Advanced LIGO Suspensions

Brett Shapiro, for the SUS Group

Detector Characterization Telecon

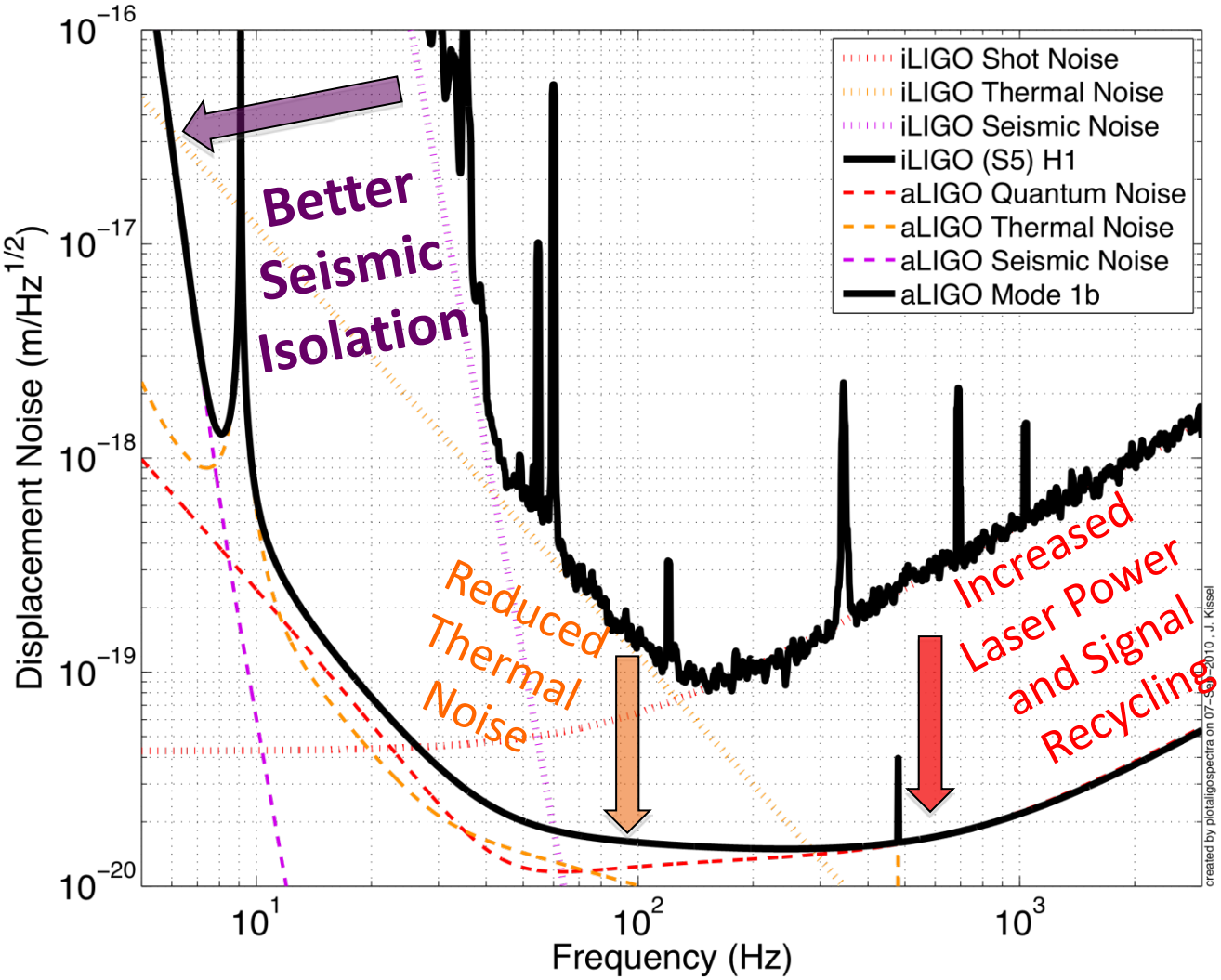
25 August 2011

LIGO

Contents

- iLIGO to aLIGO
- Seismic Isolation
- Sensors and Actuators: BOSEMs and AOSEMs
- Suspension Overview
- Signals and Control
- SUS Testing
- What can you do?

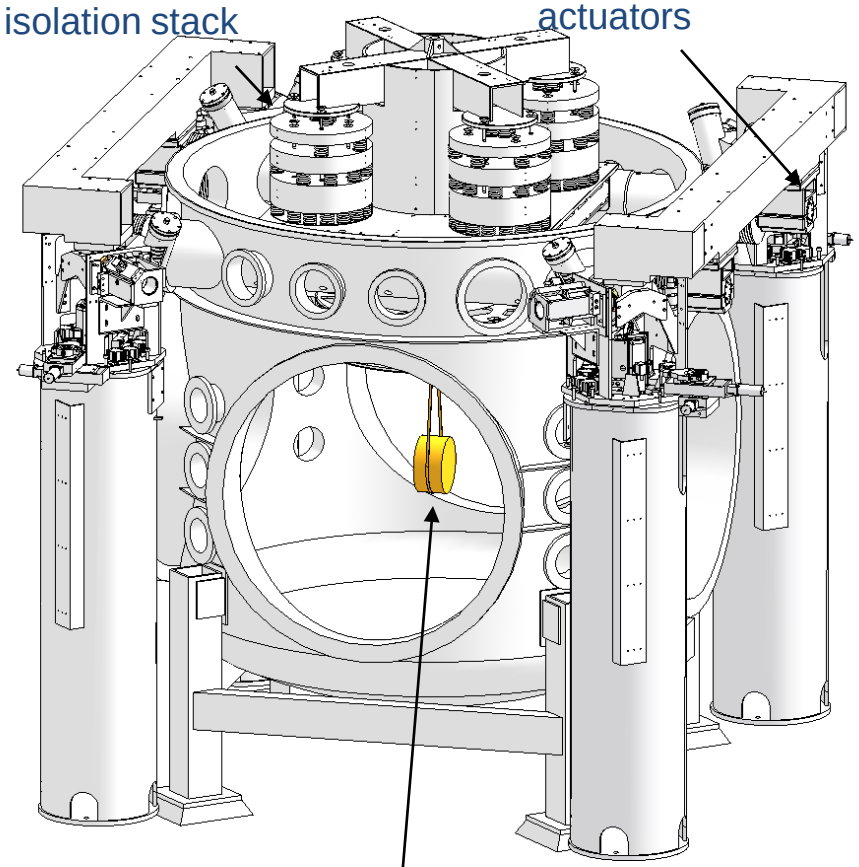
iLIGO to aLIGO



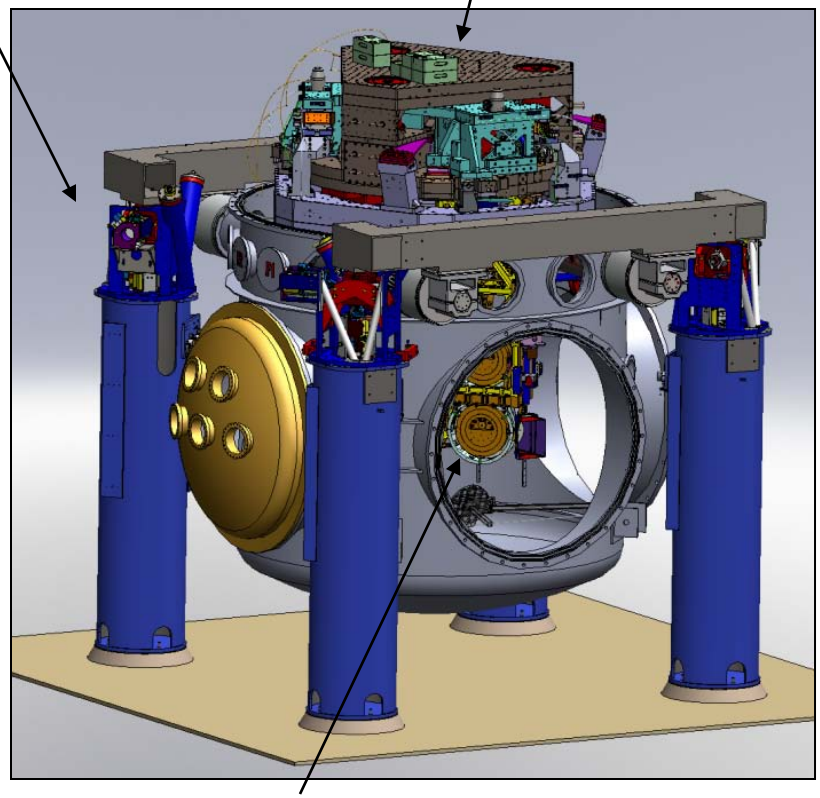
Kissel – thesis defense, P1000103

Suspensions and Seismic Isolation – From Initial to Advanced LIGO

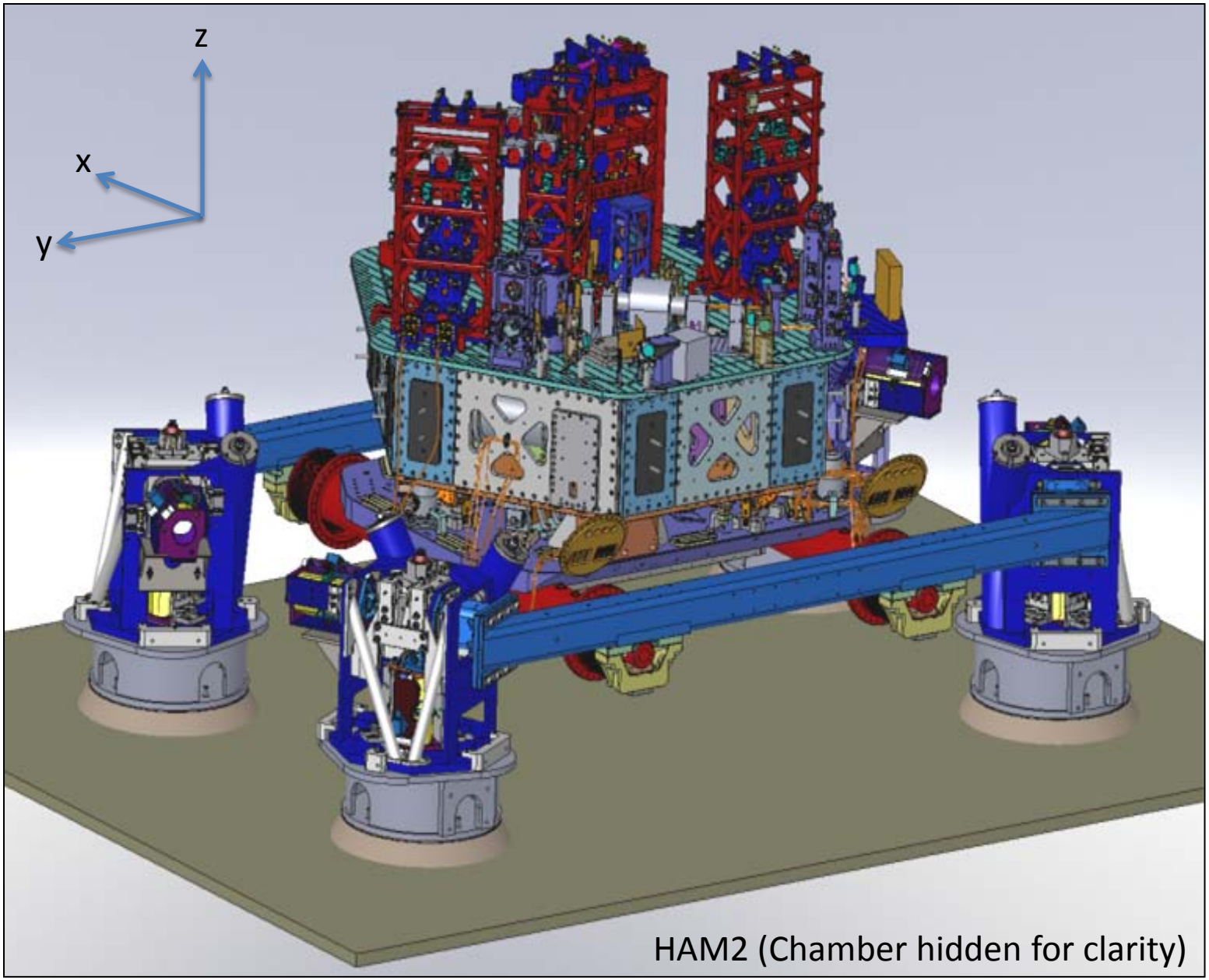
LIGO



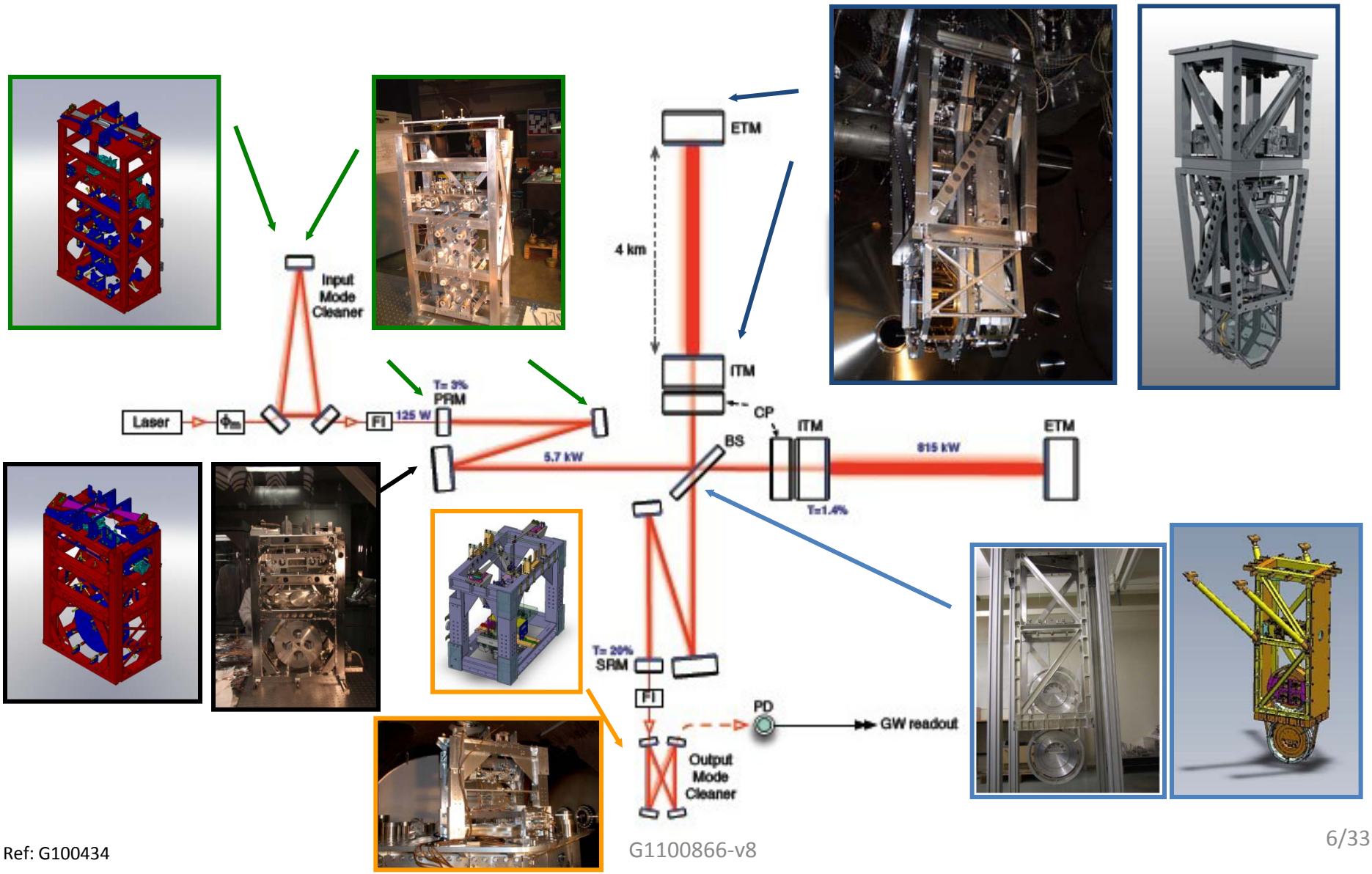
Advanced LIGO



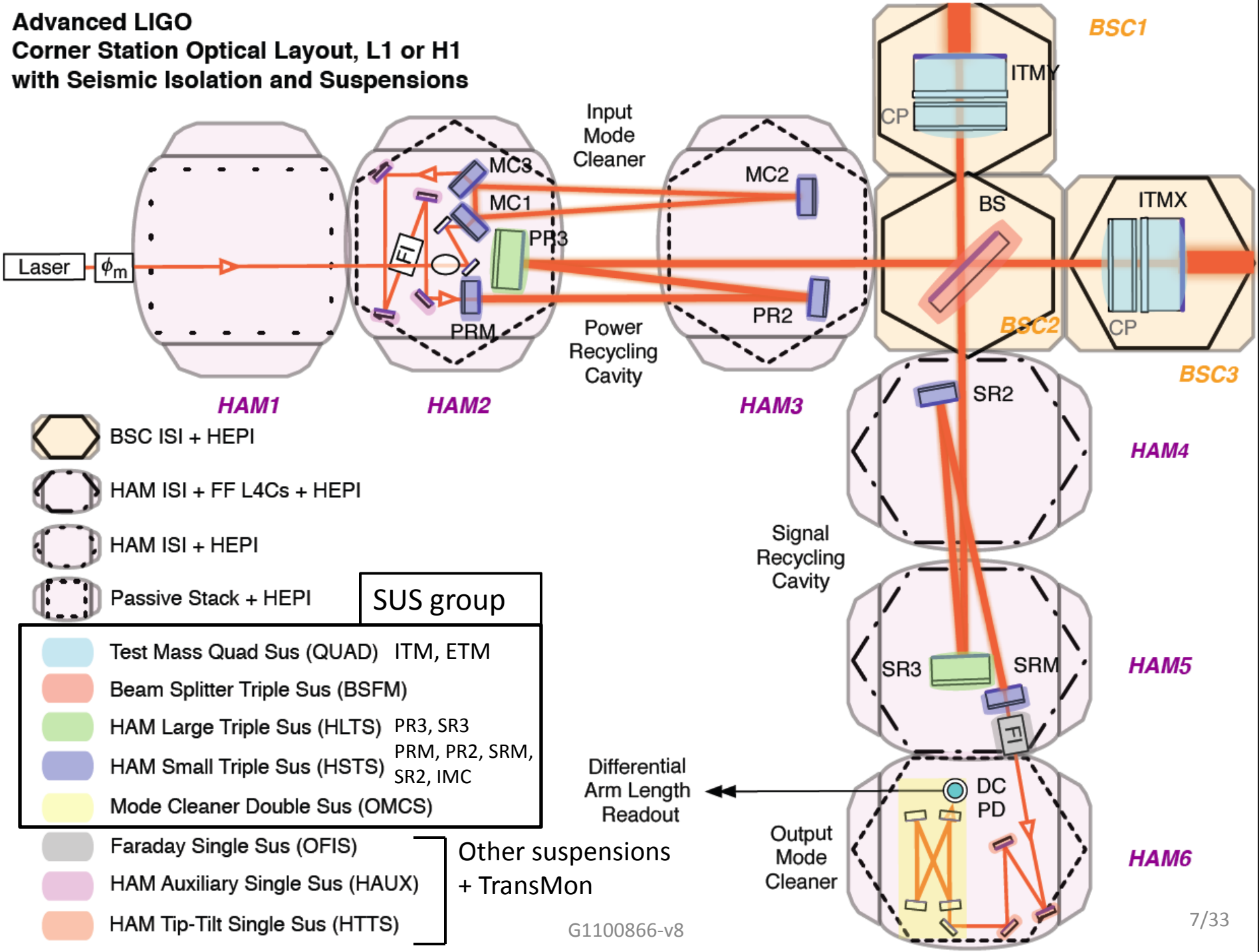
Ref: LIGO-G1000469-v1; Kissel PhD thesis


