Conceptual Design Review:
Initial LIGO Seismic Isolation System Upgrade

Introduction

Dennis Coyne

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Problem

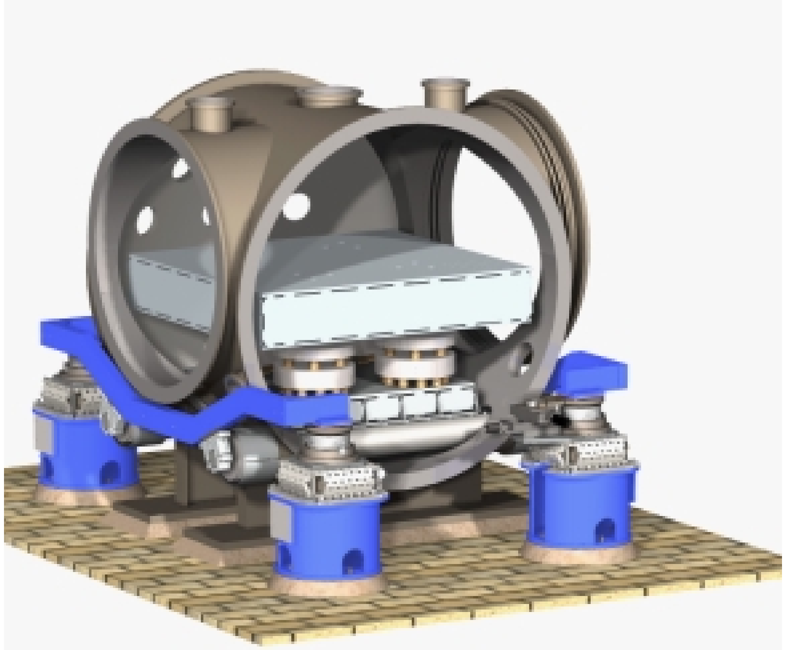
- Ground motion at LLO with the initial LIGO seismic isolation system makes it impossible to hold the interferometers locked reliably during the day
  - » Steady-state ambient noise is higher due to anthropogenic sources
  - » Transients, particularly from logging
- Wind induced seismic noise at LHO:
  - » exceeds locking threshold at ~25 mph, or 10% of the time
  - » Expect that up-conversion is a problem at significantly lower wind speeds & a large fraction of the time
- Upgrade is required to allow both reliable locking and to allow better noise performance while locked
  - » Need 90% duty cycle & lock durations > 40 hours
  - » Need to reduce noise in the control band (< 40 Hz) to permit a smaller suspension actuator authority & lower noise
  - » Suppression in the 1-3 Hz band is most important due to excitation of the lower stack modes (Q ~ 30)

Scope

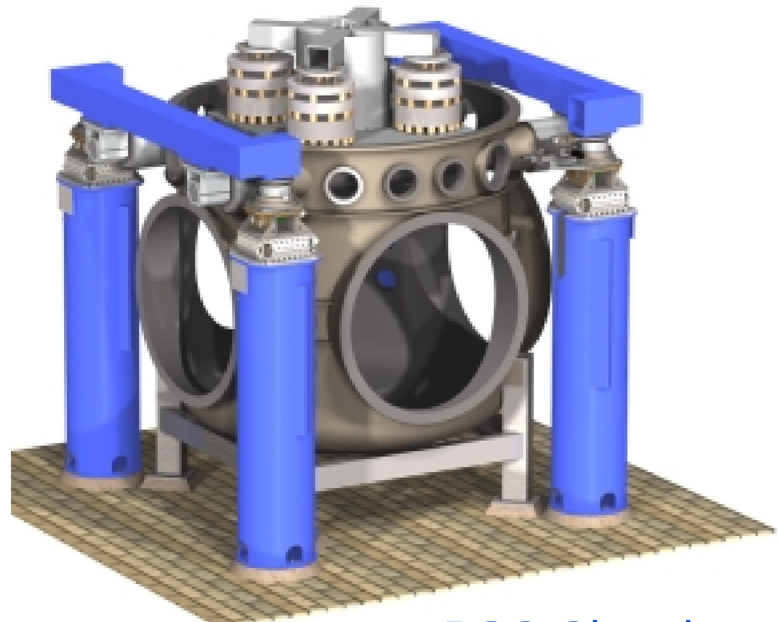
- Includes interim solution with Fine Actuation Systems on TM chambers at LLO (known as PEPI)
- Conceptual design for a retrofit to the installed seismic isolation systems
  - » BSC & HAM chambers
  - » Focused on solution for the LLO environment
- Decision on number/scope of retrofitted systems at LLO is dependent on further study
  - » baseline assumption is implementation of full solution on all chambers with suspended optics
- Decision on the number/scope of retrofitted systems at LHO is dependent on further study
  - » Could adopt same solution for LHO
  - » Baseline assumption is the addition of Fine Actuation Systems (FAS) & the PEPI system to TM and MC chambers

Initial Vibration Isolation Systems

- Reduce in-band seismic motion by 4 - 6 orders of magnitude
- Little or no attenuation below 10Hz; amplification at stack mode resonances
- Large range actuation for initial alignment and drift compensation
- Quiet actuation to correct for Earth tides and microseism at 0.15 Hz during observation

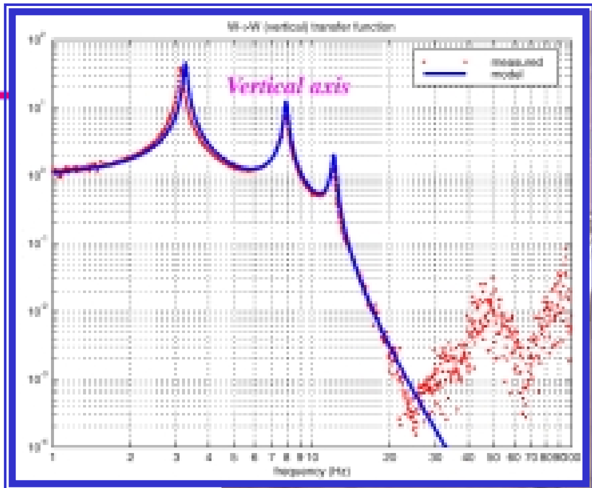


HAM Chamber

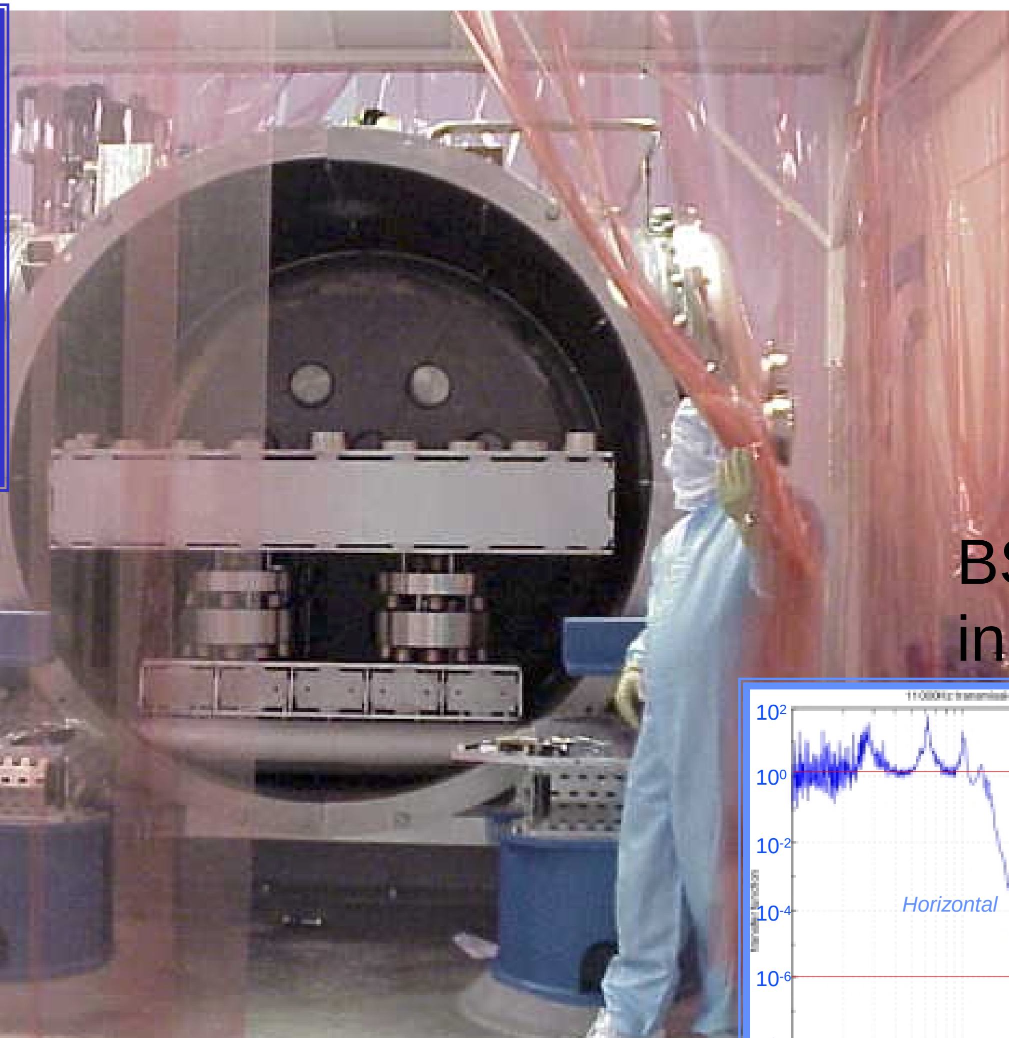


BSC Chamber

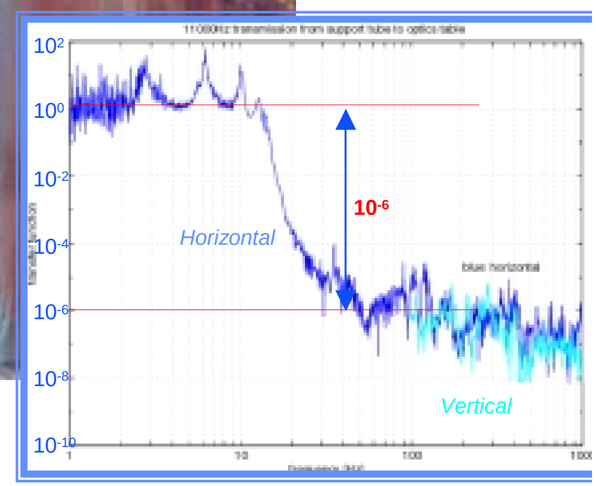
Seismic System Performance



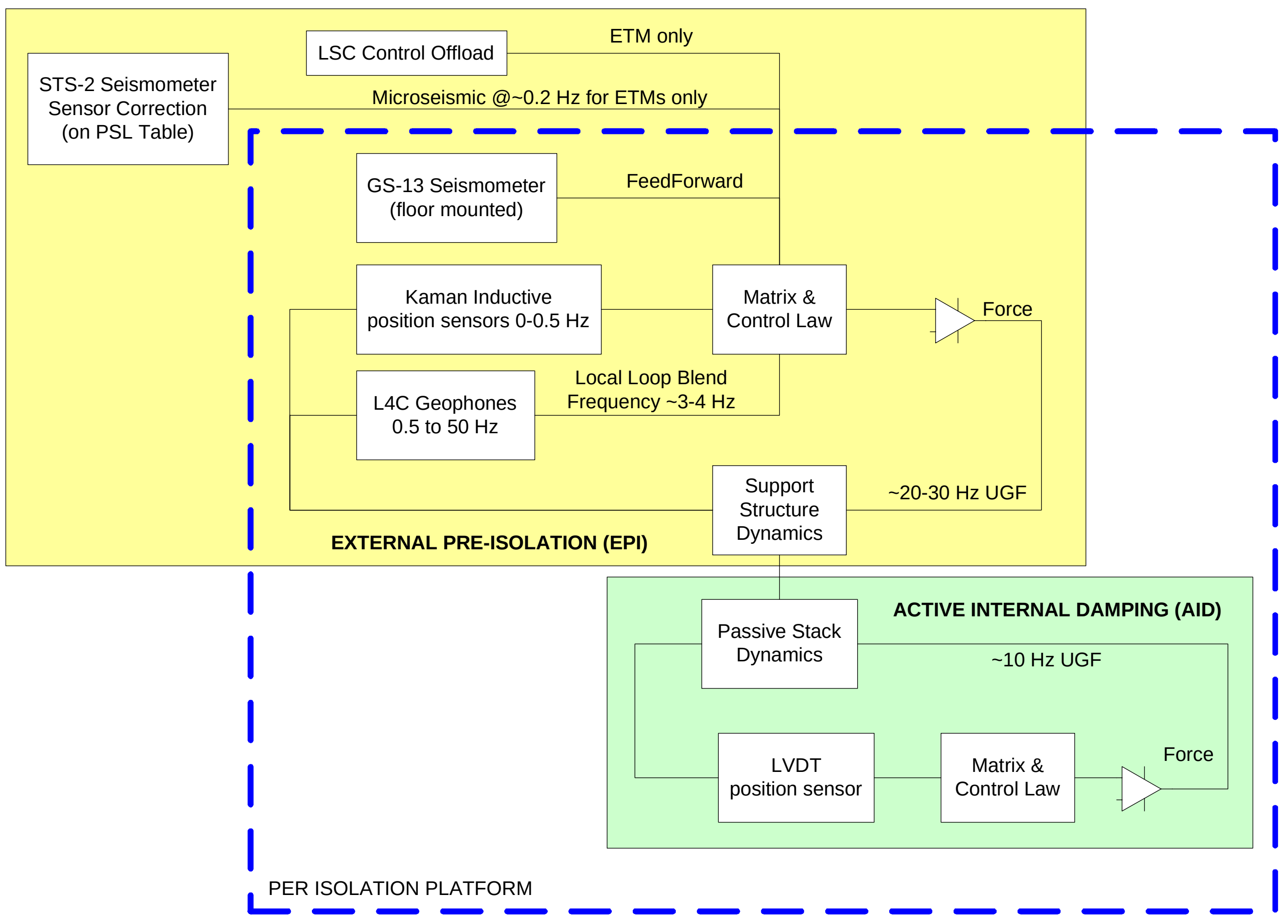
HAM stack
in air



BSC stack
in vacuum



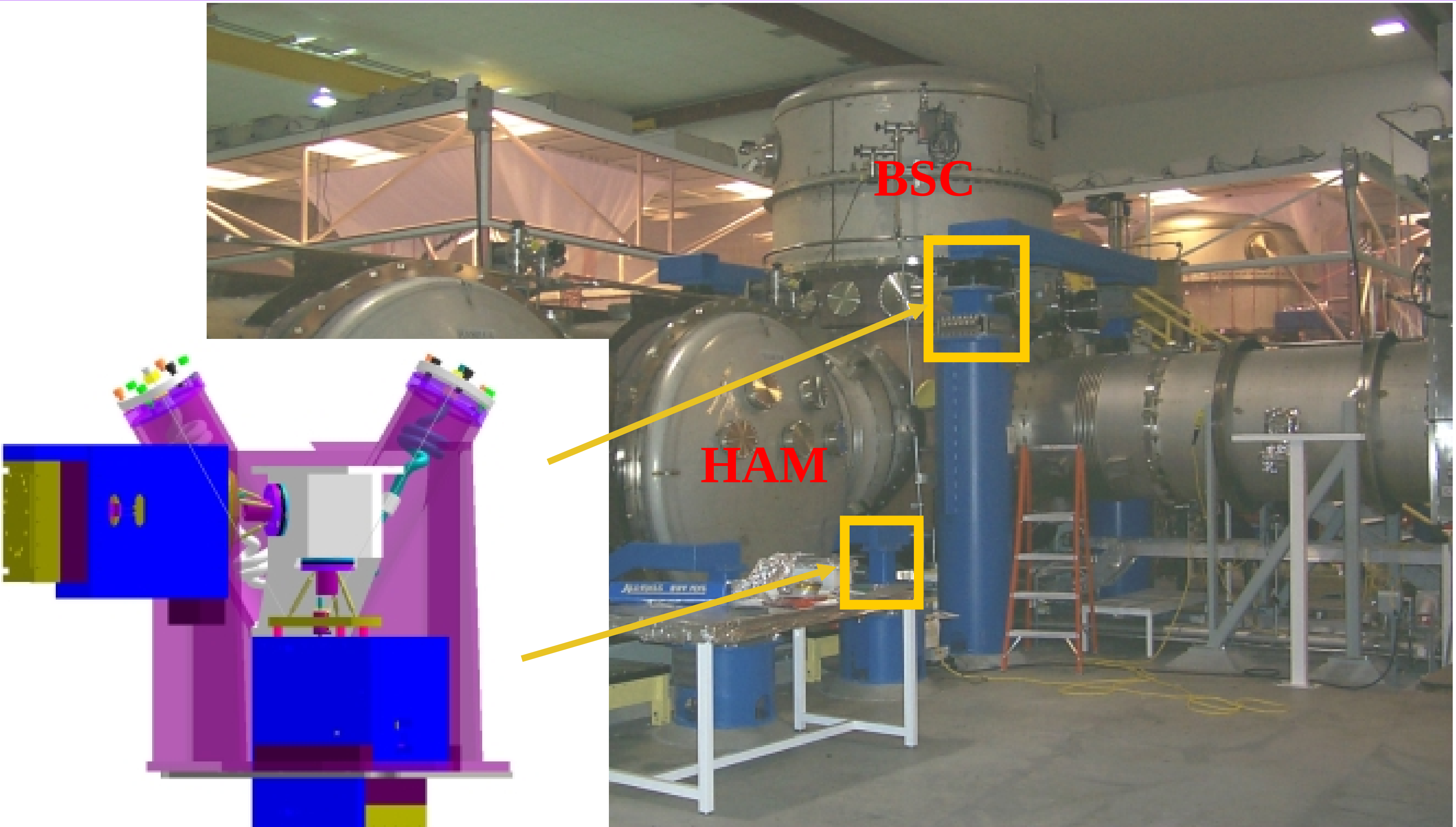
Active External Pre-Isolation (EPI) & Active Internal Damping (AID)



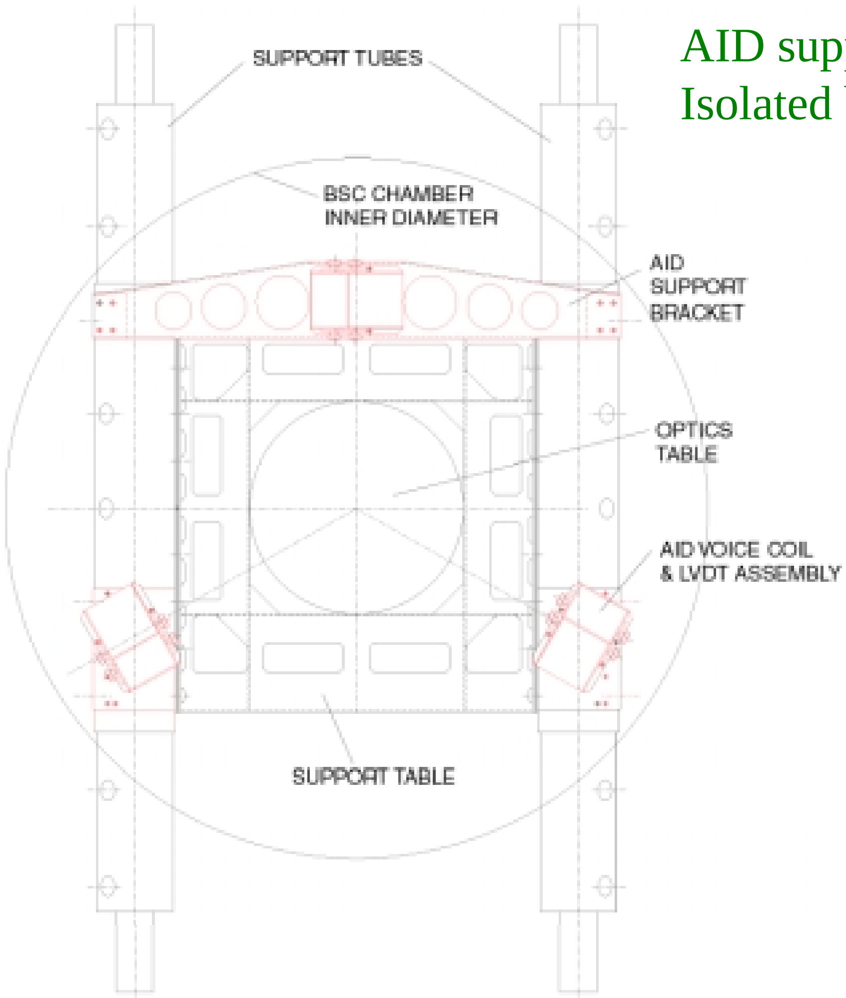
Alternate Approaches

Approach	Description/comments	Options	Isolation	Stack Damping
External pre-isolation (EPI)	6 DOF isolation with co-located sensing & actuation at the base of the passive stack; feedback & feedforward control to be explored including use of OSEM sensing	Hydraulic actuator (HEPI)	Y	?
		EM actuator (MEPI)	Y	?
Active Internal Damping (AID)	Co-located sensing and actuation on the internal optics table (e.g. LVDT and voice coil) to sense & damp from support structure to optics table. The addition of inertial sensing on the optics table may permit isolation.	Voice Coil or EM linear motor LVDT or geophone	?	Y
Existing fine actuators (PEPI)	Longitudinal & yaw velocity feedback with co-located geophones. Being pursued as an interim measure.		Y	N
COTS isolation systems	Piezo isolation systems like Stacis; minus-k compact low frequency spring, etc. which can perform the external pre-isolation task.	Various	Y	unlikely
SAS-like Implementation	A hybrid passive/active “soft” alternative approach to the stiff external pre-isolation approach.		Y	N
Tuned Mass Dampers	With existing payload mass limits the optimum reduction in stack mode resonance is ~4. This does not meet requirements and requires in-vacuum hardware	Viscous fluid, eletro-restrictive or eddy current	N	Y
Multiple pendulum or longer period suspensions	Too invasive, too large a schedule & cost impact; not clearly a solution either		Y	N
Cooled suspension coil drive electronics with larger dynamic range	Does not preclude increased noise due to bi-linear coupling mechanisms & large amplitude of real motion; might be a last ditch effort after other measures are taken		Y	N
Short across 1 layer of the HAM Stack	Compromise the better-than-needed high freq. HAM isolation performance; shift stack modes; not clear this works; seems wrong to compromise performance		N	Y
Replace some or all springs with lower Q springs	Too invasive & marginal improvement in Q without complete replacement		N	Y
Add eddy current damping between stages	Too invasive & marginal improvement in Q without the addition of many components			

Planned Initial Detector Modifications

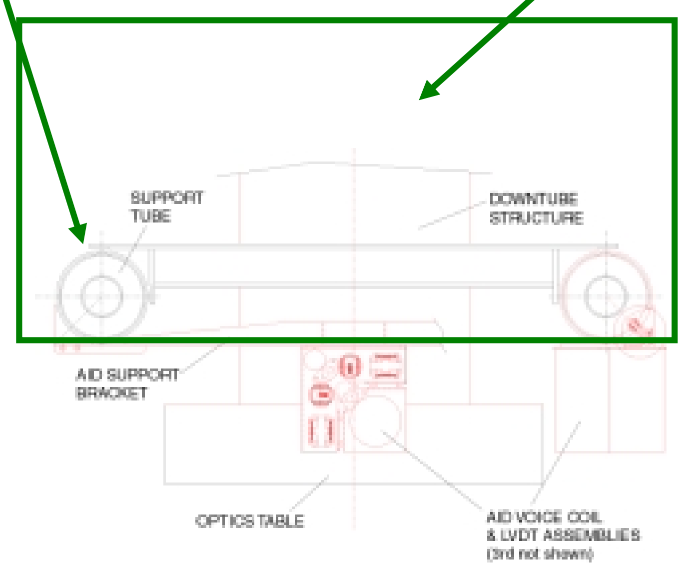


Active Internal Damping (AID) System Layout



AID support is Isolated by the EPI system

Passive isolation stacks are above the support table



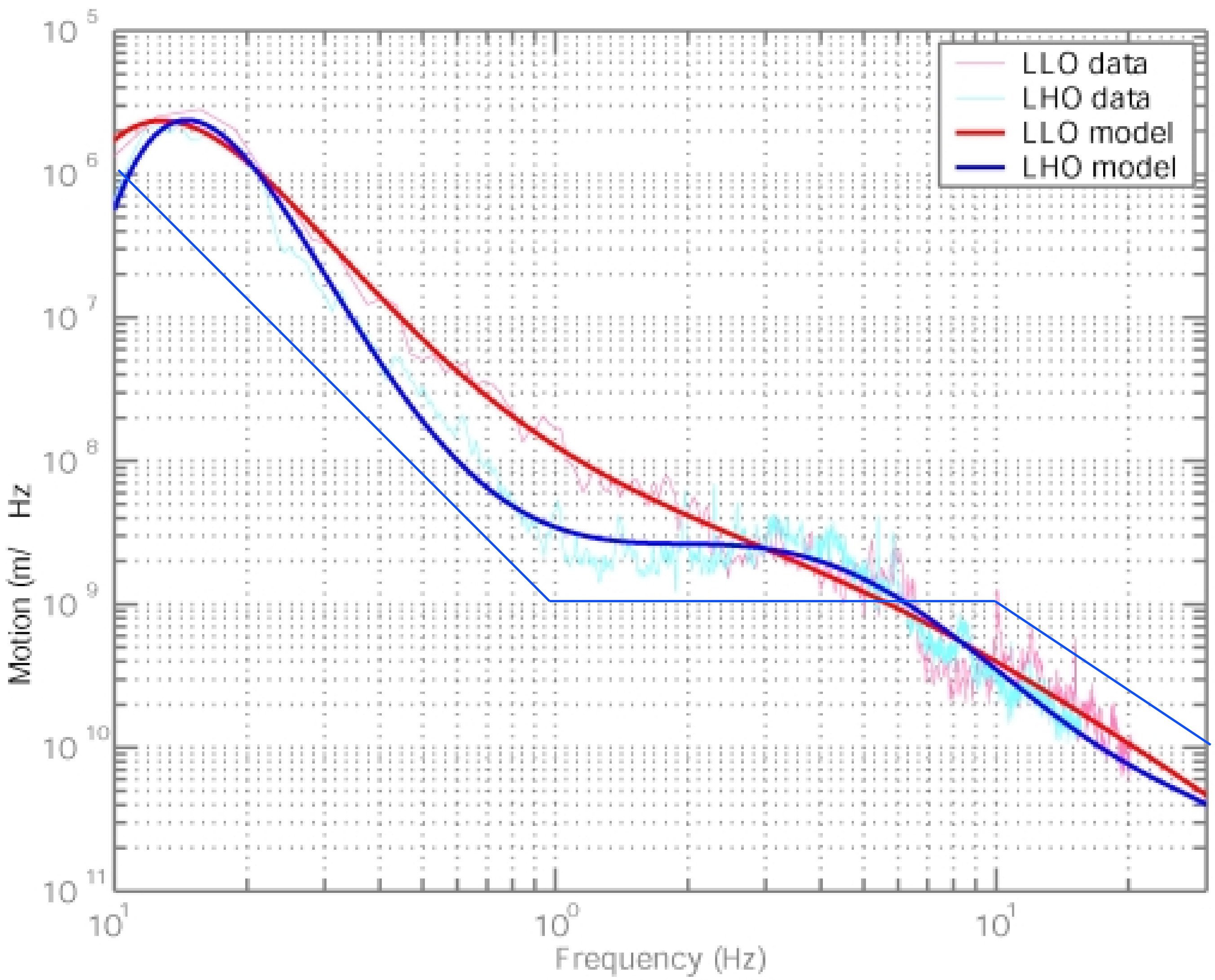
Requirements

- Environment and constraints
- Performance requirements
- Functional requirements

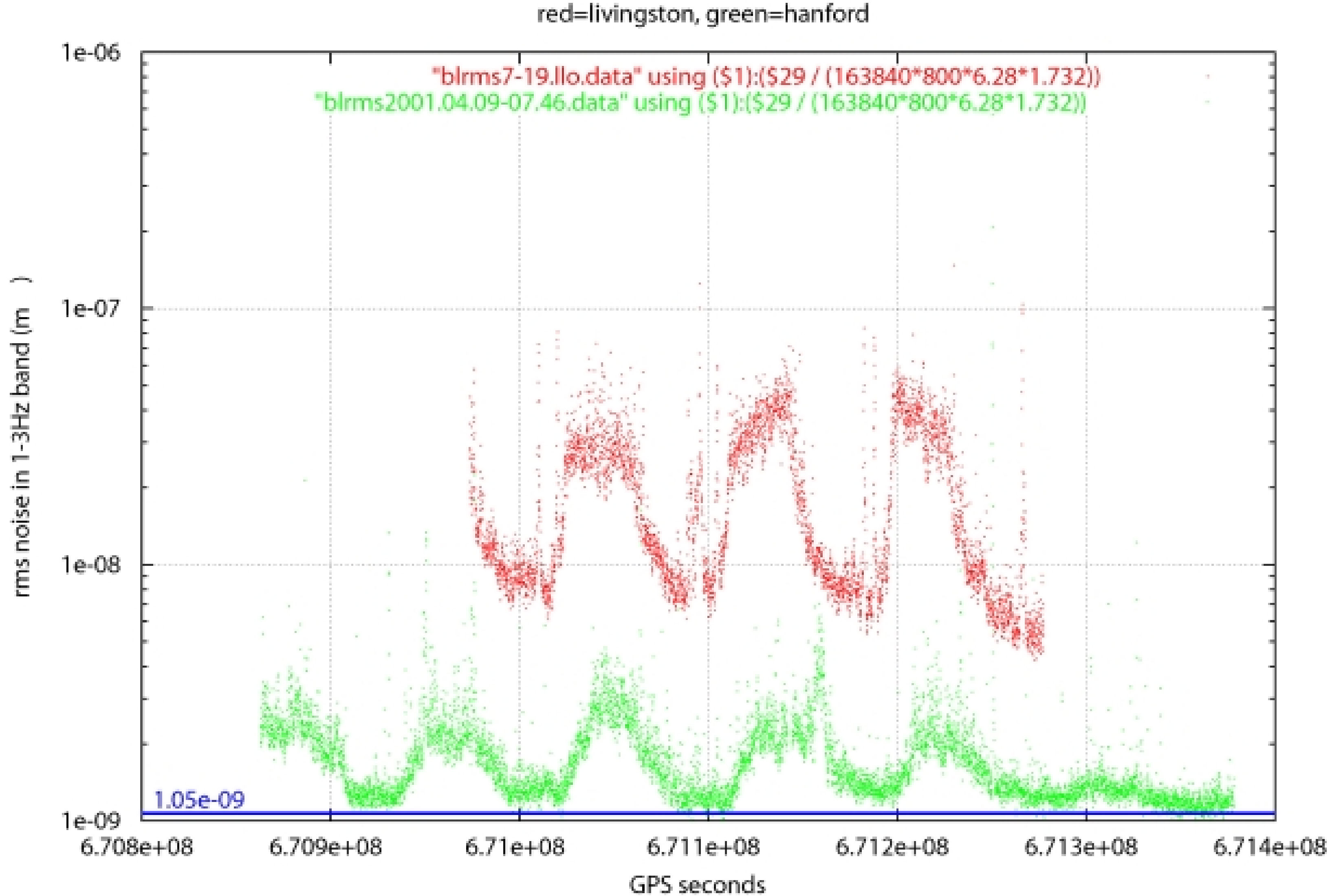
Environment

- Seismic spectra at observatories somewhat quieter than anticipated at GW frequencies
- In excess by factor 3-10 at lower frequencies
- Steady-state spectrum noisier by ~10x at LLO
- Highly non-stationary

