Advanced LIGO Seismic Isolation and Control

J. Kissel, B. Shapiro, A. Pele, S. Biscans,

for the LIGO SEI, SUS, ISC Teams

Part 1: Overview of aLIGO isolation systems

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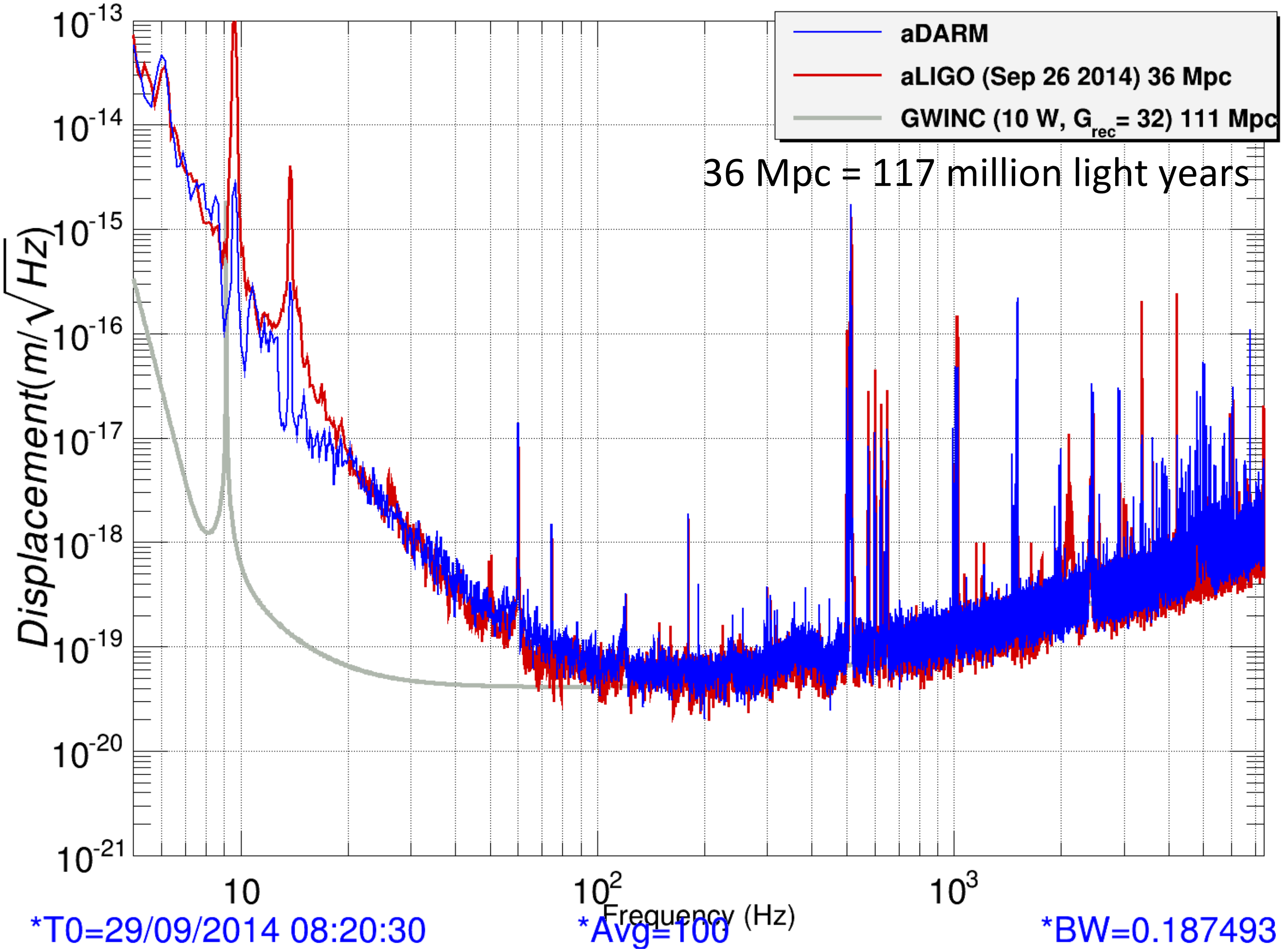
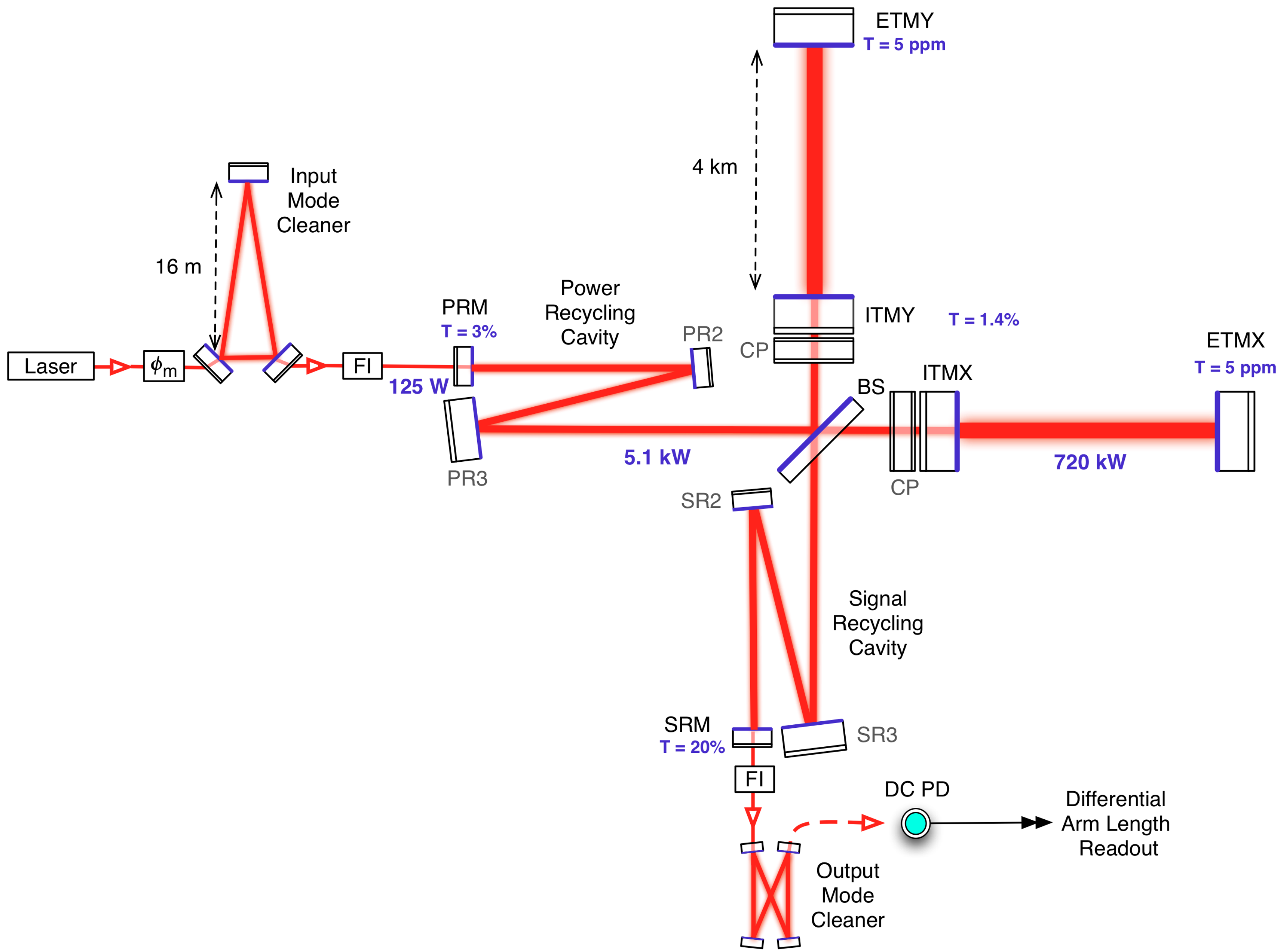
Recent Livingston Noise Floor



Sept 29, 2014. https://alog.ligo-la.caltech.edu/aLOG/uploads/4853_20140929051255_DARM_09_29.png

aLIGO (Simplified) Interferometer Layout

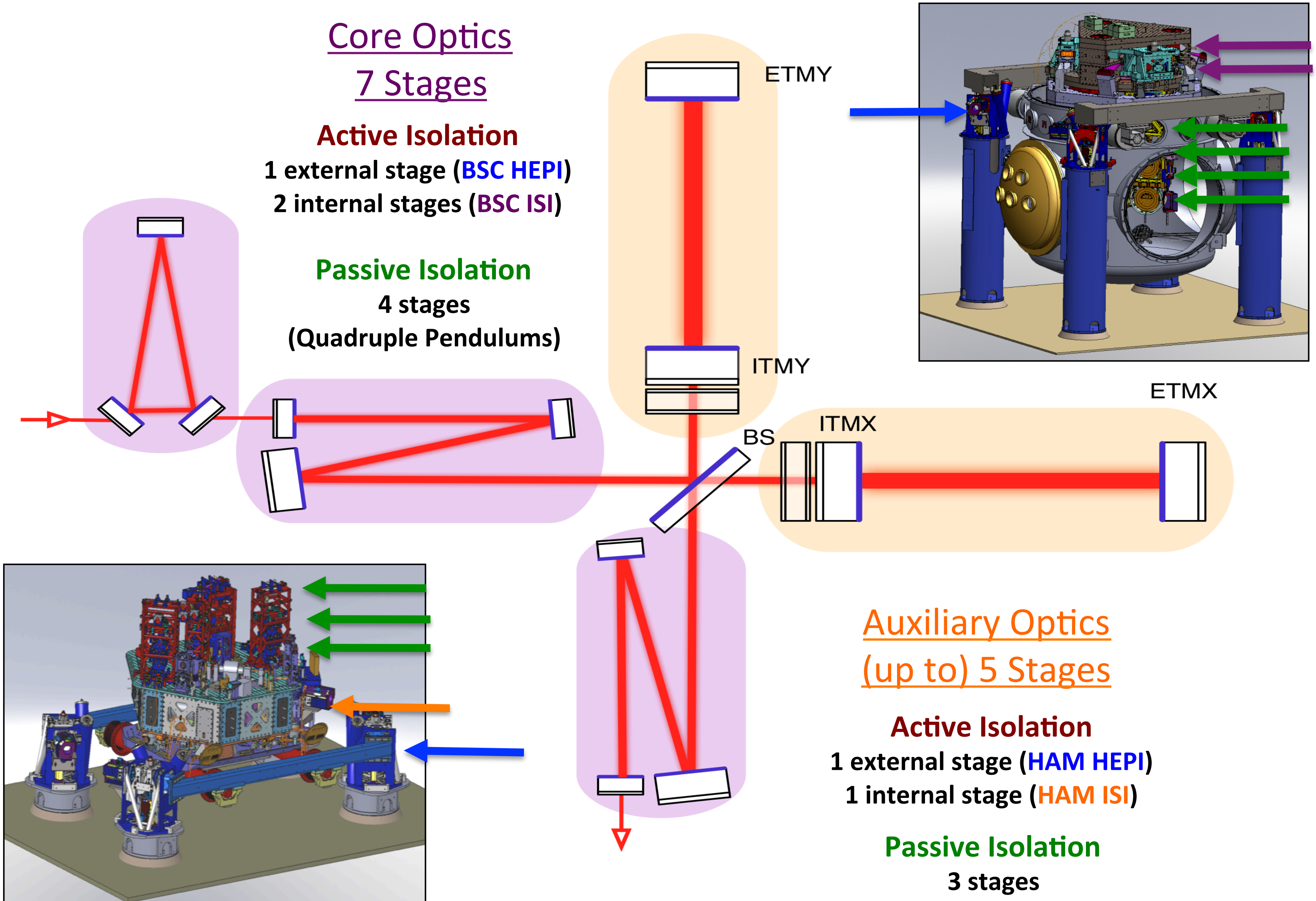


aLIGO Seismic Isolation

Core Optics
7 Stages

Active Isolation
1 external stage (BSC HEPI)
2 internal stages (BSC ISI)

Passive Isolation
4 stages
(Quadruple Pendulums)

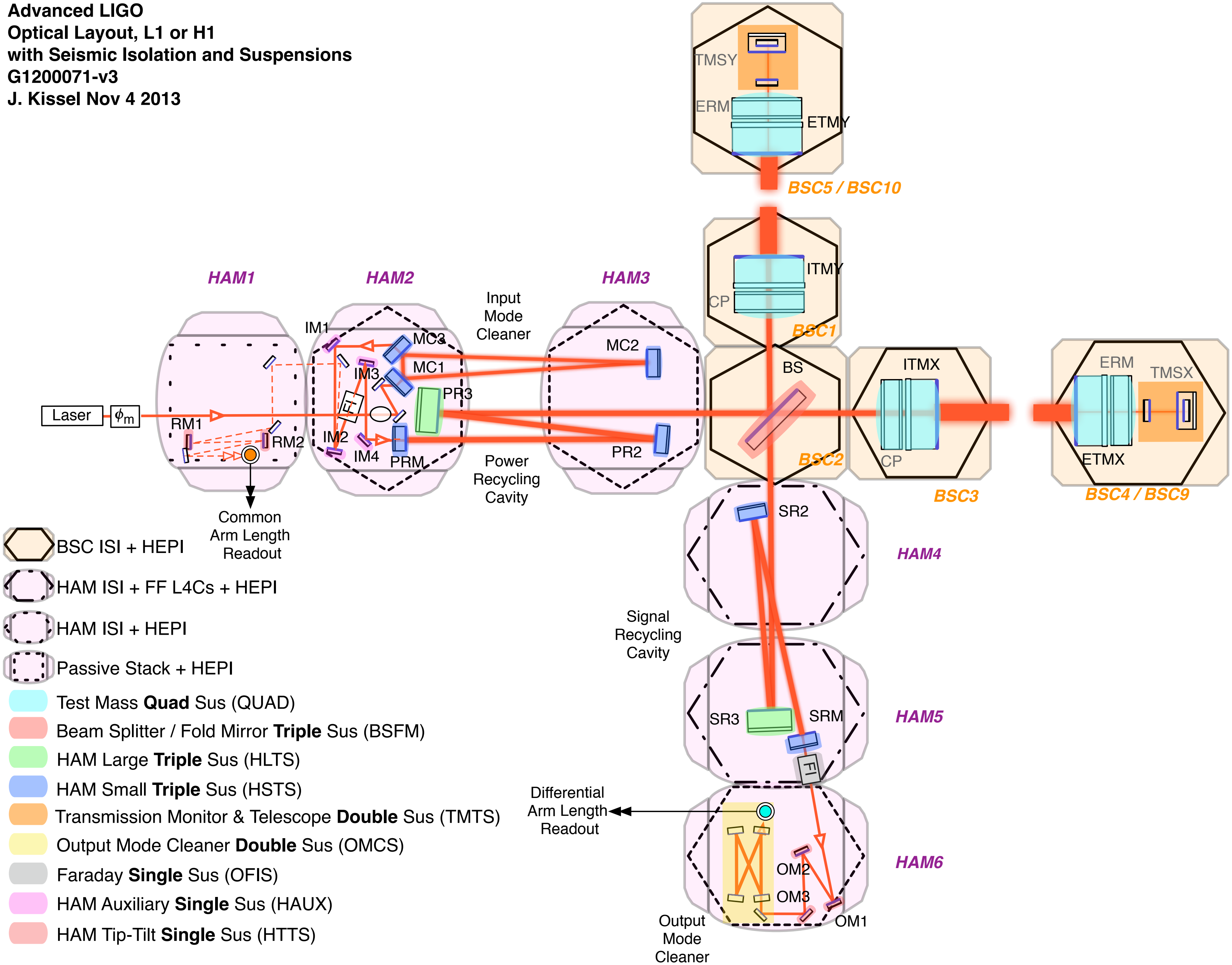


Auxiliary Optics
(up to) 5 Stages

Active Isolation
1 external stage (HAM HEPI)
1 internal stage (HAM ISI)

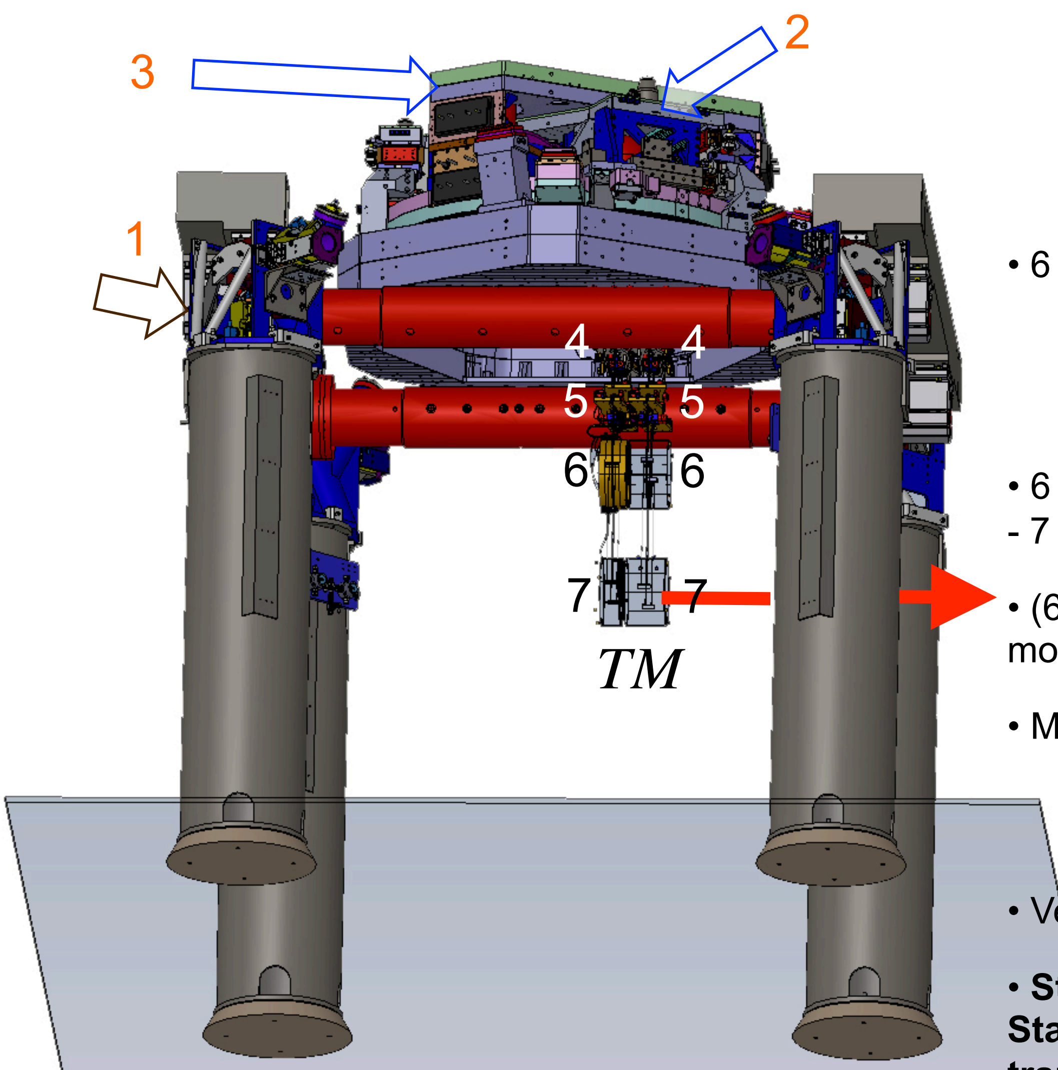
Passive Isolation
3 stages
(Triple Pendulums)

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



Hybrid Systems

Advanced LIGO - The Design



- 7 Stages of Isolation
  - Hydraulic Preisolation
  - Blade spring and wire flexures
  - Monolithic Final Stage
- 6 DOF sensing on stages 1 – 4, 3 DOF on 5 – 6
  - Inertial and displacement on stages 1-3
  - Displacement only on stages 4 - 6
- 6 DOF DC - 1kHz actuation on Stages 1 – 4, 3 DOF on 5 - 7
- (6+6+6+[3*6+4]) = 40 out of 42 Trans./Rot. resonant modes sensed and controlled
- Many-control-loop system
  - Sensor blending, Feed back, Feed forward, Sensor Correction, Heirarchical control
- Versatile 800 kg payload
- **Stage 1 – 3 "Performance limited by sensor noise," Stage 4 – 7 "Performance limited by direct transmission of platform motion"**

Hybrid Systems
The Comparison

All isolation systems are hybrid.

