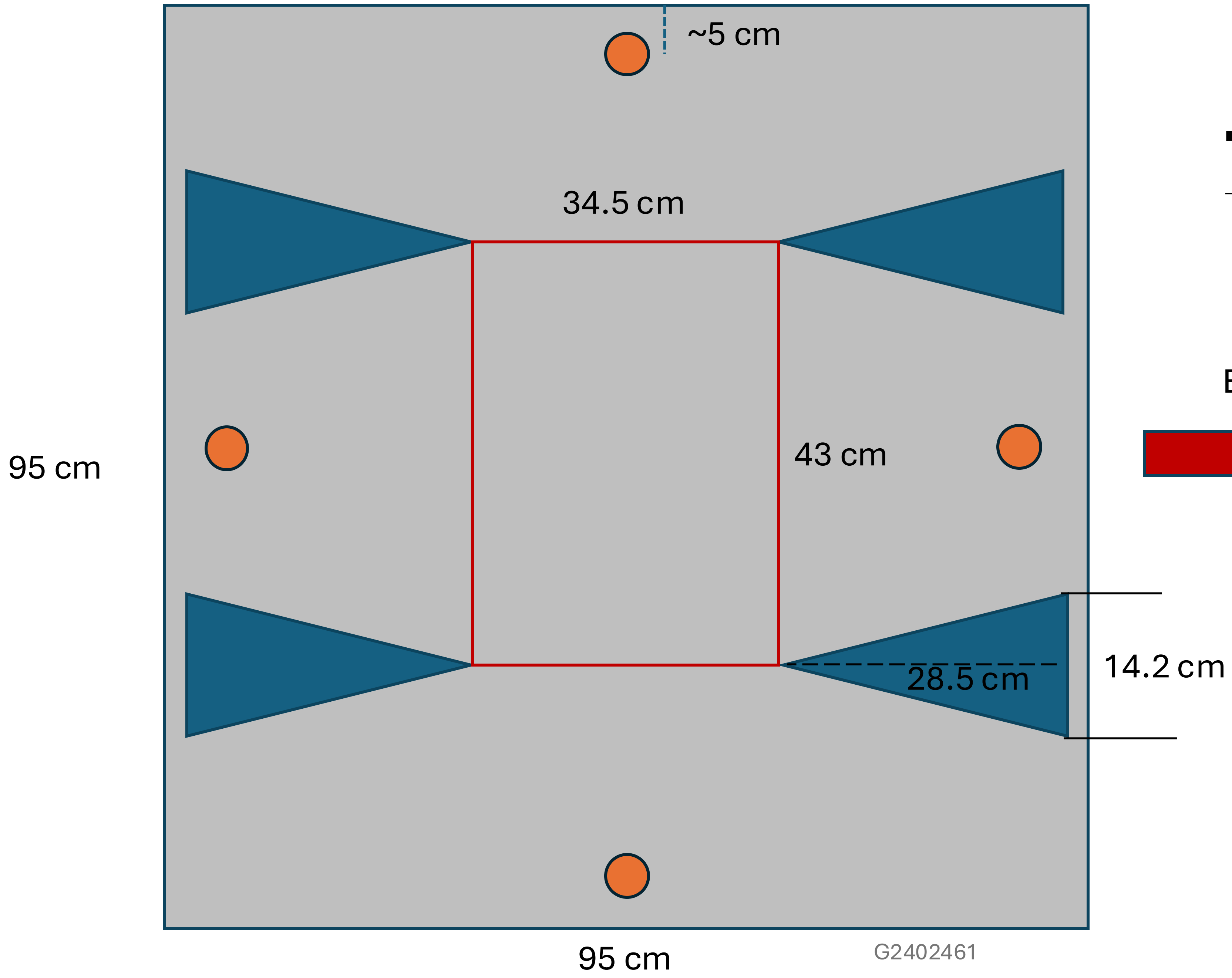
3rd BHQS Workshop Slides

Edgard Bonilla

Outline

- Design refresher
- Numbers for the design
- Show the LSC | ASC loops
  - It works easily at 800 kW
  - Challenging at 1.5 MW
- Uncertainty analysis
  - 0.25 mm seems like the d-value uncertainty
  - At 1 mm we would just get more low-f RMS
- How good do the sensors need to be?
  - 1 e-11 is good enough for all dofs.
  - 1 e-12 for UIM sensors would get most of the design where we want it.
- Anything we missed?
  - Roll mode estimate – 9.5 Hz? – Let’s not cut the PUM
  - Smaller PUM – Depends on Roll
  - Higher resonance in Pitch – I think it is worth it, but only helps above 1 MW power

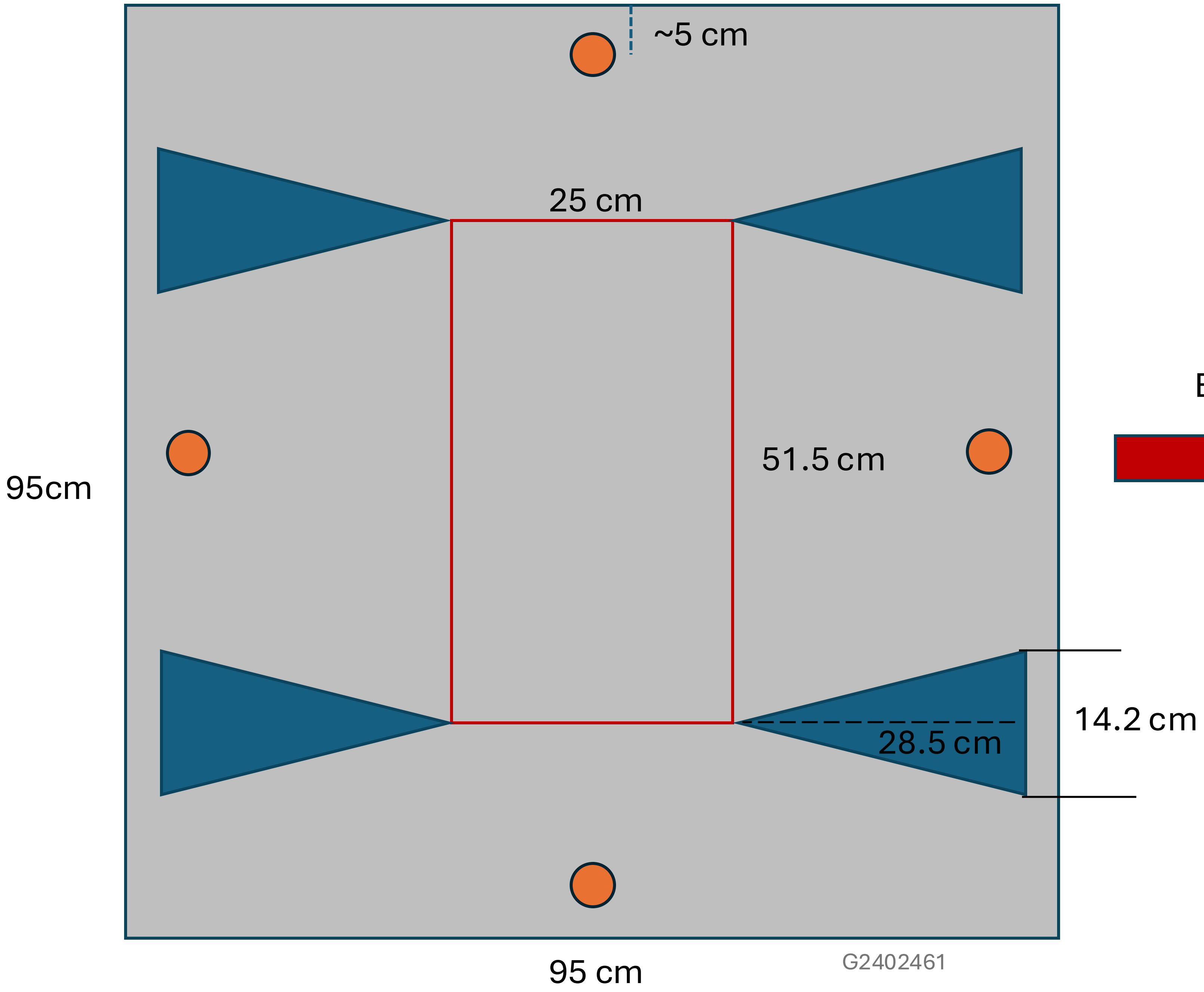


Top Mass

(top view)

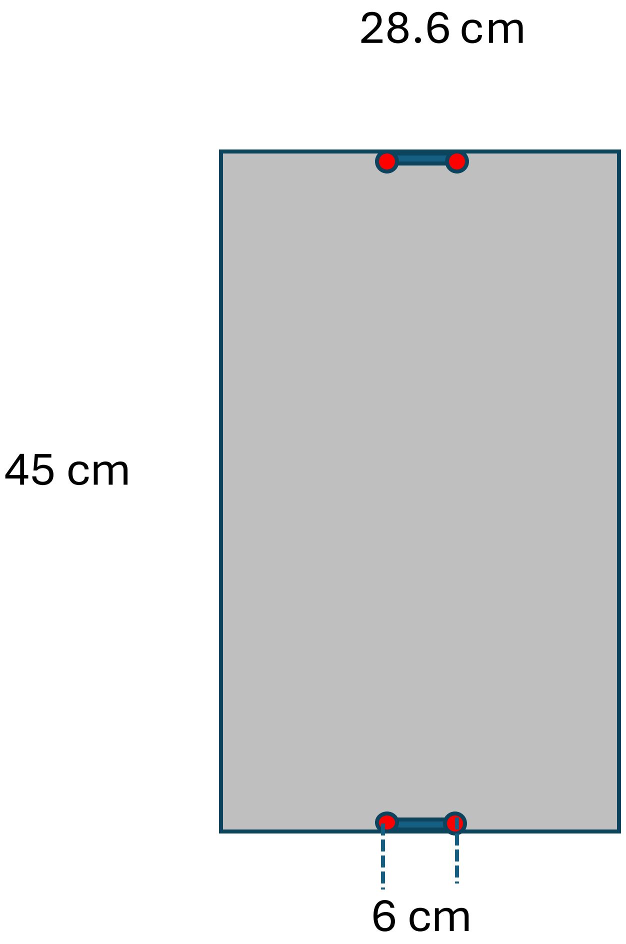
Beam tube direction

- **TOP:** 7 Sensors/Actuators.
- **UIM:** 7 Sensors/Actuators.
- **PUM:** **4** Sensors/Actuators. (L/P/Y)
- **TST:** **4** Sensors/Actuators. (L/P/Y)



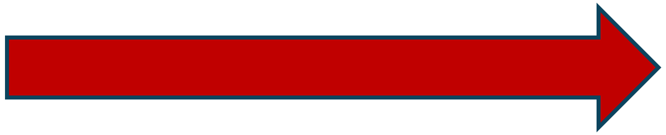
UIM
(top view)

- **TOP:** 7 Sensors/Actuators.
- **UIM:** 7 Sensors/Actuators.
- **PUM:** **4** Sensors/Actuators. (L/P/Y)
- **TST:** **4** Sensors/Actuators. (L/P/Y)



PUM
(top view)

Beam tube direction



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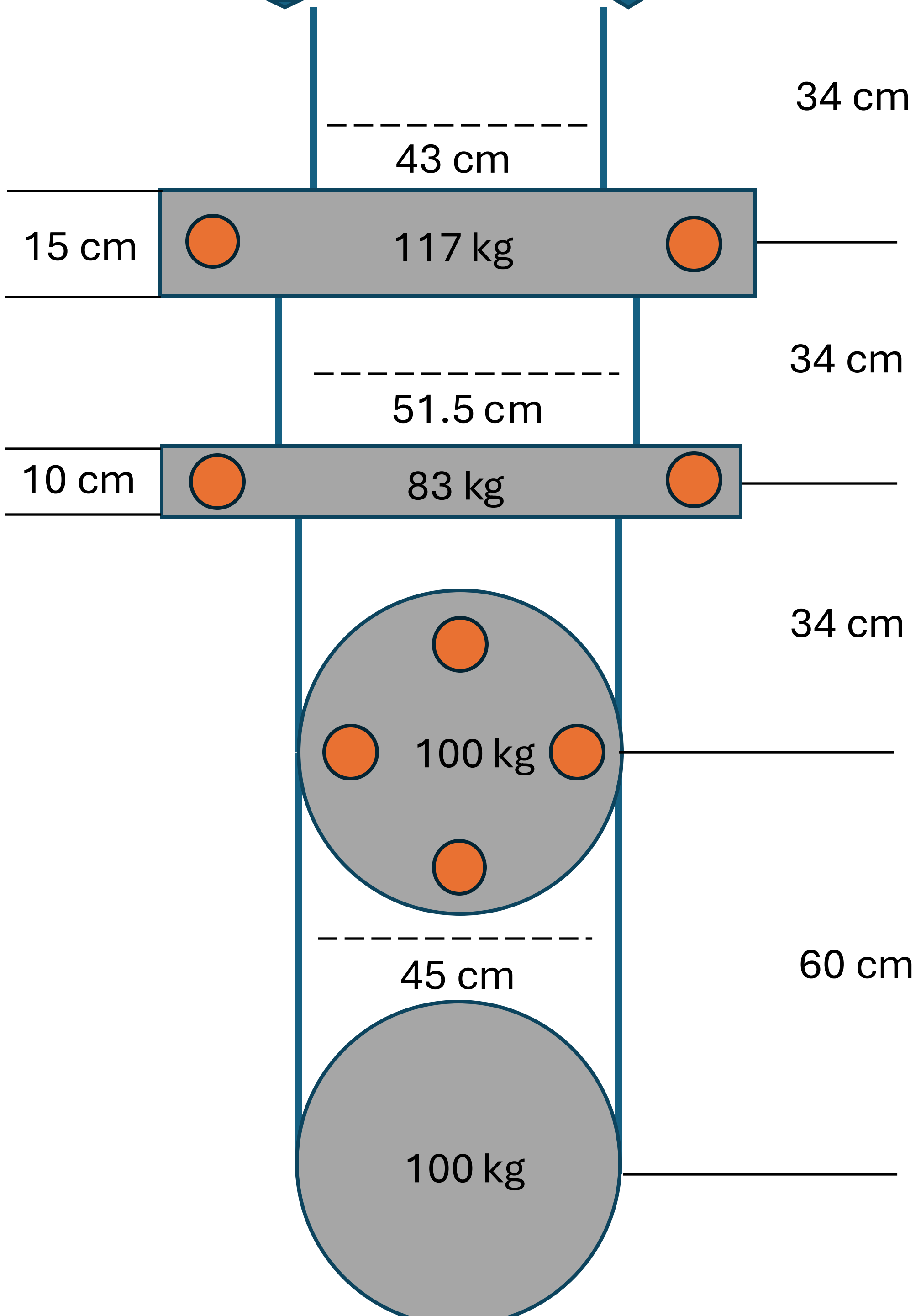
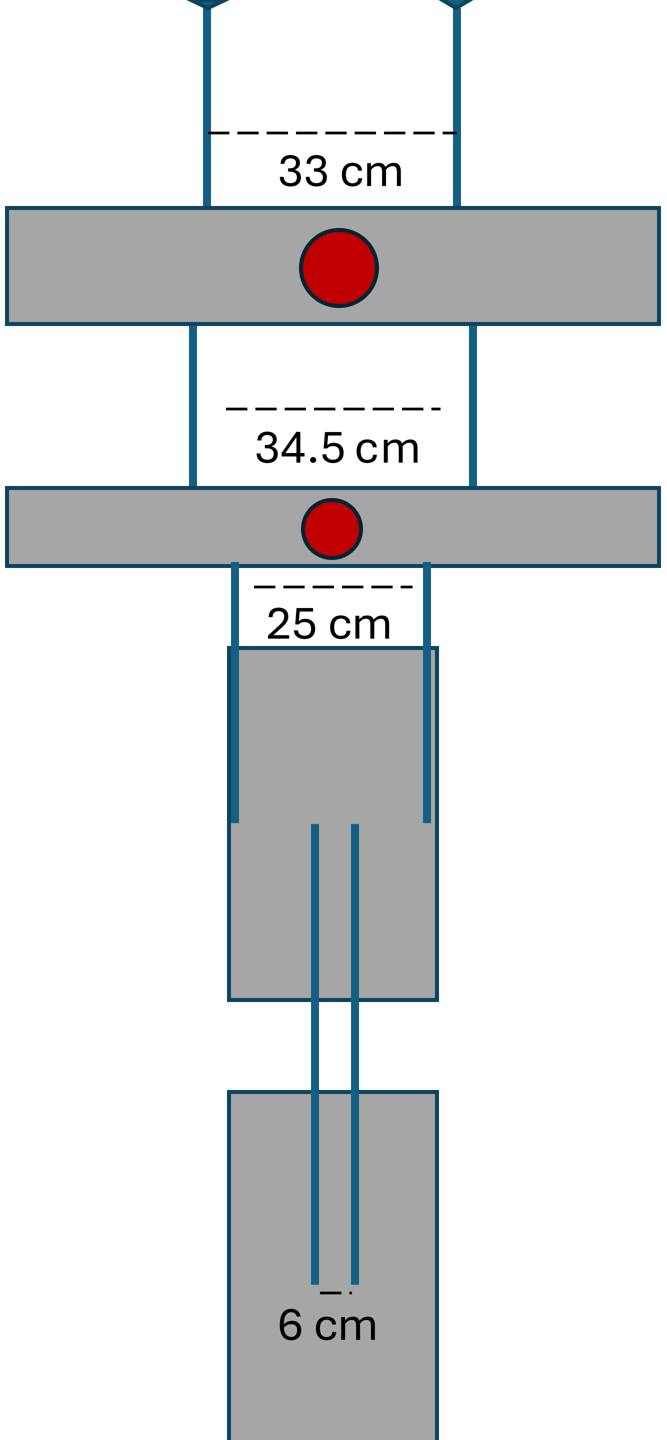


BHQS
(front view)

- **TOP:** 7 Sensors/Actuators.
- **UIM:** 7 Sensors/Actuators.
- **PUM:** **4** Sensors/Actuators. (L/P/Y)
- **TST:** **4** Sensors/Actuators. (L/P/Y)



BHQS

(side view)

- **TOP:** 7 Sensors/Actuators.
- **UIM:** 7 Sensors/Actuators.
- **PUM:** **4** Sensors/Actuators. (L/P/Y)
- **TST:** **4** Sensors/Actuators. (L/P/Y)

Design parameters (full)

Symbols	Description	Units	TOP	UIM	PUM	TST
$m_n/m_1/m_2/m_3$	Mass	[kg]	117	83	100	100
$I_{n,x}/I_{1,x}/I_{2,x}/I_{3,x}$	Roll moment of inertia	[kg·m^2]	9.7	5.9	2.6	2.6
$I_{n,y}/I_{1,y}/I_{2,y}/I_{3,y}$	Pitch moment of inertia	[kg·m^2]	10.3	6.3	1.9	1.9
$I_{n,z}/I_{1,z}/I_{2,z}/I_{3,z}$	Yaw moment of inertia	[kg·m^2]	17.6	10	1.9	1.9
$I_{n,xy}/I_{1,xy}/I_{2,xy}/I_{3,xy}$	R-P cross moment of inertia	[kg·m^2]	0	0	0	0
$I_{n,yz}/I_{1,yz}/I_{2,yz}/I_{3,yz}$	P-Y cross moment of inertia	[kg·m^2]	0	0	0	0
$I_{n,zx}/I_{1,zx}/I_{2,zx}/I_{3,zx}$	Y-R cross moment of inertia	[kg·m^2]	0	0	0	0
$k_{cn}/k_{c1}/k_{c2}$	Vertical spring stiffness (per side)	[kN/m]	6.5	9.3	5.2	N/A
$k_{xn}/k_{x1}/k_{x2}$	Lateral spring stiffness (per side)	[kN/m]	2500	2600	2200	N/A
$Y_n/Y_1/Y_2/Y_3$	Young's moduli of wires	[GPa]	212	212	212	72
$l_n/l_1/l_2/l_3$	Stretched wire length	[m]	0.34	0.34	0.34	0.60
$r_n/r_1/r_2/r_3$	radii of wires	[µm]	1400	1200	1000	220
$d_{\mathrm{top}}/d_n/d_1/d_3$	(upper) wire vertical attachment distance	[mm]	0	0	0	0
$d_m/d_0/d_2/d_4$	(lower) wire vertical attachment distance	[mm]	0	0	0	0
$s_n/s_u/s_i/s_l$	front-back wire attachment distance	[cm]	16.5	17	12.5	2.95
$n_{n0}/n_0/n_2/n_4$	(upper) wire transverse attachment distance	[cm]	21.6	25.7	22.5	22.5
$n_{n1}/n_1/n_3/n_5$	(lower) wire transverse attachment distance	[cm]	21.6	25.7	22.5	22.5

Design parameters (full)

Description	Units	ST2	TOP	UIM
Length	[cm]	44.0	28.5	28.5
Width	[cm]	22.0	14.2	14.2
Thickness	[mm]	3.4	2.9	2.4
Stress	[MPa]	1000	1000	1000
Deflection	[cm]	23.8	22.0	24.0
Radius of curvature	[cm]	31.6	26	22.8
Internal mode	[Hz]	74	80.1	73.5

Blade Springs:

These were changed in Dec 2023 so the TOP|UIM fit within 1 square meter.