'Standard' seismic spectrum

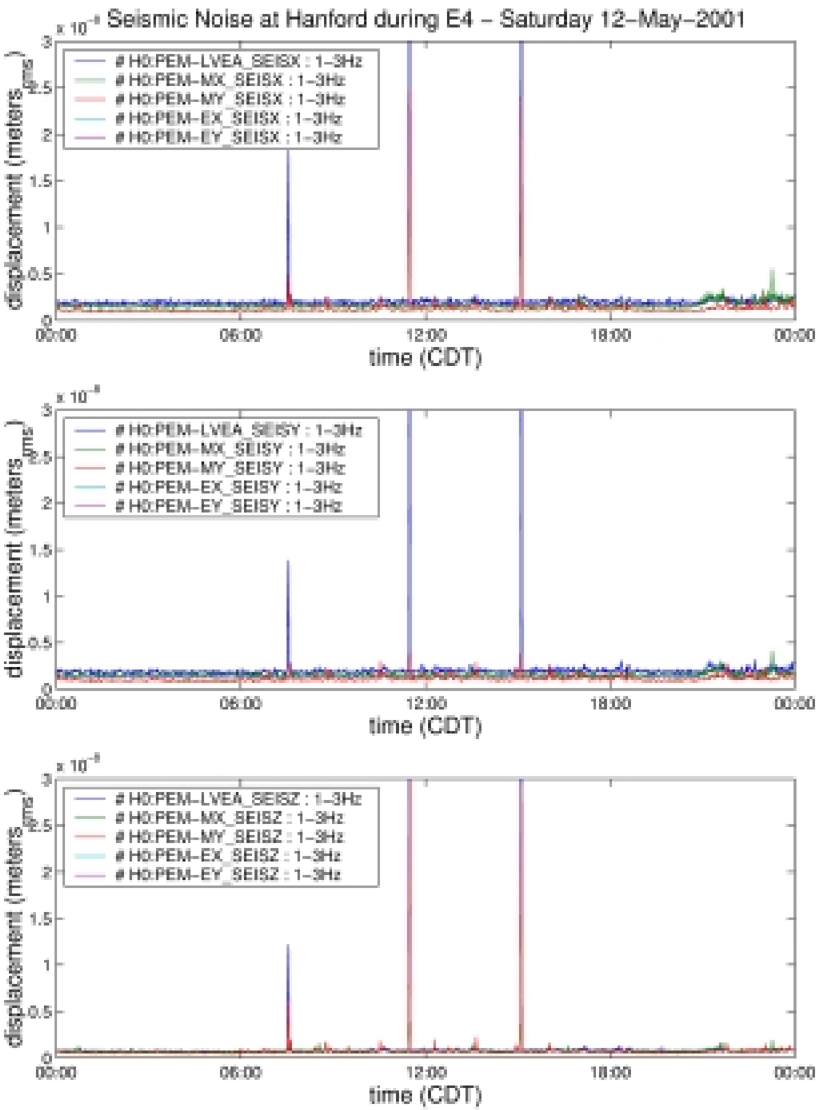


Daily variability

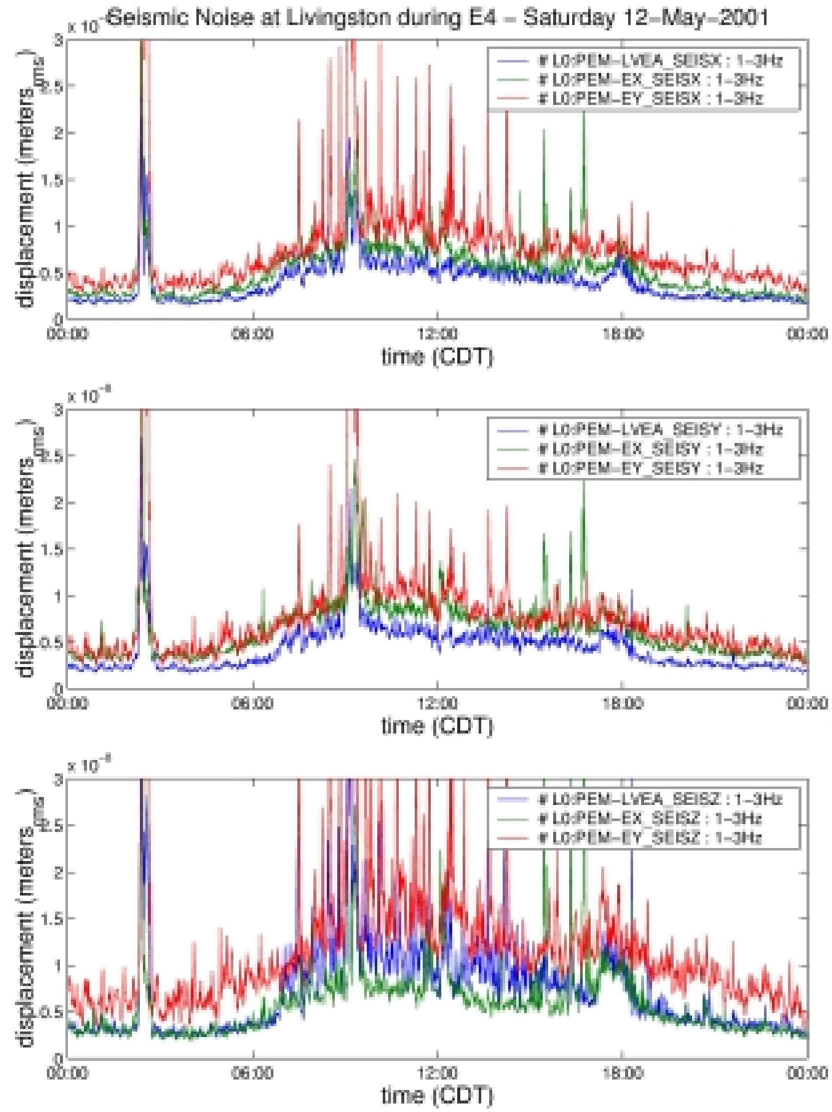


Impulsive nature

LHO



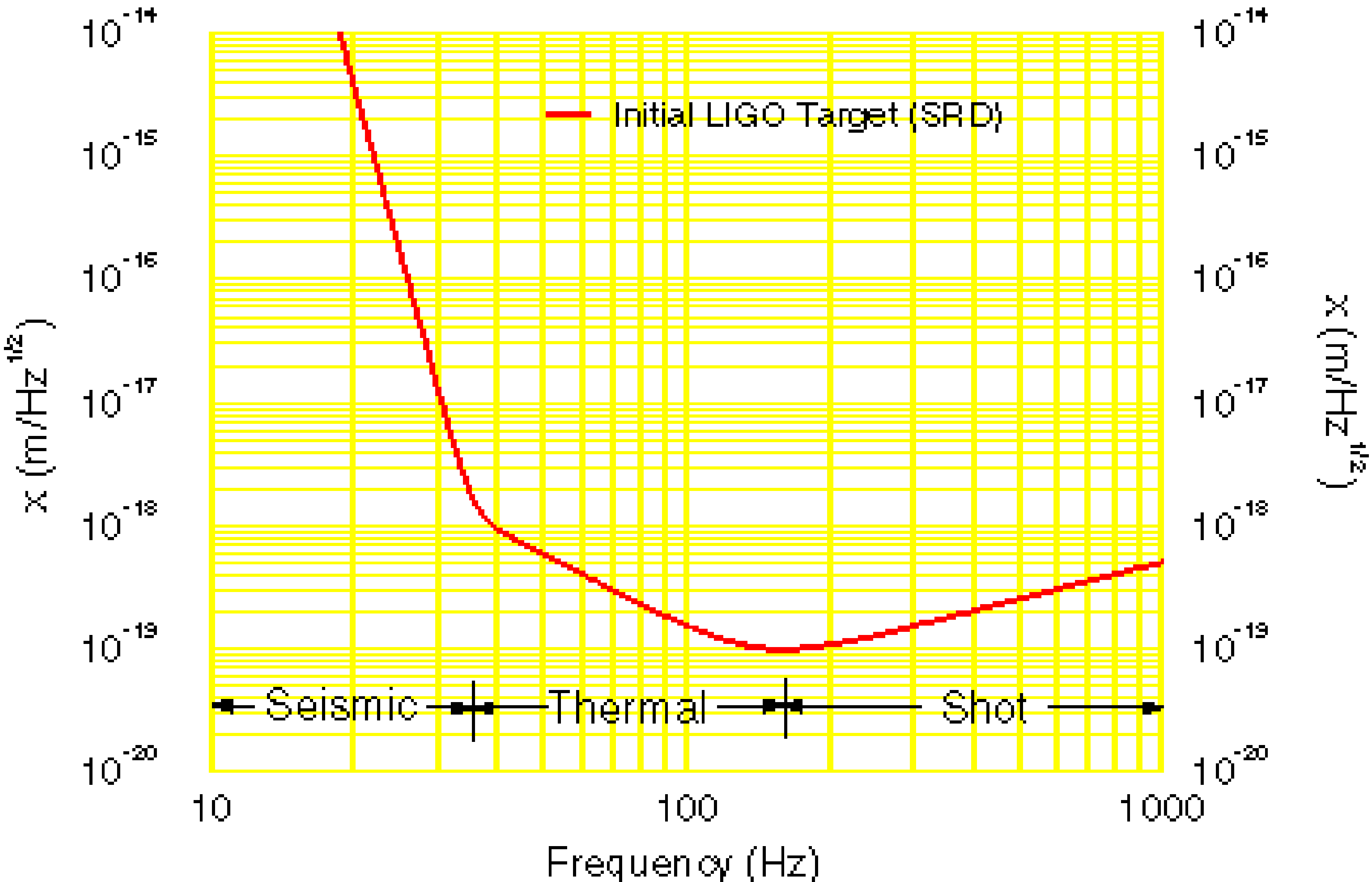
LLO



Top-level performance requirements

- Objective:
  - » To reach the SRD sensitivity,
  - » With the prescribed interferometer duty cycle,
  - » Given the present seismic environment and detector components.
- Constraints
  - » The transfer function, and especially the resonant character, of the initial LIGO seismic isolation system.
  - » The pendulum transfer function – assume $1/f^2$
  - » The finite dynamic range of the suspension controller coil drivers –
    - – 100 micron pk-pk range in “acquisition mode”; in “run mode” 20 micron pk-pk authority below the pendulum resonant frequency; and 5e-20 m/√Hz noise performance at 40 Hz on the optical axis (local longitudinal damping turned off)
- Need:
  - » Significant reduction in the uncontrolled velocity of the suspended optics in the ‘control’ band (frequencies less than 40 Hz)

Science Requirements Document Sensitivity



Functions

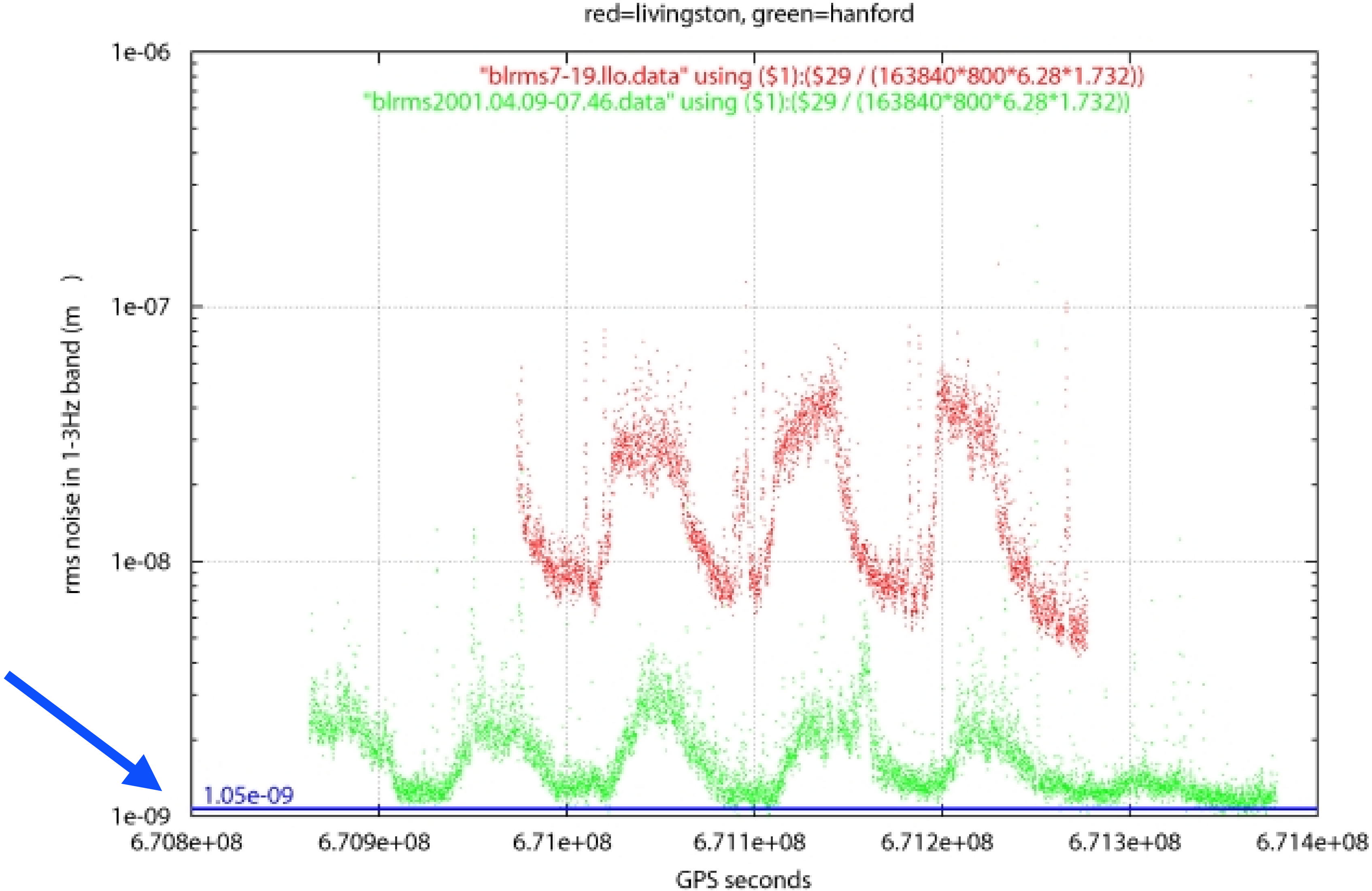
- The external pre-isolator will
  - » Provide coarse positioning of the seismic load
  - » Compensate for tidal motions (6 and 12 hour periods) and quasi-static alignment offsets (replacing this function of the original initial LIGO PZT fine actuator)
  - » Compensate for the ~6 second period microseismic motion (replacing this function of the original initial LIGO PZT fine actuator)
  - » Reduce the input seismic motion in the region of the stack solid-body resonances, especially 1-3 Hz to a level permitting performance according to the SRD
- The internal damping system will
  - » Damp the solid-body resonances of the initial LIGO seismic isolation system, in particular from1-3 Hz

External Pre-Isolator performance requirements

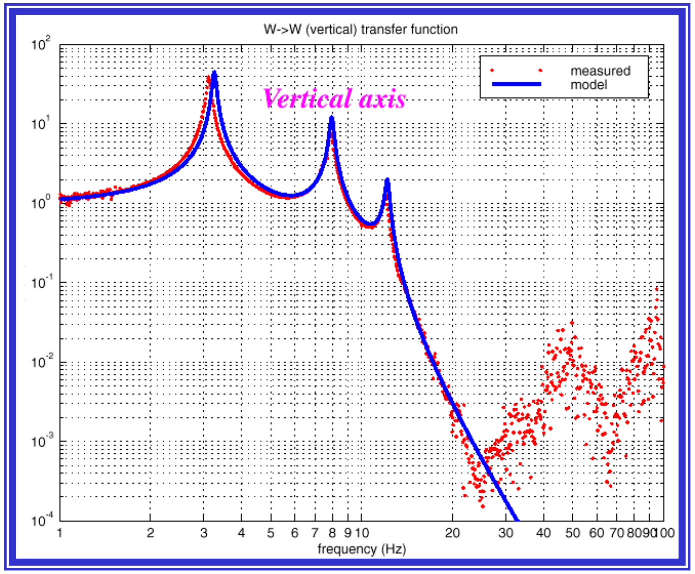
- Basic tenets:
  - » The pre-isolator must not increase the present noise in the GW-band, and
  - » Must bring the day LLO environment to the level of the LHO night environment.

1 month 100 seconds	10 microns pk-pk 1 micron pk-pk	Presently observed stability of system
0.16 Hz	4e-7 m/√Hz	To original seismic model
1 Hz	1e-9 m/√Hz	Hanford night-time
10 Hz	4e-10 m/√Hz	spectrum in 1-3 Hz band
15 Hz 30 Hz 50 Hz and higher	2e-10 m/√Hz 6e-11 m/√Hz 2e-11 m/√Hz	Not to exceed presently observed spectrum

Daily variability – and requirement



Internal Stack Damping performance requirements



- Basic tenets:
  - » The internal stack damping system must not contribute more than 1/10 of the seismic noise in the GW band, and
  - » Must reduce the targeted stack mode peaks by a factor of 10 (from ~30 to ~3)
- BSC noise requirements:
  - » Horizontal: 1.2e-13 m/√Hz at 20 Hz, 2.5e-17 m/√Hz, ≥ 50 Hz
  - » Vertical: 5e-13 m/√Hz at 20 Hz, 1e-16 m/√Hz, ≥ 50 Hz
- HAM noise requirements:
  - » Horizontal: 4e-12 m/√Hz at 20 Hz, 2.5e-16 m/√Hz, ≥ 50 Hz Vertical: 2e-11 m/√Hz at 20 Hz, 1e-15 m/√Hz, ≥ 50 Hz

Pre-Isolator: Notes

- Dynamic range: to handle microseismic and tidal input
  - » 260 μm tidal differential, 40 μm microseismic, 300 μm total
  - » Must be able to perform all correction from End Mass
  - » Goal of 1 mm
  - » Coarse positioning through shimming, etc.
- 6 DOF to allow pitch, yaw correction
- Must survive moderate earthquakes
- Installation:
  - » The BSC EPI is to fit into the space between the support piers and the spherical knuckle attached to the crossbeam
  - » Must allow installation without disturbing optic alignment
- The design must assure that that no oils or lubricants will be released in the vicinity of the vacuum equipment
- The design must not create magnetic fields at a level which leads to noticeable test mass disturbance
- The EPI must interface via the observatory installed data acquisition system and EPICS control system

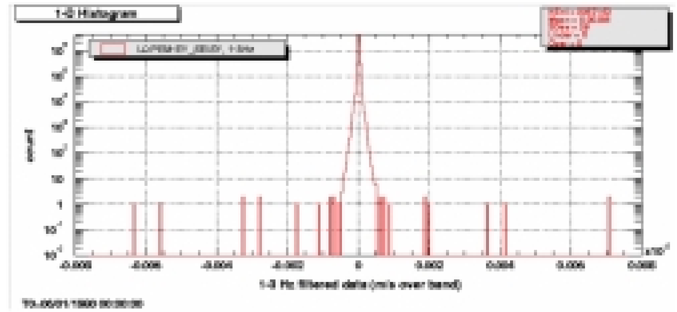
Internal Stack Damping: Notes

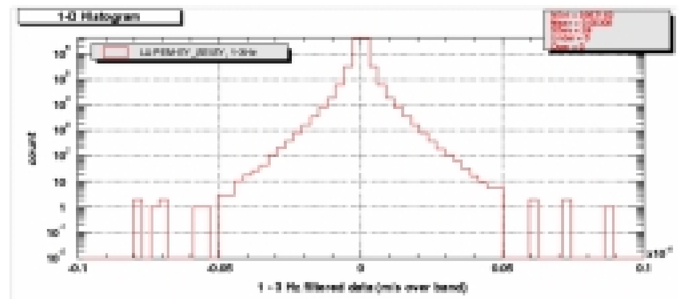
- Dynamic range: guarantee of no interference
  - » Normal motion
  - » Moderate earthquakes
- Must be capable of 6 DOF; but will target specific modes (e.g., 1.2, 2.1 Hz in BSC)
- Installation:
  - » Must use existing structures and points of attachment
  - » Must allow installation without disturbing optic alignment
- In-vacuum components:
  - » Must obey (the usual) strict Class-A vacuum requirements (materials and preparation)
  - » Must protect against overheating (outgassing)
  - » Reliability requirements: 10 years MTBF
- The design must not create magnetic fields at a level which leads to noticeable test mass disturbance
- No interference with installed optical systems (main, ghost, optical lever)

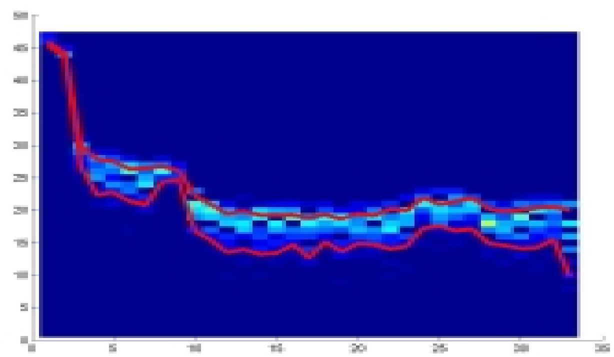
Requirements: to be done

- Characterization of initial LIGO stacks
- More complete statistical analysis of noise at both sites
- Interpretation in terms of gain profile, availability

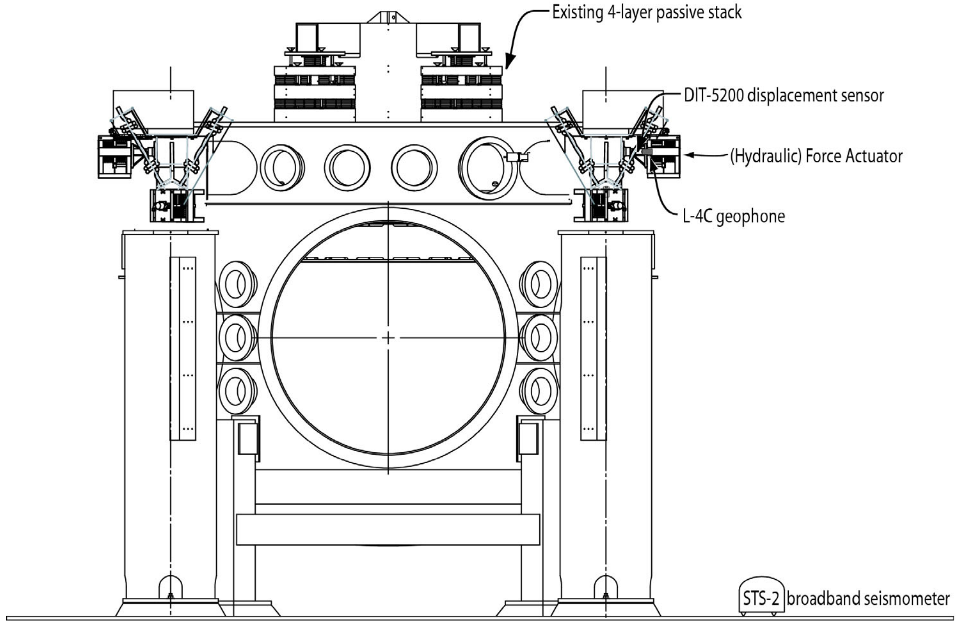
- Anticipated that this information will refine design, loop parameters, not change the conceptual design



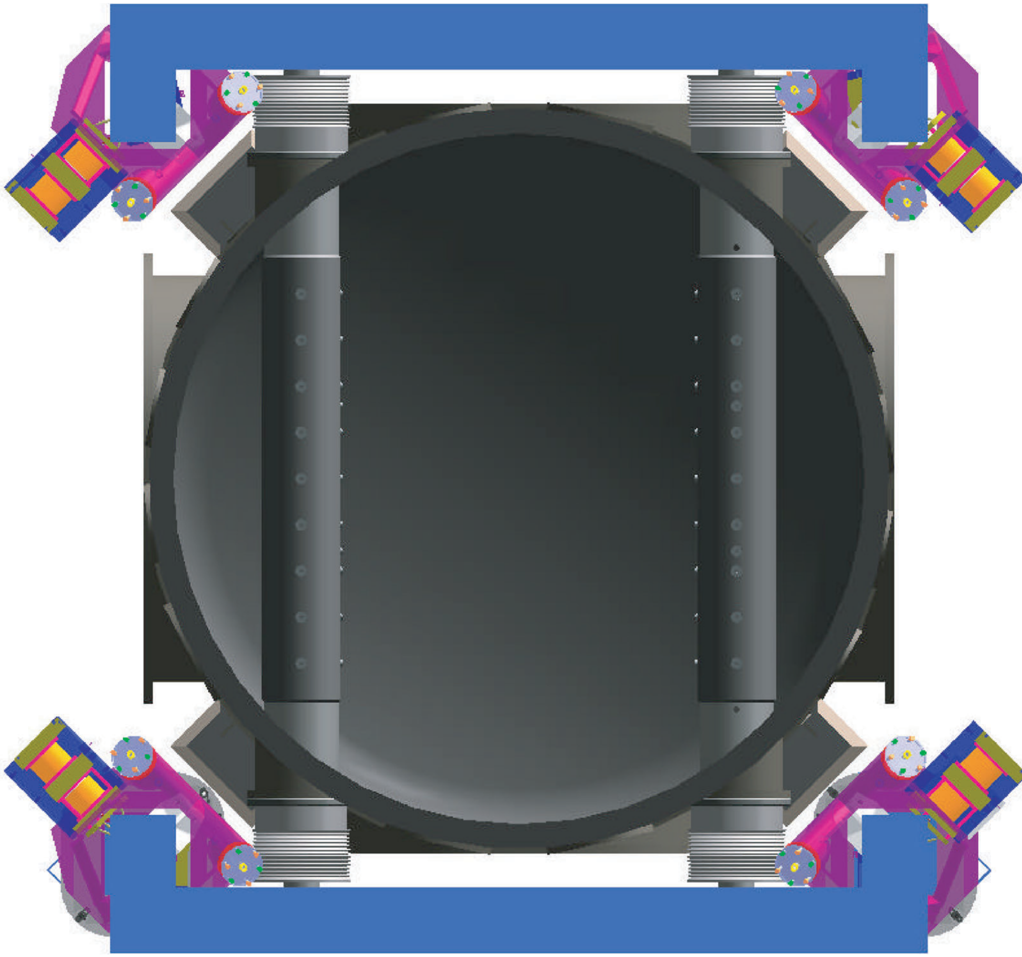


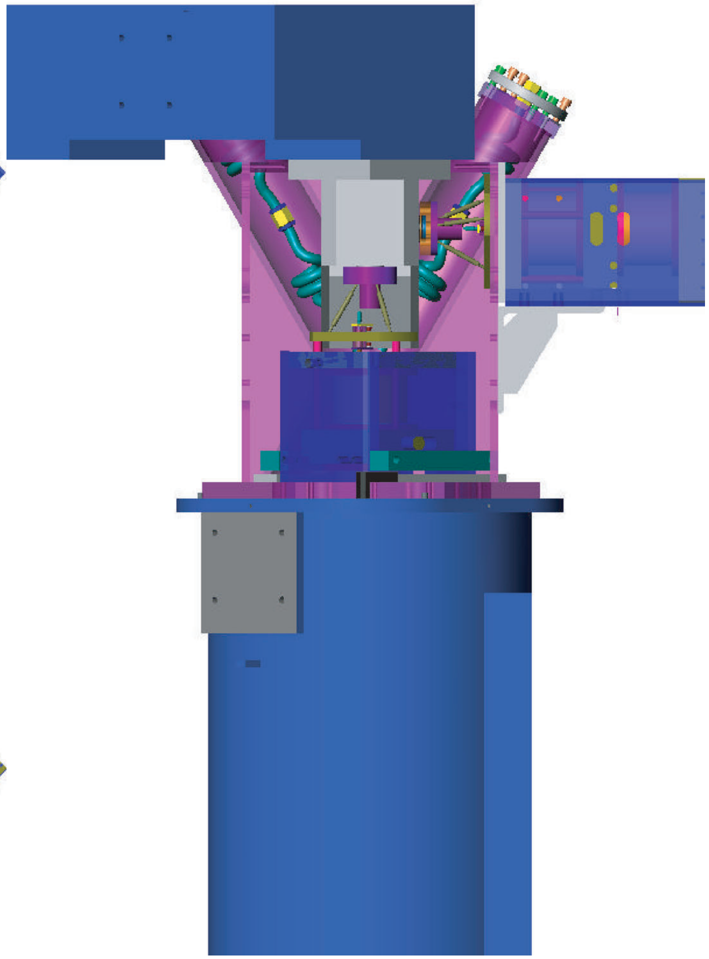


External pre-isolation



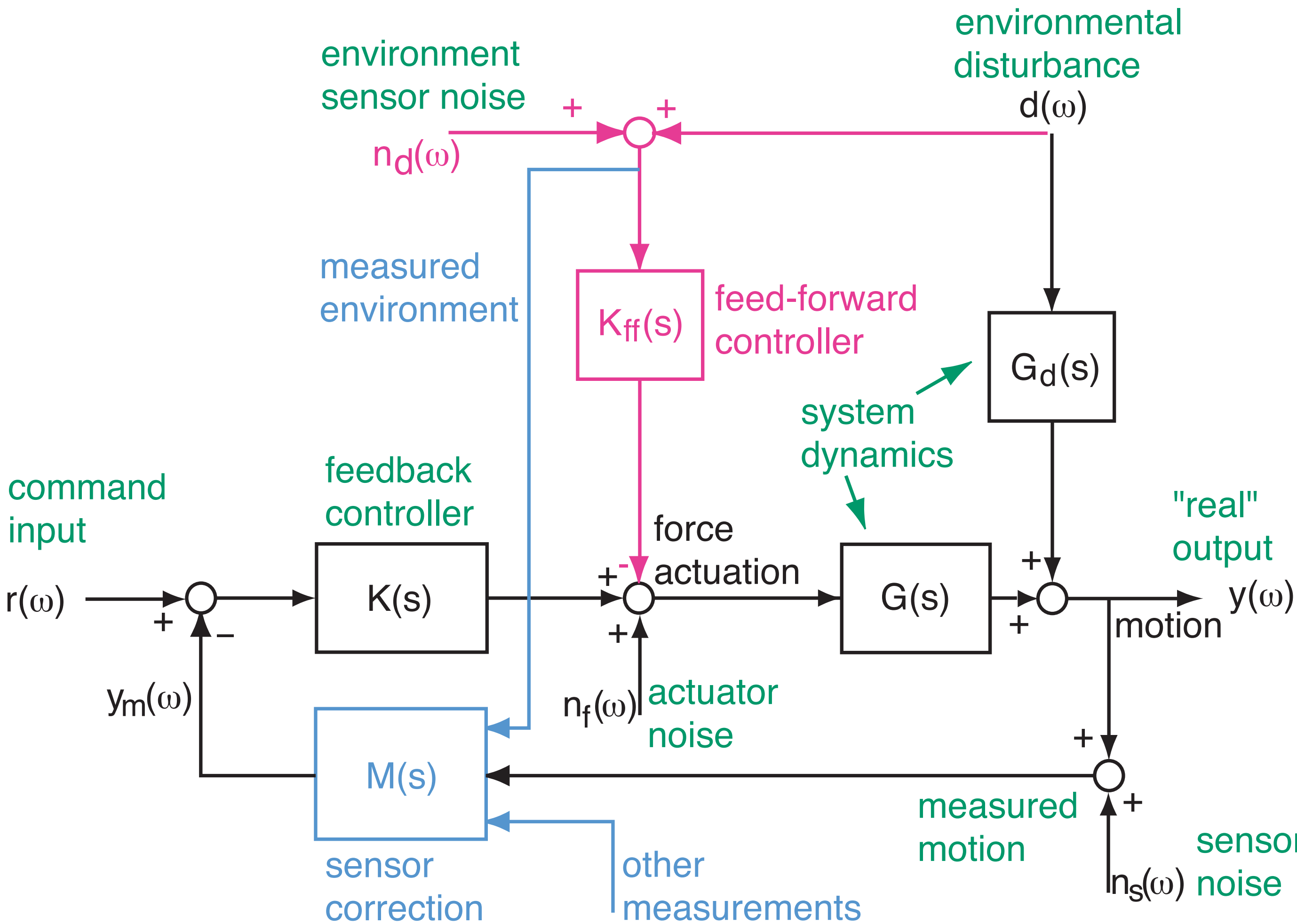
- Each corner actuation package replaced with 2-DOF long-throw 50 Hz bandwidth actuator.
- Weight supported by stiff springs, putting natural resonance in 3 - 5 Hz range.
- If the baseline hydraulic actuators are used, their stiffness will dominate that of the support springs for system dynamics.



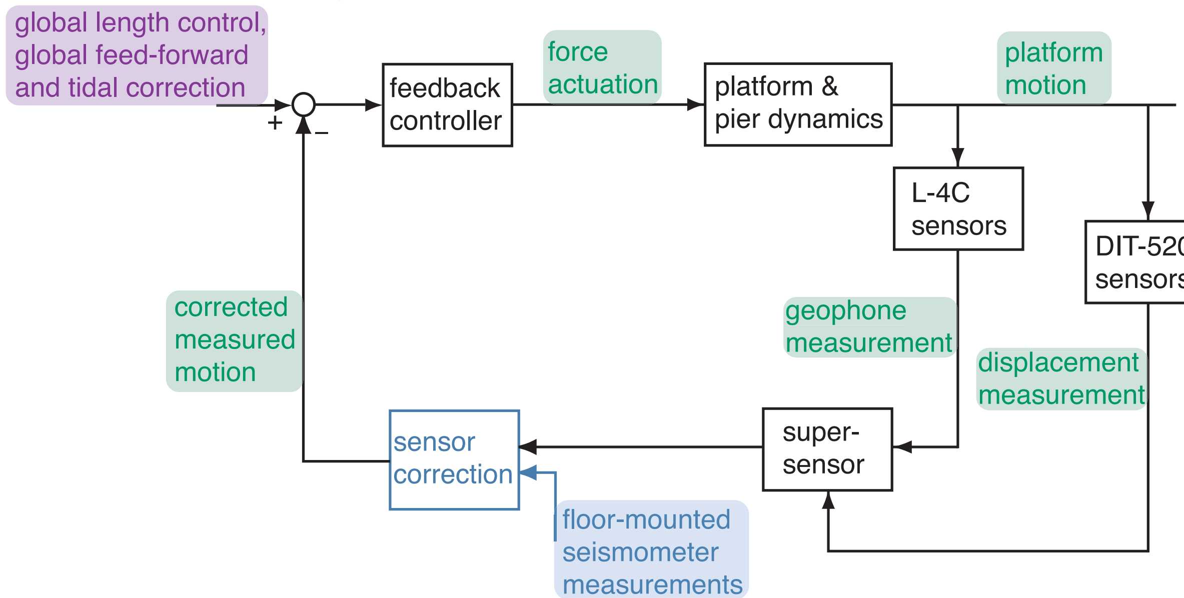


Control techniques

- **Feedback:** Force applied to payload in response to error signal derived from frequency-blended intertial and displacement sensors.
- **Sensor correction:** Feedback error signal corrected for known motion of "fixed" side of displacent sensor and/or tilt sensitivity of inertial sensor. Used in prototypes of hydraulic pre-isolator and Advance LIGO SEI.
- **Feed-forward:** Measured disturbance and known transfer function to payload used to apply corrective force to payload. Used for the microseism band in LIGO-I.


environment
sensor noise
$n_d(\omega)$
+
+
environmental
disturbance
$d(\omega)$
measured
environment
$K_{ff}(s)$
feed-forward
controller
$G_d(s)$
system
dynamics
command
input
feedback
controller
force
actuation
"real"
output
$r(\omega)$
+
−
K(s)
+
-
+
G(s)
+
+
$y(\omega)$
motion
$y_m(\omega)$
M(s)
$n_f(\omega)$
actuator
noise
+
+
measured
motion
sensor
noise
$n_s(\omega)$
sensor
correction
other
measurements

Servo at each actuator



- Each of 8 super-sensor/actuator pairs closed in largely SISO loop.
- Displacement sensor signal drift and DC offset slowly corrected to avoid fighting within over-determined system.
- Sensor correction and global feed-forward and LSC signals mapped to the 8 DOFs and applied as a command input to each.

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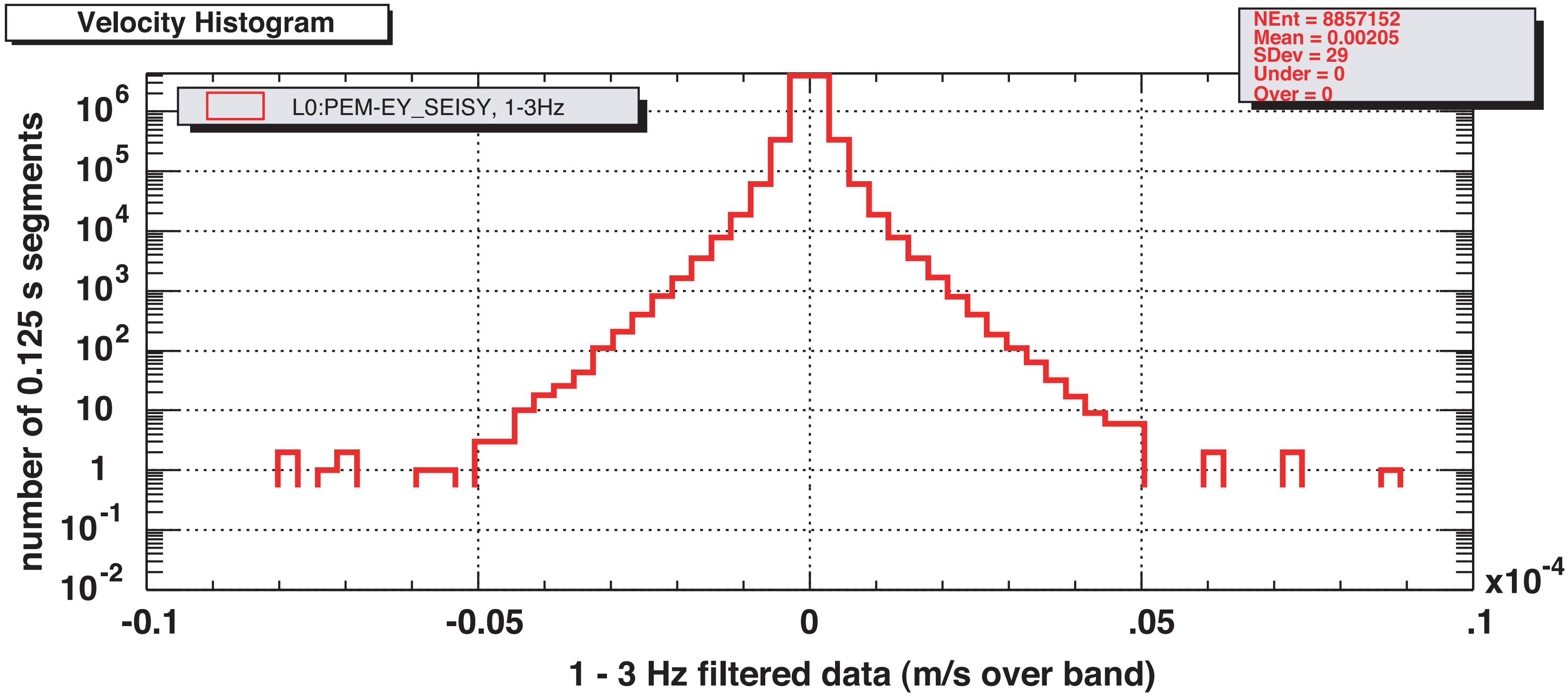
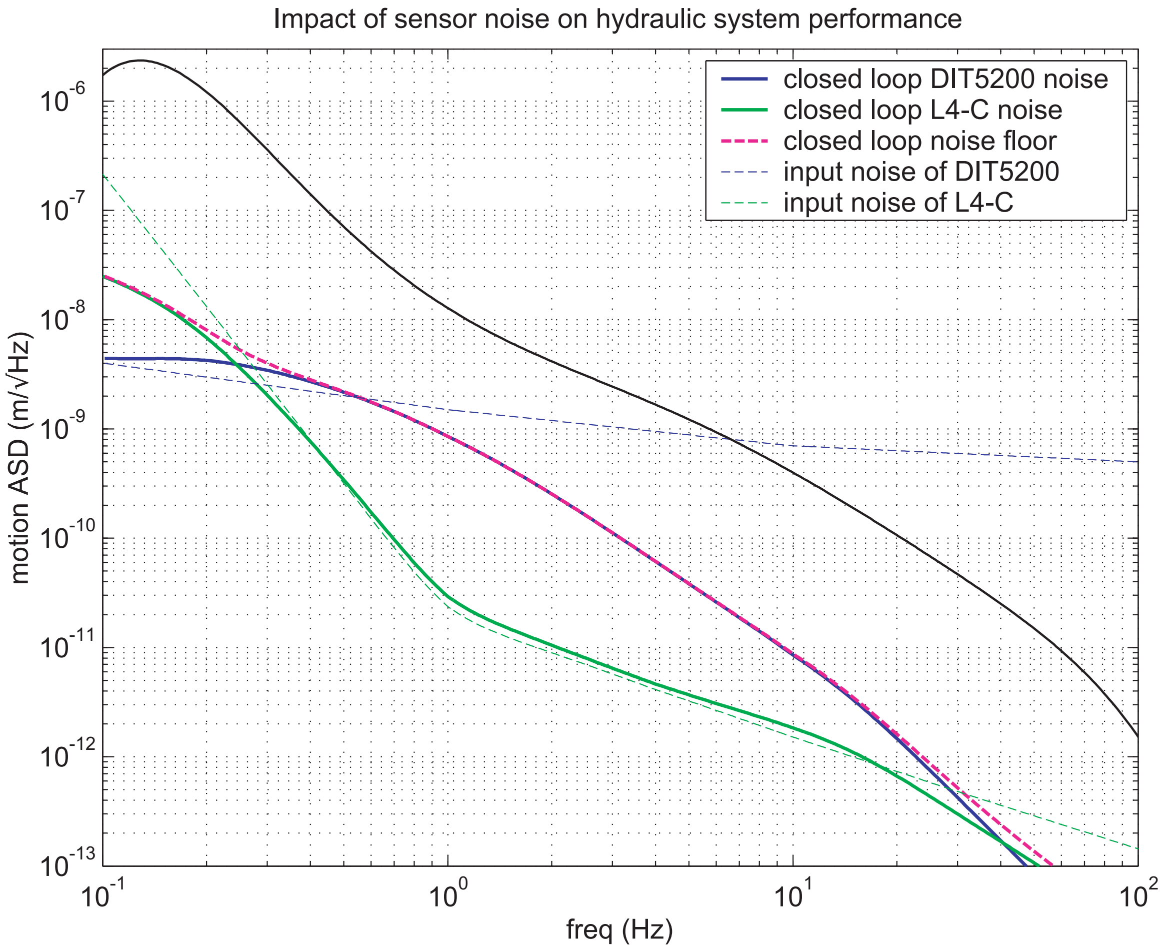


- Bandlimited LLO seismometer data, decimated at 8 Hz; 13 days, 8.8 million points.
- Most data fall in central peak, $v < 5\mu\mathrm{m/s}$, plus a few outliers, shown here, thanks to Ed Daw. A few more as far out as $70\ \mu\mathrm{m/s}$. We don't know the data well enough to know what they are.