z
x
y
HAM2 (Chamber hidden for clarity)

Five Suspension Designs

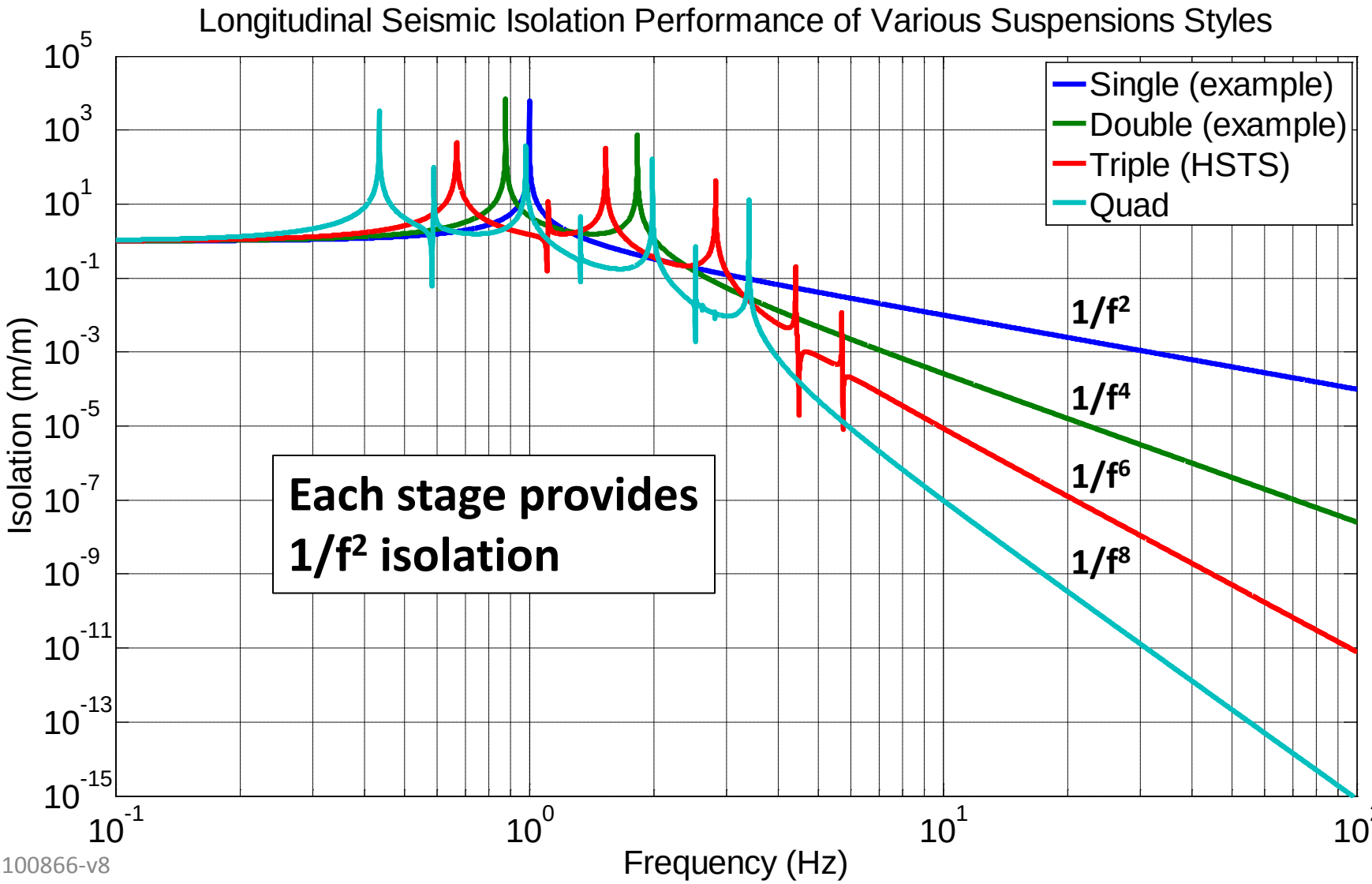


Advanced LIGO
Corner Station Optical Layout, L1 or H1
with Seismic Isolation and Suspensions



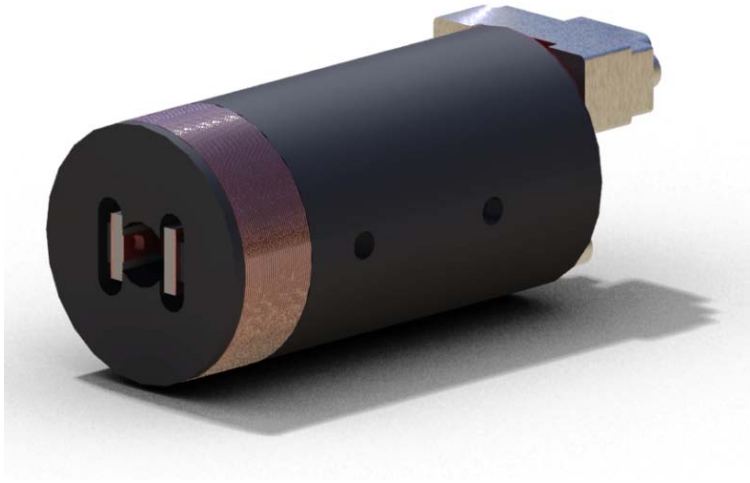
LIGO

Suspension Isolation Performance

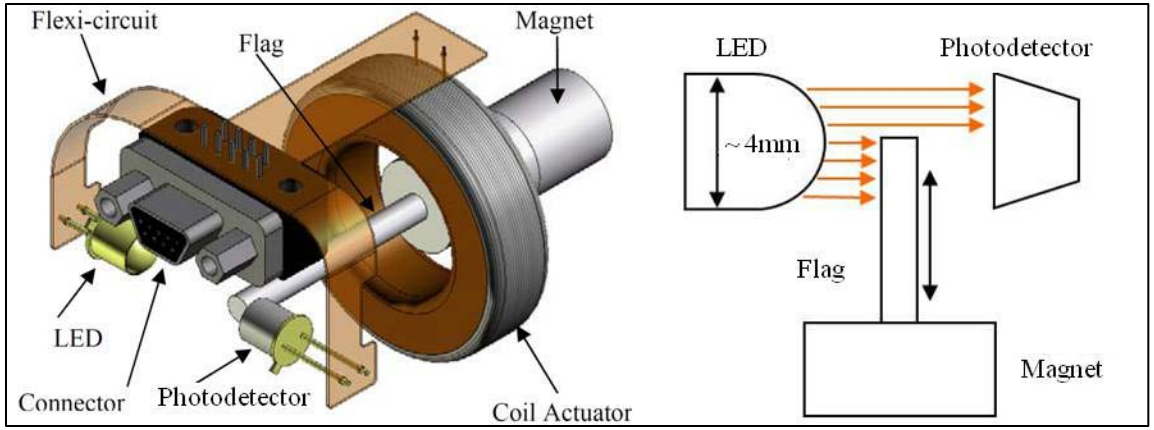


Optical Sensor ElectroMagnet (OSEM)

Birmingham OSEM (BOSEM)



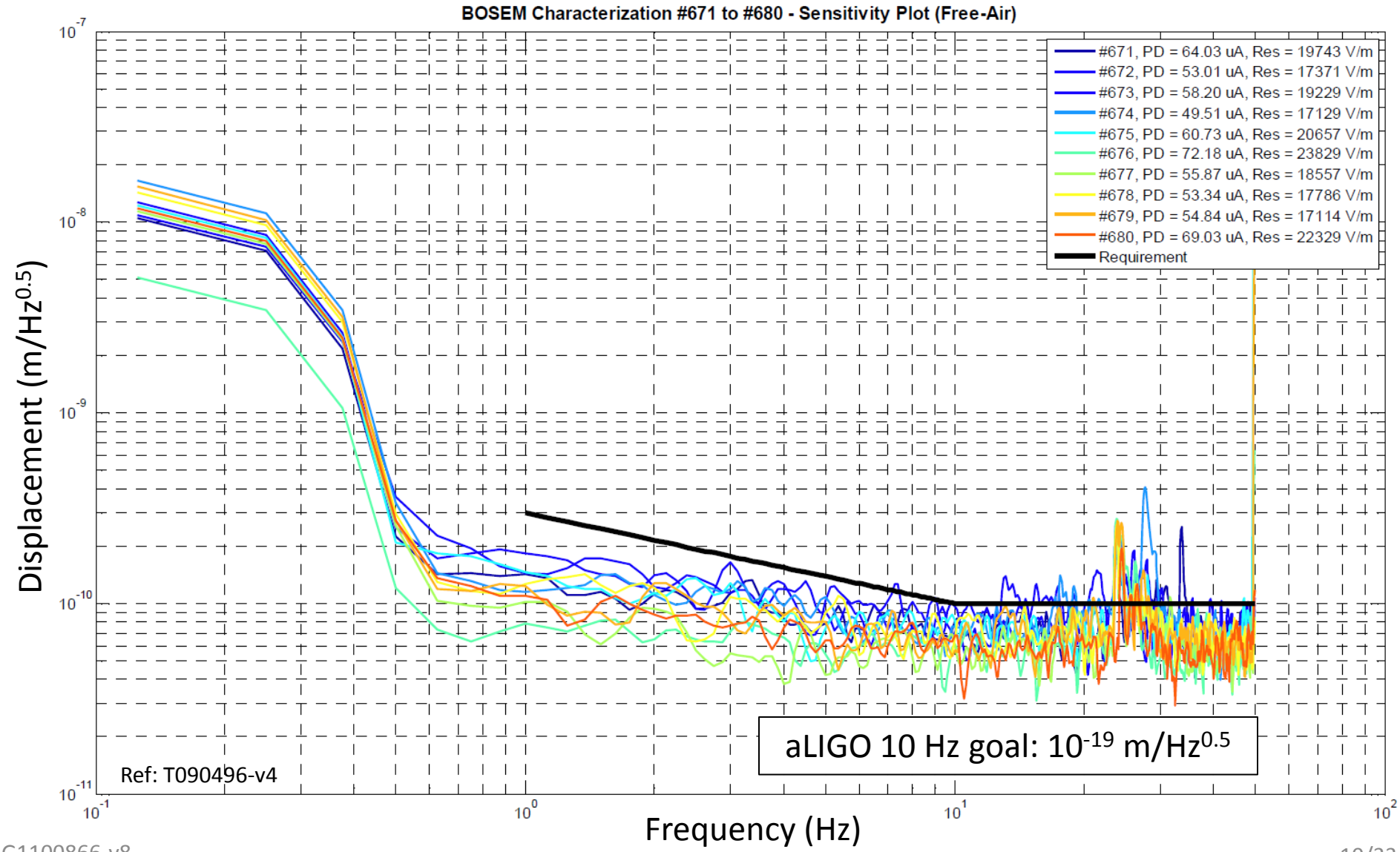
Advanced LIGO OSEM (AOSEM)
- modified iLIGO OSEM



BOSEM Schematic

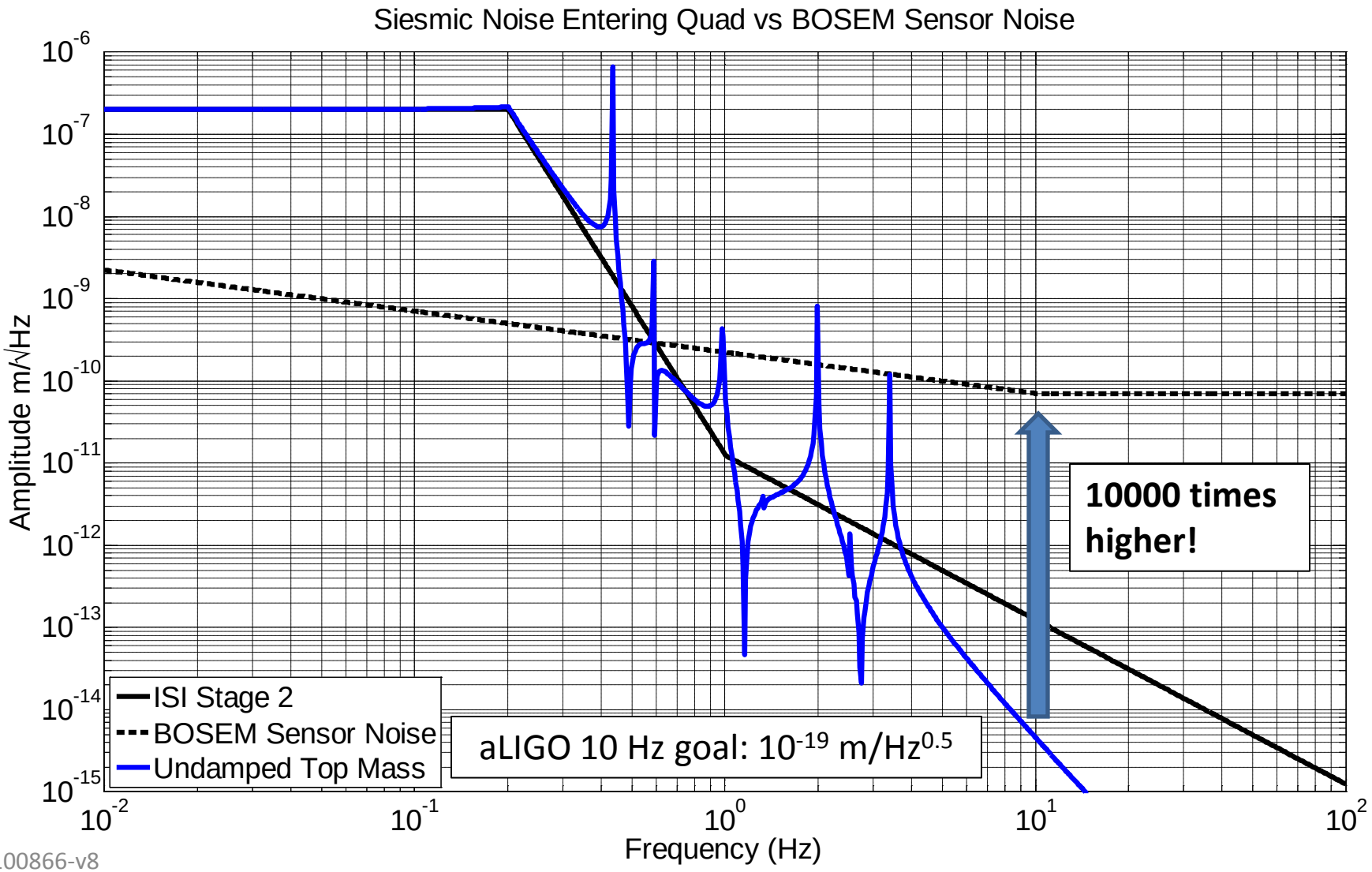
Magnet Types (M0900034)
- BOSEM – 10 X 10 mm, NdFeB , SmCo
  10 X 5 mm, NdFeB, SmCo
- AOSEM – 2 X 3 mm, SmCo
  2 X 6 mm, SmCo
  2 X 0.5 mm, SmCo