It makes the vertical plant stiffer.
G2302370

Fiber stress: **1.6 Gpa** - [Double that of Advanced LIGO]
Thin radius: **220 μm**
Thick radius: **650 μm** - [For nulling thermoelastic]
Nulling length: **4 mm** - [On each end]

Design parameters (Simplified)

Symbols	Description	Units	TOP	UIM	PUM	TST
L	Distance to the previous stage	[cm]	34	34	34	60
m	Mass of the stage	[kg]	117	83	100	100
I_{RR}	Stage moment of inertia (Roll)	[kg·m^2]	9.7	5.9	2.6	2.6
I_{PP}	Stage moment of inertia (Pitch)	[kg·m^2]	10.3	6.3	1.9	1.9
I_{YY}	Stage moment of inertia (Yaw)	[kg·m^2]	17.6	10	1.9	1.9
k_L	Longitudinal stiffness above stage	[kN/m]	11.5	8.1	5.7	1.6
k_T	Transverse stiffness above stage	[kN/m]	11.5	8.1	5.7	1.6
k_V	Vertical stiffness above stage	[kN/m]	13	18.6	11	84.9
k_R	Roll rotational stiffness above stage	[N·m]	610	1200	560	4300
k_P	Pitch rotational stiffness above stage	[N·m]	355	550	170	74
k_Y	Yaw rotational stiffness above stage	[N·m]	852	785	380	84

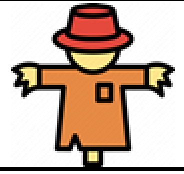
Design parameters (Simplified)

Degree of freedom	Units	f_1	f_2	f_3	f_4
Longitudinal	[Hz]	0.45	0.96	1.7	2.6
Transverse	[Hz]	0.45	0.96	1.7	2.6
Vertical	[Hz]	0.67	1.91	3.6	6.7
Roll	[Hz]	0.77	1.86	3.3	9.4
Pitch	[Hz]	0.55	0.93	1.77	2.23
Yaw	[Hz]	0.68	1.05	1.86	2.72

Bounce and roll recalculated to account for fiber nulling region [4 cm on each side]

LSC | ASC loops

LSC Loops

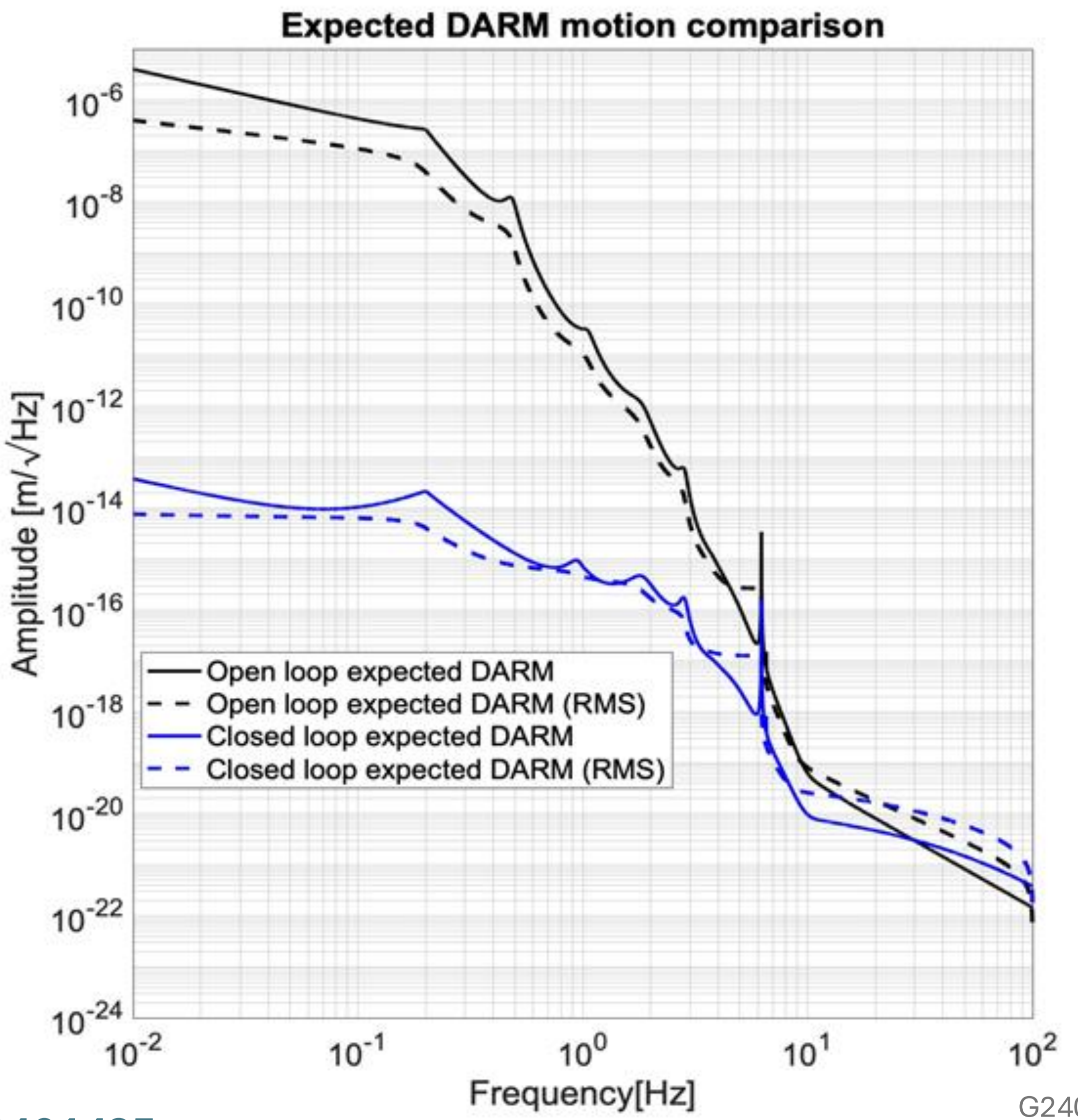


Full strawman design: G2401425

DAC (20 bit) → V_{DAC} [V] → Input Gain → Low Pass Filters → V_{filter} [V] → Drive (Gain) Stage → V_{drive} [V] → Electro-Mechanics → F_{act} [N] → Number of Actuators → F_{drive} [N]

DAC (20 bit)	Input Gain	Low Pass Filters	Drive (Gain) Stage	Electro-Mechanics	Number of Actuators
TST	Instrumentation amplifier 2x signal | √2x noise	**2p @ 0.7 Hz** **2z @ 20 Hz**	Gain 4x signal | 4x noise	**Gain [N/V]** **2.9 E-8**	ESD quadrants 4x signal | √4x noise
PUM	Gain 2x signal | 2x noise	**2p @ 0.7 Hz** **2z @ 20 Hz**	Differential Drive 2x signal | √2x noise	**Gain [N/V]** **1.9 E-5**	Four OSEMs 4x signal | √4x noise
UIM	Gain 2x signal | 2x noise	**2p @ 0.7 Hz** **2z @ 20 Hz**	Differential Drive 2x signal | √2x noise	**Gain [N/V]** **1.4 E-3**	Two OSEMs 2x signal | √2x noise

LSC Loops

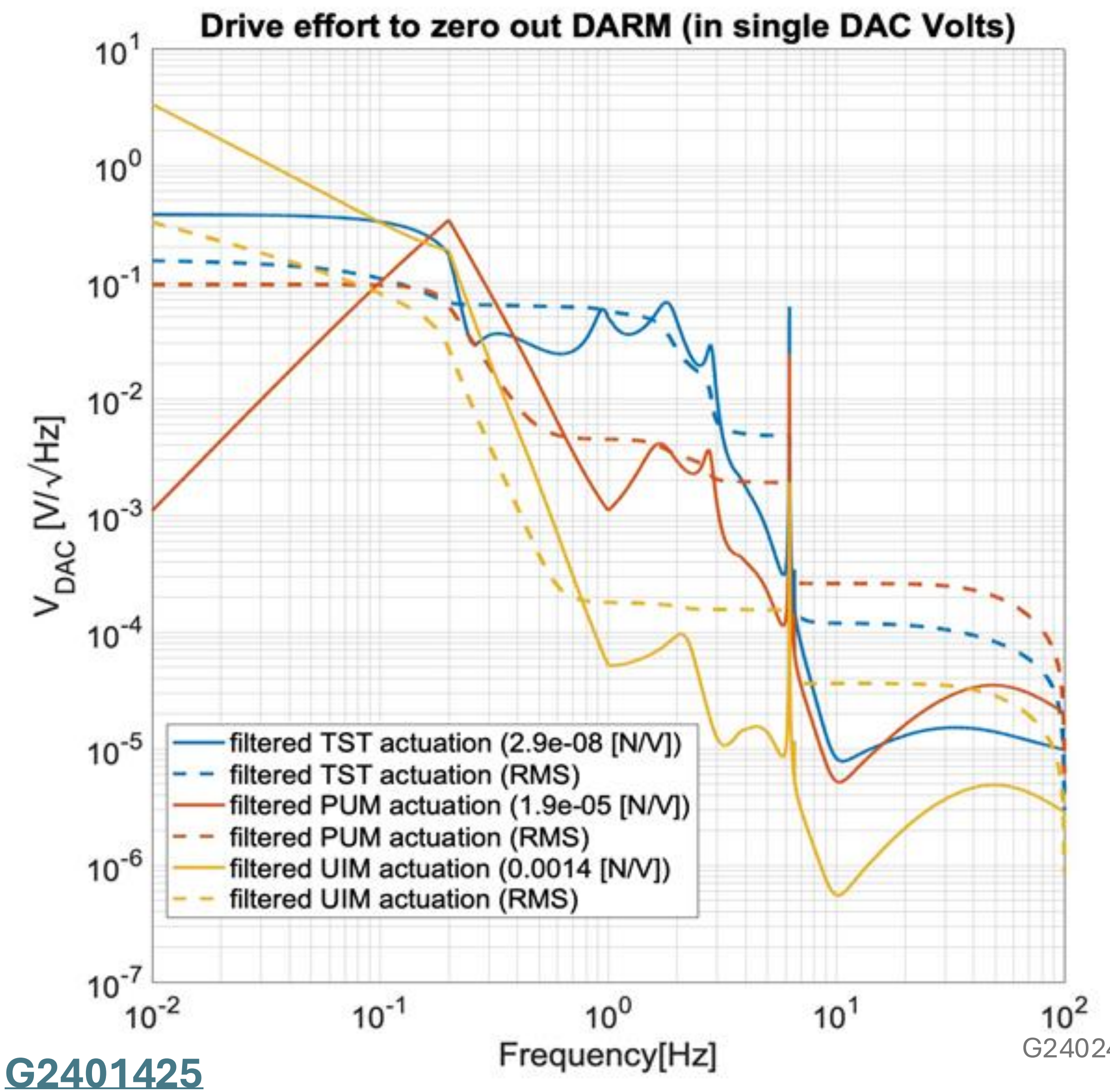


Strawman controller performance

- 70 Hz unity gain frequency.
- Conditionally stable (but that's ok)
- 10^{-14} m RMS in closed loop (as required)

See **G2401425**

LSC Loops

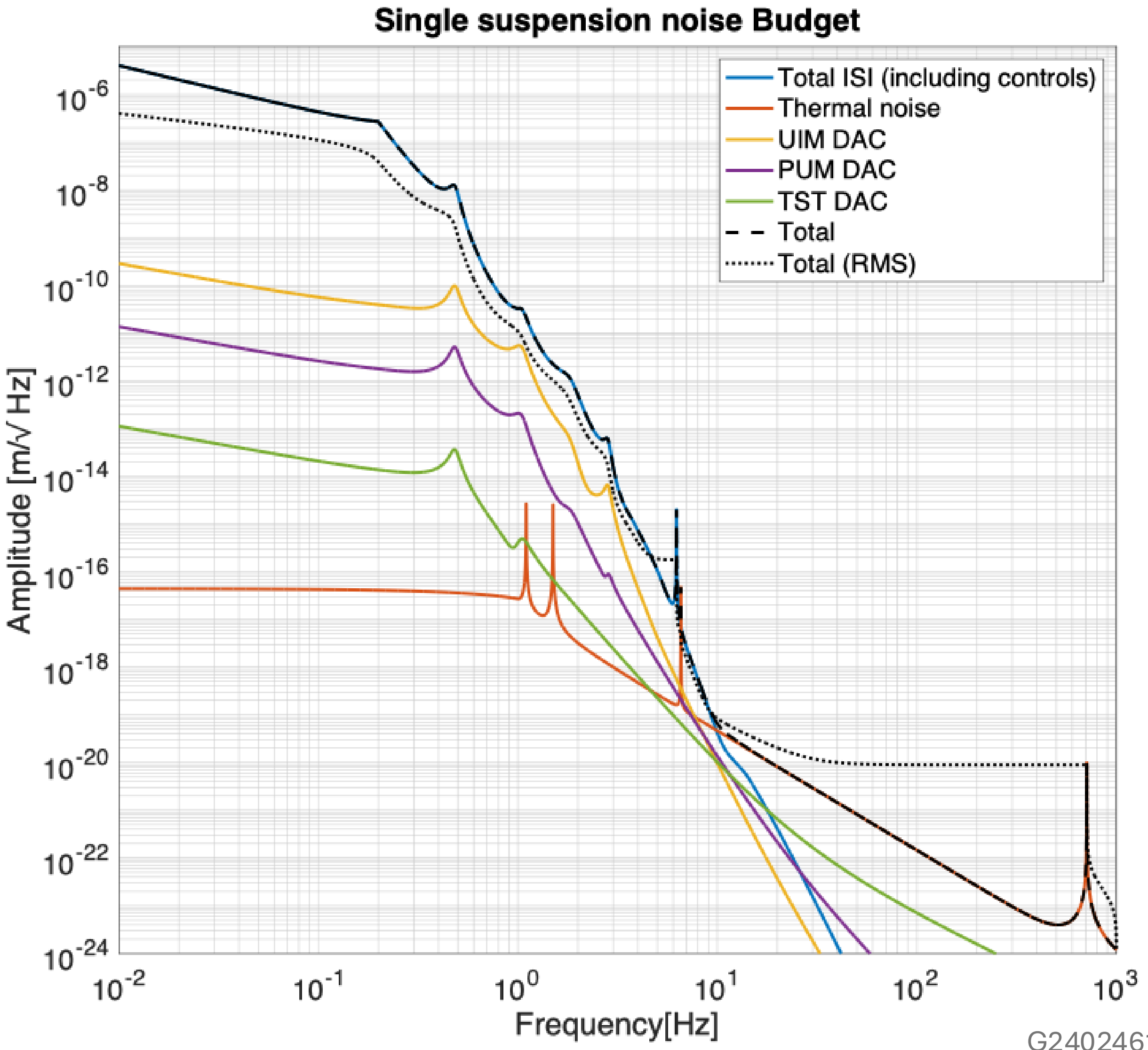


Strawman controller performance

- 70 Hz unity gain frequency.
- Conditionally stable (but that's ok)
- 10^{-14} m RMS in closed loop (as required)
- The drive effort is distributed among the UIM, PUM and TST stages.
- The RMS voltage for all three does not exceed 1 V.

See G2401425

LSC Loops



Strawman controller performance

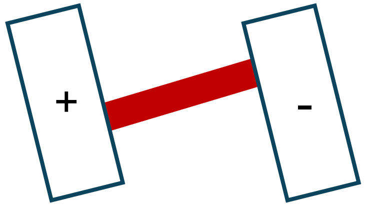
- 70 Hz unity gain frequency.
- Conditionally stable (but that's ok)
- 10^{-14} m RMS in closed loop (as required)
- The drive effort is distributed among the UIM, PUM and TST stages.
  - The RMS voltage for all three does not exceed 1 V.
- The DAC noise is consistently 5x below the ISI+Thermal noise contribution above 4 Hz.

