LIGO Commissioning Update

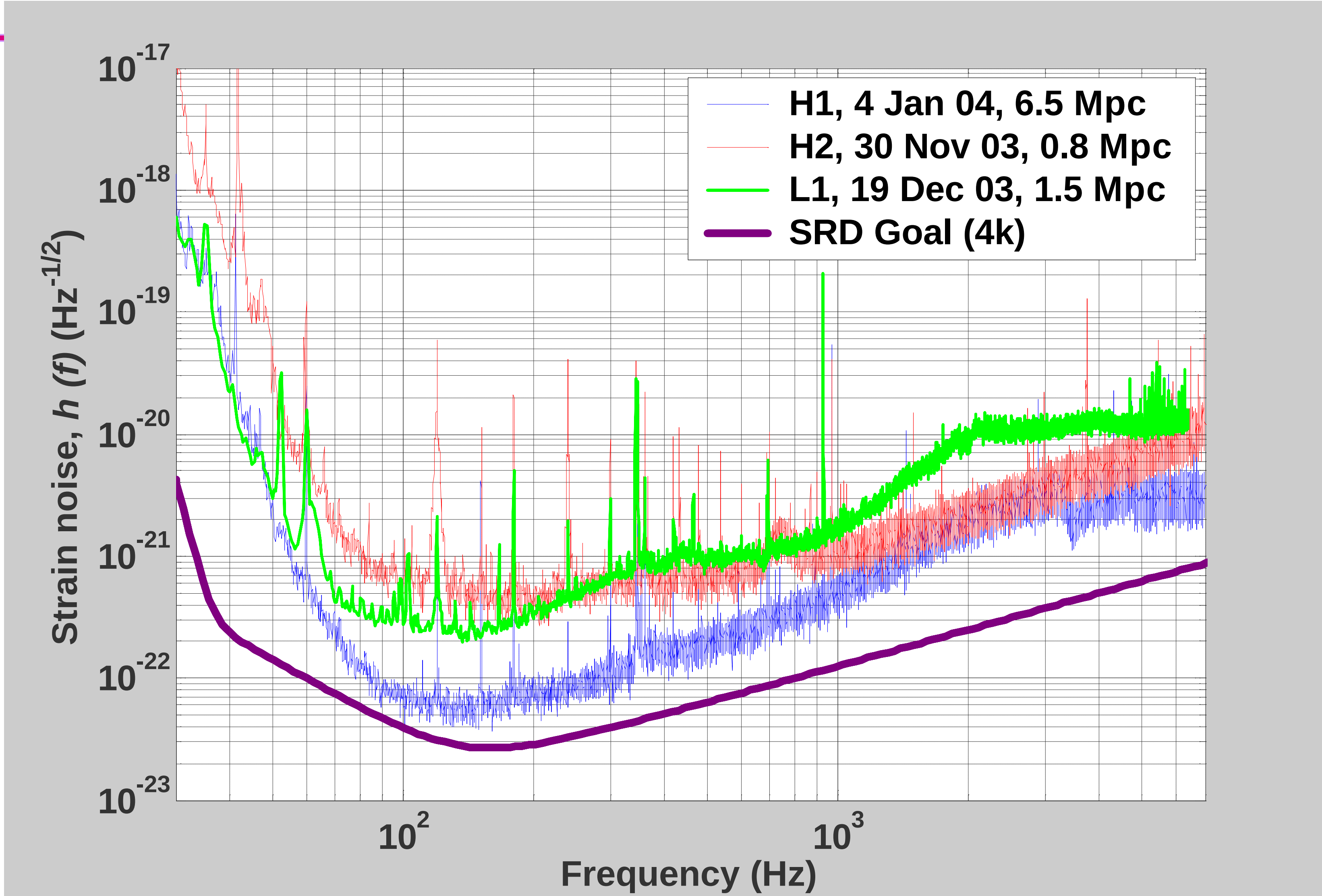
PAC Meeting, June 3, 2004

Dennis Coyne