BOSEM Sensor Noise



LIGO

Sensor Feedback Only to Top Mass



Output Mode Cleaner Double (OMCS)

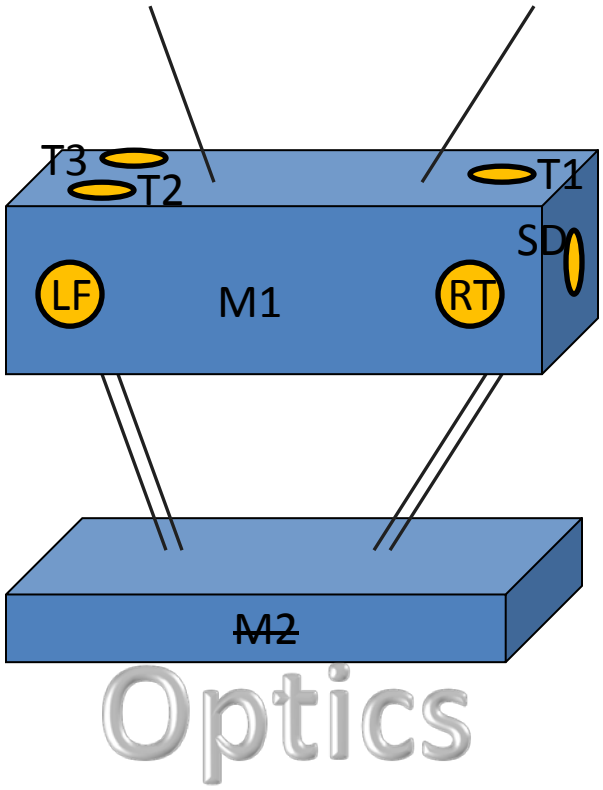
Location
- HAM 6, (12)

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

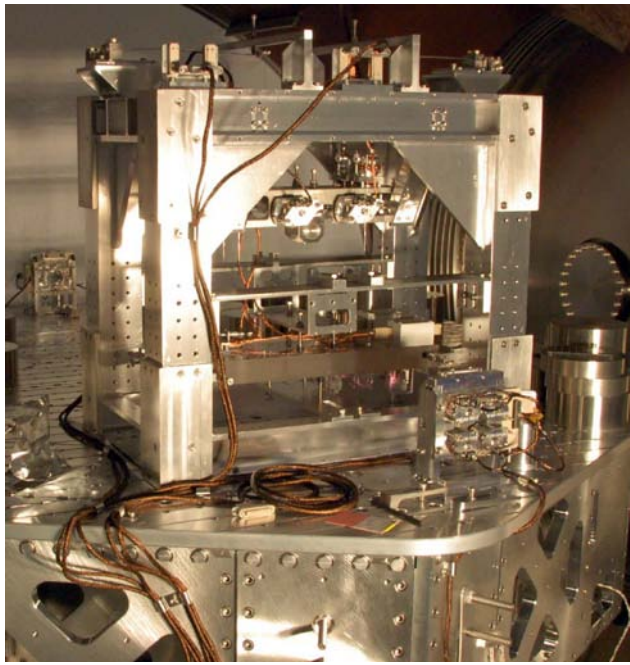
Sensors/Actuators
- BOSEMs at top mass

Top mass naming convention
- L1:SUS-OMC_M1…

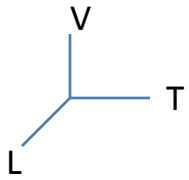
site 2 | subsystem 3 | unit 3,4 | stage 2



In use during S6



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



Local coordinates

HAM Small Triple Suspension (HSTS)

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

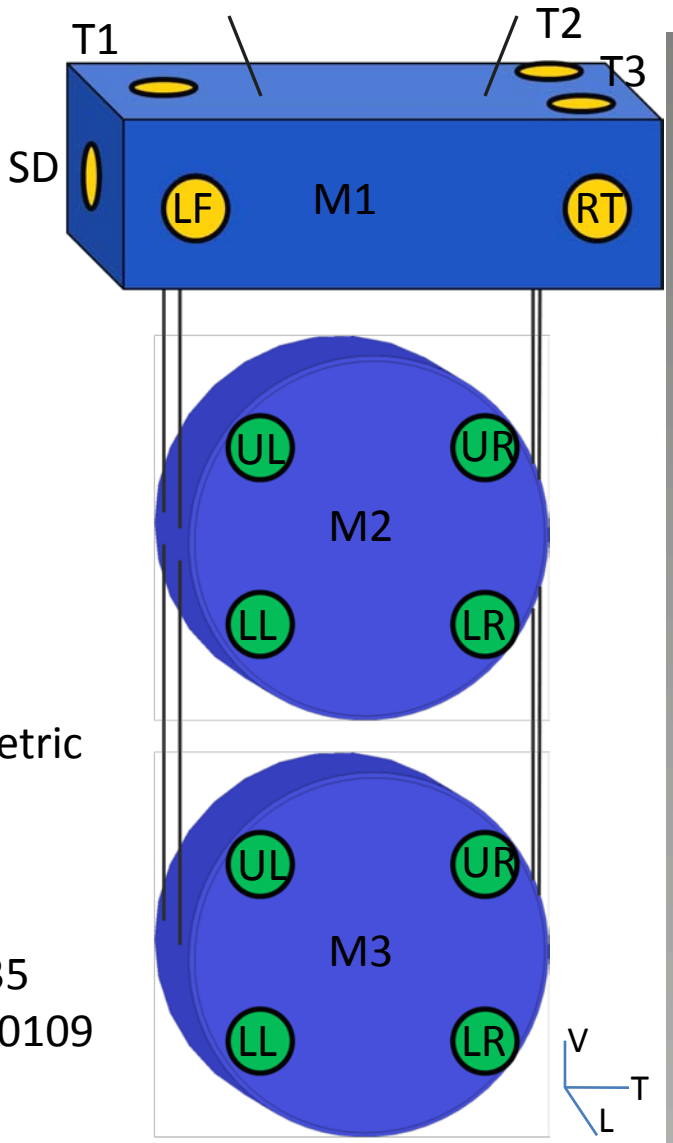
Location
- HAM 2, 3, 4, 5, (8, 9, 10, 11)

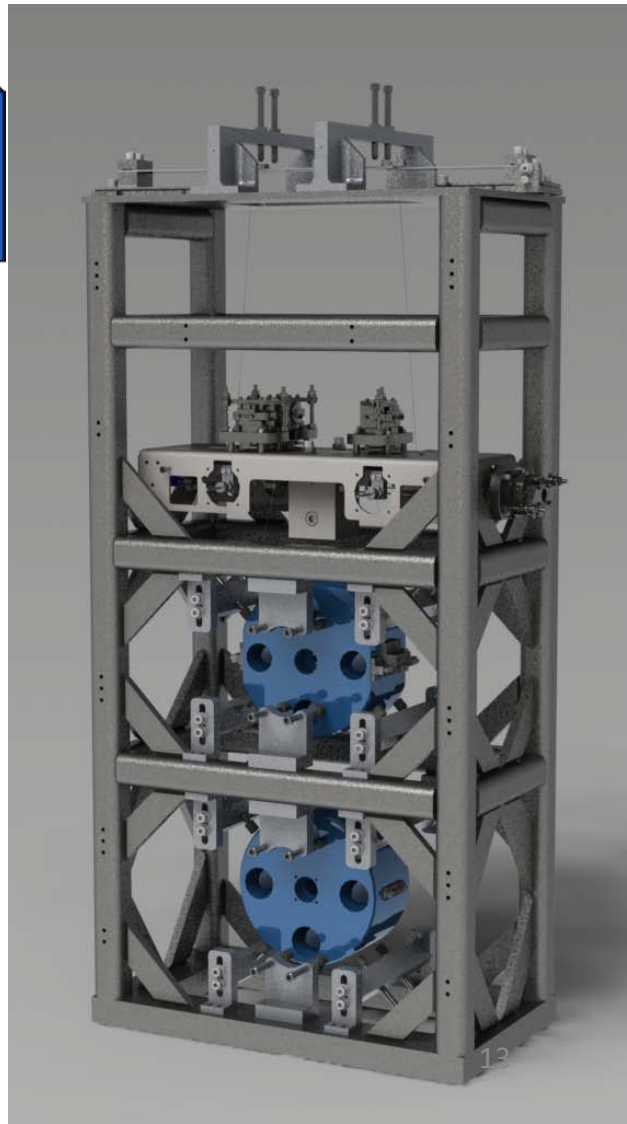
Control
- Local – damping at M1
- Global – LSC & ASC at all 3

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





HAM Large Triple Suspension (HLTS)

Purpose
- PR3, SR3

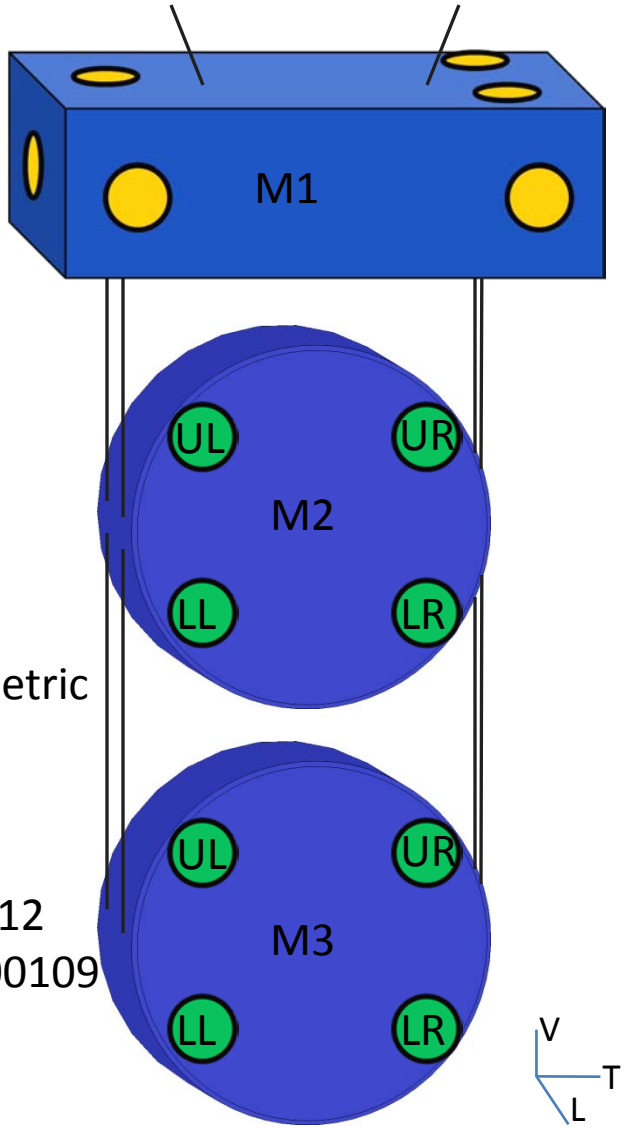
Location
- HAM 2, 5, (8, 11)

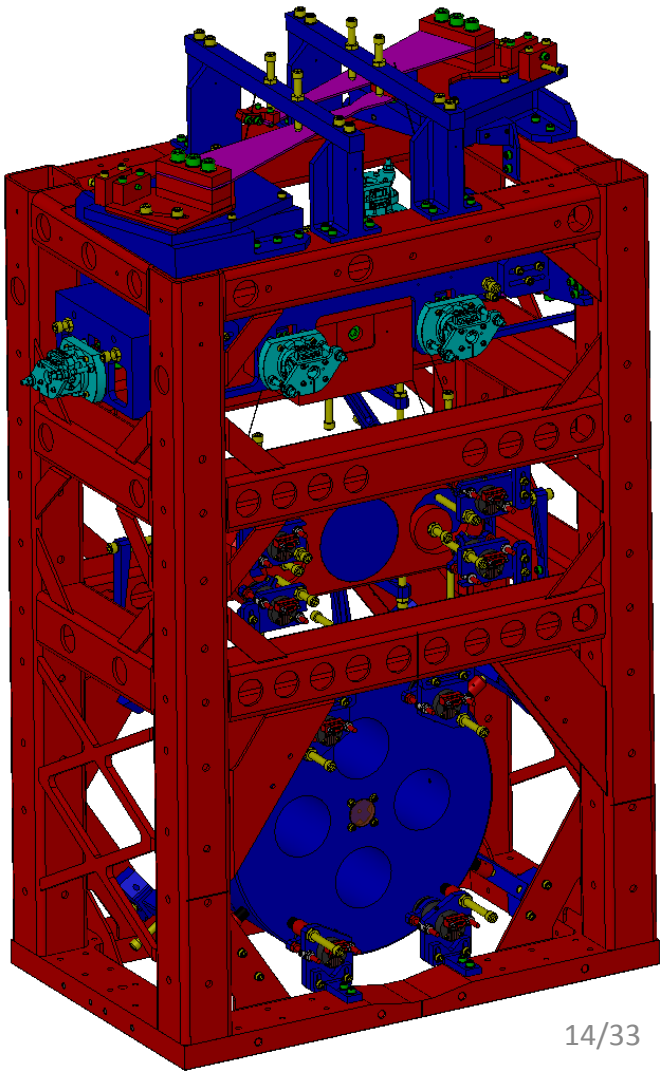
Control
- Local – damping at M1
- Global – LSC & ASC at all 3

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





Beamsplitter/Folding Mirror (BSFM)

Purpose
- BS, (FMX and FMY)

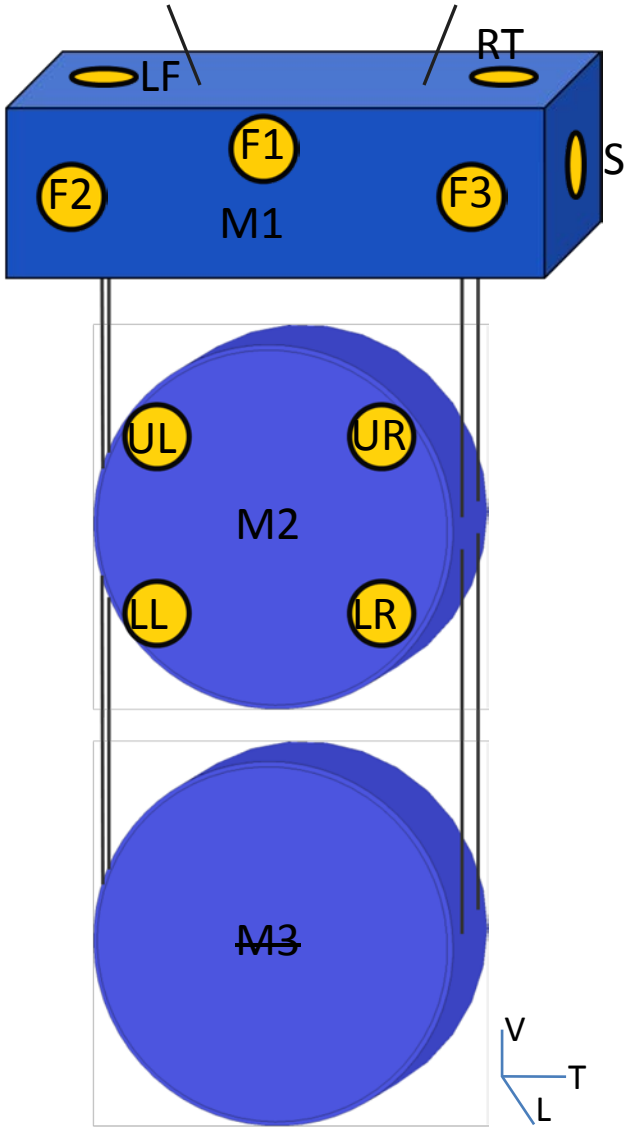
Location
- Beamsplitter – BSC 2, (4)
- (Fold Mirror – BSC 6, 8)

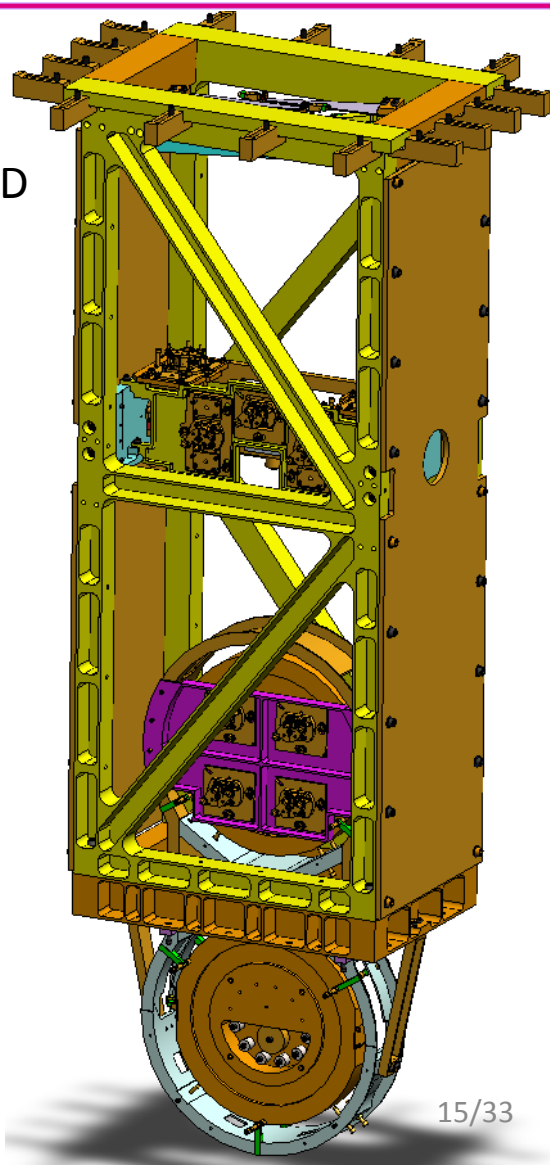
Control
- Local – damping at M1
- Global – LSC & ASC at M2

