Brief Introduction to Advanced LIGO Suspensions

Brett Shapiro

LAAC Session

24 August 2014

Installing the Quad Prototype at MIT
23 January 2009

My experience

2001-2005 Undergrad: Penn State Engineering Science

2005-2012 PhD: MIT Mechanical Engineering

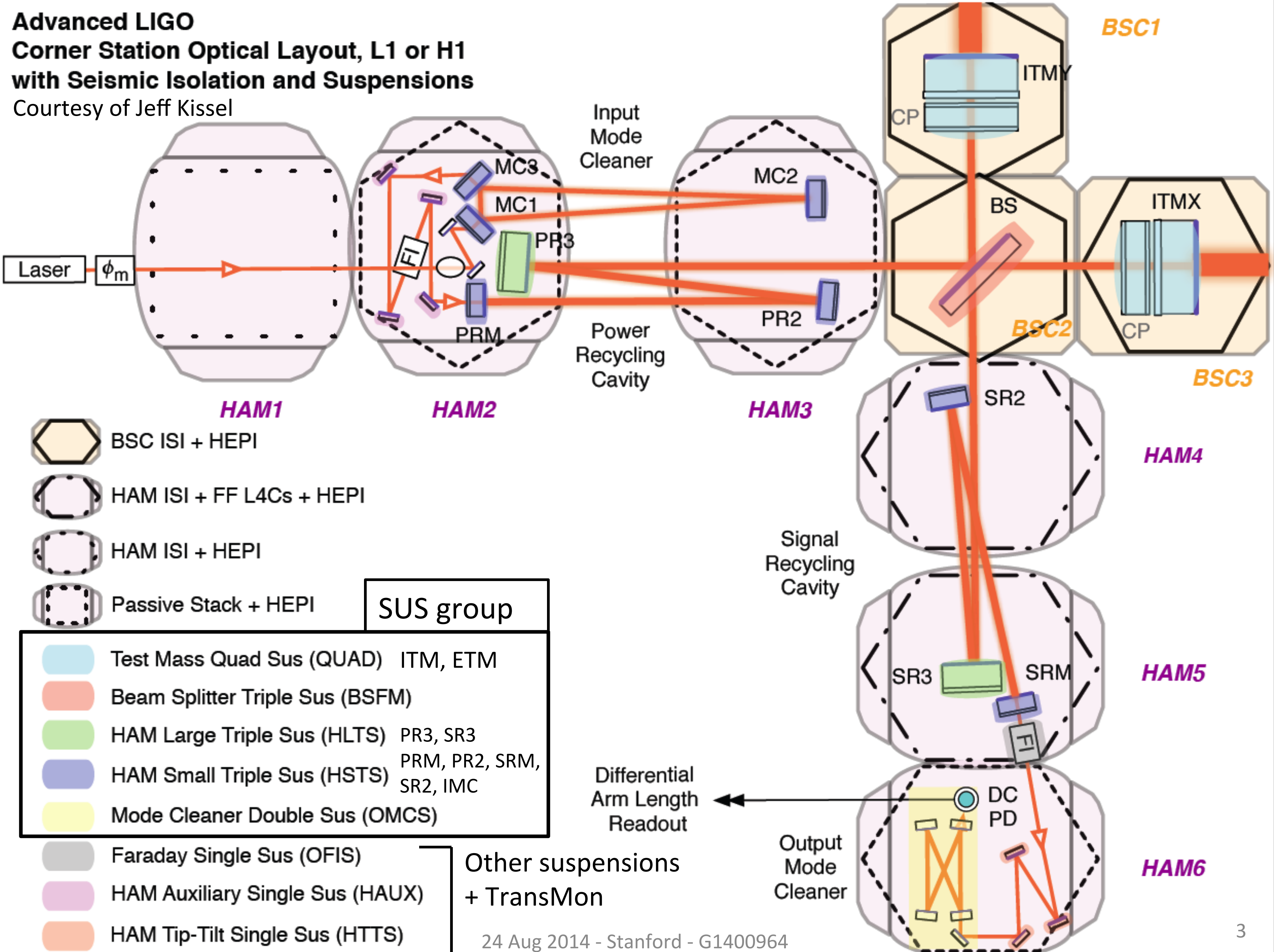
- Worked on the controls, modeling, assembly, and testing of the prototype quadruple pendulums at the LASTI facility.

2012-now postdoc: Stanford University

- Still some involvement in the suspensions group
- Mostly working on cryogenic technologies for 3rd generation LIGO observatories

Advanced LIGO
Corner Station Optical Layout, L1 or H1
with Seismic Isolation and Suspensions

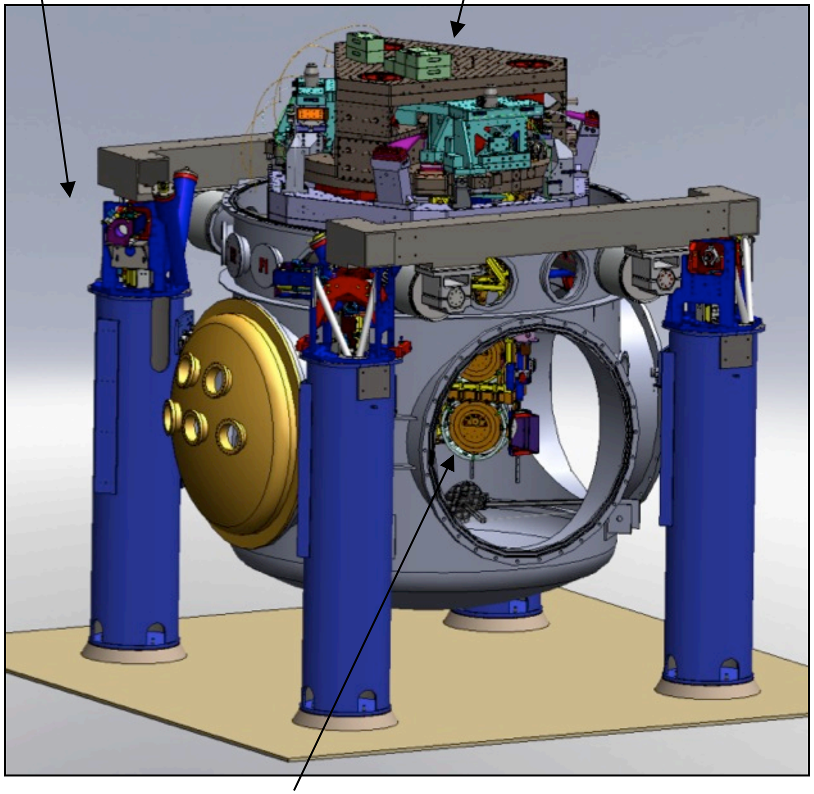
Courtesy of Jeff Kissel



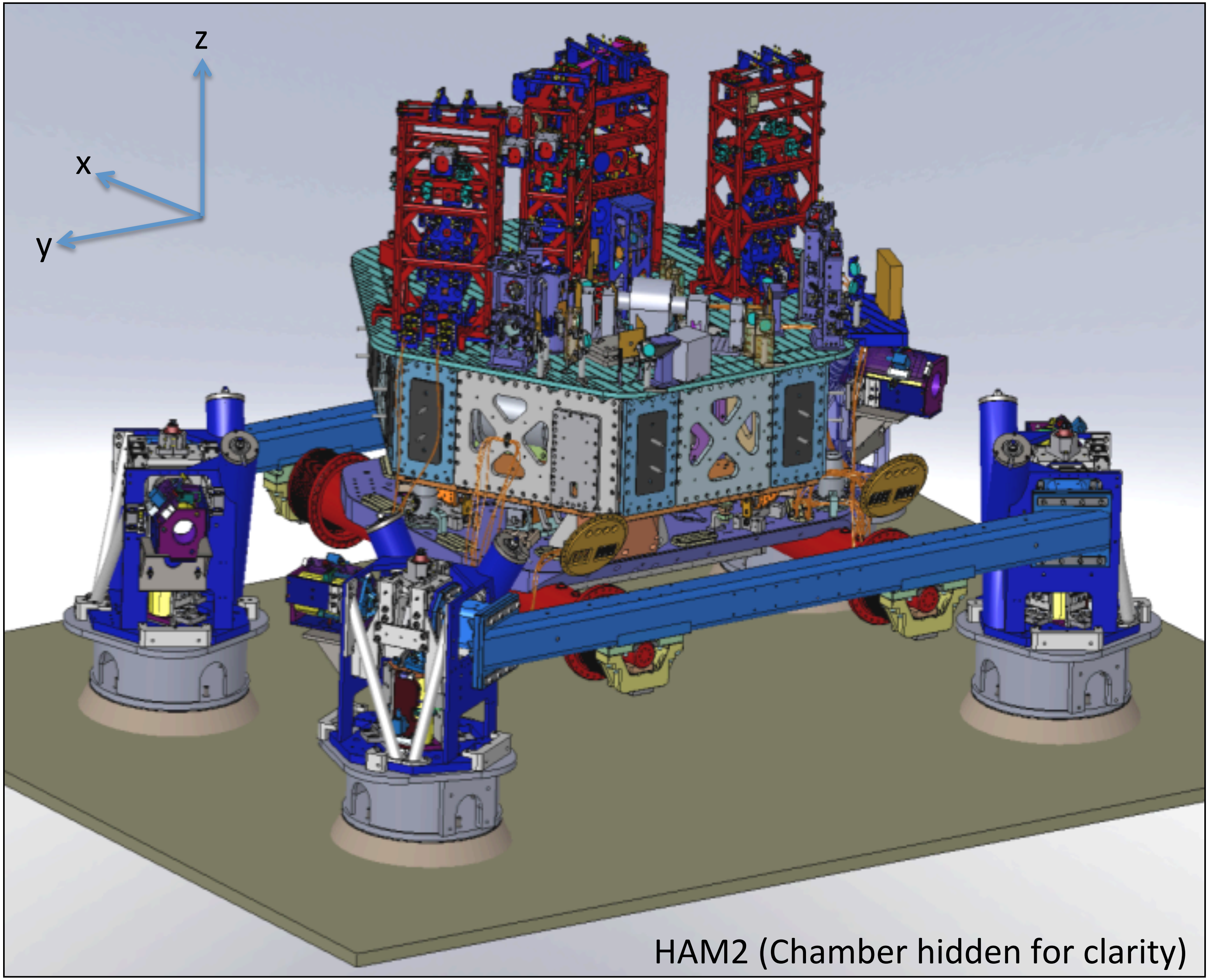
BSCs – core optics

hydraulic external pre-isolator (HEPI) (one stage of isolation)

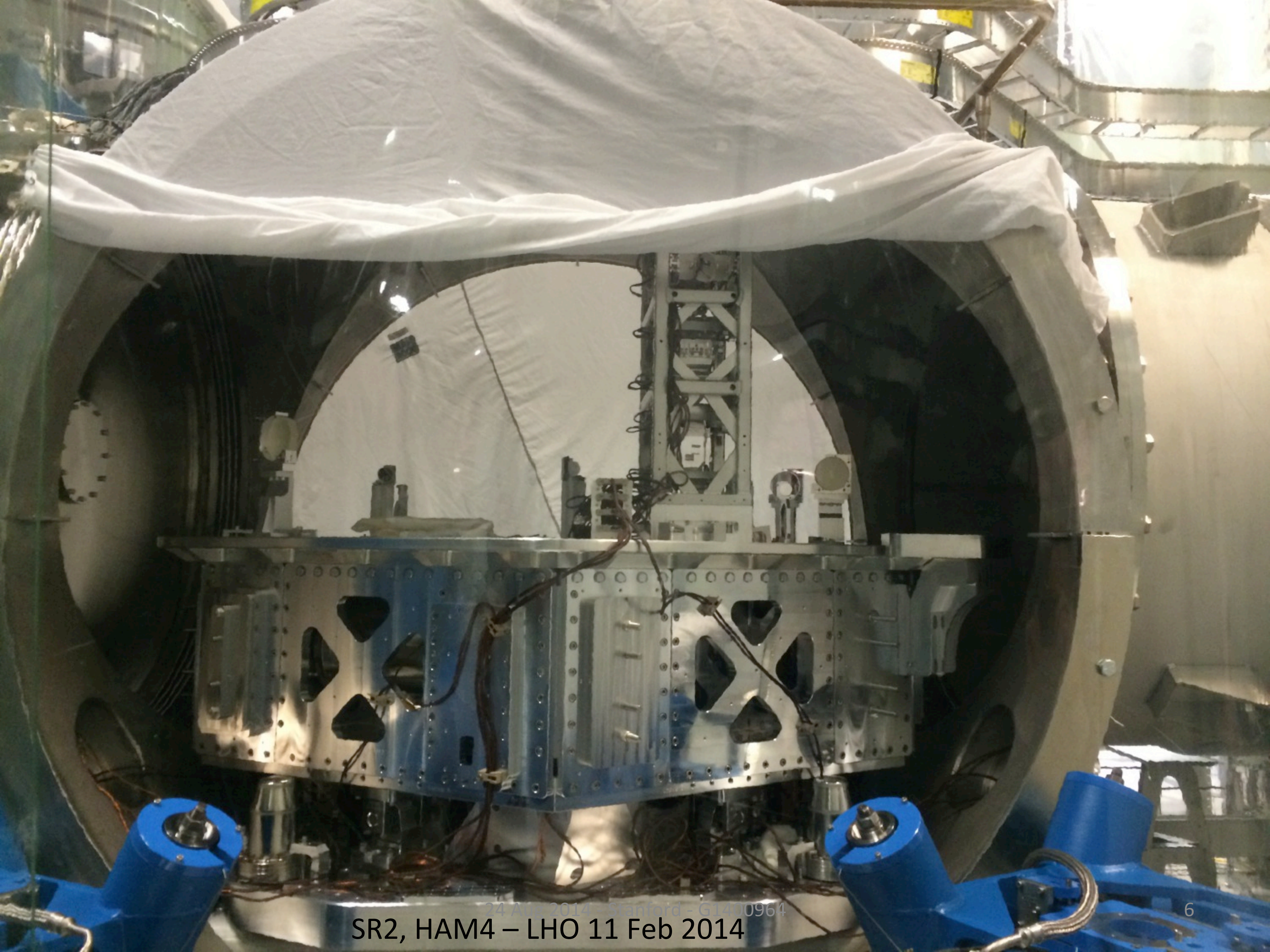
active isolation platform (2 stages of isolation)



quadruple pendulum (four stages of isolation) with monolithic silica final stage



HAM2 (Chamber hidden for clarity)



SR2, HAM4 – LHO 11 Feb 2014

HAM Small Triple Suspension (HSTS)

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

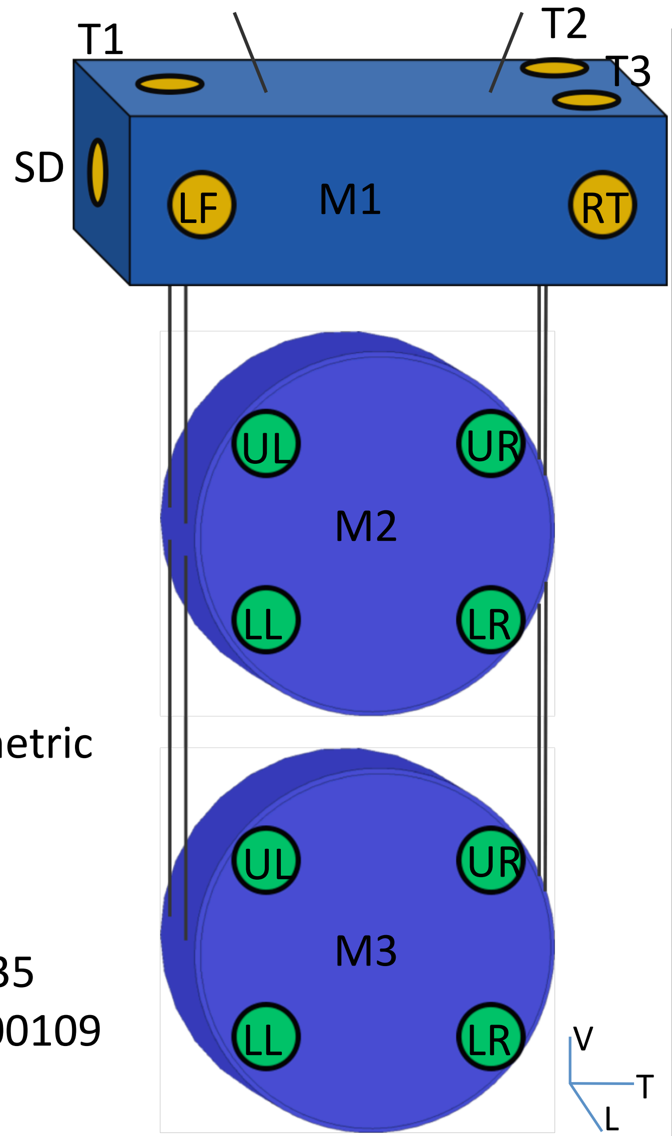
Location
- HAM 2, 3, 4, 5, (8, 9, 10, 11)