See **G2401425**

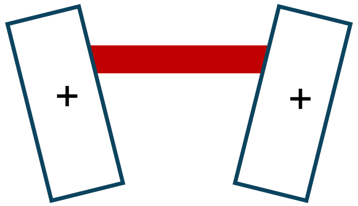
ASC loops

ASC Loops

- They are actuated from the PUM in the hard/soft basis



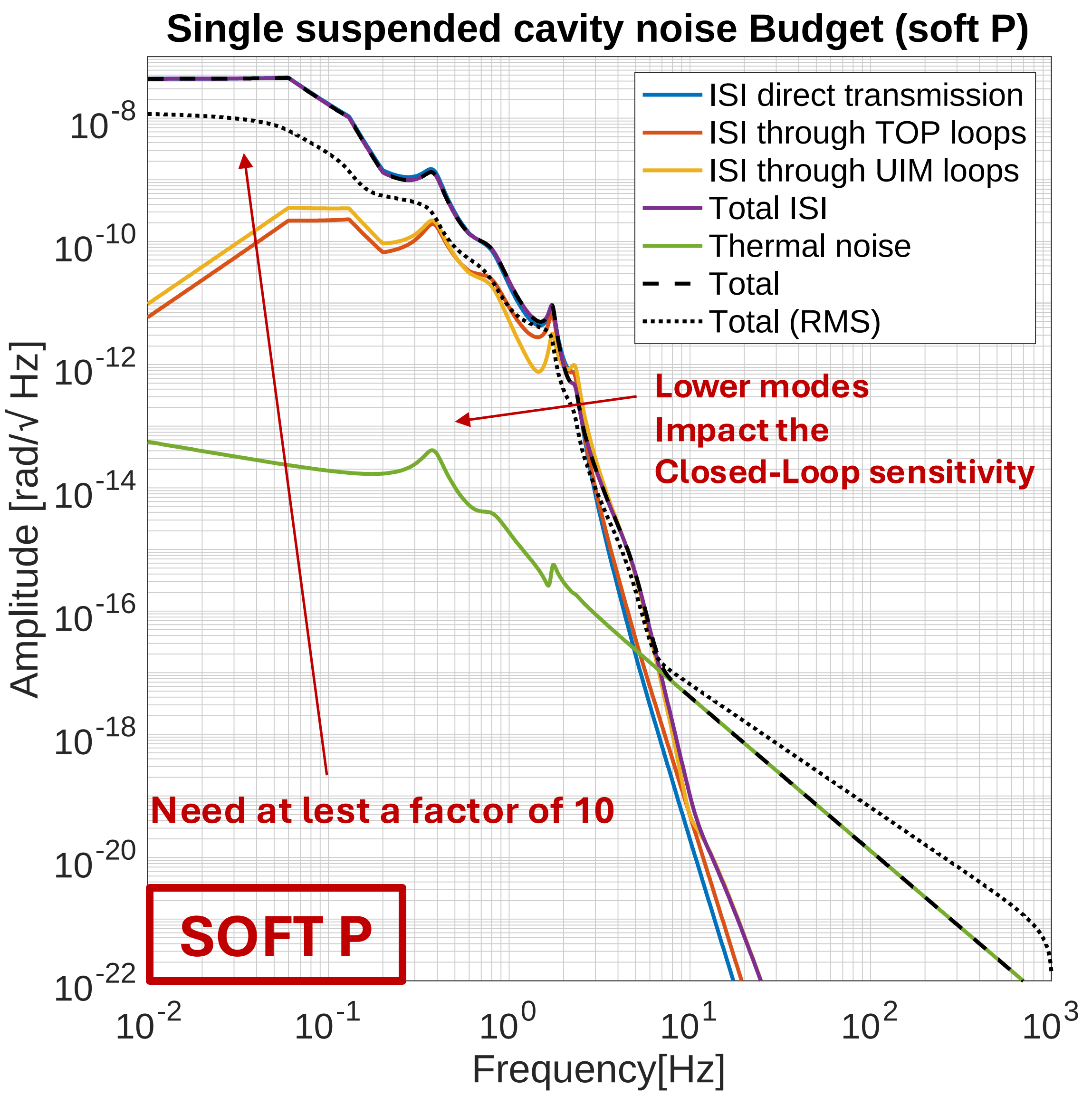
Hard DOF

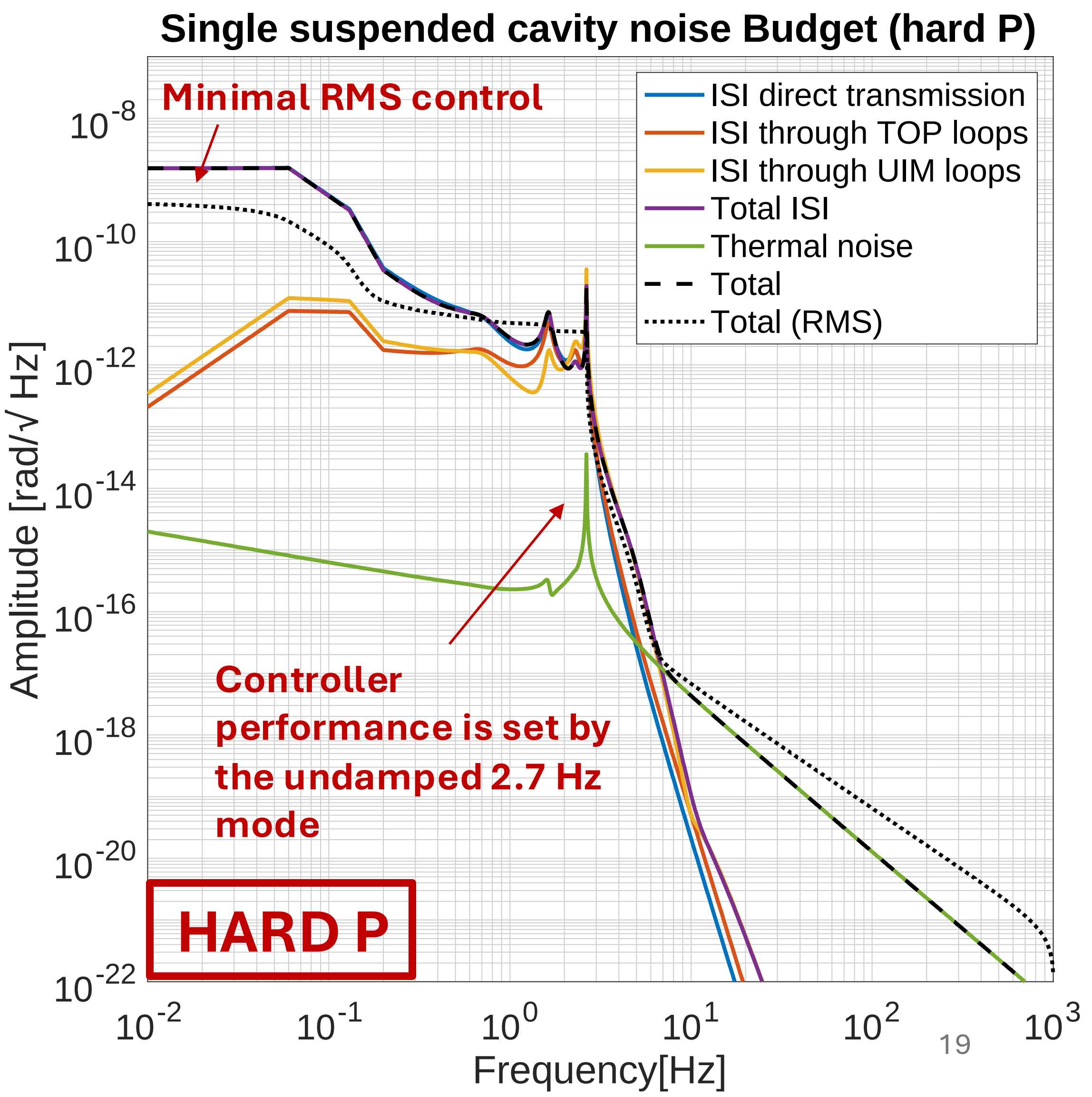


Soft DOF

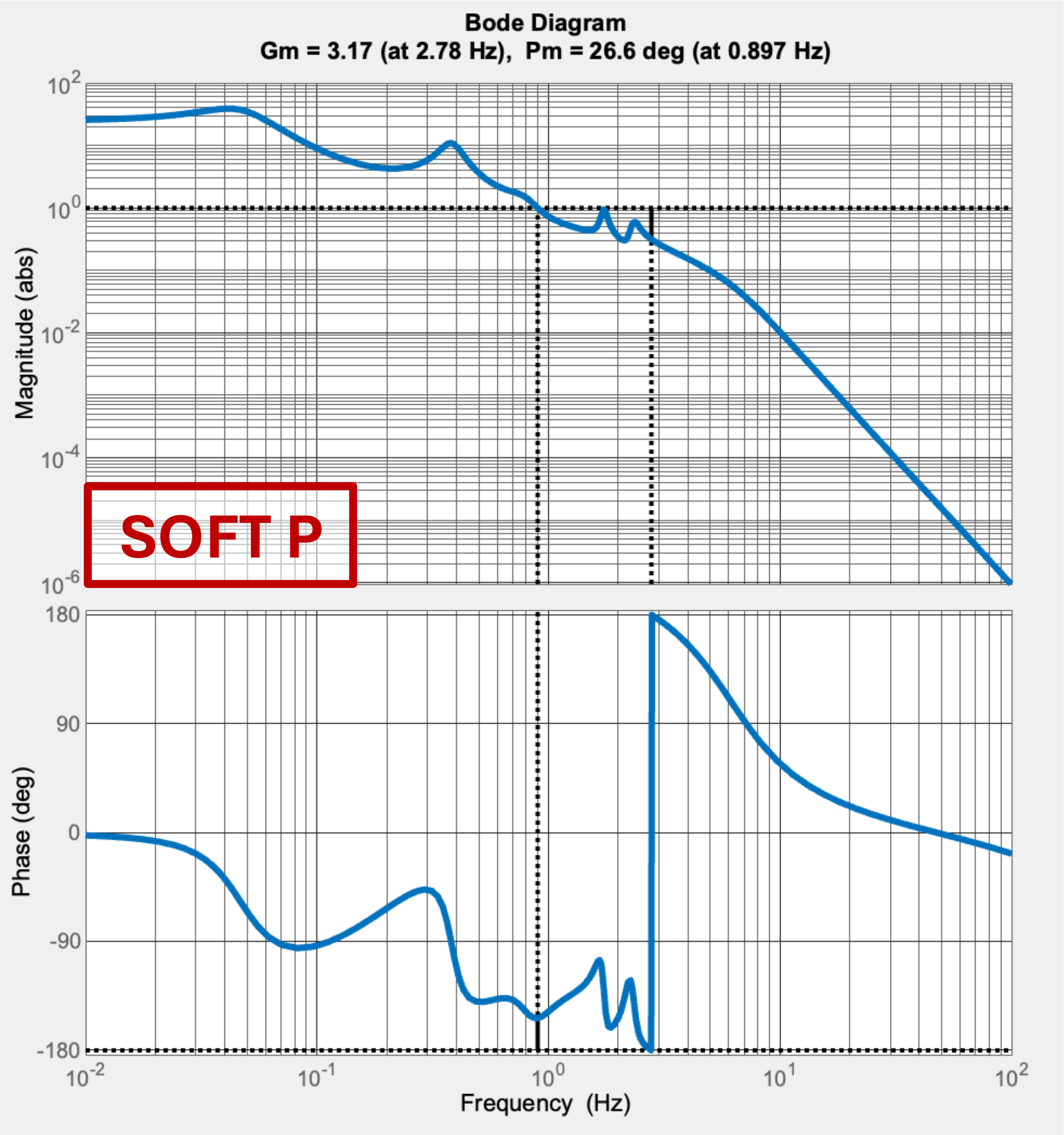
- We assume a WFS noise of 1e-15 rad/Hz$^{1/2}$. Order of magnitude based on G2100751

