Advanced LIGO Suspensions and Control

Brett Shapiro

For the Suspensions group

LITRAb – IUCAA

19-21 Dec 2016

G1602410

Advanced LIGO Suspensions and Control

- Monday – Part I: Suspension overview
- Tuesday – Part II: Focus on suspension controls

Advanced LIGO Suspensions and Control

- Monday – Part I: Suspension overview
- Tuesday – Part II: Focus on suspension controls

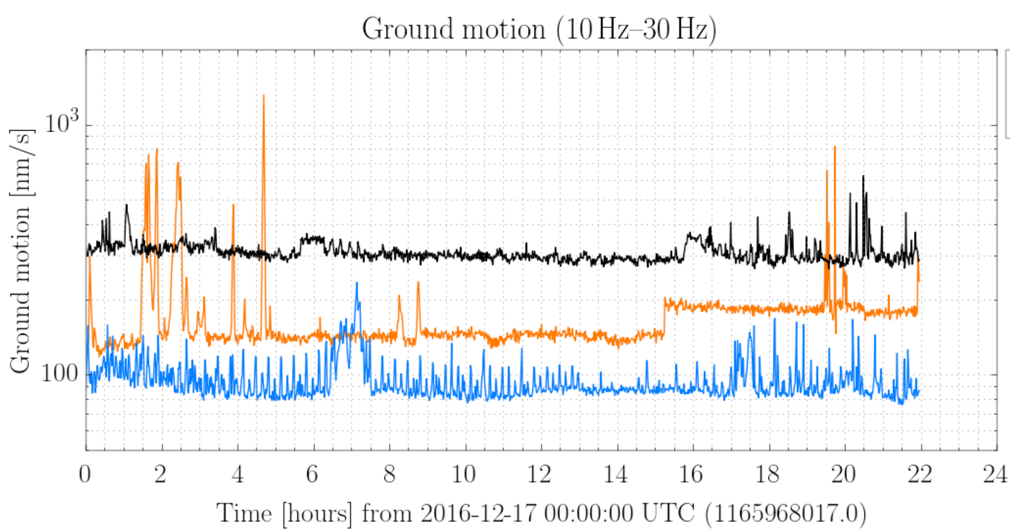
NOTE: It is tempting to think of the suspension and its controls as two separate systems, but really they are a **single system**. A suspension is *designed and built to be controlled*.

Part I – Suspension Overview

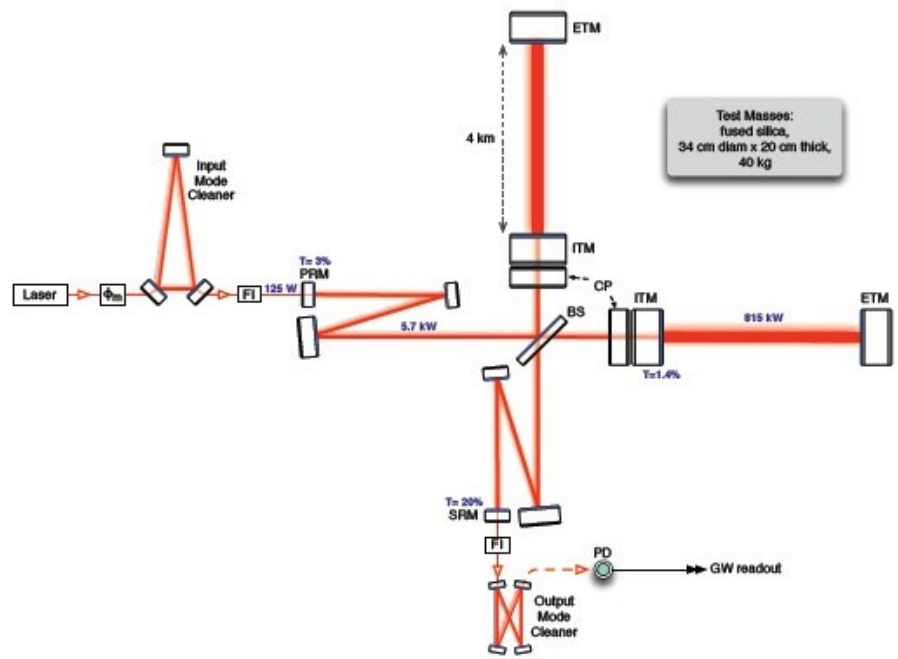
- Description of the suspensions
- How to build a working suspension
  - Assembling, testing, debugging
  - Things to watch out for
- Models – MATLAB/Mathematics
- Examples of recent improvements
  - BRDs
  - Squeezed film damping mitigation

Why suspensions?

Isolate optics from ground vibrations

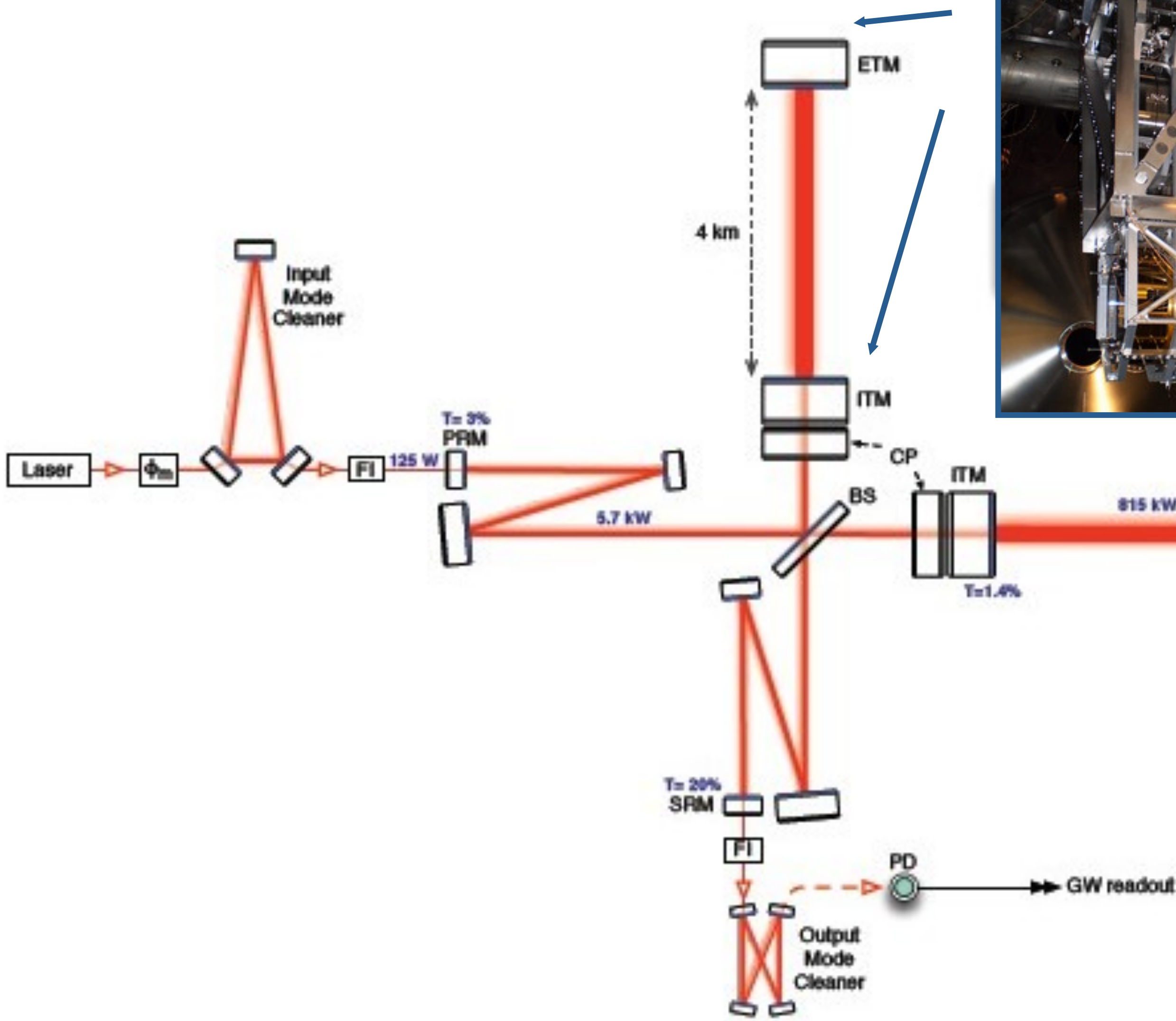


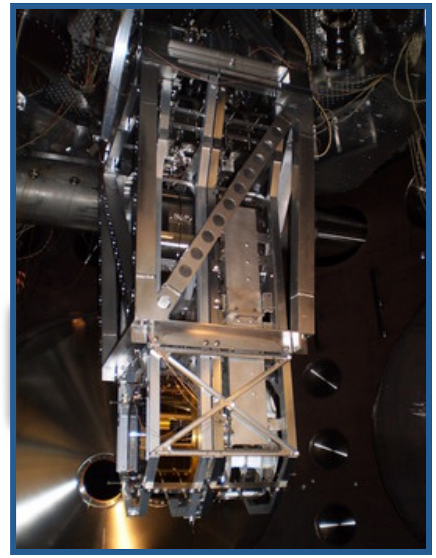
RMS seismic noise between 10 Hz and 30 Hz
Hanford December 17, 2016



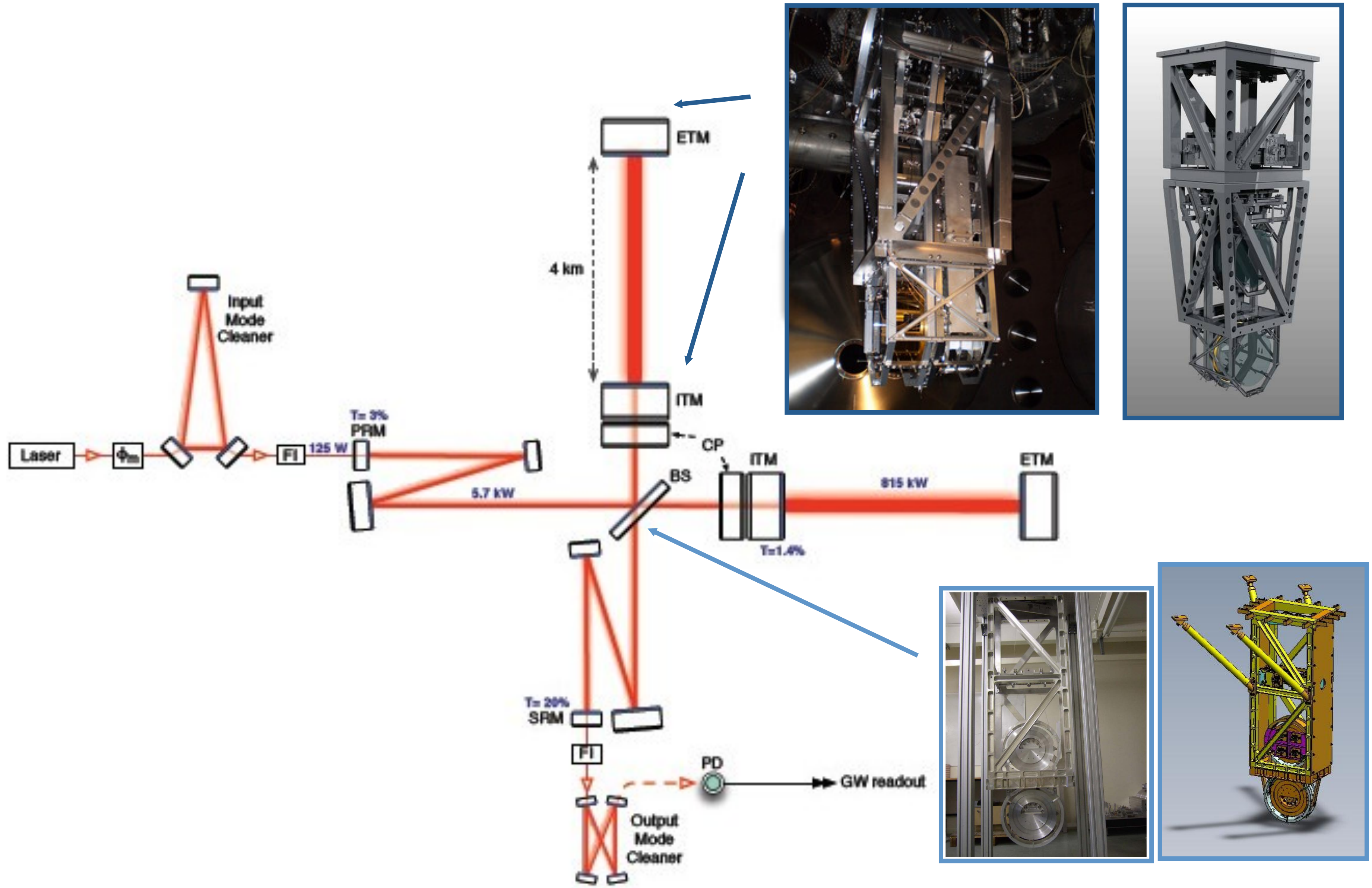
Advanced LIGO Optical Layout

Suspended Optics in Advanced LIGO



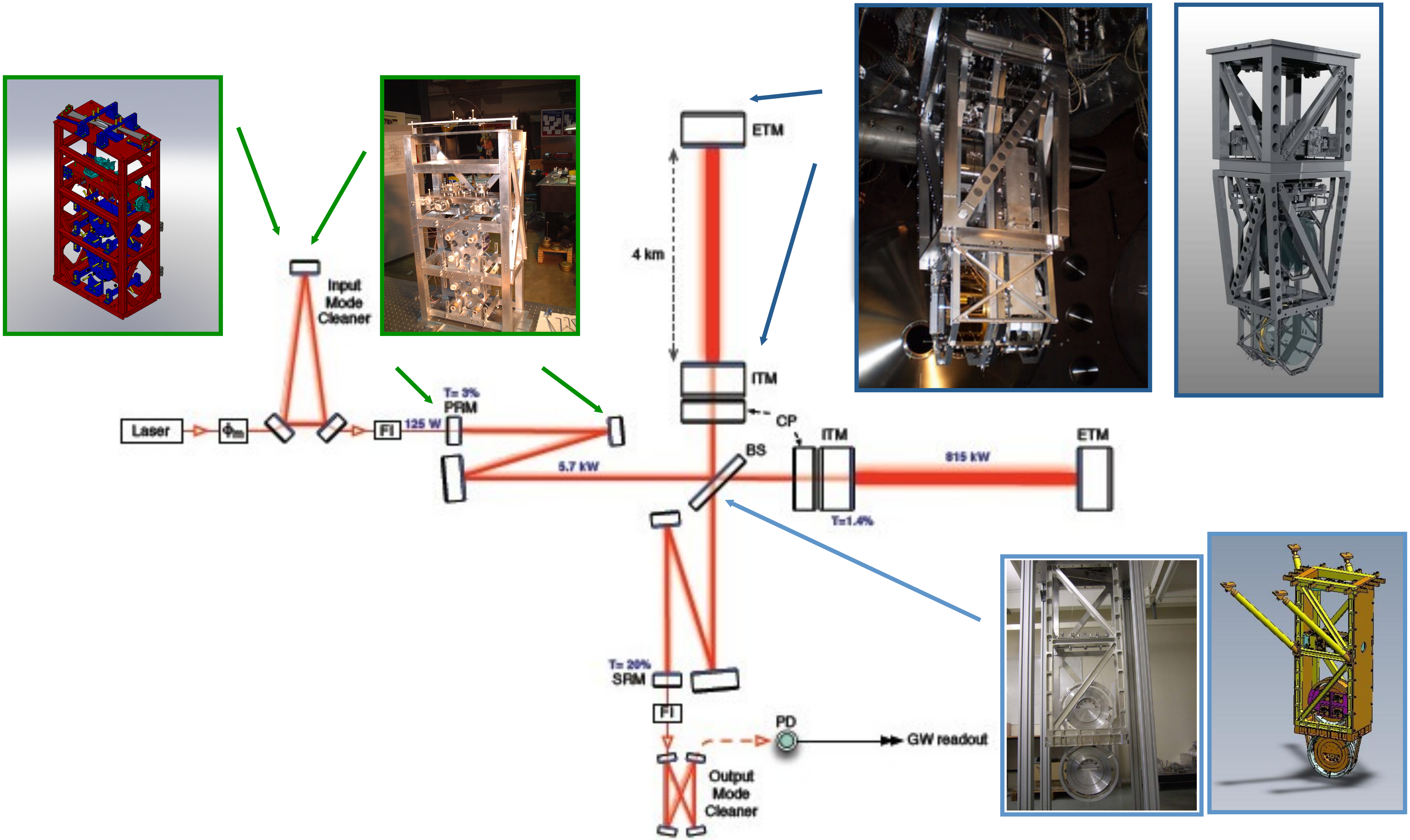


Suspended Optics in Advanced LIGO

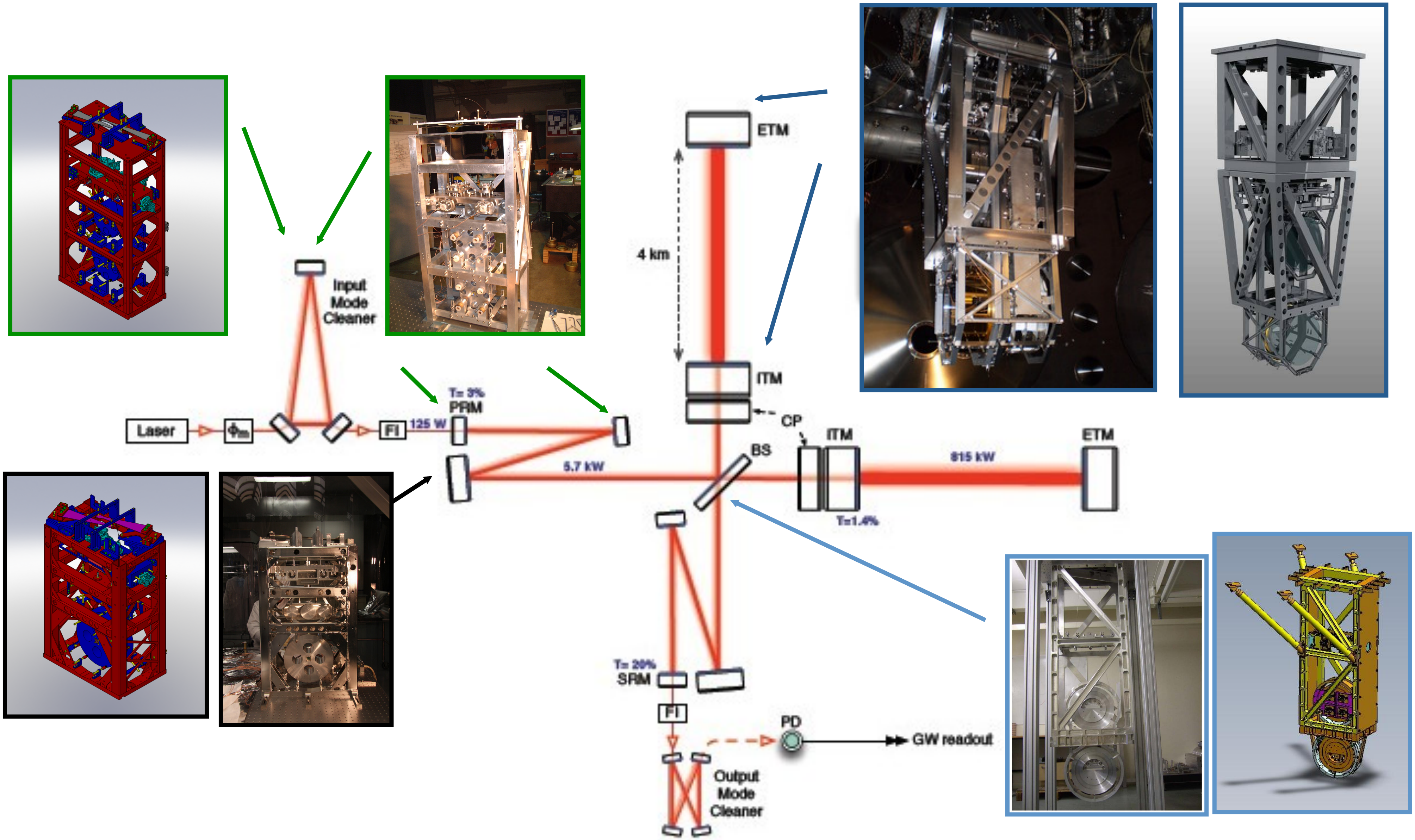


Ref: G1100434-v2

Suspended Optics in Advanced LIGO

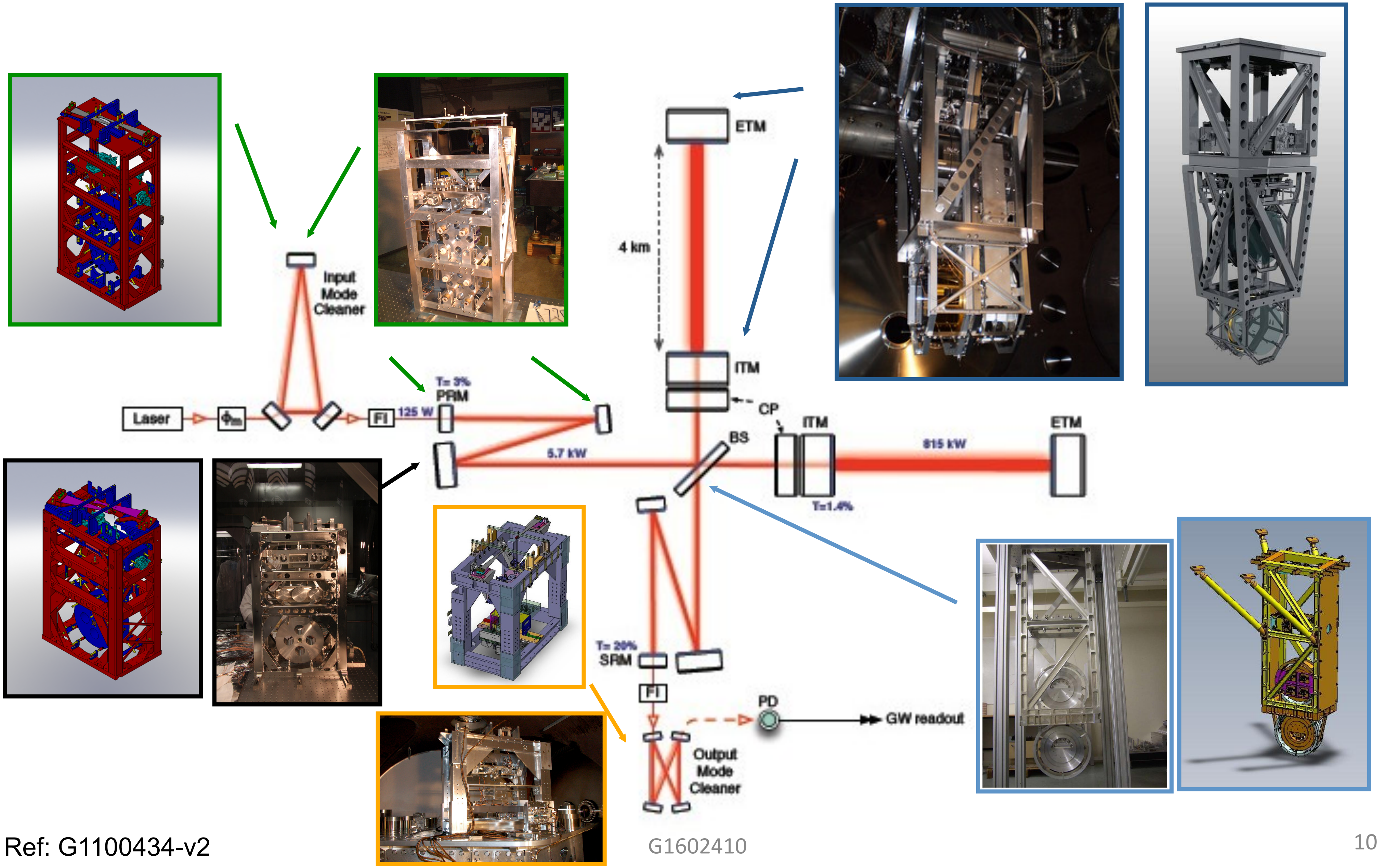


Suspended Optics in Advanced LIGO

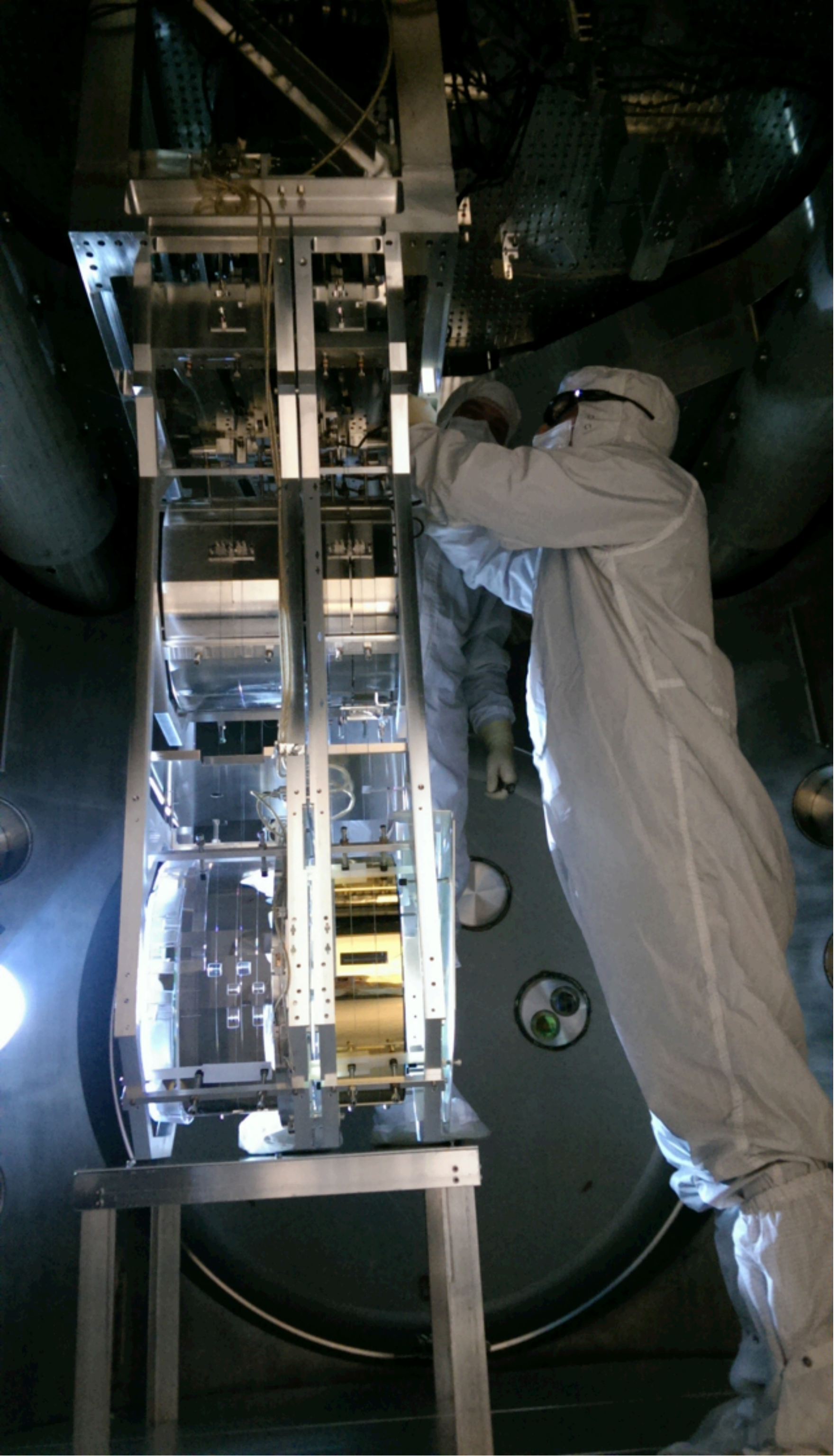


Ref: G1100434-v2

Suspended Optics in Advanced LIGO

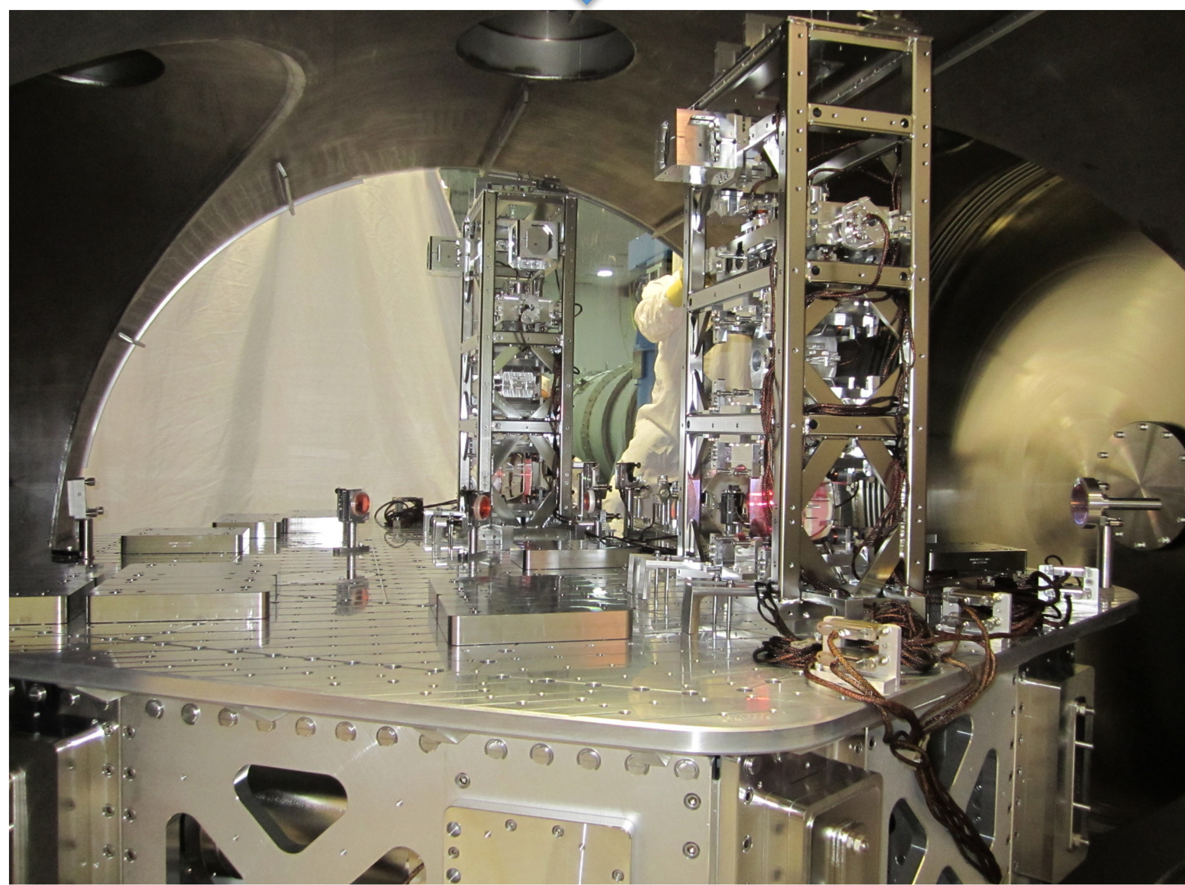


Ref: G1100434-v2

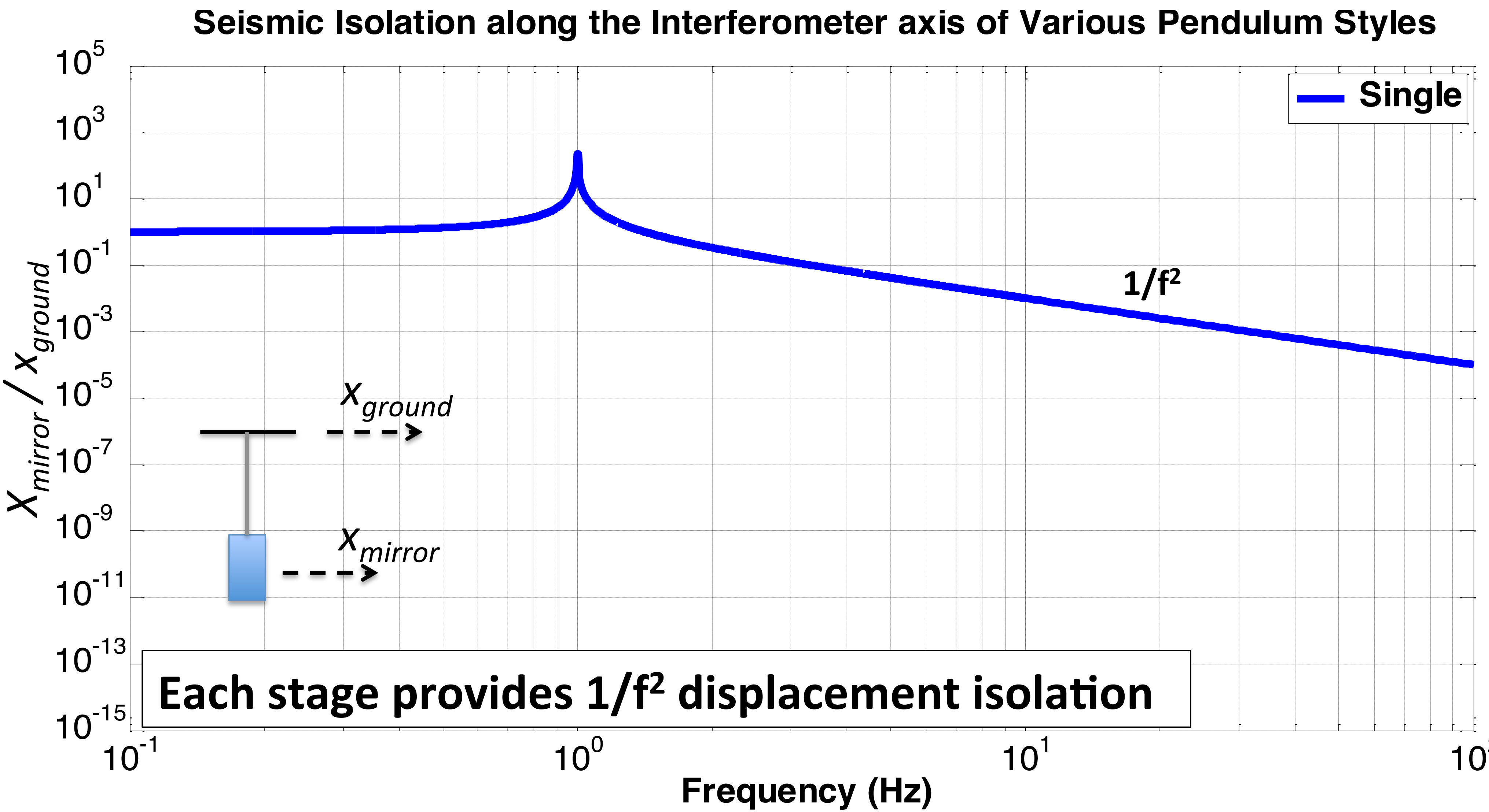


Test mass suspension on 2-stage in-vacuum isolation table

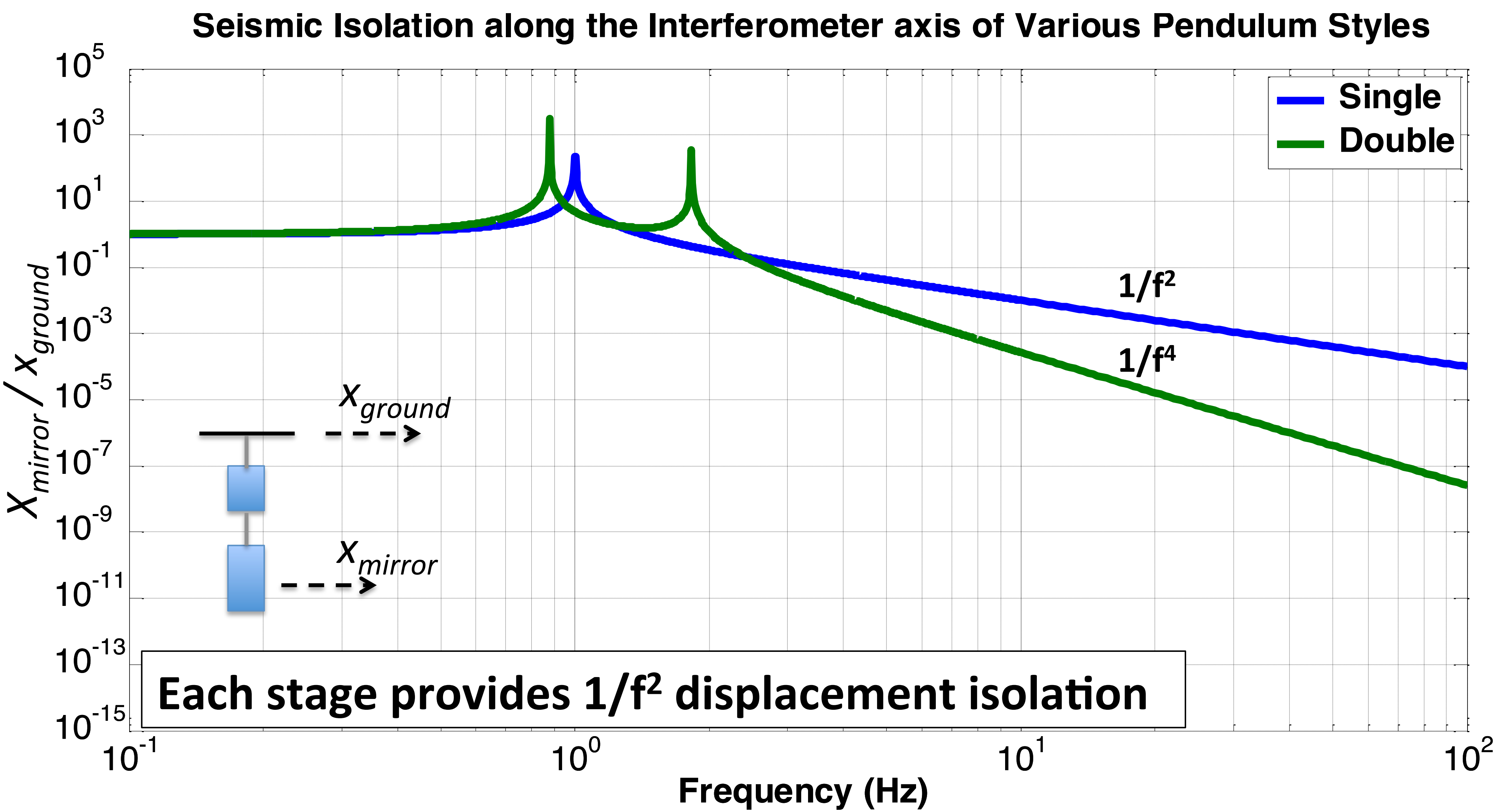
Auxiliary optics on 1-stage in-vacuum isolation table



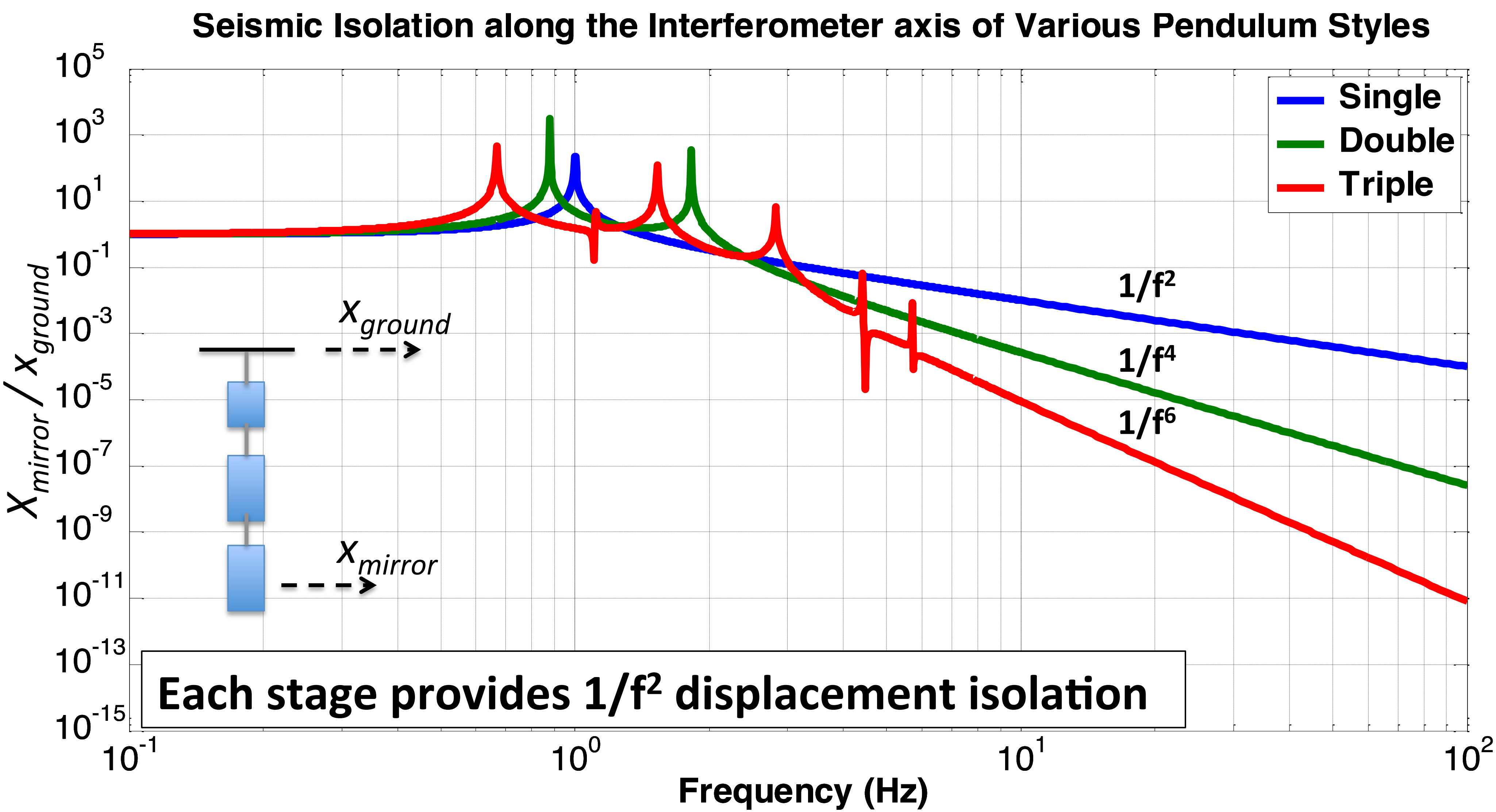
Multi-stage Isolation Performance



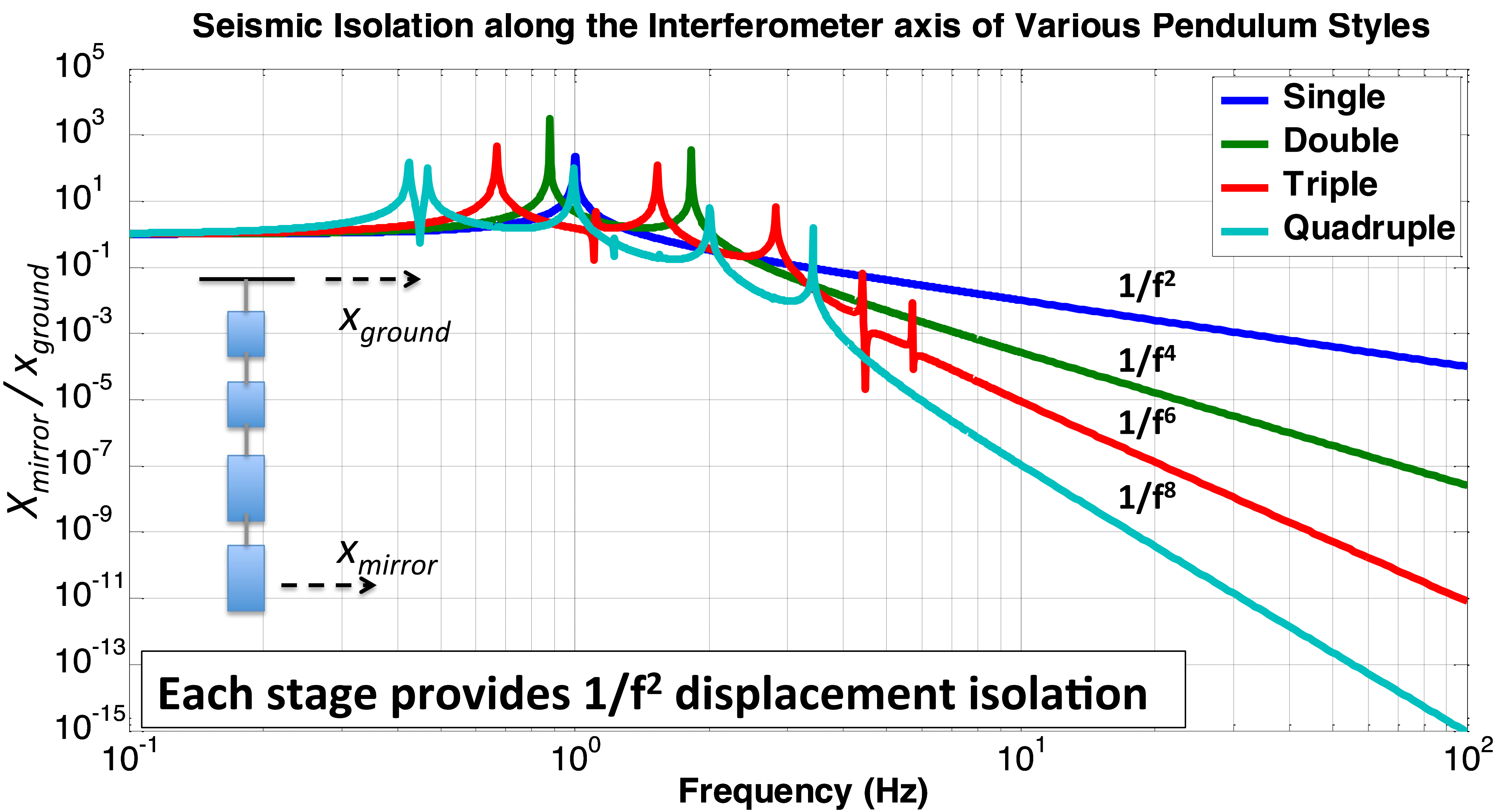
Multi-stage Isolation Performance



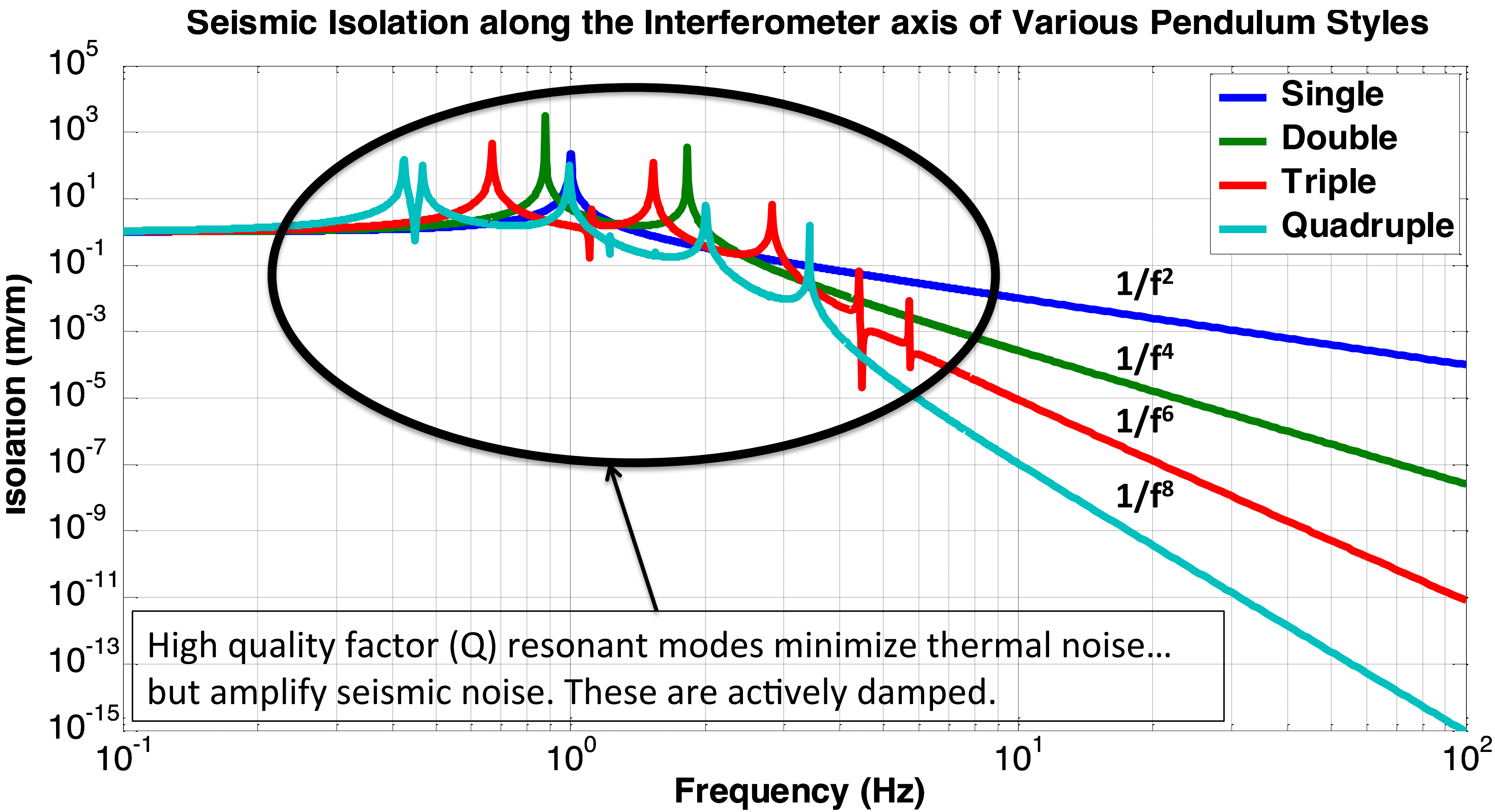
Multi-stage Isolation Performance



Multi-stage Isolation Performance

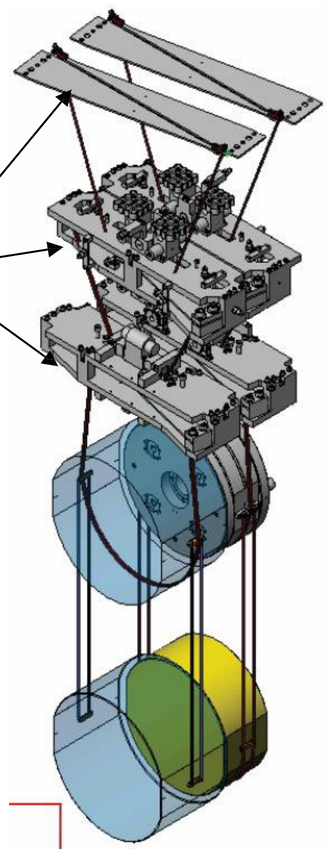


Multi-stage Isolation Performance



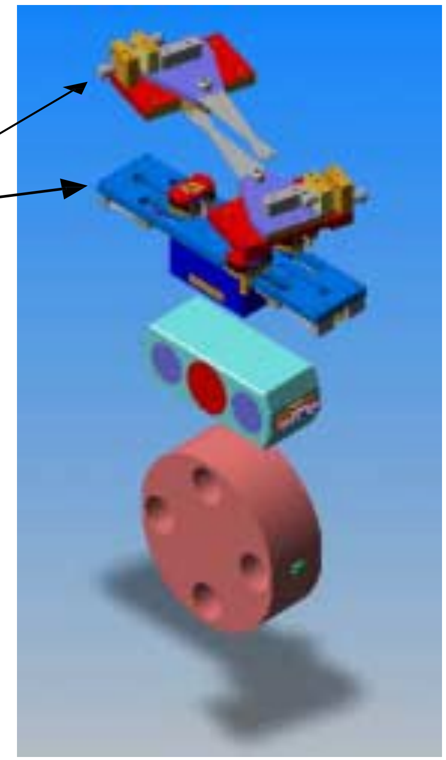
Cantilever blade springs

3 spring stages



Quads

2 spring stages

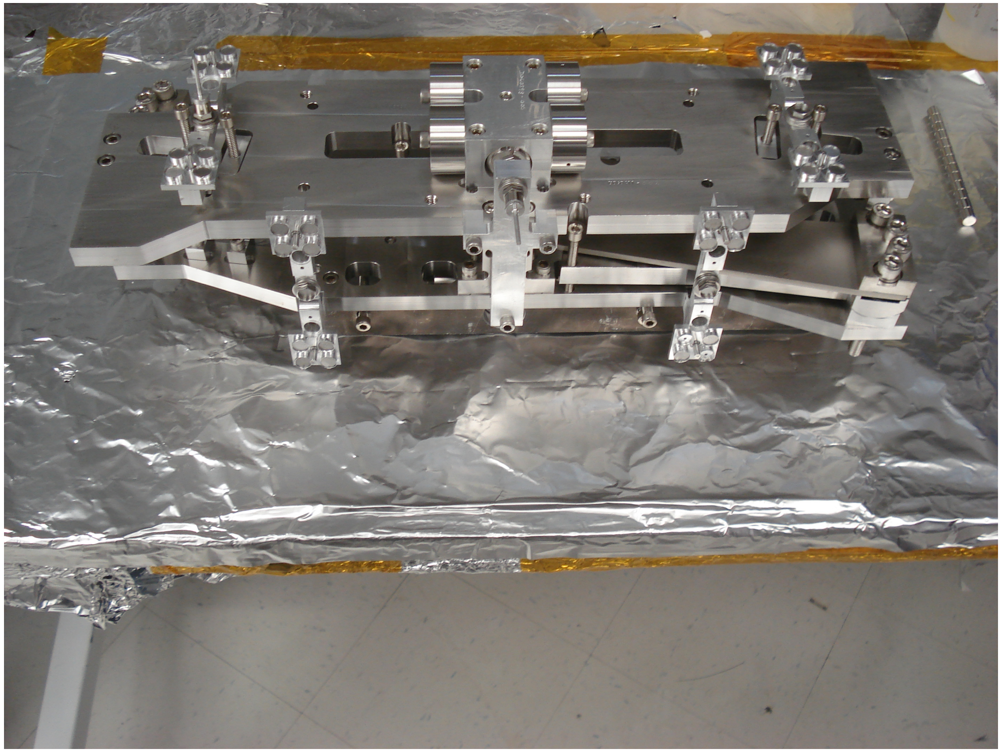


Triples

- Springs provide vertical isolation.
- No springs on lowest stages. Vertical isolation OK without them, also minimizes thermal noise. Lack of springs does produce problematic bounce & roll modes.

Cantilever blade springs

Quad top mass partial assembly

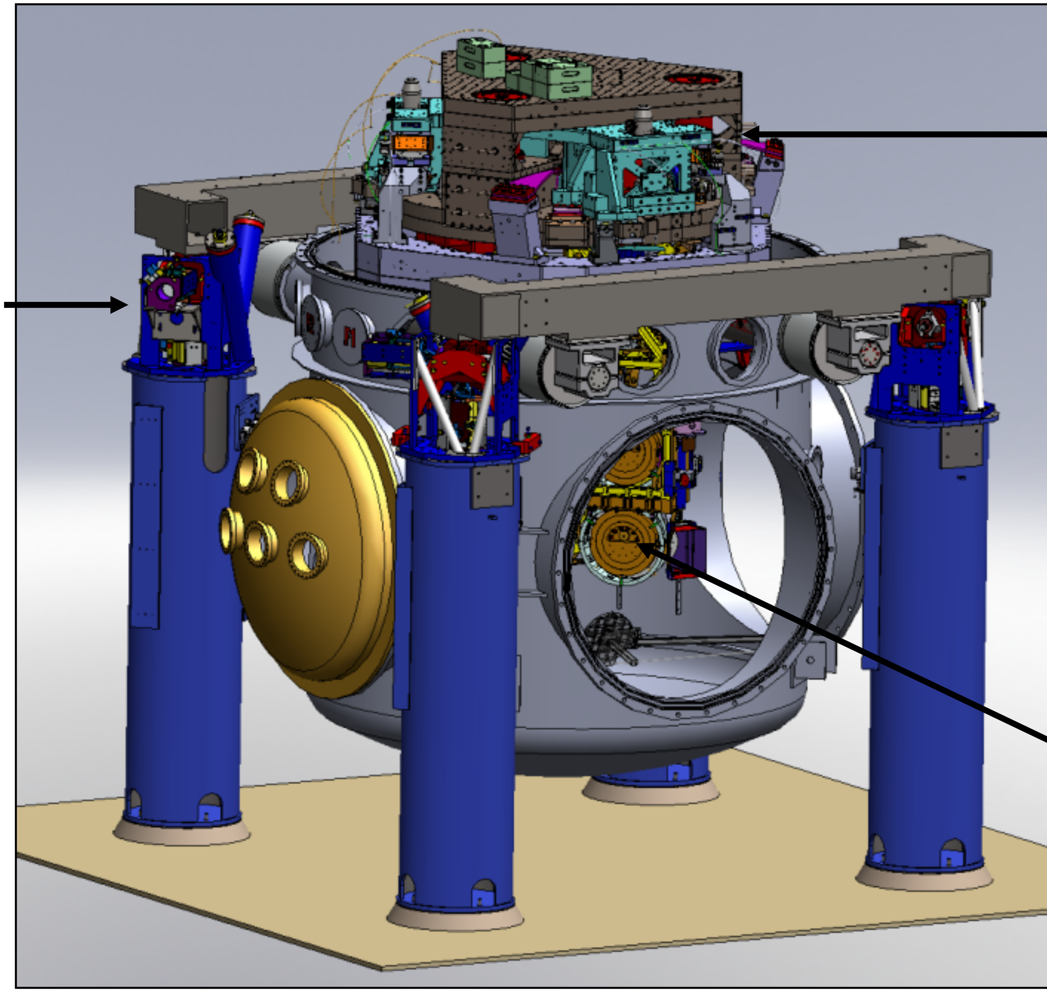


Quad top mass complete assembly

Advanced LIGO seismic isolation

HEPI: **H**ydraulic **E**xternal **P**re-**I**solator

1 stage of isolation



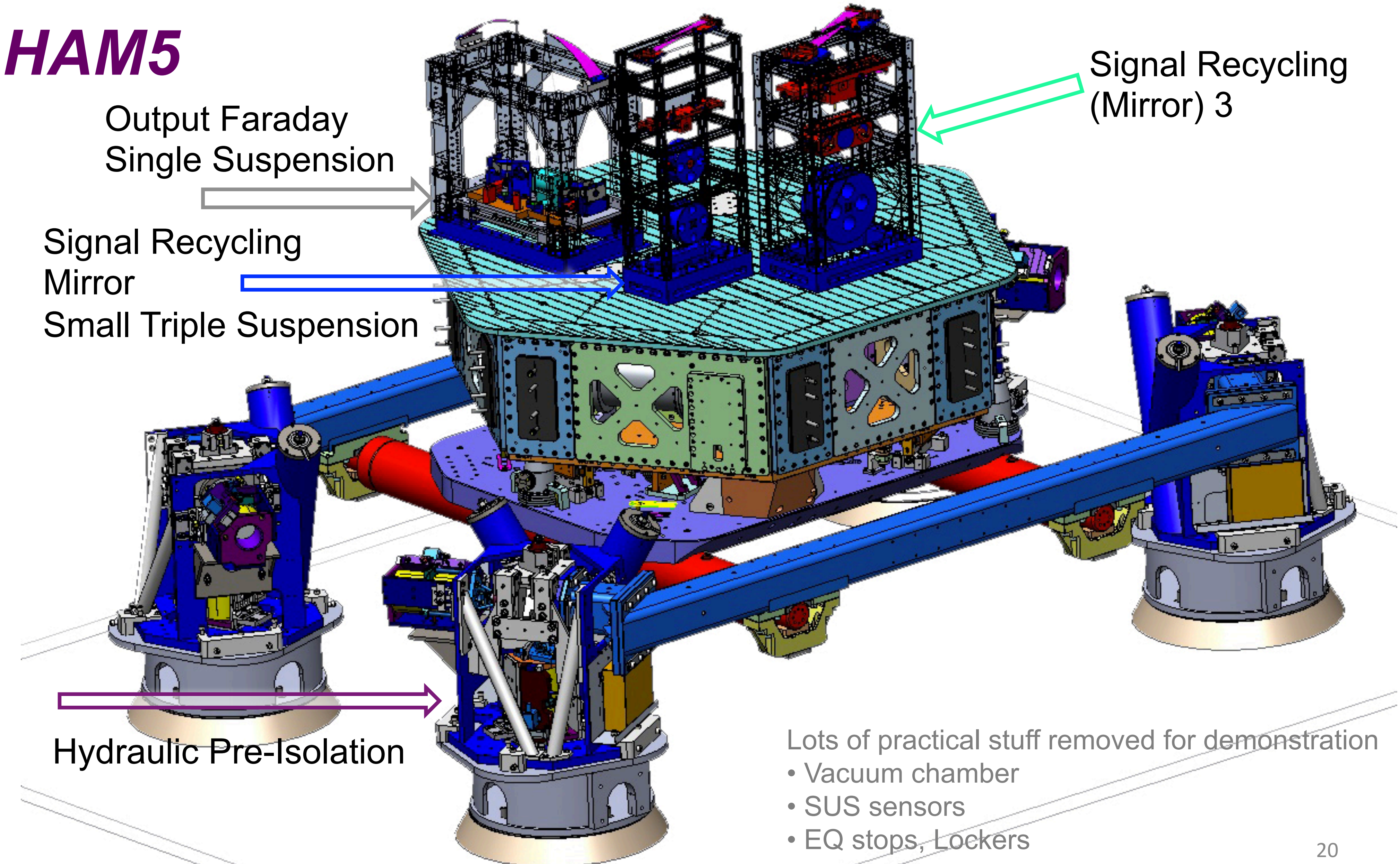
ISI: **I**nternal **S**eismic **I**solation

2 stages of active/ passive isolation

Test mass

Ref: LIGO-G1000469-v1; Kissel PhD thesis

Advanced LIGO seismic isolation



Lots of practical stuff removed for demonstration
- Vacuum chamber
- SUS sensors
- EQ stops, Lockers

Suspension noise requirements

Test mass noise requirements

Requirement	Value
Residual Seismic Noise	10^{-19} m/√ Hz at 10 Hz (assumes seismic platform noise 2×10^{-13} m/√ Hz)
Suspension Thermal Noise	10^{-19} m/√ Hz at 10 Hz (longitudinal) 10^{-16} m/√ Hz at 10 Hz (vertical)
Pitch and Yaw Noise	10^{-17} rad/√ Hz at 10 Hz (assumes beam centering to 1 mm)
Active control noise	1/10 of longitudinal thermal noise for each source

Cavity Optics Suspension Subsystem Design Requirements Document
https://dcc.ligo.org/LIGO-T010007/public

HAM Small Triple Suspension (HSTS)

Purpose
- PRM, PR2, SRM, SR2
- MC1, MC2, MC3

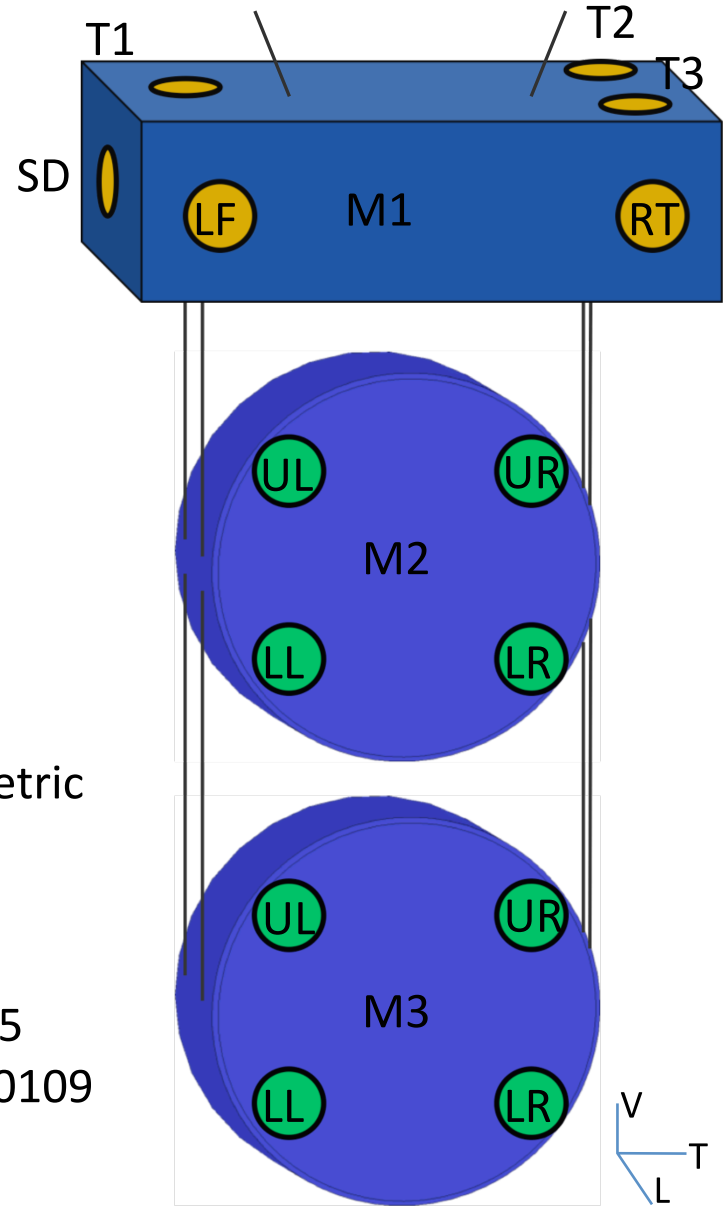
Location
- HAM 2, 3, 4, 5, (8, 9, 10, 11)

Control
- Local – damping at M1
- Global – LSC & ASC at all 3

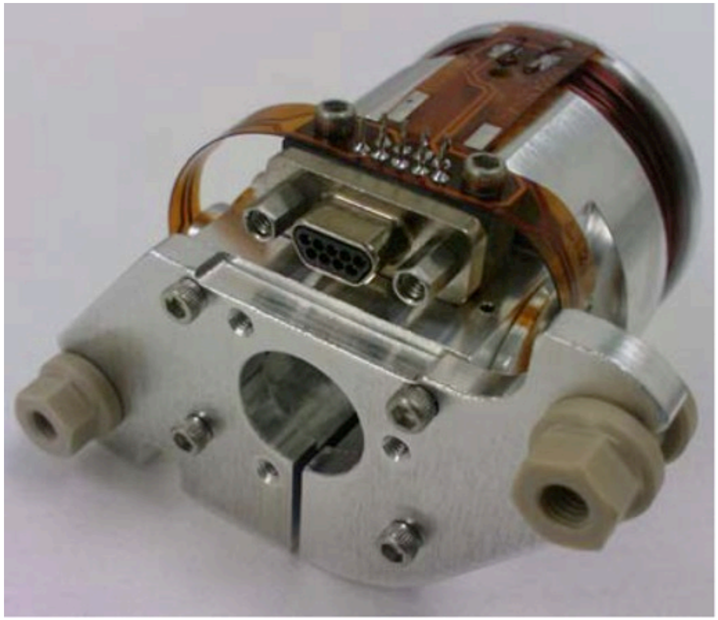
Sensors/Actuators
- (yellow circle) BOSEMs at M1
- (green circle) AOSEMs at M2 and M3
- Optical levers and interferometric signals on M3

Naming: L1:SUS-PRM_M1…

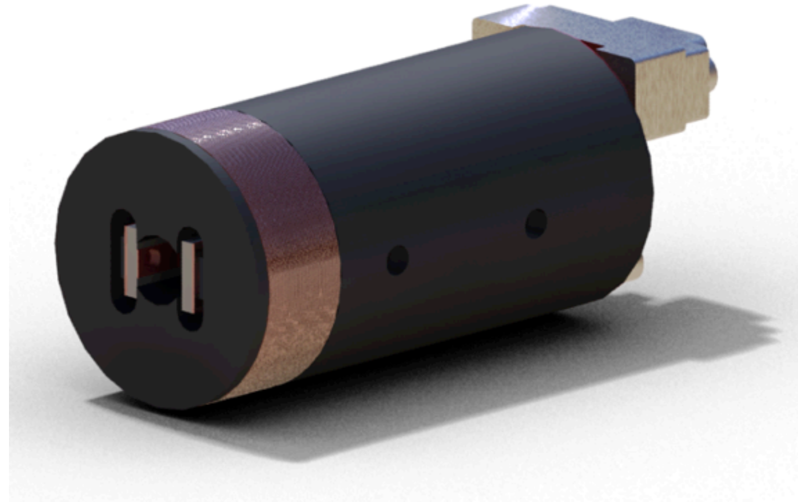
Documentation
- Final design review - T0900435
- Controls arrangement – E1100109



Optical Sensor ElectroMagnet (OSEM)

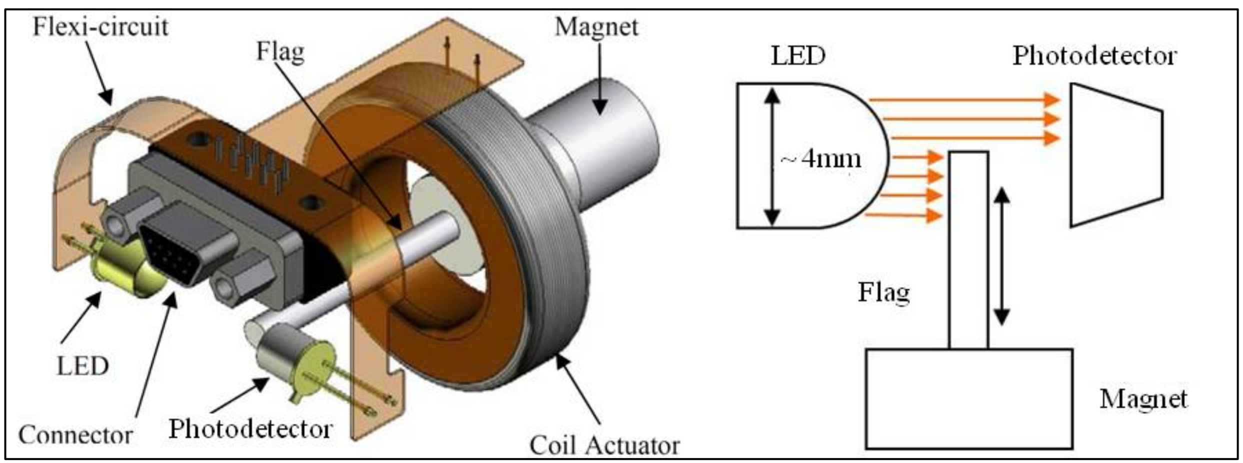


Birmingham OSEM (BOSEM)



Advanced LIGO OSEM (AOSEM)
- modified iLIGO OSEM

BOSEM Schematic

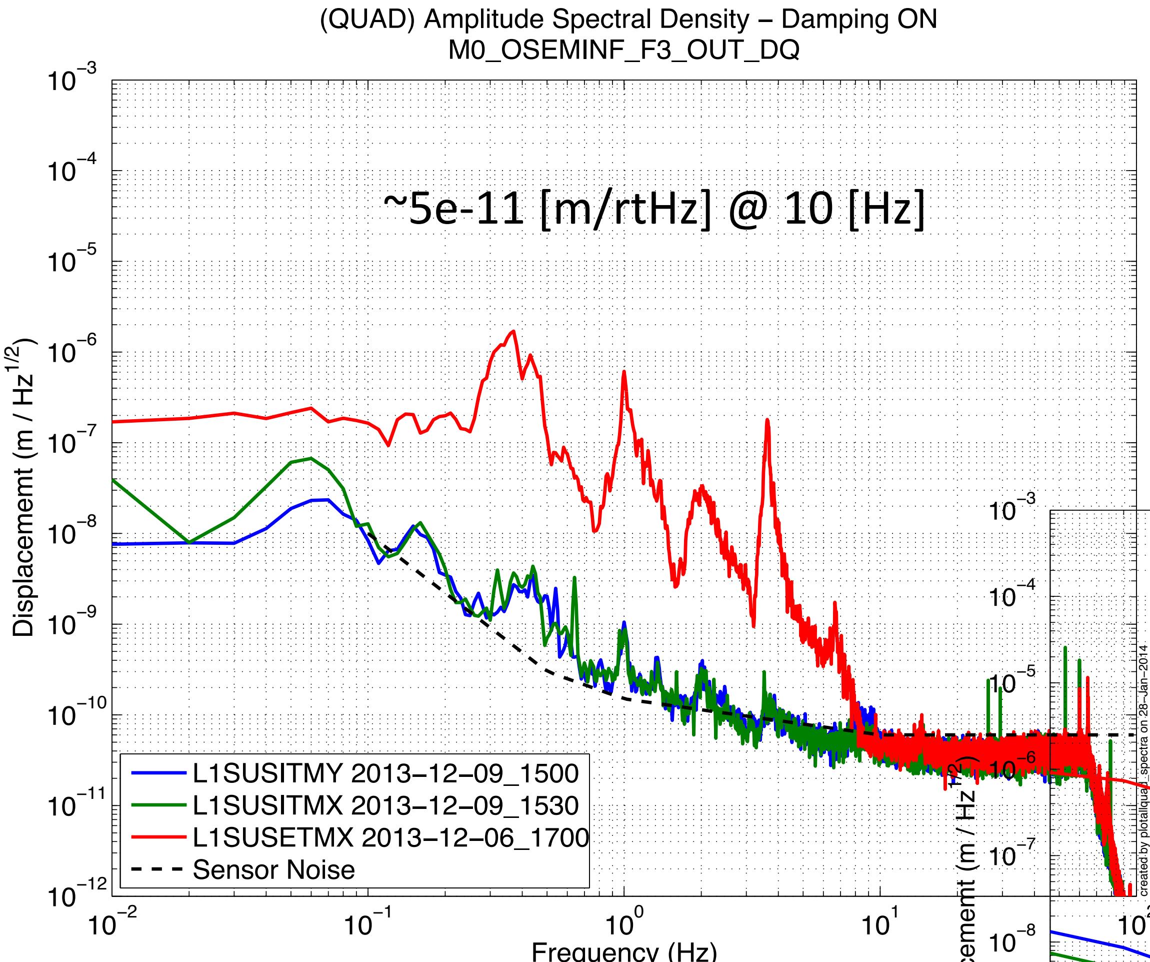


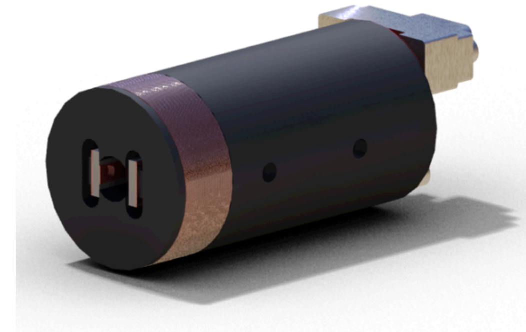
Magnet Types (M0900034)