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

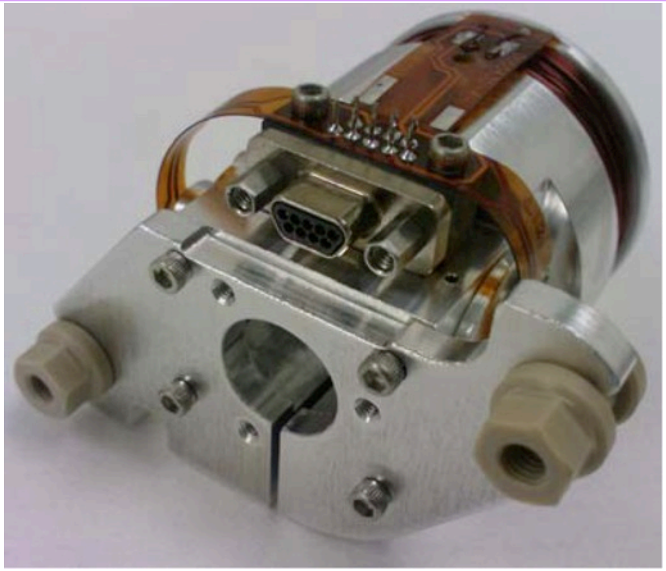
Sensors/Actuators
- BOSEMs at M1
- AOSEMs at M2 and M3
- Optical levers and interferometric signals on M3

Naming: L1:SUS-PRM_M1…

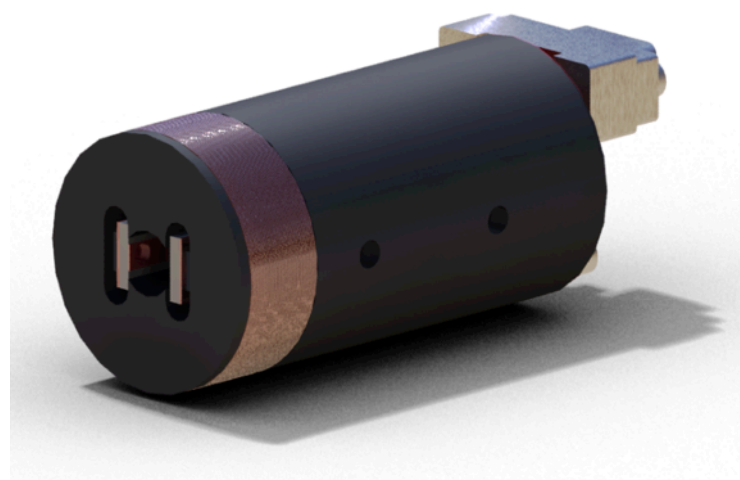
Documentation
- Final design review - T0900435
- Controls arrangement – E1100109



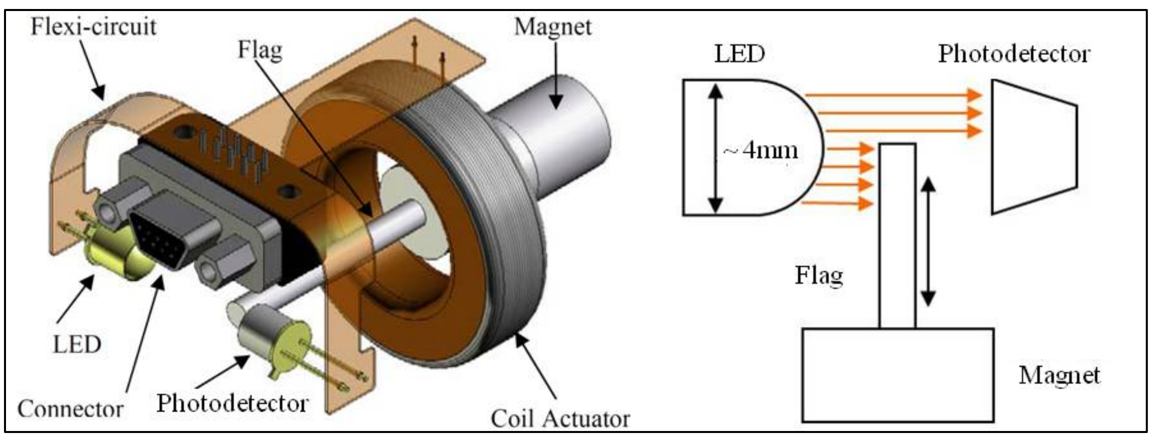
Optical Sensor ElectroMagnet (OSEM)



Birmingham OSEM (BOSEM)



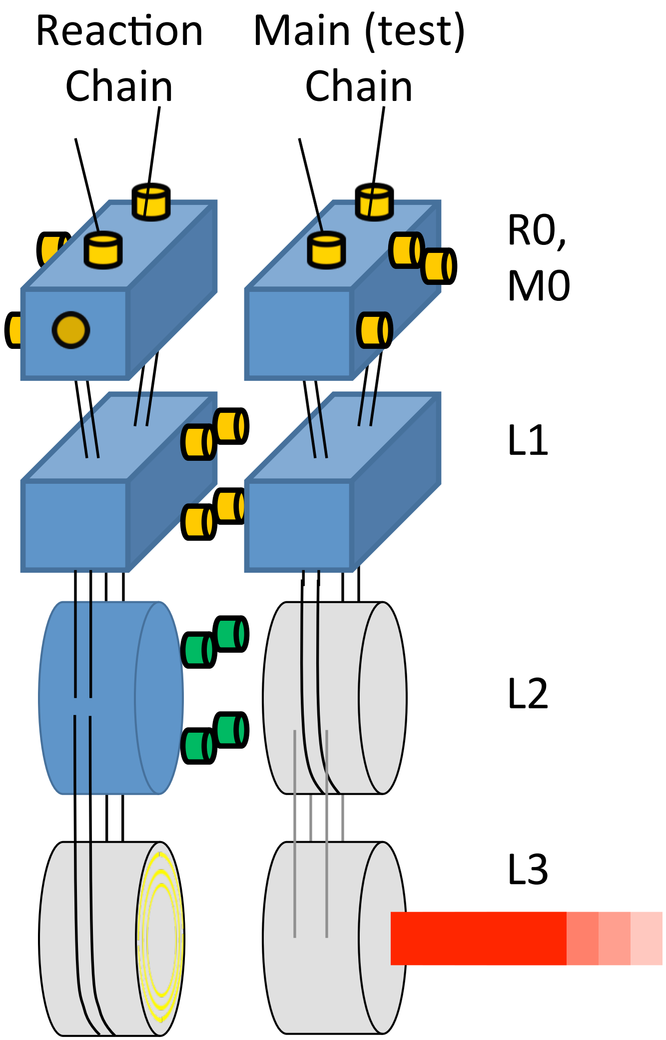
Advanced LIGO OSEM (AOSEM)
- modified iLIGO OSEM



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

Quadruple Suspension (Quad)



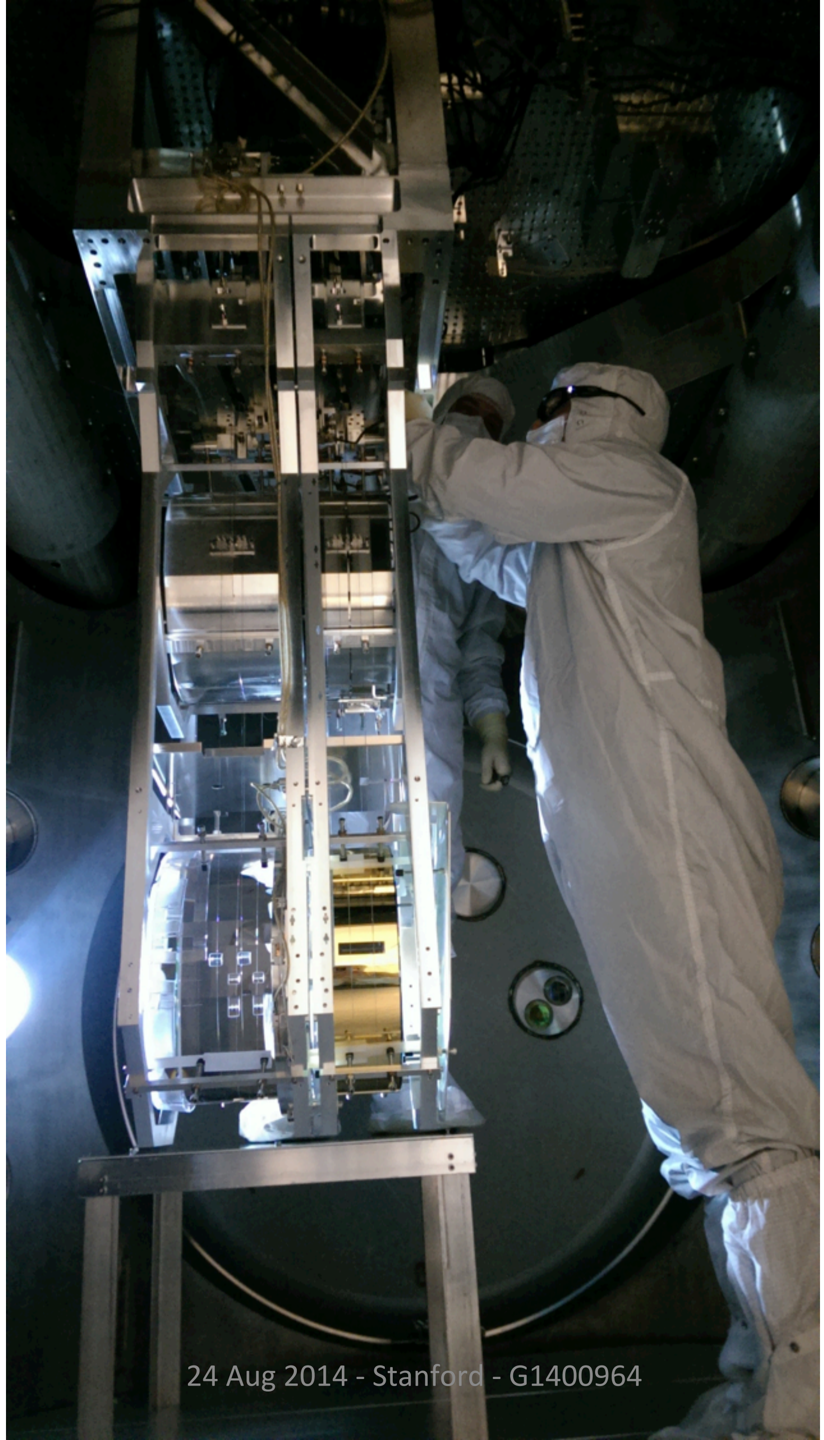
Purpose
- Input Test Mass (ITM, TCP)
- End Test Mass (ETM, ERM)

Location
- H1 - BSC 1, 3, 9, 10
- H2 - BSC 7, 8, 5, 6
- L1 – BSC 1, 3, 4, 5

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

Sensors/Actuators
- BOSEMs at M0, R0, L1
- AOSEMs at L2
- Opt. levs. and interf. sigs. at L3
- Electrostatic drive (ESD) at L3

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

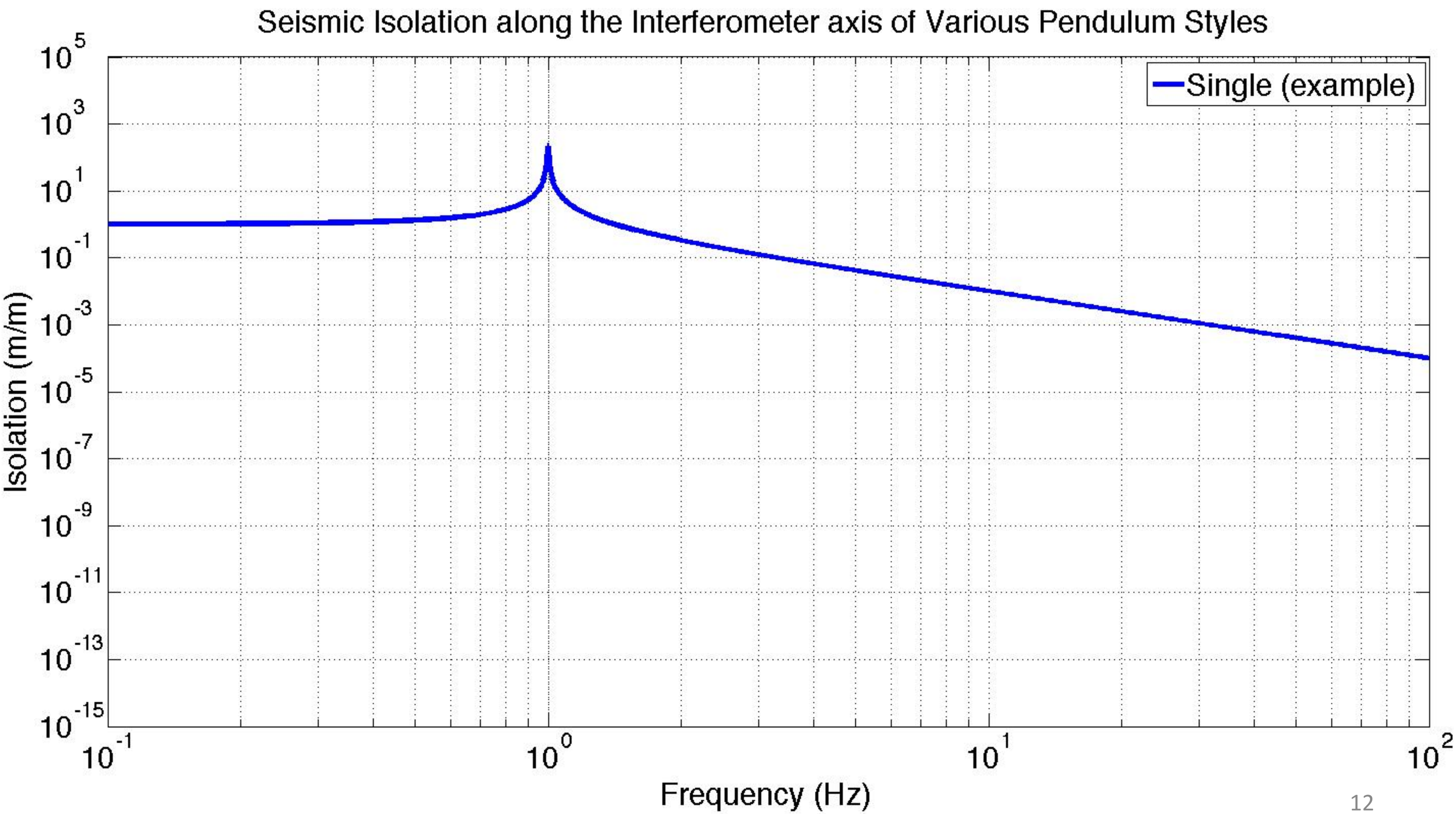


H1ITMX
LHO alog 12211
10 June 2014

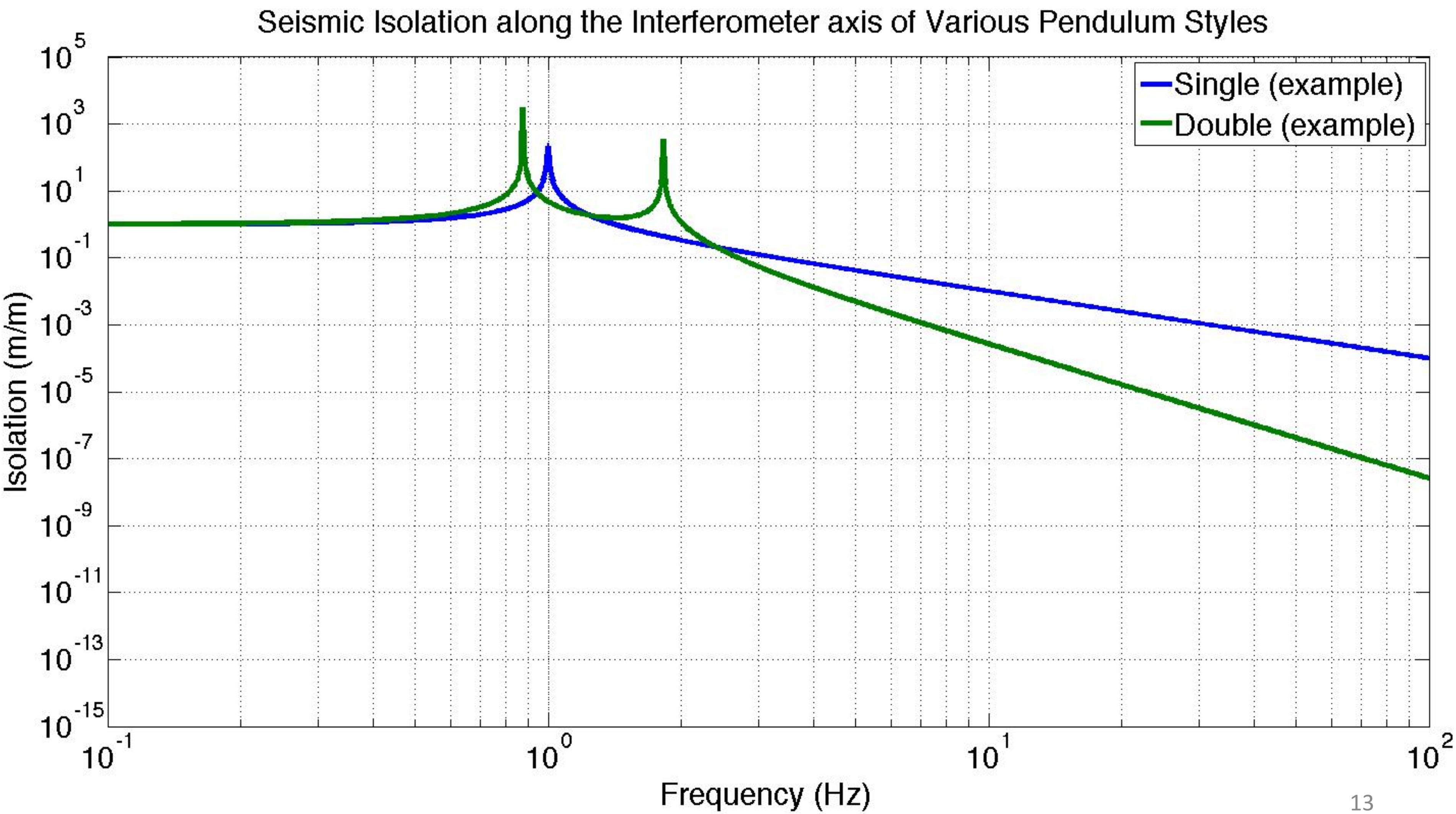
De-install for silica fiber installation