• **Not** “Passive” vs. “Active”

Every isolation system uses a combination of “passive” pendula as well as “active” sensors and actuators for some degrees of freedom

• **Not** “ISI” or “SA” vs. “Payload

Controls and mechanics don’t care how you’ve divided up assembly, all parts are connected and affect all dynamics

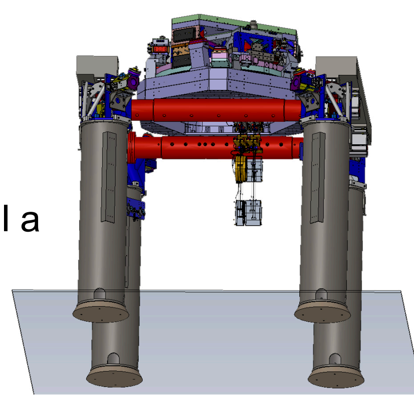
• **Not** “Soft” vs. “Stiff”

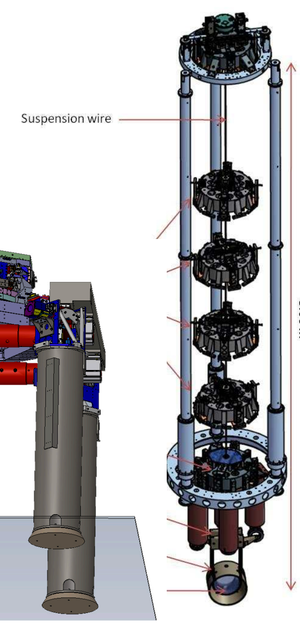
Instead “Soft” vs. “Very Soft”

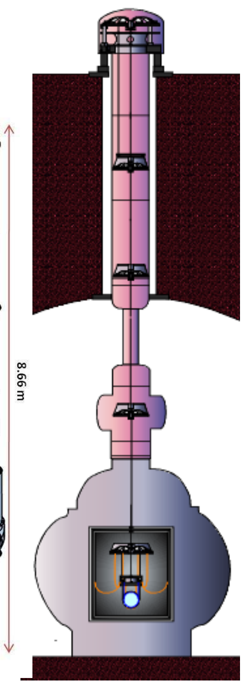
Every isolation system has some DOFs low frequency resonant modes and some with high frequency resonant modes. There *is* a difference between a 30 mHz system and a 400 mHz isolation system

• **Not** “Cheap” vs. “Expensive”

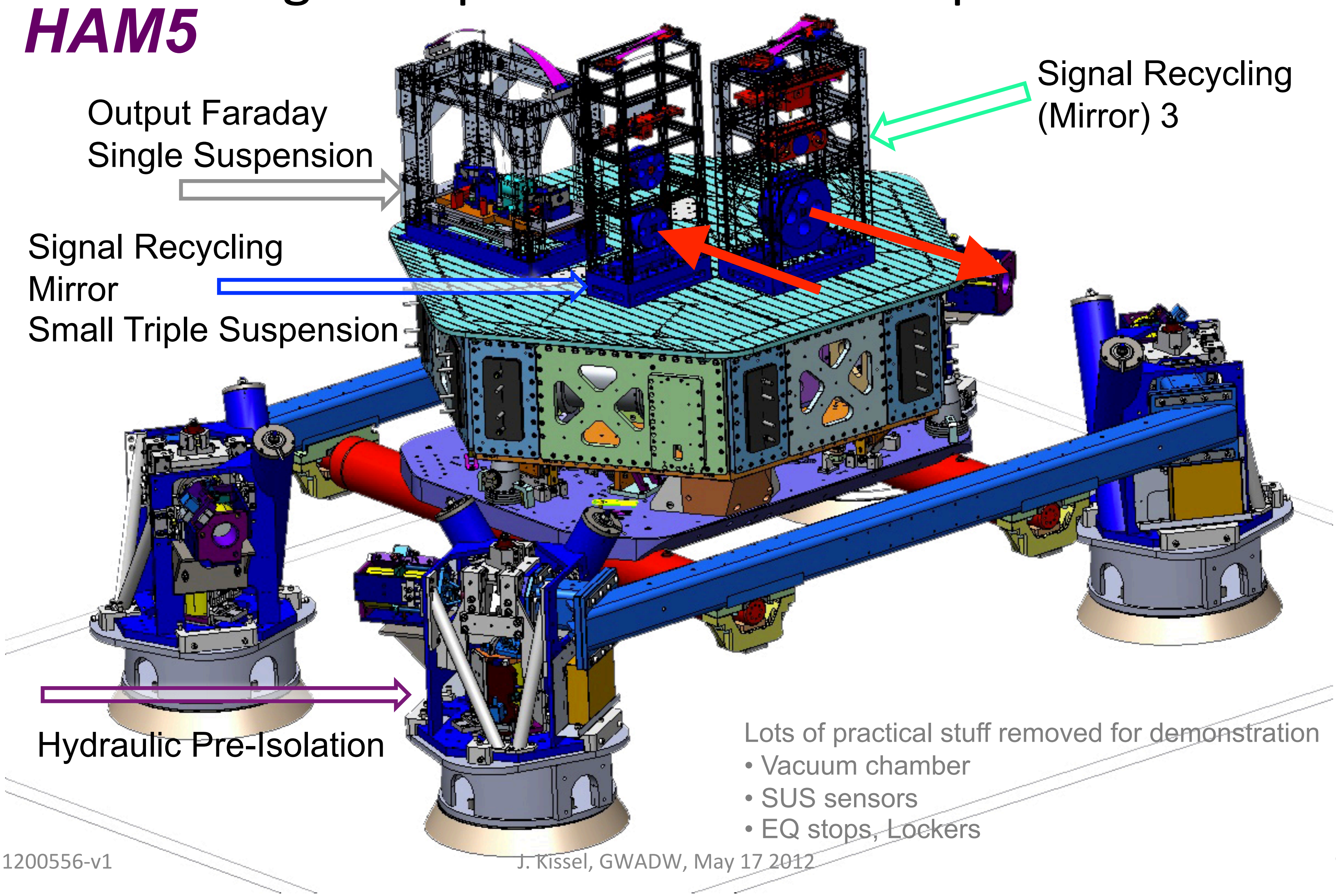
Each system has a whole bunch of precision engineered metal, some fancy sensors, digital control system, man-hours … it’s all a wash in the end







Advanced LIGO
A single output chamber is complicated!

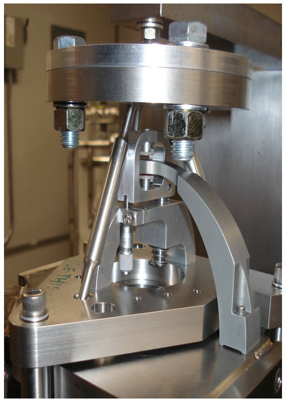


Lots of practical stuff removed for demonstration
- Vacuum chamber
- SUS sensors
- EQ stops, Lockers

SEI Sensors and Their Noise

"Low" Frequency

DC



IPS

Kaman's Inductive Position Sensors

Used On: HEPIs

Used For: ≤ 0.5 Hz Control, Static Alignment

Used 'cause: Reasonable Noise, Long Range

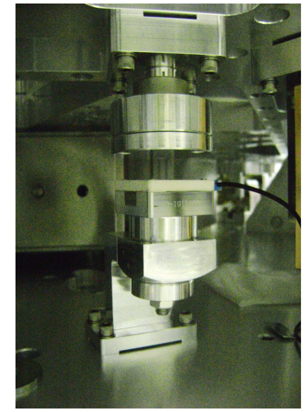
CPS

MicroSense's Capacitive Displacement Sensors

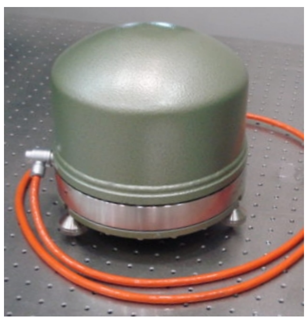
Used On: HAM-ISIs and BSC-ISIs

Used For: ≤ 0.5 Hz Control, Static Alignment

Used 'cause: Good Noise, UHV compatible



10 mHz



STS2

Strekheisen's STS-2

Used On: HEPIs

Used For: 0.01 ≤ f ≤ 1Hz Control

Used 'cause: Best in the 'Biz below 1 Hz, Triaxial

T240

Nanometric's Trillium 240

Used On: BSC-ISIs

Used For: 0.01 ≤ f ≤ 1Hz Control

Used 'cause: Like STS-2s, Triaxial, no locking mechasim -> podded

1 Hz

GS13

GeoTech's GS-13

Used On: HAM-ISIs and BSC-ISIs

Used For: ≥ 0.5 Hz Control

Used 'cause: awesome noise above 1Hz,

no locking mechanism -> podded

L4C

Sercel's L4-C

Used On: All Systems

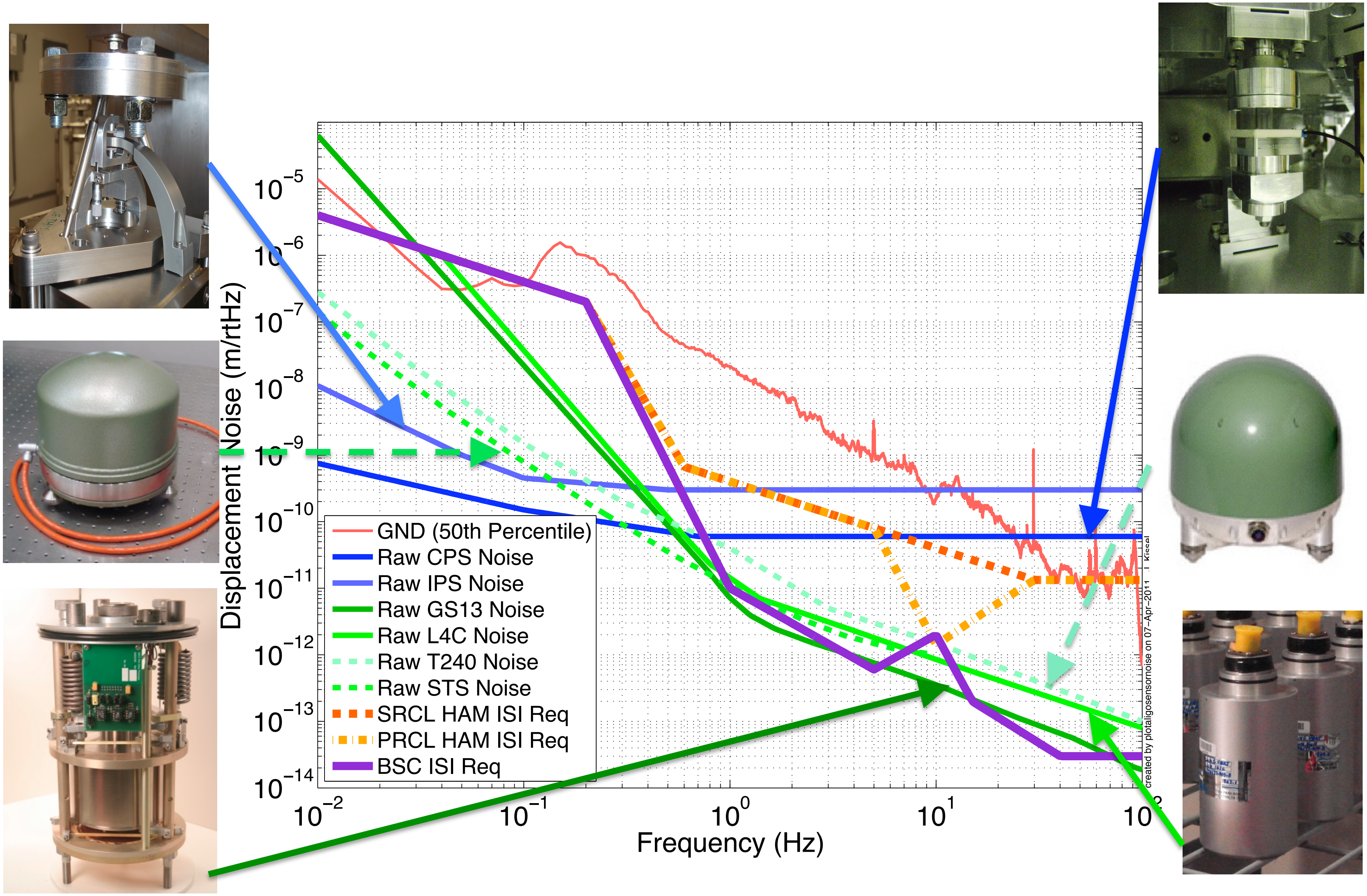
Used For: ≥ 0.5 Hz Control

Used 'cause: Good Noise, Cheap, no locking mechanism -> podded

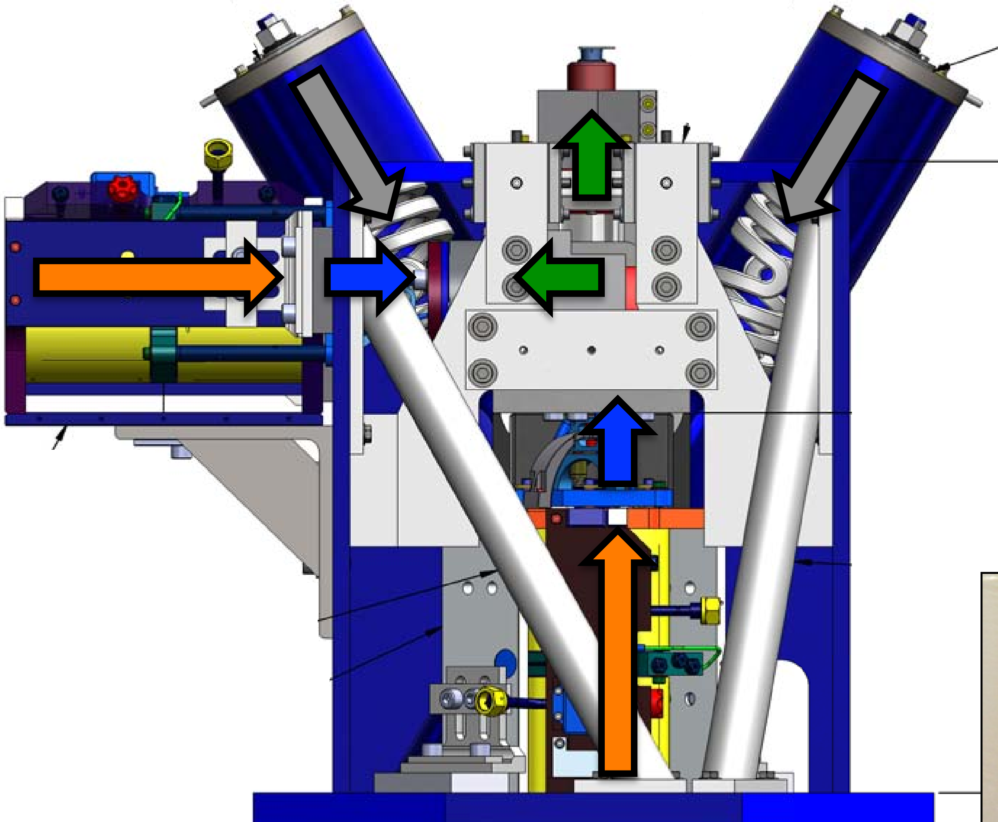
800 Hz

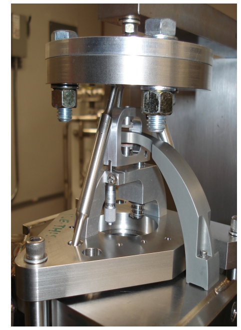
"High" Frequency

SEI Sensors and Their Noise



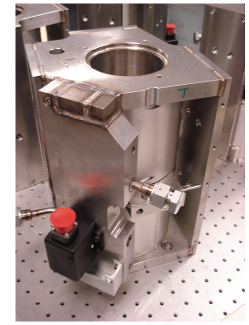
Where stuff is on HEPI



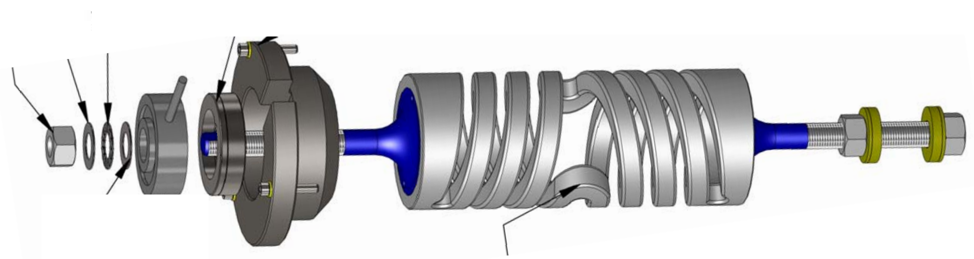


IPS
Position
Sensor

L4C
f = ~1 Hz
Inertial
Sensor

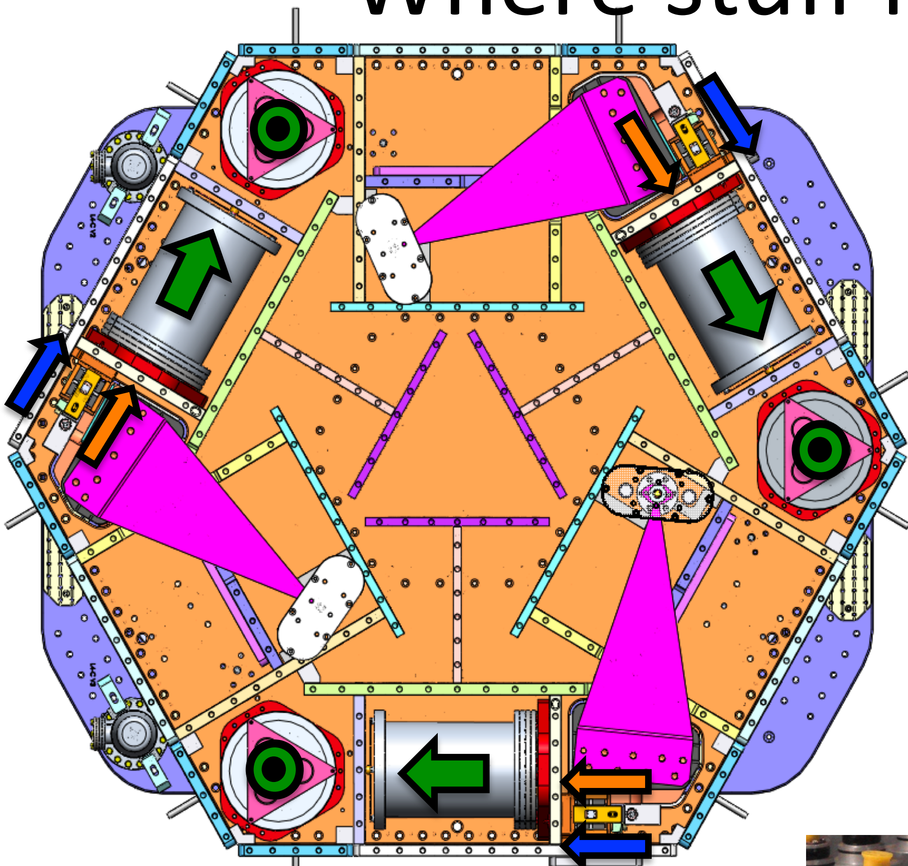


ACT
Hydraulic
Actuators

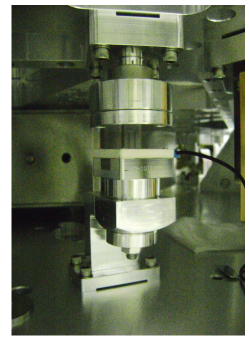


Euler Springs

Where stuff is on a HAM-ISI



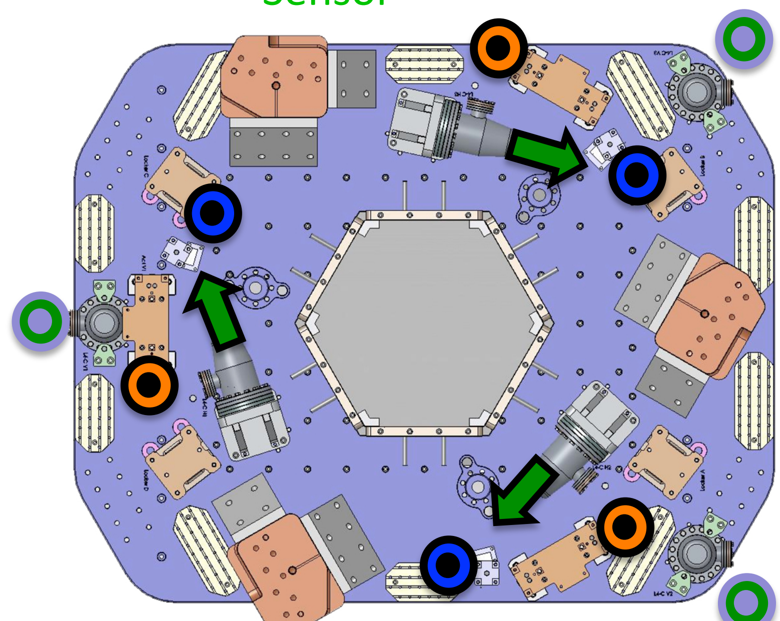
STAGE 1 (ST1)



CPS
Displacement Sensor

GS13
f = ~1 Hz
Inertial Sensor

L4C
f = ~1 Hz

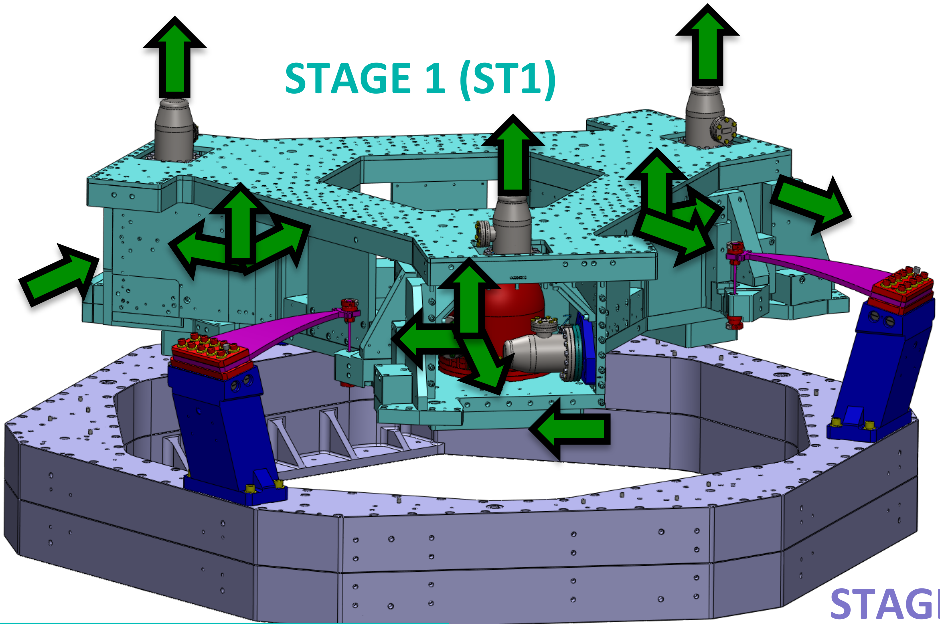


STAGE 0 (ST0)

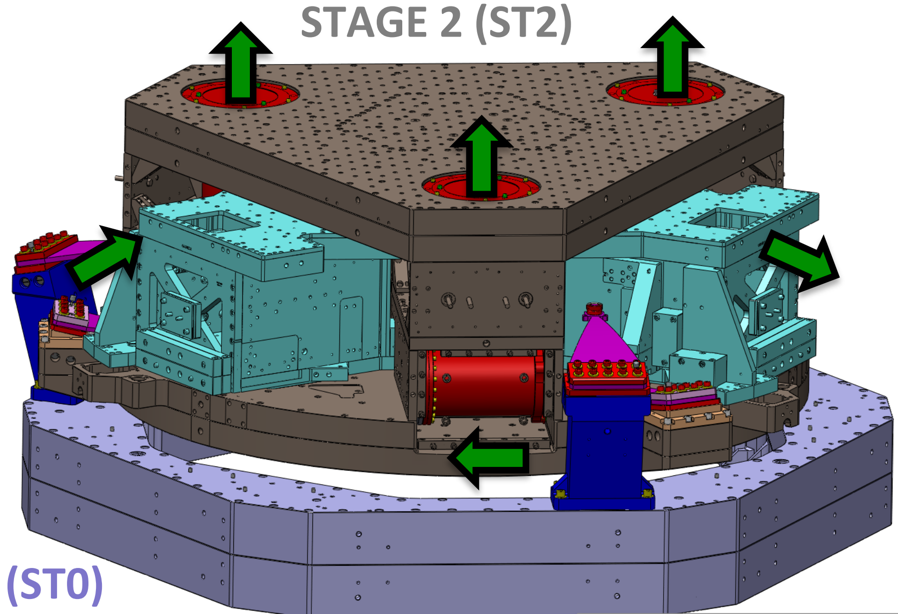
SRCL HAM-ISIs will have "extra" L4Cs on the support stage (ST0) for feed-forward use around 10 Hz