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

Naming: L1:SUS-FMX_M1…

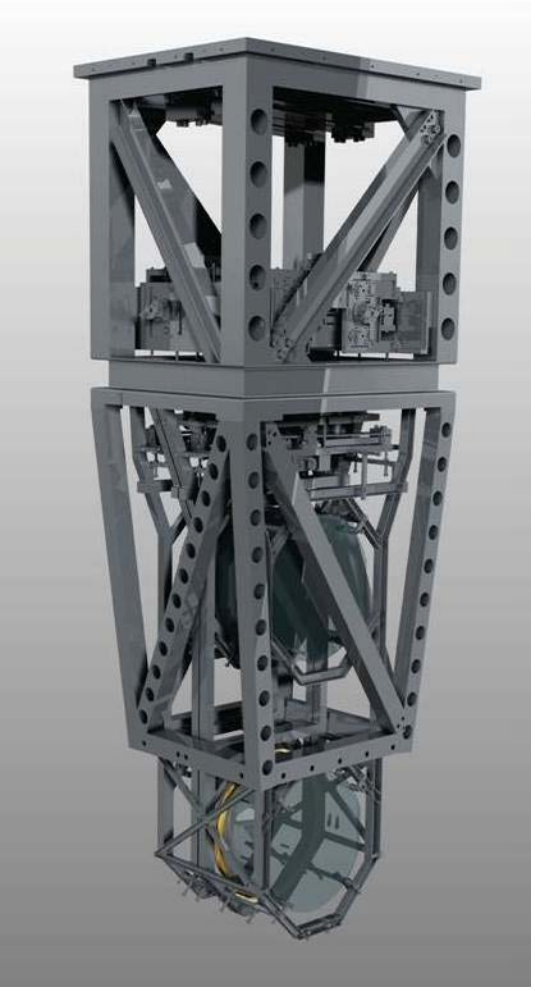
Documentation
- Final design review - T080218
- Controls arrangement – E1100108

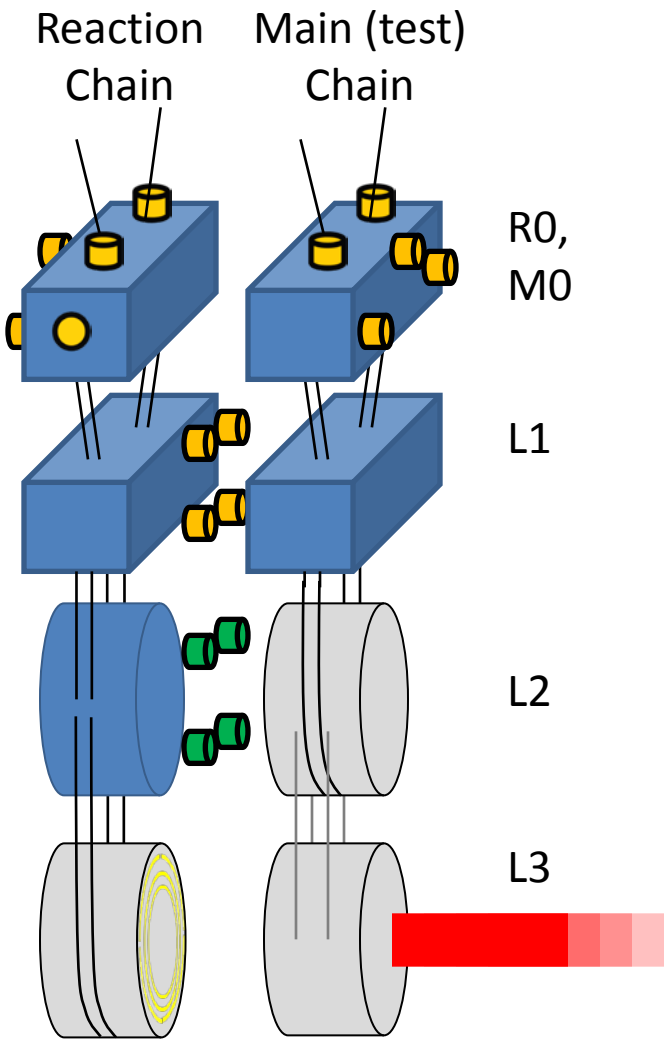




LIGO

Quadruple Suspension (Quad)





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

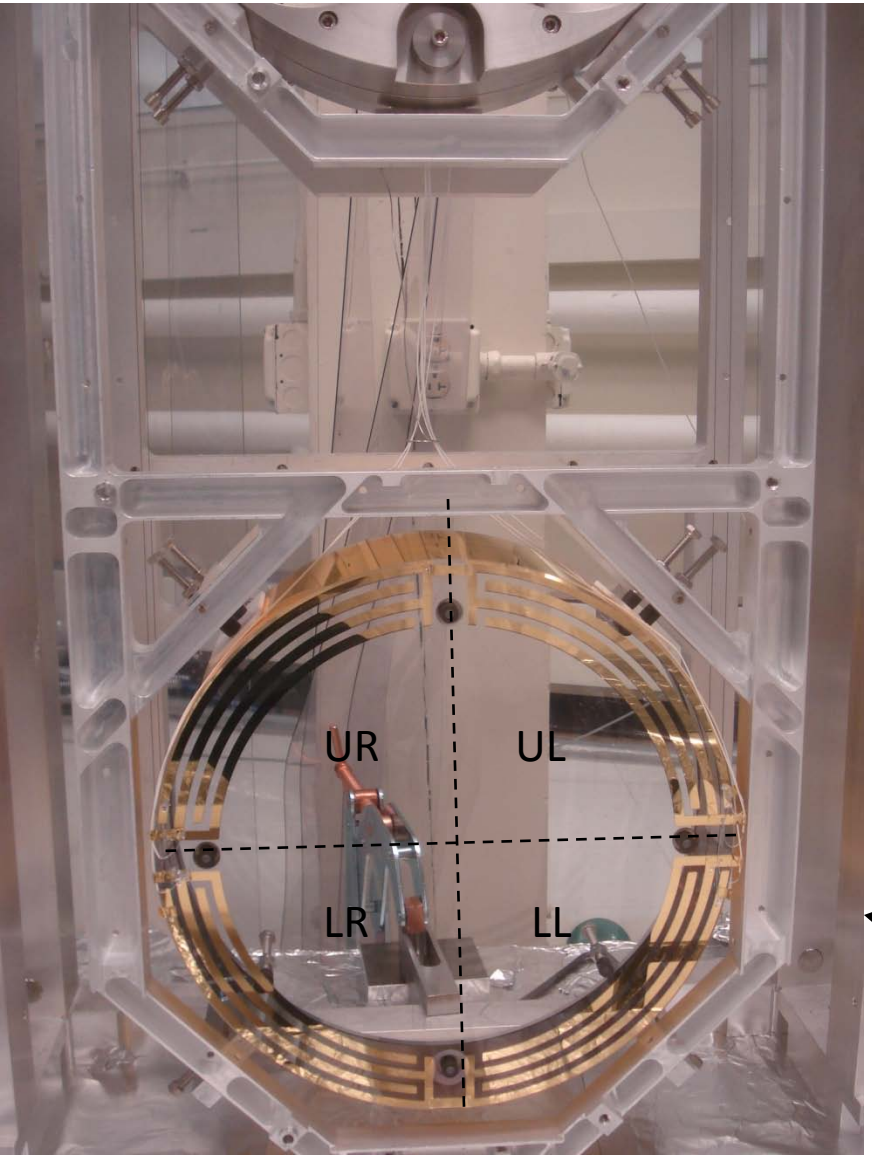
Location
- H1 - BSC 1, 3, 9, 10
- H2 - BSC 7, 8, 5, 6
- L1 – BSC 1, 3, 4, 5

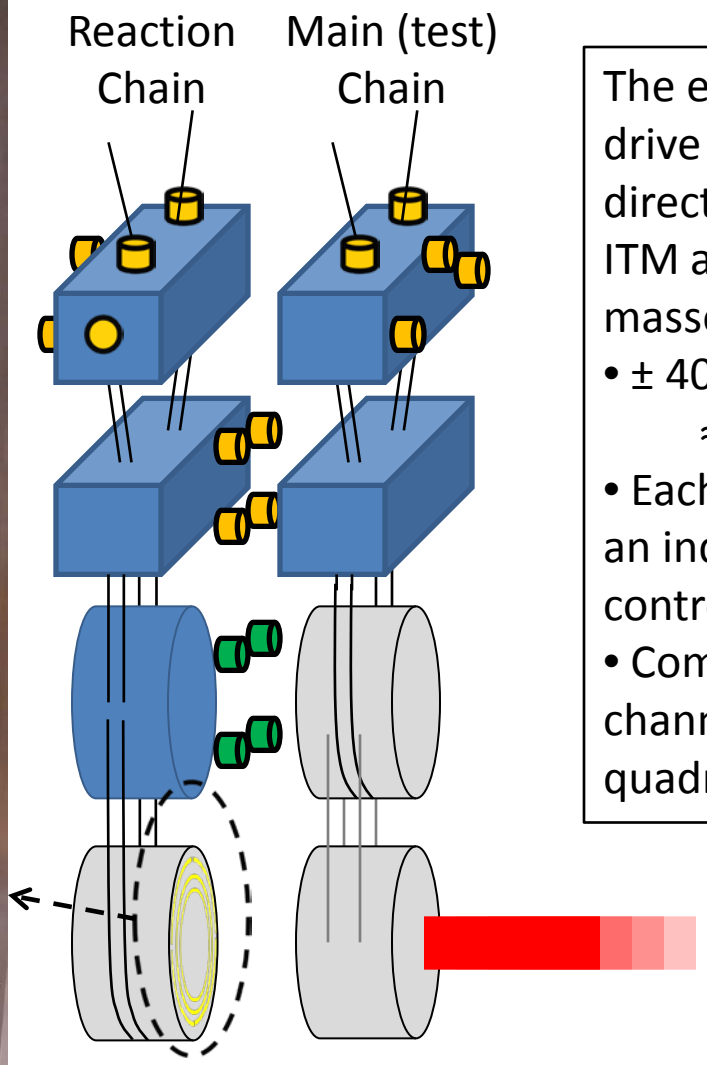
Control
- Local – damping at M0, R0
- Global – LSC & ASC at all 4

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

Quadruple Suspension ESD





The electrostatic drive (ESD) acts directly on the test ITM and ETM test masses.

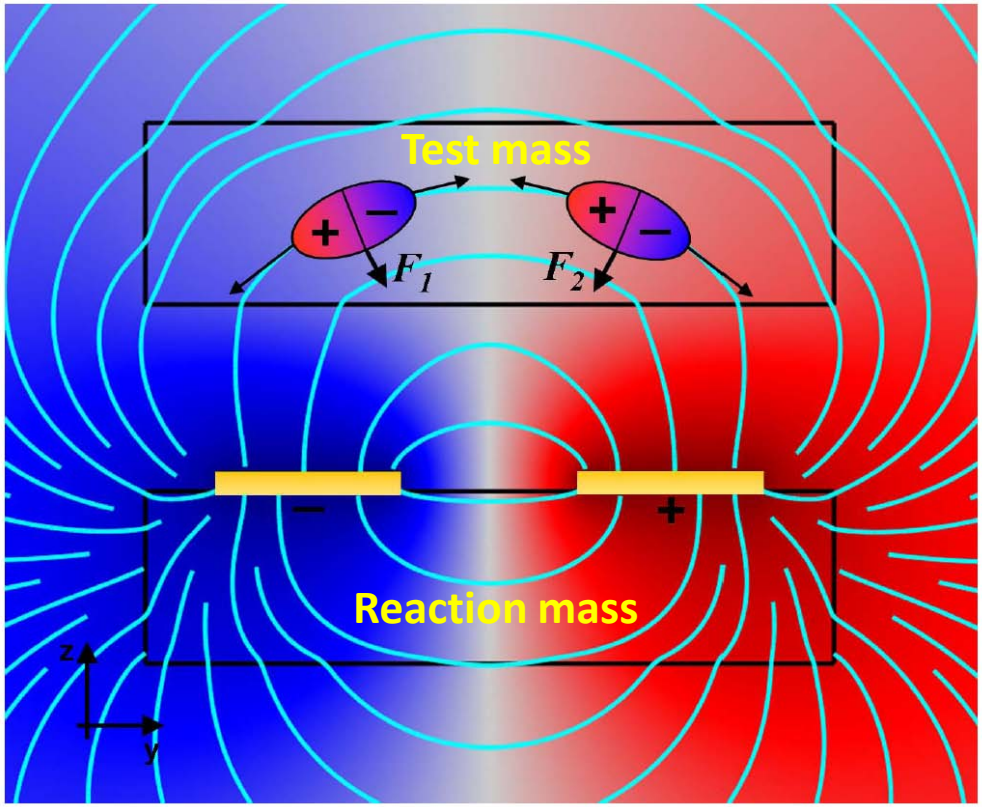
- ± 400 V (ΔV 800 V) ≈ 100 µN
- Each quadrant has an independent control channel
- Common bias channel over all quadrants

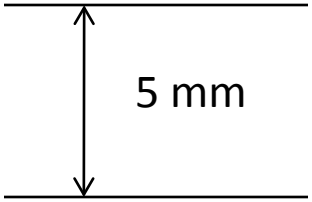
Quadruple Suspension ESD

$F = \alpha \Delta V^2$

- α = coupling coefficient, depends on geometry
- ΔV = differential voltage across traces

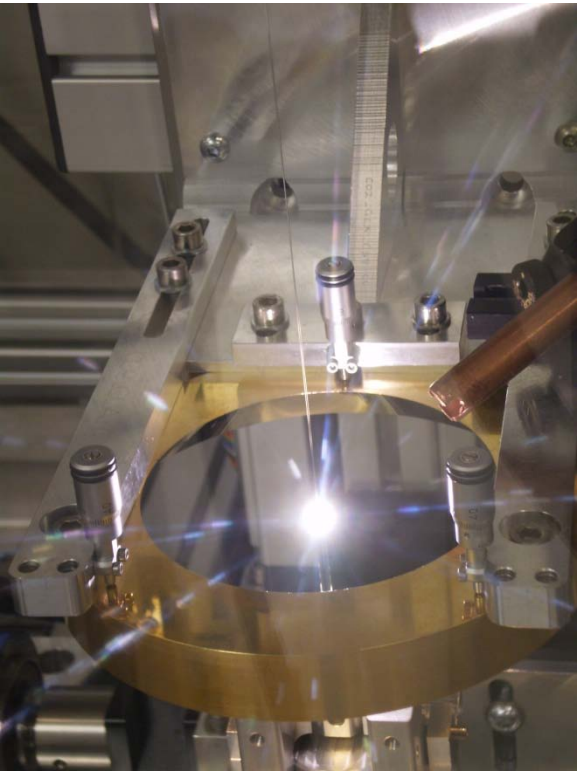
Linearization occurs in the control!