Control system design

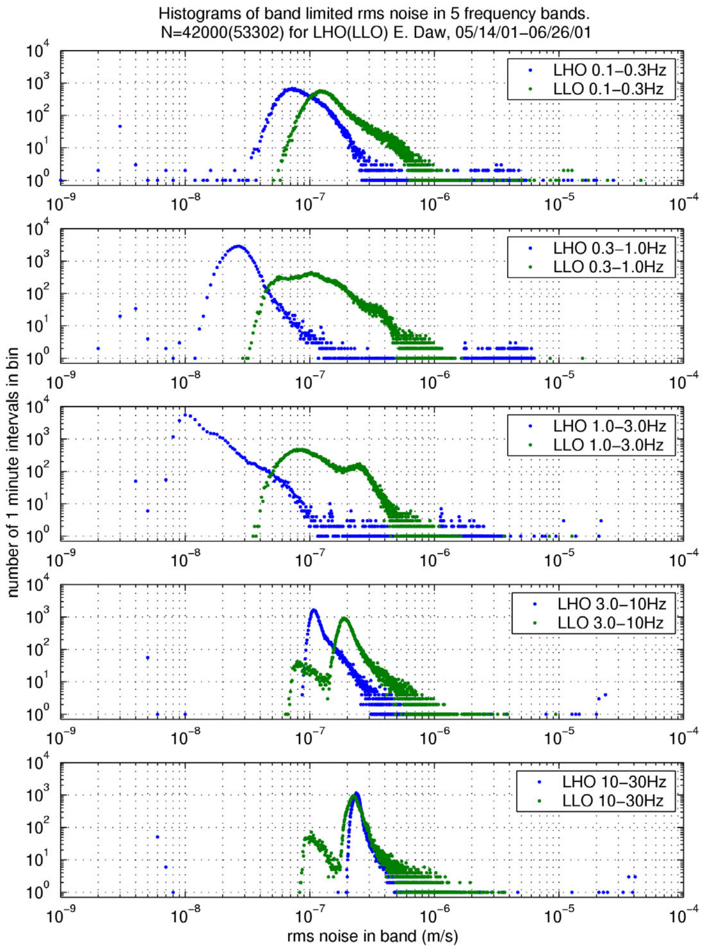
- Want about factor of 15 reduction in 1 - 3 Hz band.
- Plan is for broadband feedback from super-sensor, with UGF at approximately 20 Hz, and gain of about 5 - 10 in 1 - 3 Hz band.
- Blend between displacement/sensor-correction zone and inertial feedback at 0.5 Hz.
- Extra resonant peaked gain in inertial feedback path at troubling stack modes (*i.e.*, 1.2 and 2.1 Hz), to bring effective noise reduction there to about 20.

Sensor noise sources



Low-frequency actuation allocation

- Much attention was paid during LIGO's design to avoid parasitic interferometers between the core optics and non-seismically-isolated structures and optical elements
- A consensus seems to exist that as long as the moving (and light-scattering) object's velocity is less than about $10\ \mu\mathrm{m/s}$ there is less concern about fringe-wrapping effects inserting noise in the GW band.

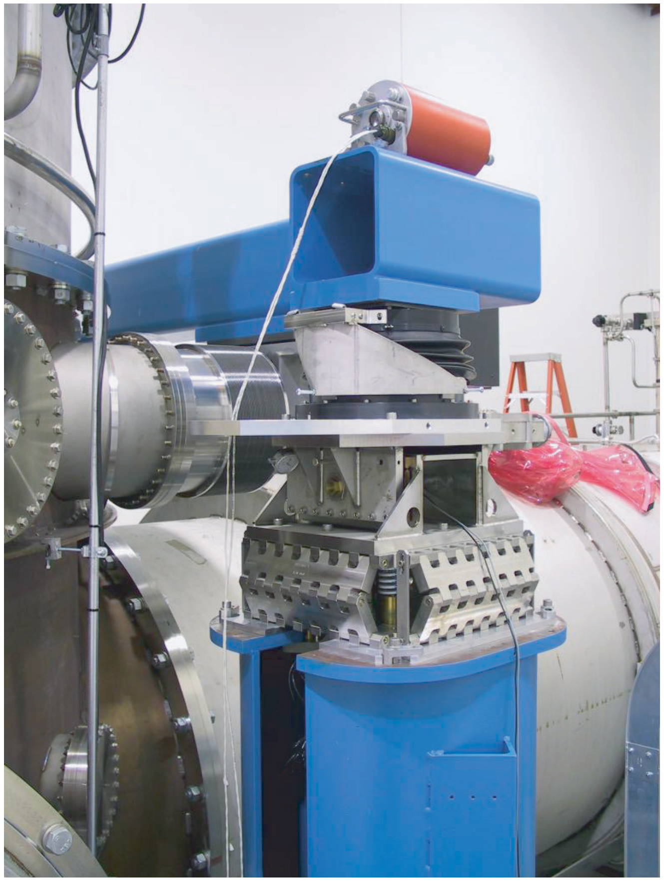


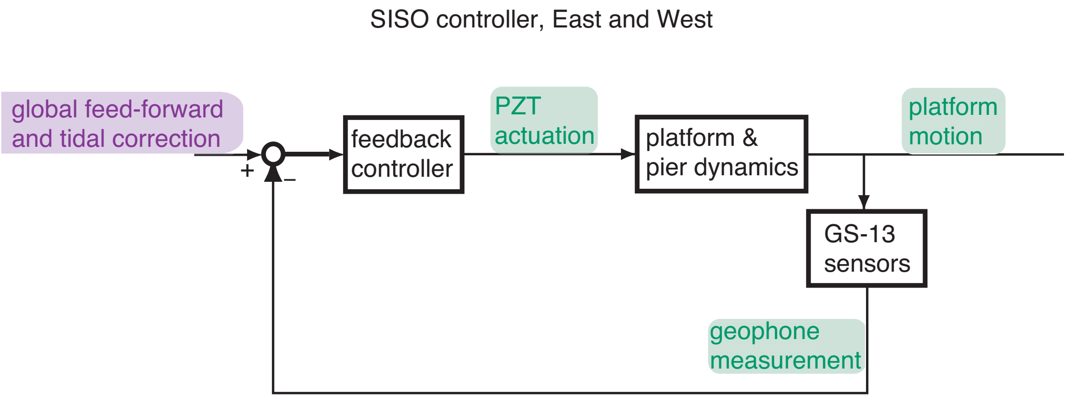
- 40 Days of LLO and LHO band-limited RMS ground velocity data from E. Daw.
- Peak values in each band are about the same, several $\mu\mathrm{m/s}$
- Microseism band of order $10\mu\mathrm{m/s}$ regularly, so we may continue to allocate FF to end tanks.
- To minimize chance of fringe-wrapping in parasitic interferometers between isolated and ground-mounted optics, in/out tables may need isolation.

2-DOF external active seismic isolation test

- Proof-of-principle test for external seismic isolation layer.
- Existing fine actuators in end (and mid) station, driven in pairs, can move stack base in beam direction and in yaw.
- 'Borrowed' GS-13 seismometers placed on crossbeams above FAS provide inertial error signals for 2, 1-DOF SISO servos.
- dSpace signal processing board and software in PC allows rapid controller/compensation development and provides GUI control panel.

Geophone and Fine Actuator





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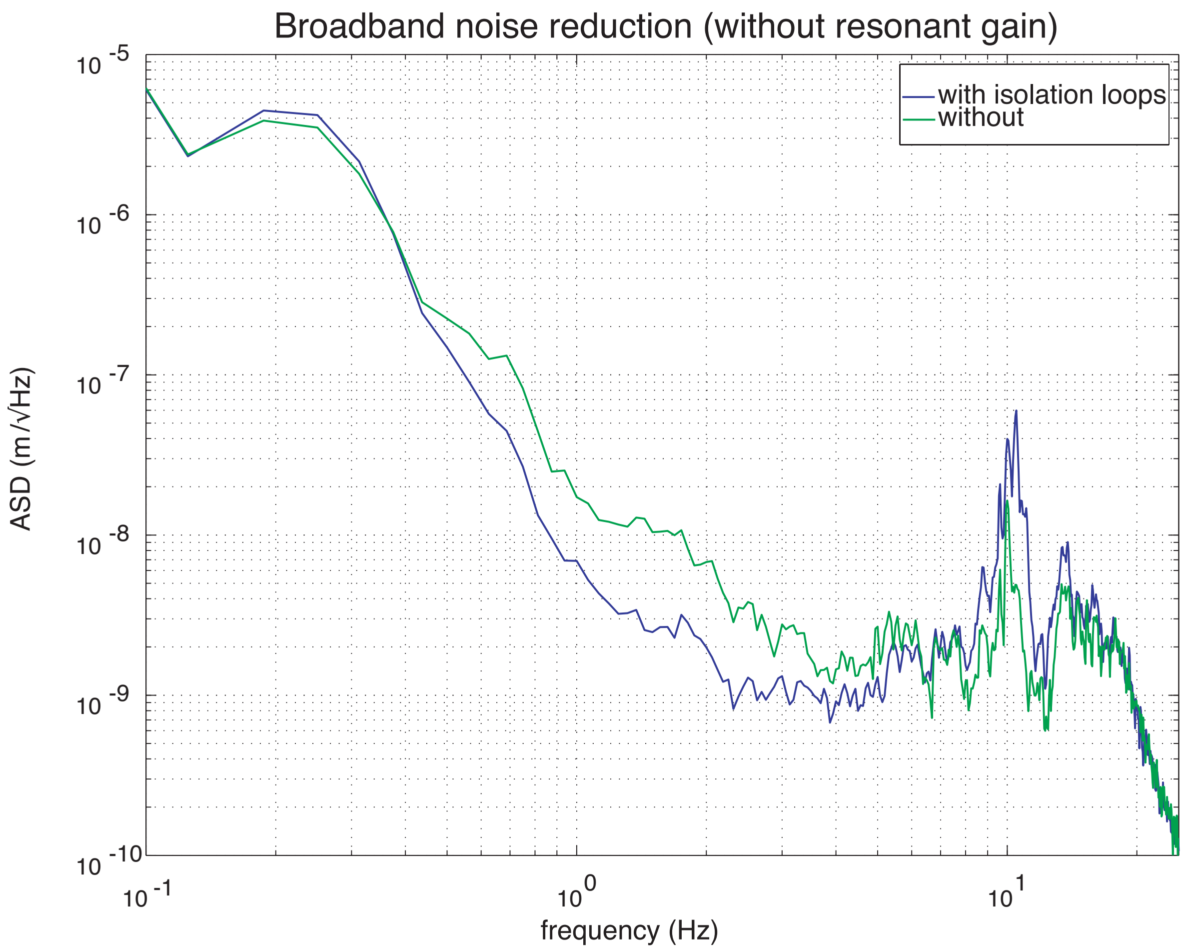
Noise reduction at crossbeam



Noise reduction at test mass

- Test mass (ETMY) and its LED/photodiode local sensors used measure vibration on stack payload, with and without external active isolation.
- Resonant gain added at two troublesome stack modes (1.2 and 2.1 Hz), allowing factor of a few more gain there without destabilizing overall servo.
- This resulted in about a factor of 7 decrease in motion seen by the test mass at the stack modes.

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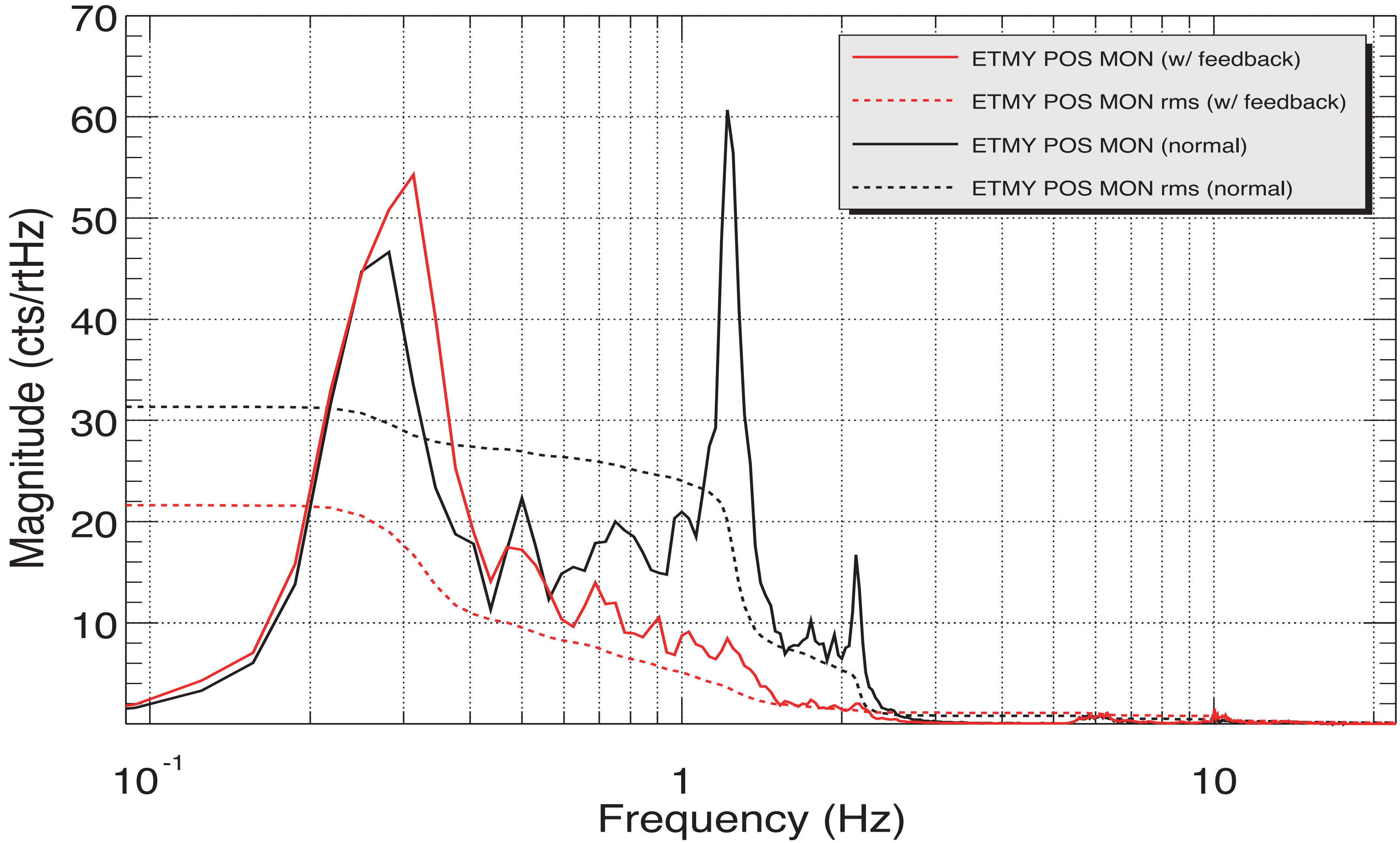
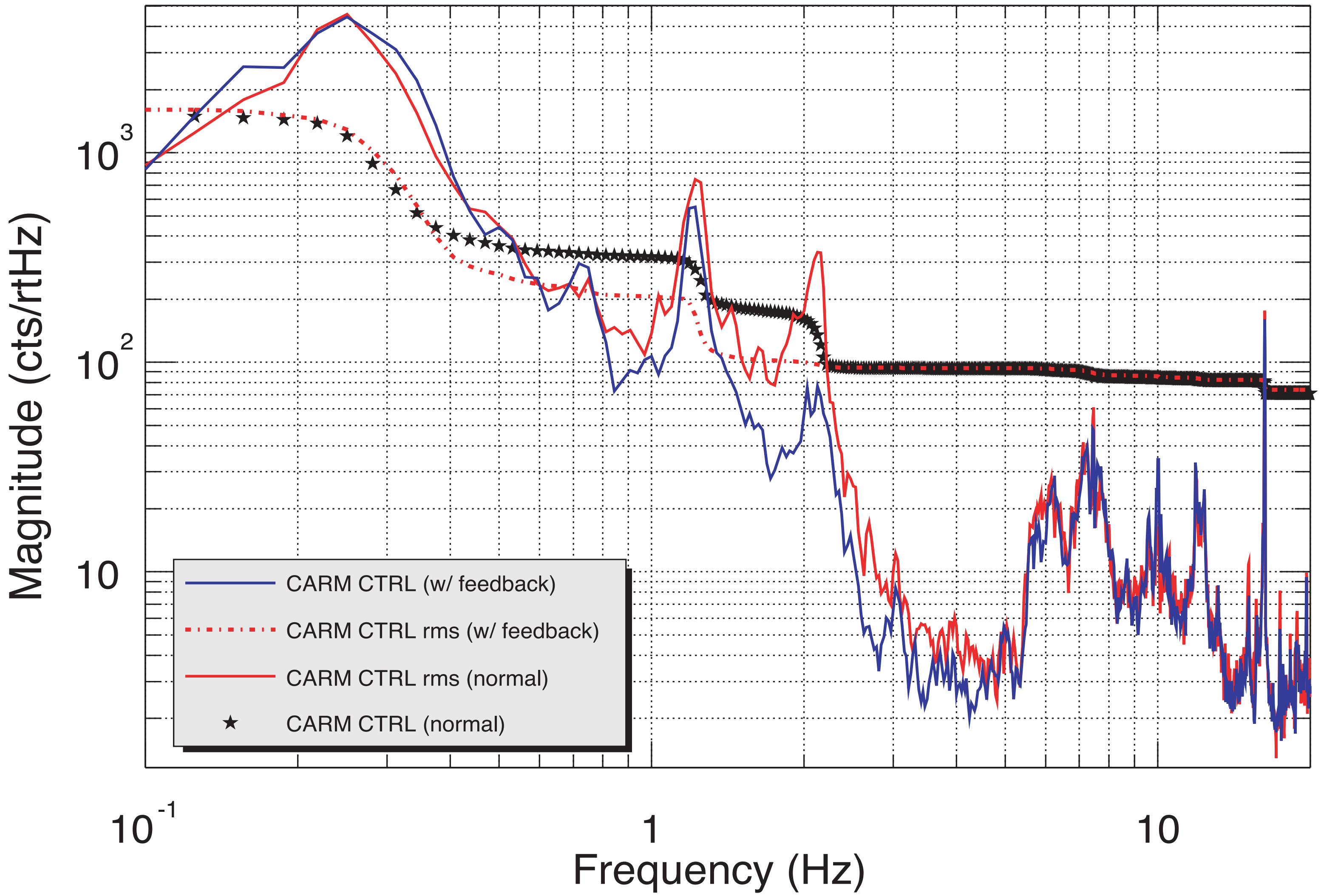


Magnitude (cts/rtHz)
70
60
50
40
30
20
10
10^{-1}
1
10
Frequency (Hz)
ETMY POS MON (w/ feedback)
ETMY POS MON rms (w/ feedback)
ETMY POS MON (normal)
ETMY POS MON rms (normal)

Noise reduction in arm control signal

- LLO Y-arm was locked with ETMY's experimental experimental seismic isolation loop closed.
- Naively expected to see factor of $\sqrt{2}$ improvement in arm control signal, since only one end was affected.
- Since most of the 2.1 Hz noise happened to be coming from the Y-end that night, we saw a factor of 5 decrease in that peak.



Magnitude (cts/rtHz)
10^3
10^2
10
10^-1
1
10
Frequency (Hz)
CARM CTRL (w/ feedback)
CARM CTRL rms (w/ feedback)
CARM CTRL rms (normal)
CARM CTRL (normal)

Hydraulic Actuators for the LIGO Seismic Retrofit

Stanford, Caltech, LSU, MIT, LLO

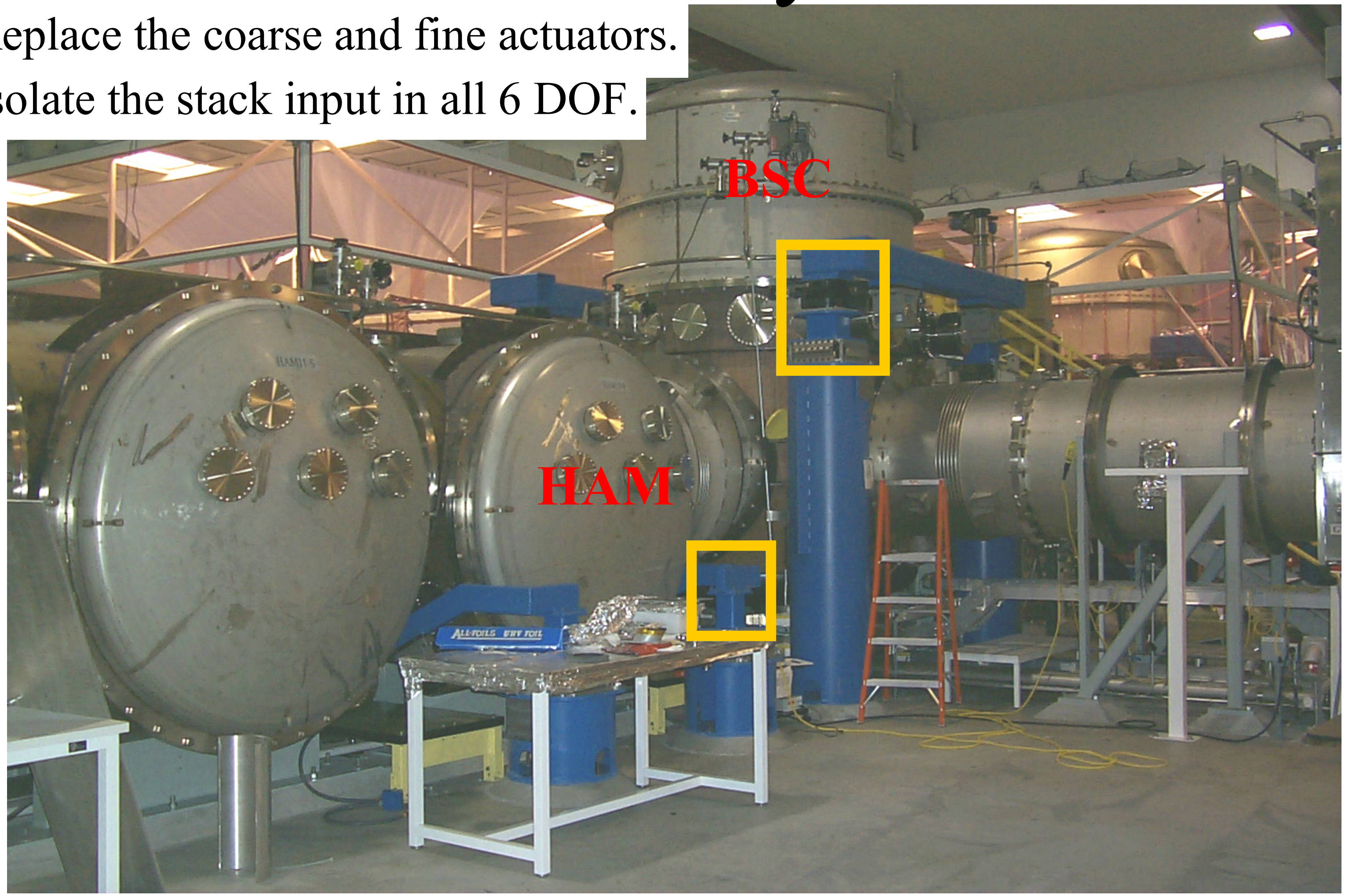
Rich Abbott, Graham Allen, Daniel DeBra, Dennis Coyne, Jeremy Faludi, Amit Ganguli, Joe Giaime, Marcel Hammond, Corwin Hardham, Wensheng Hua, Jonathan Kern, Brian Lantz, Ken Mailand, Ken Mason, Rich Mittleman, Jamie Nichol, Joshua Phinney, David Shoemaker, Michael Smith

Outline

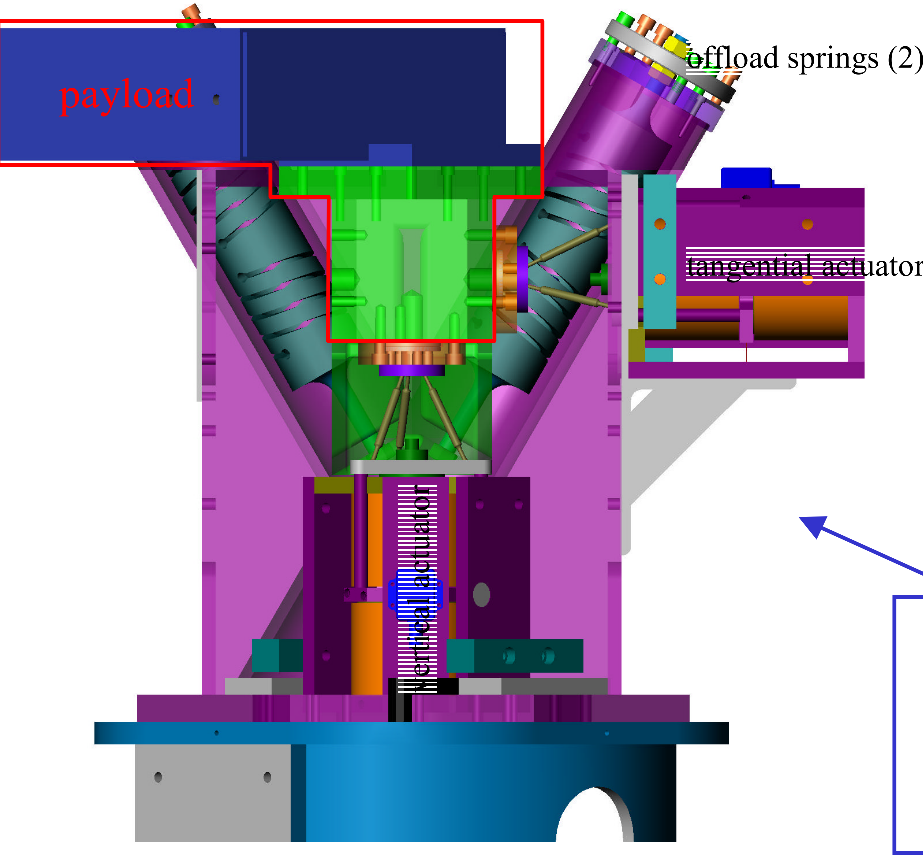
- Placement of Sensors and Actuators in the system.
- Description of Actuator.
  - Mechanical Configuration.
    (Housing, Offload springs, sensor location)
  - Laminar flow hydraulic bridge.
- Performance considerations.
  - Range, velocity and bandwidth.
  - Noise performance.
    Sensors and ground motion. (already covered by Joe)
    Fluid supply noise and cross-regulation noise.
- Sample isolation at Stanford.
- Test Plan

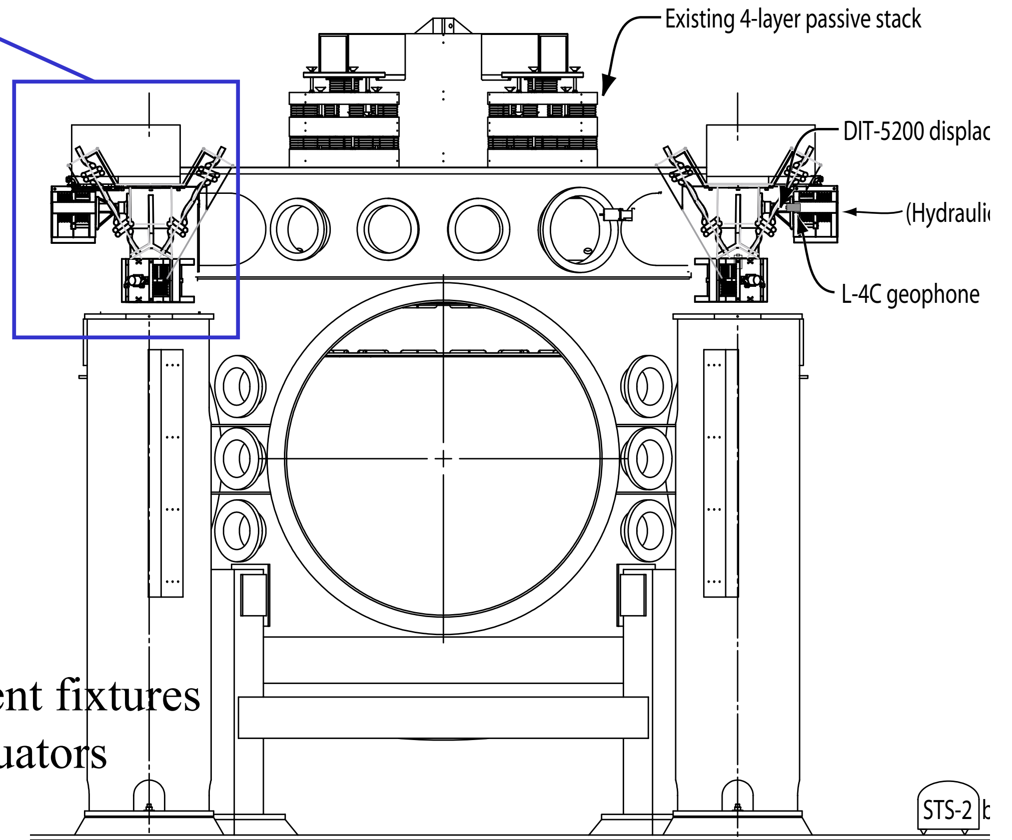
Placement of an External Isolation System

- Replace the coarse and fine actuators.
- Isolate the stack input in all 6 DOF.



Placement of the Actuators and Offload Springs



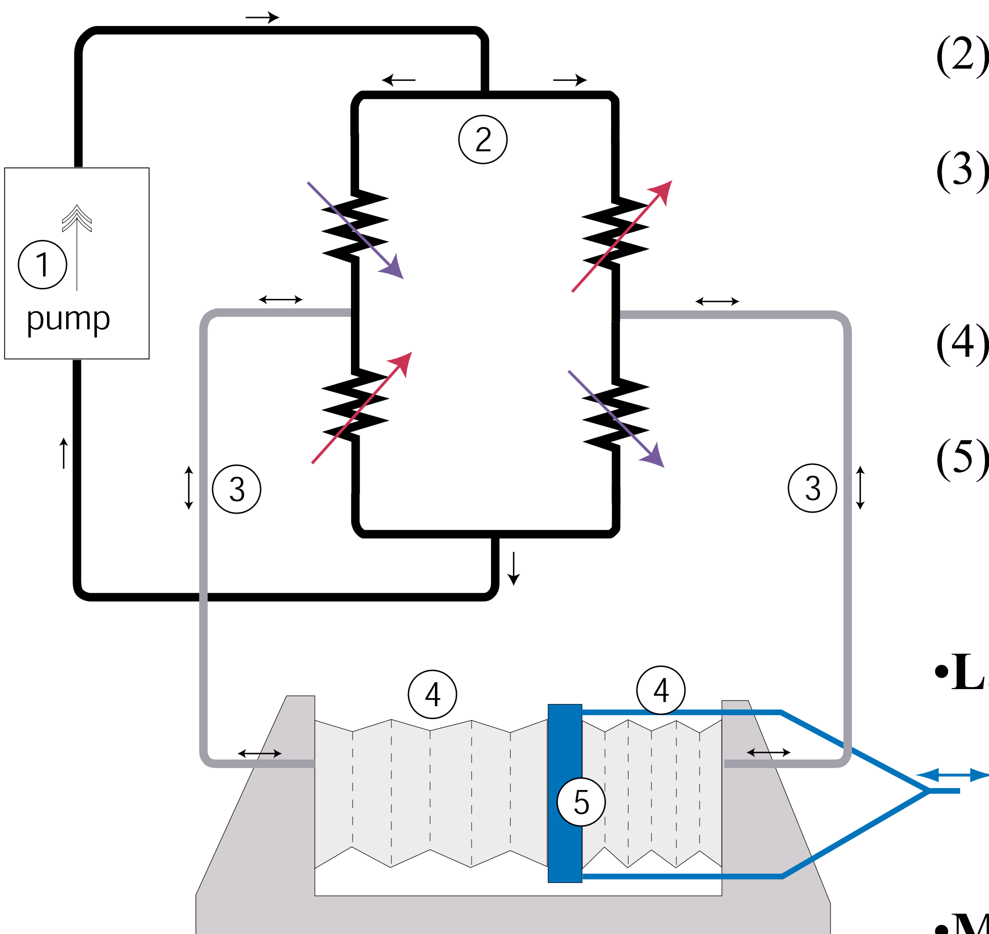


All the pier-top components are mounted into a frame

Frame holds:

- 1 vertical and 1 tangential actuator, (isolation and alignment in 6 DOF)
- Pair of offload springs and initial alignment fixtures
- Sensors which are not included in the actuators

Hydraulic Actuator Basics



(1) Pump supplies a constant flow of fluid to the actuator.

(2) Fluid flows continuously through a hydraulic Wheatstone bridge.

(3) By controlling the resistance, one generates differential pressure across the bridge, which are connected to

(4) Differential bellows which act as a stiction-free piston.

(5) The actuator plate is between the bellows, and is connected to the payload with a flexure stiff in 1 DOF

- **Laminar flow**

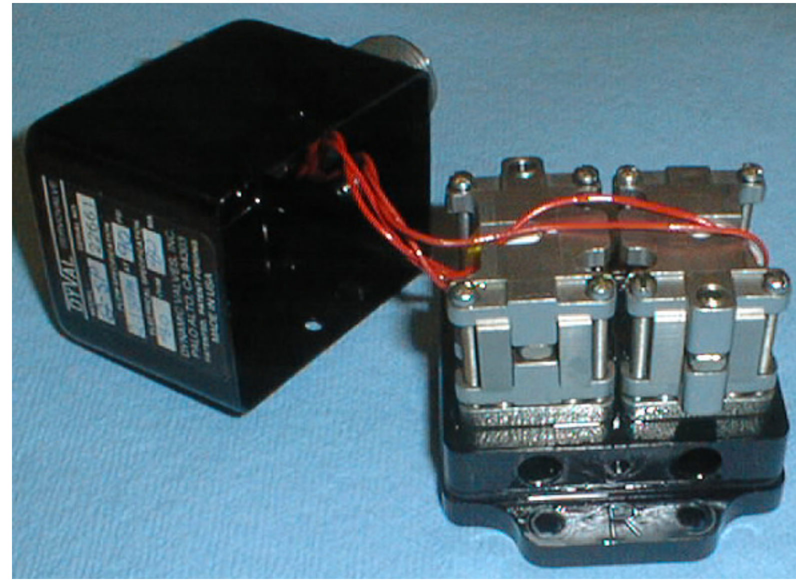
  high viscosity (100x water),
  low velocity (80 microns/ sec.),
  fluid path geometry.