Where stuff is on a BSC-ISI

STAGE 1 (ST1)



STAGE 2 (ST2)



STAGE 0 (ST0)

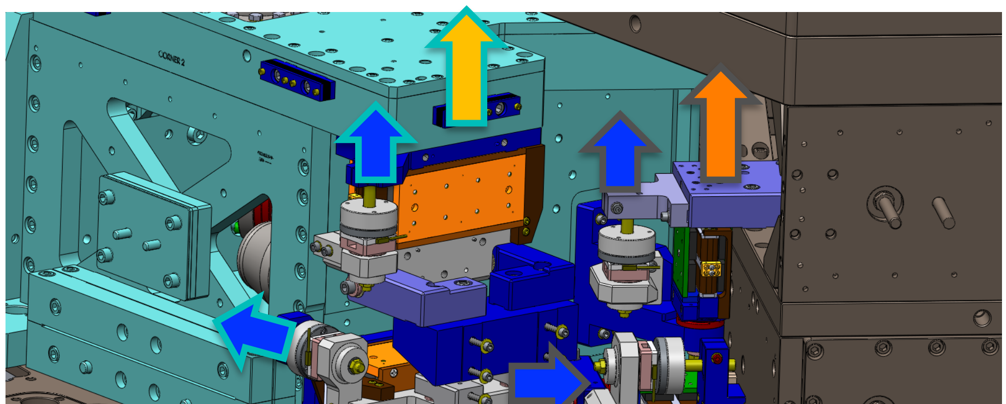
L4C

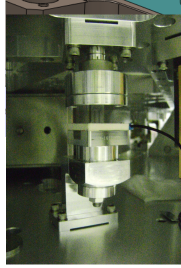
f = ~1 Hz

T240

f = ~5 mHz

Inertial Sensors





One corner's ST0-1 and ST1-2 position sensors and actuators

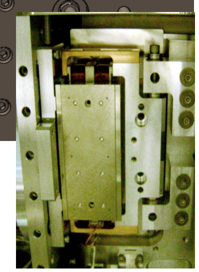
GS13

f = ~1 Hz

Inertial Sensor

CPS

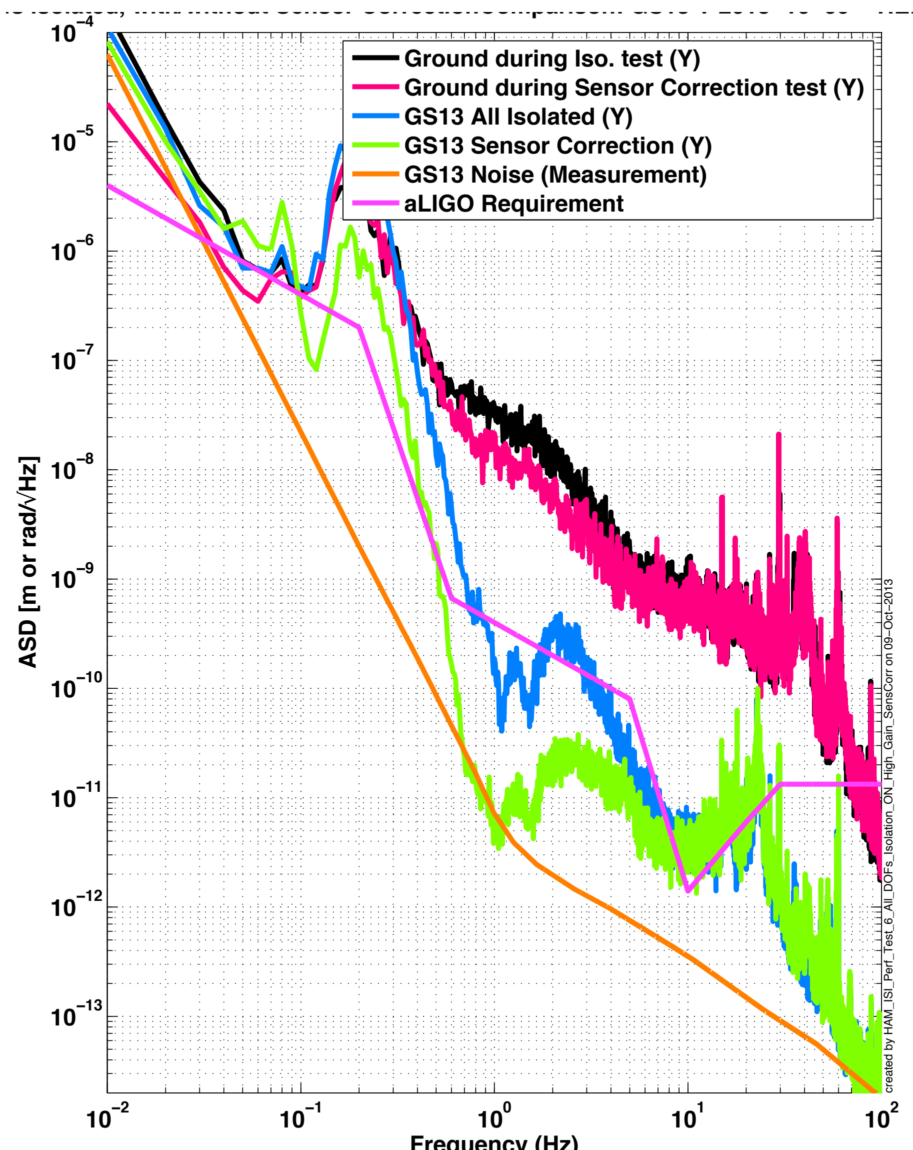
Displacement Sensor



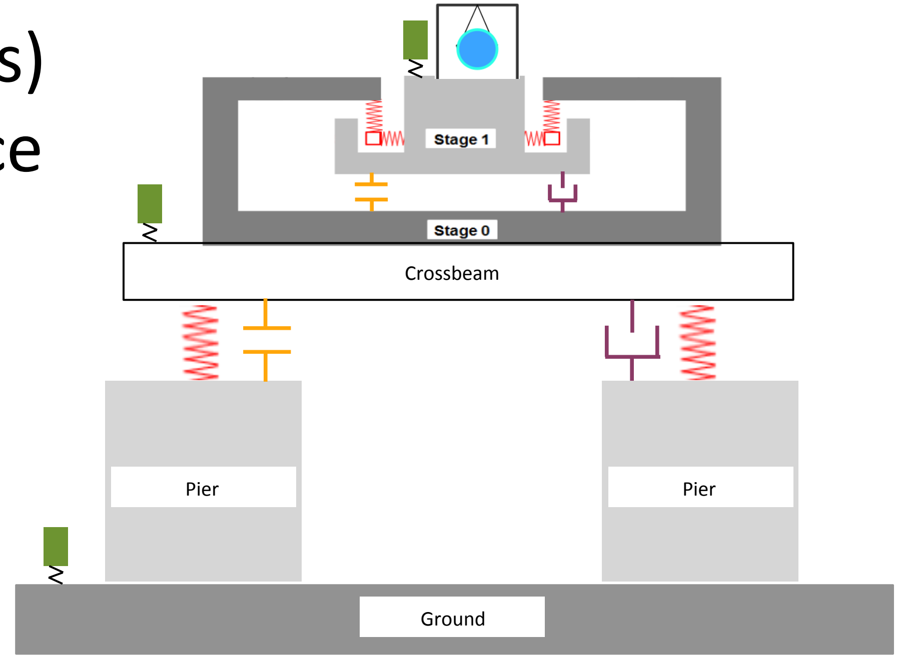
ACT

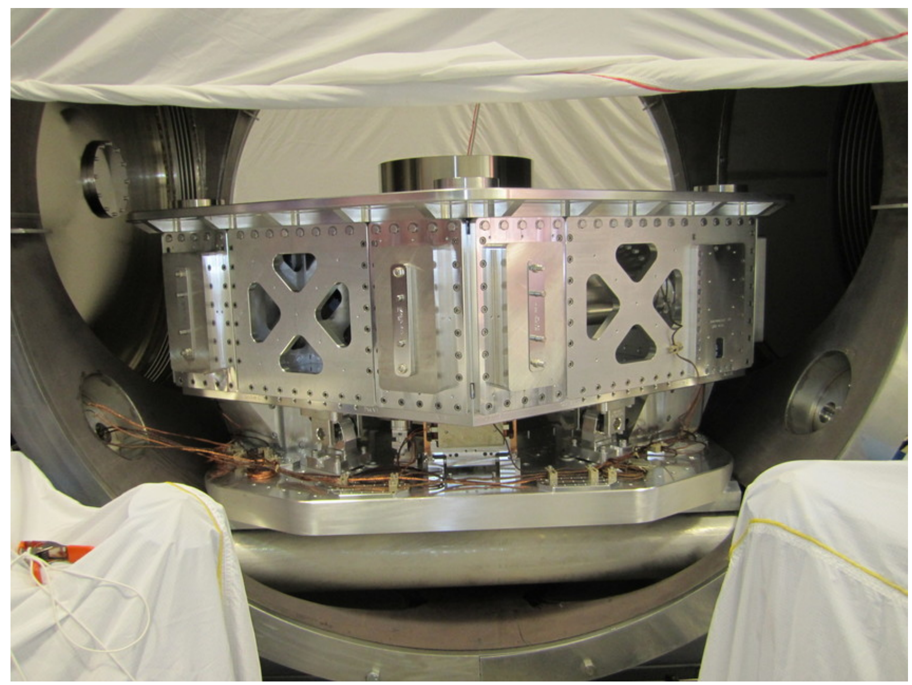
Electromagnetic Actuators

HAM chamber (auxiliary optics) configuration and performance

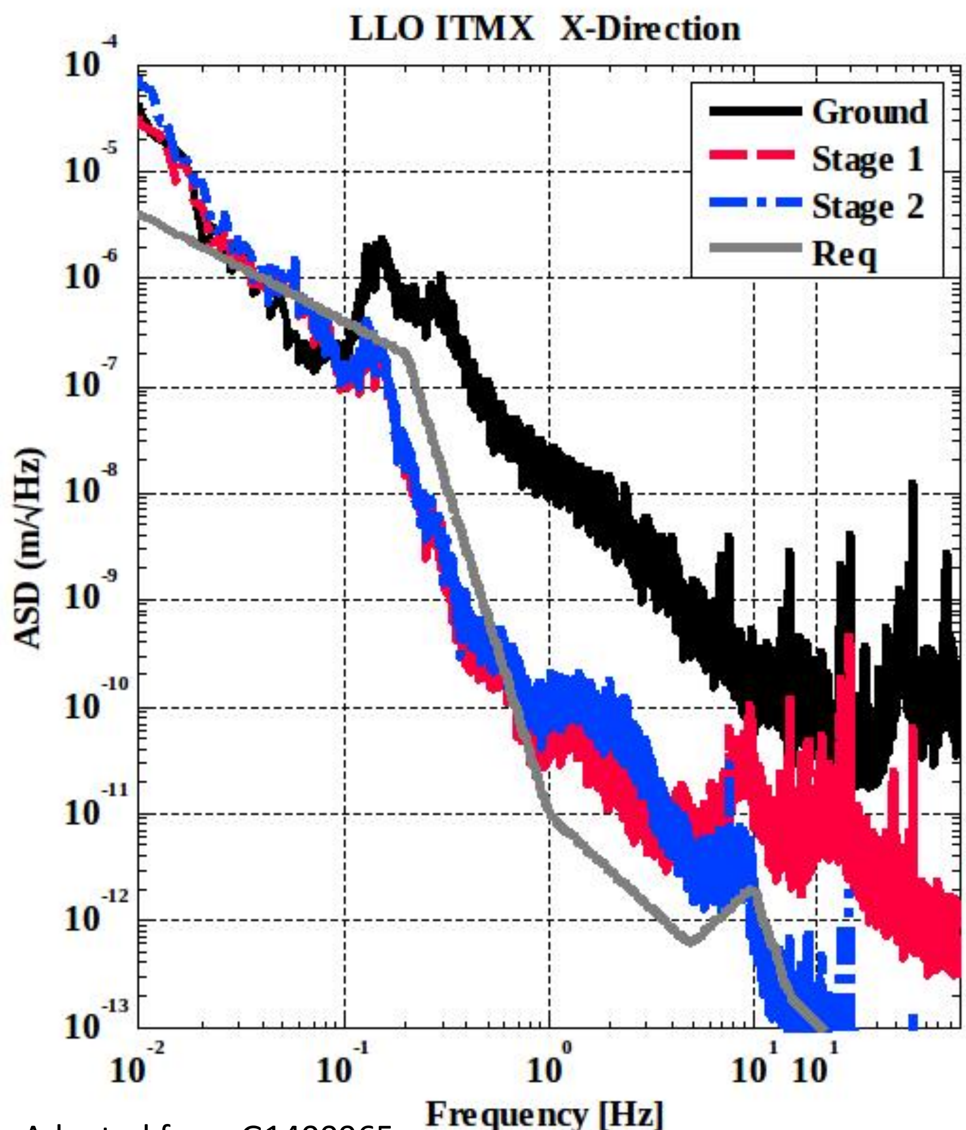


Adapted from G1400965

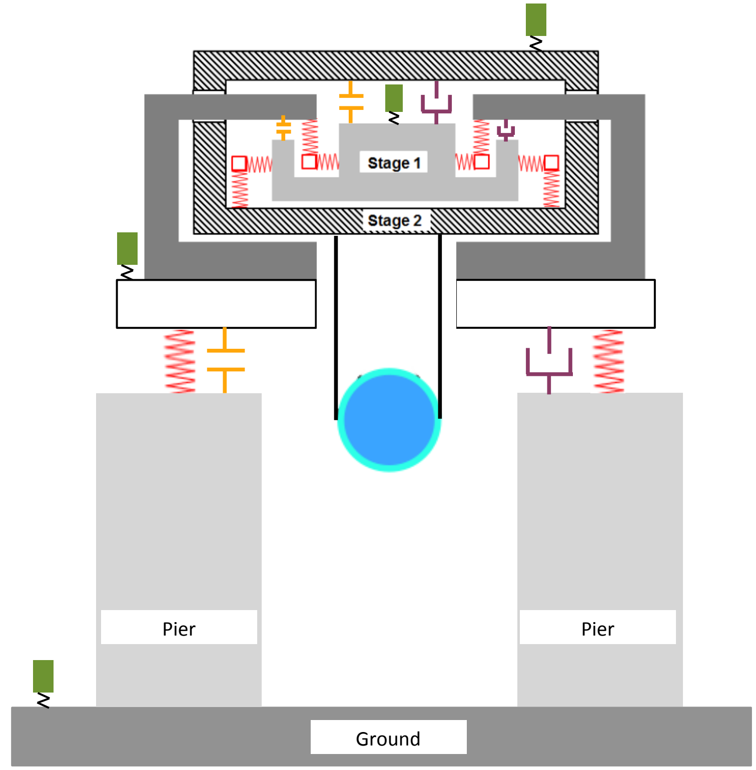


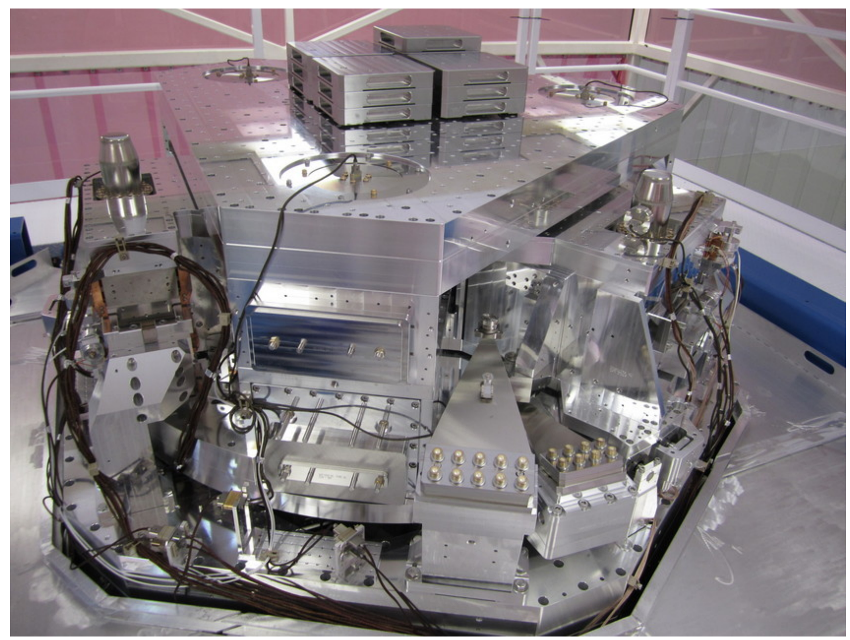


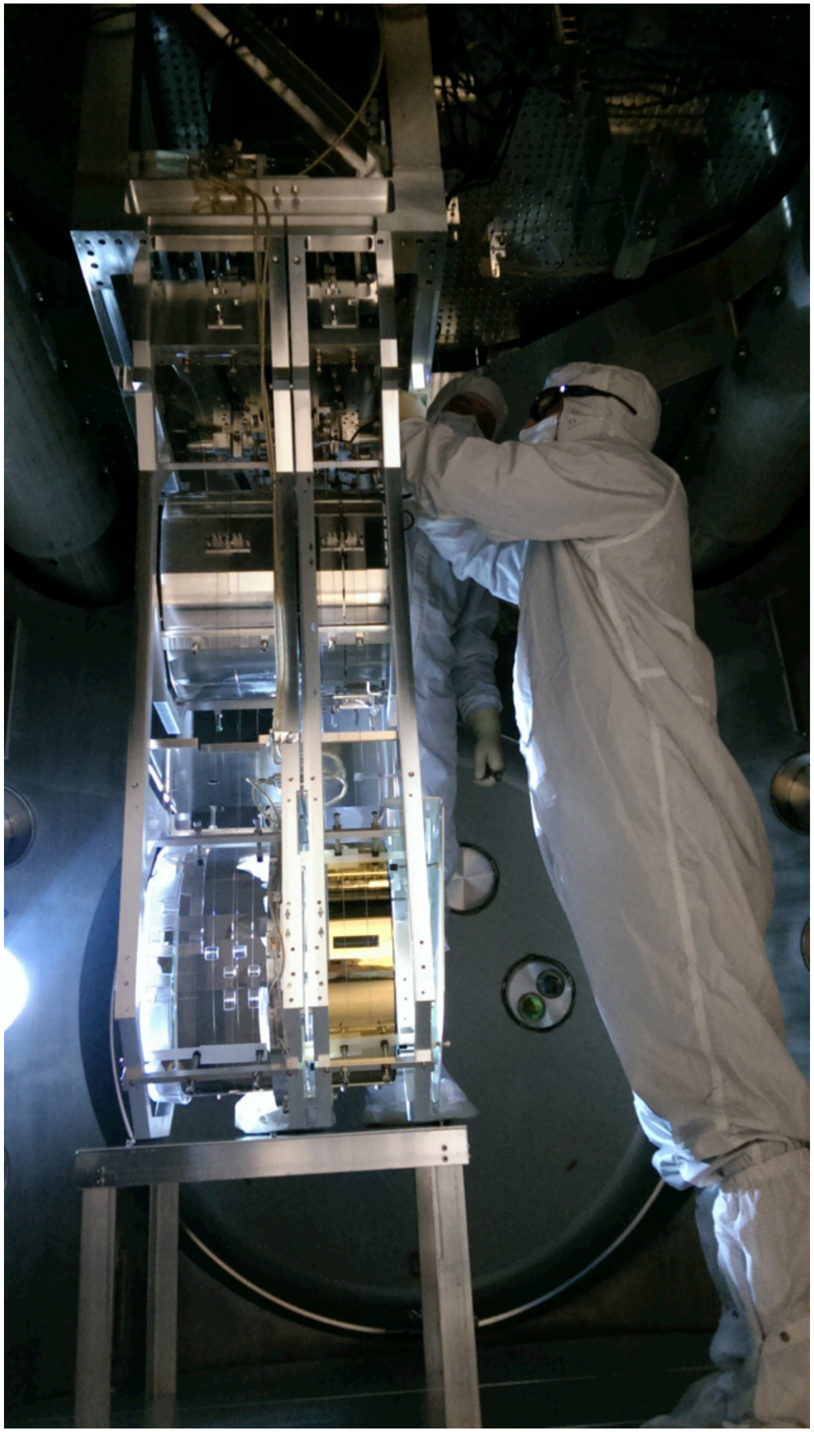
BSC chamber (core optics) configuration and performance