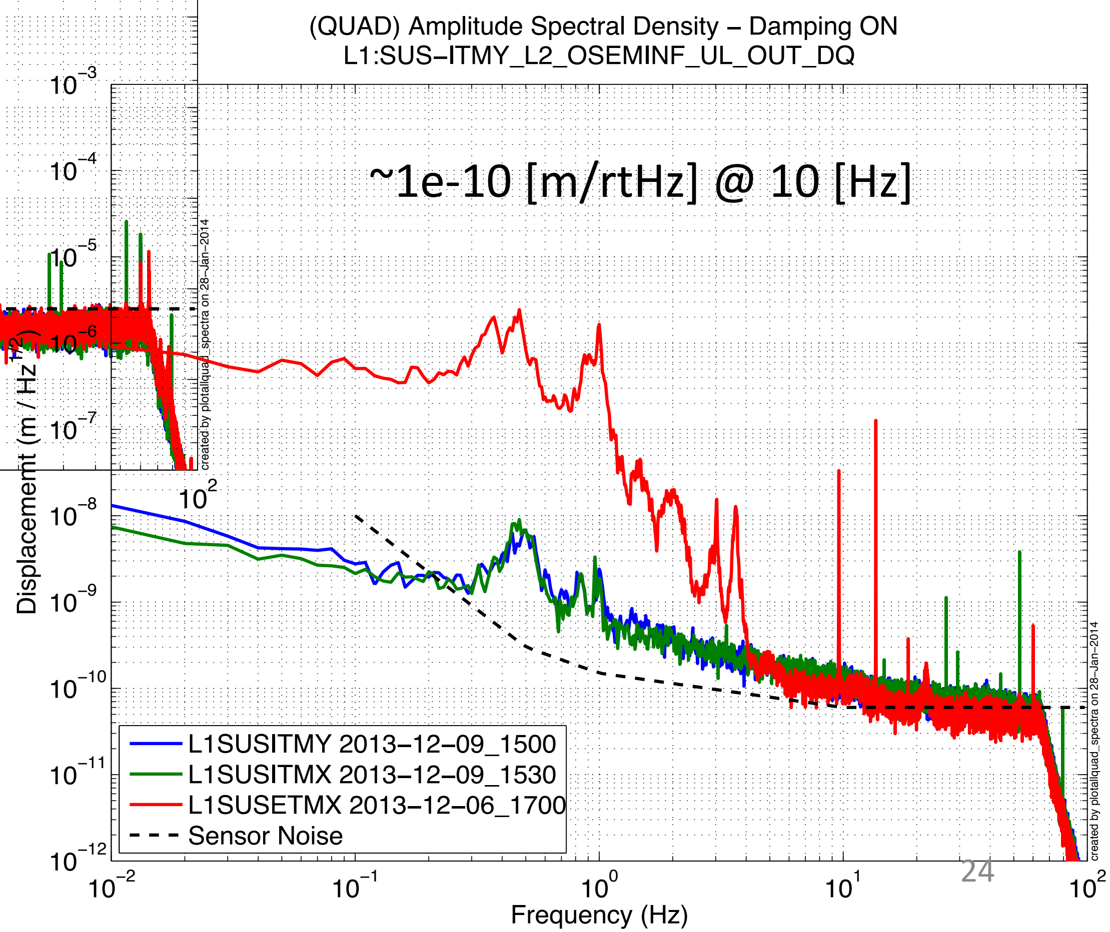
- BOSEM – 10 X 10 mm, NdFeB , SmCo
  10 X 5 mm, NdFeB, SmCo
- AOSEM – 2 X 3 mm, SmCo
  2 X 6 mm, SmCo
  2 X 0.5 mm, SmCo

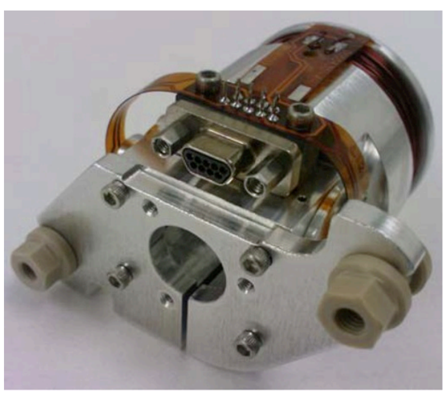
Ref: L. Carbone et al. "Sensors and Actuators for the Advanced LIGO Mirror Suspensions", Class. Quantum Grav. **29**, 115005 (2012)

Optical Sensor ElectroMagnet (OSEM)







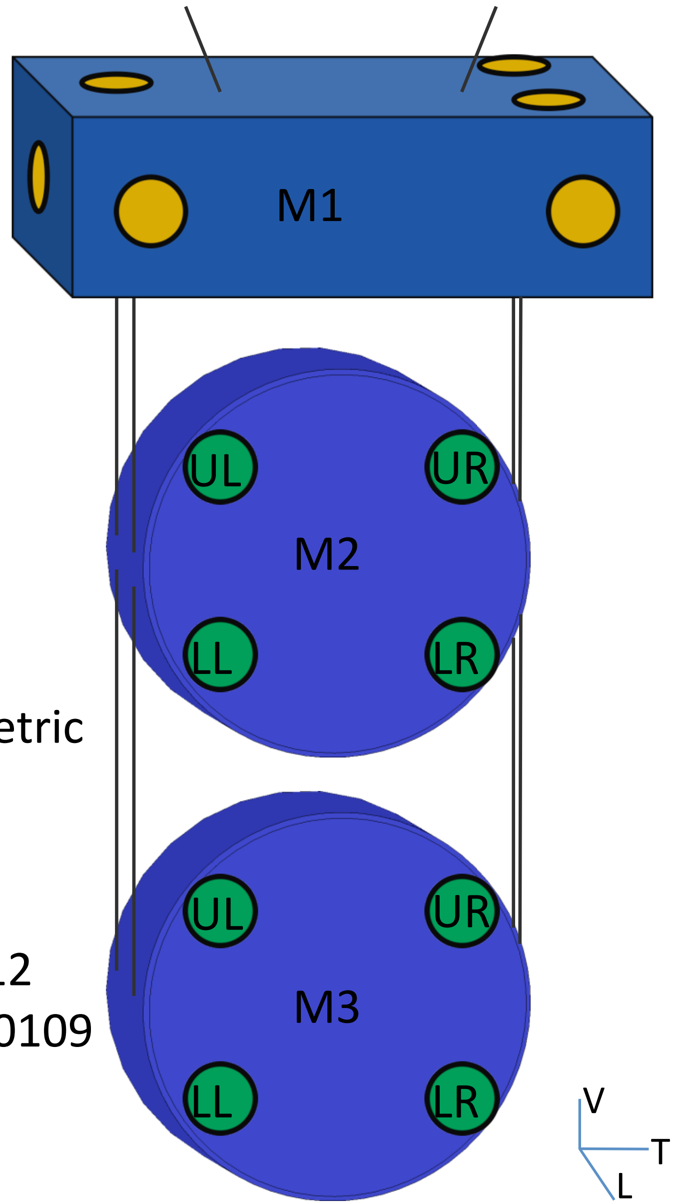


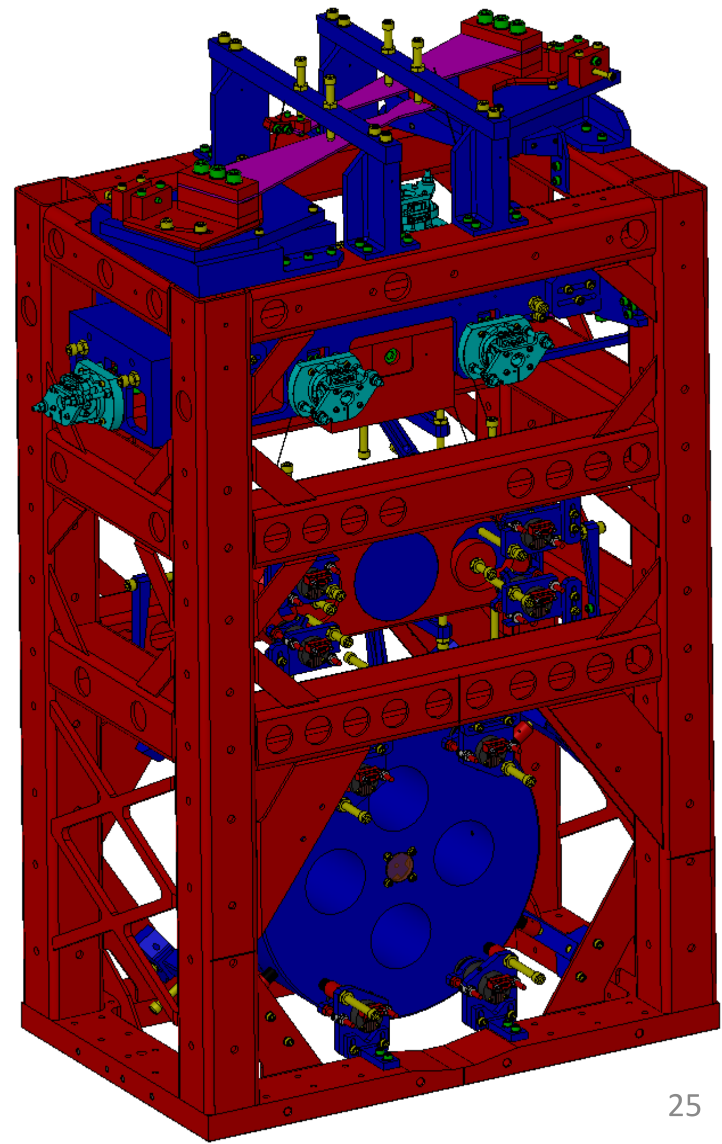
HAM Large Triple Suspension (HLTS)

Purpose
• PR3, SR3
Location
• HAM 2, 5, (8, 11)

Control
• Local – damping at M1
• Global – LSC & ASC at all 3
Sensors/Actuators
• (yellow circle) BOSEMs at M1

• (green circle) AOSEMs at M2 and M3
• Optical levers and interferometric signals on M3
Naming: L1:SUS-SR3_M1…
Documentation
• Final design review – T1000012
• Controls arrangement – E1100109





LIGO

Beamsplitter/Folding Mirror (BSFM)

Purpose
- BS, (FMX and FMY)

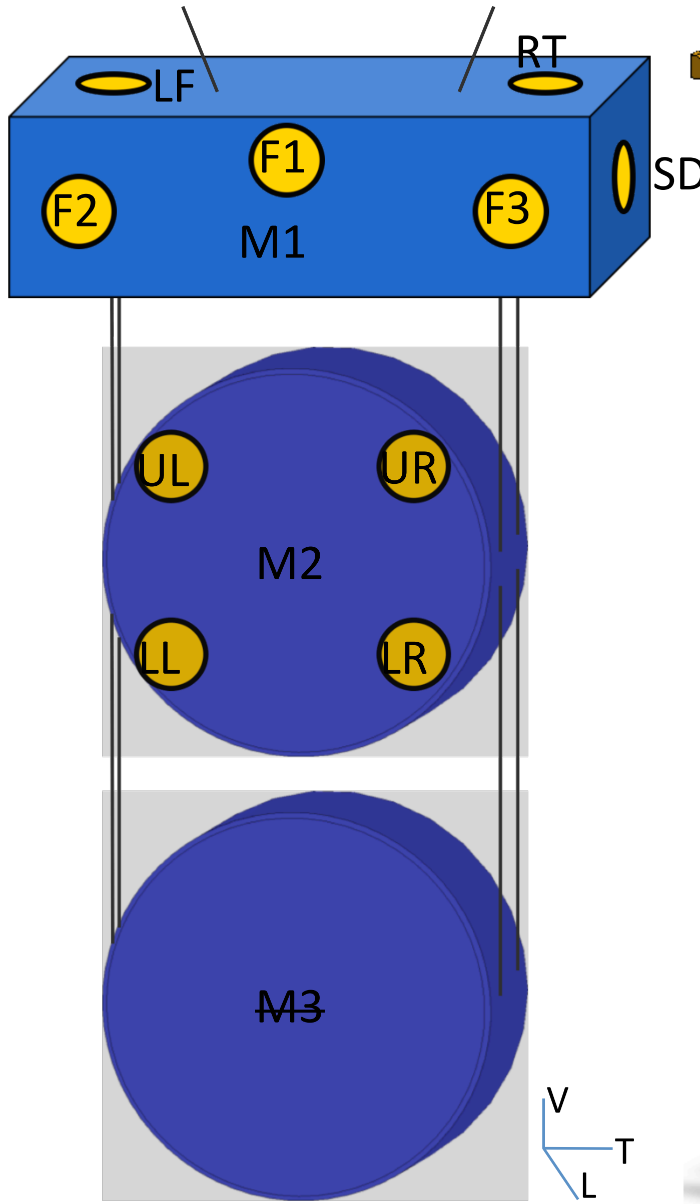
Location
- Beamsplitter – BSC 2, (4)
- (Fold Mirror – BSC 6, 8)

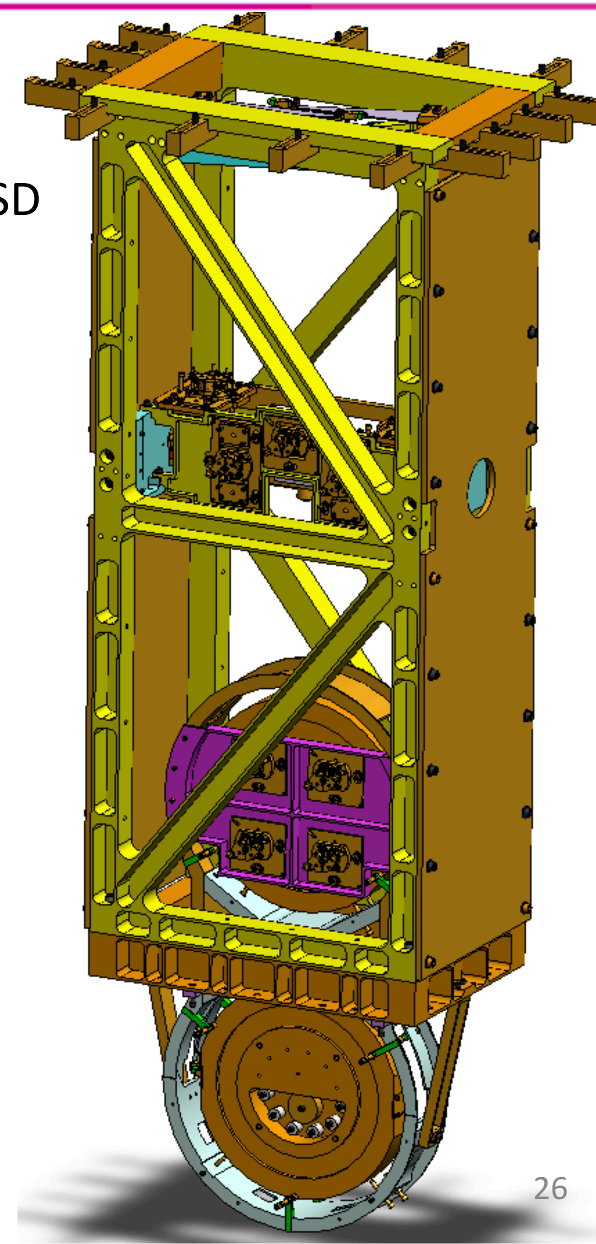
Control
- Local – damping at M1
- Global – LSC & ASC at M2

Sensors/Actuators
- ● BOSEMs at M1 and M2
- Optical levers and interferometric signals on M3

Naming: L1:SUS-FMX_M1…

Documentation
- Final design review - T080218
- Controls arrangement – E1100108





Output Mode Cleaner Double (OMCS)

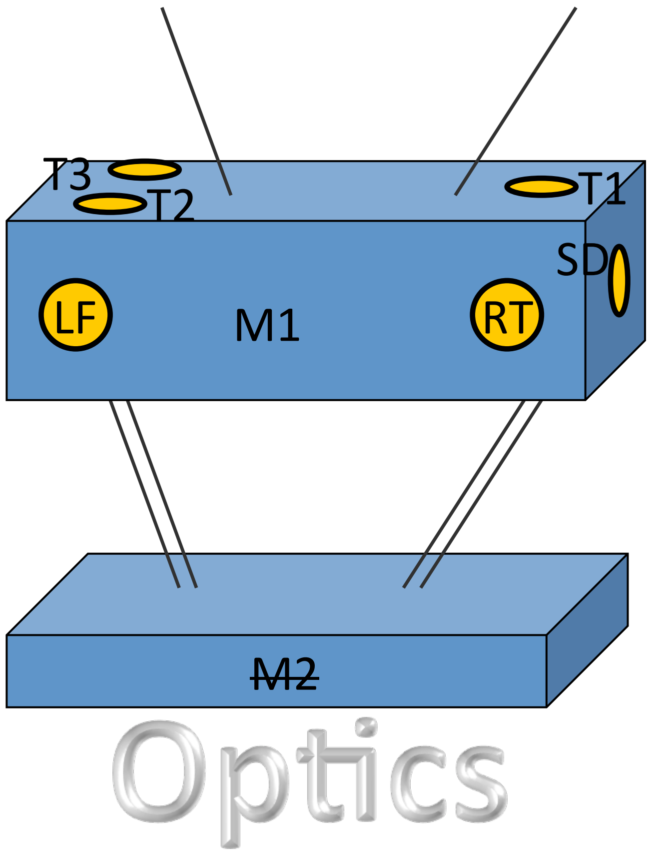
Location
- HAM 6, (12)

Control
- Local – damping at M1
  (true for all SUS's)

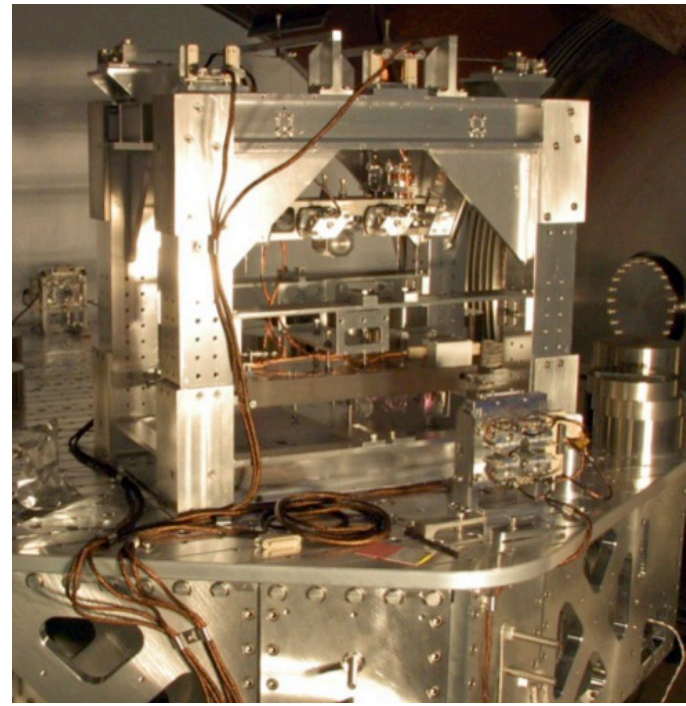
Sensors/Actuators
- ● BOSEMs at top mass

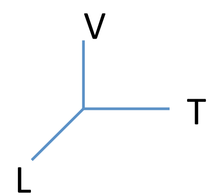
Top mass naming convention
- L1:SUS-OMC_M1…

site 2 | subsystem 3 | unit 3,4 | stage 2



In use during S6





Local coordinates

Documentation
- Final design review - T0900060
- HAM SUS controls arrangement – E1100109

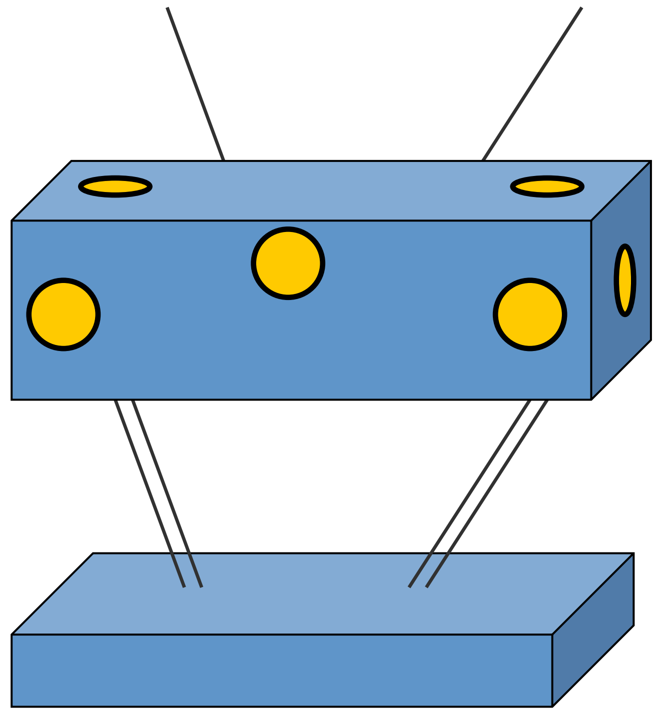
TransMon Double

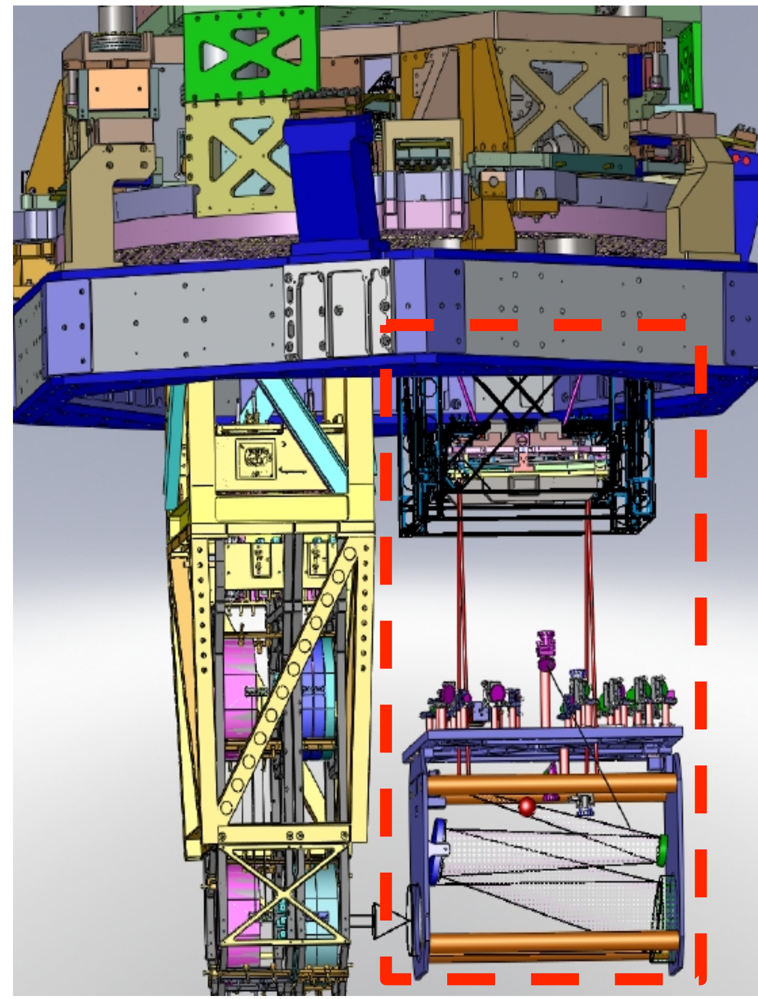
Location
- BSC 9, 10

Control
- Local – damping at top mass

Sensors/Actuators
- BOSEMs at top mass

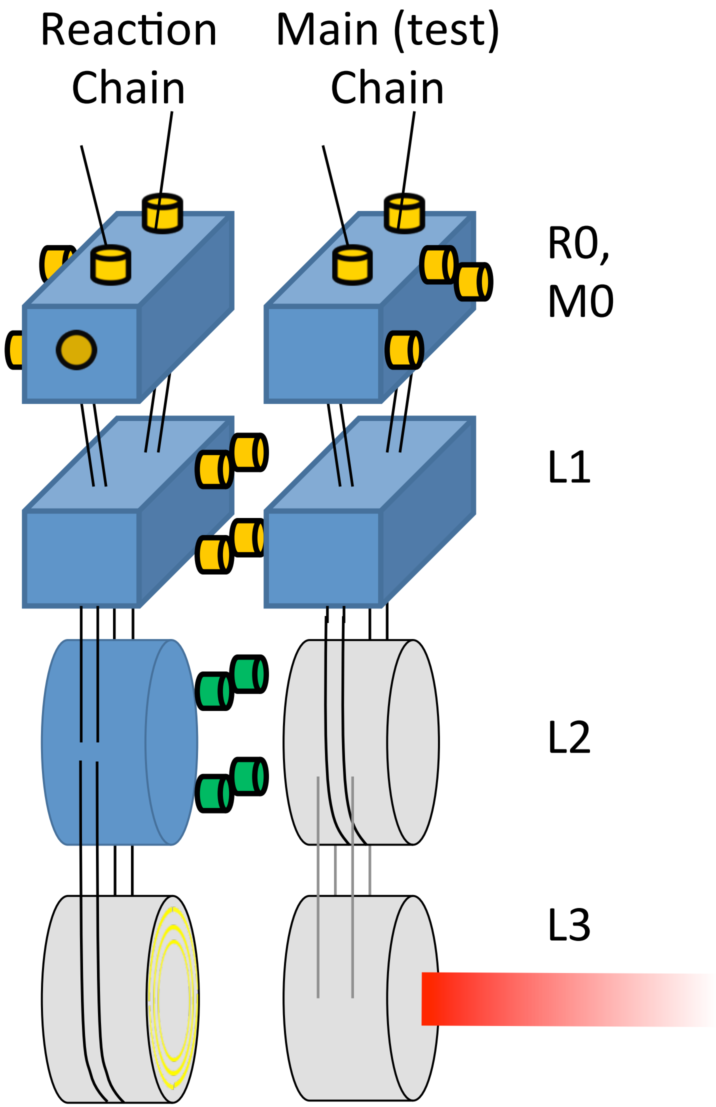
Top mass naming convention
- L1:SUS-TRMX_M1…





Ref: E1000040

Suspension Sensors & Actuators



Purpose
- Input Test Mass (ITM, TCP)
- End Test Mass (ETM, ERM)

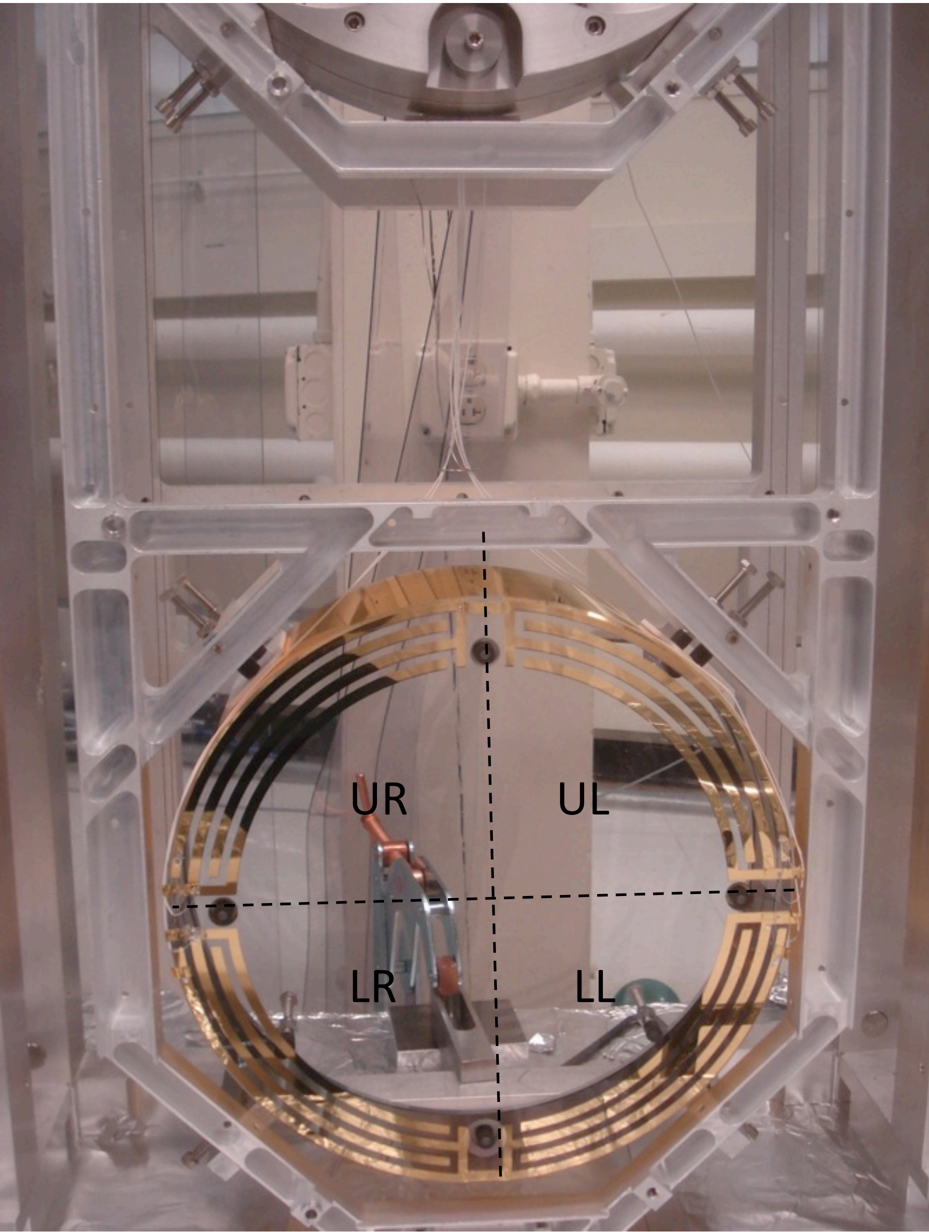
Location
- End Test Masses, Input Test Masses

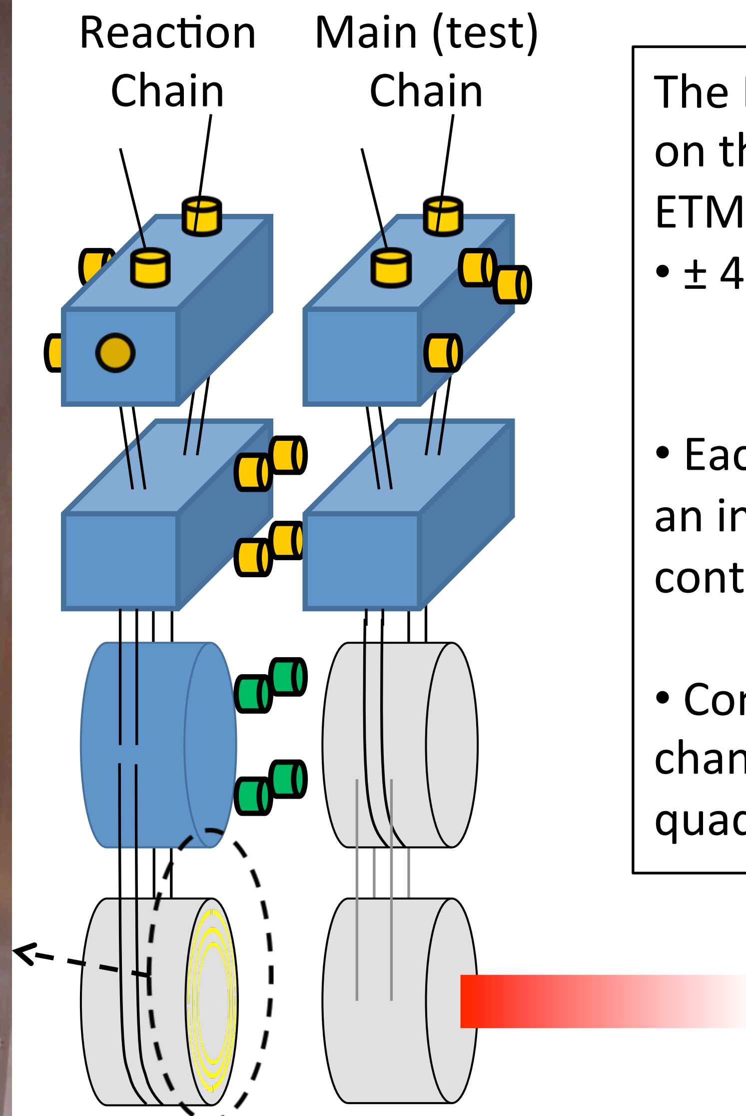
Control
- Local – damping at M0, R0
- Global – LSC & ASC at all 4

Sensors/Actuators
- 🟡 BOSEMs at M0, R0, L1
- 🟢 AOSEMs at L2
- Optical levers and interf. sigs. at L3
- Electrostatic drive (ESD) at L3

Documentation
- Final design review - T1000286
- Controls arrang. – E1000617

Test Mass Electrostatic Drive (ESD)





The ESD acts directly on the test ITM and ETM test masses.

- ± 400 V (ΔV 800 V) ≈ 100 µN
- Each quadrant has an independent control channel
- Common bias channel over all quadrants

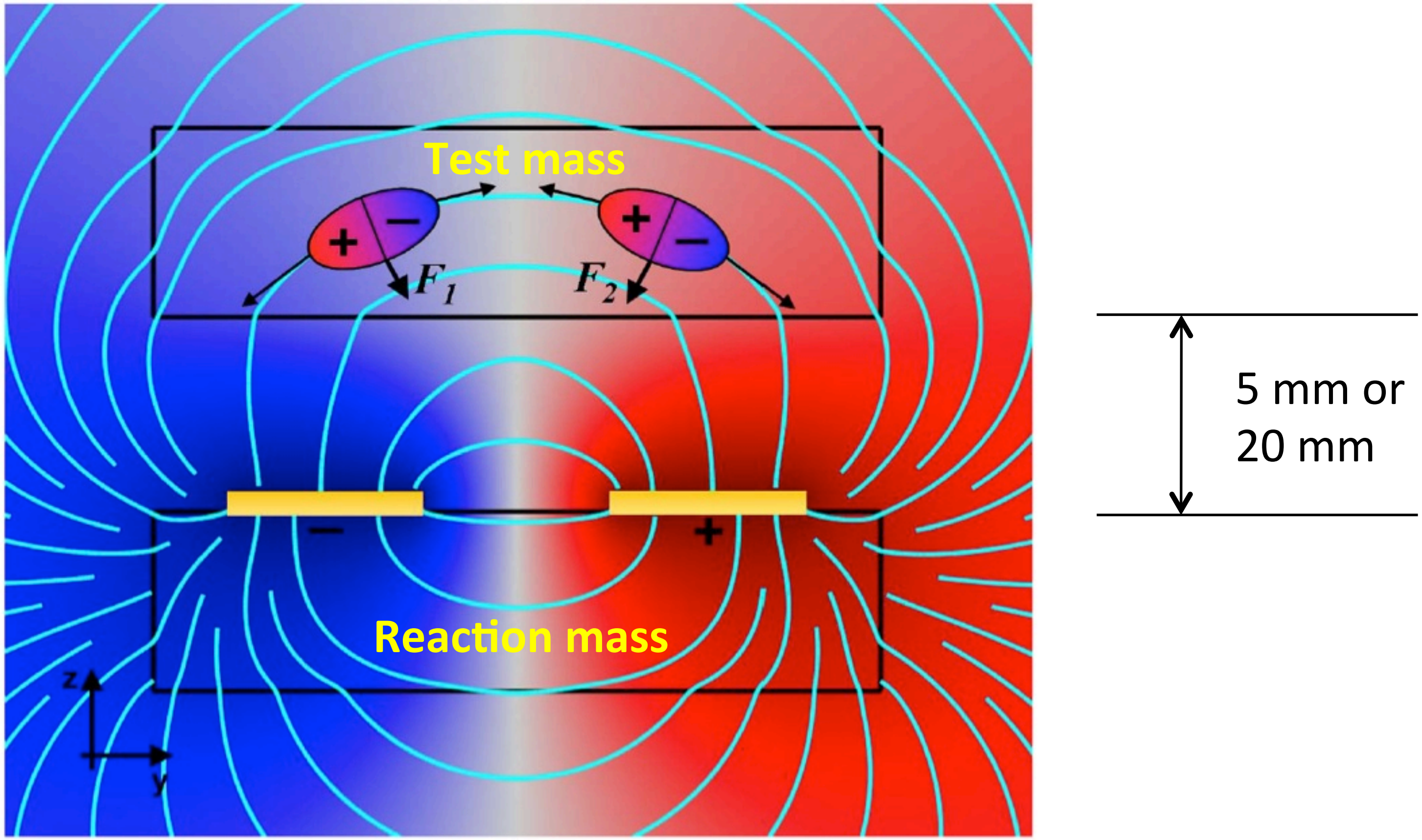
Quadruple Suspension ESD

F = αΔV²

- α = coupling coefficient, depends on geometry

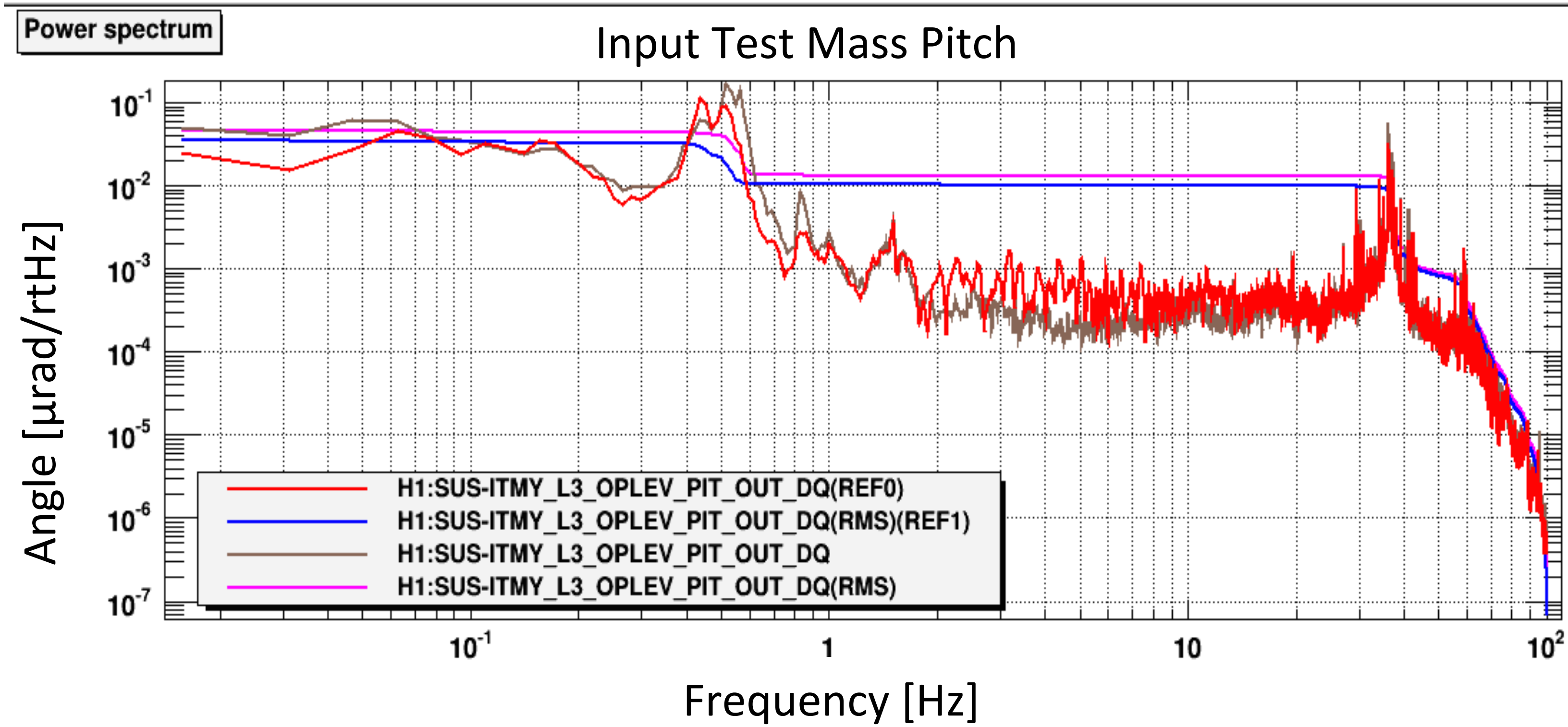
- ΔV = differential voltage across traces

Linearization occurs in the control!

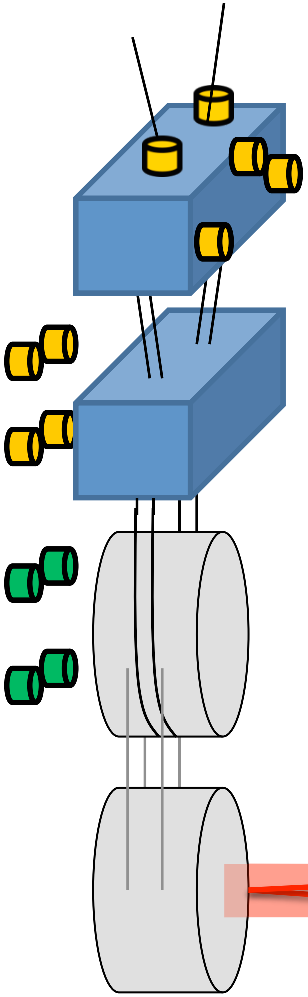


Cartoon diagram illustrating the working principle of the ESD. The upper rectangle represents the test mass containing two polarized molecules; the lower rectangle represents the reaction mass bearing two electrodes. Surface plot shows electrical potential with electric field lines shown in cyan (John Miller PhD thesis, P1000032).

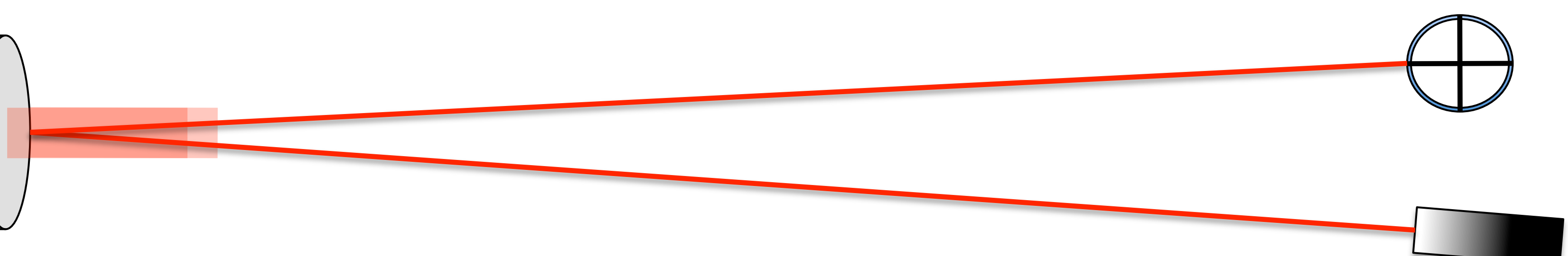
Optical Levers



Main (test) Chain

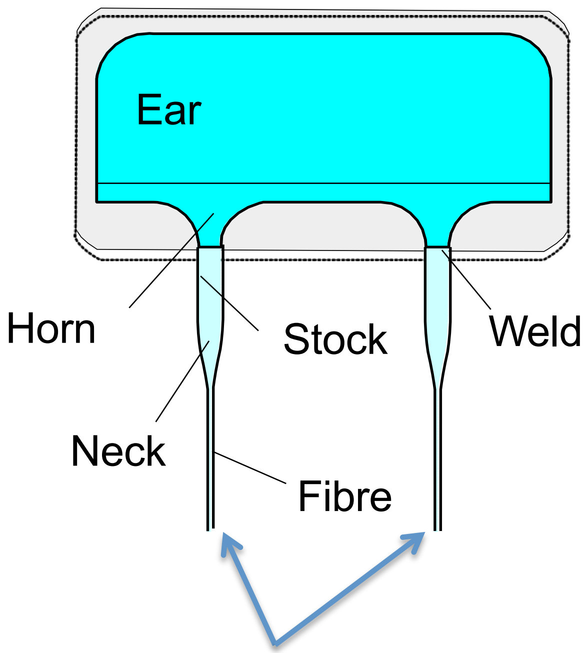


~10 [m] lever arm
~ 1e-9 [rad/rtHz] sensitivity at from 0.1-10 [Hz]

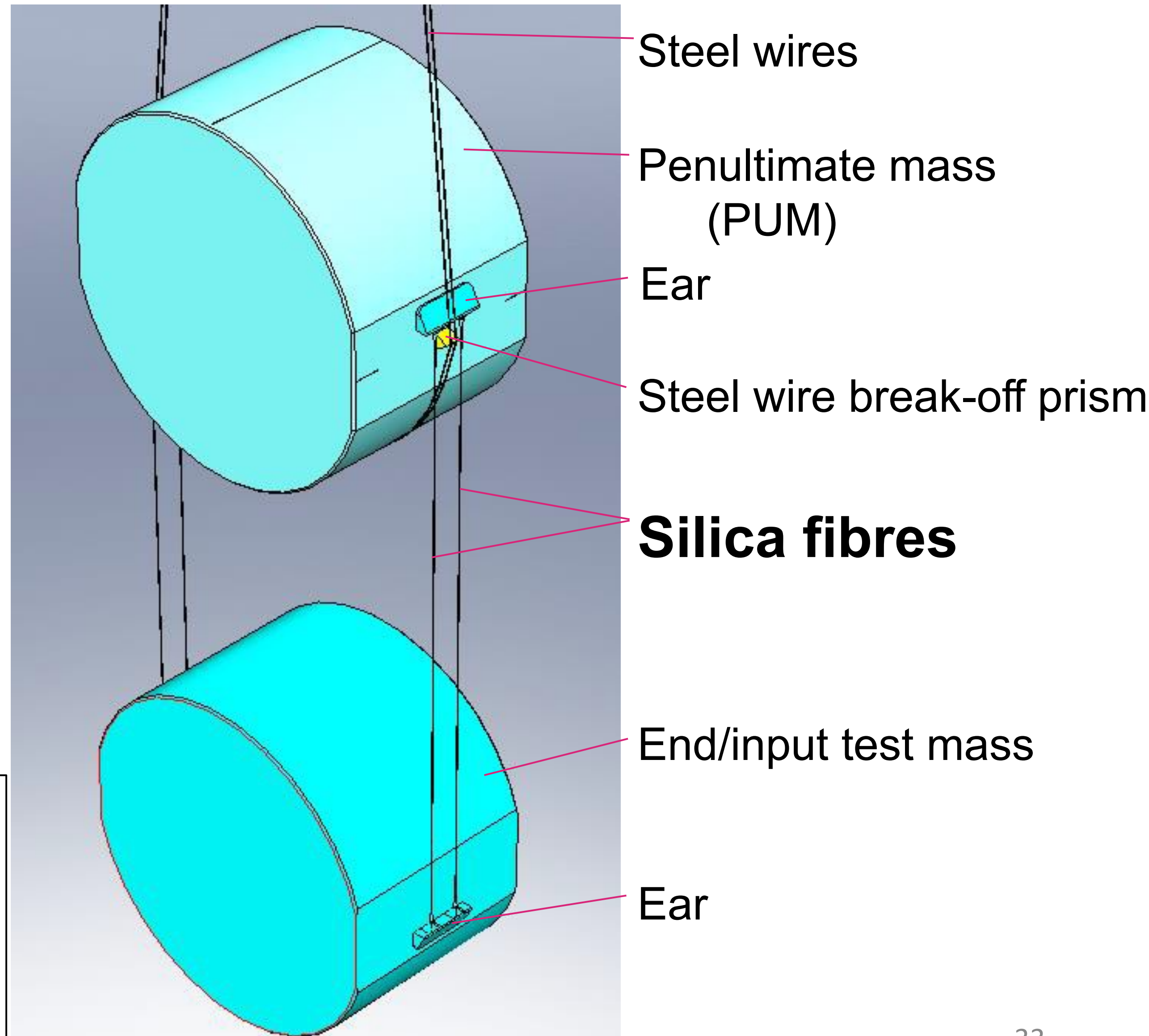


Ref: G1401207

Monolithic Test Mass Suspension

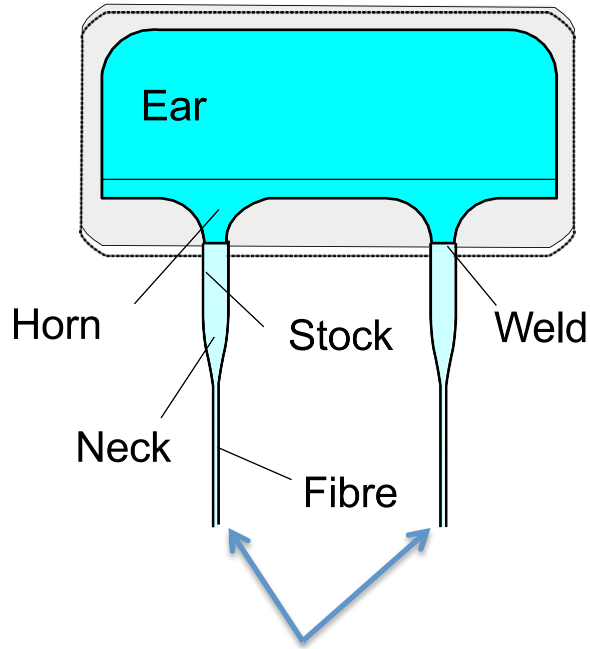


400 μm diameter neck



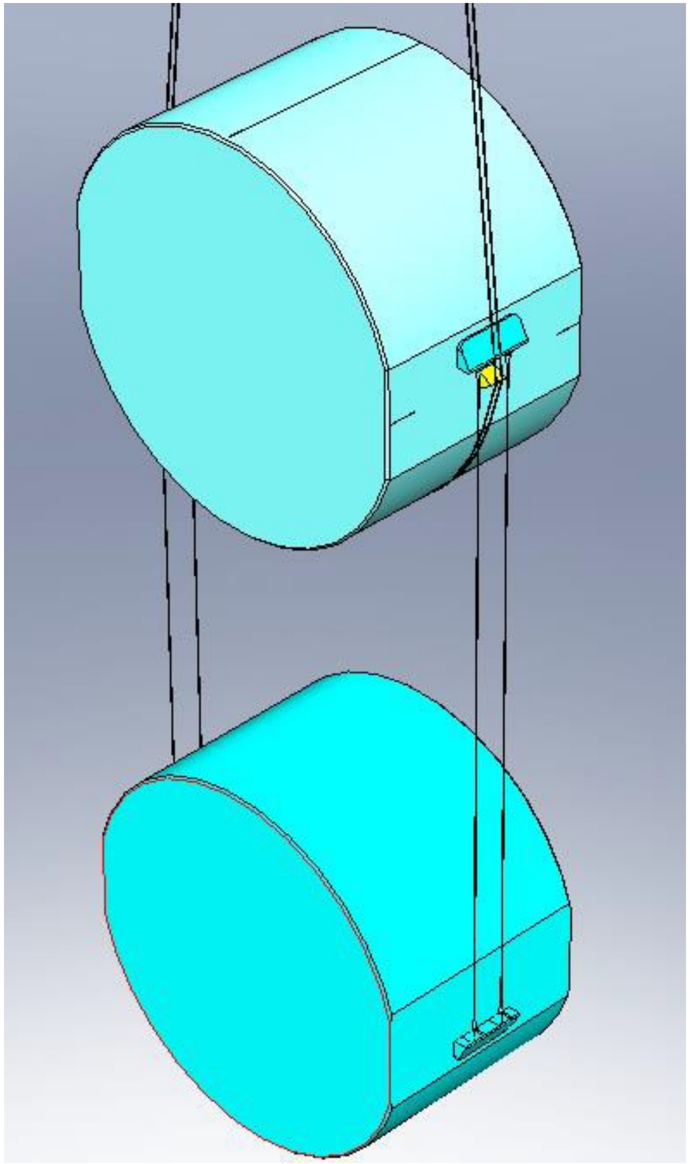
- Keeps mechanical loss low near test mass to minimize thermal noise
- Source of 10 Hz and 14 Hz bounce and roll modes

Thinner test mass fibers?



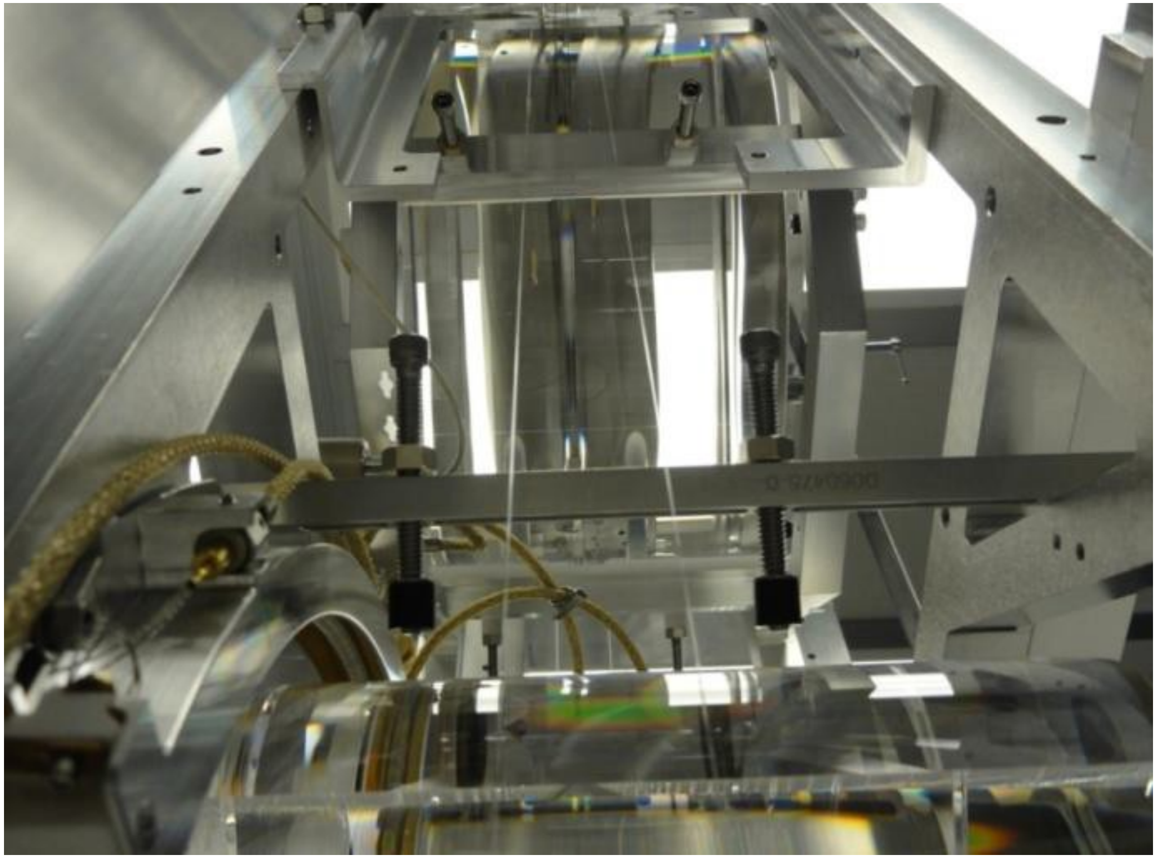
< 400 μm neck diameter

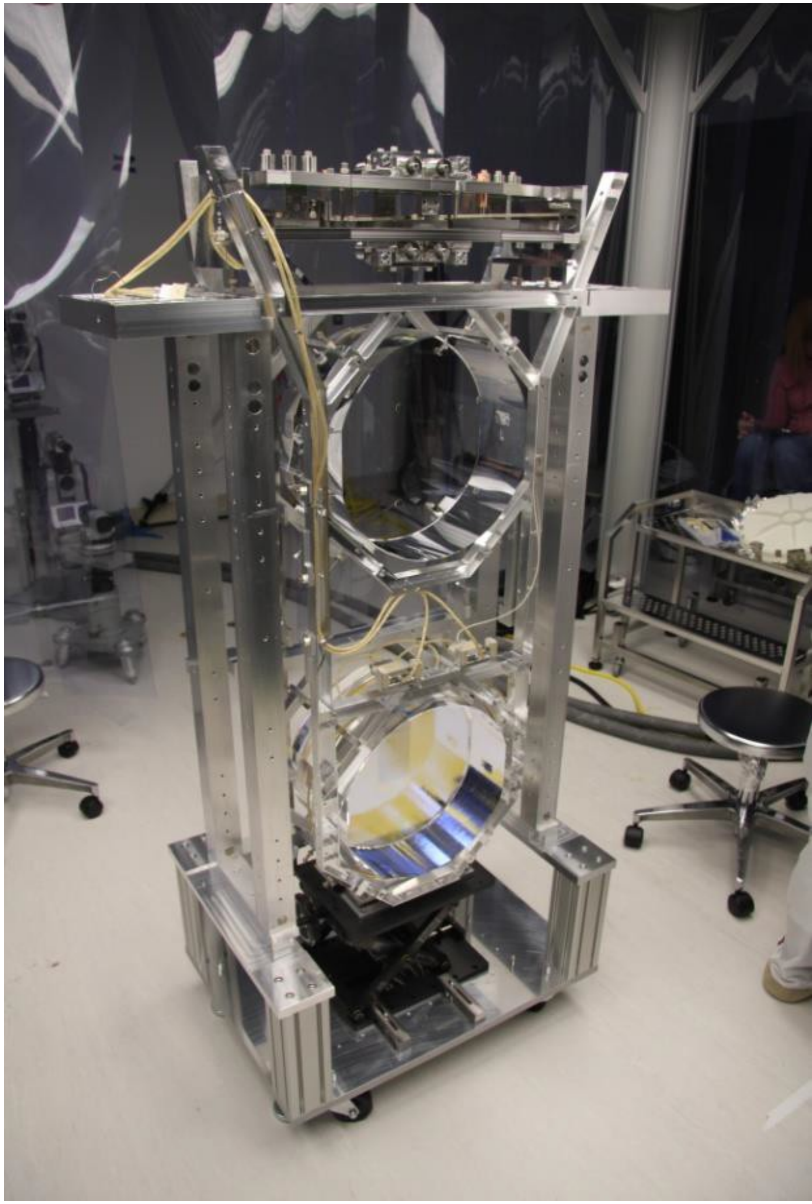
Neck Diameter (μm)	Stress (MPa)	Bounce (Hz)	1st violin (Hz)
400 (current)	780	9	520
320	1200	7	650
300	1600	6.3	750



Reference: Giles Hammond, LITRA Aug 2016

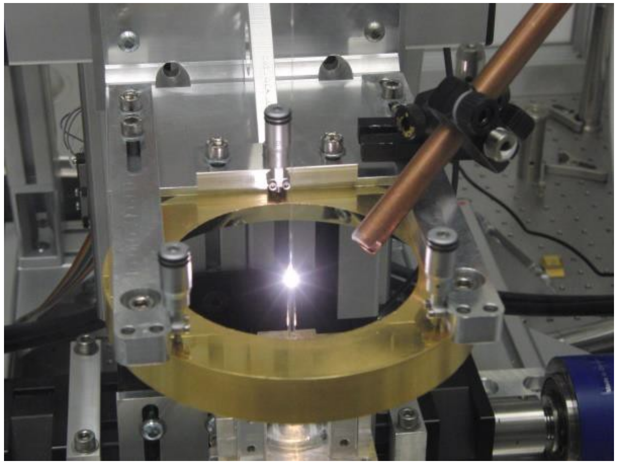
Monolithic Test Mass Suspension

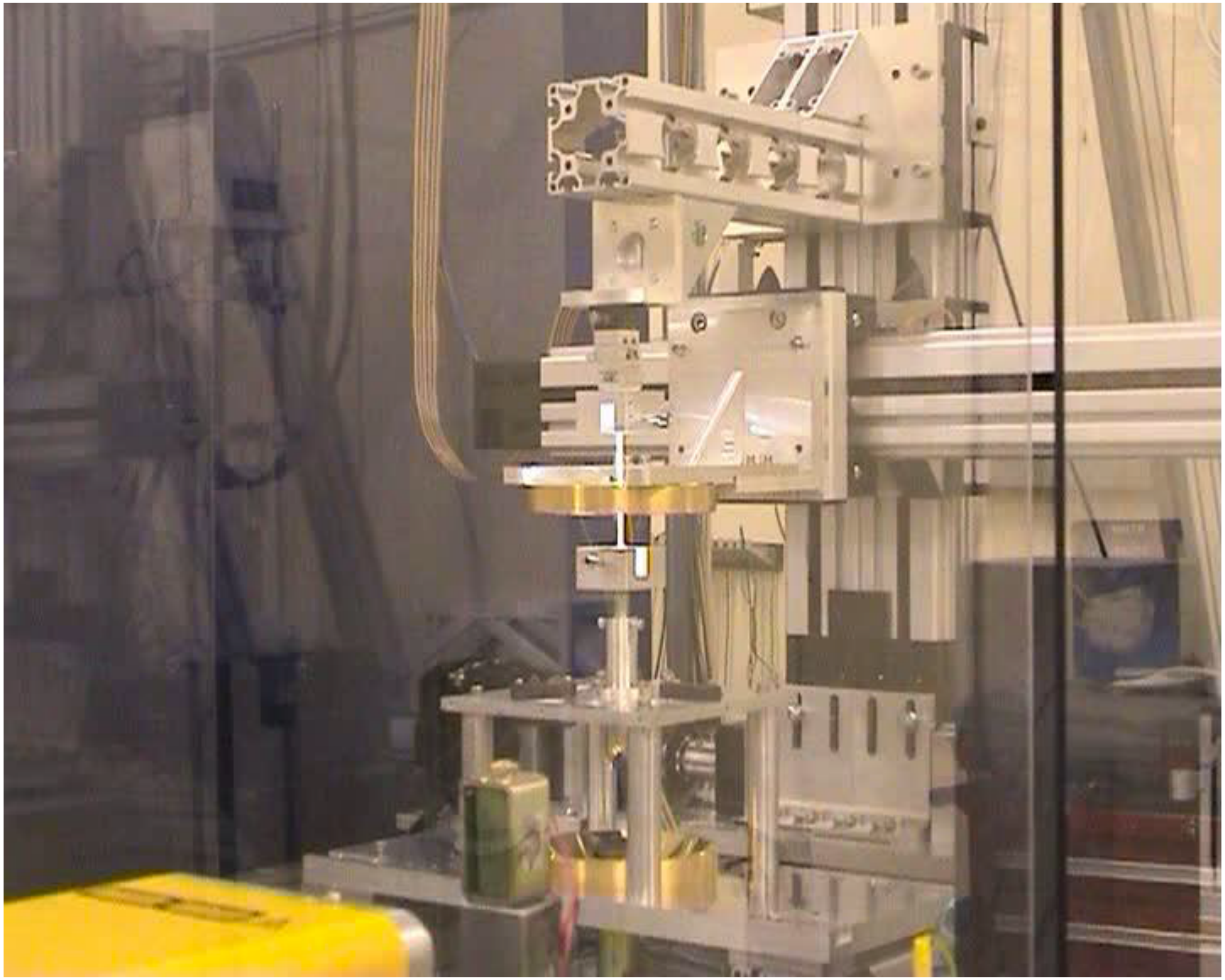




Laser Pulling the Fibers

Fibers are laser pulled, then laser welded to the suspension. Uses a 100 W CO_2 laser.

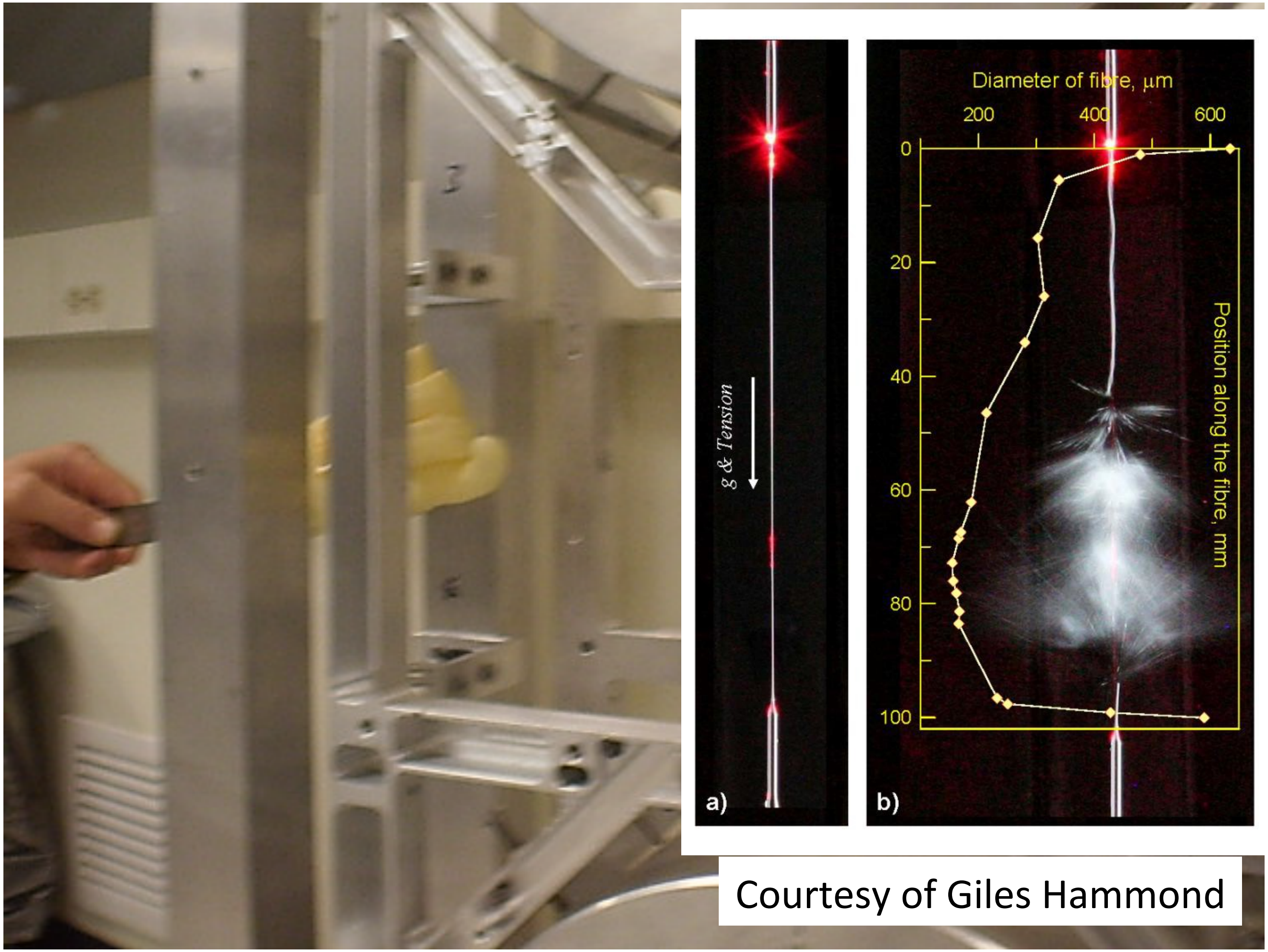




Silica fibers are strong

VIRGO 2009 – 21 kg mass hanging on four 285 micron diameter fibers

Silica fibers are strong…yet fragile



Courtesy of Giles Hammond

Silica Fiber Break Test – MIT 5 Nov 2010

Thermal Compensation System (TCS)

The thermal lensing problem

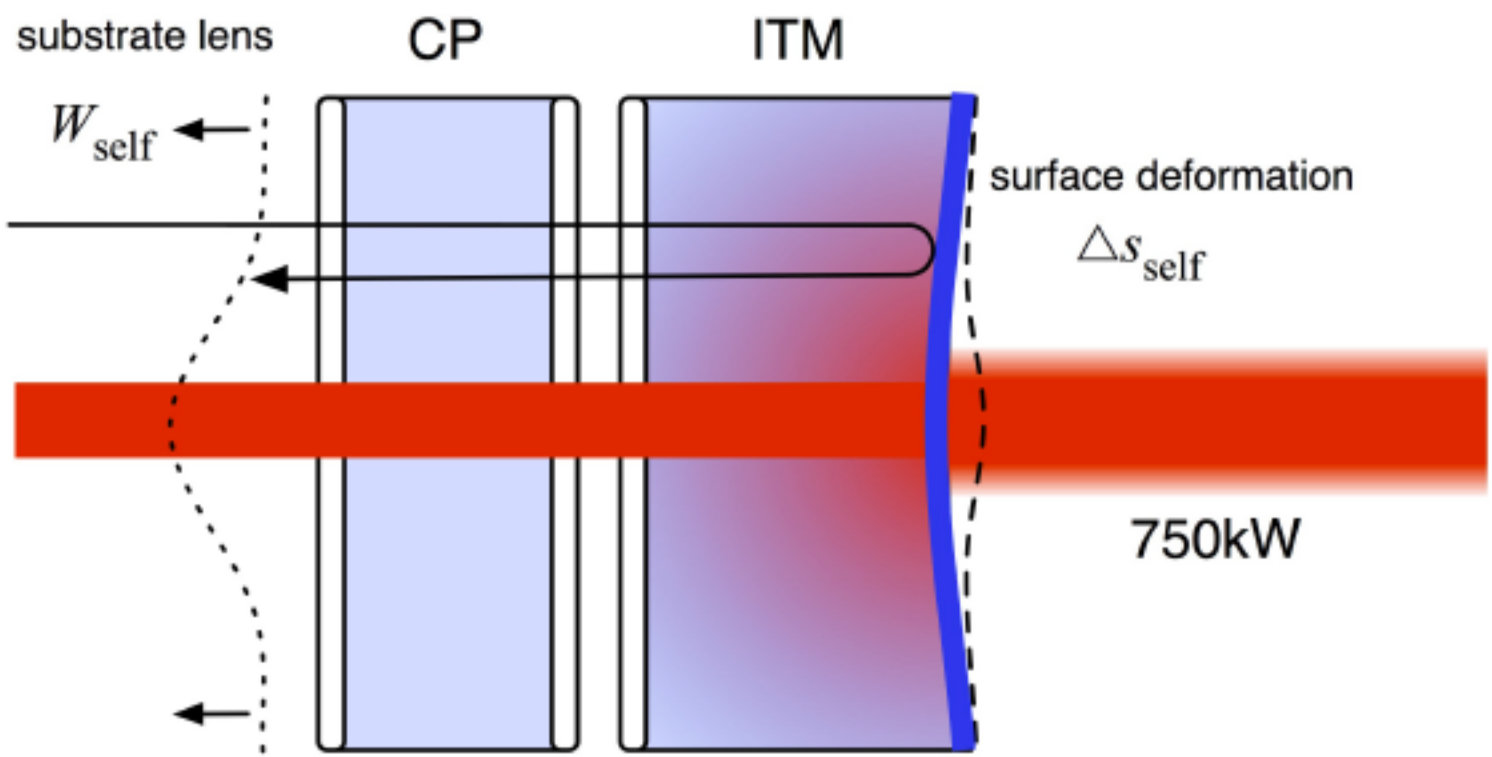
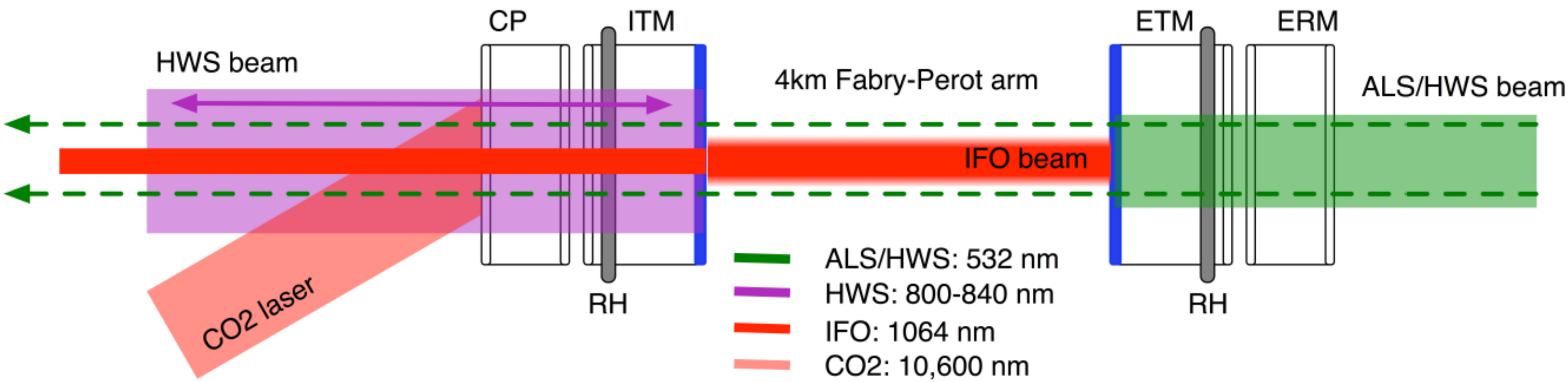


Fig. 3. An illustration of the thermo-refractive substrate lens, W_{self}, and the thermo-elastic surface deformation, Δs_{self}, from self heating.