H1 ITMX – 30 July 2014 - LHO alog 13044

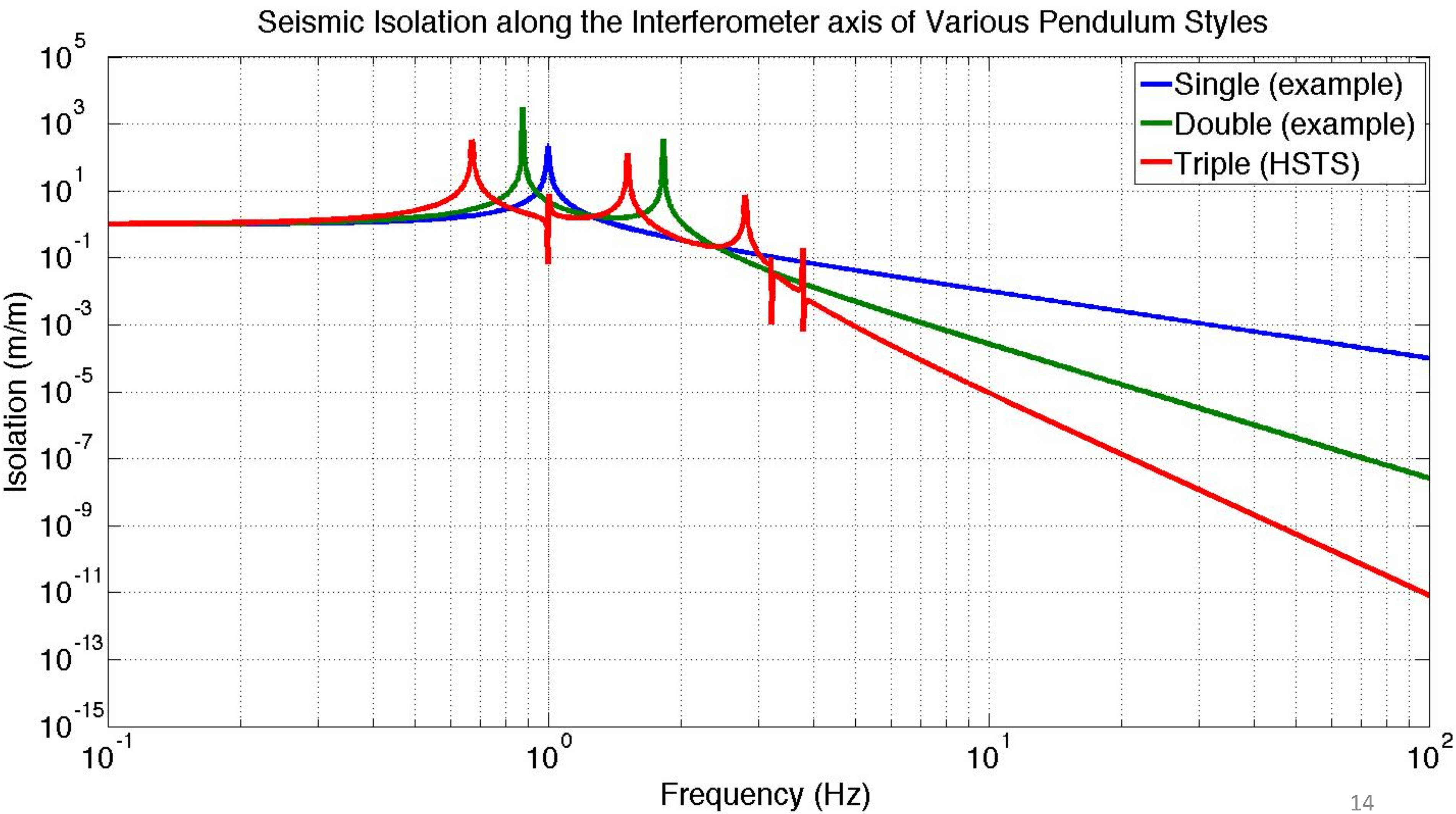
Suspension Isolation



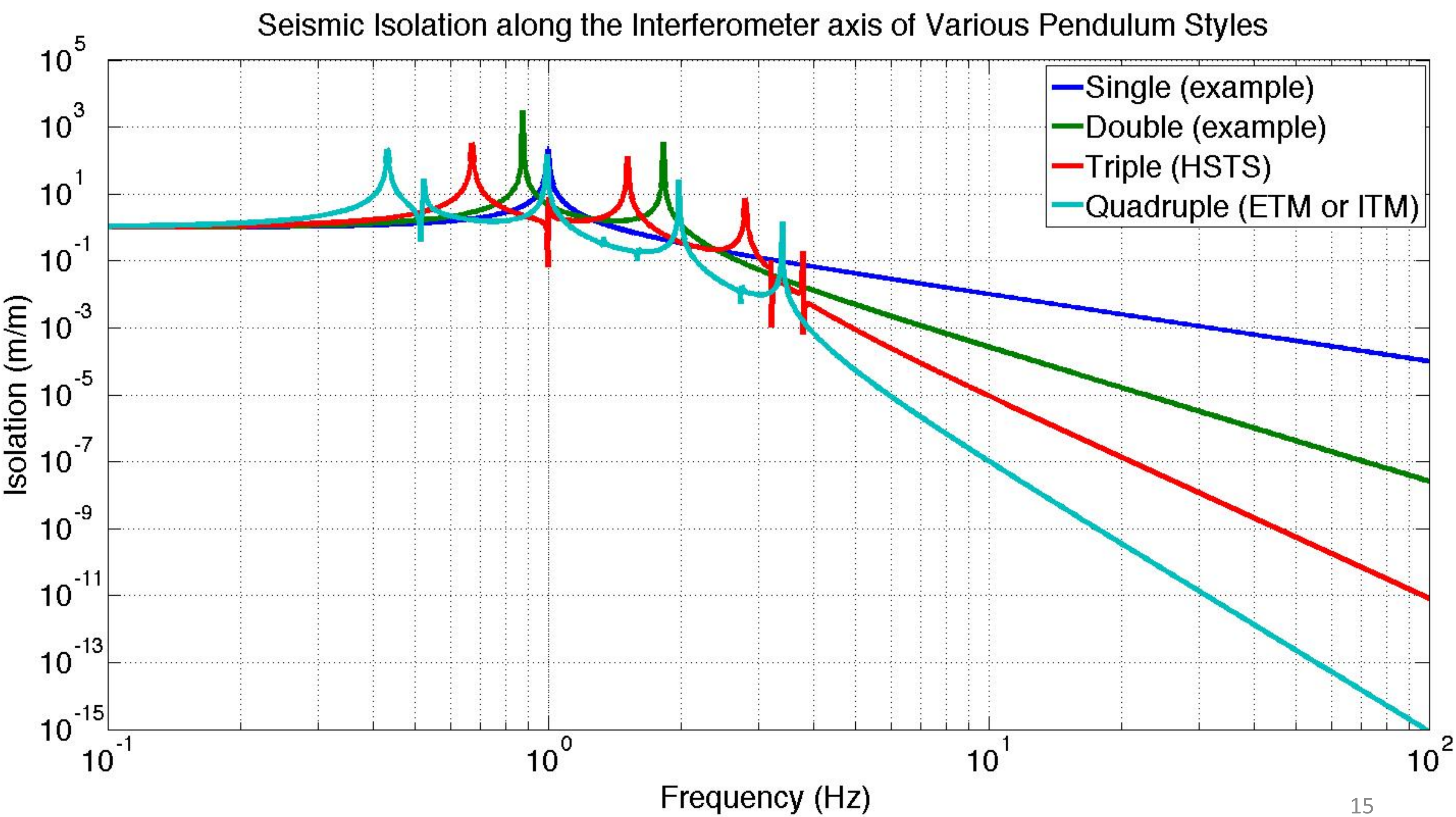
Suspension Isolation



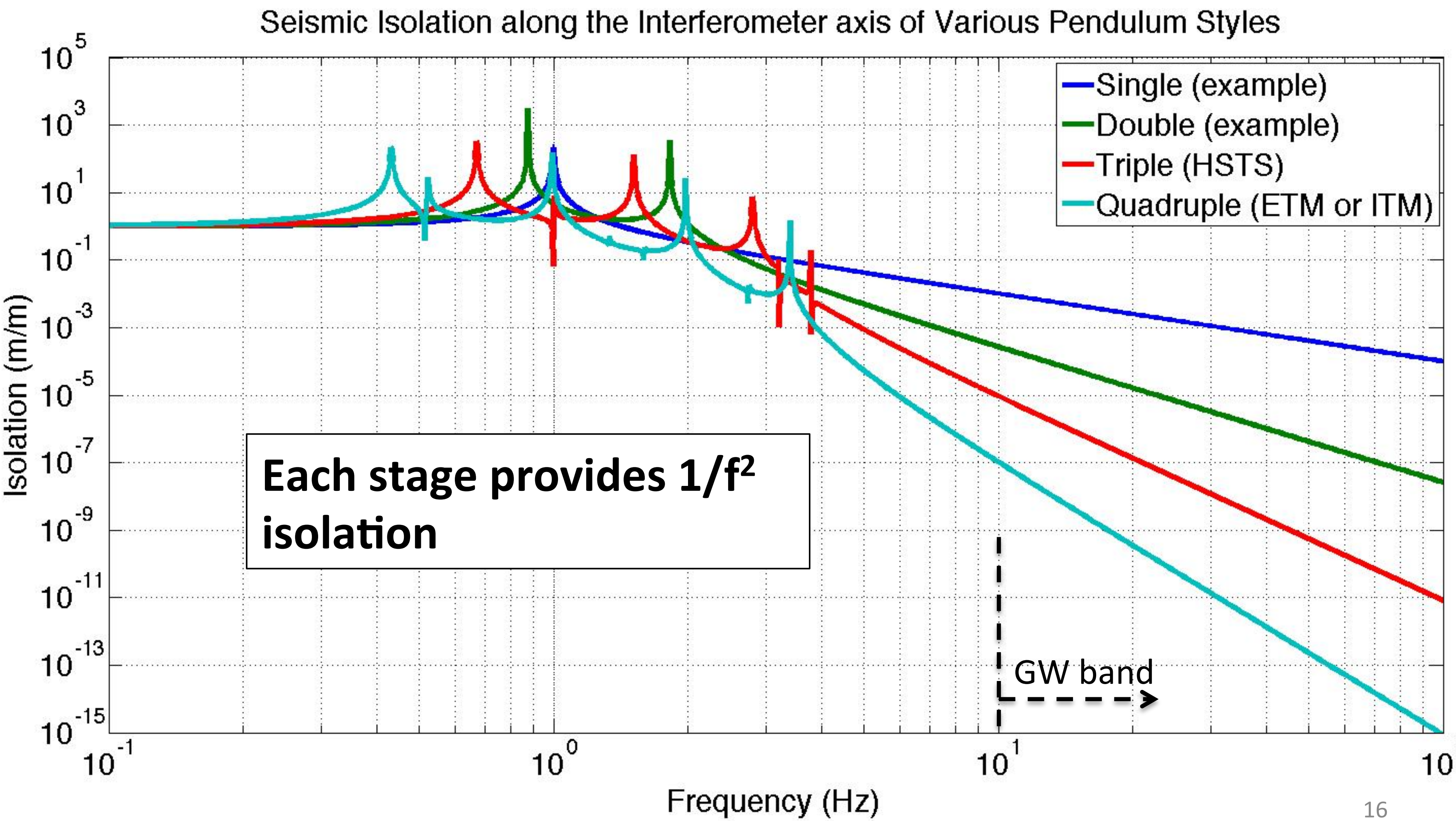
Suspension Isolation



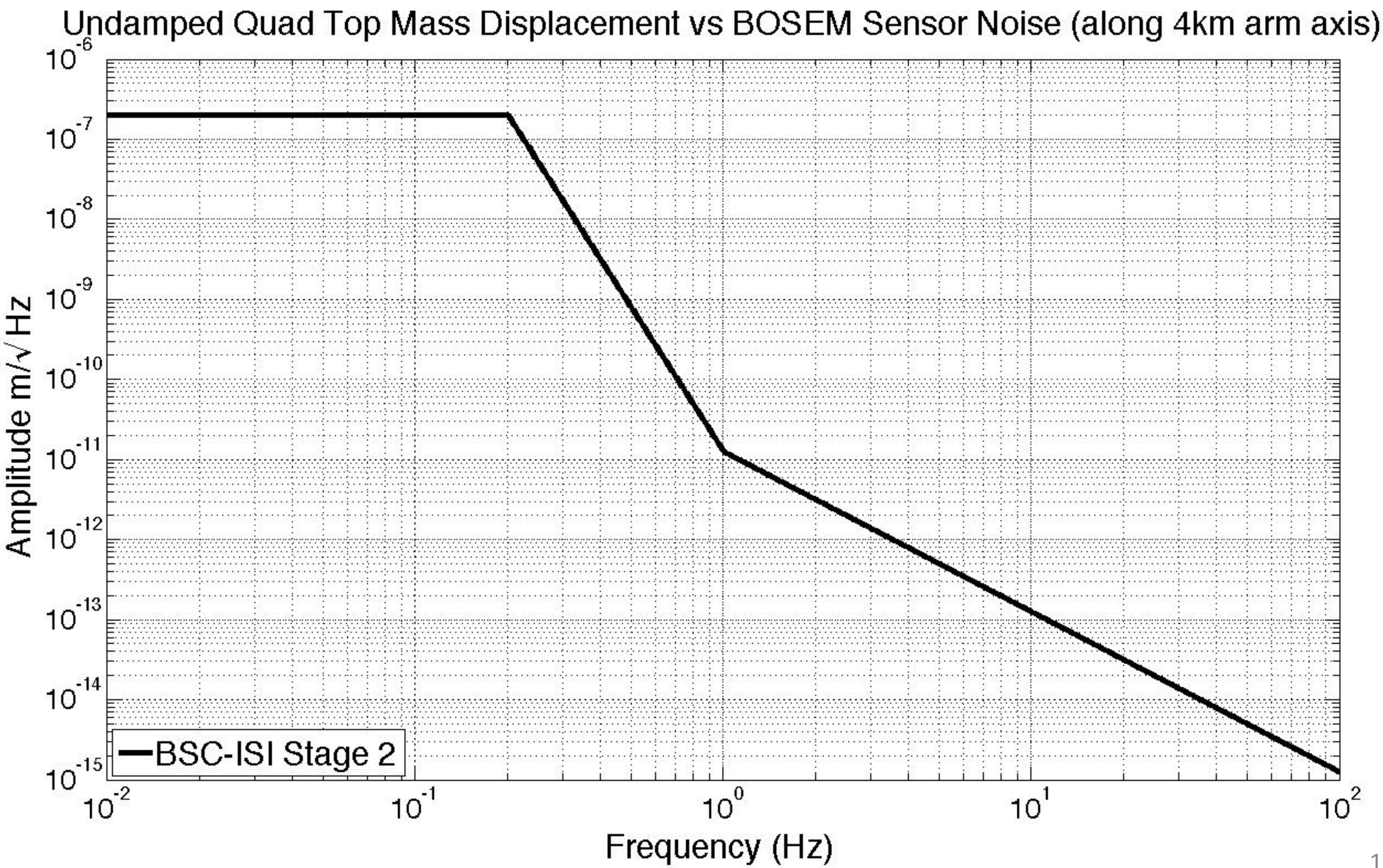
Suspension Isolation



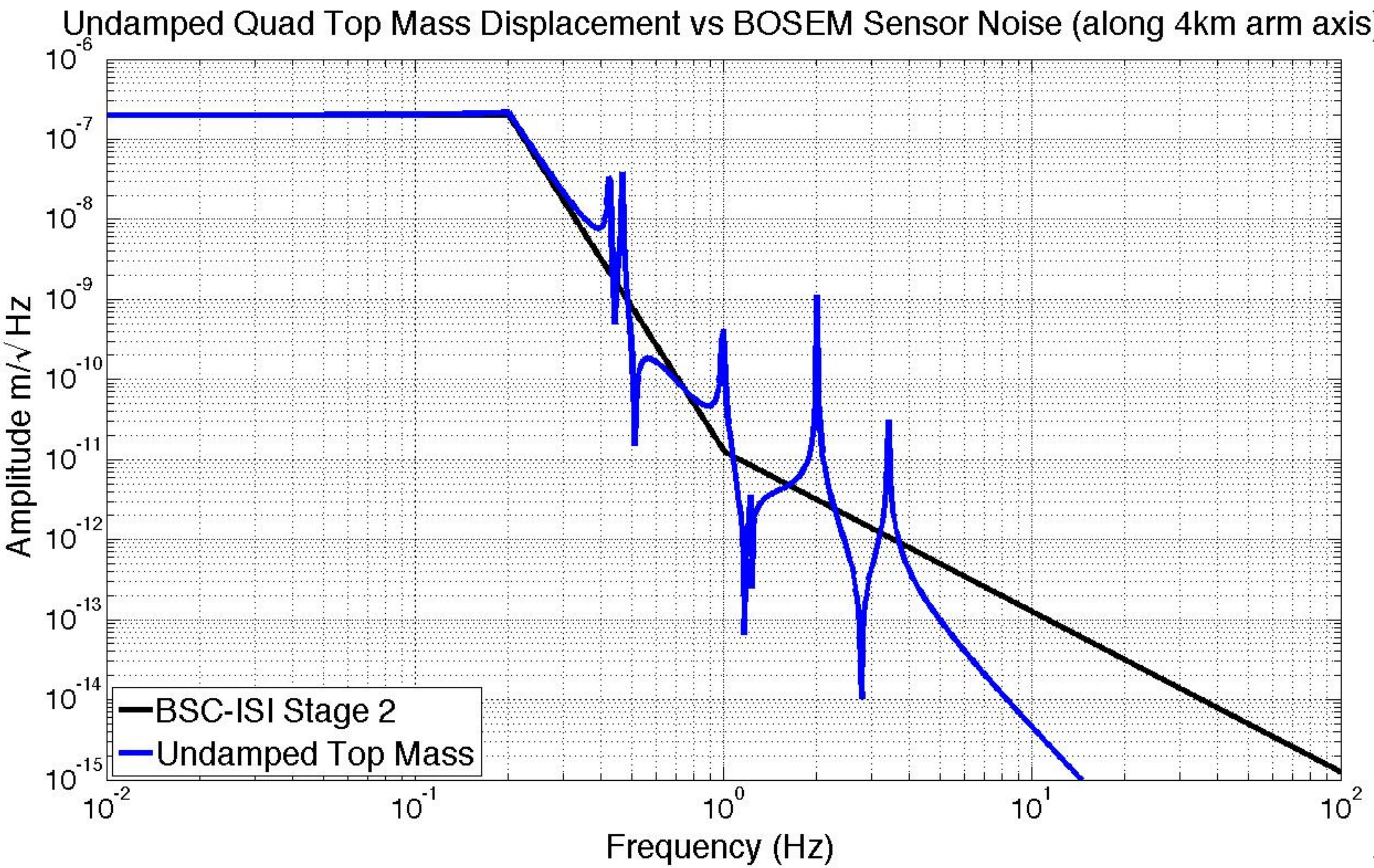
Suspension Isolation



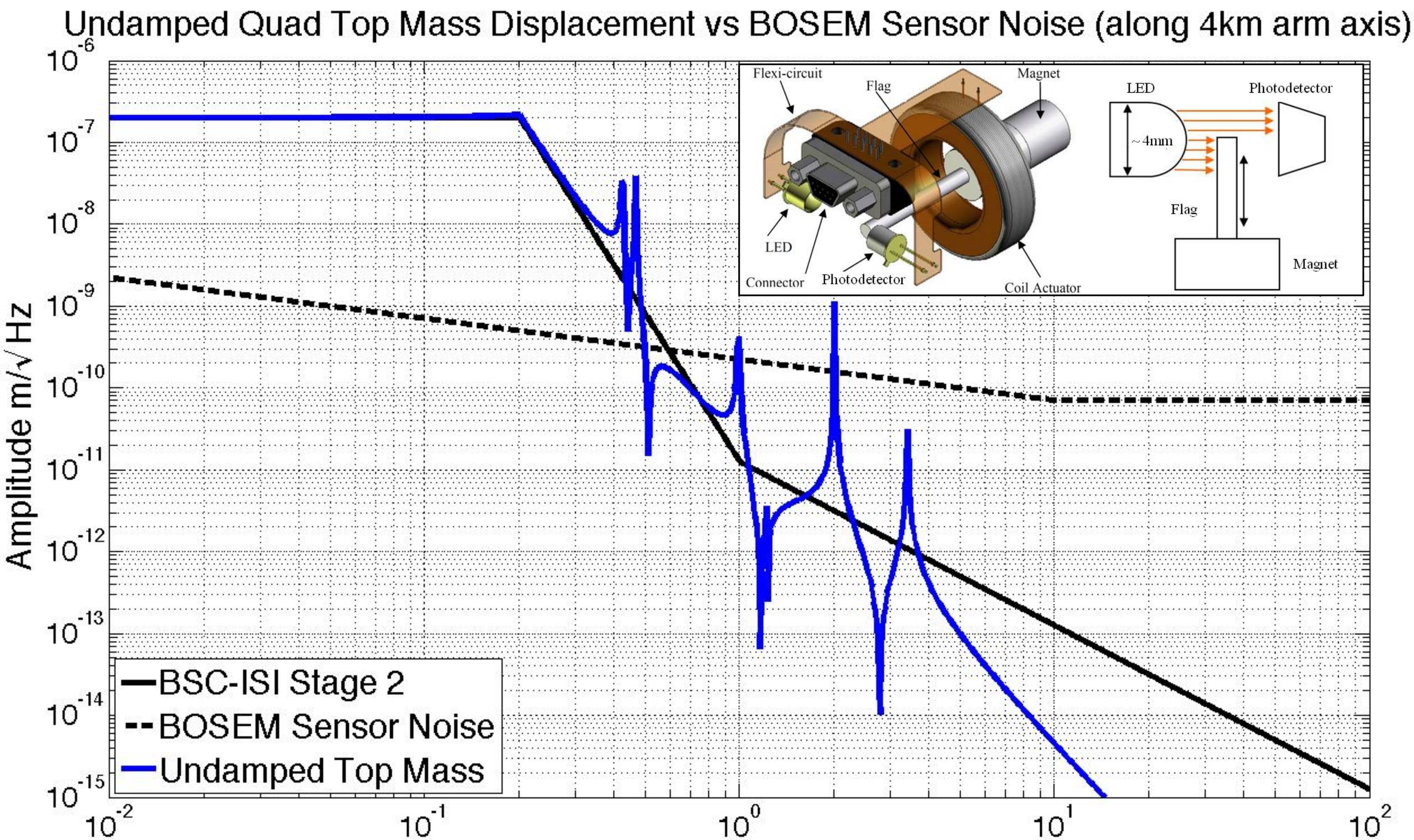
The damping challenge



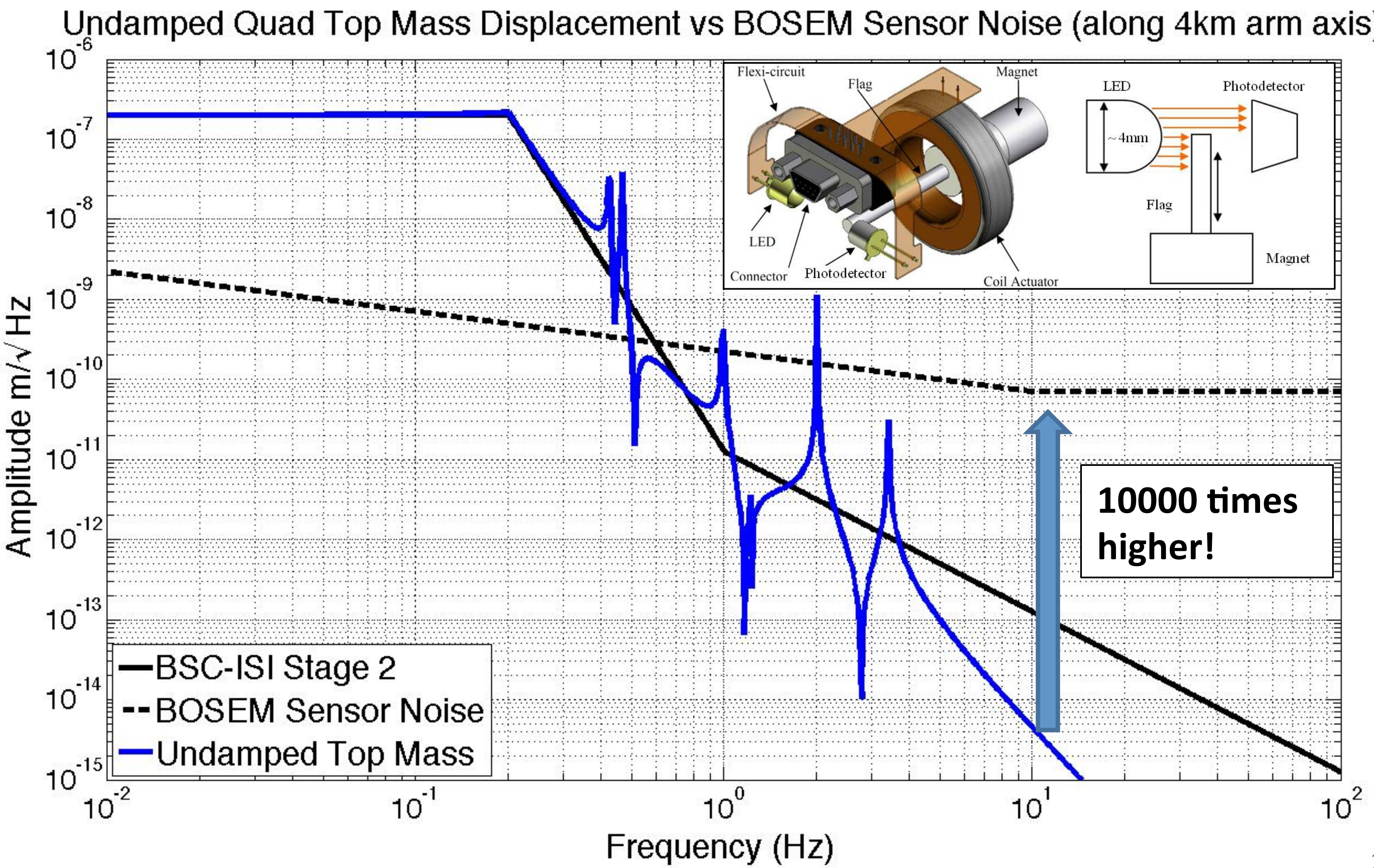
The damping challenge



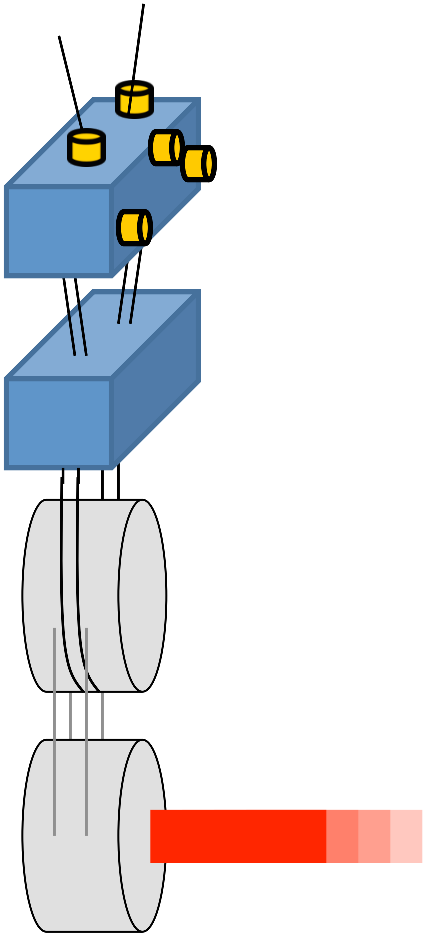
The damping challenge



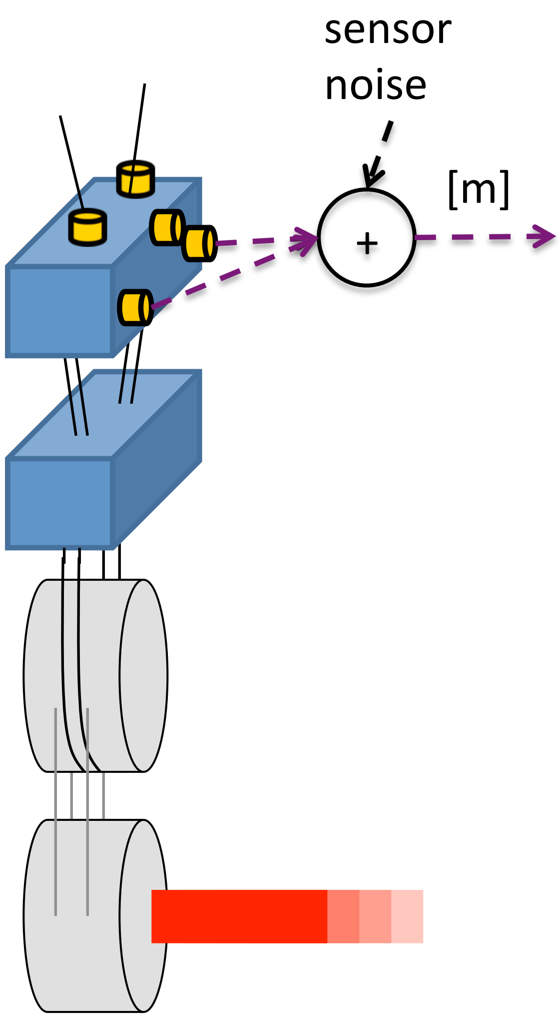
The damping challenge



