycling cavity optics	3	steel wire	1×10^{-17}
Input mode cleaner mirrors	3	steel wire	3×10^{-15}
Output mode cleaner	2	steel wire	1×10^{-13}
Output Faraday isolator	1	steel wire	
ETM transmission monitor	2	steel wire	
IO SM/MM optics	1	steel wire	

???

Table 4: Summary of suspension types in the interferometer. The test mass suspensions

Other refs which I've looked at:
Cavity Optics Suspension Subsystem Design Requirements - T010007
Displacement Noise in Advanced LIGO Triple Suspensions - T080192