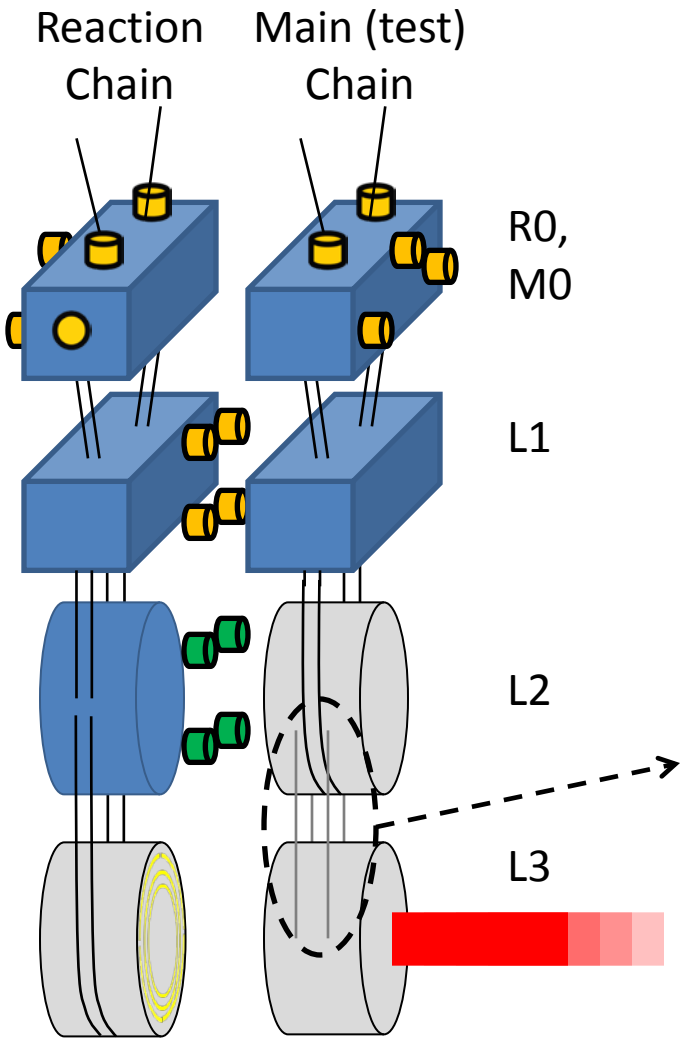


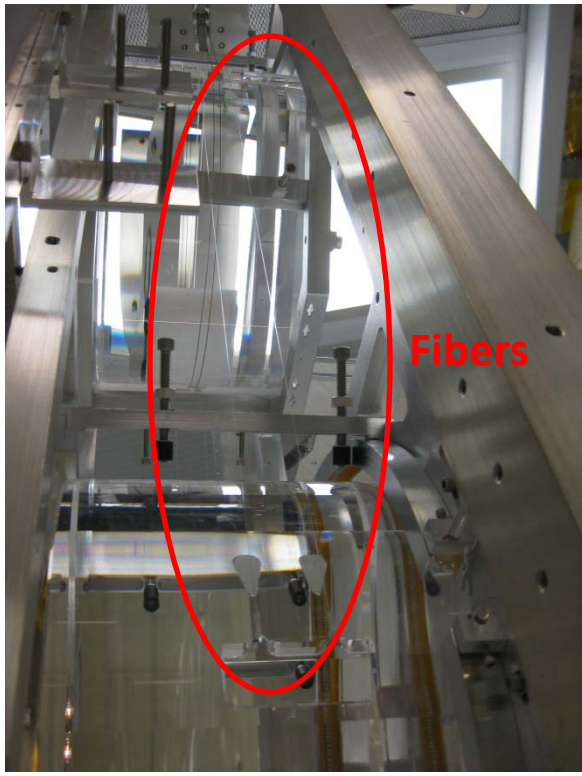
Cartoon diagram illustrating the working principle of the ESD. The upper rectangle represents the test mass containing two polarized molecules; the lower rectangle represents the reaction mass bearing two electrodes. Surface plot shows electrical potential with electric field lines shown in cyan (John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

Quadruple Suspension (Quad)



Pulling a fiber at MIT
7 May 2010





Newly welded
monolithic quad at MIT
11 May 2010

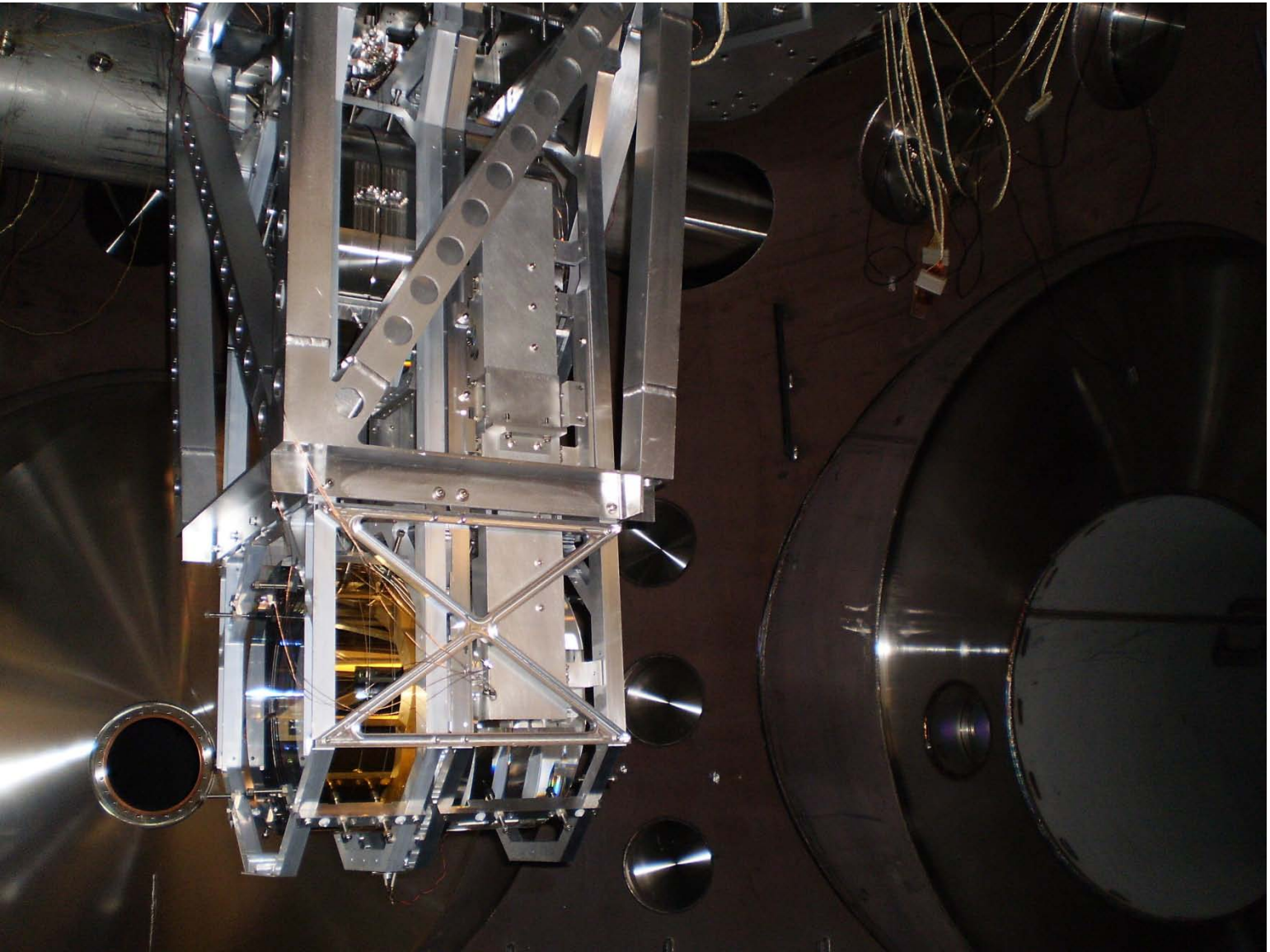
Delicate Fibers

Video of breaking the monolithic test suspension fibers at MIT, 5 Nov 2010.

To see how robust they are when they are not touched see http://www.youtube.com/watch?v=qlJ0o7R4-LU

LIGO

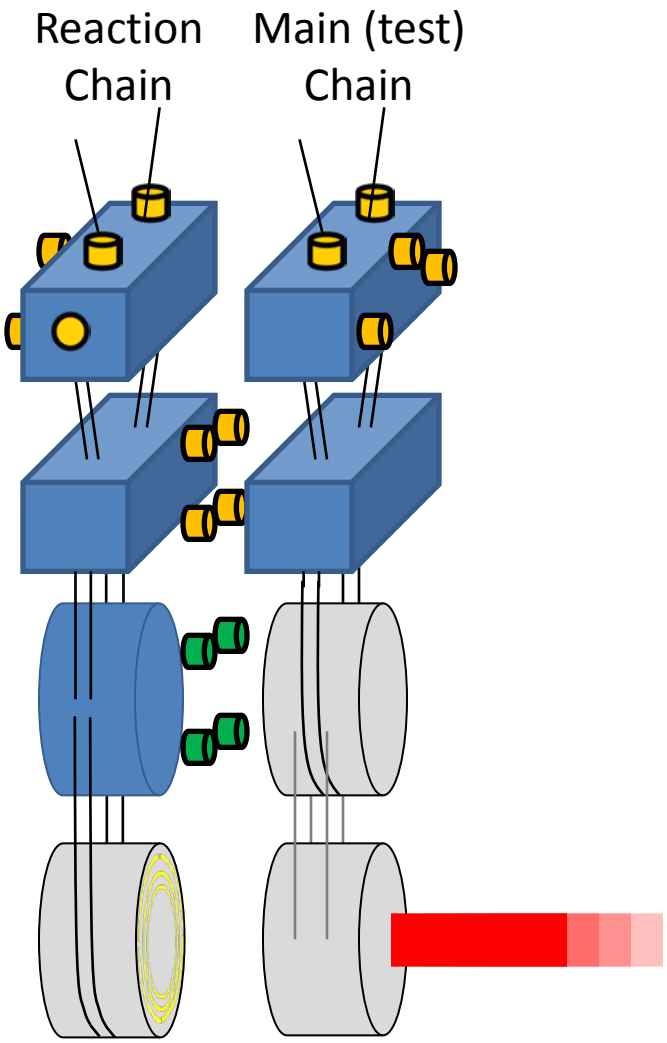
Quadruple Suspension (Quad)



MIT monolithic quad in BSC

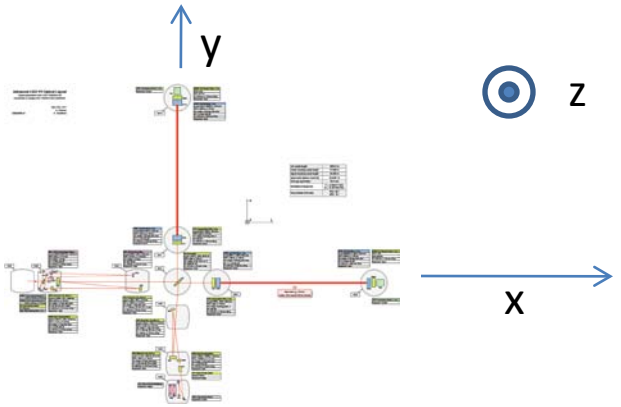
June 2010

Pendulum Coordinates

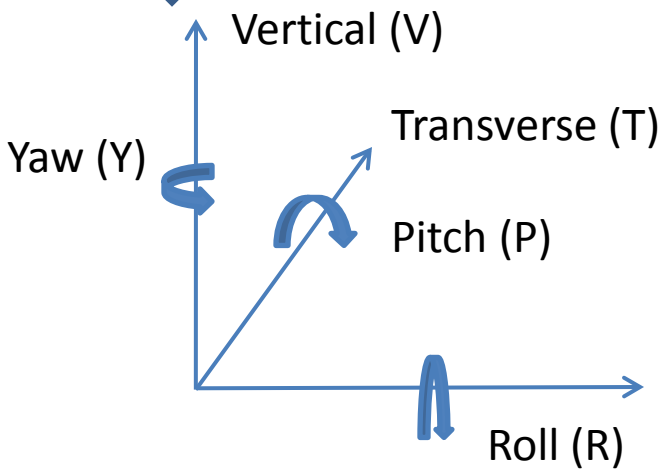


- SUS control follows local pendulum coordinates
- The 'beam line' does not always correspond to the IFO coordinates

Interferometer coordinates

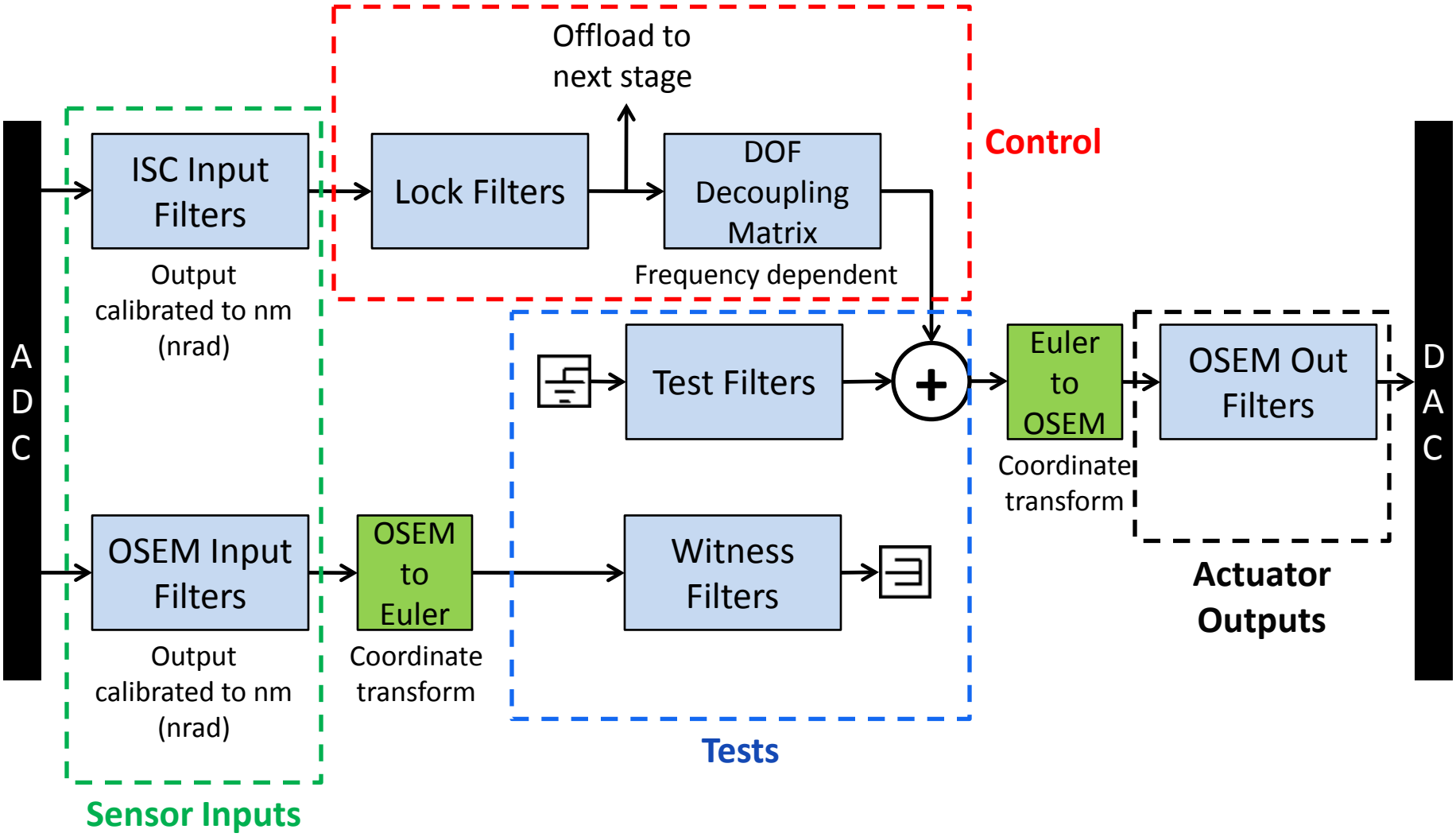


Local Coordinates



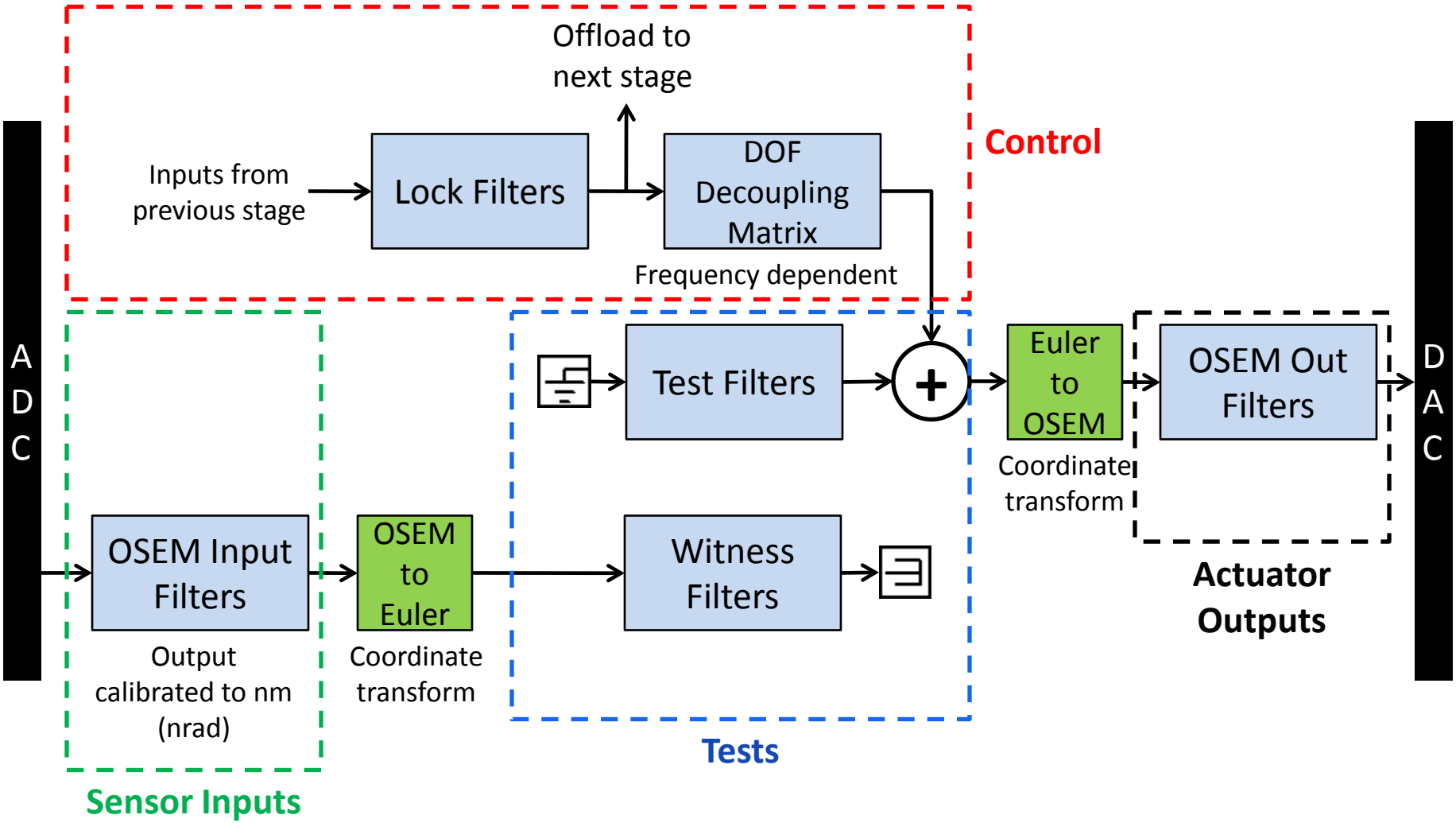
Main chain top mass longitudinal: L1:SUS-ITMX_M0_L

