Advanced LIGO, nouvelle génération d'interféromètres pour la détection d'ondes gravitationnelles.

Présentation du projet - Isolation des sources de bruits - Focus sur les méthodes d'isolation sismique.

Fabrice Matichard, Caltech-MIT

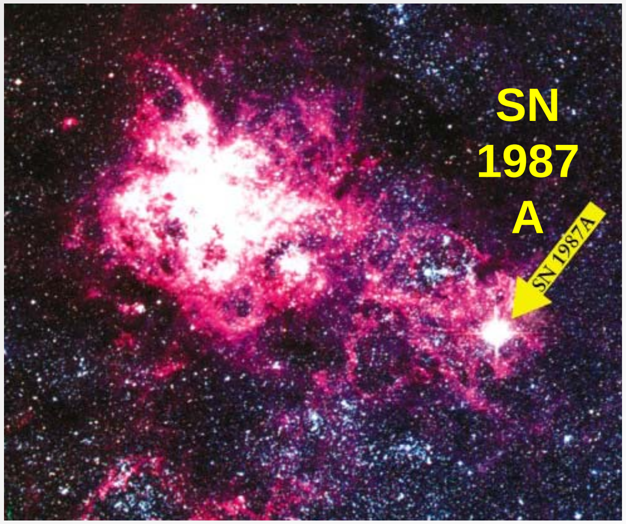
05 janvier 2010, à l'ENSIM, Le Mans.

Contact: fabrice@ligo.mit.edu

Astrophysical searches

Transient

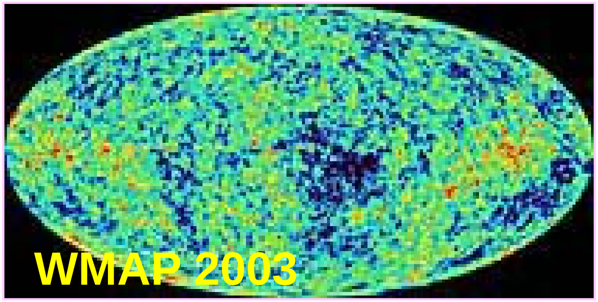
- Coalescence of binary compact objects (neutron stars, black holes, primordial BH)
- Core collapse supernovae
- Black hole normal mode oscillations
- Neutron star rotational instabilities
- Gamma ray bursts
- Cosmic string cusps



High duty cycle

- Periodic emission from pulsars (esp. accretion driven)
- Stochastic background (incoherent sum of many sources or very early universe)
- Expect the unexpected!

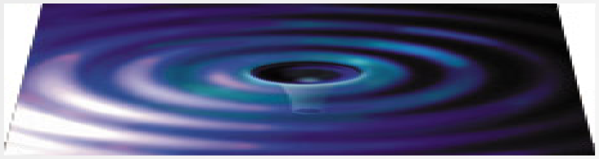
Modeled & Unmodeled waveforms



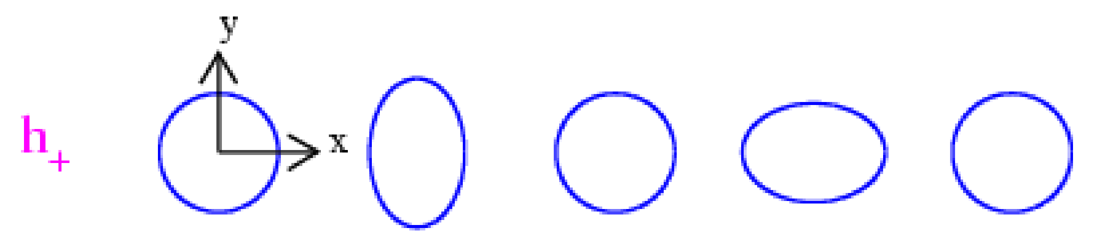
Gravitational Waves

Gravitational Waves
“Ripples in space-time”
Stretch and squeeze the space
transverse to direction of propagation

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)h = 0$$



Example:
Ring of test masses responding
to wave propagating along z



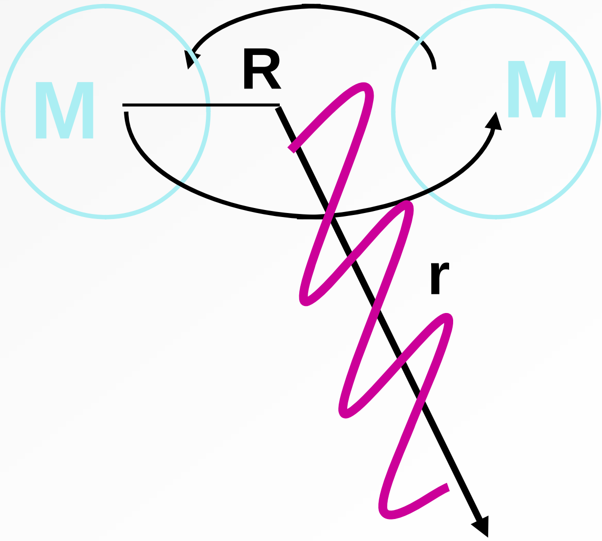
For a binary neutron star

~1.4 Mo pair in Virgo cluster

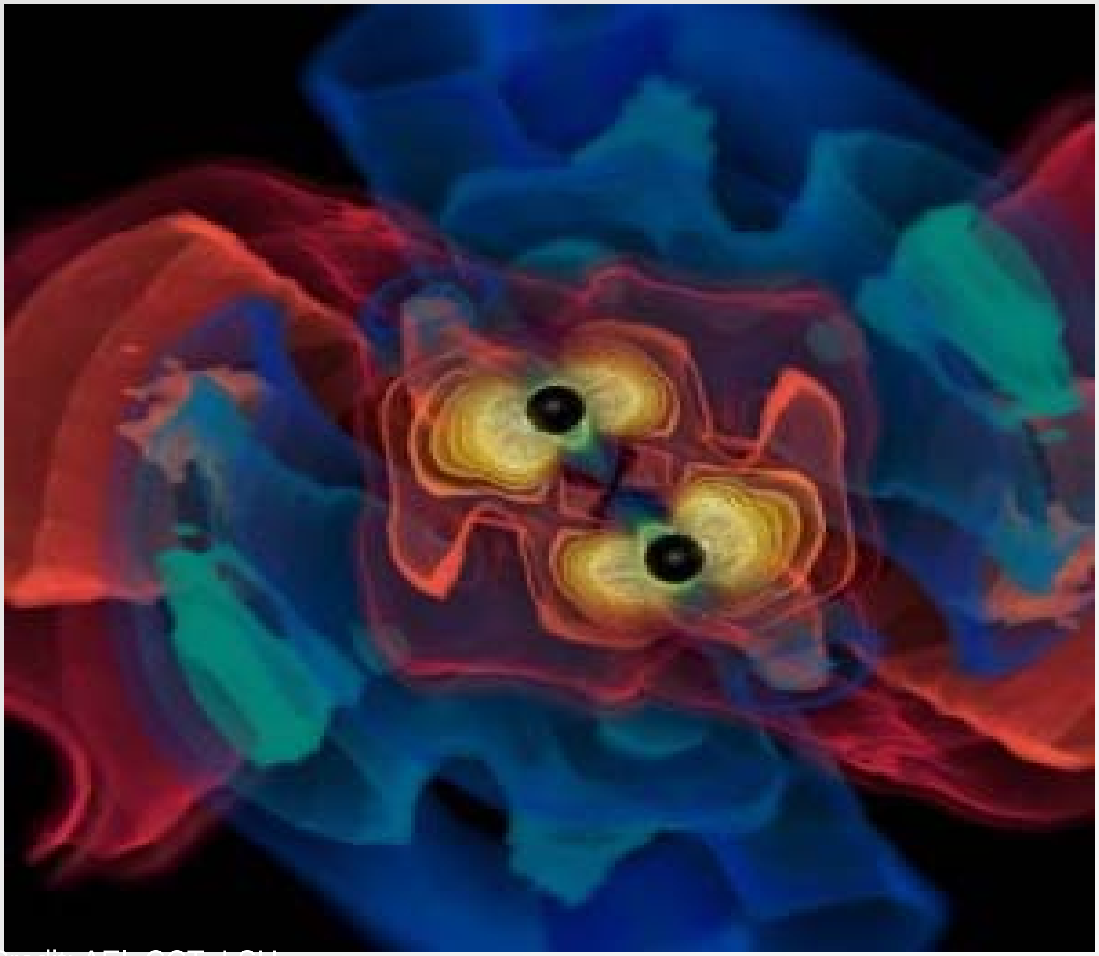
$$M \approx 10^{30}\ \mathrm{kg}$$
$$R \approx 20\ \mathrm{km}$$
$$f \approx 400\ \mathrm{Hz}$$
$$r \approx 10^{23}\ \mathrm{m}$$

$$\Rightarrow$$

$$\boxed{h \sim 10^{-21}}$$



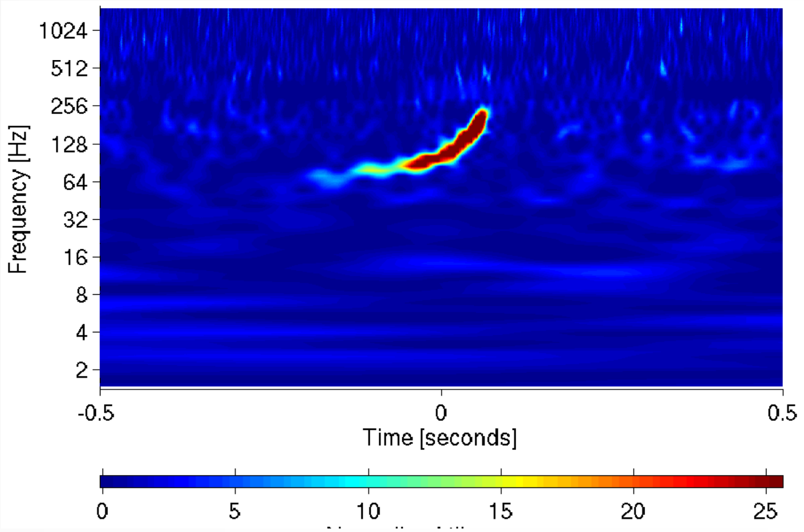
Astrophysical searches



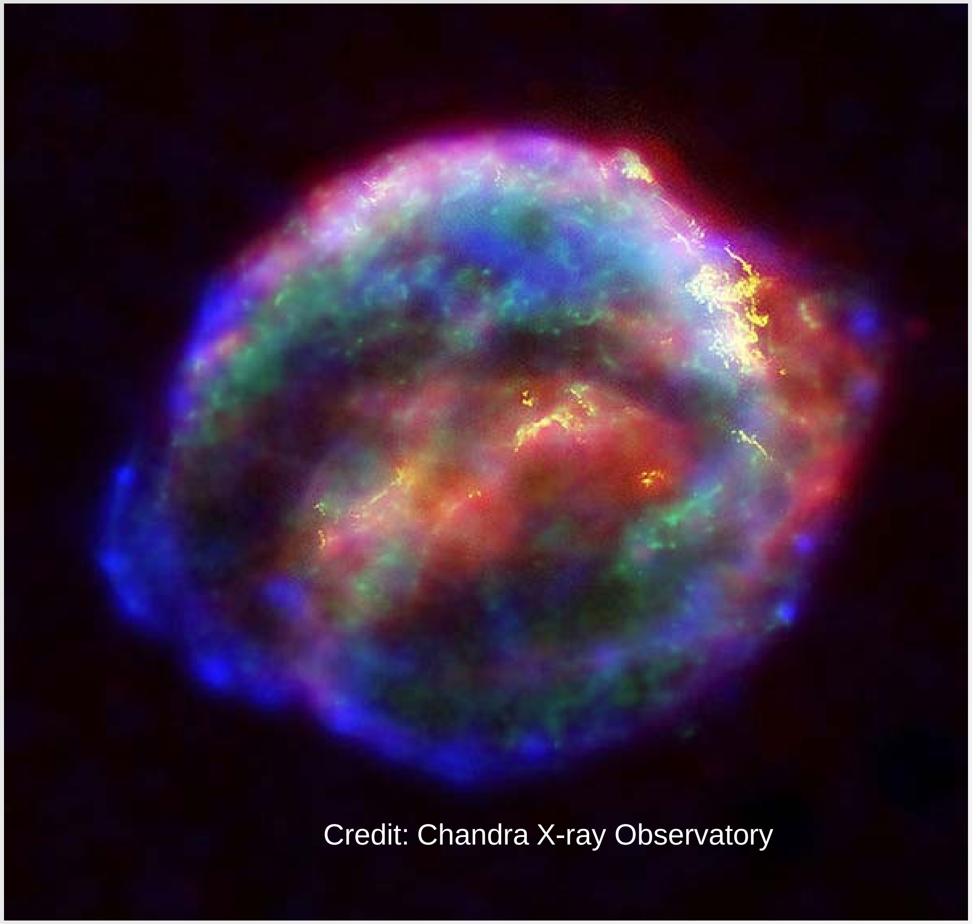
Credit: AEI, CCT, LSU

Coalescing Binary Systems

- Neutron stars, black holes
- ‘chirped’ waveform



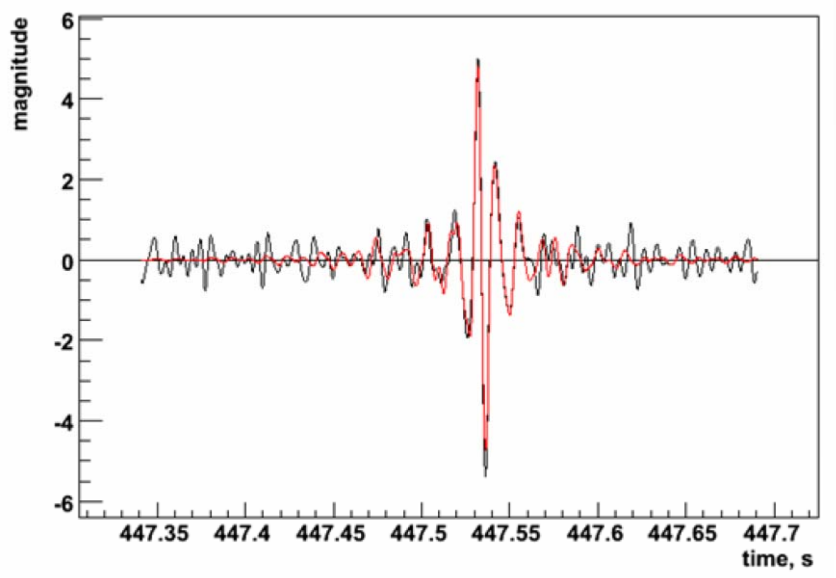
Astrophysical searches



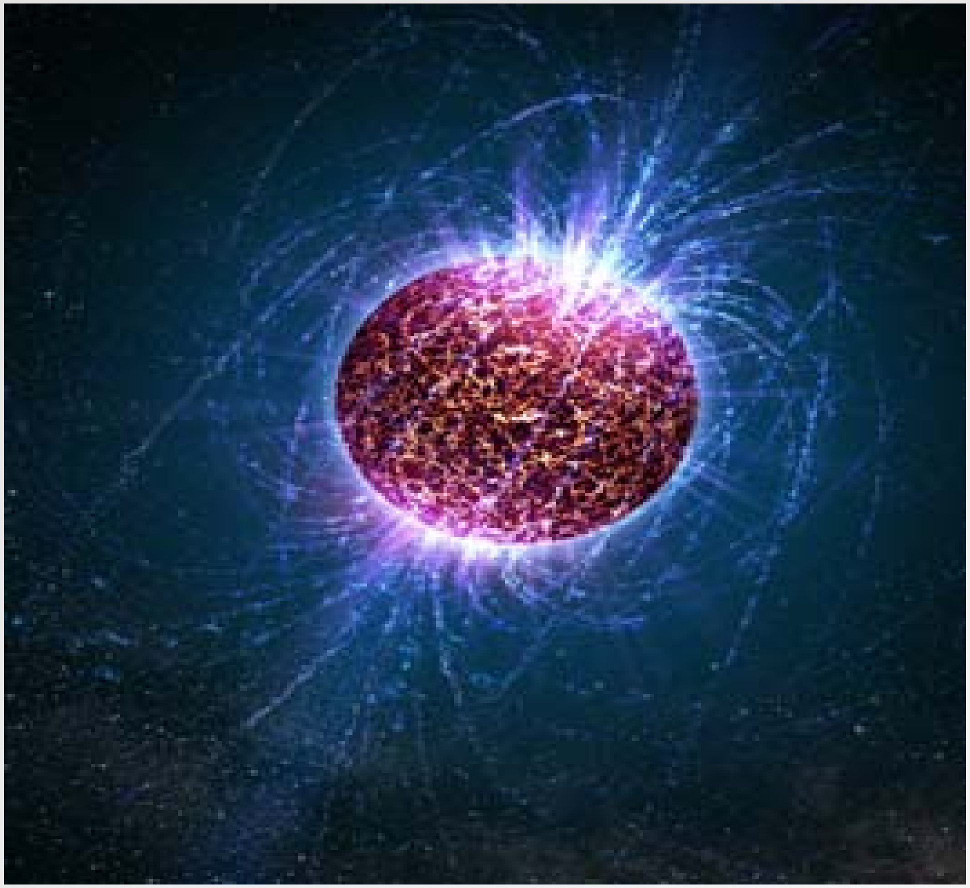
Credit: Chandra X-ray Observatory

'Bursts'

- asymmetric core collapse supernovae
- cosmic strings
- ? (sources we haven't thought about)



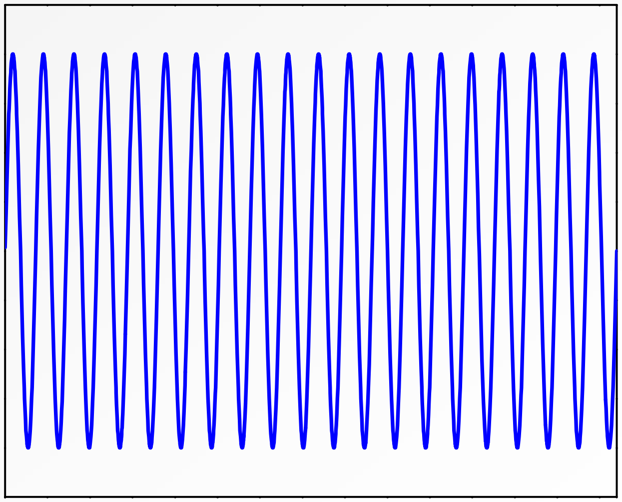
Astrophysical searches



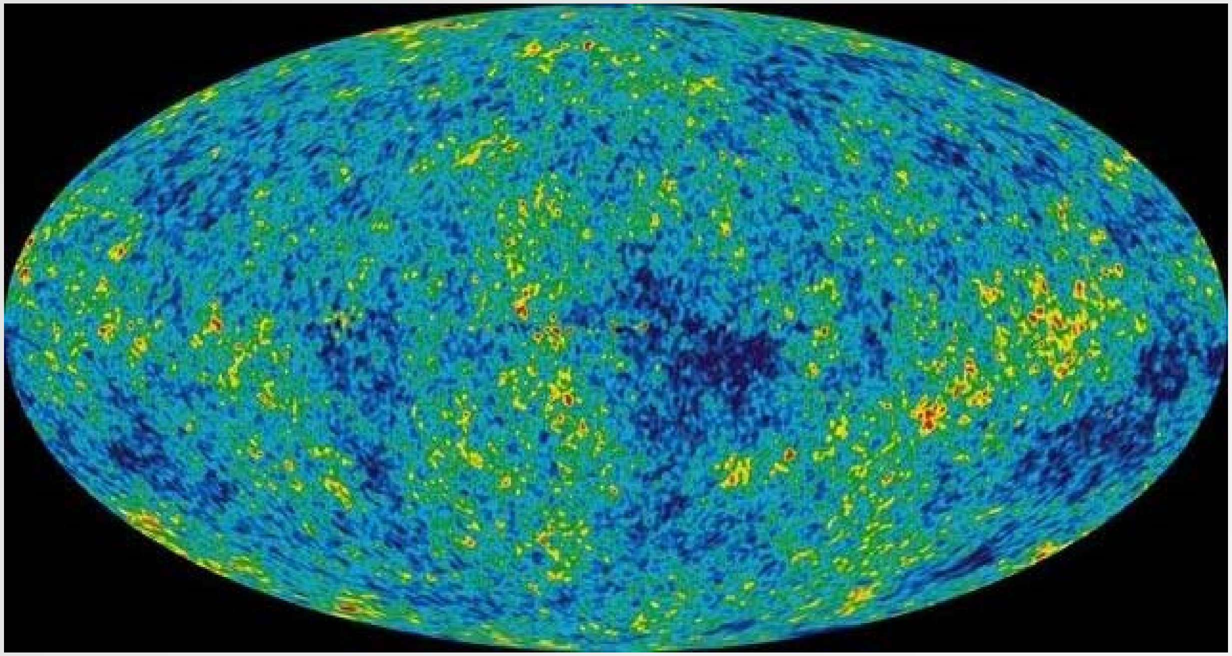
Casey Reed, Penn State

Continuous Sources

- Spinning neutron stars
- monotone waveform



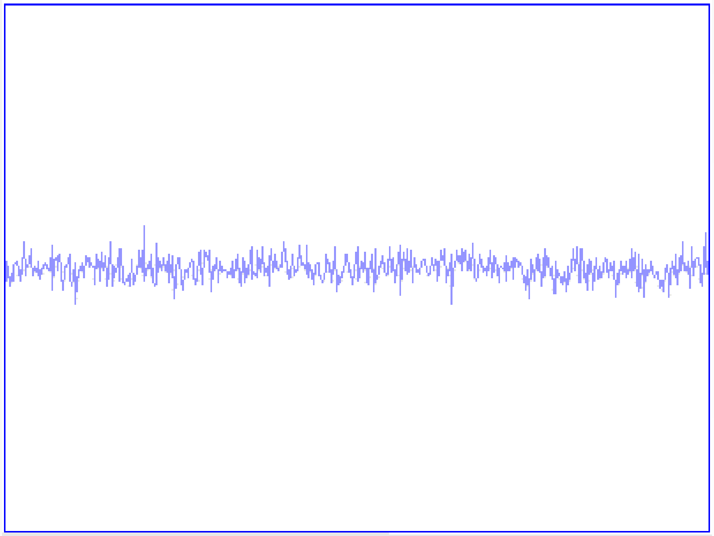
Astrophysical searches



NASA/WMAP Science Team

Cosmic GW background

- residue of the Big Bang
- probes back to 10^{-21} s after the birth of the universe
- stochastic, incoherent background



Global network of detectors

LIGO

Hanford, WA
4 km interferometer
2 km interferometer

GEO

Hannover, Germany
600 m interferometer

VIRGO

Pisa, Italy
3 km interferometer

TAMA

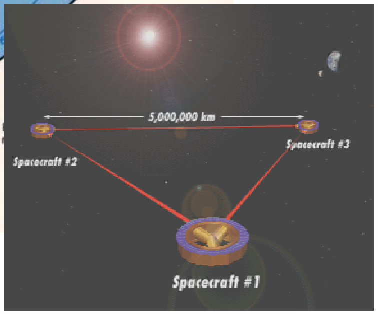
Tokyo, Japan
300 m interferometer

AIGO

LIGO

Livingston, LA
4 km interferometer

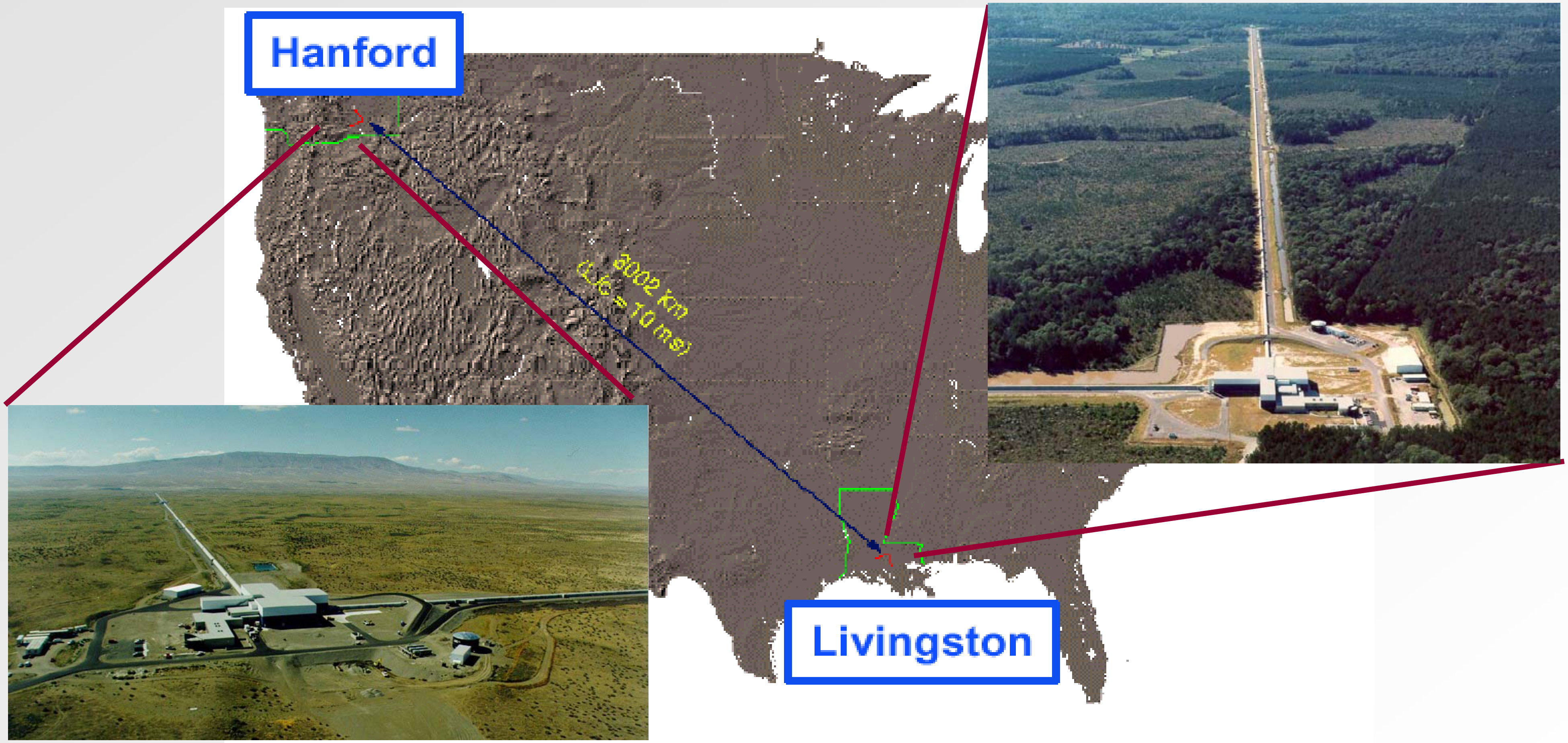
LISA



- Coincident detection to eliminate instrumental artifacts
- Source localization in the sky
- Wave polarization