Adapted from G1400965

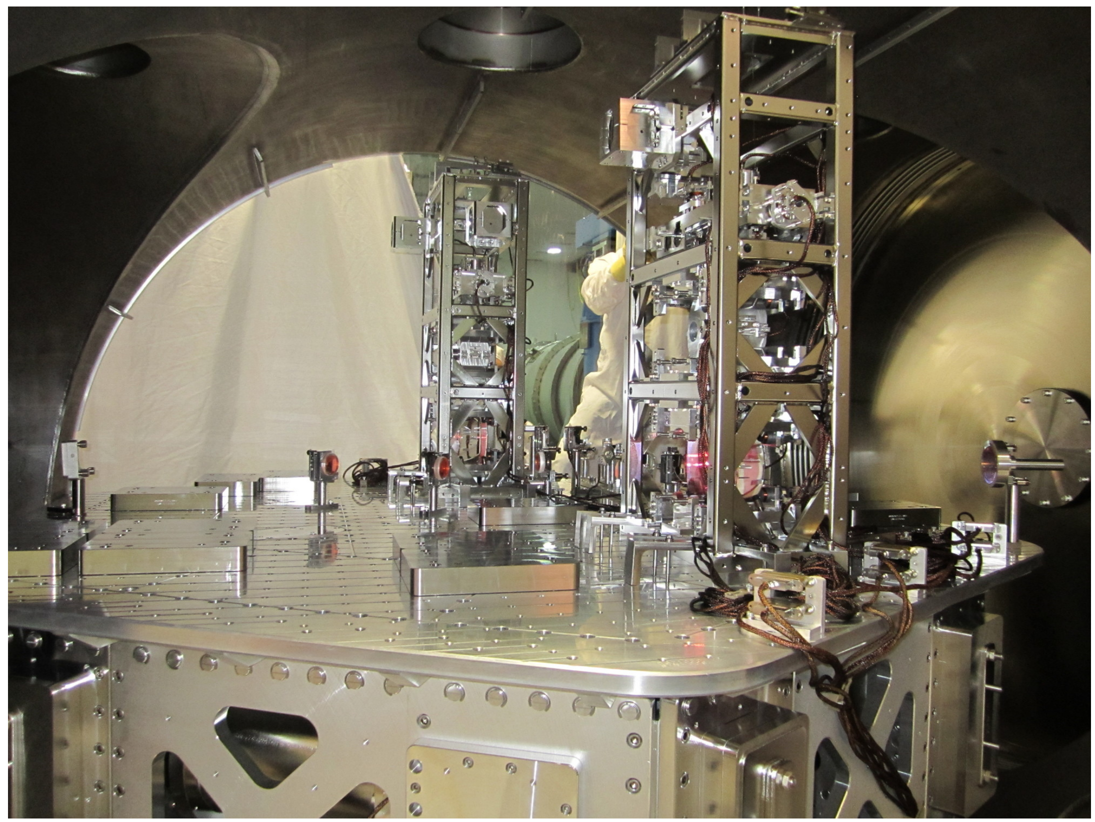




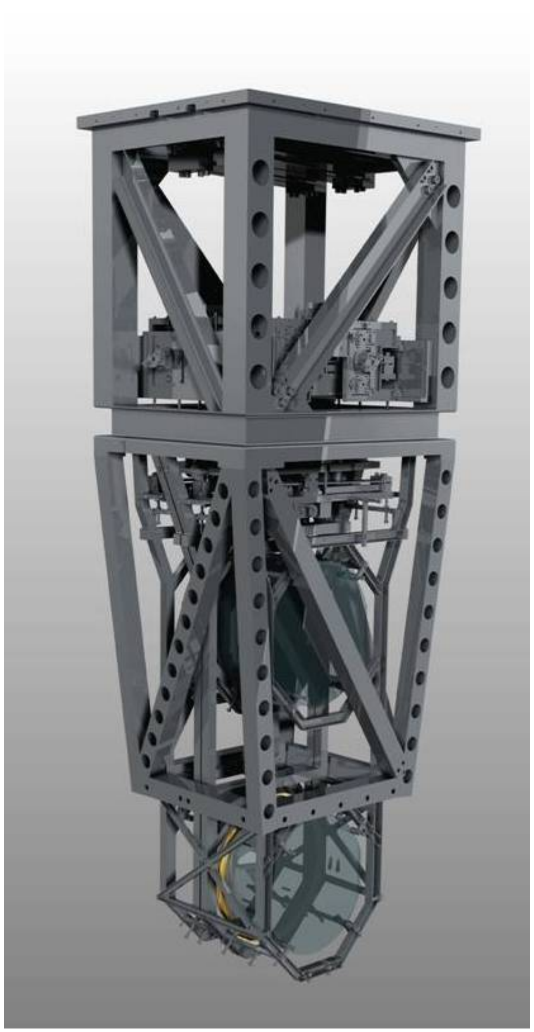


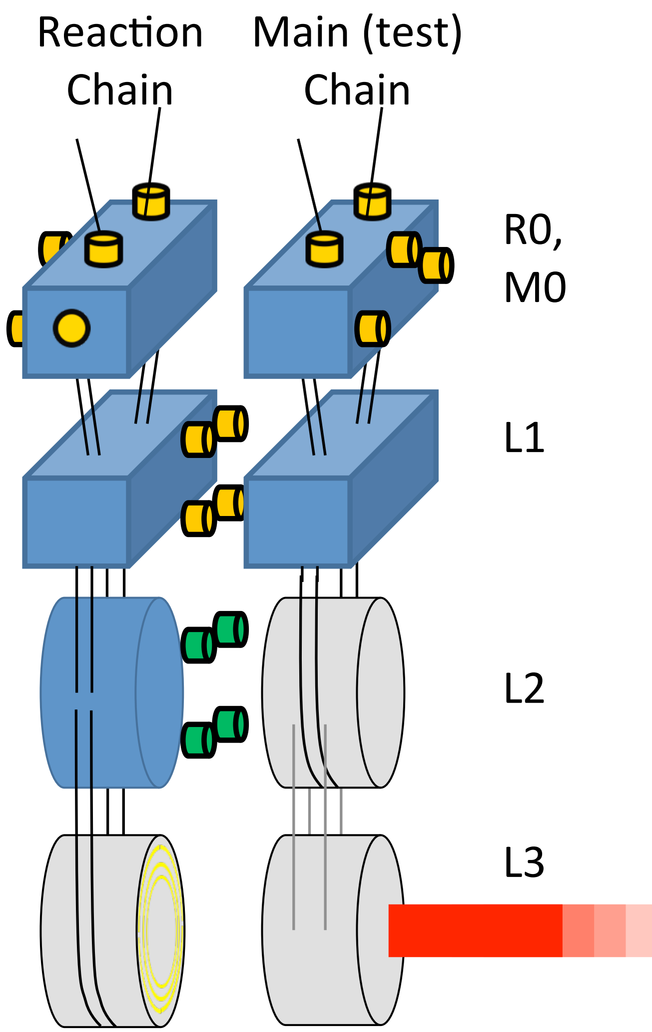
Test mass suspension on 2-stage in-vacuum isolation table

Auxiliary optics on 1-stage in-vacuum isolation table



Quadruple Suspension (Quad)





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

HAM Small Triple Suspension (HSTS)

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

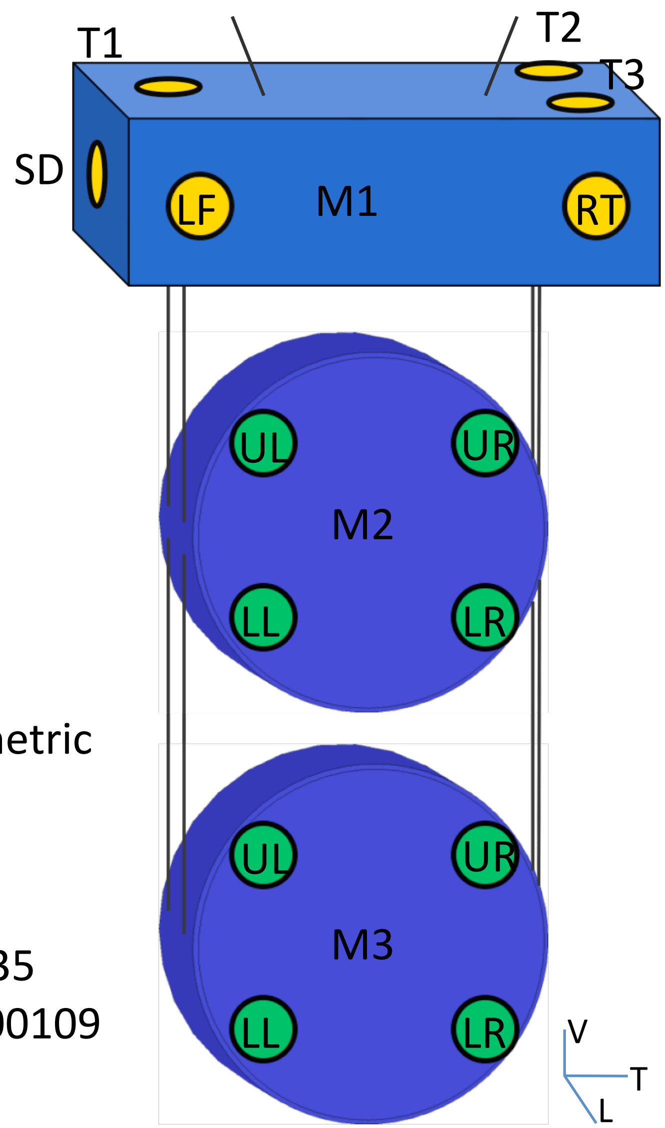
Location
- Auxiliary Chambers

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

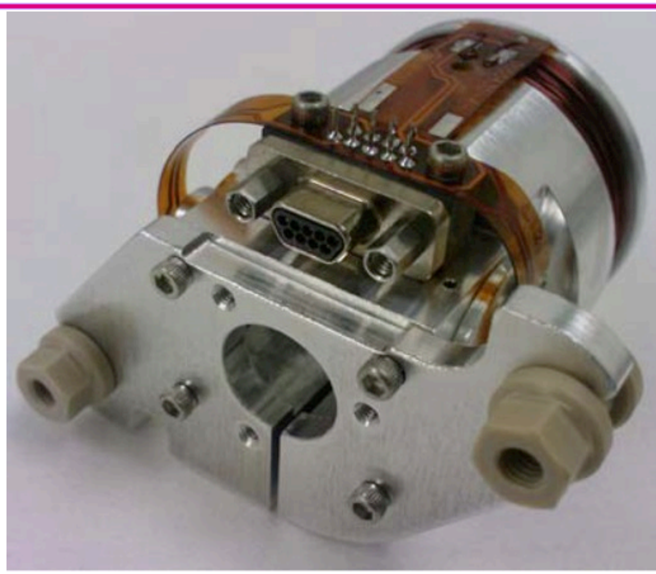
Sensors/Actuators
- (yellow circle) BOSEMs at M1
- (green circle) AOSEMs at M2 and M3
- Optical levers and interferometric signals on M3

Naming: L1:SUS-PRM_M1…

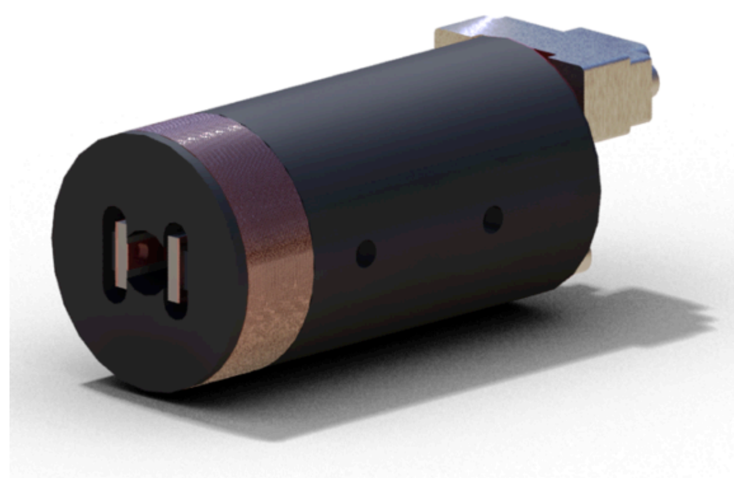
Documentation
- Final design review - T0900435
- Controls arrangement – E1100109



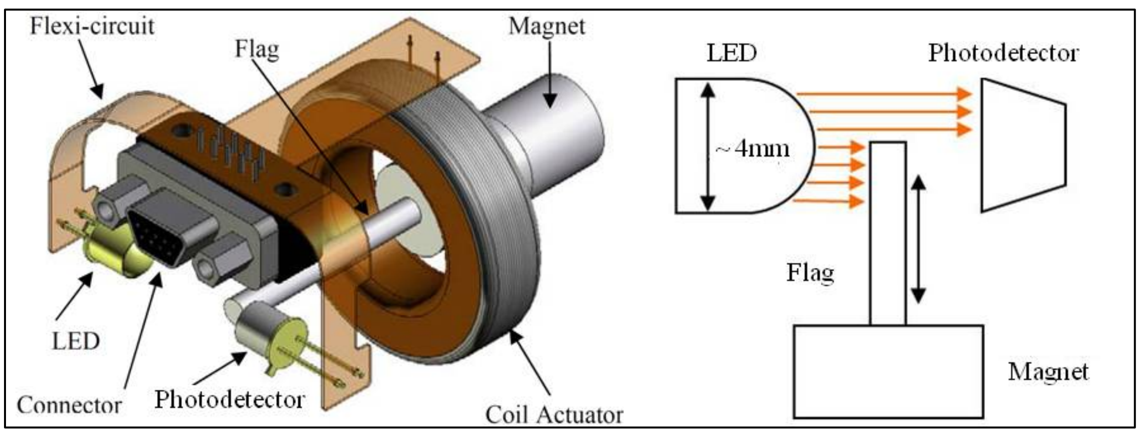
Optical Sensor ElectroMagnet (OSEM)



Birmingham OSEM (BOSEM)



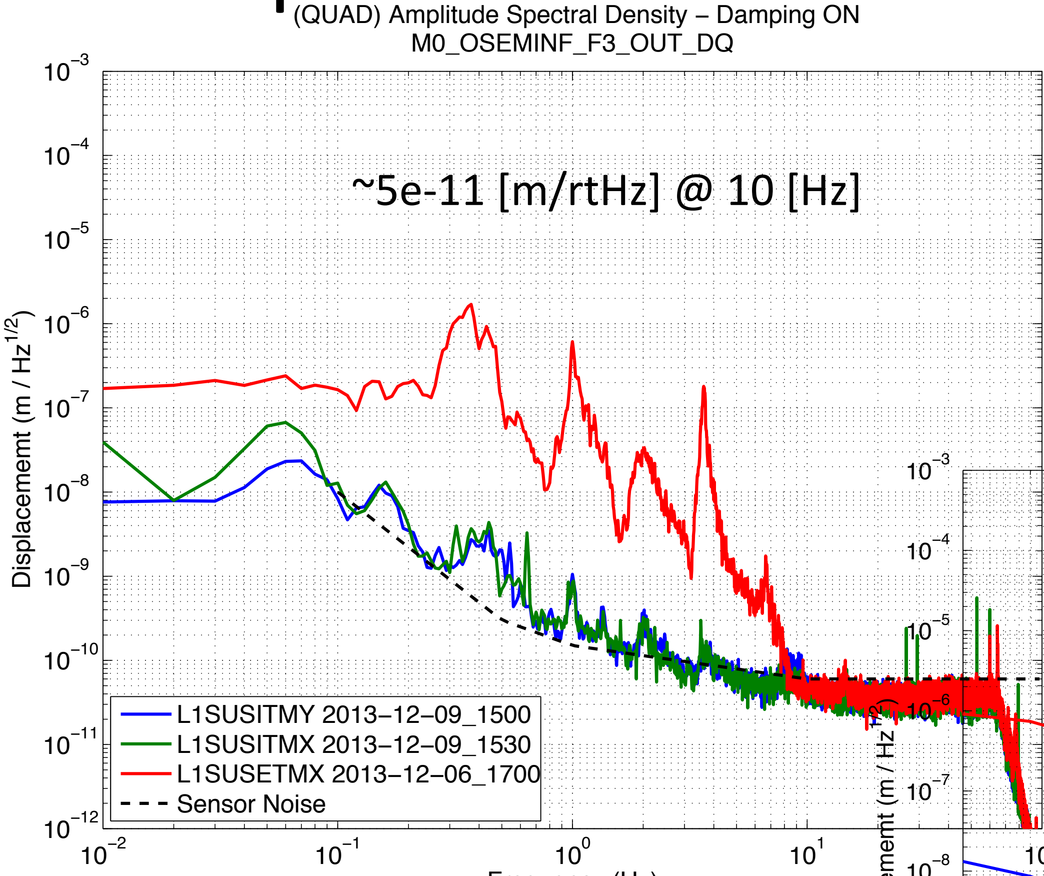
Advanced LIGO OSEM (AOSEM)
- modified iLIGO OSEM

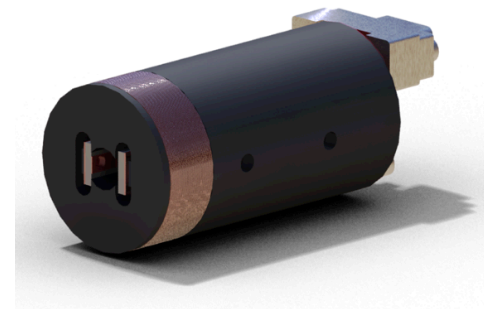


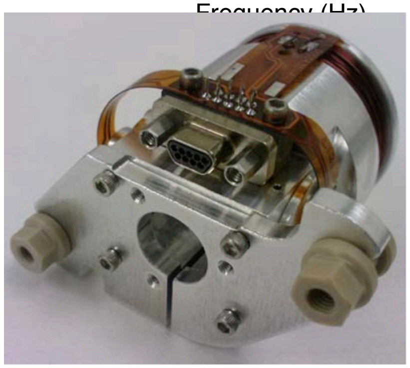
BOSEM Schematic

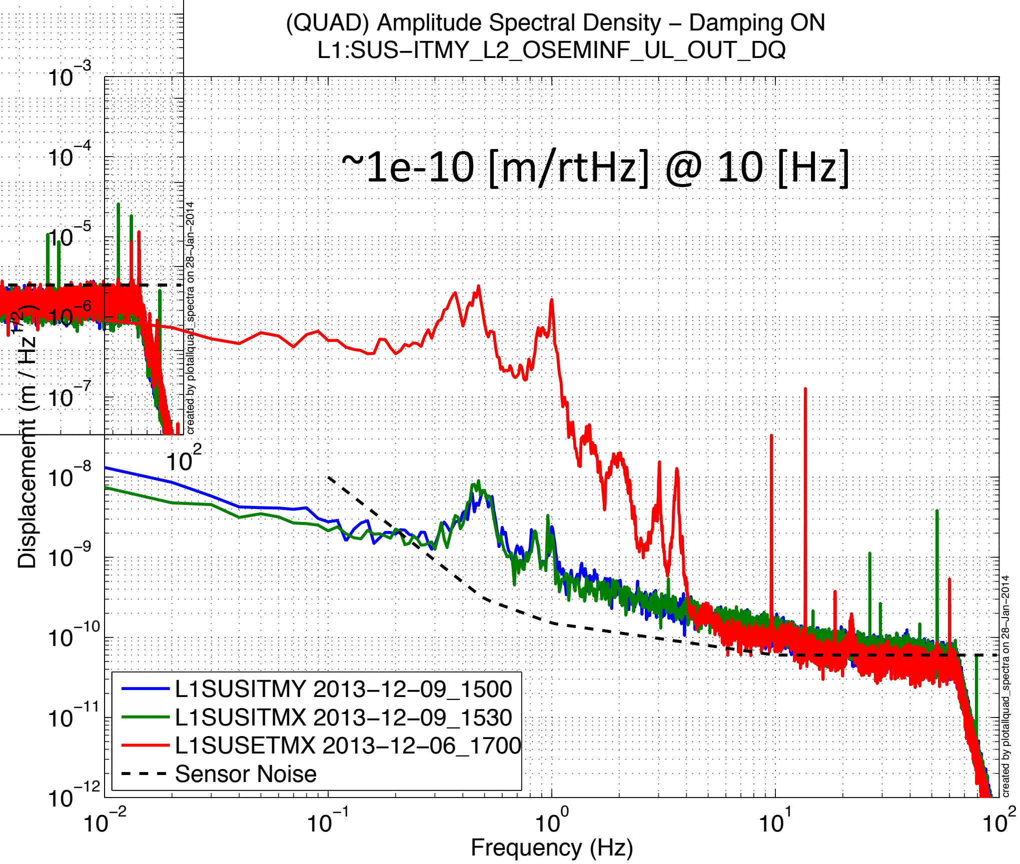
Magnet Types (M0900034)
- BOSEM – 10 X 10 mm, NdFeB , SmCo
  10 X 5 mm, NdFeB, SmCo
- AOSEM – 2 X 3 mm, SmCo
  2 X 6 mm, SmCo
  2 X 0.5 mm, SmCo

Optical Sensor ElectroMagnet (OSEM)