- **Motion with flexures**
- **Offload springs to keep bridge balanced**

  common mode rejection of pump noise

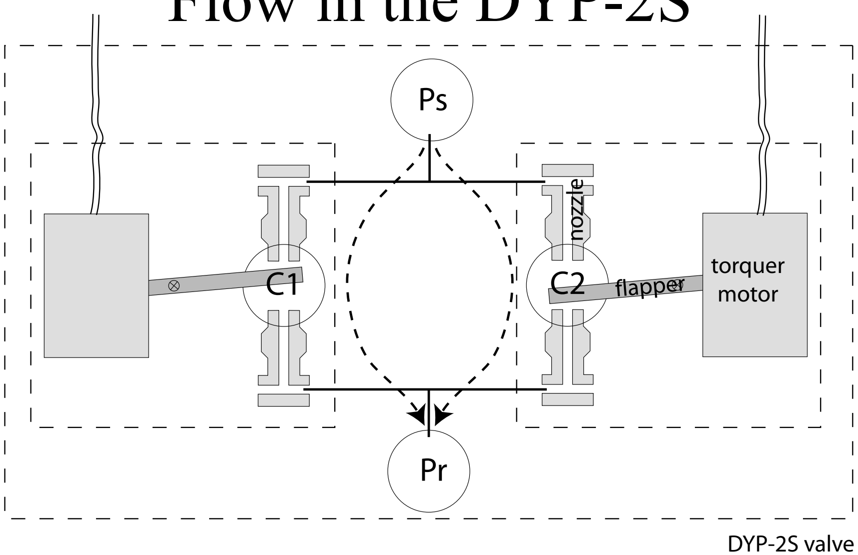
Hydraulic Valve forms the bridge

- Differential bridge in a single valve body
- 4 nozzles – one for each resistor in the bridge
- Original nozzles replaced with custom units shown below right.



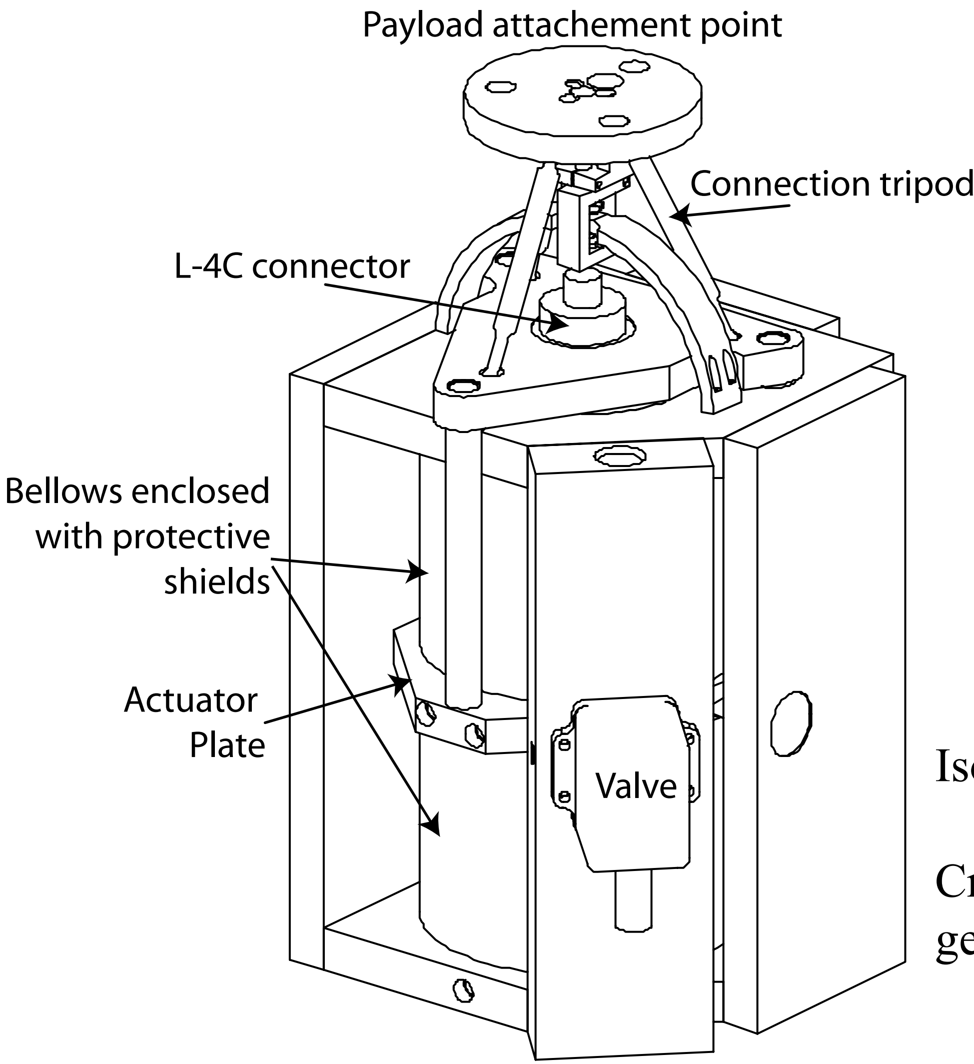
Parker DYP-2S valve

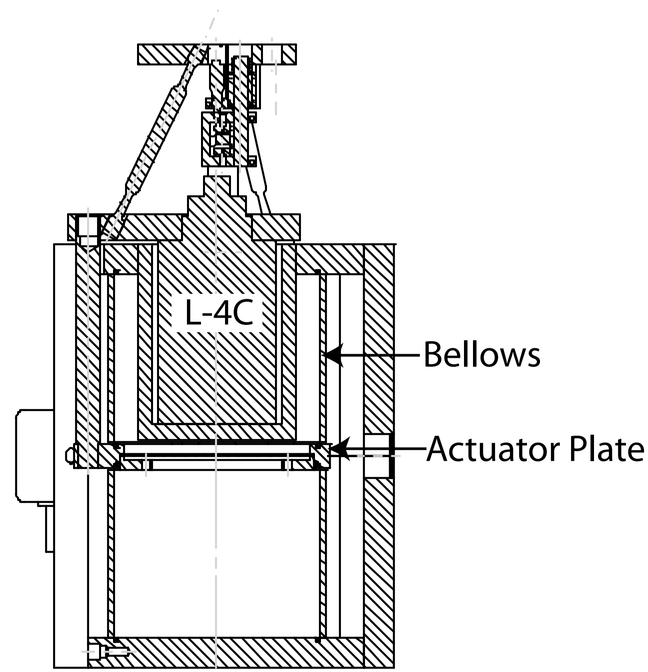
Flow in the DYP-2S



The new nozzle

Drawings of the Actuator

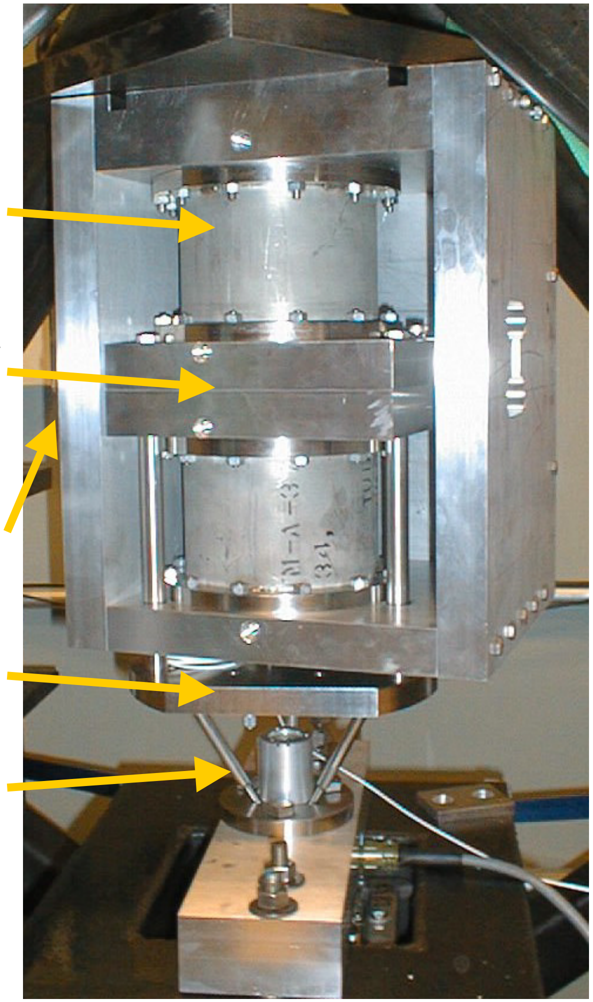




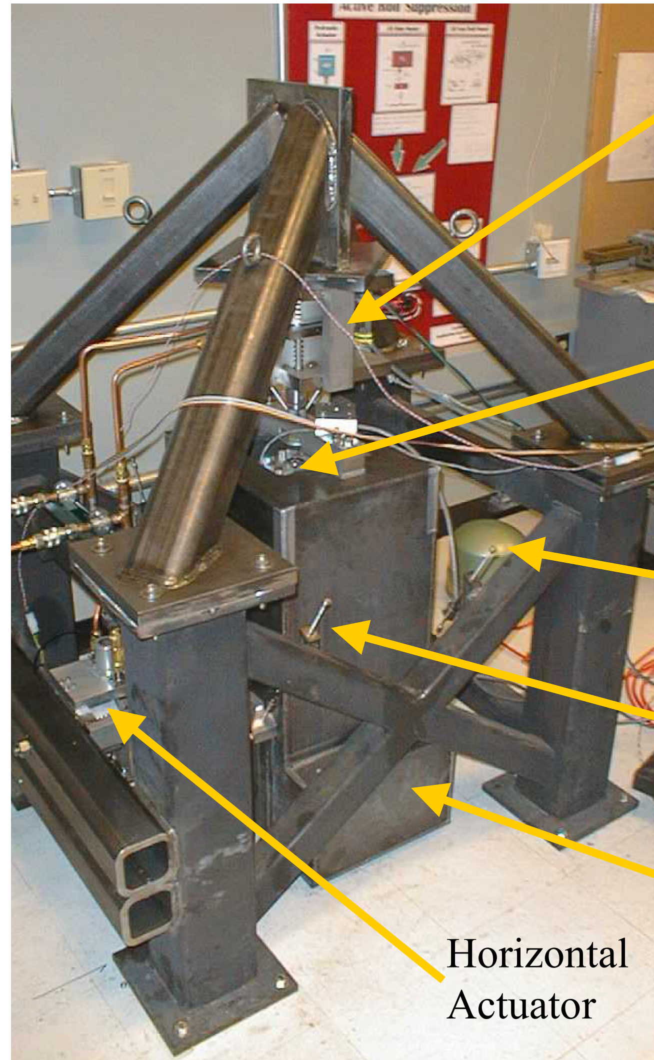
Isometric view left shows major components

Cross section above shows buried L-4C geophone

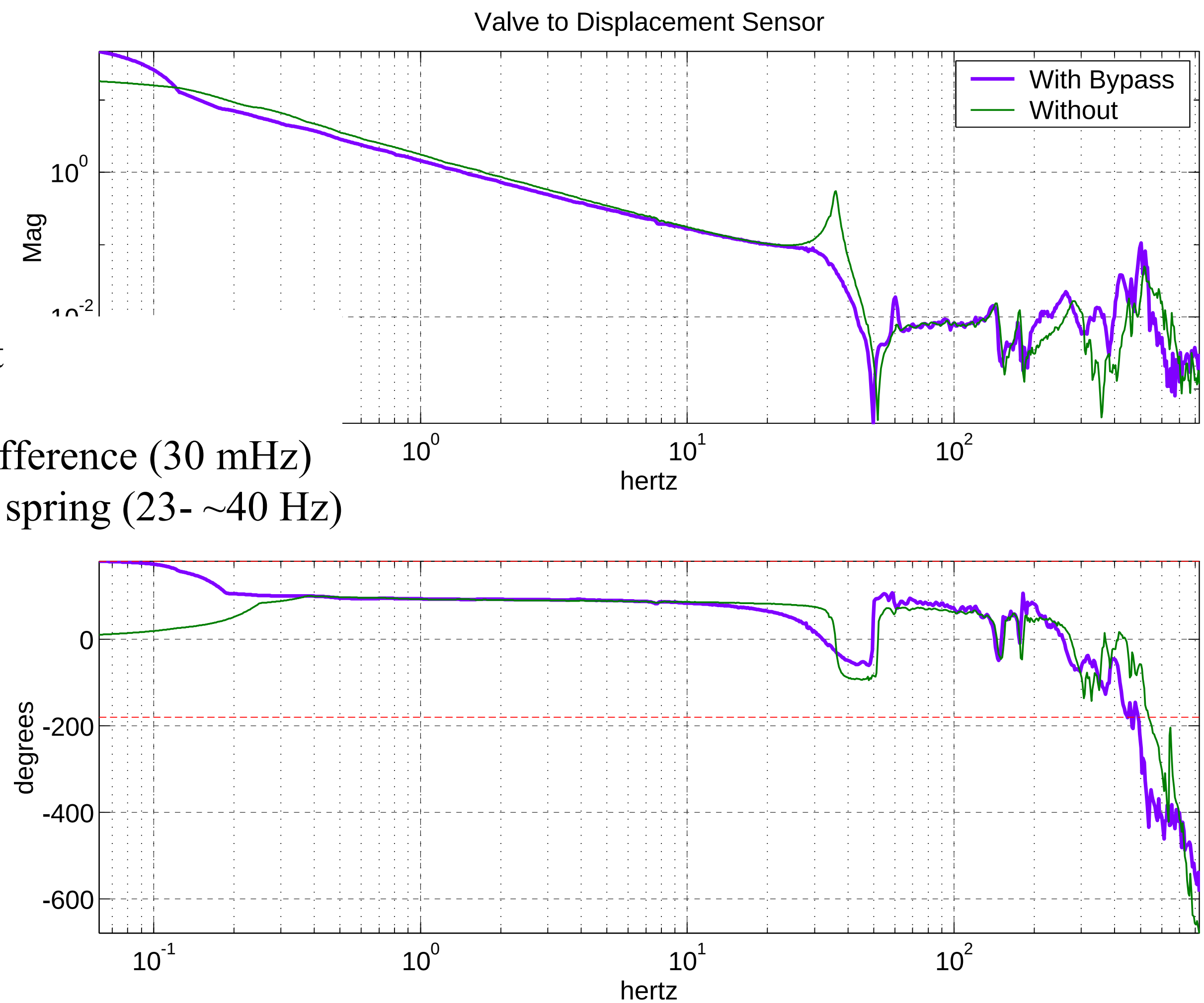
The Test Platform at Stanford



Vertical Actuator –version 2

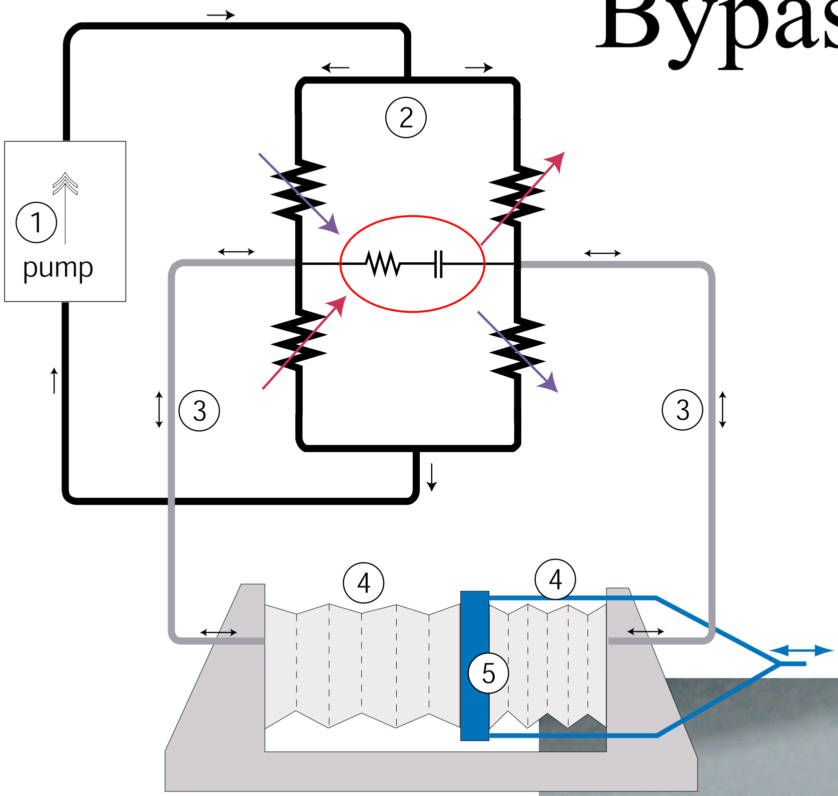


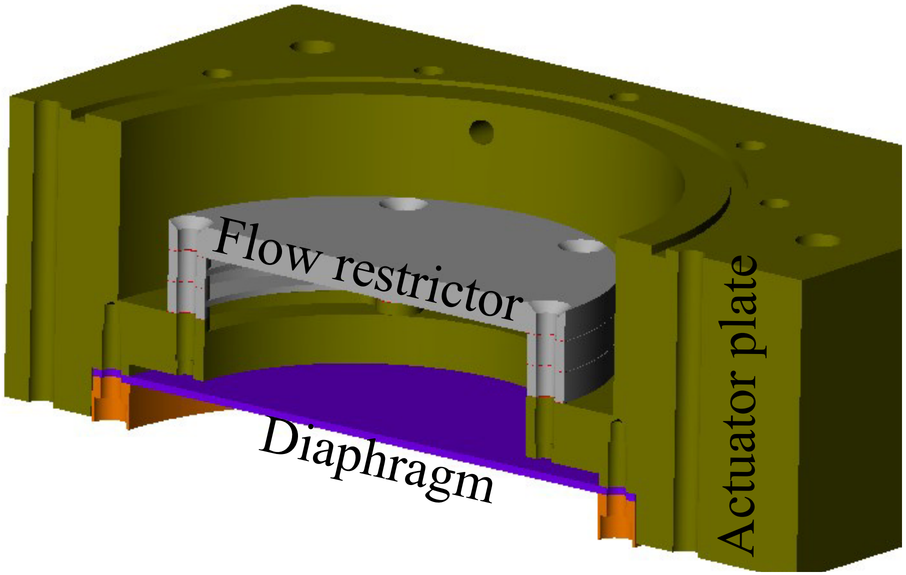
Test Platform Dynamics



Valve drive -> Payload displacement
System acts like an integrator until:
- offload spring balances pressure difference (30 mHz)
- payload resonance against bellows spring (23- ~40 Hz)

Bypass Network





Performance Measures

Bandwidth = 20-30 Hz,
mass/ spring resonance of actuator against the payload.

Max range = +/- 1 mm, to accommodate long term locking,
set by bellows geometry.

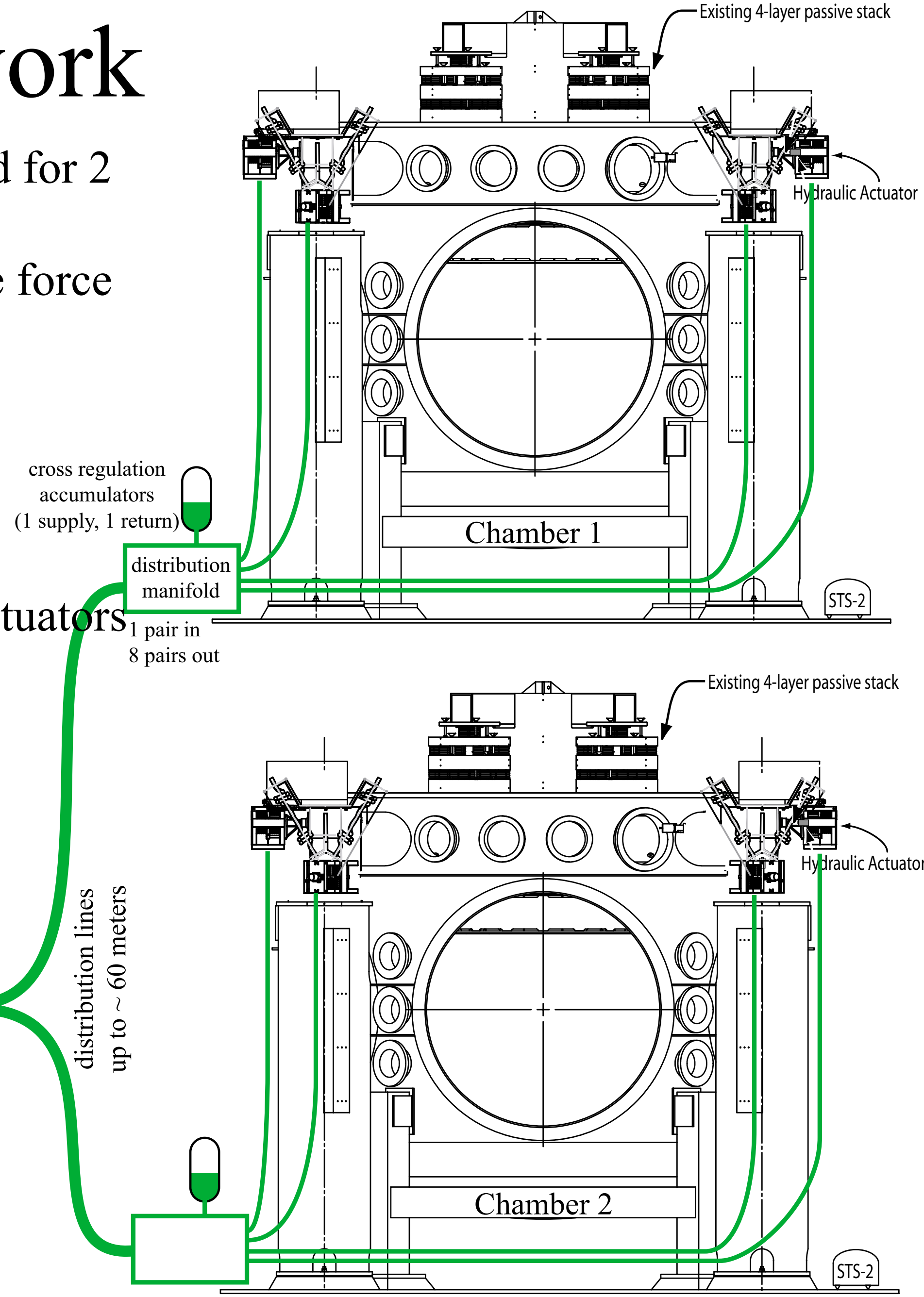
Velocity = 80 microns/sec, well beyond typical peak velocity,
set by bellows area and bridge flow.

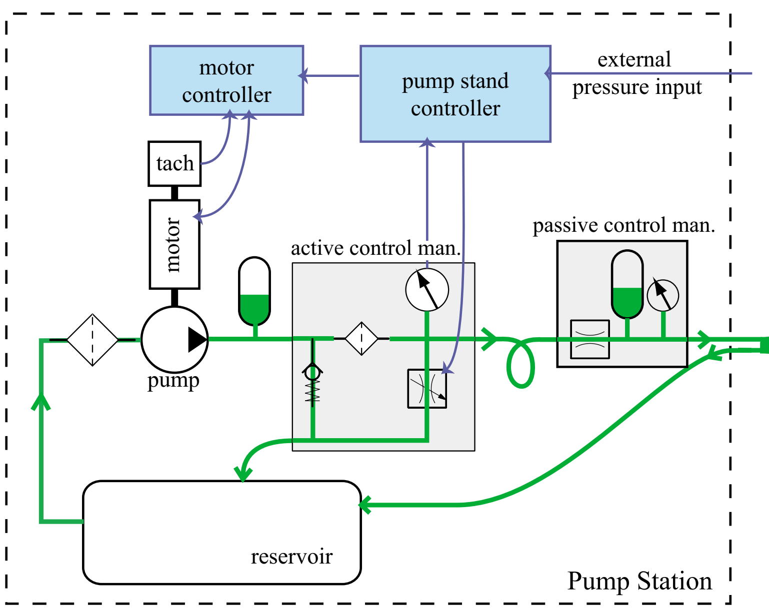
Three dominant noise sources:

- Ground motion coupling
  (limited by loop gain, sensor matching, low frequency tilt)
- Sensor noise
  (limited by cost, dynamic range, space)
- Pump noise
  (limited by line dynamics, acceptable power loss to filtering)

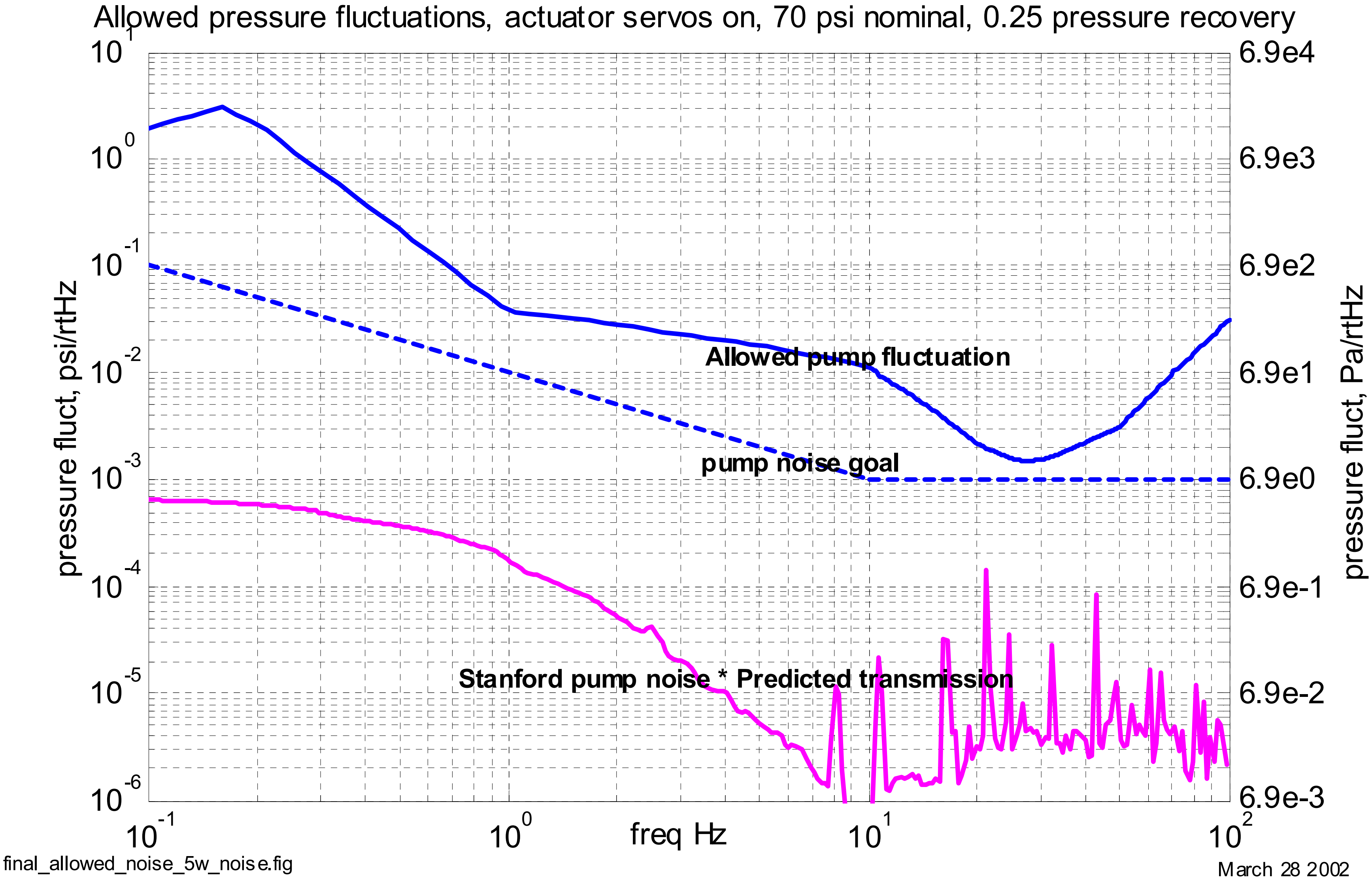
Distribution Network

- Pump station provides source of quiet fluid for 2 vacuum chambers.
- Pump pressure fluctuations couple to drive force when the hydraulic bridge is unbalanced (lose common mode rejection.)
- Pump fluctuations are controlled both actively and passively.
- Accumulators at the distribution manifold attenuate the cross-modulation amongst actuators

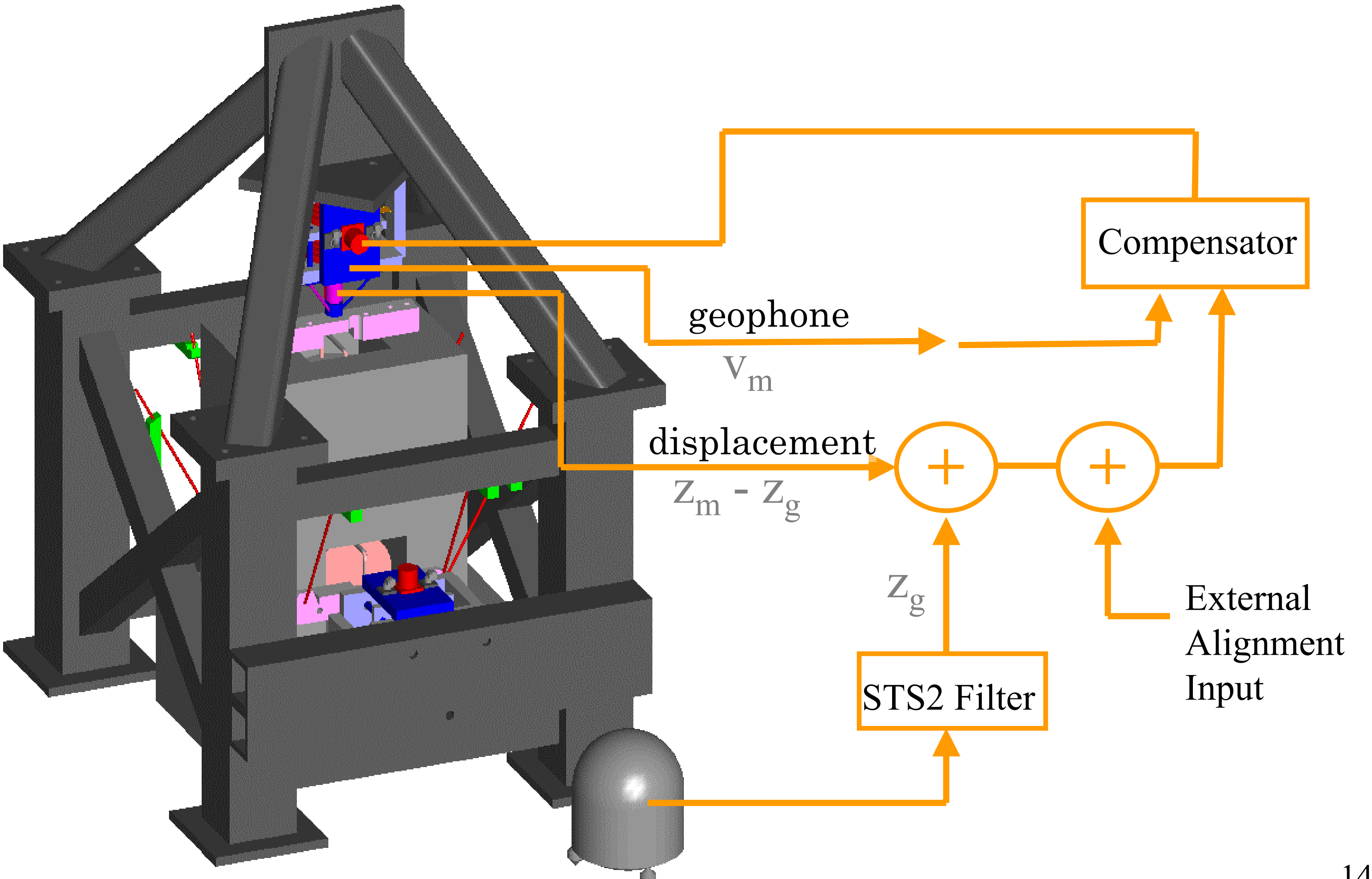




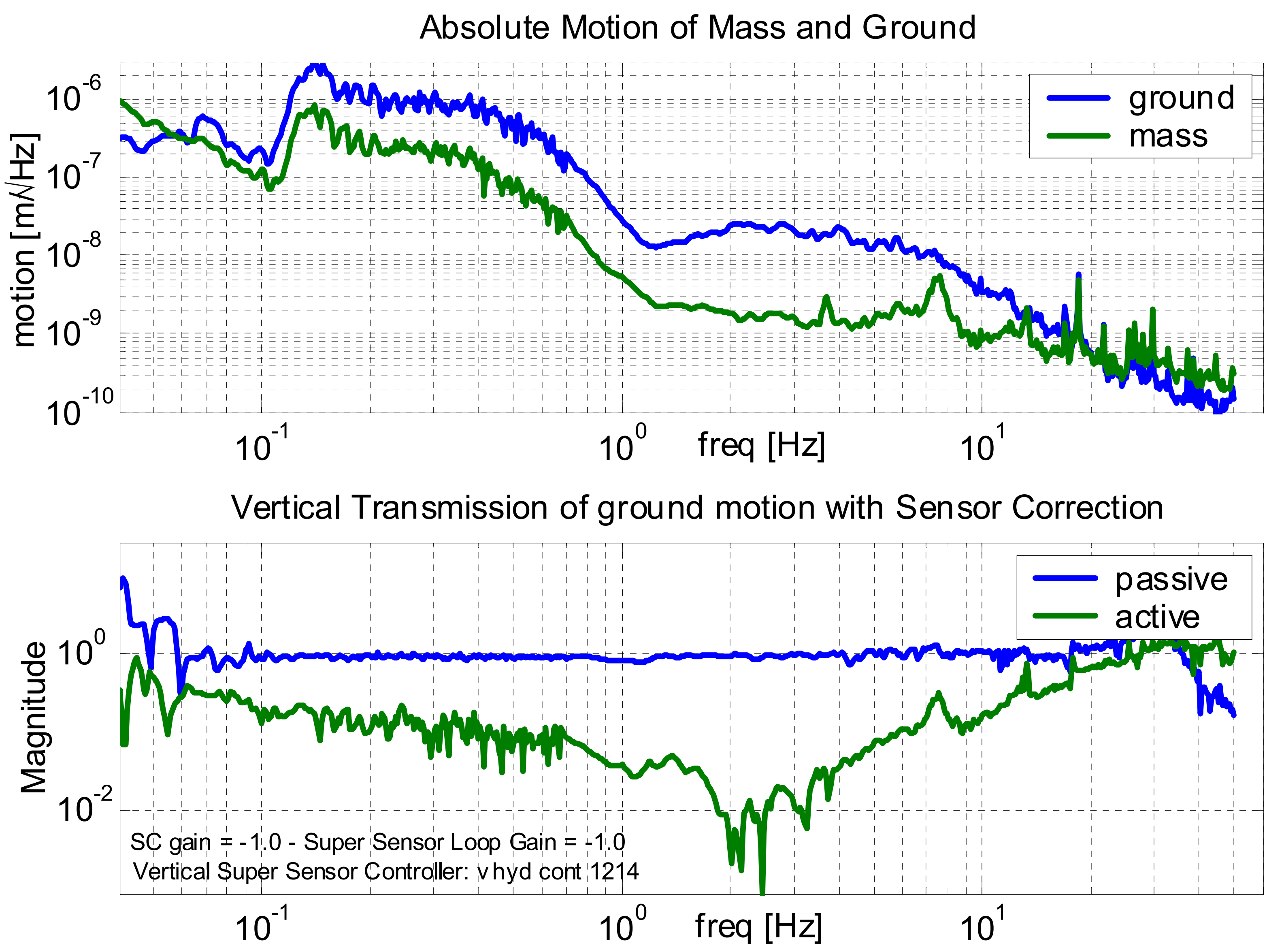
Allowed Pump Noise



Performance of the Test Stand



Vertical Isolation



Test Plan

There are 3 versions of the actuator:

version 1 – welded design, testing complete

version 2 – bolted design, testing underway at Stanford

version 3 – welded design, for use in LASTI, design almost complete

Major Test Areas

•Characterize the version 2 actuator at Stanford and new valve at Stanford.

•Prove pump station noise at Caltech.

•Build and test all the interface and control electronics

•Use LASTI to practice installation and cleanliness techniques

•Install the system at LASTI

Conduct real Sys-ID

Isolated and Align 6 DOF with 8 Actuators

Integrate with LDAS

That's all, folks!