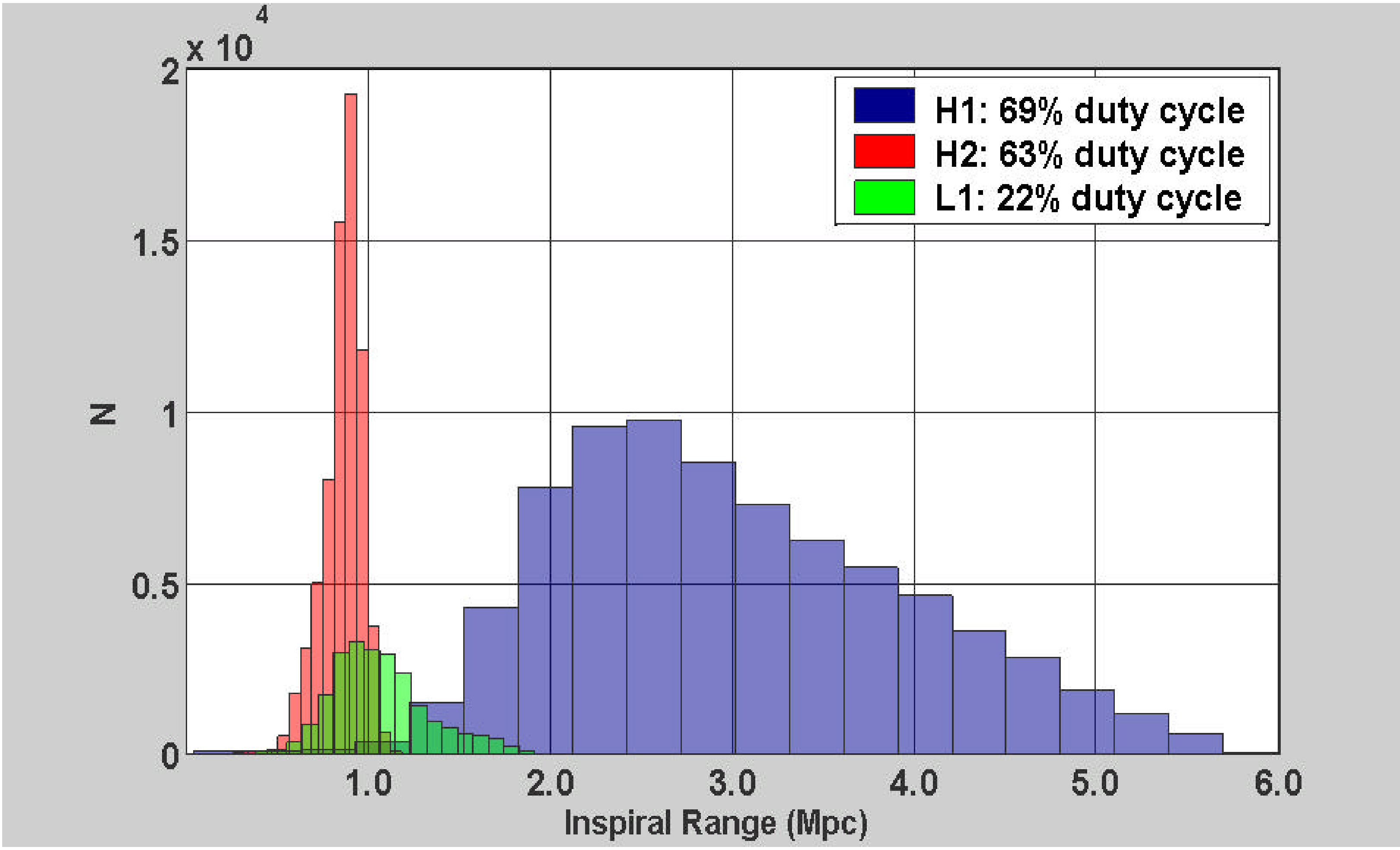
[update of Peter Fritschel's LSC Talk, G040066-00, 3/16/2004]