LIGO

LIGO Livingston Observatory
- 1 interferometers
  - 4 km arms



LIGO Hanford Observatory
- 2 interferometers
  - 4 km, 2 km arms

LIGO Observatories are operated by Caltech and MIT

GW detector at a glance

$h = \Delta L/L$

$L \sim 4$ km

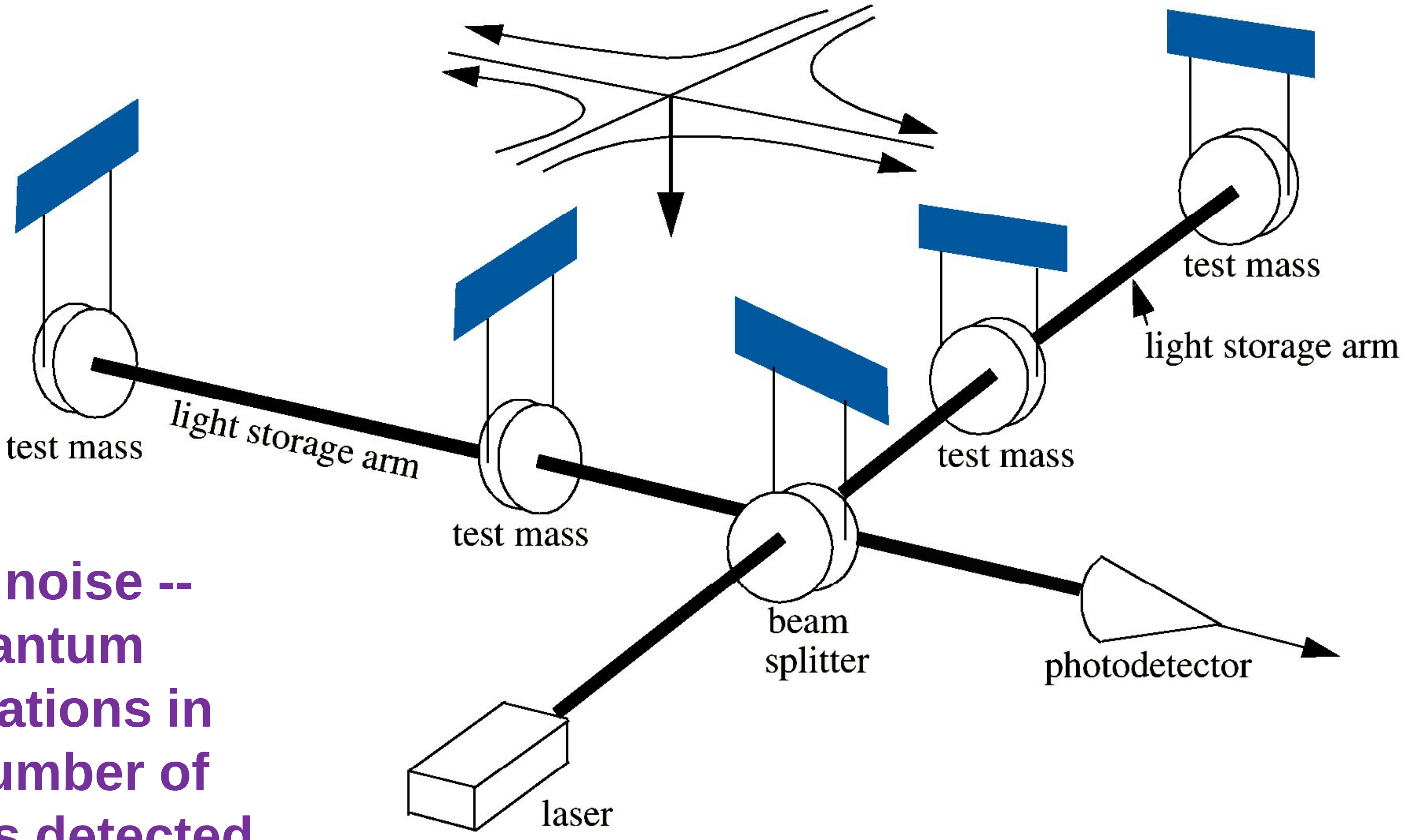
We need $h \sim 10^{-21}$

We have $L \sim 4$ km

We see $\Delta L \sim 10^{-18}$ m

Thermal noise -- vibrations due to finite temperature

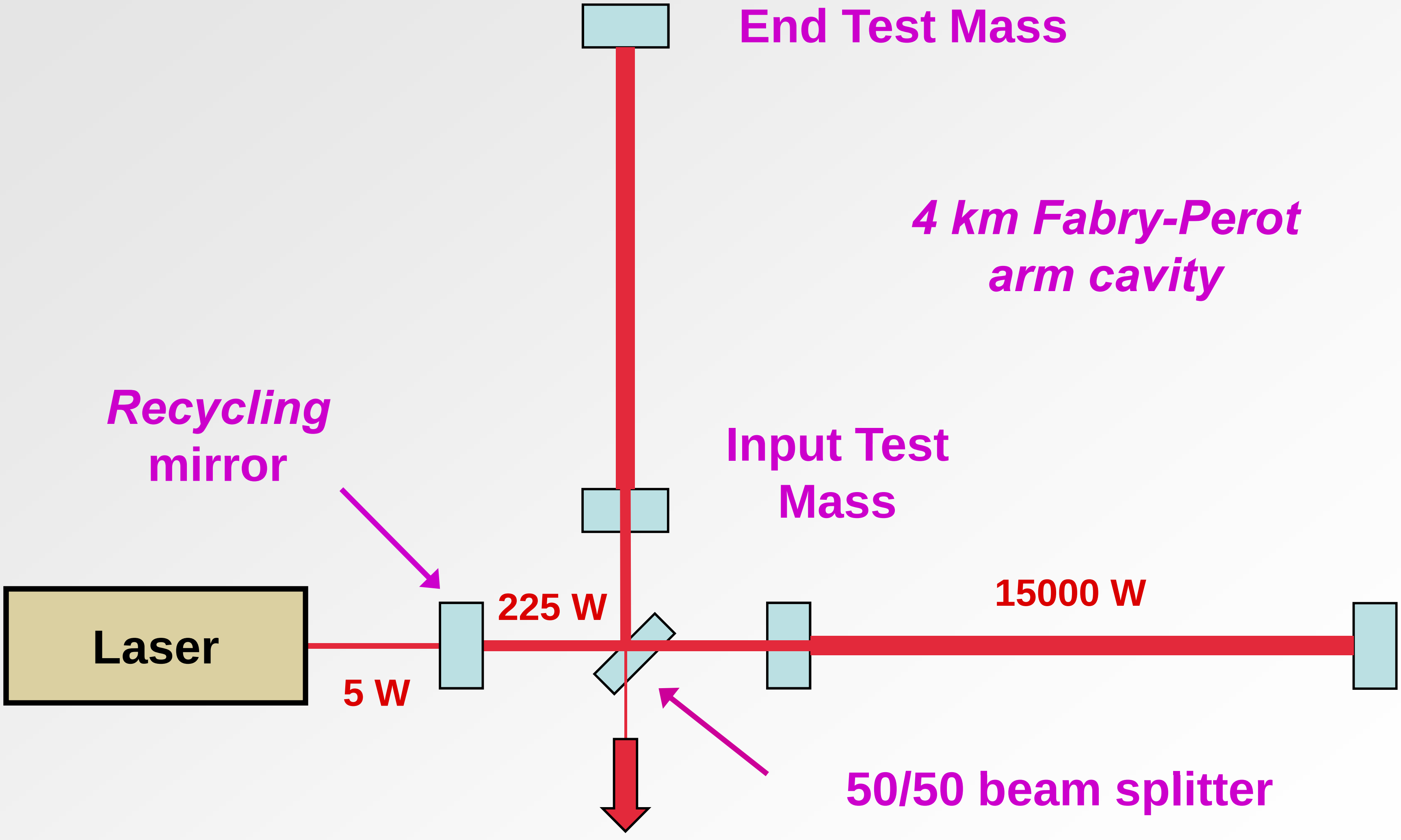
Seismic motion -- ground motion due to natural and anthropogenic sources



Shot noise -- quantum fluctuations in the number of photons detected

Optical Configuration

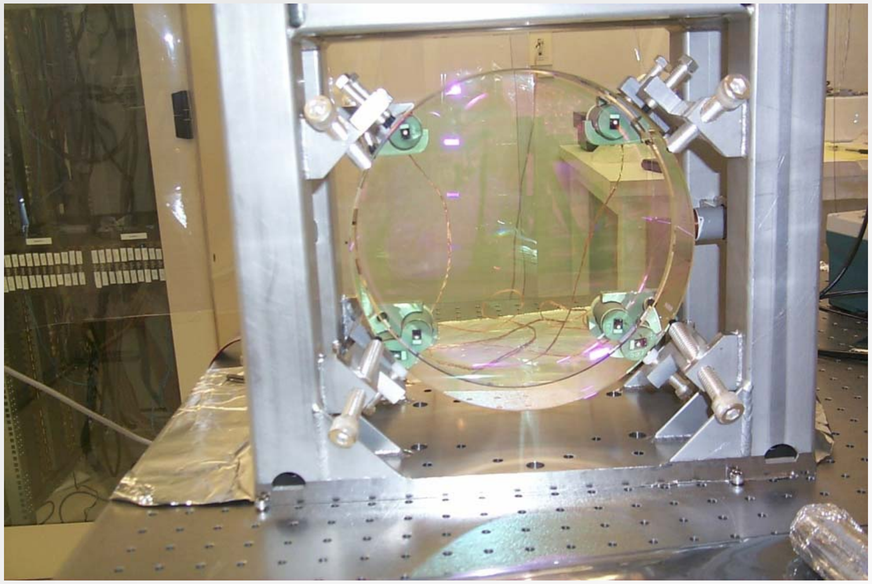
- Power Recycled
    - Michelson Interferometer
        - with Fabry-Perot Arm Cavities



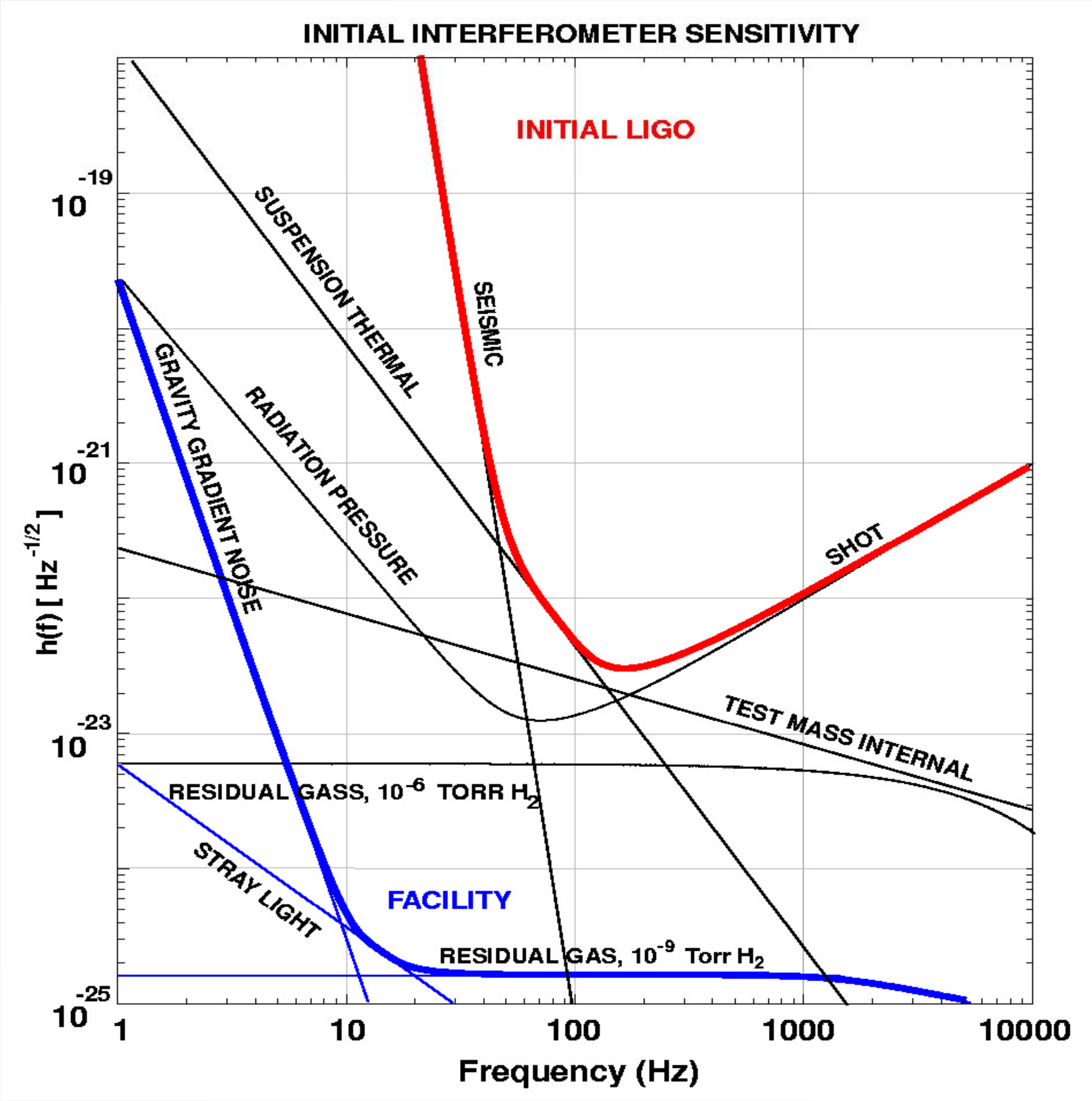
Infrastructures and systems

18,000 m^3 of vacuum at 10^{-9} torr.

Beam Tubes: 1.2 m diameter - 3mm stainless, 50 km of weld….
and not one leak!



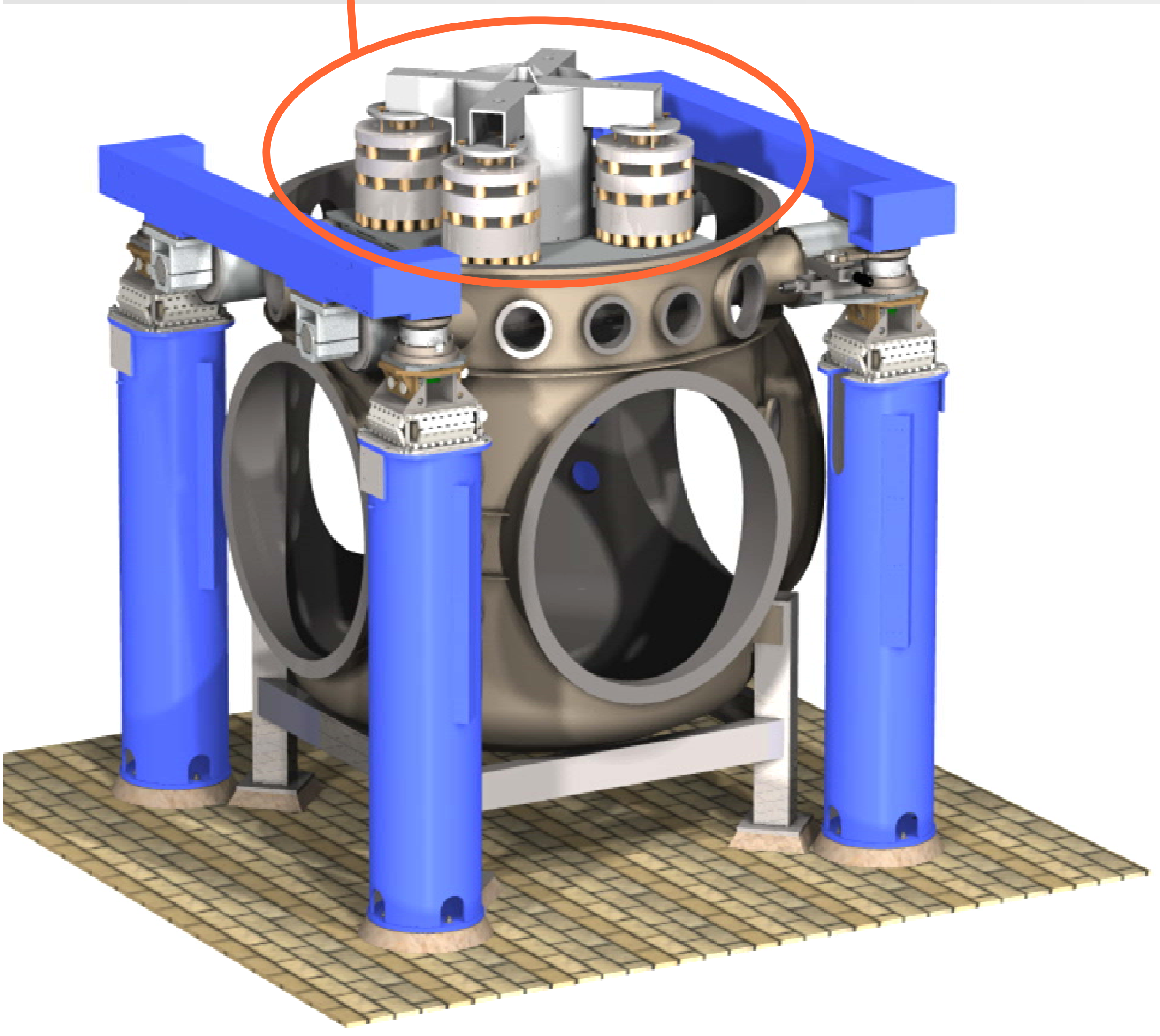
Initial LIGO Sensitivity Goal

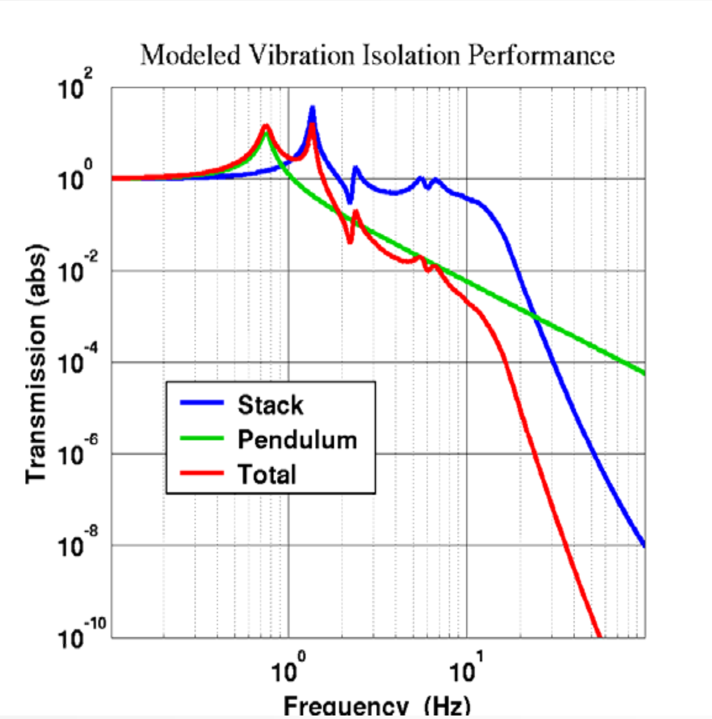


- Strain sensitivity:
  10^{-21} rms in a 100 Hz bandwidth
- Instrument strain noise density:
  3×10^{-23} /$\mathrm{Hz}^{1/2}$
  at 150 Hz
- Displacement Noise
  - Seismic motion
  - Thermal Noise
  - Radiation Pressure
- Sensing Noise
  - Photon Shot Noise
  - Residual Gas

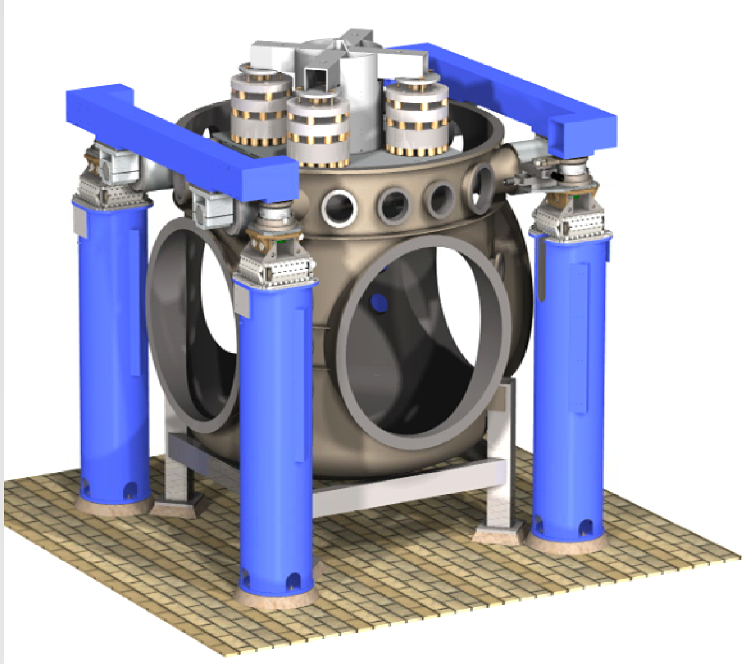
Seismic Isolation

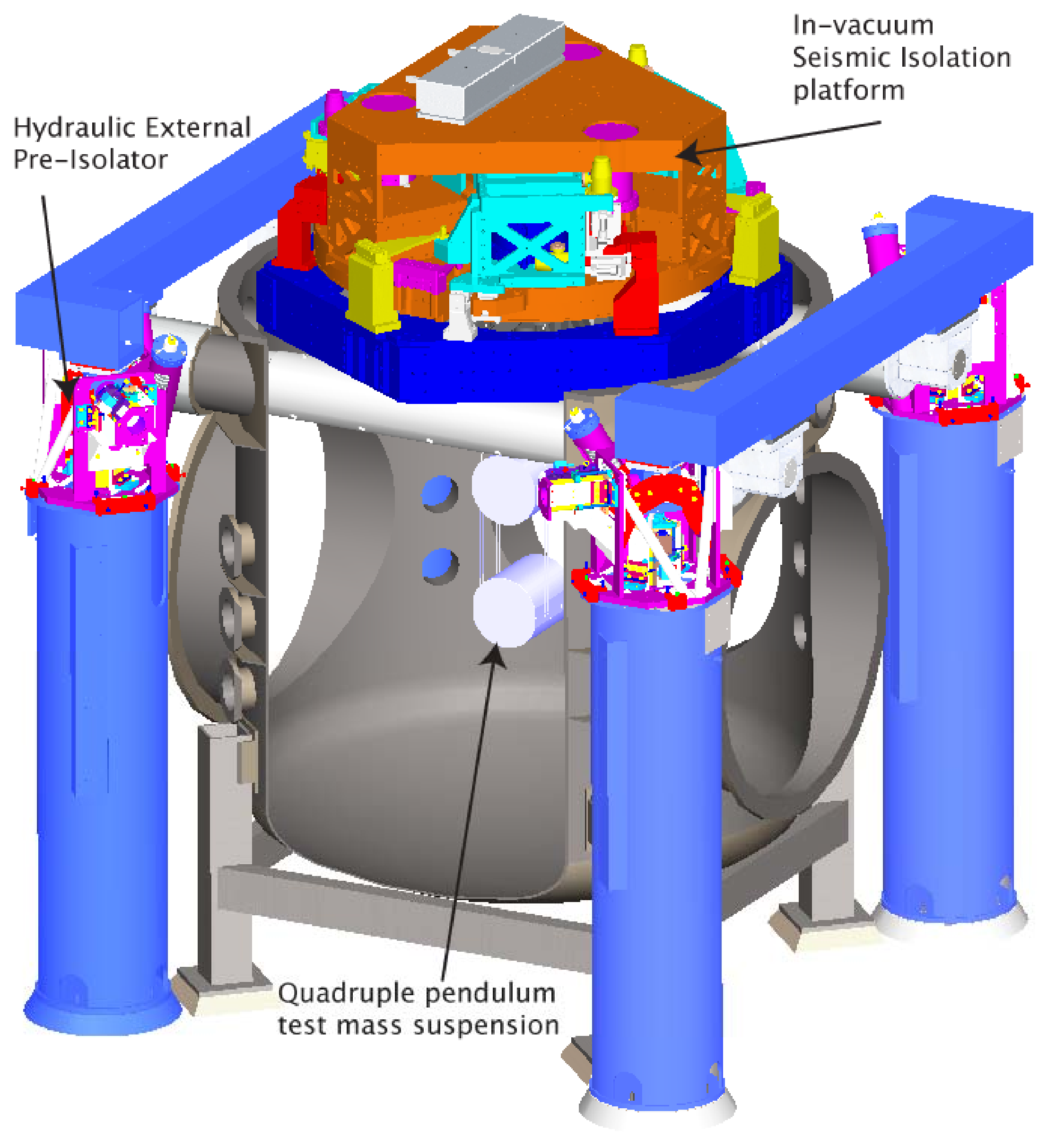
stack of mass-springs





Advanced LIGO Seismic Isolation



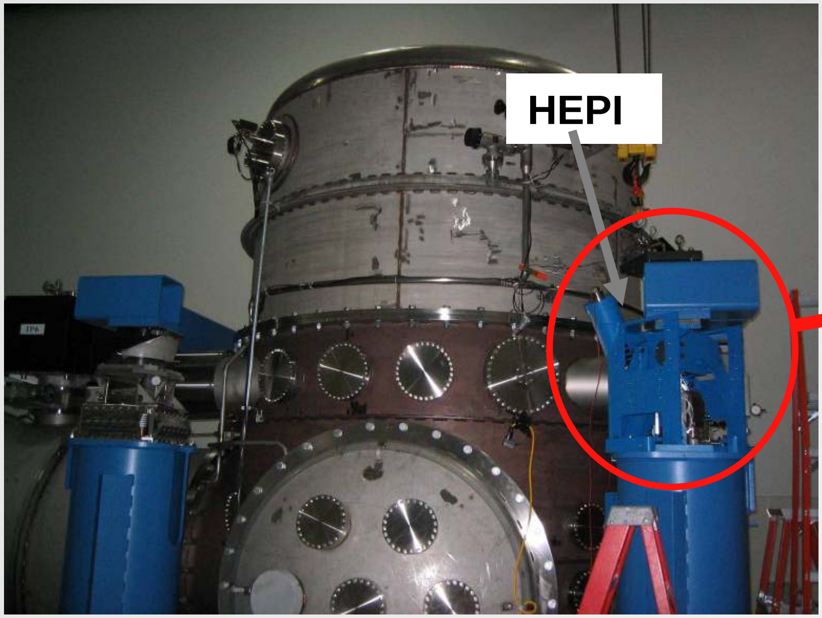


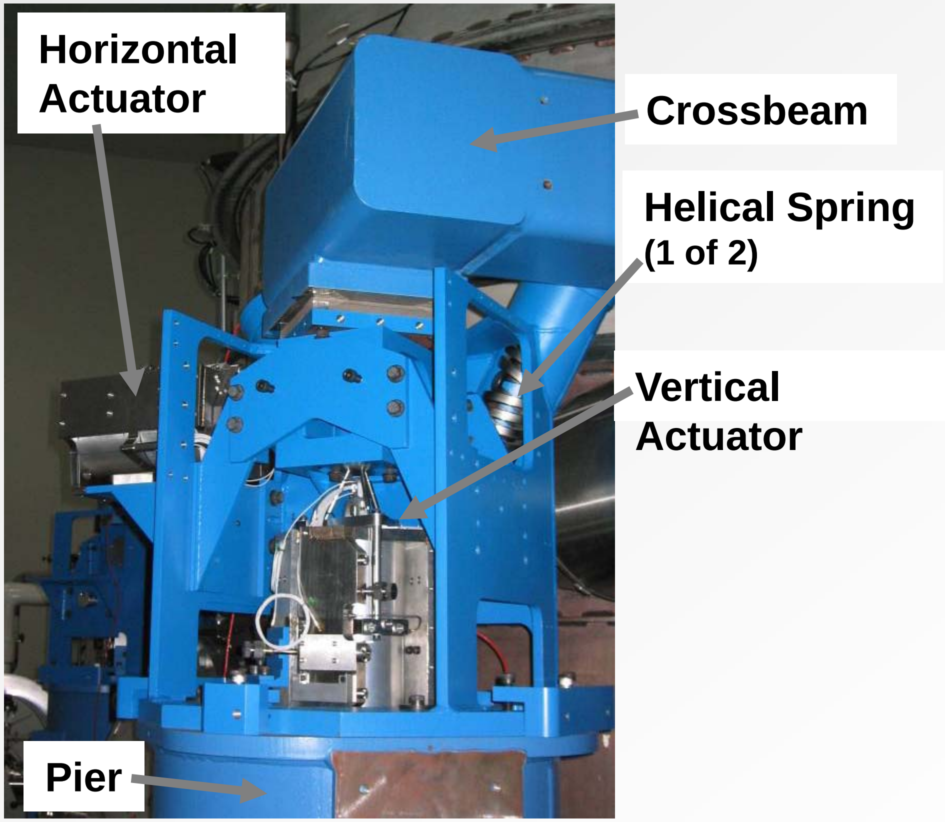
Hydraulic External Pre-Isolator

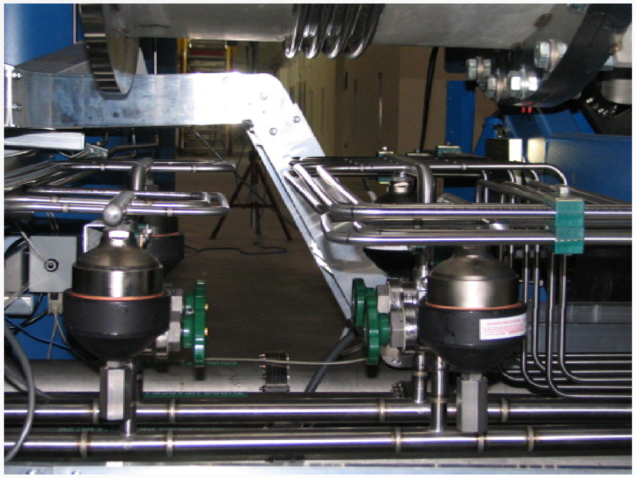
In-vacuum Seismic Isolation platform

Quadruple pendulum test mass suspension

Seismic Isolation, HEPI Subsystem Installation at LIGO Livingston Observatory







BSC Internal Seismic Isolation (BSC-ISI) system

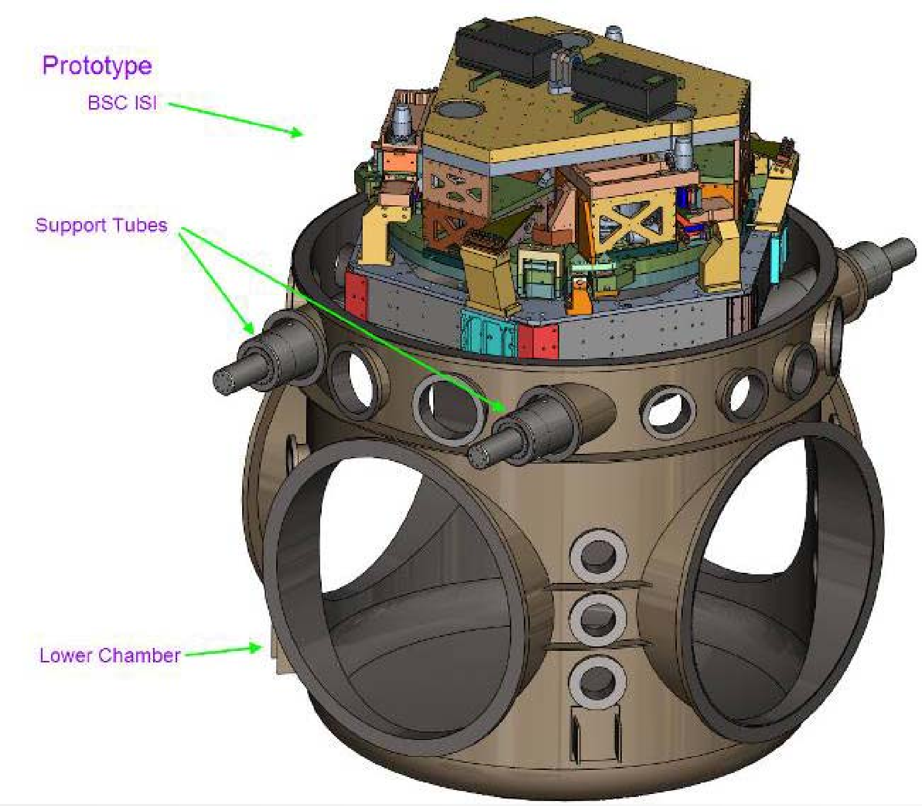
BSC Internal Seismic Isolation (BSC-ISI) system