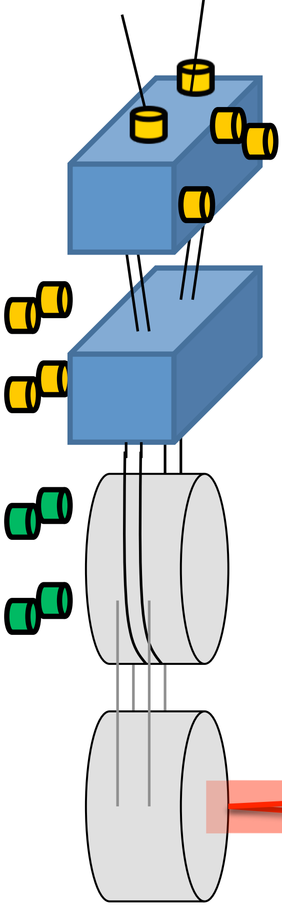


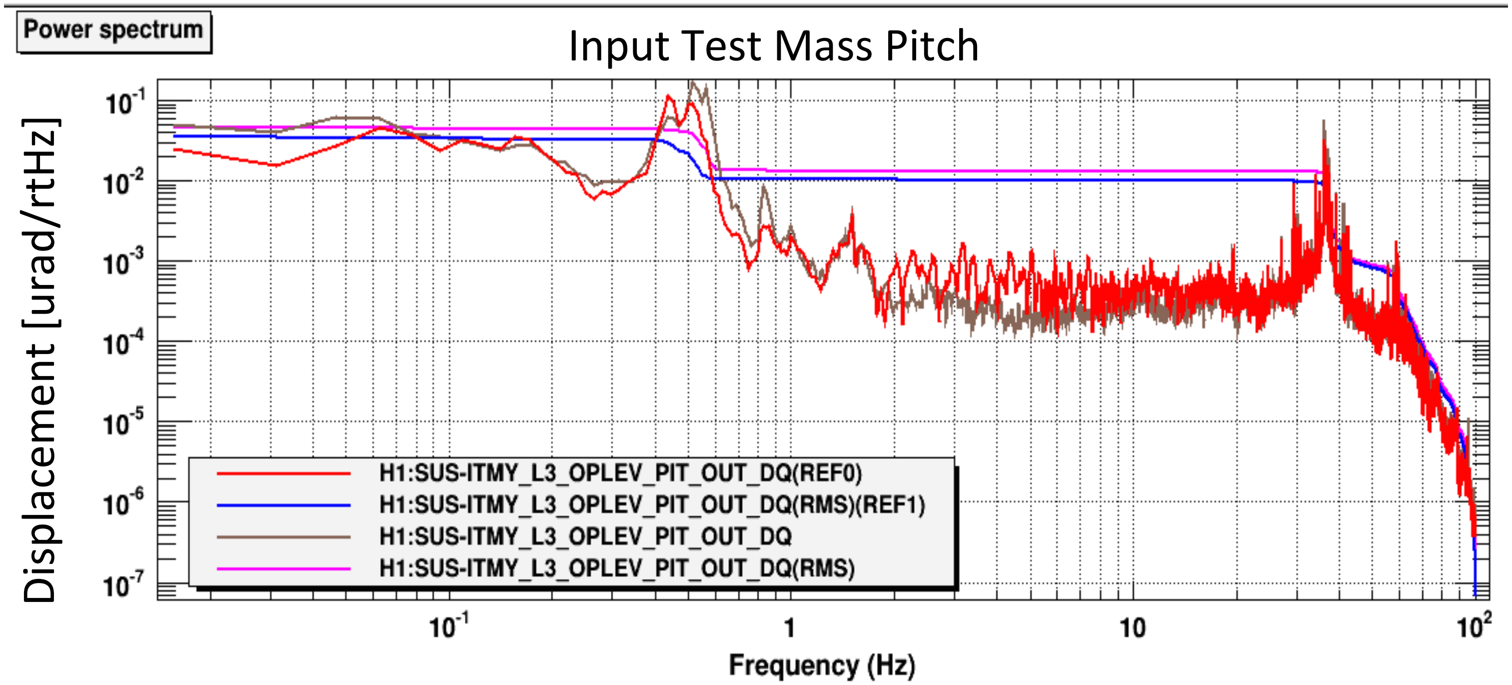


Optical Levers

Invaluable local sensor of the test masses

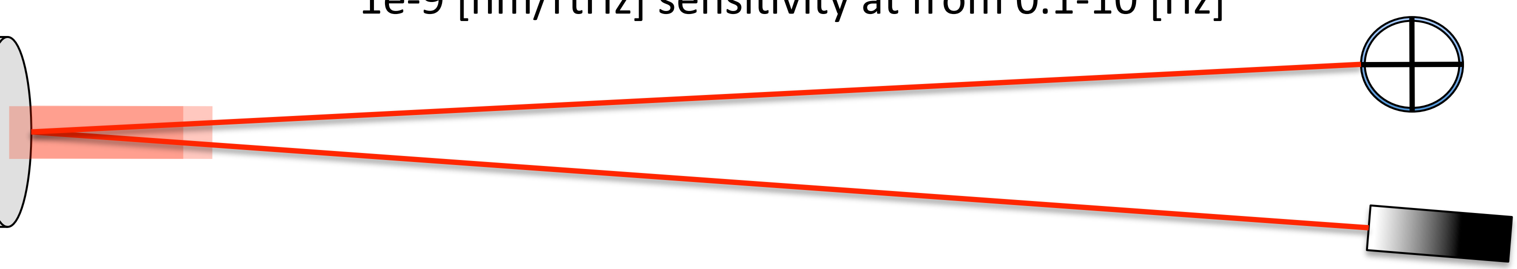
Main (test) Chain



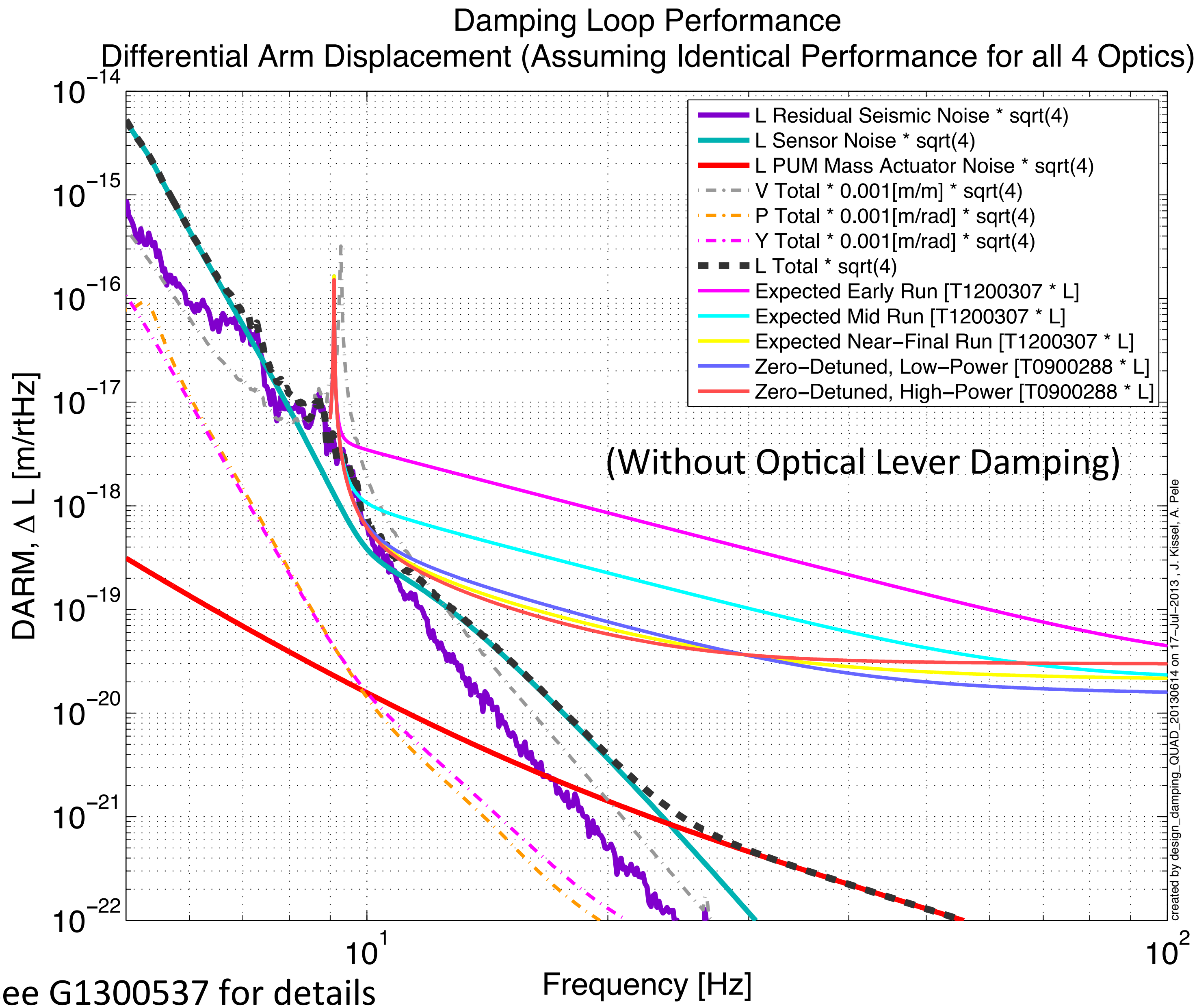


~10 [m] lever arm

~ 1e-9 [nm/rtHz] sensitivity at from 0.1-10 [Hz]



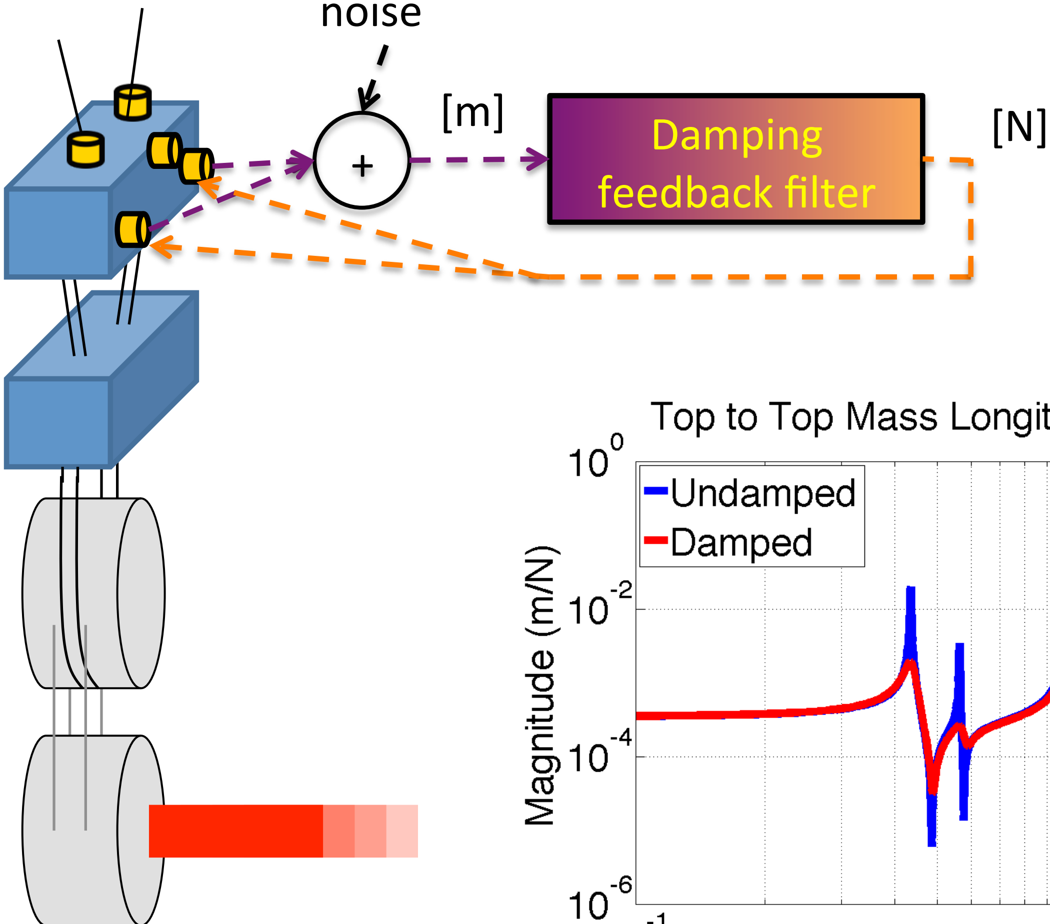
Predicted Performance



See G1300537 for details

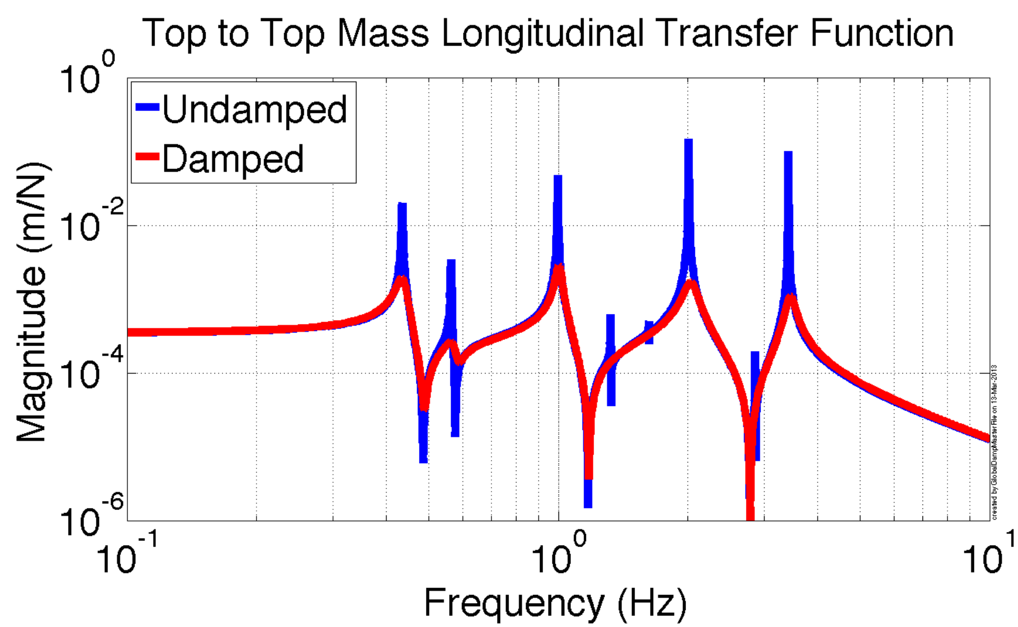
Control of Seismic Isolation Systems

Suspension damping feedback

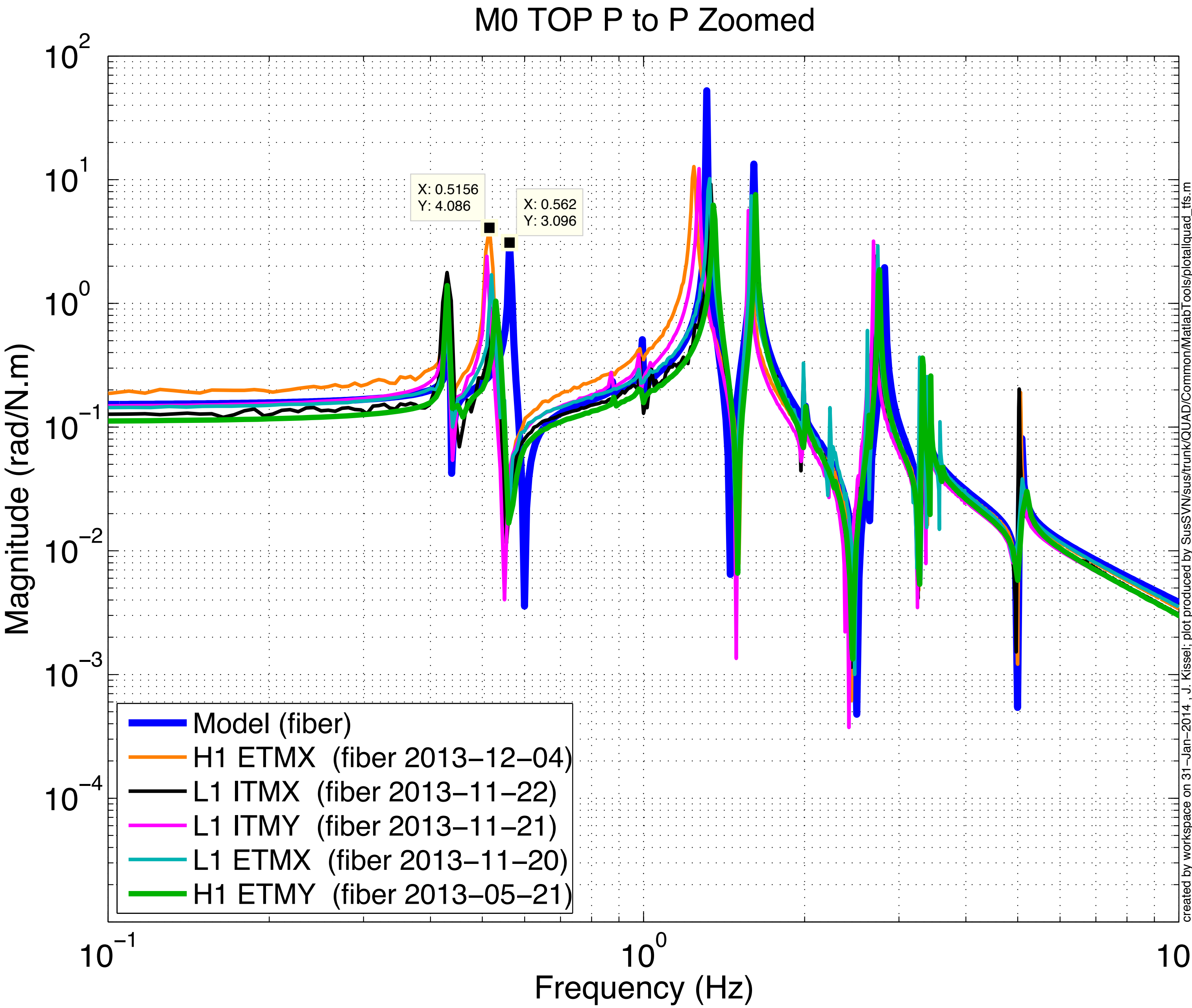


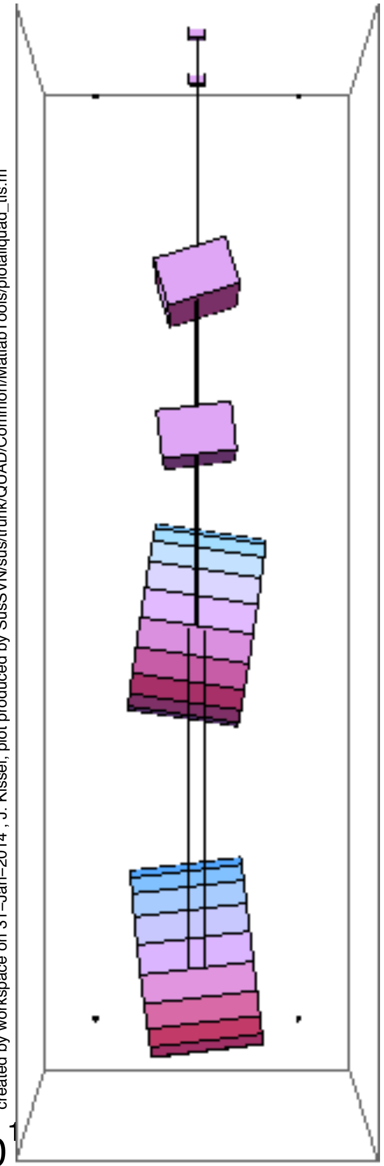
- Simple, high-gain velocity damping with HF roll-off for lock acquisition