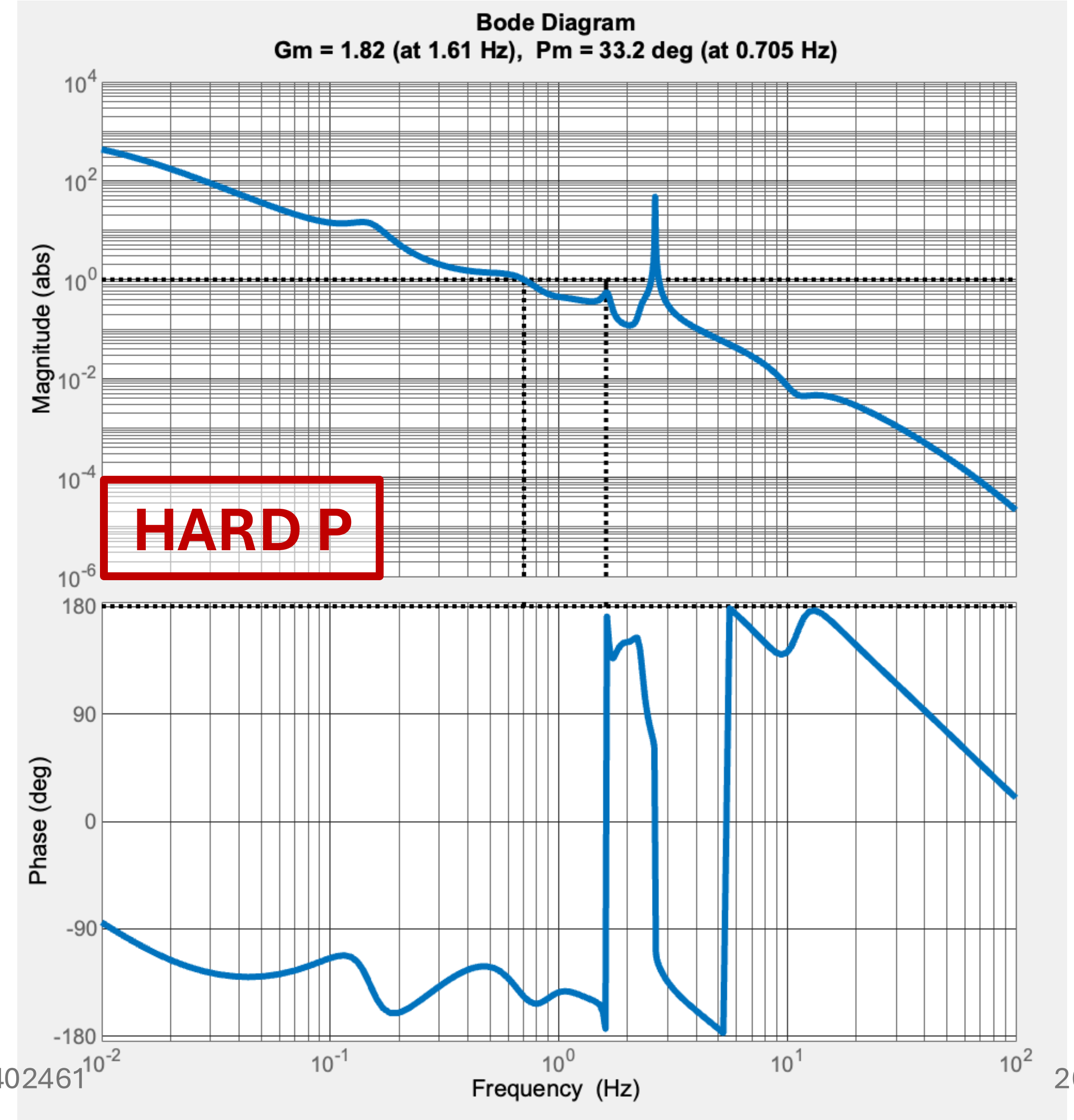
Pitch ASC (1.5 MW): *Open-Loop Motion*



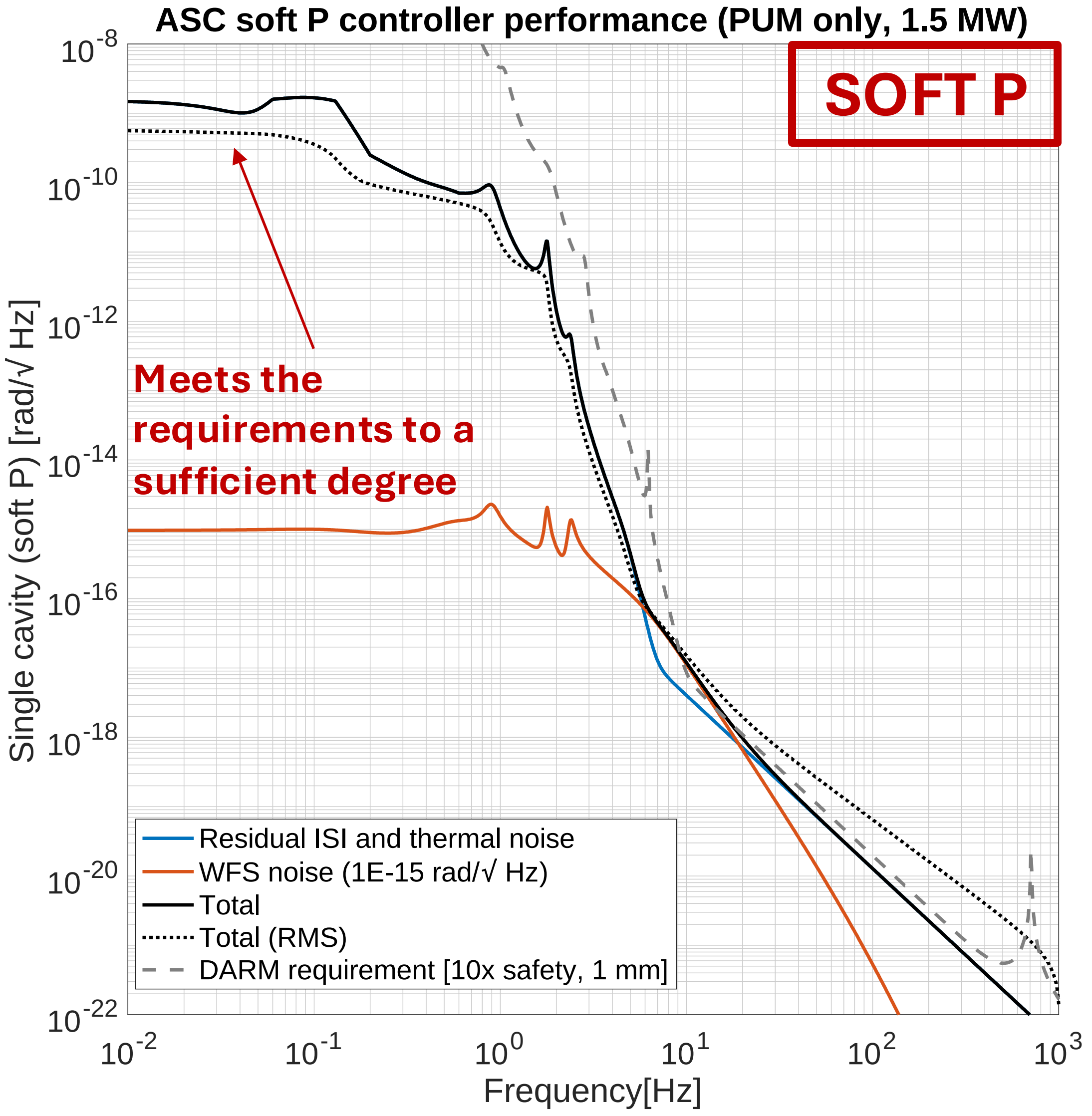


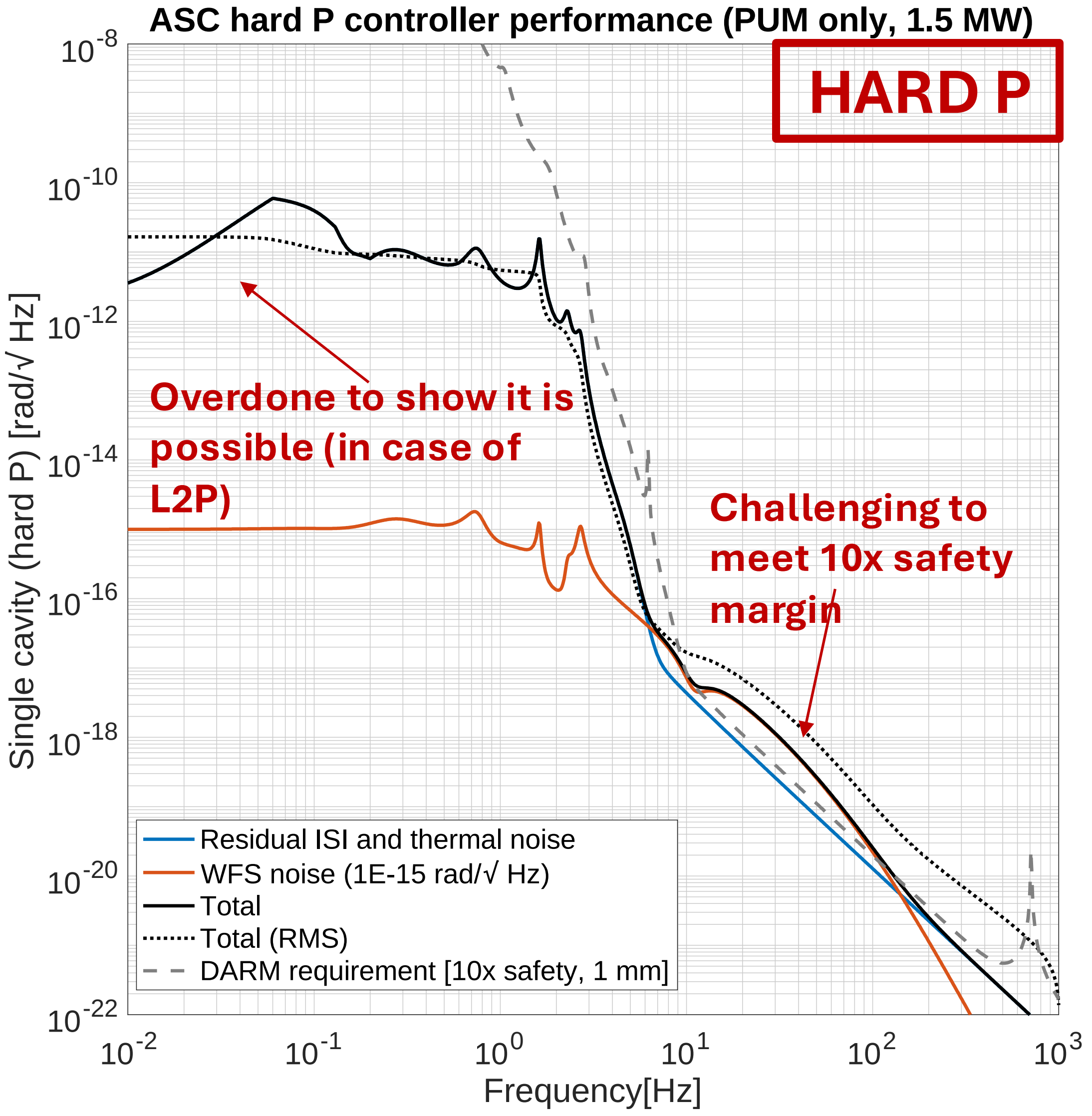
Pitch ASC (1.5 MW): *Open-Loop Gains*



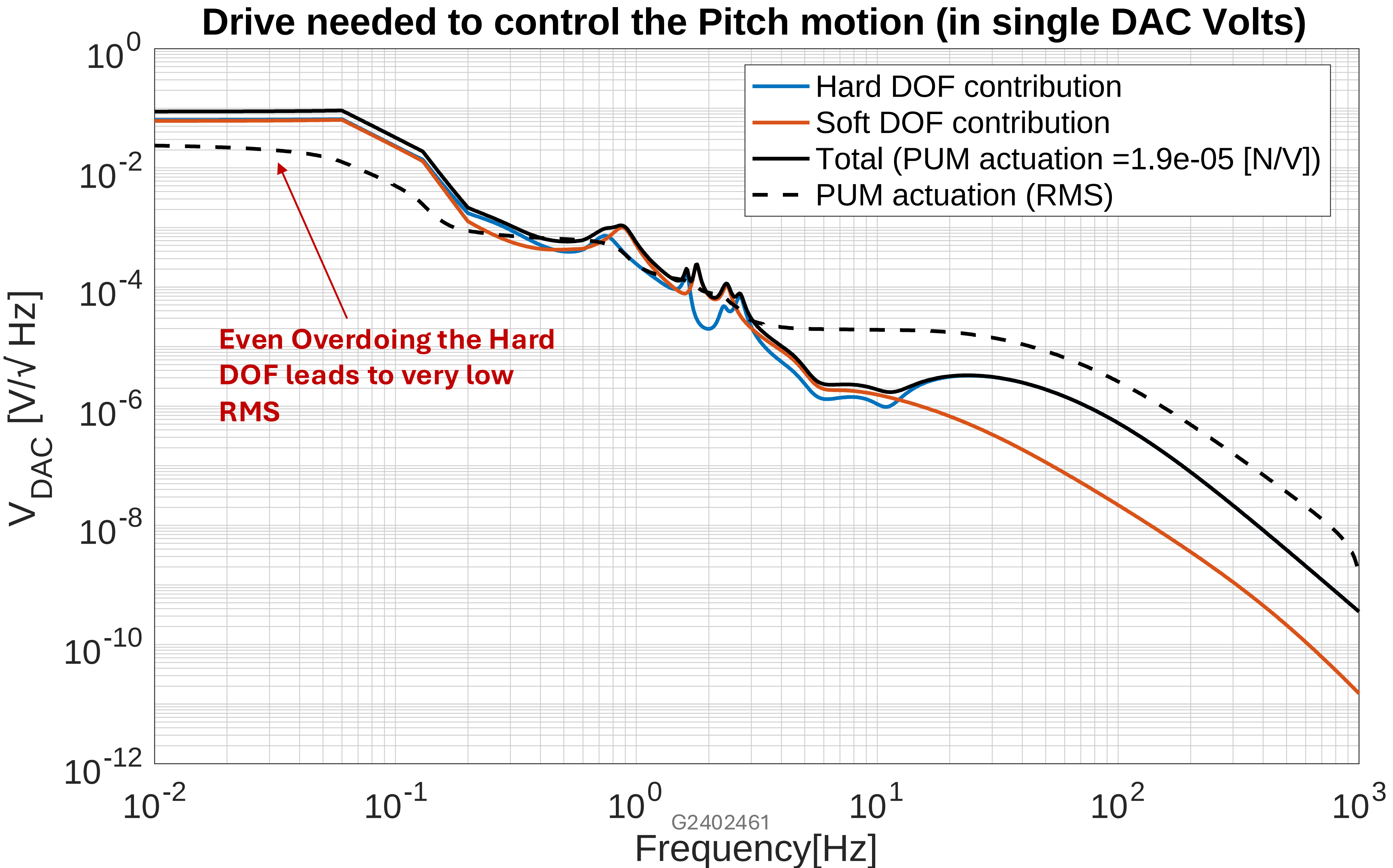


Pitch ASC (1.5 MW): *Closed-Loop Motion*

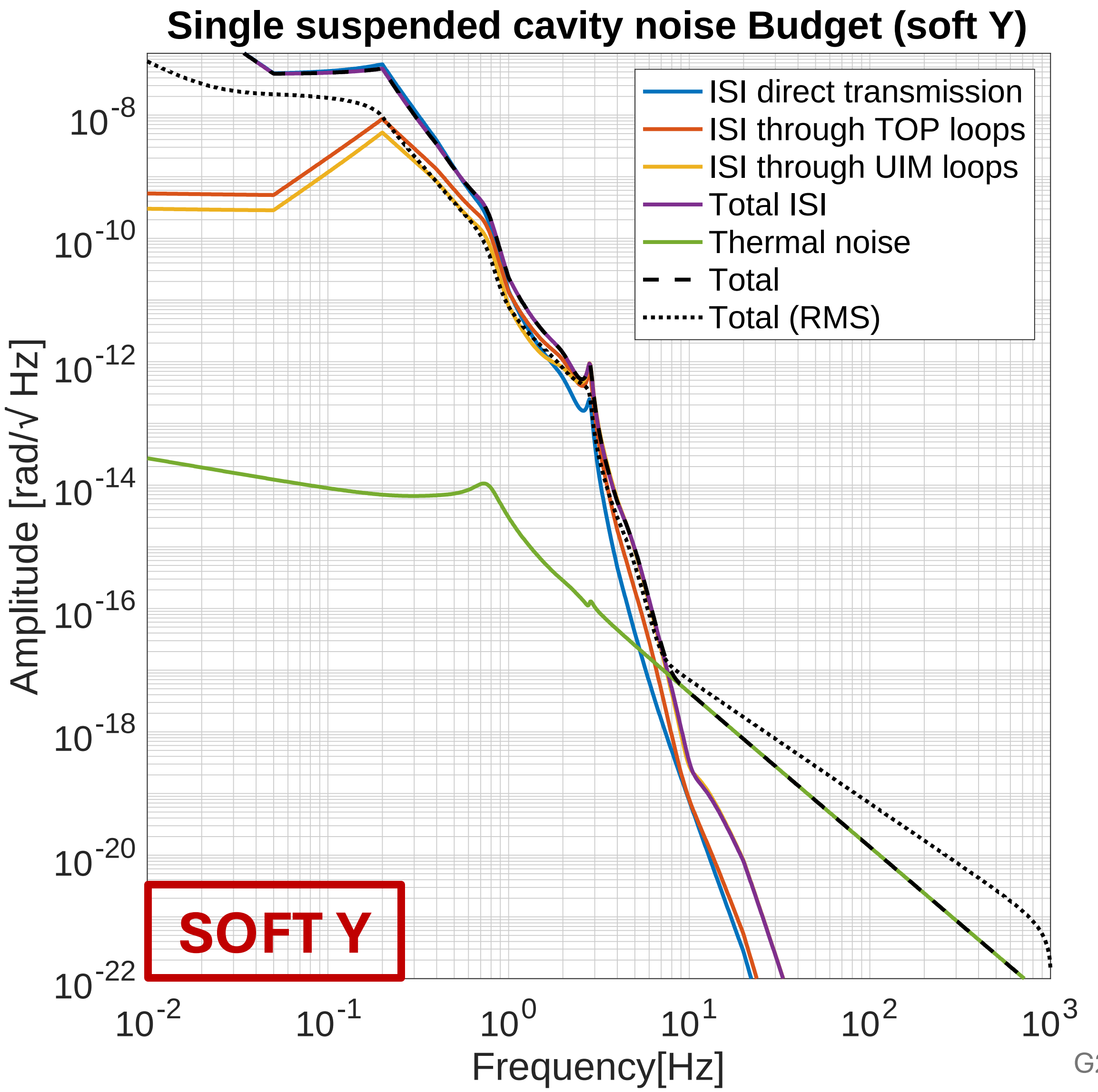


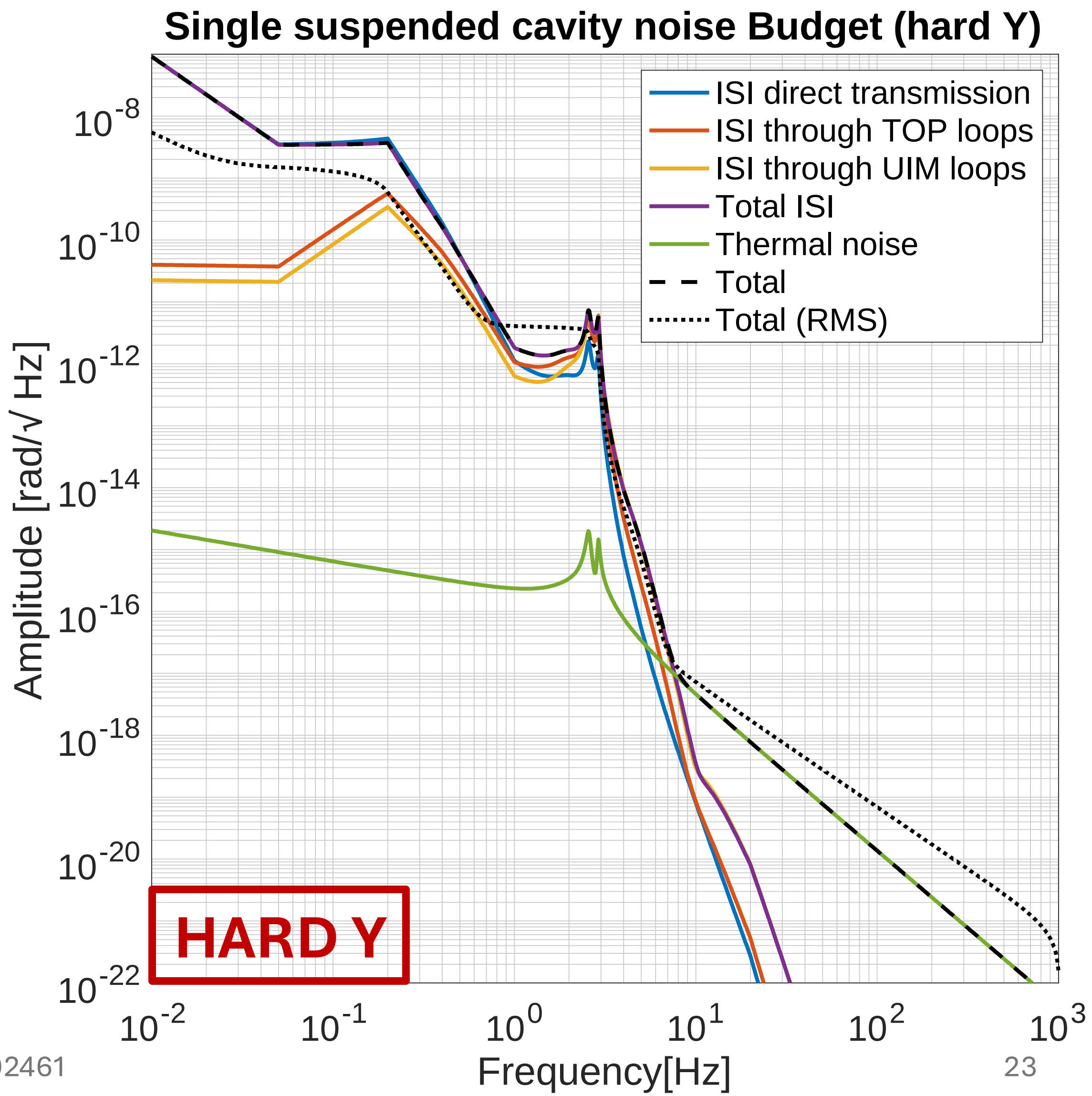


Pitch ASC (1.5 MW): *Upper-Limit DAC volts*

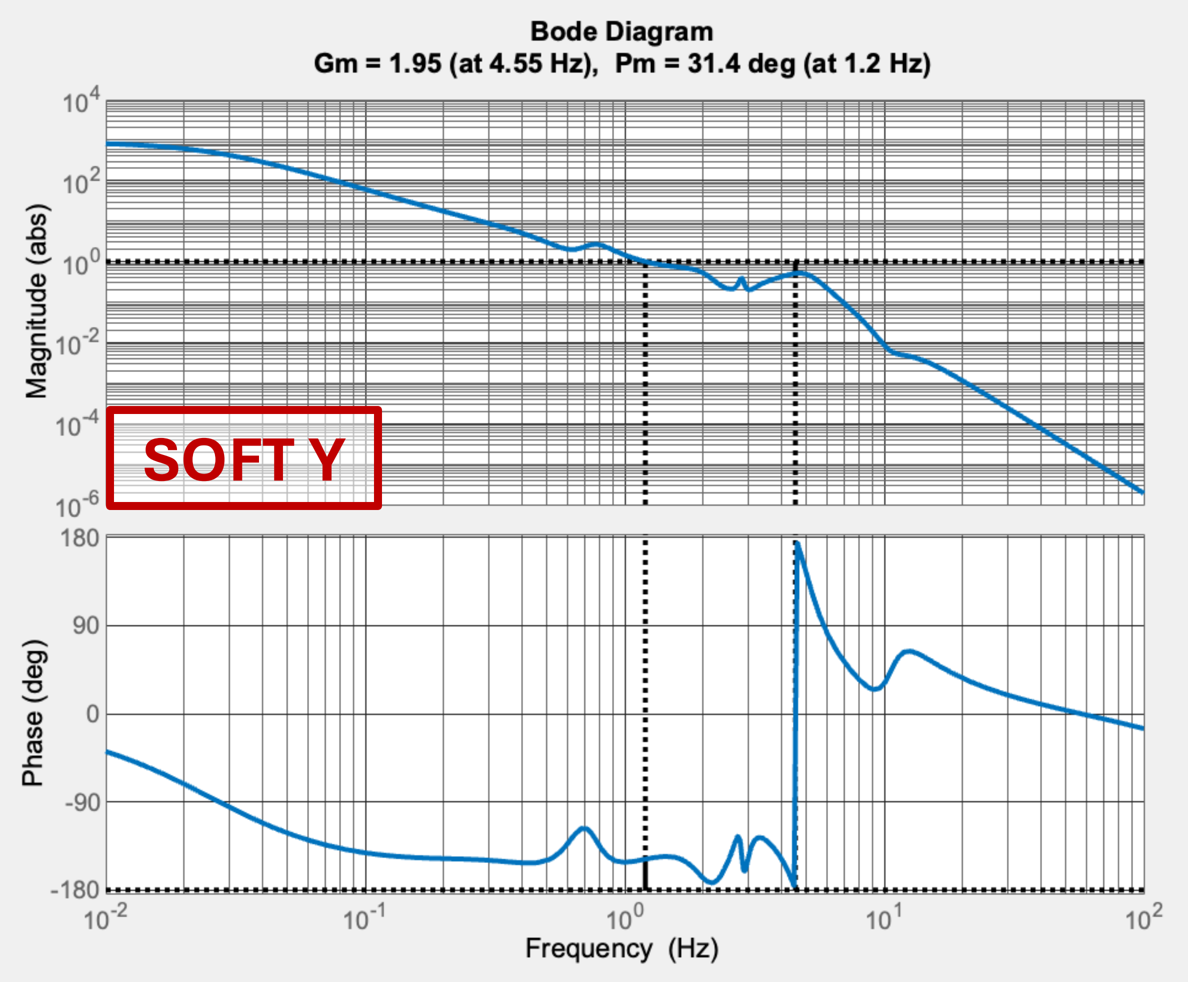


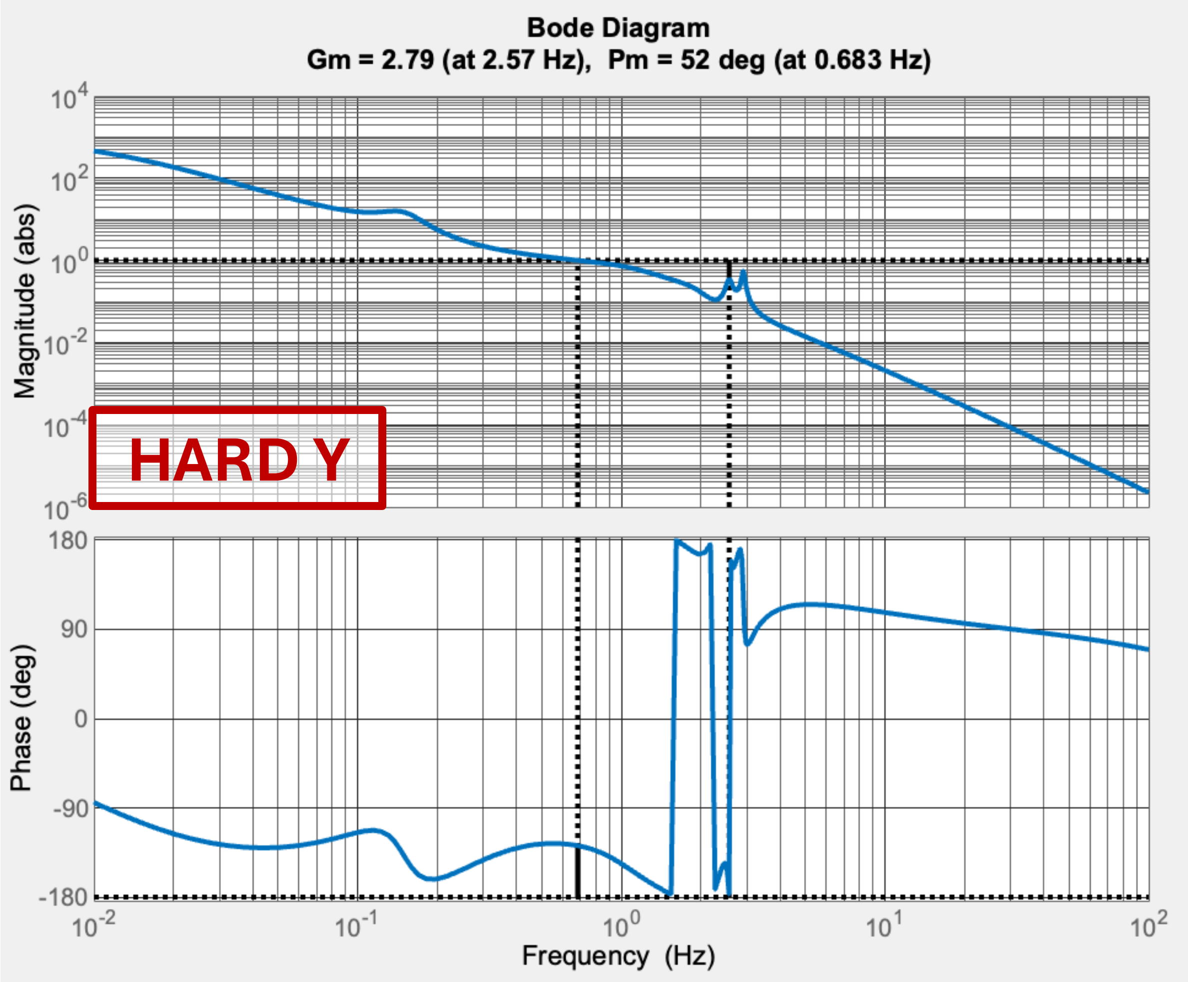
Yaw ASC (1.5 MW): *Open-Loop Motion*





Yaw ASC (1.5 MW): *Open-Loop Gains*





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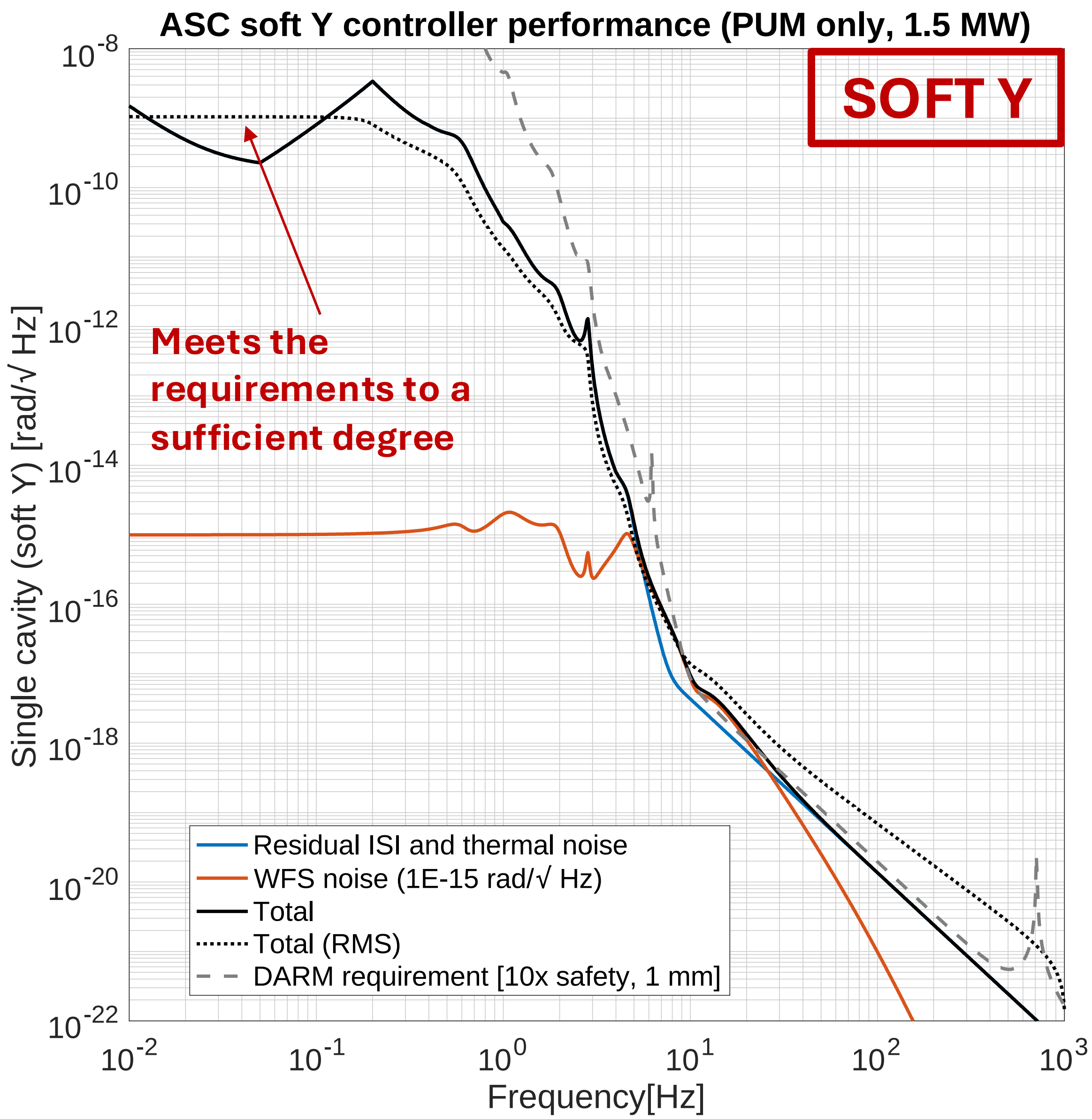
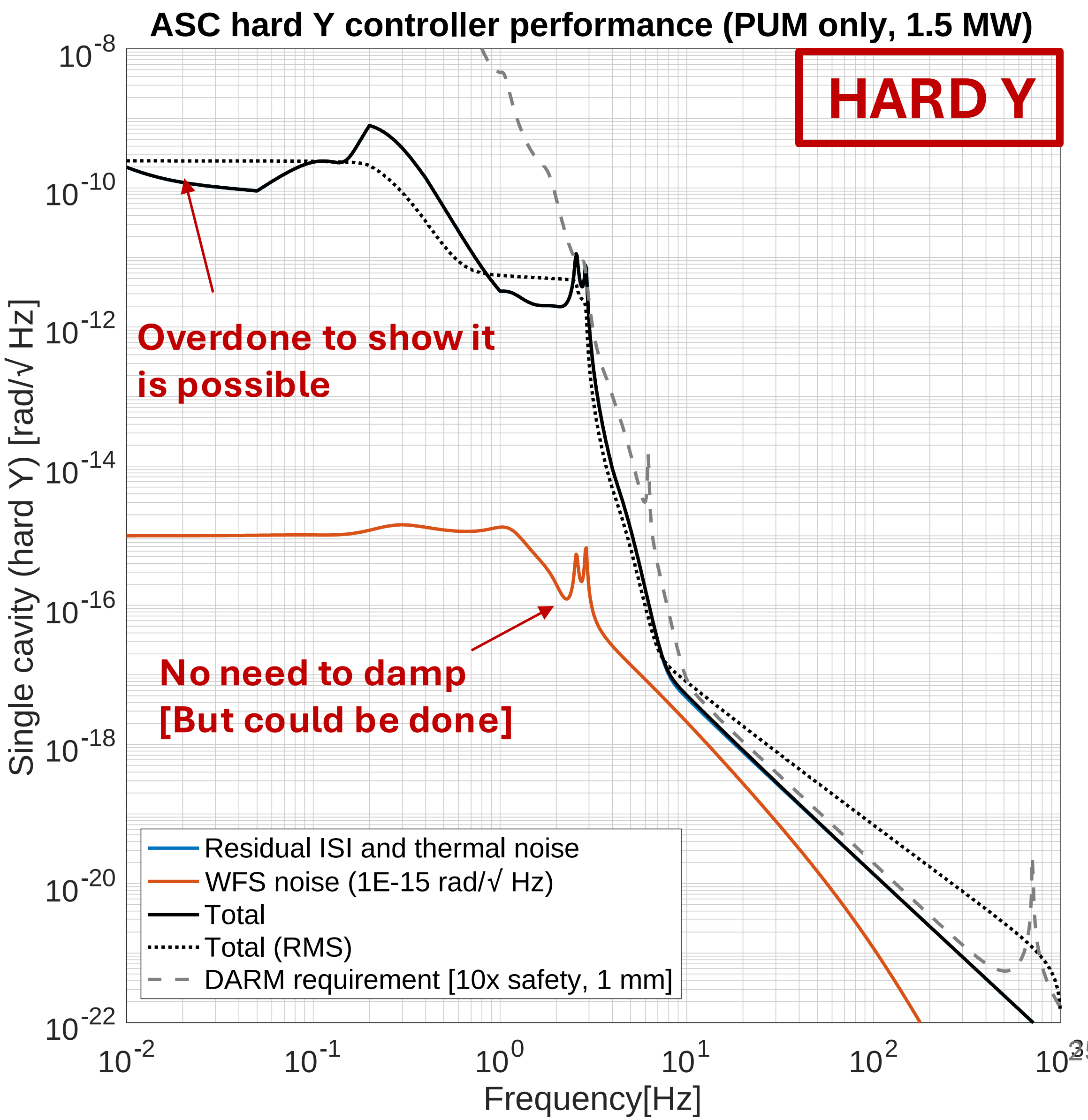
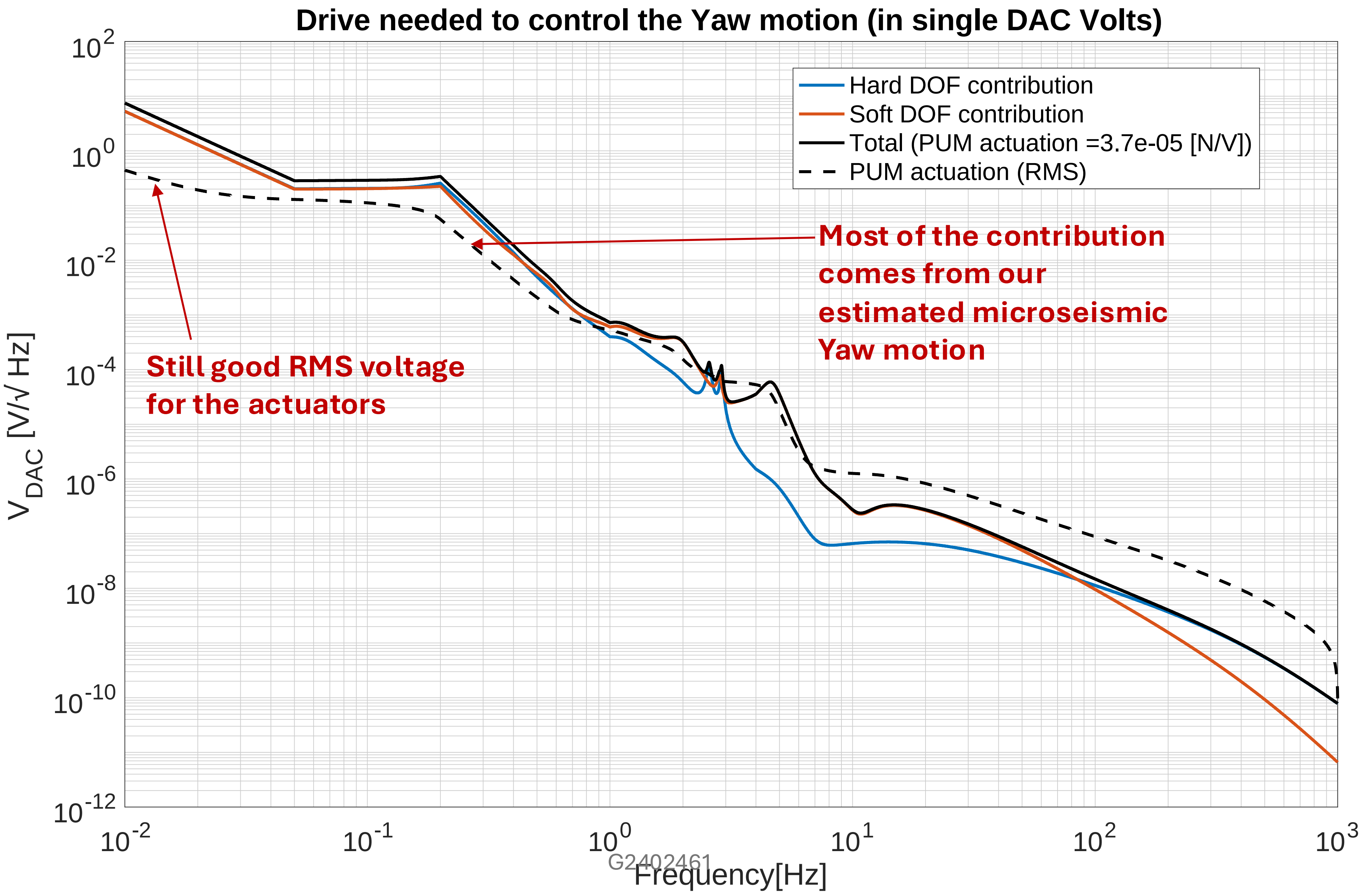