Extra Slides

Time Line

April 12: Preliminary design review

Next stage: Testing in LASTI

2 DOF, simple structure -> 6 DOF, dynamic payload

(tests continue at Stanford & Caltech)

April: Design of LASTI actuator and frame finalized

parts start arriving

May: housing arrive

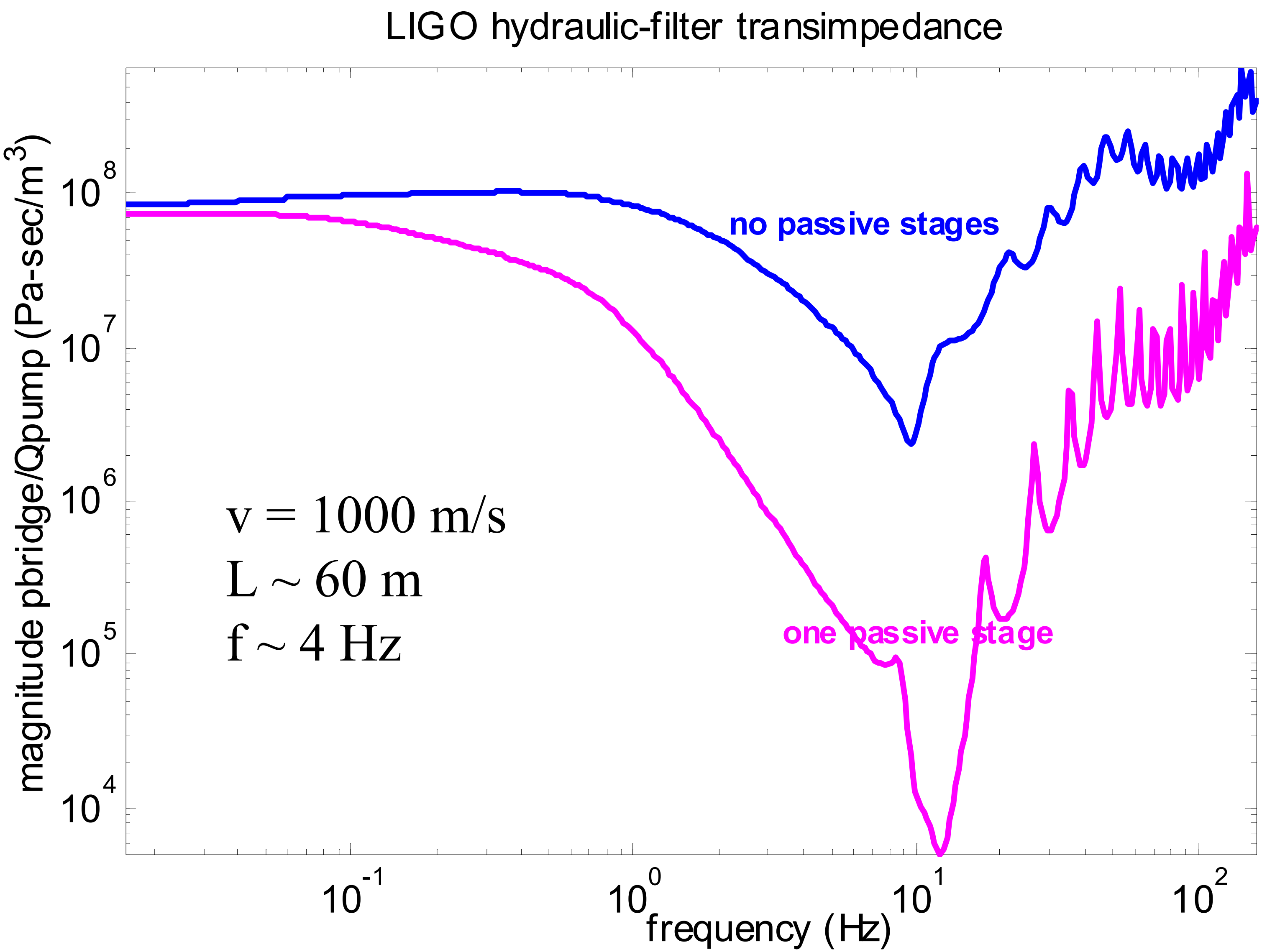
June: Sensors, actuators, fixturing arrive at LASTI

July: Springs arrive

Aug-Sept: Assemble system

Oct: Begin LASTI system tests

Pipeline dynamics impact filtering



Equations of Motion

Mass

$$m\cdot\frac{d^2}{dt^2}z = -\left(p_2 - p_1\right)\cdot A - k\cdot\left(z - z_g\right) + D$$

Volumes

$$\frac{\frac{d}{dt}p_1\cdot V}{\beta} = Q_1 - A\cdot\left(\frac{d}{dt}z - \frac{d}{dt}z_g\right)$$

$$\frac{\frac{d}{dt}p_2\cdot V}{\beta} = Q_2 + A\cdot\left(\frac{d}{dt}z - \frac{d}{dt}z_g\right)$$

Flow

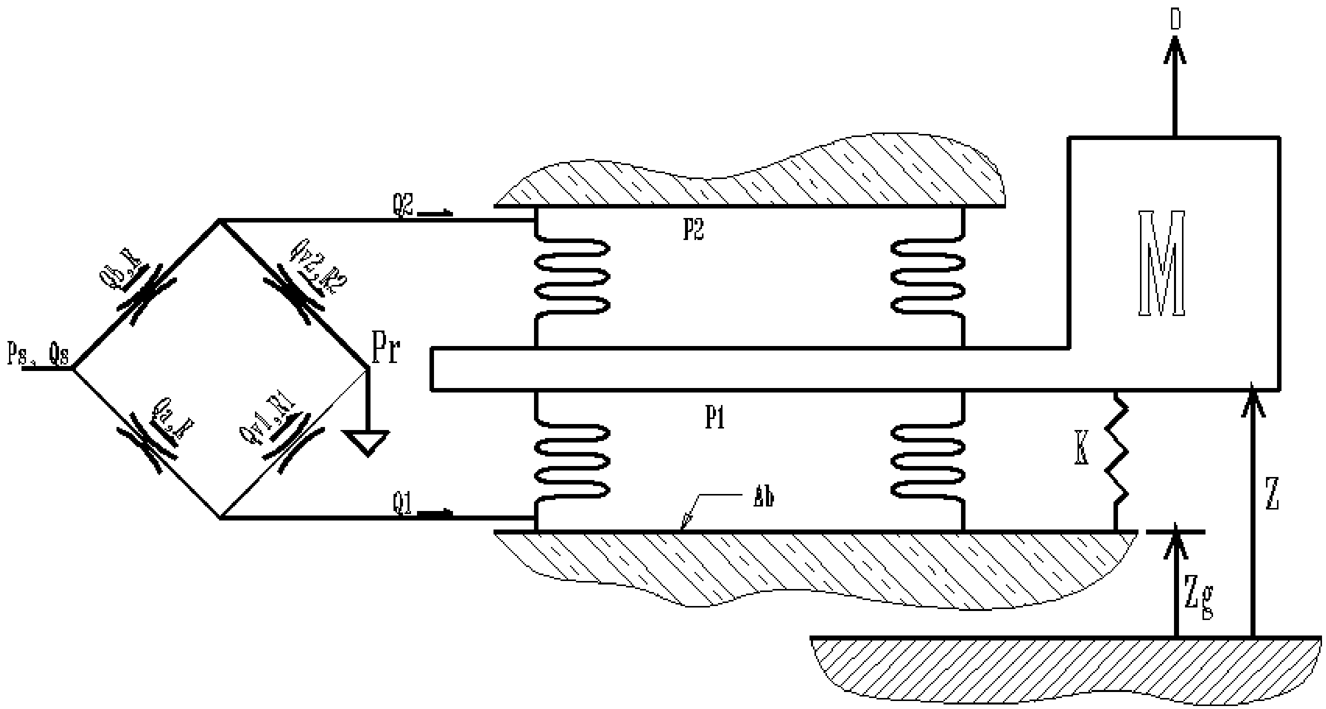
$$\frac{p_s - p_1}{R} - Q_1 - \frac{p_1 - p_R}{R_1} = 0$$

$$\frac{p_s - p_2}{R} - Q_2 - \frac{p_2 - p_R}{R_2} = 0$$

Valve

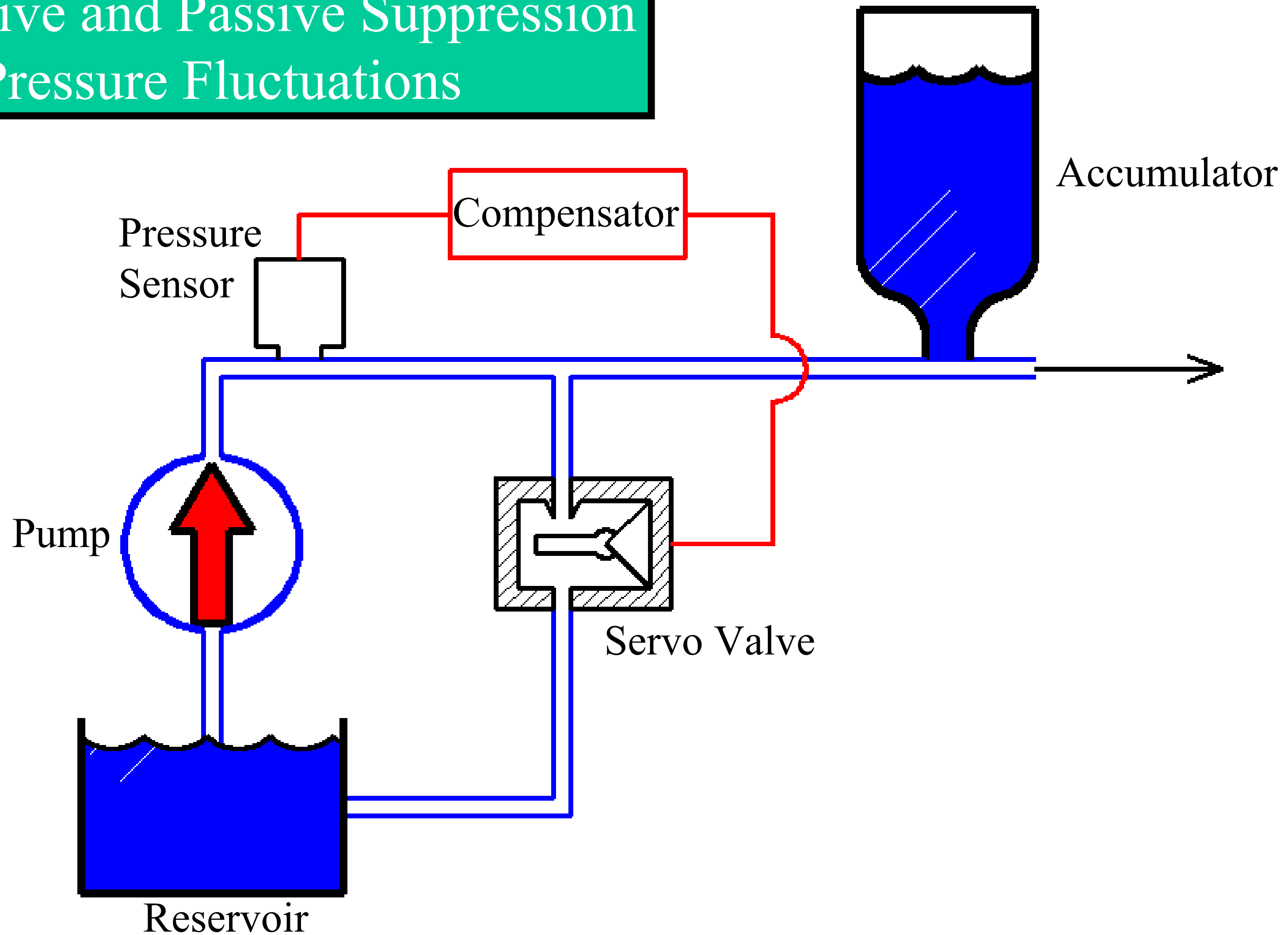
$$R_1 = \frac{R}{1 + Cv\cdot i}$$

$$R_2 = \frac{R}{1 - Cv\cdot i}$$

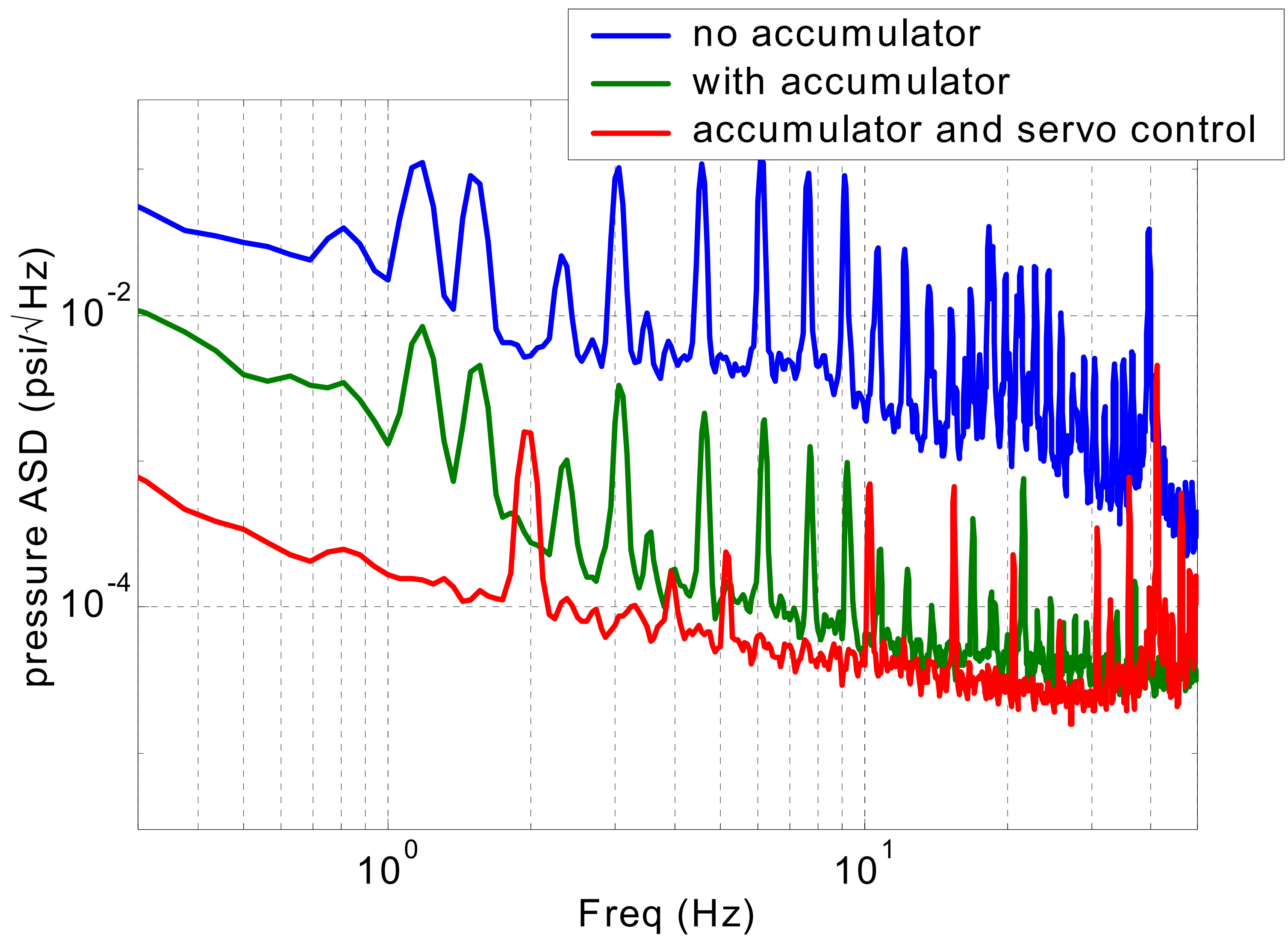


Conditioning a Pressure Source

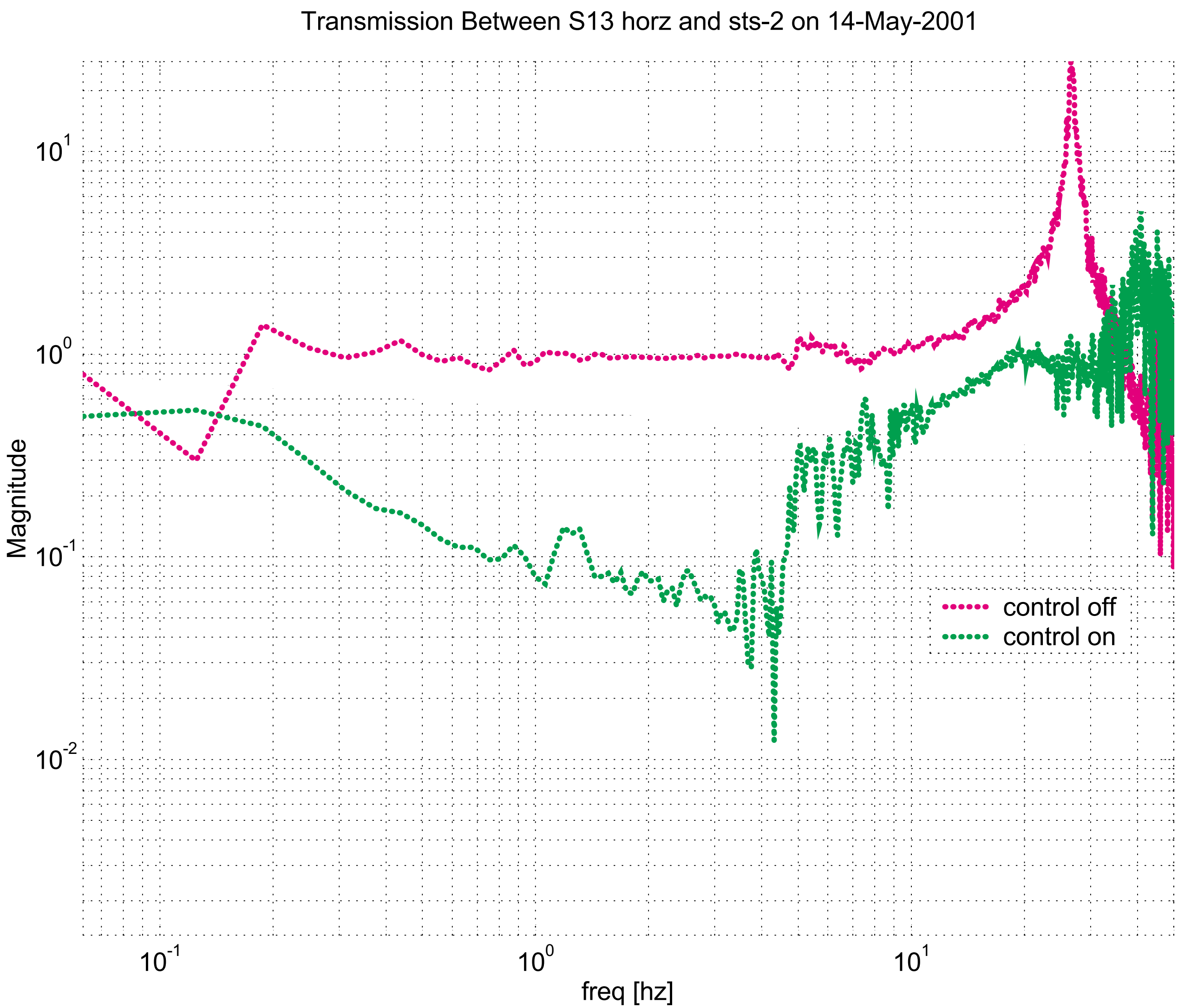
Active and Passive Suppression of Pressure Fluctuations



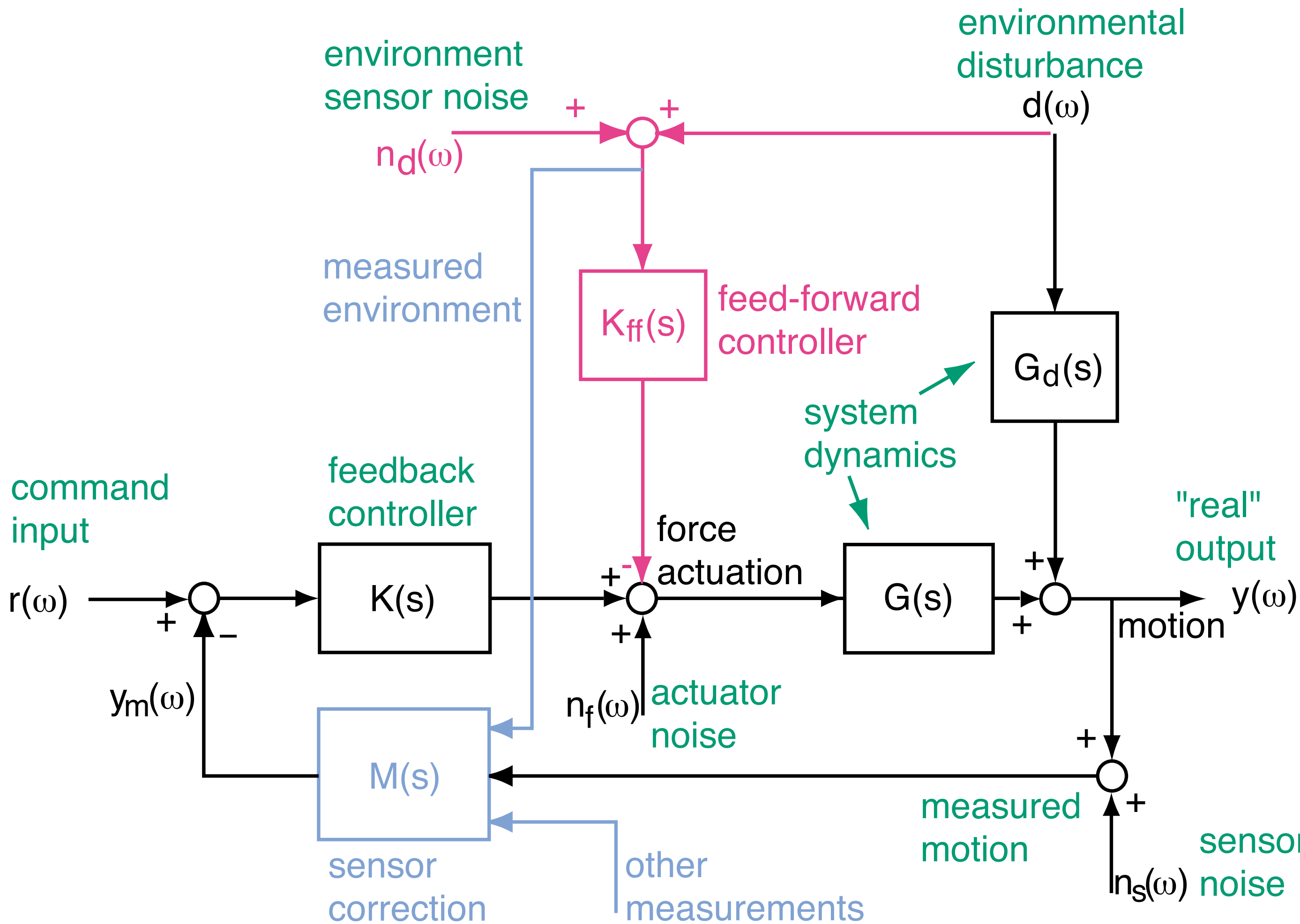
Pressure Noise at the Actuator



Horizontal Isolation



More complete servo diagram



MEPI

- electroMagnetic External Pre-Isolator
- Backup alternative to the Hydraulic actuator approach
- Goal: maximum commonality with HEPI

- Same performance requirements
- Same mechanical superstructure
- Same servo sensors

- Different actuator (force instead of displacement)
- Different servo (how different is TBD)

Motivations for MEPI

- Increased robustness of EPI solution – a second path
- Familiar technology (in contrast to hydraulics, for me)
- Reduced risk of contamination

Choice of alternate actuator

	PZT	**Electromagnetic motor**
Force	>1000 N easy to get	200 N hard to find
Stroke	30 microns hard	1cm easy
Servo similarity to hydraulic actuator	Rather similar	Rather different
Servo limits	High-Q internal resonances	Probably high internal resonances, maybe low Q
Earthquake response	Probably broken	Maybe broken
GW-band character	Probably ‘stiff’	Maybe an 8 Hz double pole
Heat dissipation	Probably negligible	~4 W RMS, 13 W peak
Magnetic field – sensor/TM	Not an issue	TBD, may be significant
Mechanical interface	Requires constraint and flexible coupling for multiple axes	Adequate clearance to allow fixed armature and magnets
Electrical interface	HV amplifiers	Low-voltage systems
Linearity	Requires closed-loop; hysteretic	Linear
Self noise	May create impulsive noise	As quiet as the amplifier
Reliability concerns	Humidity; breakdown; fragility	Good reliability if not overdriven

Derived requirements: Force

- For MEPI, stroke requirements lead to force requirements
  - » exerted against springs; dominates over inertial forces
- Vertical:
  - » 40 micron microseismic pk-pk requirement leads to…
  - » Force requirement of 60 N pk-pk per actuator
  - » Used to provide pitch actuation
- Horizontal:
  - » 300 micron pk-pk requirement leads to…
  - » Force requirement of 112 N pk-pk per actuator
  - » Used to provide microseismic and tidal correction, in yaw and in translation

Derived requirements: misc

- Depend upon play of coil in field ass'y to accommodate perpendicular motions – coil is free
- 1 mm free play, perpendicular (for 300 micron motion)
- 1%-10% accidental (perpendicular) forces, for ±500 μm
  - » 200 μm initial alignment tolerance
  - » Actual stroke on axis is 5 mm
- Servo characteristics
  - » ≥50 Hz (to match hydraulic actuator servo design)
- Safety: caging needed
  - » Relatively 'soft' suspension (stiffer than stack!)
  - » Behavior in an earthquake different than HEPI – better?

Risks for MEPI: Magnetic fields

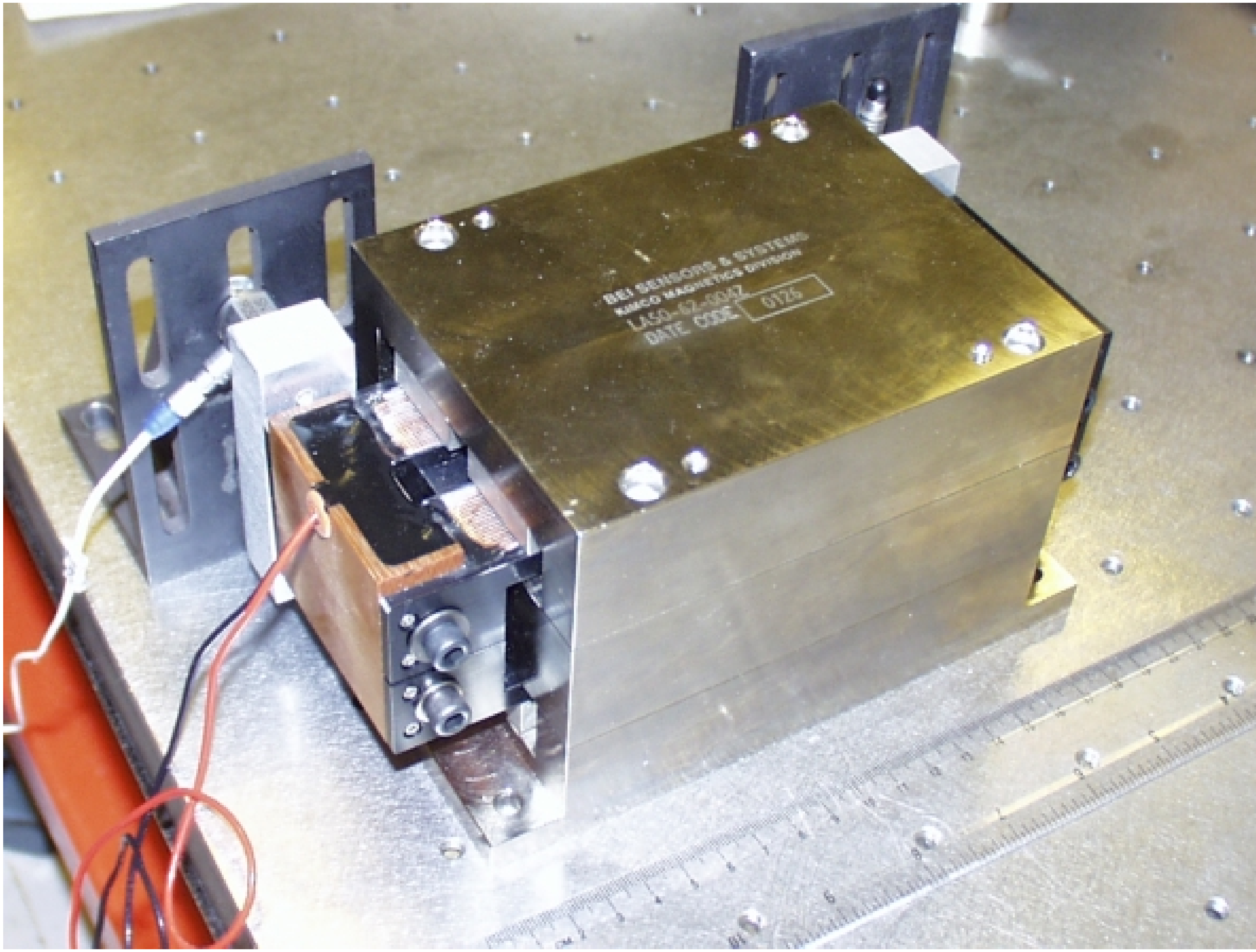
- Coupling to geophone (voice coil sensor)
  - » Possible instability or performance compromise
  - » Measurements show this probably manageable –
    - – ~10^-2 at 20 Hz , increases with frequency
  - » Can increase geophone-actuator spacing (loss of collocality…), add shielding if needed
- Coupling to test mass
  - » Control frequencies: unintended alignment changes
  - » GW frequencies: noise coupling due to residual control currents
  - » Observe ~10^-11 Tesla/rHz in LVEA in GW band
  - » GW band from MEPI ~10^-17 Tesla/rHz

Risks for MEPI: Heat dissipation

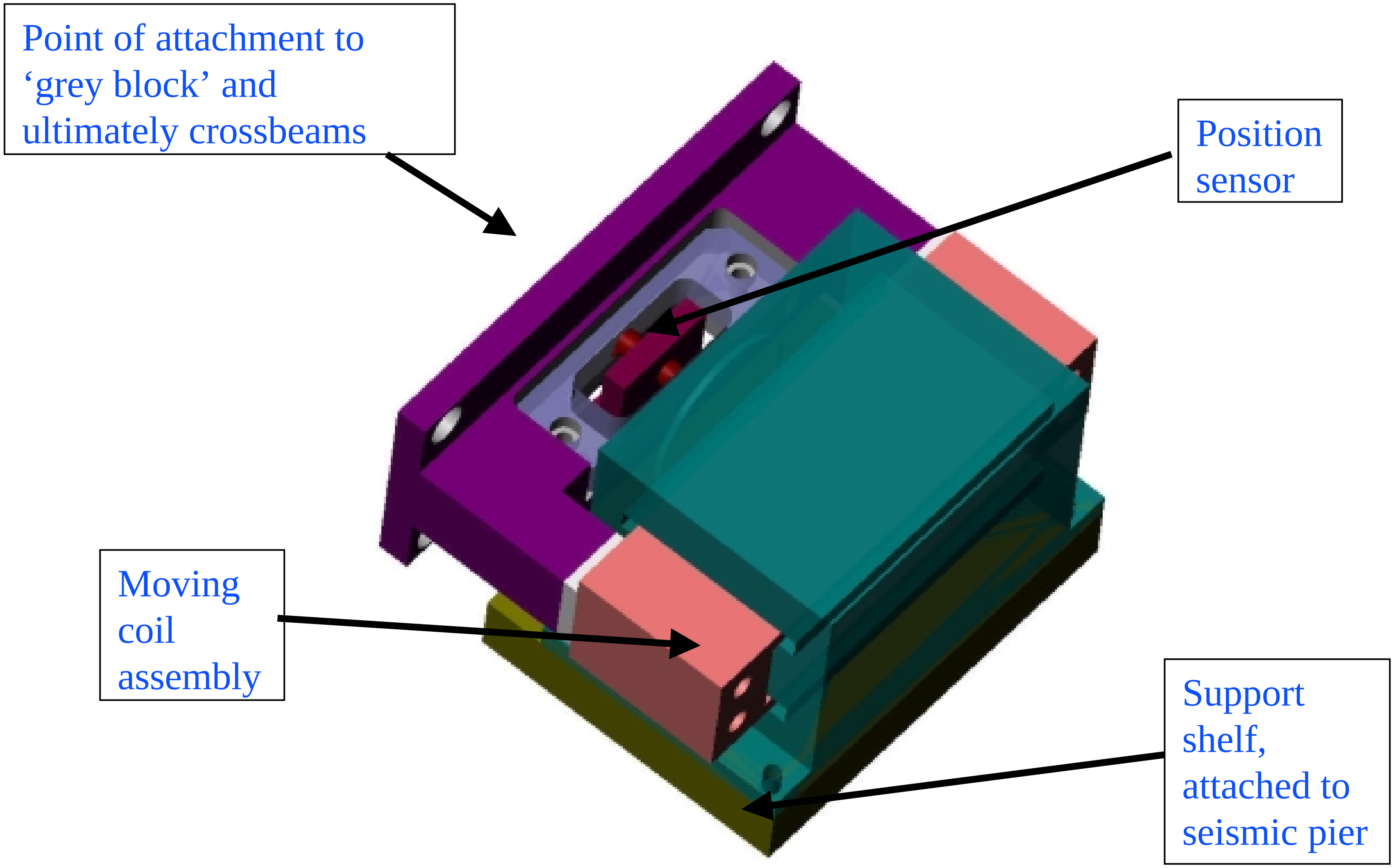
- Heat of inefficiency into coils
- 4 W RMS, 12 W peak (where peak held for ~1 hour)
- Could change dimensions of mount, length of springs, reading of position sensor
- Could lead to servo runaway or oscillation (slow)

- Isolate coil thermally from field, frame; pull heat away from coil without heating structure, coil, sensors
- Try progressively more invasive approaches as needed:
  - » Convection, chimney
  - » Complementary loss (resistor) to keep dissipation constant
  - » Low-velocity cooling air

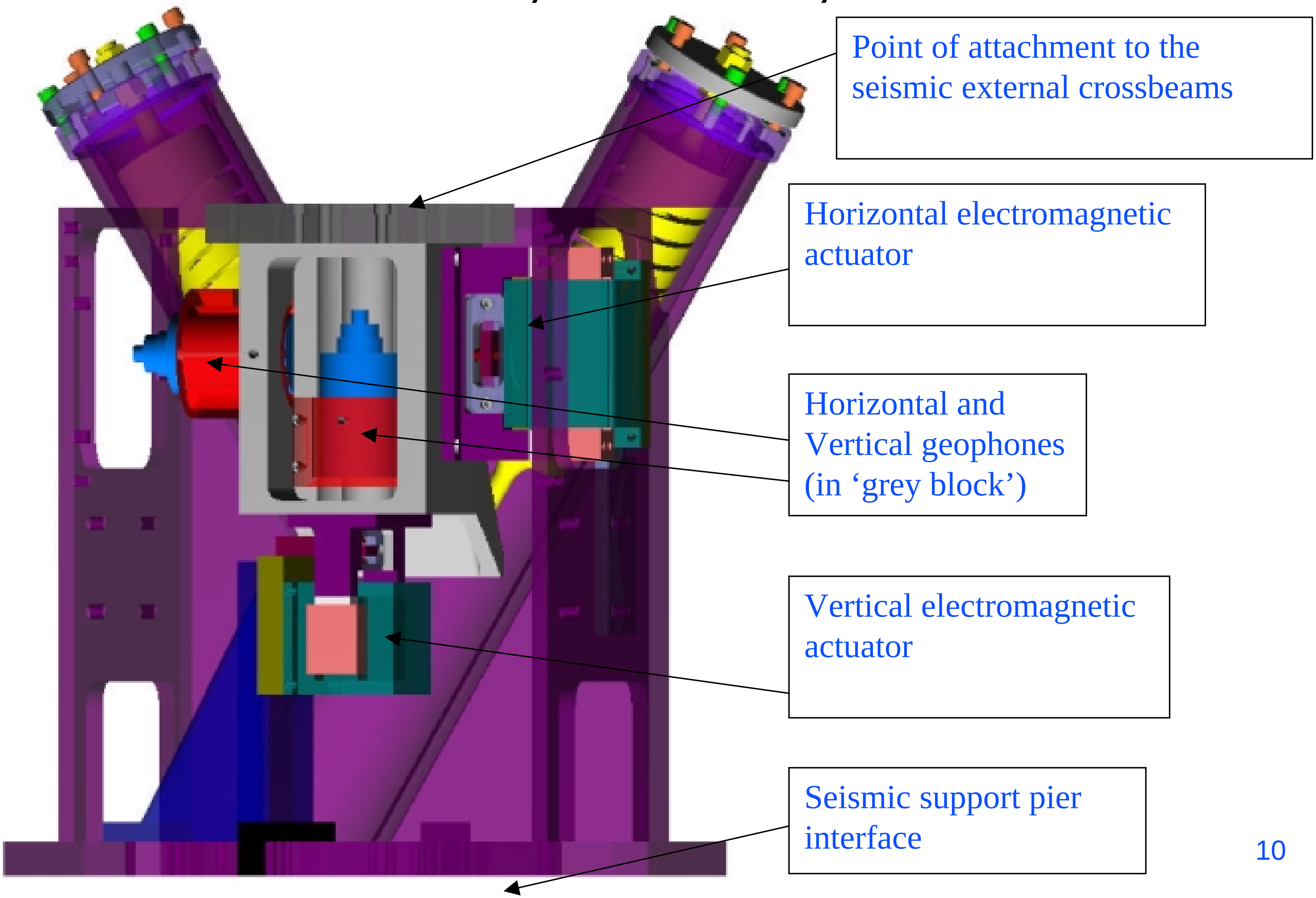
Basic actuator



Actuator with position sensor, frame

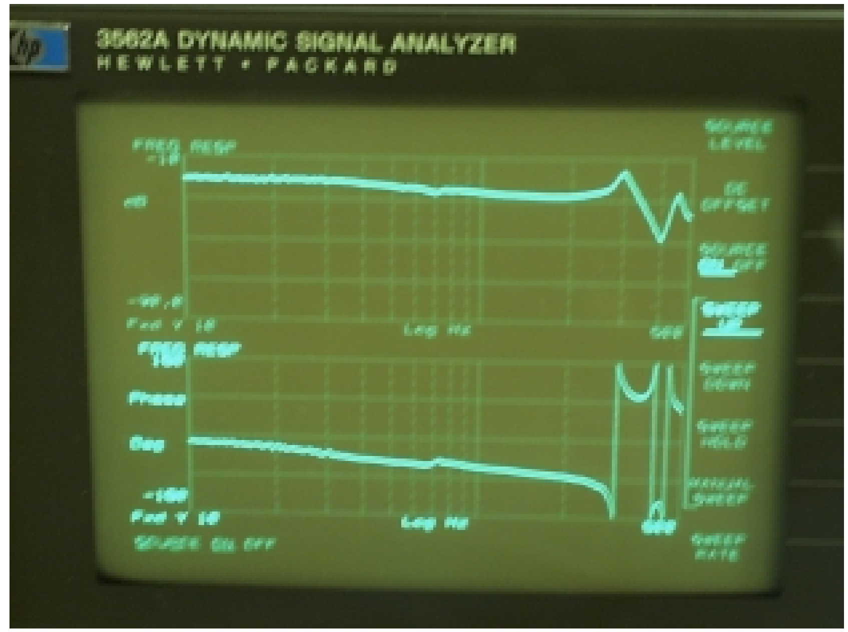


Actuators, sensors, in ‘V-block’



Design status

- Mechanical conceptual design: well advanced
- Actuator characterization: advancing and encouraging
  - » Magnetic coupling probably ok, want to double check #
  - » Mechanical resonance ok (350 Hz)
  - » mm displacements and mrad angles of coil wrt field make <10% force changes, ok
  - » Thermal properties TBD



- Servo design, testing: not even started
  - » Will build on hydraulic servo design, Adv LIGO design
  - » Same actuator used for Adv LIGO
  - » Force instead of displacement – worse? Better? TBD
  - » Actual installed behavior, relationship of actuator to sensors, will all be full of surprises – hopefully not all bad.
- Testing on HAM, one corner ('test stand'), starting in May

Active Internal Damping (AID) notes for the Seismic Retrofit design review

CIT 2002 April

AID working group: Alessandro Bertolini, Riccardo DeSalvo, Francesco Fidecaro, **Szabolcs Marka**[O],Luca Matone, **Virginio Sannibale**[C], Duccio Simonetti, Akiteru Takamori, Hareem Tariq

[O] Overview, [C] Controls

LIGO

AID Requirements

- **Noise contribution in the GW band must be < 1/10 of the Science Requirements Document (SRD), or at the optics table:**
  - »**BSC:**
    - Horizontal: 1.2e-13 m/√Hz at 20 Hz, 2.5e-17 m/√Hz at > 50 Hz
    - Vertical: 5e-13 m/√Hz at 20 Hz, 1e-16 m/√Hz at > 50 Hz
  - »**HAM:**
    - Horizontal: 4e-12 m/√Hz at 20 Hz, 2.5e-16 m/√Hz at > 50 Hz
    - Vertical: 2e-11 m/√Hz at 20 Hz, 1e-15 m/√Hz at > 50 Hz
- **Damping to Q~3 on at least the 1.2 and 2.1 Hz BSC modes, with no 'spillover' in excess of 1.5 x total rms**

Note that these are very stringent rules!