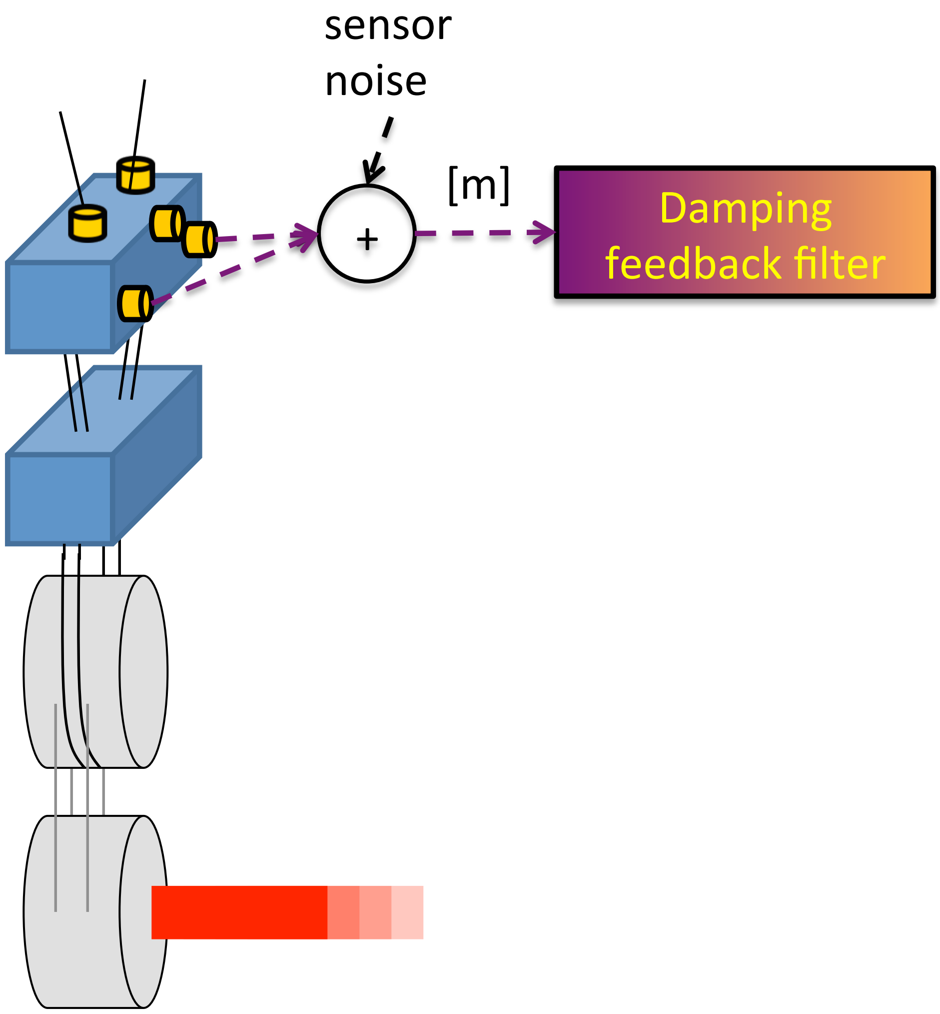
Damping feedback loop



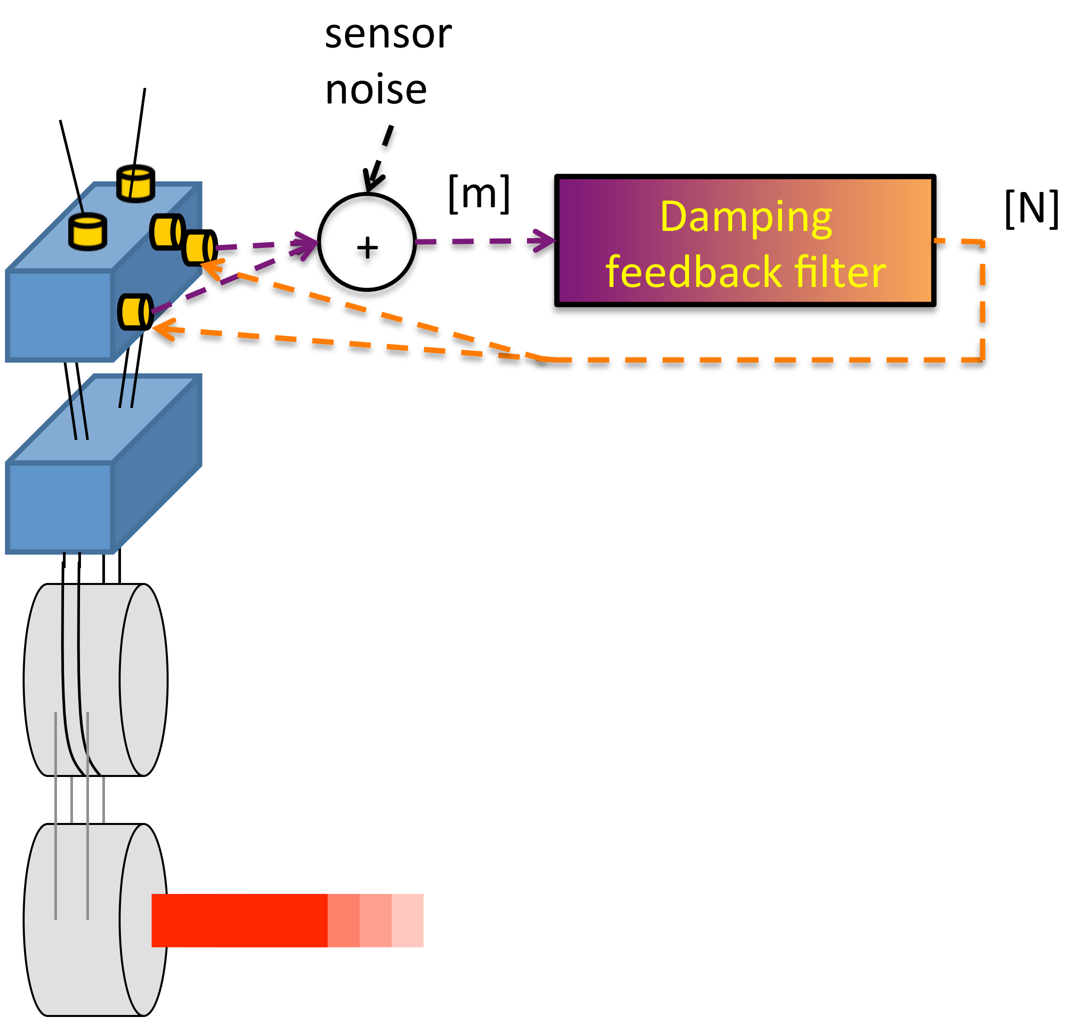
Damping feedback loop



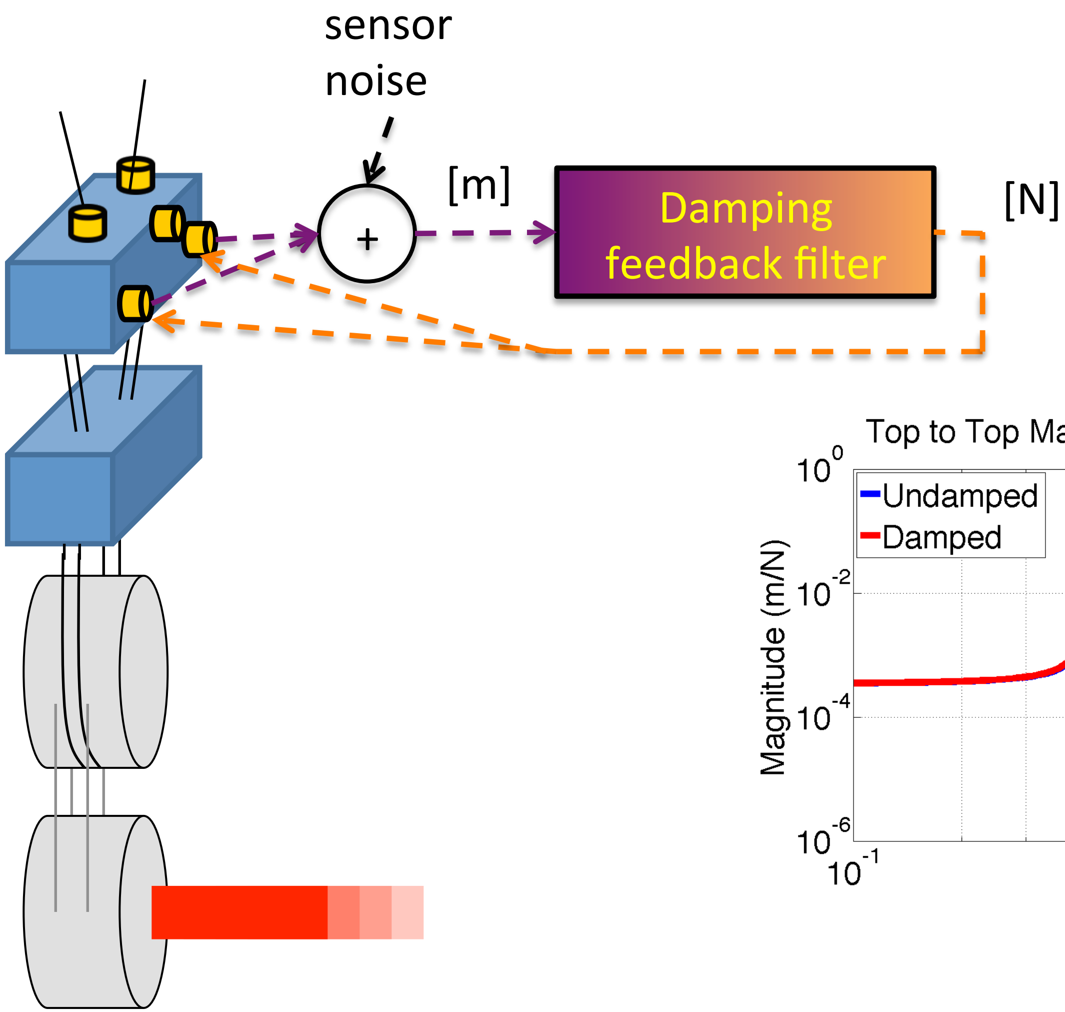
Damping feedback loop

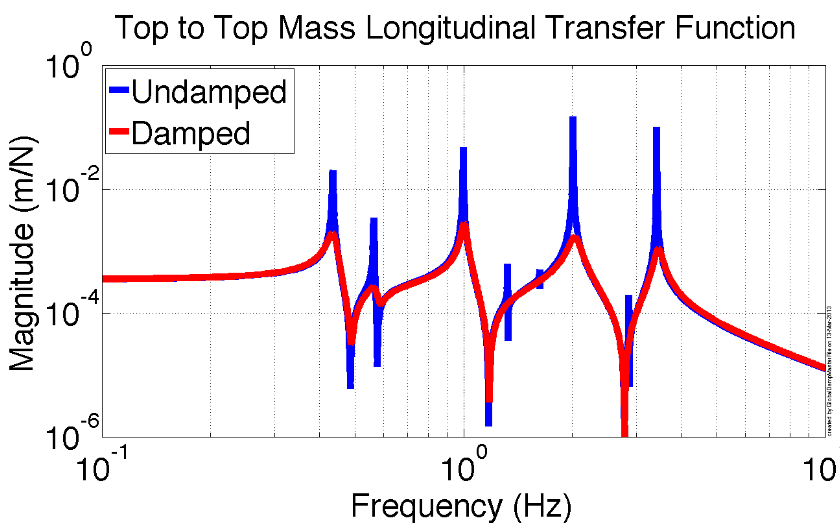


Damping feedback loop

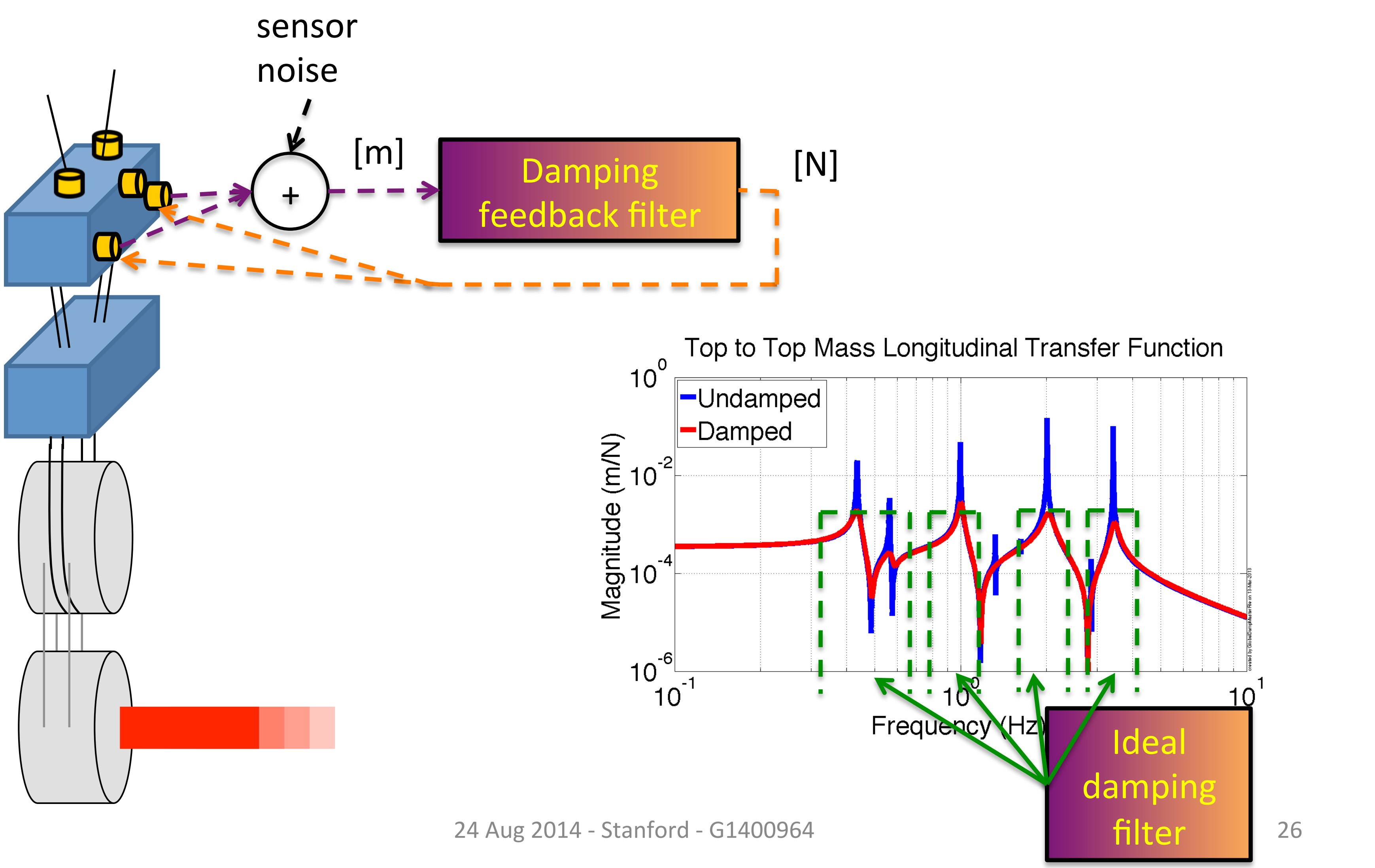


Damping feedback loop

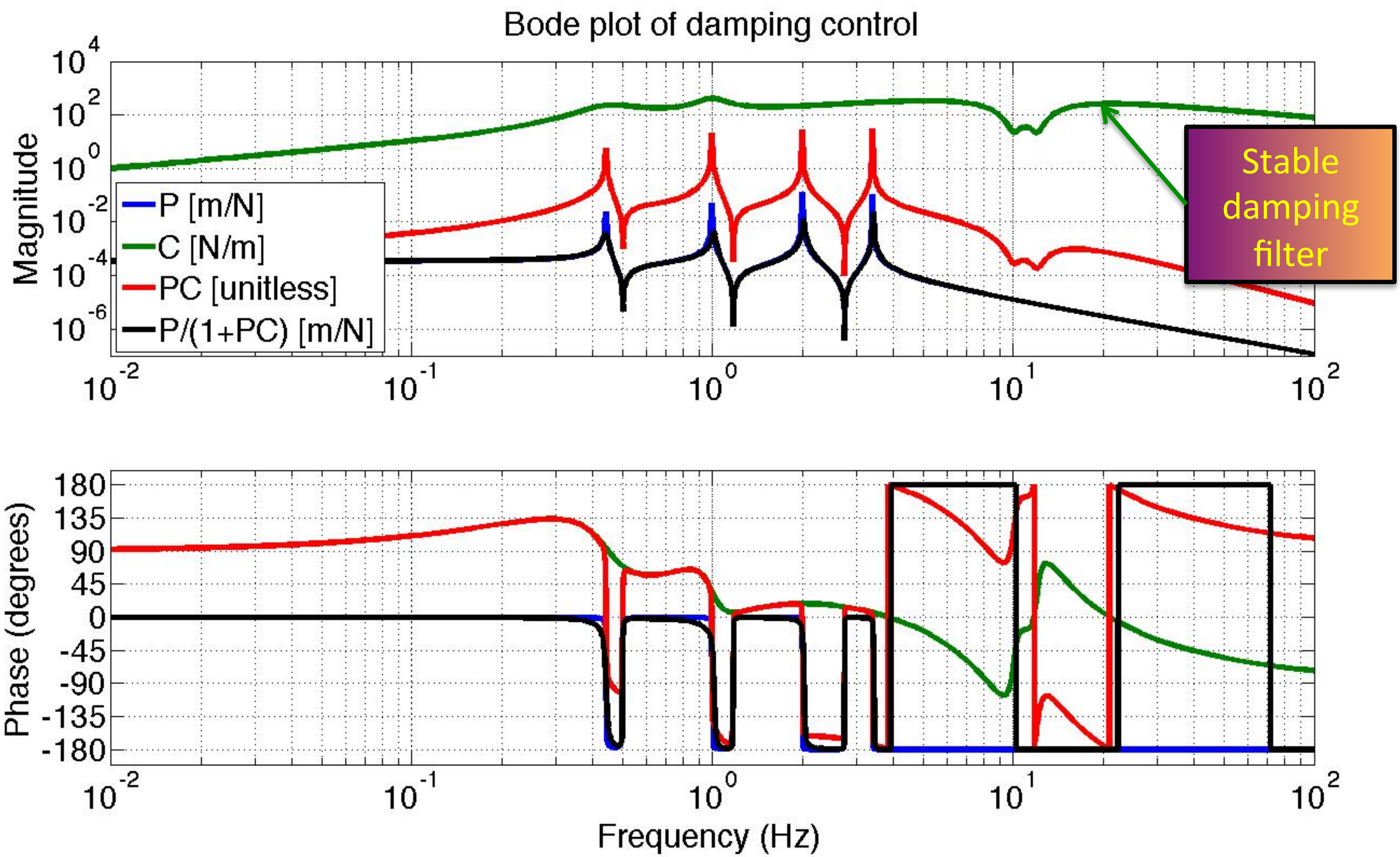




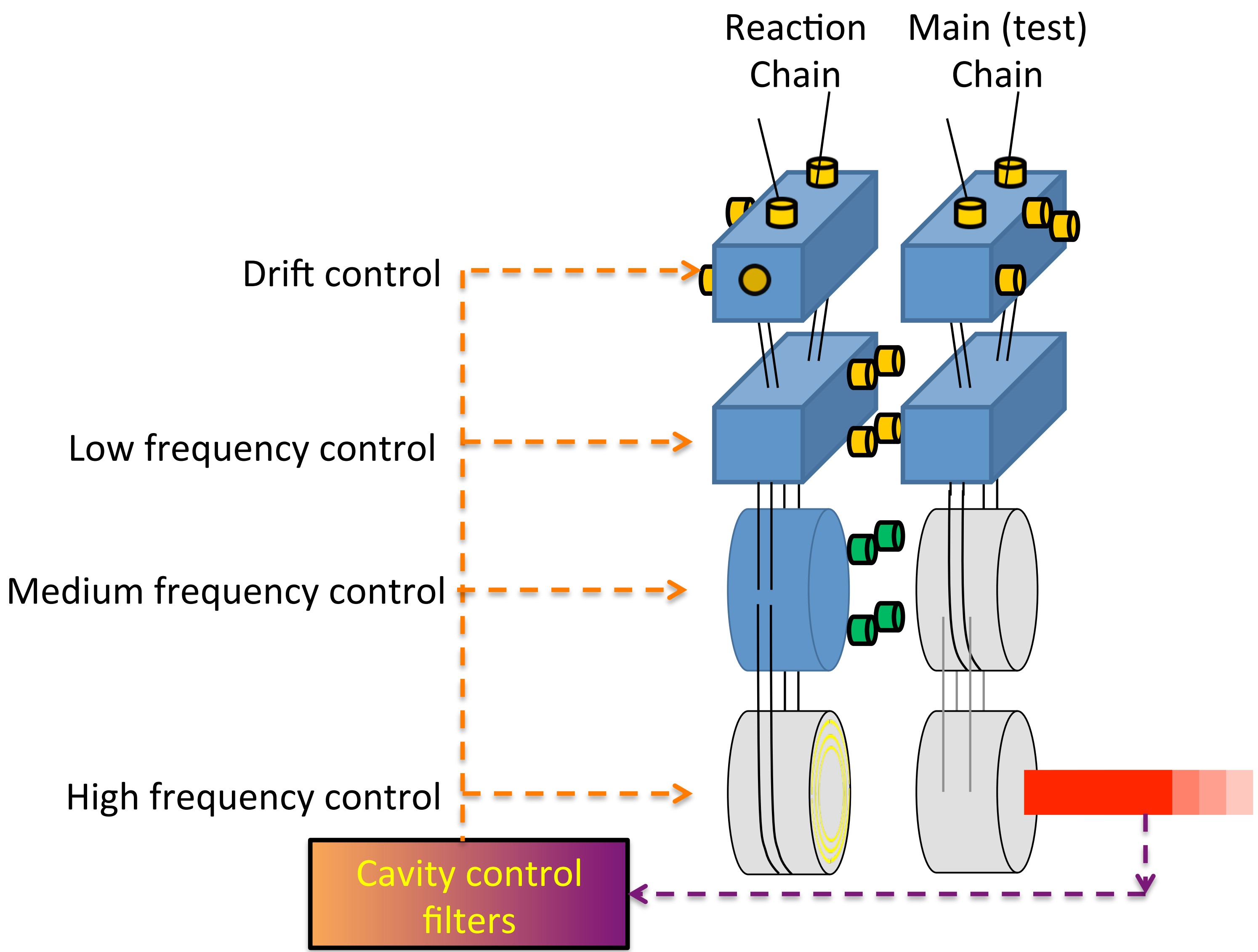
Damping feedback loop



Damping filters in practice



Cavity control

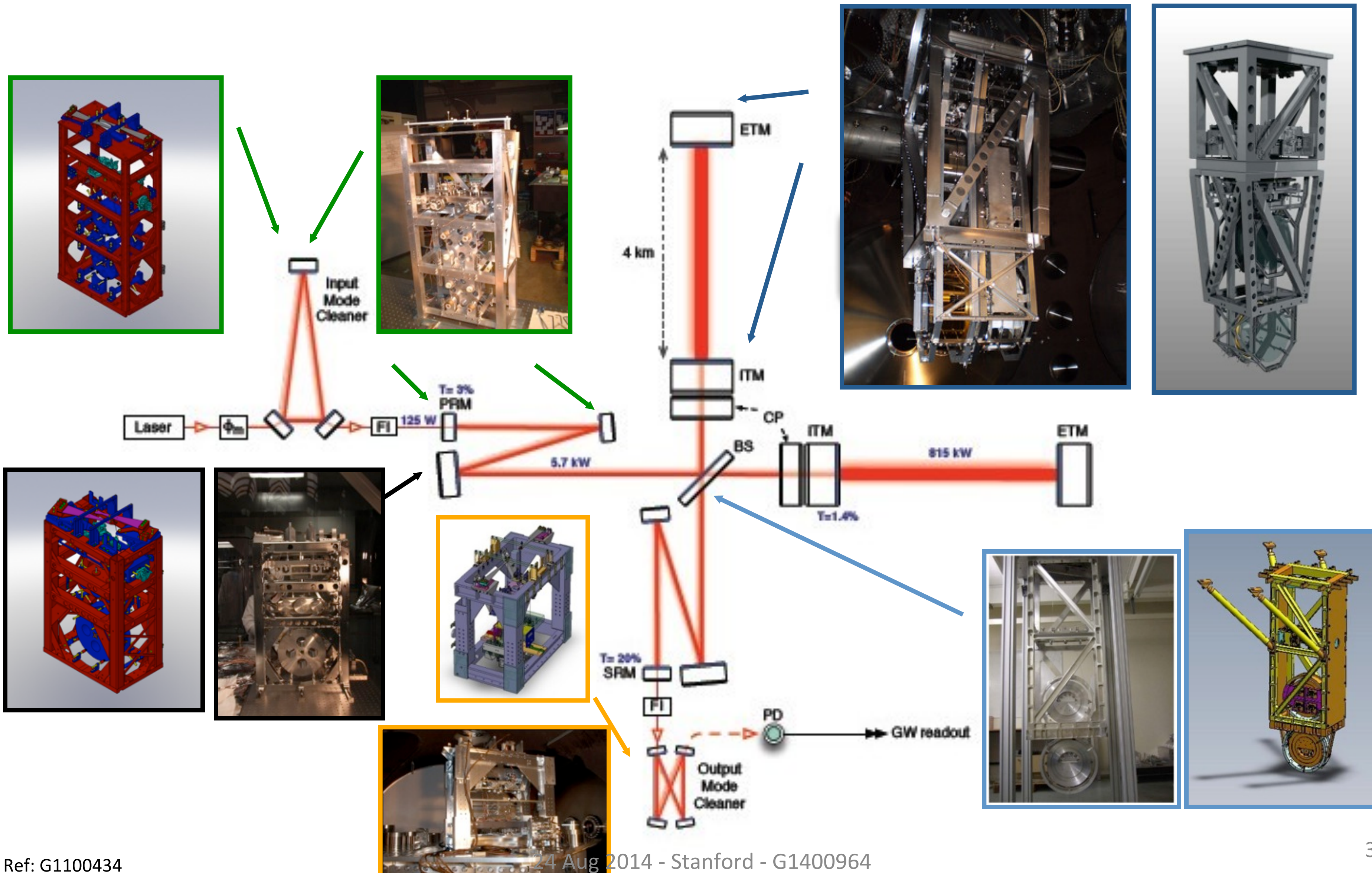


Resources on control techniques

- Damping
  - Loop shaping and modal damping - P1200009 http://scitation.aip.org/content/aip/journal/rsi/83/4/10.1063/1.4704459?ver=pdfcov