Reference: P1600169

Thermal Compensation System (TCS)

The thermal lensing solution



Sensors

Hartmann Wavefront Sensors (HWS)

Actuators

1) Ring heaters (RH)

2) CO_2 laser

Reference: P1600169 - https://arxiv.org/abs/1608.02934

How to make a working suspensions

Test mass suspension procedures:

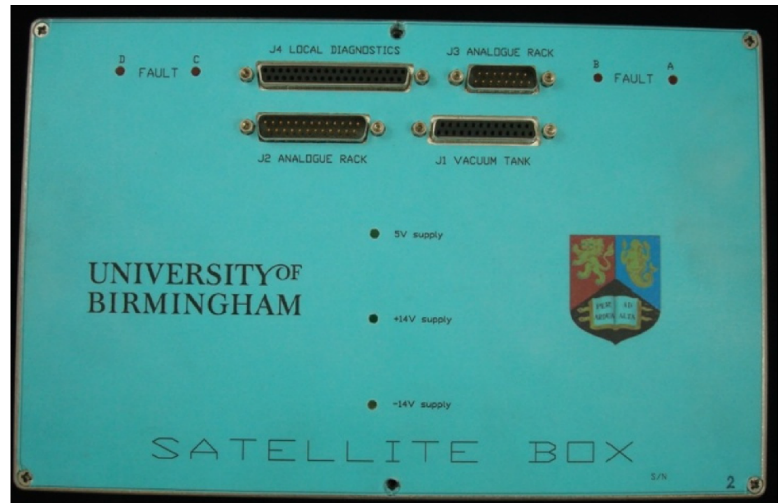
- https://dcc.ligo.org/LIGO-G1100693/public - Ideal Order/Contents of aLIGO QUAD Testing/Commissioning
- https://dcc.ligo.org/LIGO-E1000006/public - Advanced LIGO Quad Suspension Metal-Build Assembly Procedure
- https://dcc.ligo.org/LIGO-E1000007/public - aLIGO SUS Quad Suspension Monolithic Build Assembly Procedure
- https://dcc.ligo.org/LIGO-E1000078/public - Electronic setup and testing of aLIGO suspensions
- SUS Operations Manual - https://awiki.ligo-wa.caltech.edu/aLIGO/Suspensions/OpsManual. Also archived at https://dcc.ligo.org/LIGO-E1200633

Assemble and install sensors/actuators & electronics

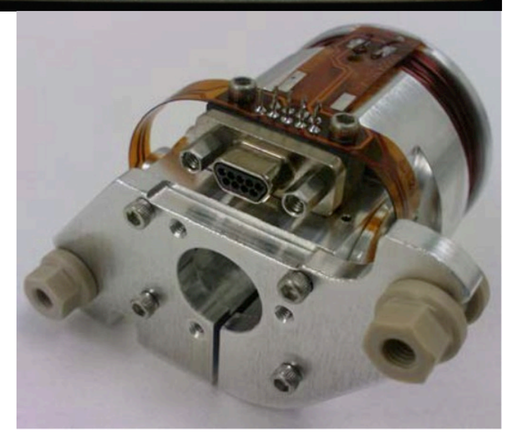
1) Assemble

Top mass being installed

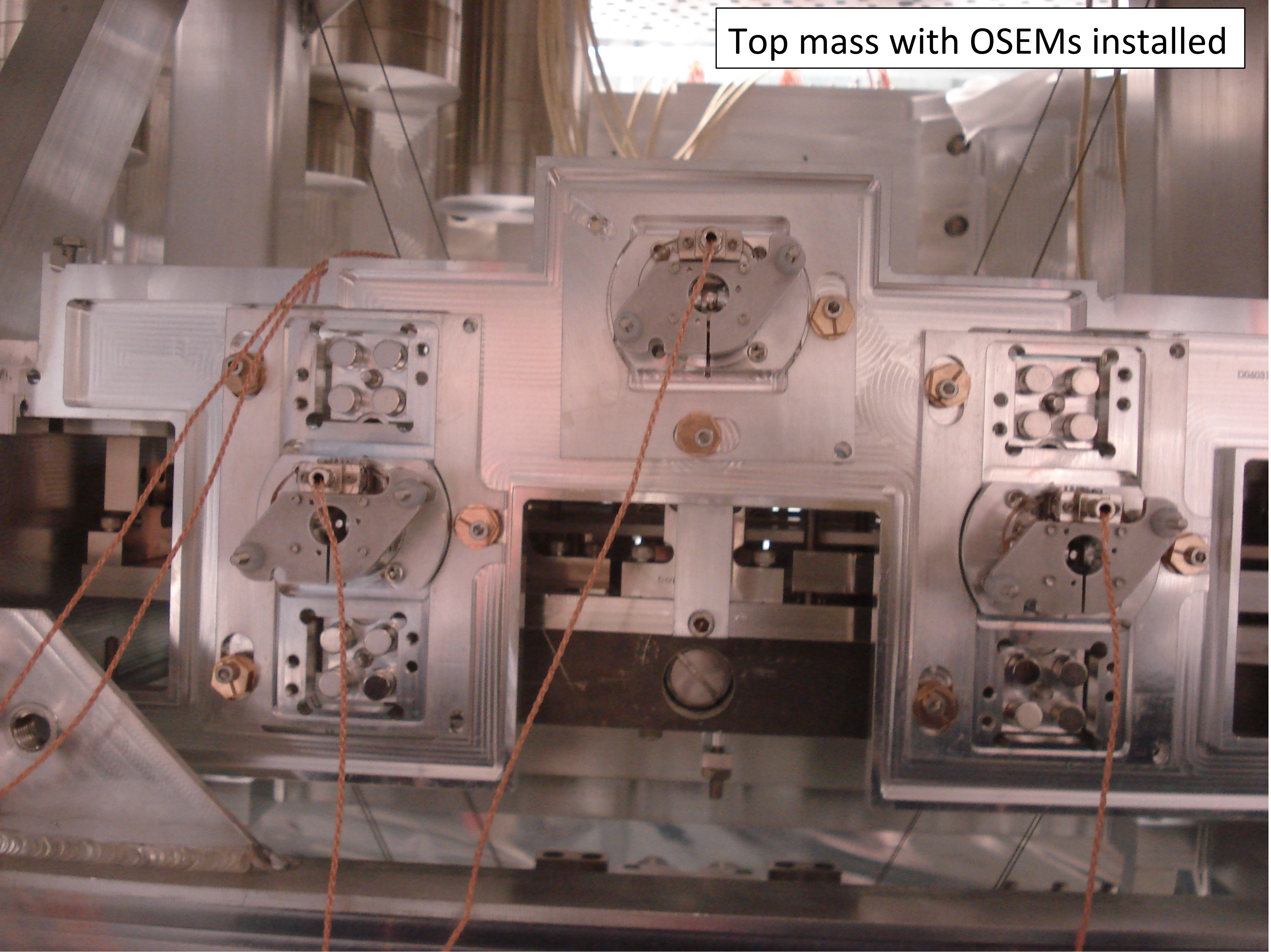
2) Install electronics & sensors & actuators



D0900900



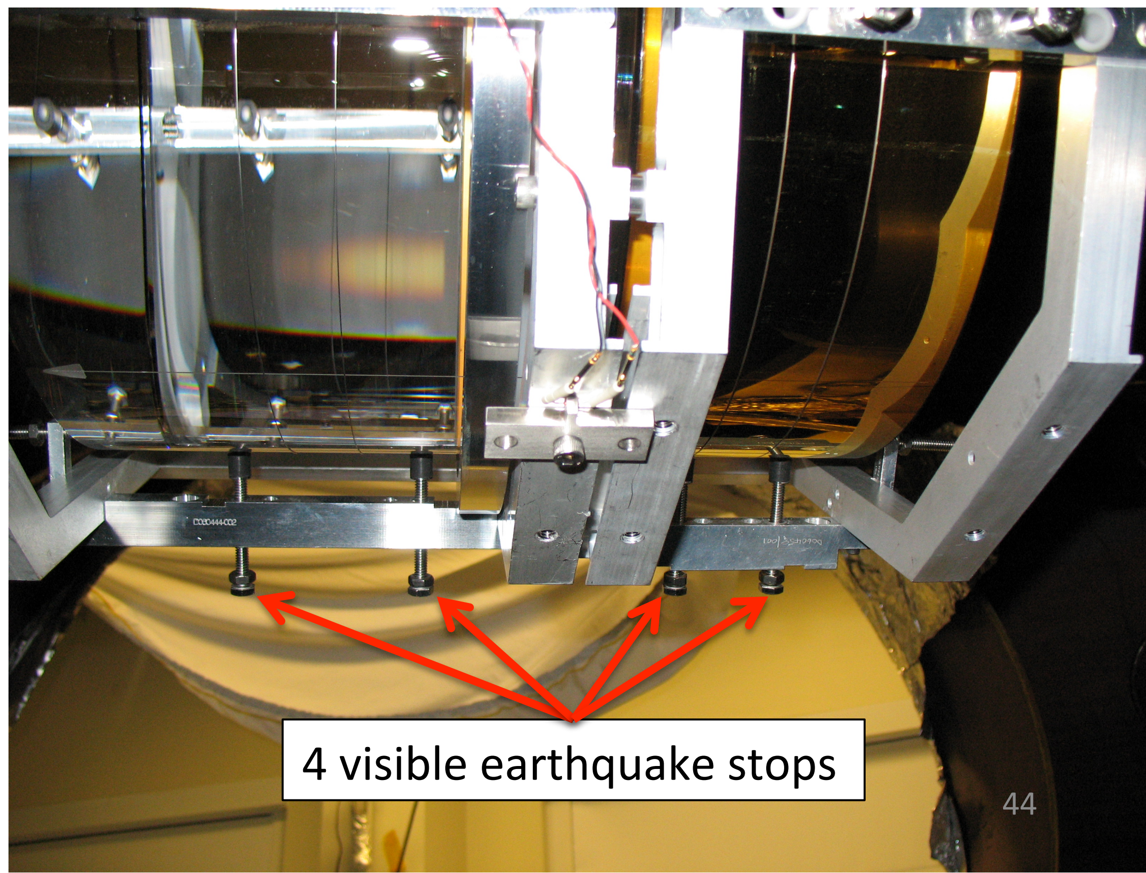
A BOSEM and its electronics



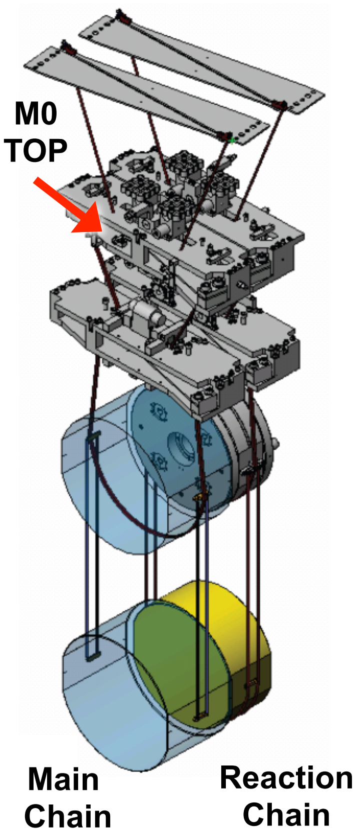
Top mass with OSEMs installed

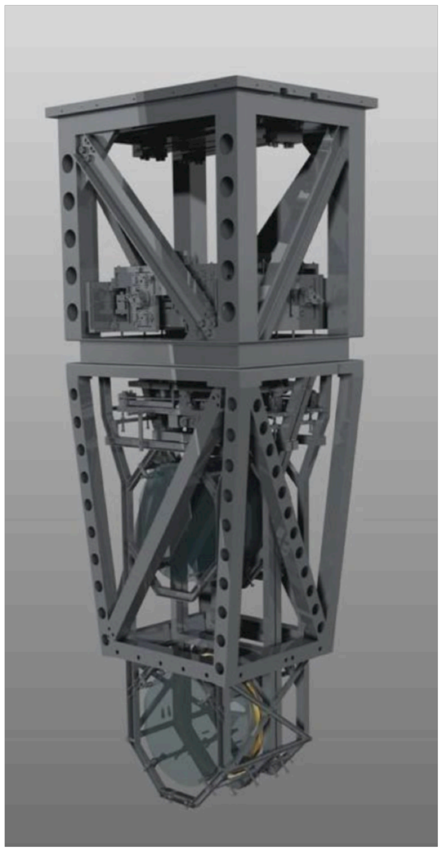
3) Hang the masses

Hang the masses by turning the earthquake stops away 1 mm from the masses

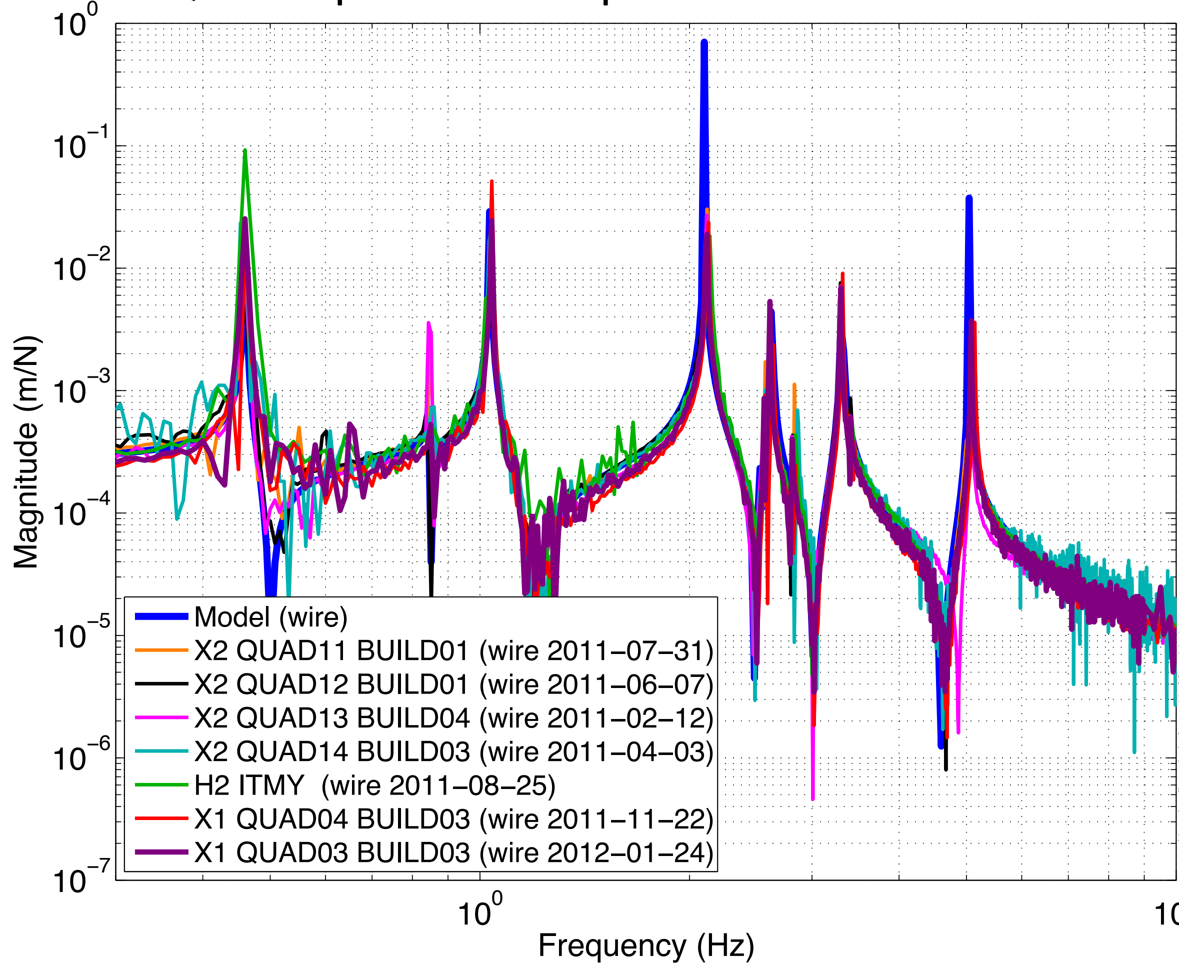


4a) Suspension Testing





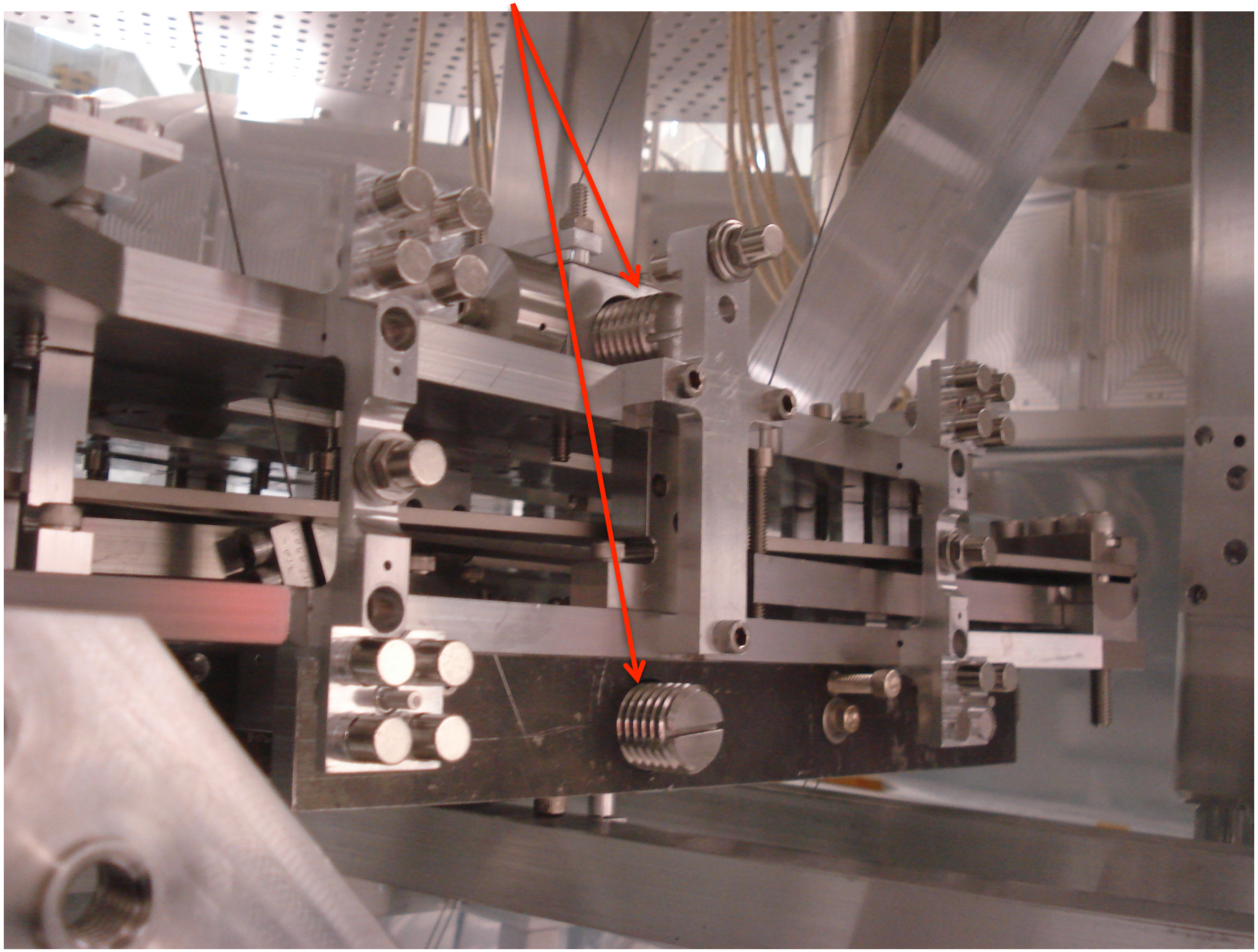
Quad top mass to top mass transfer function



The suspensions are tested using transfer function measurements throughout the assembly and install procedures. See https://dcc.ligo.org/LIGO-E1000078

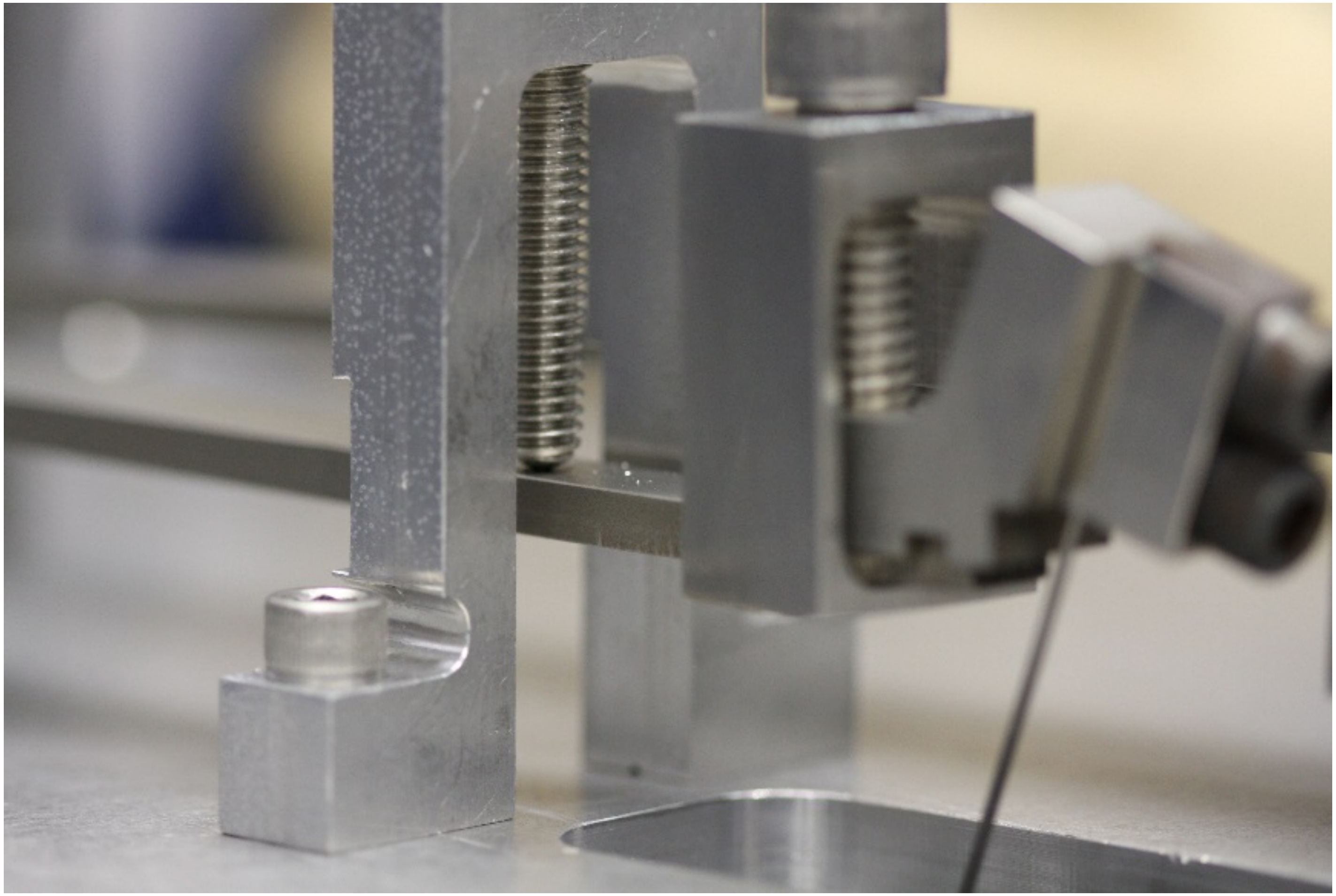
4b) Suspension Alignment

Pitch fine tuning screws



The quad prototype top mass at MIT Nov, 2007

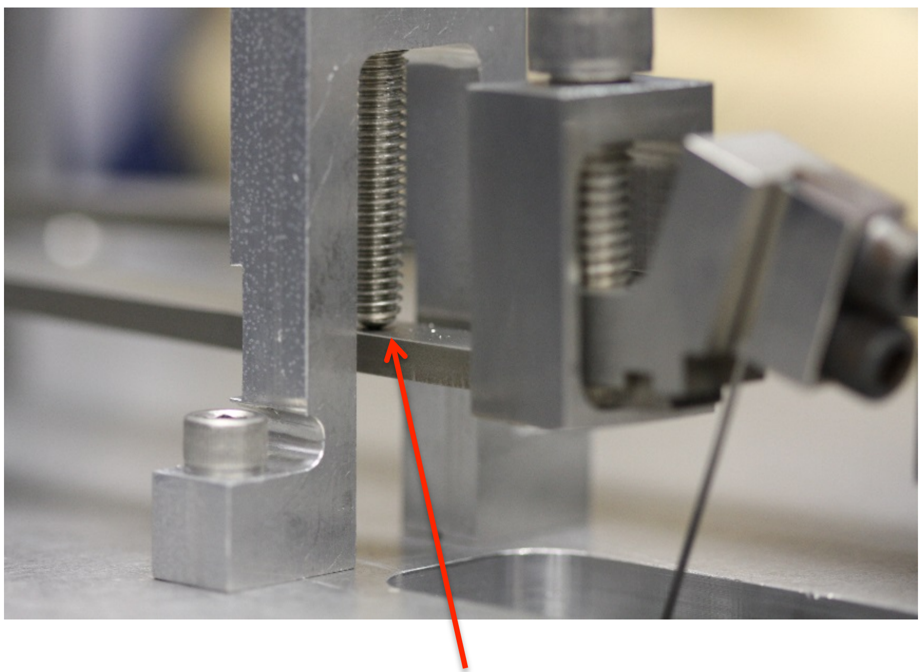
4b) Suspension Alignment



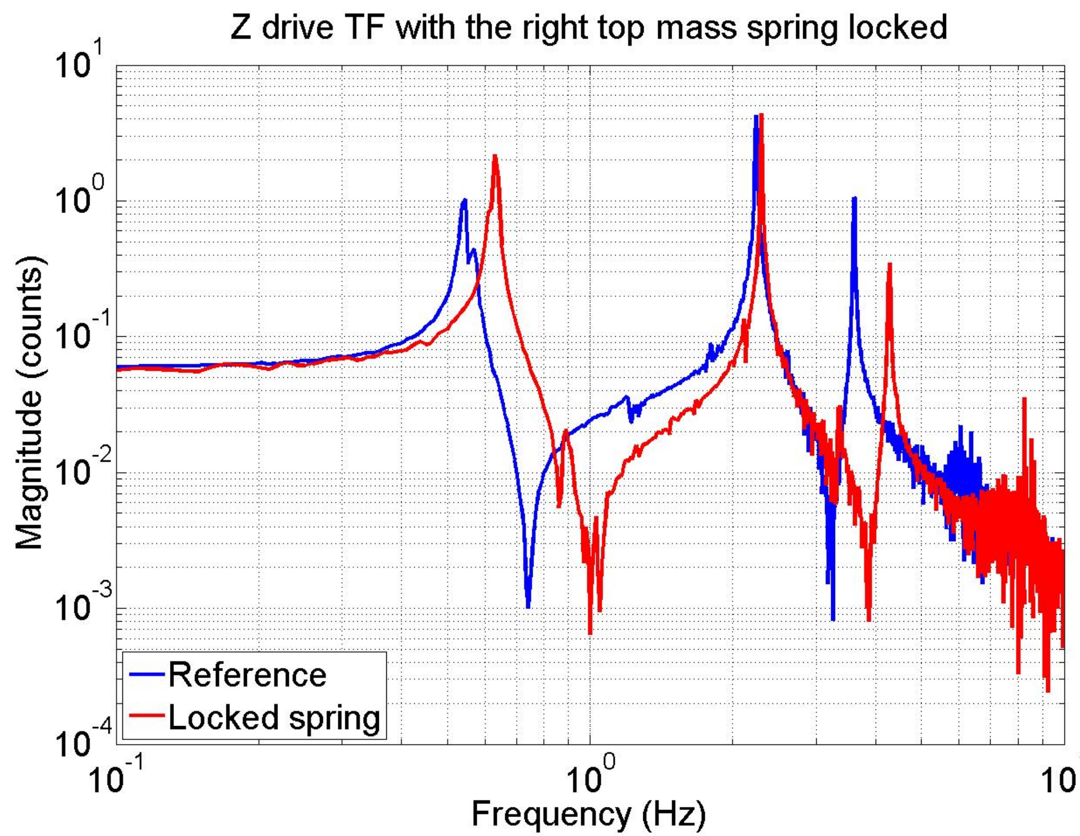
Spring tip touching clamping screw

5) Debug With Measurements and Model

Regular Measurements Identify Problems Early



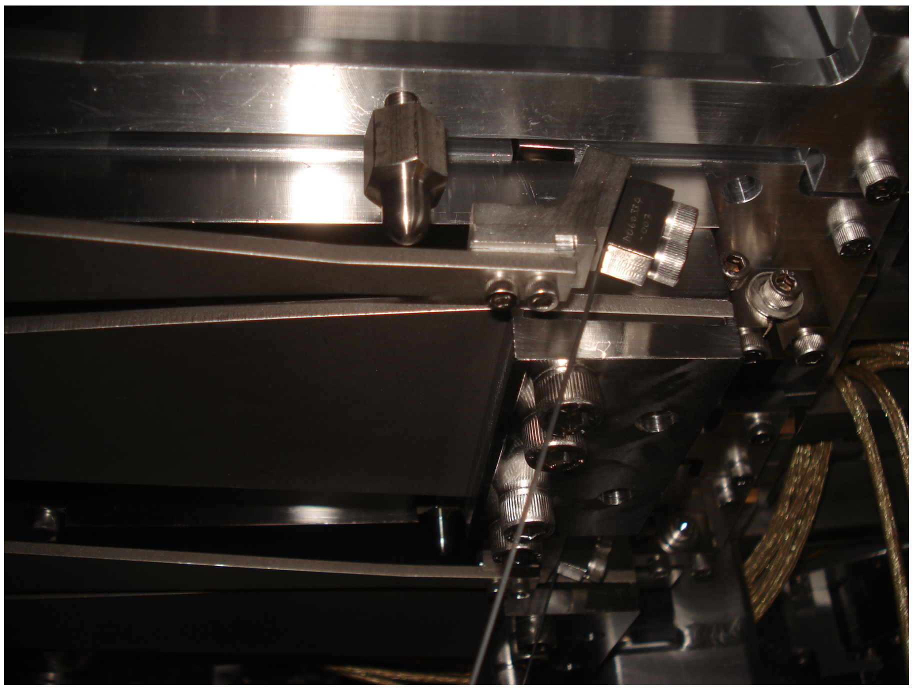
Spring tip touching clamping screw



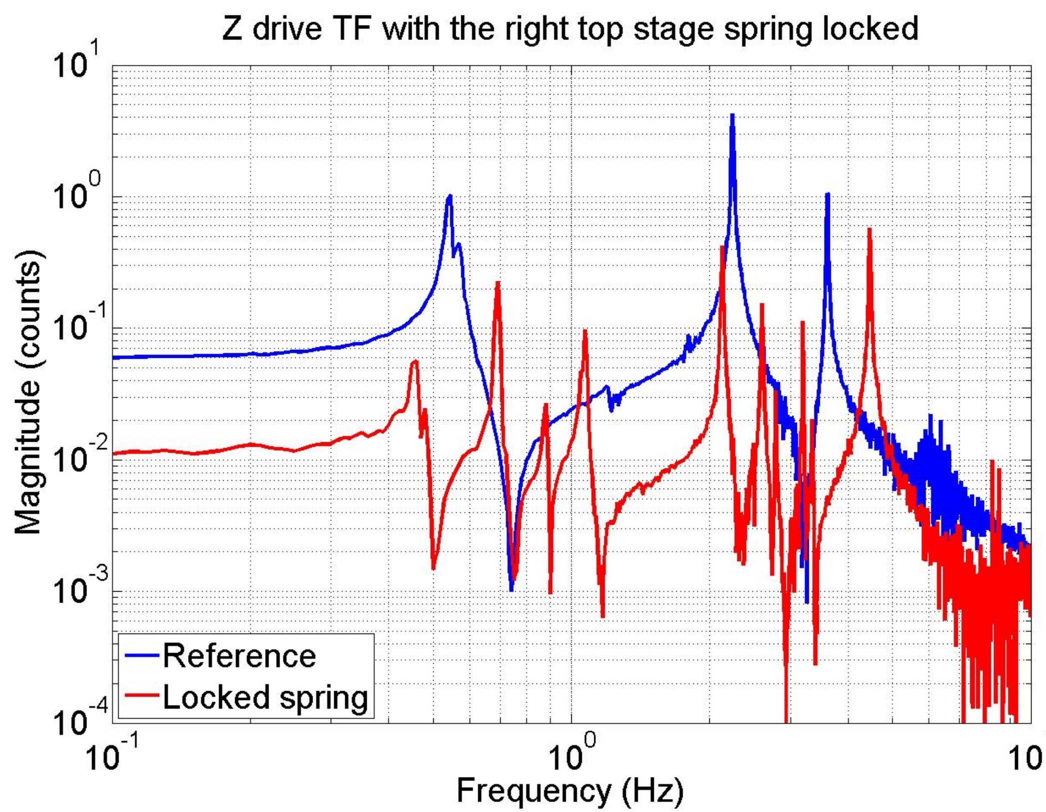
Top mass spring tip touching clamp

5) Debug With Measurements and Model

Regular Measurements Identify Problems Early

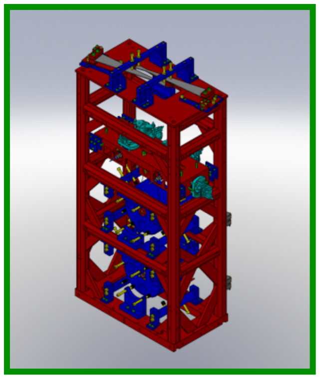


Top spring and top spring clamp



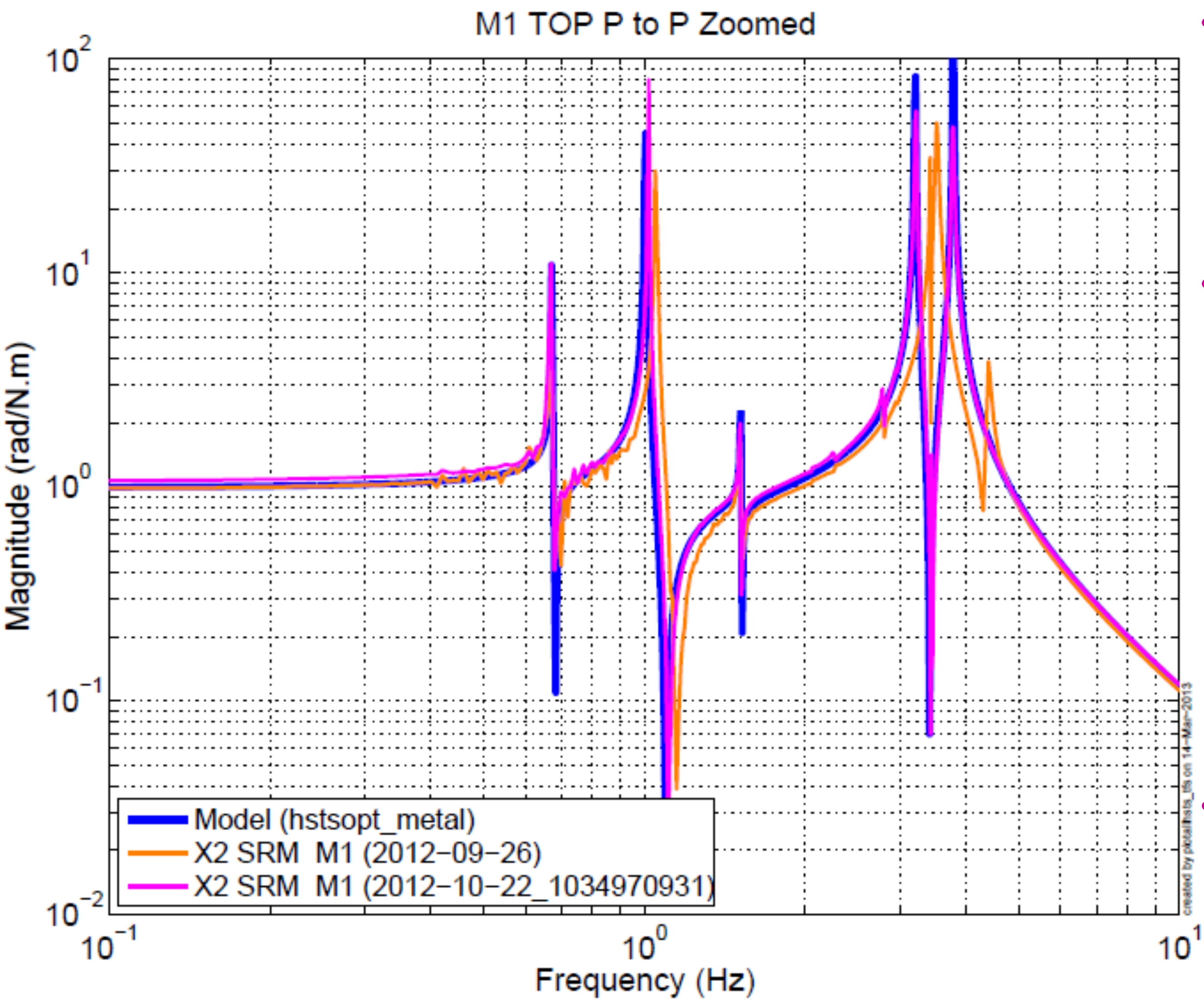
Top spring touching the clamp

Comparing measurements to **models** helps identify problems



HSTS

Measuring lower wire diameter



Ref: G1300132

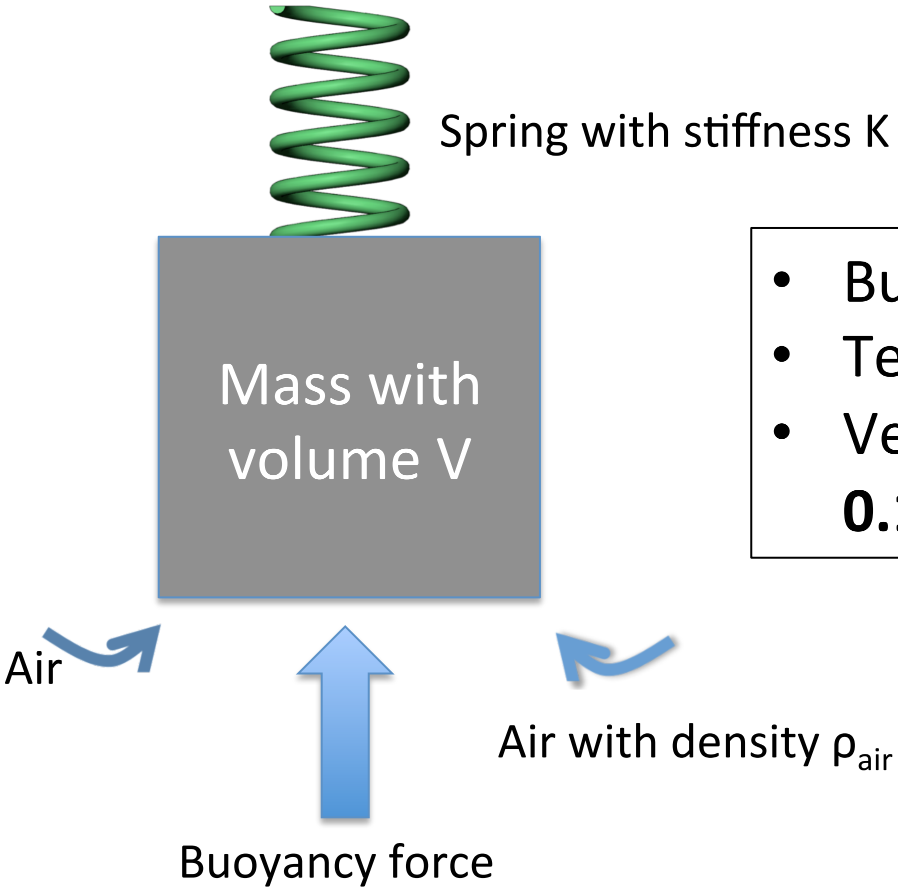
- All DOFs for SRM (HSTS) looked good, except for an ugly feature in Pitch (orange)
- Modeling suggested that most likely the incorrect diameter lower wire could be the culprit (see LLO aLOG 4766 i.e ø = 0.006" instead of ø = 0.0047"
- This was later confirmed, and replaced with the correct wire diameter (magenta)

Libraries of messed up transfer function examples

- https://awiki.ligo-wa.caltech.edu/aLIGO/TransferFunctionColoringBook

- https://dcc.ligo.org/LIGO-E1000078

Atmospheric Buoyancy

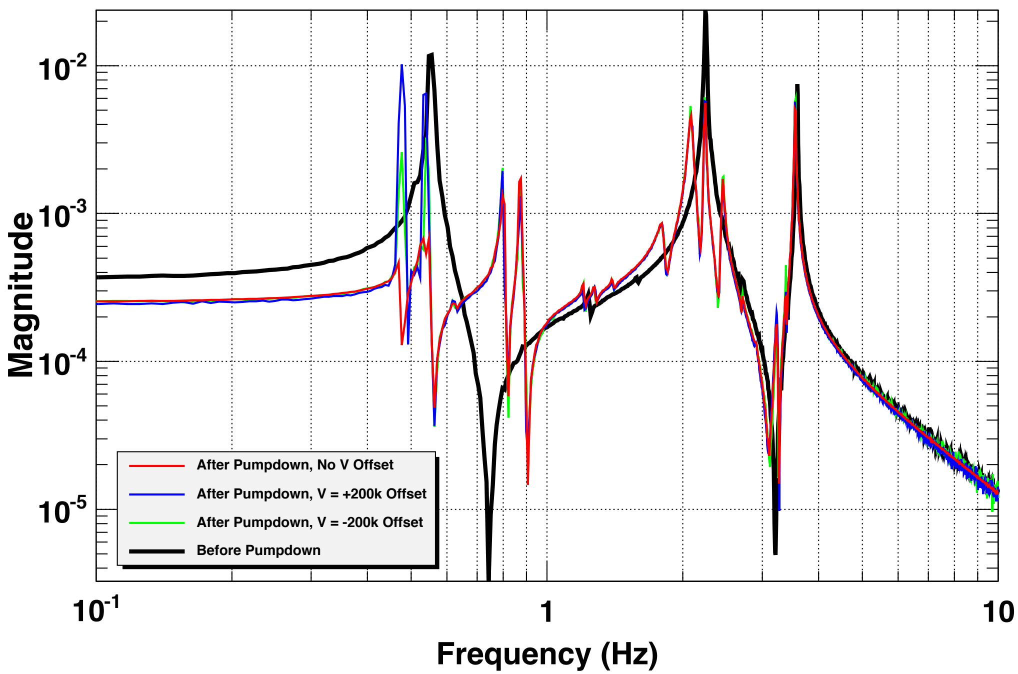


- Buoyancy displacement = ρ_{air}*V*g / K
- Test mass displacement = **0.4 mm**
- Vertical OSEMs must be pre-compensated by **0.17 mm ≈ 1/3 of the range**

Reference: https://dcc.ligo.org/LIGO-T1100616

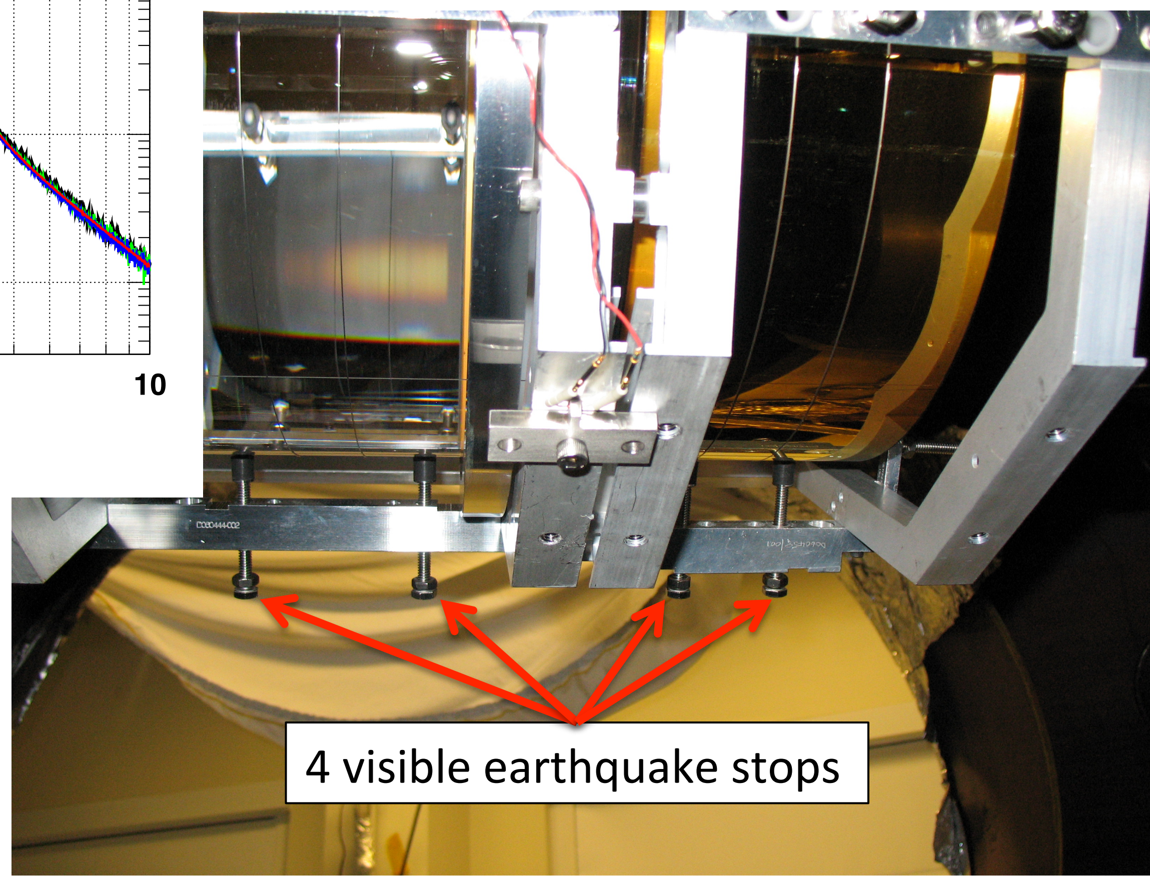
Buoyancy is important!

In-vac transfer function showing rubbing stop



*T0=06/01/2015 00:11:04 *Avg=5

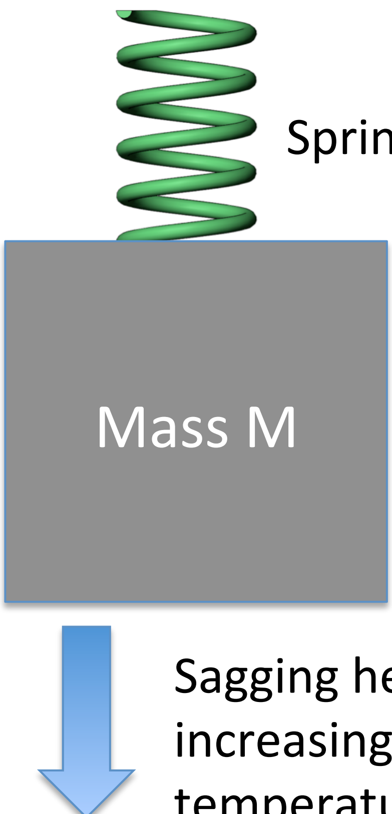
On Jan 9, 2015 LHO had to vent just to give one of these stops more room



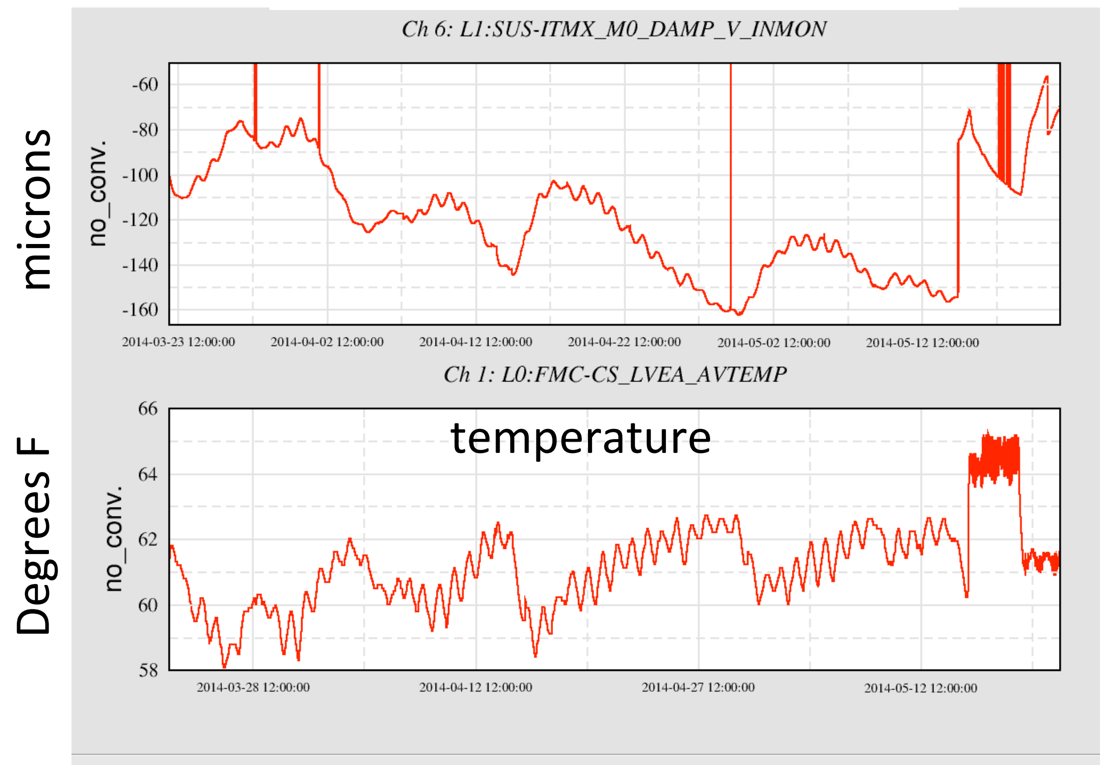
- https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=15878
- https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=15985

Thermal sagging

Spring stiffness is temperature dependent. Test mass sags by 0.225 mm / C.



Top mass vertical displacement



https://alog.ligo-la.caltech.edu/aLOG/index.php?callRep=14027

Modeling reference: https://dcc.ligo.org/LIGO-T1400749

Suspension MATLAB Models

- On SUS SVN at
  https://redoubt.ligo-wa.caltech.edu/svn/ or
  https://redoubt.ligo-wa.caltech.edu/websvn/ 9
  - *Quads*: ../sus/trunk/Quad/Common/MatlabTools/QuadModel_Production/
  - *Triples*: ../sus/trunk/Common/MatlabTools/TripleModel_Production
  - *Doubles*: ../sus/trunk/Common/MatlabTools/DoubleModel_Production
  - *Singles*: ../sus/trunk/Common/MatlabTools/SingleModel_Production
- Summary of features and instructions at G1401132
- Information also on CSWG wiki
  https://wiki.ligo.org/CSWG/ALIGO_Suspensions

Suspension Matlab/Mathematica Models

Mechanical parameters

- Masses
- Wire lengths
- Spring stiffnesses
- etc

→ MATLAB or Mathematica →

Suspension response

- Equations of motion
- Impulse response
- Transfer functions
- Noise predictions

Suspension Matlab/Mathematica Models

Mechanical parameters
- Masses
- Wire lengths
- Spring stiffnesses
- etc

Higher order dynamics
- Violin modes
- Mystery dynamics

MATLAB
(not mathematica)

Suspension response
- Equations of motion
- Impulse response
- Transfer functions
- Noise predictions

Suspension Matlab/Mathematica Models

Mechanical parameters
- Masses
- Wire lengths
- Spring stiffnesses
- etc

MATLAB
(not mathematica)

Suspension response
- Equations of motion
- Impulse response
- Transfer functions
- Noise predictions

Higher order dynamics
- Violin modes
- Mystery dynamics

Measured data
- Resonant frequencies
- Mass values

Suspension Matlab/Mathematica Models

Radiation pressure from the interferometer

Mechanical parameters
- Masses
- Wire lengths
- Spring stiffnesses
- etc

MATLAB
(not mathematica)

Suspension response
- Equations of motion
- Impulse response
- Transfer functions
- Noise predictions

Higher order dynamics
- Violin modes
- Mystery dynamics

Measured data
- Resonant frequencies
- Mass values

Suspension Matlab/Mathematica Models

Radiation pressure from the interferometer

Controls
- Damping
- TBD

Mechanical parameters
- Masses
- Wire lengths
- Spring stiffnesses
- etc

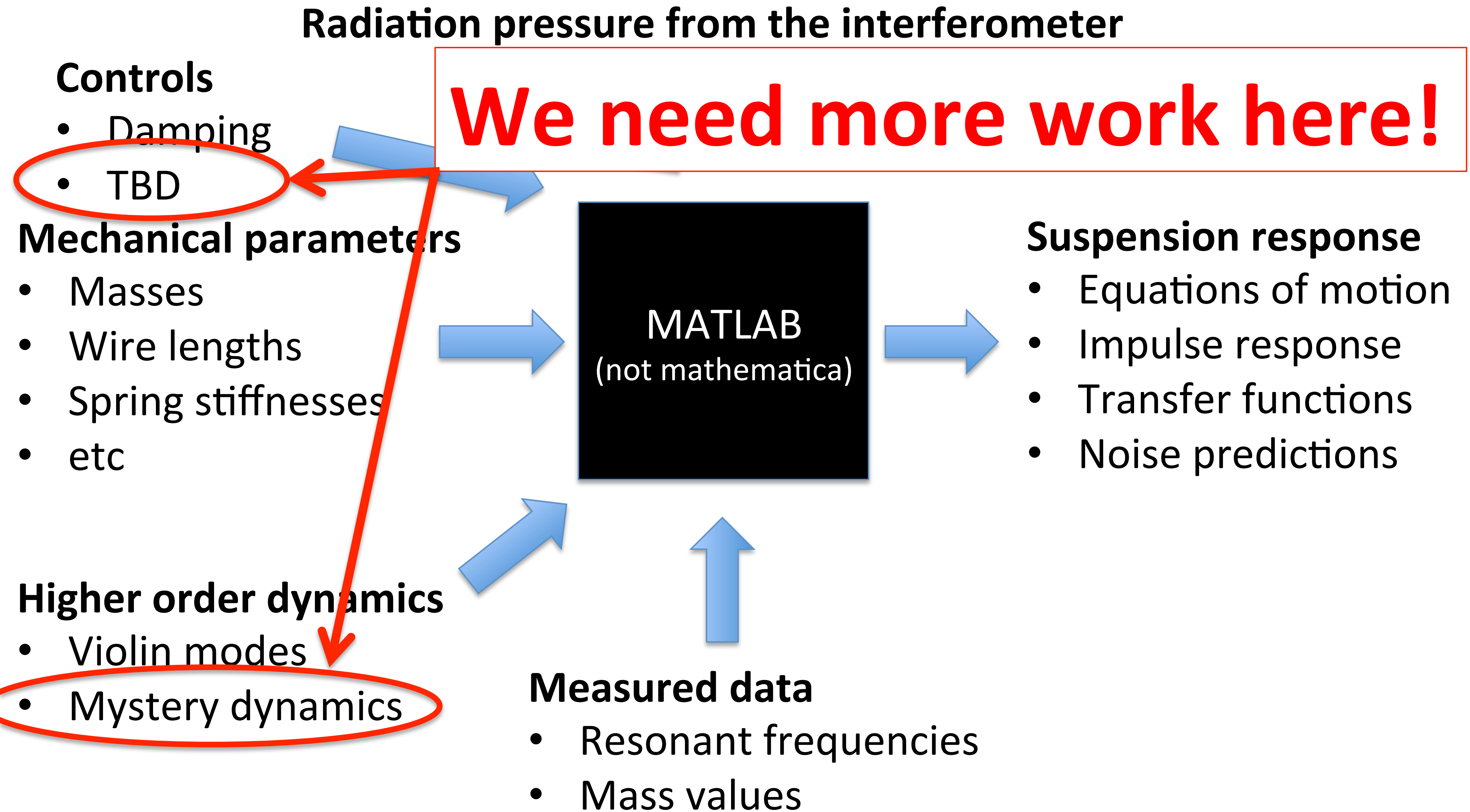
MATLAB
(not mathematica)

Suspension response
- Equations of motion
- Impulse response
- Transfer functions
- Noise predictions

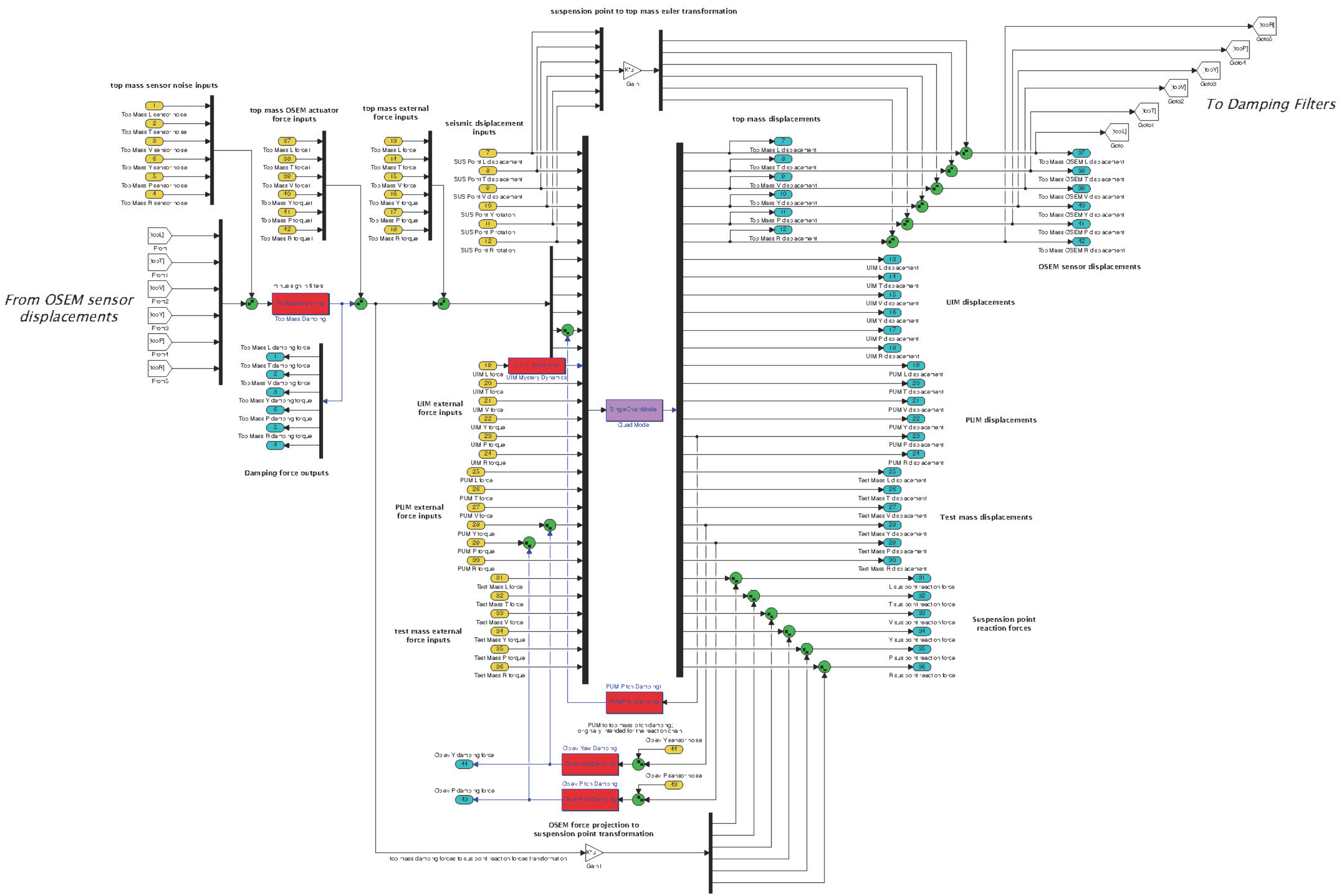
Higher order dynamics
- Violin modes
- Mystery dynamics

Measured data
- Resonant frequencies
- Mass values

Suspension Matlab/Mathematica Models



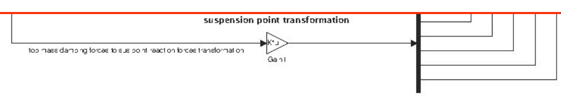
Example – Damped Quad Model



Example – Damped Quad Model

Still to add:

- **Length control**
- **Angular control**
- **Fully integrated radiation pressure**
- **Integration with the active seismic isolation**
- **Better predictions of cross-coupling**
- **More user friendly interface**
- **All the above for the smaller suspensions**



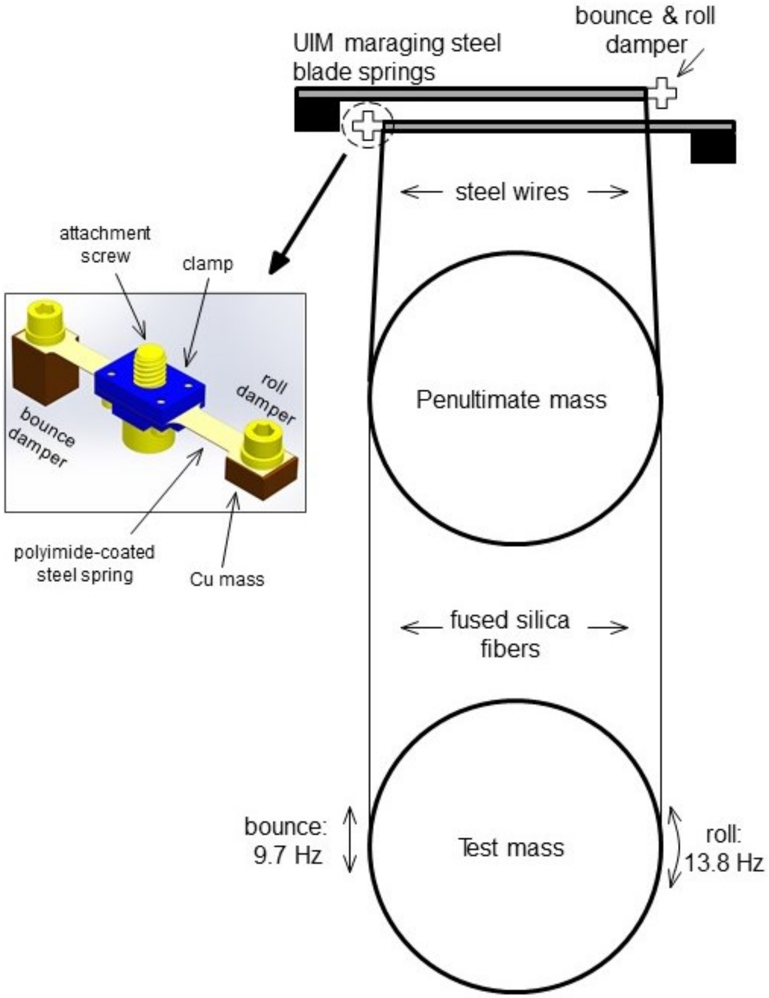
Recent work to improve suspensions

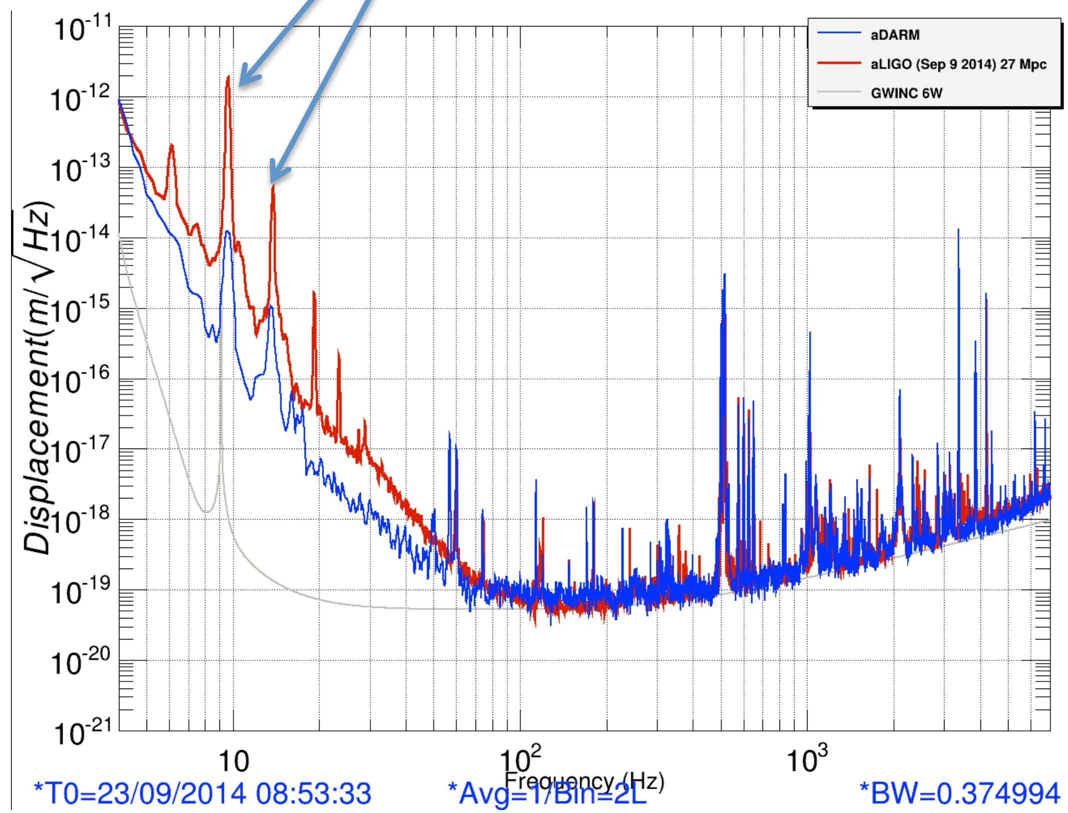
- Will need to be repeated in LIGO-India Observatory

List of ongoing modifications at https://dcc.ligo.org/LIGO-E1600265

Bounce Roll dampers (BRDs)

10 Hz and 14 Hz Qs decreased from 5e5 to ≈3000





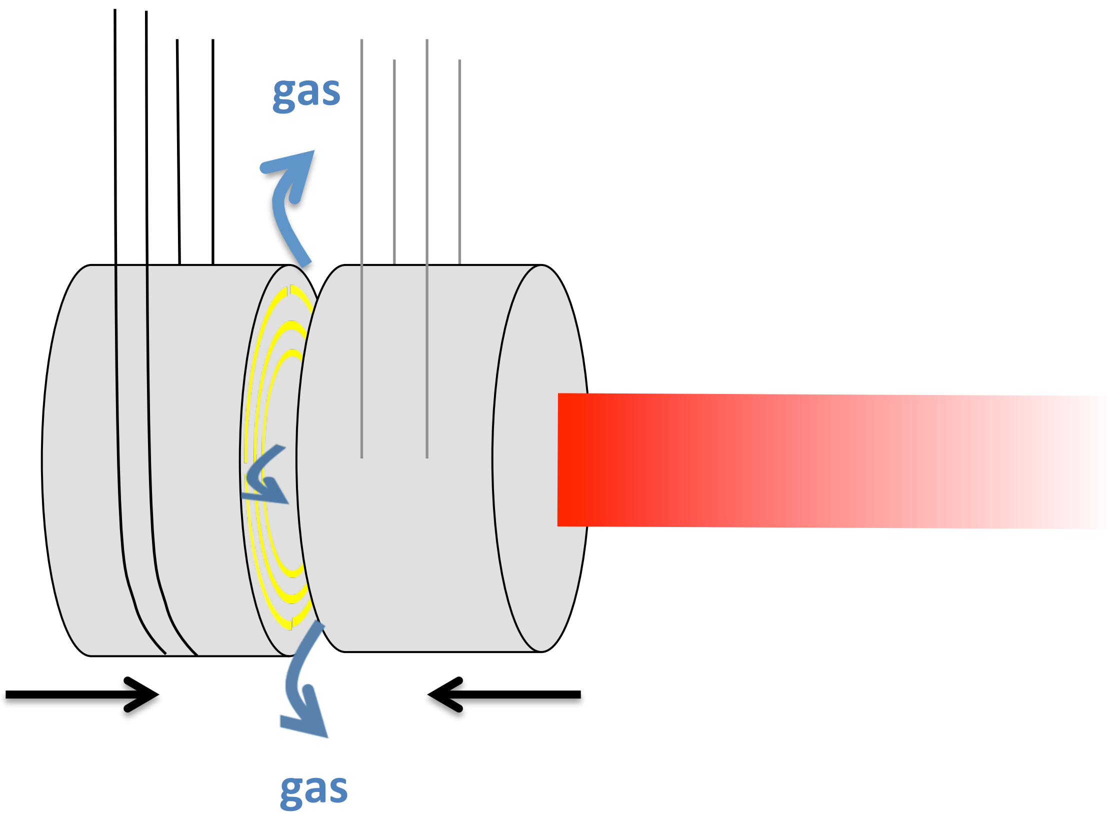
Reference: https://dcc.ligo.org/LIGO-P1600328

Squeezed film damping

The problem

Oscillating gap size squeezes residual gas in and out of the gap

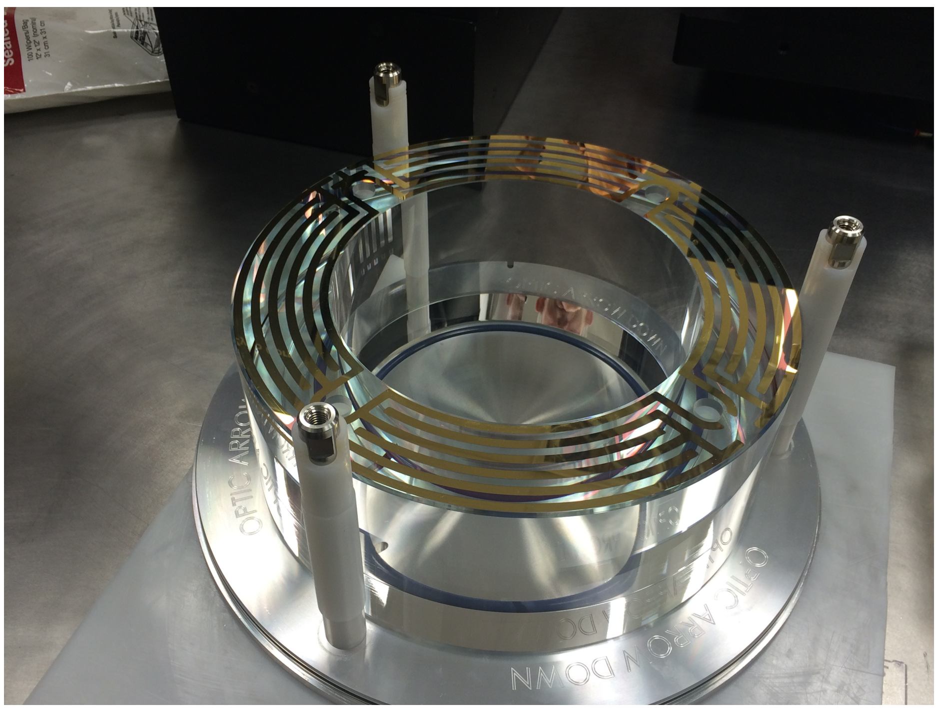
This results in passive damping -> therefore thermal noise



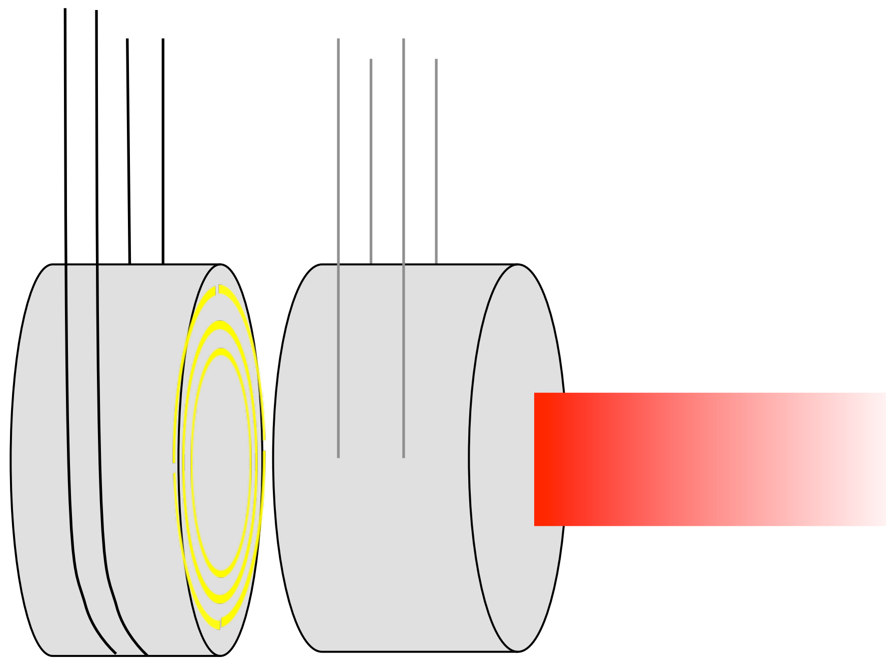
Squeezed film damping

The solutions

ETMs: Cut big hole in the End Reaction Mass



ITMS: Gap with Compensation Plate increased from 5mm to 20 mm



Summary of how India can help

- Better suspension models
- Consider thinner, higher stress silica fibers for test masses
- Help improve test mass thermal compensation
- Make lower noise, more reliable optical levers
- Controls, lots of control…but this is tomorrow's topic


Questions?