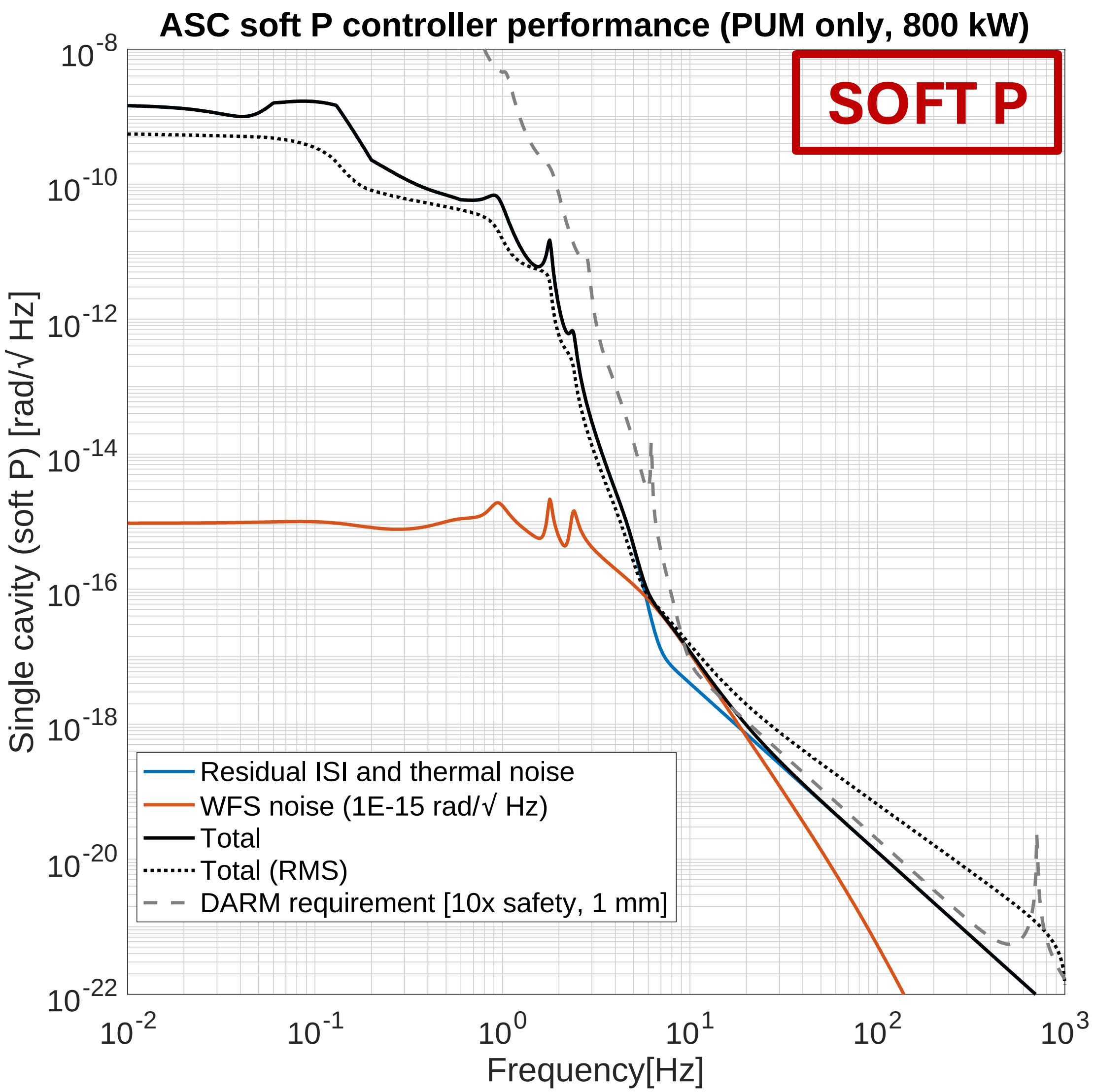


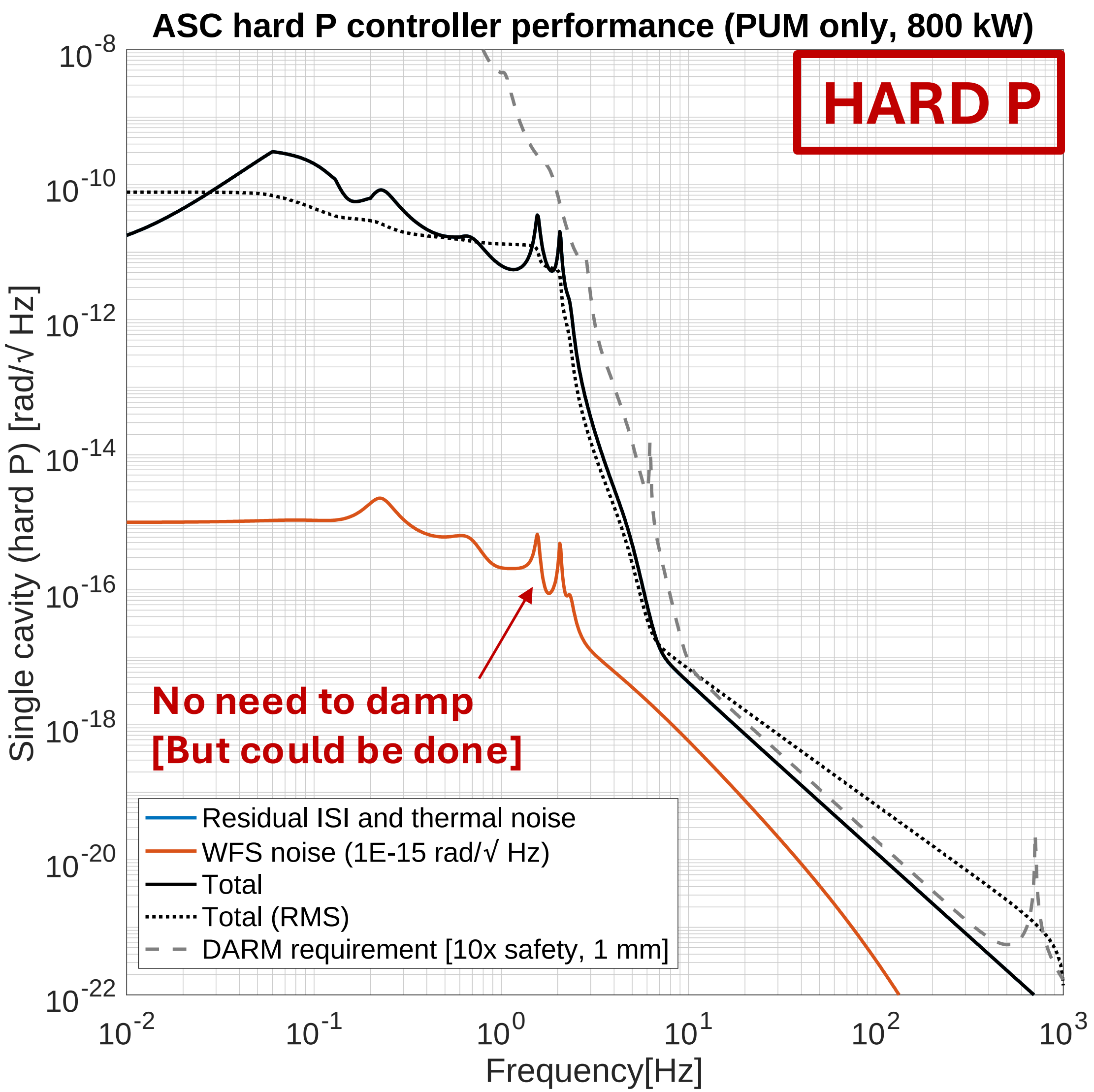
Yaw ASC (1.5 MW): *Upper-Limit DAC volts*



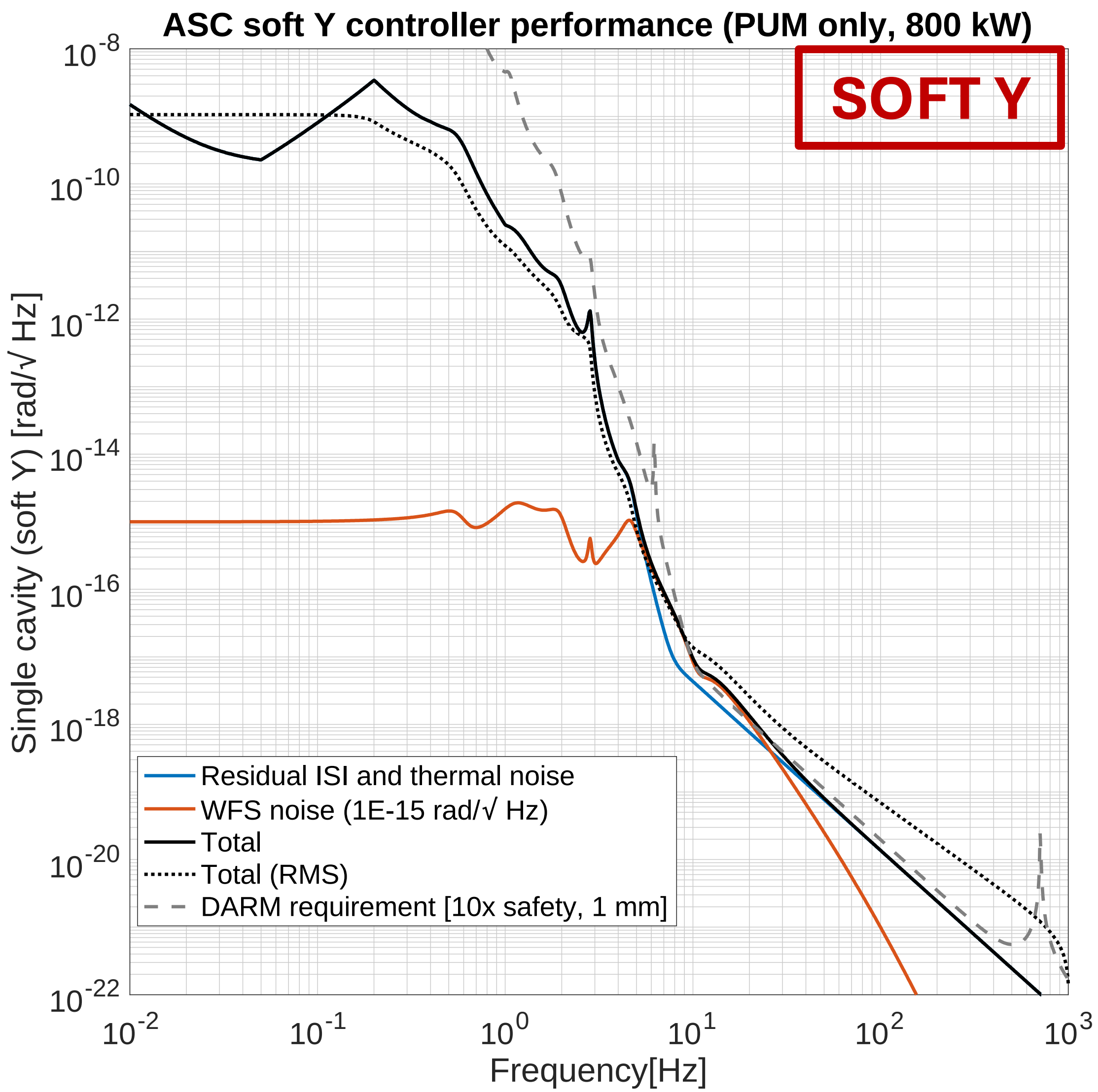
What about ASC at lower powers?

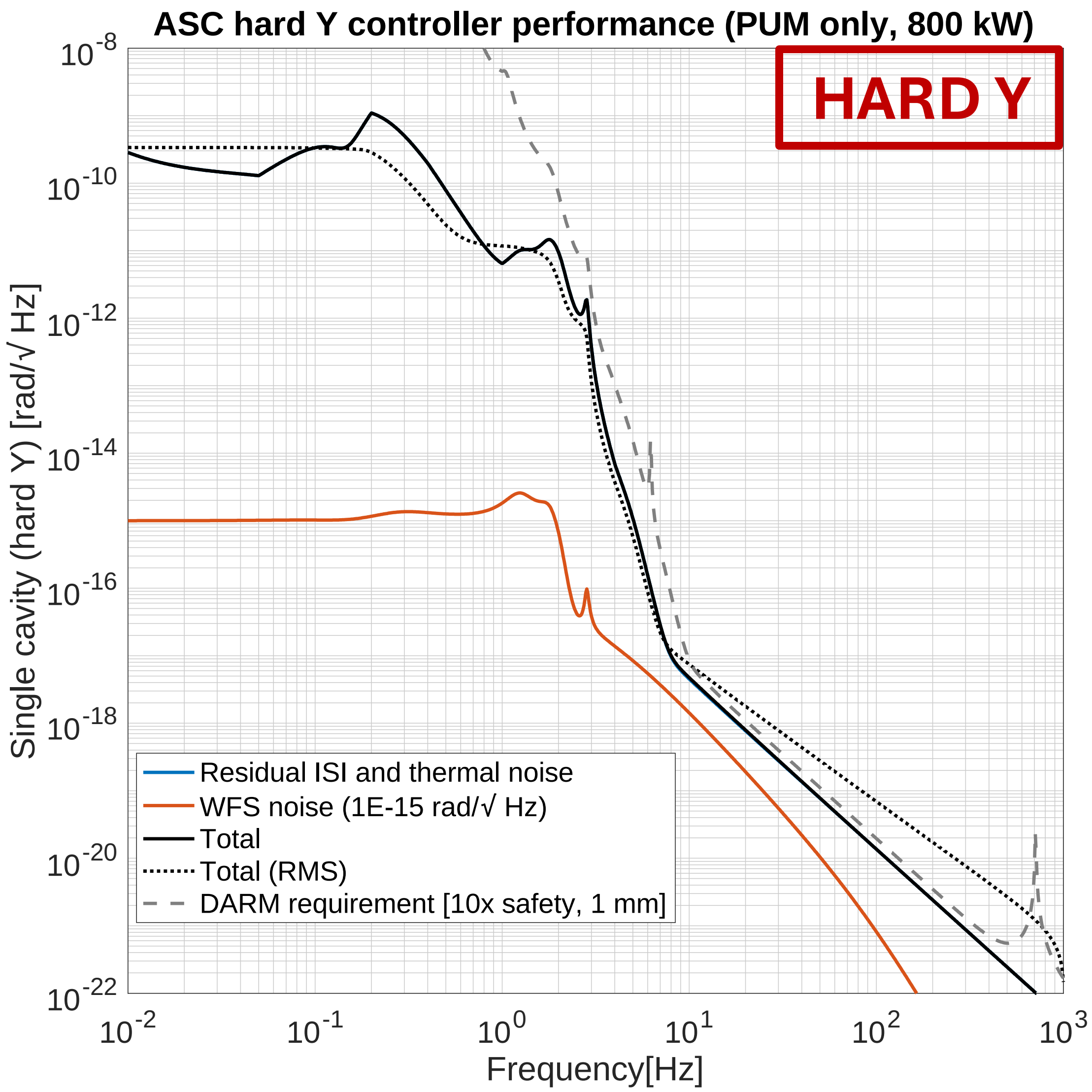
800 kW ASC performance





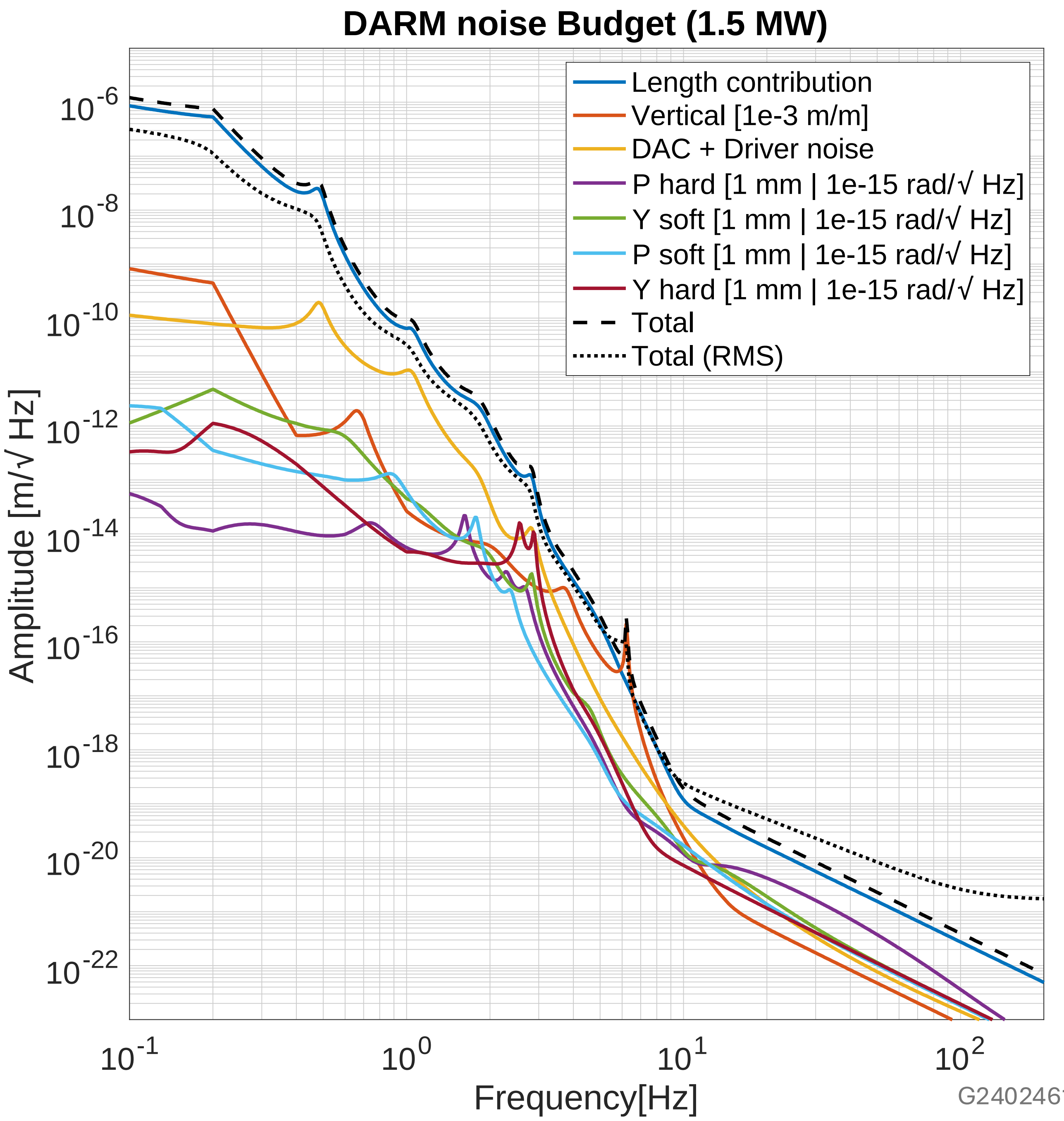
800 kW ASC performance





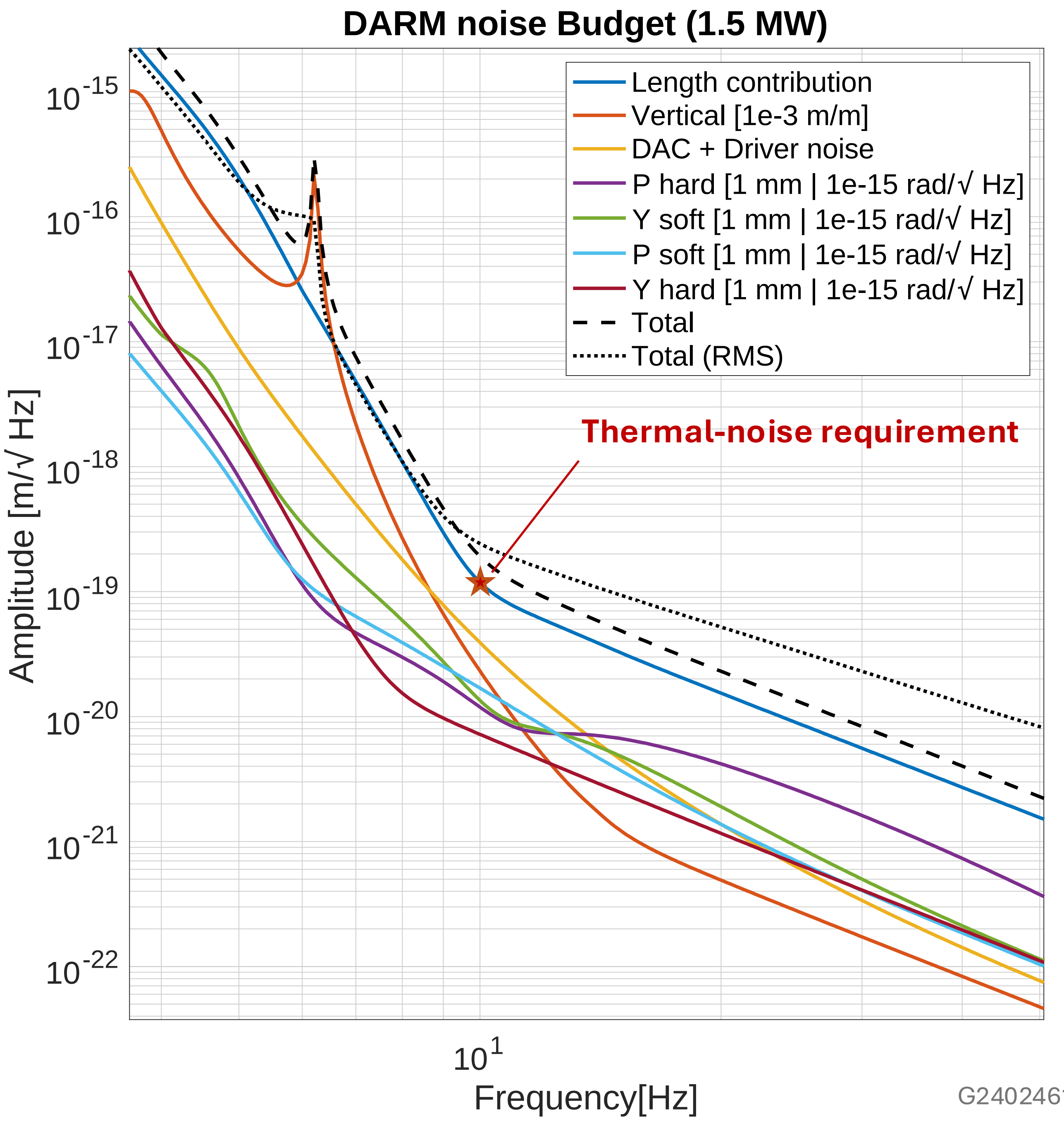
ASC takeaways (for now)

- At lower powers (less than 1 MW) it should be possible to damp the hard mode locally, simplifying the ASC loops.
- Building a reasonable controller for the well-damped angular plants (< 1 MW) is doable.
- At lower powers, the limiting factor is likely to be our ability to control the soft mode RMS.
- At 1.5 MW we must resort to more complicated controllers to deal with the hard Pitch degree of freedom.