G040257-01-D

S3: peak sensitivities



S3: reliability & stability

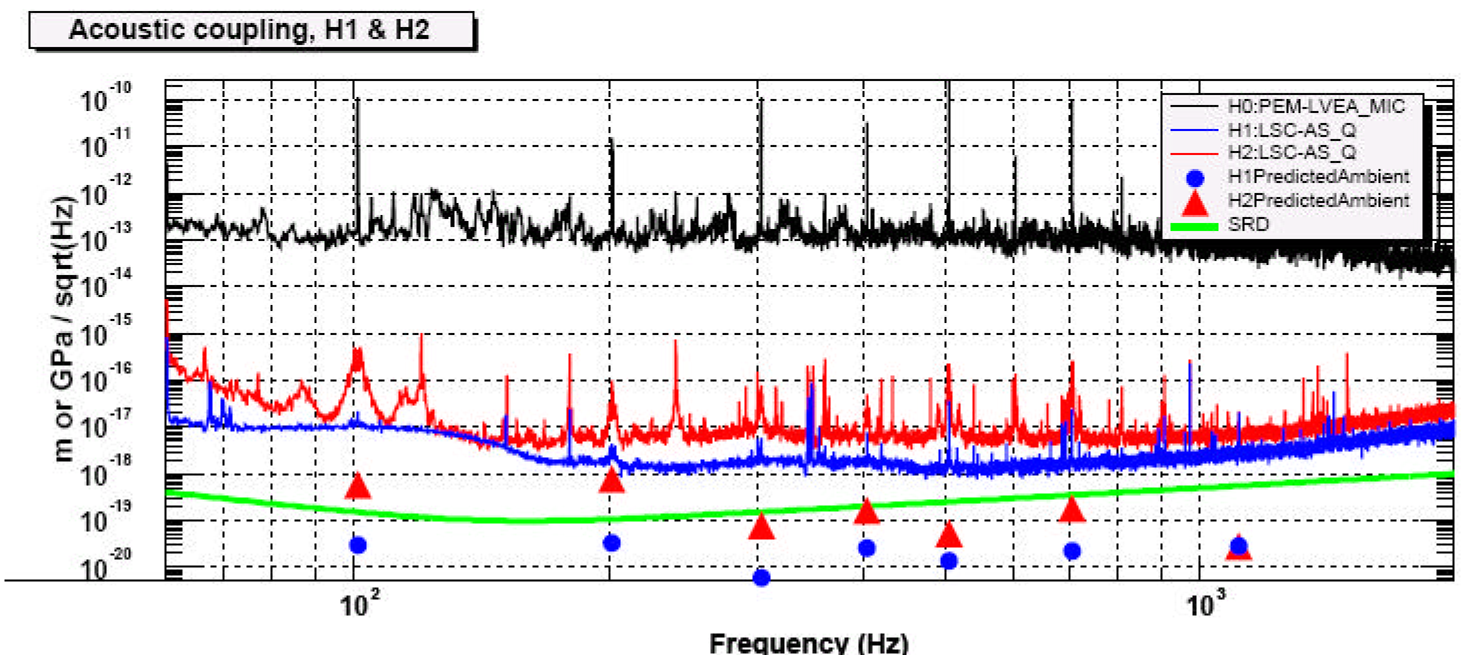


Major Goals and Tasks After S3

- Sensitivity
  - Operate at high power: achieve designed optical gain
    - Laser
    - Thermal compensation system (TCS)
    - Improved anti-symmetric port detection efficiency (Output mode cleaner (OMC) or more RF photodetectors)
  - Finish(?) environmental effects mitigation (acoustics, dust, HVAC pulsing, …)
  - Manage noise in auxiliary degrees-of-freedom
  - Clean up electronics: RFI mitigation
- Reliability & Stability
  - Seismic retrofit at LLO: HEPI
  - Auto-alignment system: all degrees-of-freedom, at full bandwidth
  - Address causes of lock-loss

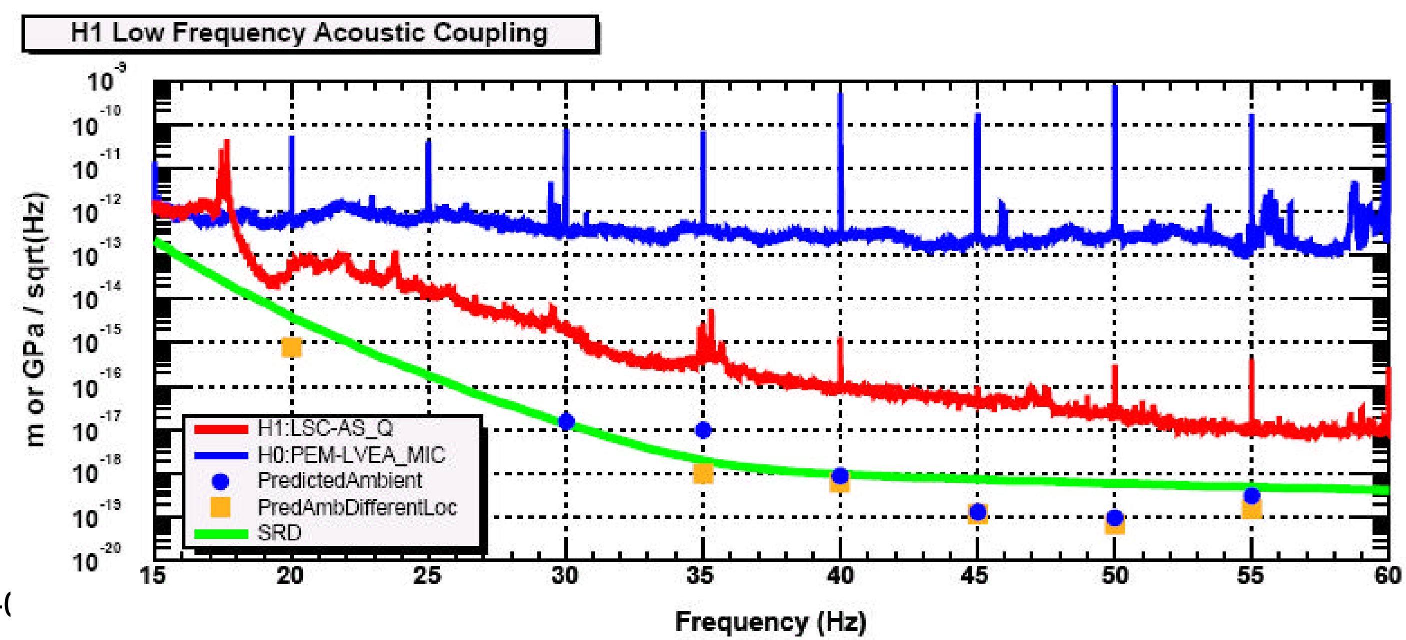
Acoustic Mitigation

- Recall: significant improvements between S2 & S3
  - Problem: acoustical vibrations of optical elements in the output beam path
  - No acoustic peaks left in S3 spectra
  - Acoustic enclosures around AS port sensing tables: ~10x reduction
  - Improvements and simplifications to beam sensing path: ~10x
- Original goals: 100x-1000x reduction, reached for H1