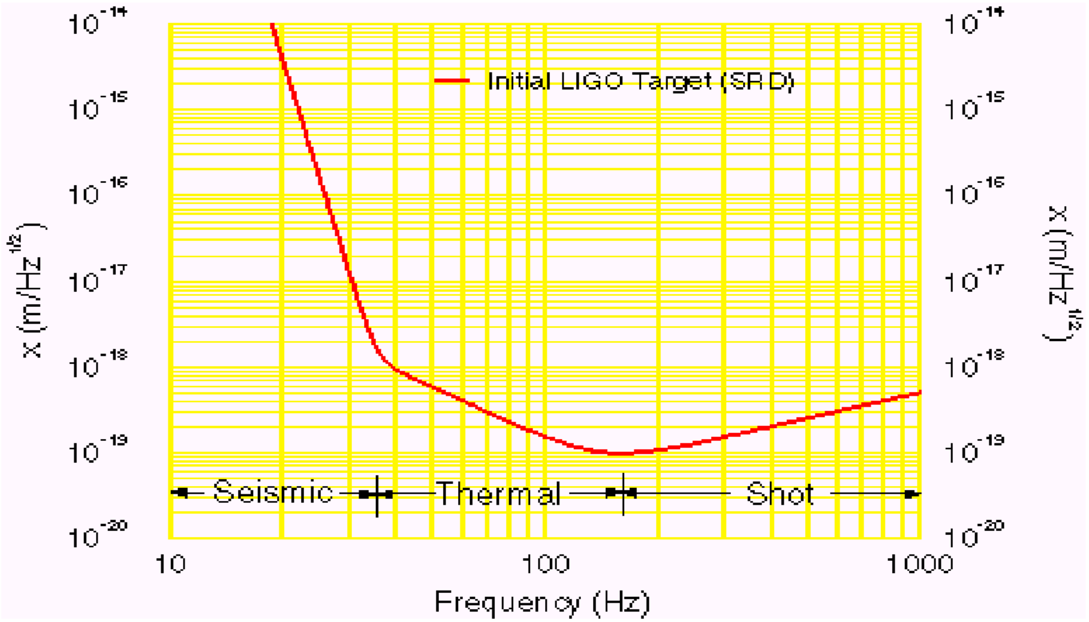


Figure 3: Science Requirements Document (SRD) sensitivity curve.

LIGO

Modest goals

• It is a possible solution to our problem due to excess noise in LLO (LHO?)

• Prototype evaluation steps

  • In-band noise performance simulations based on the characterization of real parts

  • Caltech test bench

    • Control strategies

    • Various geometries

  • LASTI test installation

    • Validation of chosen control strategy

    • Vacuum validation

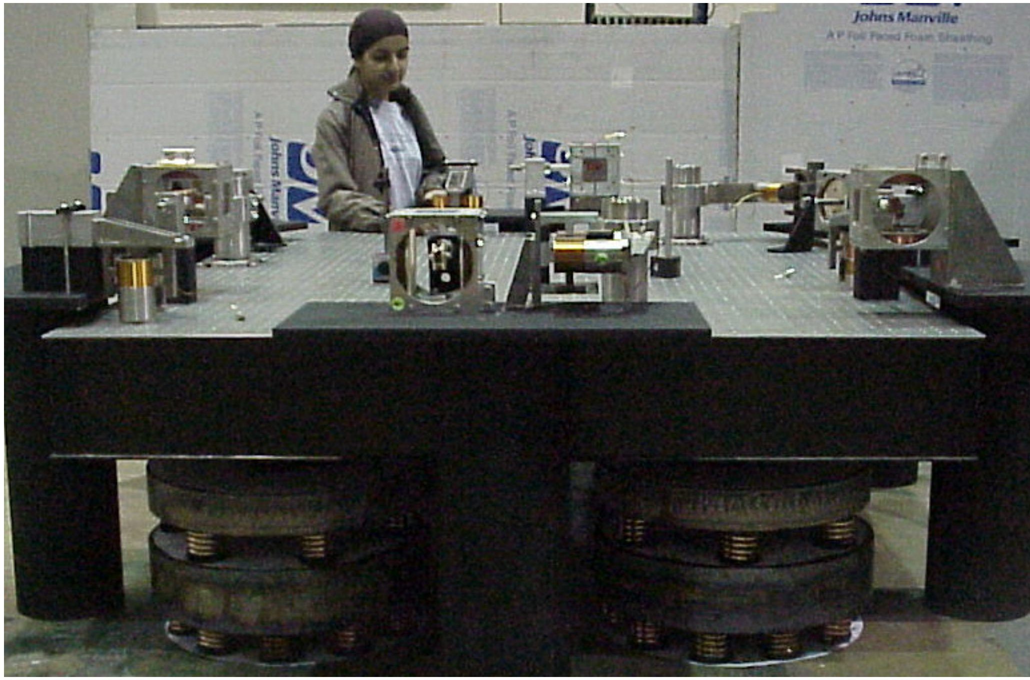
    • Look at noise reduction performance

      • BSC version

• Propose and fully document a system for LIGO

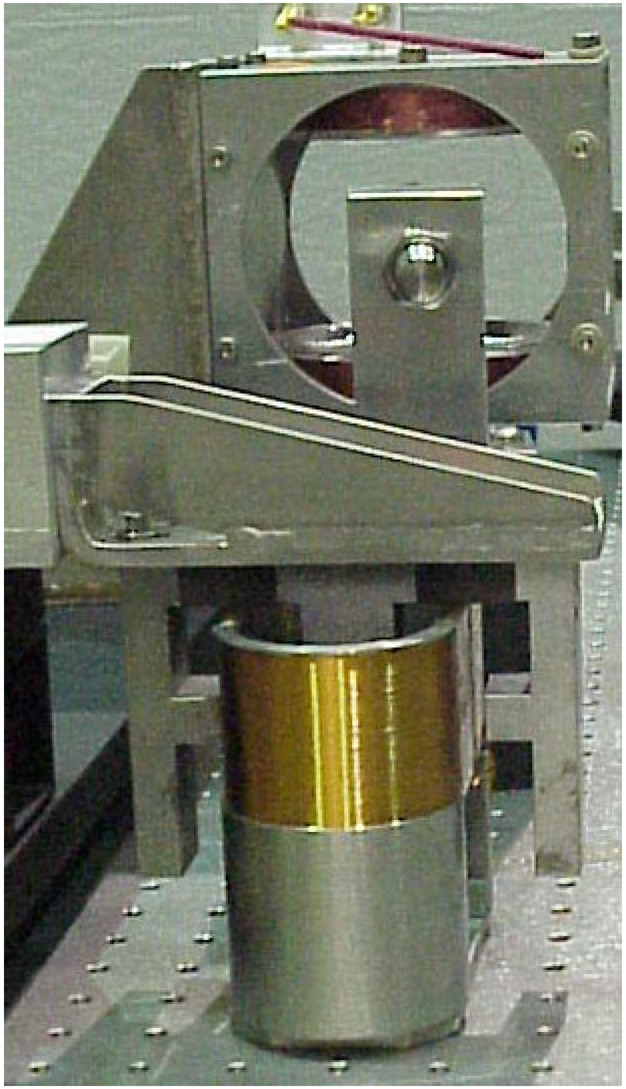
  • Based on the test results

  • Construction group gets comprehensive documentation



Some possible show stoppers and uncertainties

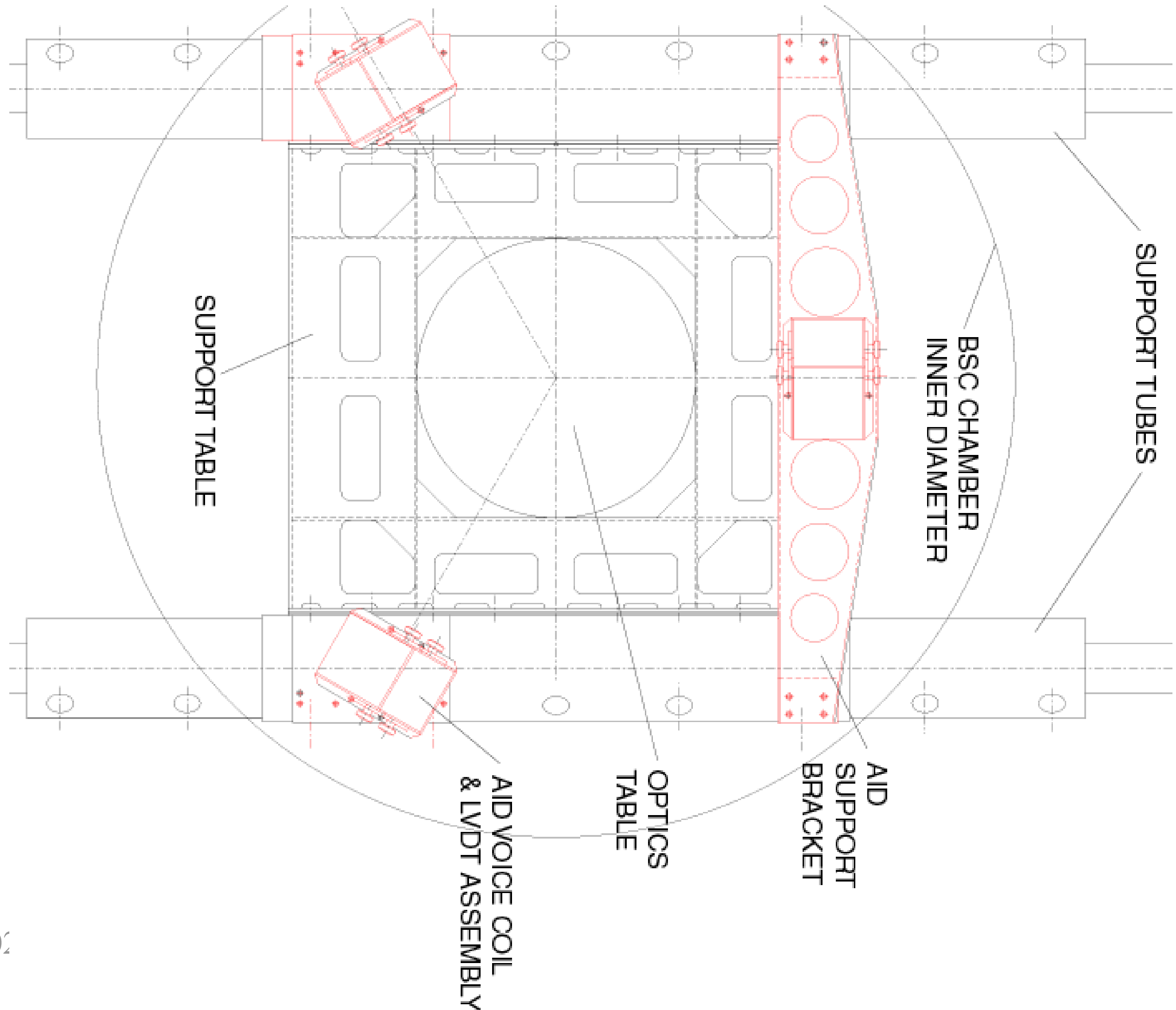
- Vacuum testing of Kapton and parts
- Interface requirement on EPI alignment accuracy is needed to set dynamic range
- Noise problems due to
  - Sensor sensitivity/noise performance
  - Servo
  - Actuator
    - Shorting the table to the EPI platform
    - Electronics noise
    - Coupling degrees of freedom
    - Direct magnetic coupling between the mirror and actuator
- Potential barriers for installation
  - Vacuum waterload and contamination hazards
  - Realignment is probably necessary
- HAM is probably easier to tame than a BSC…



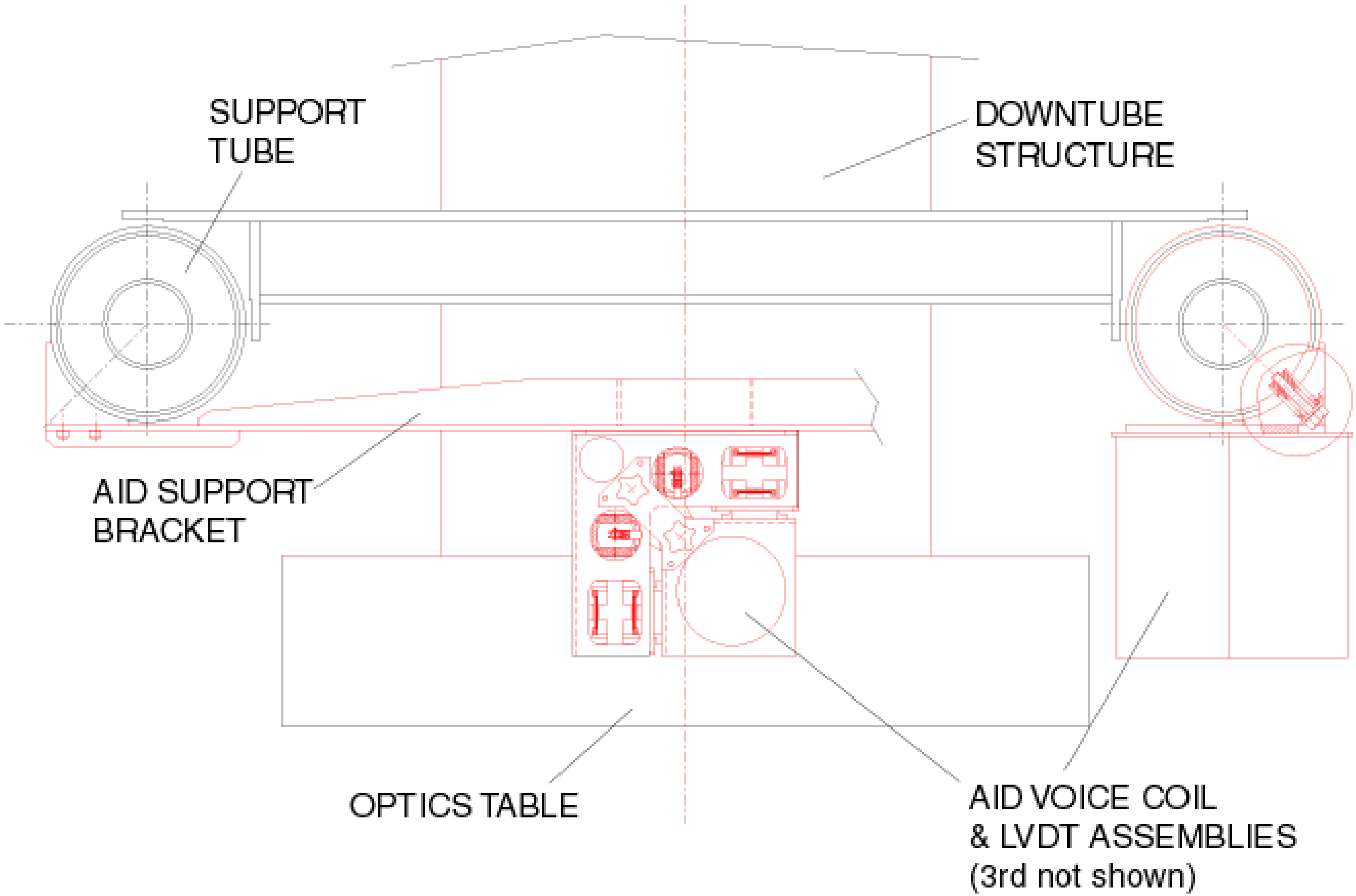
Current strategy and scope

- Use existing, vacuum qualified and known designs and hardware to proceed rapidly
- Construct test systems for “real life” checks
- Find and validate viable control strategies
- Explore the limits of practically achievable performance
- Evaluate the viability and performance of a BSC mounted system
- Find and eliminate or point out possible show stoppers
- Design a possible production system

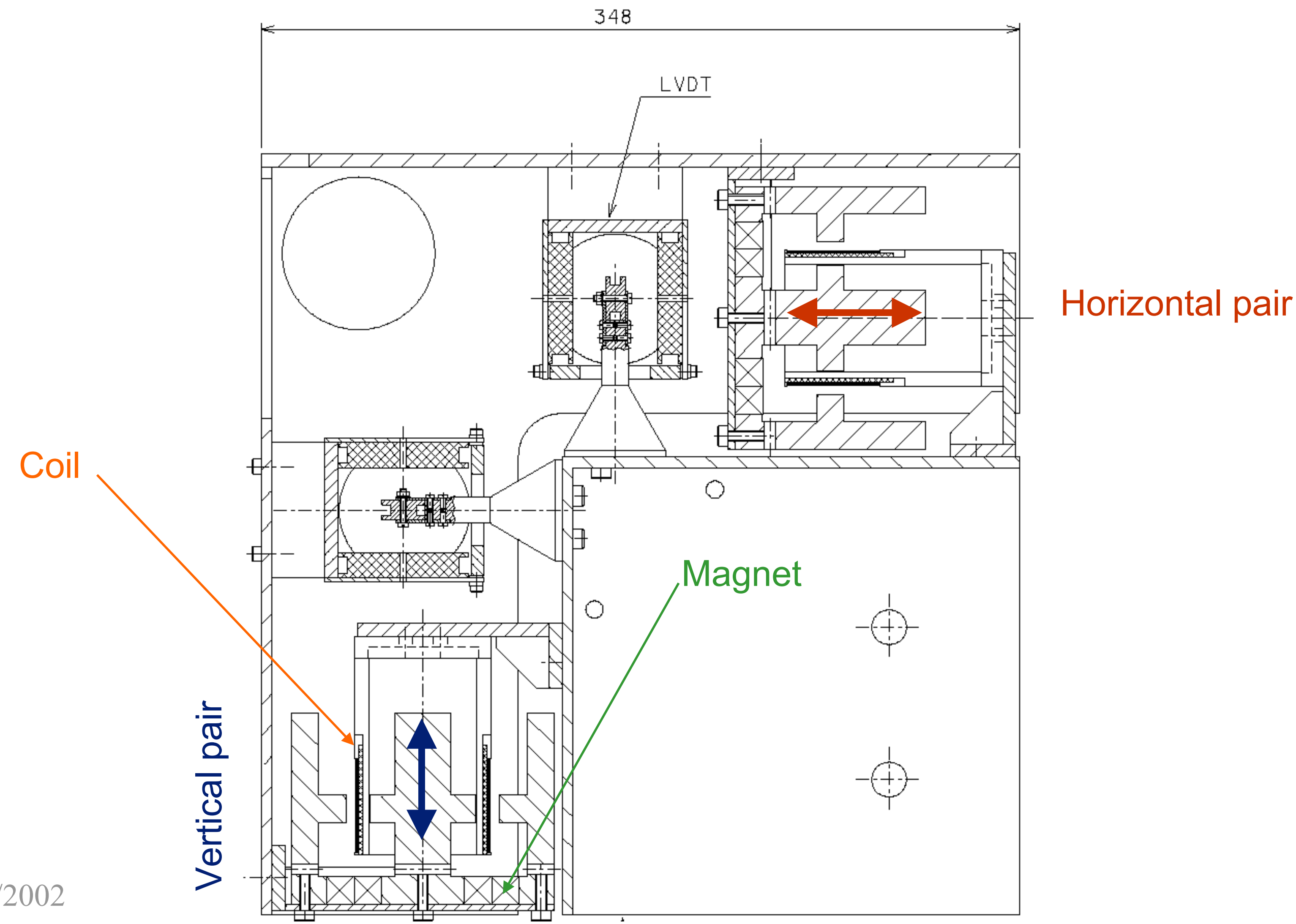
AID: LASTI Test System Conceptual Layout: Top View



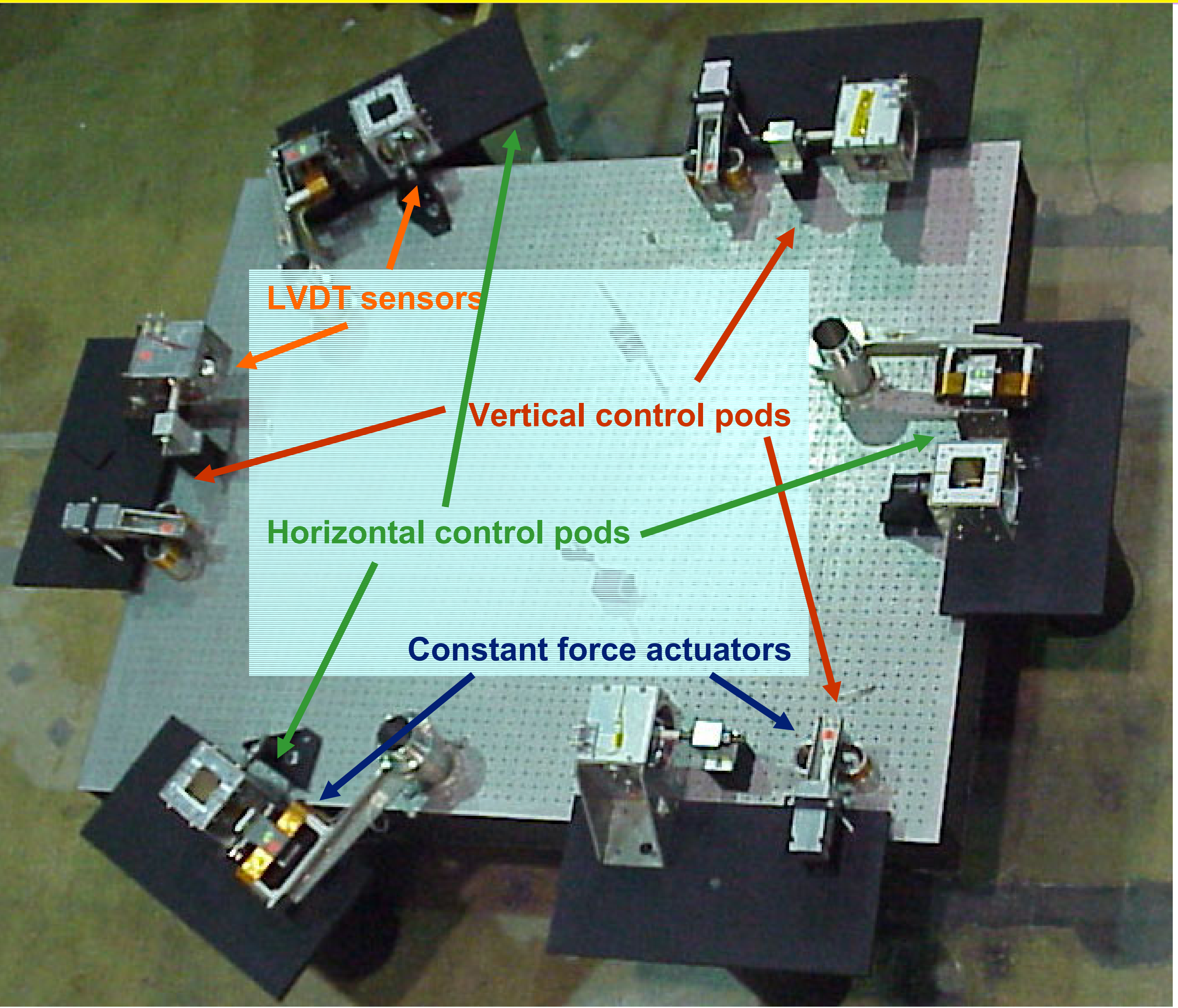
AID: LASTI Test System Conceptual Layout: Side View



AID: LASTI Test System
Conceptual Layout: Sensor-Actuator pod

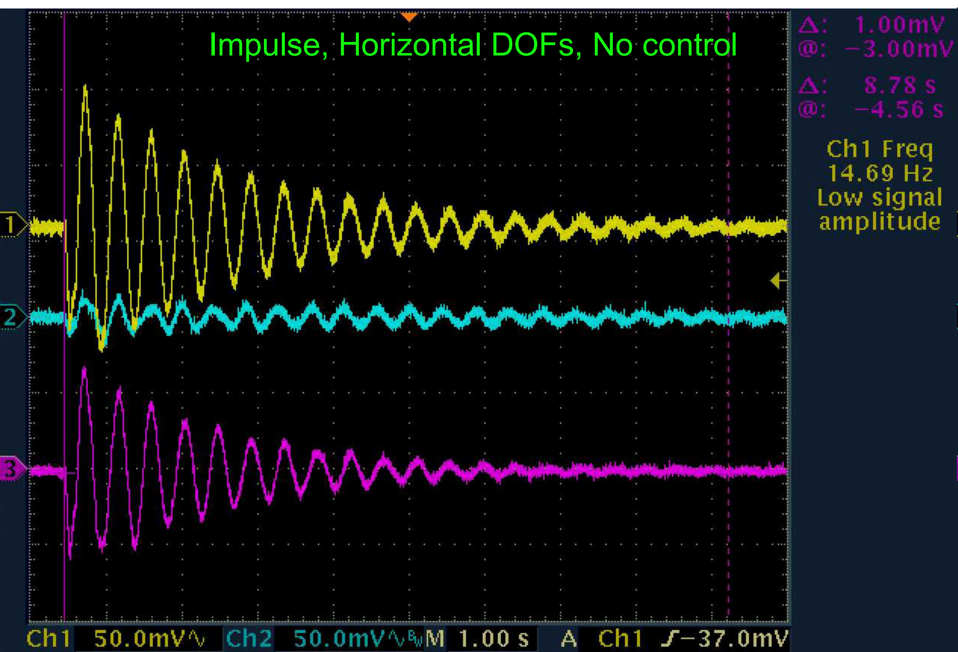


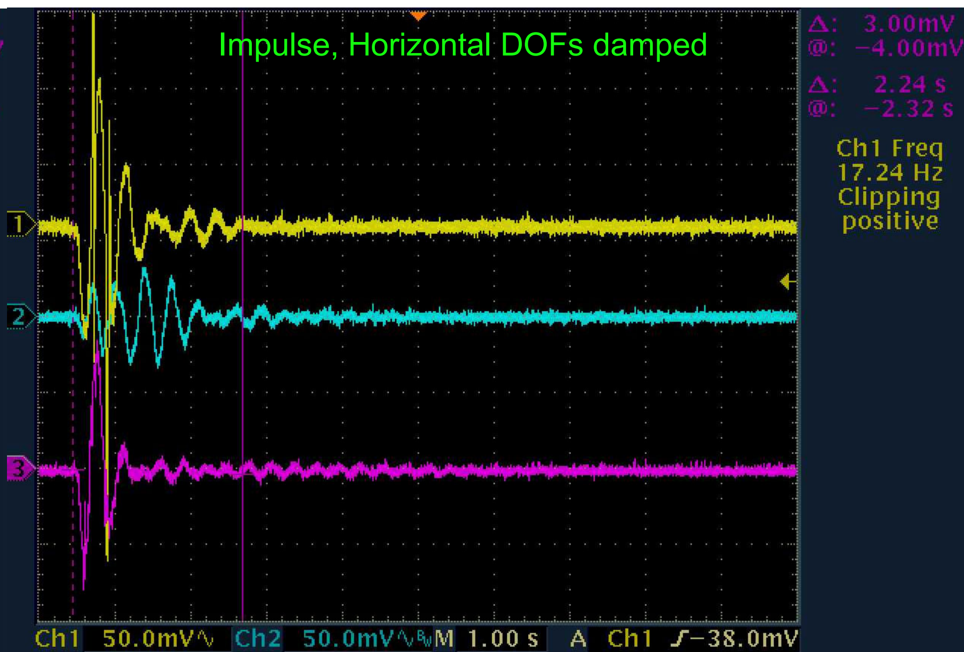
HAM-like AID prototype system at CIT



Control ⇒ Virginio

- Possible strategies
- What we have tried
- Experiences
- Where do we go





Caltech April 12, 2002

Seismic Retrofit Design Review

Active Internal Damping,

Control Strategy, and Preliminary Results

on the HAM Stack Prototype

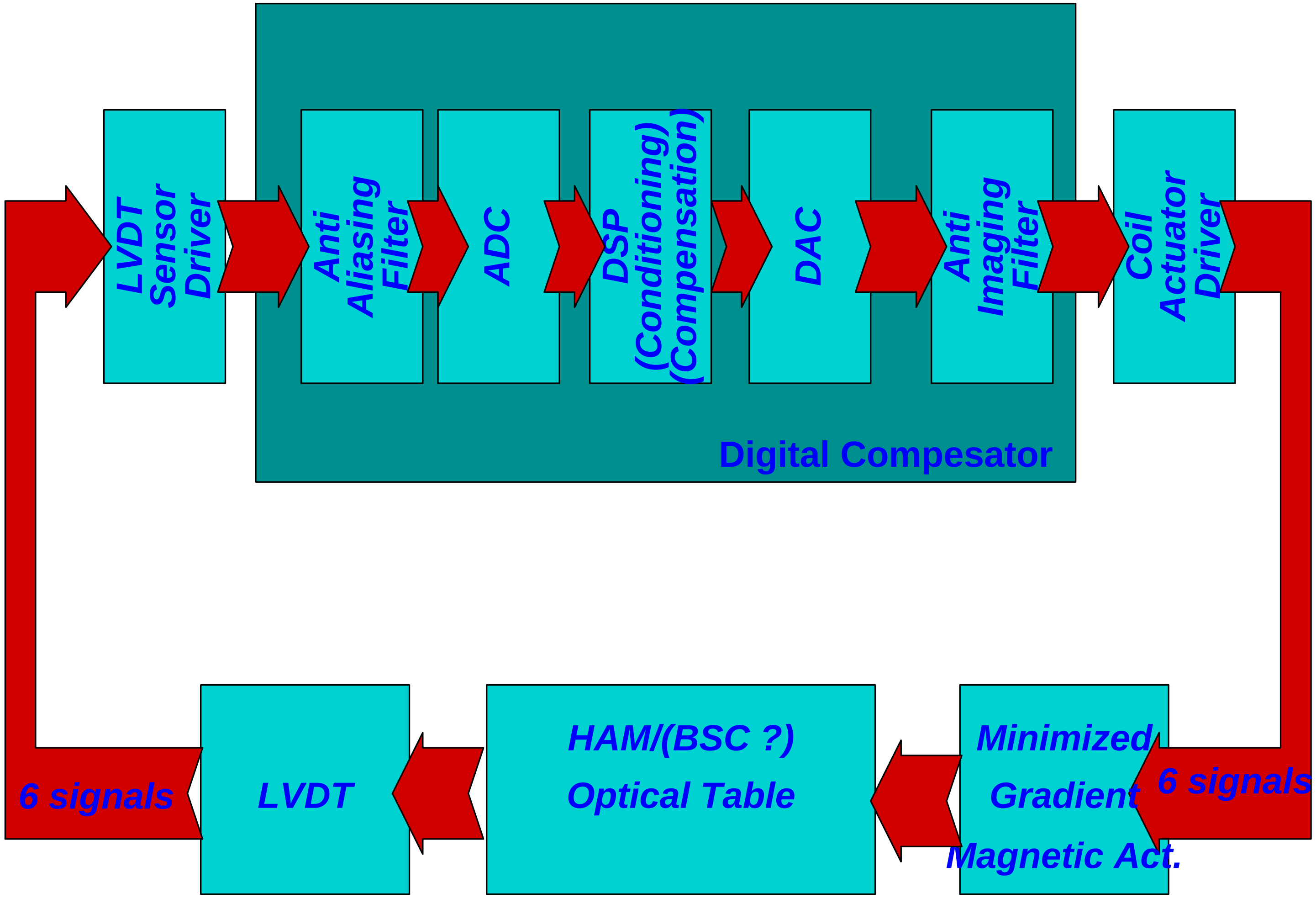
Presented by

Virginio Sannibale.