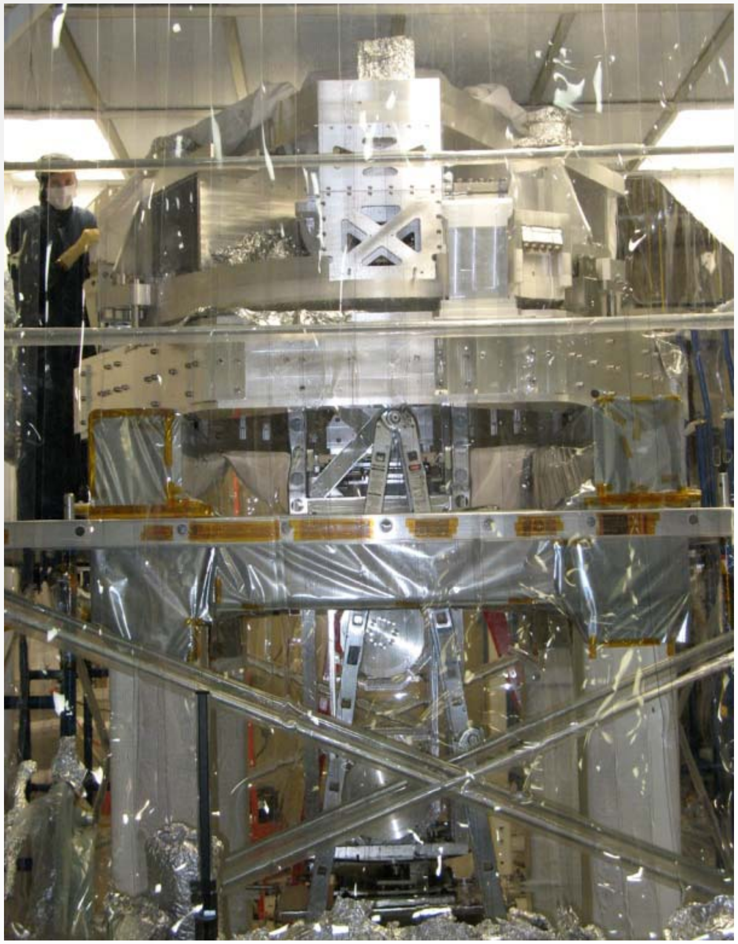
✓ A support structure (Stage 0) and Two suspended active stages (Stage 1 & 2).

✓ Will be installed for Advanced LIGO into the BSC chambers.

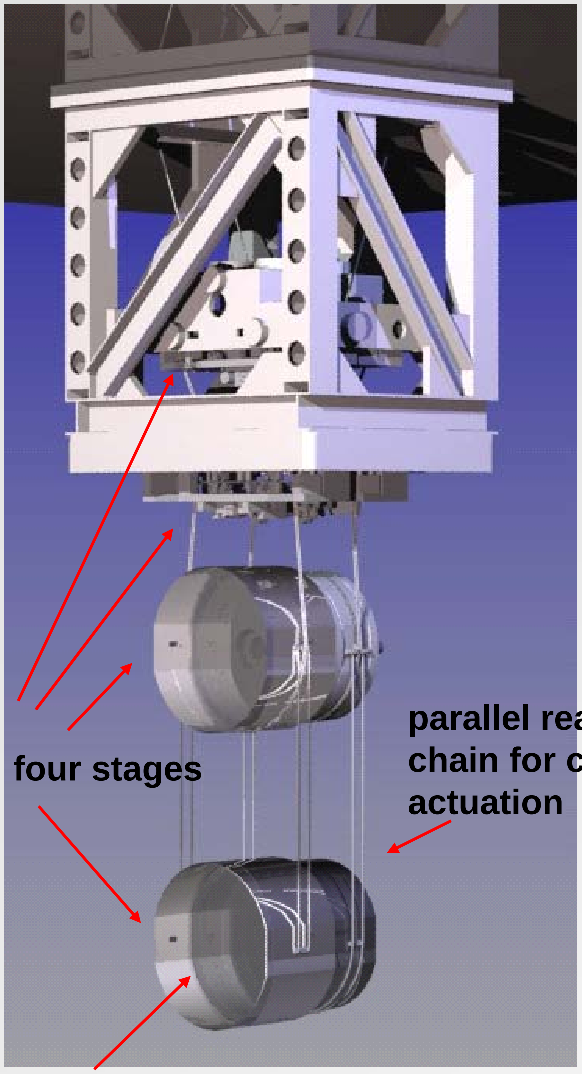
✓ A BSC-ISI system in each of the 15 BSC chambers.

✓ Optic table supports the test masses and beam splitters.





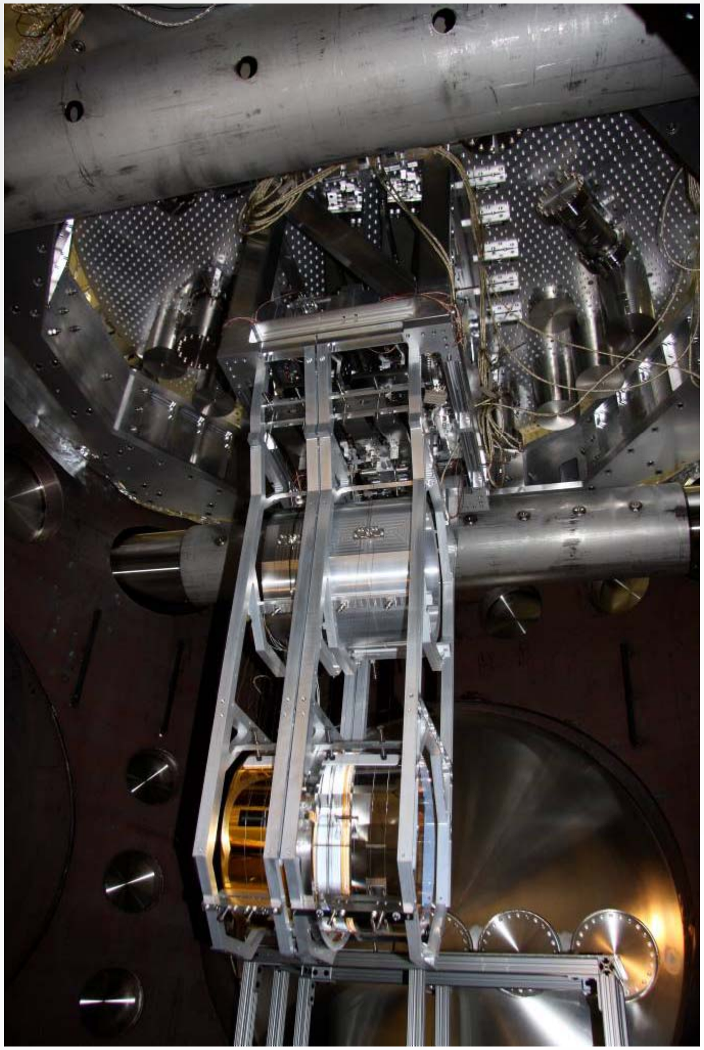
2. Advanced LIGO



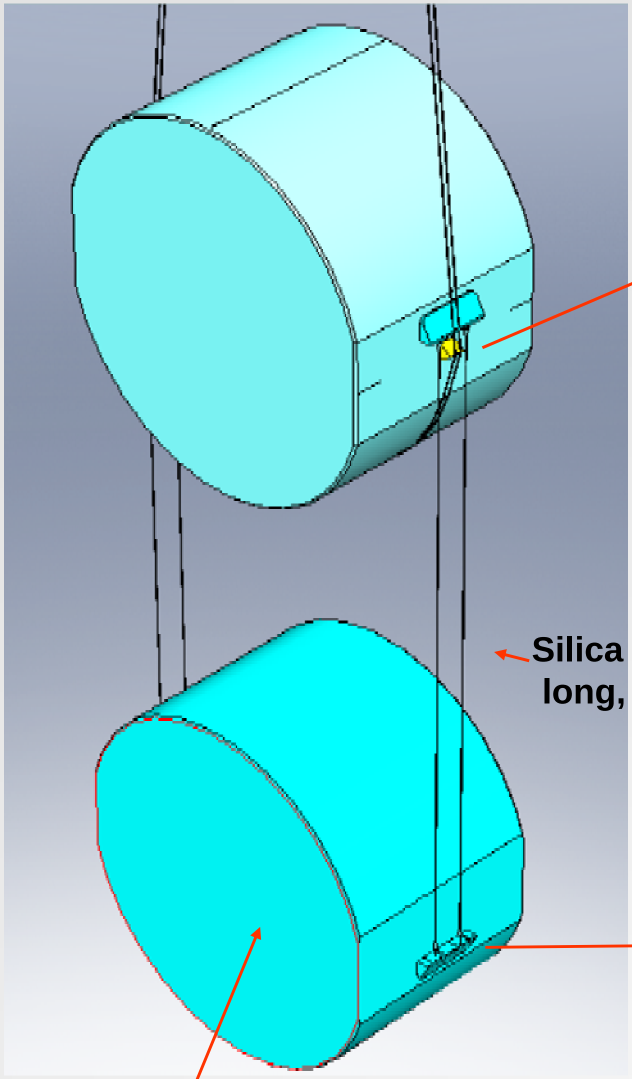
four stages

parallel reaction chain for control actuation

40 kg silica test mass

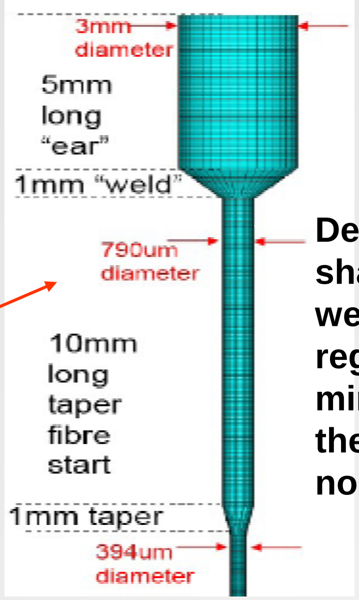


Development of Monolithic Suspensions for Advanced LIGO

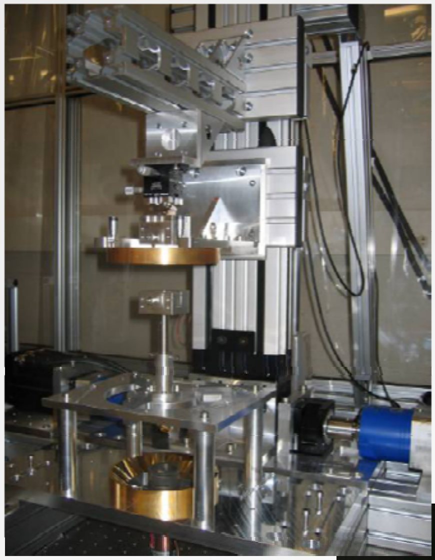


Silica fibres 600 mm long, 0.4 mm diam.

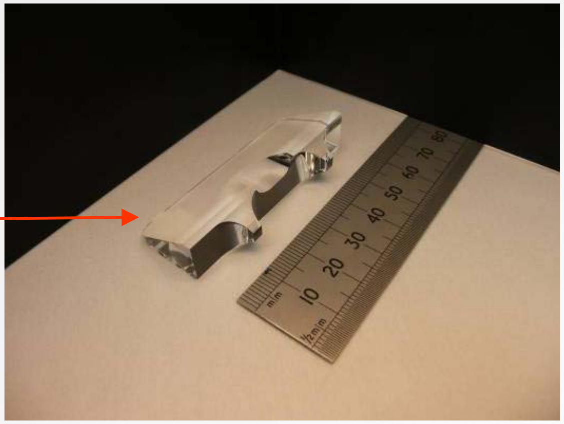
Mirror: 40 kg silica mass



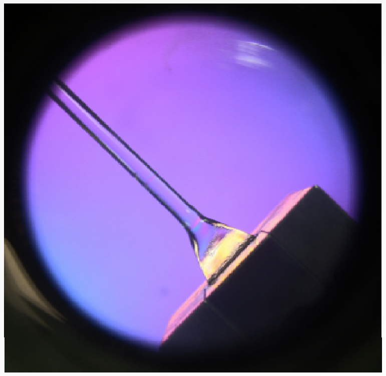
Detail of fibre shape close to weld: thick flexure region used to minimise thermoelastic noise



Fibre pulling machine at MIT



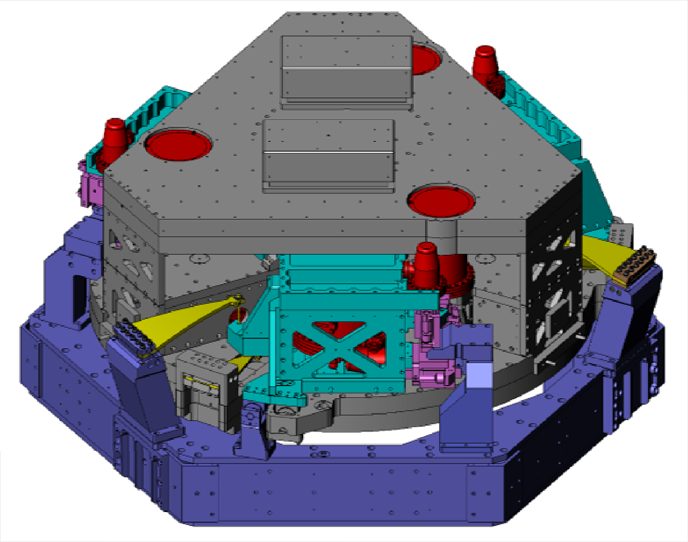
Example of ear to be bonded to silica mass



Visual inspection of test weld using crossed polarisers at Glasgow

Welding test at Glasgow

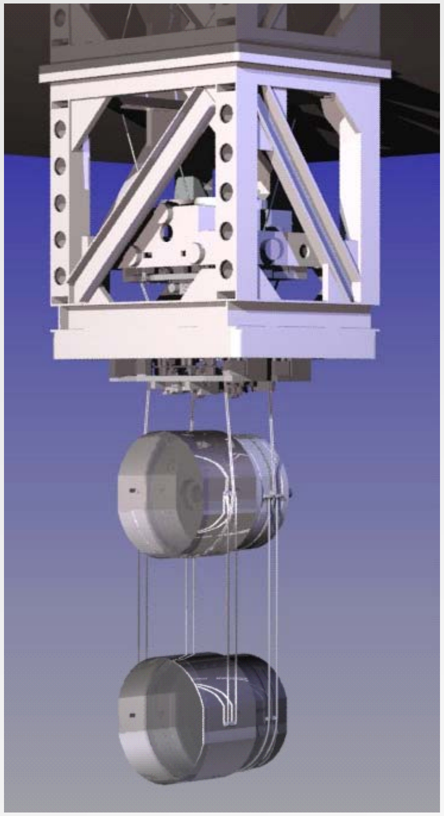
2. Advanced LIGO

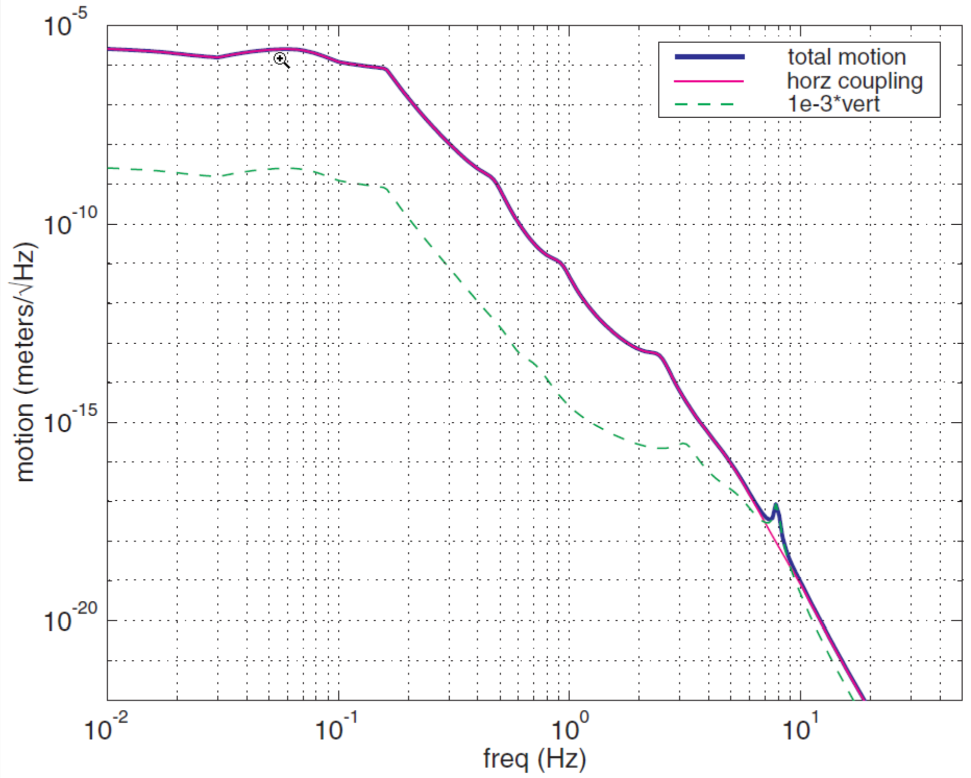


Test mass suspension complements seismic isolation

All instruments using several pendulums in series for improved isolation, staging of control forces and dynamic range

Combined attenuation of seismic noise ~10 orders of magnitude at 10 Hz



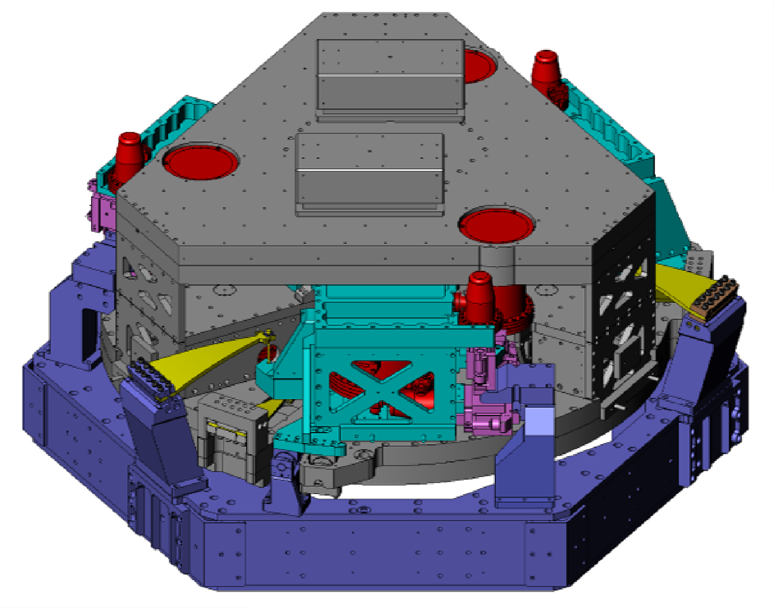


BSC Internal Seismic Isolation (BSC-ISI) system

Both suspended stages and have 6 degrees of freedom:

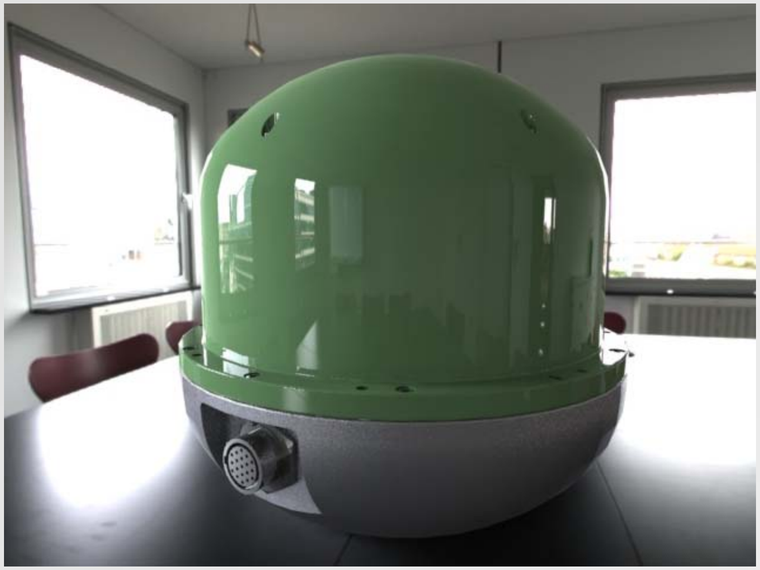
- ✓ Blades provide the vertical flexibility
- ✓ Rods provide the horizontal one
- ✓ Suspension frequencies in the 1Hz-7Hz range
- ✓ Passive isolation from few Hz to ~ 100Hz
- ✓ Active isolation in the 0.1Hz-20Hz range.
- ✓ Active control positioning

BSC-ISI as built for the prototype installed at MIT

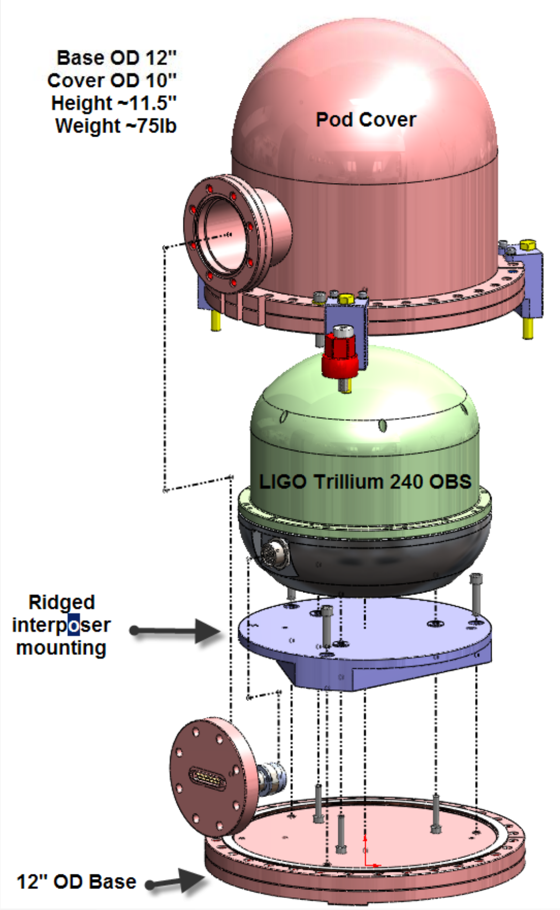


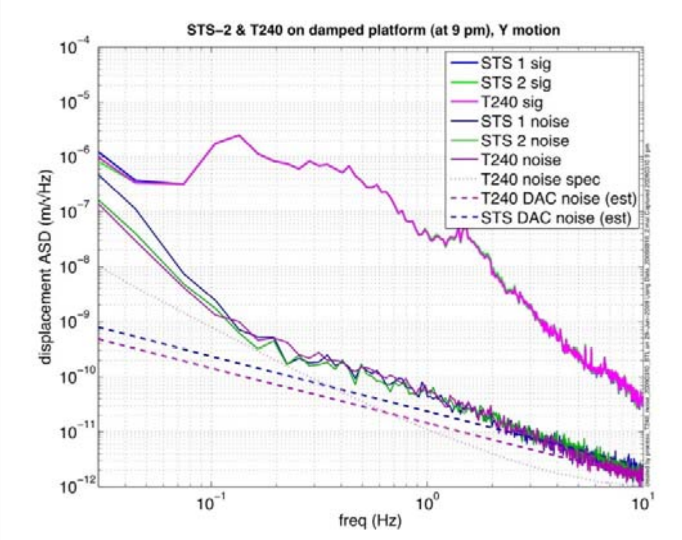
- Stage 0 in violet
- Stage 1 in cyan
- Stage 2 in grey
- Blades and flexure in yellow
- Sensors in Red
- Actuators in Pink