Advanced LIGO Suspensions and Control

Brett Shapiro
For the Suspensions group
LITRAb – IUCAA
19-21 Dec 2016

G1602410

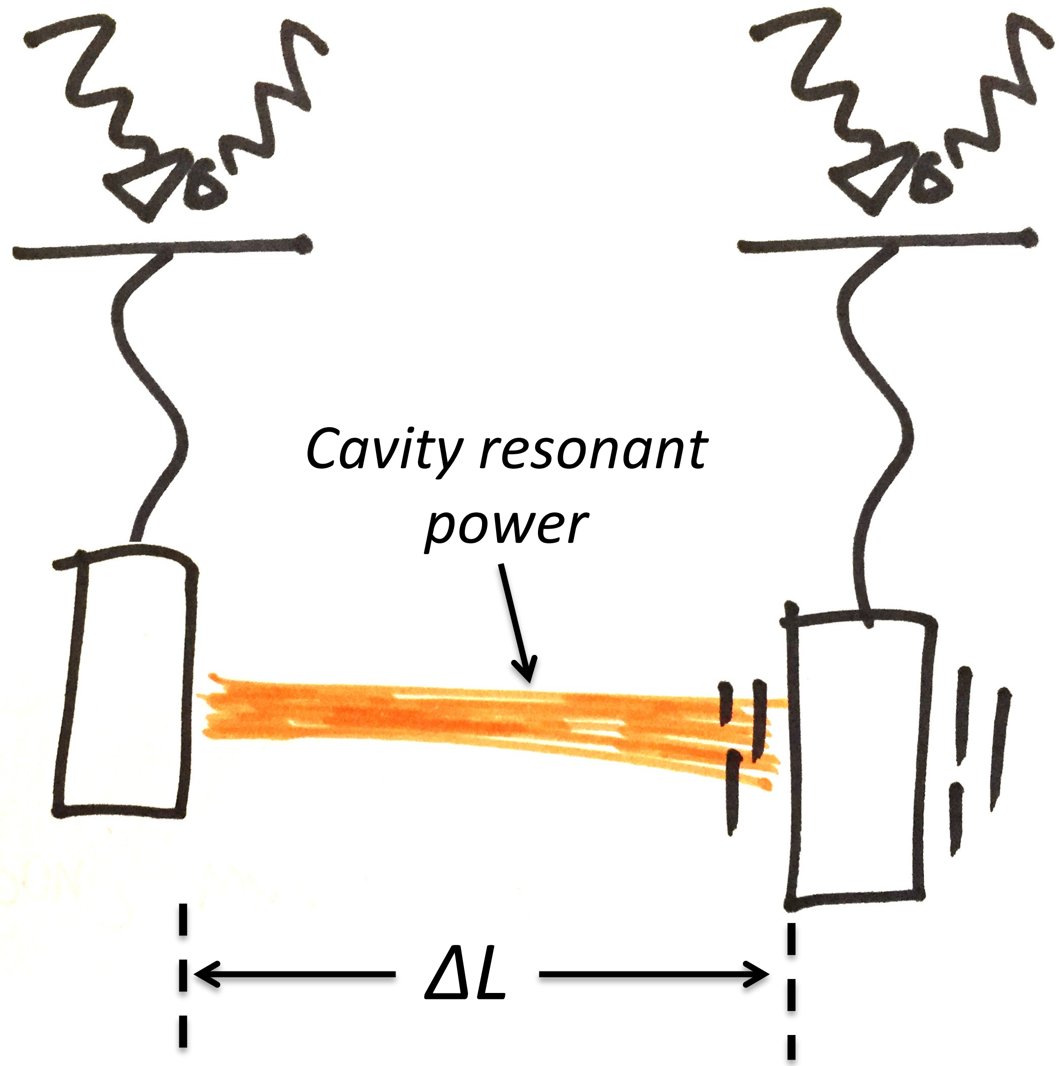
Part II – Suspension Control

- Why we need control
- Local control: top mass damping, violin mode damping
- Global control: cavity length, angular control, paramtric instabilities
- Ongoing work to improve suspension performance
- Other work that could be done (perhaps in India) to improve performance further

Why we need suspension control

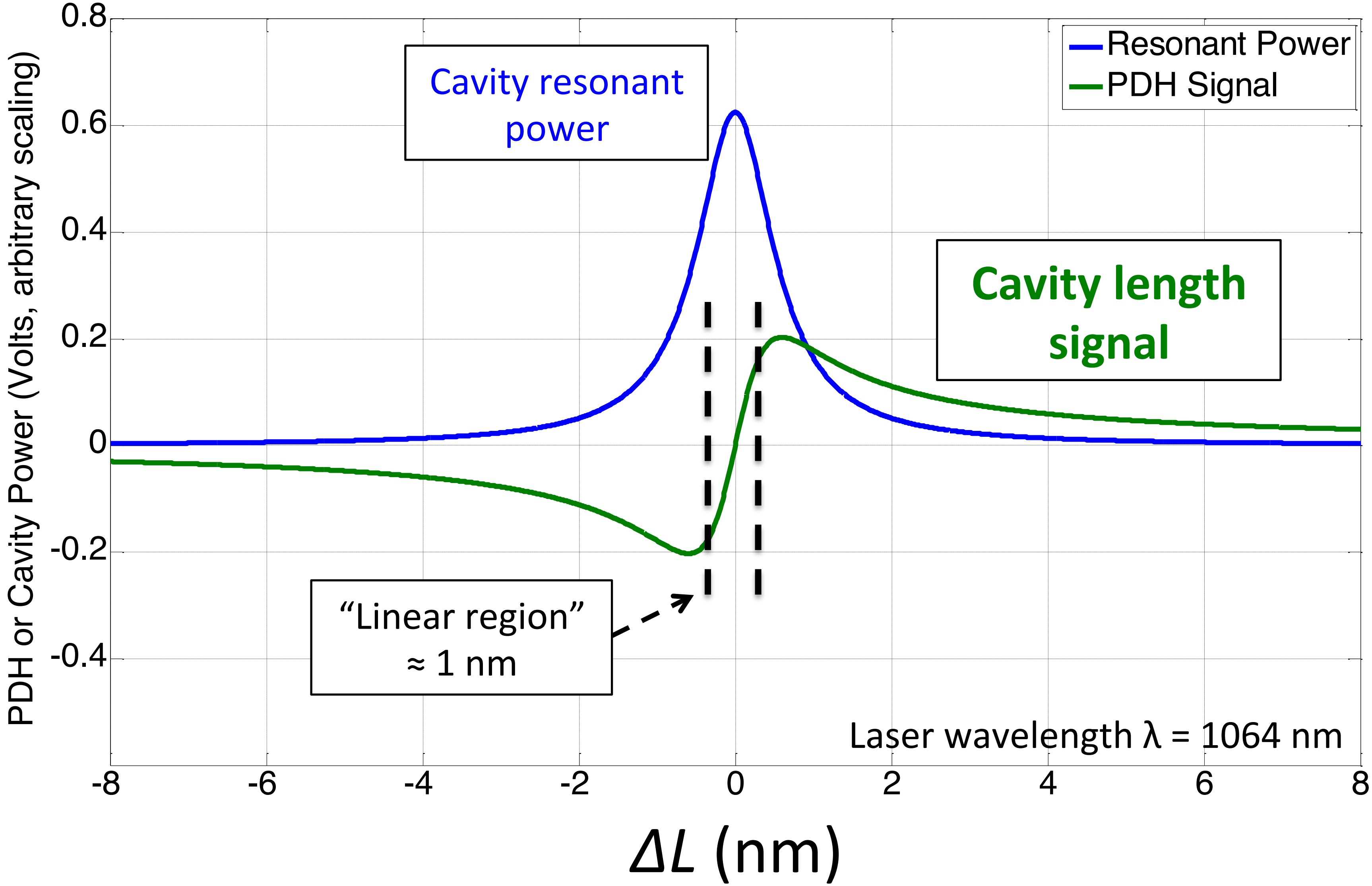
- The ground moves and disturbs our mirrors.
- The 4k arms must be aligned to **1 nrad** and fixed in length to **+-10^{-14} m** RMS.

https://dcc.ligo.org/LIGO-T070236/public

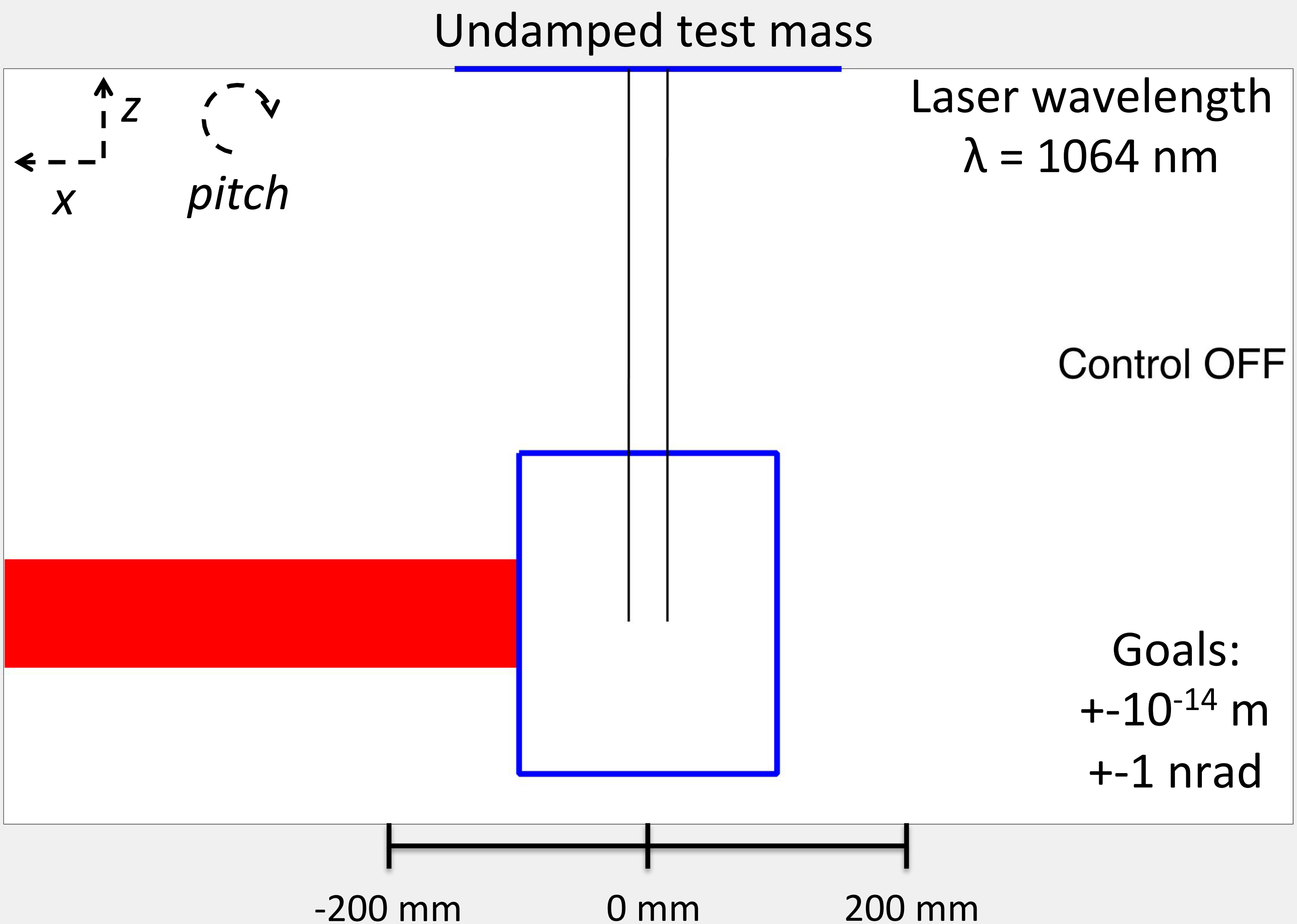


Adapted from G1600525

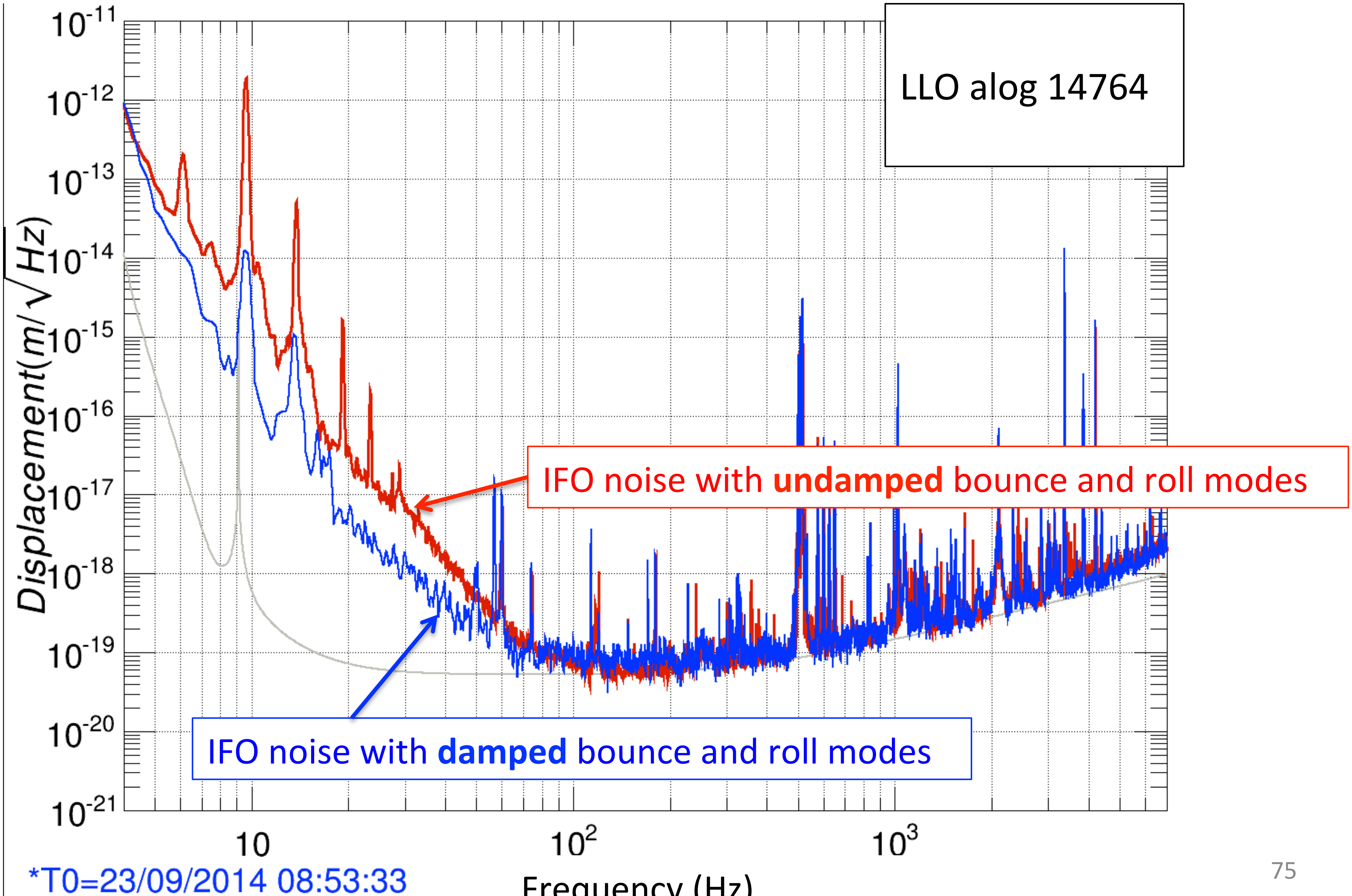
Nonlinear Interferometer Response



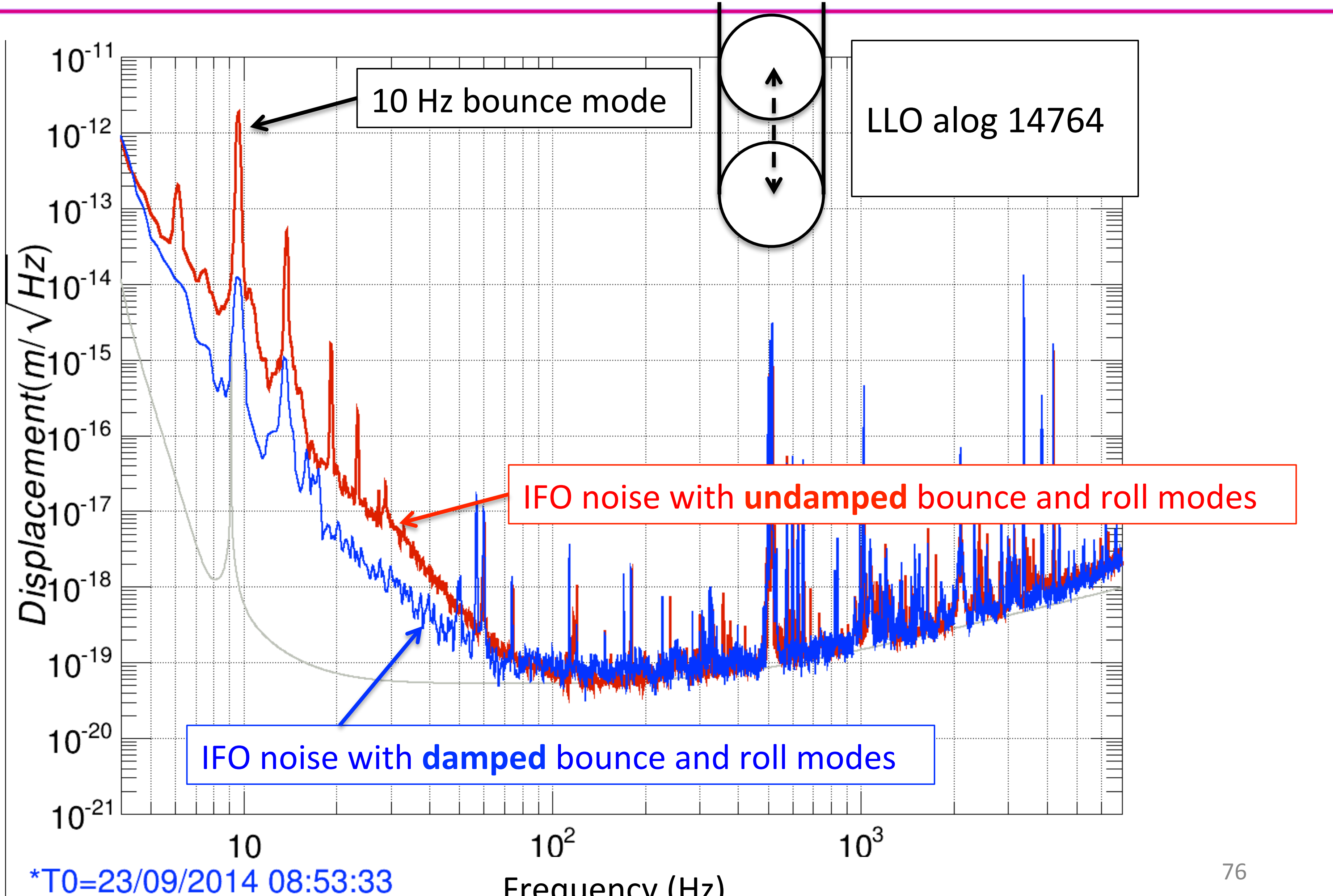
Why we need suspension control



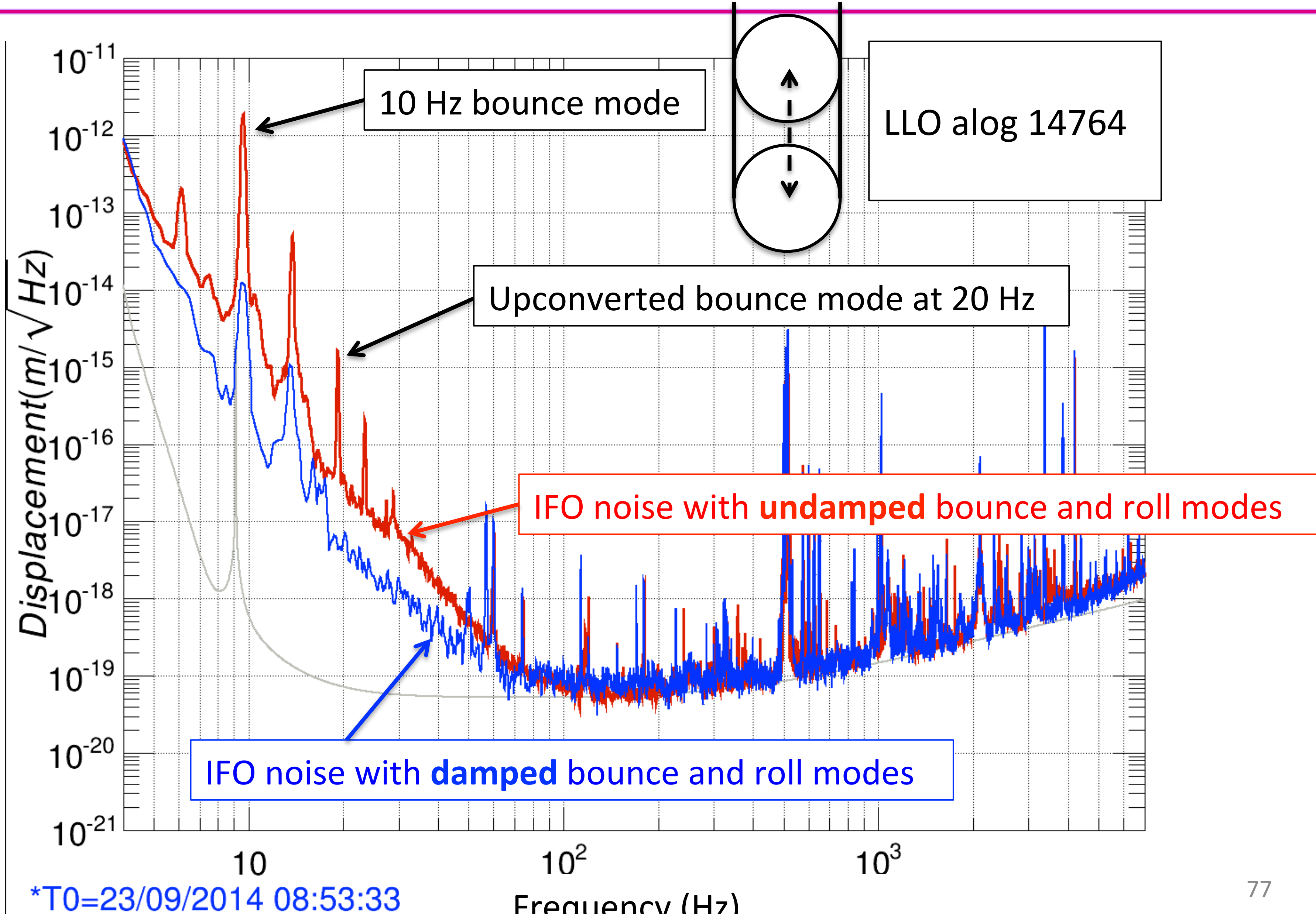
Nonlinear Upconversion



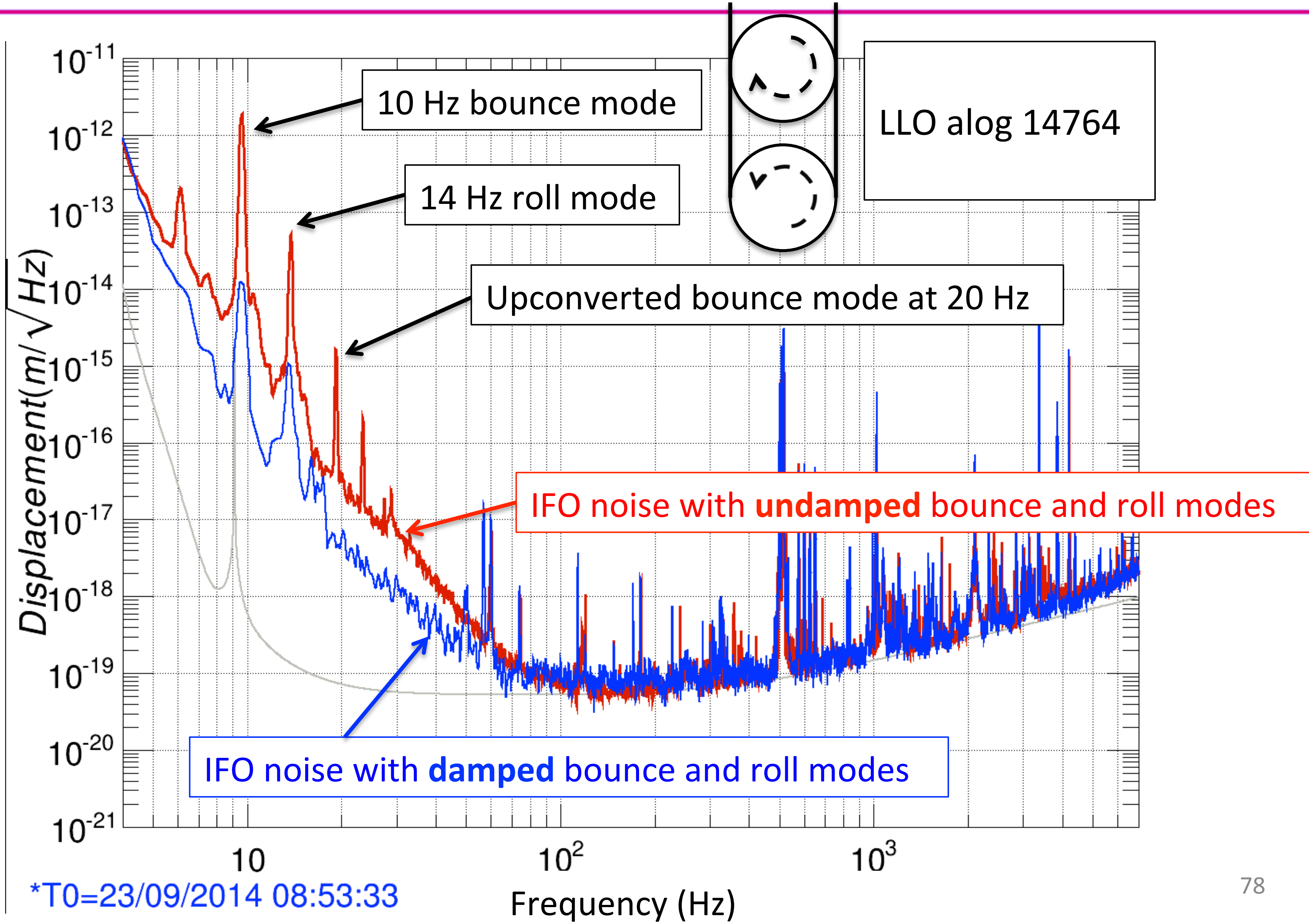
Nonlinear Upconversion



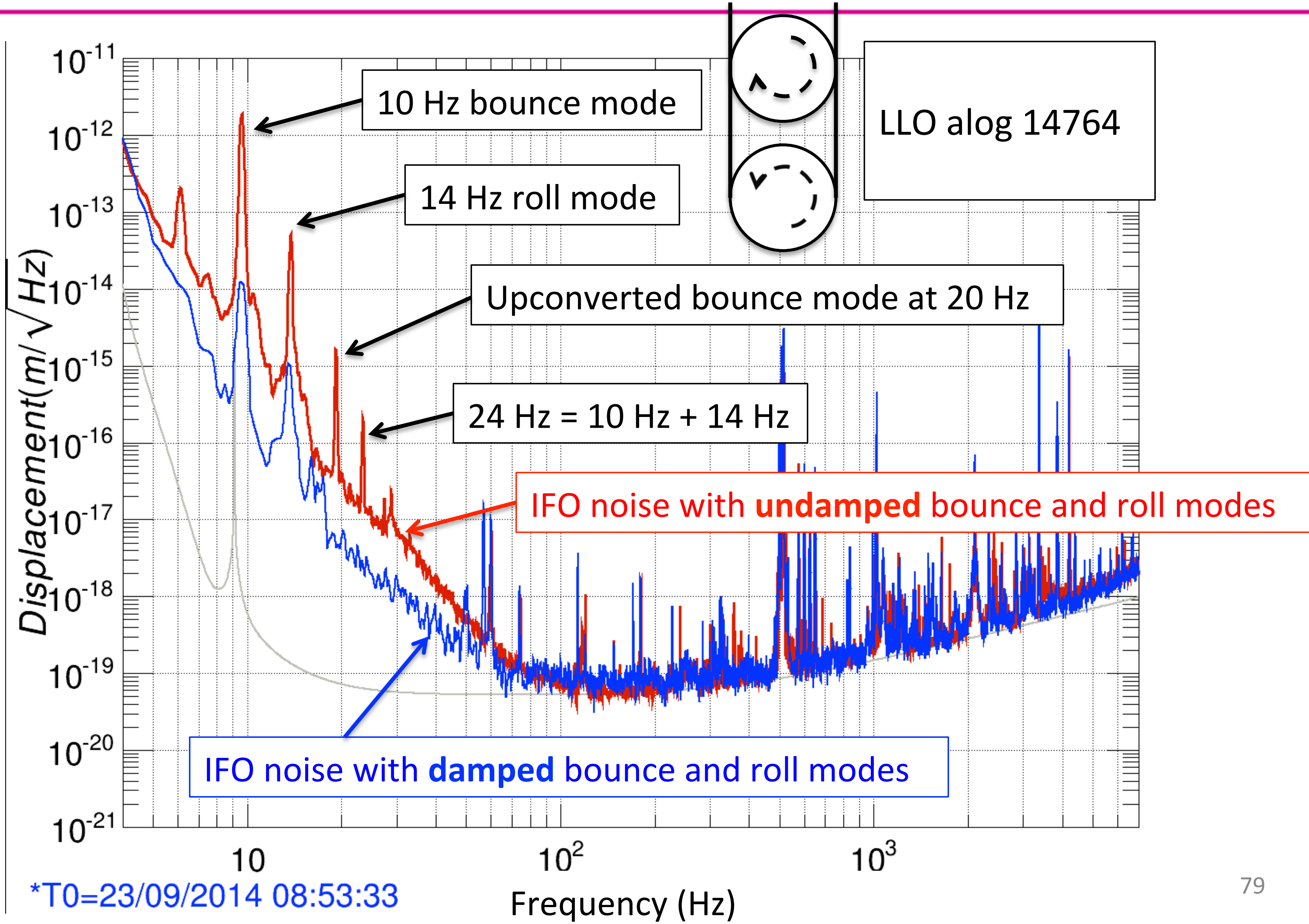
Nonlinear Upconversion



Nonlinear Upconversion

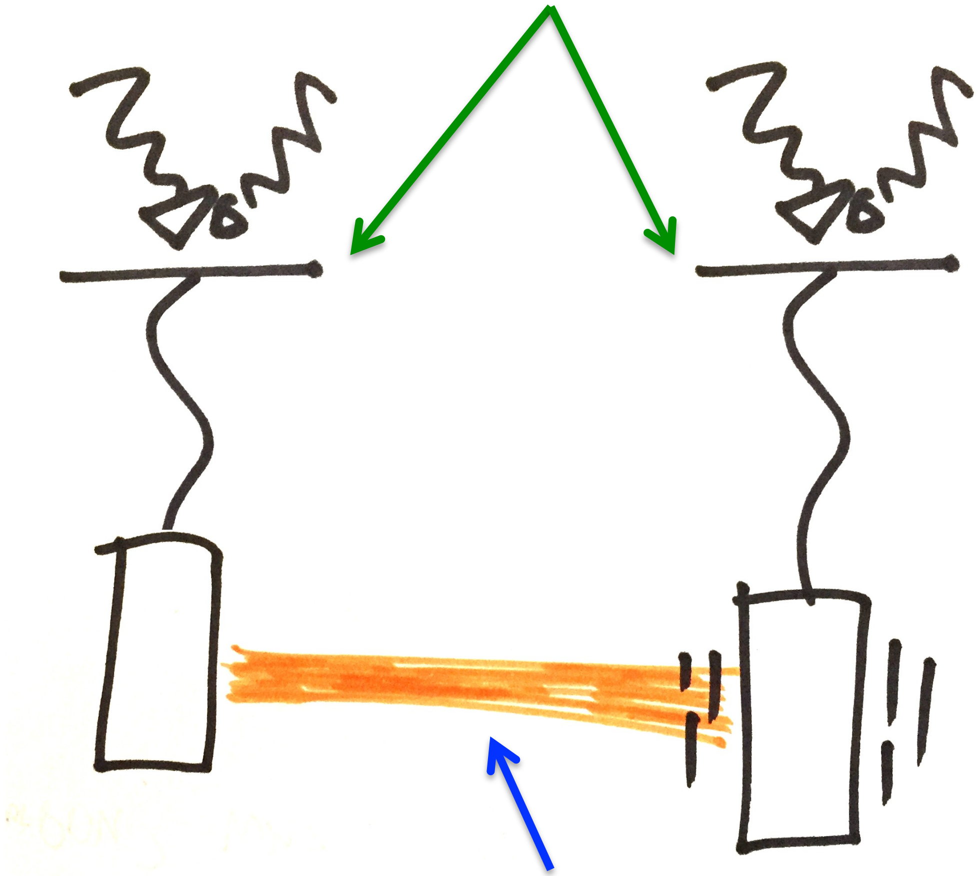


Nonlinear Upconversion



Two classes of control

'Local control' on each suspension to damp resonant motion



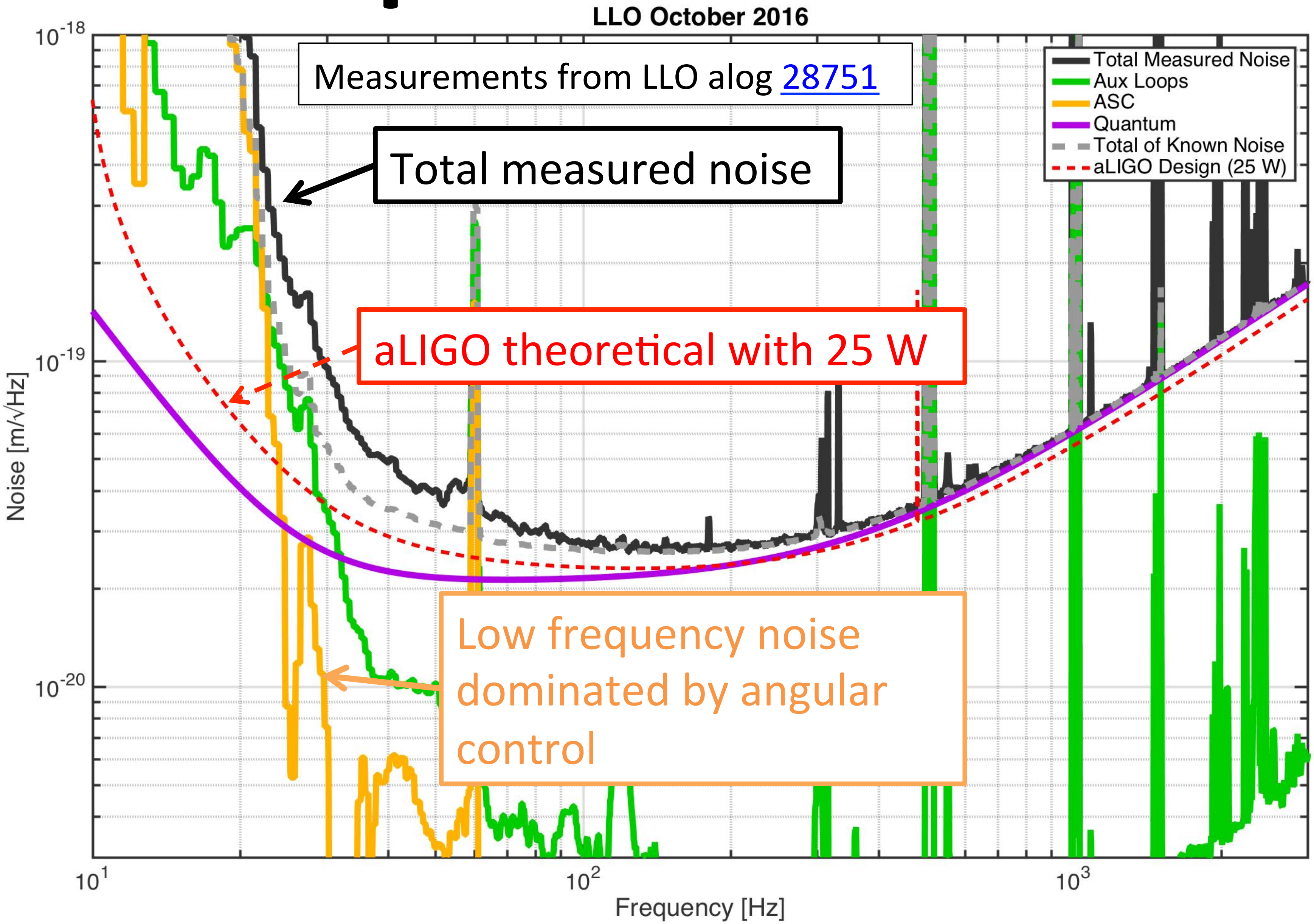
'Global control' between suspensions for cavity length and alignment

Image adapted from G1600525

Summary of Suspension Control

Type of control	Purpose	Challenges
Top mass damping	Damp the suspension resonances	Noise above 10 Hz. Dynamics affected by global control and radiation pressure.
Local violin mode damping	Damp the fiber violin modes	The suspension wasn't designed to damp these
Global cavity length	Control the cavity length to 10^{-14} m RMS	Don't saturate the actuators. Dynamics affected by top mass damping. Minimize coupling to angle.
Global cavity alignment	Keep the mirrors pointing at each other to 1 nrad RMS	Noise above 10 Hz. Dynamics affected by top mass damping and radiation pressure. Minimize coupling to length.
Test mass parametric instability damping	The test mass modes > 6 kHz interact unstably with the high power cavity	At high cavity power there are dozens to damp

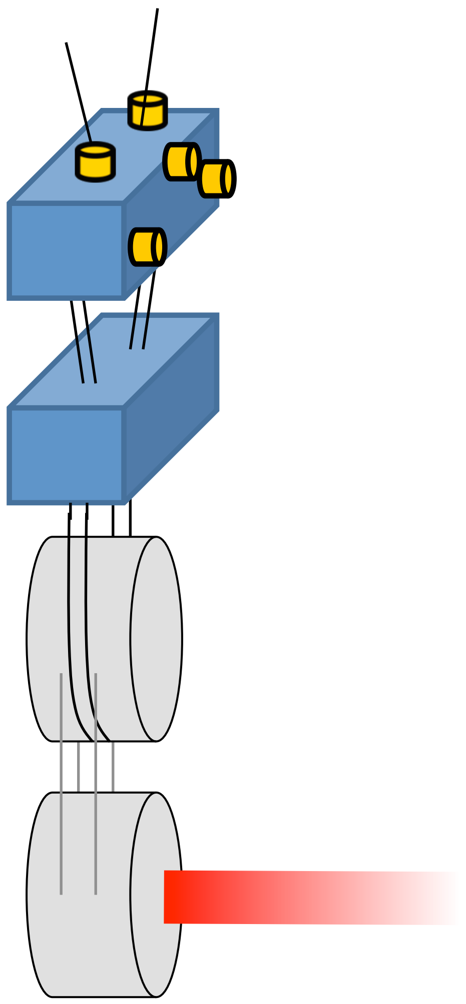
Keep Noise Low



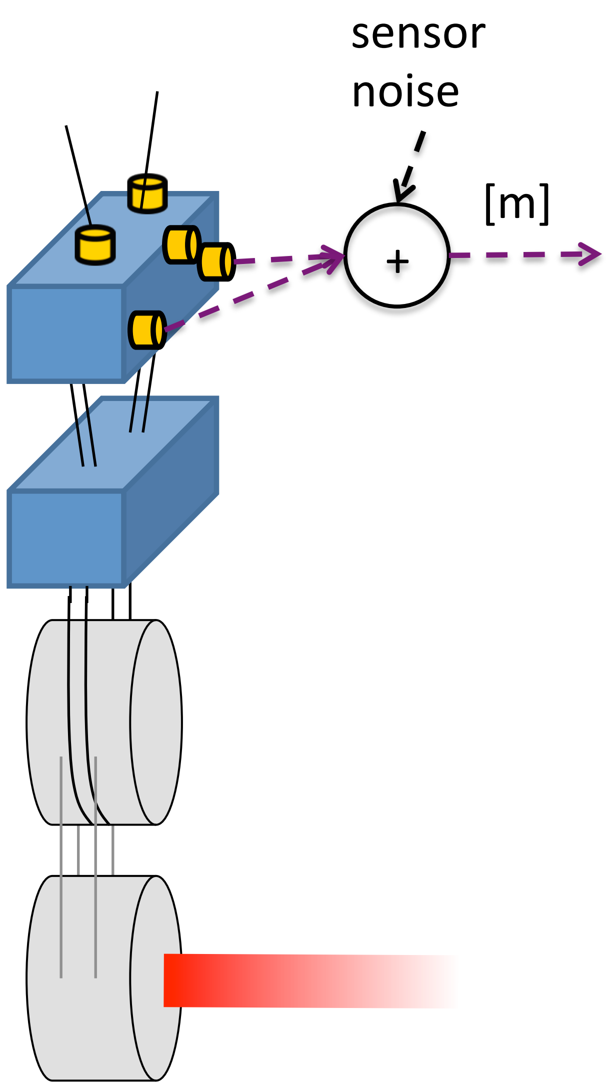
Local Control
Following the Quad SUS example

- Top mass damping
- Violin mode damping

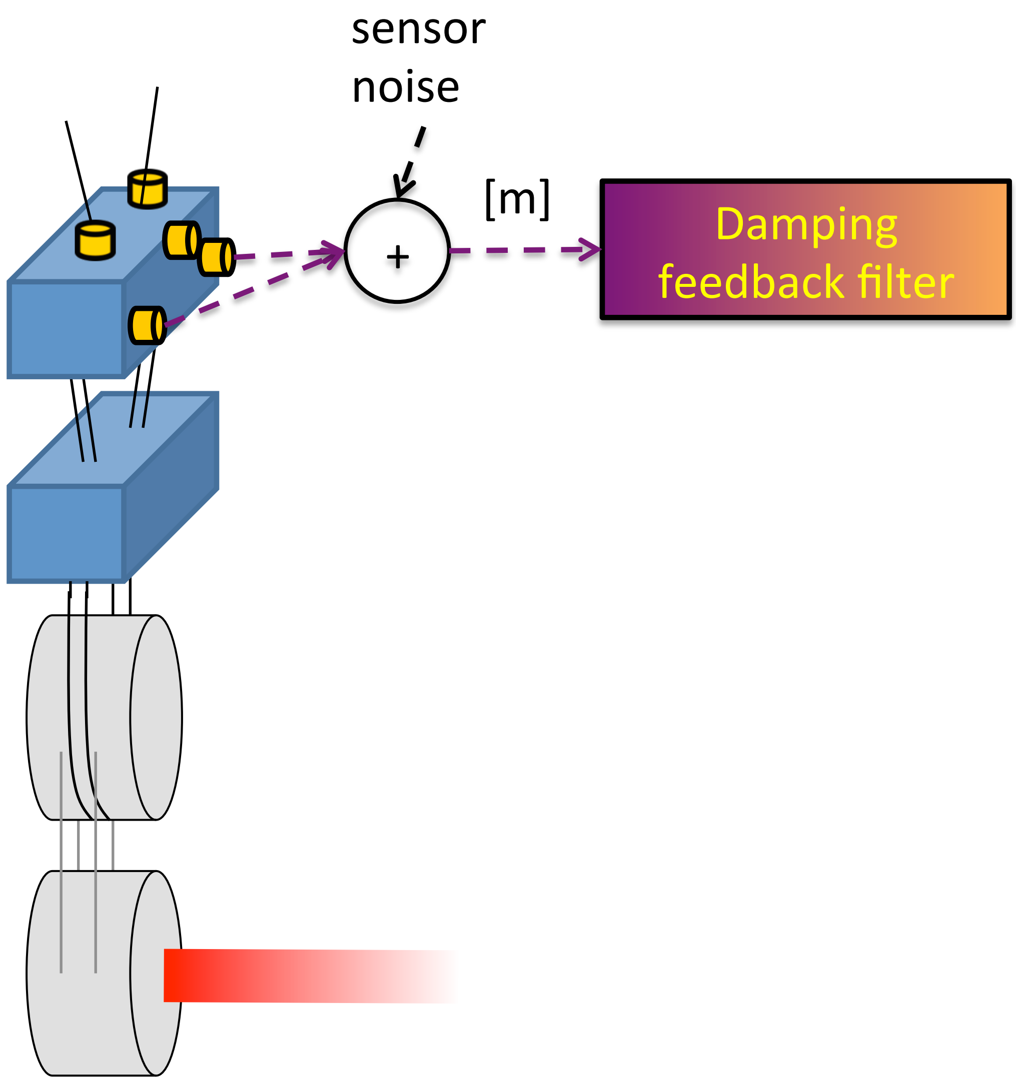
Top Mass Damping



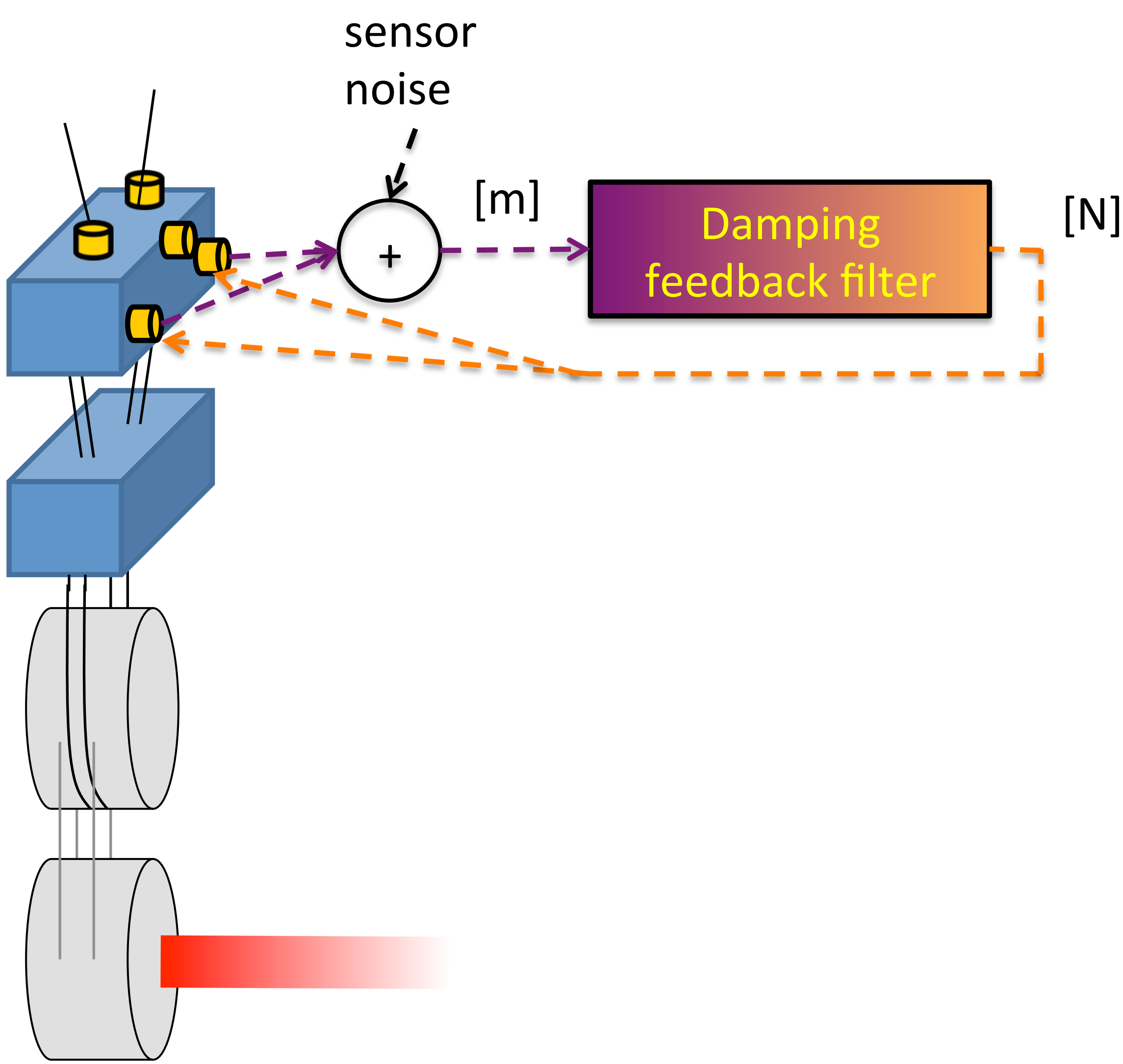
Top Mass Damping



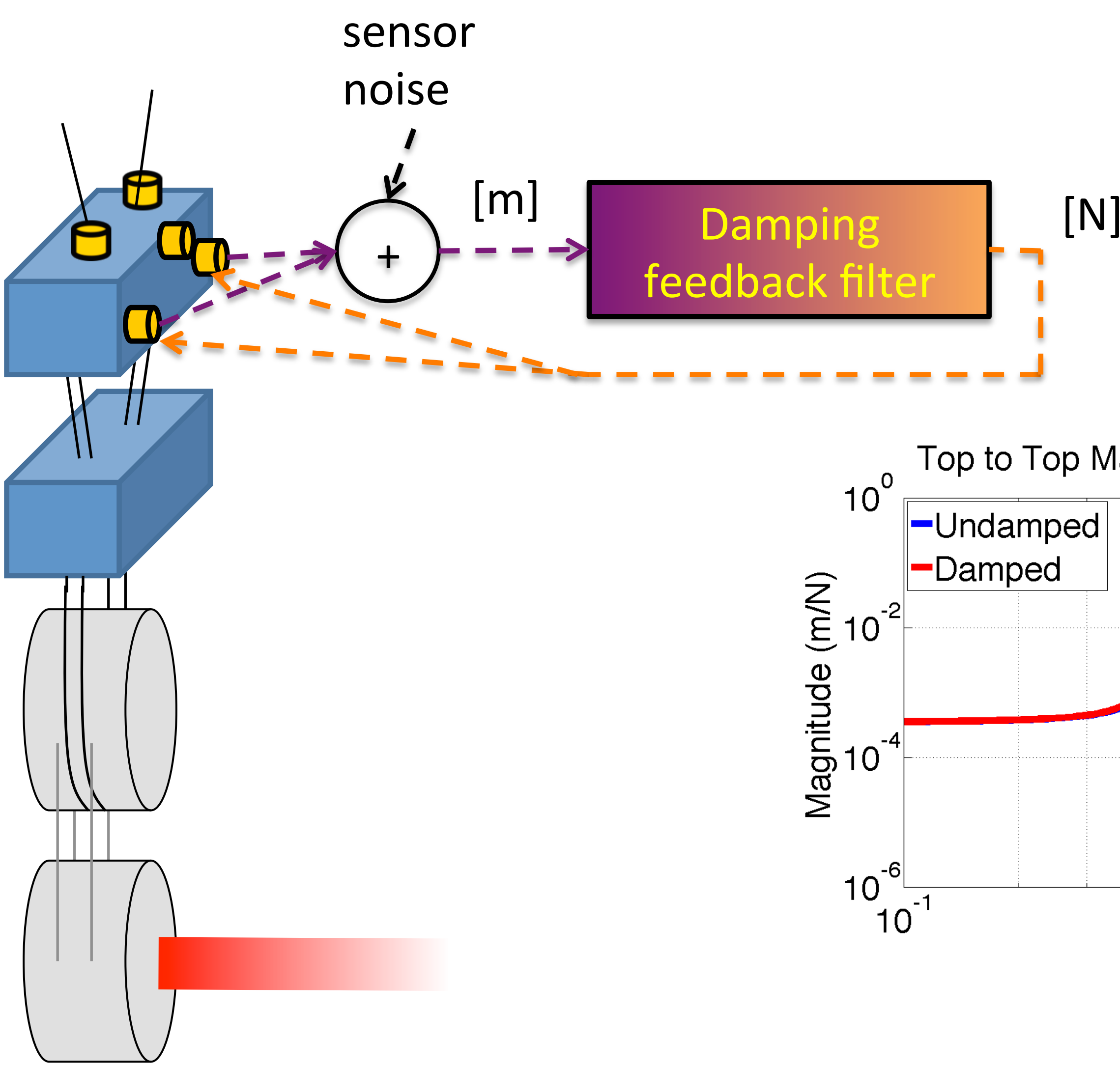
Top Mass Damping

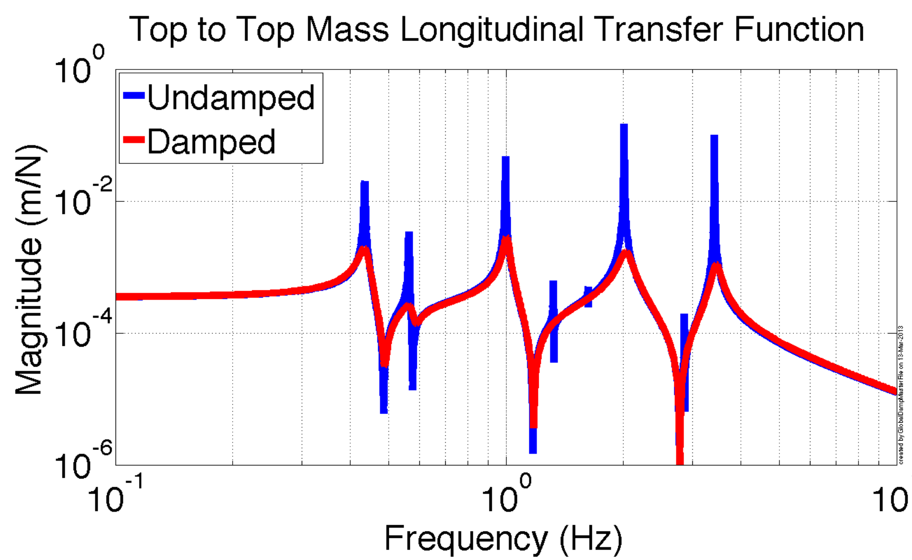


Top Mass Damping



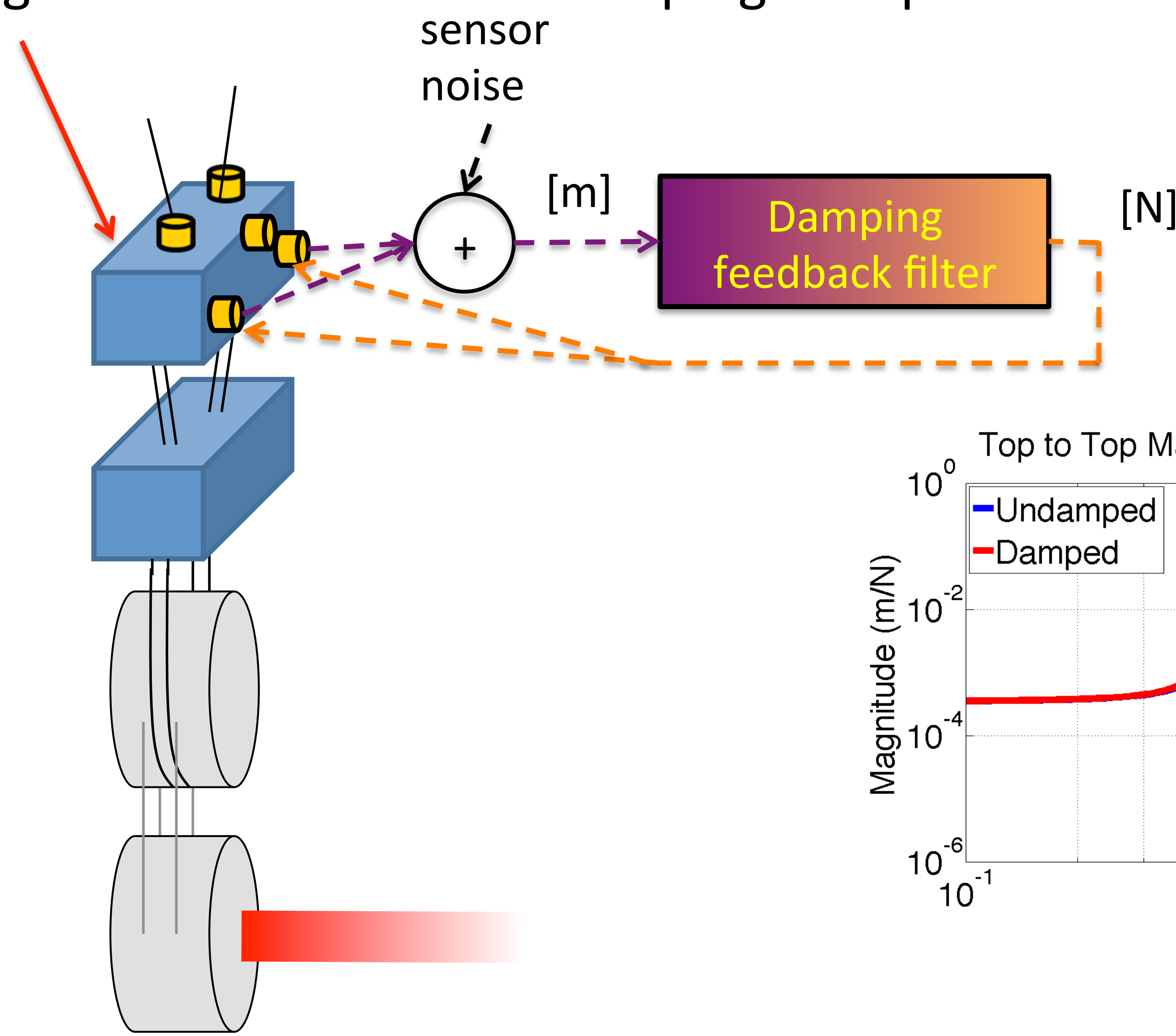
Top Mass Damping

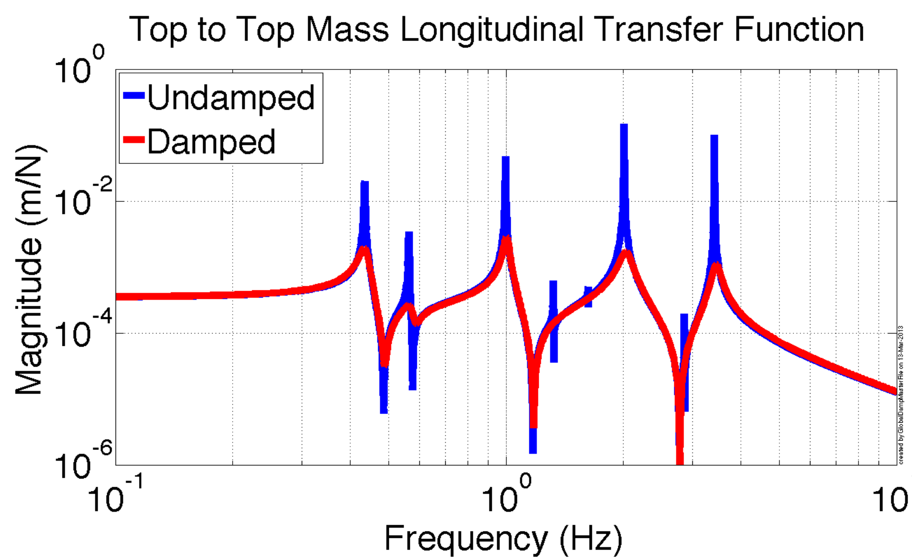




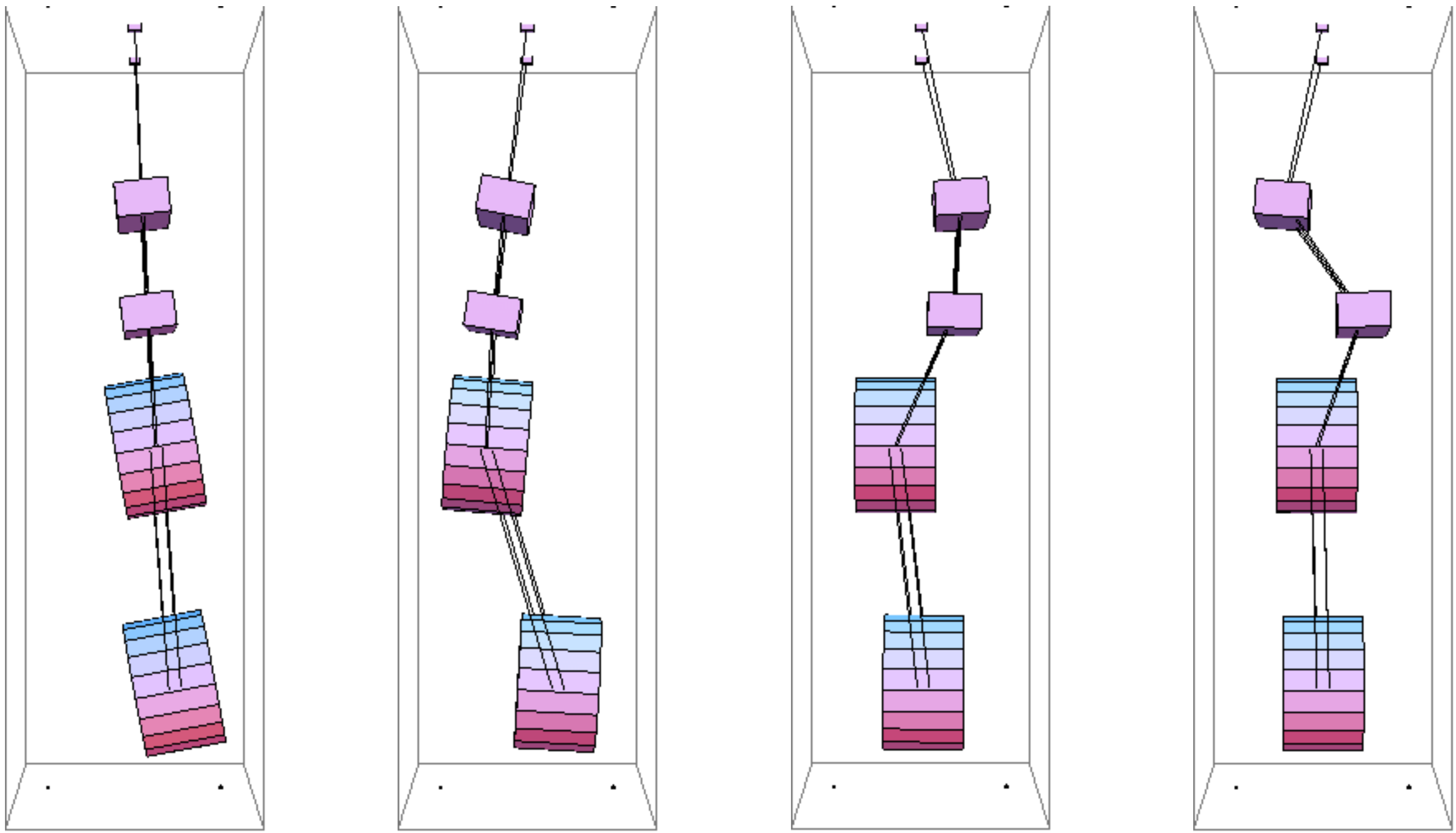
Top Mass Damping

High sensor noise limits damping to top mass



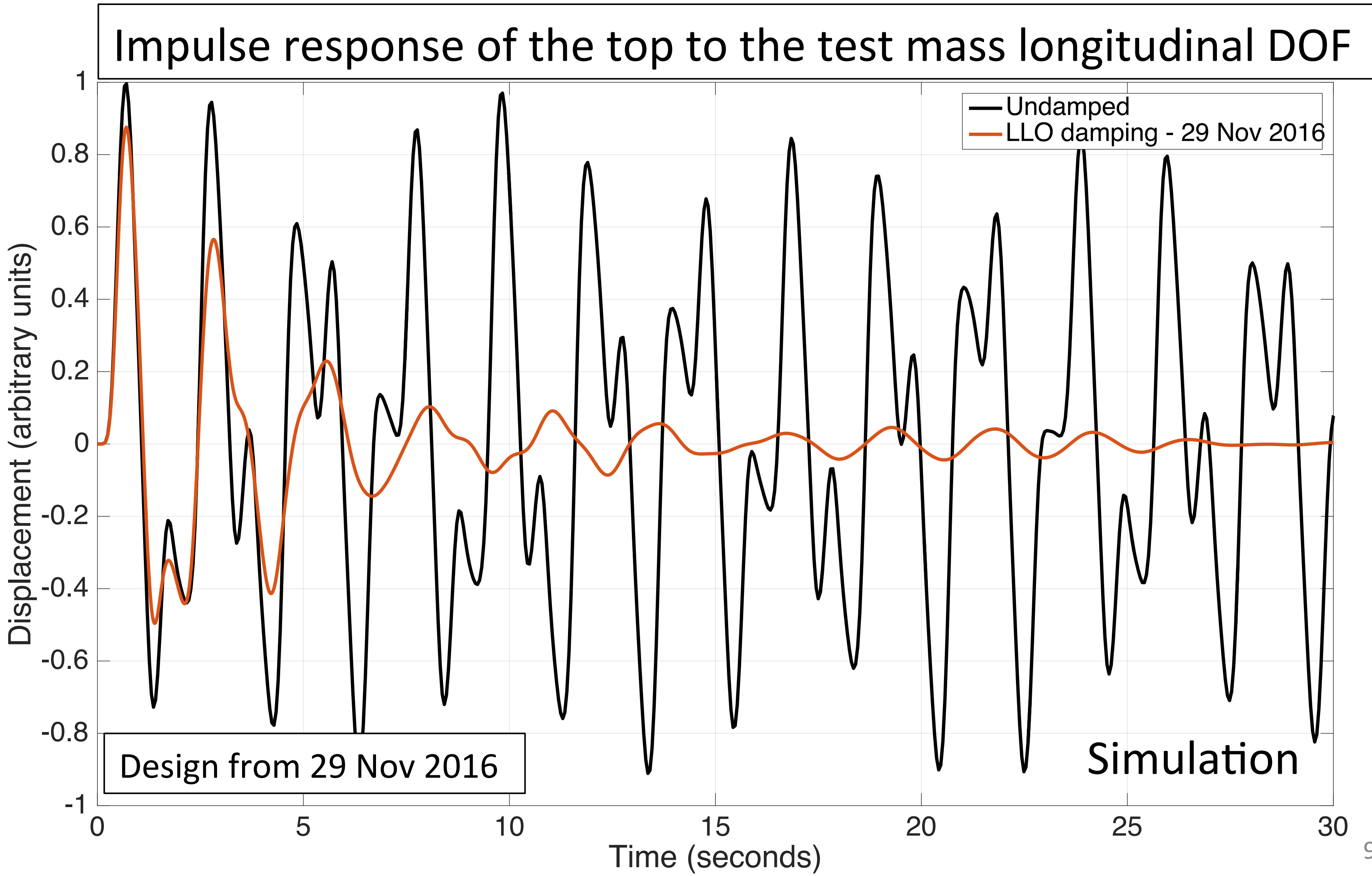


Mode shapes couple to top mass



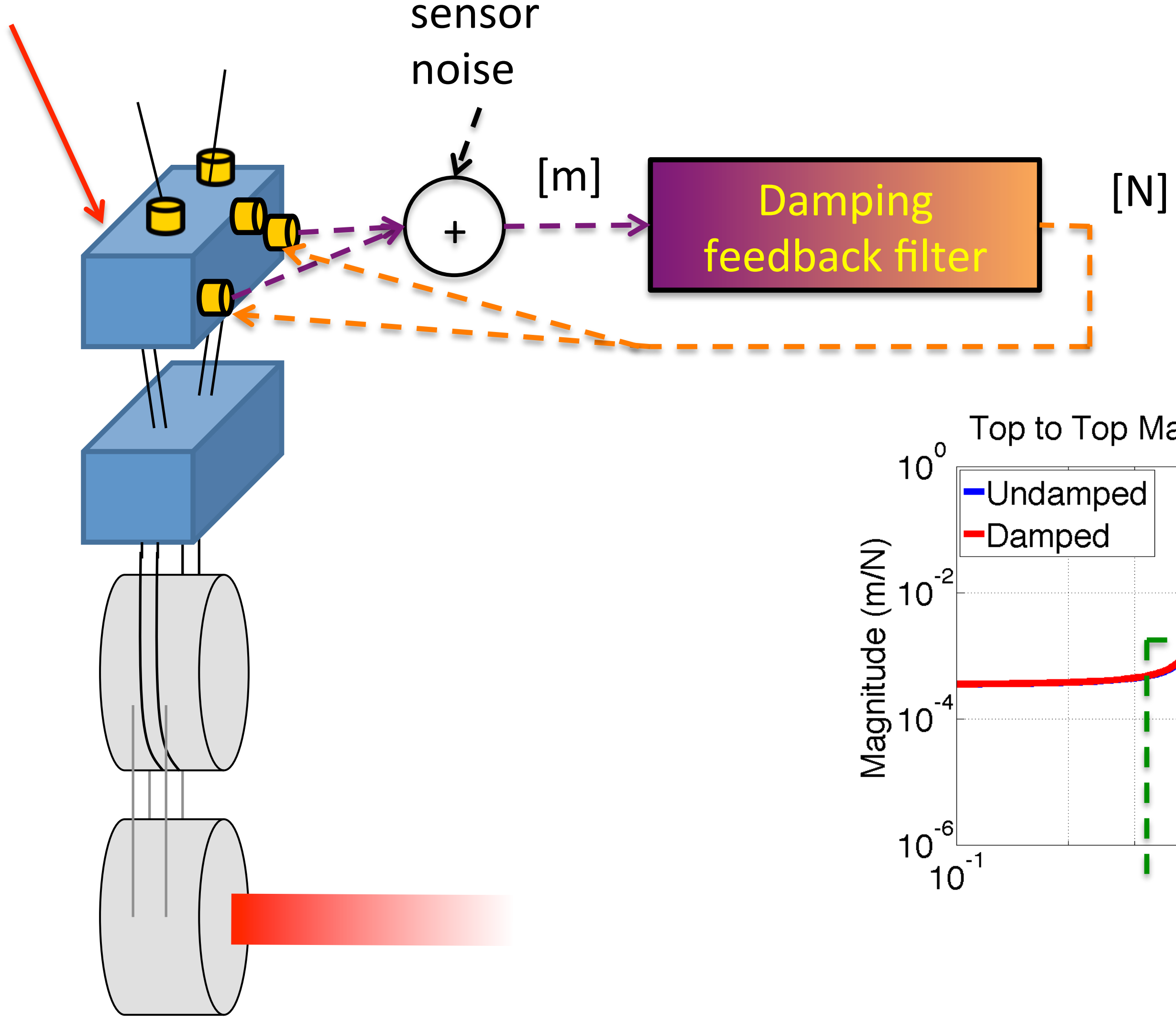
0.43 Hz **1.0 Hz** **2.0 Hz** **3.4 Hz**

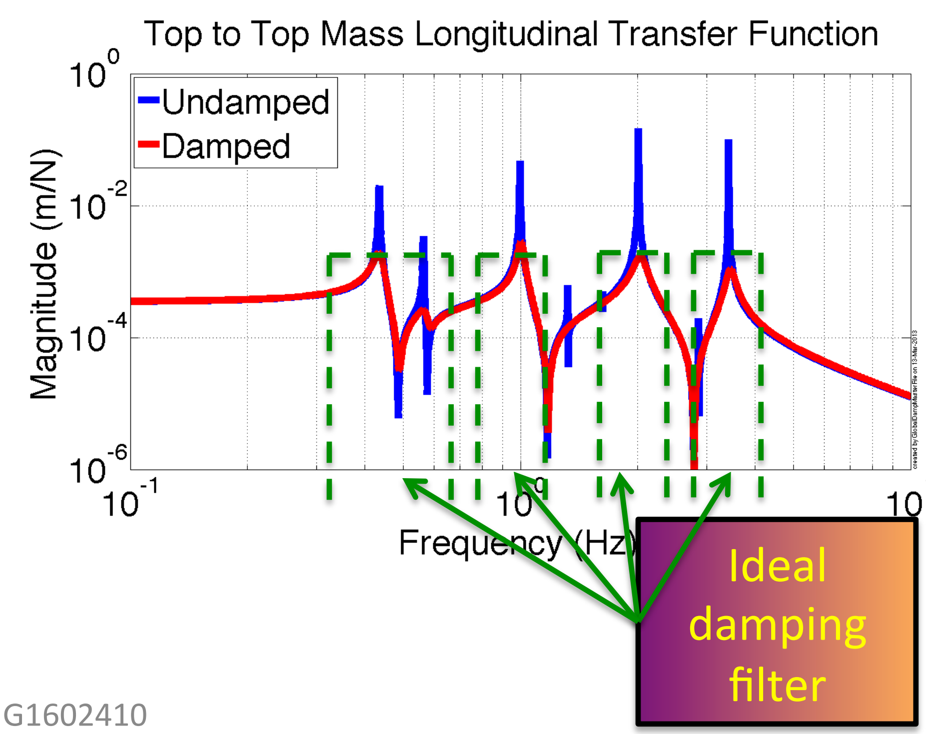
Damping at Livingston (LLO)



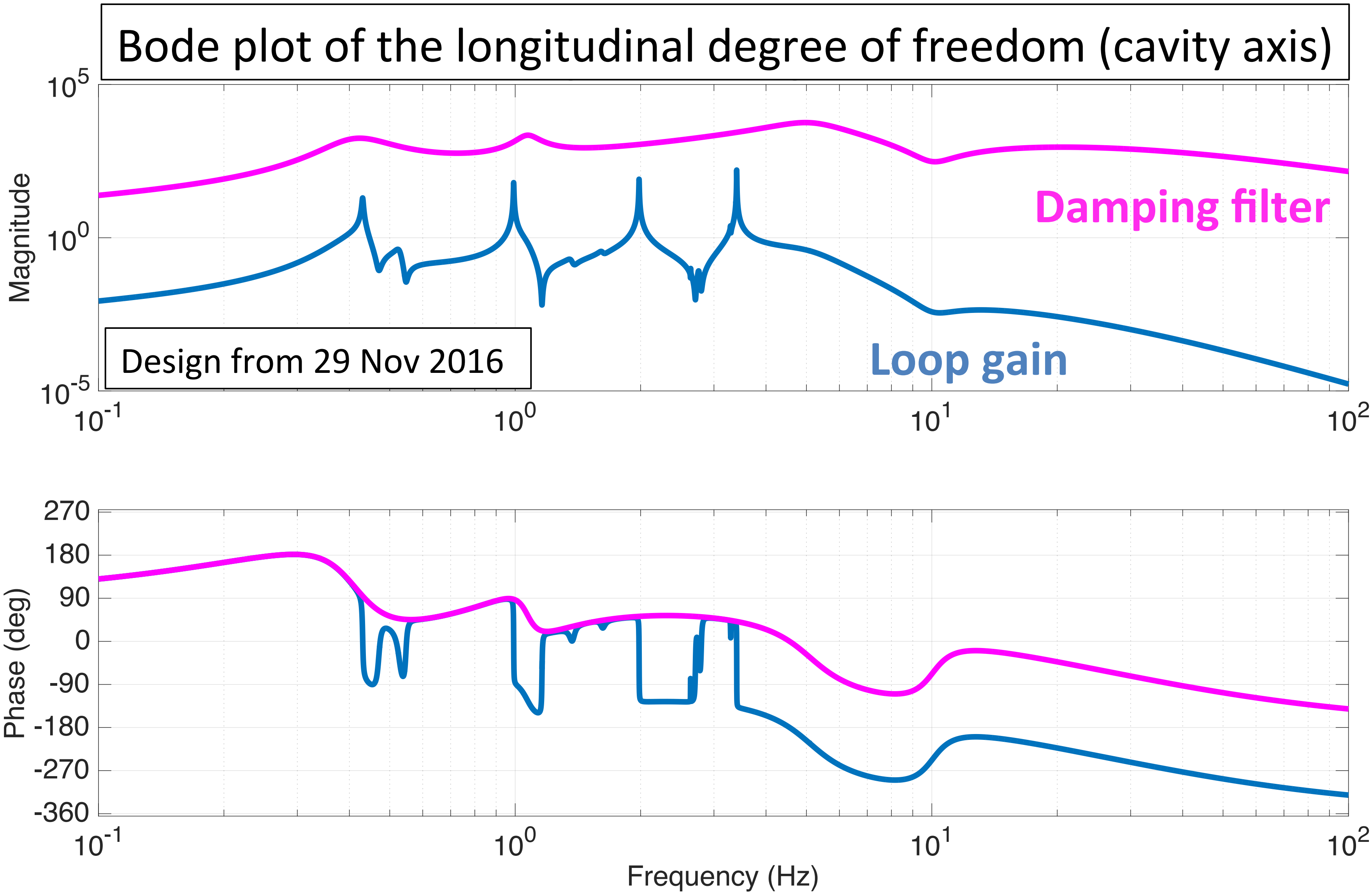
Top Mass Damping

High sensor noise limits damping to top mass



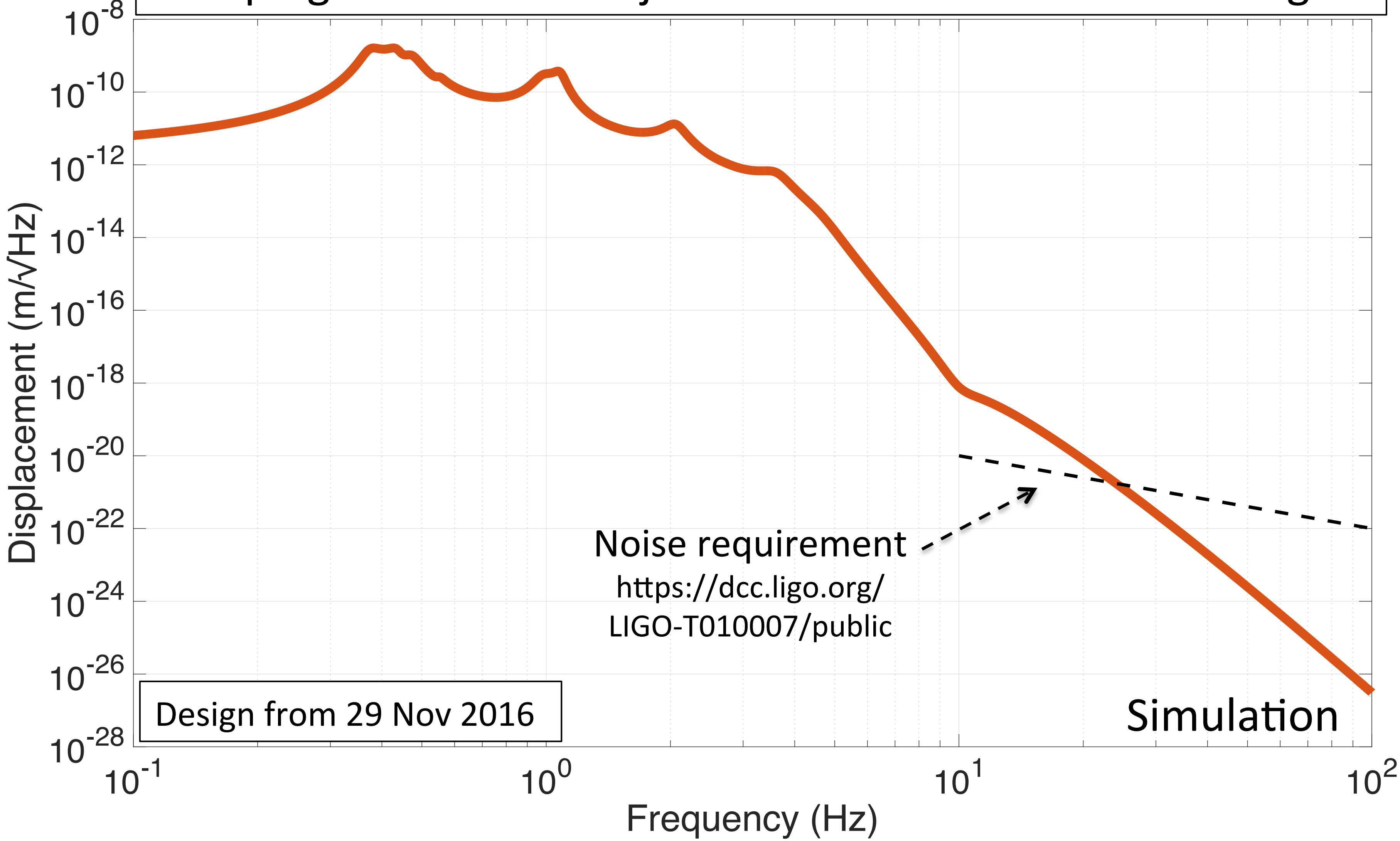


Damping at Livingston (LLO)