- A little more complex design for low-noise operation
  - see T1100232

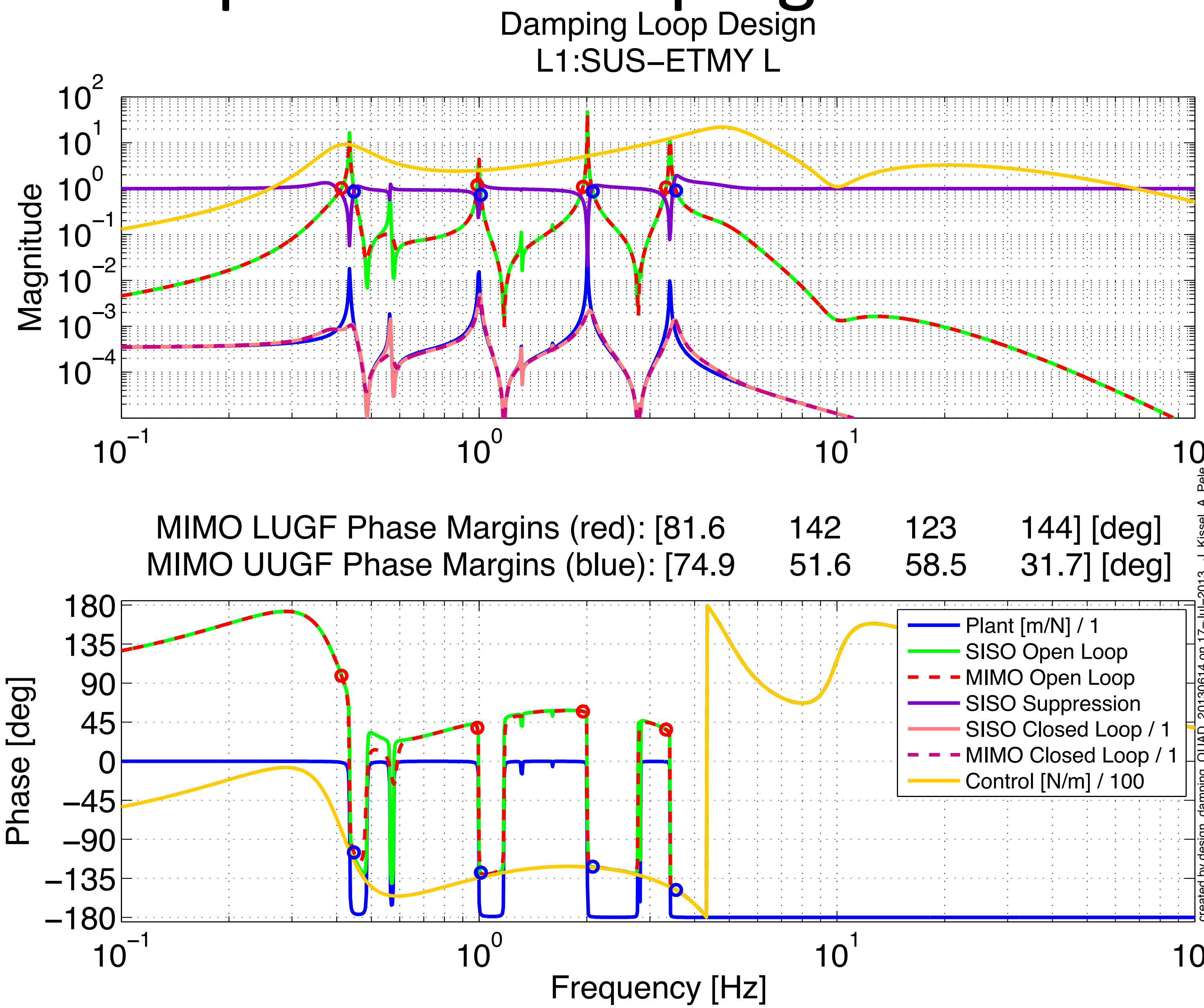


Suspension Damping Feedback

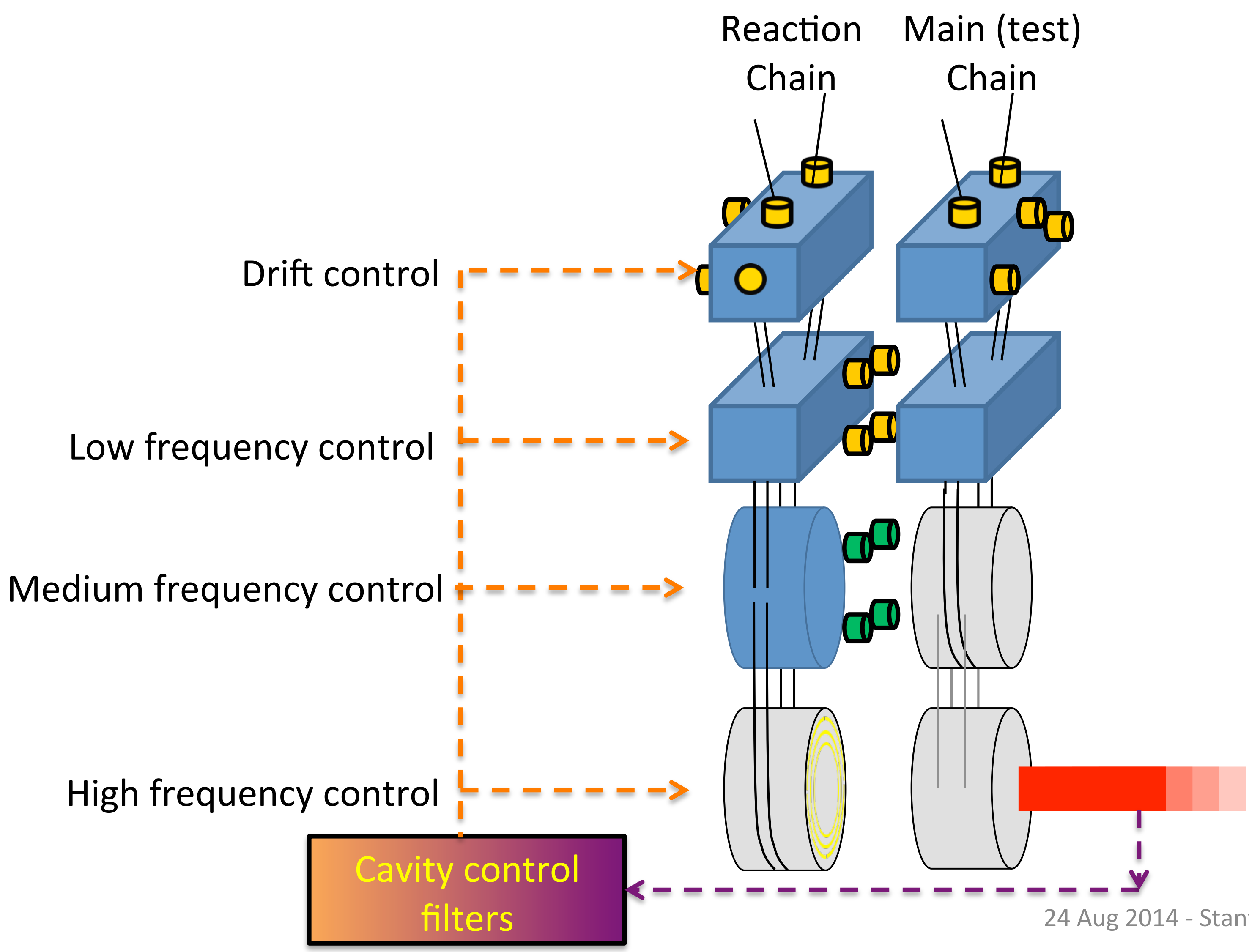




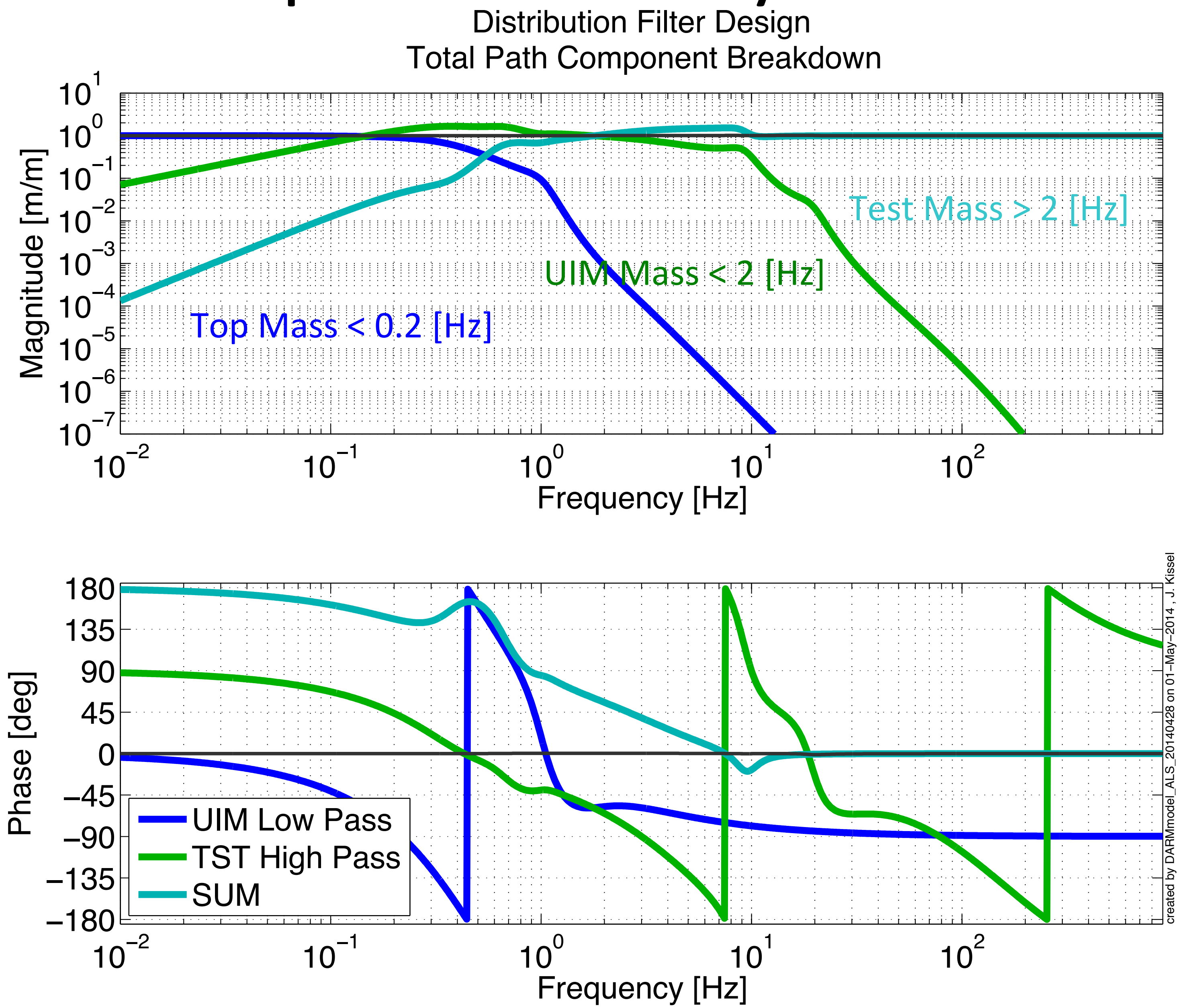
Suspension Damping Feedback



Suspension cavity control

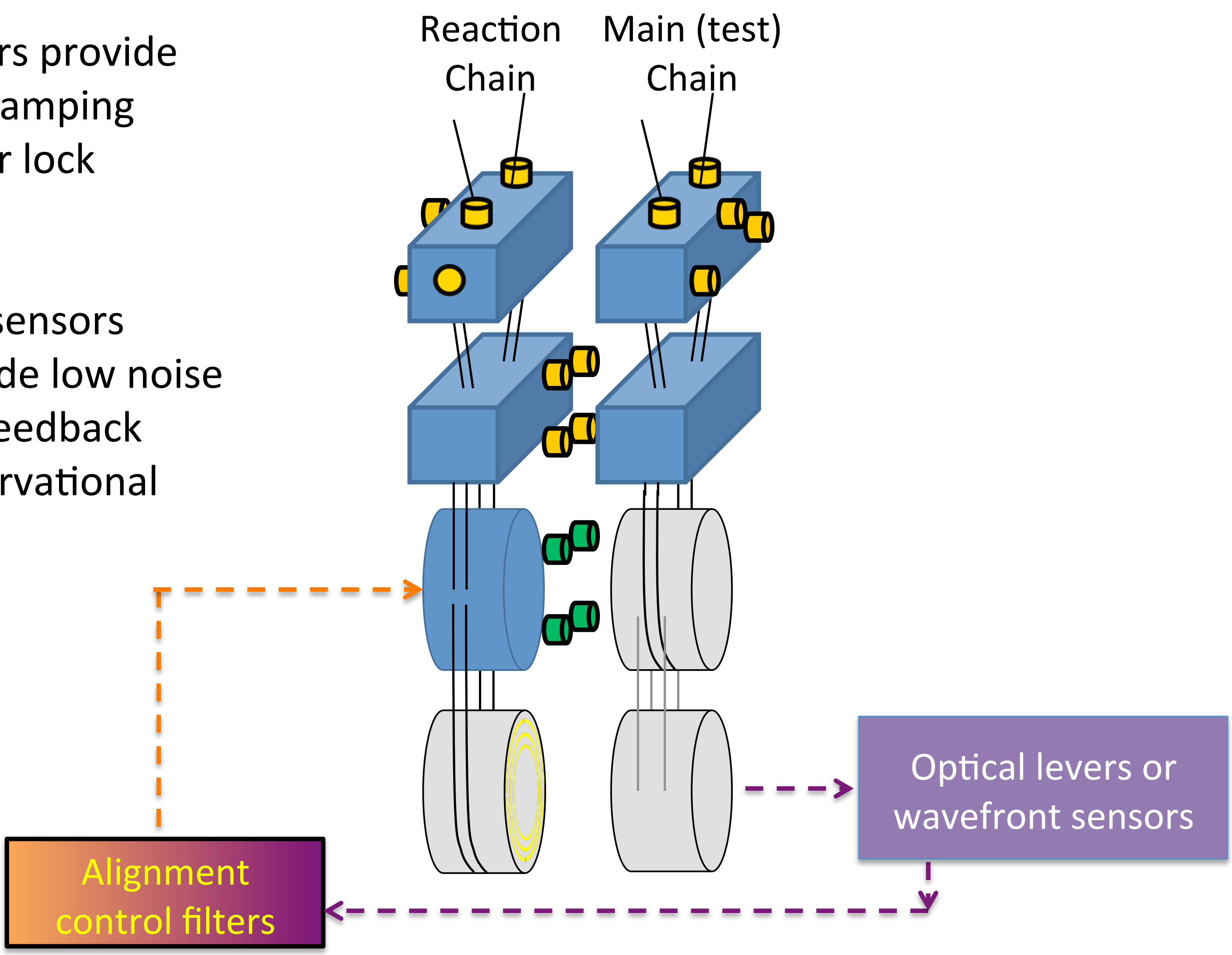


Suspension Cavity Control

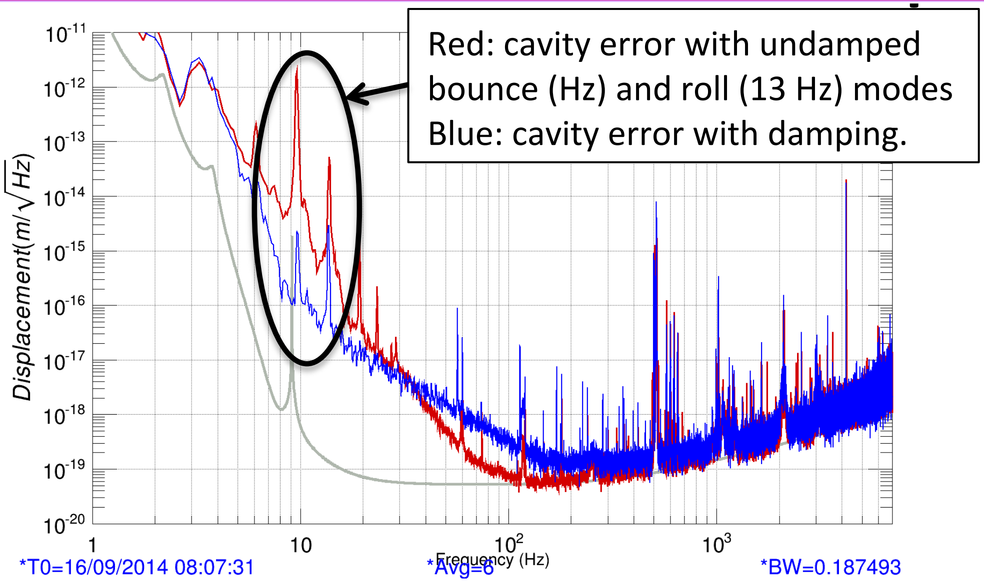


Suspension angular control

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

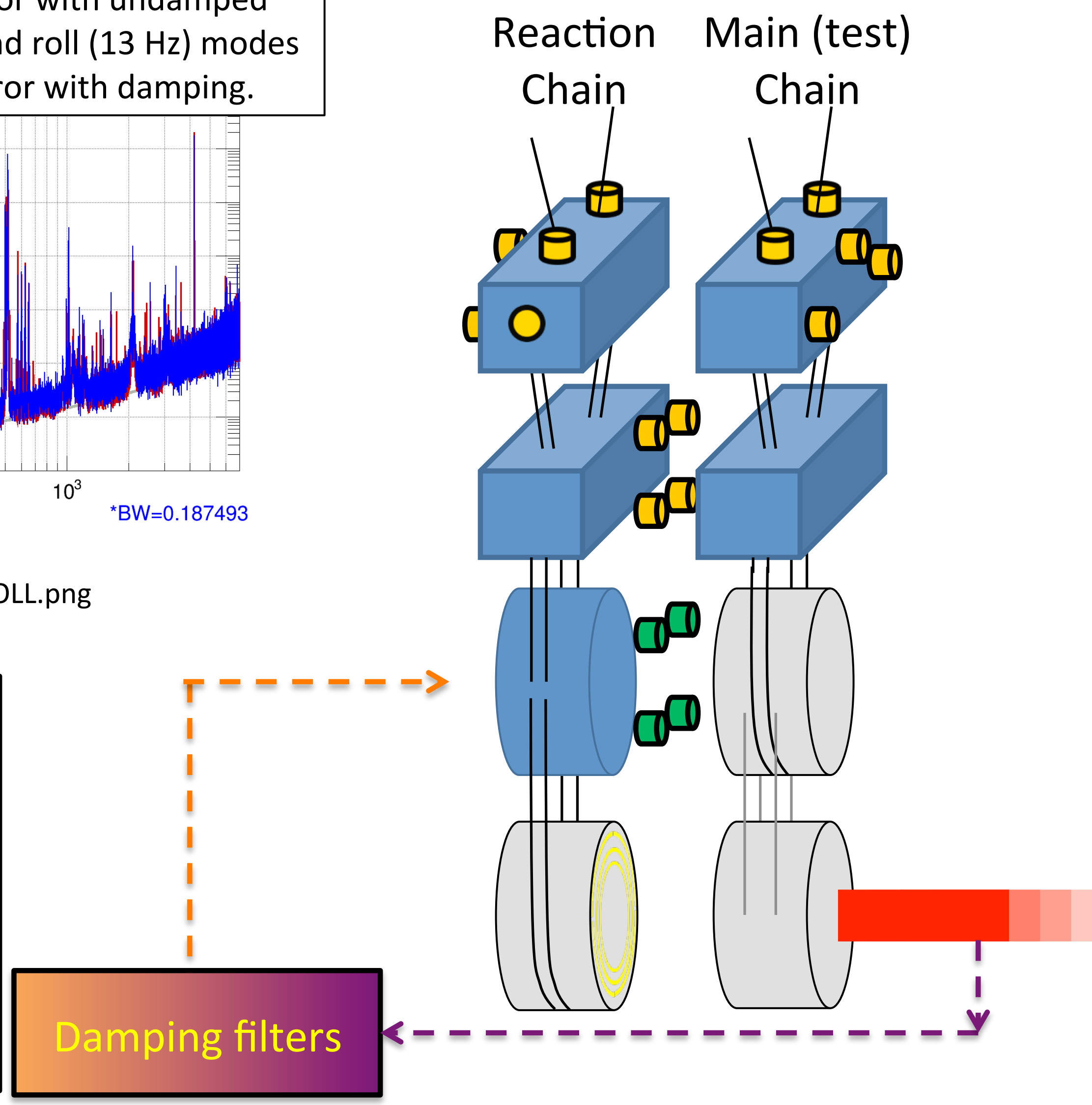


Suspension bounce and violin mode damping

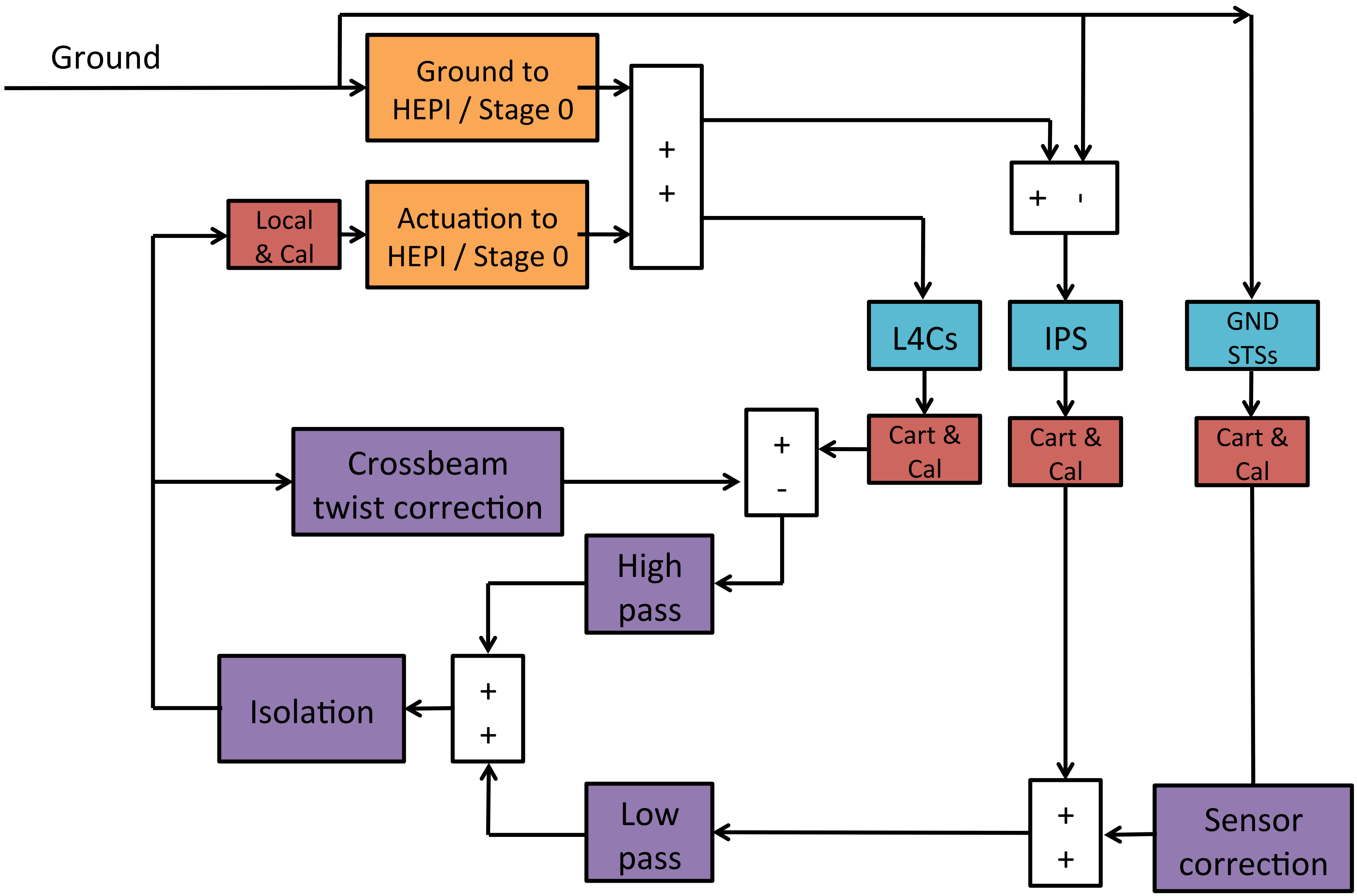


https://alog.ligo-la.caltech.edu/aLOG/uploads/14605_20140916043743_DAMPING_BOUNCE_ROLL.png

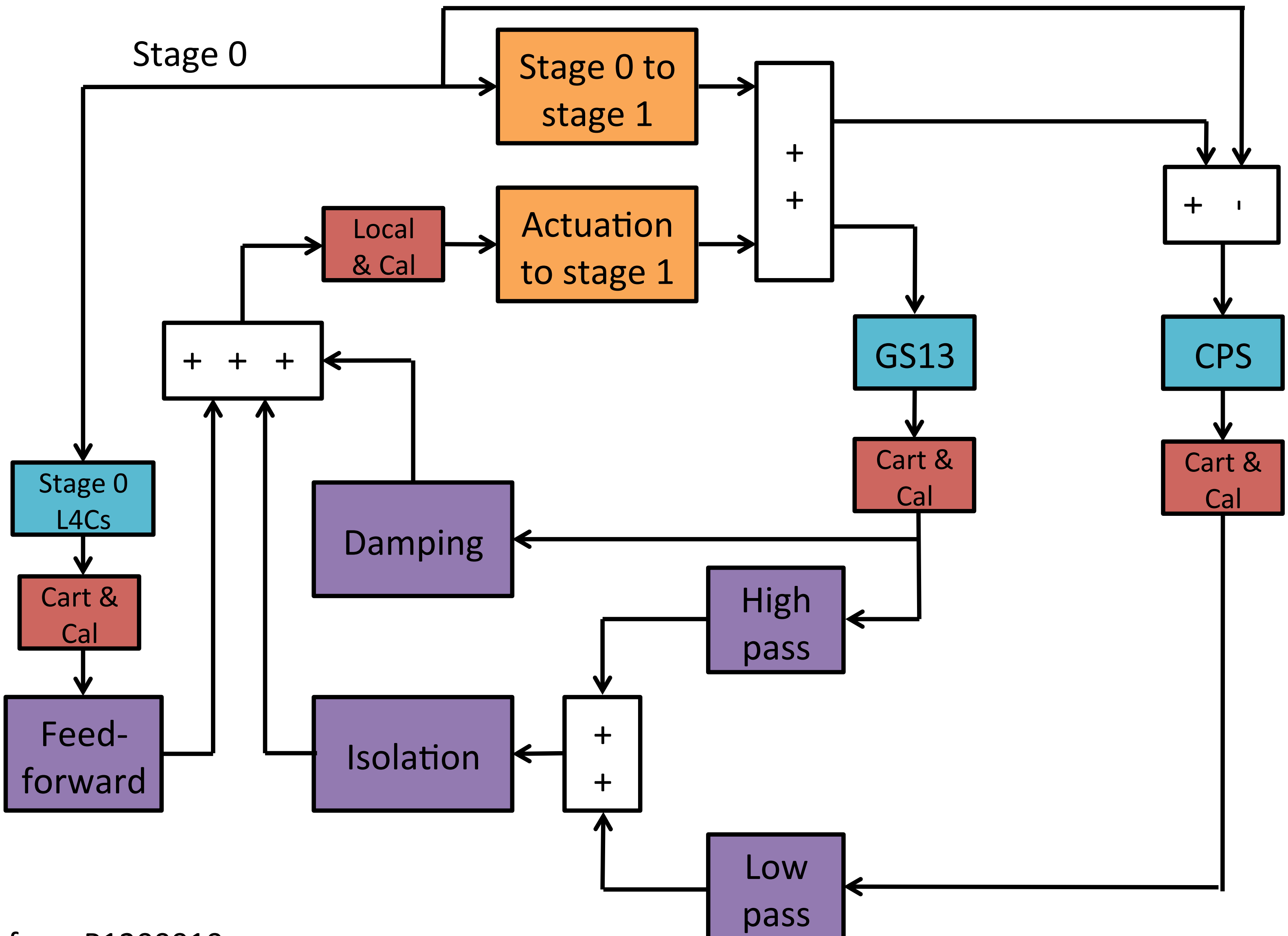
- Very high Q vertical bounce and roll modes between the lowest two stages. Top OSEMs cannot damp them.
- Very high Q (~1 billion) silica fiber violin modes at 510 Hz and higher harmonics.