Let's put it all together into a noise budget

- The main contributors to the noise that can be mitigated are:
  - ➢ The TST stage DAC noise
  - ➢ The P hard dof due to the undamped mode
  - ➢ The Y hard dof due to the poorly damped mode



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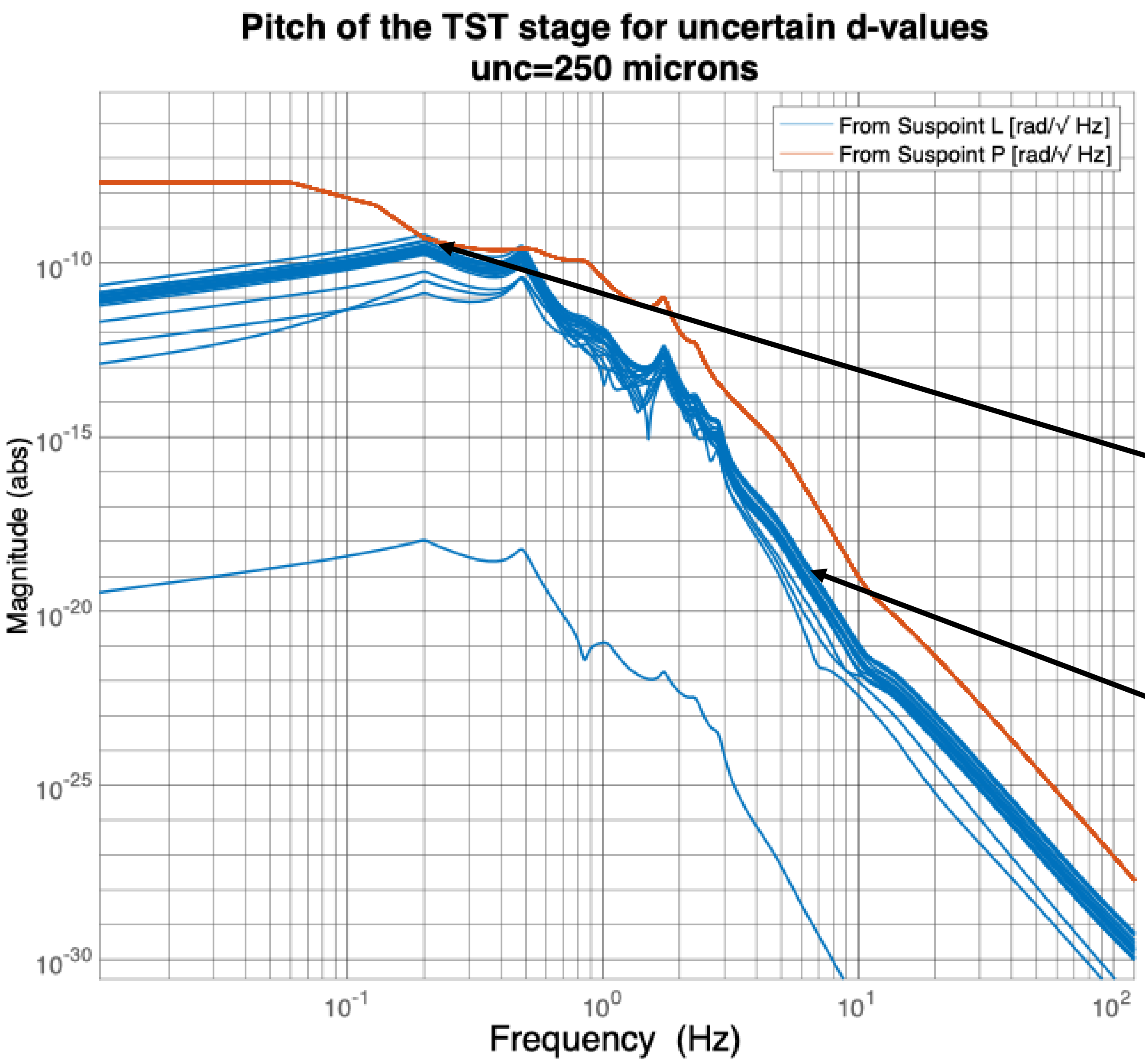
- **<u>Note:</u>** This assumes the scenario where the WFS noise is at the 1e-15 rad/Hz$^{1/2}$.

- **<u>Note:</u>** This assumes the dofs are well damped and decoupled

Caveats

- How much uncertainty can we tolerate on this design?
- Can we reduce the actuator noise?
- How good do the sensors need to be?

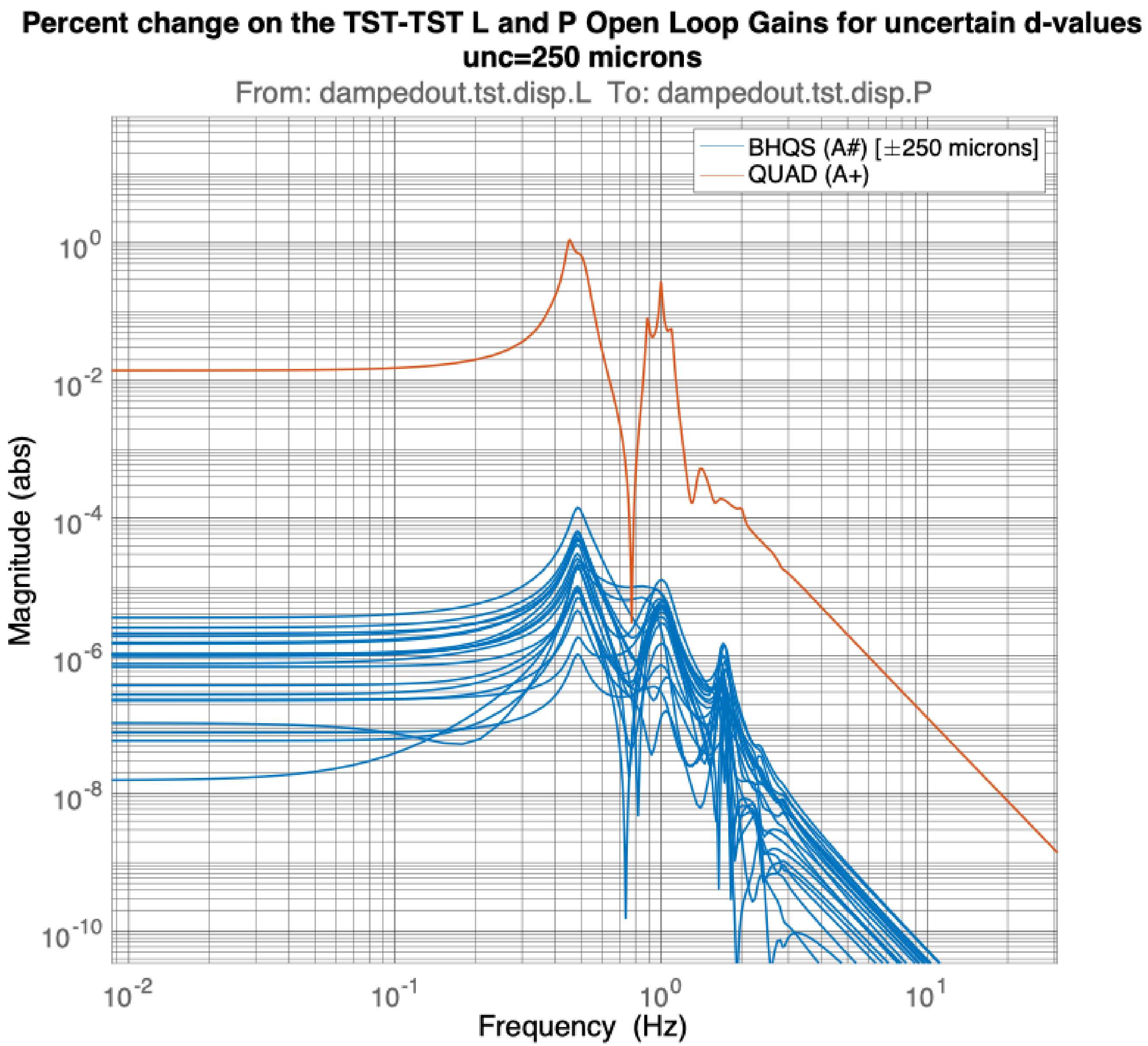
How much uncertainty?



Length-to-pitch cross-coupling

From ISI

- 250 μm tolerance is enough to ensure the Length-to-Pitch coupling is lower everywhere except for the microseism.
- The Length-to-Pitch coupling in this case is 100 times lower above the resonances, even when including the Length controls



How much uncertainty?

- 250 microns keeps the loop interaction on the 0.01% level.
- 1% is the limit of what we would consider "decoupled" (about 3cm for the BHQS)

In a 2x2 Multi-input / Multi-output system

L2L	P2L
L2P	P2P

the fraction

$$\boxed{\frac{(L2P)(P2L)}{(L2L)(P2P)}}$$

represents the fractional interaction between two **high-gain** Single-input / Single-output loops like the ones used for interferometric controls.

Caveats

- How much uncertainty can we tolerate on this design?

  About 250 microns on the d-values ⟶ Limited by microseism

  Loop decoupling resists d-value uncertainties of at least 1cm

- Can we reduce the actuator noise?

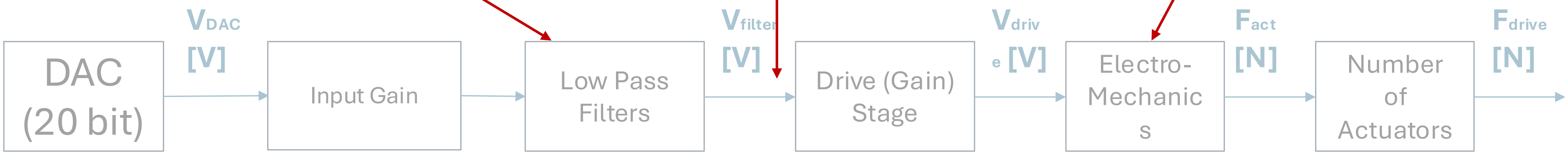
- How good do the sensors need to be?

About the actuator noise

1) We can tune up the low pass stage

2) We will be limited by electronics noise here

3) We can consider reducing the authority. There is enough margin since the RMS is all low frequency anyways



TST	Instrumentation amplifier 2x signal | √2x noise	**2p @ 0.7 Hz 2z @ 20 Hz**	Gain 4x signal | 4x noise	**Gain [N/V] 2.9 E-8**	ESD quadrants 4x signal | √4x noise
PUM	Gain 2x signal | 2x noise	**2p @ 0.7 Hz 2z @ 20 Hz**	Differential Drive 2x signal | √2x noise	**Gain [N/V] 1.9 E-5**	Four OSEMs 4x signal | √4x noise
UIM	Gain 2x signal | 2x noise	**2p @ 0.7 Hz 2z @ 20 Hz**	Differential Drive 2x signal | √2x noise	**Gain [N/V] 1.4 E-3**	Two OSEMs 2x signal | √2x noise

Caveats

- How much uncertainty can we tolerate on this design?

  About 250 microns on the d-values → Limited by microseism

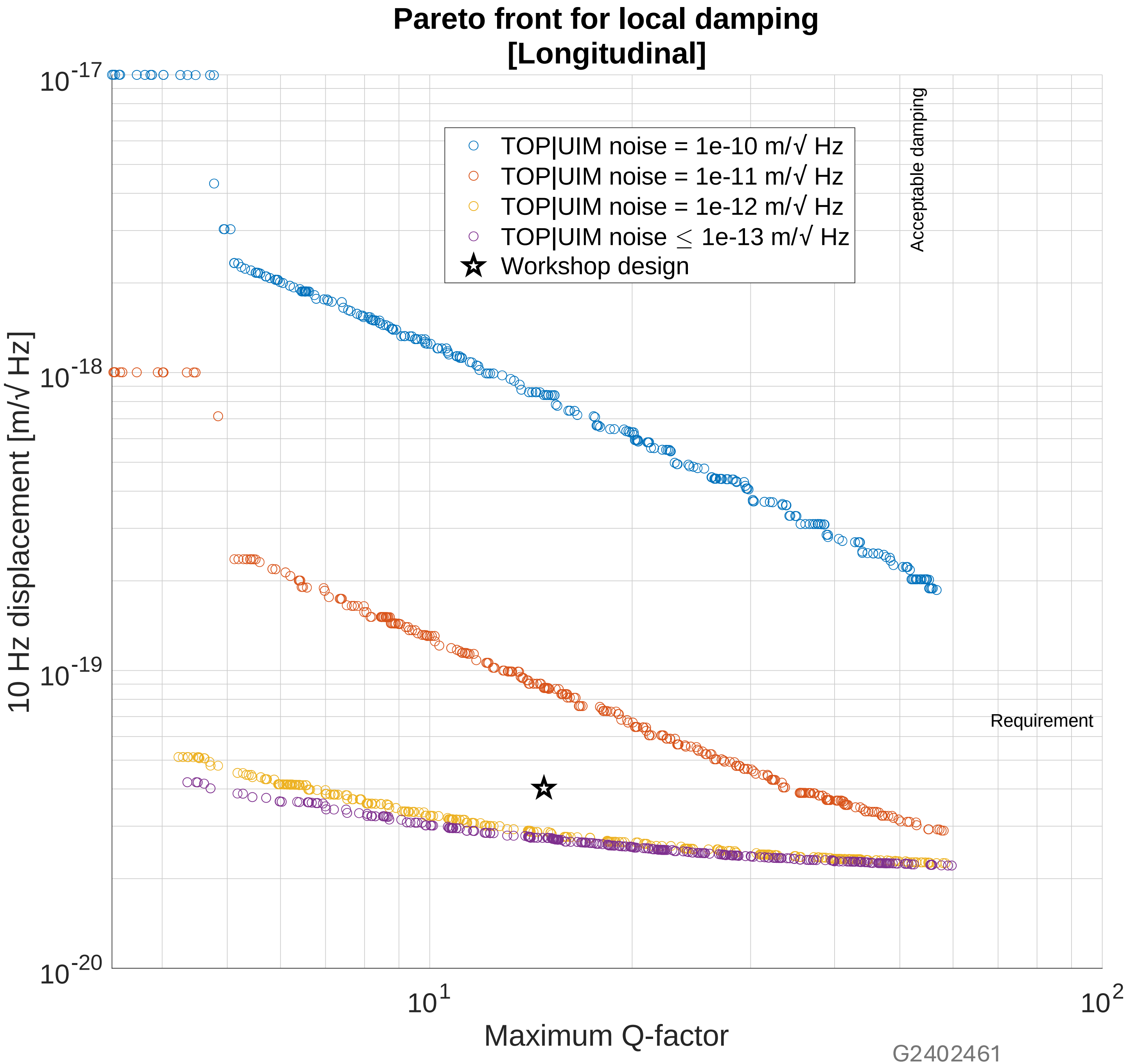
  Loop decoupling resists d-value uncertainties of at least 1cm

- Can we reduce the actuator noise?

  There should be enough margin to reduce the ESD's authority without saturating the DACs

  The noise comes from the TST stage, but most of the actuation RMS happens at the UIM.

- How good do the sensors need to be?

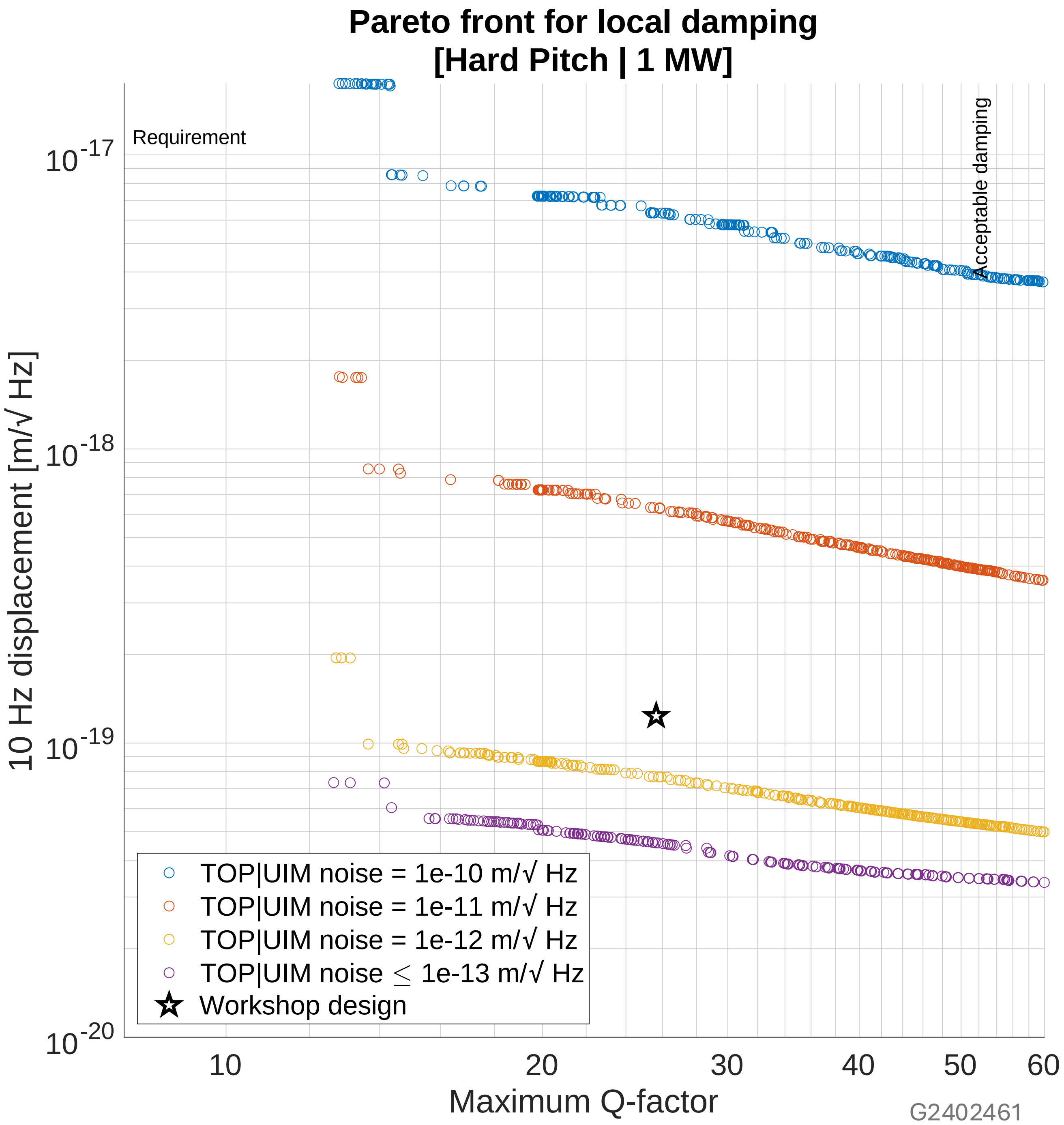


What noise for sensors?

Assumed controller:
2 real zeros at 0 Hz, 2 real poles , elliptic filter for rolloff.

For Longitudinal:

- Any sensor performing better than 1 e-13 $m/Hz^{1/2}$ will be limited by ISI noise.
- Sensors with noise above 3 e-11 $m/Hz^{1/2}$ are unlikely to meet our requirements
- A performance better than 5 e-12 $m/Hz^{1/2}$ is enough to rival the idealized calculations.

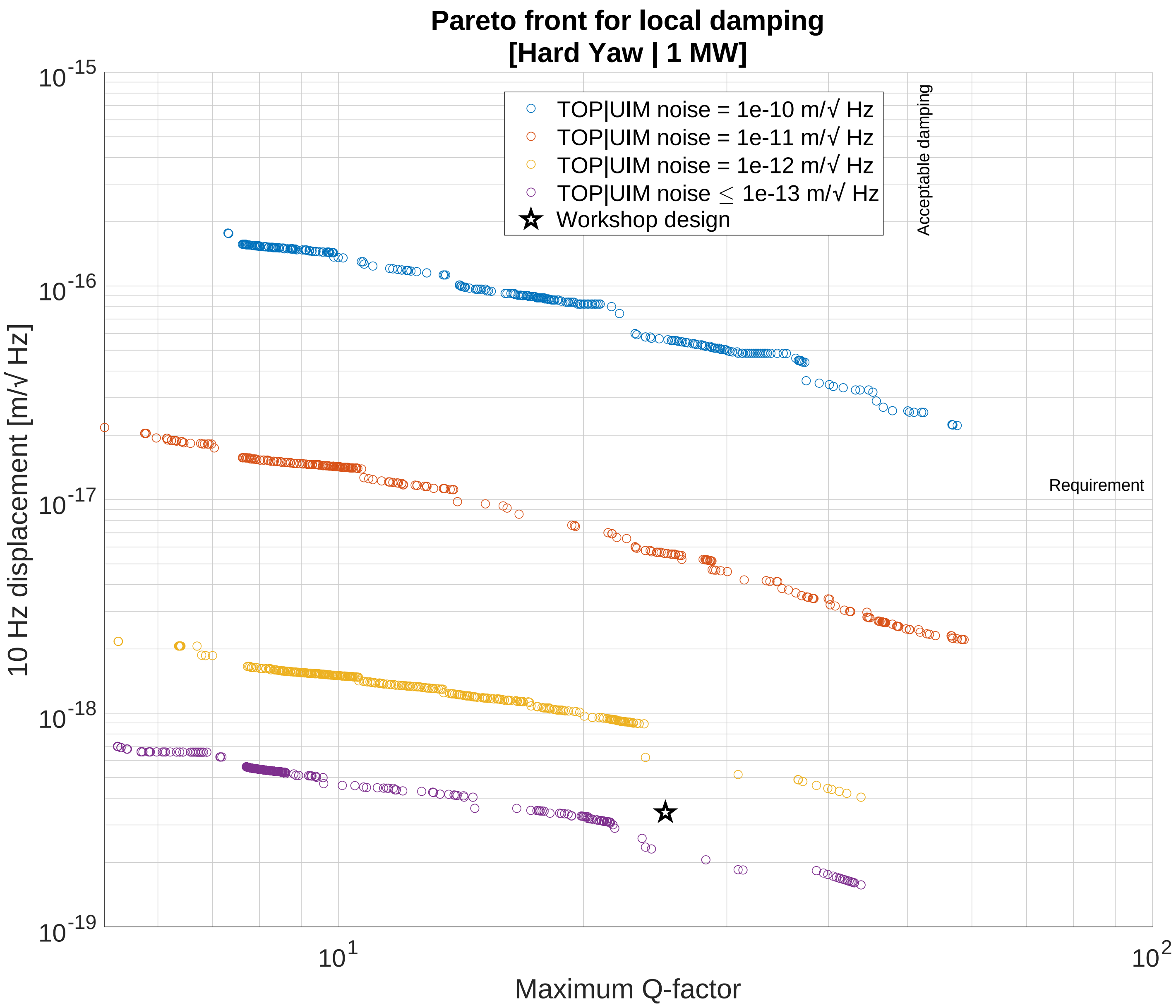


What noise for sensors?