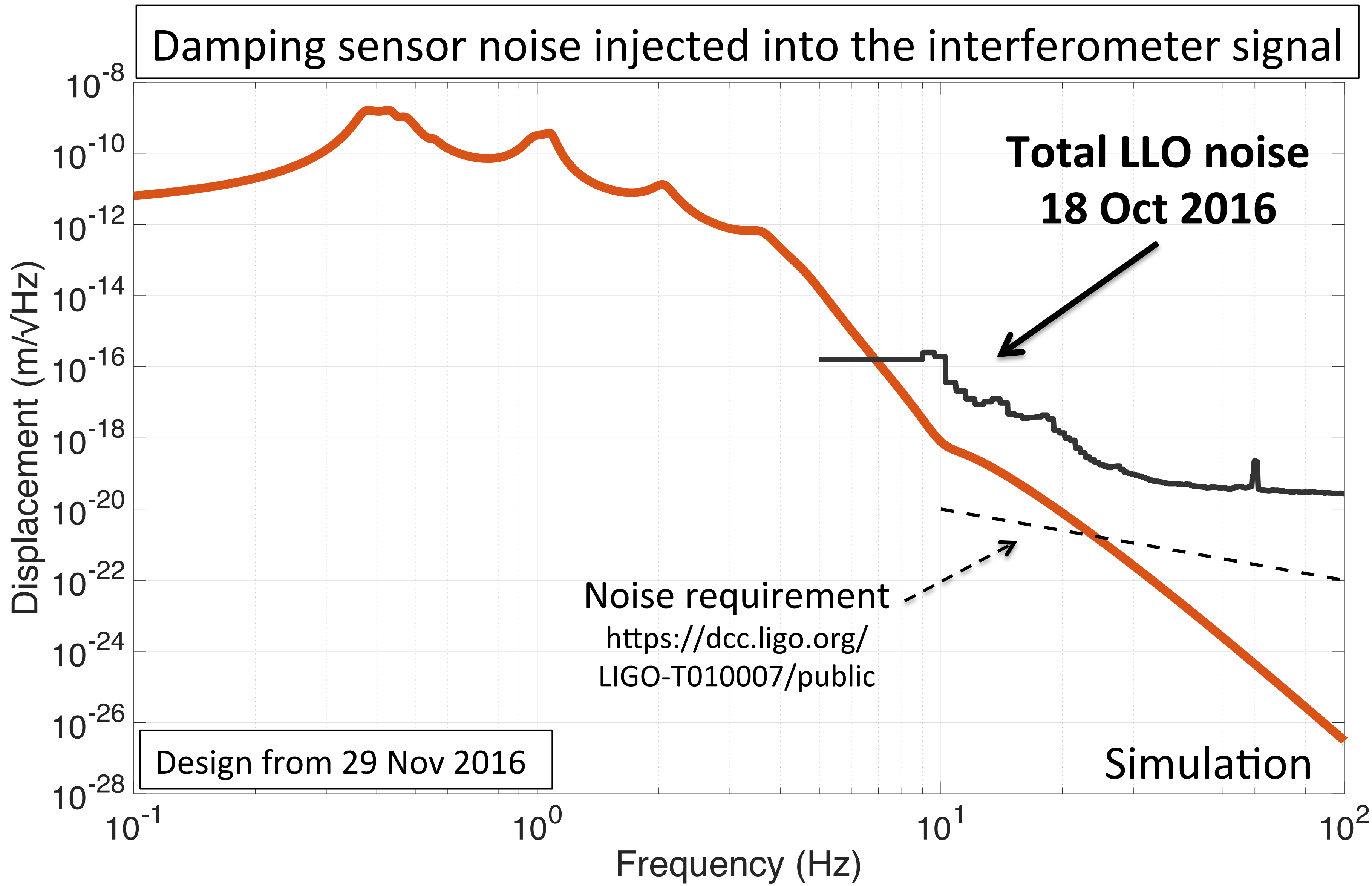


Damping at Livingston (LLO)

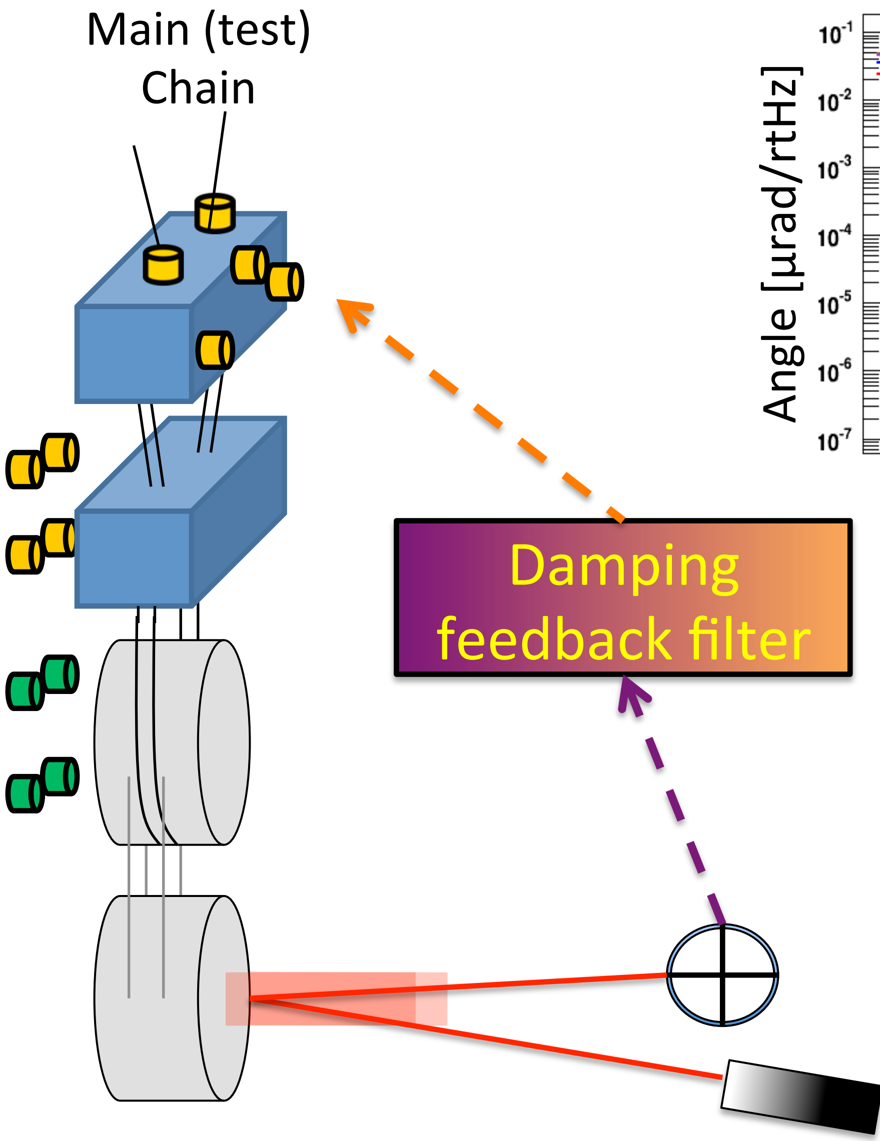
Damping sensor noise injected into the interferometer signal



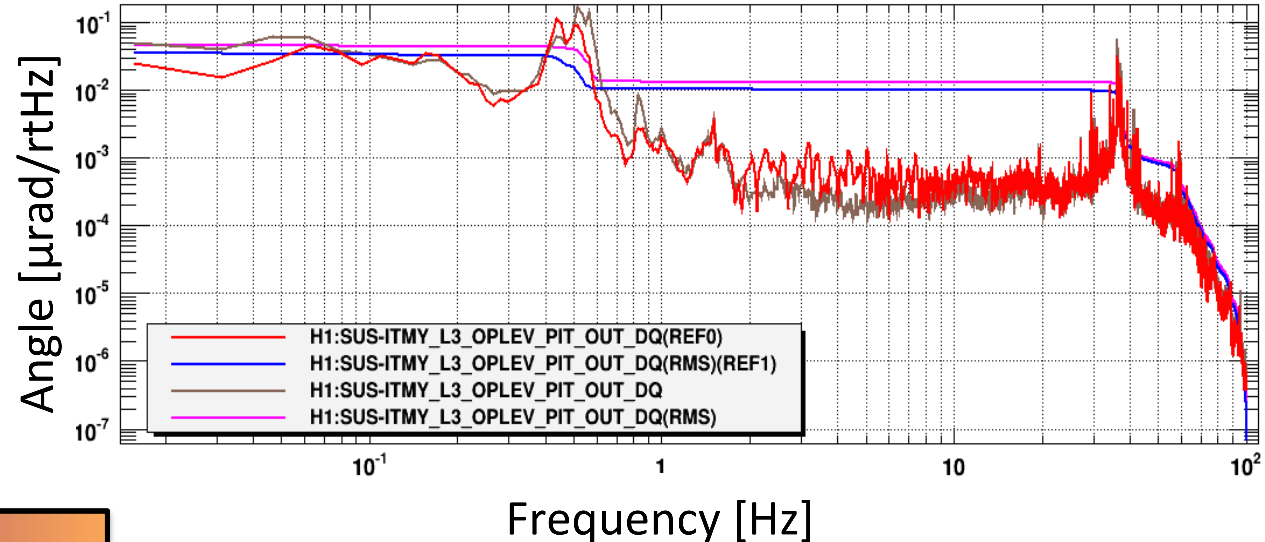
Damping at Livingston (LLO)



Better Optical Levers for Better Damping



Optical lever noise

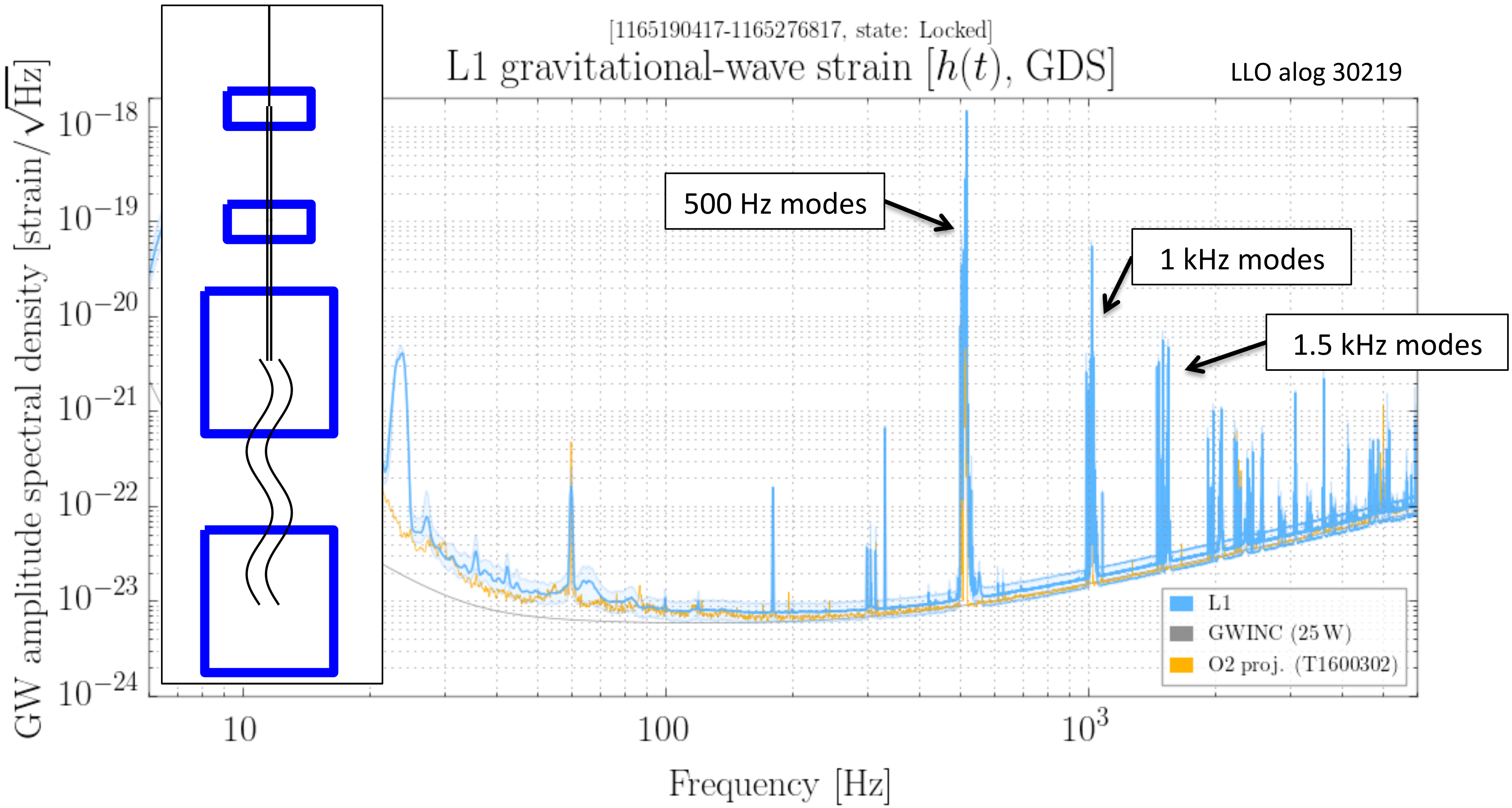


Damping the test mass works best if you can sense the test mass

- Need to lower the oplev noise
- Need to make it less glitchy

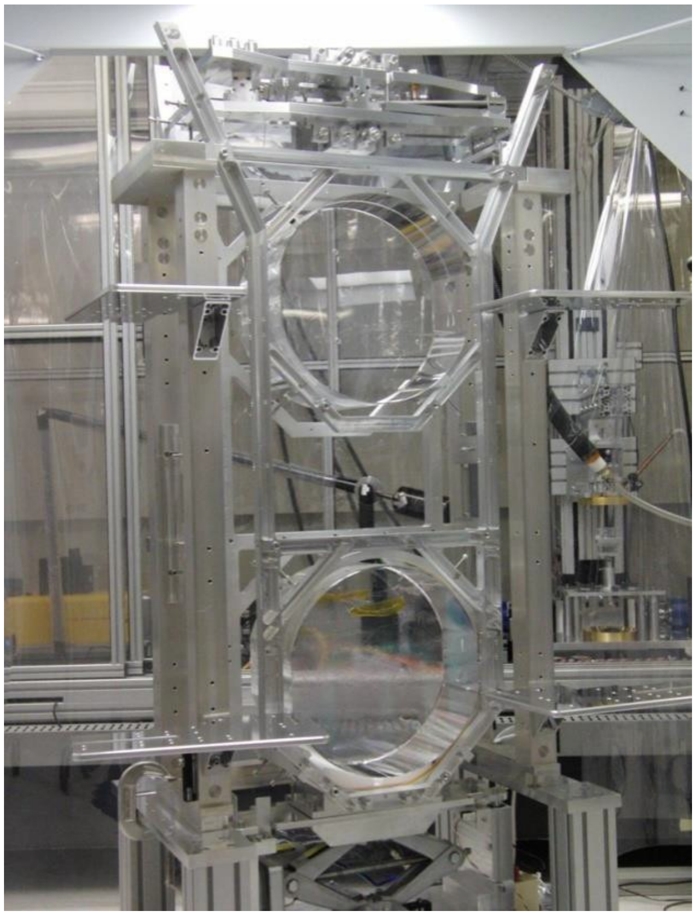
-> less angular control required -> less angular control noise

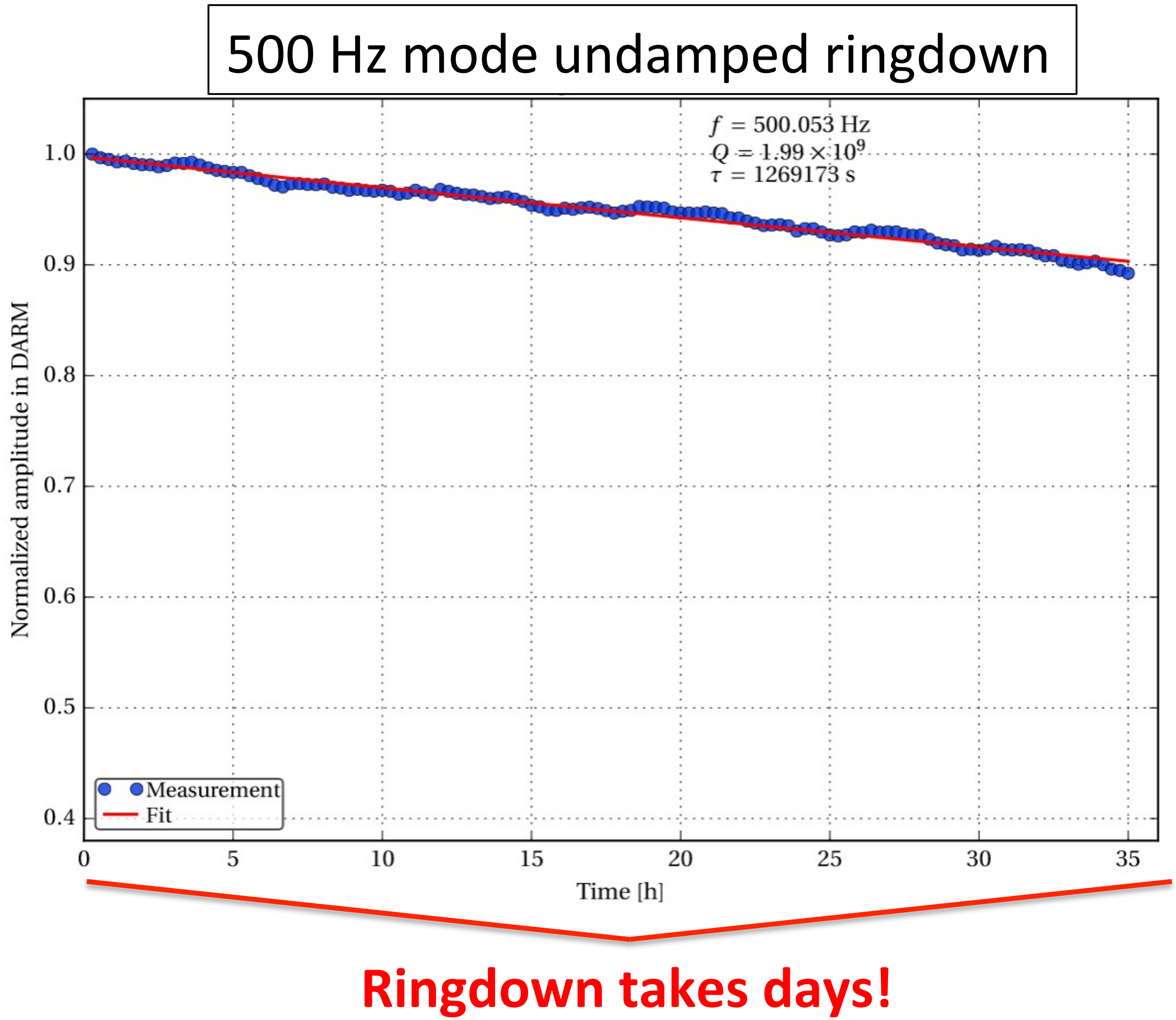
Suspension violin modes



Very high Q (~1 billion) silica fiber violin modes at 500 Hz and higher harmonics.

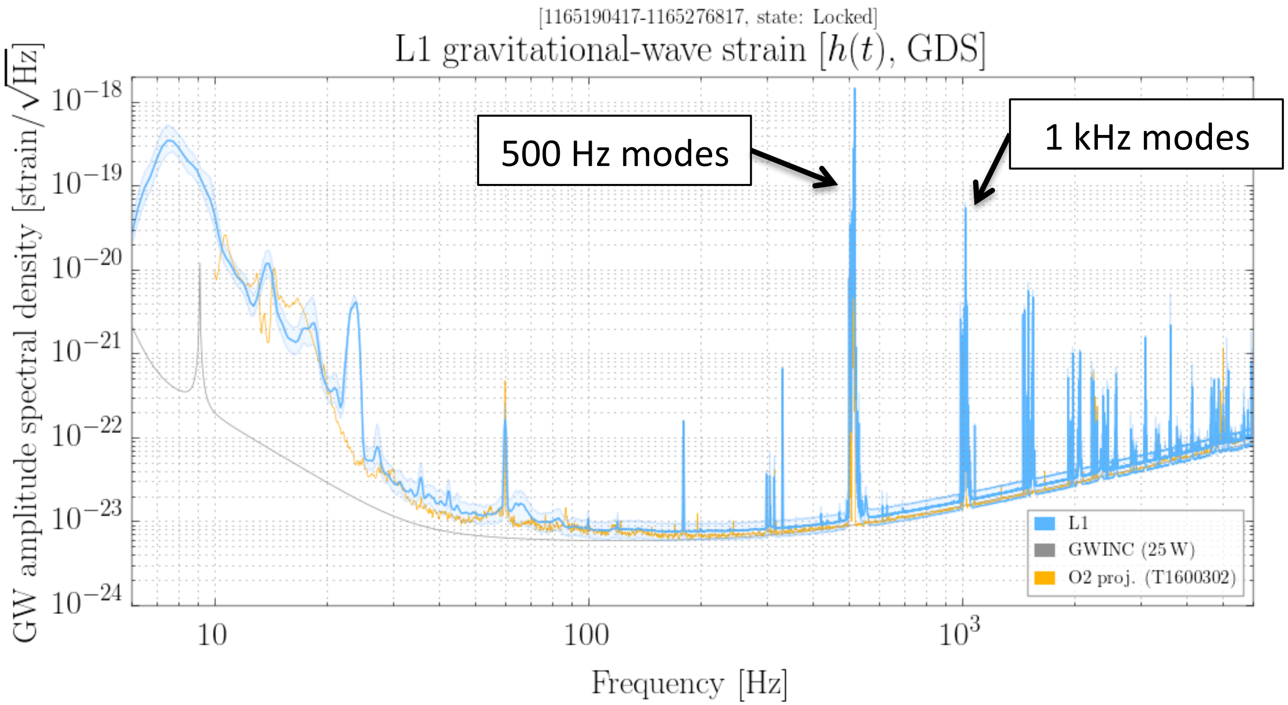
Suspension violin modes





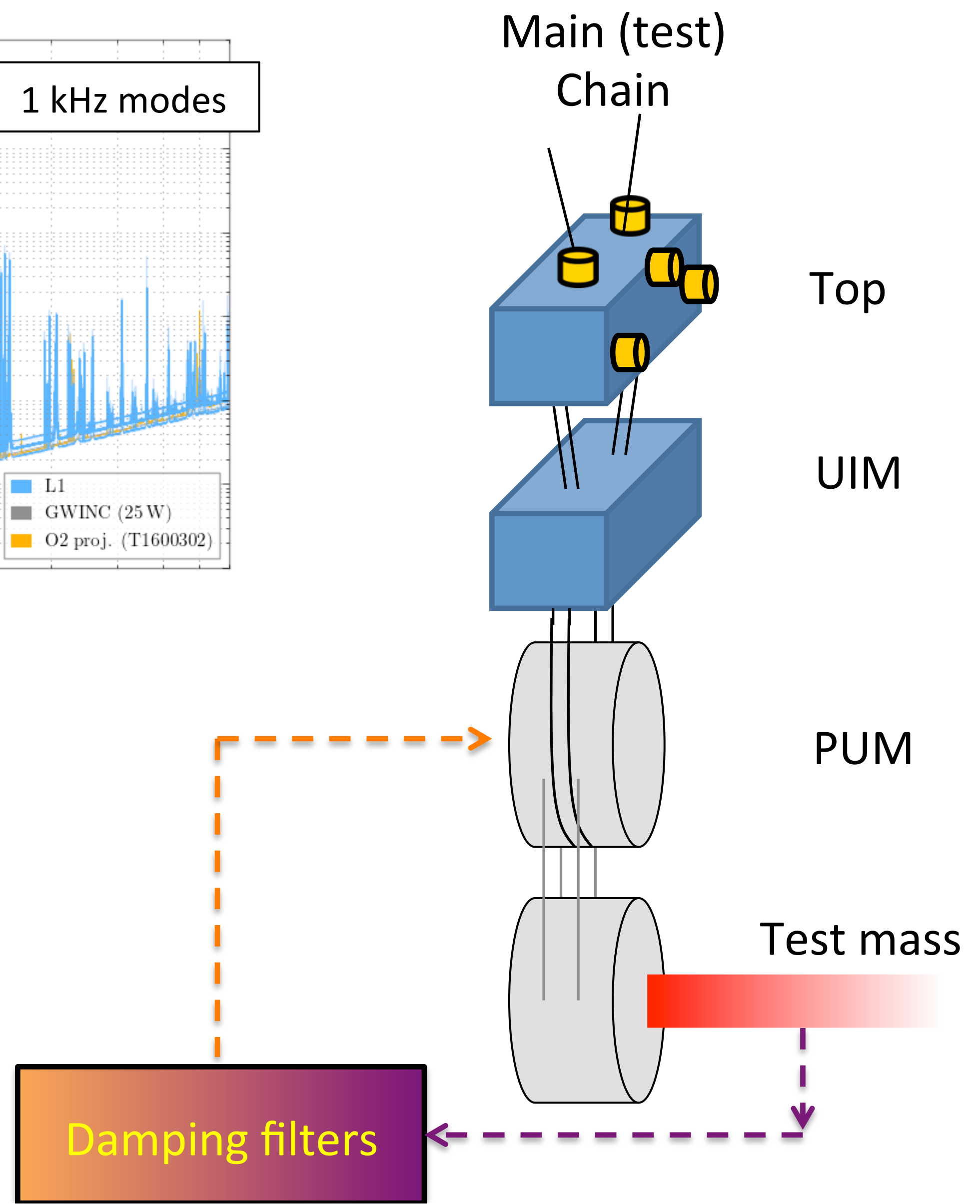
Reference: Giles Hammond, LITRA Aug 2016

Suspension violin mode damping

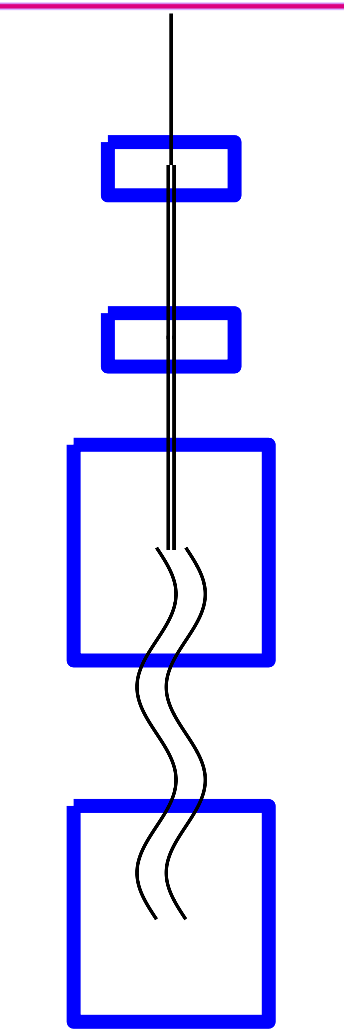


Damping uses the cavity as a sensor, actuates at the PUM.

Not so robust, operators spend many hours keeping them damped.



Possible Violin Mode Sensor



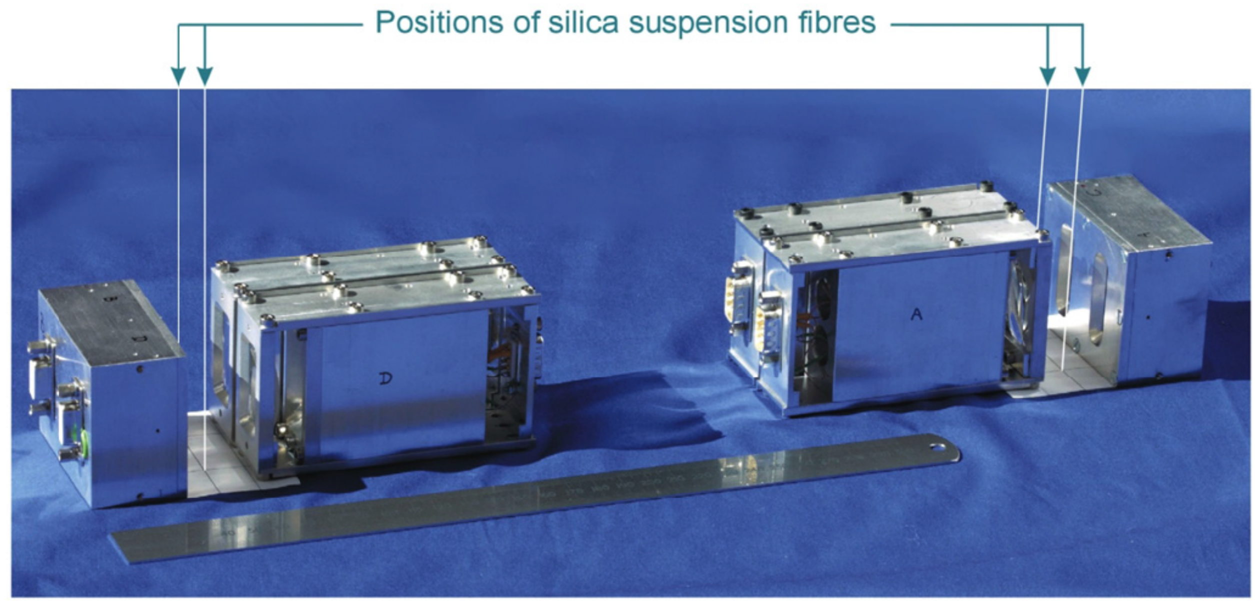


Figure 1 VM shadow-sensor system (prototype). Each of the four fused-silica suspension fibres had its own separately housed source of illumination (emitter): *B* and *C* at the rear, *D* and *A* at the front (as in the experiments at MIT). The two shadow-sensor (detector) enclosures each housed the sensors for a pair of fibres. The four emitter housings were at the centre of the suspension, so as to have their NIR beams directed outwards—towards the two detector housings shown at the left and right edges of the figure (photo taken at the University of Strathclyde, before shipment out to MIT of these parts). The 300 mm steel rule gives the scale of this apparatus.

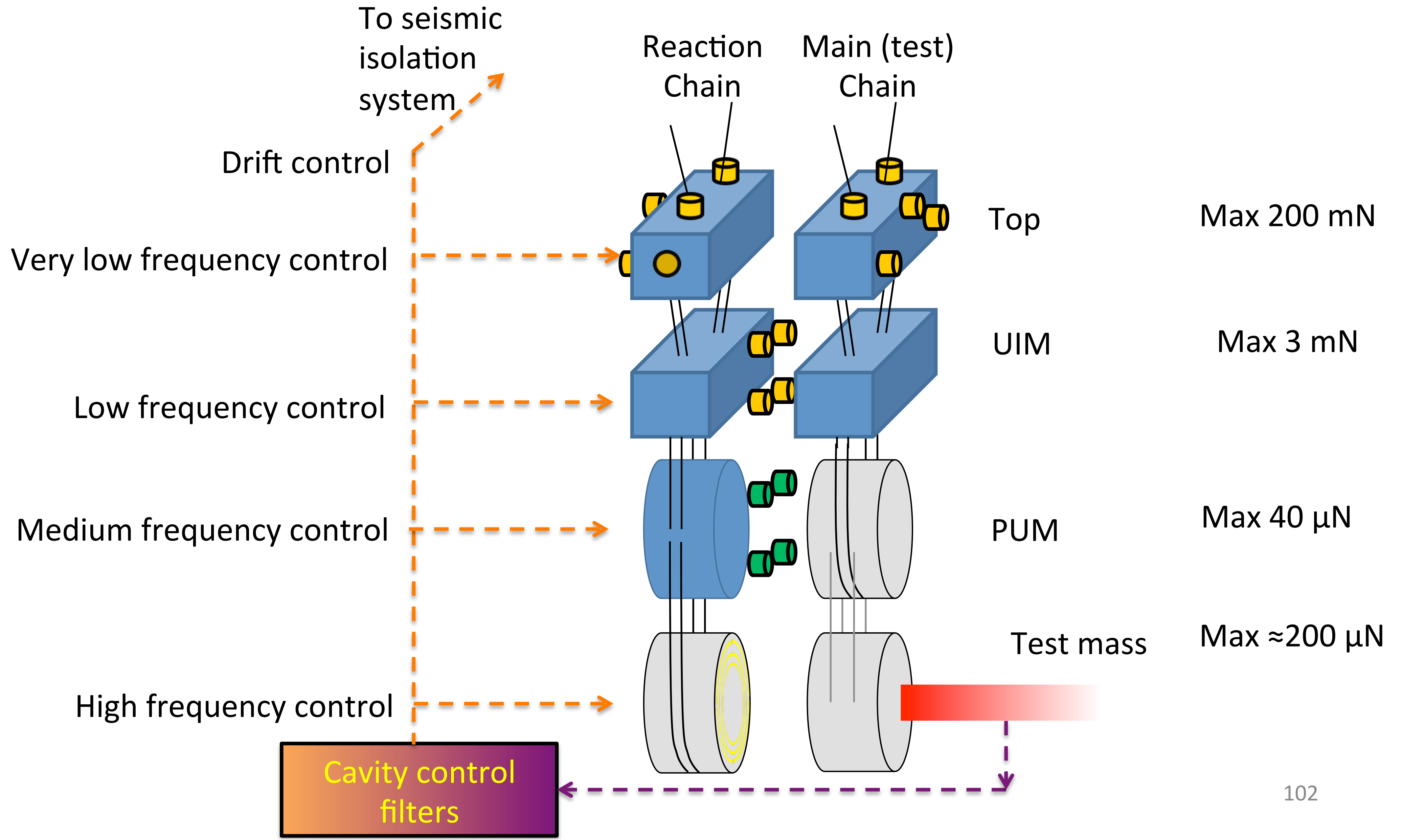
- Would make violin mode damping feedback more reliable

N. Lockerbie et al. "First results from the 'Violin-Mode' tests on an advanced LIGO suspension at MIT". 2011 Class. Quantum Grav. 28 245001. Also https://dcc.ligo.org/LIGO-G0900588/public

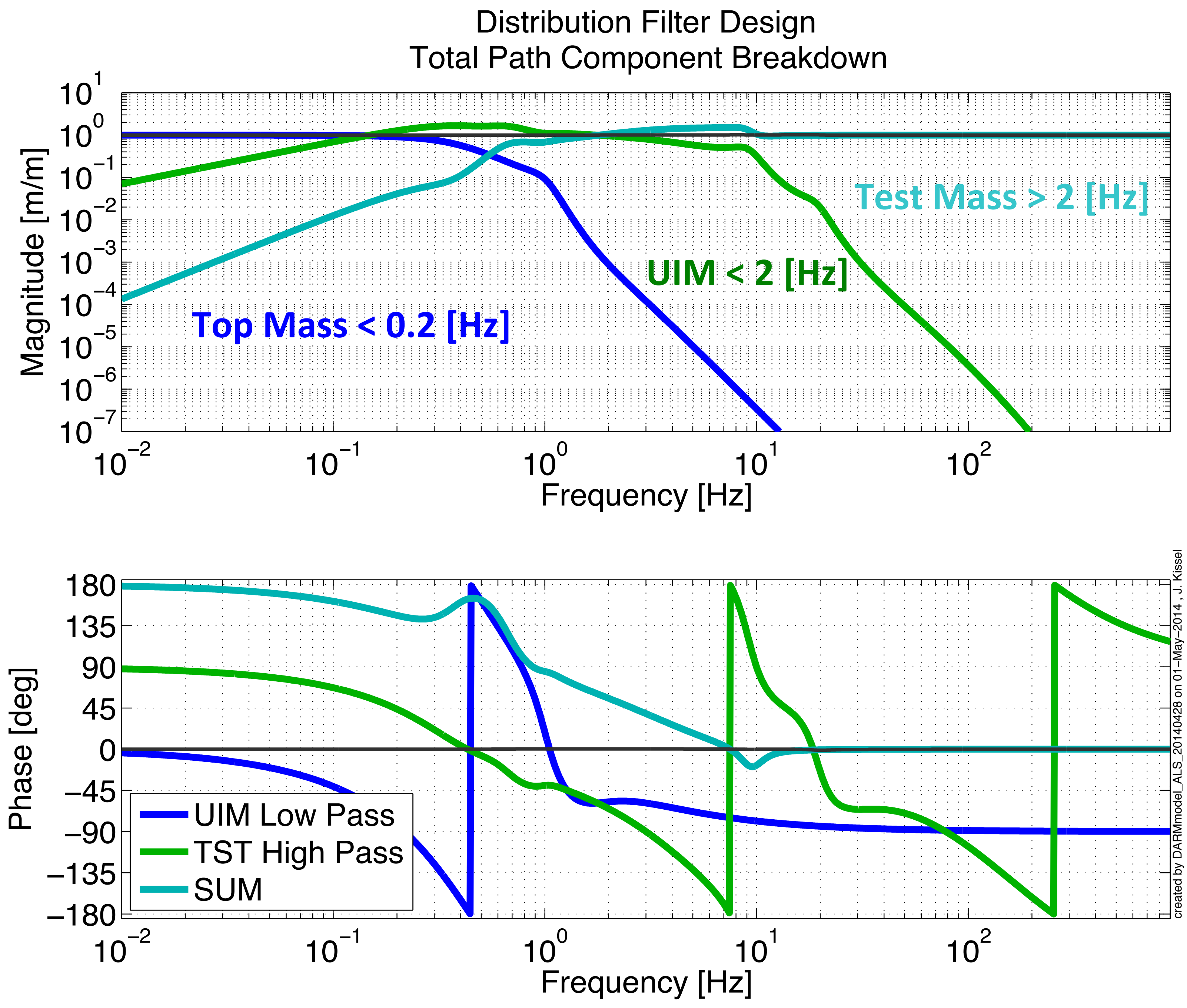
Global Control
Following the Quad SUS example

- Cavity Length Control
- Alignment (angular) Control

Cavity Length Control

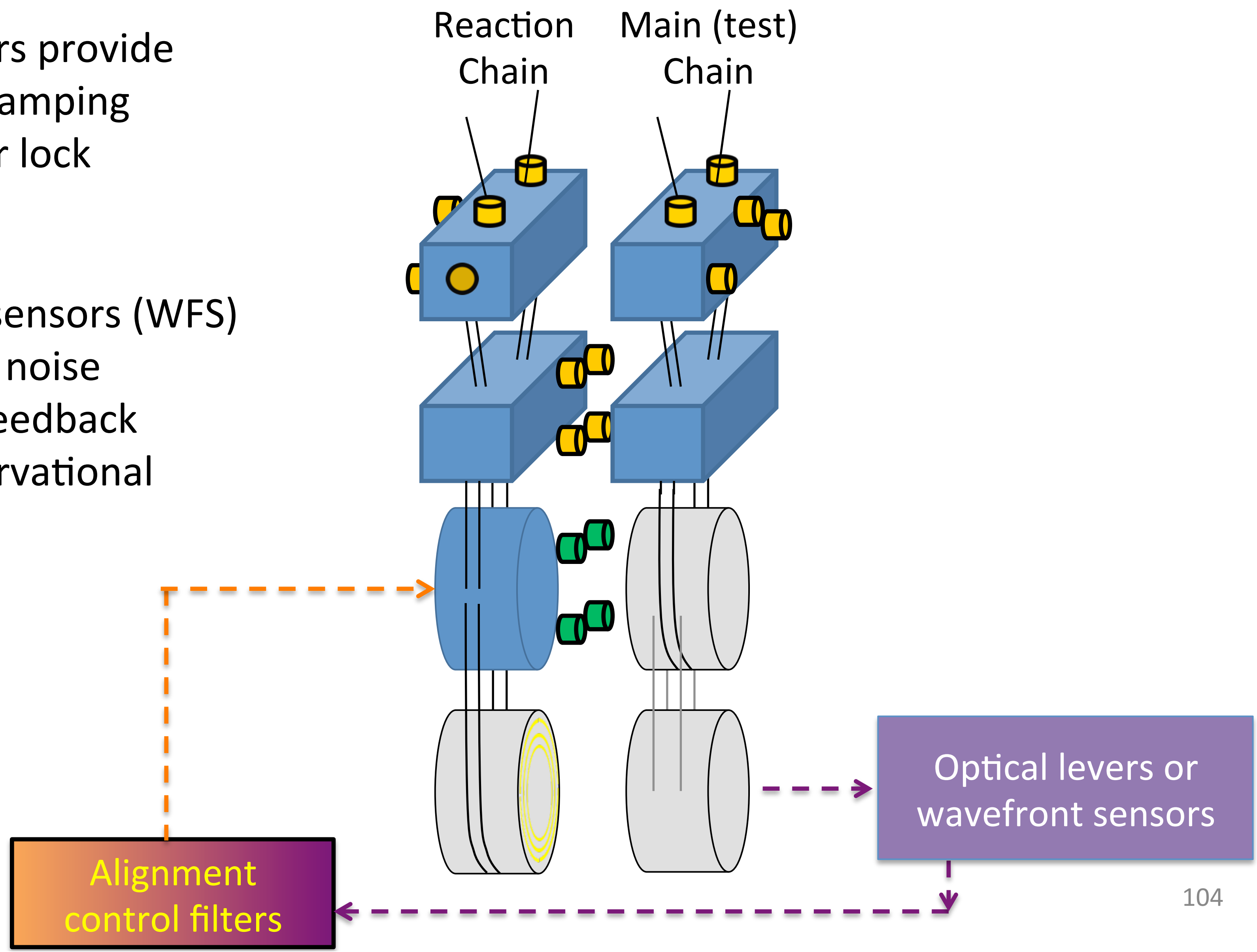


Cavity Length Control



Suspension Angular Control

- Optical levers provide additional damping feedback for lock acquisition.
- Wavefront sensors (WFS) provide low noise alignment feedback during observational runs.



Degrees of Freedom to Control

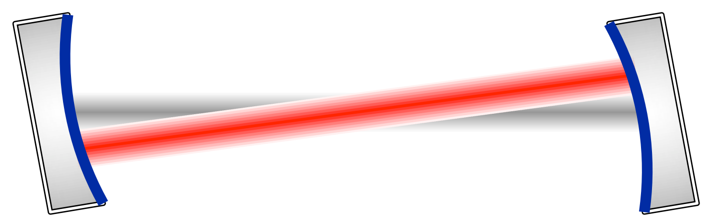
Reference: G1601167

Degrees of Freedom to Control

Global angular sensor

Angular degrees of freedom (pitch and yaw)

SOFT mode
reduced stability

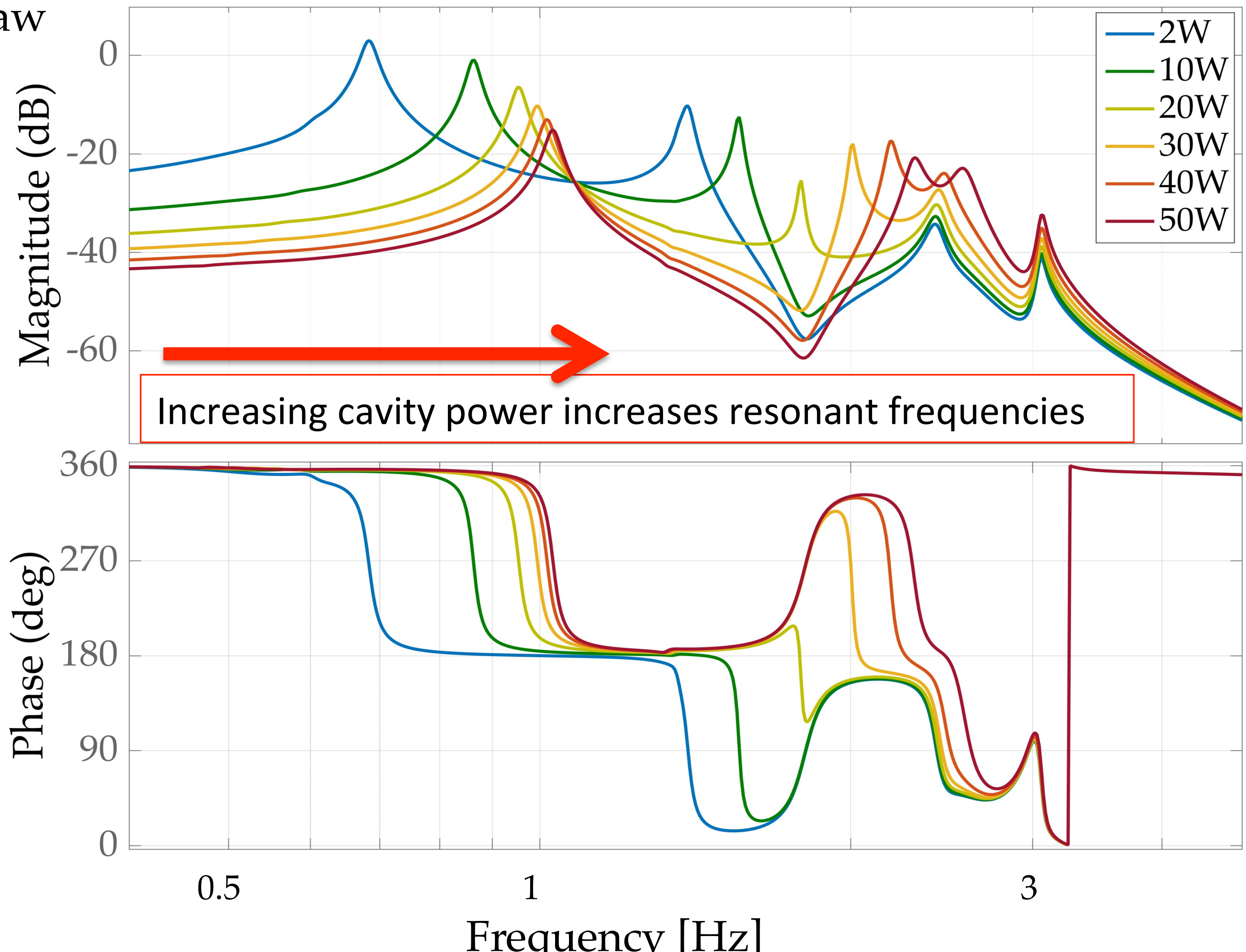


HARD mode
increased stability

Reference: G1601167

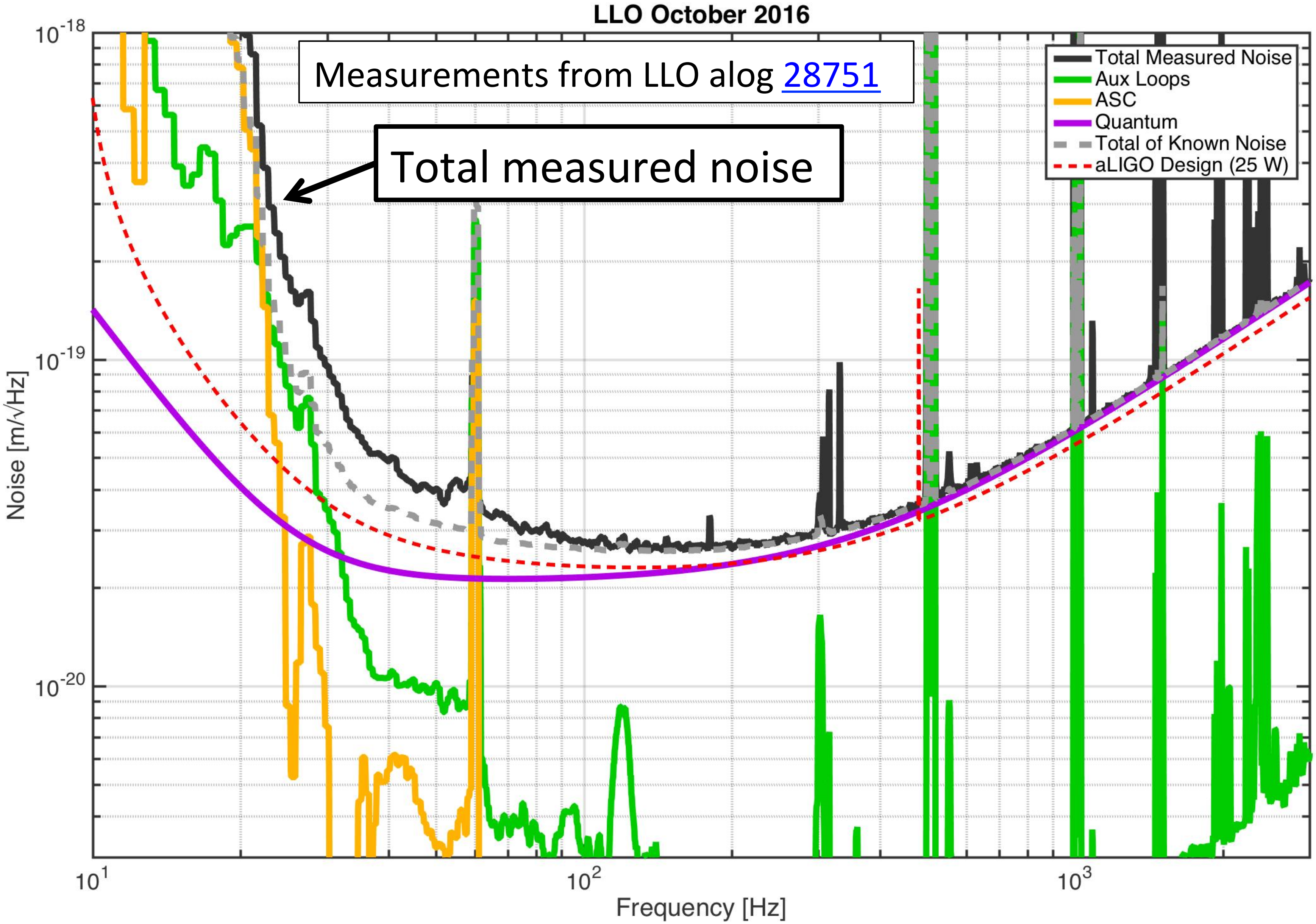
Changing Plant Dynamics

HARD Yaw

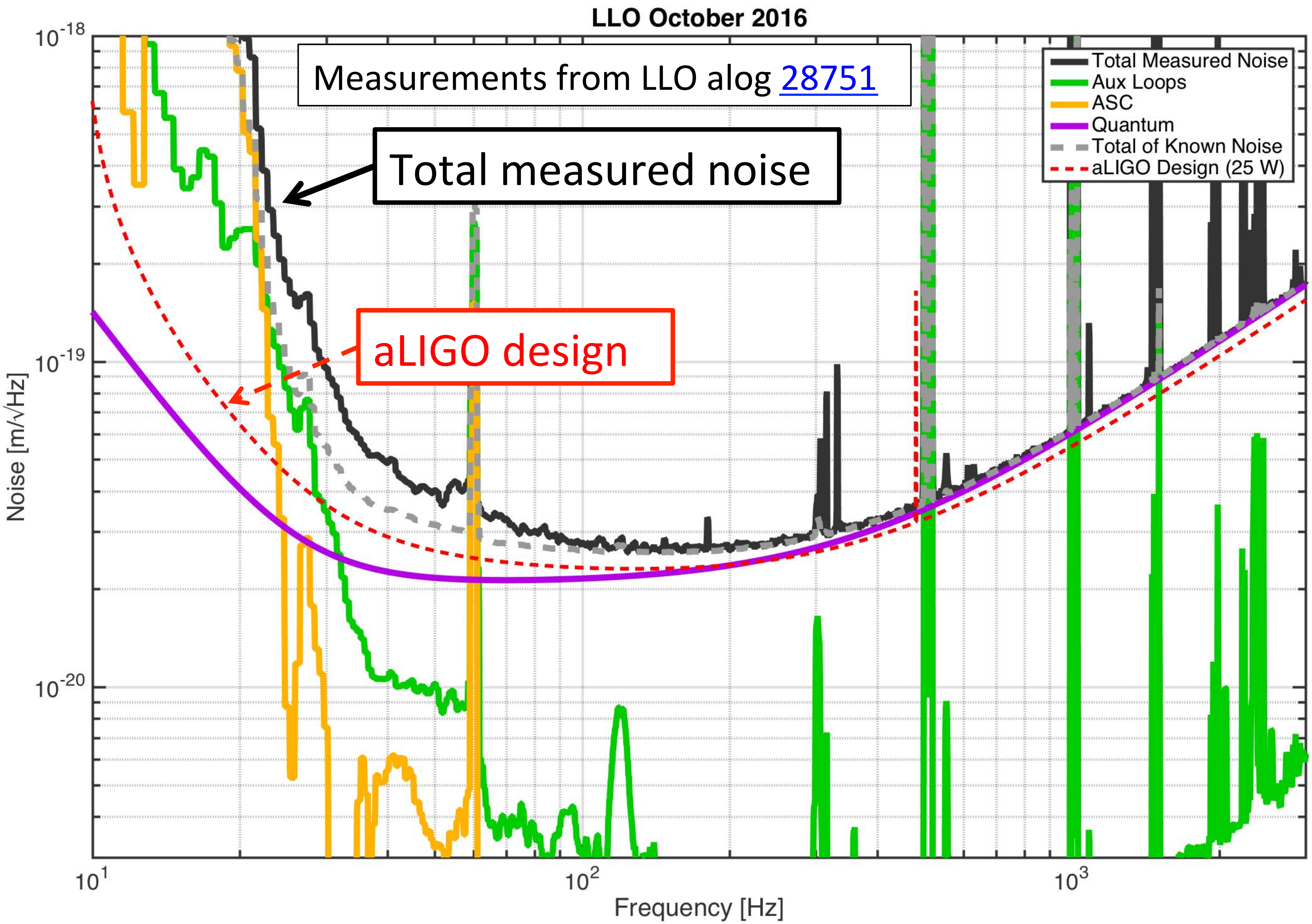


Reference: G1601167

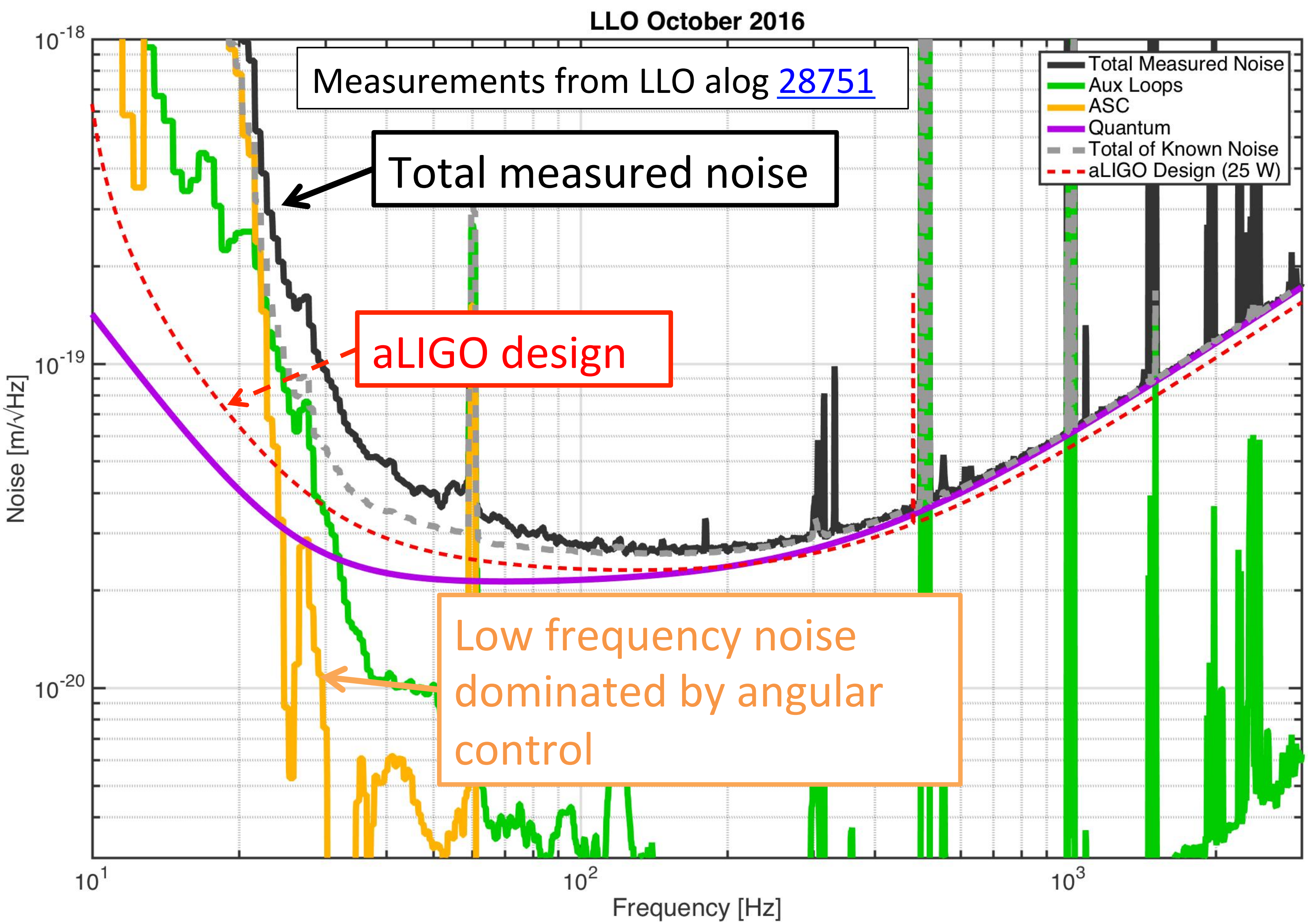
Livingston Noise – 18 Oct 2016



Livingston Noise – 18 Oct 2016

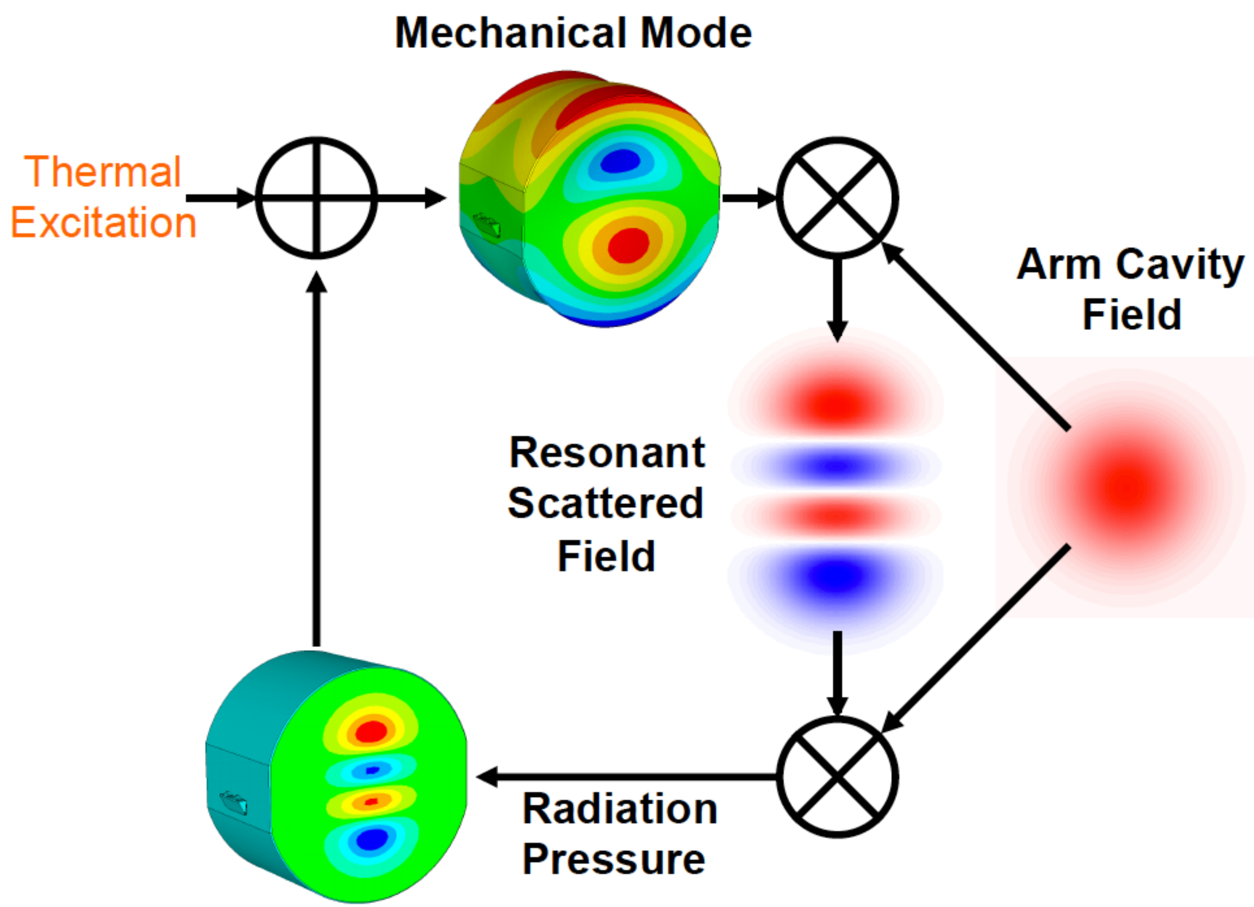


Livingston Noise – 18 Oct 2016



Parametric Instability damping

Unstable positive feedback between mechanical and optical modes at high power

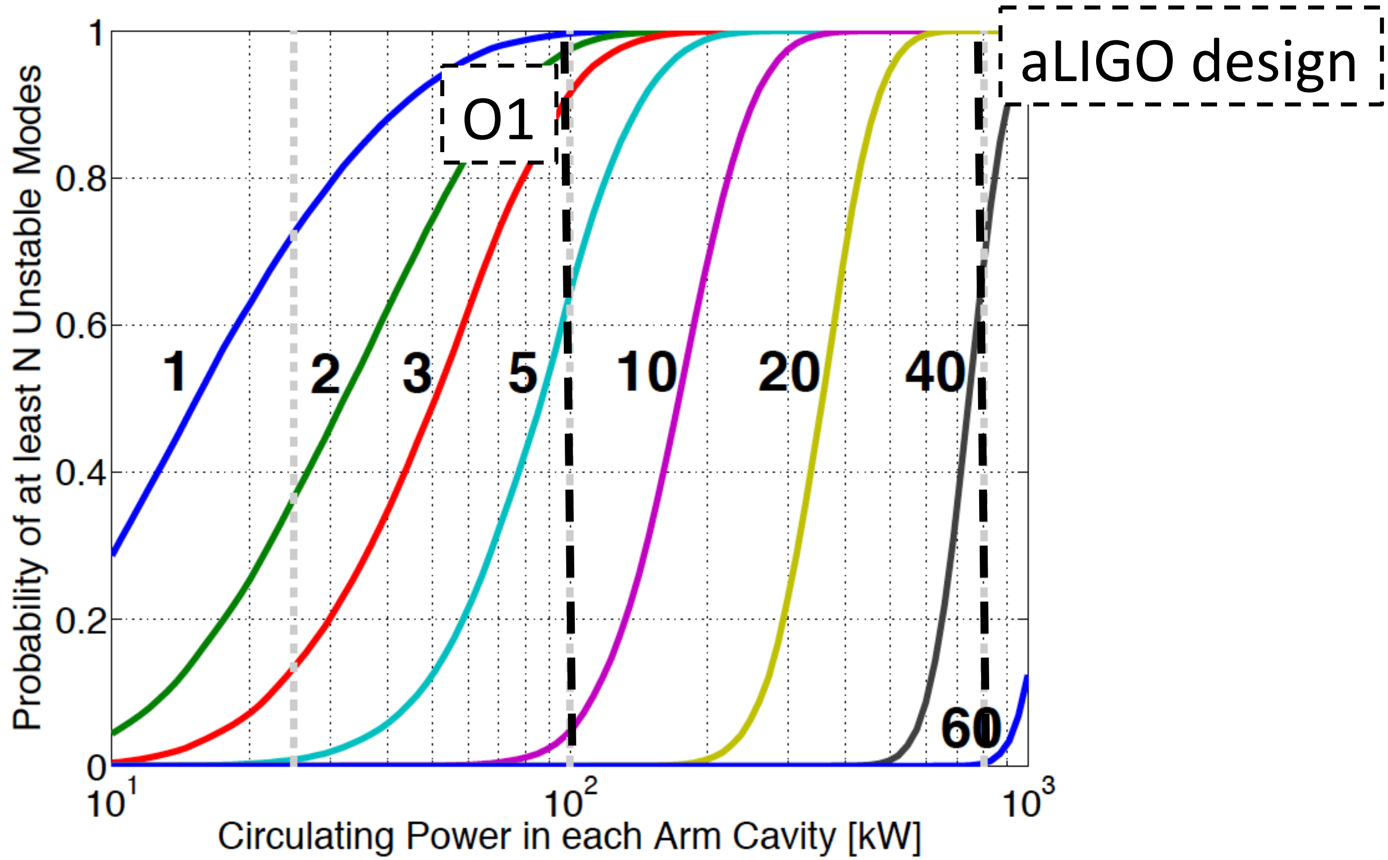


Combination of active feedback and thermal tuning of test mass damps the first few in O1 and O2 where the power is ≈ 100 kW out of the 750 kW aLIGO design

Reference P1400254

Parametric Instabilities

Increasing number of unstable modes with higher power



- First few modes actively controlled in O1 & O2
- Passive damping option in development
- Will these methods be enough at full power?