HEPI Control

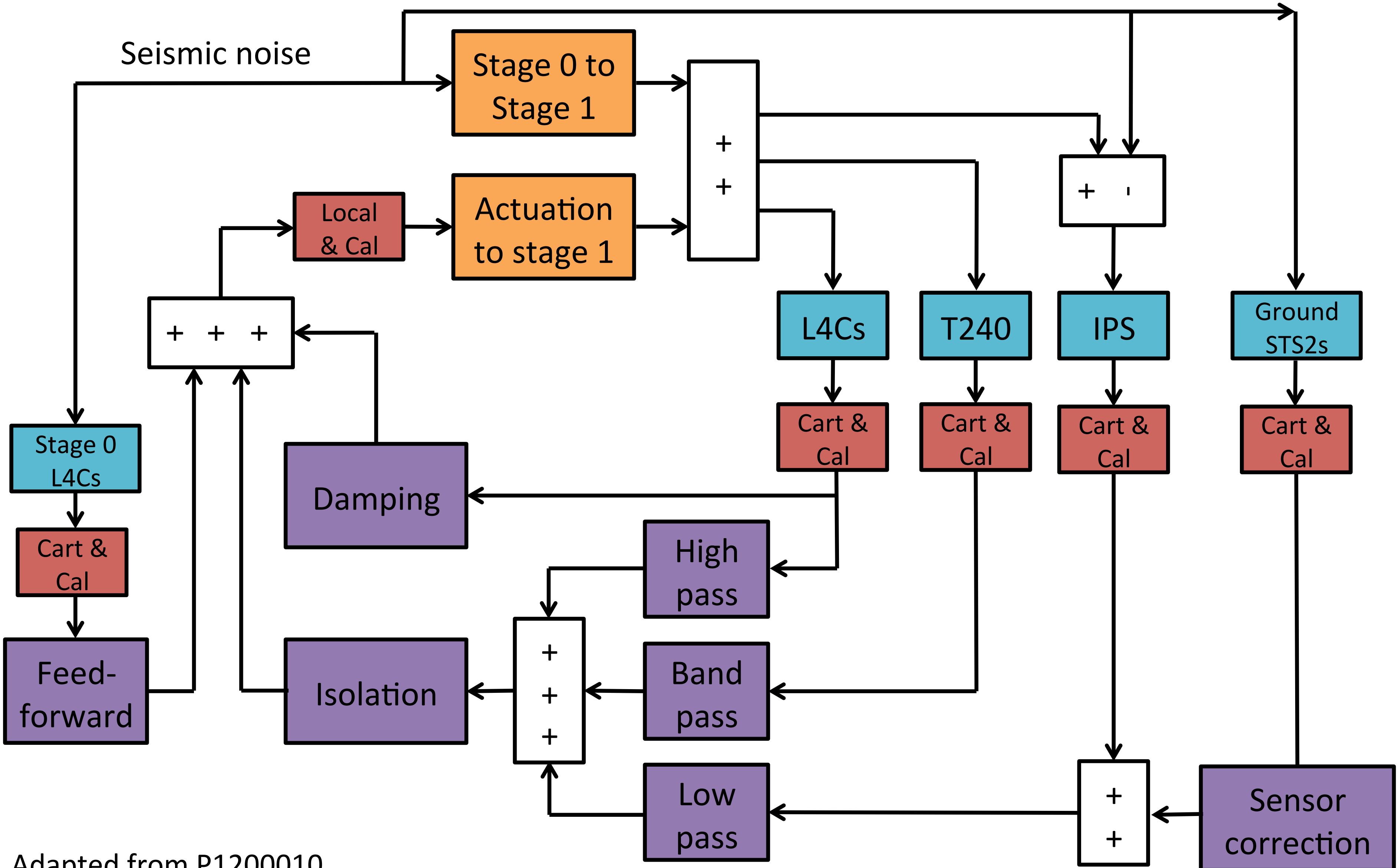


Stage 1 of 1-stage of in-vacuum isolation table (HAM-ISI)



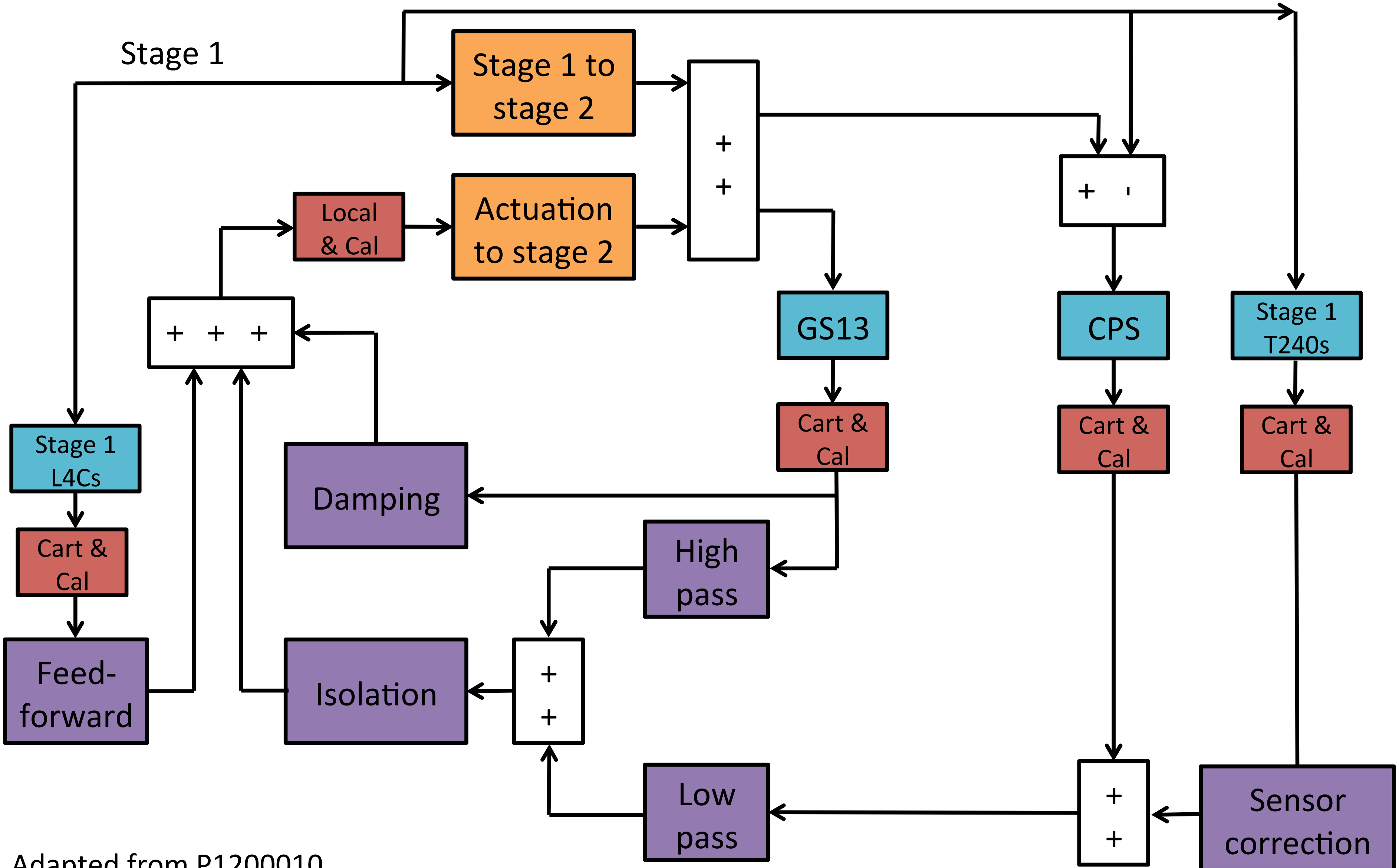
Adapted from P1200010

Stage 1 of 2-stage of in-vacuum isolation table (BSC-ISI)



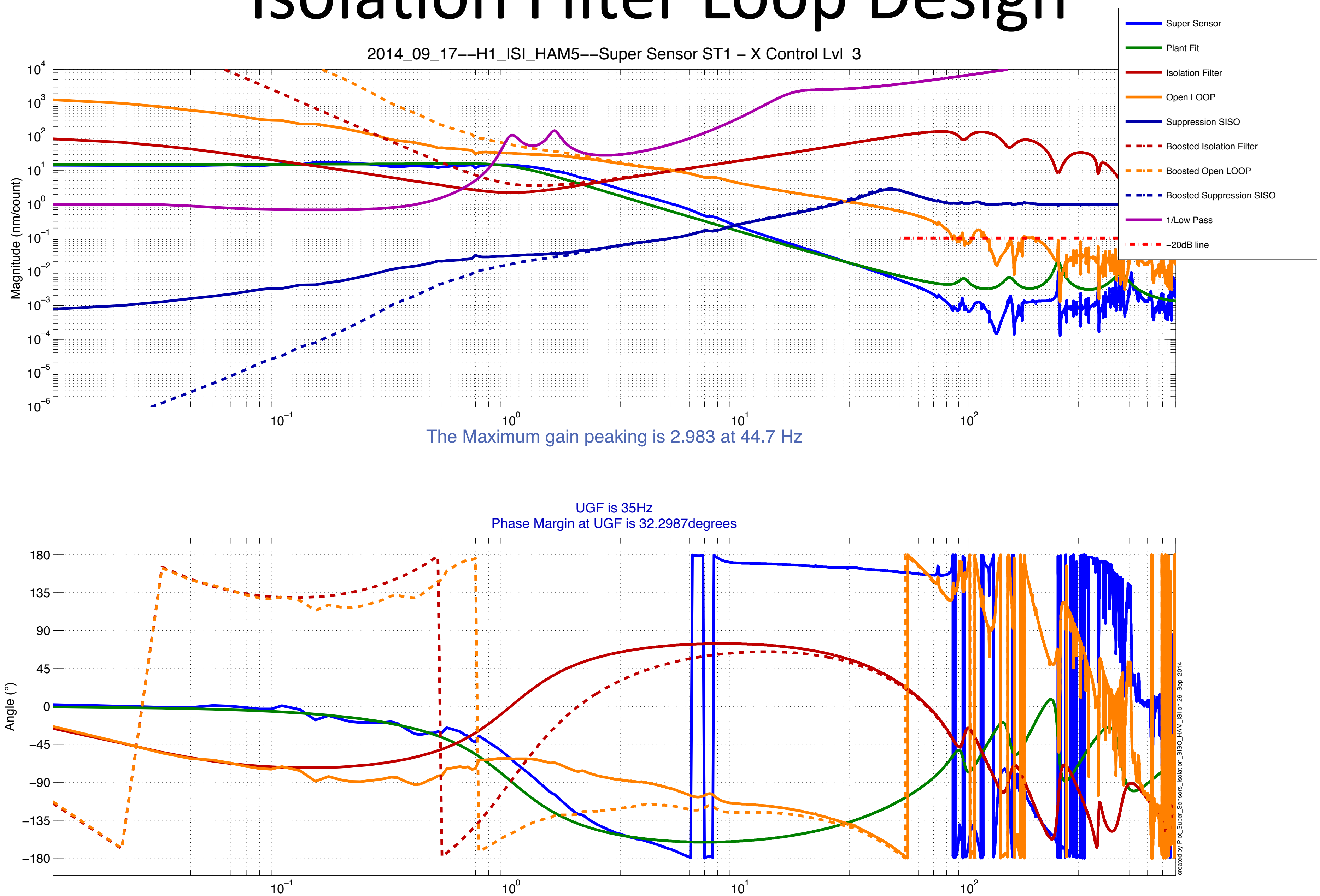
Adapted from P1200010

Stage 2 of 2-stage of in-vacuum isolation table (BSC-ISI)



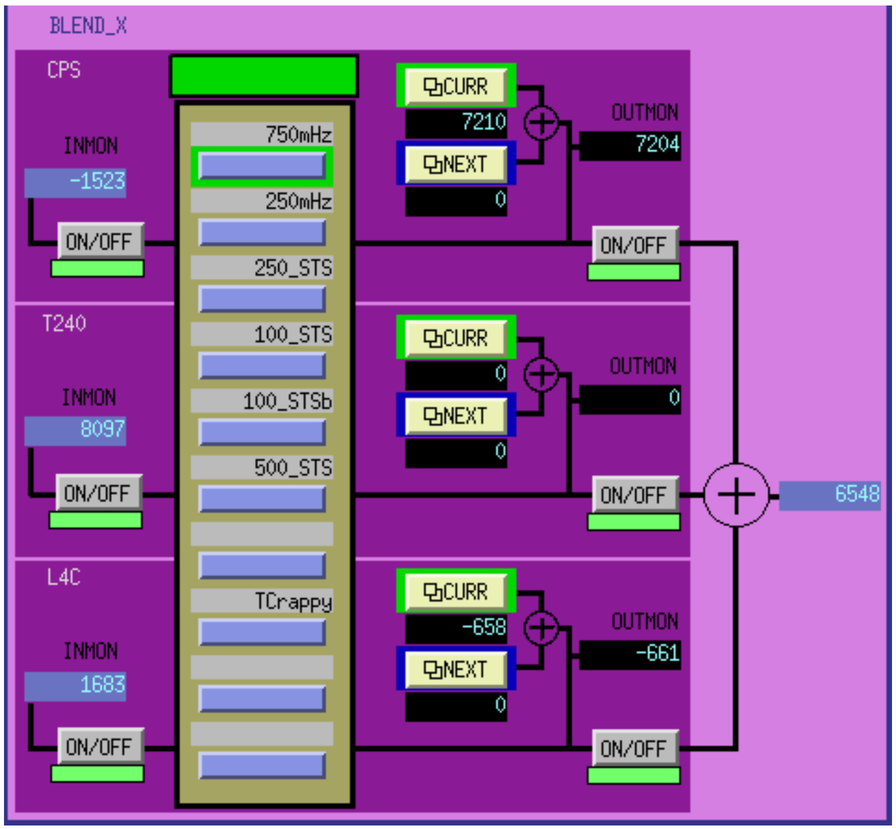
Adapted from P1200010

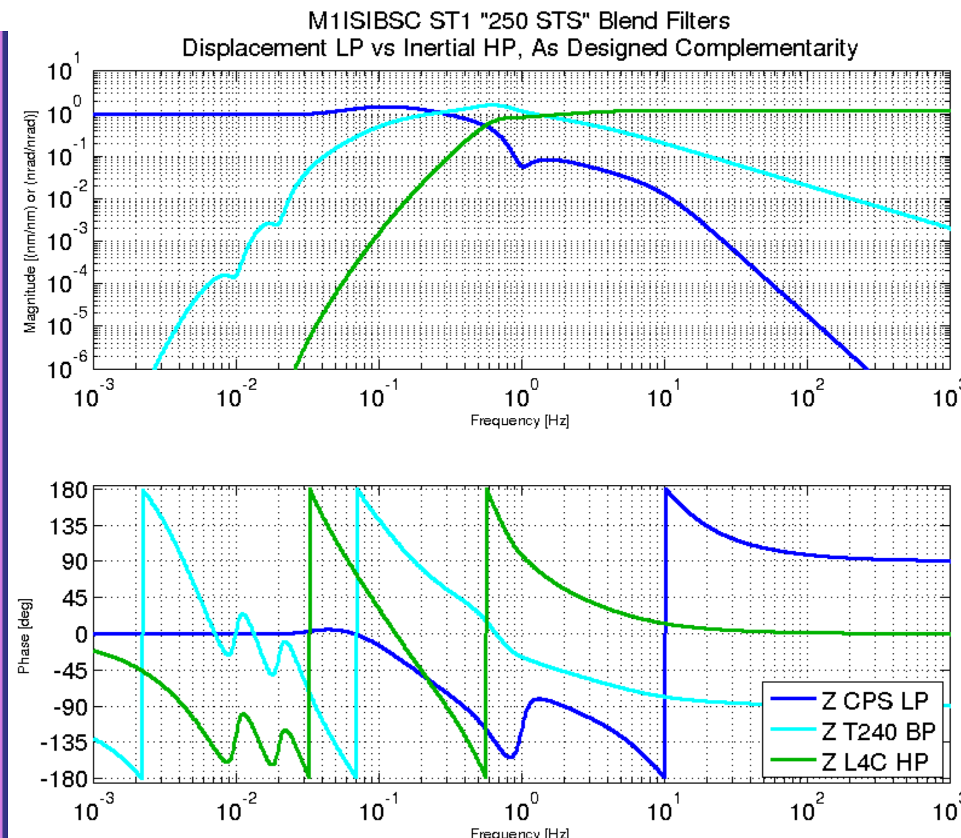
Isolation Filter Loop Design



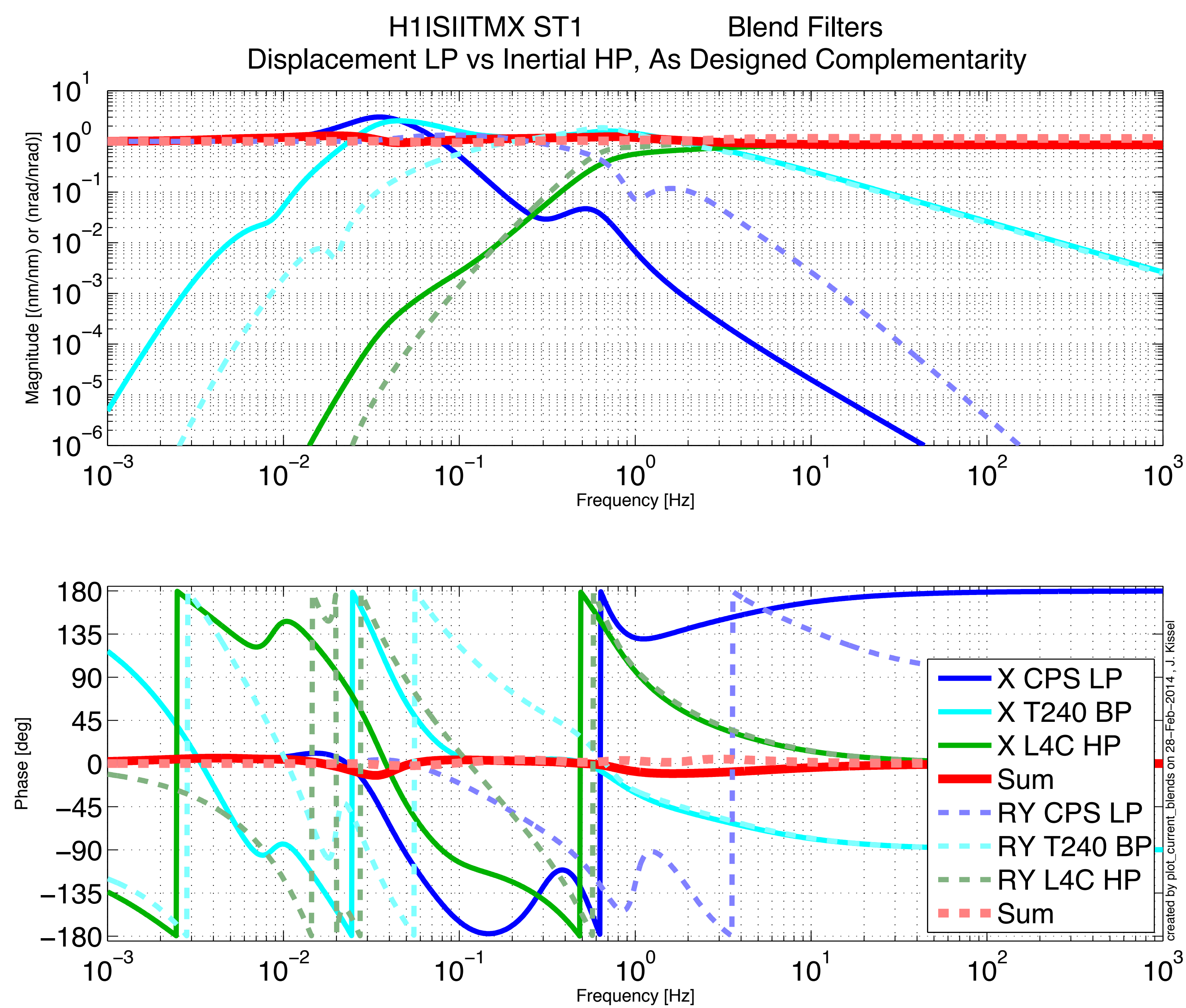
Sensor Blending and Blend Switching

- Can't use inertial sensors at DC (tilt, magnetic coupling, etc.) → Use position sensors
- Blend position and inertial sensors to create a “super sensor”
- Several blend combinations are implemented and can easily be switched via real-time blend switching





G1400965 and T1400284



H1ISIITMX ST1 Blend Filters
Displacement LP vs Inertial HP, As Designed Complementarity
Magnitude [(nm/nm) or (nrad/nrad)]
Frequency [Hz]
Phase [deg]
Frequency [Hz]
X CPS LP
X T240 BP
X L4C HP
Sum
RY CPS LP
RY T240 BP
RY L4C HP
Sum
created by plot_current_blends on 28−Feb−2014 , J. Kissel

BackUps

~~Conclusions~~

Open Questions

• Is the temperature susceptibility of the lowest frequency modes of these hybrid systems a problem?

• aLIGO's low-stress, minimal force design claims less non-gaussian noise. Is it true?

• aLIGO's "sensors everywhere" policy is supposed to aid in identifying unknown unknowns. Will it help?

• Can we read out our sensors / use our actuators [[CABLES]] without spoiling the mechanical isolation?

• Can any of these hybrid systems – the *entire* system, not just the test masses – meet their claimed fundamental noise sources (ground transmission and/or sensor noise)
  - Cables shorting isolation
  - Heat links shorting isolation
  - Reinjection of Sensor Noise
  - Thermal Noise
  - Magnetic Coupling Noise

~~Conclusions~~
Open Questions

• Integration of large number of platforms together using inteferometric signals …

• How to encorporate new / better sensors? e.g. ground rotation sensors

• Can we use computers to "simulate" the mechanical dynamics in real-time?

• Operations during sensor failure

• How to create / encorporate a global array of sensors for Newtonian Noise Subraction?