Assumed controller:
2 real zeros at 0 Hz, 2 real poles , elliptic filter for rolloff.

For Pitch:

- Up to 1 MW, we should be able to pick sensors up to 1e-10 m/Hz$^{1/2}$.
- To get some margin, we would still prefer something below 1e-11 m/Hz$^{1/2}$.

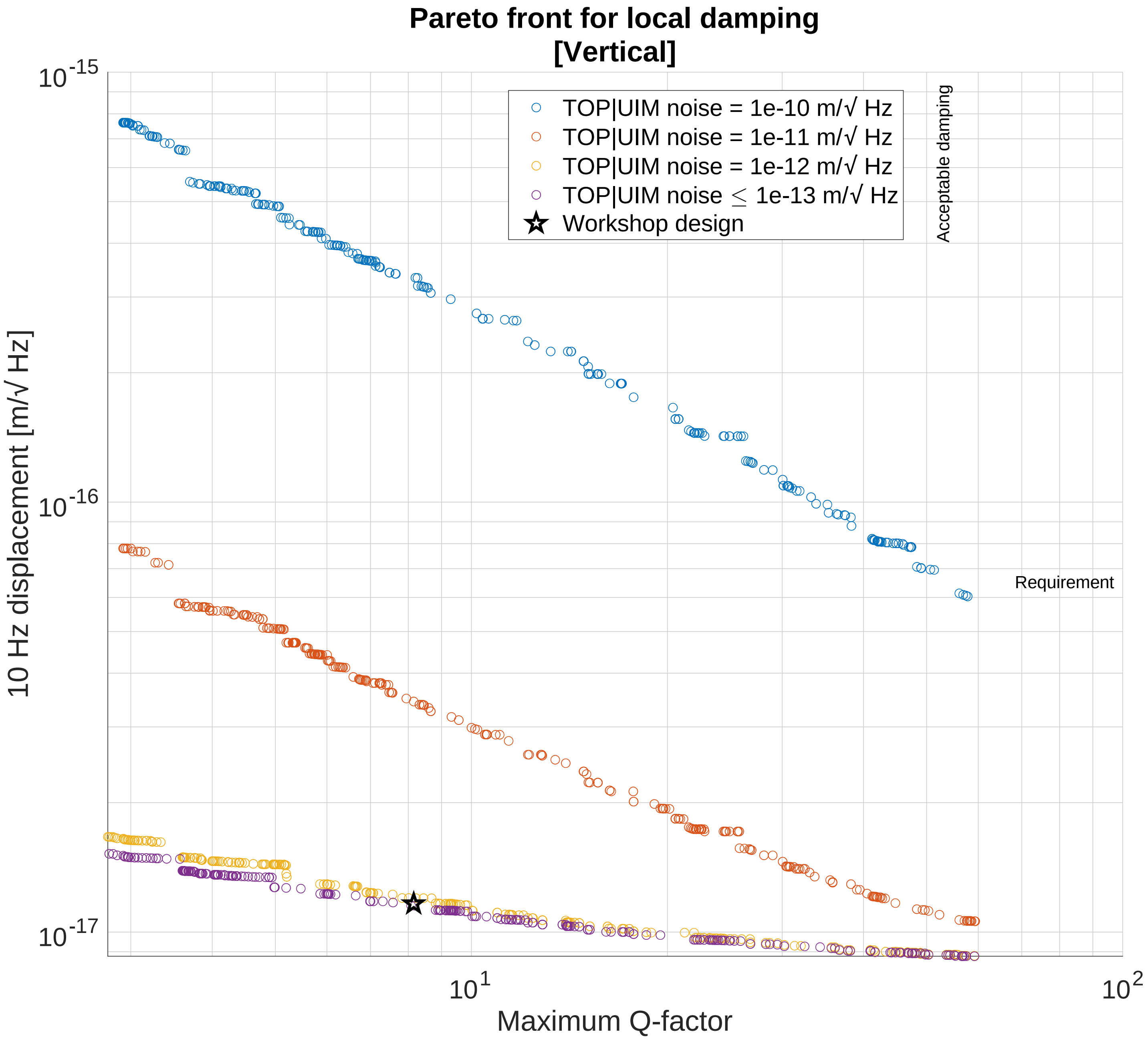


What noise for sensors?

Assumed controller:
2 real zeros at 0 Hz, 2 real poles , elliptic filter for rolloff.

For Yaw:

- We must use the UIM to aid with damping
- At 1 MW, we to damp the Yaw mode a sufficient amount, we want a sensor with noise below 1e-11 m/Hz$^{1/2}$.

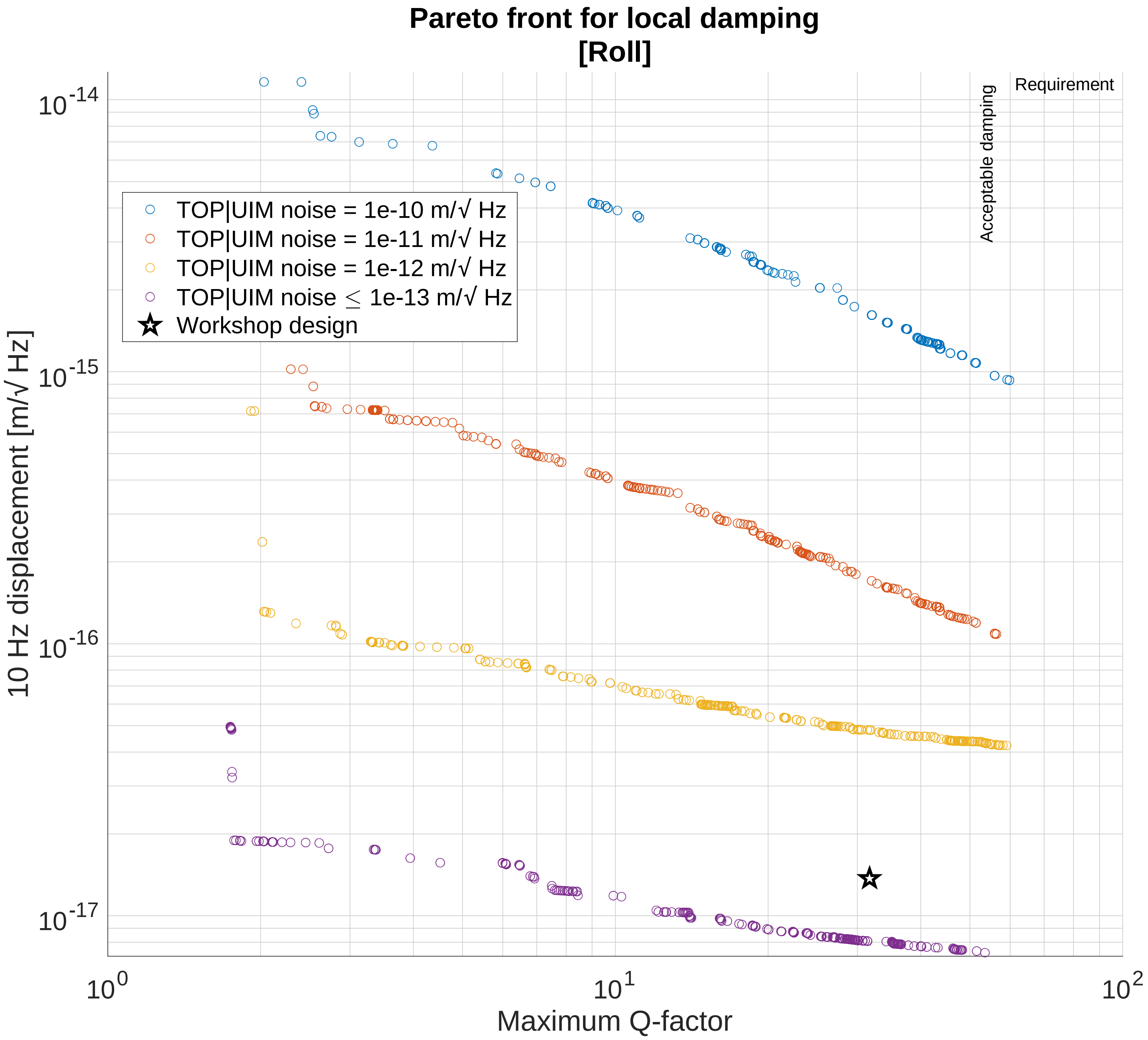


What noise for sensors?

Assumed controller:
2 real zeros at 0 Hz, 2 real poles , elliptic filter for rolloff.

For Vertical (excluding the bounce mode):

- Only the TOP mass is needed for good performance.
- A sensing noise lower than the 3e-11 m/Hz$^{1/2}$ would allow for a Q of around 20.

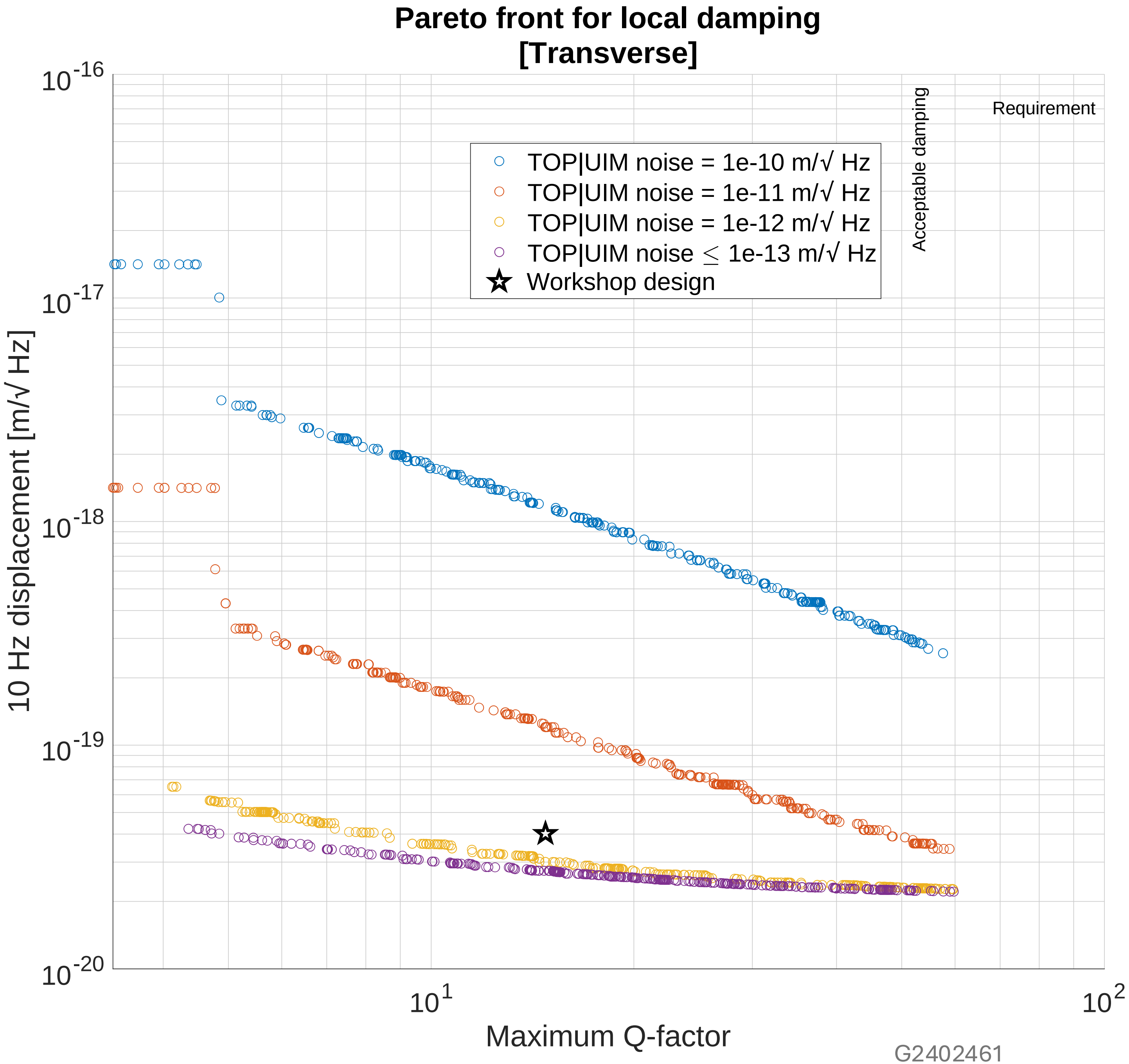


What noise for sensors?

Assumed controller:
2 real zeros at 0 Hz, 2 real poles , elliptic filter for rolloff.

For Roll (excluding the roll mode):

- We can piggyback from the other DOFs.
- The UIM is not required to achieve these loop performances.



What noise for sensors?

Assumed controller:
2 real zeros at 0 Hz, 2 real poles , elliptic filter for rolloff.

For Transverse (excluding the roll mode):

- We can piggyback from the other DOFs.

Caveats

- How much uncertainty can we tolerate on this design?

  About 250 microns on the d-values ⟶ Limited by microseism

  Loop decoupling resists d-value uncertainties of at least 1cm

- Can we reduce the actuator noise?

  There should be enough margin to reduce the ESD's authority without saturating the DACs

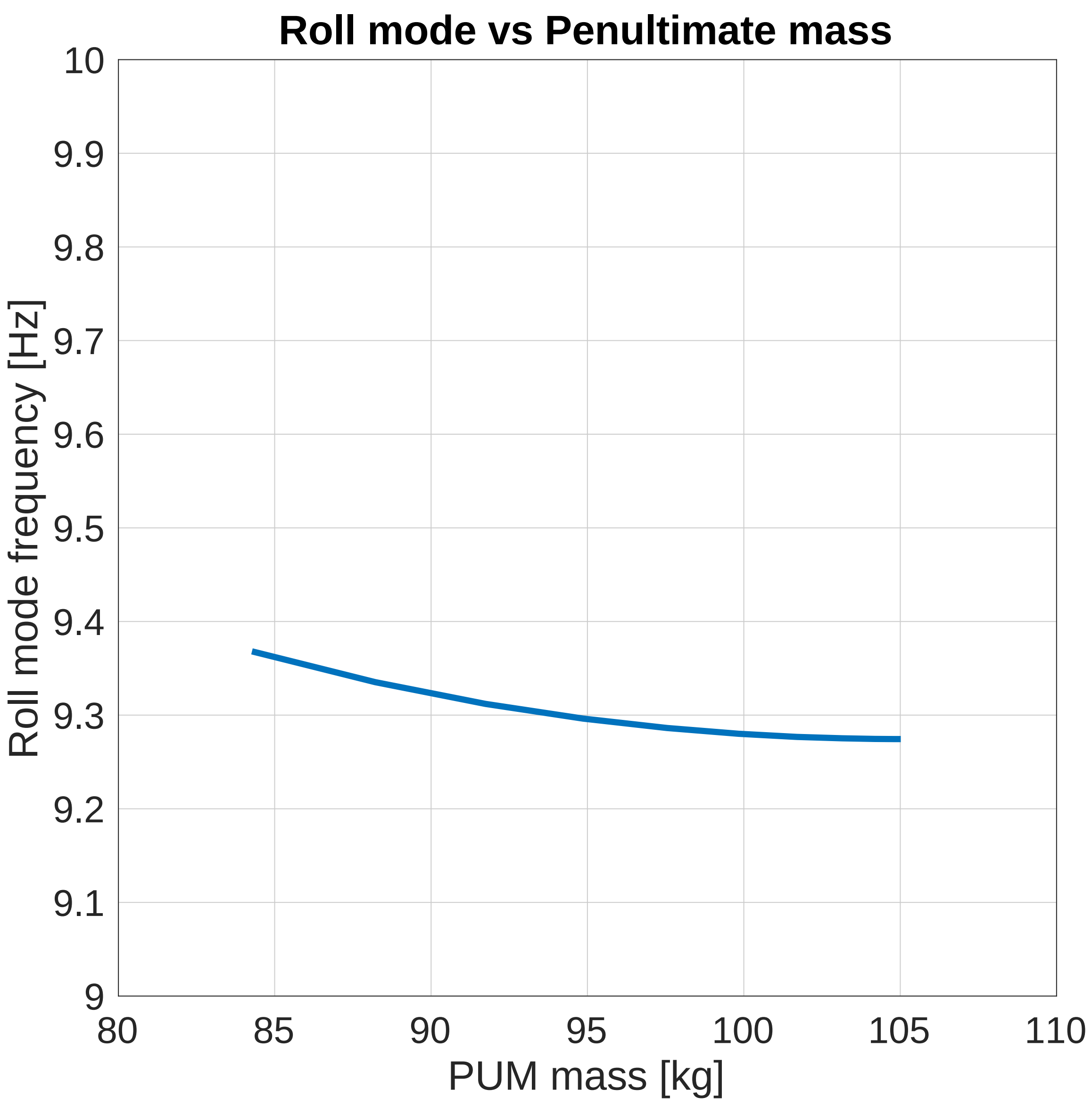
  The noise comes from the TST stage, but most of the actuation RMS happens at the UIM.

- How good do the sensors need to be?

Noise > 3e-11 m/Hz$^{1/2}$	Only for R, T
3e-11 m/Hz$^{1/2}$ > Noise > 1e-11 m/Hz$^{1/2}$	OK for all dofs (especially R,T,V)
1e-12 m/Hz$^{1/2}$ > Noise > 5e-13 m/Hz$^{1/2}$	Good enough for all dofs
1e-12 m/Hz$^{1/2}$ > Noise > 5e-13 m/Hz$^{1/2}$	Great
5e-13 m/Hz$^{1/2}$ > Noise > 5e-13 m/Hz$^{1/2}$	Excellent (we should improve the ISIs now)

Last minute things that we might want to consider

- Accurate assessment of the Roll mode frequency.
- Should we trade off Roll mode for Longitudinal isolation?
- What if we increased the mass of the test mass to 105 kg?
- What about trading Pitch at low frequencies for damping the Pitch hard mode?
- Should we change the orientation of the blade springs?



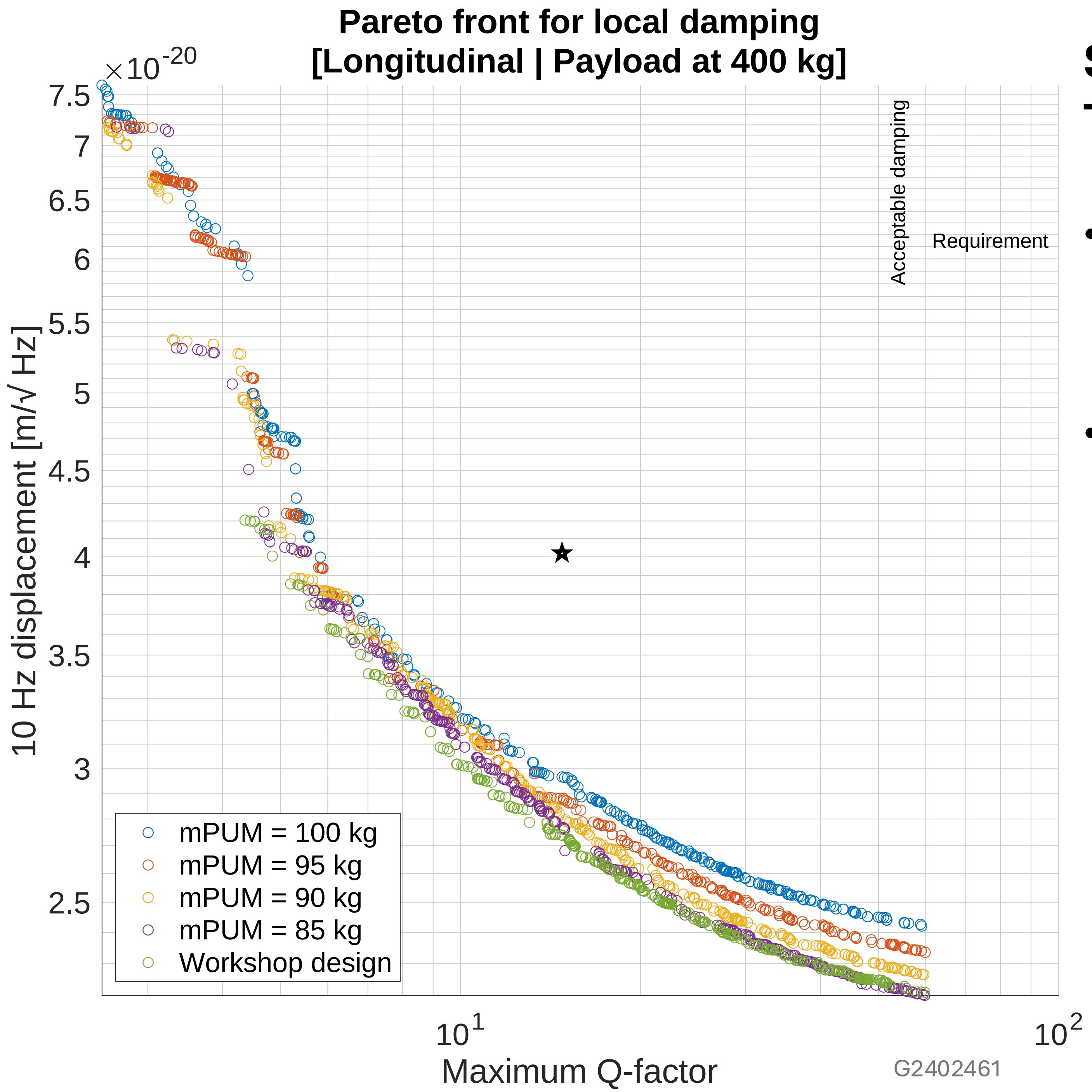
Should we trade off with the roll mode?