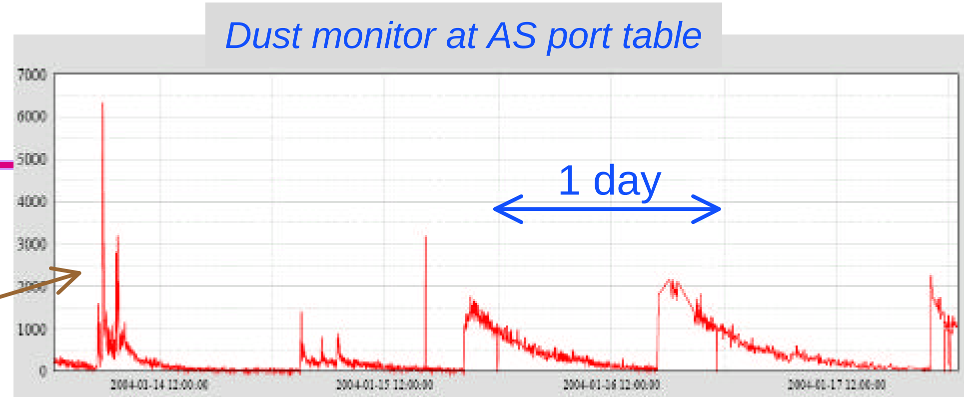
Acoustic Mitigation (2)

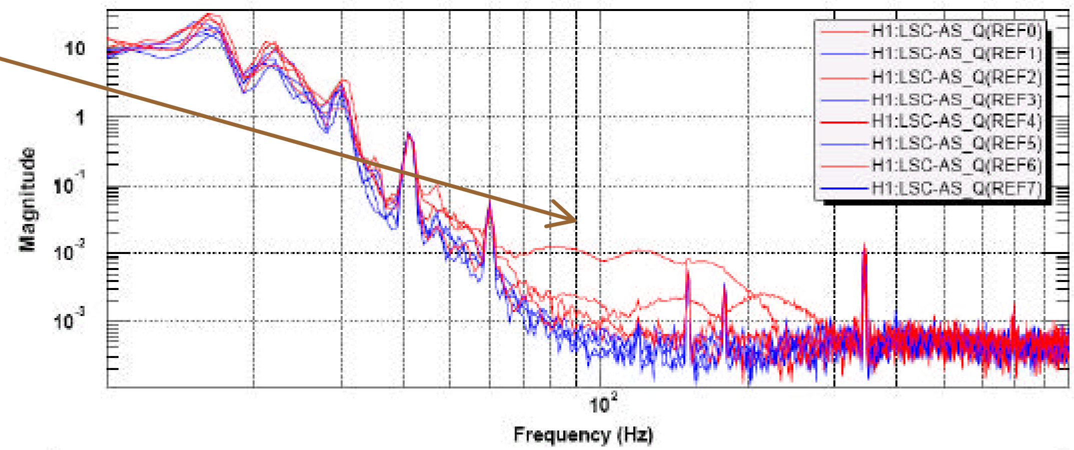
- Raise the bar at LHO: H1-H2 stochastic b.g. potential
  - H1 sensitivity now dominated by reflection port table: continue improvement/simplifications of this beam path
  - Reduce continuous sources: house or move electronics cabinets
    - Moving cabinets as part of the EMI retrofit at LLO, pre-S4
    - EMI retrofit is post-S4 for LHO; Investigating cost & “wisdom” of acoustically shielding racks in existing location
- New data on lower frequencies: seismic/acoustic
  - HVAC the main source: no easy improvements
  - Investigating ‘floating’ the detection tables on low-frequency mounts



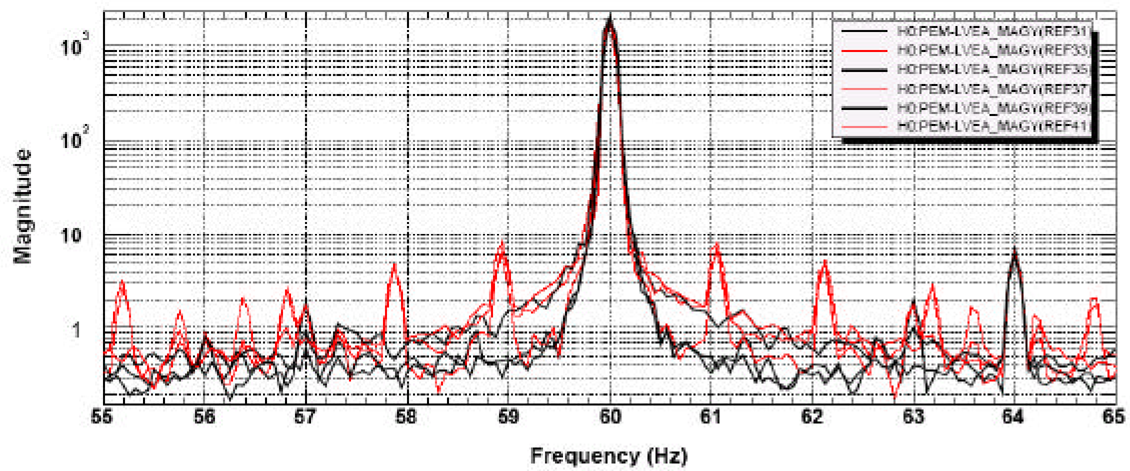
More environmental effects

- Dust in table enclosures
  - Gets stirred up by entries, takes a while to settle down
  - Causes glitches when it falls through the beam
  - To be addressed with HEPA filters, and/or covers over the beam path