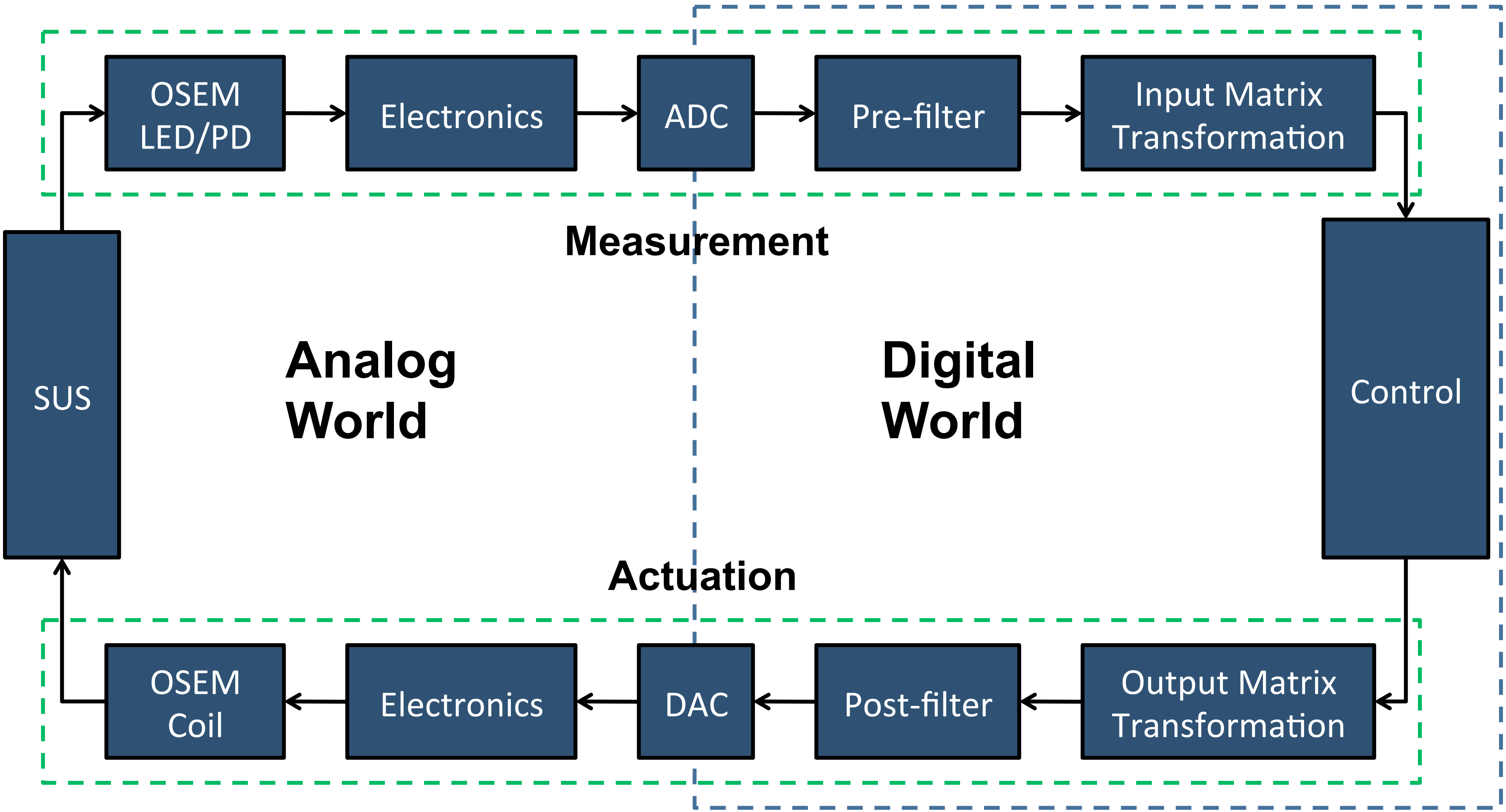
Reference P1400254

Some Parametric Instability References

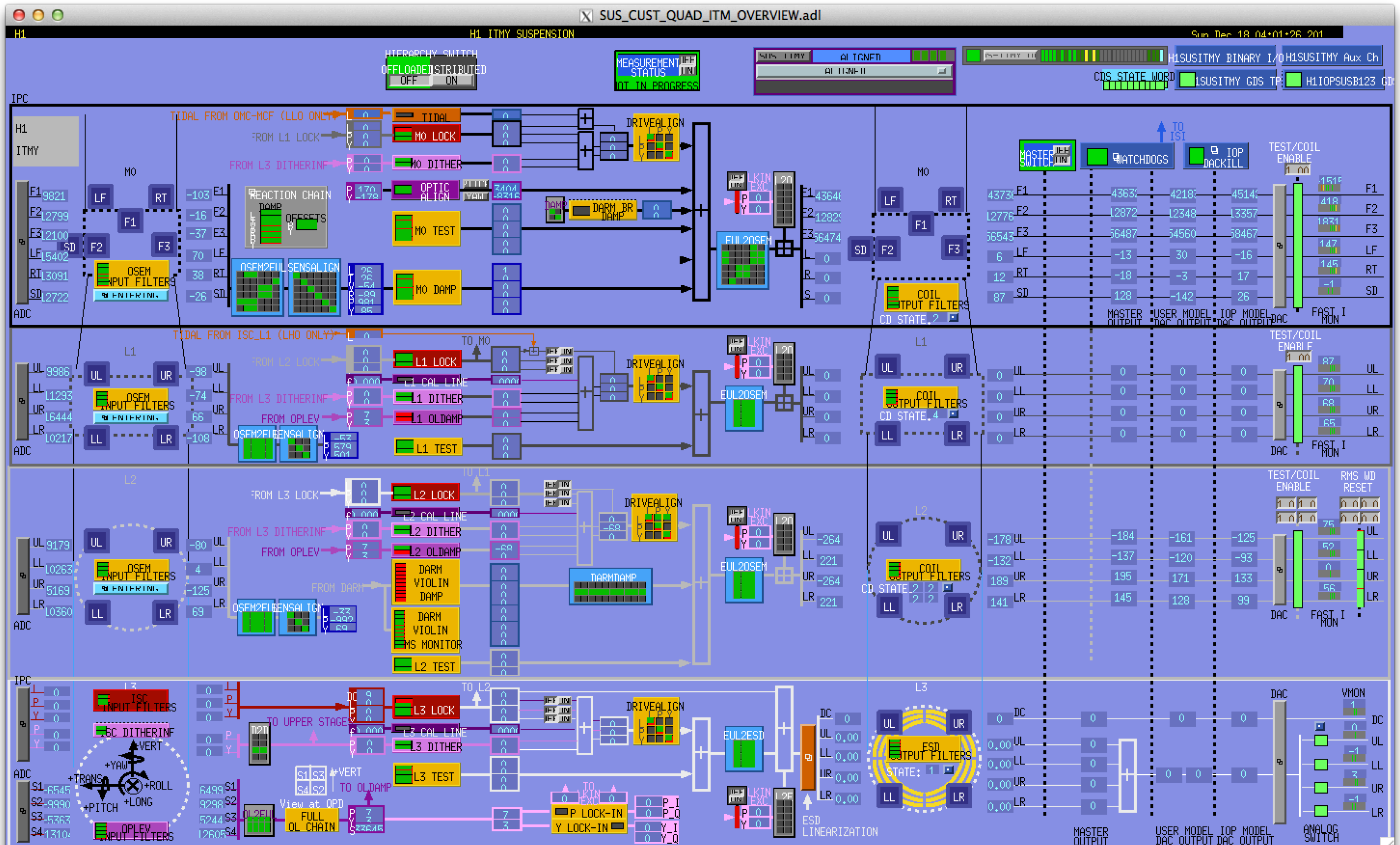
- Evans M, Barsotti L, and Fritschel P. A general approach to optomechanical parametric instabilities. Phys. Lett. A, 374 (4):665–671 (2010). URL http://dx.doi.org/10.1016/j.physleta.2009.11.023
- Gras S, Blair DG, and Zhao C. Suppression of parametric instabilities in future gravitational wave detectors using damping rings. Class. Quantum Grav., 26 (13): 135012 (2009). URL http://stacks.iop.org/0264-9381/26/i=13/a=135012
- Ju L, Blair DG, Zhao C, Gras S, Zhang Z, Barriga P, Miao H, Fan Y, and Merrill L. Strategies for the control of parametric instability in advanced gravitational wave detectors. Class. Quantum Grav., 26 (1):015002 (2009). URL http://stacks.iop.org/0264-9381/26/i=1/a=015002
- Miller J, Evans M, Barsotti L, Fritschel P, MacInnis M, Mittleman R, Shapiro B, Soto J, and Torrie C. Damping parametric instabilities in future gravitational wave detectors by means of electrostatic actuators. Physics Letters A, 375 (3): 788 – 794 (2011). URL http://dx.doi.org/10.1016/j.physleta.2010.12.032

Control Interface

Control Loop Signal Flow



Quad MEDM Overview Screen



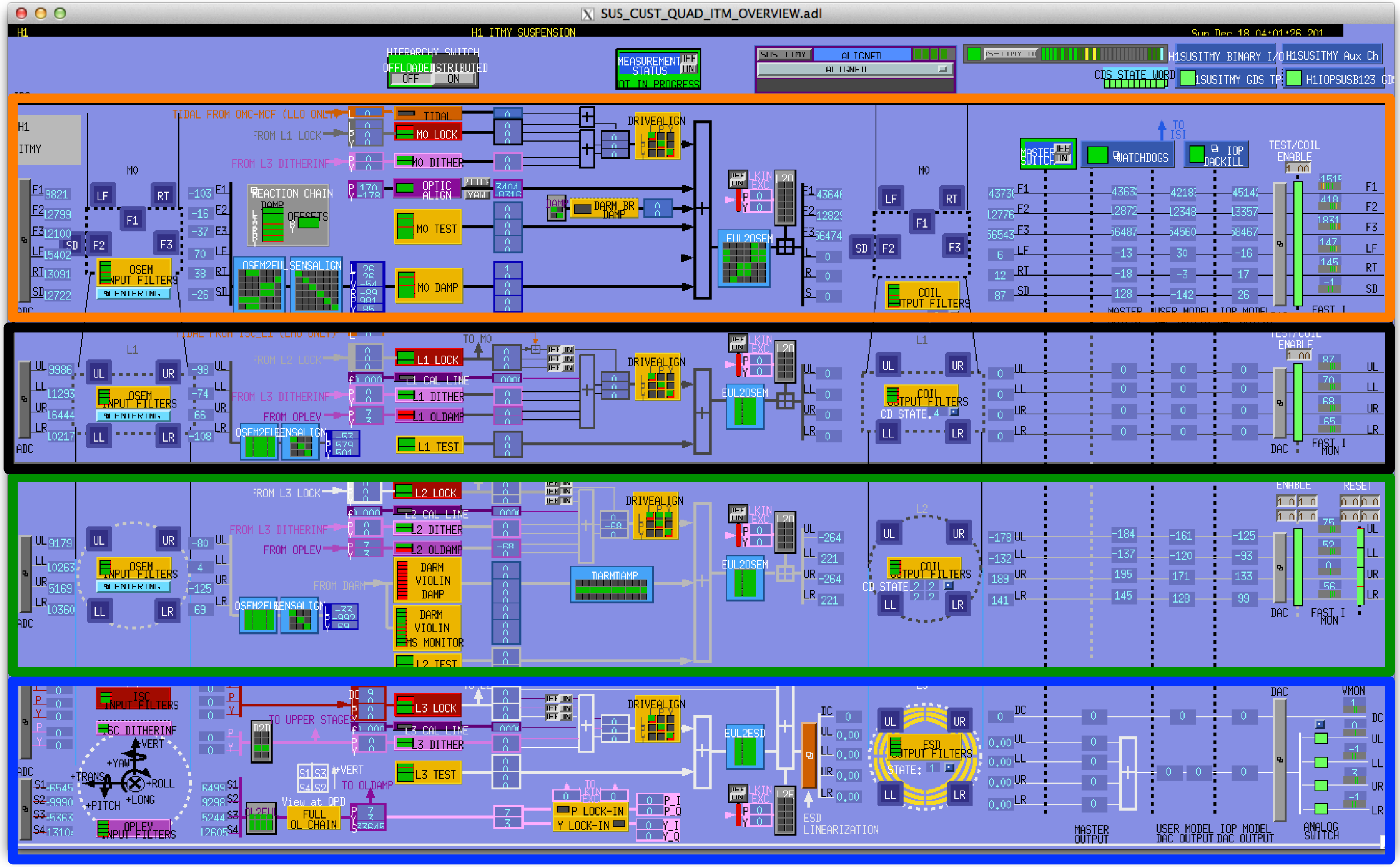
Quad MEDM Overview Screen

Top mass

Upper intermediate mass (UIM)

Penultimate mass (PUM)

Test mass



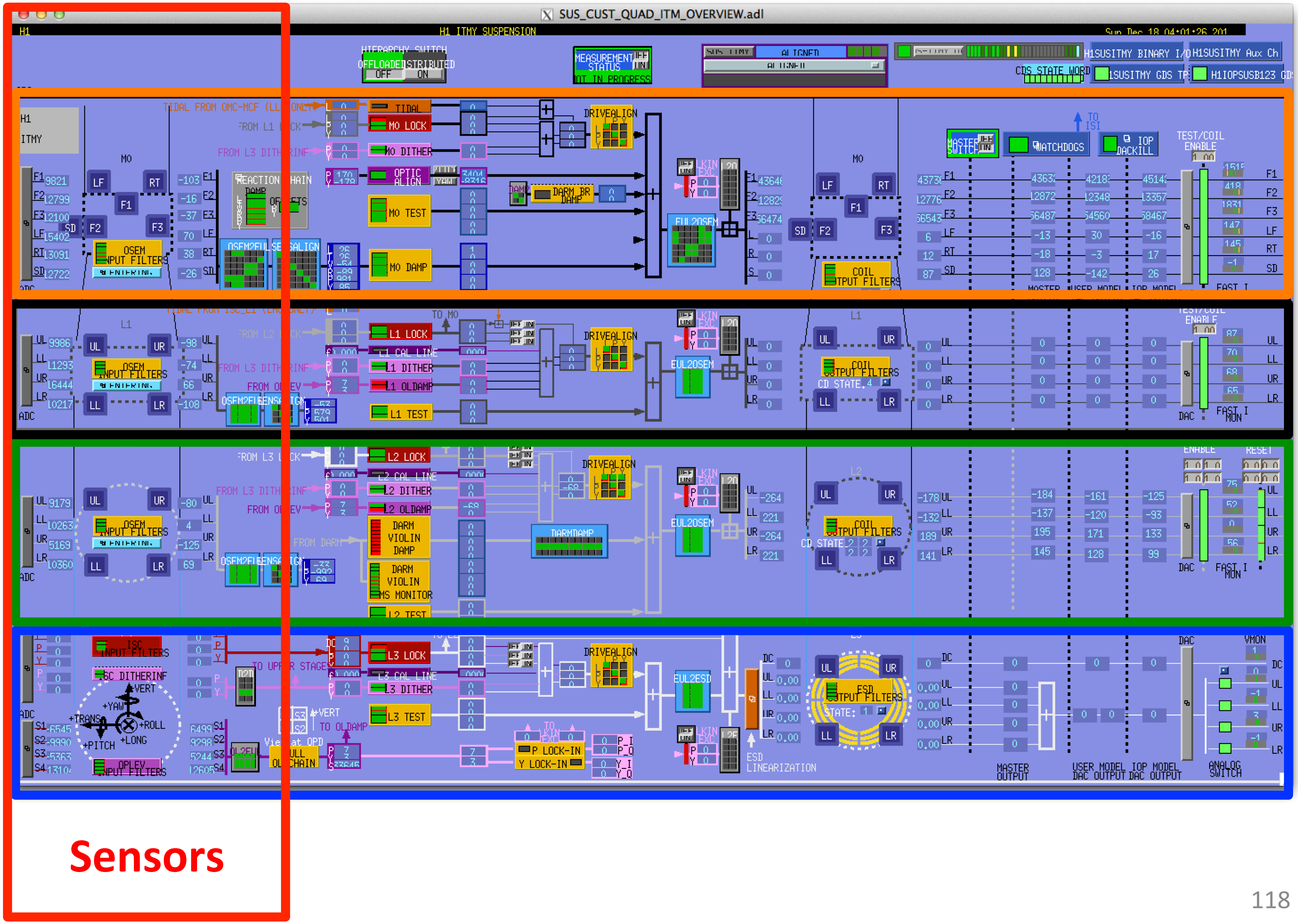
Quad MEDM Overview Screen

Top mass

Upper intermediate mass (UIM)

Penultimate mass (PUM)

Test mass



Sensors

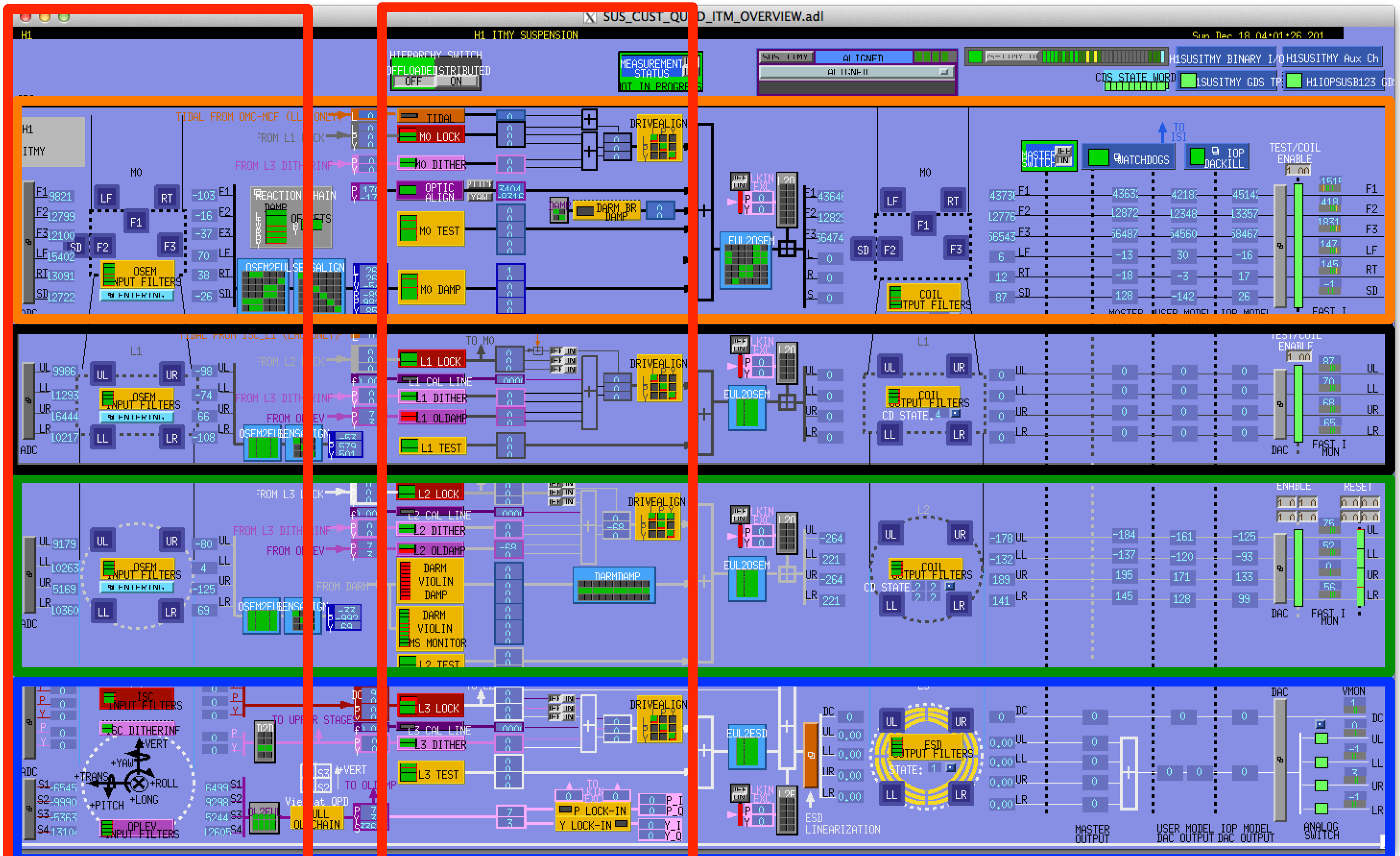
Quad MEDM Overview Screen

Top mass

Upper intermediate mass (UIM)

Penultimate mass (PUM)

Test mass



Sensors

Control

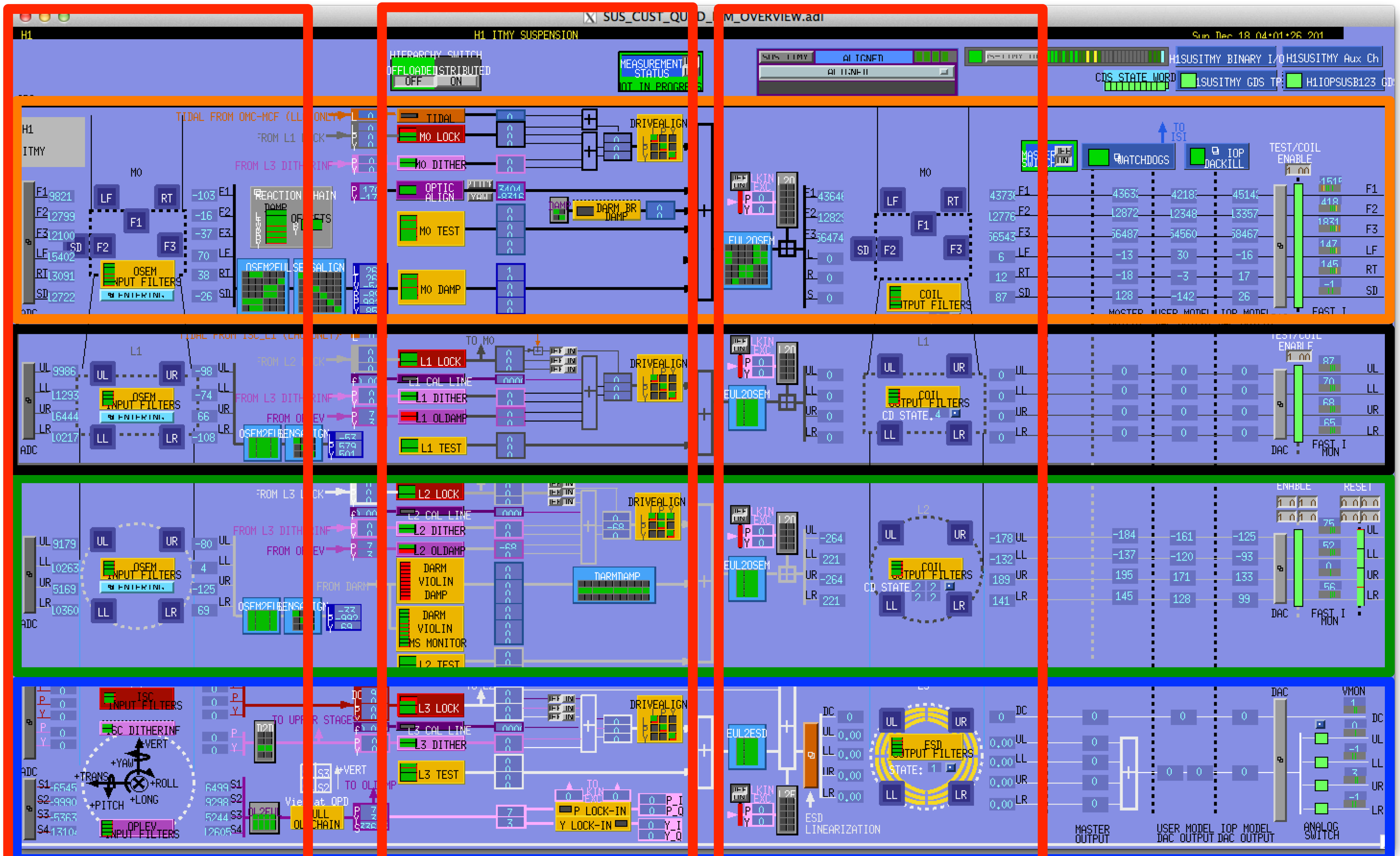
Quad MEDM Overview Screen

Top mass

Upper intermediate mass (UIM)

Penultimate mass (PUM)

Test mass

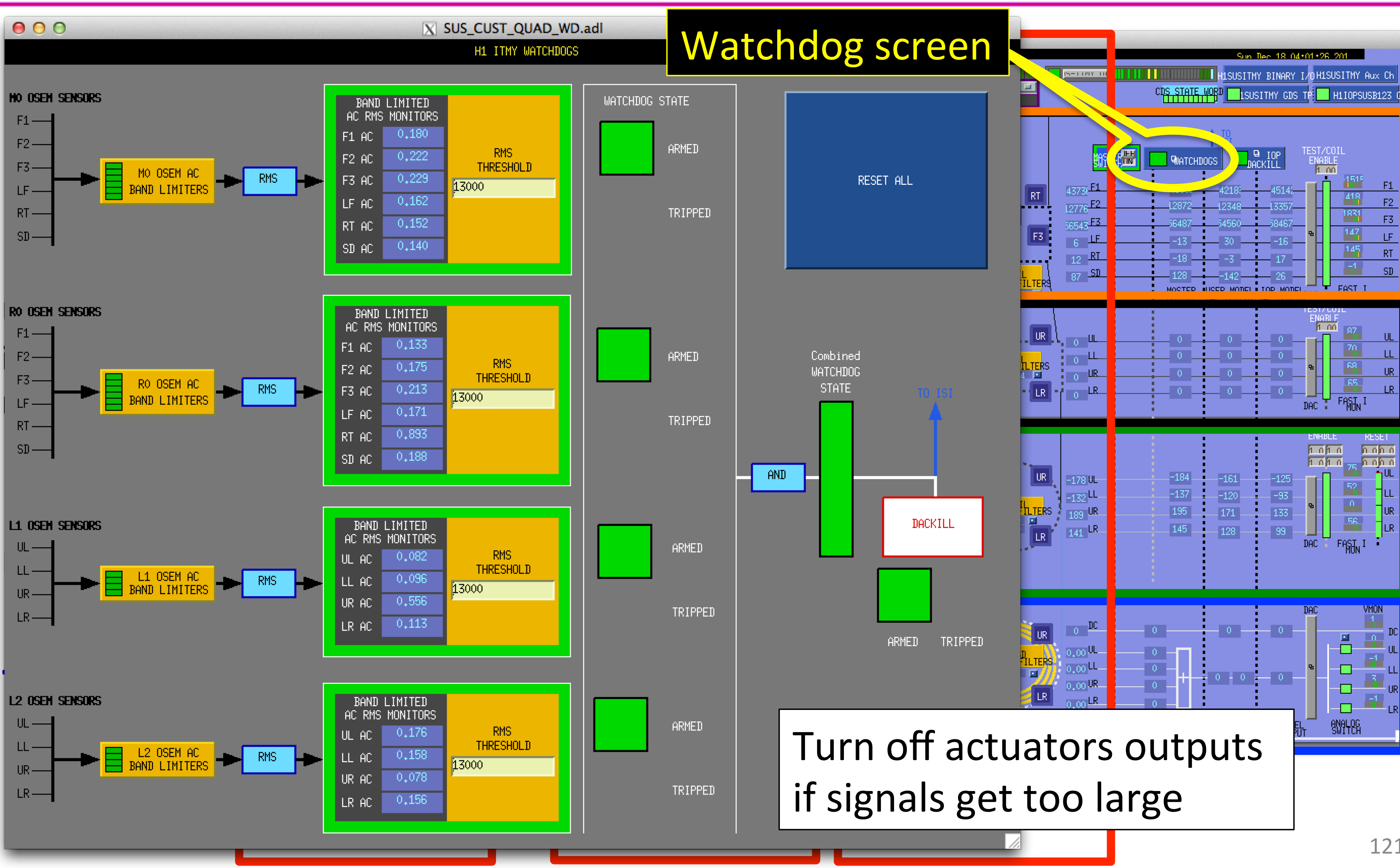


Sensors

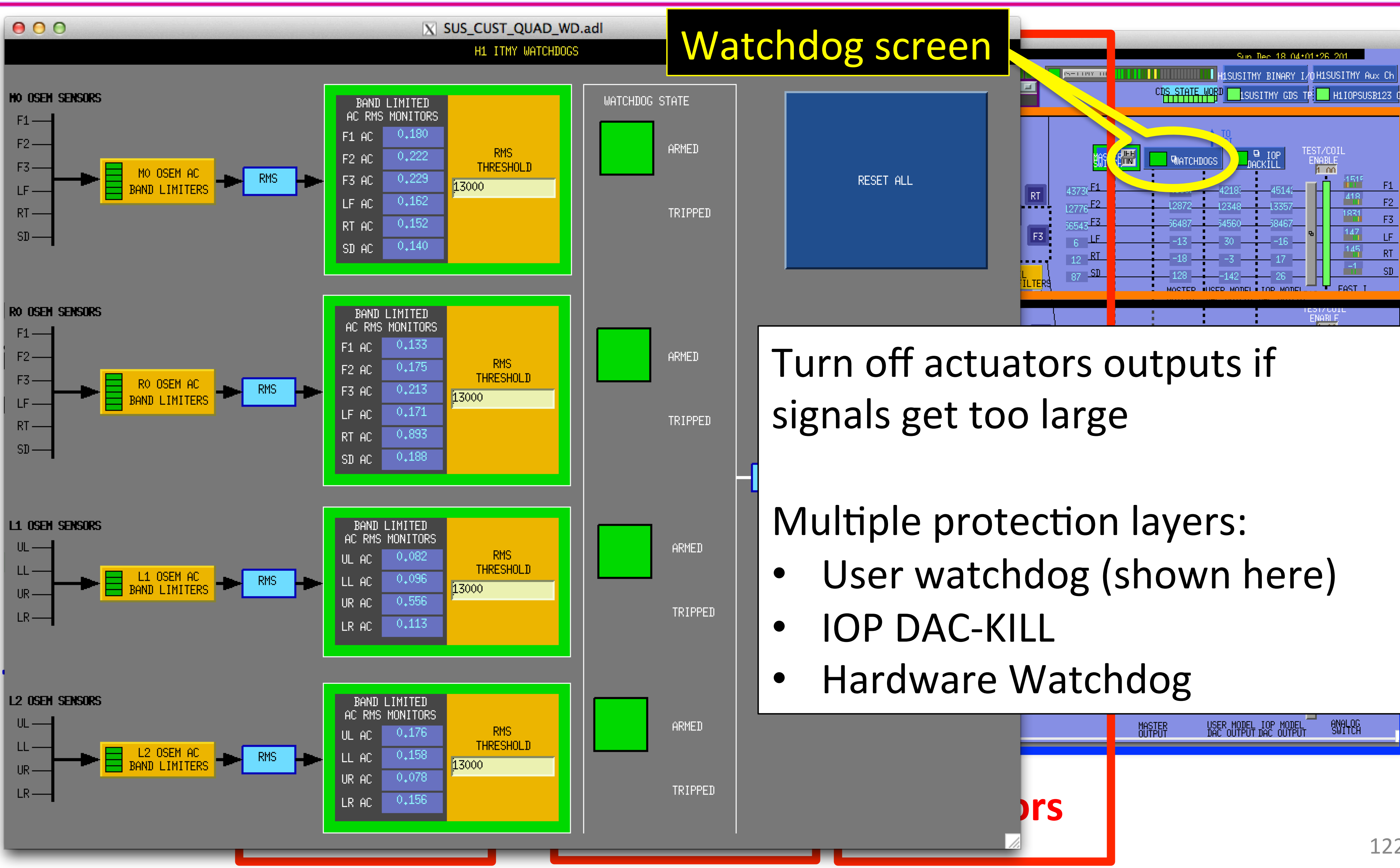
Control

Actuators

Quad MEDM Overview Screen



Quad MEDM Overview Screen

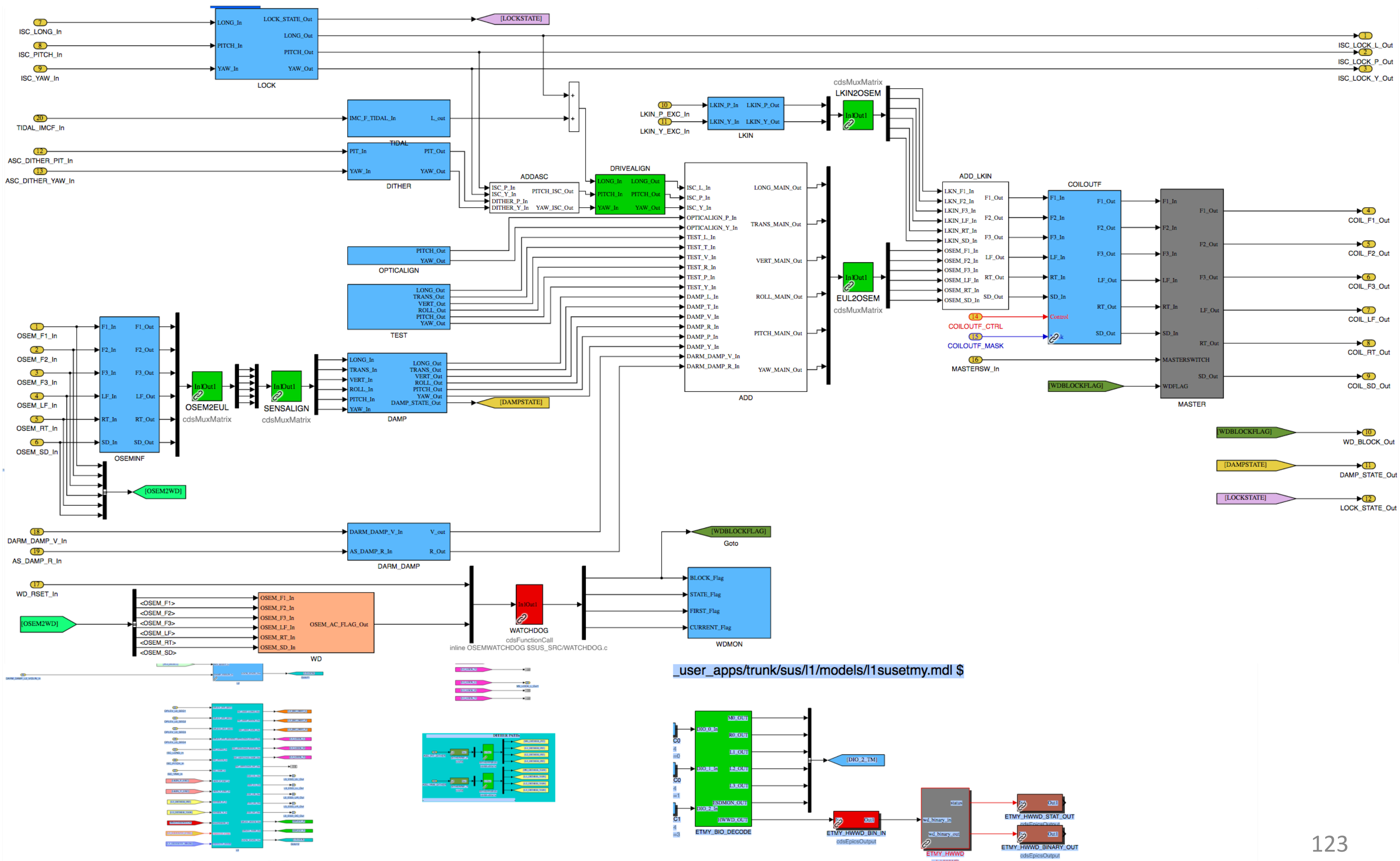


Turn off actuators outputs if signals get too large

Multiple protection layers:

- User watchdog (shown here)
- IOP DAC-KILL
- Hardware Watchdog

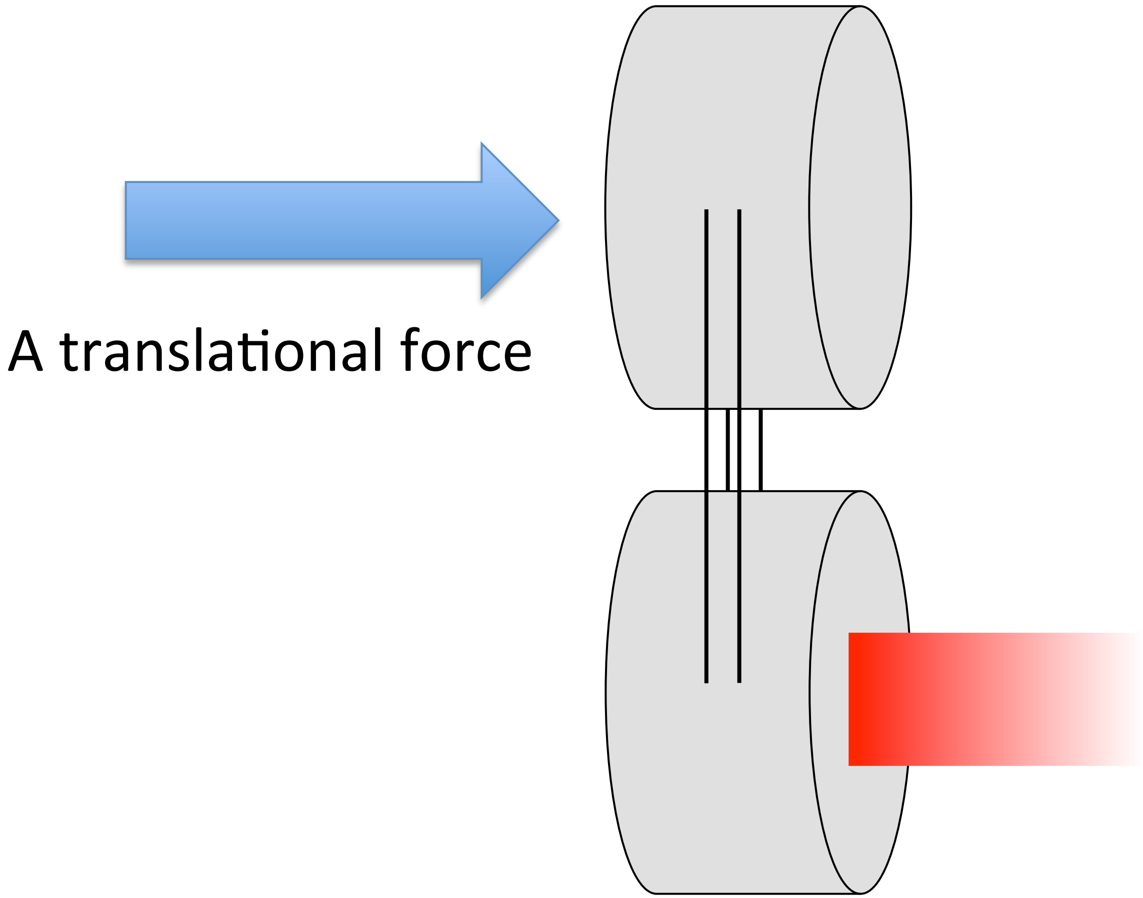
Realtime Software – designed in Matlab



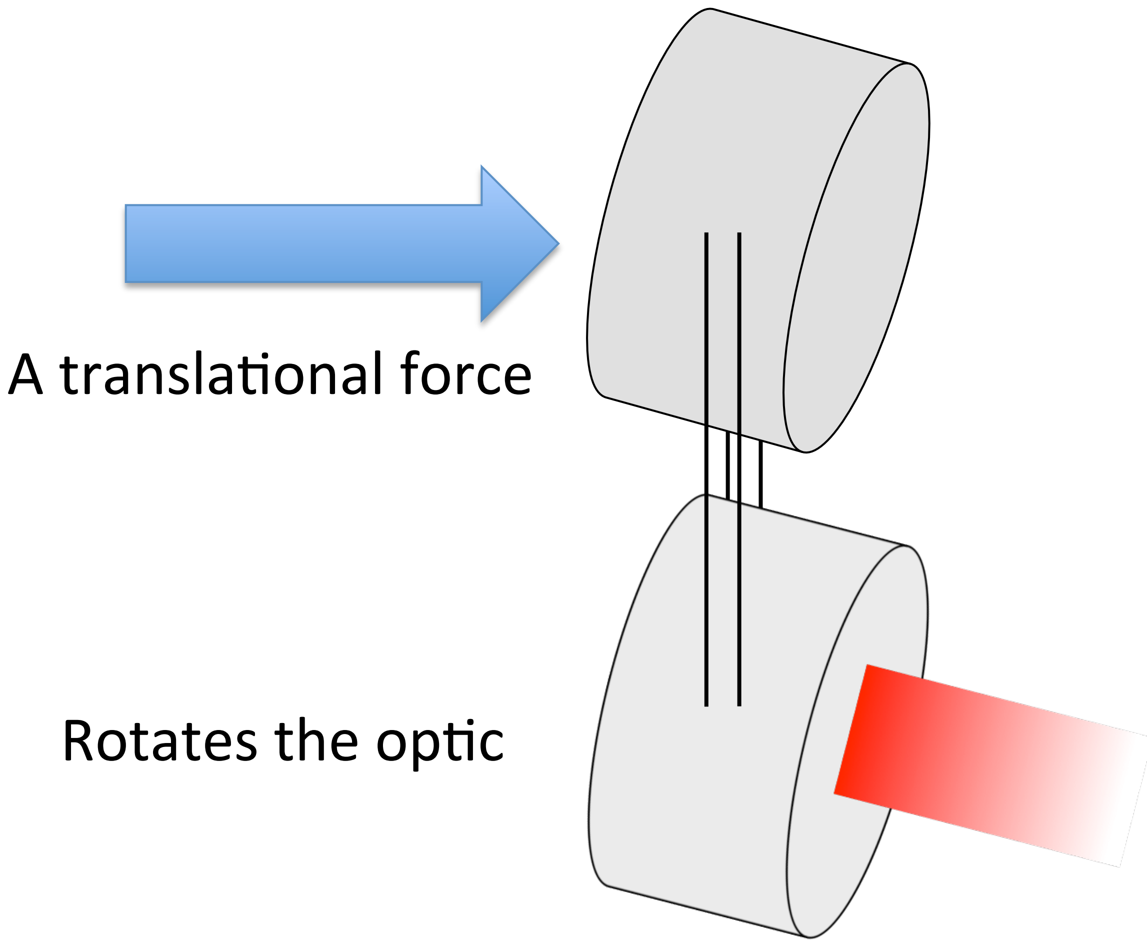
What else could be done to improve suspensions?

- Length to pitch decoupling
- Better inertial sensors
- More advanced Controls

Length to angle coupling

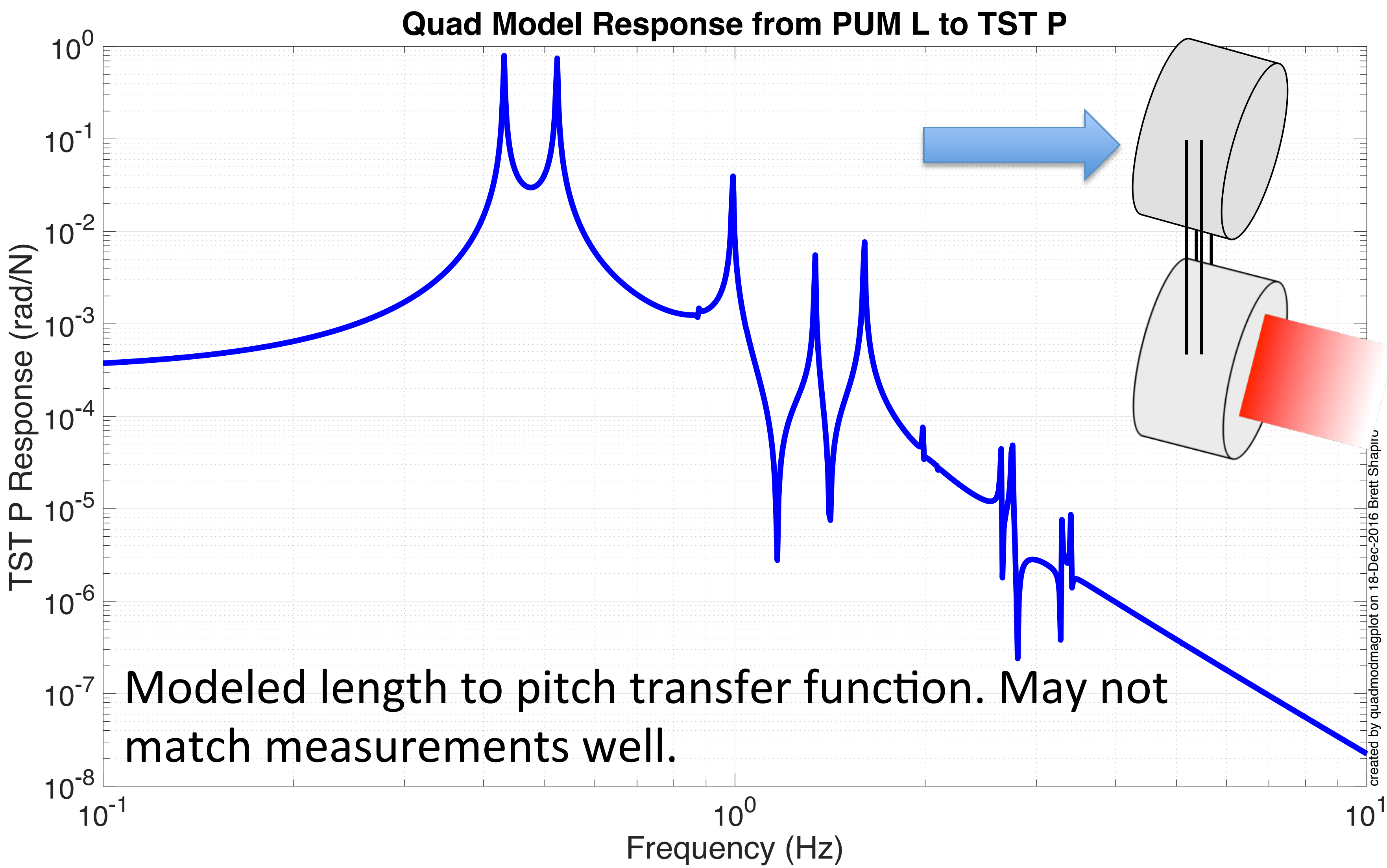


Length to angle coupling

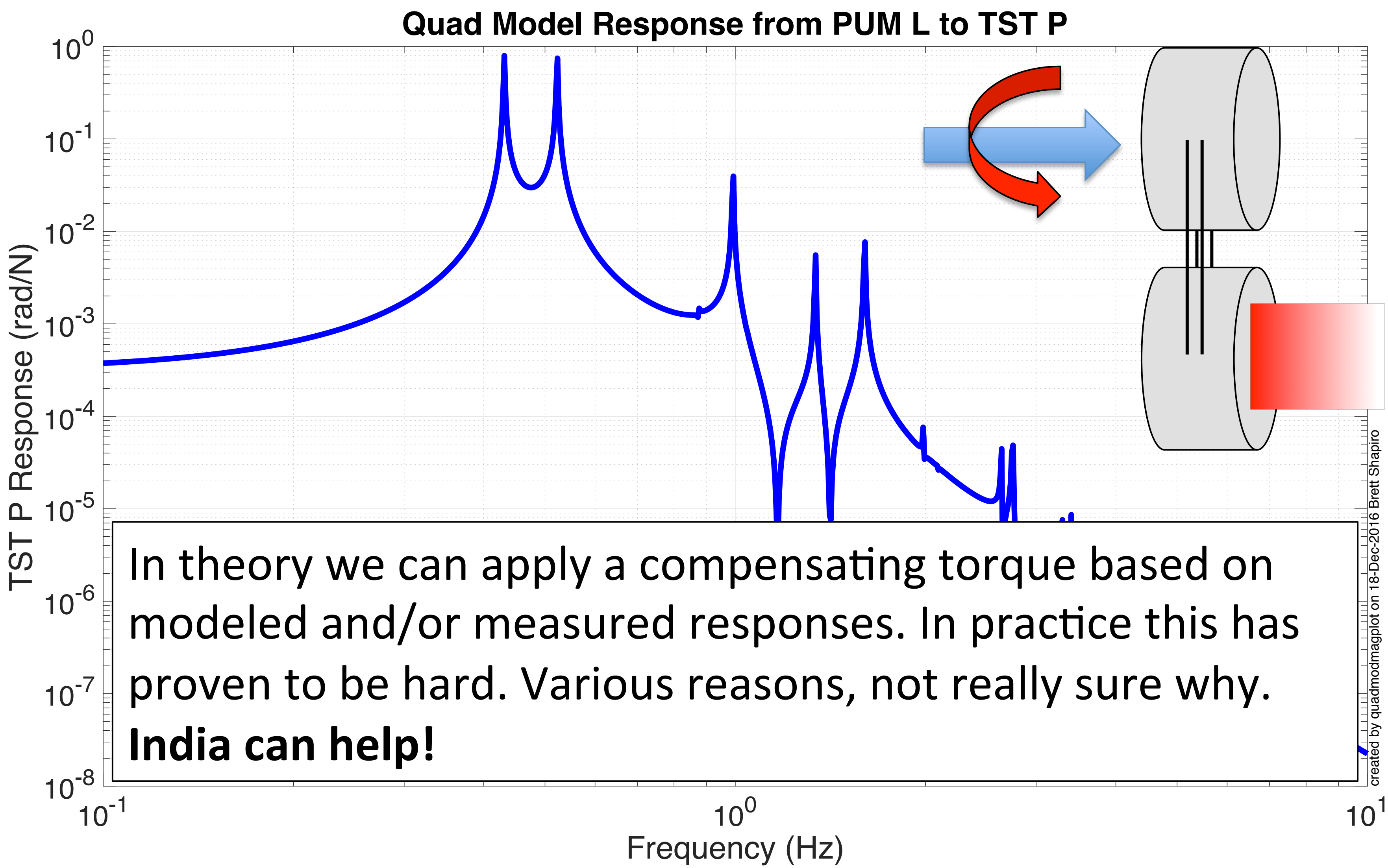


➢ This requires more noisy angular control

Length to angle coupling



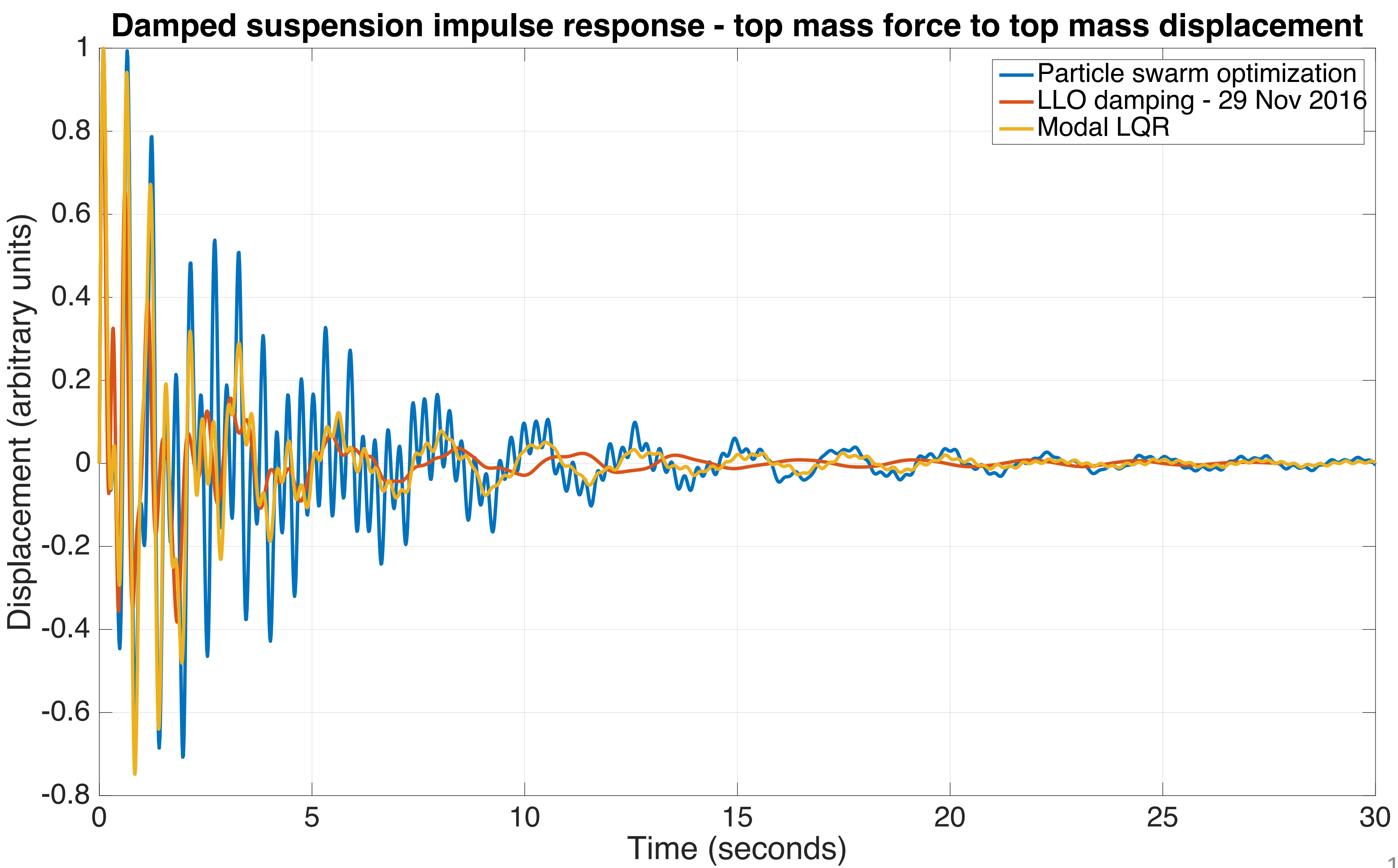
Length to angle coupling



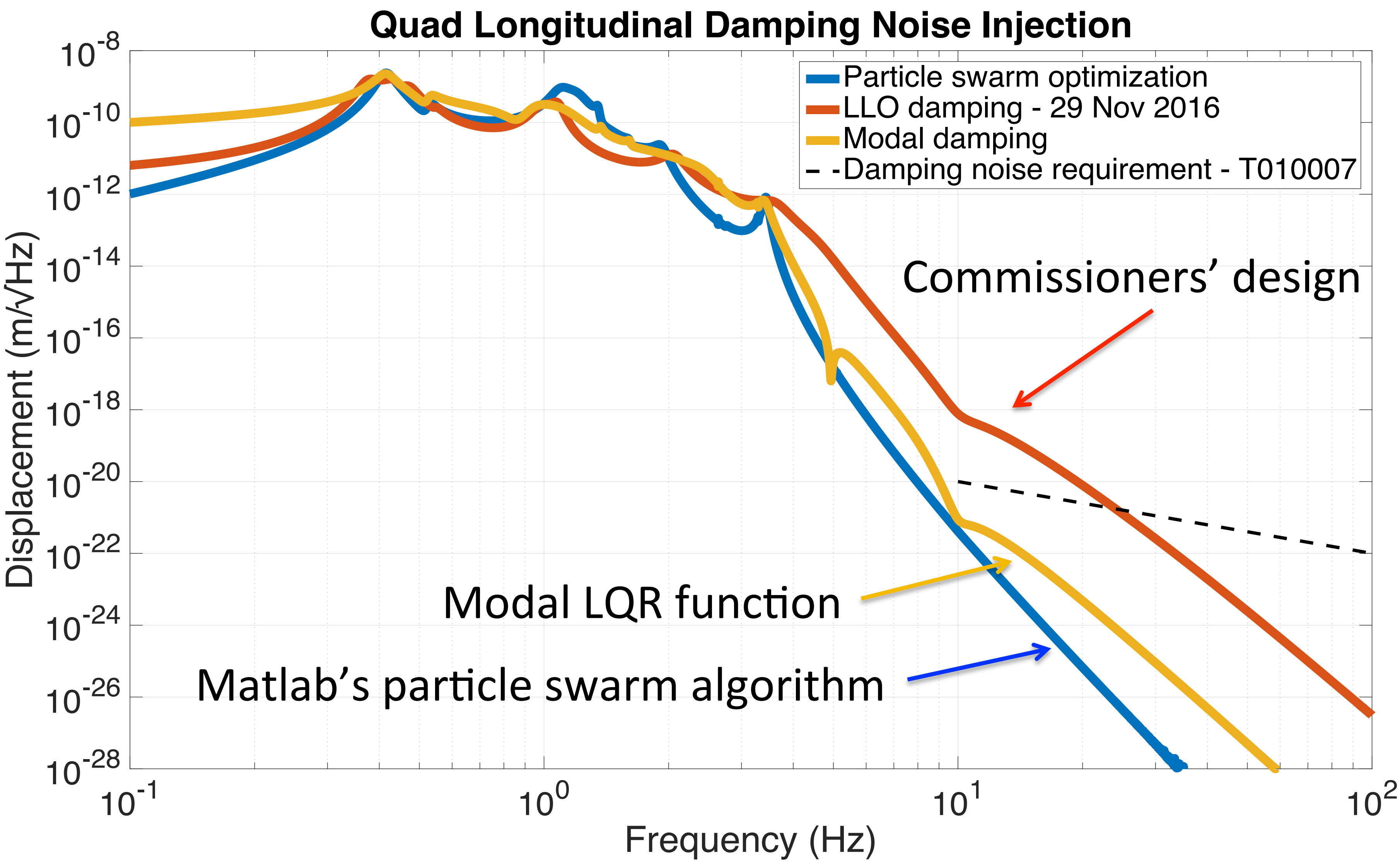
In theory we can apply a compensating torque based on modeled and/or measured responses. In practice this has proven to be hard. Various reasons, not really sure why. **India can help!**

More Advanced Controls

Various Top Mass Damping Algorithms



Various Top Mass Damping Algorithms



Control System Working Group

Ongoing topics to improve IFO performance

- Particle swarm optimization for angular control
- Length to angle decoupling: how to drive length and pitch and yaw without impacting the others
- Machine learning for lock maintenance
- Optimal transfer function fitting techniques
- Robust configurations for earthquakes

CSWG tools

- Wiki https://wiki.ligo.org/viewauth/CSWG/WebHome
- alog https://alog.ligo-la.caltech.edu/CSWG/
- Mailing list cswg@sympa.ligo.org
  Sign up at https://grouper.ligo.org/mailinglists/cswg
- Teamspeak channel CSWG
- CSWG Chair: Dennis Coyne
  Co-chairs: Rob Ward, Brett Shapiro

CSWG Meetings – Get Involved!

Bi-monthly Teamspeak meetings

- US-western hemisphere: 1st Fri of the month, 9am US-PT (6pm CET, 9:30pm IST)

- US-eastern hemisphere: 3rd US Thu of the month, 4pm US-PT (Fri 9am AET, 8am JST, 4:30am IST)

Summary of how India can help

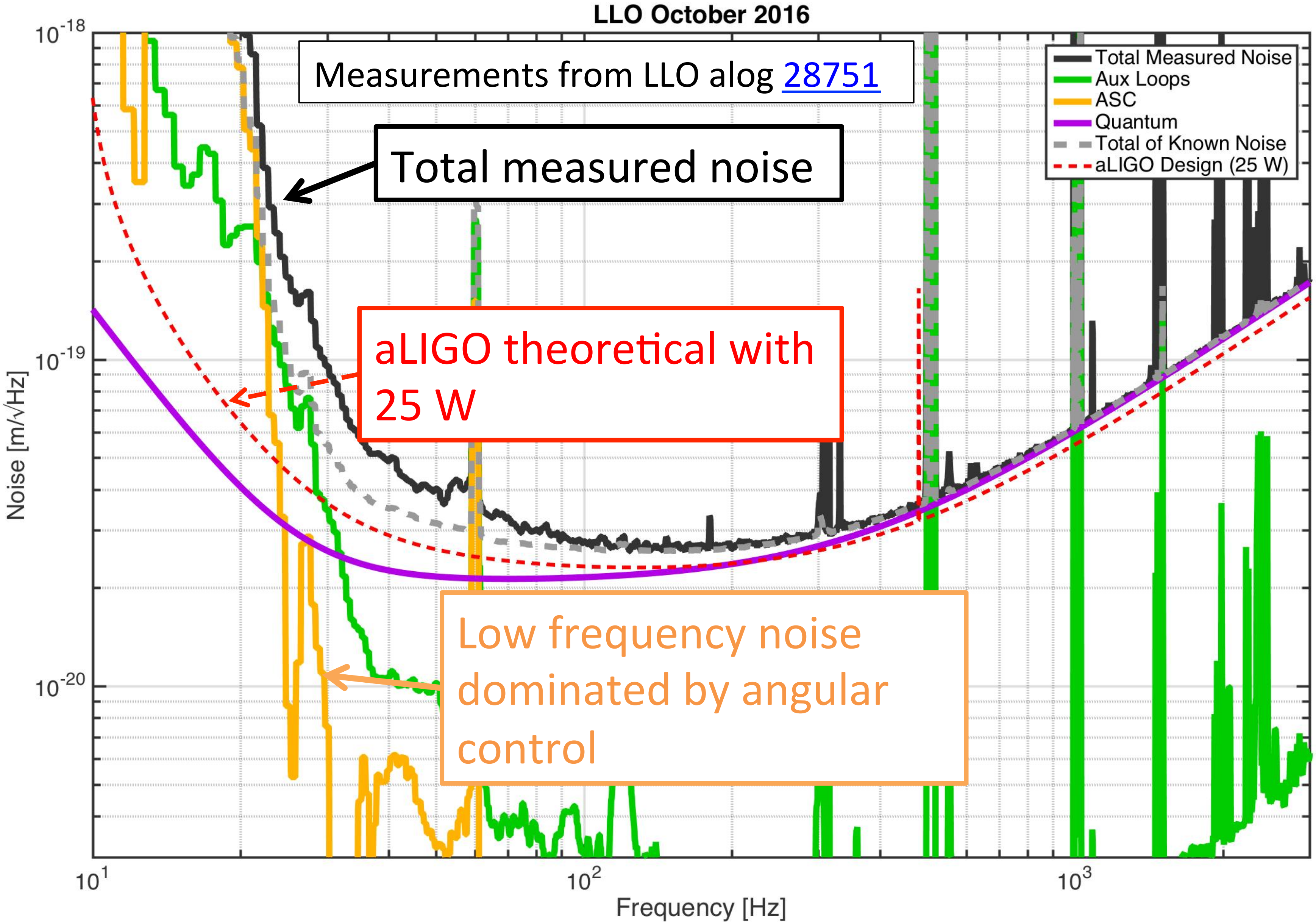
- Better suspension models
- Consider thinner, higher stress silica fibers for test masses
- Lower noise, more reliable optical levers
- Help improve test mass thermal compensation
- Length to angle decoupling
- More advanced controls techniques
- Get involved in the controls working group

Summary of how India can help

- Better suspension models
- Consider thinner, higher stress silica fibers for test masses
- Lower noise, more reliable optical levers
- Help improve test mass thermal compensation
- Length to angle decoupling
- More advanced controls techniques
- Get involved in the controls working group

Getting involved in the controls early will increase commissioning expertise in India

Questions?


LLO October 2016
Measurements from LLO alog 28751
Total measured noise
aLIGO theoretical with 25 W
Low frequency noise dominated by angular control
Total Measured Noise
Aux Loops
ASC
Quantum
Total of Known Noise
aLIGO Design (25 W)
Noise [m/√Hz]
Frequency [Hz]
10^-18
10^-19
10^-20
10^1
10^2
10^3

BackUps

Examples of things that can be done to minimize control noise

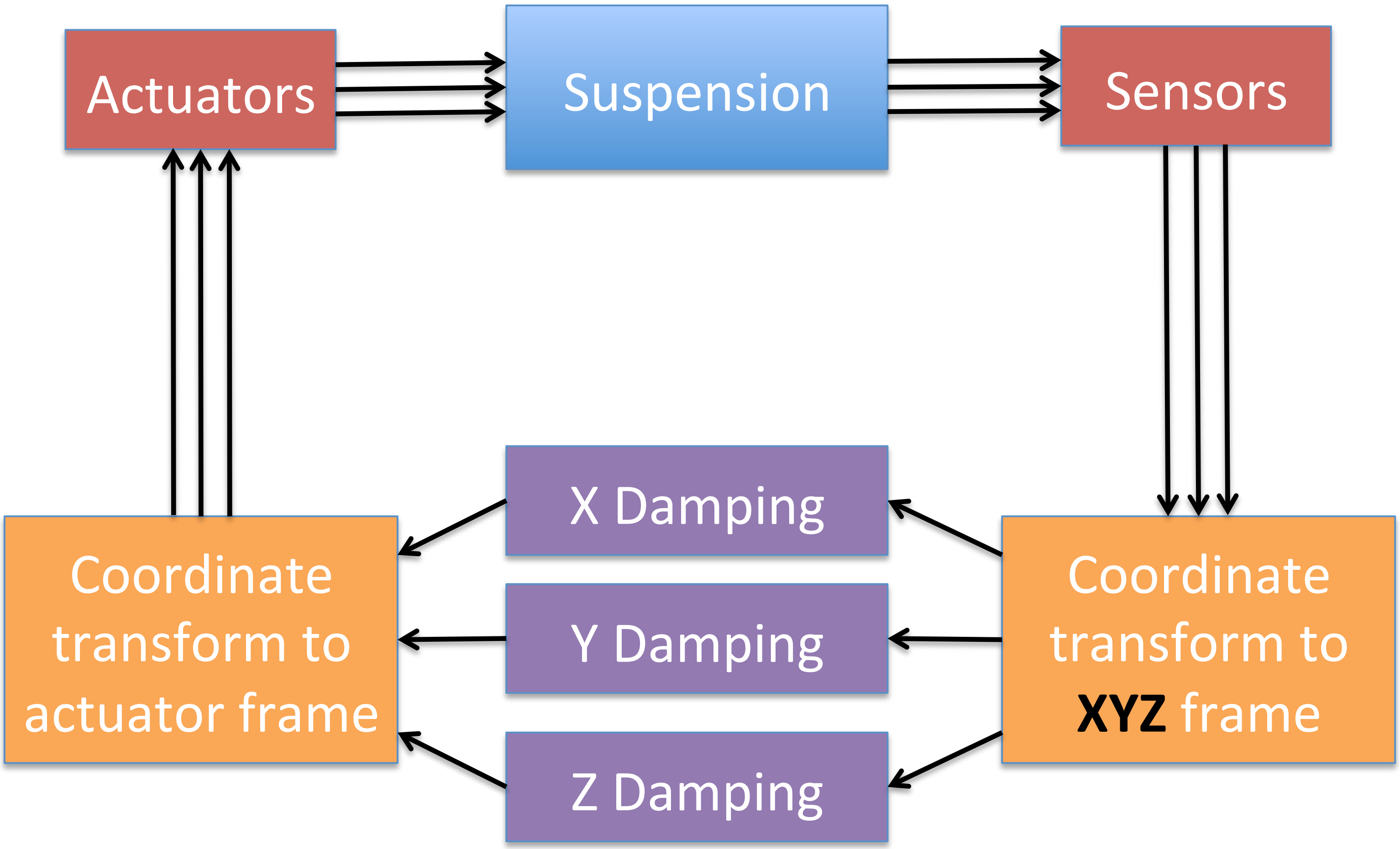
Examples are applied to damping

An alternative top mass damping technique

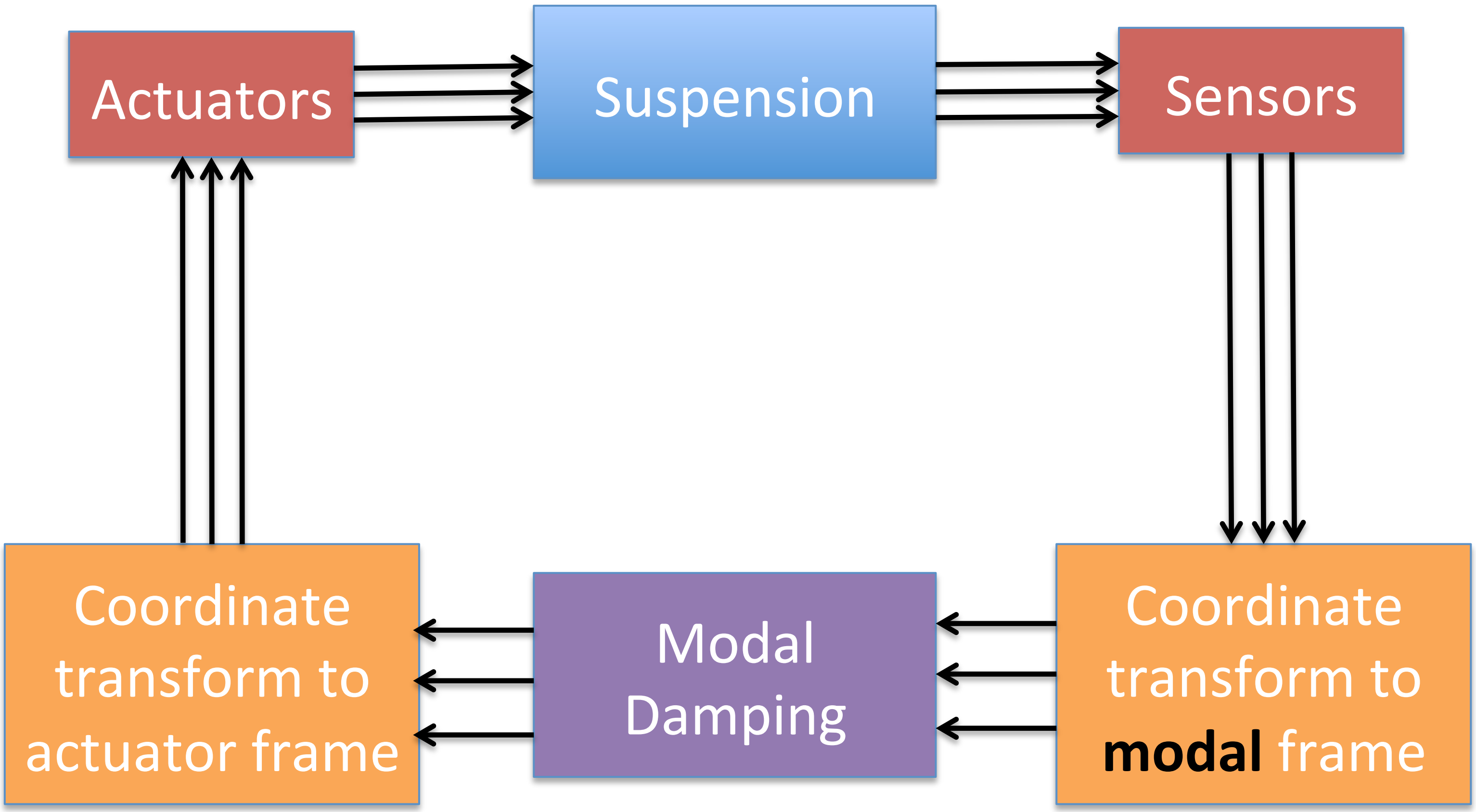
Modal Damping

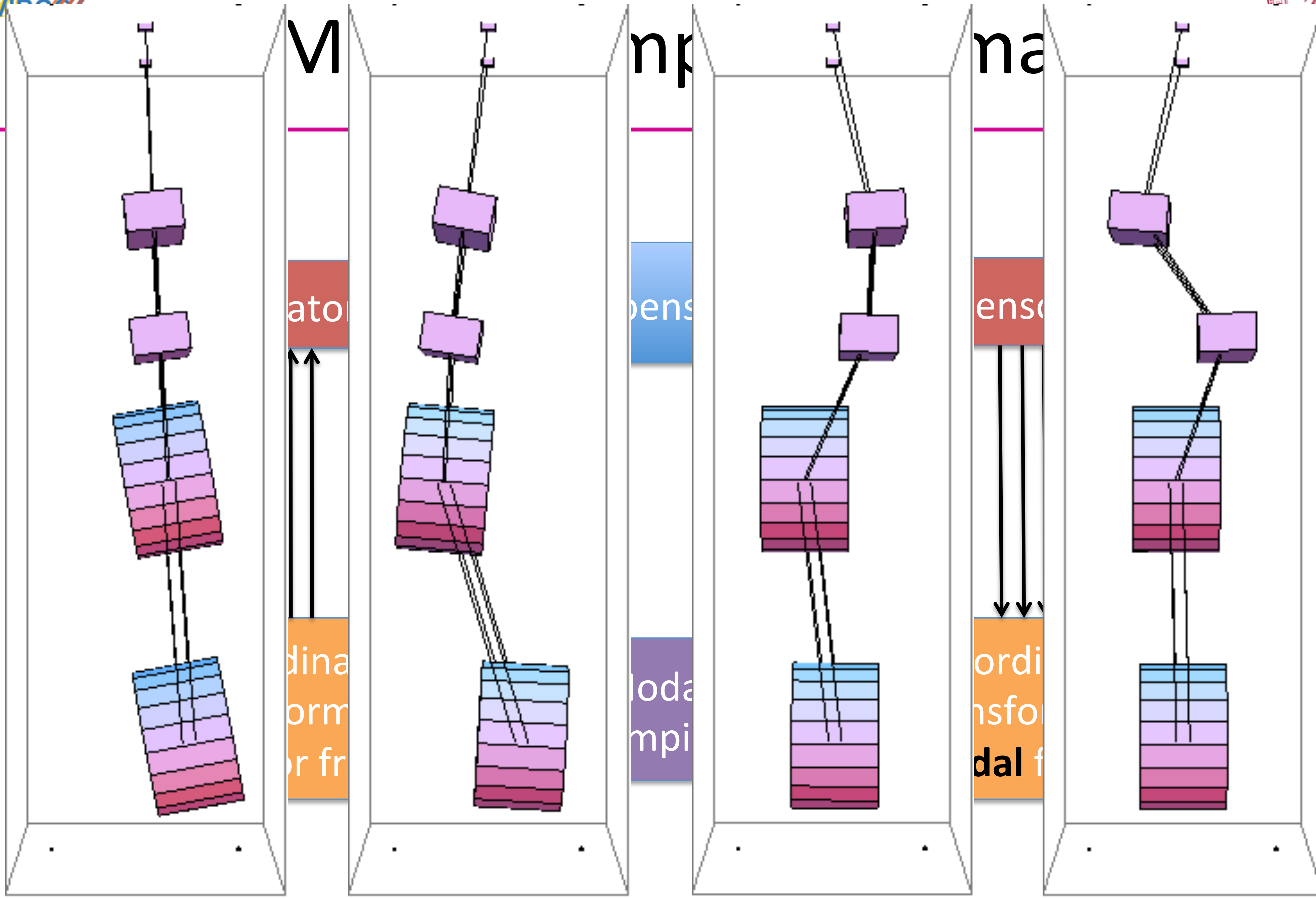
References
T1300301 – Frequency Domain LQR
P1100102 - Modal Damping of a Quadruple Pendulum
P1200057 – Adaptive Modal Damping for Advanced LIGO Suspensions

Typical Damping Format



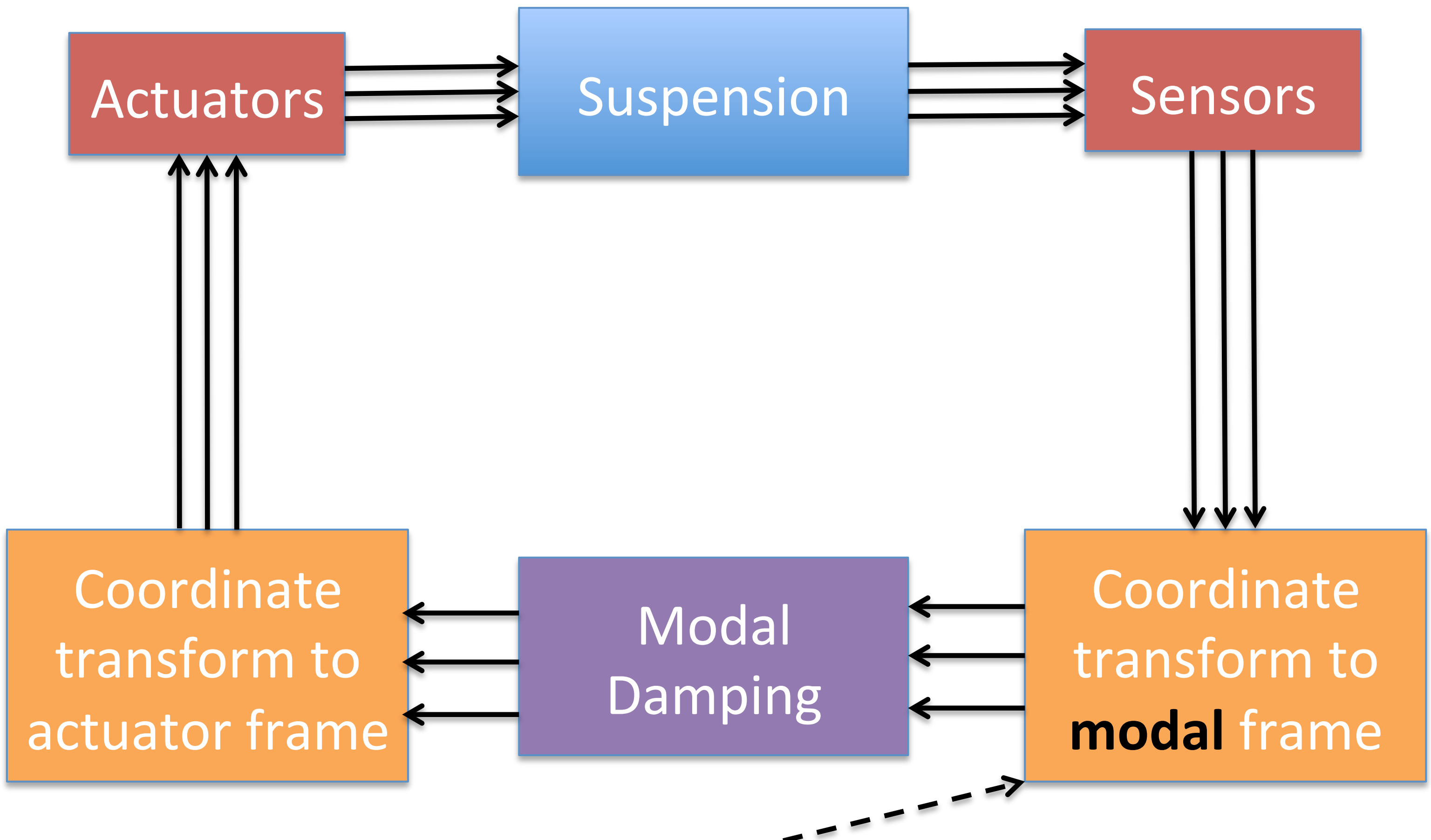
Modal Damping Format





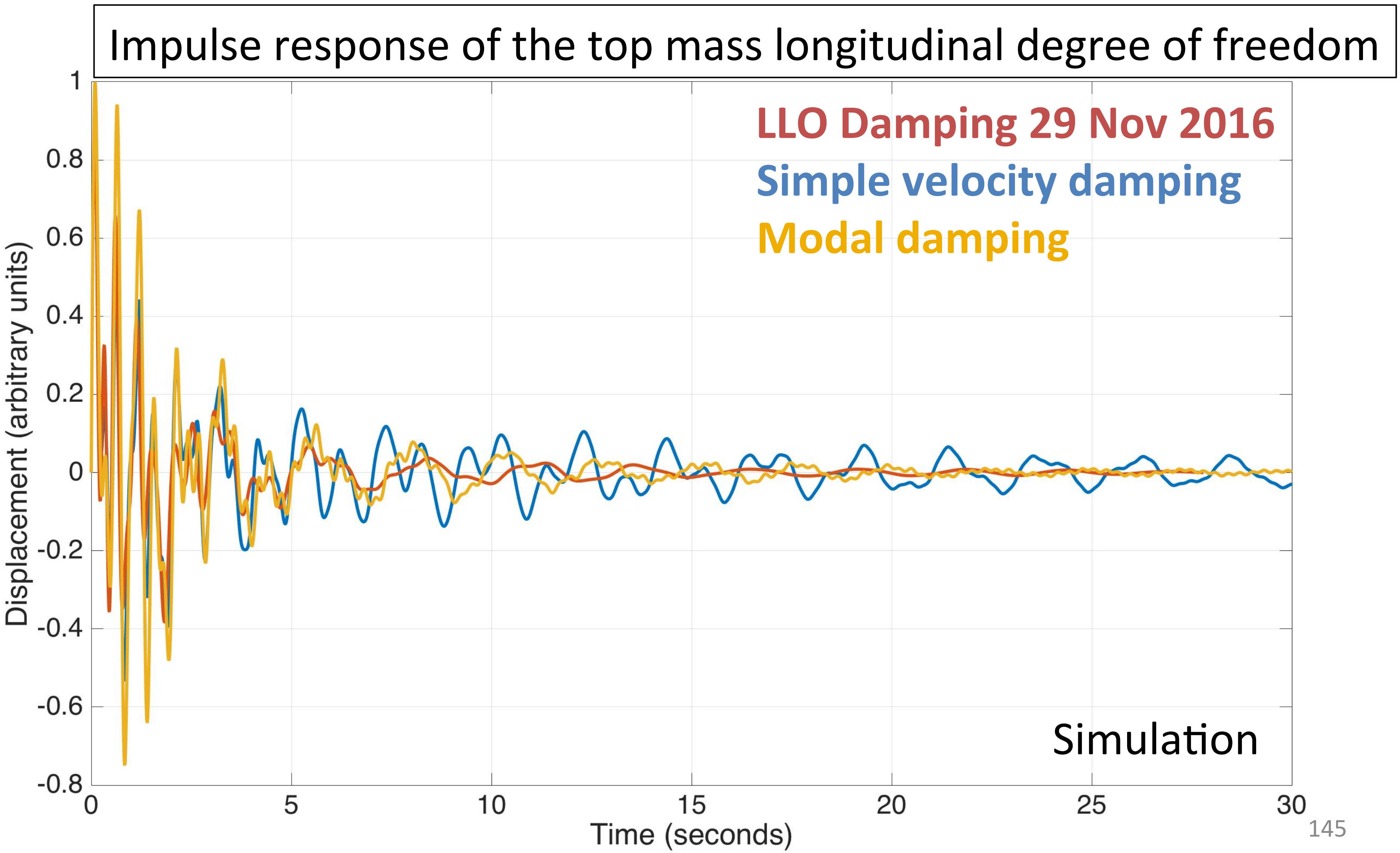
0.43 Hz **1.0 Hz** **2.0 Hz** **3.4 Hz**