List of Gotchas / Tricks

- Capacitive position sensor clock signals beating against each other – causing ~0.3 [Hz] comb
- QUAD Bounce/Roll Mode causing saturations
- Violin Mode Damping
- ISI modes seen in SUS TFs and vice-versa
- Lock acquisition kicks influencing isolation of upper stages
- HEPI mechanical tilt-horizontal ISI coupling (which first drove us to send sensor correction to the ISIs)
- ESD Charging / Electronics Noise
- HEPI Cross-beam Bending Modes
- Magnetic fields from ISI Z actuators cause ISI RZ motion
- Increase our SUS coil drive range for lock-acquisition

Resources on SUS control techniques

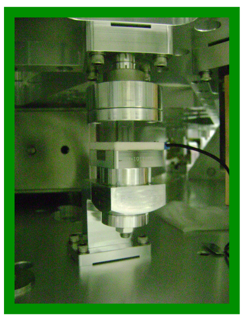
- Damping
  - Loop shaping and modal damping - P1200009
    http://scitation.aip.org/content/aip/journal/rsi/83/4/10.1063/1.4704459?ver=pdfcov
  - Modal damping - P1200057
  - Global damping - P1400085, G1200774
- Cavity control (aka hierarchical control)
  - G1200632
  - T1000242
  - Using a blended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

Sensor Noise

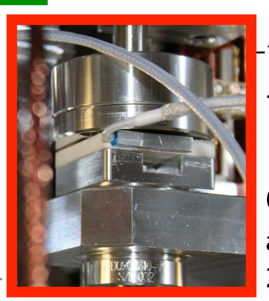
Displacement Sensors

Inductive
aLIGO Pre-isolator Stage

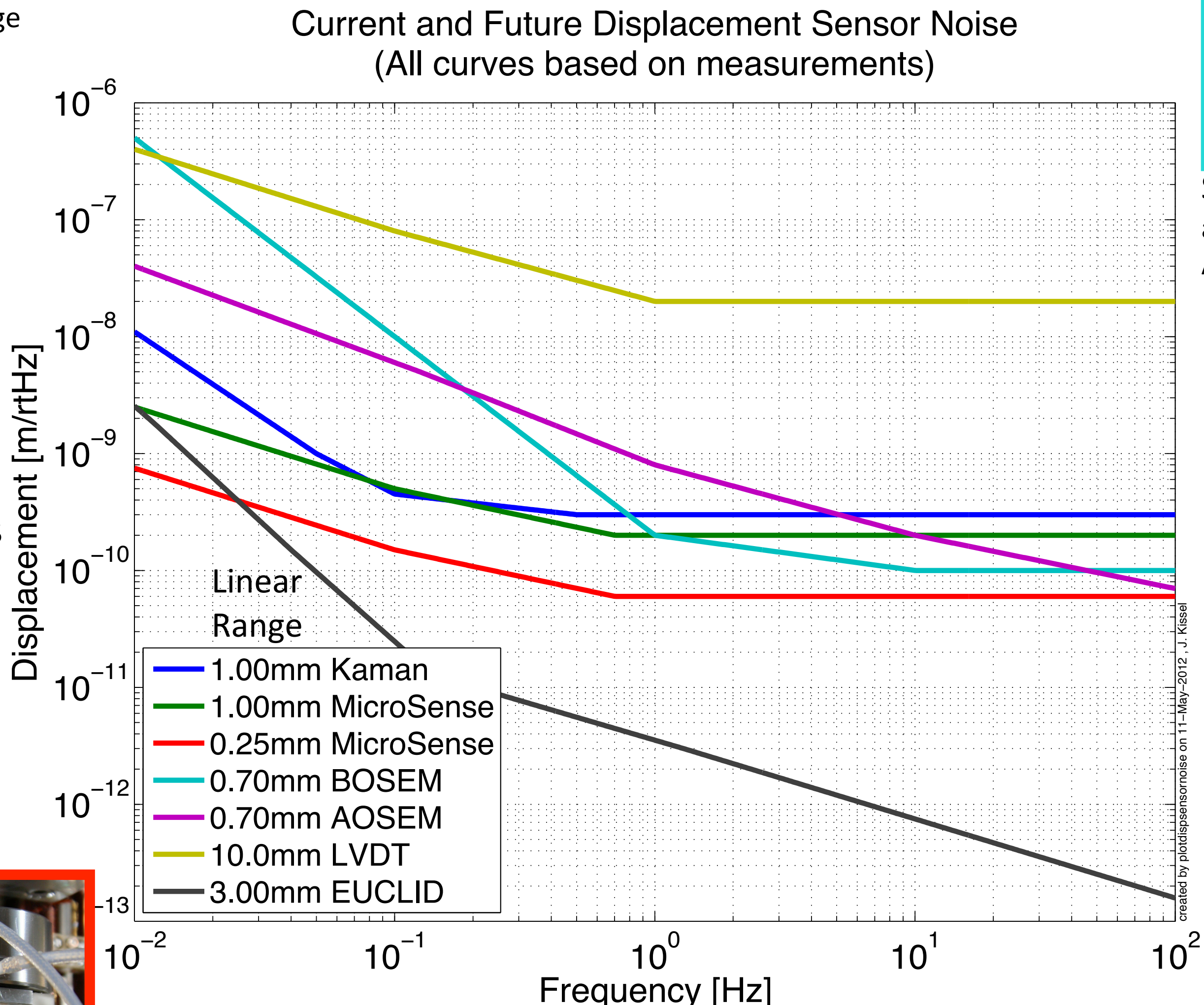
Inductive
VIRGO / GEO / KAGRA SAS

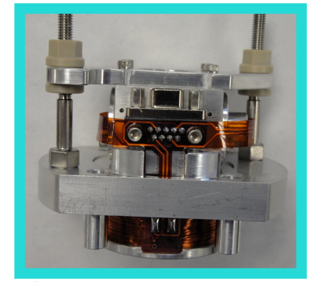


Capacitive
aLIGO Stage 1 ISIs



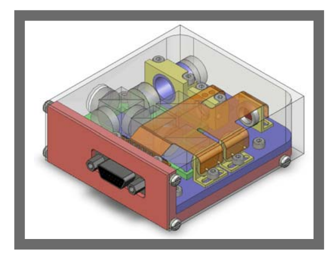
Capacitive
aLIGO Stage 2 ISIs





Shadow Sensor
aLIGO SUS Top Stages
AEI 10m SUS Top Stages

Shadow Sensor
aLIGO SUS Lower Stages



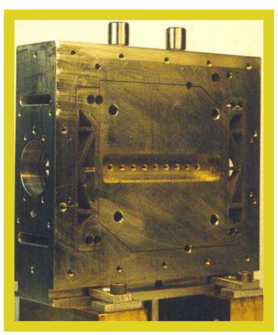
Interferometeric,
U of Birmingham Prototype (As yet Non-UHV Comp.)

Sensor Noise

Inertial Sensors

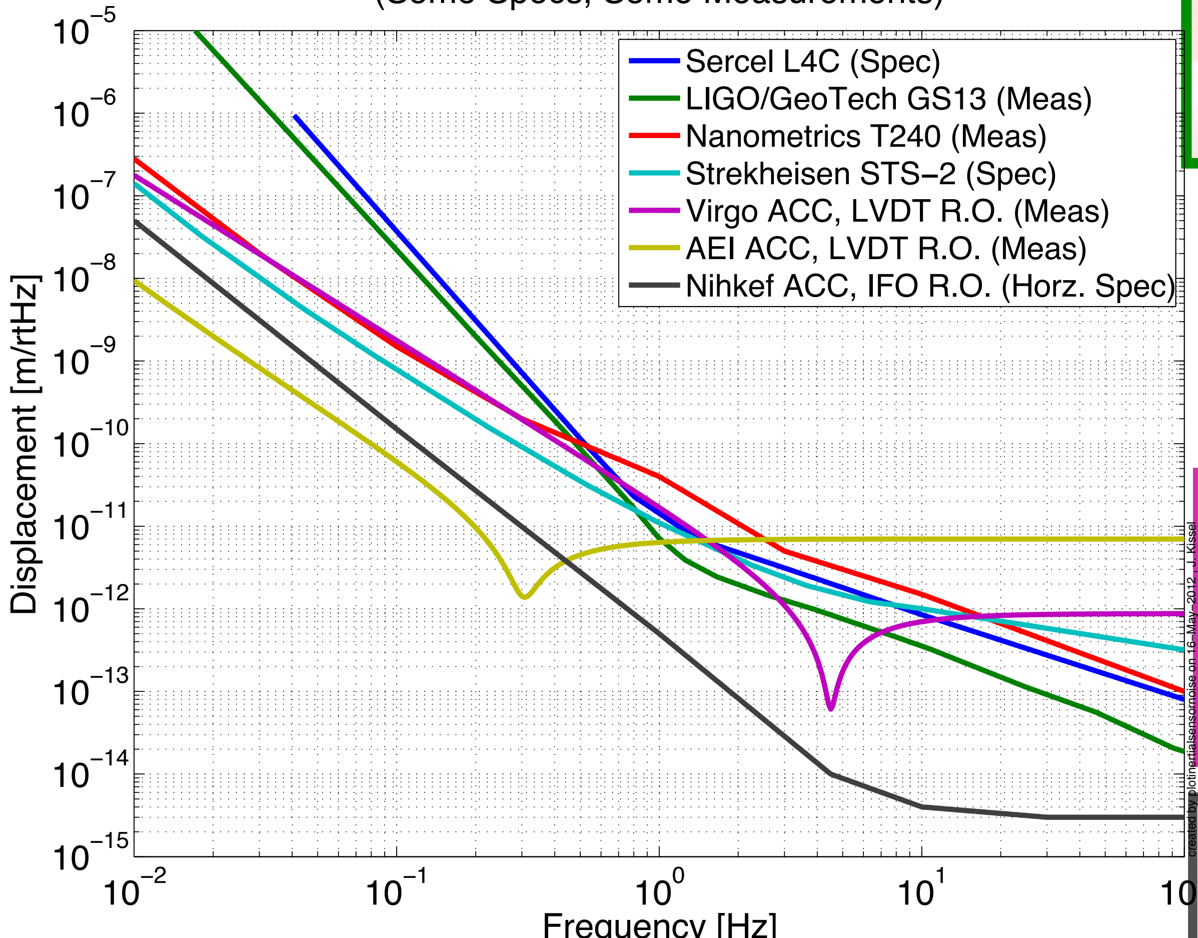
aLIGO Pre-isolator Stage
aLIGO Stage 0 & 1 ISIs
AEI-SAS Vert. Witness

aLIGO Pre-isolator Stage



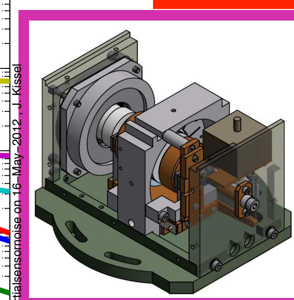
AEI-SAS Horz. Witness
(Watt Linkage)

Current Inertial Sensor Sensor Noise
(Some Specs, Some Measurements)

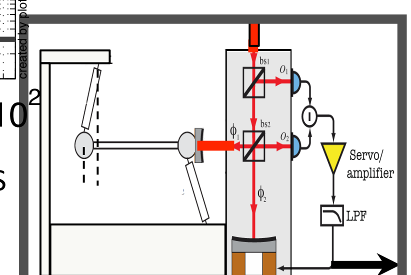


aLIGO
Stage 1
& 2 ISIs

aLIGO
Stage 1
ISIs



iVIRGO
F0, F7

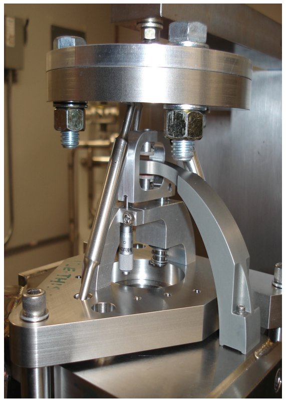


aVIRGO MultiSAS
Horz. Witness
(Watt Linkage)

SEI Sensors and Their Noise

"Low" Frequency

DC



IPS

Kaman's Inductive Position Sensors

Used On: HEPIs

Used For: ≤ 0.5 Hz Control, Static Alignment

Used 'cause: Reasonable Noise, Long Range

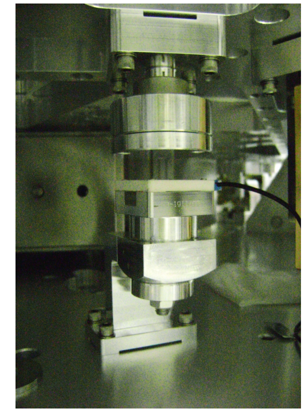
CPS

MicroSense's Capacitive Displacement Sensors

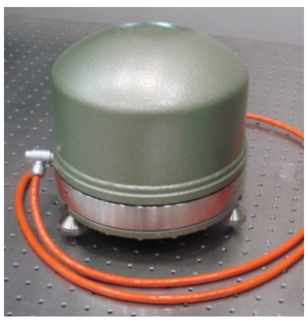
Used On: HAM-ISIs and BSC-ISIs

Used For: ≤ 0.5 Hz Control, Static Alignment

Used 'cause: Good Noise, UHV compatible



10 mHz



STS2

Strekheisen's STS-2

Used On: HEPIs

Used For: 0.01 ≤ f ≤ 1Hz Control

Used 'cause: Best in the 'Biz below 1 Hz, Triaxial

T240

Nanometric's Trillium 240

Used On: BSC-ISIs

Used For: 0.01 ≤ f ≤ 1Hz Control

Used 'cause: Like STS-2s, Triaxial, no locking mechasim -> podded

1 Hz

GS13

GeoTech's GS-13

Used On: HAM-ISIs and BSC-ISIs

Used For: ≥ 0.5 Hz Control

Used 'cause: awesome noise above 1Hz,

no locking mechanism -> podded

L4C

Sercel's L4-C

Used On: All Systems

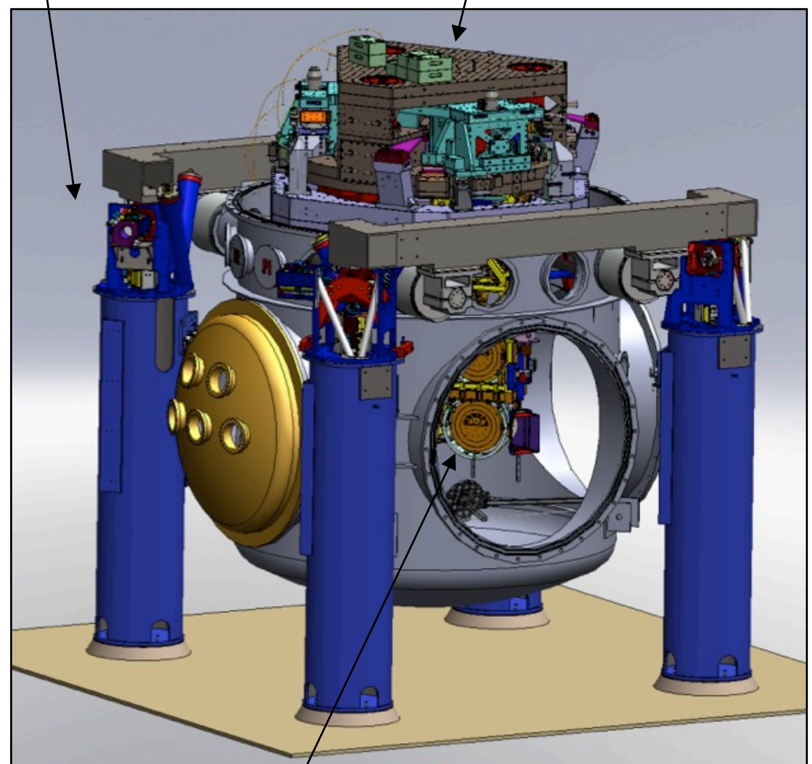
Used For: ≥ 0.5 Hz Control

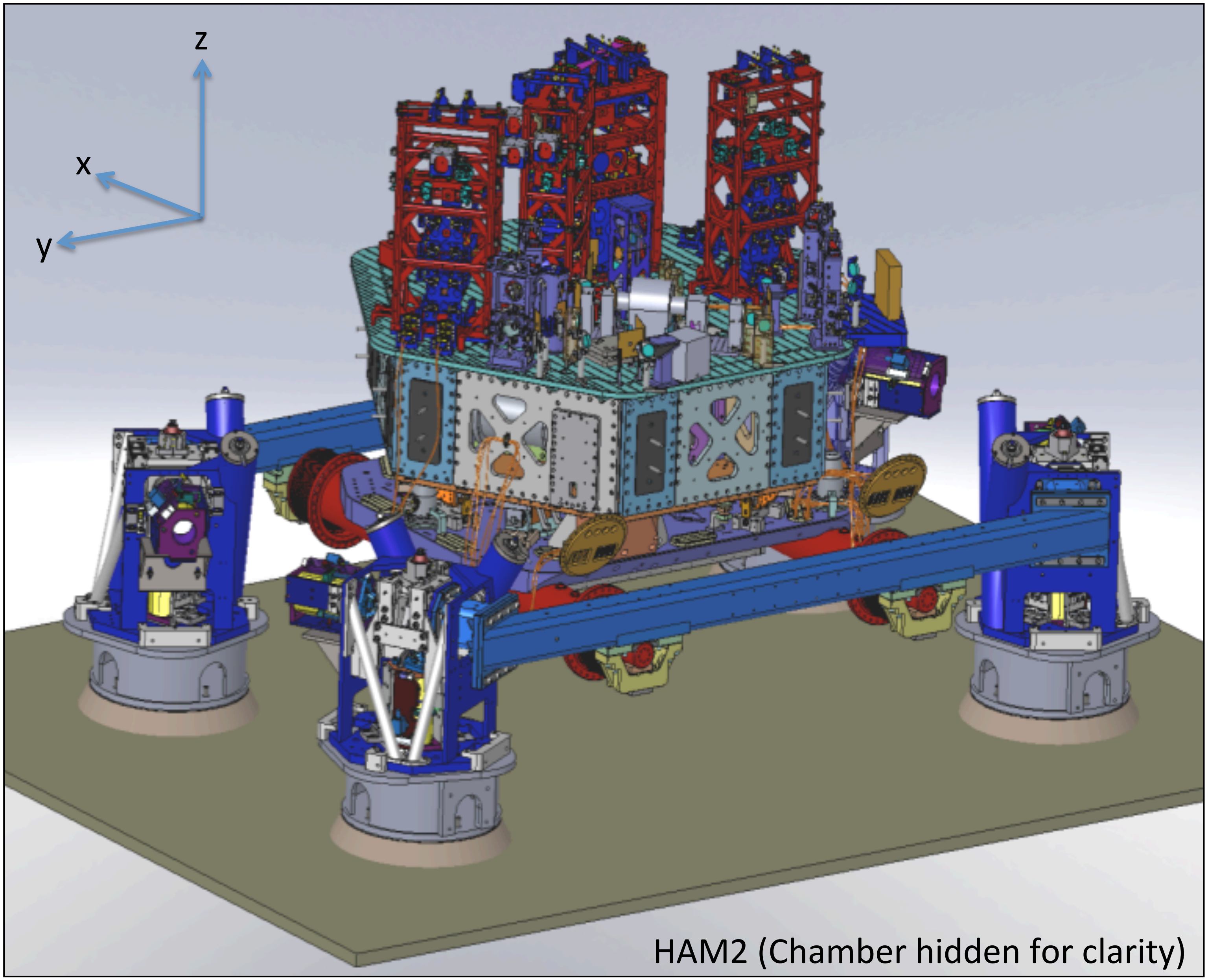
Used 'cause: Good Noise, Cheap, no locking mechanism -> podded

800 Hz

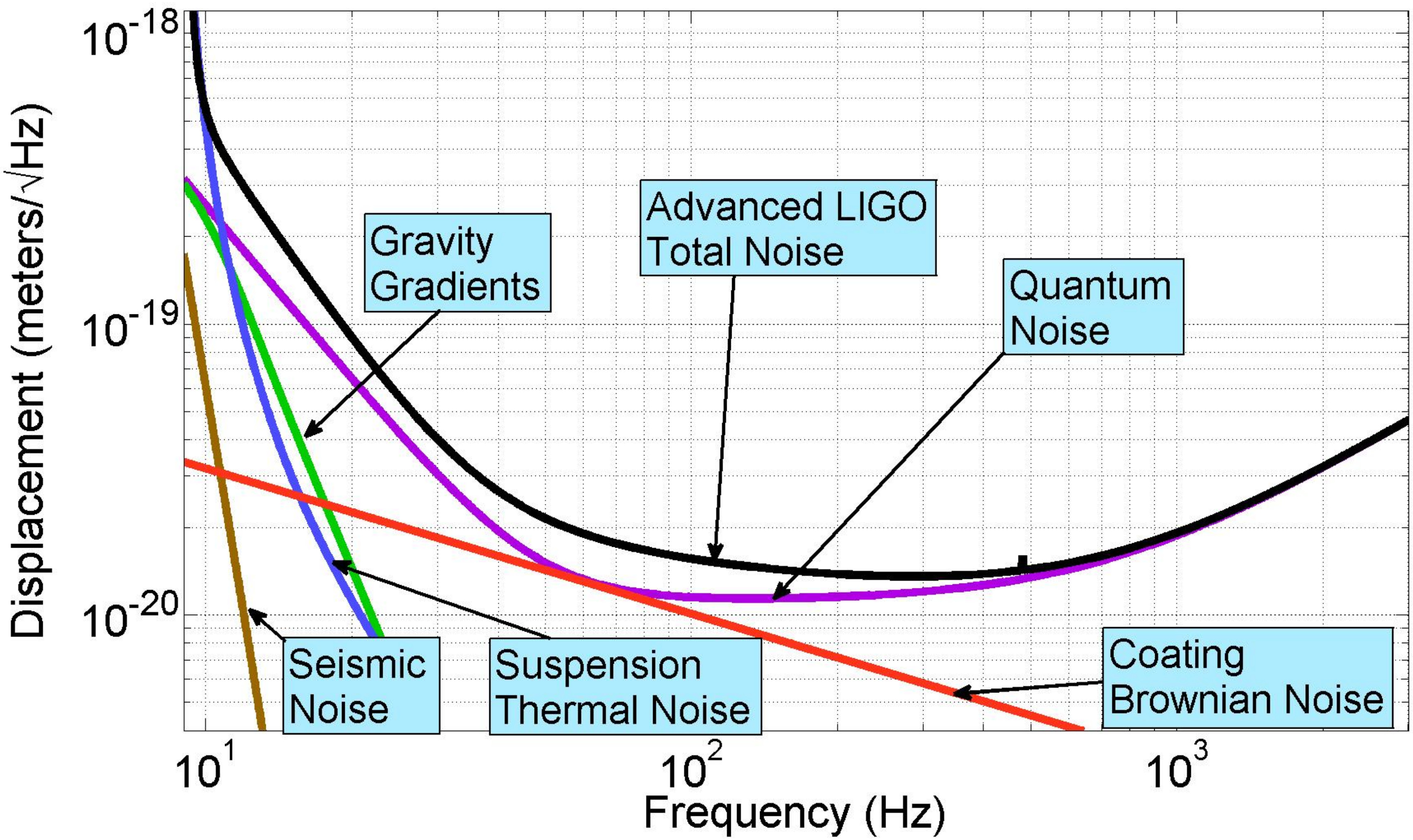
"High" Frequency

BSCs – core optics




z
x
y
HAM2 (Chamber hidden for clarity)

Predicted Advanced LIGO Sensitivity



Ground Variability