- HVAC in-duct heaters
  - Pulsing produces ~1 Hz sidebands around 60 Hz; couples magnetically to AS_Q
  - Purchasing new heater controls to mitigate the effect (from SCR to staged heating)



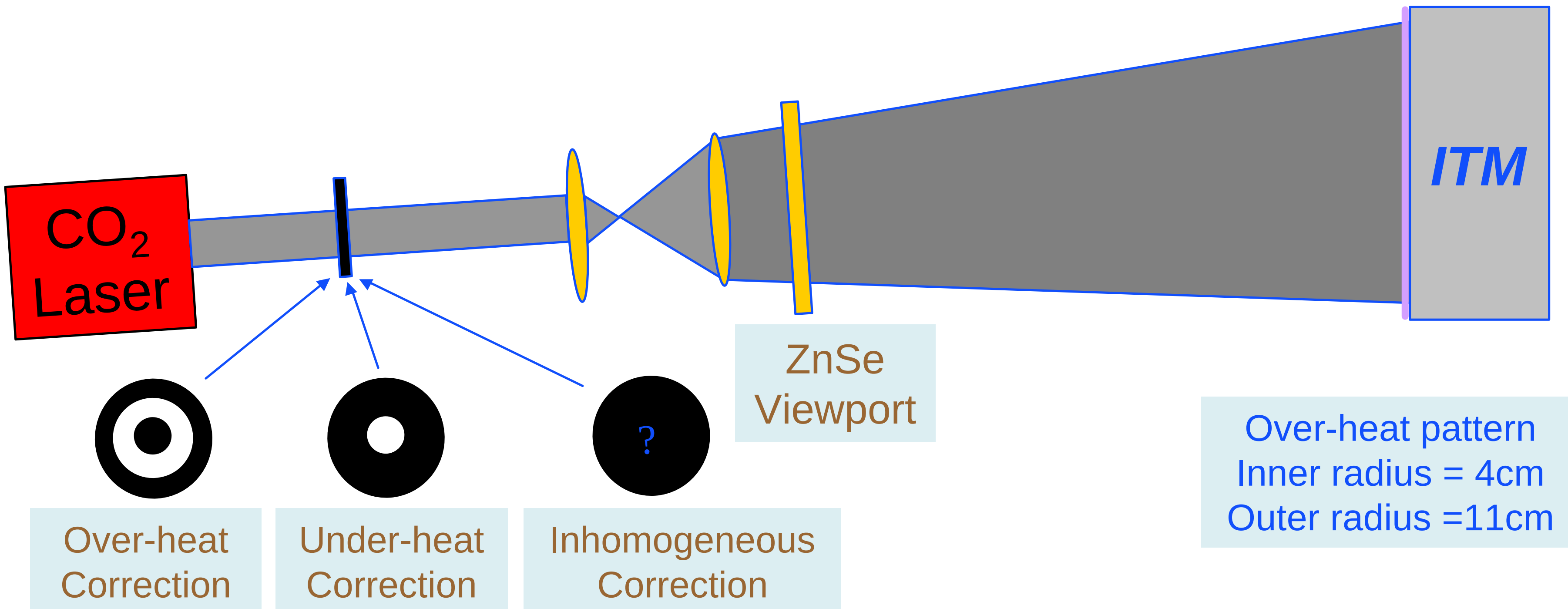
Optical gain: "10 W" laser

- Current input power levels:

	H1	H1 Reworked	H2	L1	*Design*
Laser output	4.9 W	11.0 W			
Mode cleaner input	3.6 W	7.6 W	3.7 W	6 W	*8 W*
Recycling mirror input	2.3 W		2.6 W	3.6 W	*6 W*

- Plan
  - Get H2, L1 LWE lasers back up to spec, including 1 spare before S4
  - Improve PMC transmission (H1 increased from 67% to 82%)
  - Diagnose suspended mode cleaner loss (20-30% lost)
  - Input electro-optic modulators: reduce number from 3 to 1 wideband with multiple modulation