  - Modal damping - P1200057
  - Global damping - P1400085, G1200774
- Cavity control (aka hierarchical control)
  - G1200632
  - T1000242
  - Using a blended actuator technique, using experience from the SEI group's sensor blending: G1200692

Back Ups

Five Suspension Designs



Ref: G1100434

Output Mode Cleaner Double (OMCS)

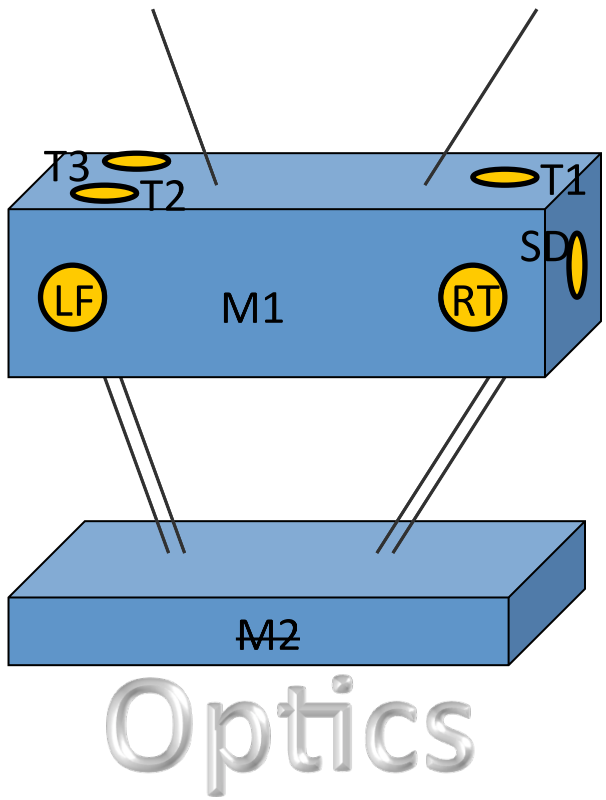
Location
- HAM 6, (12)

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

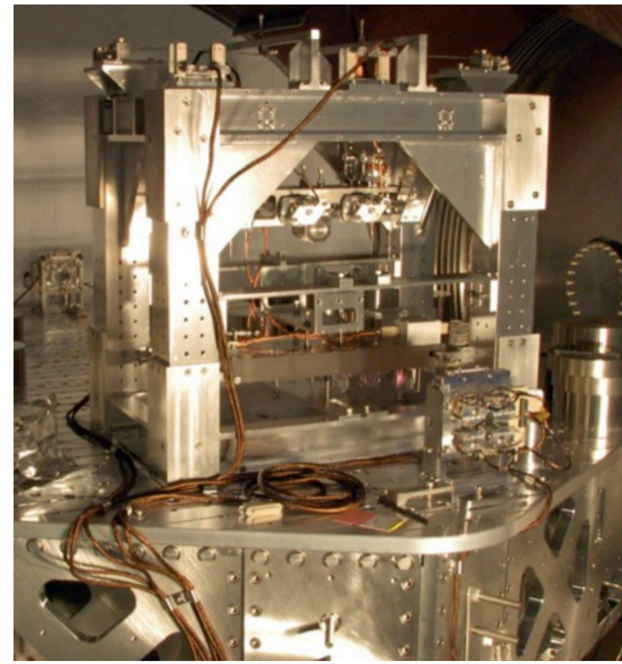
Sensors/Actuators
- BOSEMs at top mass

Top mass naming convention
- L1:SUS-OMC_M1…

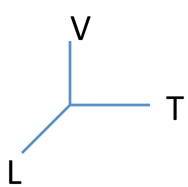