BSC-ISI seismometers

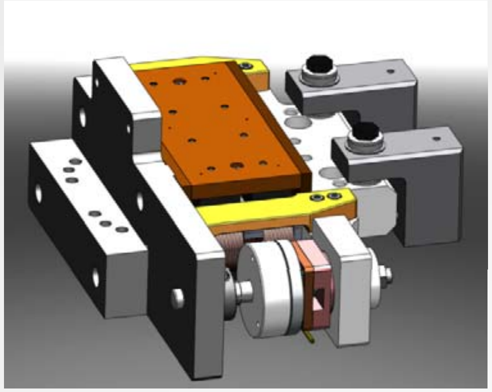


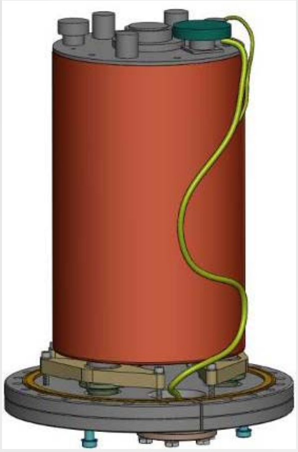
Trillium Diameter: 9.5 in
Height: 8.9 in
Weight: 21 lb
(No Locker needed)

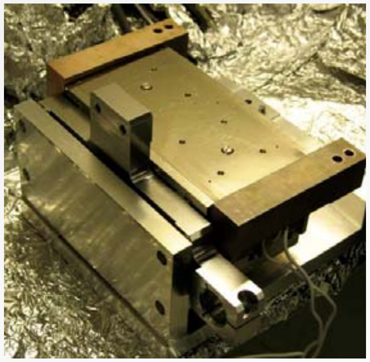


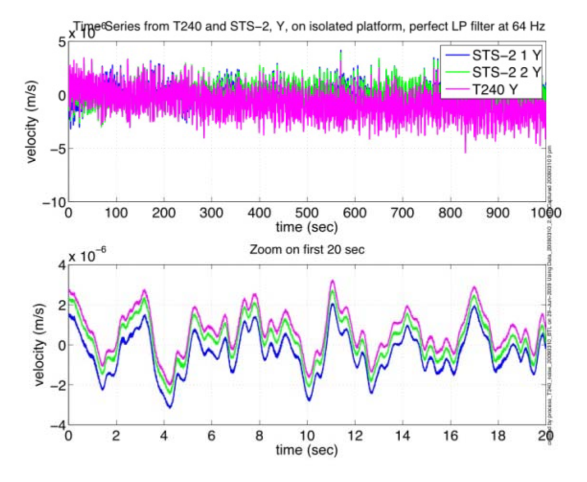


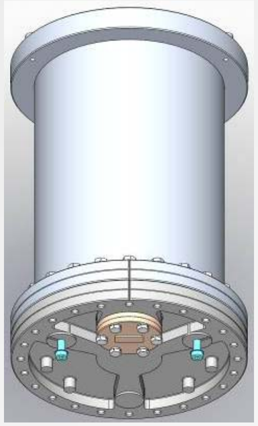
Sensors and actuators

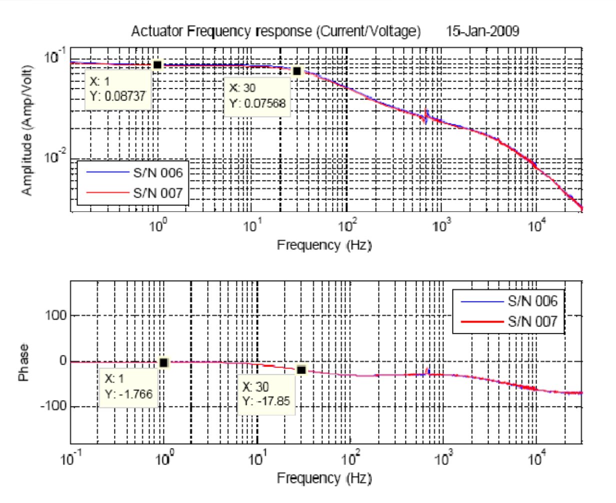


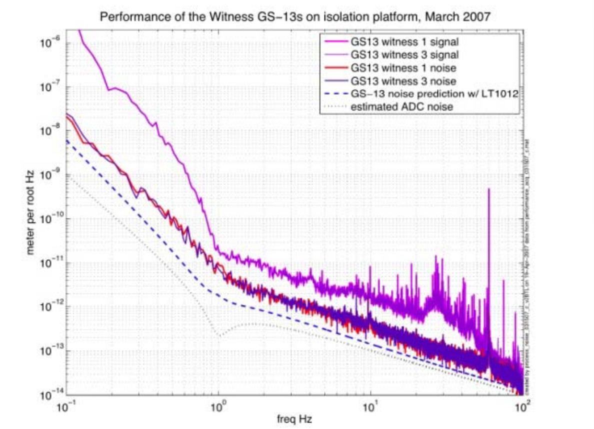






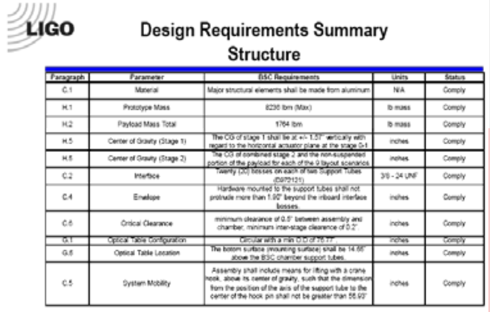






Du cahier des charges a la fabrication en serie

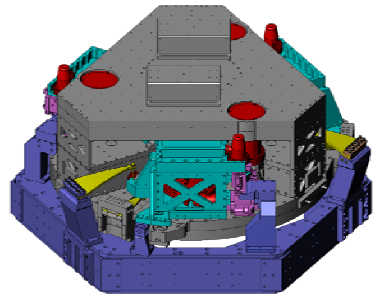
1- Cahier des charges



Design Requirements Summary
Structure

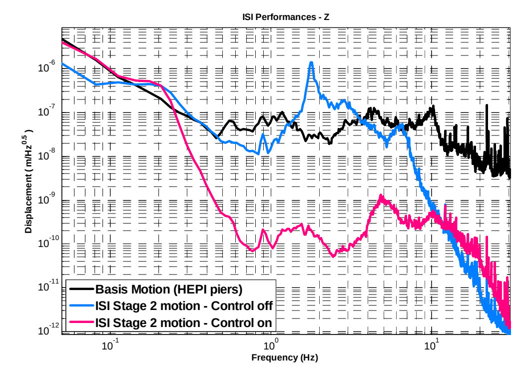
Paragraph	Parameter	BSC Requirements	Units	Status
C.1	Material	Major structural elements shall be made from aluminum	N/A	Comply
H.1	Prototype Mass	8236 lbm (Max)	lb mass	Comply
H.2	Payload Mass Total	1764 lbm	lb mass	Comply
H.5	Center of Gravity (Stage 1)	The CG of stage 1 shall be at +/- 1.57" vertically with regard to the horizontal actuator plane at the stage 0-1	inches	Comply
H.5	Center of Gravity (Stage 2)	The CG of combined stage 2 and the non-suspended portion of the payload for each of the 9 layout scenarios	inches	Comply
C.2	Interface	Twenty (20) bosses on each of two Support Tubes (D970131)	3/8 - 24 UNF	Comply
C.4	Envelope	Hardware mounted to the support tubes shall not protrude more than 1.97" beyond the inboard interface bosses.	inches	Comply
C.6	Critical Clearance	minimum clearance of 0.5" between assembly and chamber; minimum inter-stage clearence of 0.2".	inches	Comply
G.1	Optical Table Configuration	Circular with a min O.D of 76.77".	inches	Comply
G.6	Optical Table Location	The bottom surface (mounting surface) shall be 14.66" above the BSC chamber support tubes.	inches	Comply
C.5	System Mobility	Assembly shall include means for lifting with a crane hook, above its center of gravity, such that the dimension from the position of the axis of the support tube to the center of the hook pin shall not be greater than 56.93"	inches	Comply

2- Conception

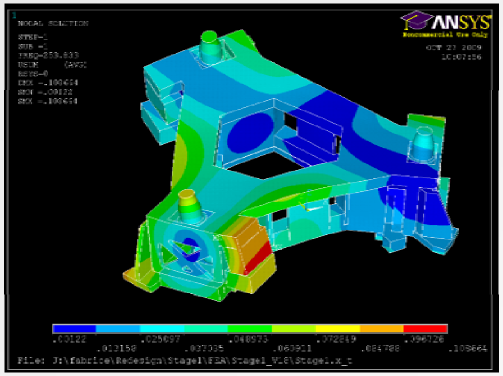


3- Prototypage

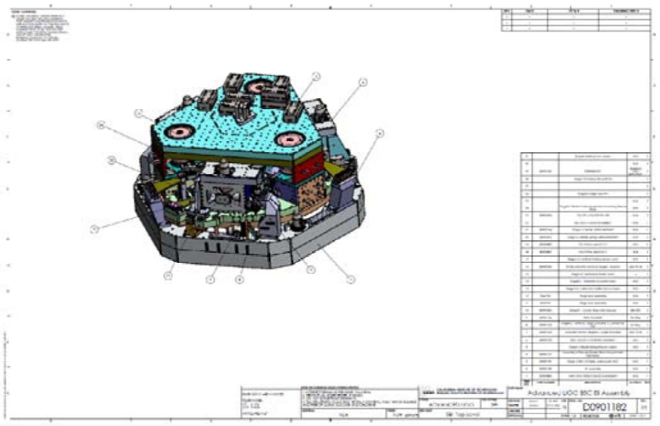
4- Test



5- Developement

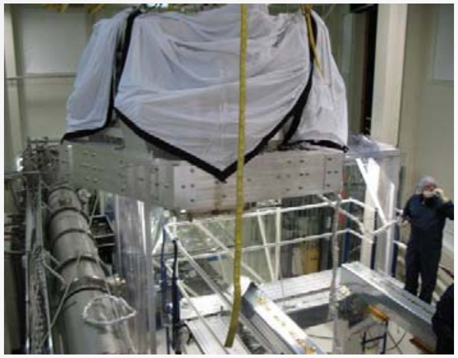


6- Fabrication en serie

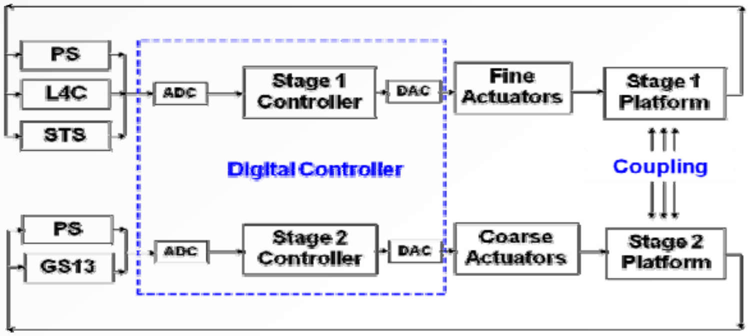


7- Assemblage

8- Installation

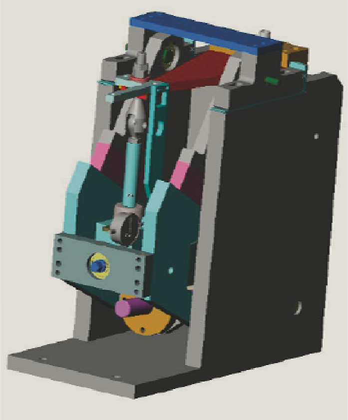


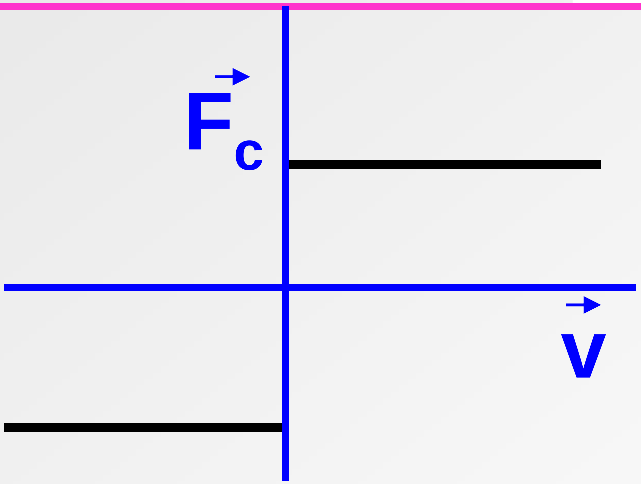
9- Mise en service

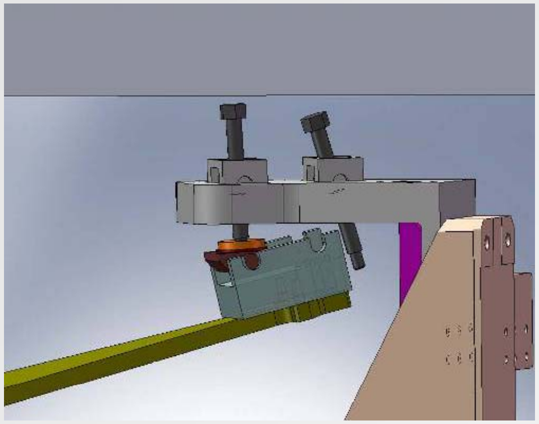


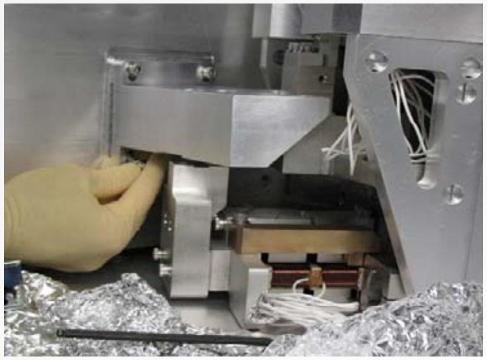
PS
L4C
STS
ADC
Stage 1 Controller
DAC
Fine Actuators
Stage 1 Platform
Digital Controller
Coupling
PS
GS13
ADC
Stage 2 Controller
DAC
Coarse Actuators
Stage 2 Platform

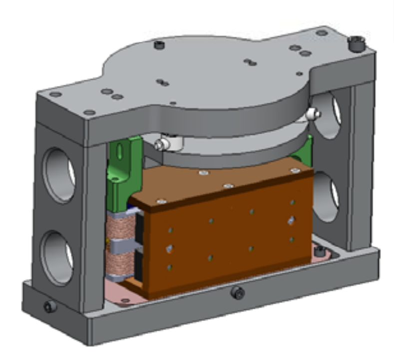
Tests – Part 1

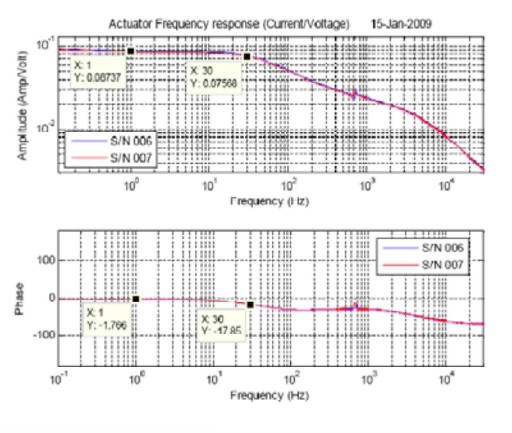



$\vec{F}_c$
$\vec{v}$



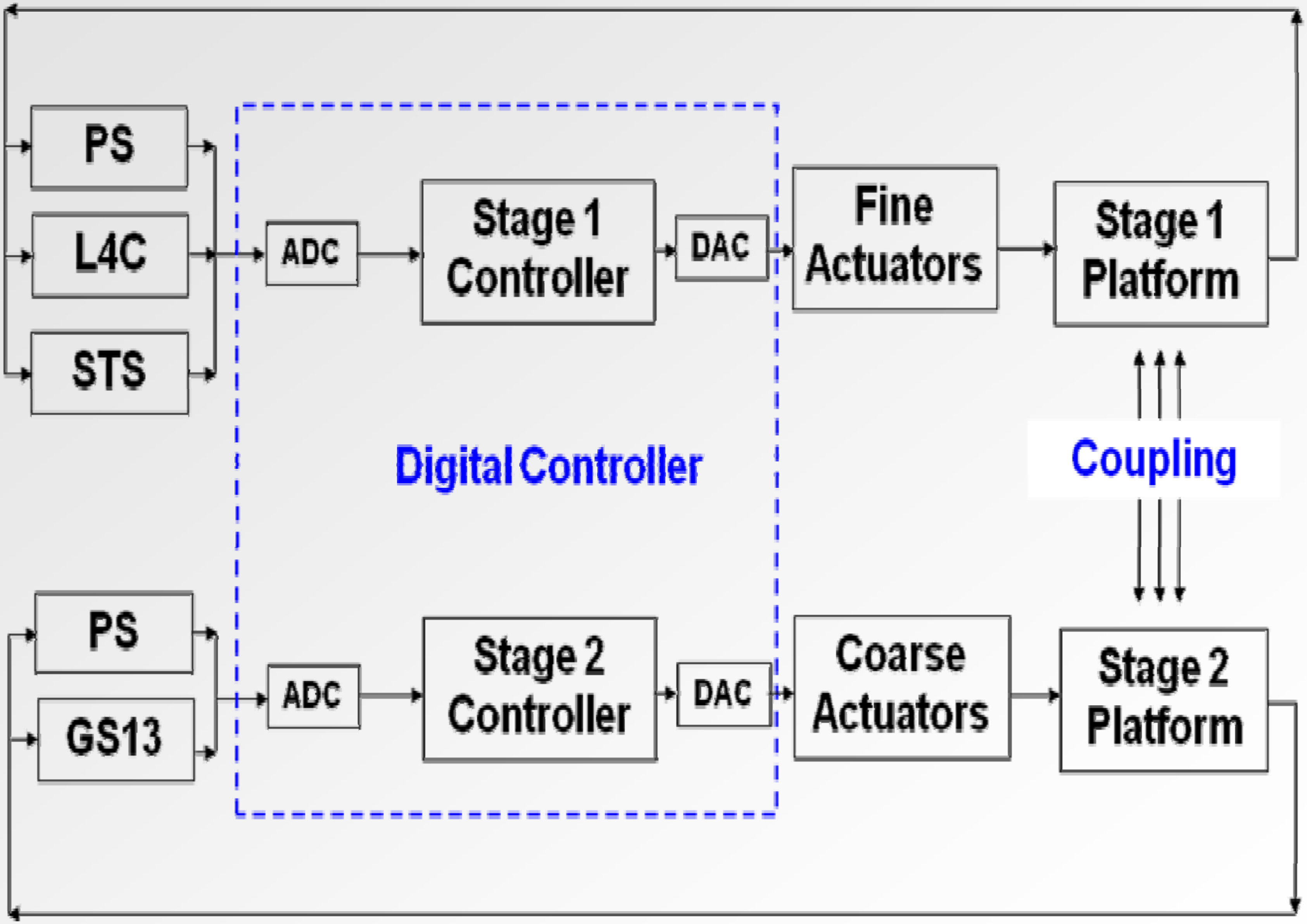




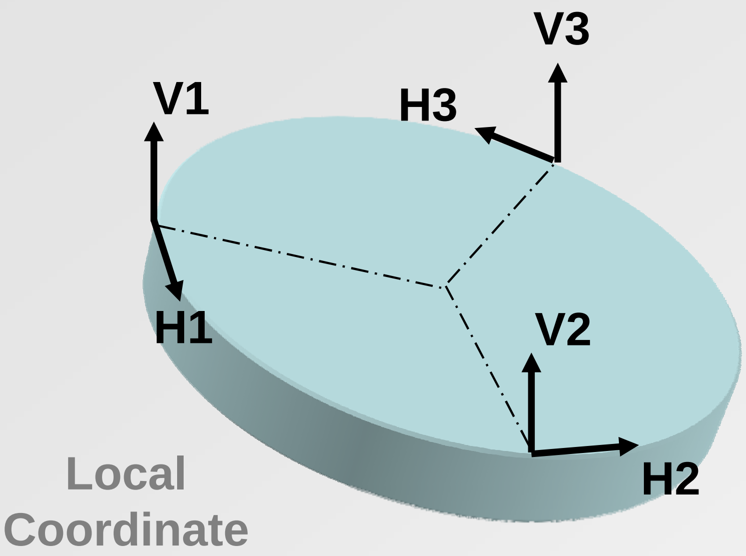

Actuator Frequency response (Current/Voltage) 15-Jan-2009
Amplitude (Amp/Volt)
10^{-1}
10^{-2}
X: 1
Y: 0.08737
X: 30
Y: 0.07568
S/N 006
S/N 007
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Frequency (Hz)
Phase
100
0
-100
X: 1
Y: -1.766
X: 30
Y: -17.85
S/N 006
S/N 007
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Frequency (Hz)