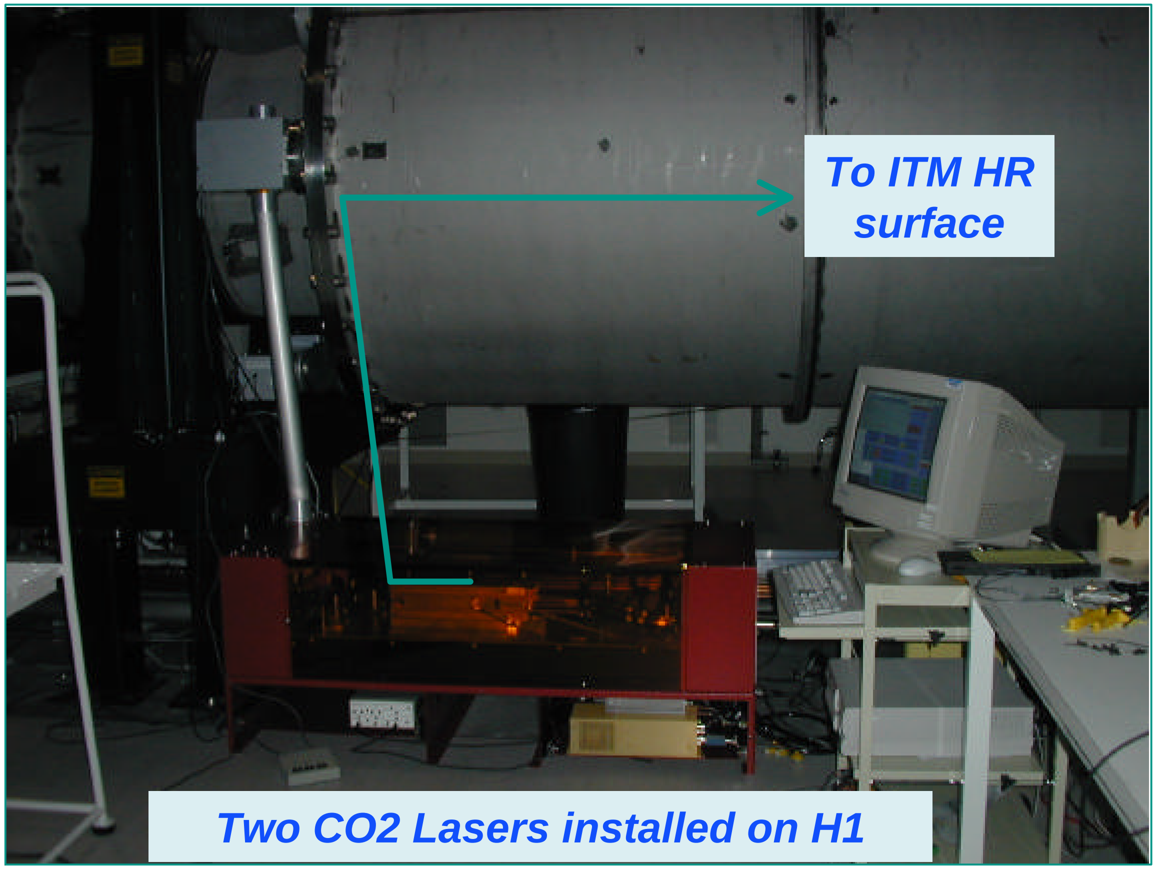
Thermal Compensation



- Cold power recycling cavity is unstable: poor buildup and mode shape for the RF sidebands
- ITM thermal lens power of ~0.00003 diopters needed to achieve a stable, mode-matched cavity
  - intended to be produced by ~25 mW absorbed from 1µm beam

TCS Installation

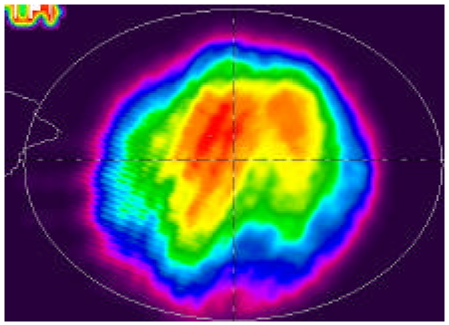
- Two CO2 Lasers are installed on H1
- Two more TCS systems (4 lasers) are being procured/fabricated for H2 and L1
- Assembly & Installation will start 6/7
- Commissioning expected to be completed ~8/1 on H2 and L1