Modal Damping Format

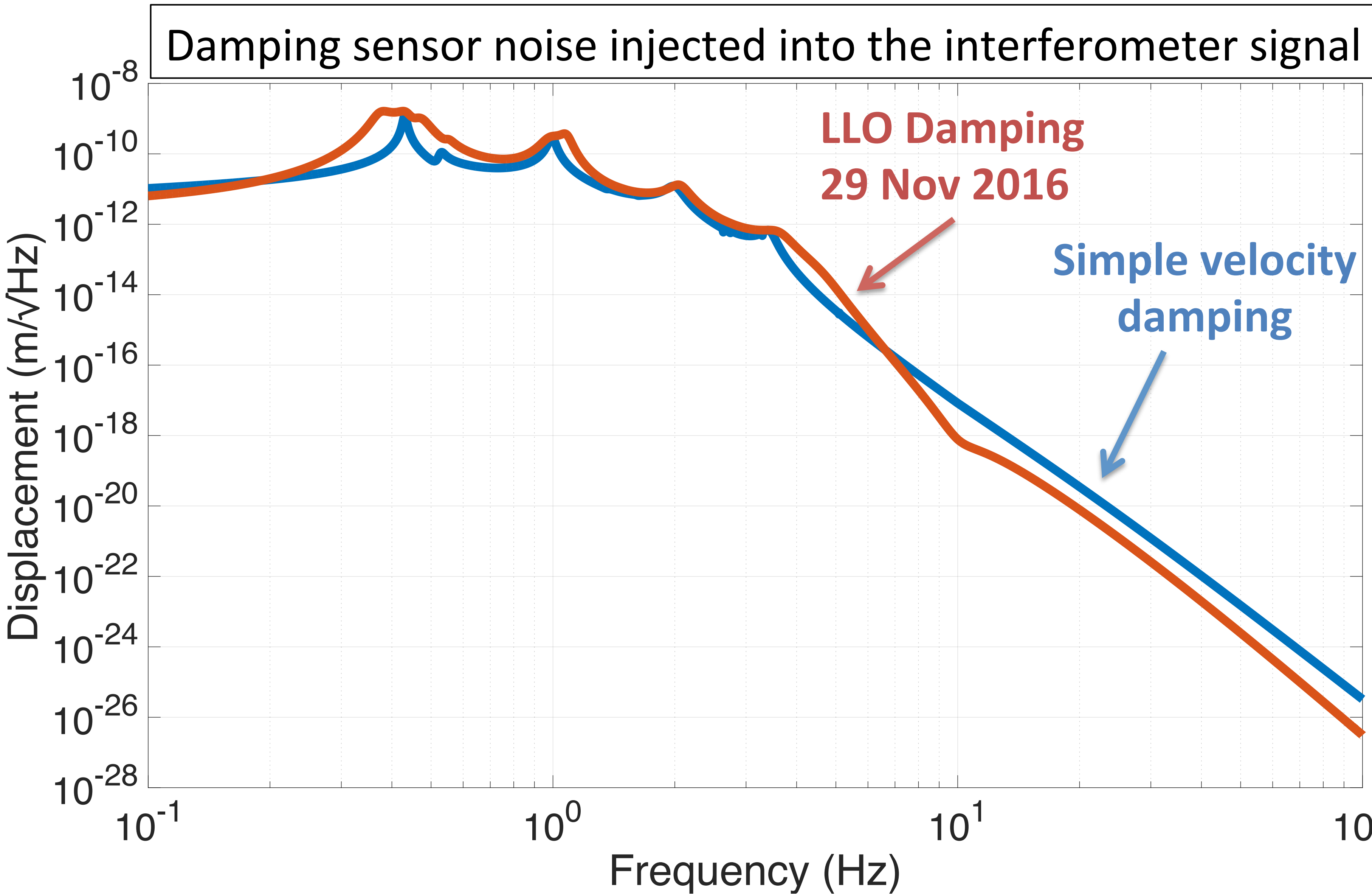


Multi-input-multi-output (MIMO) filter matrix
State estimator designed using 'optimal control' (Matlab lqr function)

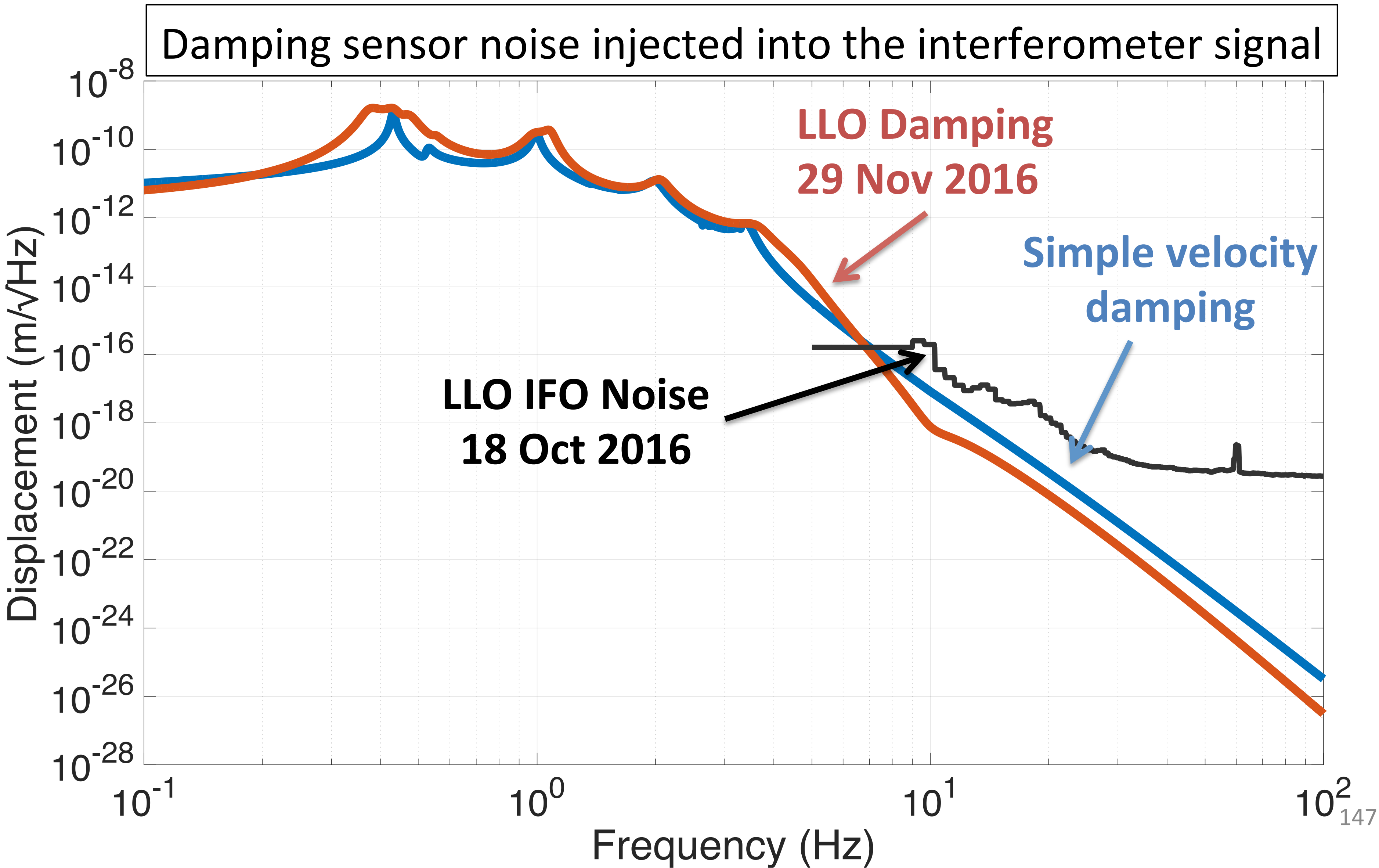
Damping Impulse Responses



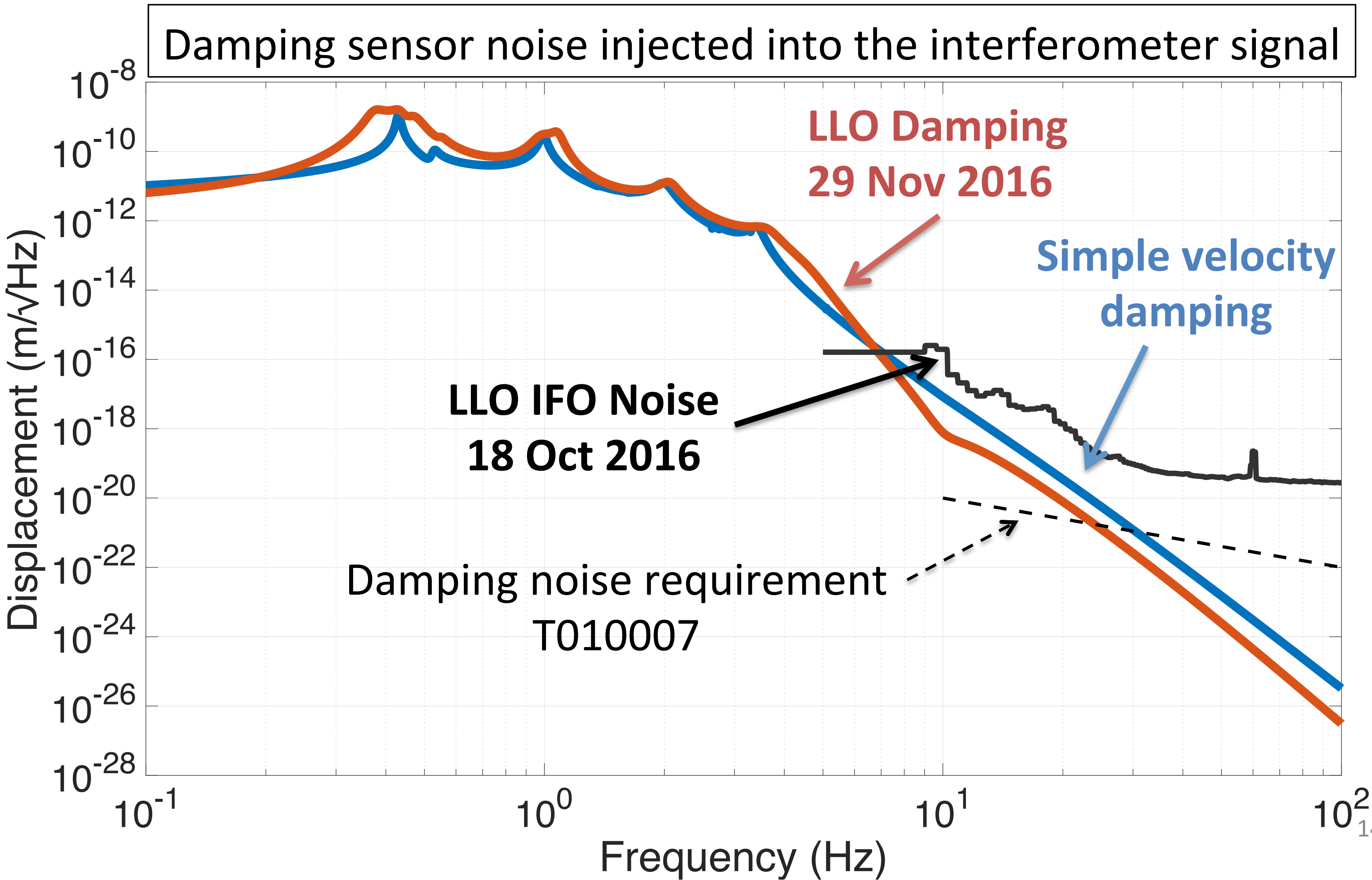
Damping Noise Performances



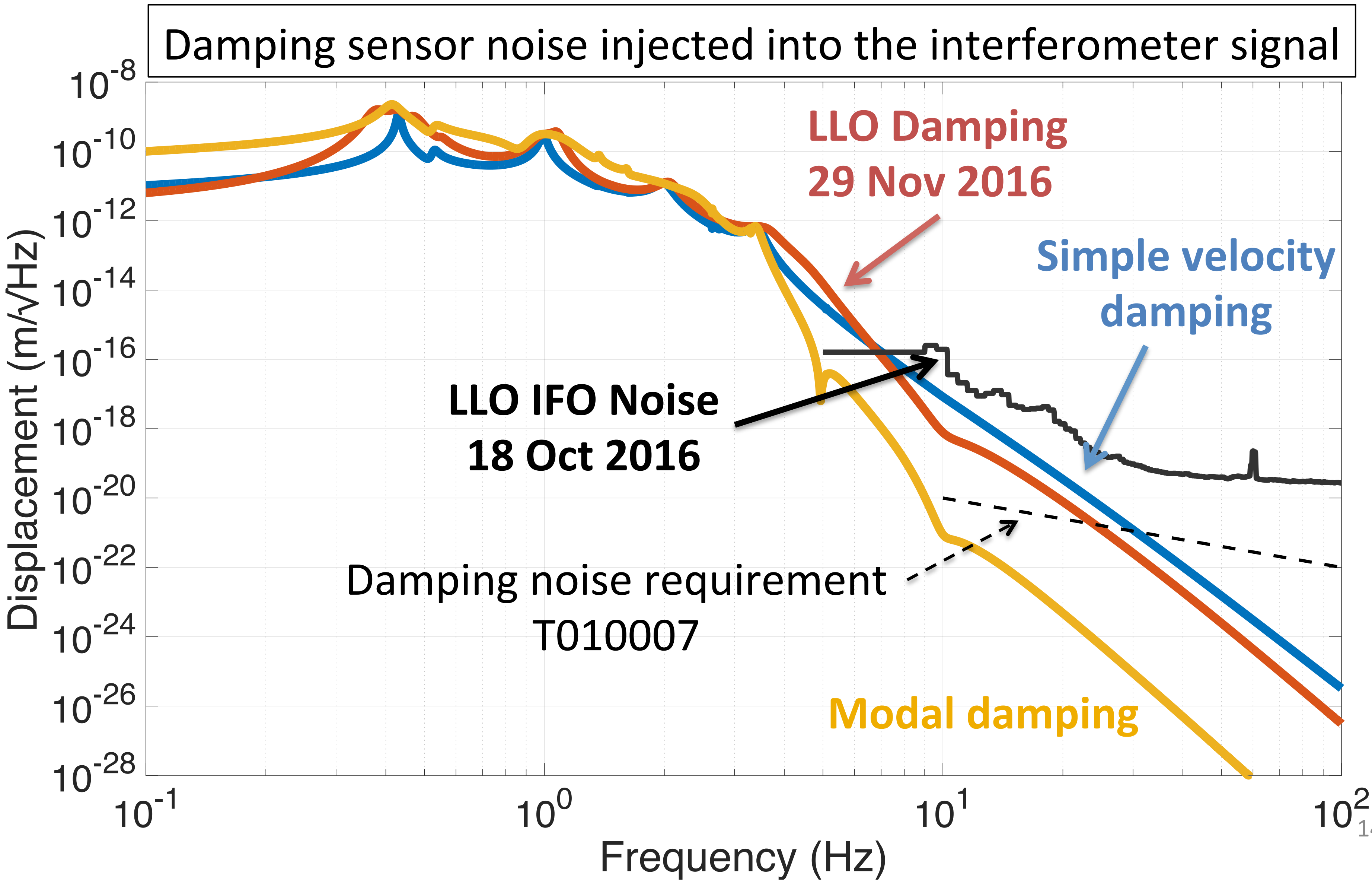
Damping Noise Performances



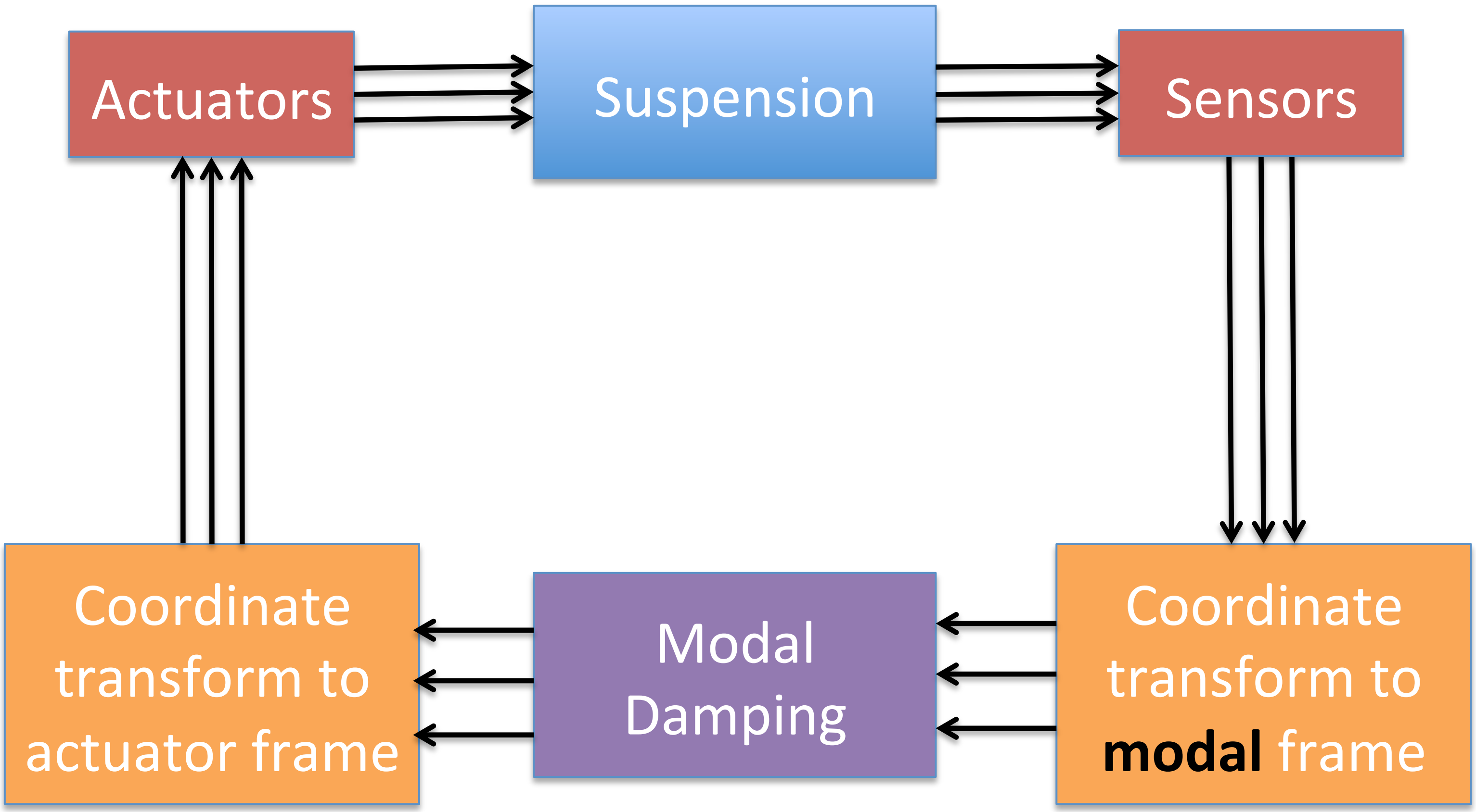
Damping Noise Performances



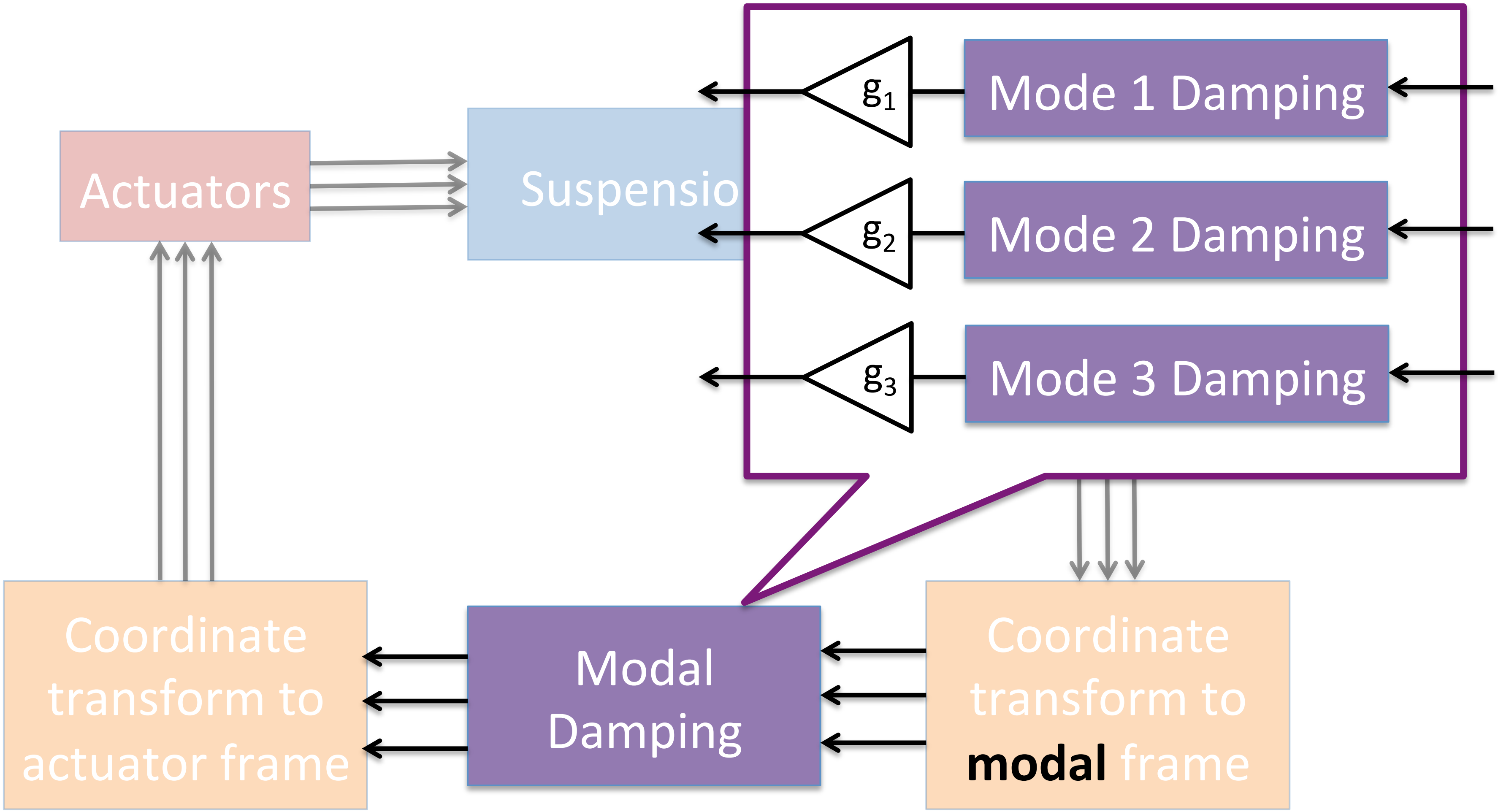
Damping Noise Performances



Modal Damping Adjustability

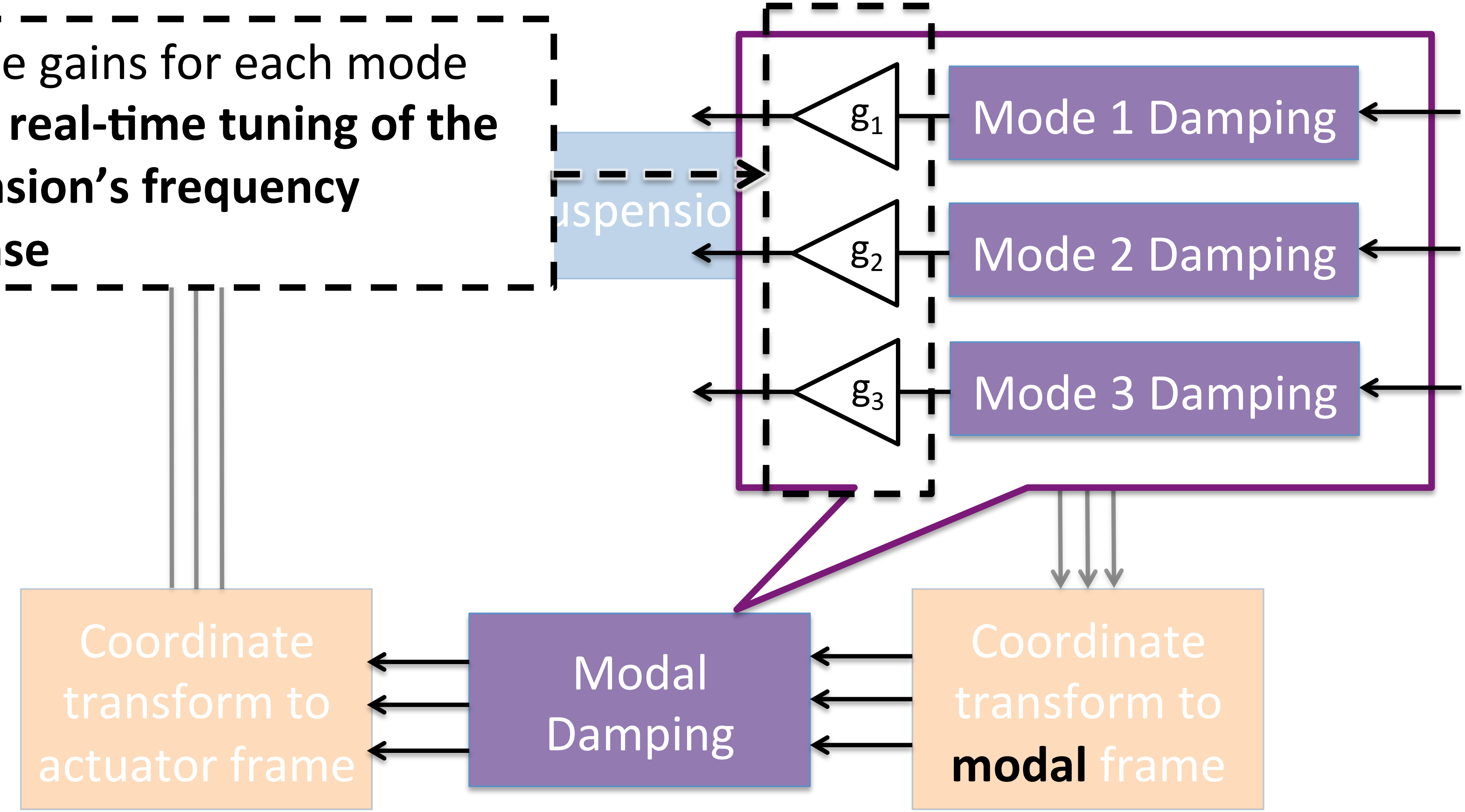


Modal Damping Adjustability



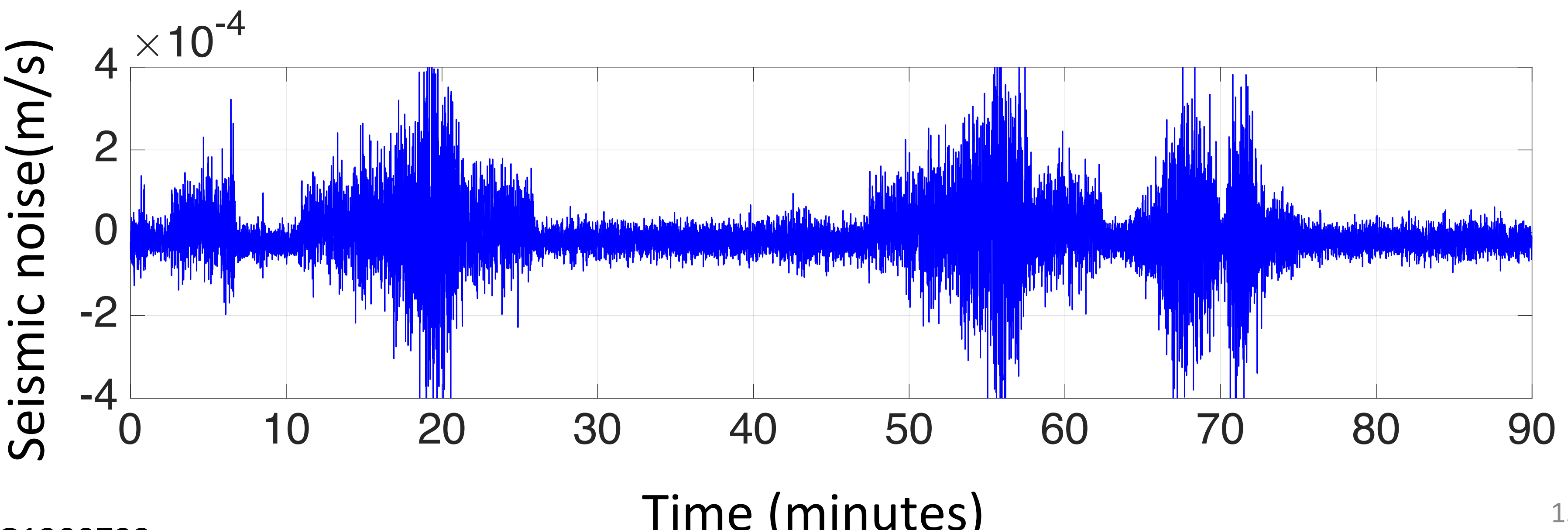
Modal Damping Adjustability

Scalable gains for each mode permit **real-time tuning of the suspension's frequency response**



Adaptive Modal Damping

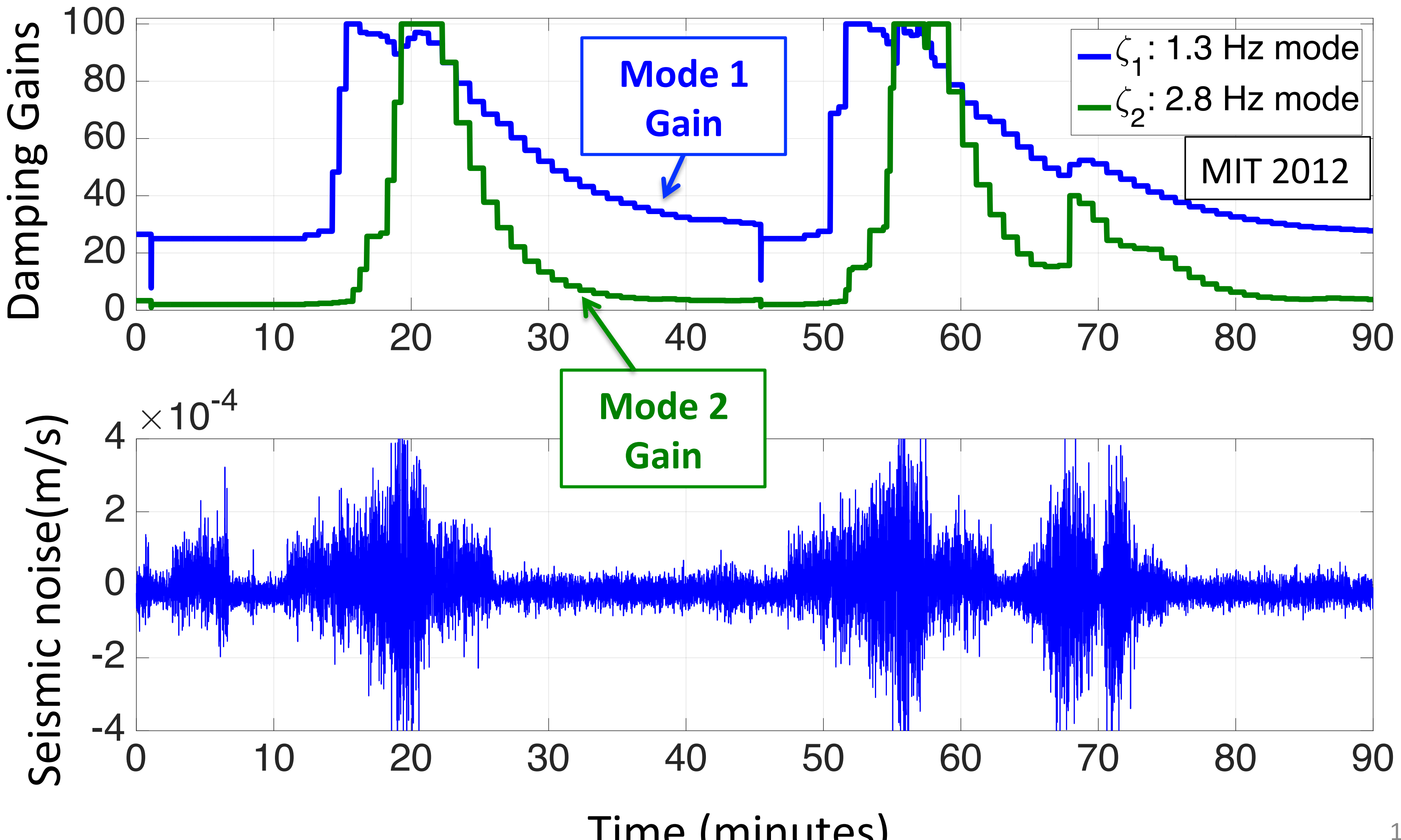
Measurements of adaptive modal damping gains responding to seismic disturbances



Ref: G1200723

Adaptive Modal Damping

Measurements of adaptive modal damping gains responding to seismic disturbances



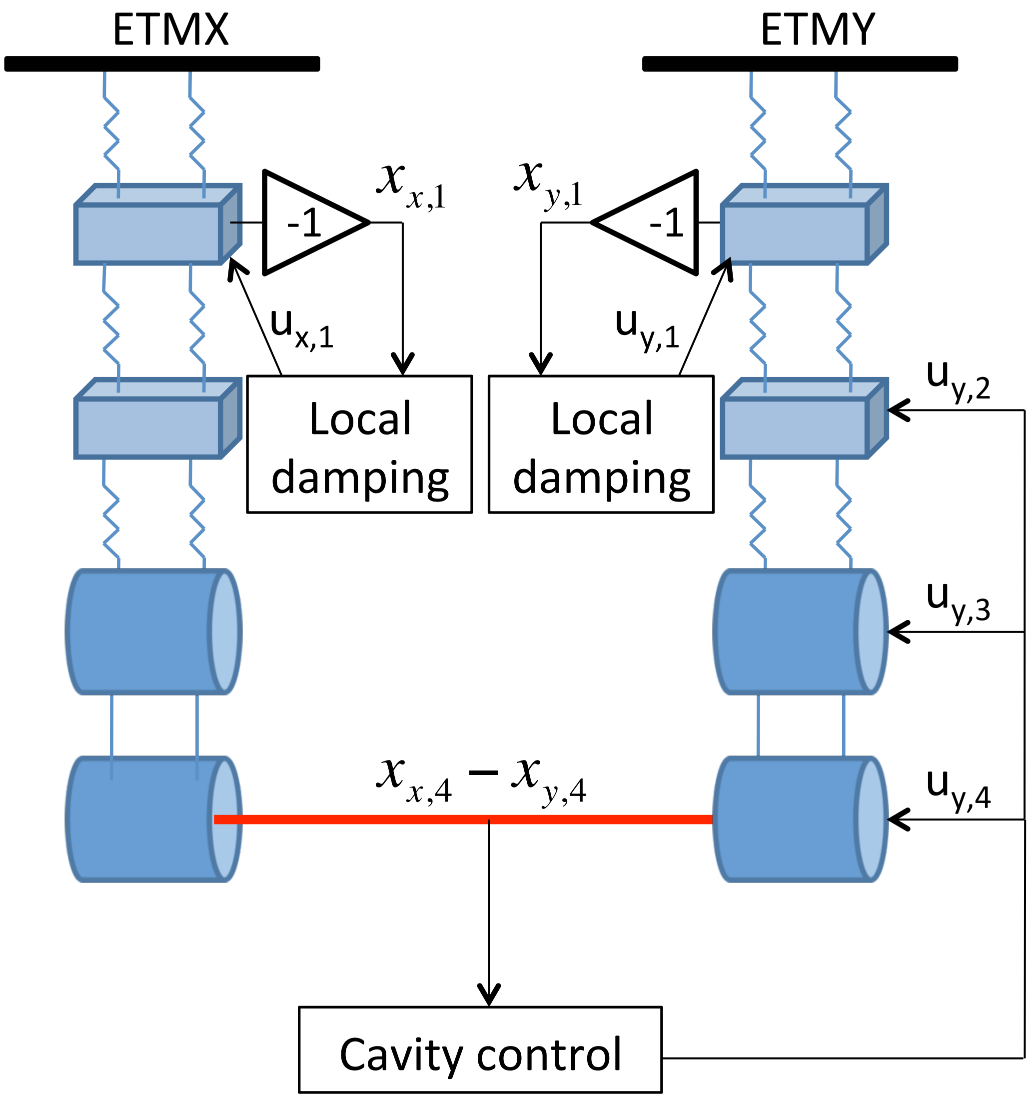
Ref: G1200723

Another top mass damping technique

Global Damping

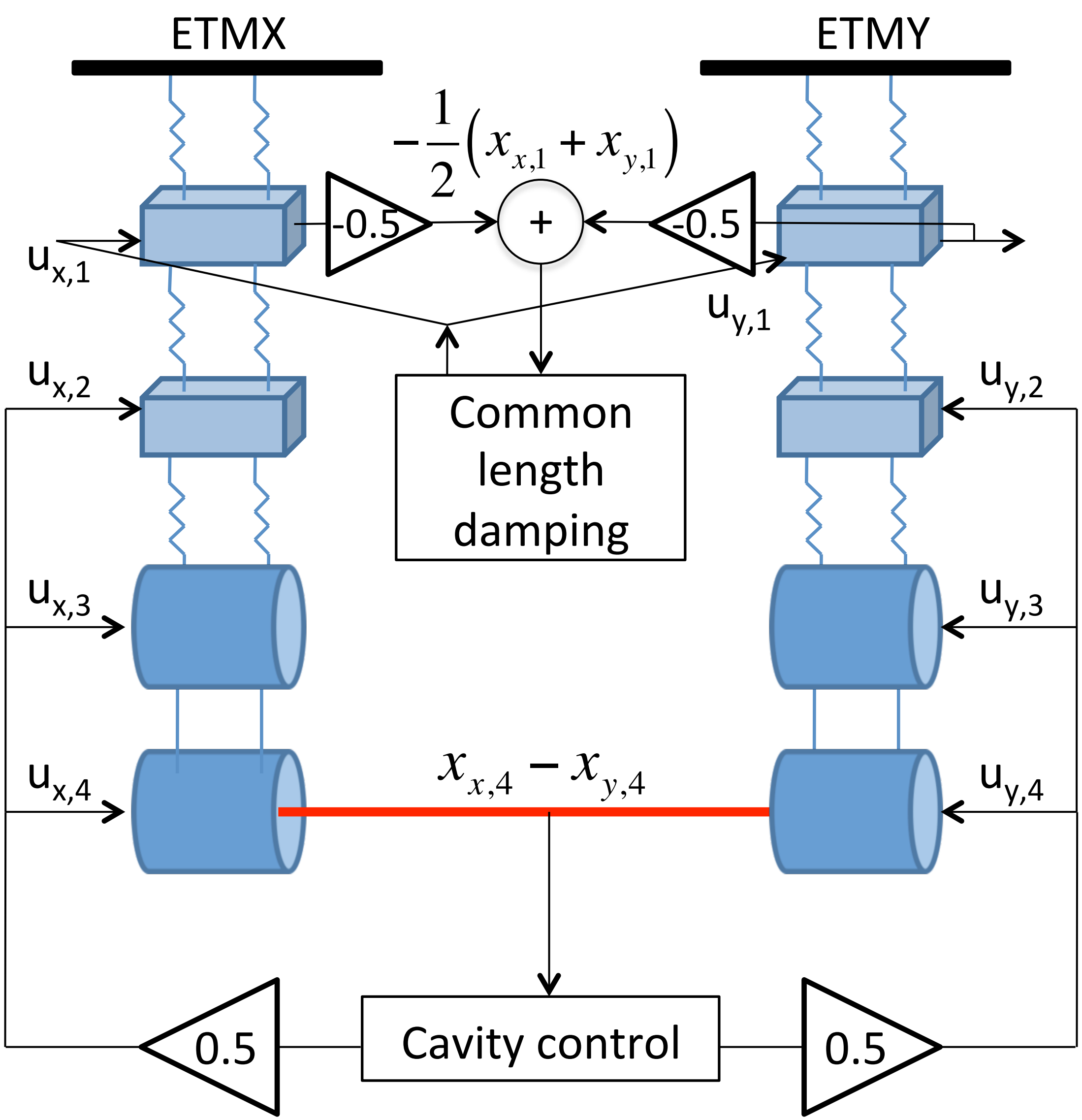
Reference: P1400085 - Noise and Control Decoupling of Advanced LIGO Suspensions

Usual Local Damping



- Each suspension is locally damped from the top mass.
- One suspension receives the cavity length control

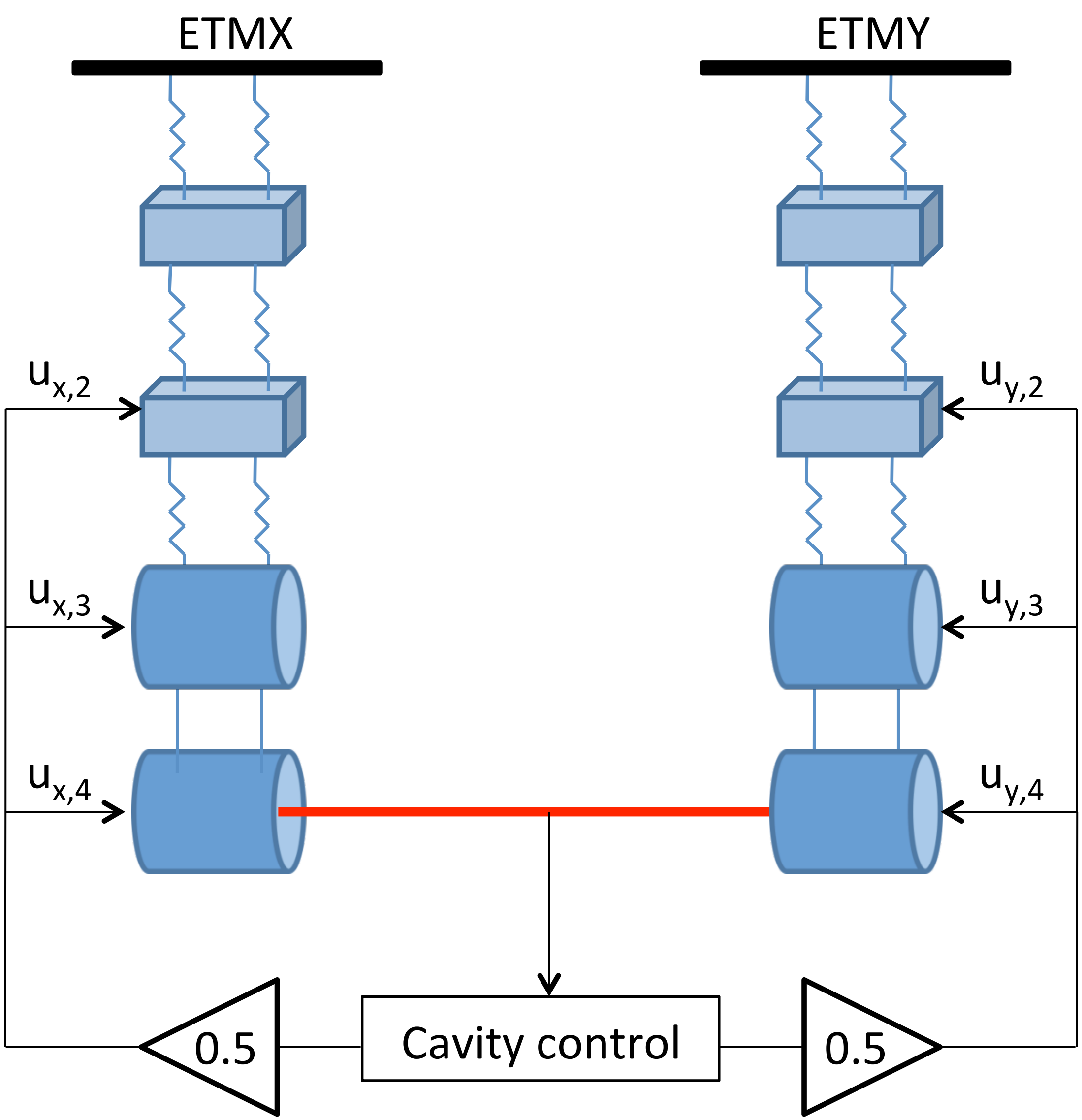
Common Arm Length Damping



- Sensors from both suspensions summed together to create 1 common signal
- Both suspensions receive same damping force in the same direction
- Cavity control split equally between suspensions
- If both pendulums are the same, the noise stays in common mode, i.e. no damping noise to cavity!

Ref: G1200774

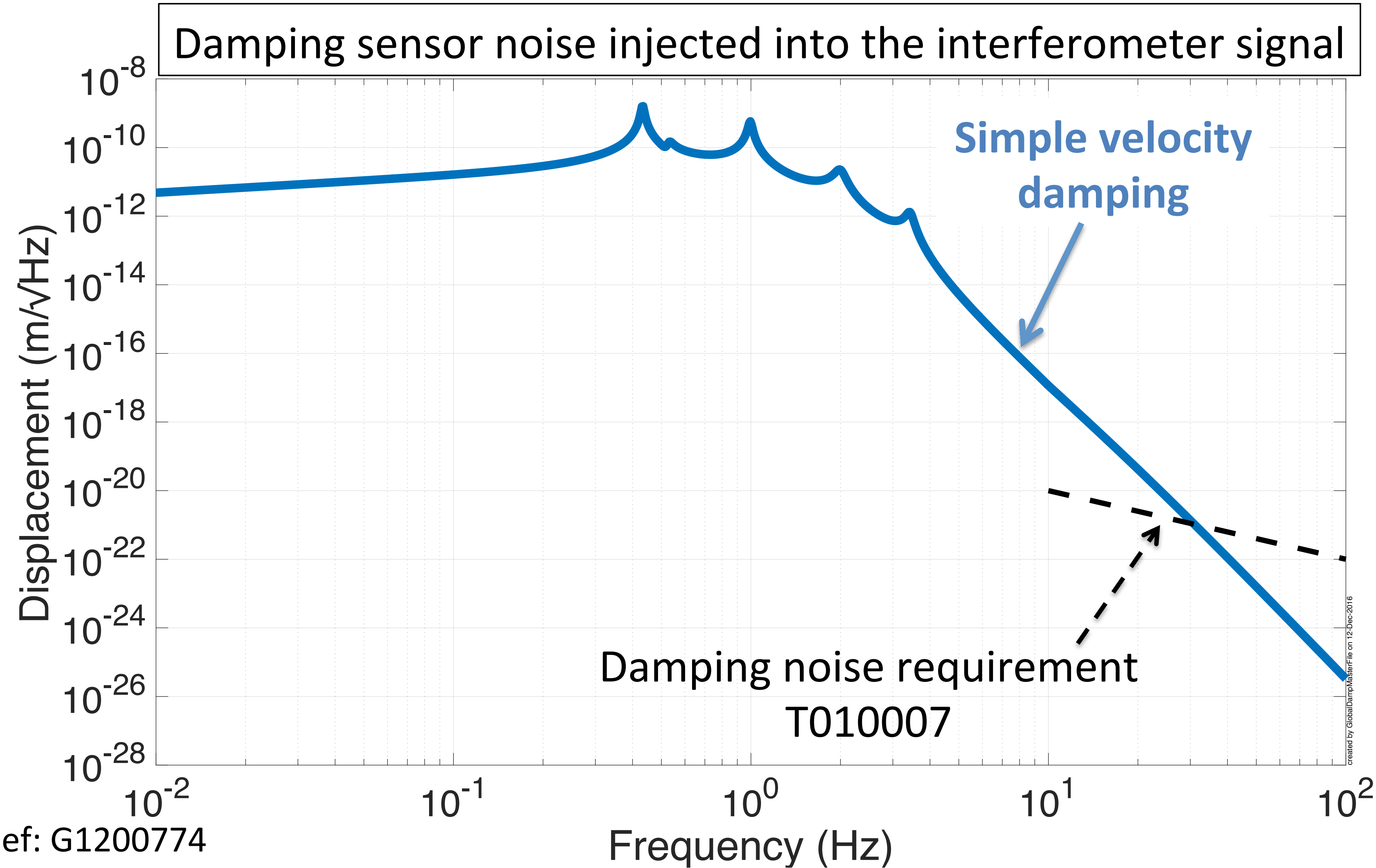
Differential Arm Length Damping



- No OSEMs are used for differential length damping
- Damping is achieved with the cavity length control, by designing it in a particular way

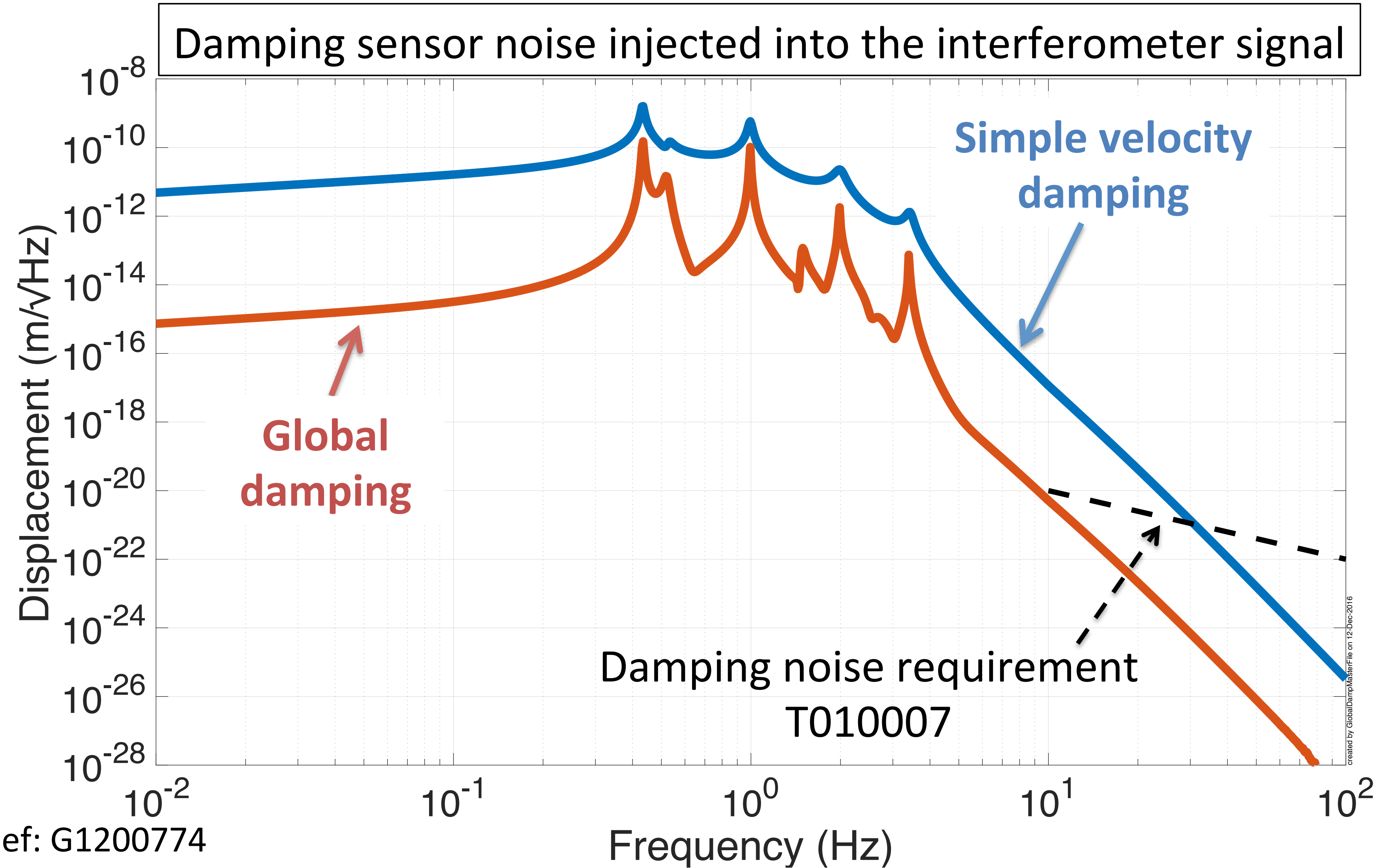
Ref: G1200774

Simulated Global Damping Noise



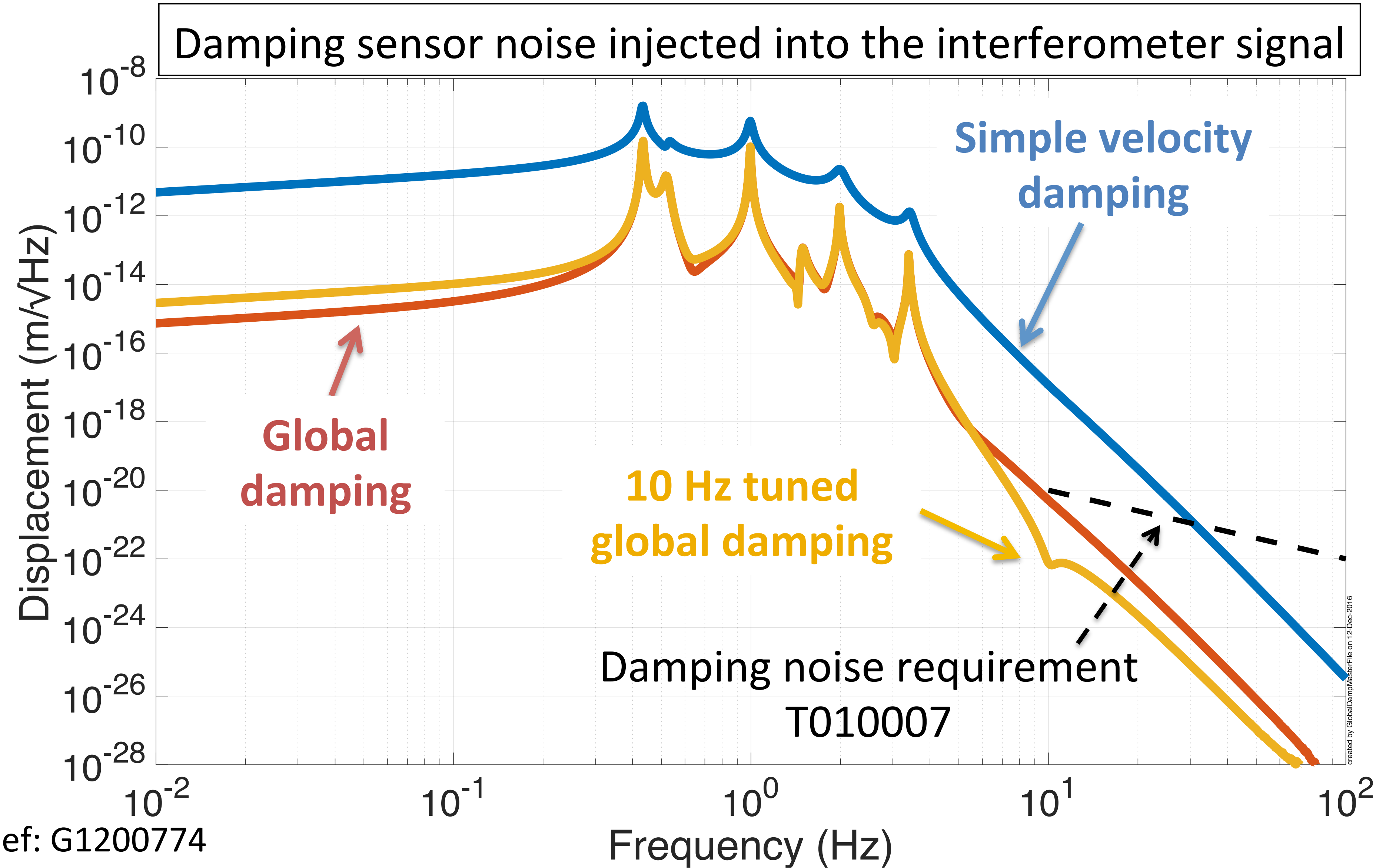
Ref: G1200774

Simulated Global Damping Noise



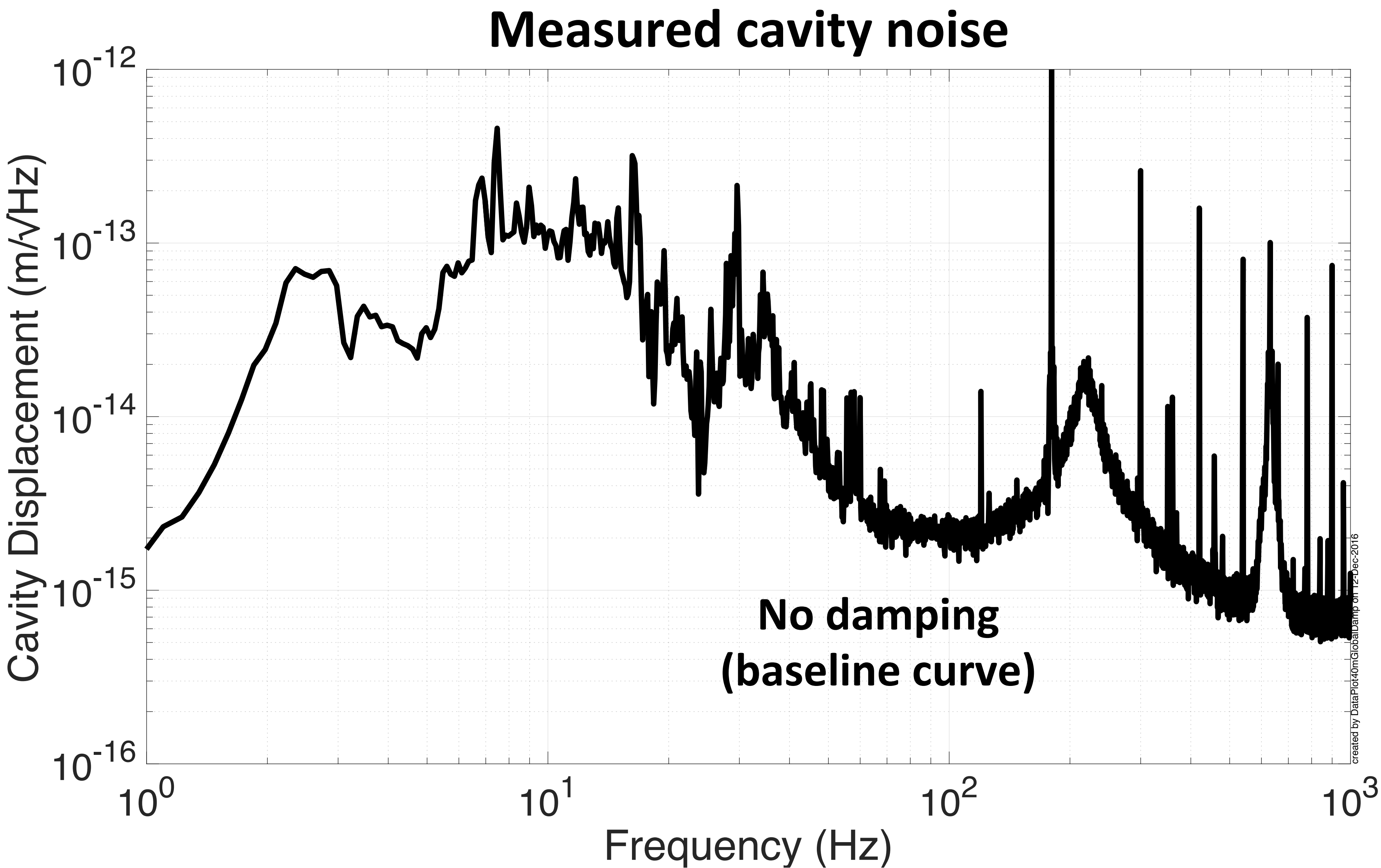
Ref: G1200774

Simulated Global Damping Noise

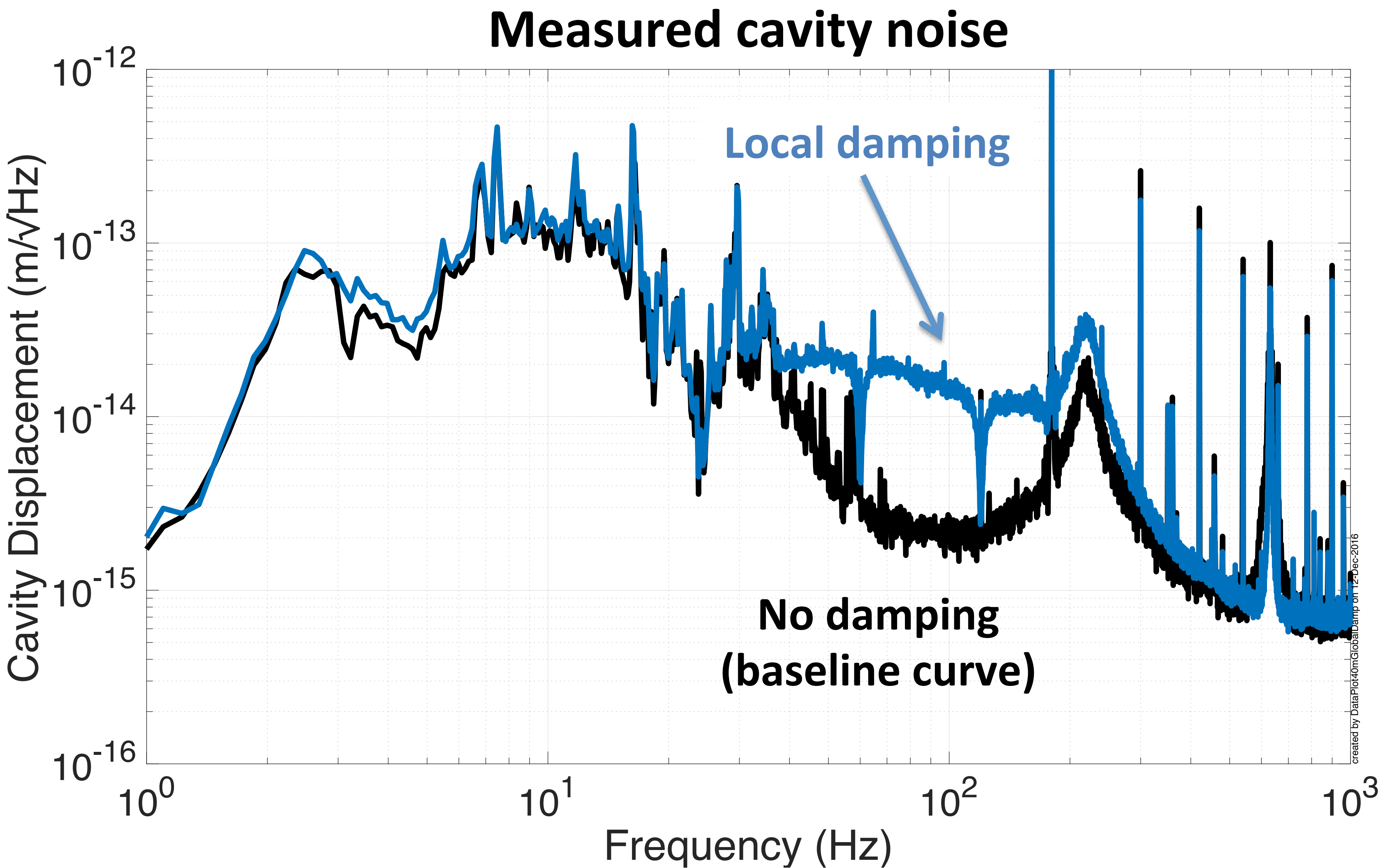


Ref: G1200774

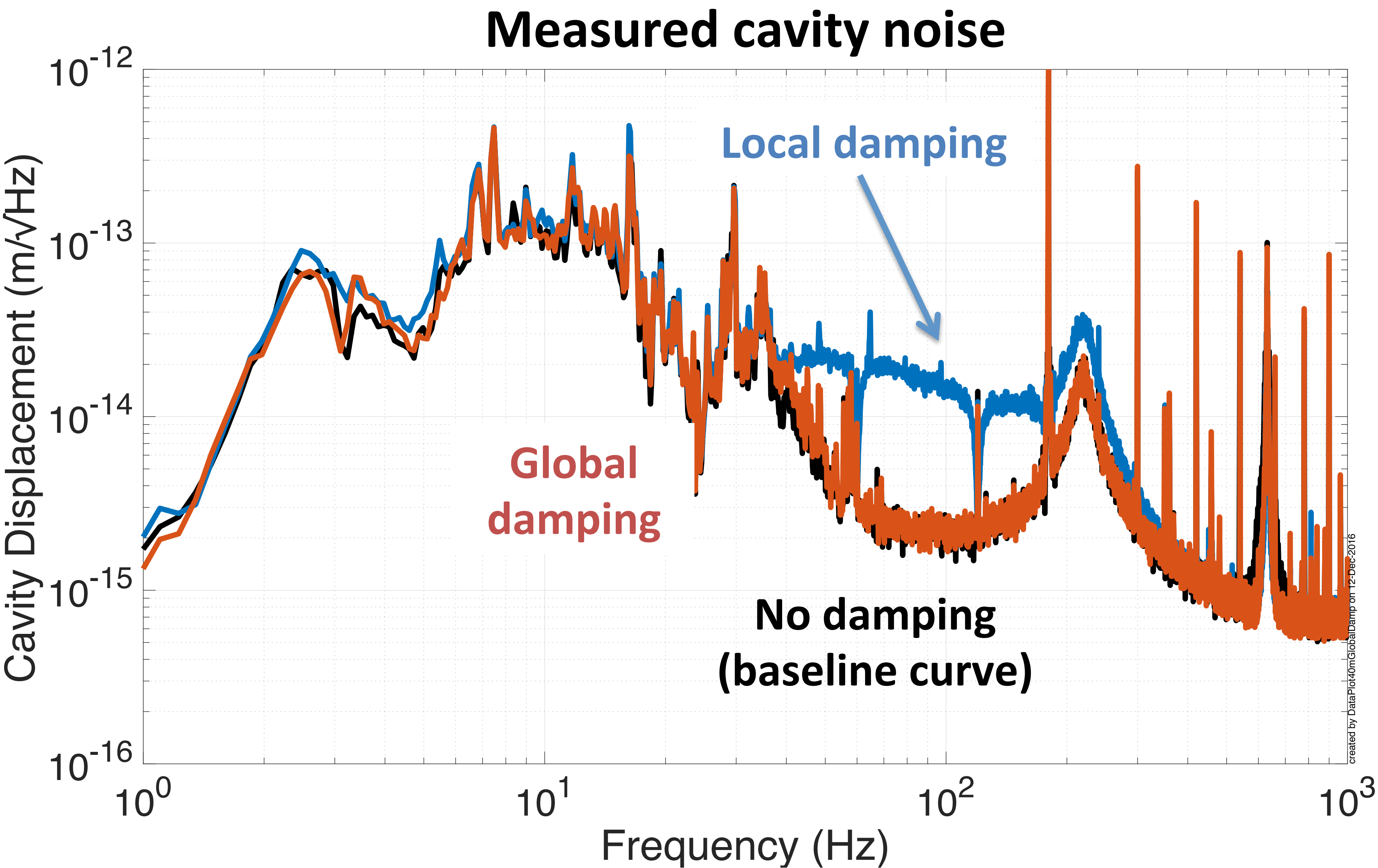
40 m Lab Noise Measurements



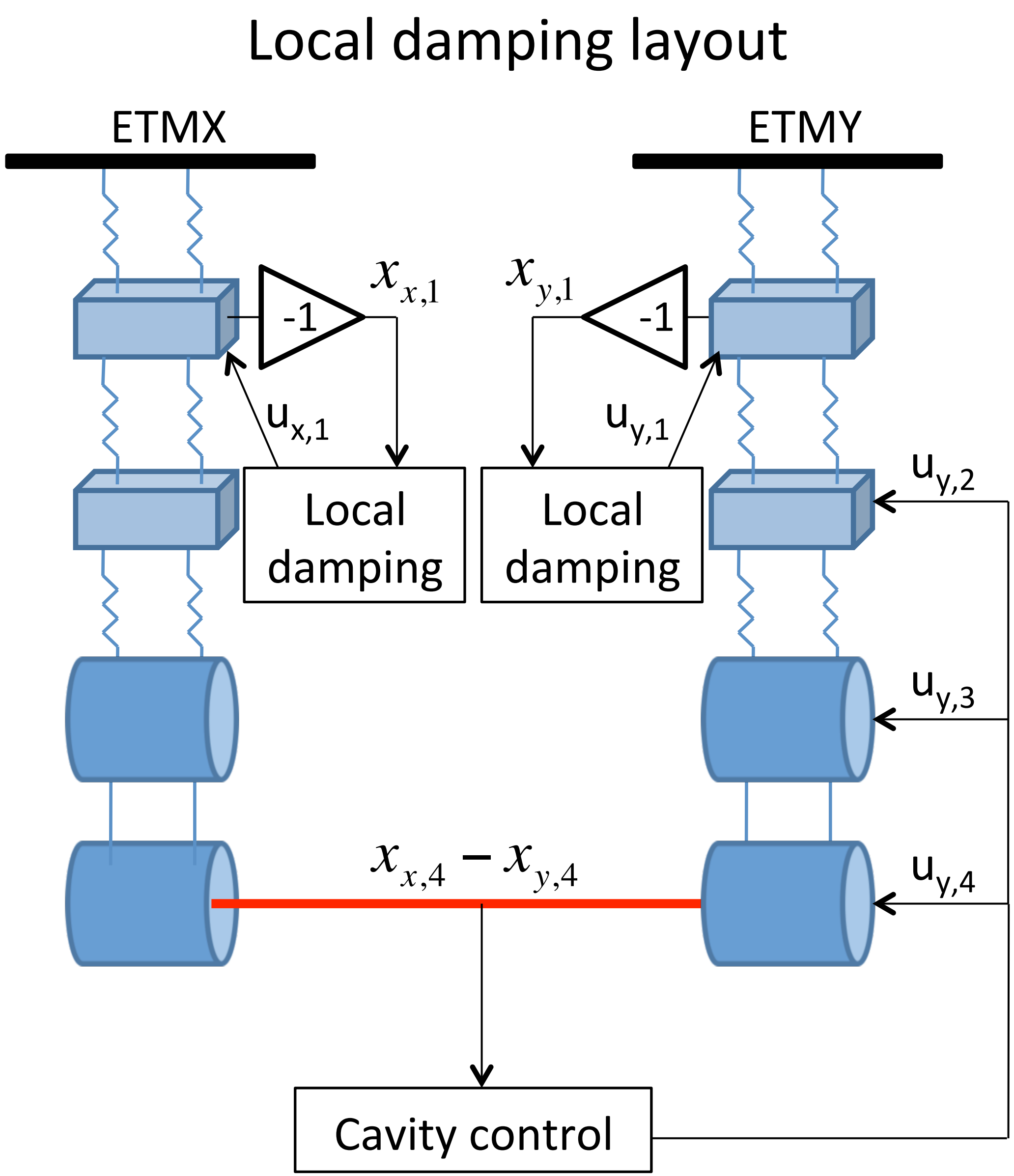
40 m Lab Noise Measurements

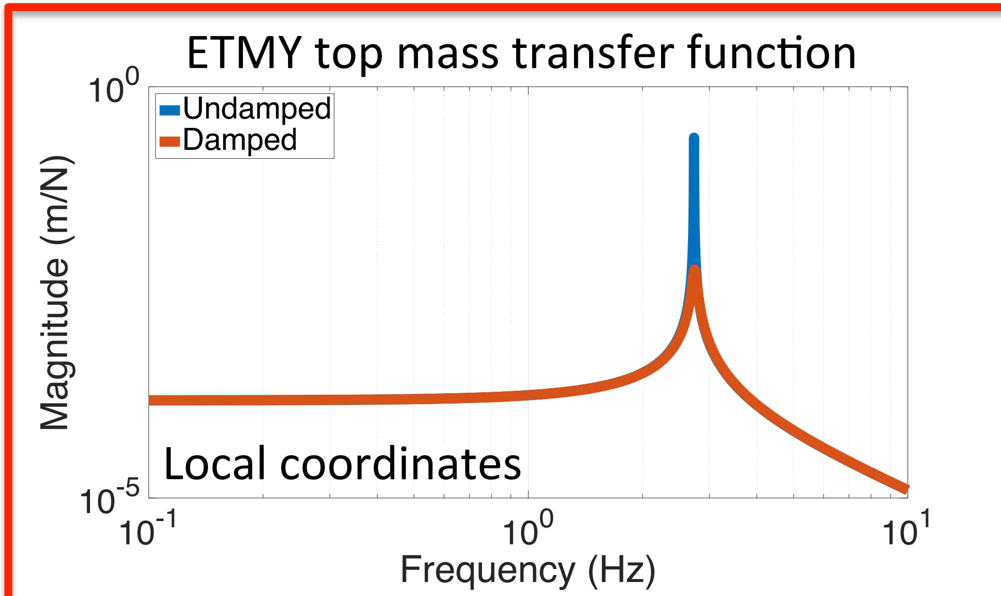


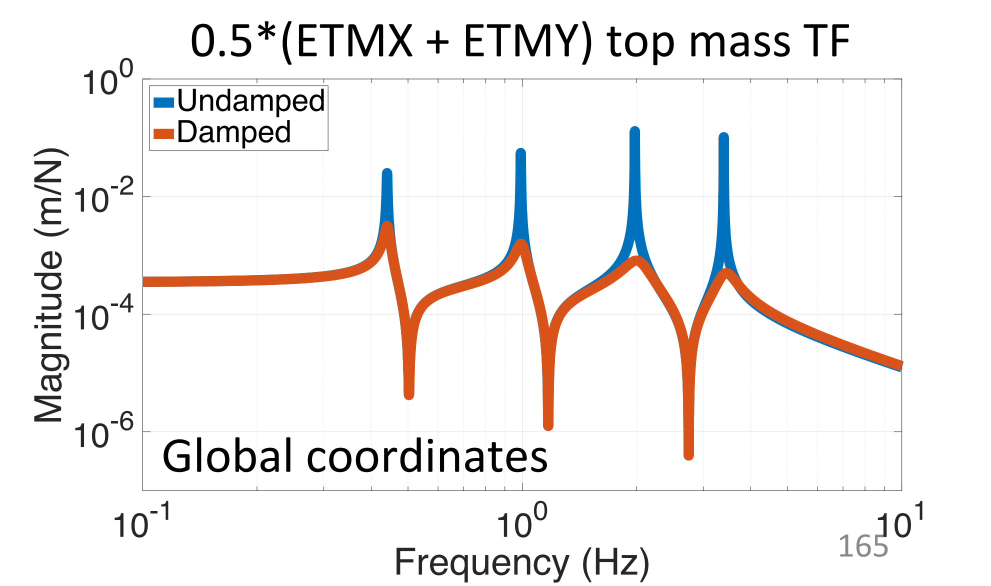
40 m Lab Noise Measurements



Decoupled Damping and Cavity Control

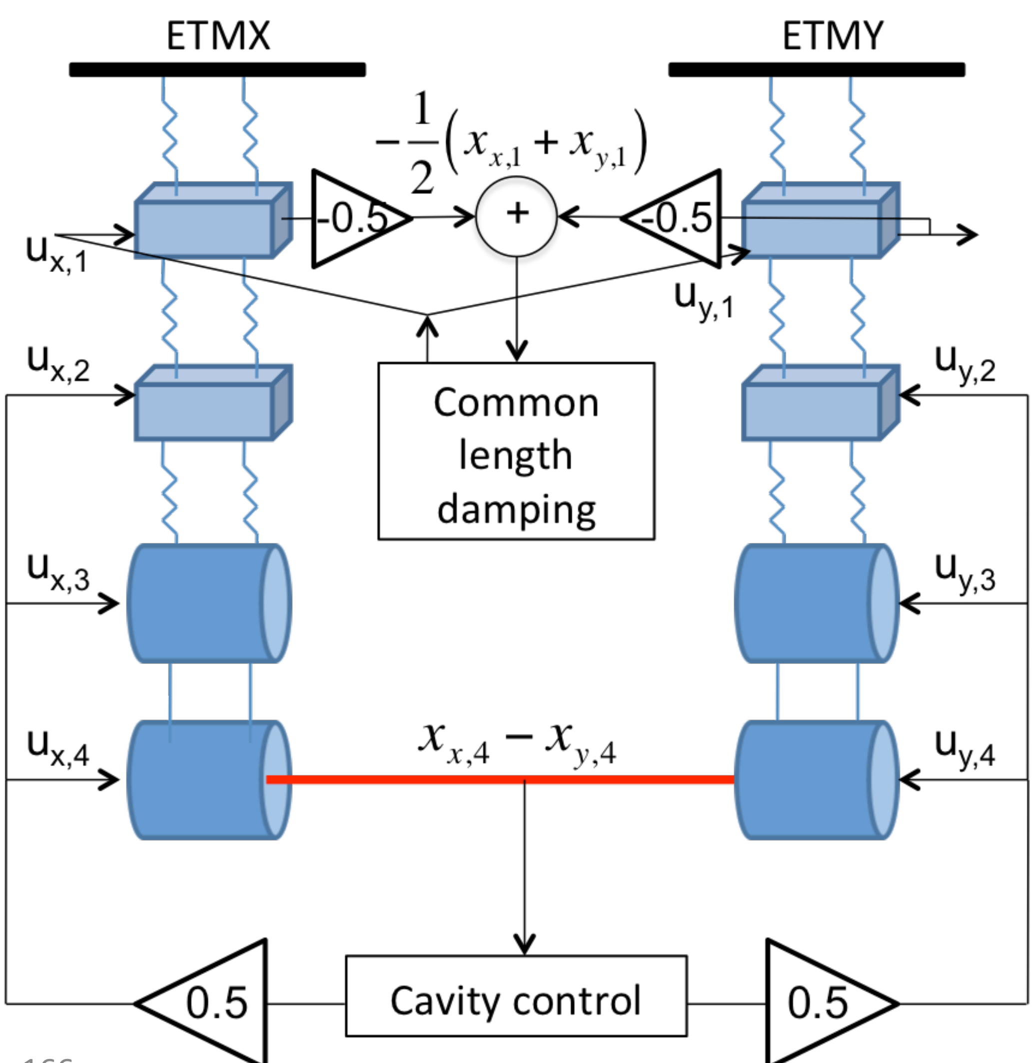


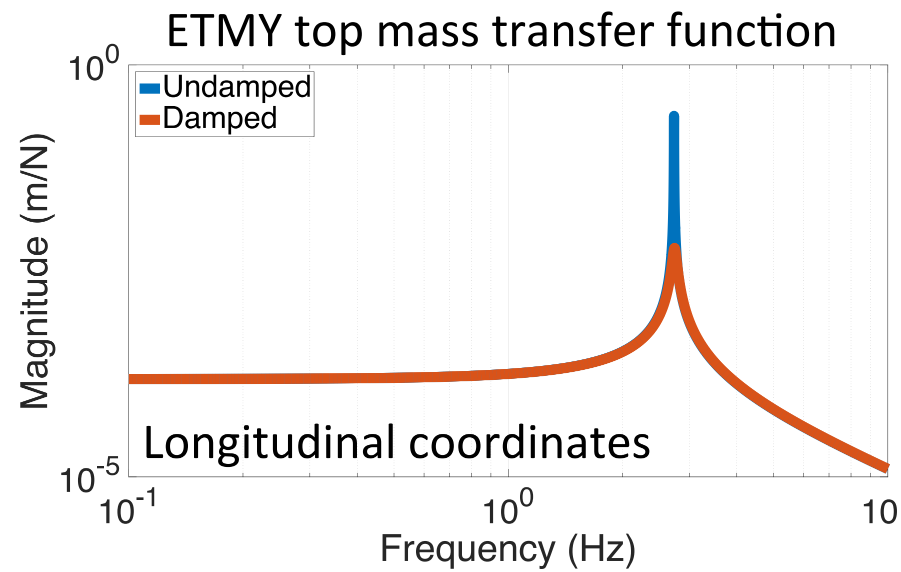


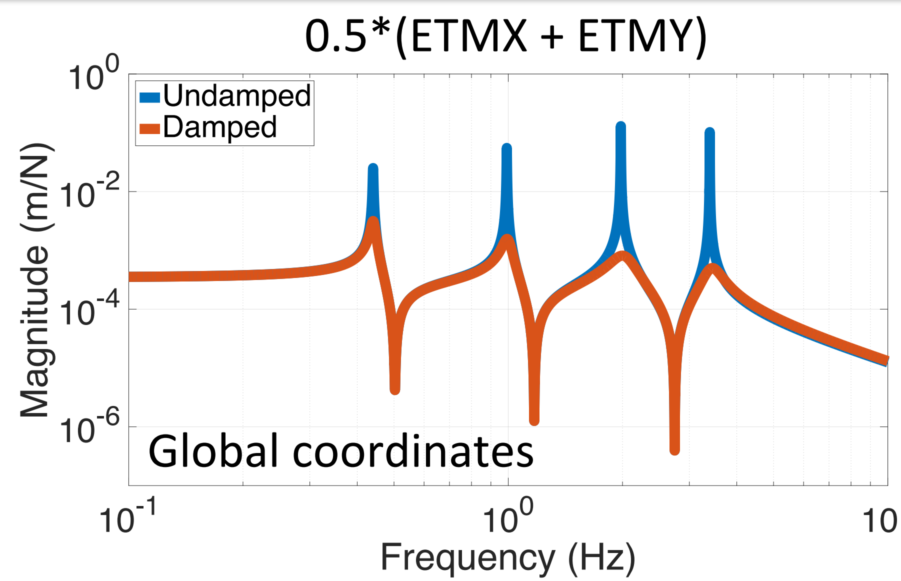


Decoupled Damping and Cavity Control

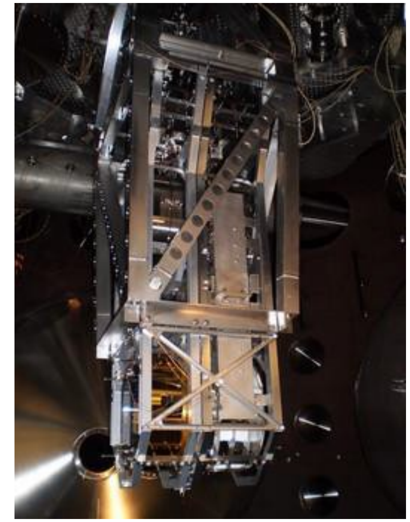
Global damping layout



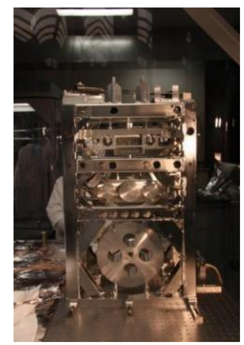


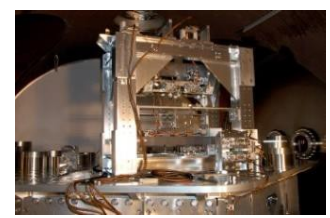


Suspension Inventory



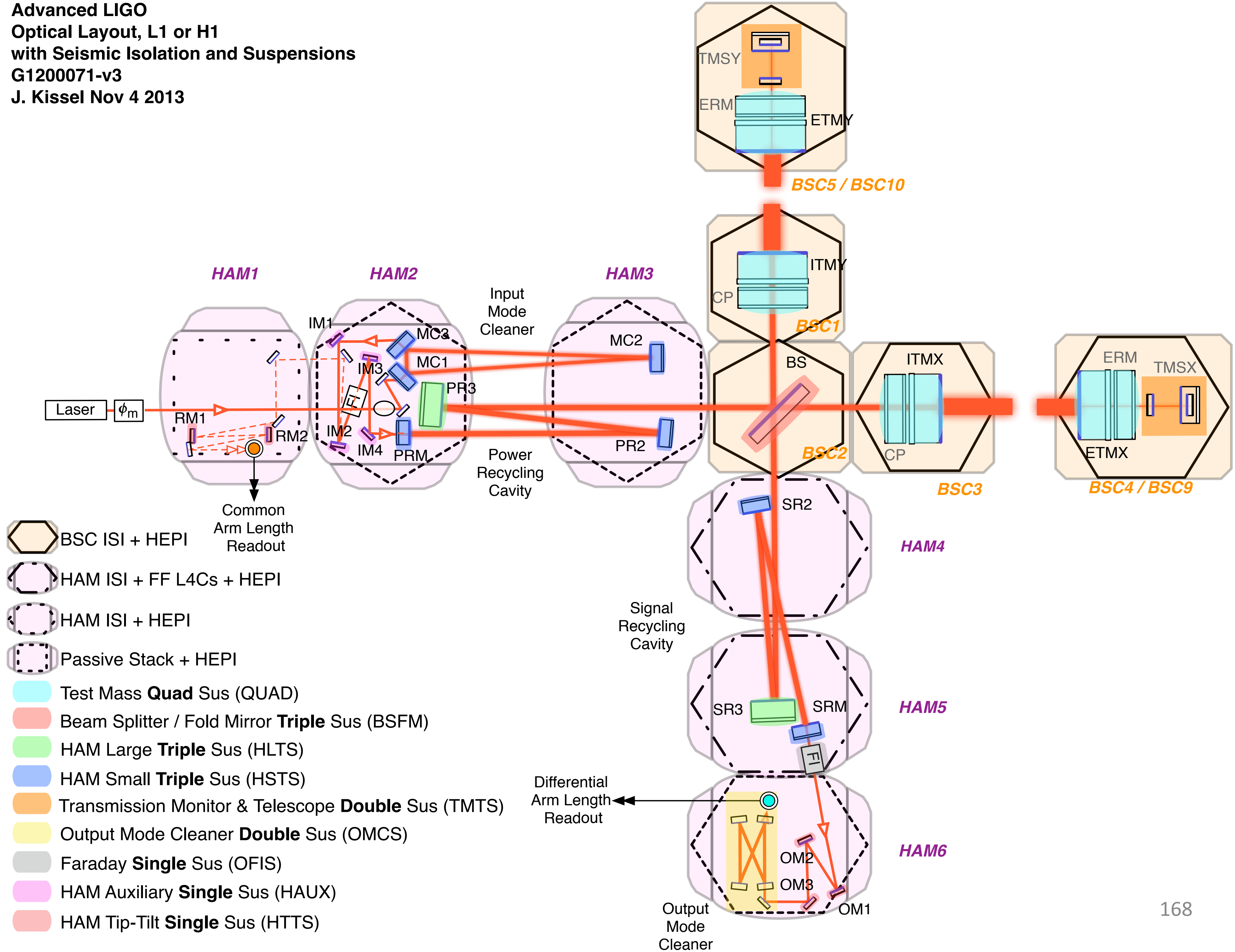
- Two Input Test Mass (ITM) suspensions
- Two End Test Mass (ETM) suspensions
- One Beamsplitter (BS) suspension
- Seven HAM Small Triple Suspensions (HSTS)
- Two HAM Large Triple Suspensions (HLTS)
- One, Output Mode Cleaner (OMC) Suspension
- SUS electronics racks
- Spare suspension components/parts
- Spare SUS electronics