Tests – Part 2

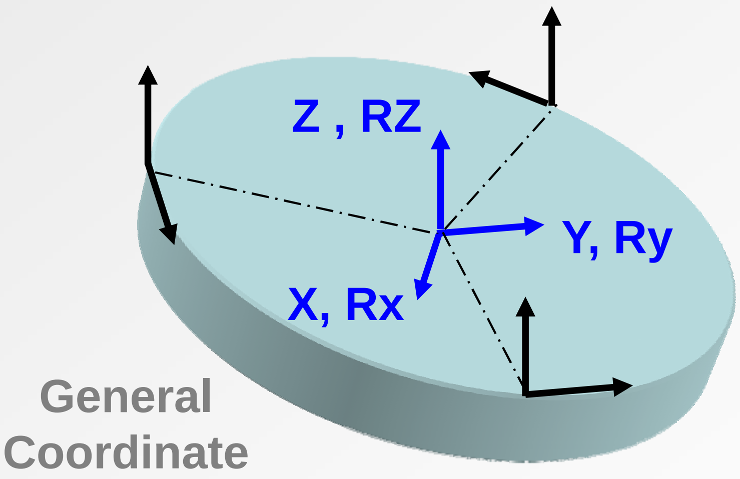
Control Strategy



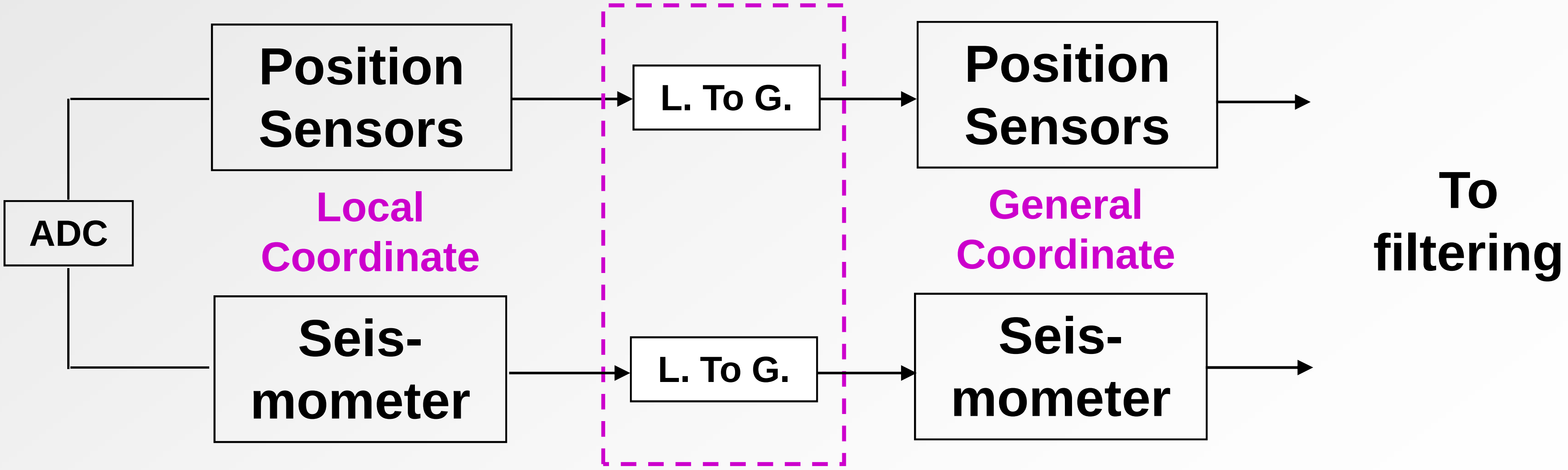
1st Step: Local to General coordinates



Local Coordinate



General Coordinate



ADC

Position Sensors

Local Coordinate

Seis-mometer

L. To G.

L. To G.

Position Sensors

General Coordinate

Seis-mometer

To filtering

Tests – Part 2

2nd Step: Damping loops

Seismometer

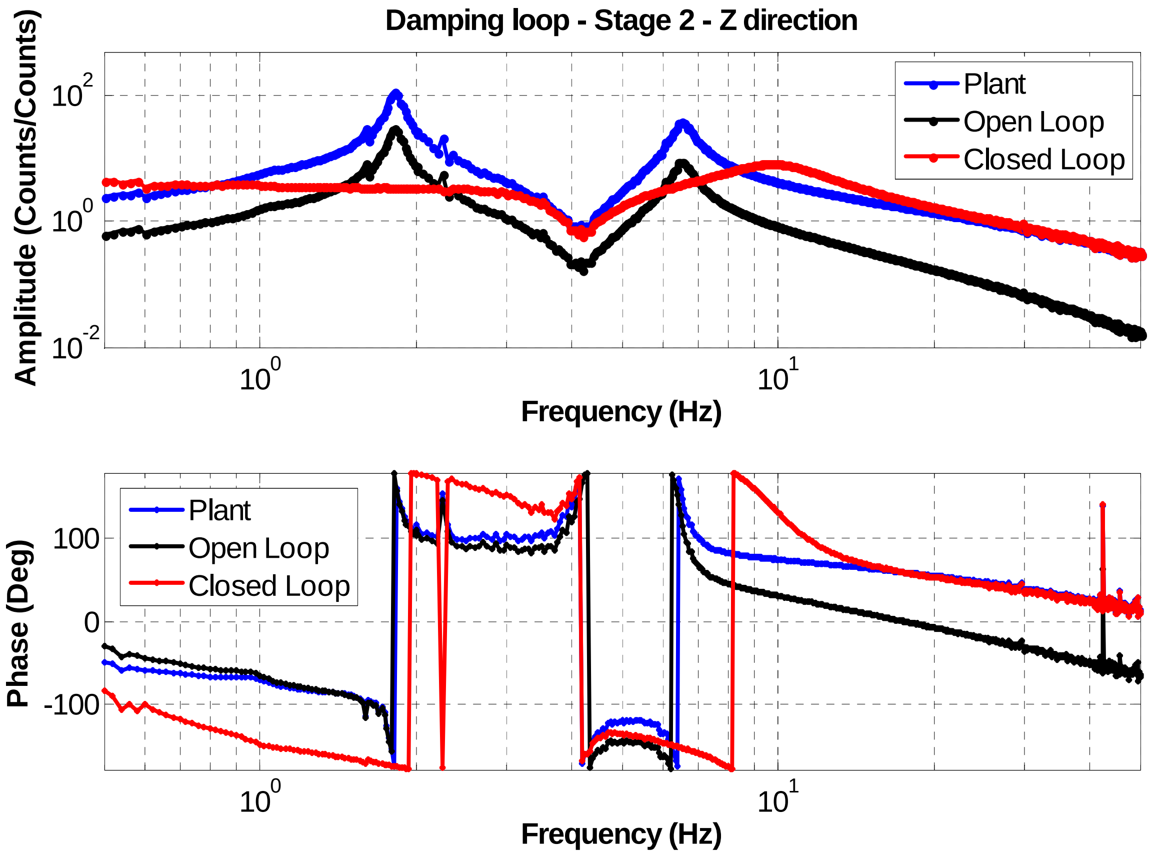
General Coordinate

Damping Filters

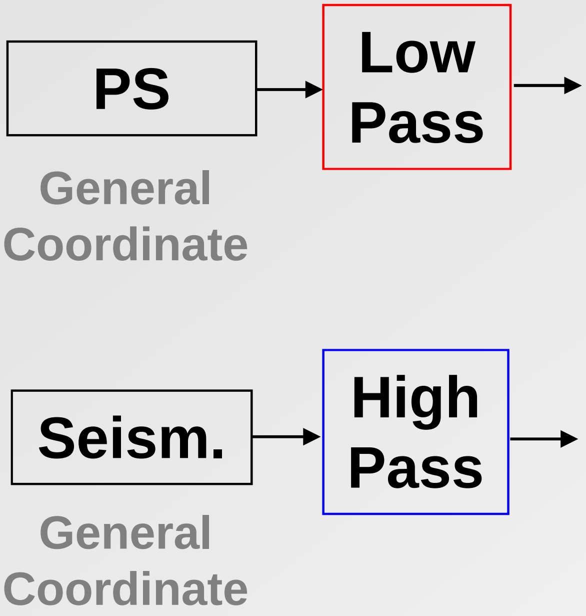
X , Y , Z, Rx, Ry, Rz

G. To L.

DAC



3^{rd} step: Sensor Blend



PS

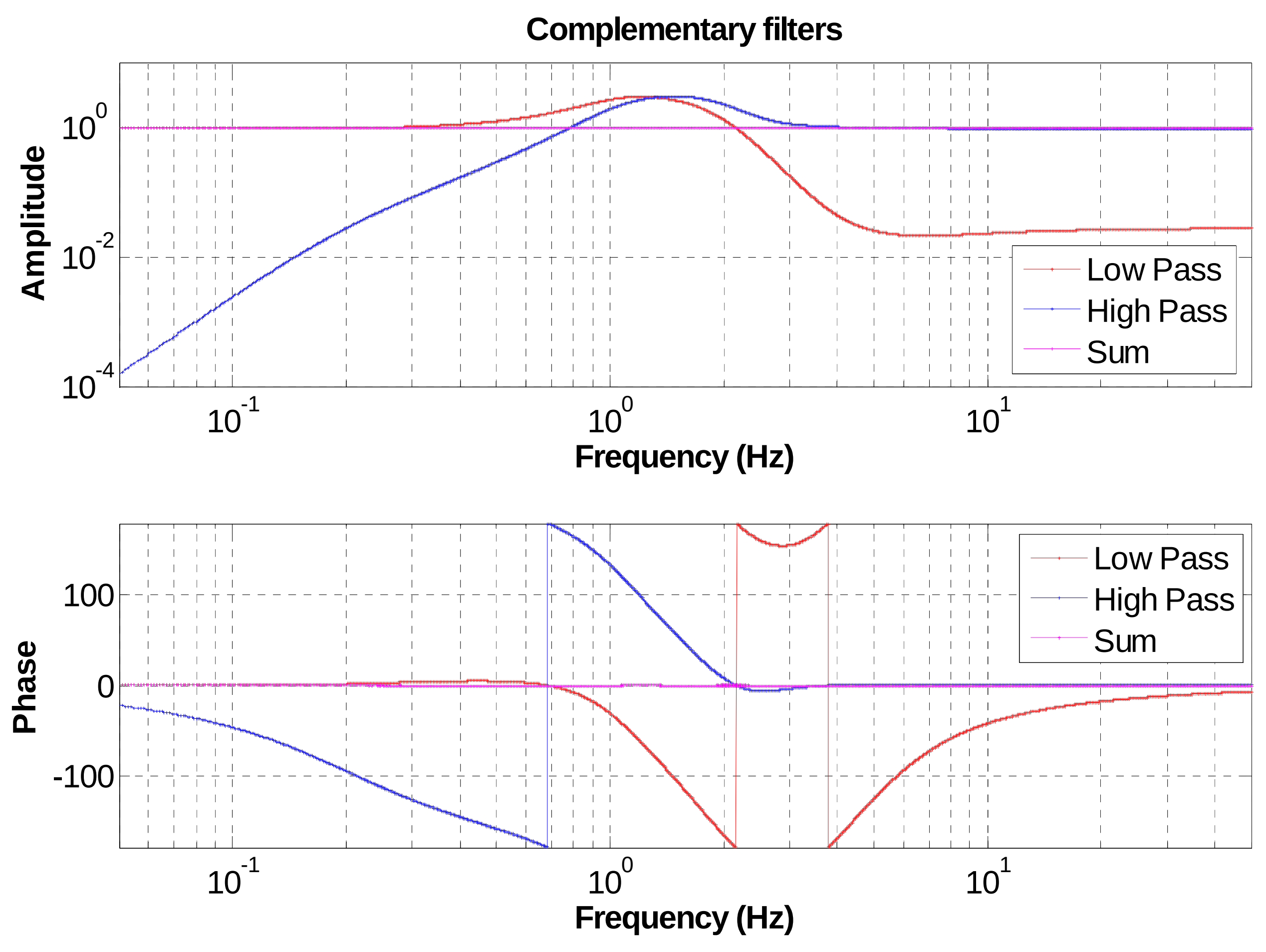
Low Pass

General Coordinate

Seism.

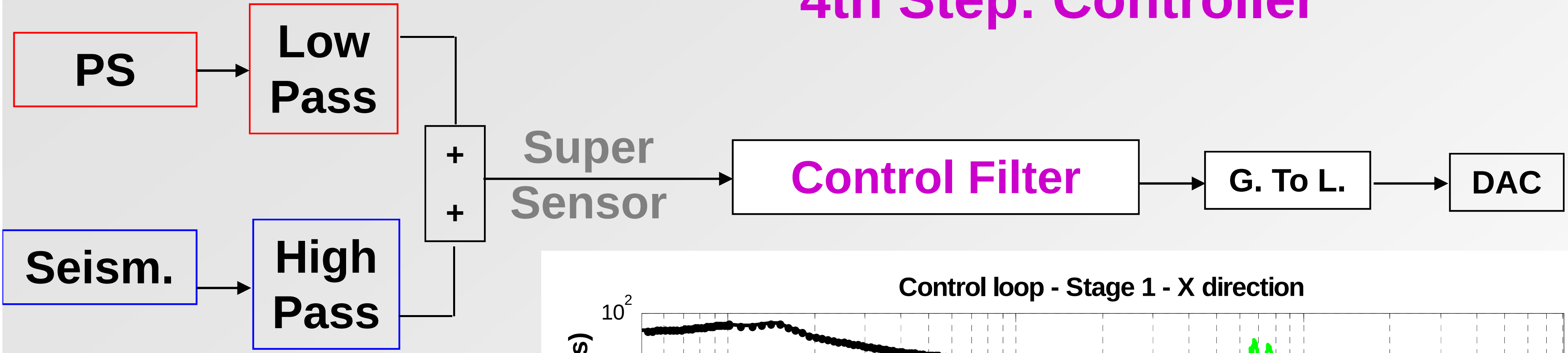
High Pass

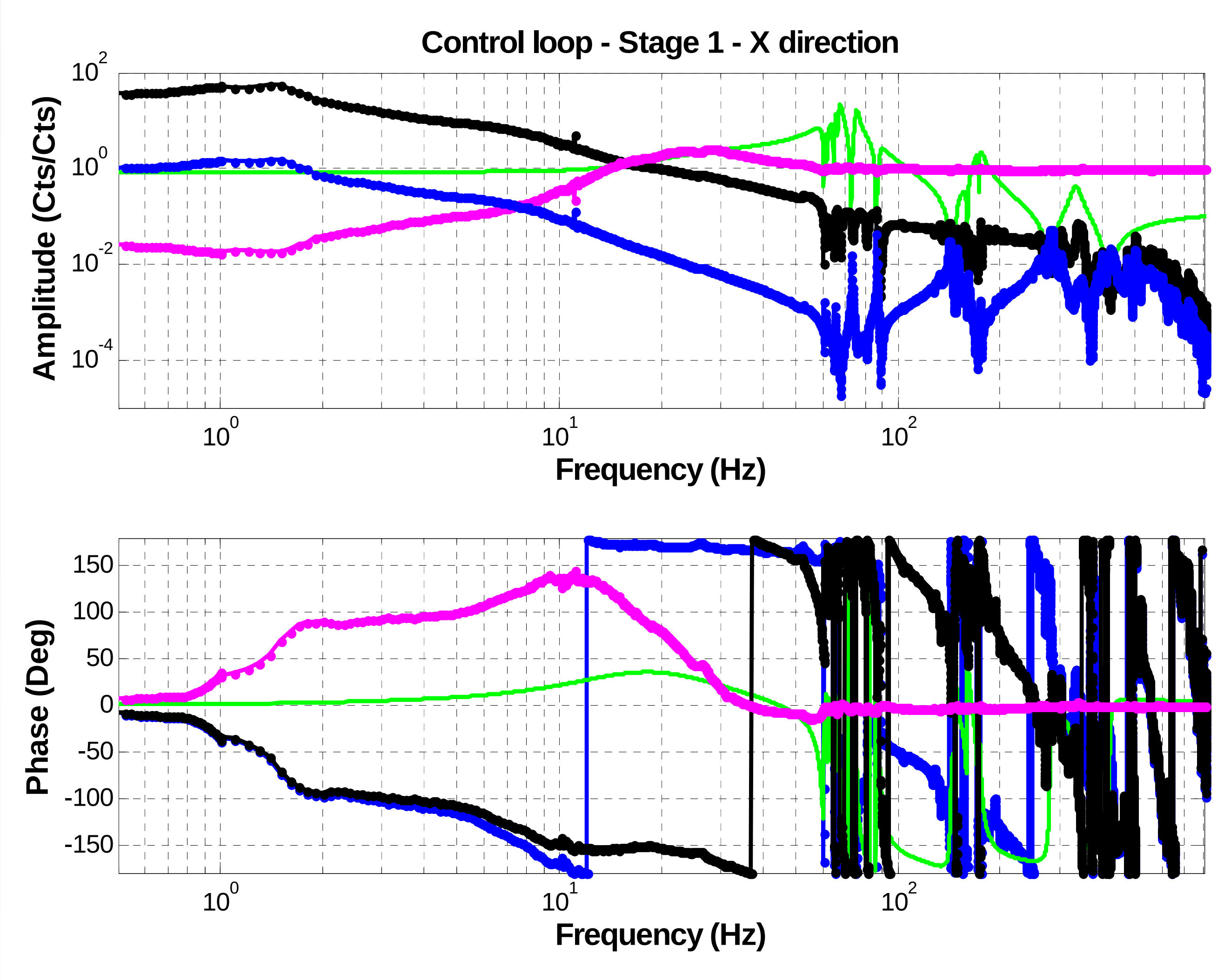
General Coordinate



Tests – Part 2

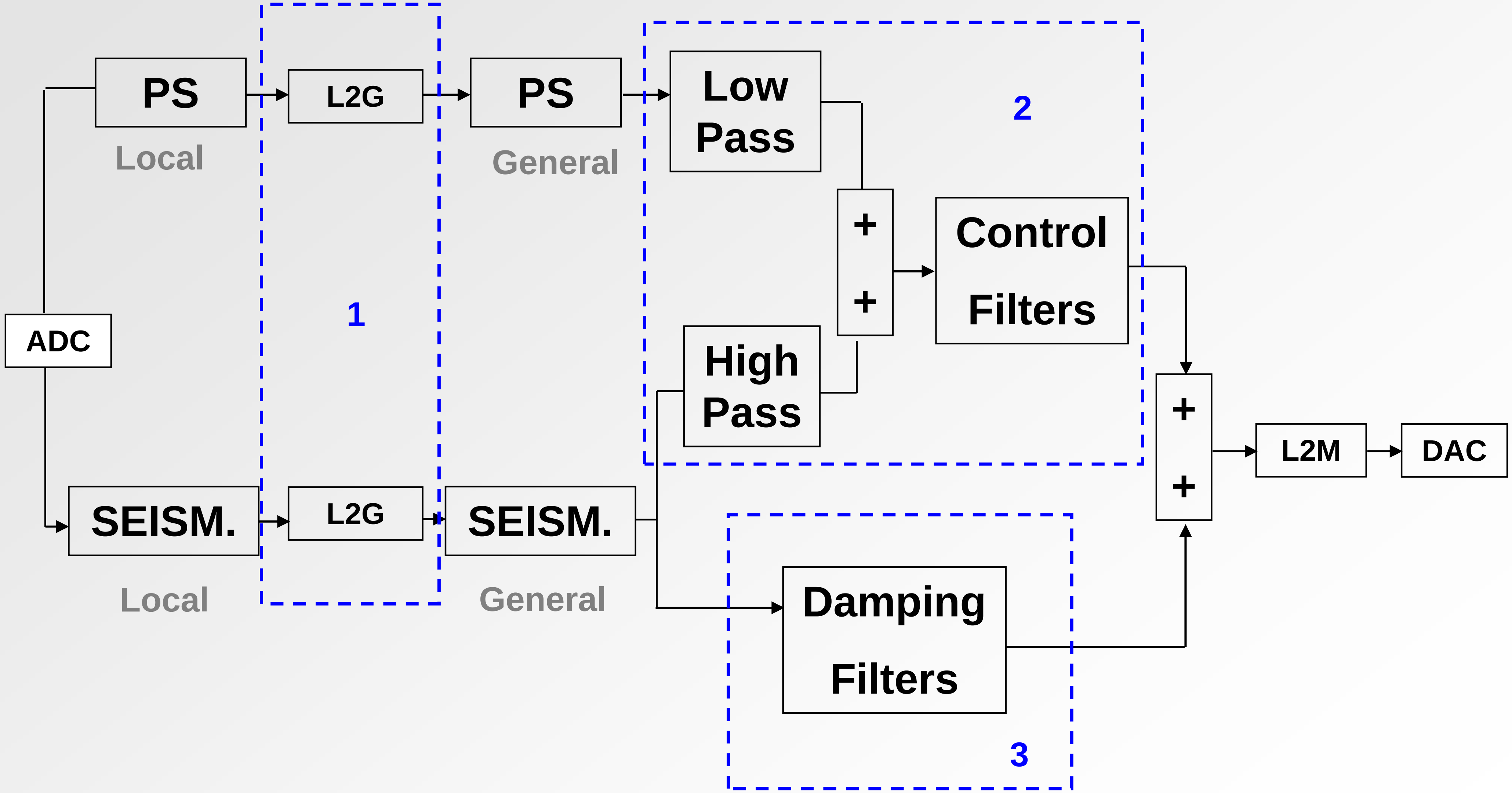
4th Step: Controller



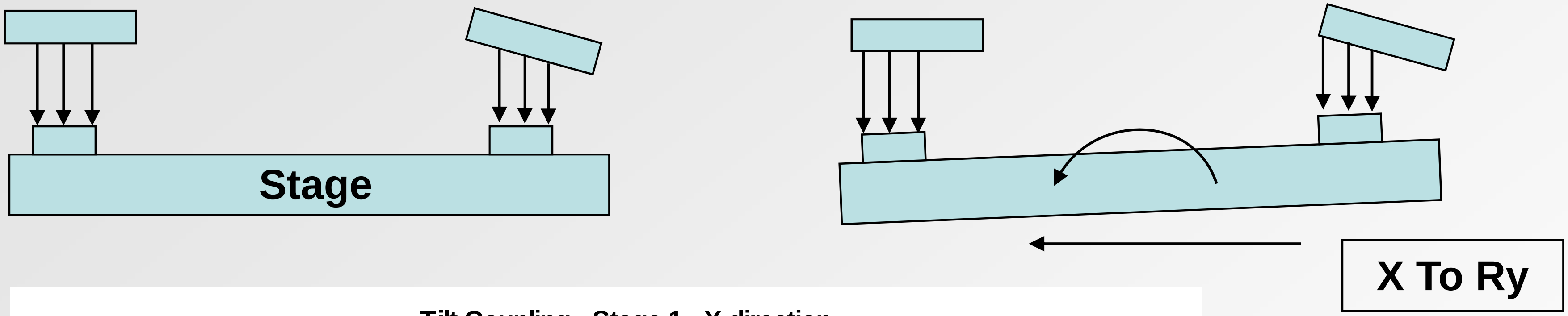


Tests – Part 2

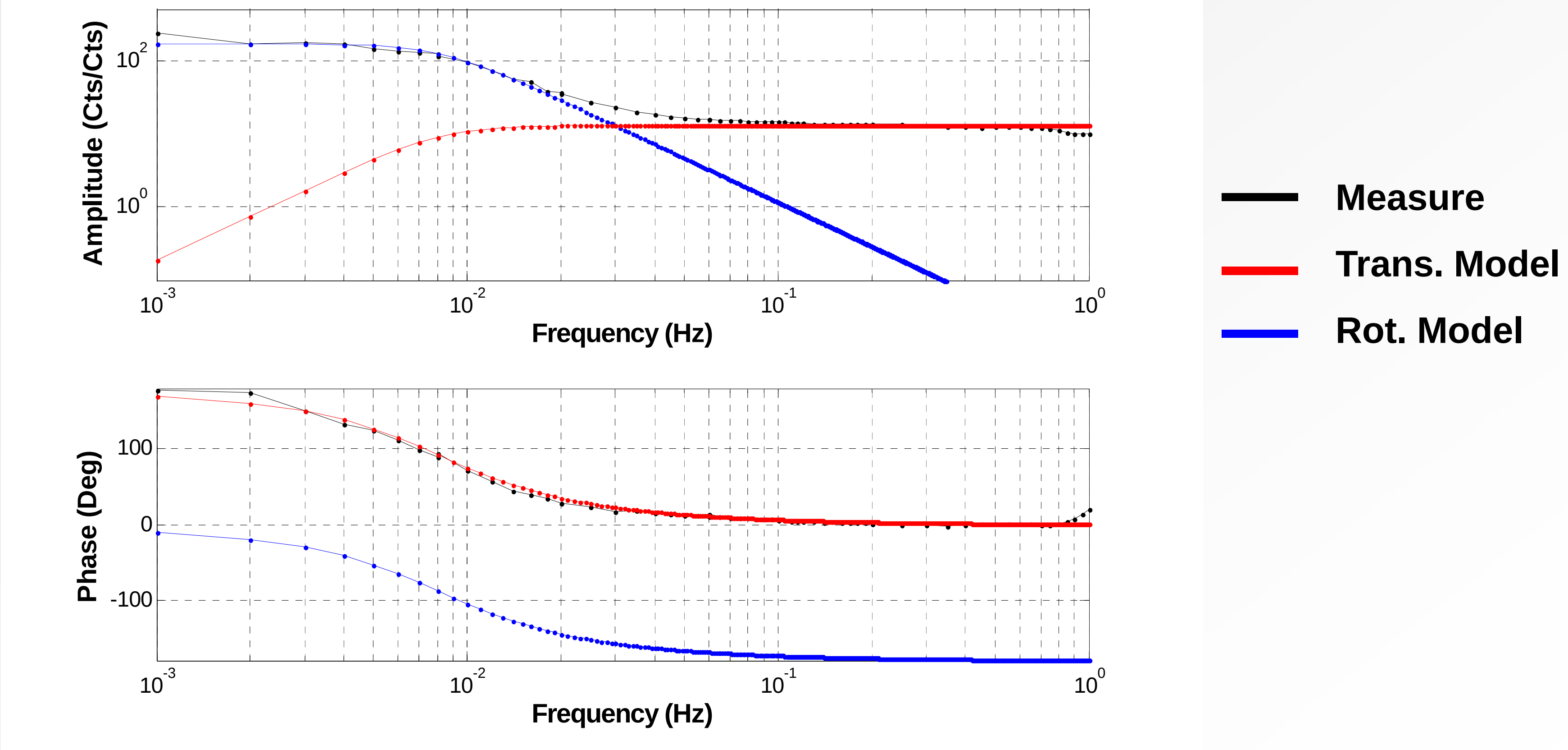
Control Strategy for each degree of freedom:



5th Step: Tilt decoupling



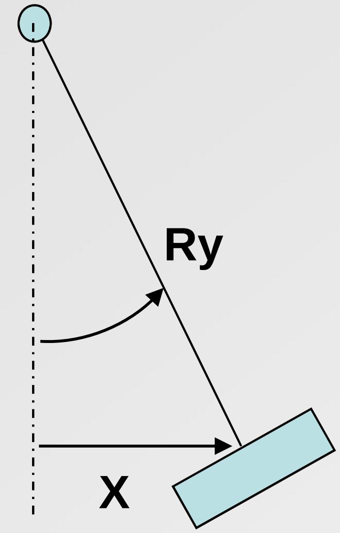
Tilt Coupling - Stage 1 - X direction



Tests – Part 2

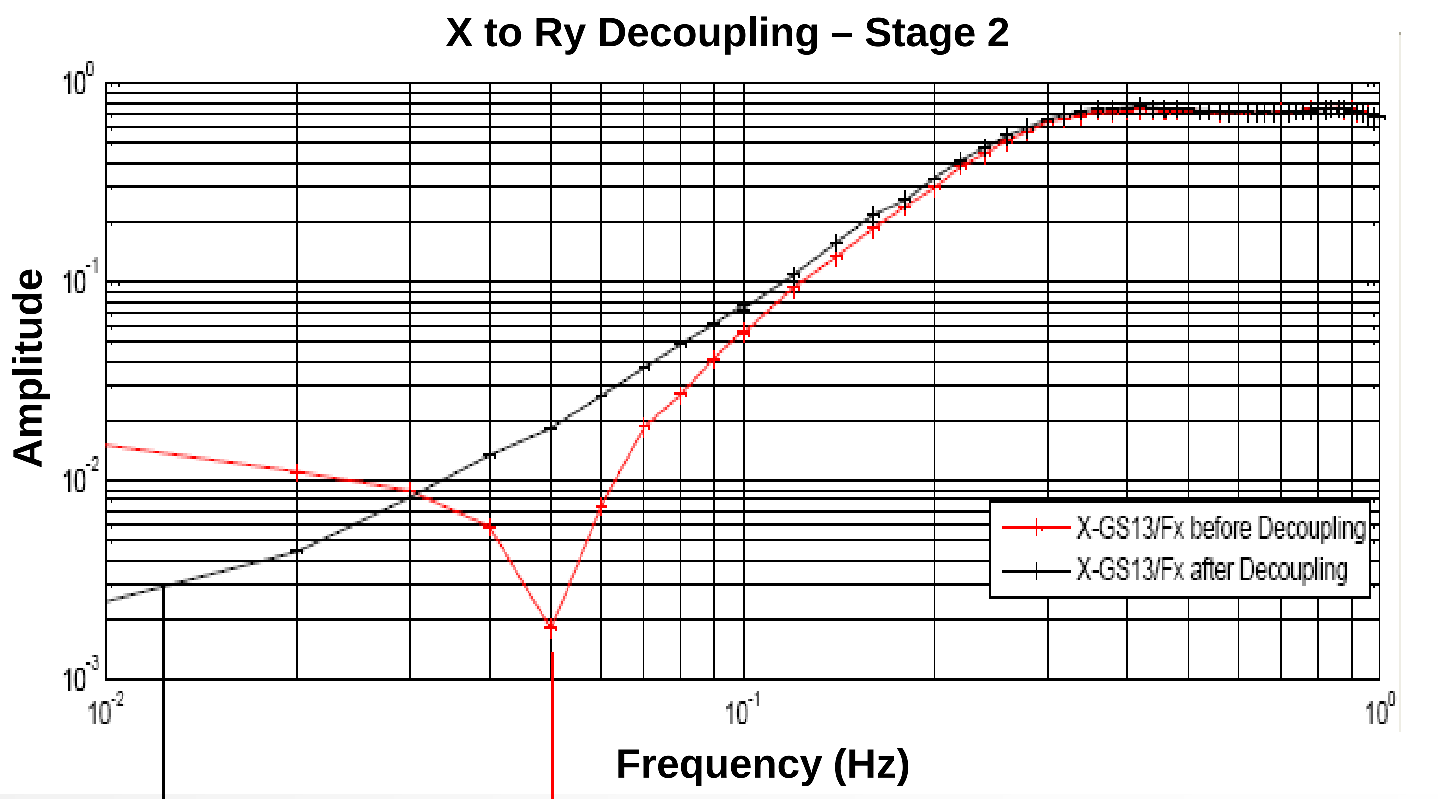
5th Step: Tilt decoupling

$$\frac{Ry}{X} \quad (\mathrm{Rad/m})$$



$$L = \frac{X}{Ry} \quad (\mathrm{m/Rad})$$

$$\omega_0 = \omega_{tilt} = \sqrt{\frac{g}{L}} \quad (\mathrm{Rad/s})$$

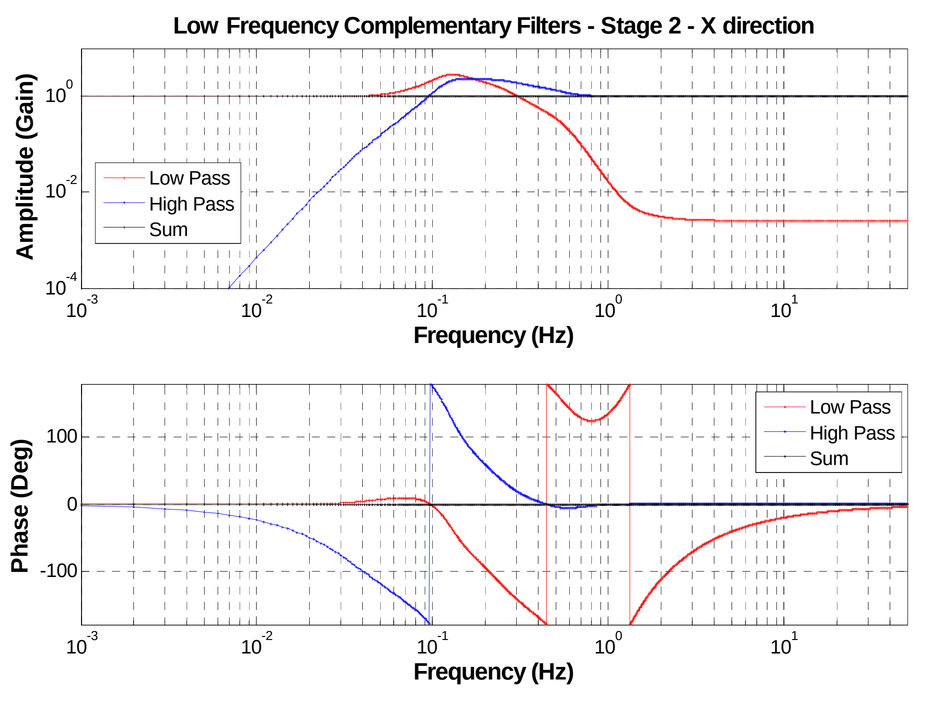


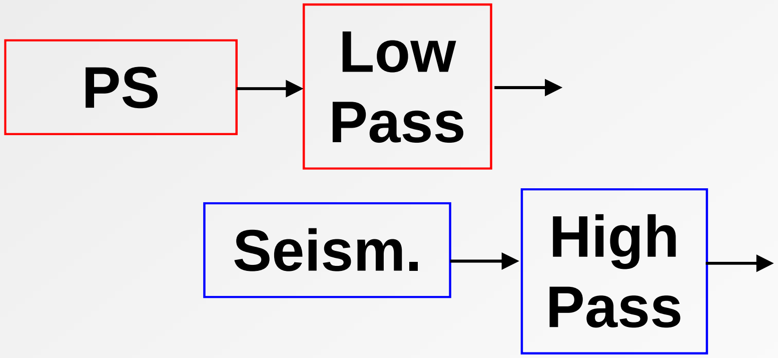
$$\omega_0 = \omega_{tilt} = 50\,\mathrm{mHz}$$