site 2 subsystem 3 unit 3,4 stage 2



In use during S6



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



Local coordinates

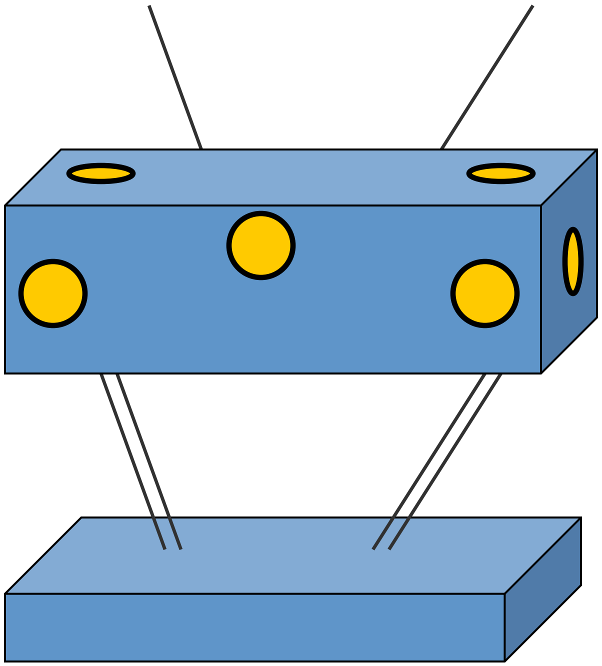
TransMon Double

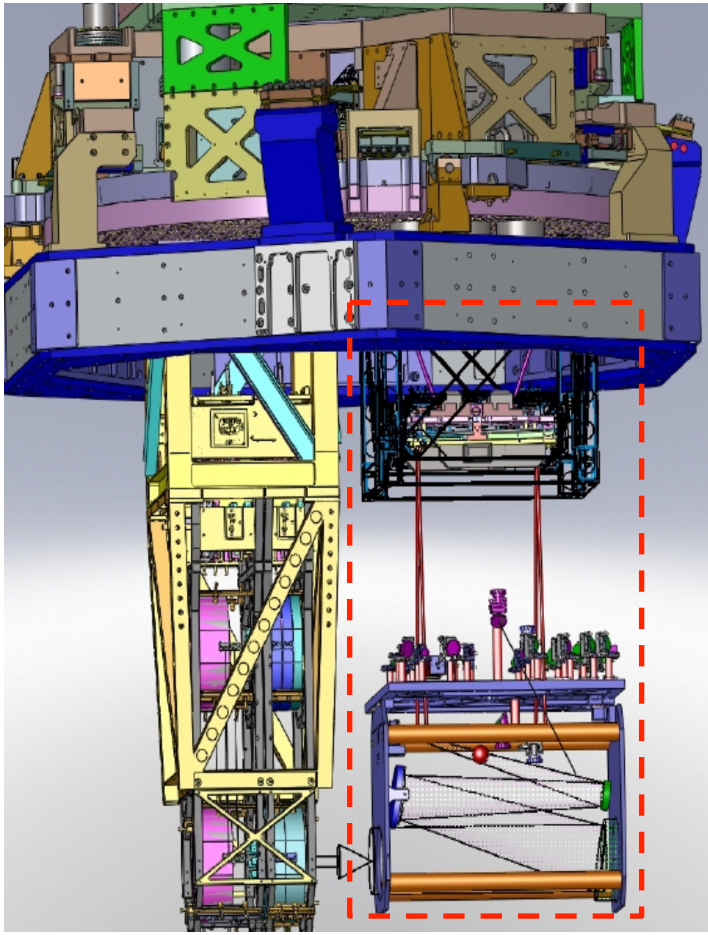
Location
- BSC 9, 10

Control
- Local – damping at top mass

Sensors/Actuators
- ● BOSEMs at top mass

Top mass naming convention
- L1:SUS-TRMX_M1…





Ref: E1000040

HAM Large Triple Suspension (HLTS)

Purpose
- PR3, SR3

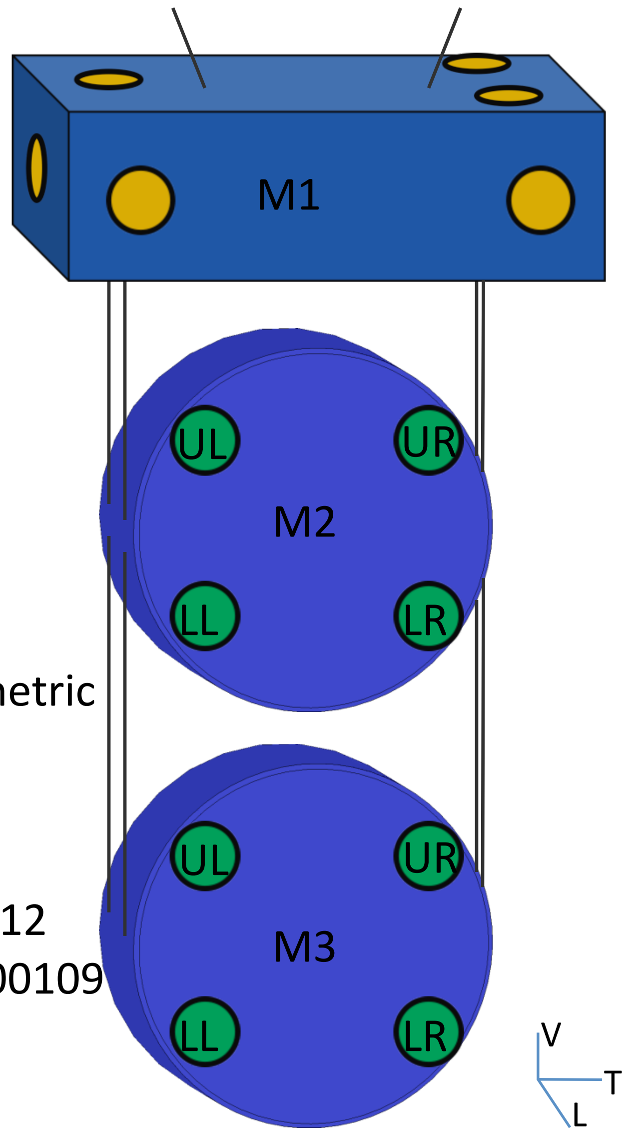
Location
- HAM 2, 5, (8, 11)

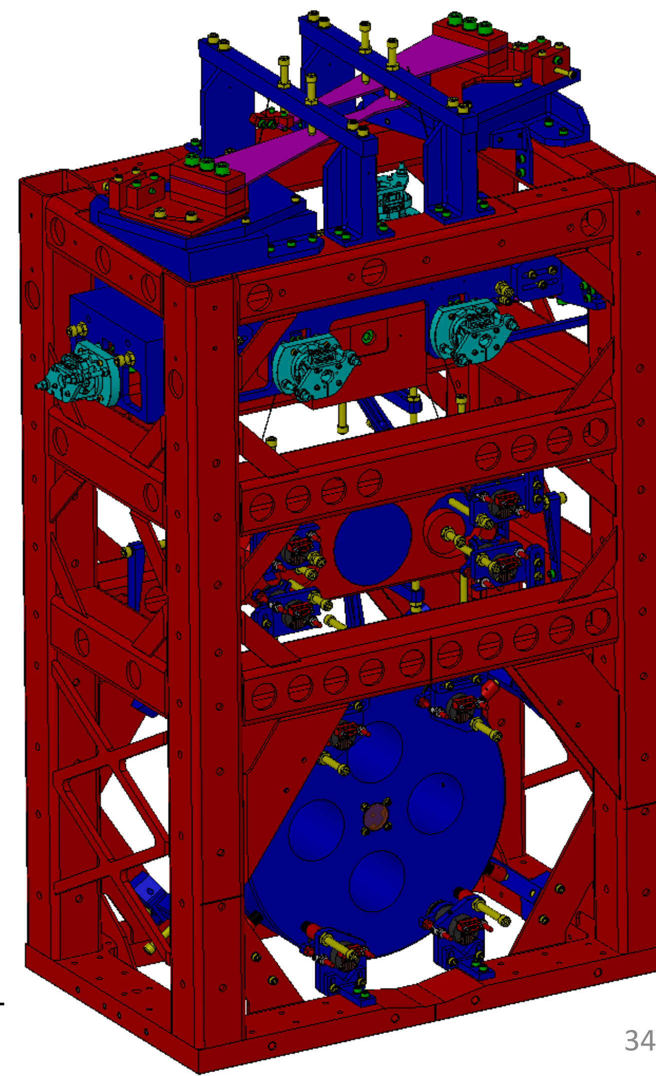
Control
- Local – damping at M1
- Global – LSC & ASC at all 3