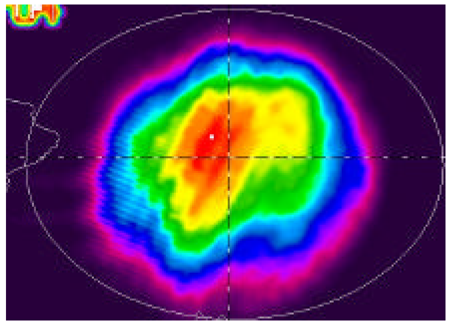
Two CO2 Lasers installed on H1

TCS on the power recycled Michelson: beam images at AS port

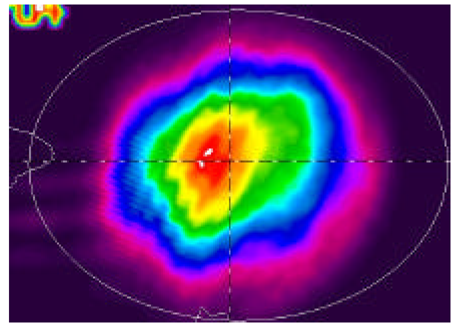
No Heating



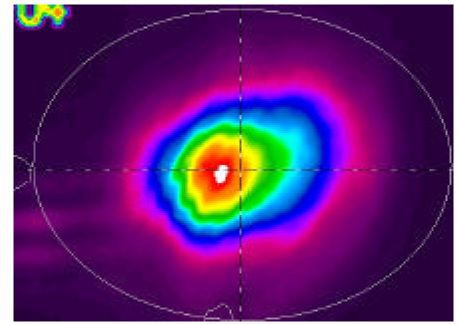
30 mW



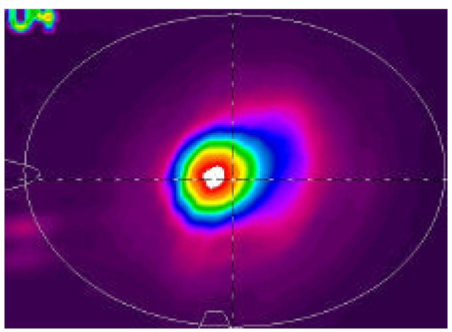
60 mW



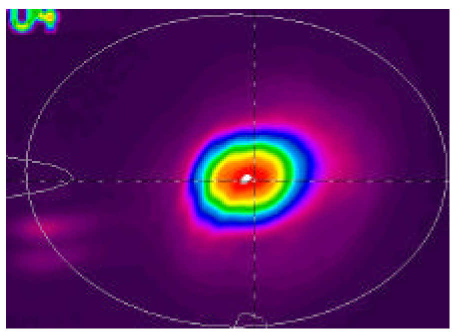
90 mW



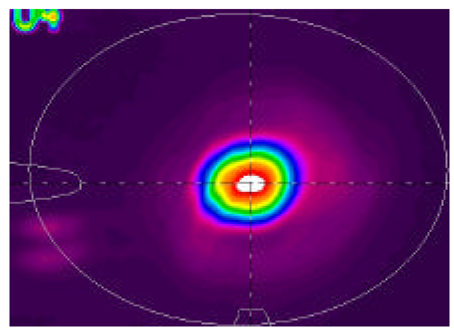
Best match



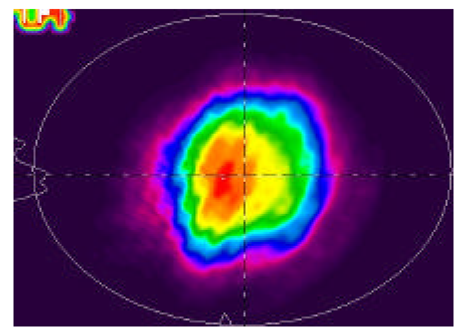
120 mW



150 mW

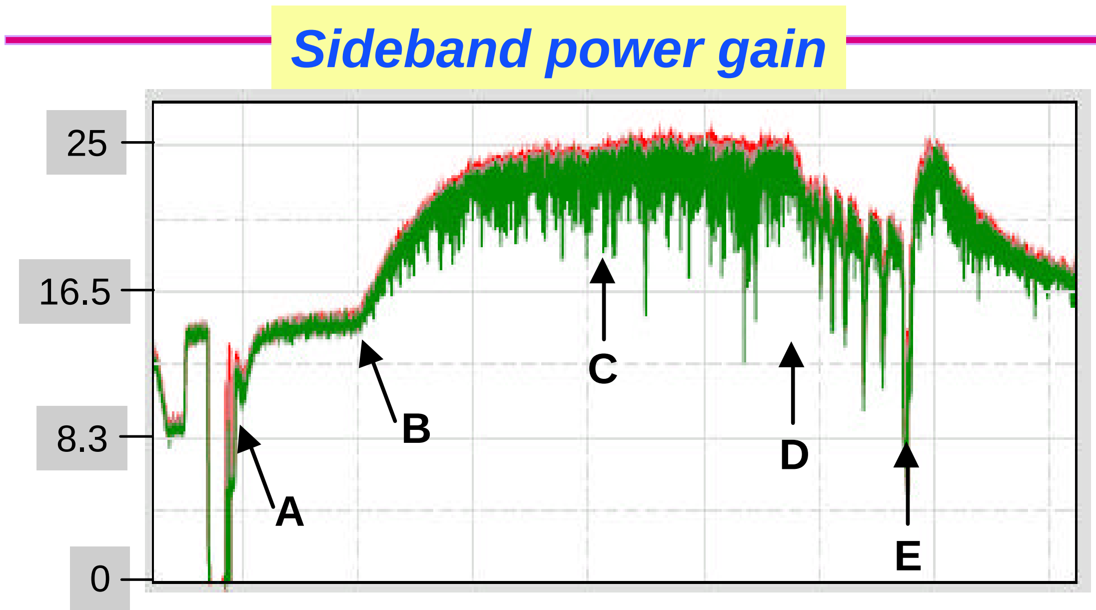


180 mW

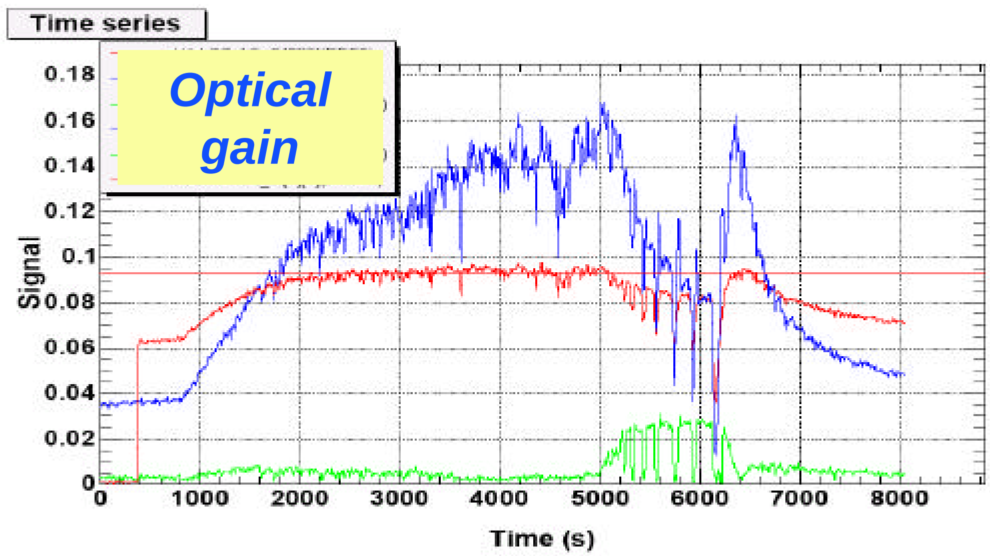


Input beam

Full Interferometer Results



A. Lock interferometer at 1 Watt