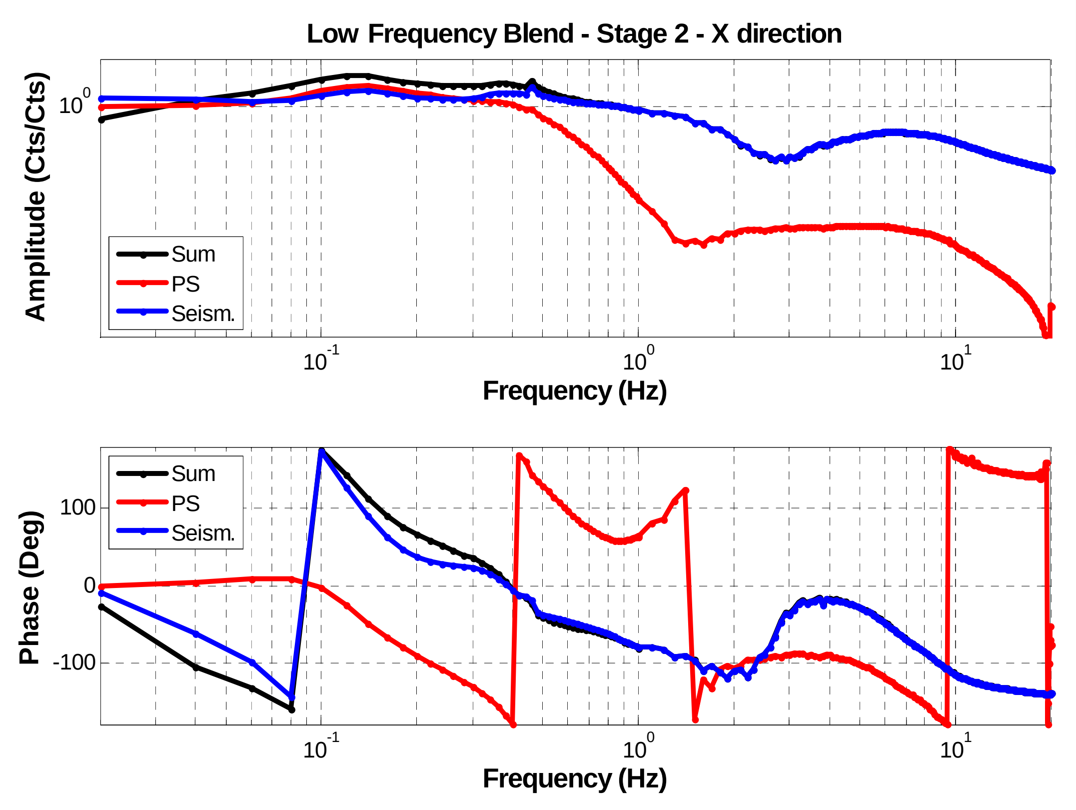
$$\omega_0 = \omega_{tilt} \approx 10\,\mathrm{mHz}$$

Tilt decoupling Matrix

6th Step: Low-Frequency Blend

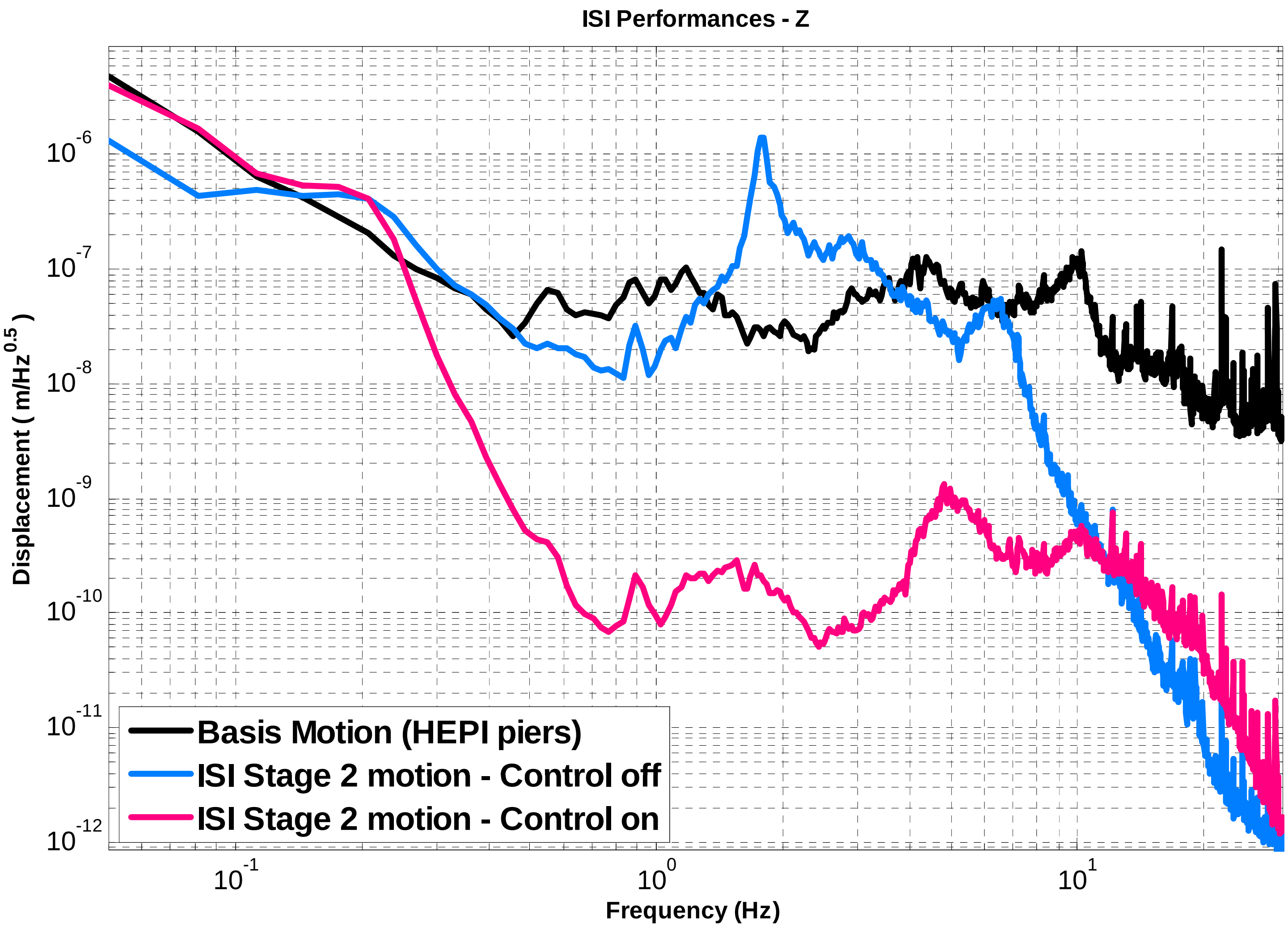




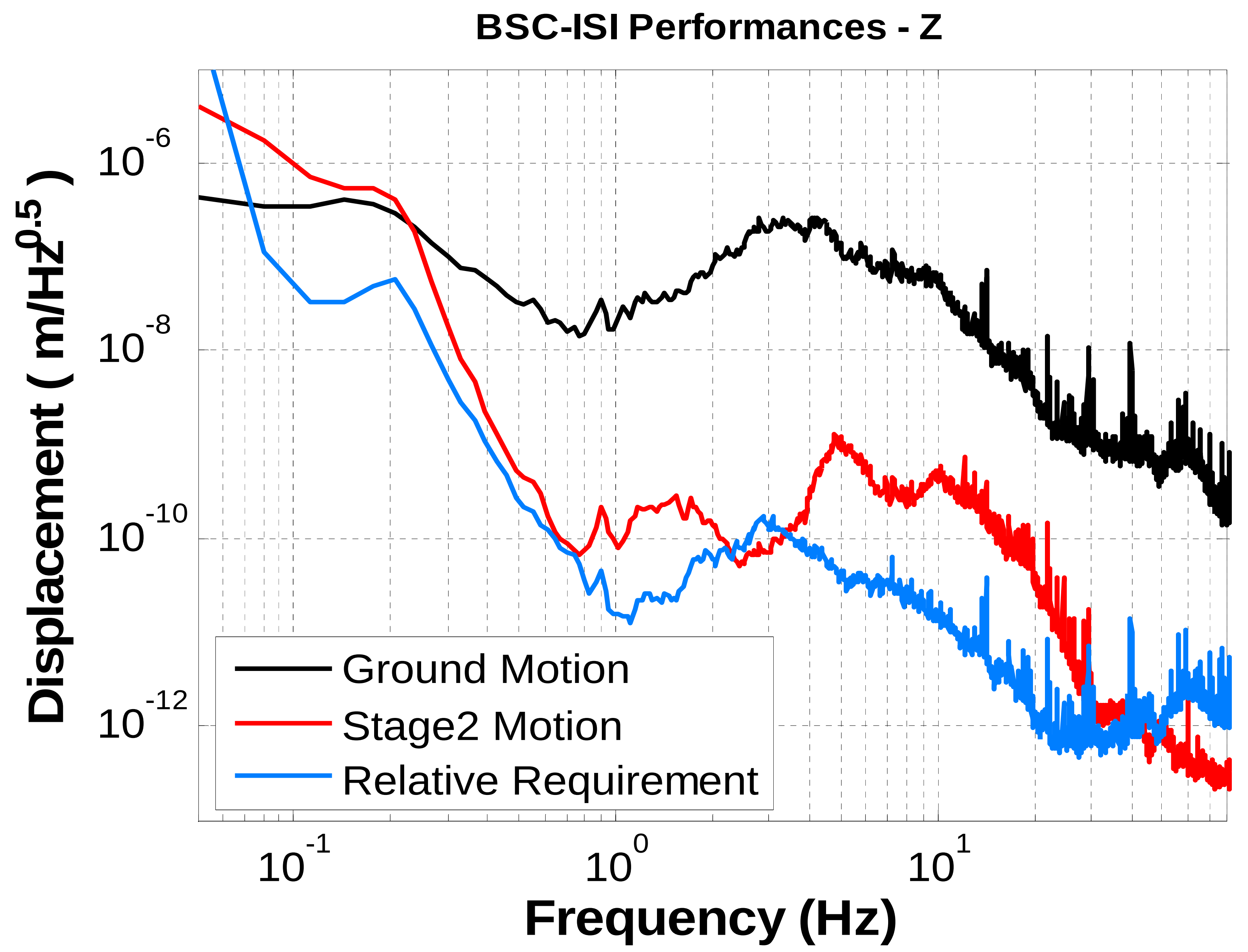


Tests – Part 2

ISI System Performance



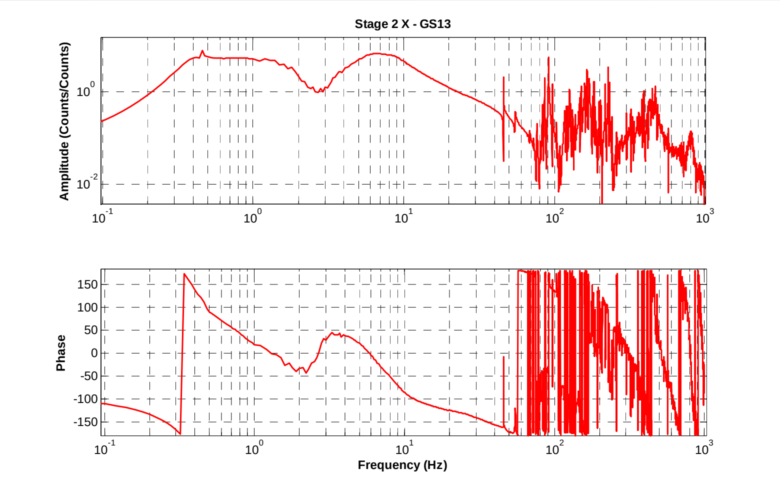
BSC Global Performance



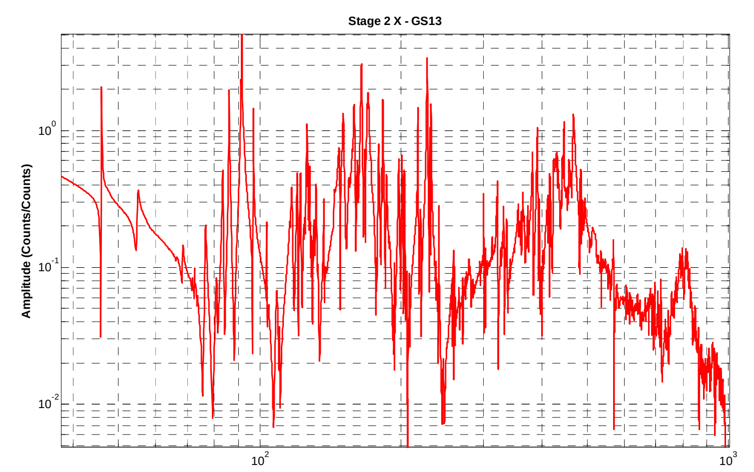
Test - Part 3

Three major problems identified:

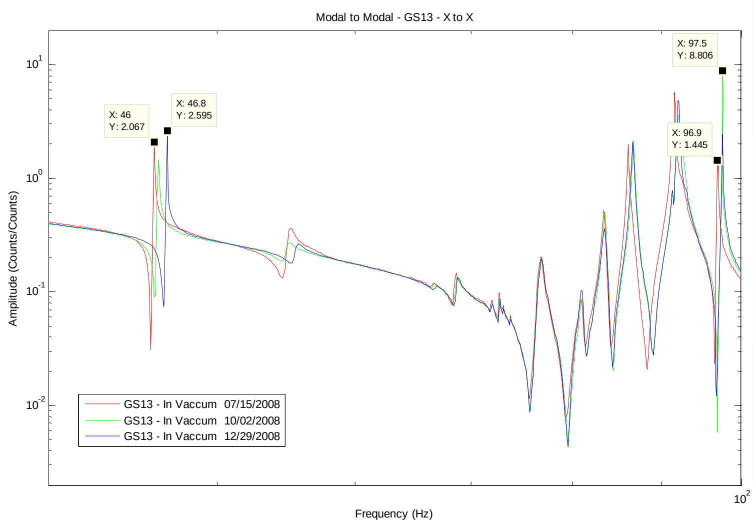
- ✓ **The first deformation resonances were much lower in frequencies than required.**
- ✓ **The modal density at high frequencies was higher than expected.**
- ✓ **The plant was variant in time.**



Low frequency modes

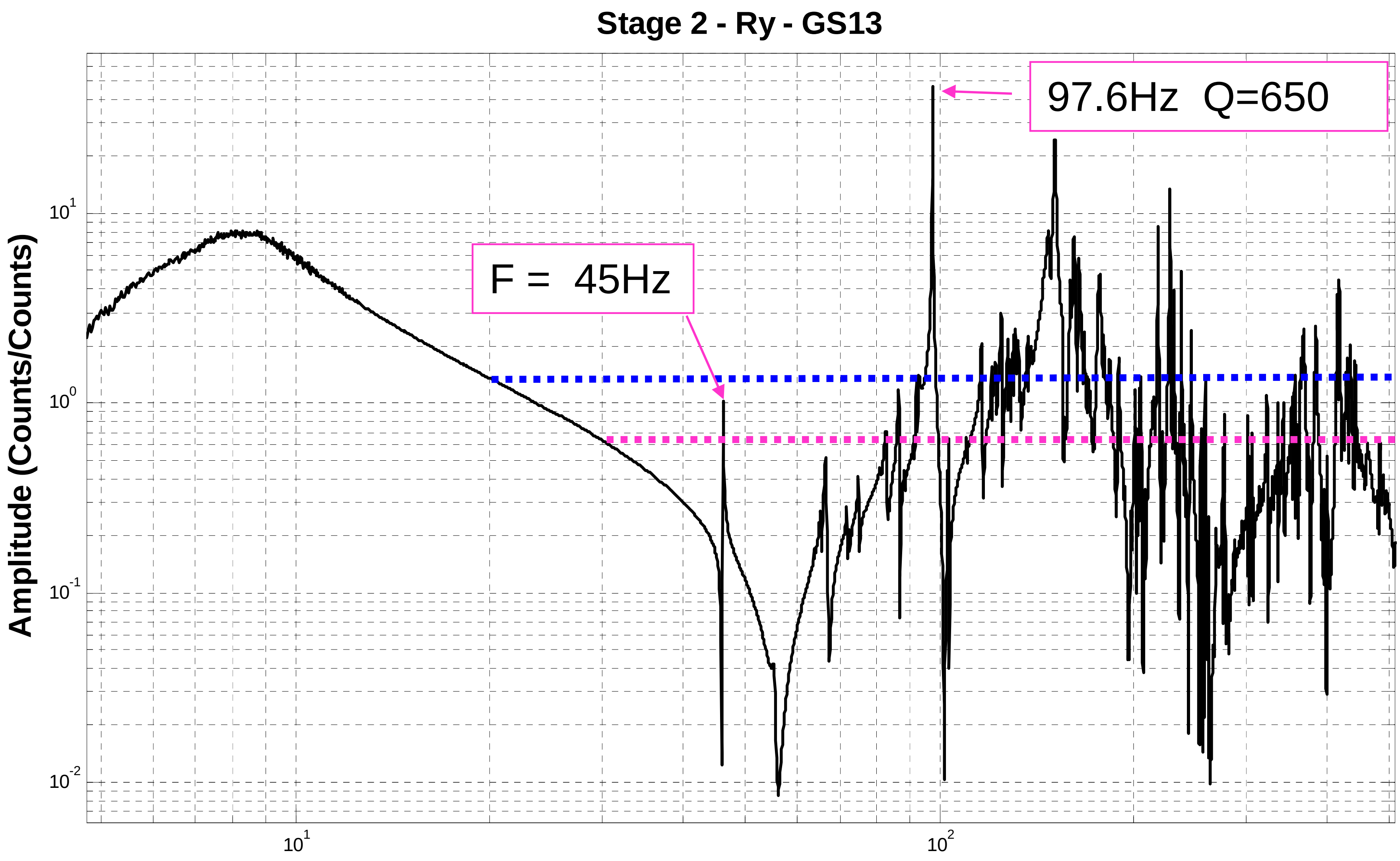


High modal density



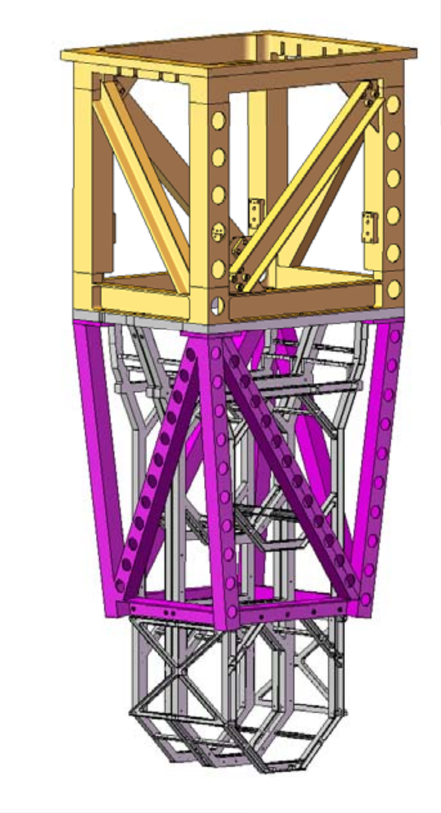
Plant variation

Test - Part 3

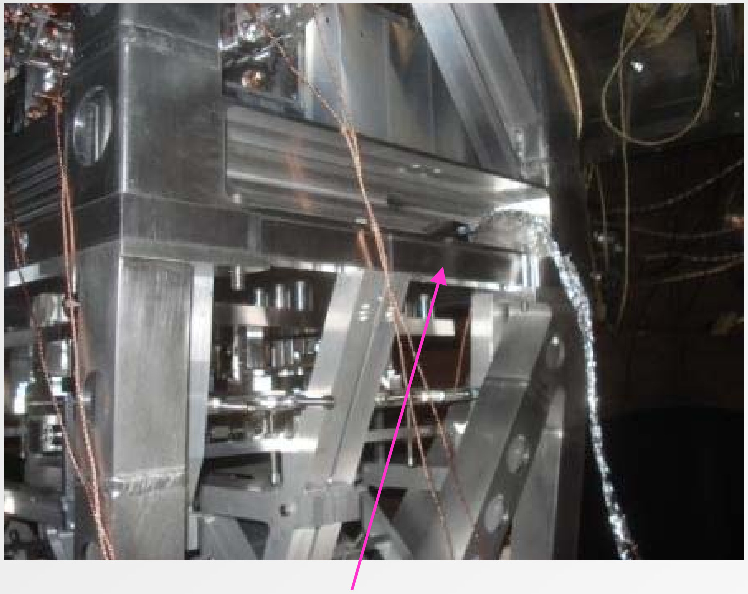


Stage 2 - Ry - GS13
Amplitude (Counts/Counts)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{1}
10^{2}
97.6Hz Q=650
F = 45Hz

Quad Modal Testing



The Quad Structure

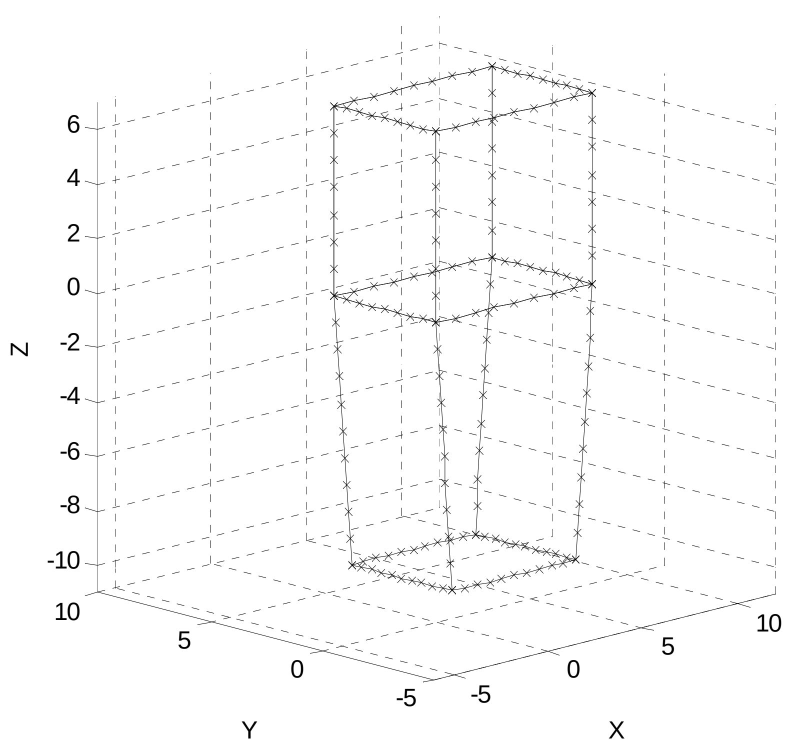


3 Axis Accelerometer

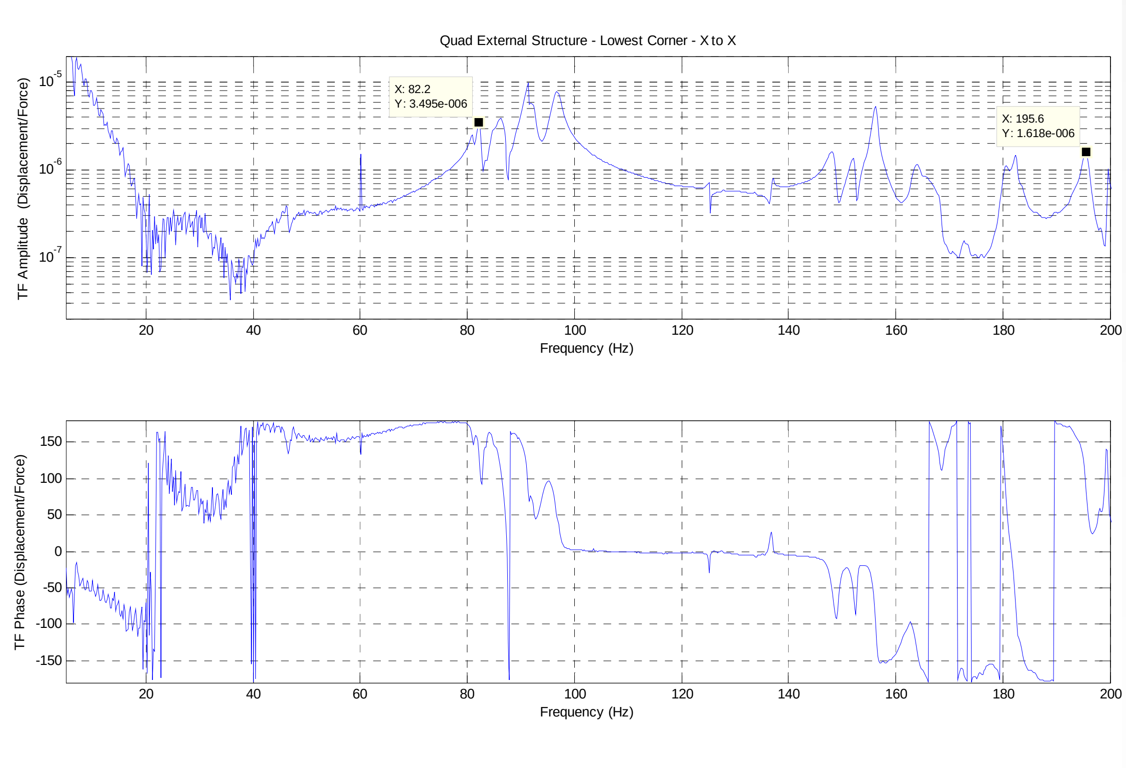
Impact Force Sensor

Test - Part 3

Experimental Meshing

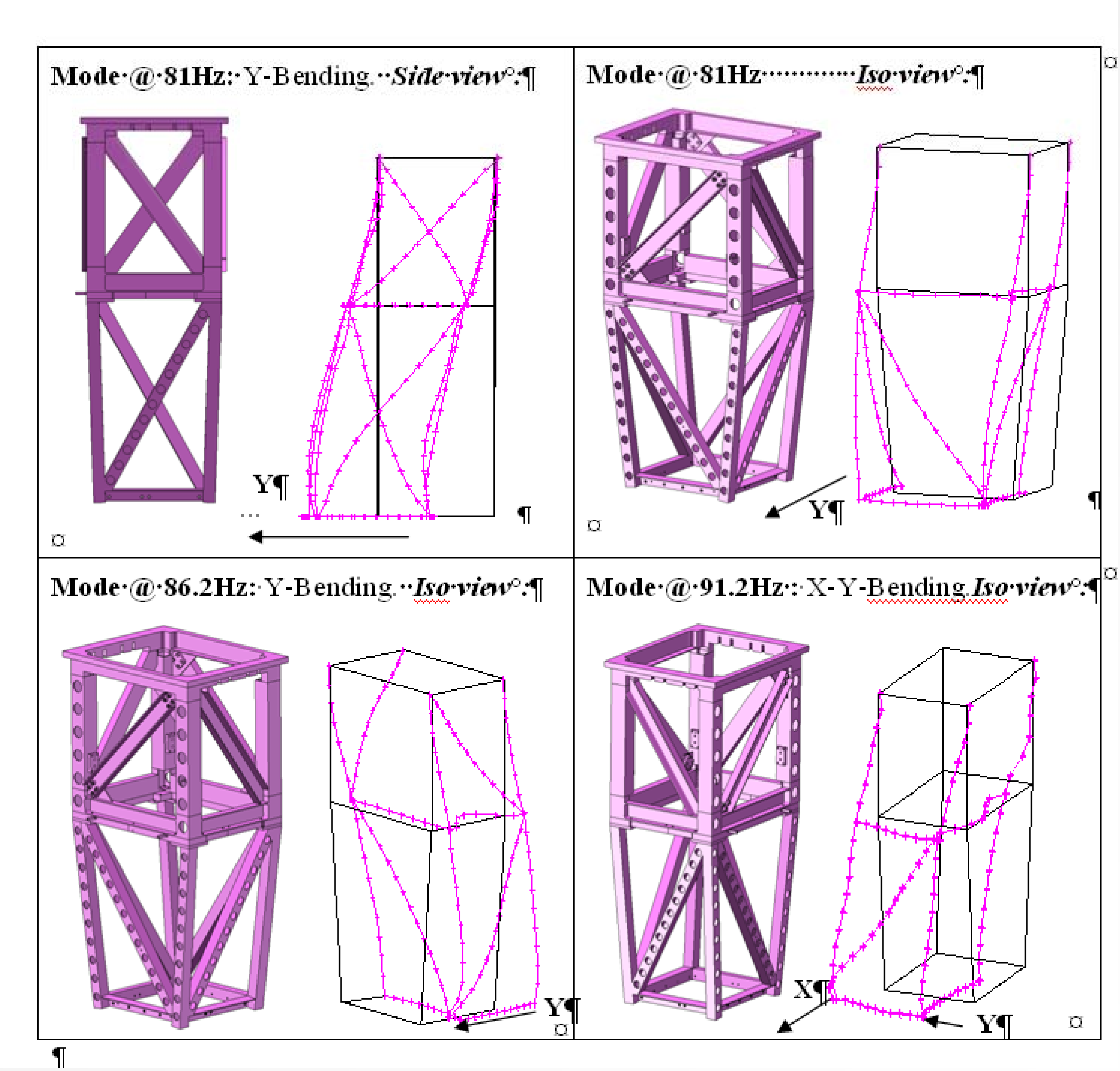


Transfer Functions



Test - Part 3

First modes measured on the Quad structure :