Control: Overview

- **Control Strategy: Damp of the resonances in the Microseismic Region,**
- **Sensing: Relative Displacement From Stacks Base to the Optical Table**
- **Actuation: From Stack Base to the Optical Table**
- **Control System : MIMO (6 SISO not excluded), with Digital Filtering**
- **Control Band: from 0.5Hz to 3-5Hz**

Control: Diagram



Control: Some of the High Freq Noise Injection Path

- Un-filtered residual sensor noise above unity gain frequency
- Un-filtered residual actuator noise above unity gain frequency
- Poor Phase/Gain Control Margin
- Residual seismic and acoustic noise through the Minimized Gradient Actuator

LIGO

Sensor Prototype: Description

- **LVDT Linear Variable Differential Transformer**
- **Senses relative displacement between primary and secondary coils**
- **Typical noise level:** $\delta x \simeq 10\mathbf{nm}\sqrt{\mathrm{Hz}}$ @ $\sim 1\mathrm{Hz}$
- **(other possible candidates: capacitive sensors)**

Sensor: Possible Ways to reduce the Noise

- **Quieter sinusoidal generator (less phase jitter),**
- **Better demodulation chips (Analog Devices)**
- **Larger sinusoidal signal amplitude (1.5 larger),**
- **Dynamic range reduction (from 20mm to 2mm),**
- **Increase on the number of Winding of the Primary Coil,**

$\Rightarrow$ **At least a factor 10 on increased resolution is expected**

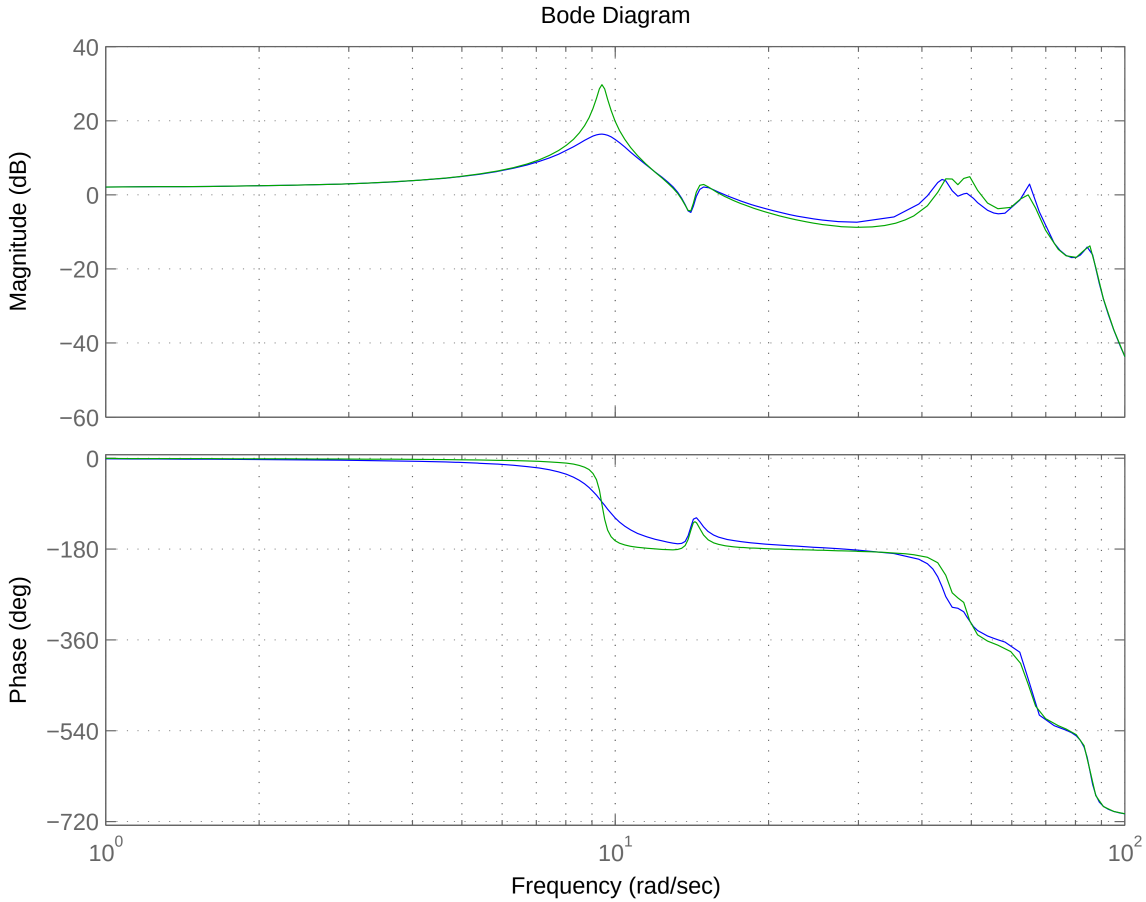
Sensor: Digital Conditioning

Actuator Prototype: Description

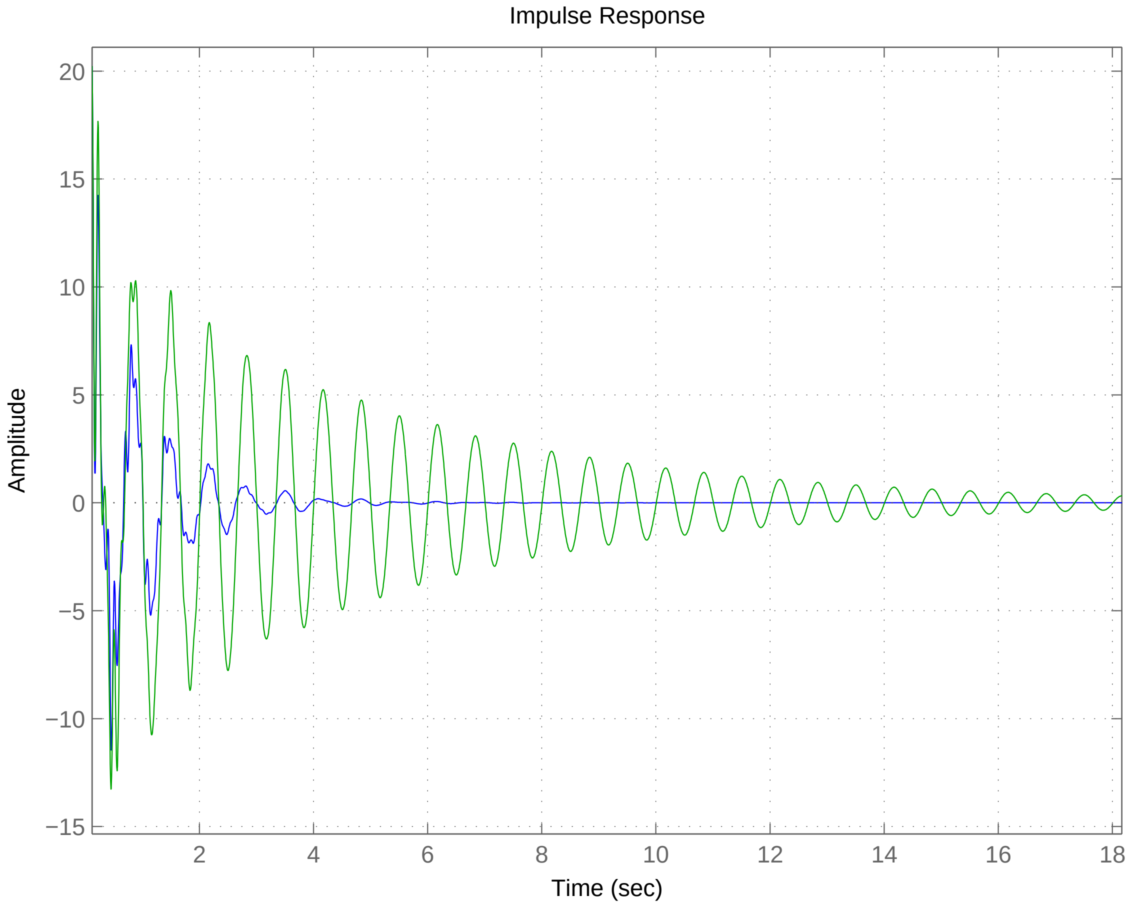
- **Derived from the voice coil topology**
- **Designed to reduce the Force noise due to the seismic noise**

  $\Rightarrow$ **Minimization of the Magnetic Field Gradient.**
- **Typical calibration factor:** $\frac{\Delta F}{\Delta I} \simeq .01 - 3$**N/A**
- **Low Impedance coil (**$\sim 50\Omega$**)**

Simulation: HAM Stack Simple Model, Controlled and Uncontrolled Plant TF



Simulation: HAM Stack Simple Model, Impulse Response



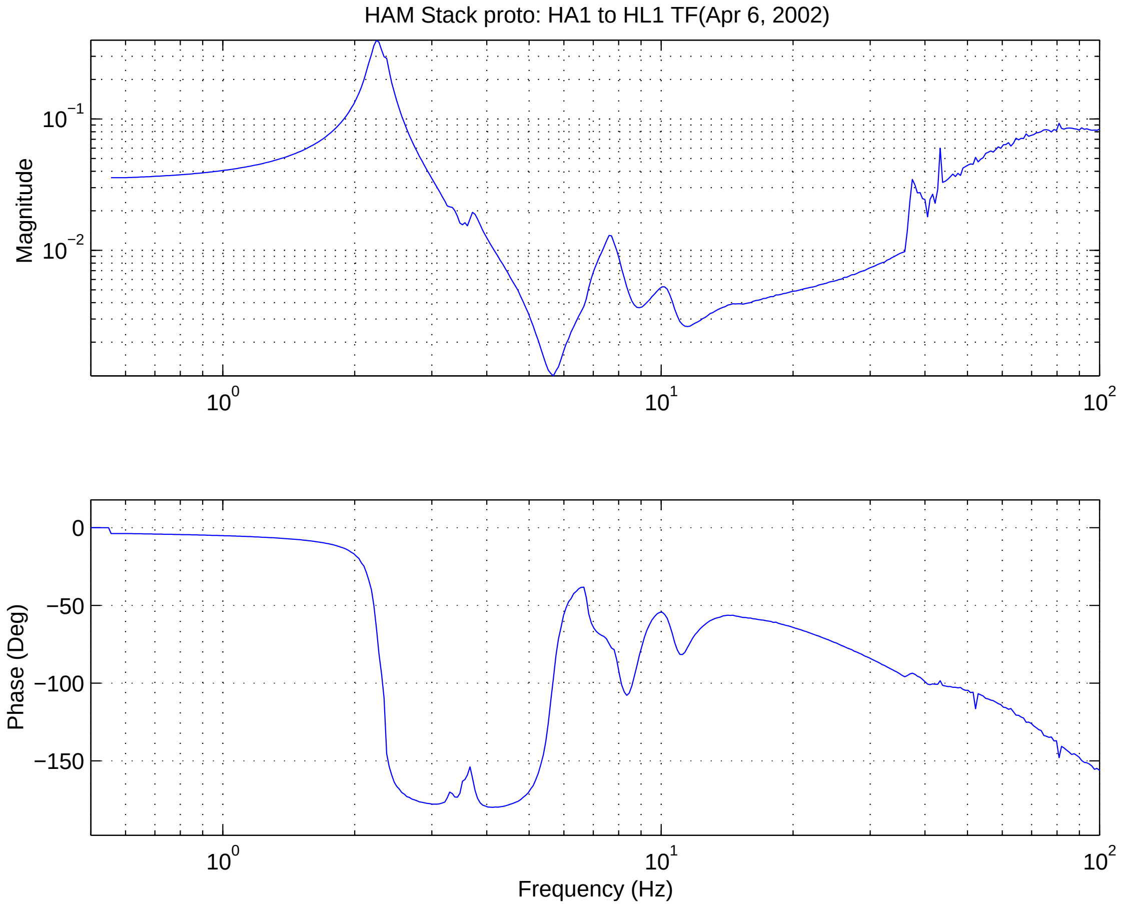
Controled HAM Proto : Main Goals

- Study different strategies for a 6DOF control (SISO, MIMO, bandwidth, etc...)
- Study the effect of some aggressive roll-off filtering
- Test-bench for different sensors (sensitivity, dynamic range, crosstalk, etc..
- Become skilled with the dSpace System

Controled HAM Proto : Reached Goals

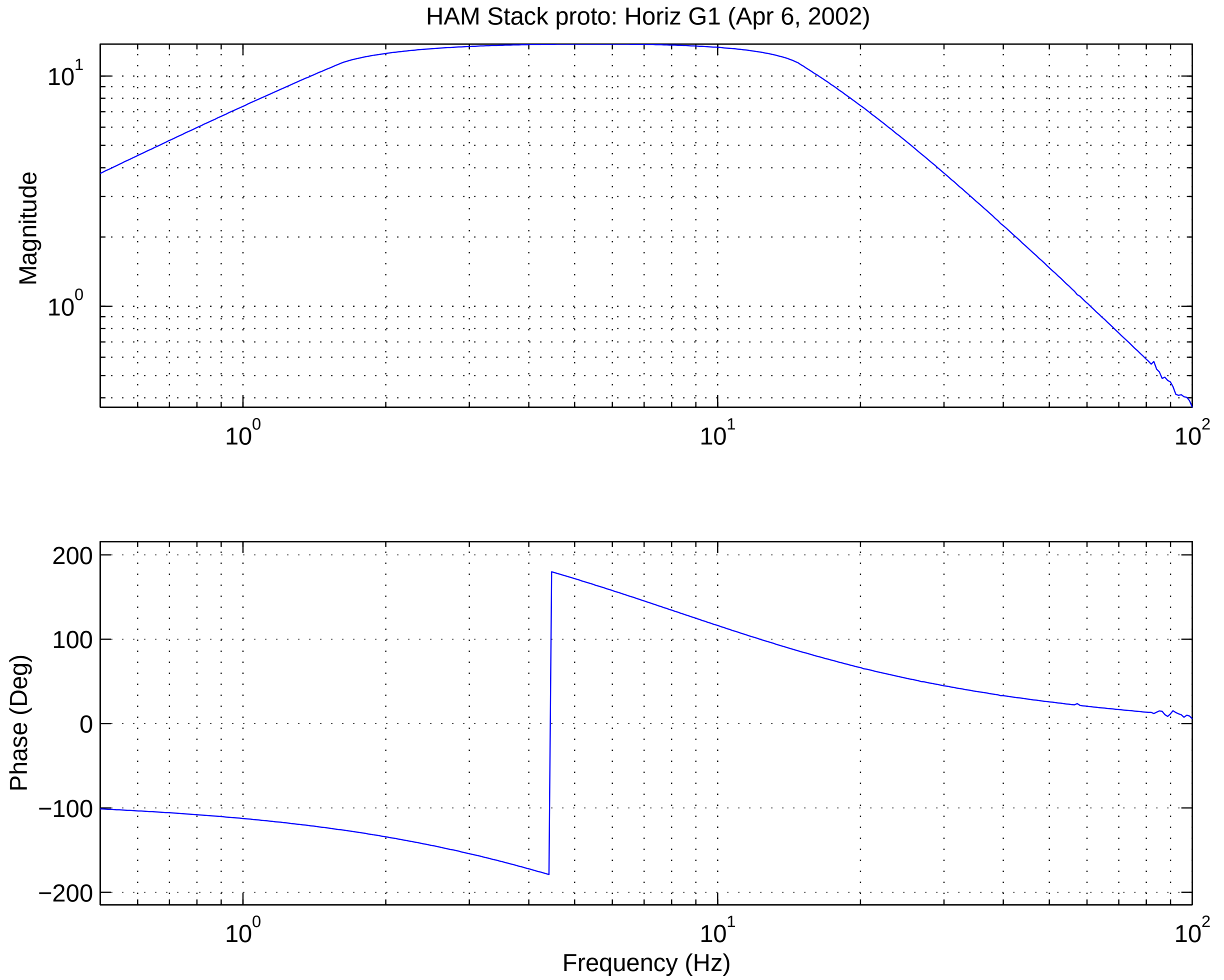
- All the 6 DOF has been closed (System stable with the 6 loop closed at the same time)
- Control Strategy: 6 SISO System
- Some impulse response studied
- Just acquainted with dSpace (Made a kludge using dSpace & Labview).

HAM Proto Very Preliminary Results: Plant Typical T.F.

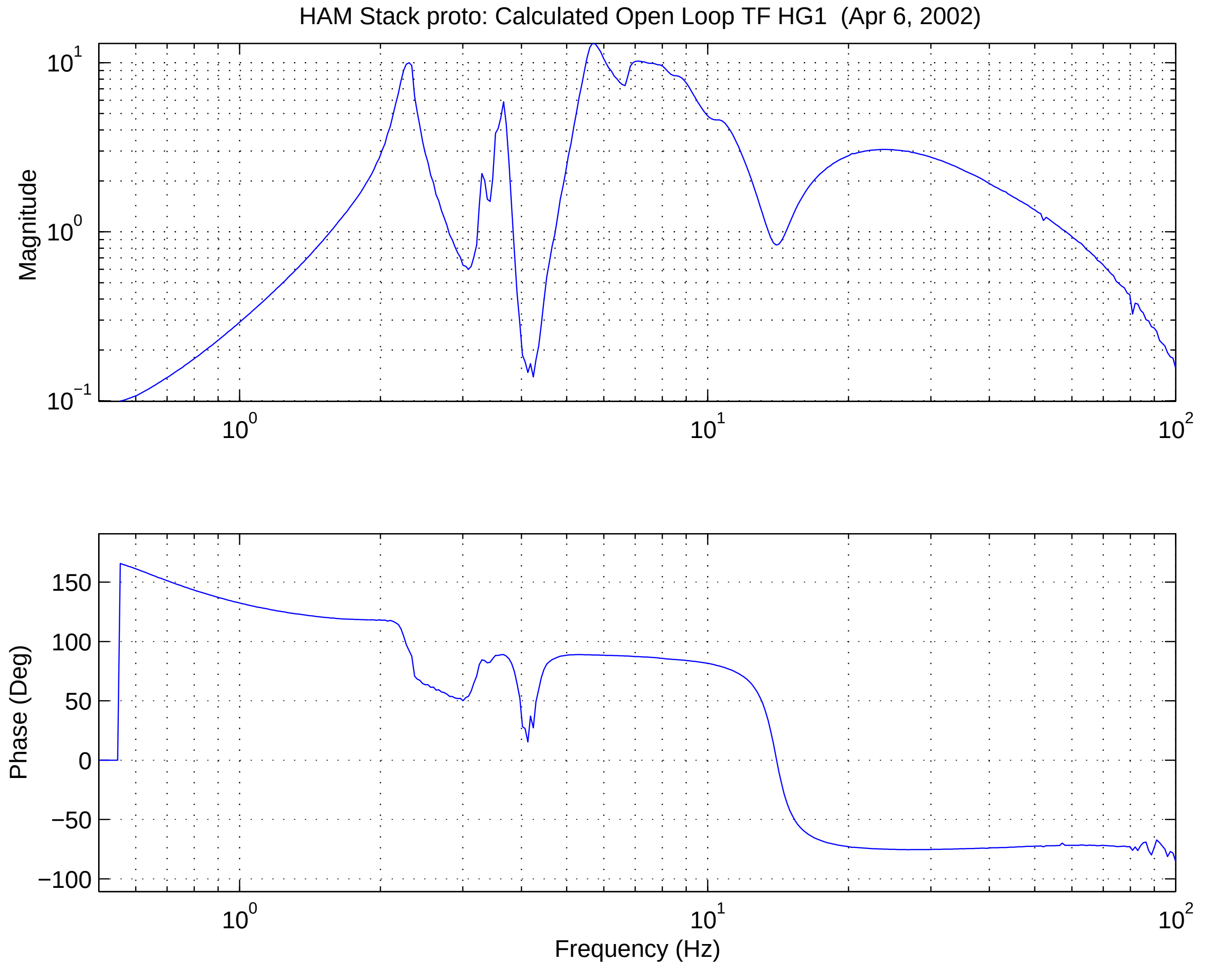


Large bump at high frequency due to the broad damping of the table internal modes ⇒ seismic attenuation completely compromised.

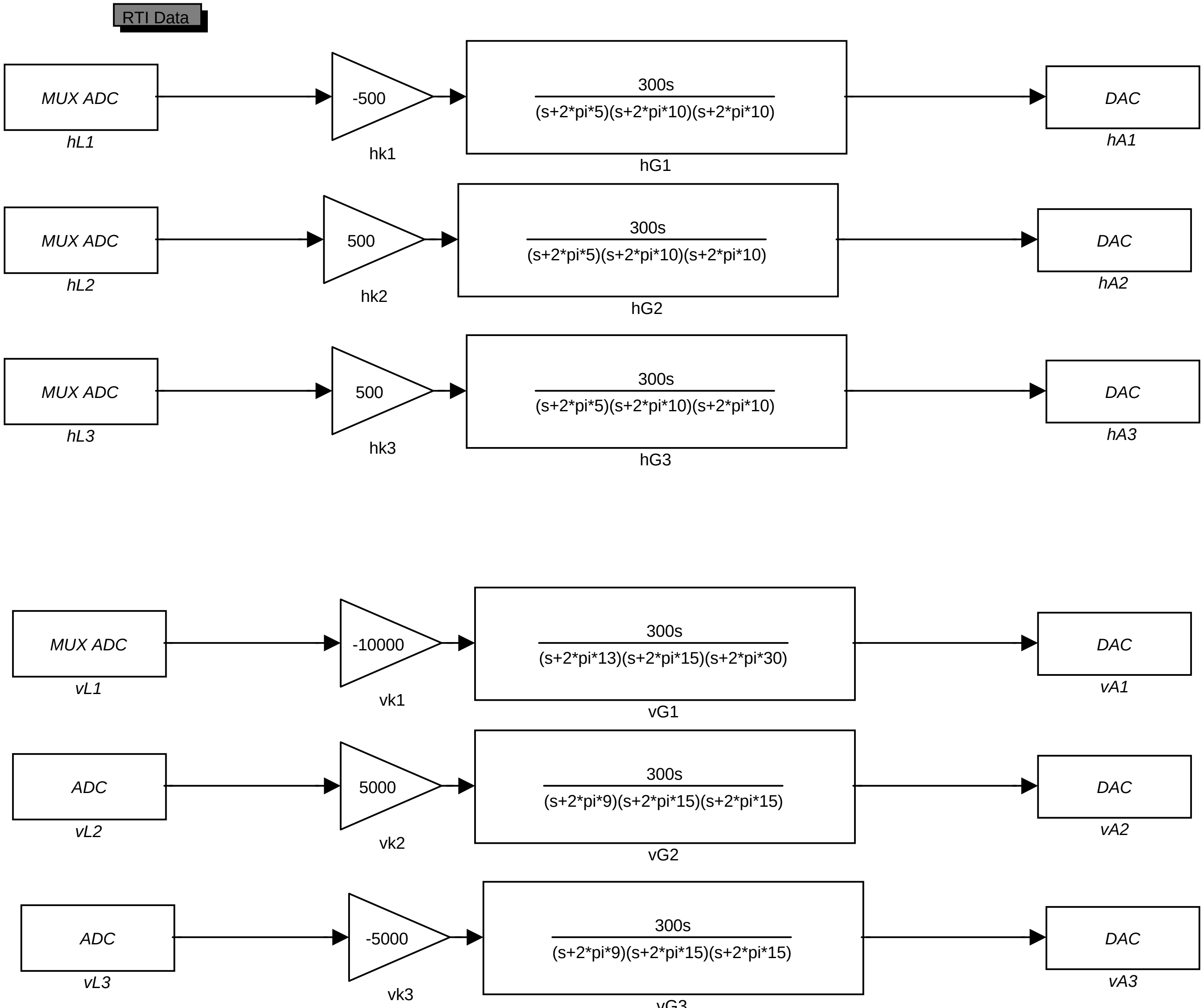
HAM Proto Very Preliminary Results: Typical Compesator



HAM Proto Preliminary Results:Typical Open Loop T.F.

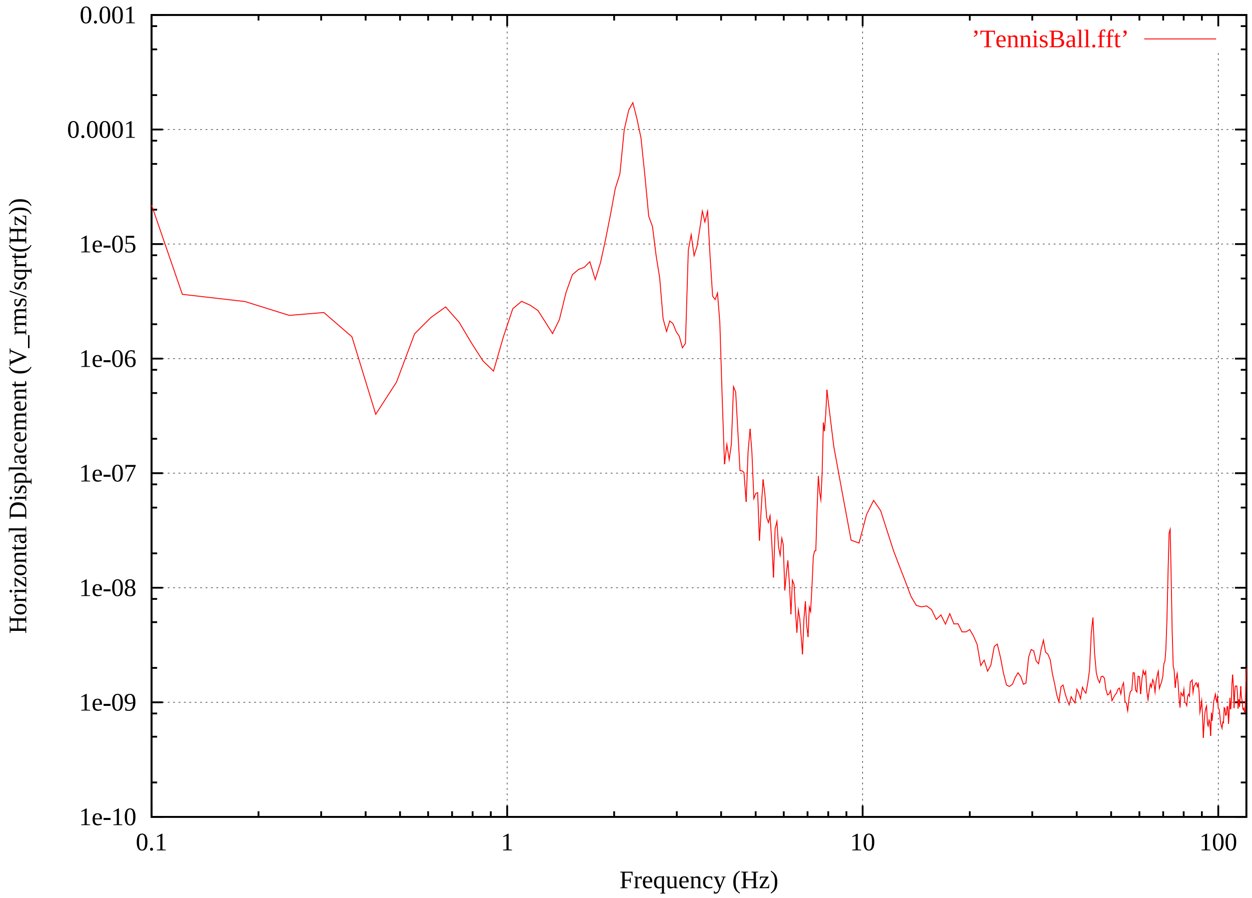


Controled HAM Proto Very Preliminary Results:Simulink Snapshot



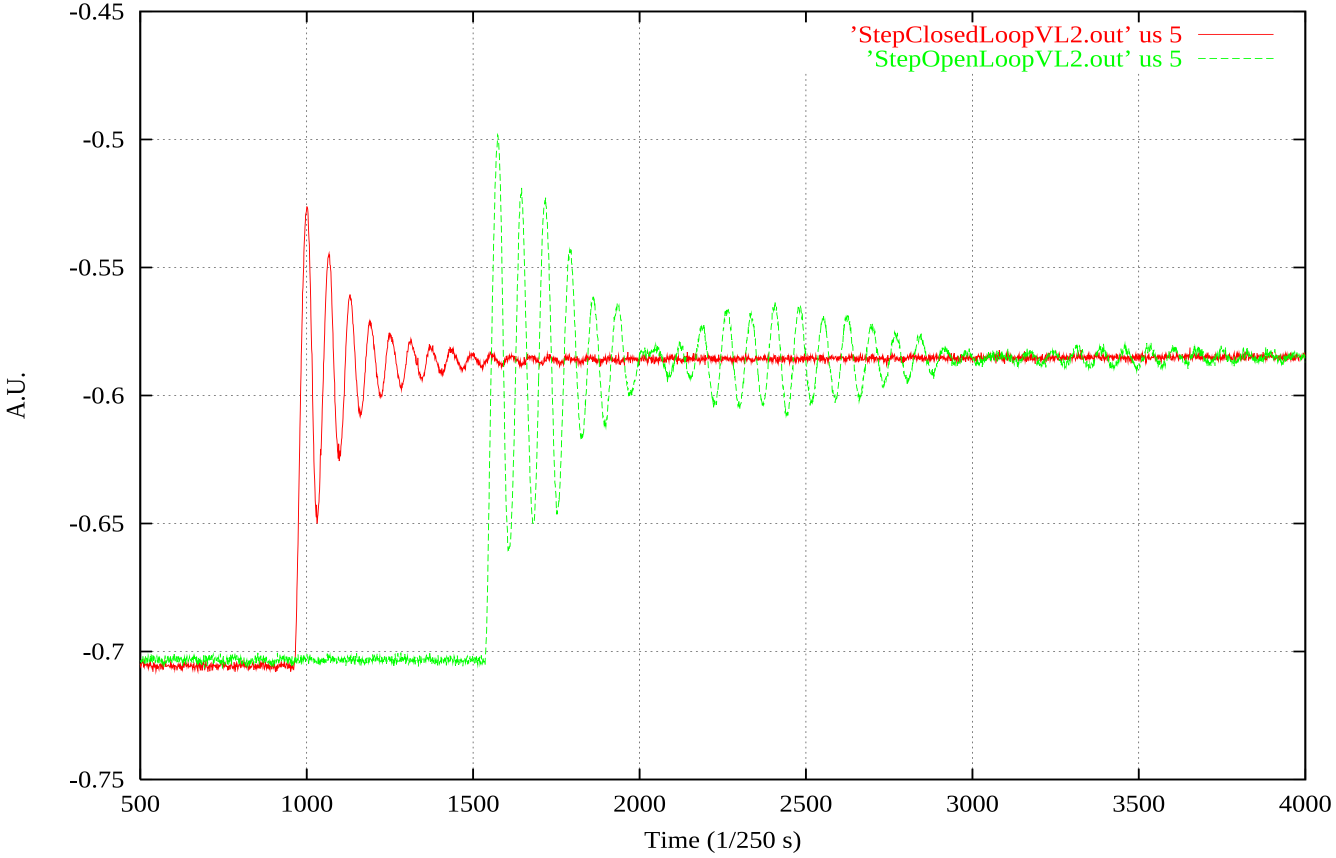
LIGO

HAM Proto Very Preliminary Results: PSD Horizontal Direction



HAM Proto Very Preliminary Results: Step Response

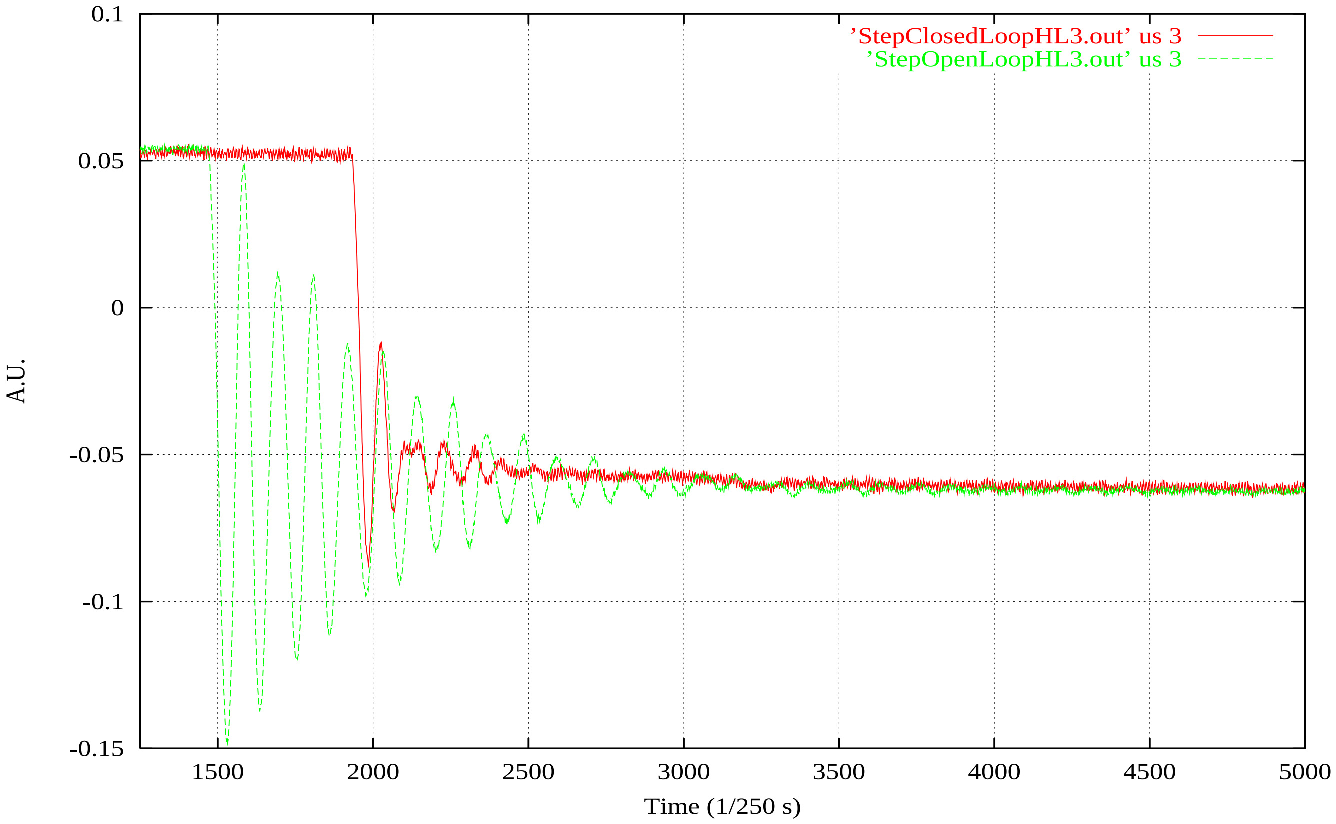
Vertical LVDT 2



Larger band noise in the closed loop signal because of the aliasing. dSpace introduces high frequency noise @~ 500MHz.

HAM Proto Very Preliminary Results: Step Response

Horizontal LVDT 3

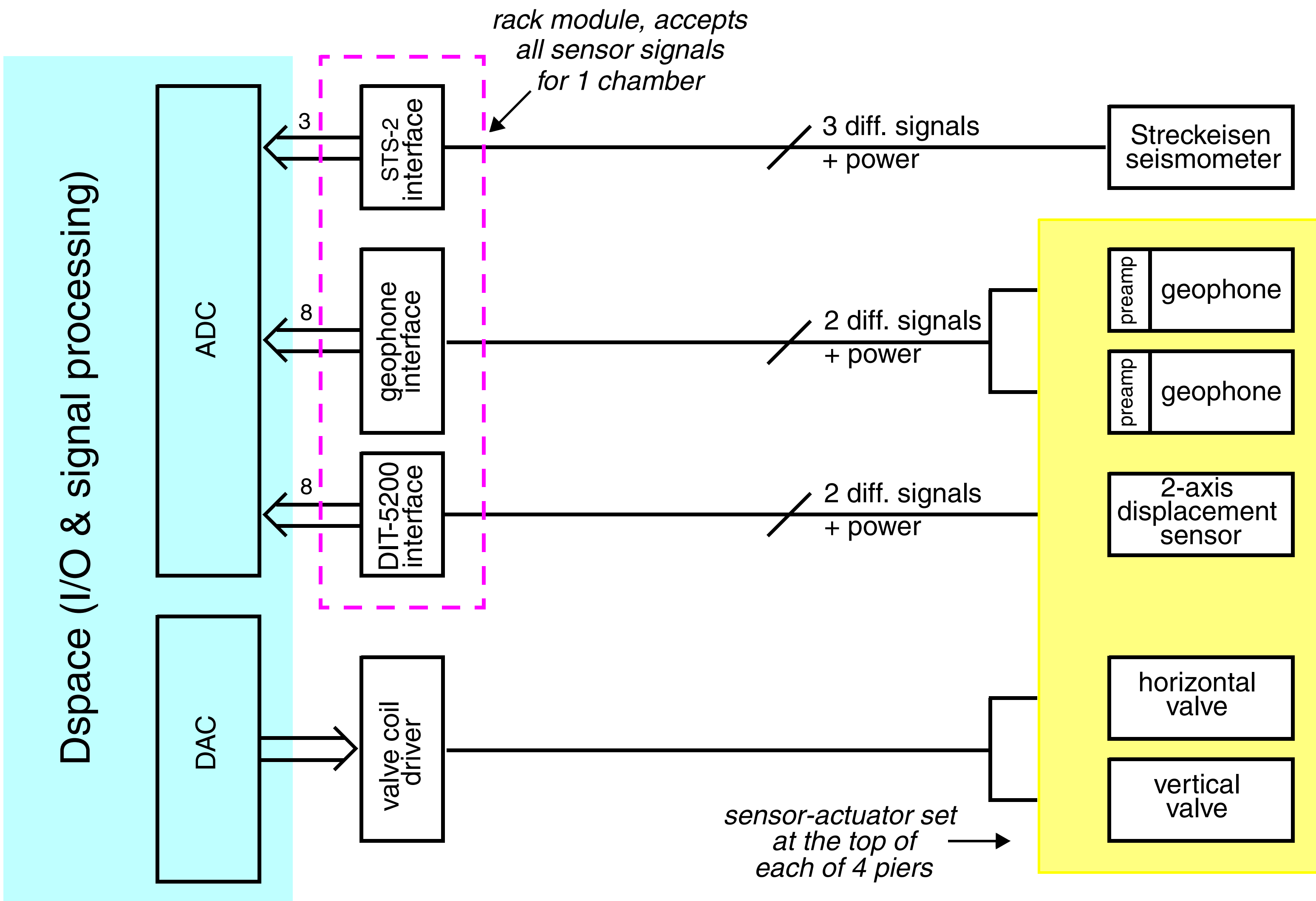


Larger band noise in the closed loop signal because of the aliasing. dSpace introduces high frequency noise @~ 500MHz.