- Taking into account the effect of the nulling region for the fibers sets the roll mode at around 9.3 Hz.
- Changing the mass of the PUM in a ‘donut’ pattern has little effect on this.

Recommendation:

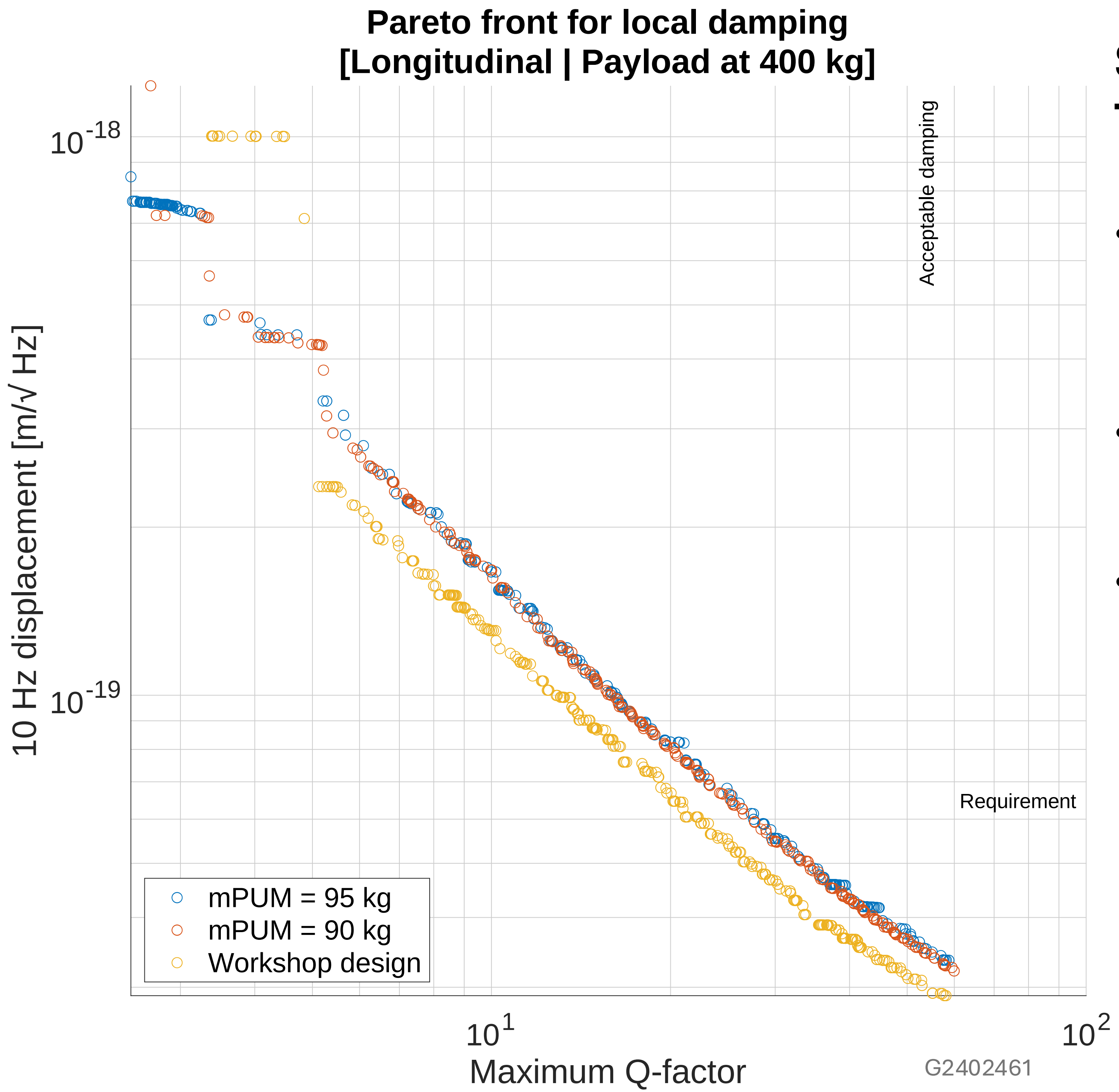
Only trade off if something would greatly benefit (Length | Pitch | Yaw)

Not very worth the risk since the $f_{Roll} > 9$ Hz



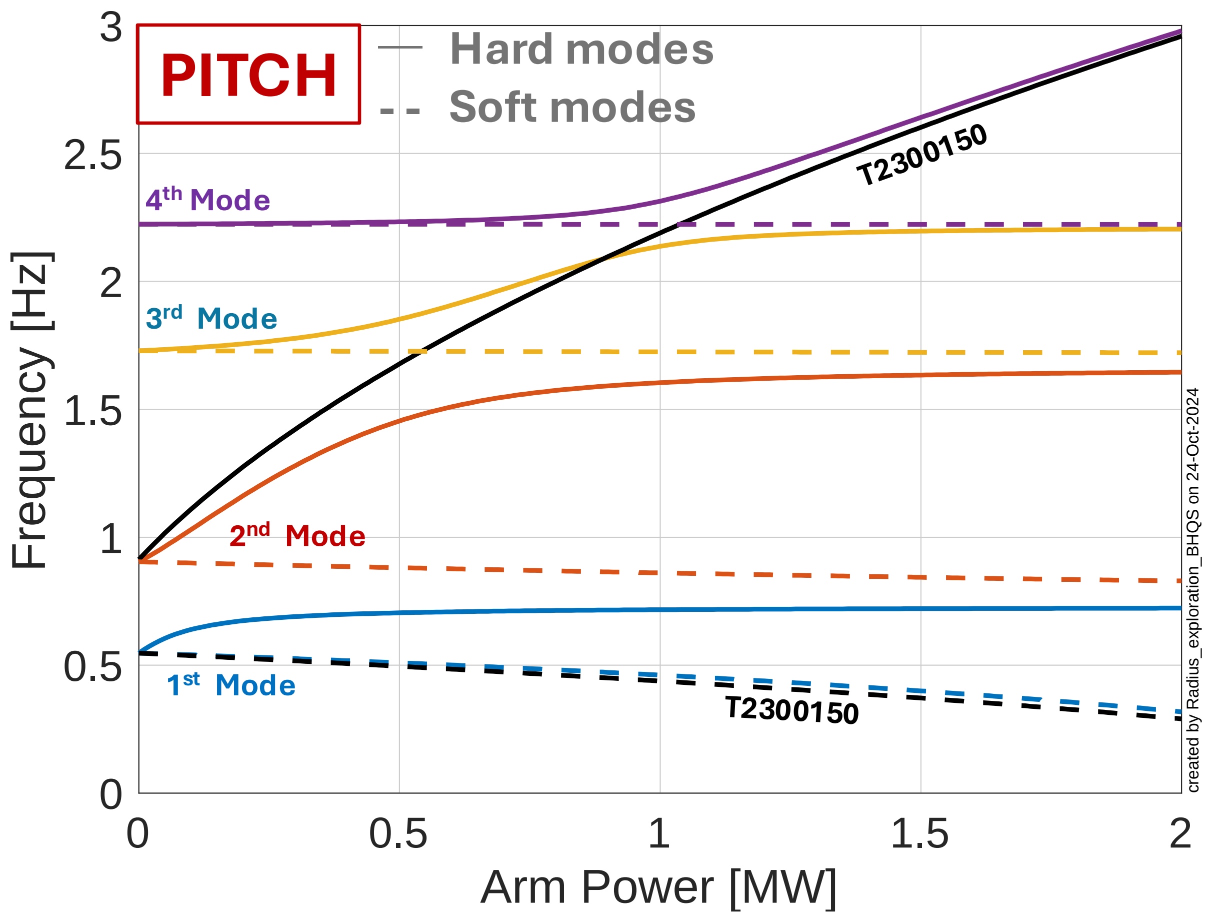
Should we increase the mass of the TST stage?

- We get marginally worse longitudinal performance <u>unless</u> we increase the payload proportionally.
- Payload should be 420 kg if we want to retain Longitudinal isolation.



Should we increase the mass of the TST stage?

- We get marginally worse longitudinal performance unless we increase the payload proportionally.
- If we added 1e-11 m/Hz$^{1/2}$ sensor noise the situation looks equally compromised.
- Payload should be 420 kg if we want to retain Longitudinal isolation.



$$f_{4,\mathrm{hard}} \approx \frac{1}{2\pi}\sqrt{\frac{k_{\mathrm{hard}} + k_4}{I_4}}$$

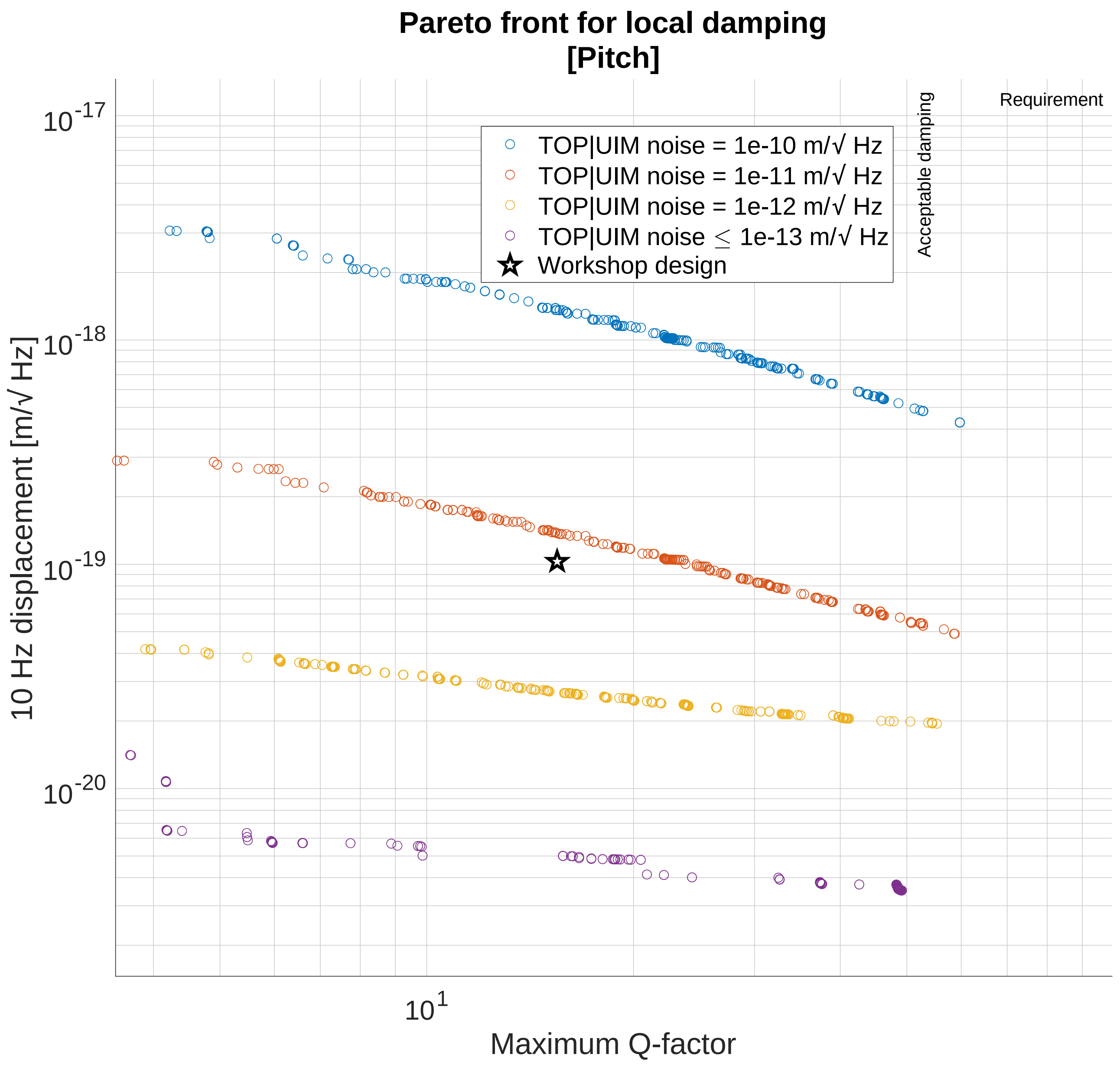
Should we increase the mass of the TST stage?

- We get marginally worse longitudinal performance unless we increase the payload proportionally.
- If we added 1e-11 m/Hz$^{1/2}$ sensor noise the situation looks equally compromised.
- Payload should be 420 kg if we want to retain Longitudinal isolation.
- Moving to 105 kg results in a 2.5 % reduction in the Pitch hard mode frequency at 1.5 MW

Recommendation:

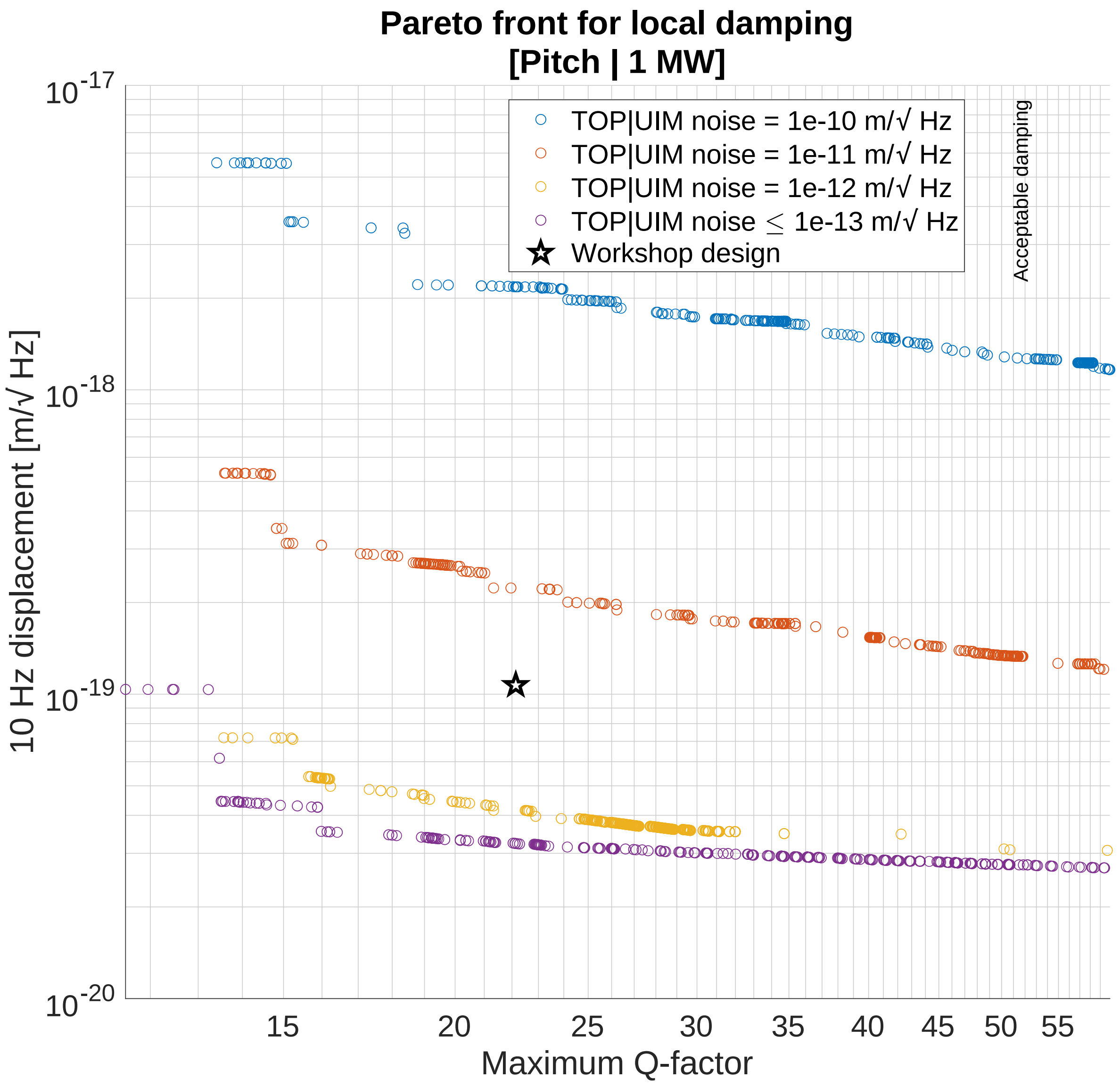
Increase proportional to the payload if possible.

Unless 2.5% change in the hard mode is worth it



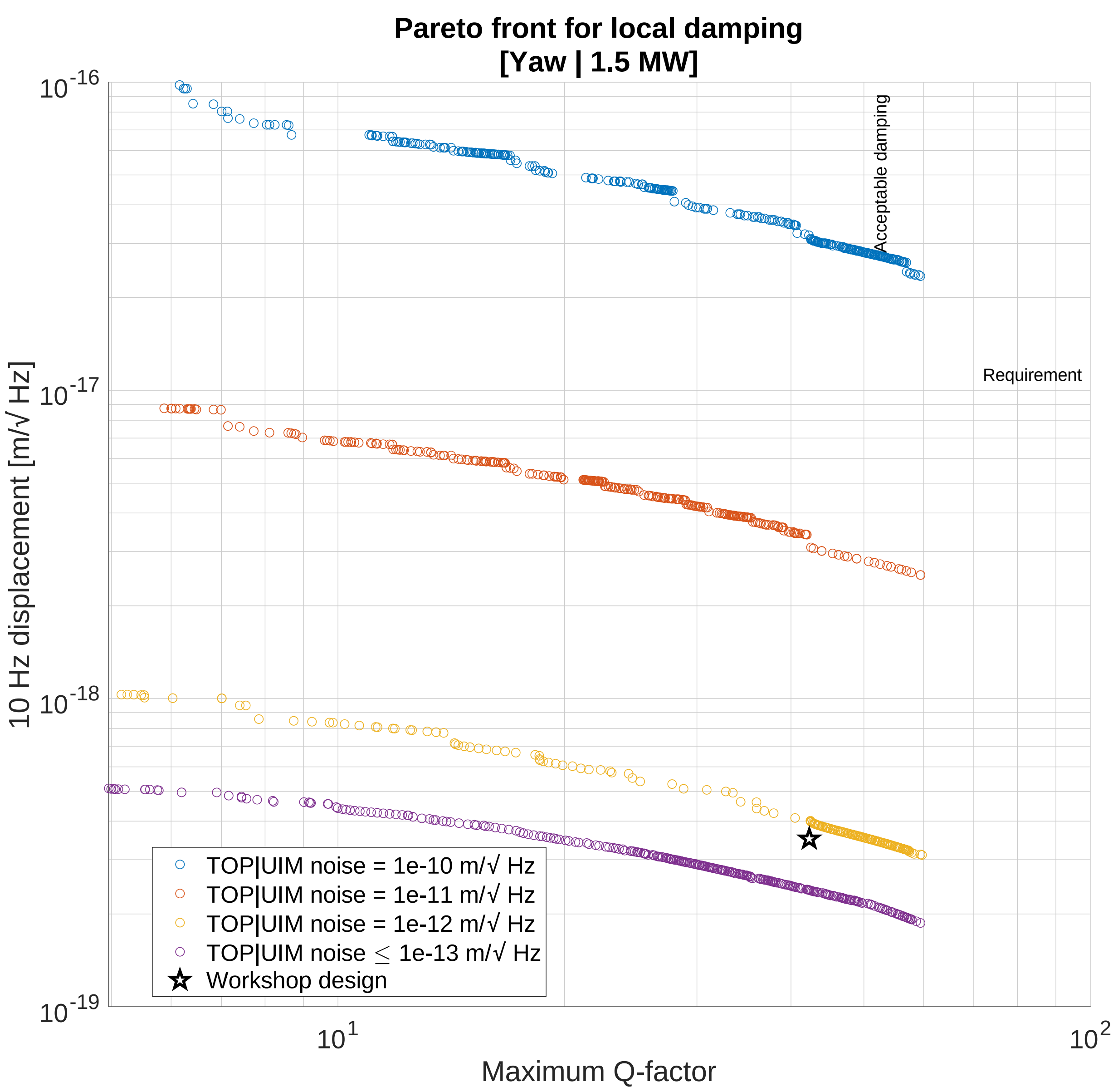
Trade off to better damp the hard Pitch mode?

- The Pitch plant is optimized to be easy to damp in any sensor noise condition at 0 W.



Trade off to better damp the hard Pitch mode?

- The Pitch plant is optimized to be easy to damp in any sensor noise condition at 0 W.
- We are in good shape (Q of 14 or so) with 1e-11 m/Hz$^{1/2}$ sensors up to 1 MW with some tuning of the local damping.
    - By 1.2 MW it is unfeasible to keep the Q below 20 with local damping



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- We are in good shape (Q of 14 or so) with 1e-11 m/Hz$^{1/2}$ sensors up to 1 MW with some tuning of the local damping.
  - By 1.2 MW it is unfeasible to keep the Q below 20 with local damping
- In contrast, Yaw can be damped to a Q of 8 while meeting the requirements with 1e-11 m/Hz$^{1/2}$

Recommendation:

Target an ‘easy to operate’ power over which we want low Qs.

Design with less margin to locally damp for longer

General conclusions

- The conceptual design of the BHQS is finalized.
  - Hopefully, all modes below 10 Hz.
  - It should perform without issues until 800 kW – should be easy to work at 1 MW power.
  - The ASC is challenging past that up to 1.5 MW

- We have a tool to compare (and codesign) damping with suspension designs. [15 second runtime per design]

- We established tolerances for the d values (0.25 mm)
- We established a target for the suspension sensors:
  - 3e-11 $m/Hz^{1/2}$ > Noise > 1e-11 $m/Hz^{1/2}$ OK for all dofs (especially R,T,V)
  - 1e-12 $m/Hz^{1/2}$ > Noise > 5e-13 $m/Hz^{1/2}$ Good enough for all dofs
  - 1e-12 $m/Hz^{1/2}$ > Noise > 5e-13 $m/Hz^{1/2}$ Great
  - 5e-13 $m/Hz^{1/2}$ > Noise > 5e-13 $m/Hz^{1/2}$ Excellent (we should improve the ISIs now)