Mode @ 81Hz: Y-Bending. Side view:

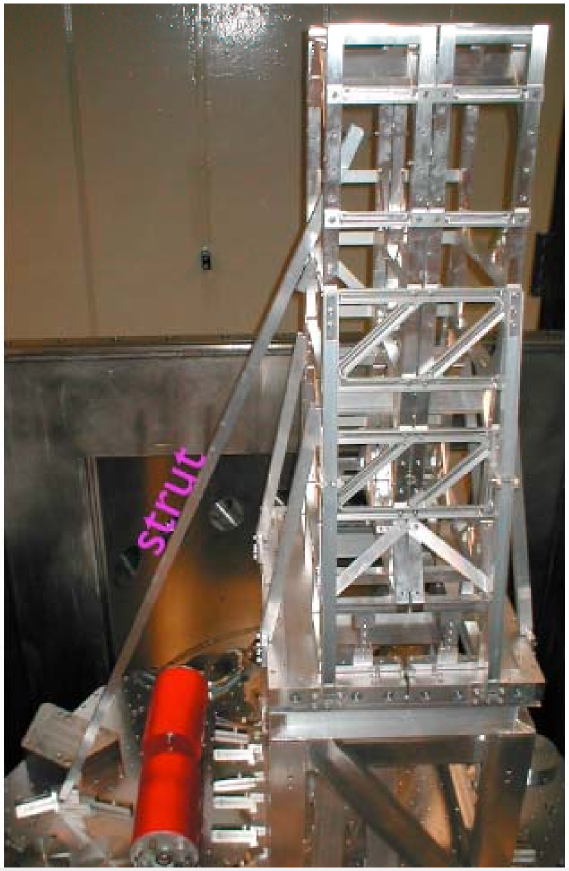
Mode @ 81Hz Iso view:

Mode @ 86.2Hz: Y-Bending. Iso view:

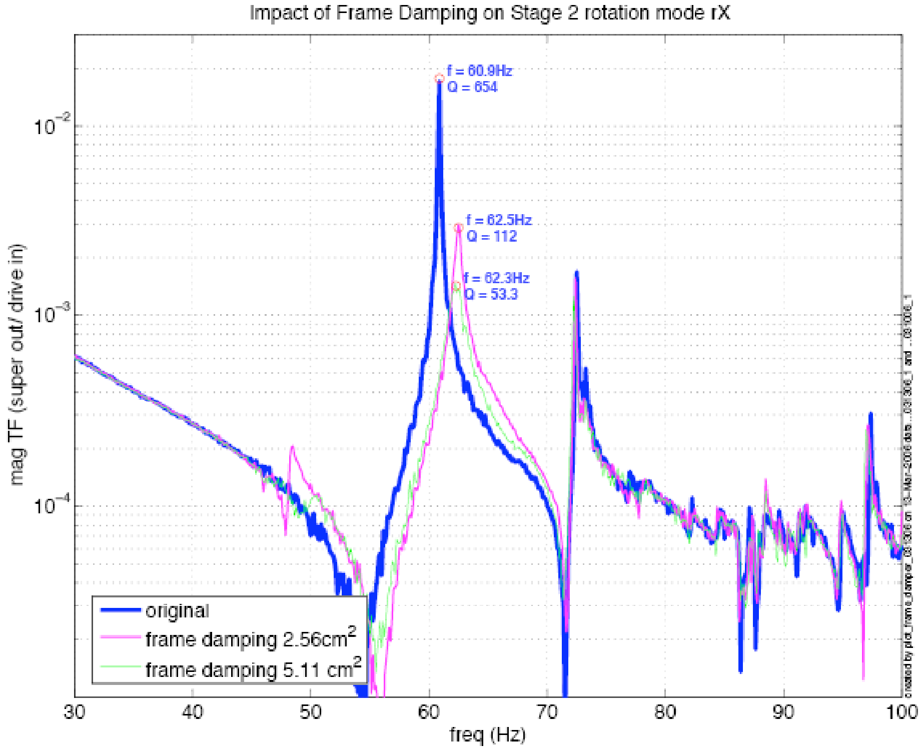
Mode @ 91.2Hz: X-Y-Bending Iso view:

Test - Part 3

Setup



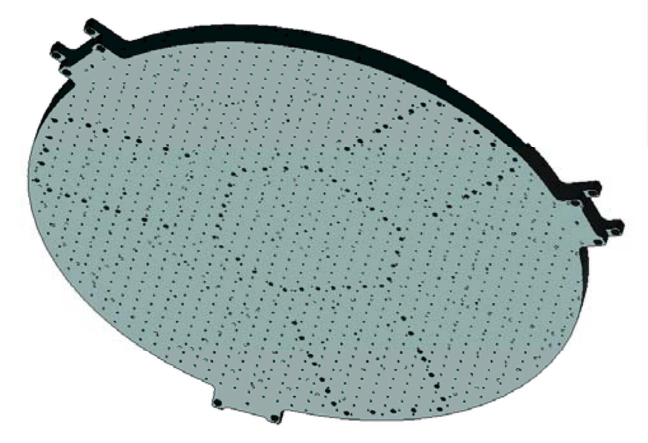
Results



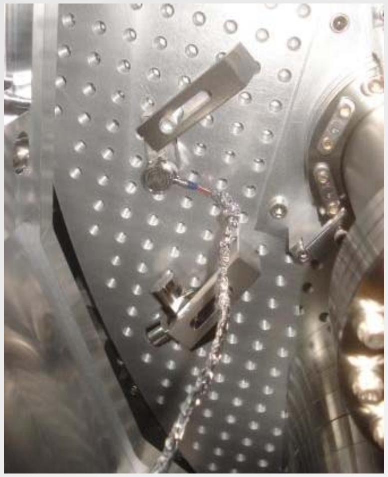
B.Lantz - Tech Demo - Stanford

Test - Part 3

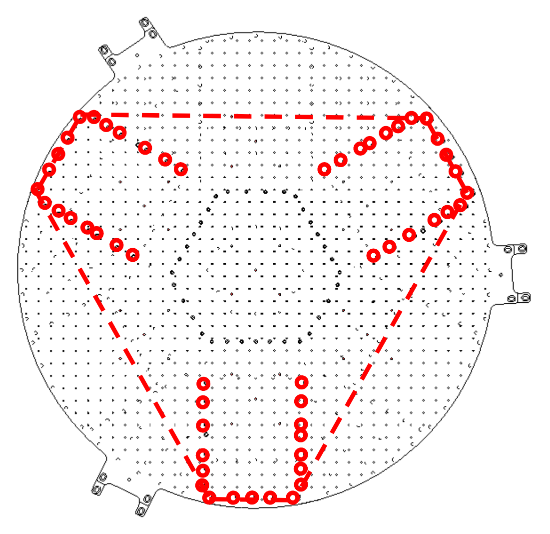
ISI Modal Testing :



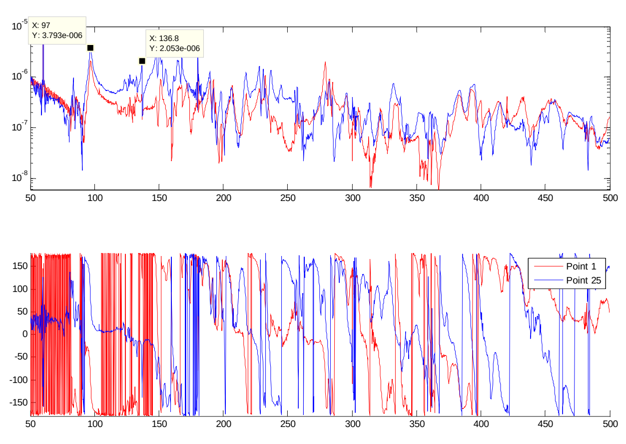
Optical Table



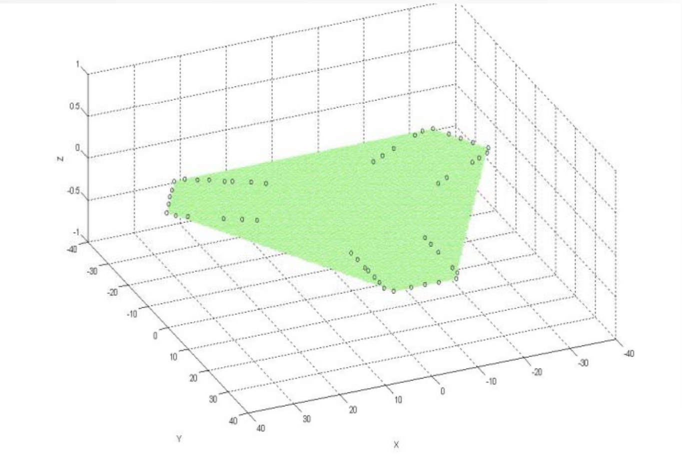
Instrumentation



Experimental Meshing



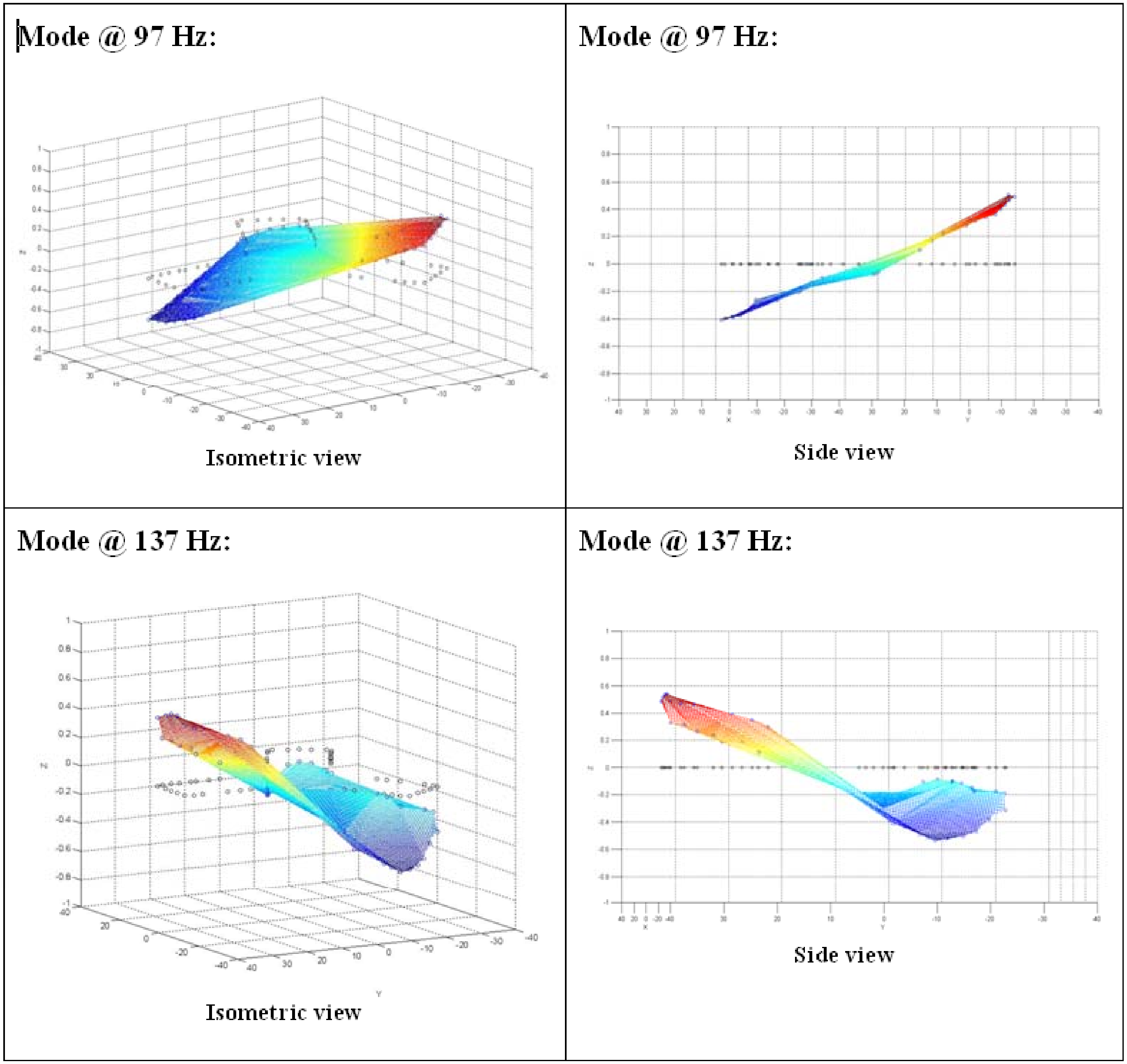
Transfer Functions



Domain of Interpolation

Test - Part 3

First modes measured on the optical table:



Mode @ 97 Hz:

Isometric view

Mode @ 97 Hz:

Side view

Mode @ 137 Hz:

Isometric view

Mode @ 137 Hz:

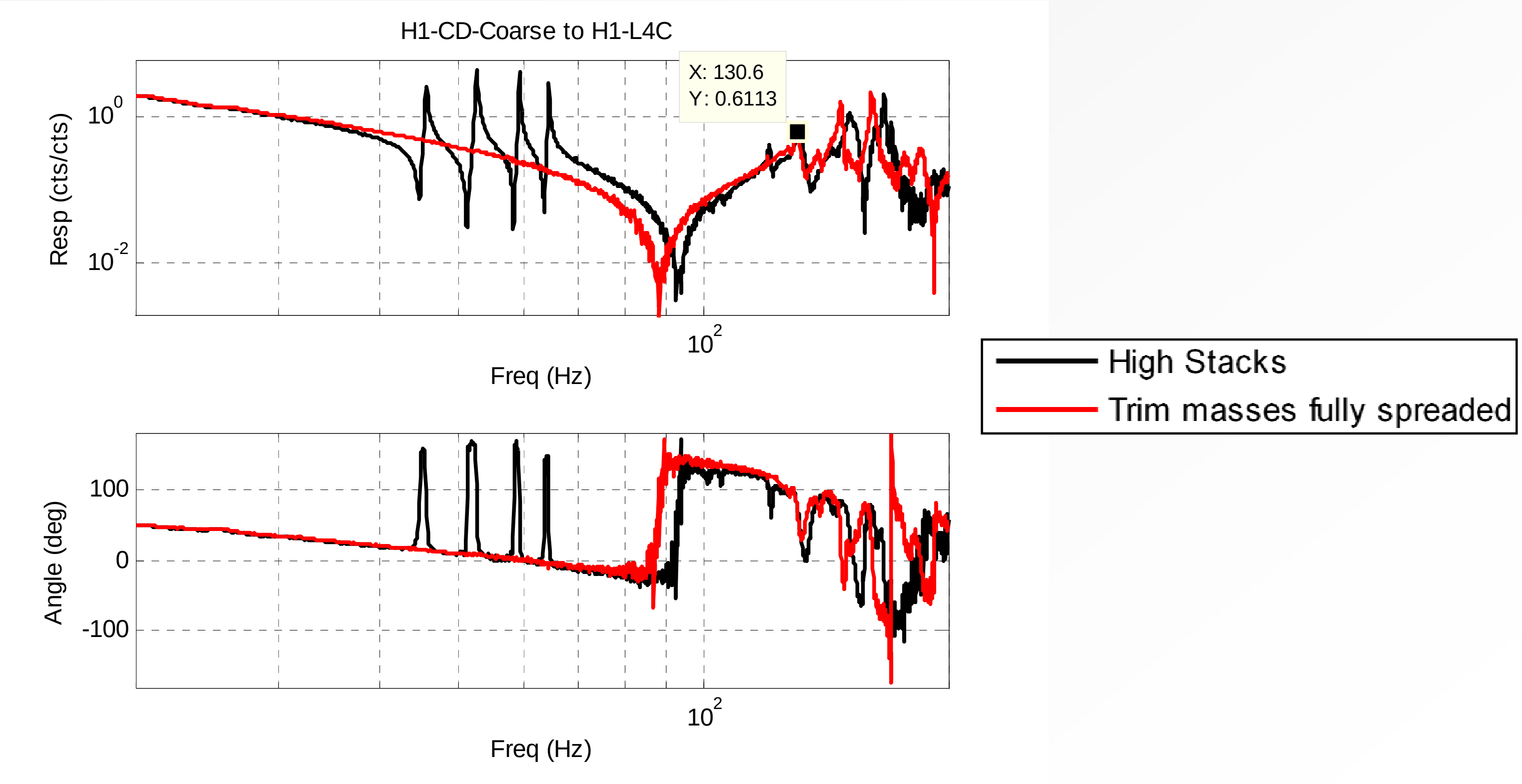
Side view

Test - Part 3

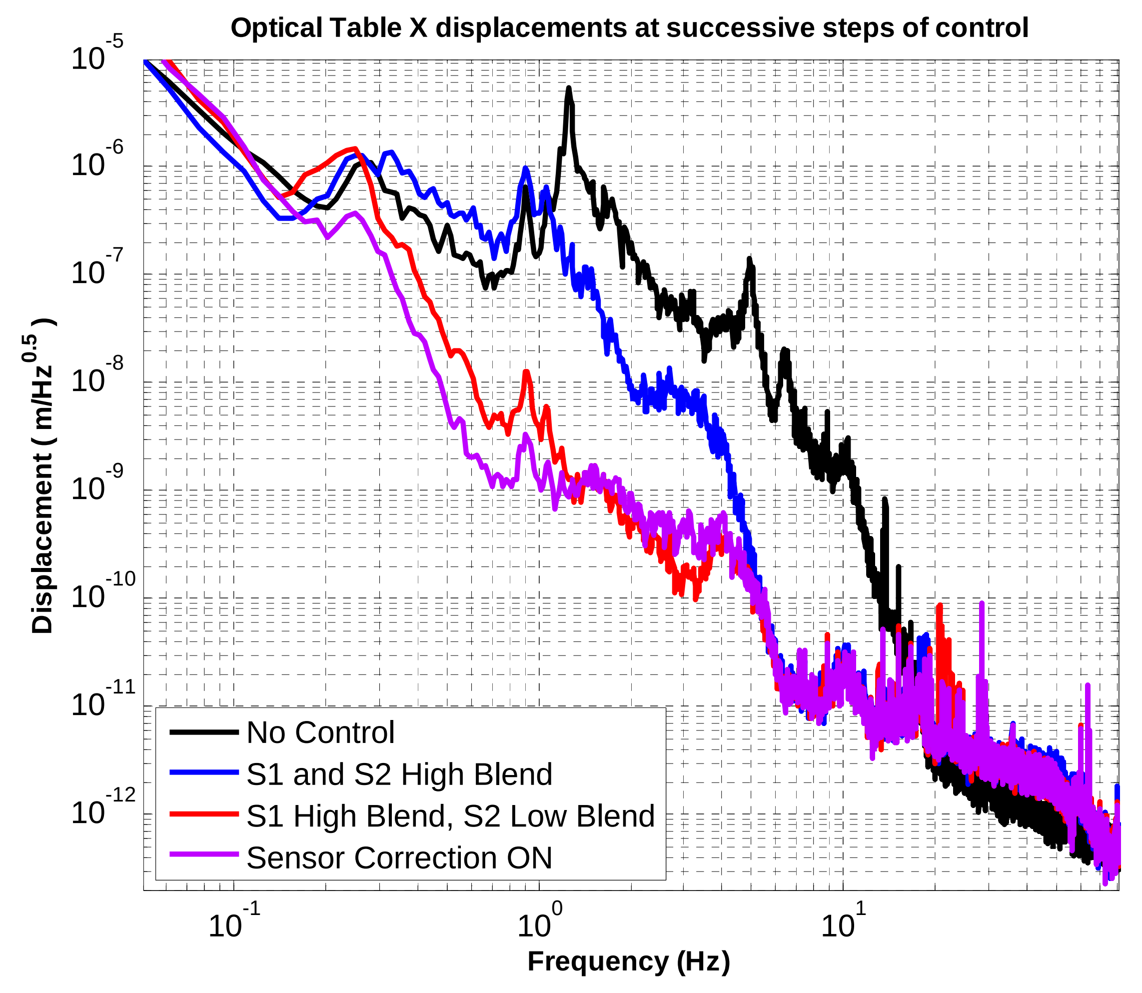
GS13 Attachment

Counter weights

Transfer function



Test - Part 3

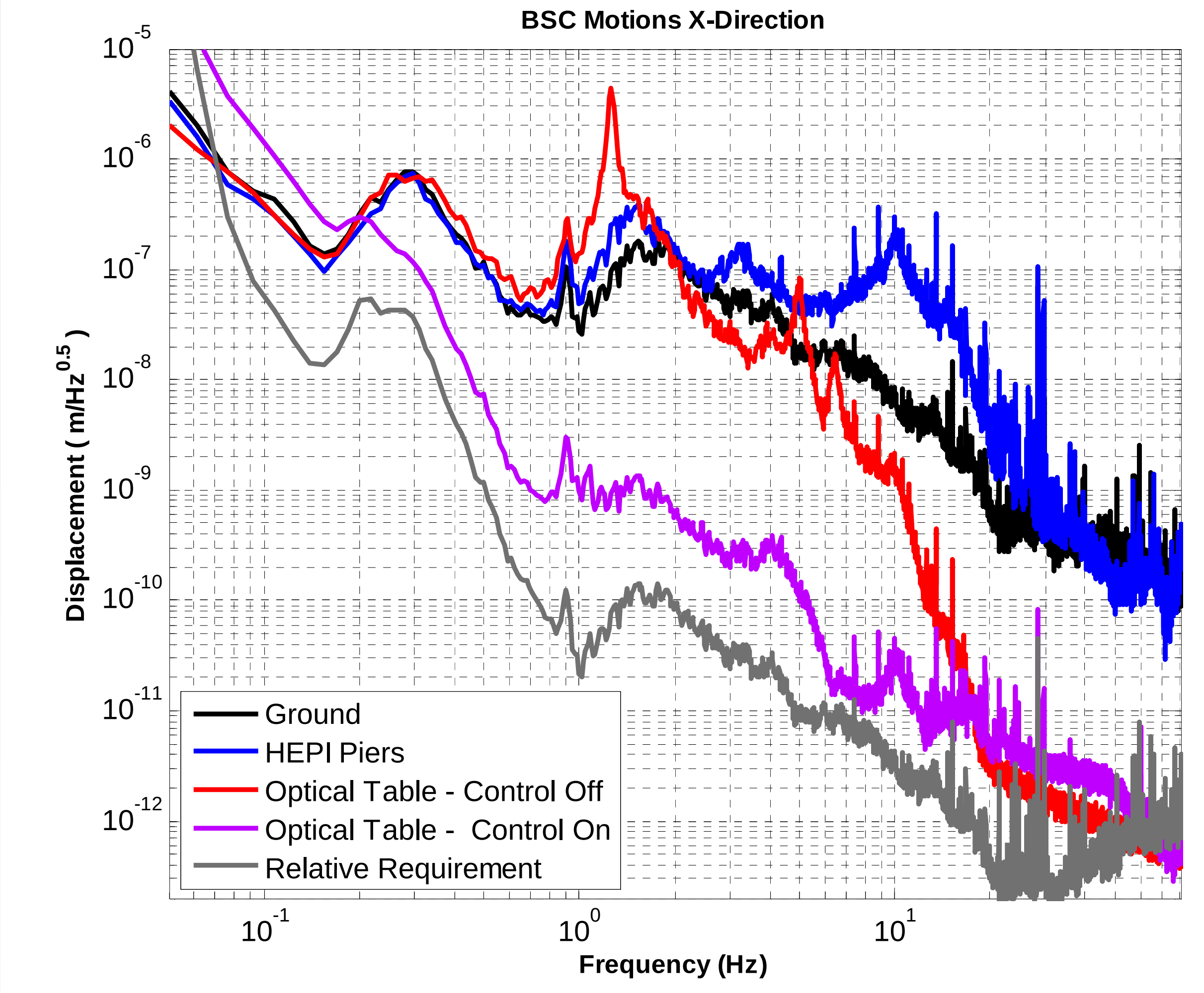


- ✓ **At low frequencies (around 0.1Hz) there is very little motion amplification.**
- ✓ **The isolation starts as low as 0.1Hz which is good.**
- ✓ **The isolation at 1Hz is close to a factor of 100.**
- ✓ **The control provides isolation up to 20Hz, which is good.**

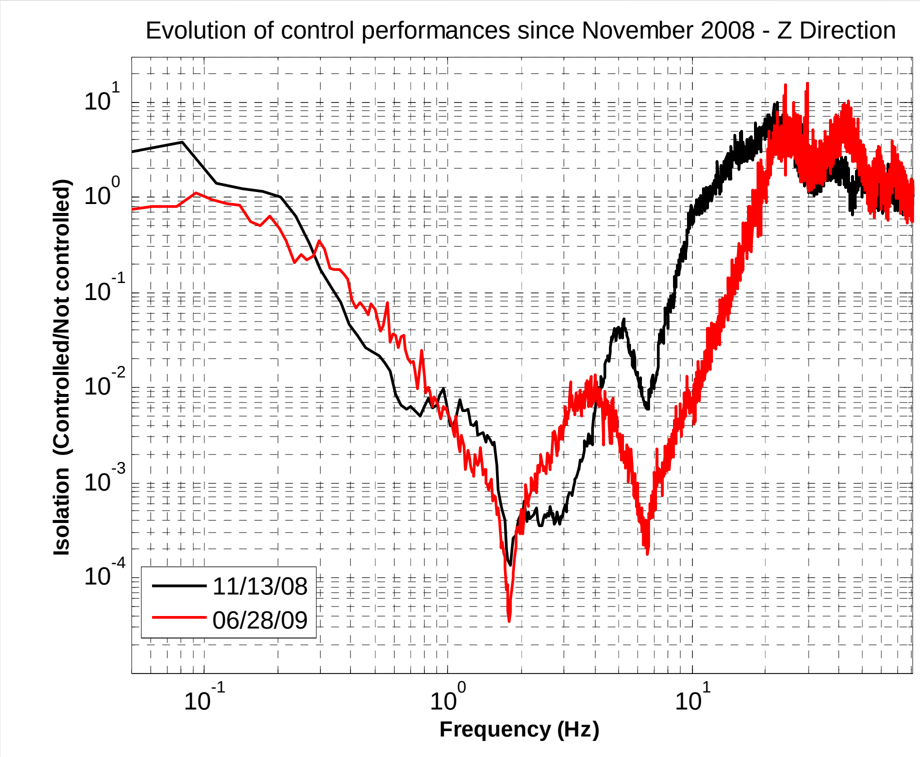
Test - Part 3

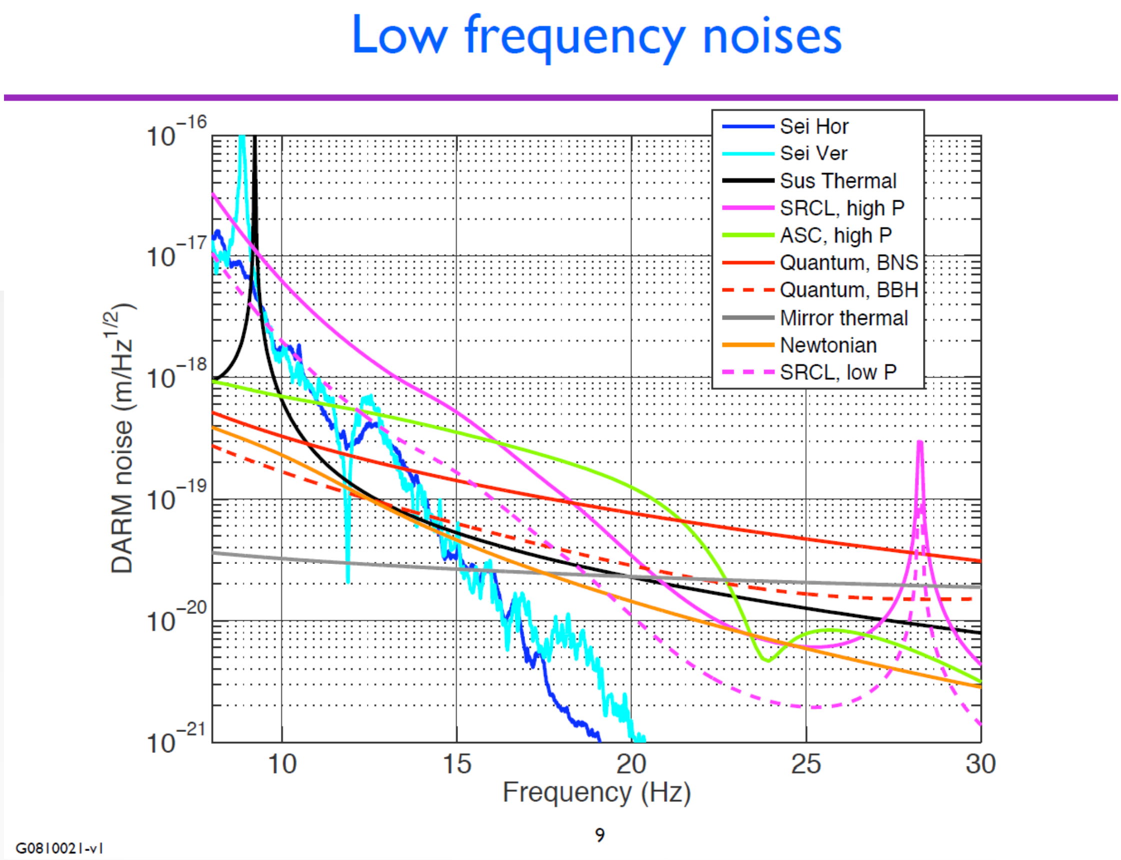
Global isolation (Active & Passive)