Sensors/Actuators
- BOSEMs at M1
- 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)

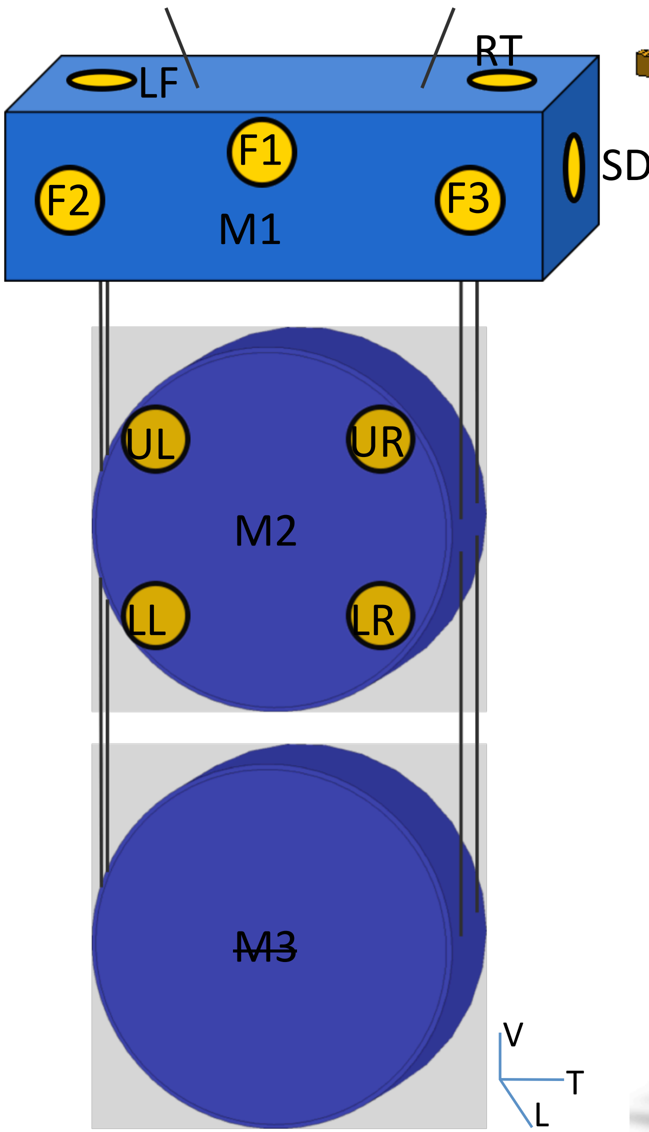
Location
- Beamsplitter – BSC 2, (4)
- (Fold Mirror – BSC 6, 8)

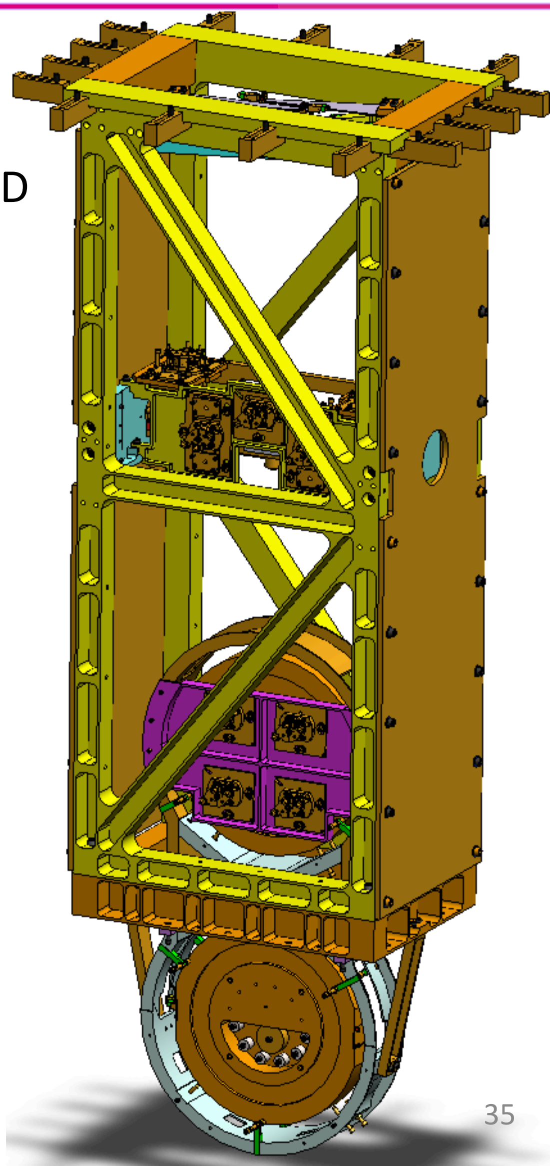
Control
- Local – damping at M1
- Global – LSC & ASC at M2

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

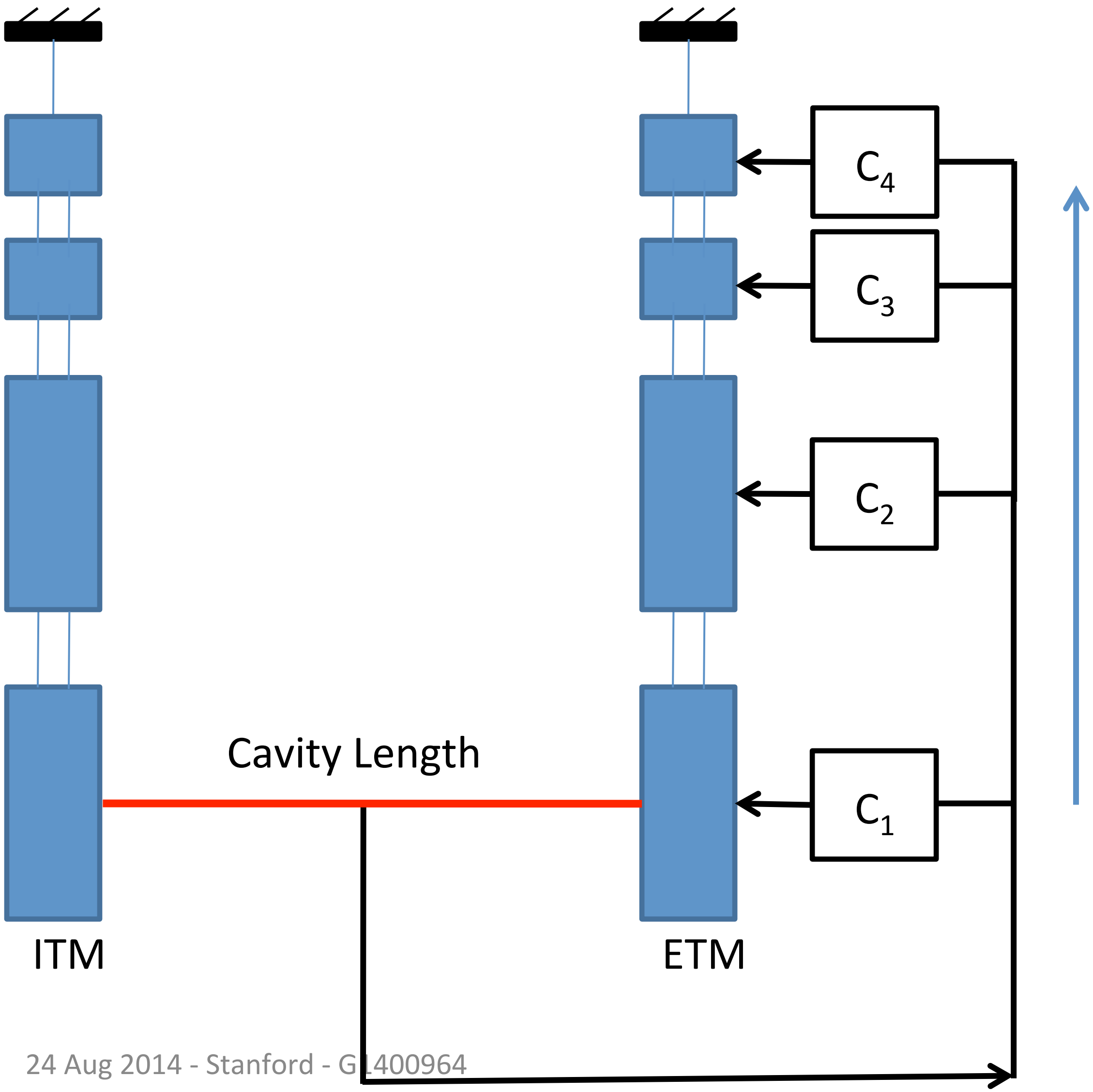
Naming: L1:SUS-FMX_M1…

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





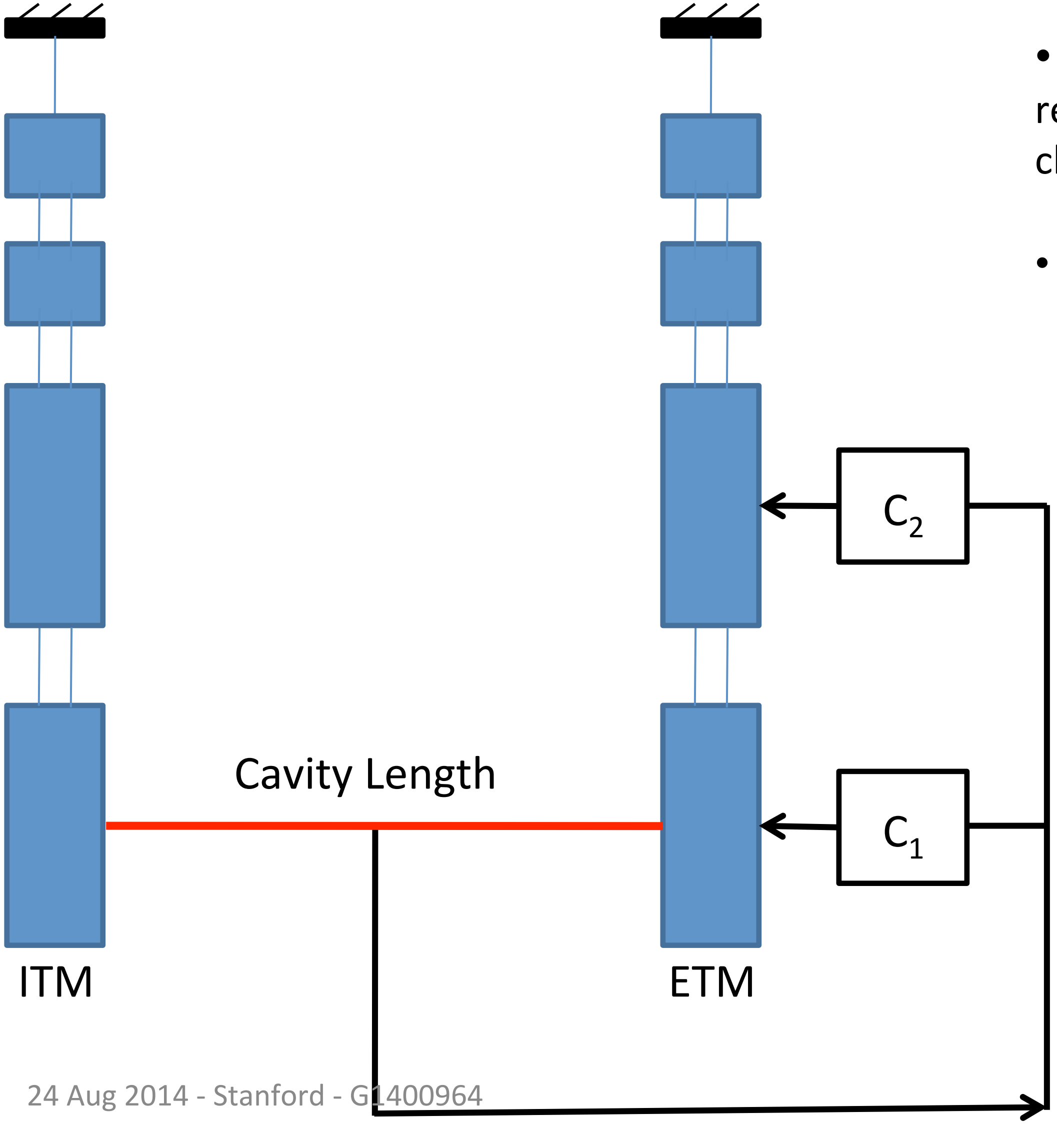
Global Cavity Control (LSC)



Each stage has limited range, so the control is distributed up the chain with:

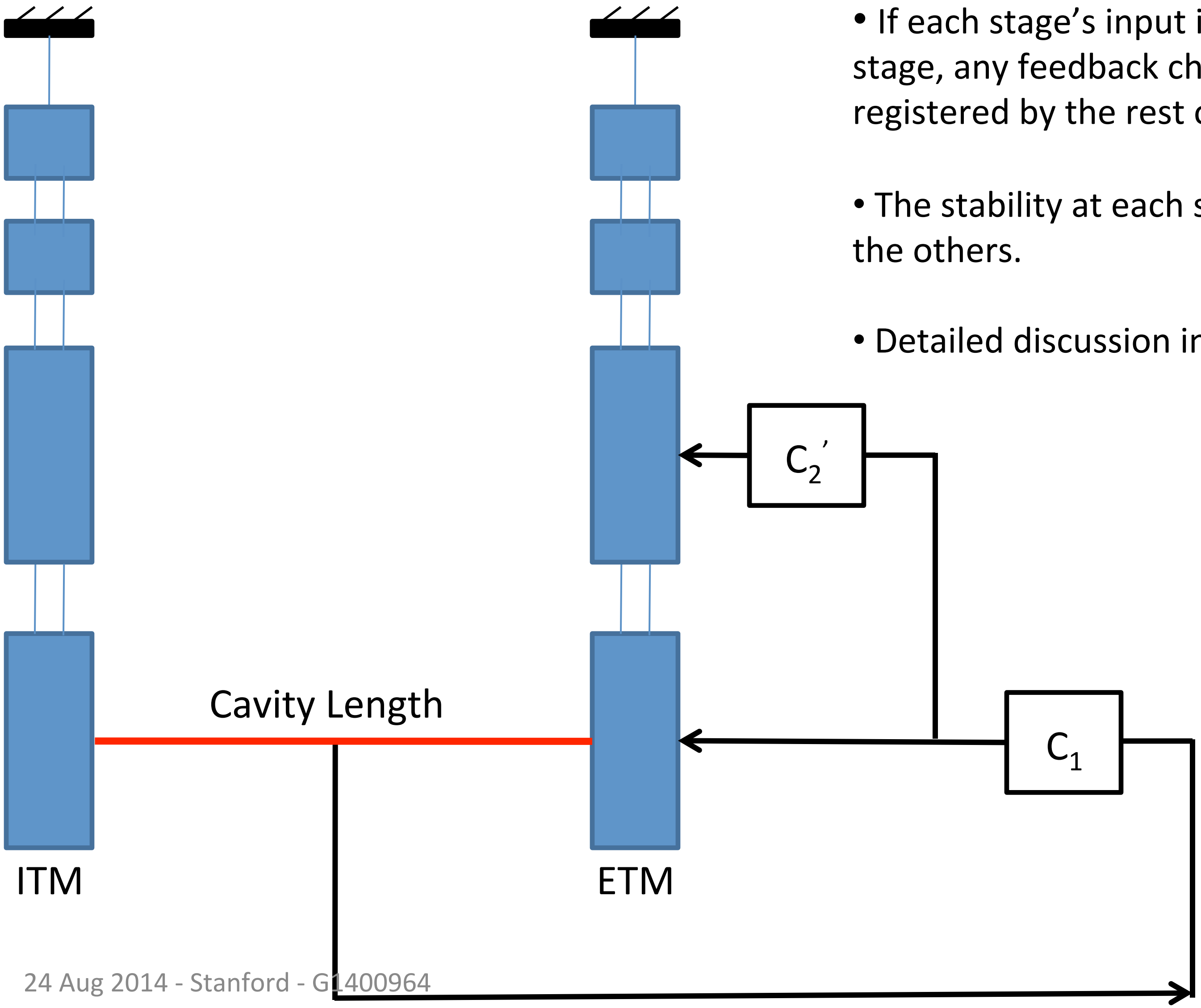
- Increasing control force
- Lower frequency control