Conclusions

- HAM Stacks 6 SISO control system works and seems promising.
- The impulse response shows a substantial reduction of the Q factor of the resonances and in the amplitude.
- The Active Internal Damping Systems can probably work fine for the HAM Stacks, where the seismic noise performance are less demanding than the BSC Stacks perf.
- AID installation in LASTI can probably tell us if the system can work sufficiently well for the BSC Stacks.

Electronics Block Diagram



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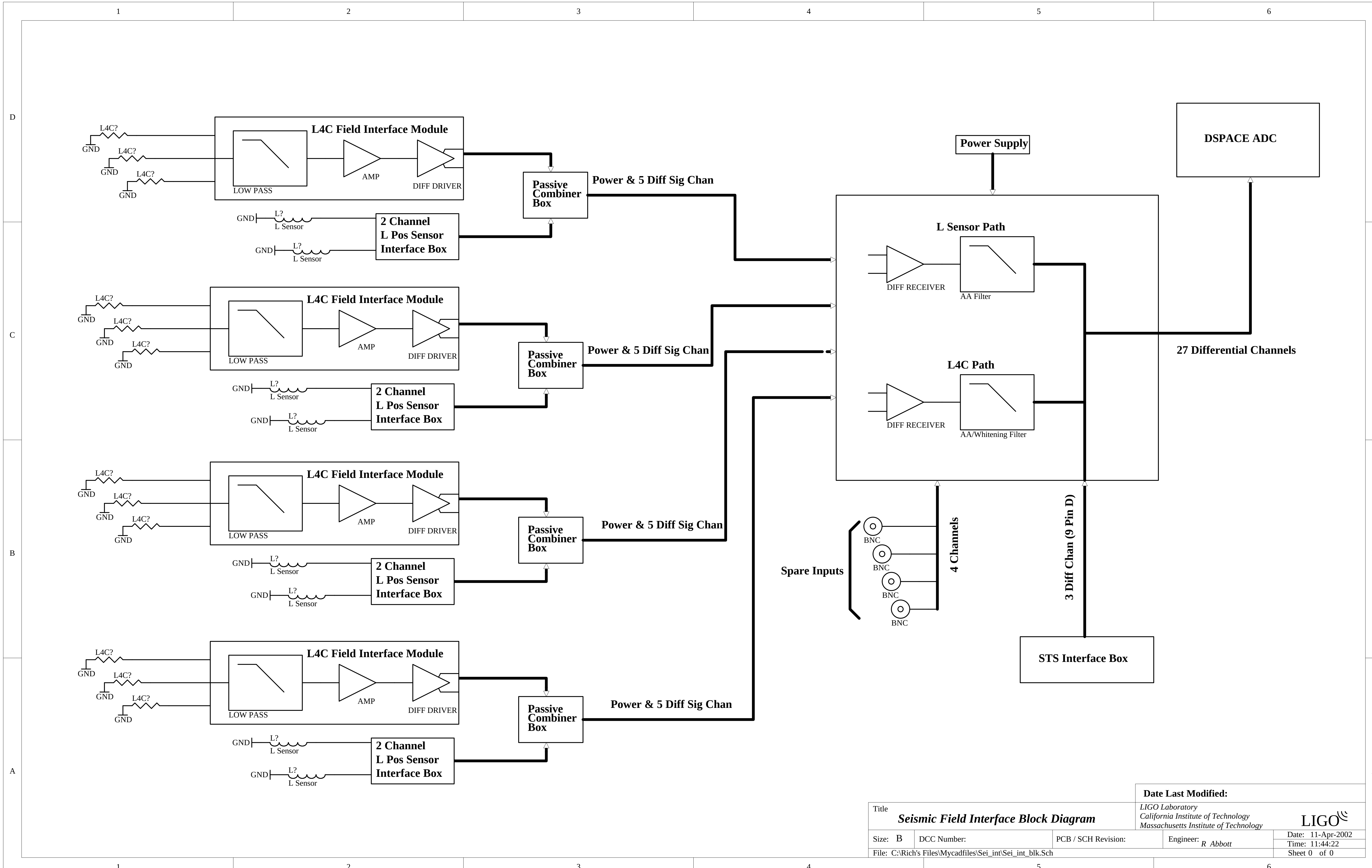
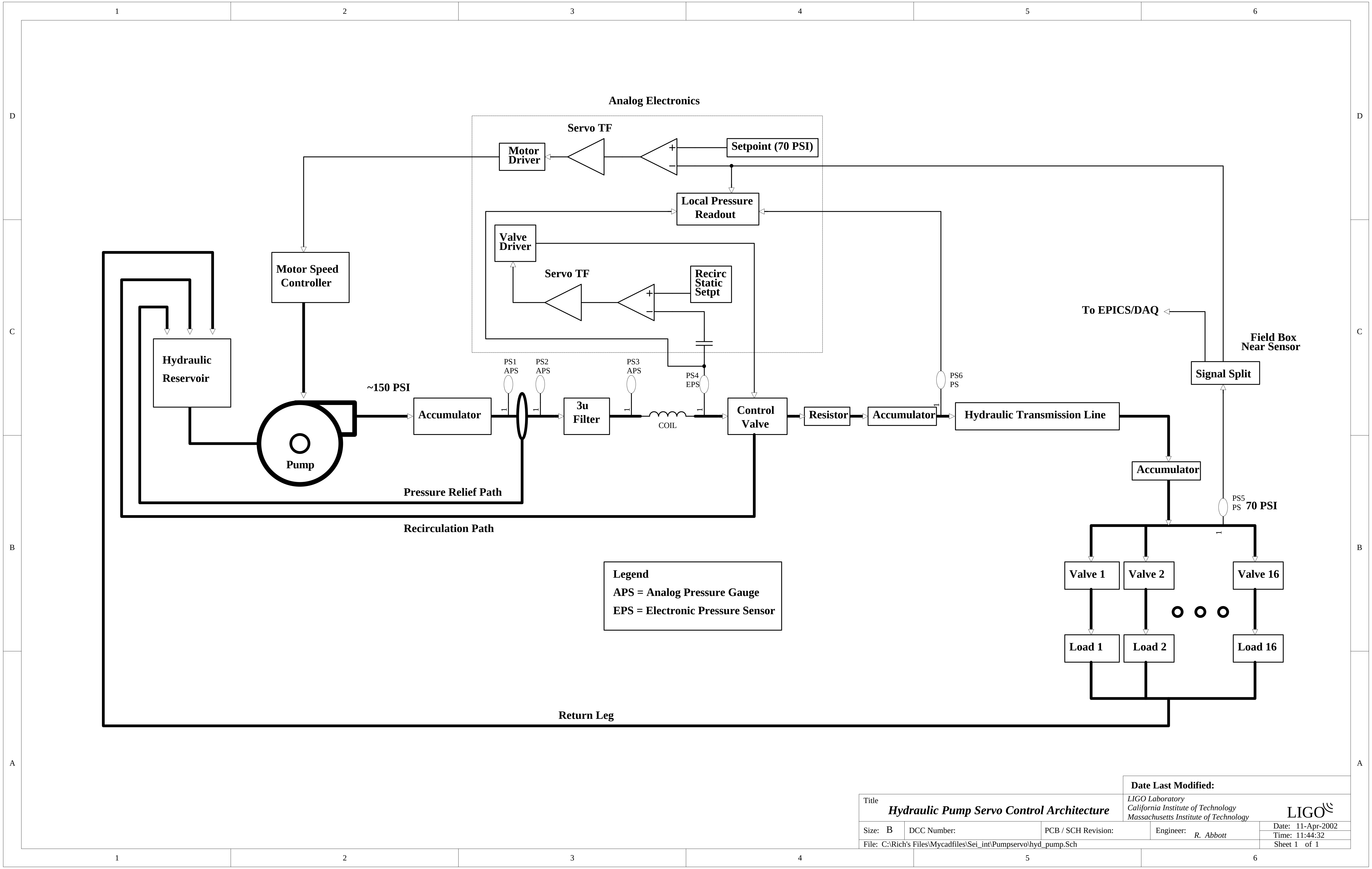


L4C Field Interface Module
L4C?
GND
LOW PASS
AMP
DIFF DRIVER
Passive Combiner Box
Power & 5 Diff Sig Chan
L?
L Sensor
2 Channel L Pos Sensor Interface Box
L4C Field Interface Module
Passive Combiner Box
Power & 5 Diff Sig Chan
2 Channel L Pos Sensor Interface Box
L4C Field Interface Module
Passive Combiner Box
Power & 5 Diff Sig Chan
2 Channel L Pos Sensor Interface Box
L4C Field Interface Module
Passive Combiner Box
Power & 5 Diff Sig Chan
2 Channel L Pos Sensor Interface Box
Power Supply
DSPACE ADC
L Sensor Path
DIFF RECEIVER
AA Filter
L4C Path
DIFF RECEIVER
AA/Whitening Filter
27 Differential Channels
Spare Inputs
BNC
4 Channels
3 Diff Chan (9 Pin D)
STS Interface Box
Date Last Modified:
Title
Seismic Field Interface Block Diagram
LIGO Laboratory
California Institute of Technology
Massachusetts Institute of Technology
LIGO
Size: B
DCC Number:
PCB / SCH Revision:
Engineer: R Abbott
Date: 11-Apr-2002
Time: 11:44:22
File: C:\Rich's Files\Mycadfiles\Sei_int\Sei_int_blk.Sch
Sheet 0 of 0


Analog Electronics
Servo TF
Motor Driver
Setpoint (70 PSI)
Local Pressure Readout
Valve Driver
Servo TF
Recirc Static Setpt
Motor Speed Controller
Hydraulic Reservoir
Pump
~150 PSI
Accumulator
PS1 APS
PS2 APS
3u Filter
PS3 APS
COIL
PS4 EPS
Control Valve
Resistor
Accumulator
PS6 PS
Hydraulic Transmission Line
To EPICS/DAQ
Field Box Near Sensor
Signal Split
Accumulator
PS5 PS
70 PSI
Valve 1
Valve 2
Valve 16
Load 1
Load 2
Load 16
Pressure Relief Path
Recirculation Path
Return Leg
Legend
APS = Analog Pressure Gauge
EPS = Electronic Pressure Sensor
Date Last Modified:
Title
Hydraulic Pump Servo Control Architecture
LIGO Laboratory
California Institute of Technology
Massachusetts Institute of Technology
LIGO
Size: B
DCC Number:
PCB / SCH Revision:
Engineer: R. Abbott
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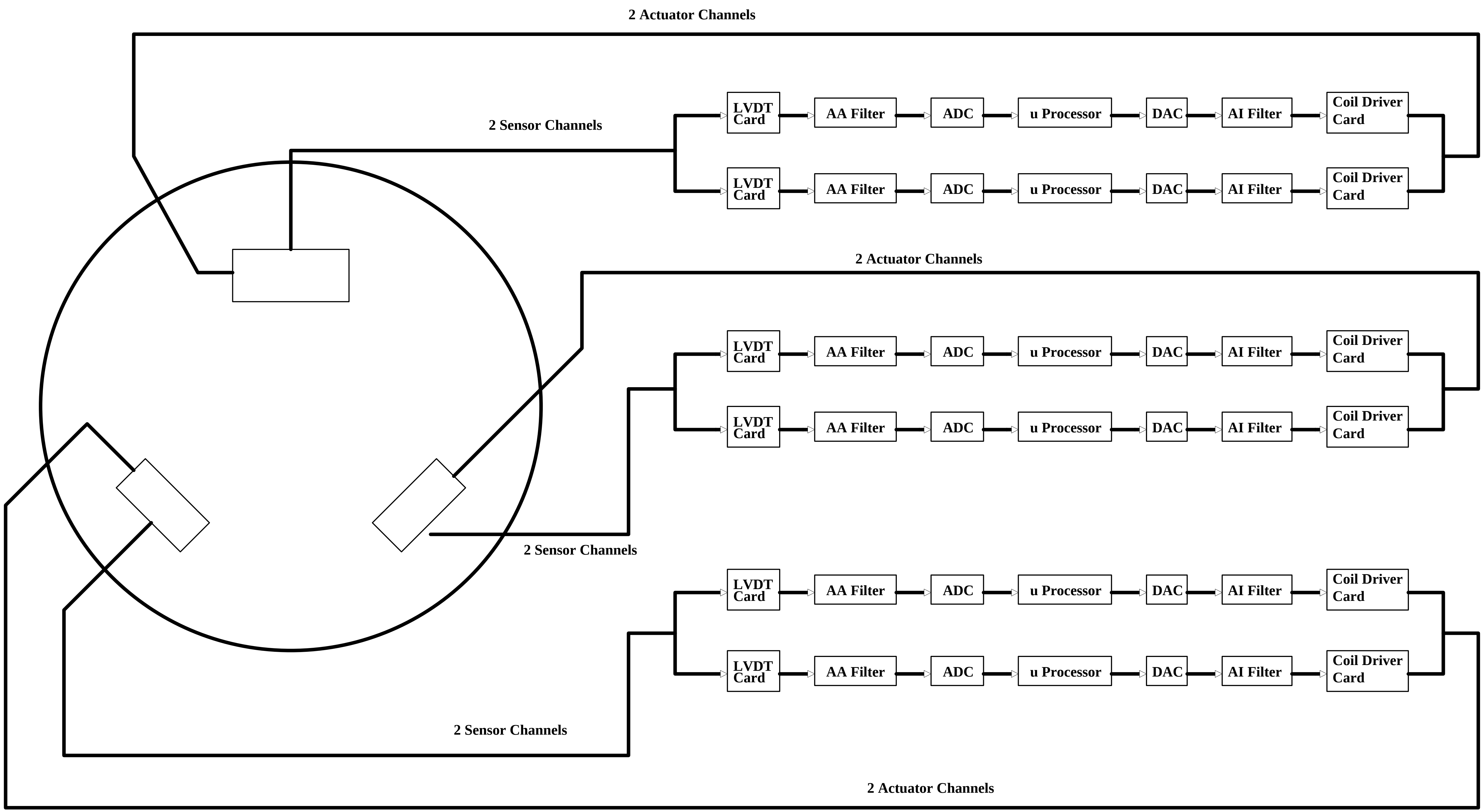

Date Last Modified:

Title

Active Internal Damping (AID) Controls

LIGO Laboratory
California Institute of Technology
Massachusetts Institute of Technology

LIGO

Size: B	DCC Number:	PCB / SCH Revision:	Engineer: *R Abbott*	Date: 11-Apr-2002 Time: 11:44:39
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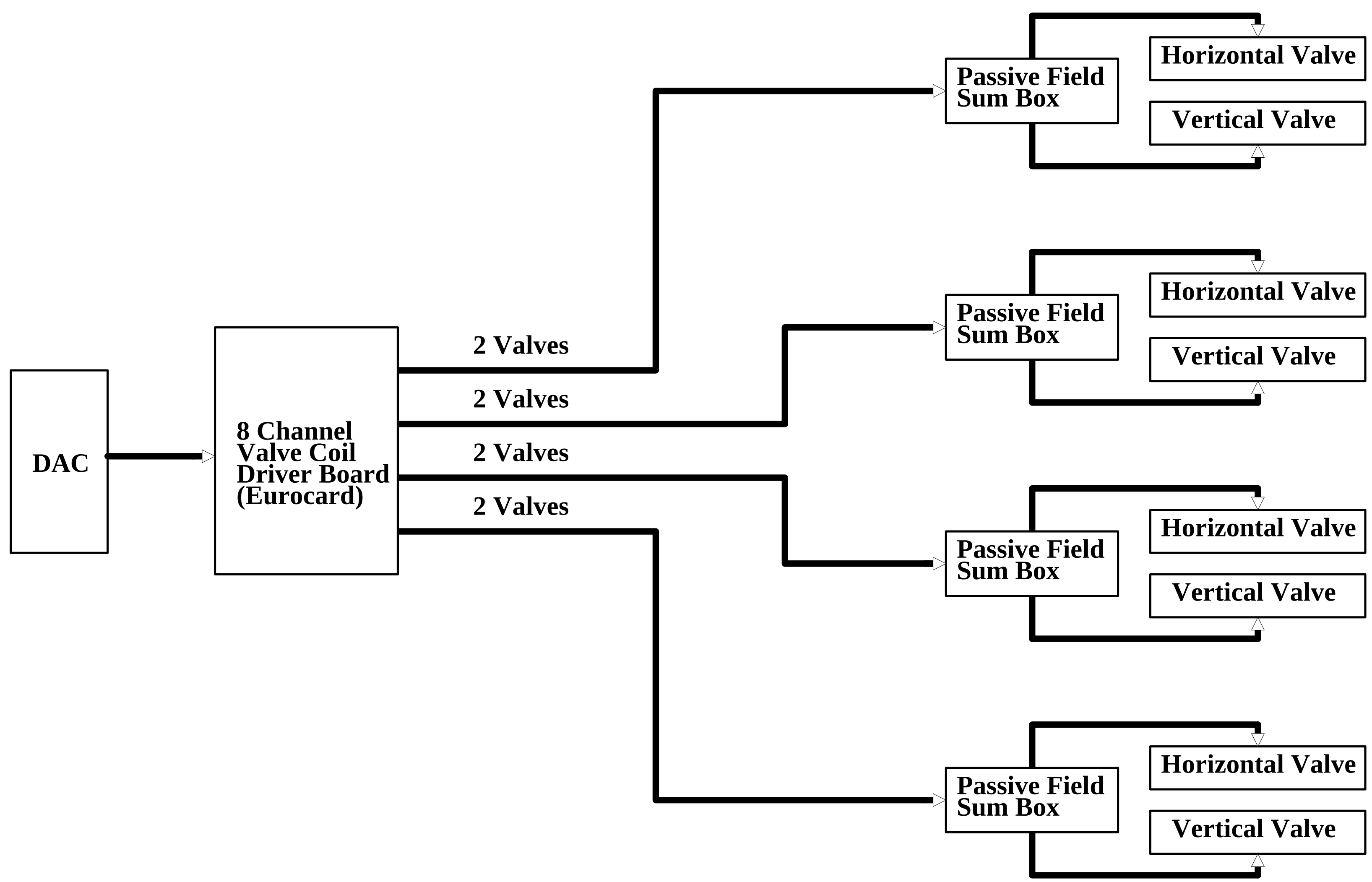

Date Last Modified:

Title: *Hydraulic Valve Driver Overview*			*LIGO Laboratory* *California Institute of Technology* *Massachusetts Institute of Technology*	LIGO
Size: A	DCC Number:	PCB / SCH Revision:	Engineer: *R Abbott*	Date: 11-Apr-2002 Time: 11:44:45
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Conceptual Design Review:
Initial LIGO Seismic Isolation System Upgrade

Development, Implementation Plan & Schedule

Dennis Coyne

April 12, 2002

System Level Issues

- Fringe wrapping can occur for the input laser beam & backscattered light from the output PD may inject too much noise
  - » The relative motion of the PSL and ISCT and the COC may need to be reduced
  - » The conceptual design currently only addresses BSC and HAM chamber isolation
  - » This should not be a significant technology challenge, and can be addressed later and incrementally, but would be added complexity and cost.
- Reduction in motion must be complemented with a change in the suspension coil driver authority and possibly filter shapes
- Should integrate these additional control degrees-of-freedom into the length and angle control systems, and the locking/unlocking procedures
- Assumed that external 2 DOF isolation with the fine (piezo) actuation system, on the test mass and mode cleaner platforms, is adequate for improved isolation during wind storms at Hanford. This requires further study.

Contamination Concerns

- AID is composed of inherently vacuum compatible materials
  - » NdBFe magnets qualified for initial LIGO test masses
    - – will RGA test the magnets from the source to be used for the AID voice coil actuator
  - » Kapton (polyimide) "paint":
    - – Virgo has tested & approved use
    - – LIGO will RGA and test in the contamination exposure optical cavity test facility (high irradiance, 1064 micron)

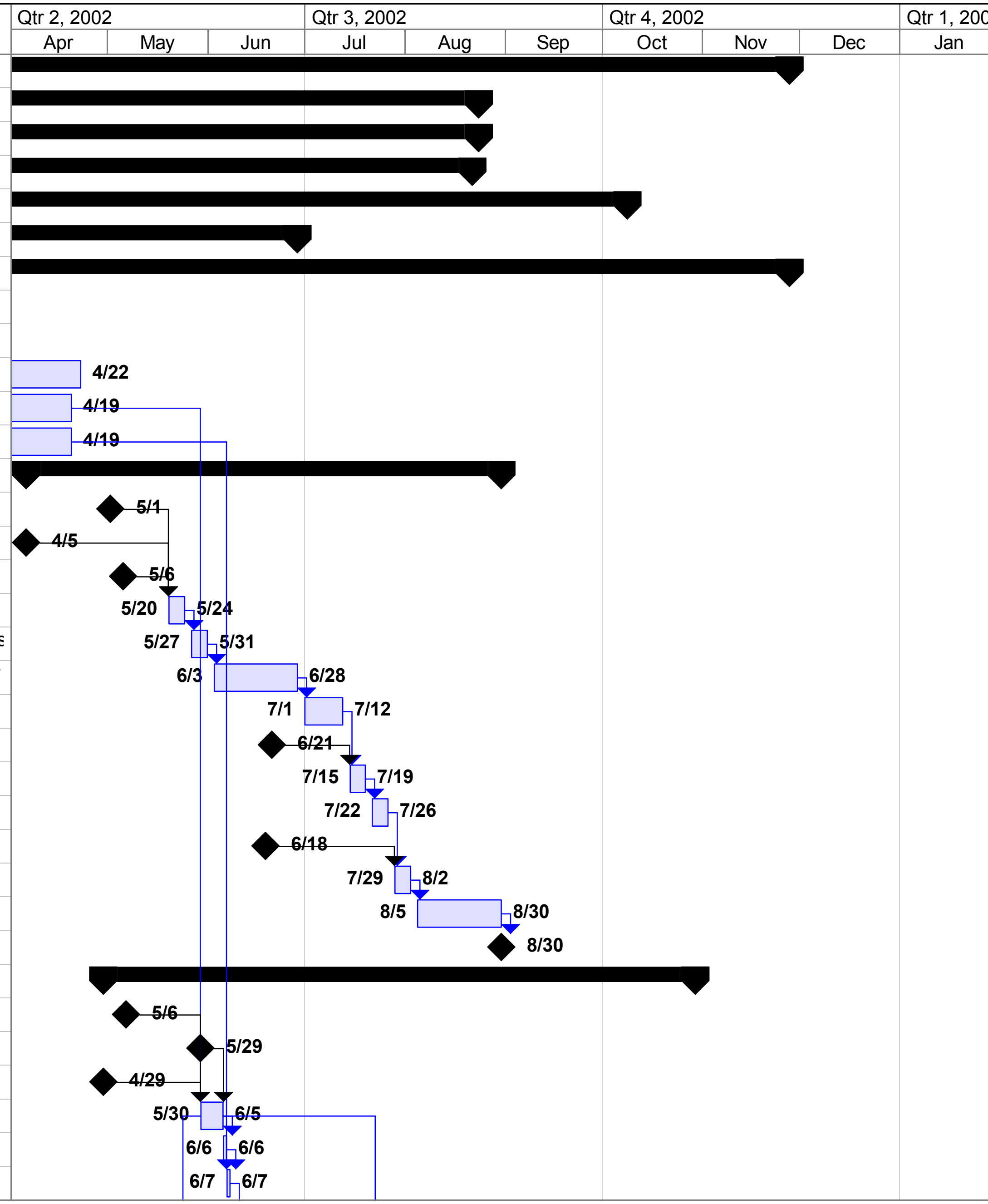
Contamination Concerns (continued)

- Measures to address HEPI hydraulic fluid contamination concerns:
  - » Will perform failure effects and modes analysis in next phase
  - » Most joints are soldered/welded to minimize potential leaks
  - » Plan to use “double jacketing” where appropriate to catch possible leaks
  - » Intend to have special tooling and tight procedures for fluid containment during filling, purging and bleeding operations
  - » Plan to test glycerin (water soluble) alternative to mineral oil
  - » Testing the effect of mineral oil & glycerin/water exposure to optics in the contamination exposure optical cavity test facility

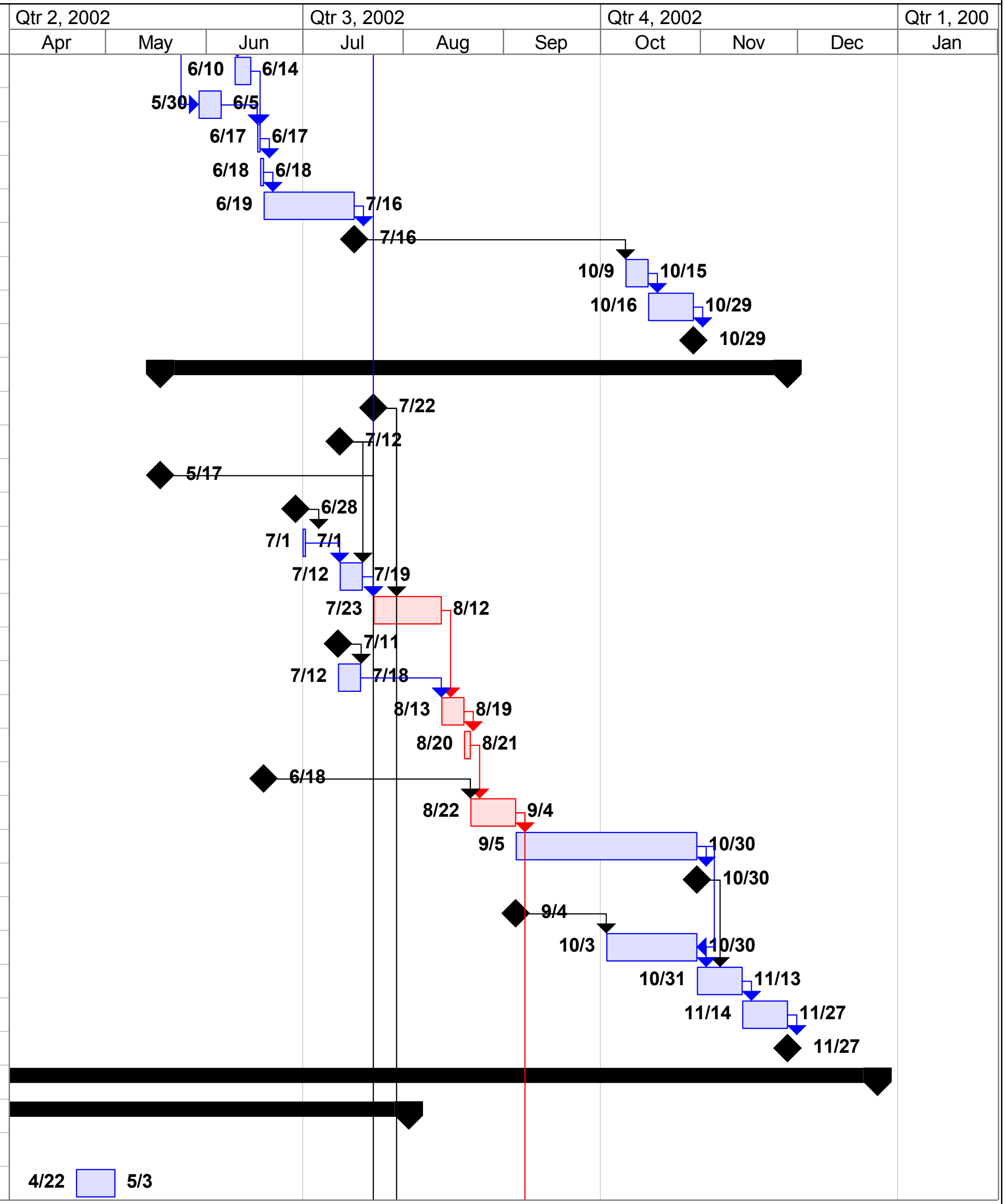
LASTI Full Scale Prototype Testing

- Stand-alone subsystem testing is underway for each subsystem
- The AID & HEPI subsystems will be tested on a BSC isolation stack/chamber at the LASTI facility (MIT) starting in June/July
- The MEPI subsystem will be tested at the same time on a LASTI HAM stack/chamber
- Initially all controls will be performed with D-Space controllers before integrating the systems into the LIGO Epics Supervisory Control & DAQ systems

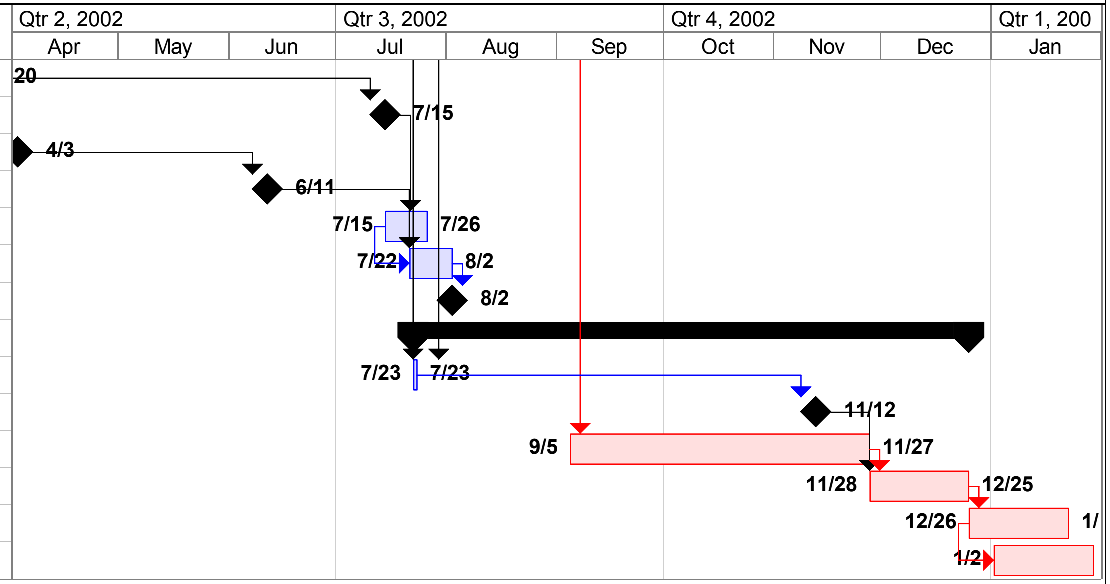
ID	WBS	Task Name
1	**1**	**System Design**
25	**2**	**Hydraulic Act./SensorAssy.**
122	**3**	**Electromagnetic External Pre-Isolation (MEPI) System**
143	**4**	**Active Internal Damping (AID) System**
172	**5**	**Electronics**
222	**6**	**EPI Installation procedures and tooling**
229	**7**	**Prototype System Testing @ LASTI**
230	7.1	Pier Compliance Measurement at LASTI
231	7.2	Pier Compliance Measurement at LLO
232	7.3	Stack Xfer Func Characterization at LASTI
233	7.4	LASTI clean tool preparaton
234	7.5	LASTI optical lever system prep
235	**7.6**	**HAM MEPI System Testing**
236	7.6.1	receive springs and assy
237	7.6.2	receive position sensors
238	7.6.3	beg/borrow/steal 2 L4C geophones?
239	7.6.4	assemble one unit (actuator, springs, frame) stand-alone
240	7.6.5	characterize actuator displacements, resonances, power dis
241	7.6.6	close loop on feedforward/feedback; demonstrate suitability
242	7.6.7	incorporate any design modifications in other units
243	7.6.8	receive geophones
244	7.6.9	assemble 8 units
245	7.6.10	install on HAM
246	7.6.11	control electronics ready (dSpace version)
247	7.6.12	integrate electrically
248	7.6.13	characterization, optimization
249	7.6.14	evaluation
250	**7.7**	**BSC AID system Testing**
251	7.7.1	receive actuator, LVDT, fasteners, misc. parts
252	7.7.2	receive mouting structures
253	7.7.3	receive special tooling
254	7.7.4	assemble, prep
255	7.7.5	vent, pull door
256	7.7.6	install opt lev mirrors on table to monitor



ID	WBS	Task Name
257	7.7.7	install system
258	7.7.8	install electronics with D-space system
259	7.7.9	integrate electronics, functional test
260	7.7.10	install door
261	7.7.11	characterization, optimization
262	7.7.12	evaluation
263	7.7.13	revise with low noise electronics
264	7.7.14	re-characterize
265	7.7.15	re-evaluate
266	**7.8**	**BSC HEPI System testing**
267	7.8.1	receive hyd. actuator/sensor assy.
268	7.8.2	receive BSC springs
269	7.8.3	receive housing parts
270	7.8.4	receive installation/alignment tooling
271	7.8.5	check alignment fixturing fit
272	7.8.6	remove spacers from BSC
273	7.8.7	install hydraulic actuator/spring assys.
274	7.8.8	receive pump station
275	7.8.9	install distn plumbing/manifold
276	7.8.10	install local distn lines
277	7.8.11	connect pump and controller
278	7.8.12	control electronics ready (dSpace version)
279	7.8.13	debug system
280	7.8.14	prove isolation perf at MIT
281	7.8.15	evaluate
282	7.8.16	control electronics ready (VME version)
283	7.8.17	code VME system
284	7.8.18	debug system
285	7.8.19	prove isolation perf at MIT
286	7.8.20	evaluate
287	**8**	**Production (TBD)**
288	**8.1**	**PEPI**
289	8.1.1	ETMy FAS PEPI testing
290	8.1.2	install/test ITMy or ETMx PEPI?



ID	WBS	Task Name
291	8.1.3	order 2 FAS systems
292	8.1.4	receive 2 FAS systems
293	8.1.5	order 3 dSpace ACE1104 systems
294	8.1.6	receive 3 dSpace ACE1104 systems
295	8.1.7	install FAS on ITMs
296	8.1.8	debug system
297	8.1.9	operational
298	**8.2**	**EPI & AID production**
299	8.2.1	Order Long Lead Items
300	8.2.2	receive long lead items
301	8.2.3	Production Fab
302	8.2.4	Assembly & Test
303	9	Installation
304	10	Commissioning



Milestones & Decision Points

- PEPI performance review, 8/2002
  - » Based on experience at Livingston, a decision on the suitability of the PEPI system for mitigation of the wind-storm induced seismic noise will be made
- Preliminary Design Review & Long-Lead Procurement Review, 9/2002
  - » After prototype installation & some preliminary experience will decide whether to go forward with the hydraulic actuator or fall back to the electro-magnetic actuator
  - » Generally all quantity decisions (implementation scope) should be made by this time
- Final Design Review, 11/2002
  - » After characterization testing has been completed and drawings updated
- Installation Readiness Review, 1/2003
  - » review readiness of equipment, personnel, procedures, supplies to initiate installation after S2

Summary

- Testing and analyses to date all look promising
- An interim solution which should enable LLO to lock reliably between the Science 1 and Science 2 runs is being installed (PEPI 2-DOF pre-isolation with the fine actuation system)
- Tentatively plan outfit LHO with FAS/PEPI systems, well after S2
- Seismic retrofit with an active pre-isolation system and an active internal damping system
  - » Will be tested at LASTI June - Nov
  - » Planned for installation at LLO after the Science 2 run, in Jan 2003