- The ground motion is shown in Black. It is measured with a STS.
- The HEPI motion is shown in Blue. It is measured with HEPI L4Cs.
- The motion of stage2 when the control is off is presented in Red
- The motion of stage2 when the control is on is presented in Purple
- The relative requirements are presented in Grey



Test - Part 3





Low frequency noises

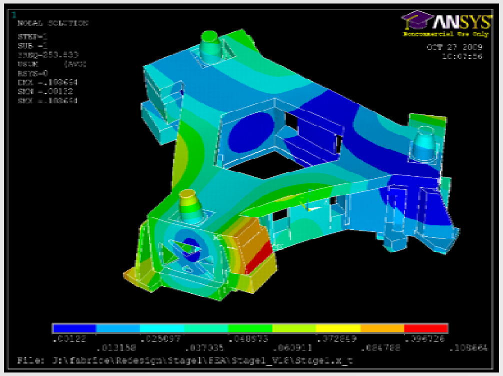
G0810021-v1

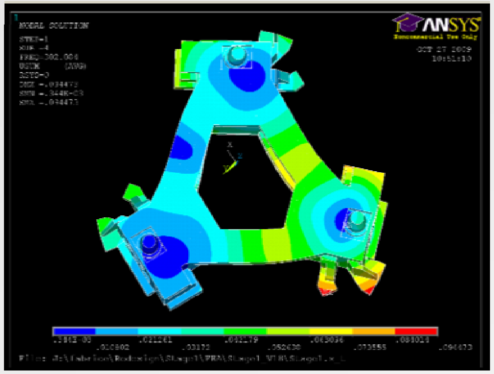
9

Step 4: Development

Stage1

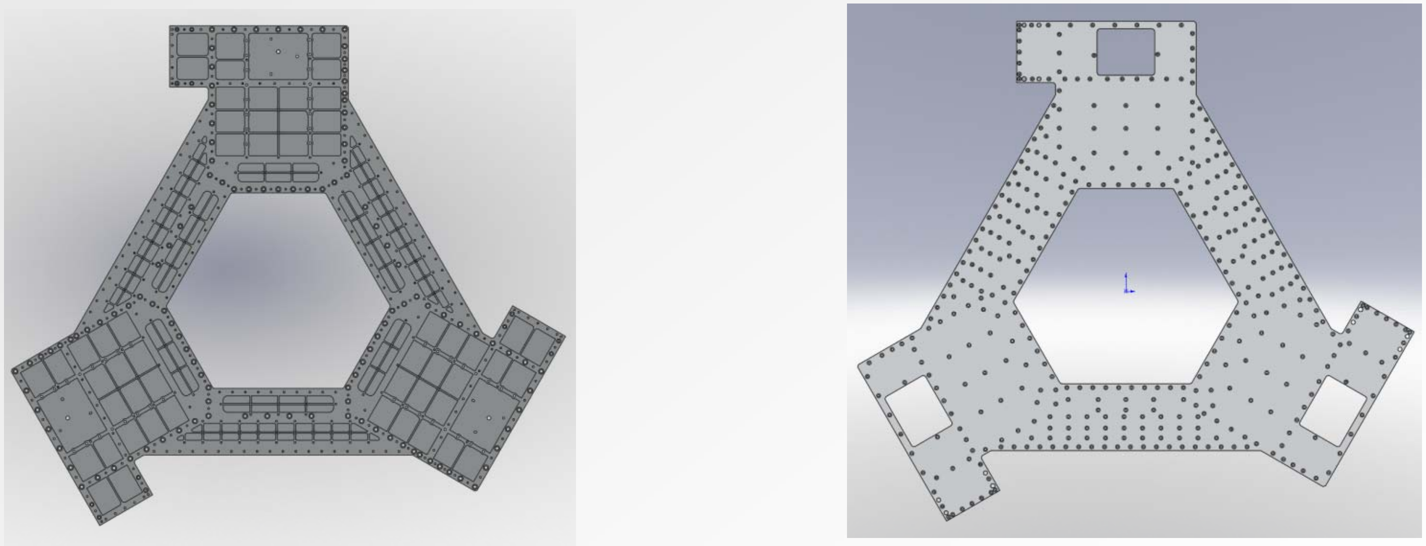
- The close out plate studied and analyzed to optimize the stiffness of Stage1
- Successive conceptual design and Finite Element analysis.
- 18 iterations led to the design presented below.
- All analysis and concepts presented E0900389





	V1, 237 Lbs	V18, 376 Lbs
1	195 Hz	254 Hz
2	195 Hz	254 Hz
3	229 Hz	302 Hz
4	229 Hz	302 Hz
5	287 Hz	326 Hz
6	319 Hz	364 Hz

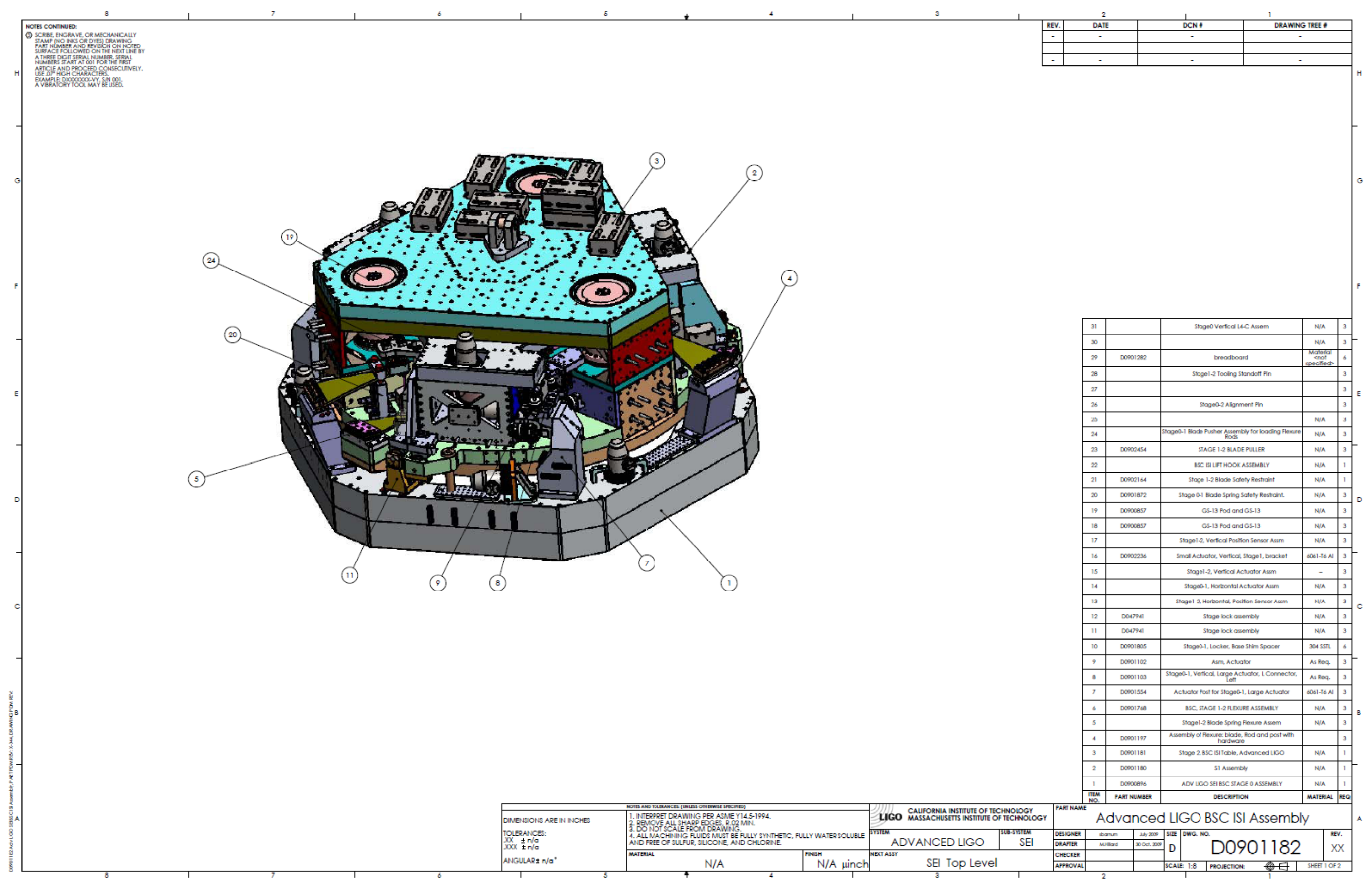
- The first two modes at 195Hz were in plane bending modes. They have moved to 302Hz.
- The next modes at 229Hz were torsion modes. They have moved to 254Hz.



The final design of the close plate and its new plate cover.

Step 5: Production

D0901182, Top Assembly Drawing:



NOTES CONTINUED:

⑤ SCRIBE, ENGRAVE, OR MECHANICALLY STAMP (NO INKS OR DYES) DRAWING PART NUMBER AND REVISION ON NOTED SURFACE FOLLOWED ON THE NEXT LINE BY A THREE DIGIT SERIAL NUMBER. SERIAL NUMBERS START AT 001 FOR THE FIRST ARTICLE AND PROCEED CONSECUTIVELY. USE .07" HIGH CHARACTERS. EXAMPLE: DXXXXXXX-VY, S/N 001. A VIBRATORY TOOL MAY BE USED.

REV.	DATE	DCN #	DRAWING TREE #
-	-	-	-
-	-	-	-

ITEM NO.	PART NUMBER	DESCRIPTION	MATERIAL	REQ
31		Stage0 Vertical L4-C Assem	N/A	3
30			N/A	3
29	D0901282	breadboard	Material <not specified>	6
28		Stage1-2 Tooling Standoff Pin		3
27				3
26		Stage0-2 Alignment Pin		3
25			N/A	3
24		Stage0-1 Blade Pusher Assembly for loading Flexure Rods	N/A	3
23	D0902454	STAGE 1-2 BLADE PULLER	N/A	3
22		BSC ISI LIFT HOOK ASSEMBLY	N/A	1
21	D0902164	Stage 1-2 Blade Safety Restraint	N/A	1
20	D0901872	Stage 0-1 Blade Spring Safety Restraint.	N/A	3
19	D0900857	GS-13 Pod and GS-13	N/A	3
18	D0900857	GS-13 Pod and GS-13	N/A	3
17		Stage1-2, Vertical Position Sensor Assm	N/A	3
16	D0902236	Small Actuator, Vertical, Stage1, bracket	6061-T6 Al	3
15		Stage1-2, Vertical Actuator Assm	–	3
14		Stage0-1, Horizontal Actuator Assm	N/A	3
13		Stage1-2, Horizontal, Position Sensor Assm	N/A	3
12	D047941	Stage lock assembly	N/A	3
11	D047941	Stage lock assembly	N/A	3
10	D0901805	Stage0-1, Locker, Base Shim Spacer	304 SSTL	6
9	D0901102	Asm, Actuator	As Req.	3
8	D0901103	Stage0-1, Vertical, Large Actuator, L Connector, Left	As Req.	3
7	D0901554	Actuator Post for Stage0-1, Large Actuator	6061-T6 Al	3
6	D0901768	BSC, STAGE 1-2 FLEXURE ASSEMBLY	N/A	3
5		Stage1-2 Blade Spring Flexure Assem	N/A	3
4	D0901197	Assembly of Flexure: blade, Rod and post with hardware		3
3	D0901181	Stage 2 BSC ISI Table, Advanced LIGO	N/A	1
2	D0901180	S1 Assembly	N/A	1
1	D0900896	ADV LIGO SEI BSC STAGE 0 ASSEMBLY	N/A	1

DIMENSIONS ARE IN INCHES

TOLERANCES:
.XX ± n/a
.XXX ± n/a
ANGULAR± n/a°

NOTES AND TOLERANCES: (UNLESS OTHERWISE SPECIFIED)
1. INTERPRET DRAWING PER ASME Y14.5-1994.
2. REMOVE ALL SHARP EDGES, R.02 MIN.
3. DO NOT SCALE FROM DRAWING.
4. ALL MACHINING FLUIDS MUST BE FULLY SYNTHETIC, FULLY WATERSOLUBLE AND FREE OF SULFUR, SILICONE, AND CHLORINE.

MATERIAL: N/A
FINISH: N/A µinch

LIGO CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

SYSTEM: ADVANCED LIGO
SUB-SYSTEM: SEI
NEXT ASSY: SEI Top Level

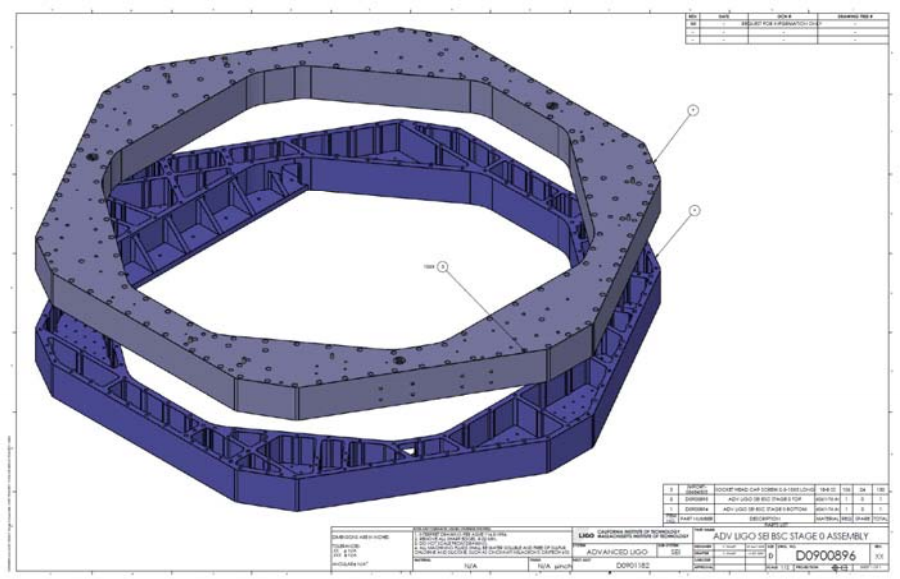
PART NAME: Advanced LIGO BSC ISI Assembly

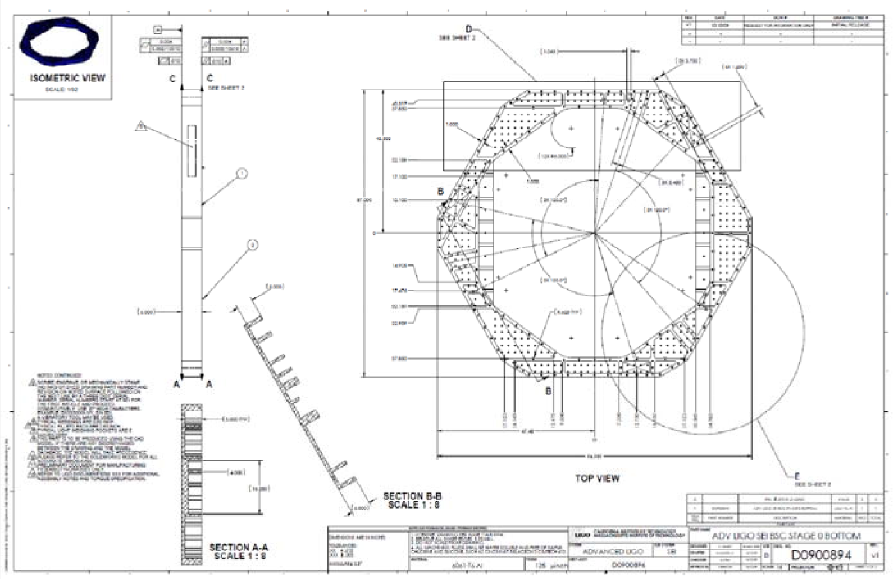
DESIGNER	sbarnum	July 2009	
DRAFTER	M.Hillard	30 Oct. 2009	
CHECKER			
APPROVAL			

SIZE: D
DWG. NO.: D0901182
REV.: XX
SCALE: 1:8
PROJECTION:
SHEET 1 OF 2

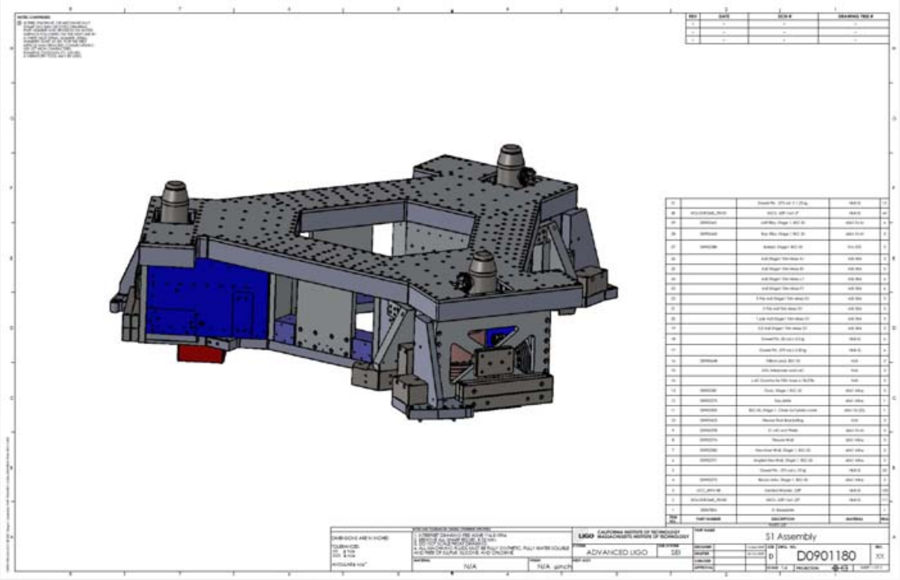
5. Drawings

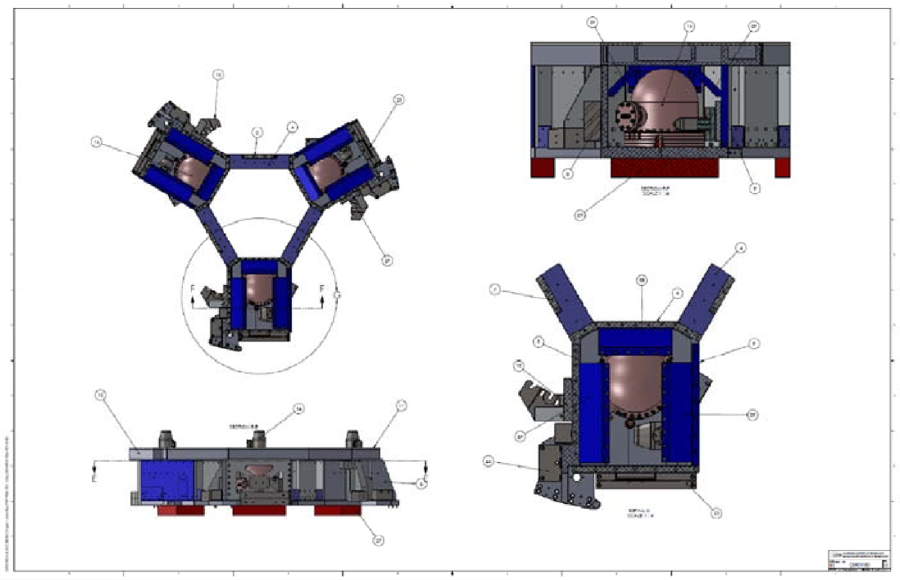
D09000896, Stage 0 Assembly and D09000895, Stage 0 Bottom part





D0901180, Stage 1 Assembly

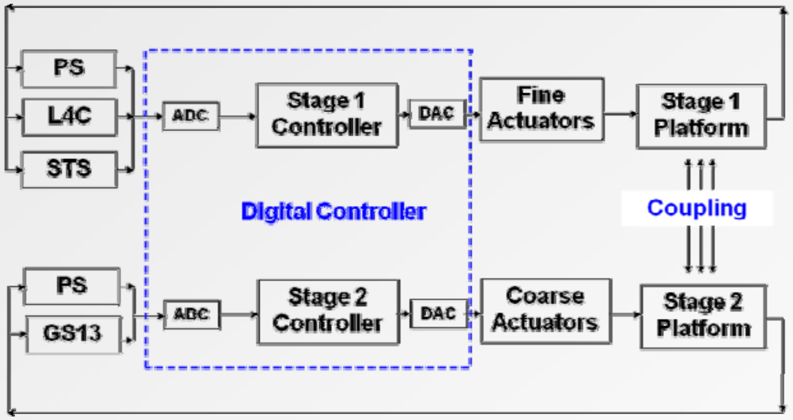


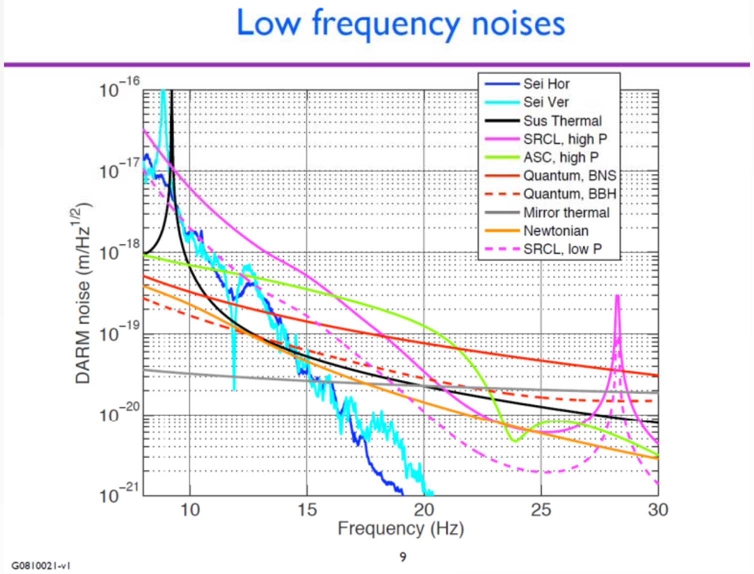


7- Assemblage

8- Installation

9- Mise en service





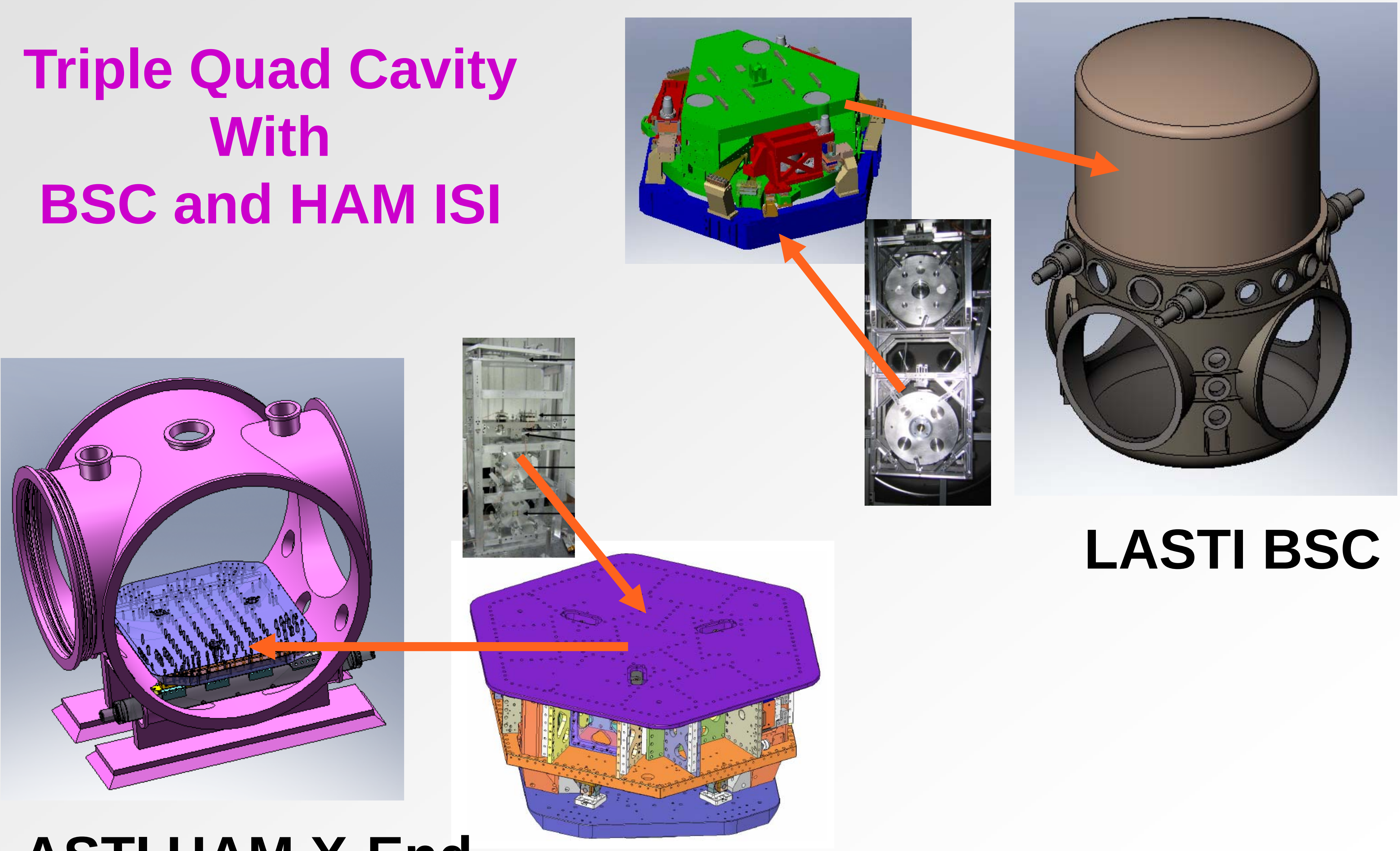
Low frequency noises

G0810021-v1

9

Coming up at MIT

Triple Quad Cavity
With
BSC and HAM ISI



LASTI BSC

LASTI HAM X-End