Parallel Control of Cavity Length



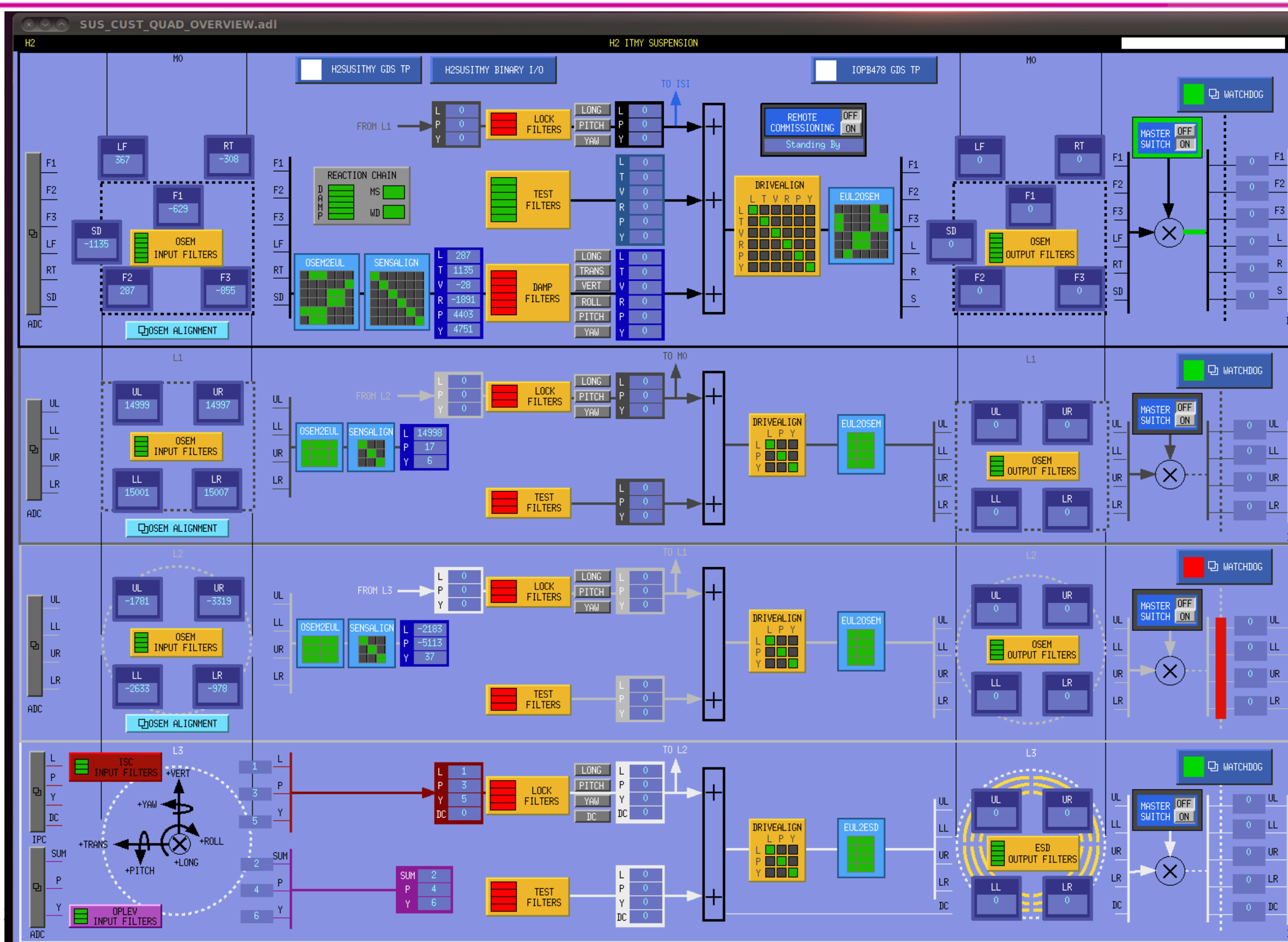
- With parallel feedback, changing one loop requires changing the others to account for changes in gain and stability.
- The stability of all stages are coupled

Hierarchical Control of Cavity Length

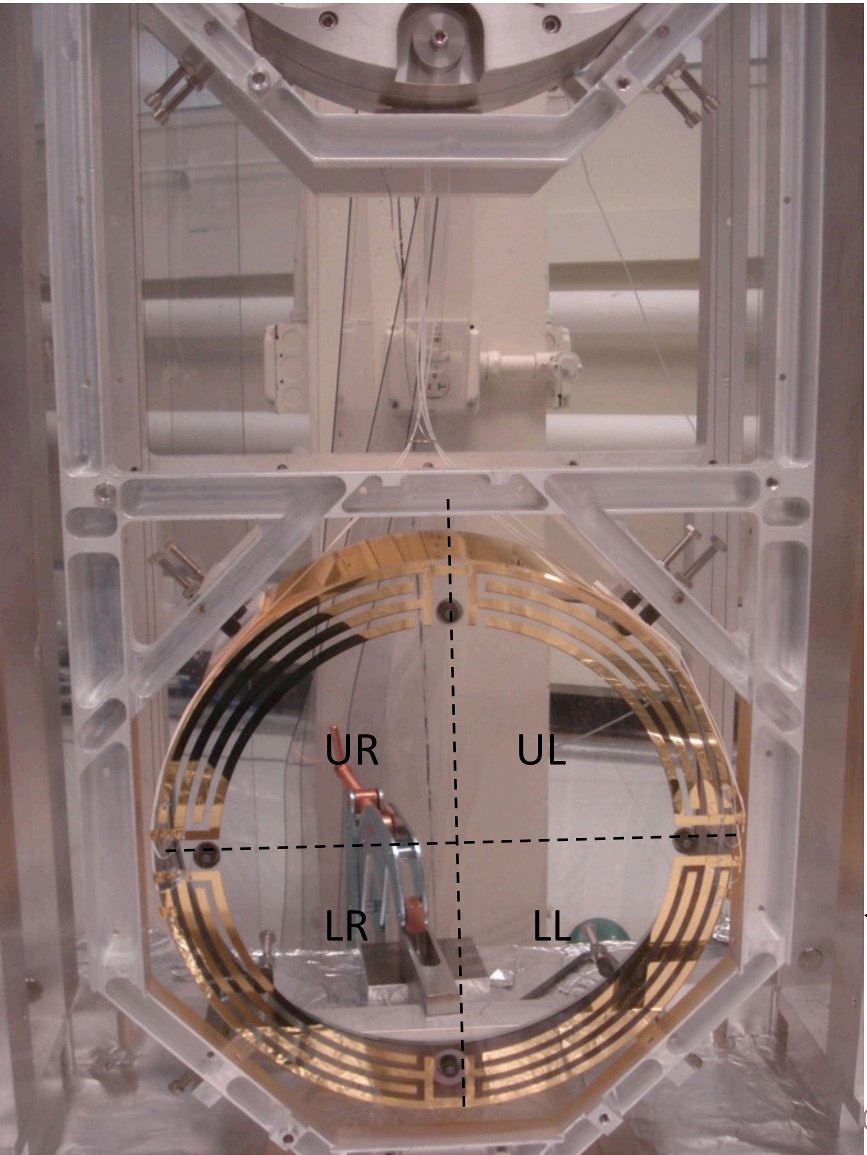


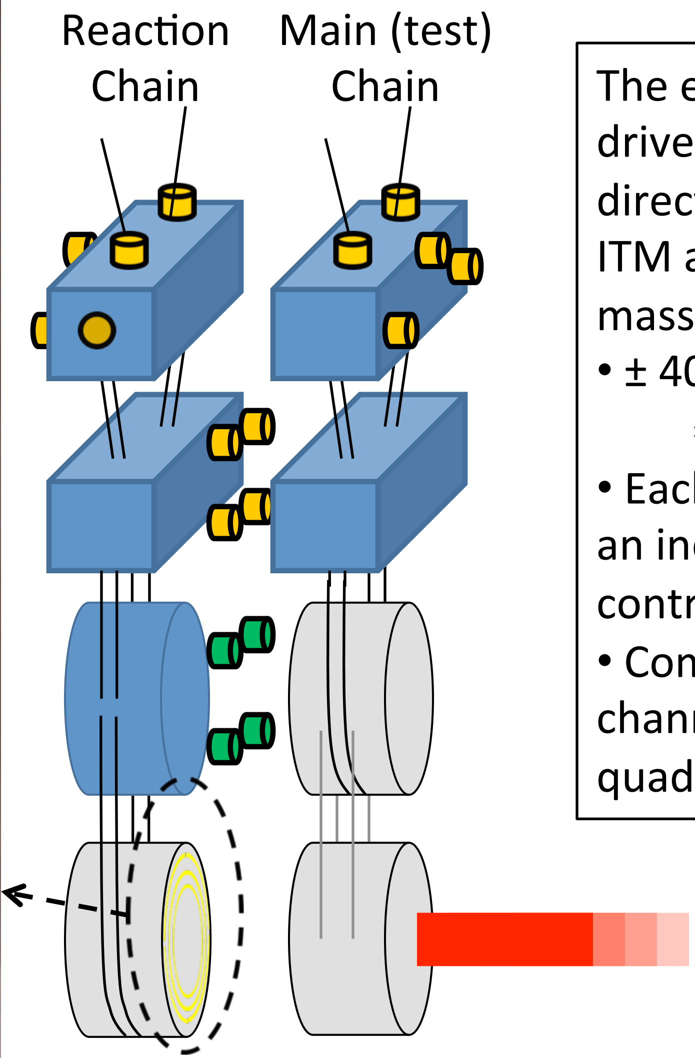
- If each stage's input is the output of the previous stage, any feedback change is automatically registered by the rest of the loop.
- The stability at each stage is independent from the others.
- Detailed discussion in T1000242.

Quad MEDM Overview Screen



Quadruple Suspension ESD





The electrostatic drive (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

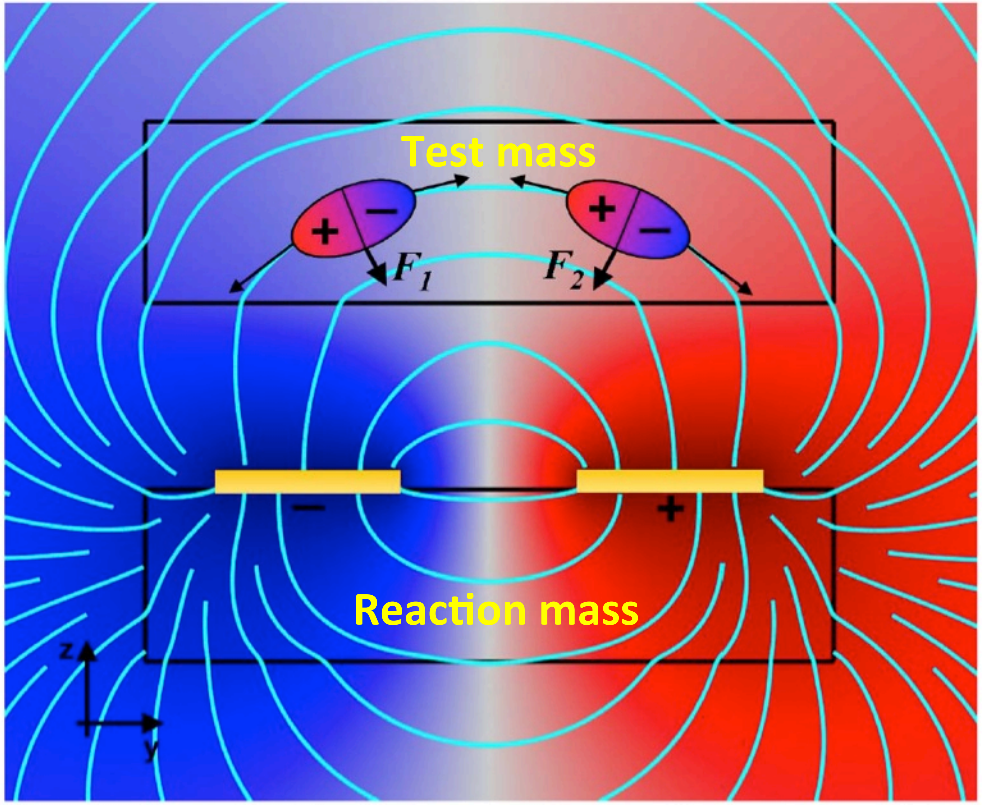
Quadruple Suspension ESD

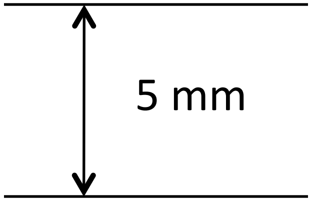
$F = \alpha \Delta V^2$

- α = coupling coefficient, depends on geometry

- ΔV = differential voltage across traces

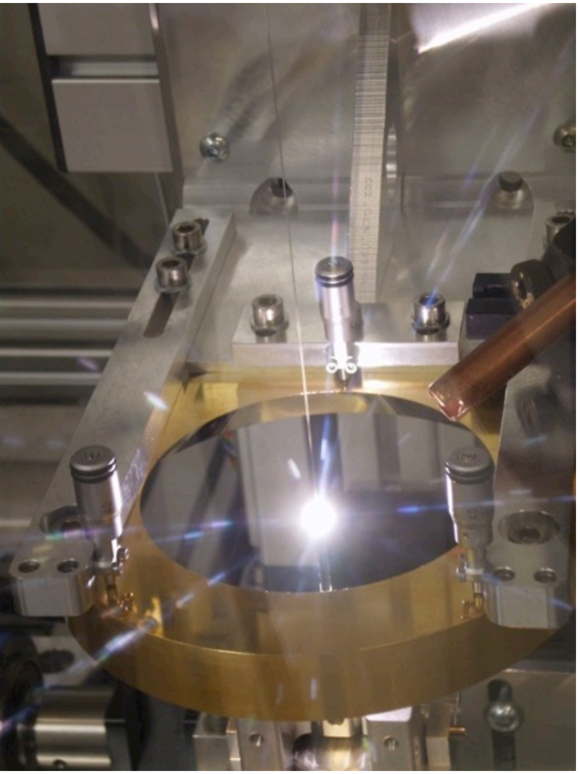
Linearization occurs in the control!



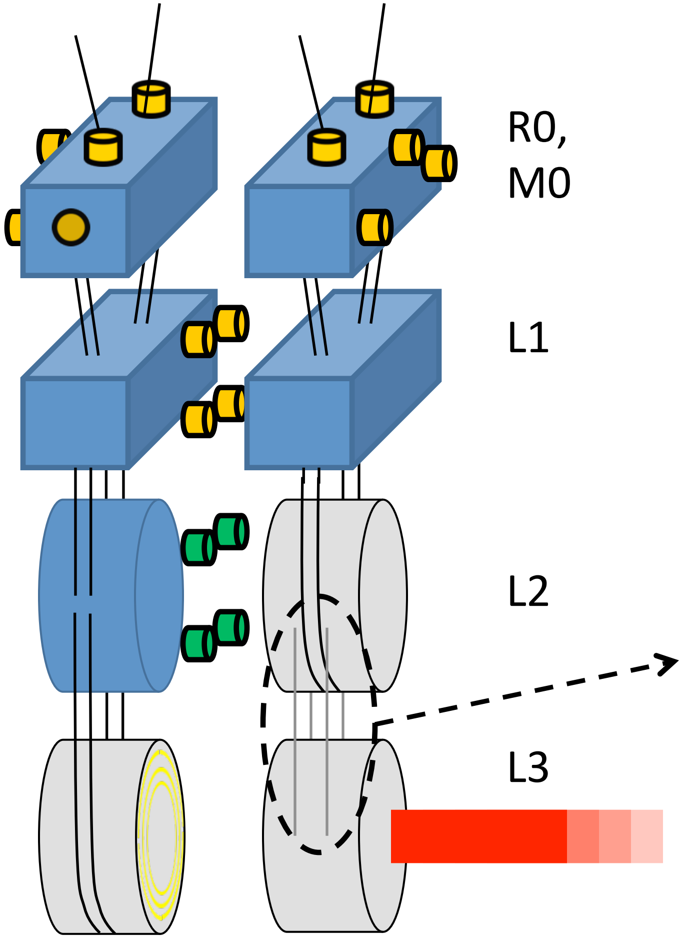


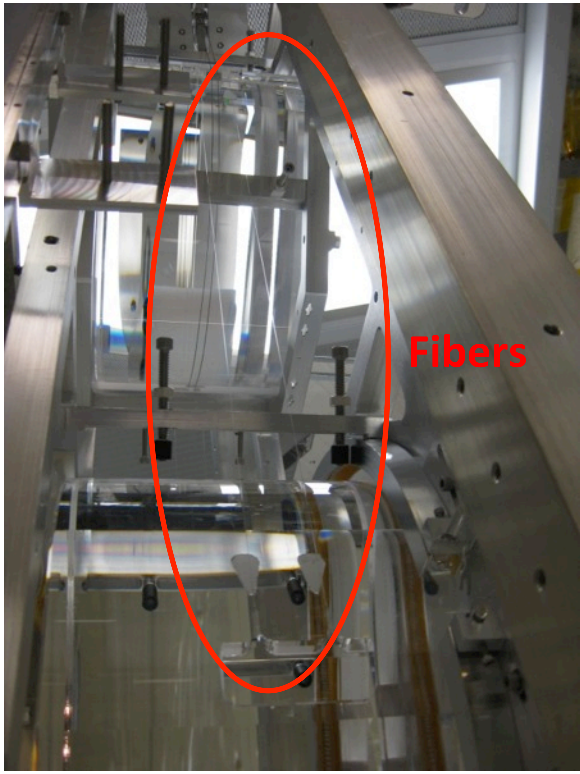
Cartoon diagram illustrating the working principle of the ESD. The upper rectangle represents the test mass containing two polarized molecules; the lower rectangle represents the reaction mass bearing two electrodes. Surface plot shows electrical potential with electric field lines shown in cyan (John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

Quadruple Suspension (Quad)



Pulling a fiber at MIT
7 May 2010





Newly welded monolithic quad at MIT
11 May 2010

aLIGO Noise Budget