Signal Flow – HSTS Bottom Stage



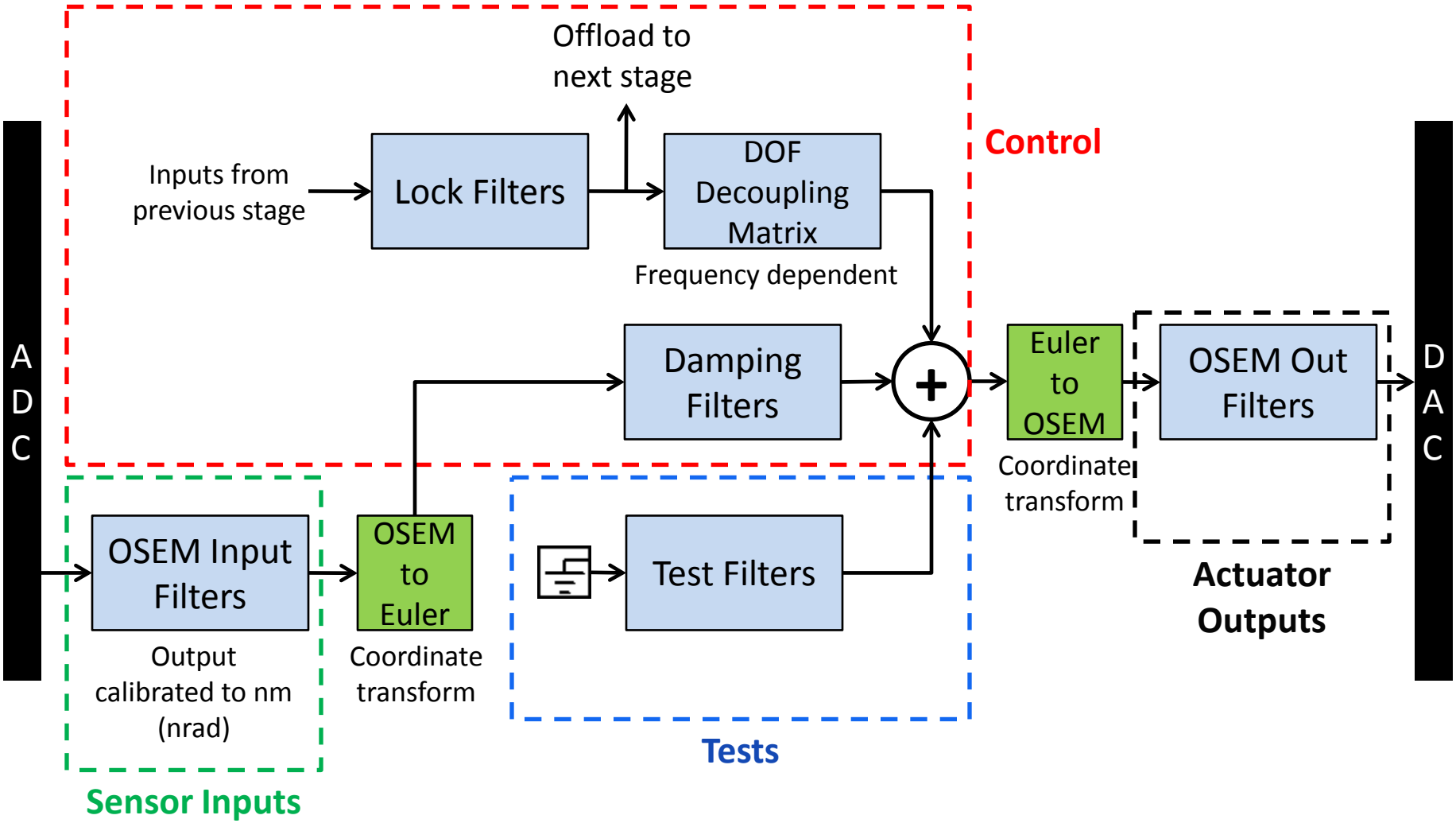
WIKI reference: https://awiki.ligo-wa.caltech.edu/aLIGO/NamingConventions

Signal Flow – HSTS Middle Stage



WIKI reference: https://awiki.ligo-wa.caltech.edu/aLIGO/NamingConventions

Signal Flow – HSTS Top Stage



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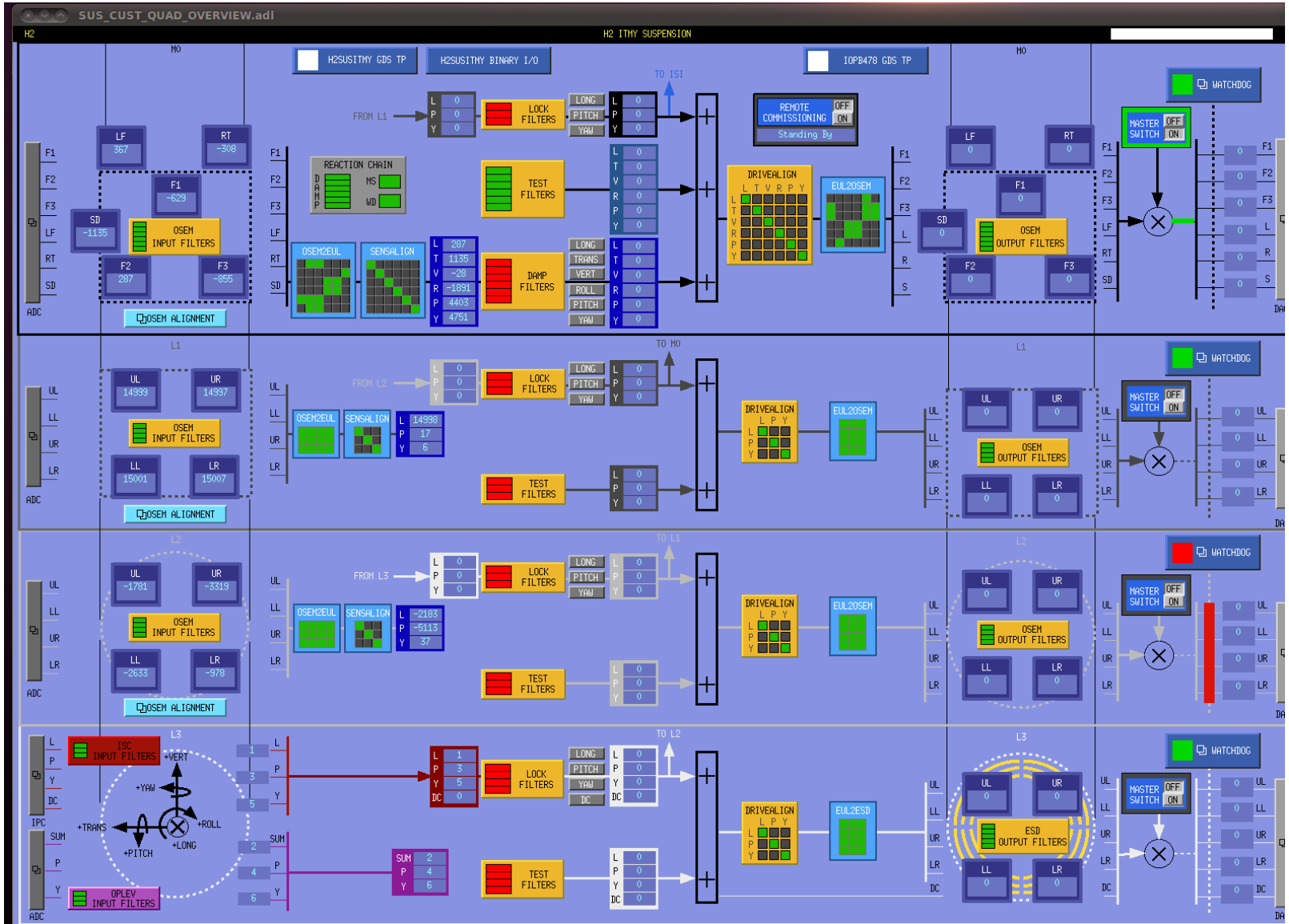
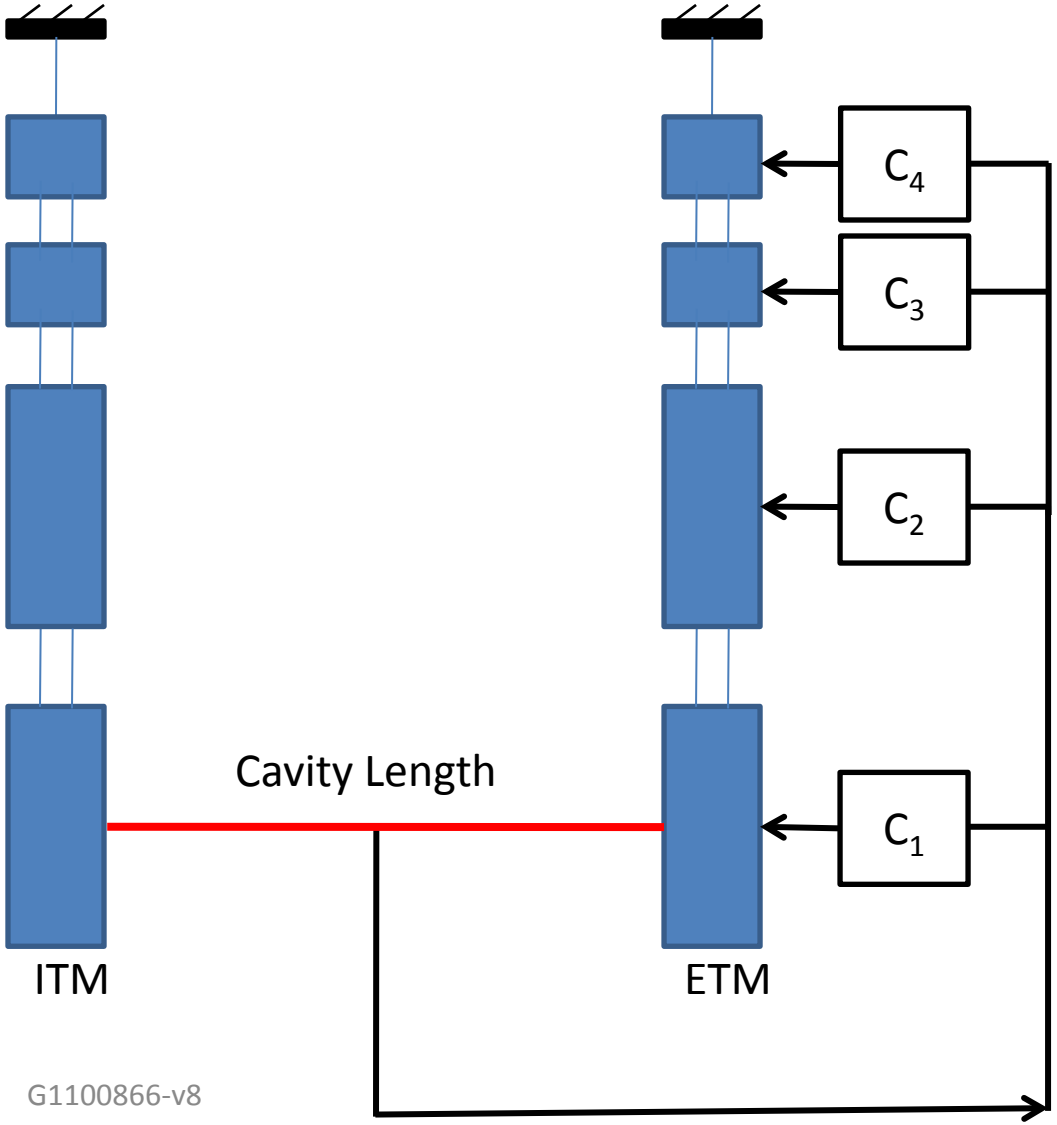
Quad MEDM Overview Screen



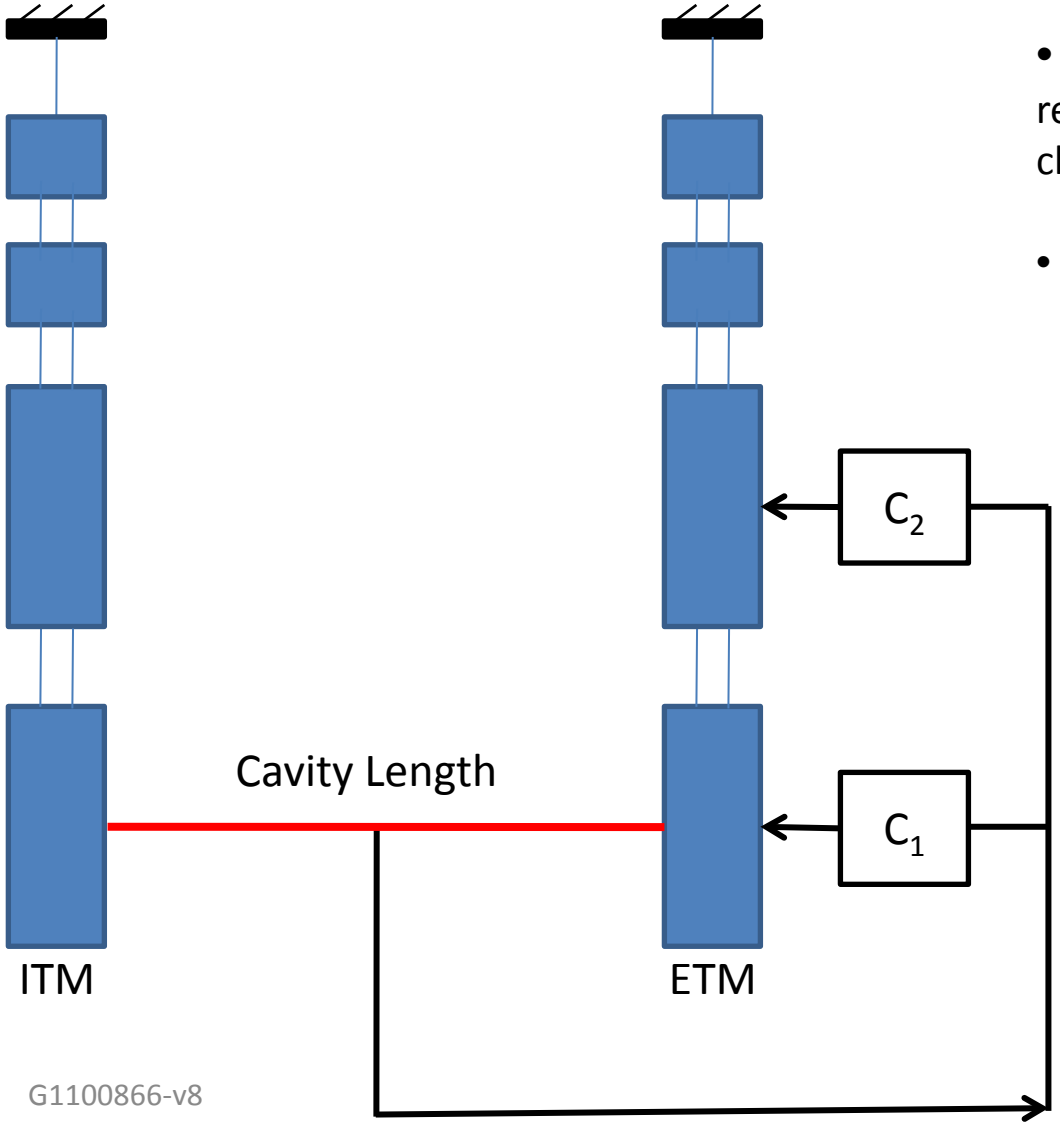
Global Cavity Control (LSC)



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

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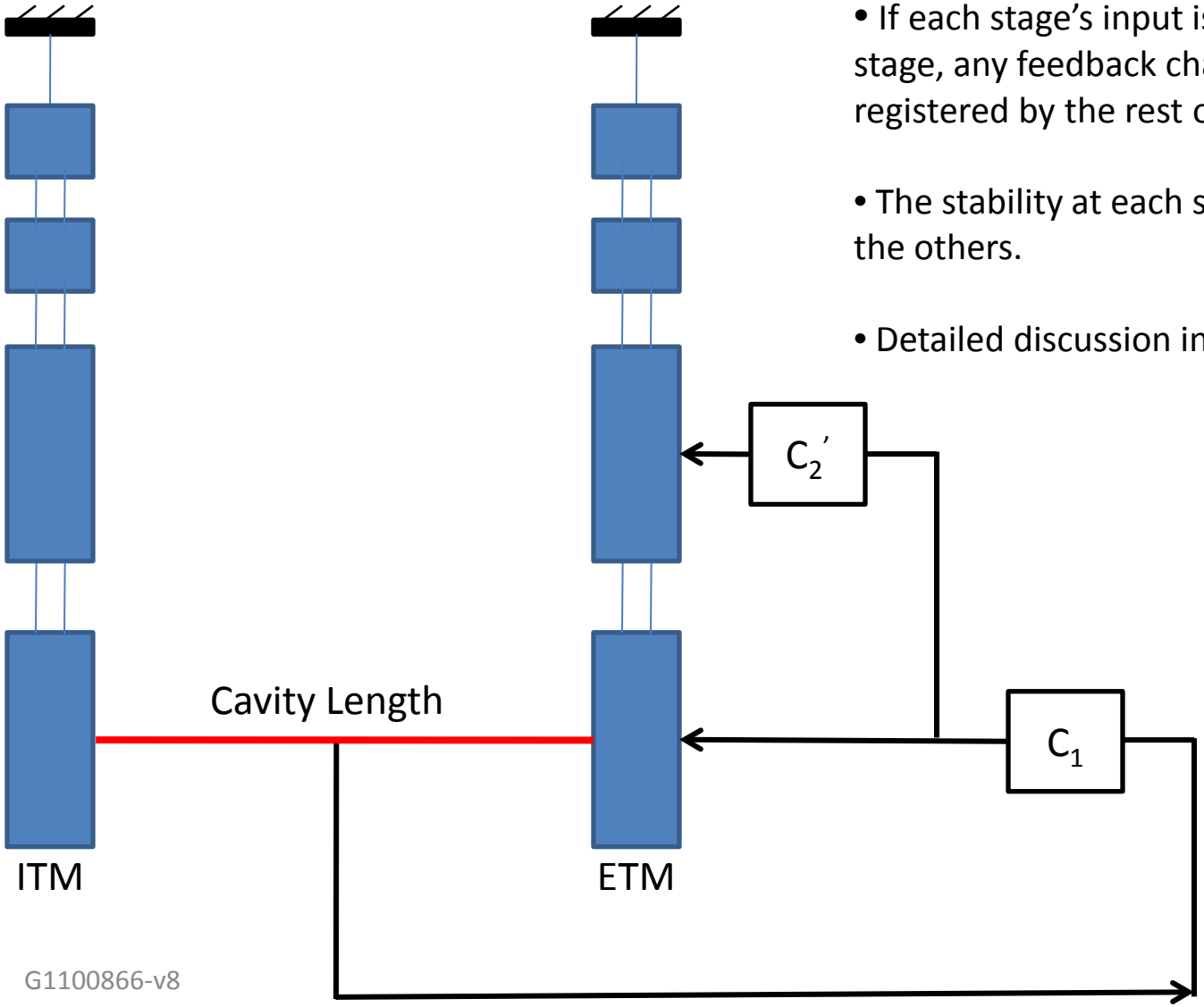
Hierarchical Control of Cavity Length



- 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.