Reference: Giles Hammond, LITRA Aug 2016

Advanced LIGO
Optical Layout, L1 or H1
with Seismic Isolation and Suspensions
G1200071-v3
J. Kissel Nov 4 2013

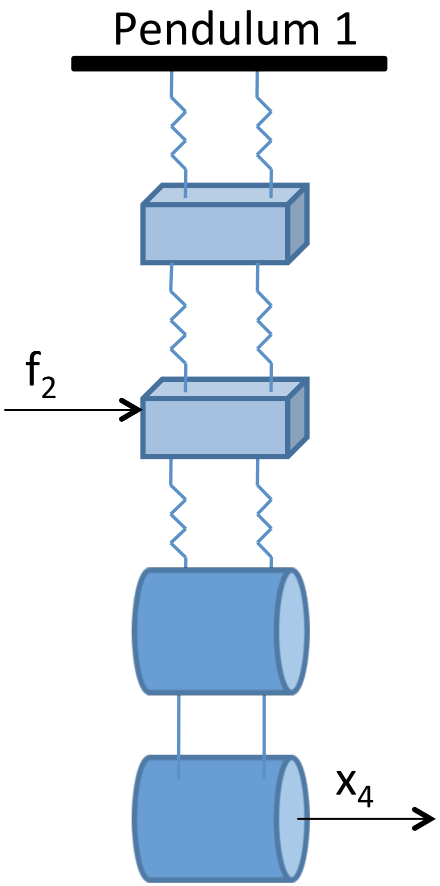


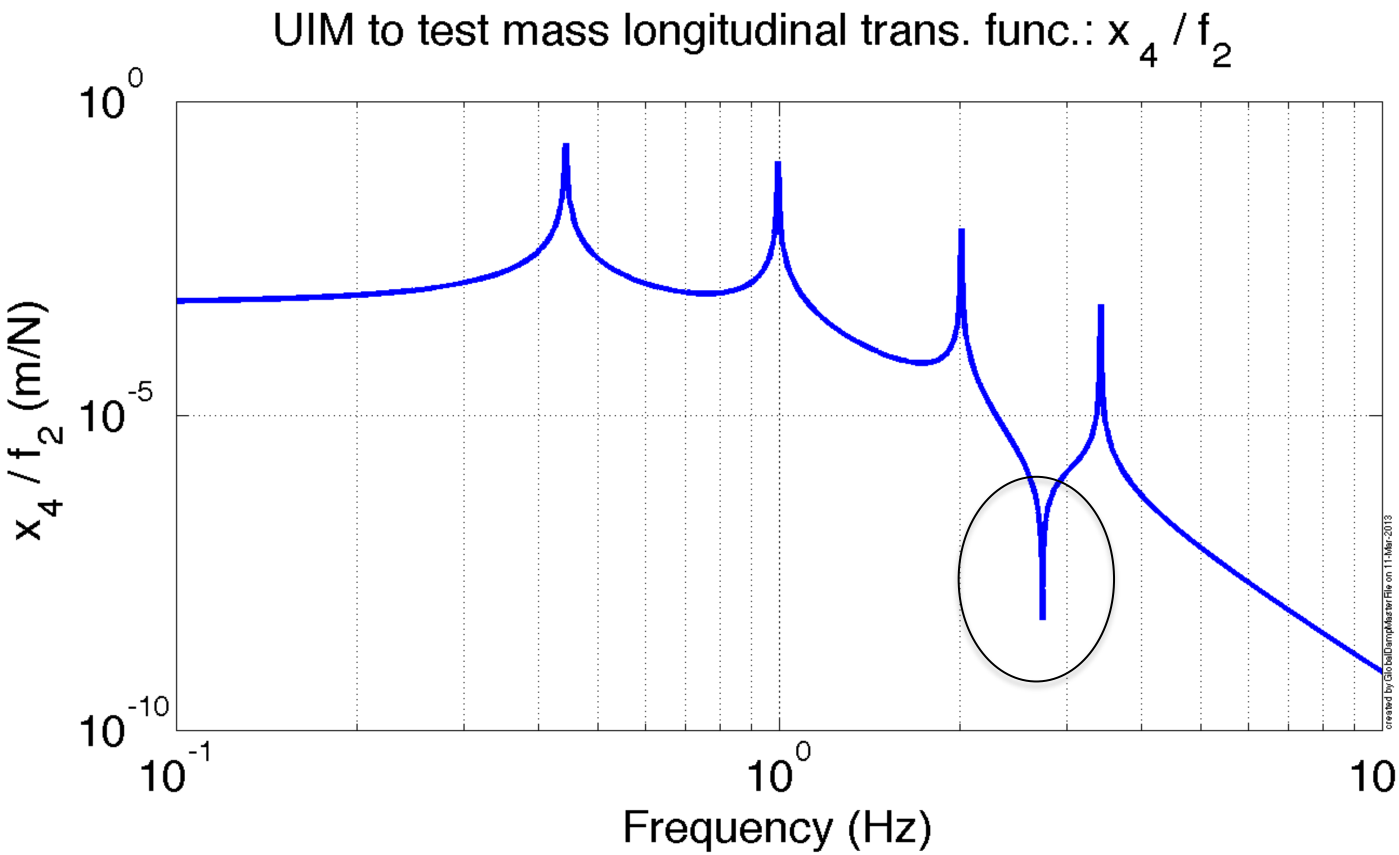
Global Damping Backup Slides

Measurements from LHO

Slides from G1200774

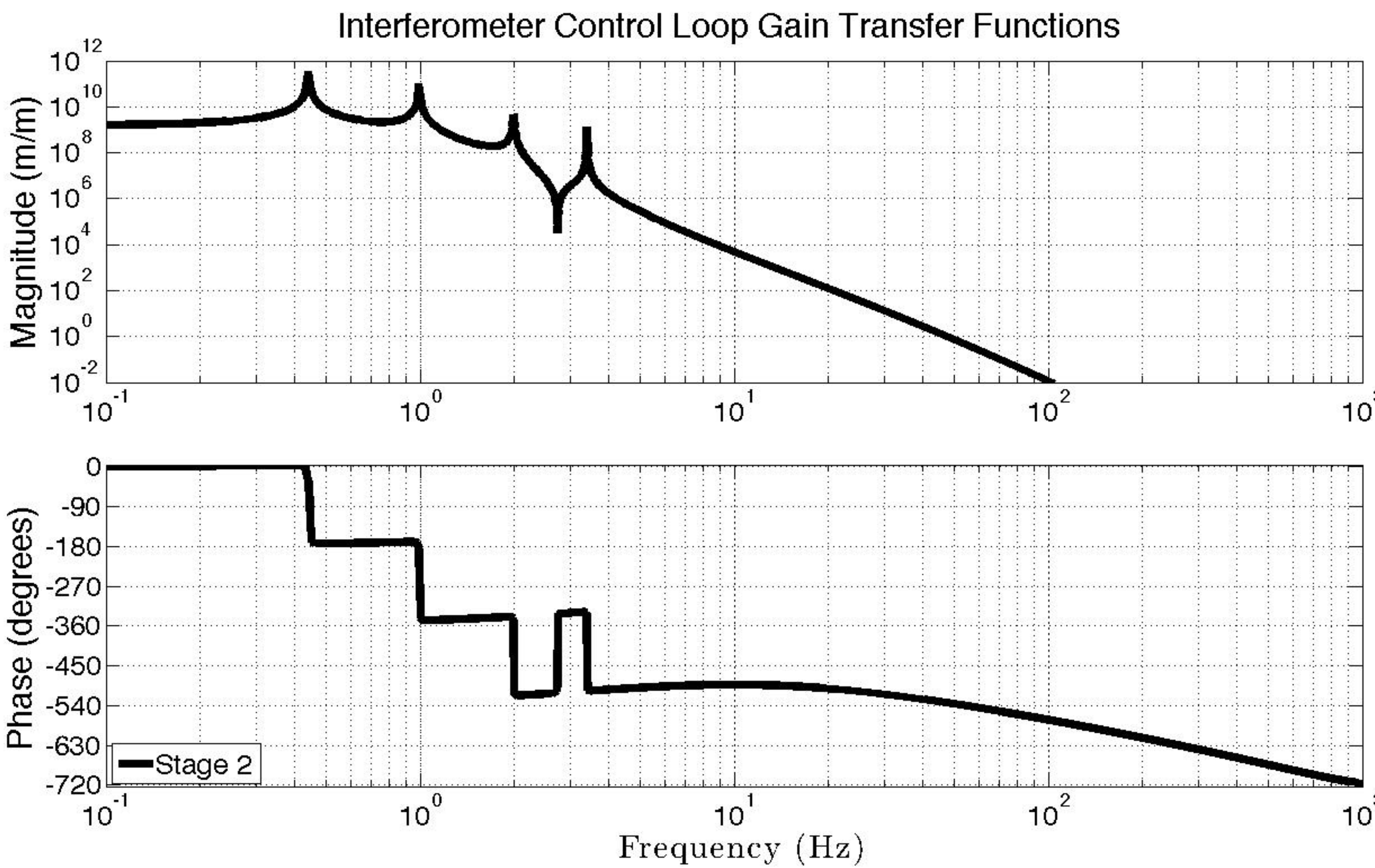
Differential Arm Length Damping



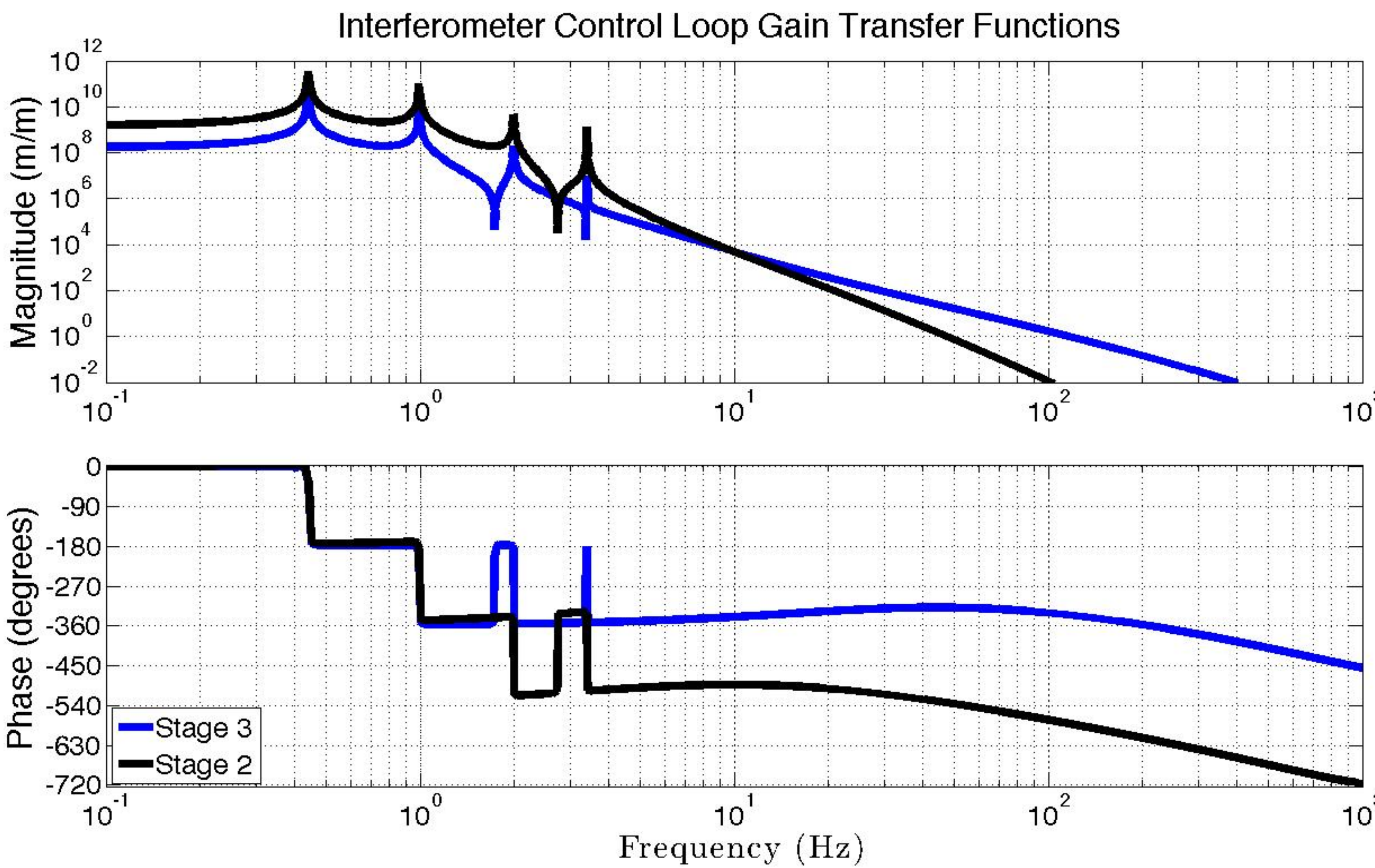


- The new top mass modes come from the zeros of the TF between the highest stage with large cavity UGF and the test mass. See more detailed discussion in the 'Supporting Math' section.
- This result can be generalized to the zeros in the cavity loop gain transfer functions (based on observations, no hard math yet).

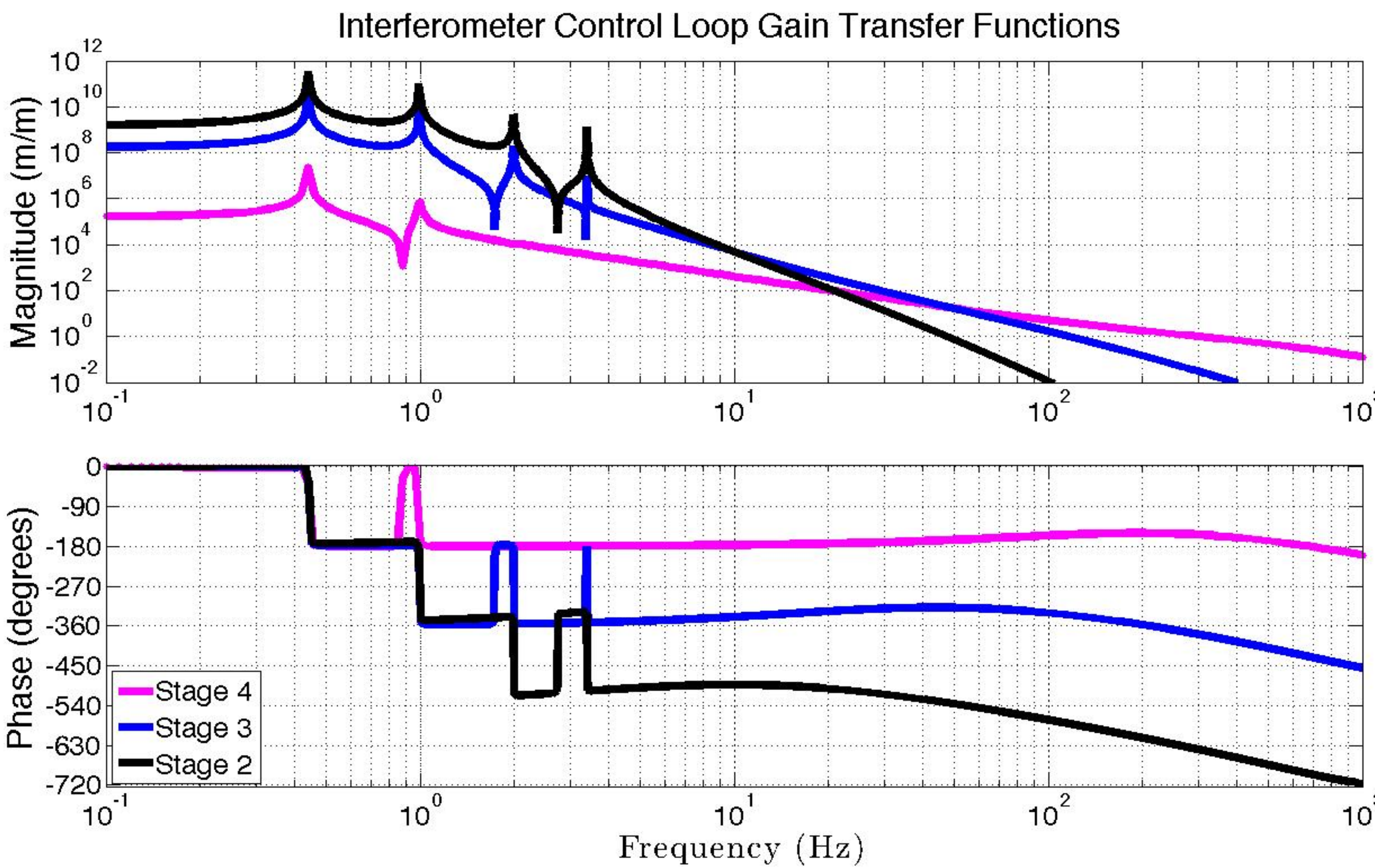
Differential Arm Length Damping



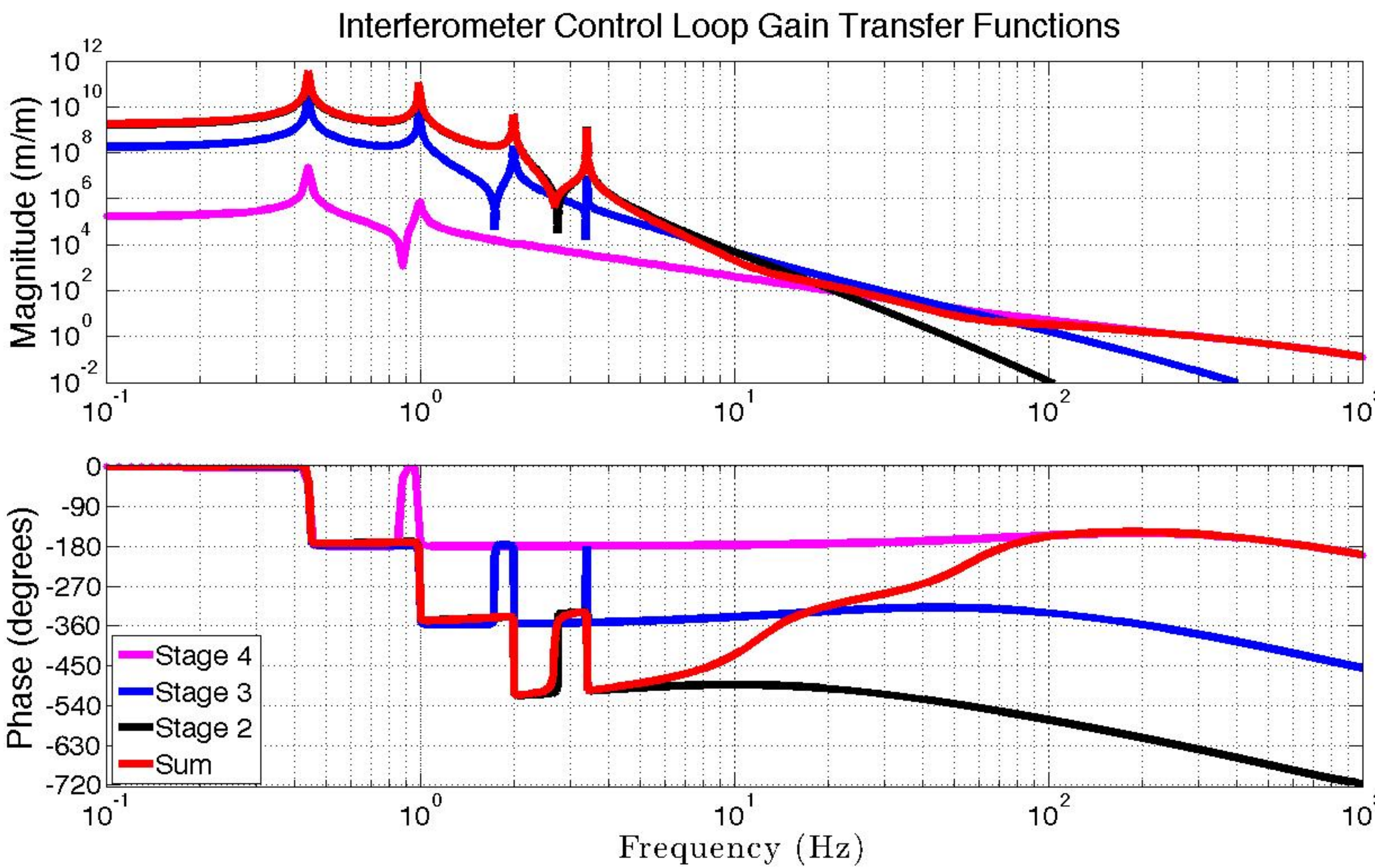
Differential Arm Length Damping



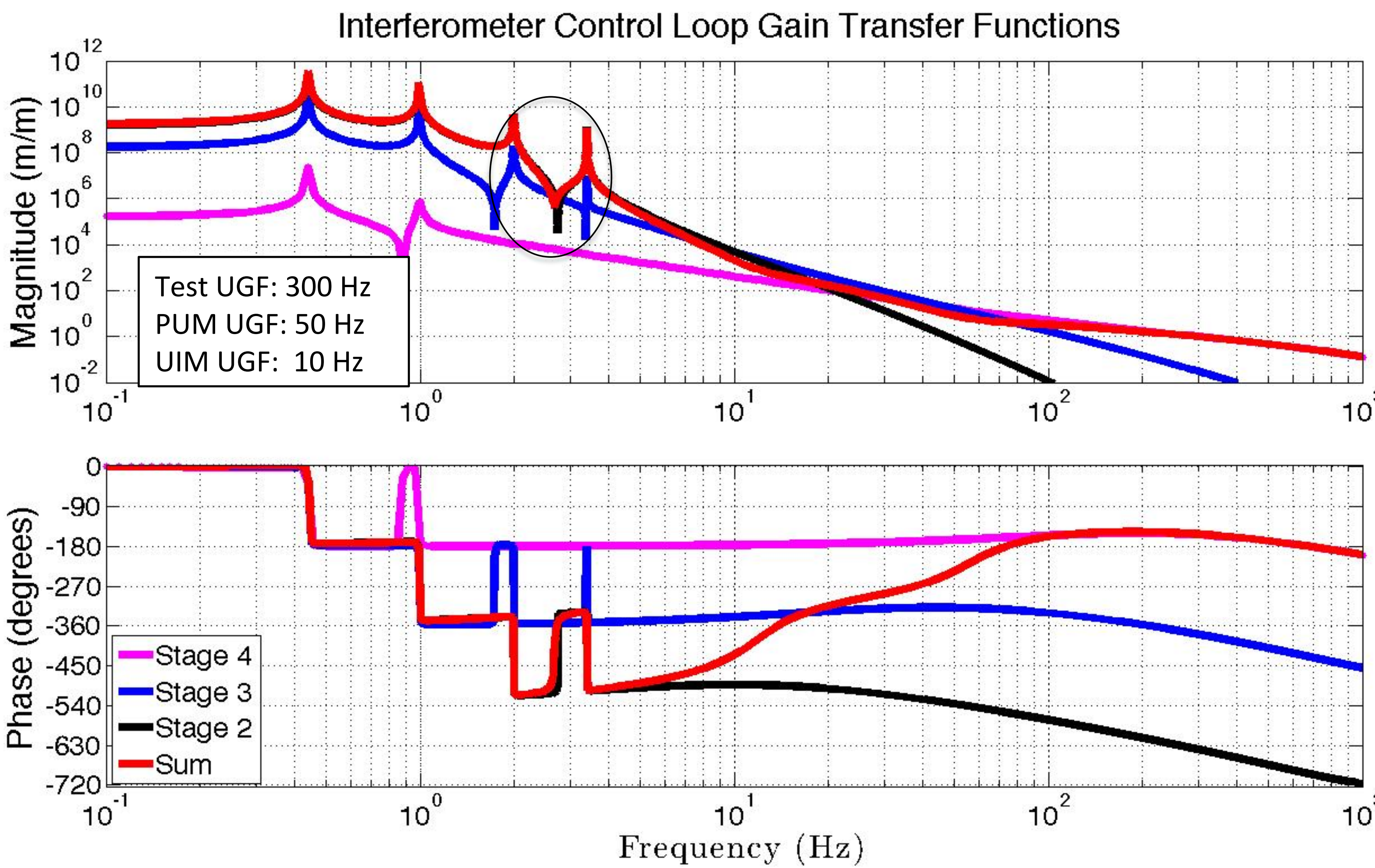
Differential Arm Length Damping



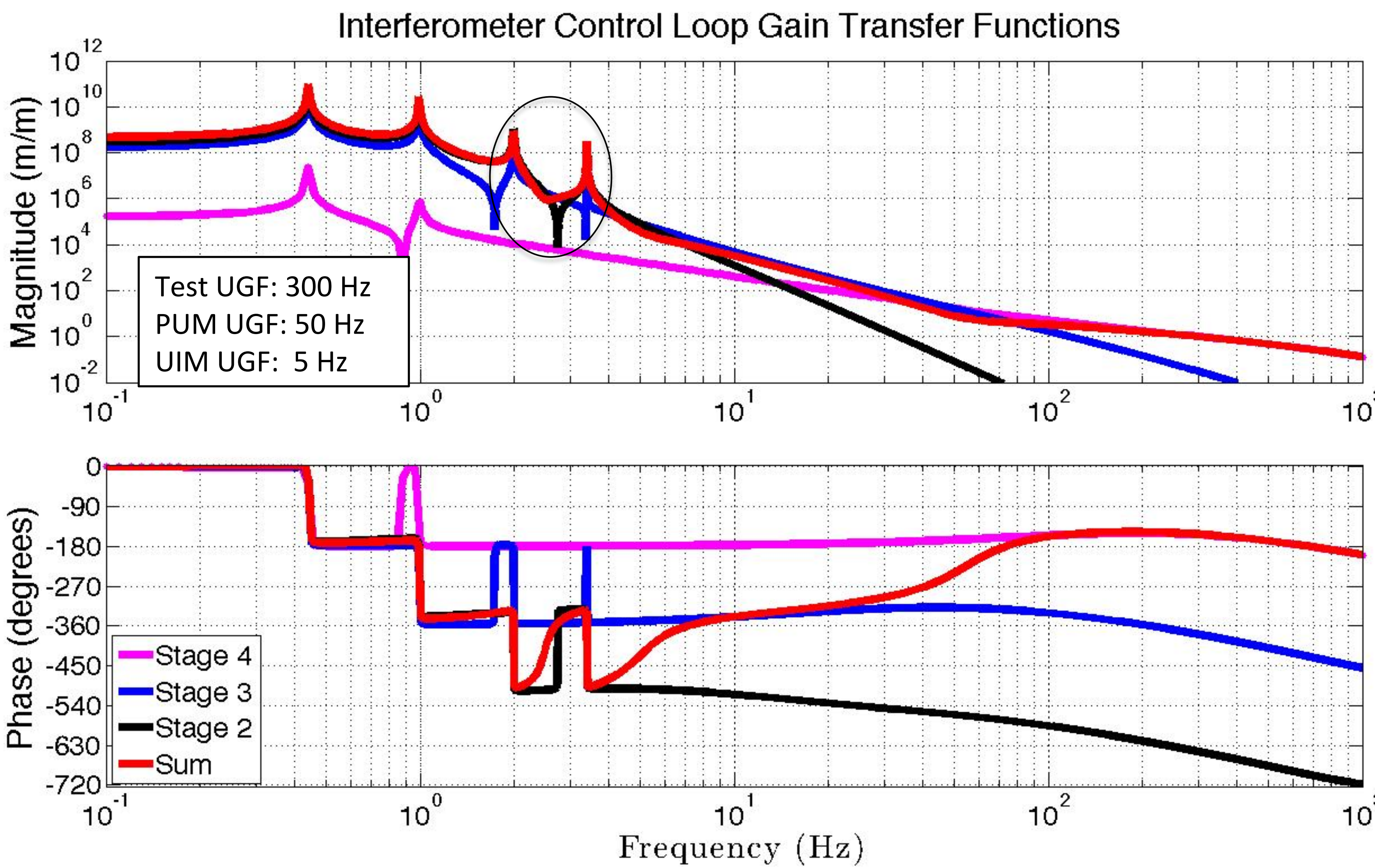
Differential Arm Length Damping



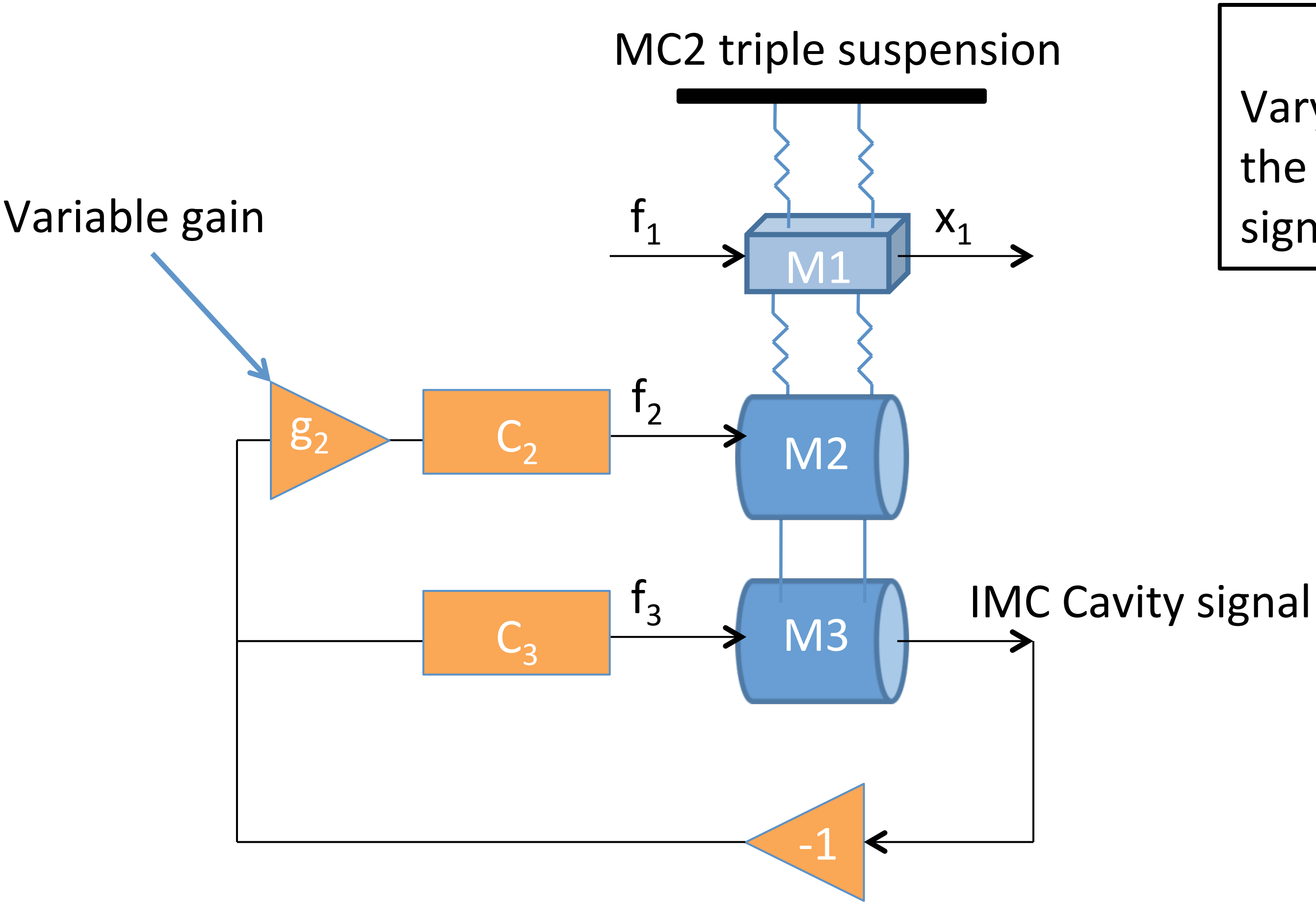
Differential Arm Length Damping



Differential Arm Length Damping



LHO Damping Measurements Setup

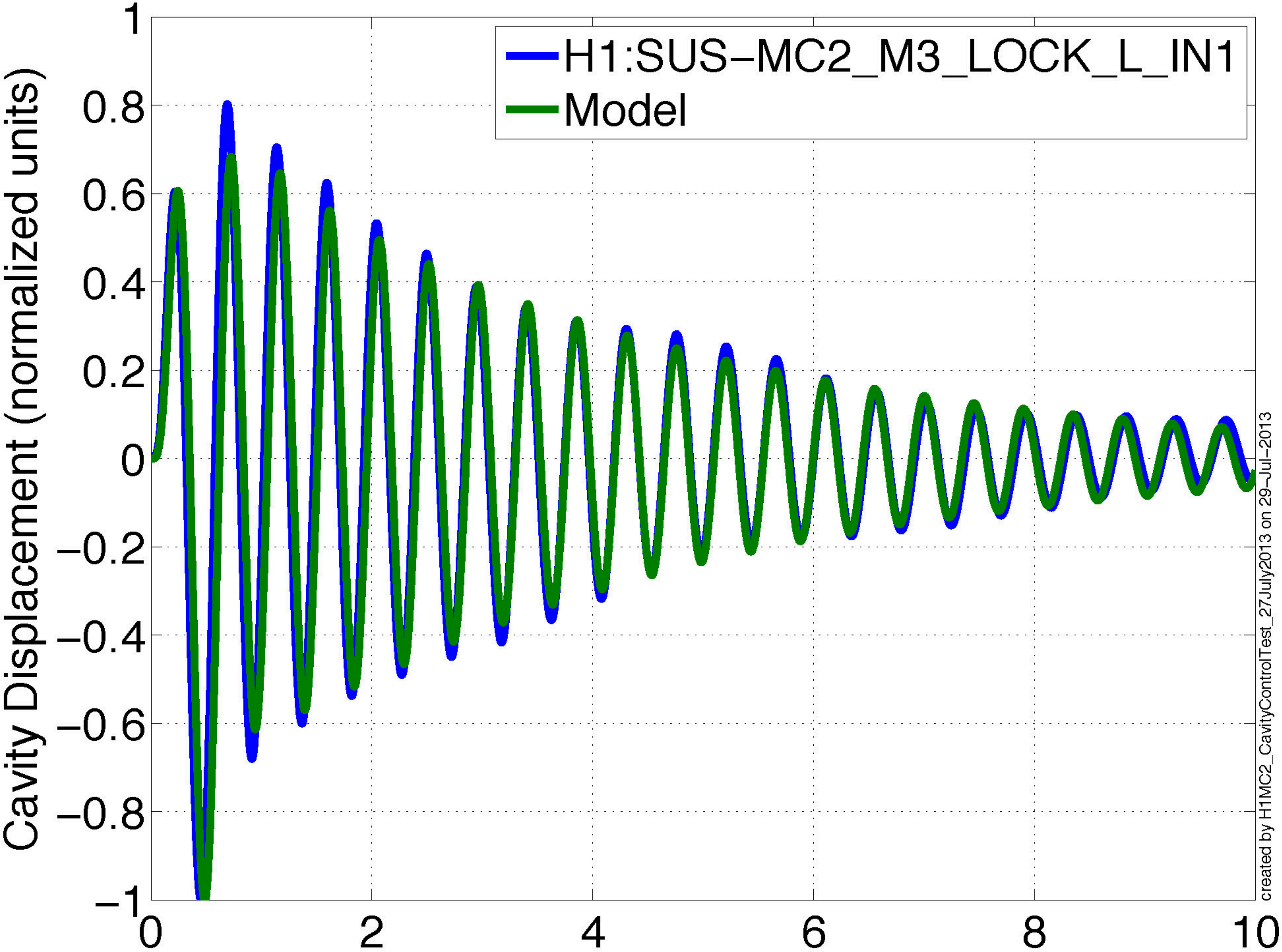


Test procedure
Vary g_2 and observe the changes in the responses of x_1 and the cavity signal to f_1.

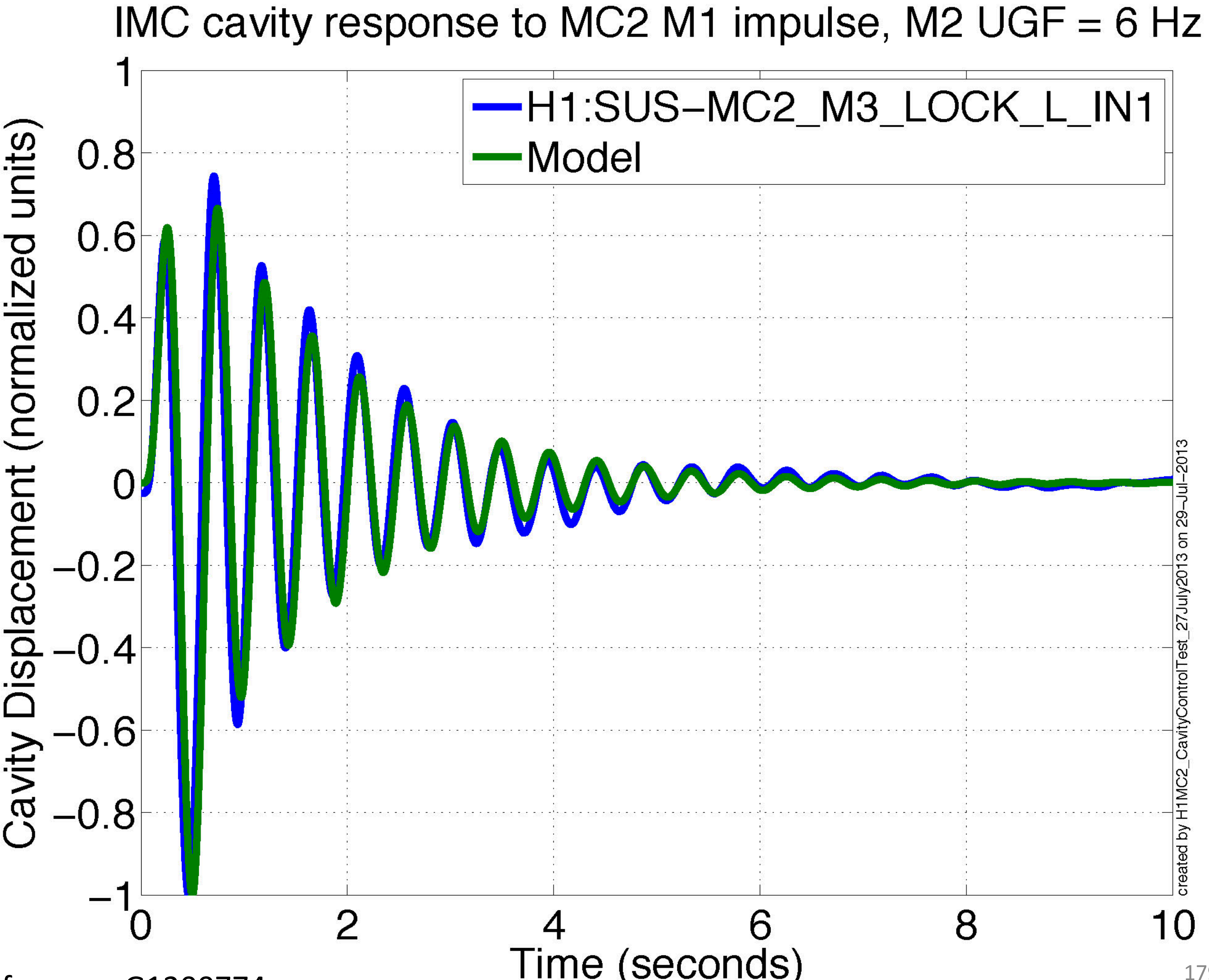
Terminology Key
IMC: input mode cleaner, the cavity that makes the laser beam nice and round
M1: top mass
M2: middle mass
M3: bottom mass
MC2: Mode cleaner triple suspension #2
C_2: M2 feedback filter
C_3: M3 feedback filter

Reference: G1200774

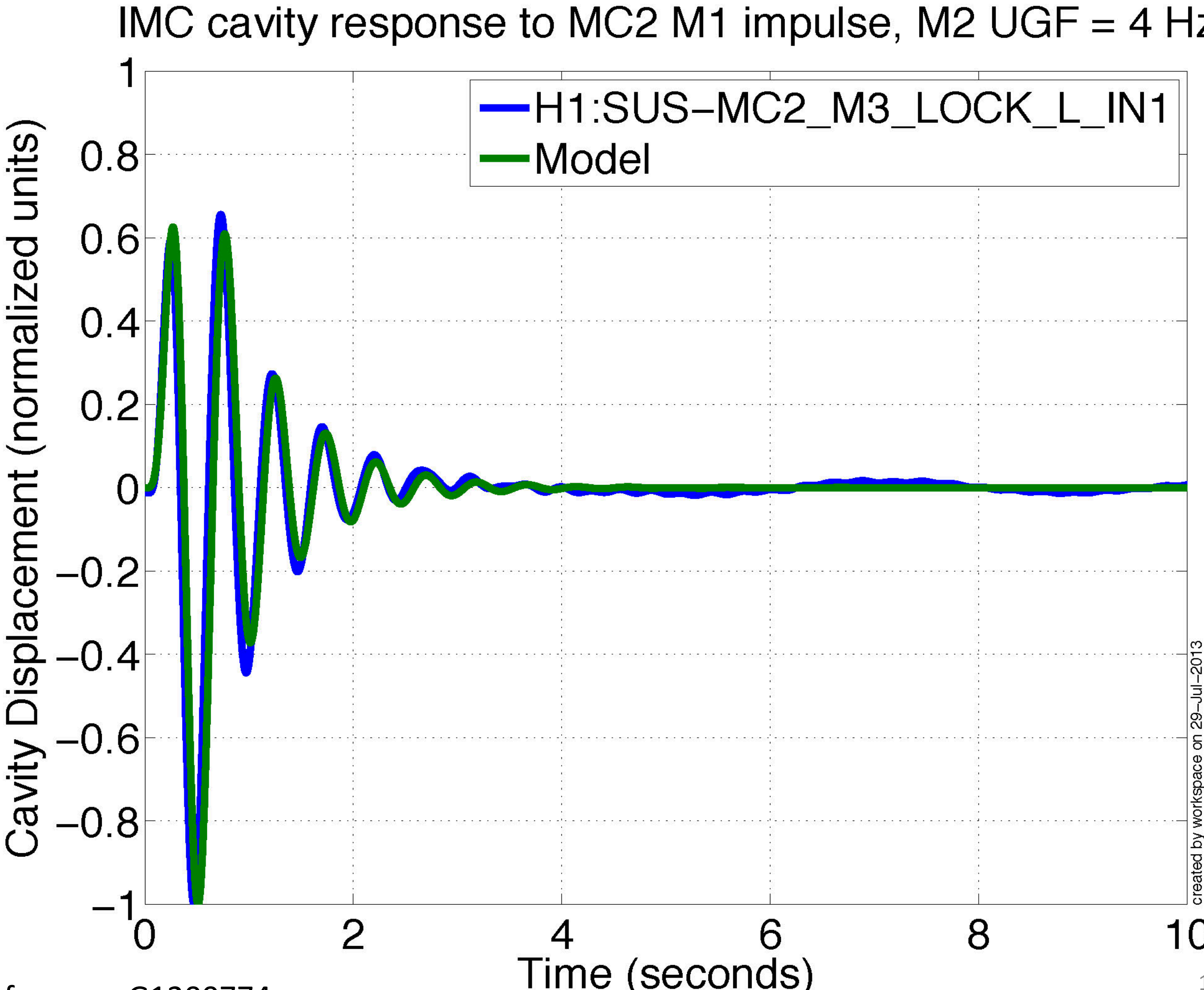
IMC cavity response to MC2 M1 impulse, M2 UGF = 14.7 Hz



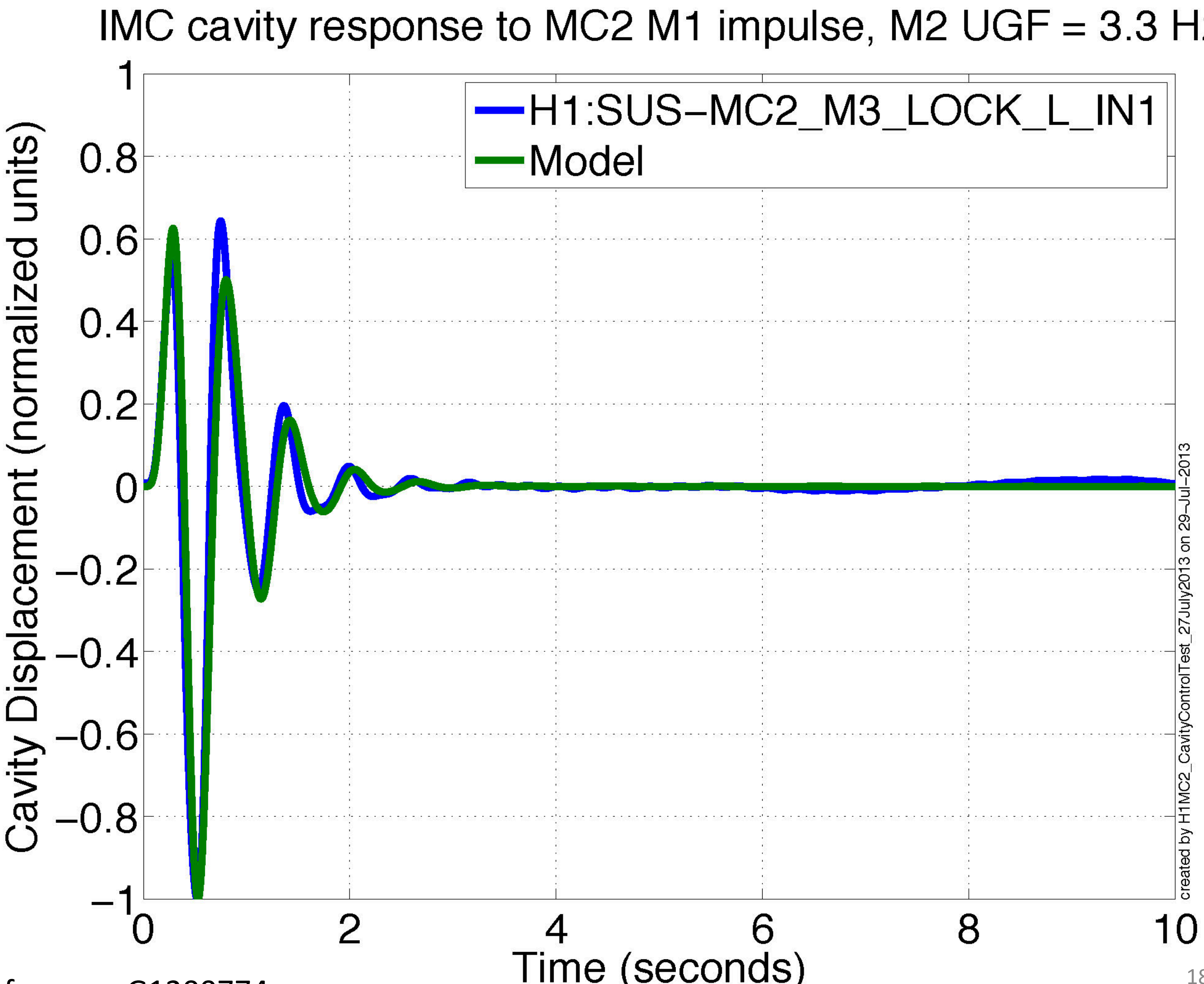
Reference: G1200774



Reference: G1200774

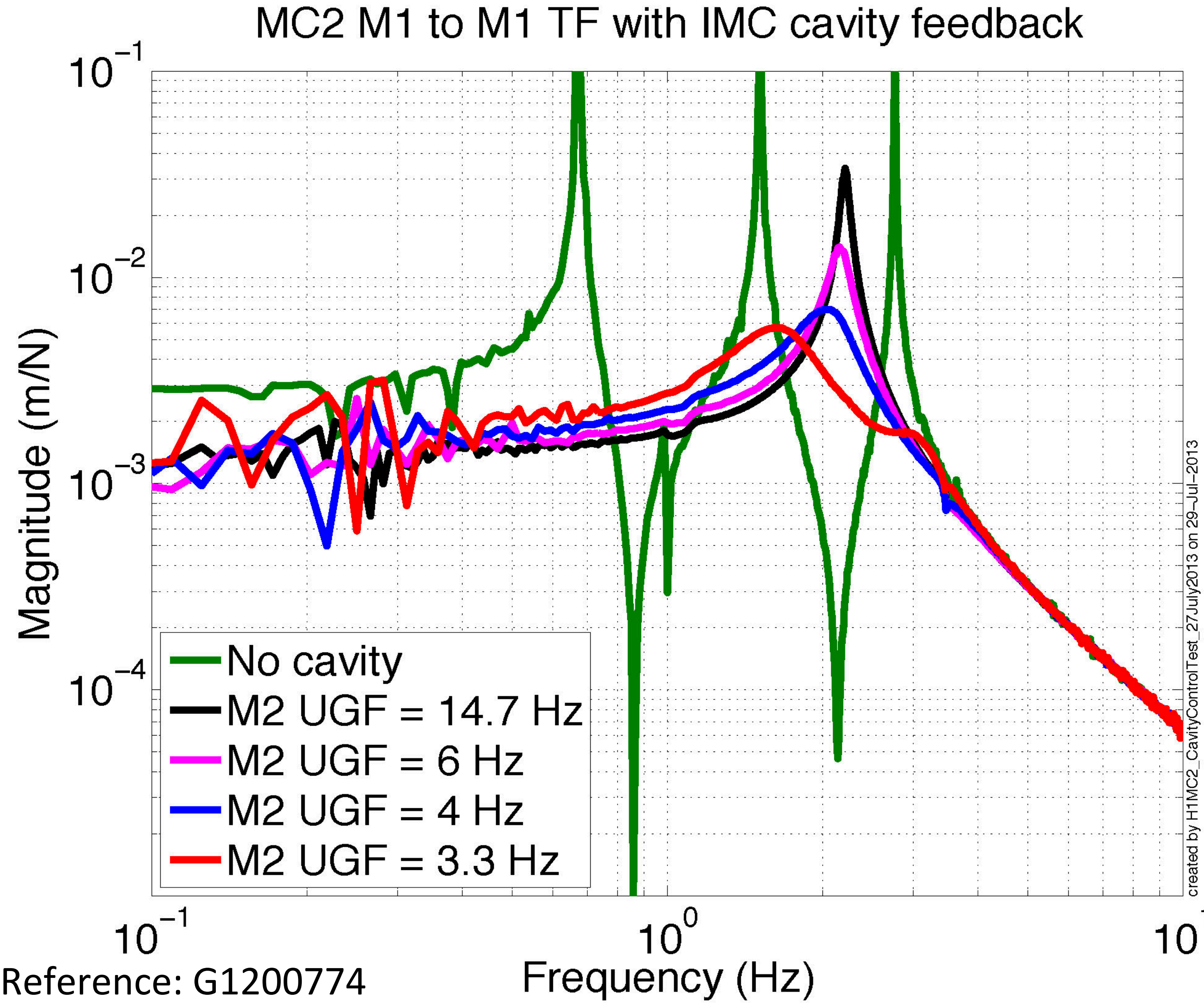


Reference: G1200774



Reference: G1200774

LHO Damping Measurements



Terminology Key

M1: top mass

M2: middle mass

M3: bottom mass

MC2: triple suspension

UGF: unity gain frequency or bandwidth

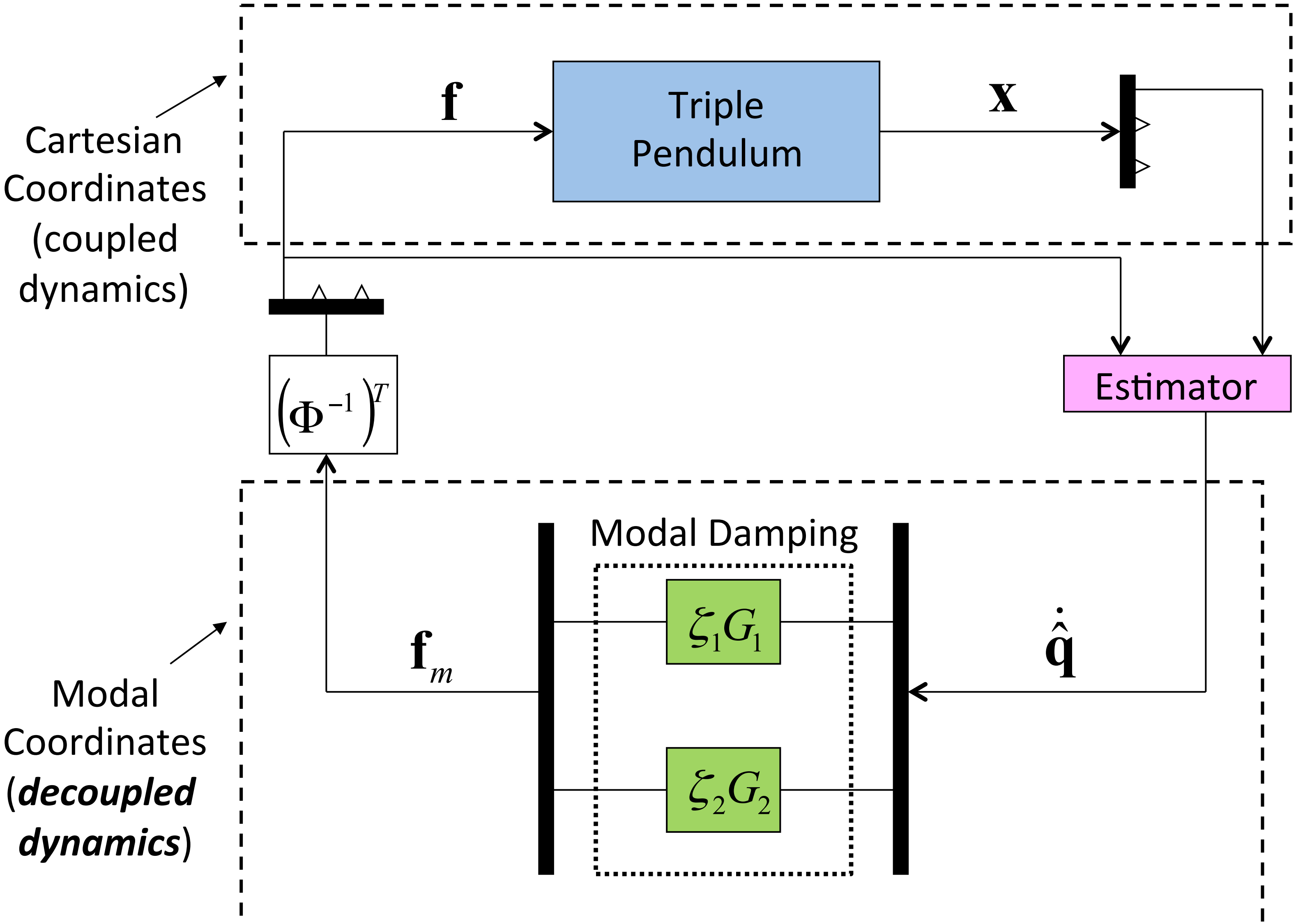
Reference: G1200774

Summary of global damping

- Can isolate nearly all longitudinal damping noise from the interferometer signal
- The damping and cavity control designs decouple from each other
- Requires extra constraints on the cavity control.
- Only works for longitudinal degree of freedom, but this is the ‘noisiest’ one

Modal Damping Backups

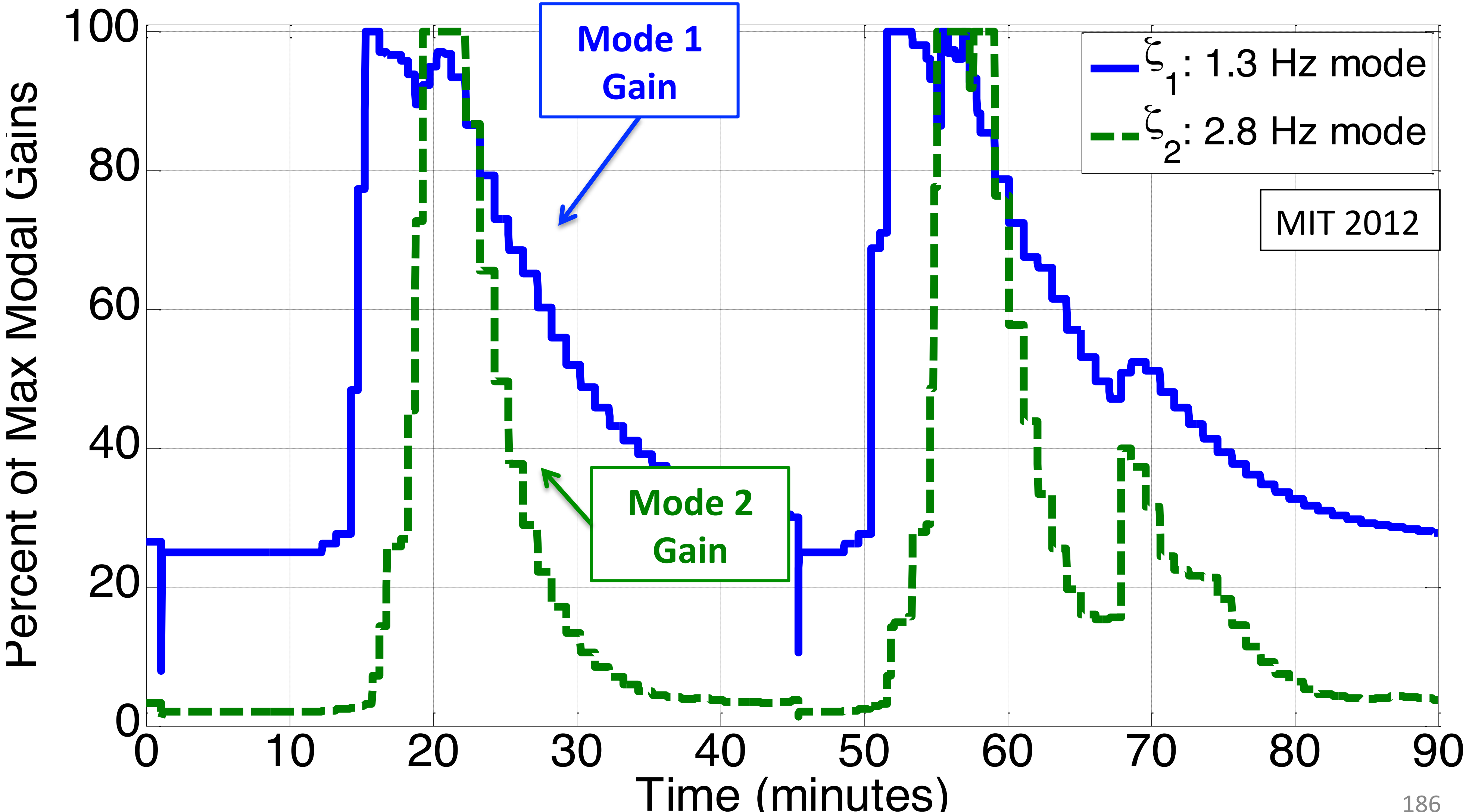
Modal Damping with State Estimation



- $\mathbf{x} = \Phi \mathbf{q}$
- Φ = pendulum eigenvector matrix
- $\mathbf{x}$ = Cartesian coordinates
- $\hat{\mathbf{q}}$ = estimated modal coord.
- $\mathbf{f}$ = Cartesian damping forces
- $\mathbf{f}_m$ = modal damping forces
- $G_i = i_{\text{th}}$ mode damping filter
- $\zeta_i = i_{\text{th}}$ mode damping gain

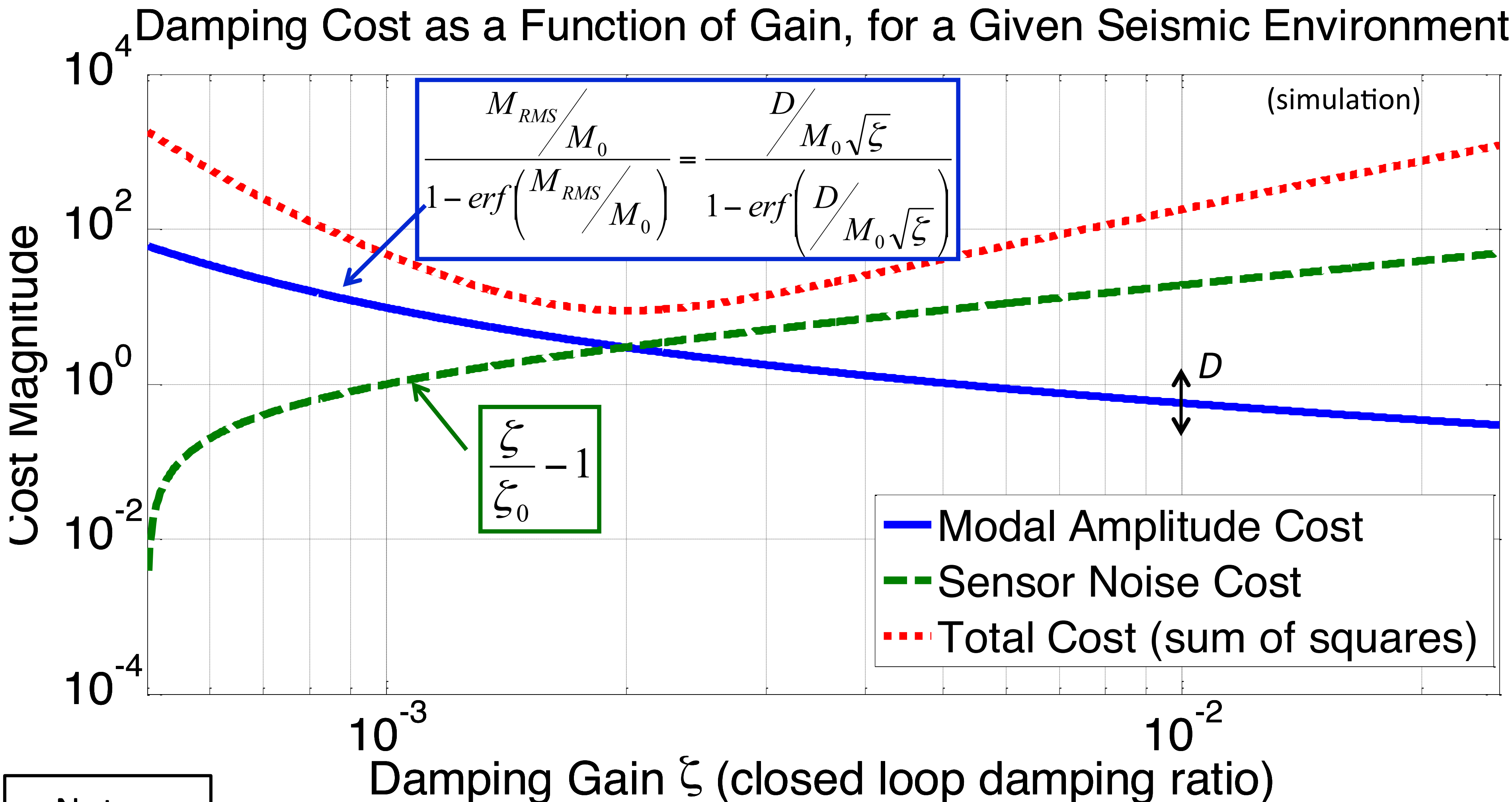
Adaptive Modal Damping

Measurements of adaptive modal damping gains responding to seismic disturbances



Ref: G1200723

Adaptive Modal Damping



Notes:

$$M_{RMS} = D/\sqrt{\zeta}$$

D = seismic amplitude at the modal frequency.

M_{RMS} = measured modal amplitude
M_0 = constant scaling term
ζ_0 = highest value where sensor noise is negligible.
In this case, D = 0.53, $M_0 = 15$, and ζ_0 = 5e-4.

Summary of modal damping

- ‘Optimal’ - more damping with less noise
- MIMO (Multi-Input-Multi-Output) – takes advantage of cross couplings between DOFs
- Uses a modal coordinate frame rather than a standard XYZ frame
- Real-time frequency domain tuning – each mode’s gain independently adjustable

aLIGO design Sensitivity