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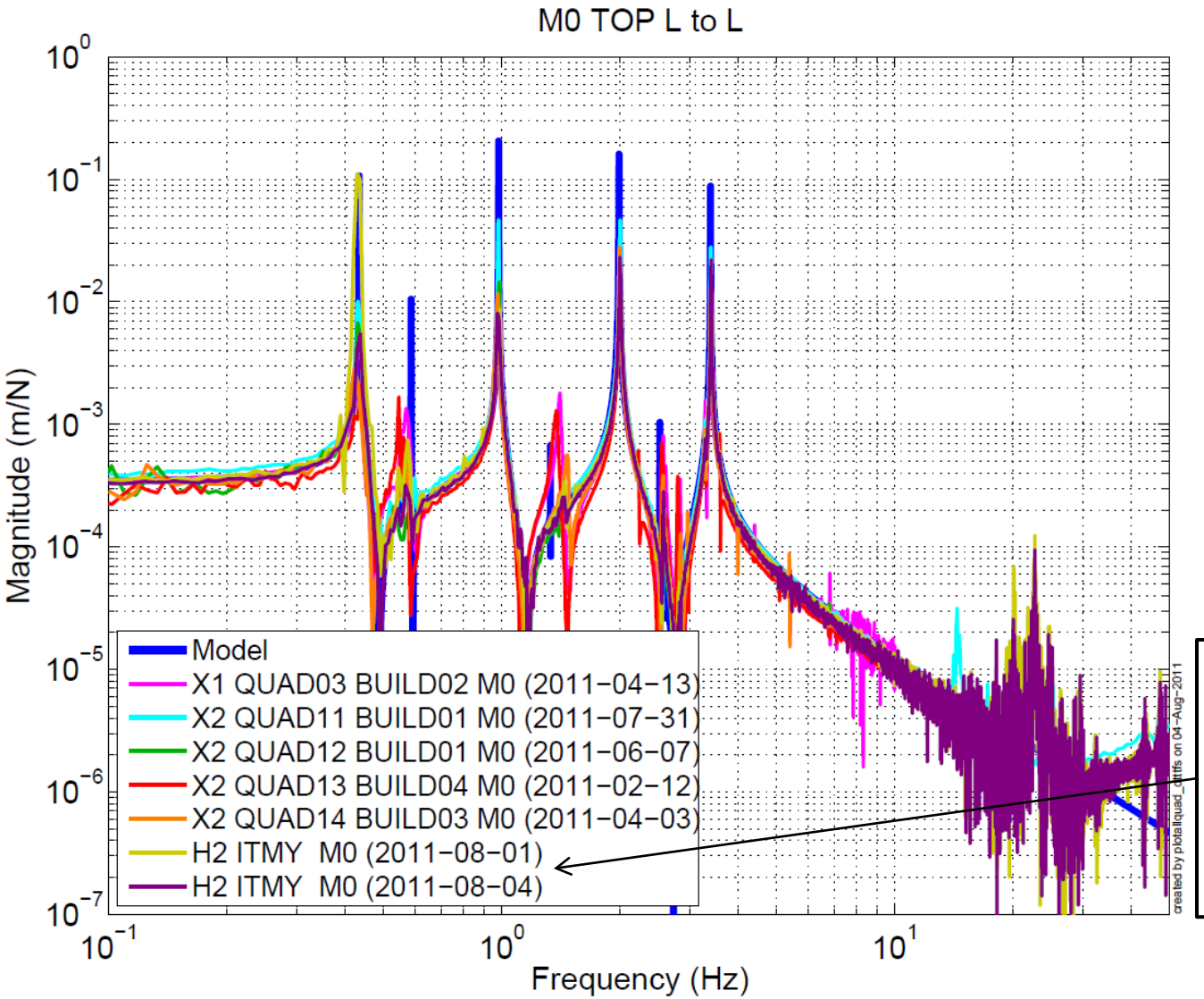
SUS Testing – G1100693

- Top mass transfer functions
- Sub-pendulum resonance measurements (lock stages down)
- OSEM calibration – sensors and actuators
- Cross-coupling tests
- Magnet polarity checks
- Active damping tests
- Alignment range tests (drive OSEMs)
- Structure resonances
- The testing plan is still a work in progress!

Recent Transfer Functions



H2 ITMY just installed on BSC-ISI last week!

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What can DetChar do?

- Damping: measure how much OSEM sensor noise makes it to DARM; look for pendulum resonant frequencies and Q's. This will tell us how optimal our damping control is.
- Study impact of undamped bounce and roll modes. Each triple and quad has a pair. How big are the peaks, do they ring up often? What are the Q's?
- Study impact of wire and fiber violin modes and acoustic modes of the optics. How big are the peaks? Ring up often? Some of these will have active damping.
- Look for actuator saturation and RMS history; will tell us if the global control is distributed properly between stages.
- Monitor long term alignment drifts in the suspensions. Ex. The masses rise and fall slightly with variations in temperature and pressure (quad mirror drops 1/3 mm under vacuum).
- More ideas welcome.

aLIGO SUS Team

LLO SUS Team:
Janeen Romie – HAM SUS lead eng
Gary Traylor – SUS Install lead
Carl Adams
Anna Aitken
Richard Biedenharn
Derek Bridges
Virginia Brocato
William Elliott
Anamaria Effler
Matt Heintze
Ed Merilh
Mike Meyer
Ralph Moffatt
Bobby Moore
Danny Sellers
Gene Winton

MIT SUS Team:
Jeff Kissel – Testing lead
Rich Mittleman – LASTI lead
Sam Barnum
Michael Hillard
Brett Shapiro
Sam Waldman

LHO SUS Team:
Mark Barton – HAM-SUS cog scientist
Betsy Bland – SUS Install lead
Jeff Bartlett
Doug Cook
Jesse Garner
Robert Lane
Gerardo Moreno
Andres Ramirez
Travis Sadecki
Vern Sandberg

University of Glasgow (UK):
Angus Bell
Nicola Beveridge
Alan Cumming
Liam Cunningham
Giles Hammond
Jim Hough
Russell Jones
Rahul Kumar
Sheila Rowan
Ken Strain
Marielle Van Veggel

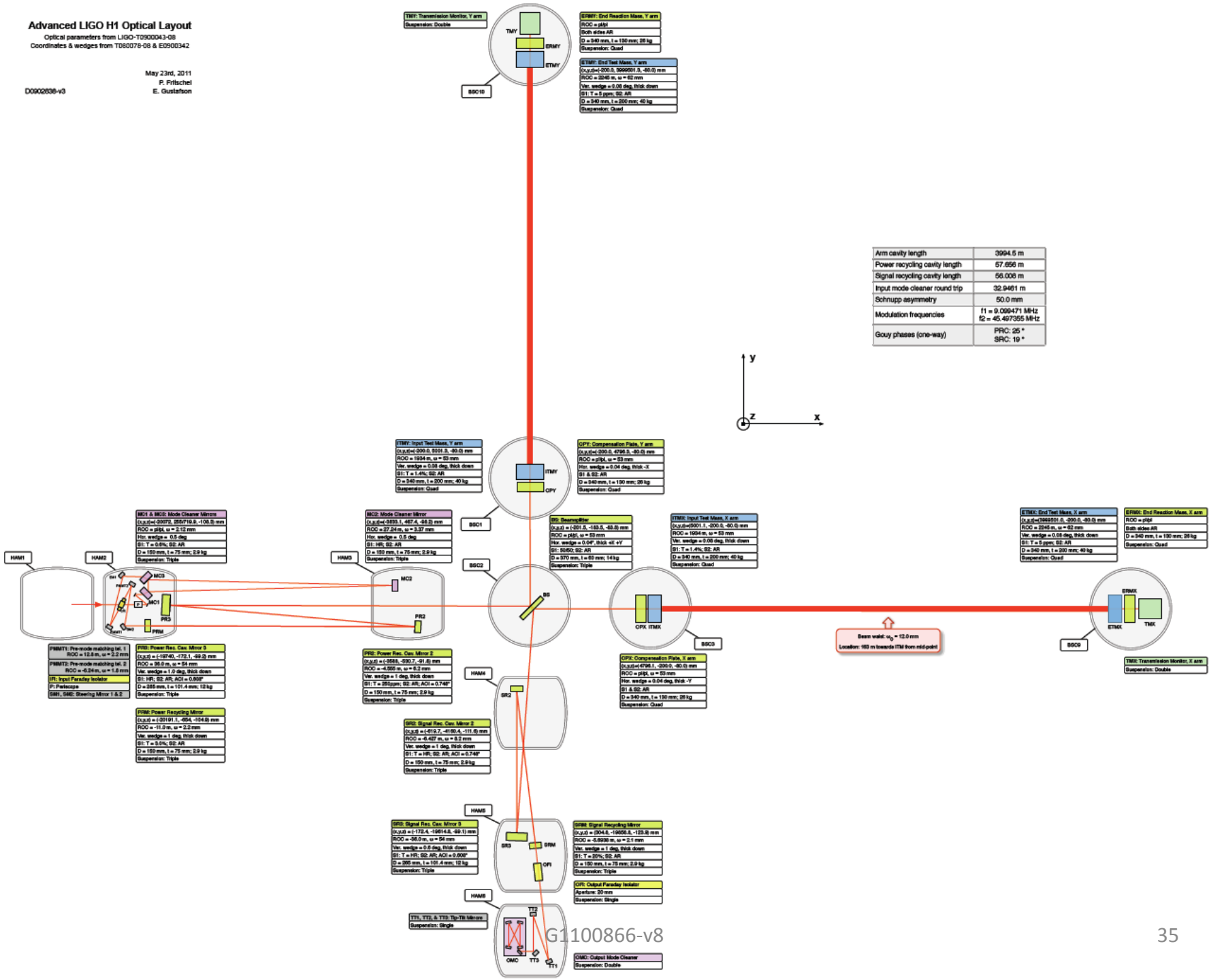
Caltech SUS Team:
Norna Robertson – SUS Leader
Jay Heefner – SUS Electronics Lead
Jay Copti
Phillip Croxton
Todd Etzel
Kate Gushwa
Alastair Heptonstall
Kristen Holtz
Tim MacDonald
Gary McIntyre
Margot Phelps

Rutherford Appleton Lab (UK):
Justin Greenhalgh
Joe O'Dell

University of Strathclyde (UK):
Nick Lockerbie
Kirill Tokmakov

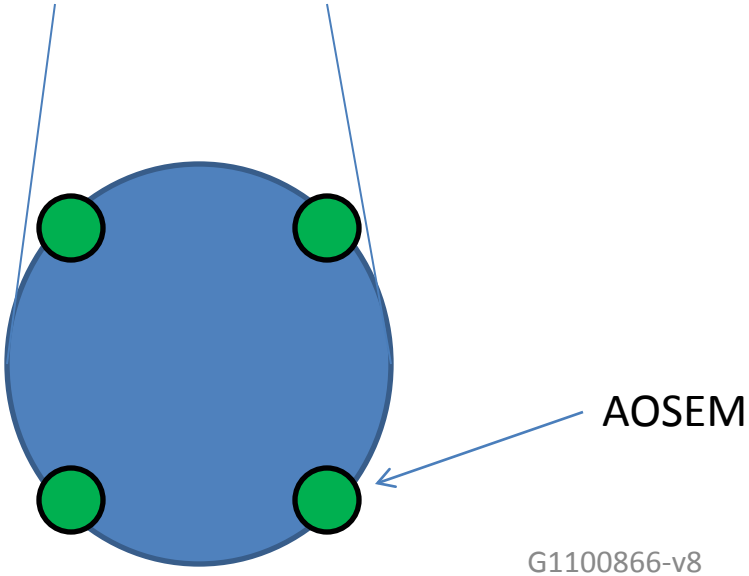
University of Birmingham (UK):
Stuart Aston
Ludovico Carbone
Ron Cutler

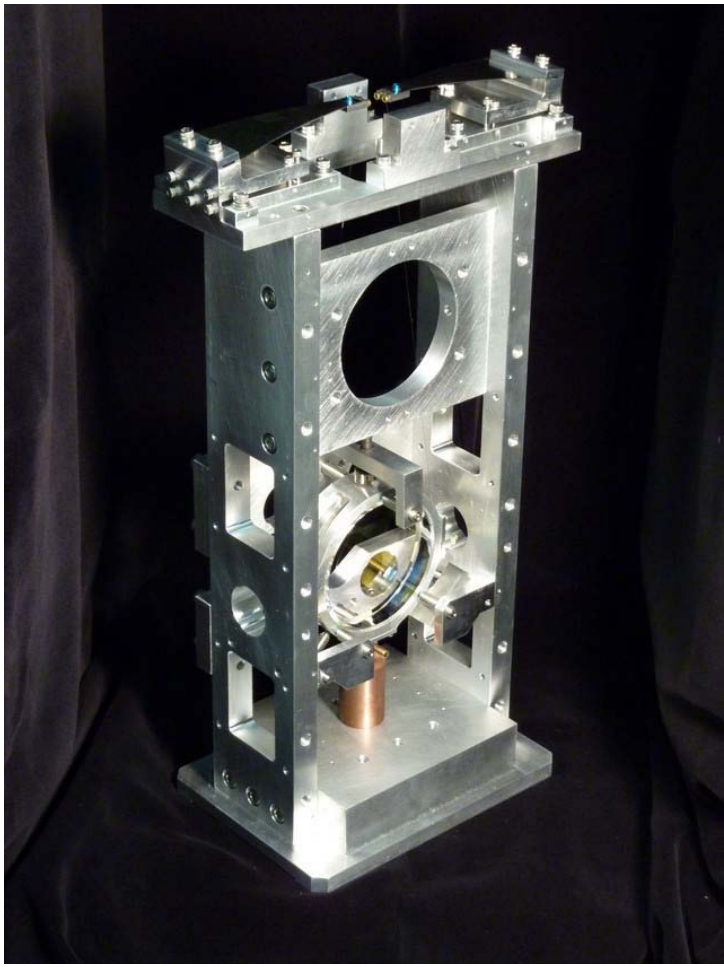
Back Ups


Advanced LIGO H1 Optical Layout
Optical parameters from LIGO-T0900043-08
Coordinates & wedges from T080078-08 & E0900342
May 23rd, 2011
P. Fritschel
E. Gustafson
D0902836-v3
Arm cavity length 3994.5 m
Power recycling cavity length 57.656 m
Signal recycling cavity length 56.008 m
Input mode cleaner round trip 32.9461 m
Schnupp asymmetry 50.0 mm
Modulation frequencies f1 = 9.099471 MHz f2 = 45.497355 MHz
Gouy phases (one-way) PRC: 25 ° SRC: 19 °
TMY
ETMY
ITMY
CPY
BSC10
BSC1
BSC2
BSC3
BSC9
HAM1
HAM2
HAM3
HAM4
HAM5
HAM6
MC1
MC2
MC3
PR2
PRM
BS
SR2
SR3
SRM
OFI
ITMX
CPX
ETMX
TMX
OMC
TT1
TT2
TT3
y
z
x

Single Suspensions

- Modified iLIGO SOS's (Small Optic Suspension)
  - Addition of blade springs
  - Removal of side OSEM
  - Addition of eddy current damping
- Steering and focusing auxiliary mirrors.
- Located in HAM 2, 8





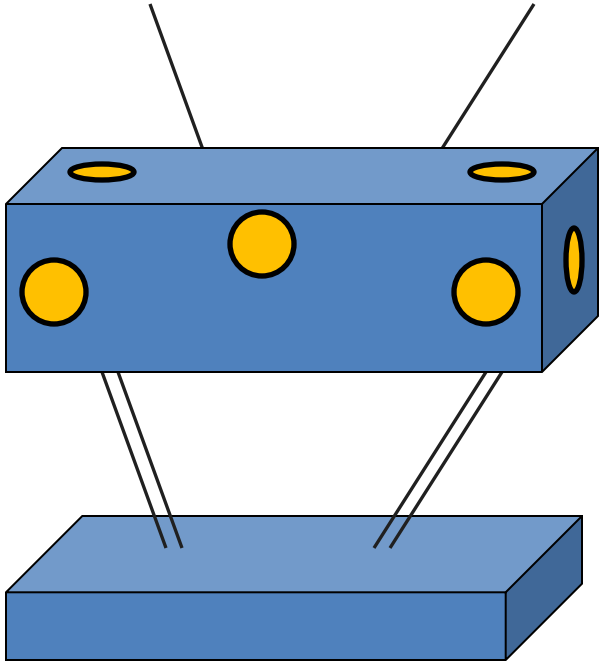
TransMon Double

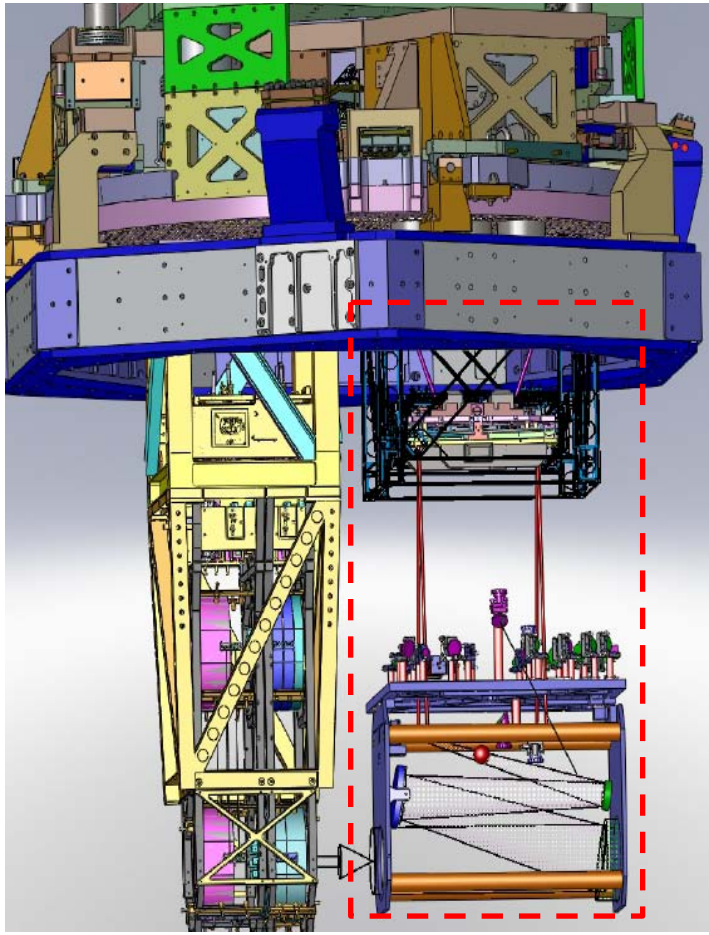
Location
- BSC 9, 10

Control
- Local – damping at top mass

Sensors/Actuators
- BOSEMs at top mass

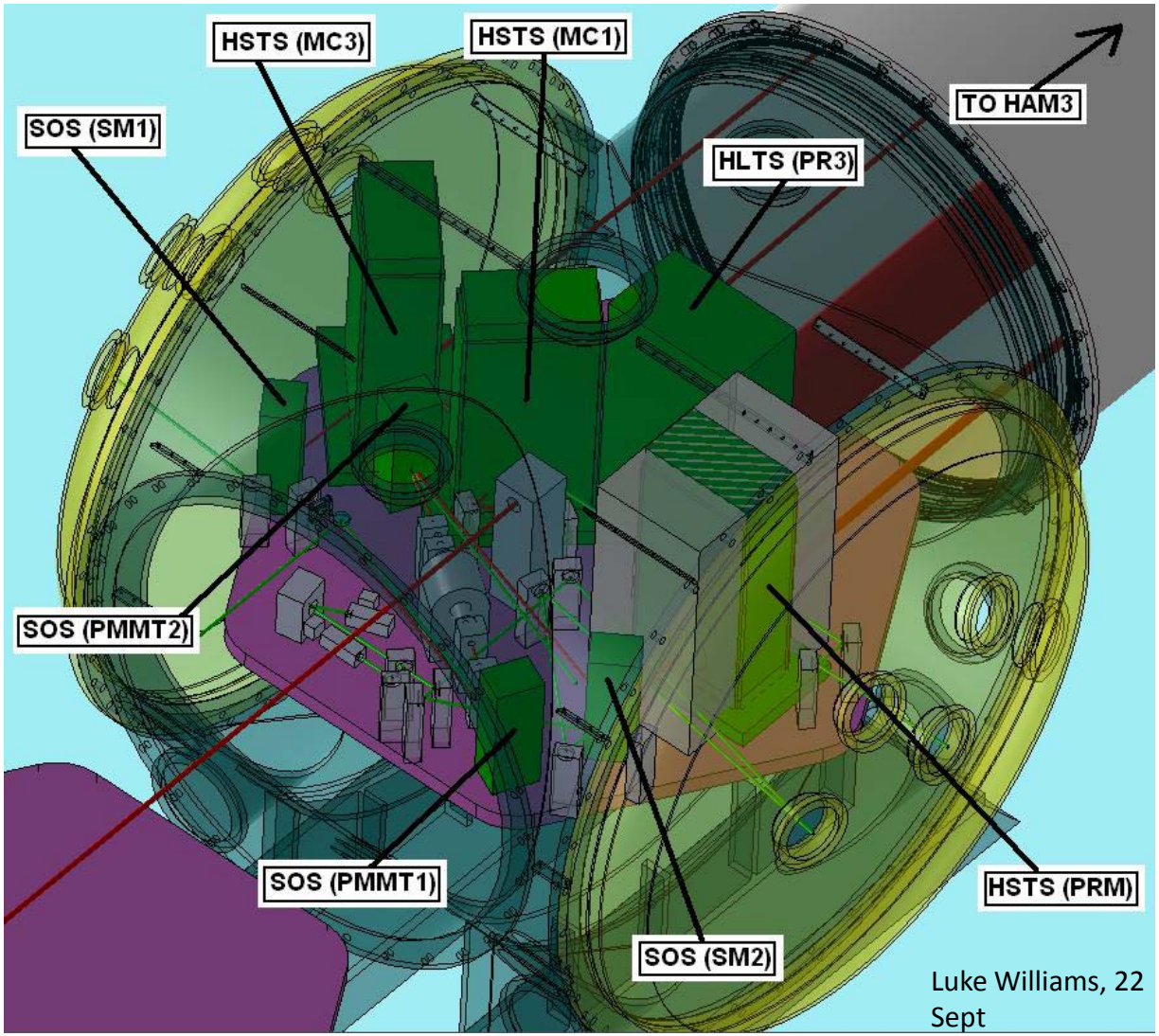
Top mass naming convention
- L1:SUS-TRMX_M1…



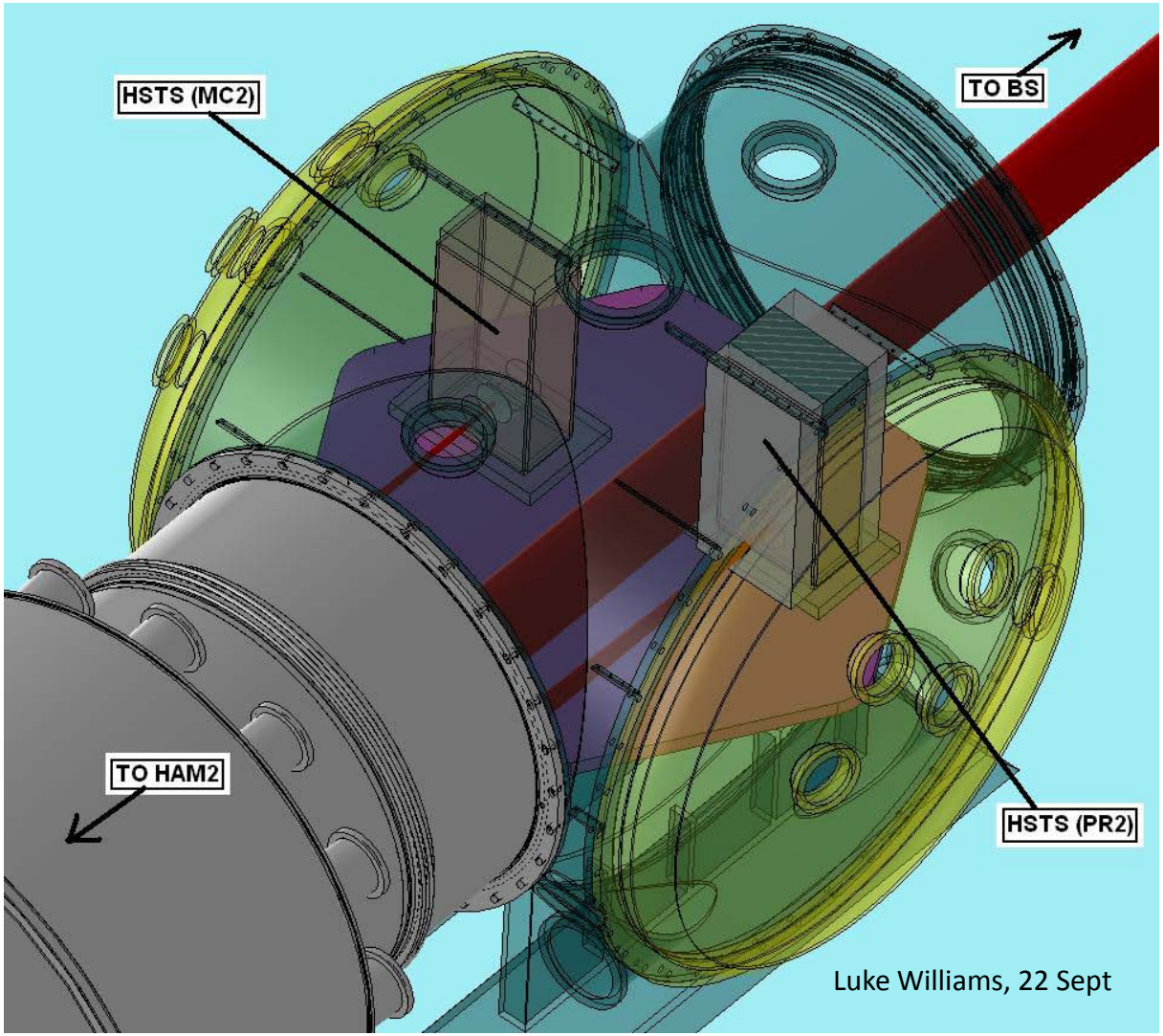


Ref: E1000040

HAM2 Layout


HSTS (MC3)
HSTS (MC1)
TO HAM3
SOS (SM1)
HLTS (PR3)
SOS (PMMT2)
SOS (PMMT1)
HSTS (PRM)
SOS (SM2)
Luke Williams, 22 Sept

HAM3 Layout



Different Suspensions

ADVANCED LIGO SUSPENSION CHART – Stable Recycling

BSC Suspensions – Quad
BSC Suspensions - Triple

HAM Large Triple Suspension, HLTS (aka RM)
HAM Small Triple Suspension, HSTS (aka IMC)
HAM Cavity Optics Suspension - Double

Ham Aux. Modified Small Optic Suspension (MSOS)- Single

IFO 1 (L1)	IFO 2 (H1)	IFO 3 (H2)	Responsibility
2 ETM	2 ETM	2 ETM	SUS UK/COC
2 ITM/CP	2 ITM/CP	2 ITM/CP	SUS UK/COC/AOS
BS	BS	BS	SUS UK/COC
		2 FM	SUS UK/COC
PR 3	PR 3	PR 3	SUS US/COC
SR 3	SR 3	SR 3	SUS US/COC
IMC1	IMC1	IMC1	SUSUS/IO
IMC2	IMC2	IMC2	SUS US/IO
IMC3	IMC3	IMC3	SUS US/IO
PRM	PRM	PRM	SUS US/IO
PR 2	PR 2	PR 2	SUS US/IO
SRM	SRM	SRM	SUS US/IO
SR 2	SR 2	SR 2	SUS US/ IO
OMC	OMC	OMC	SUS US/ISC
SM1	SM1	SM1	SUS US/IO
SM2	SM2	SM2	SUS US/IO
IMMT1	IMMT1	IMMT1	SUS US/IO
IMMT2	IMMT2	IMMT2	SUS US/IO
8 Tip/Tilt Mirrors	8 Tip/Tilt Mirrors	8 Tip/Tilt Mirrors	ISC[1]

SPARES: 1 of each type per site. 2 ETM/ITM (4 total), 1 total BS/FM, 1 HLTS, 1 HSTS, 1 OMC.
No spares for SOS-based suspensions.

ETM = end test mass

ITM = input test mass

BS = beamsplitter

FM = folding mirror

CP = compensator plate

PR = power recycling mirror

SR = signal recycling mirror

IMC = input mode cleaner

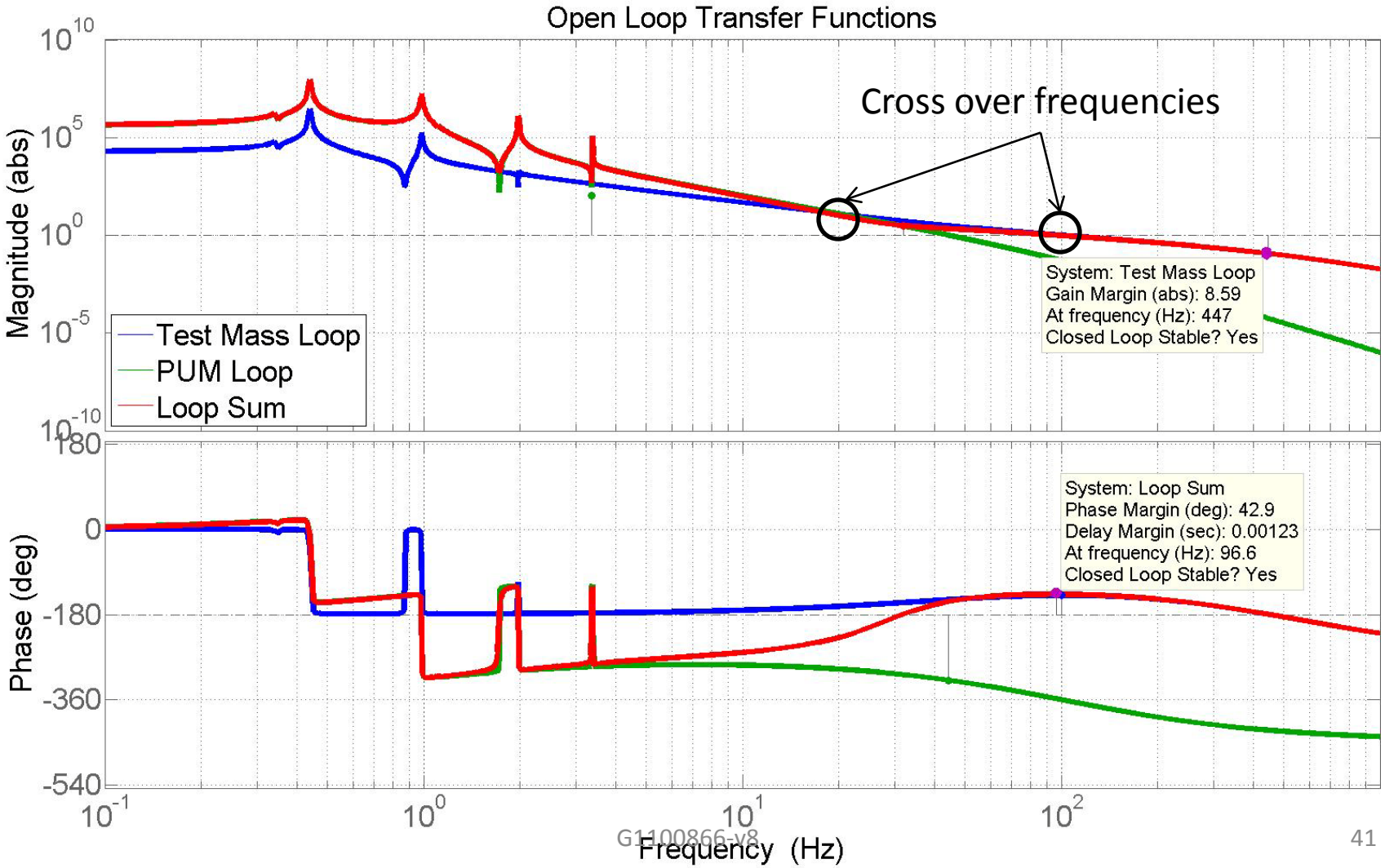
OMC = output mode cleaner

SM = steering mirror

IMMT = input mode matching telescope

Ref: LIGO-G1000469-v1

Example Loop Gain of Cavity Control



SUS SVN

T1100117-File Directory Naming Convention

E1000617-v3

QUAD SUSPENSION

CONTROLS ARRANGEMENT