B. Apply 45 mW Common central heating
C. Increase to 60 mW
D. Increase to 90 mW
E. Turn off TCS



- AS_Q gain: increases by 40%
  - doesn't increase as fast as expected
- PRC & MICH (pick-off) gains increase by factor of 4
  - gain scales as $(G_{SB})^2$

Summary of TCS Results

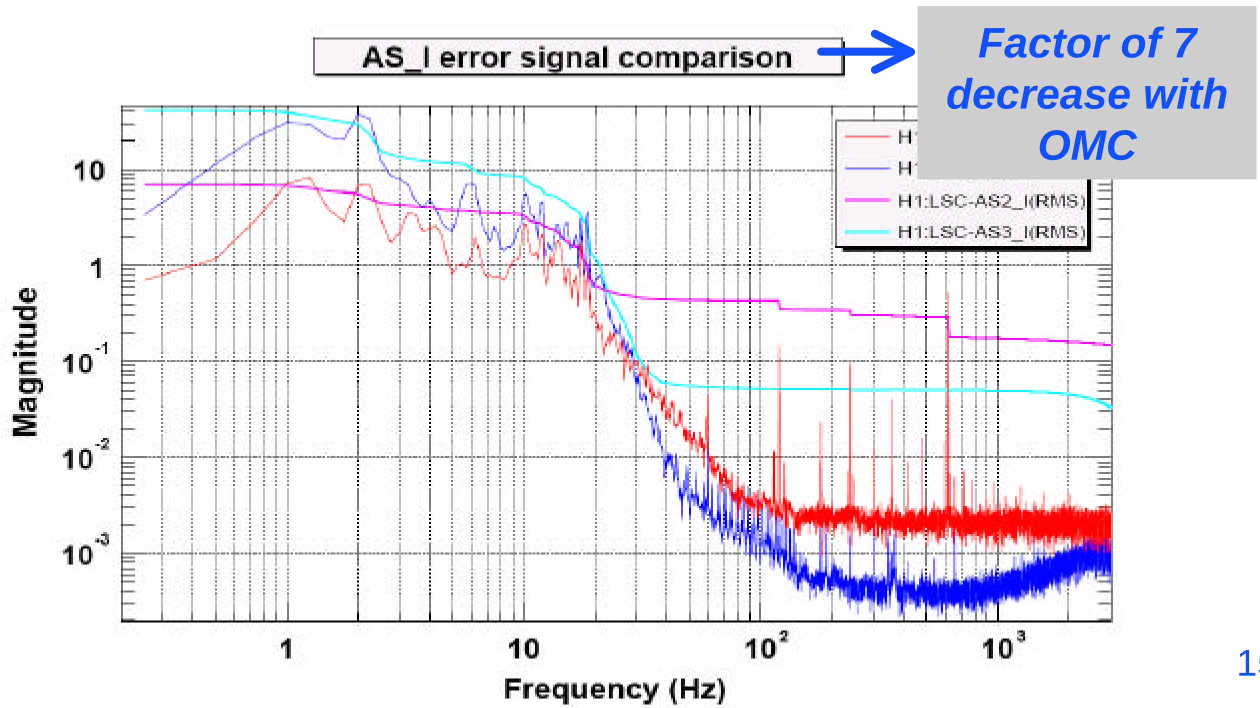
State	GSB
State 2 cold	7.0
State 2 hot (90 mW CO_2)	12.5
State 2 max $(tRM / (1 - rRM\ rM\ rITM))^2$	***14***
State 4 cold	13
State 4 warm (0.8W input)	16
State 4 hot (2.3W input, no TCS)	20
State 4 hot (0.8W input, 45mW CO2)	26.5
State 4 max $(tRM / (1 - rRM\ rM))^2$	***30***

Output mode cleaner: motivation

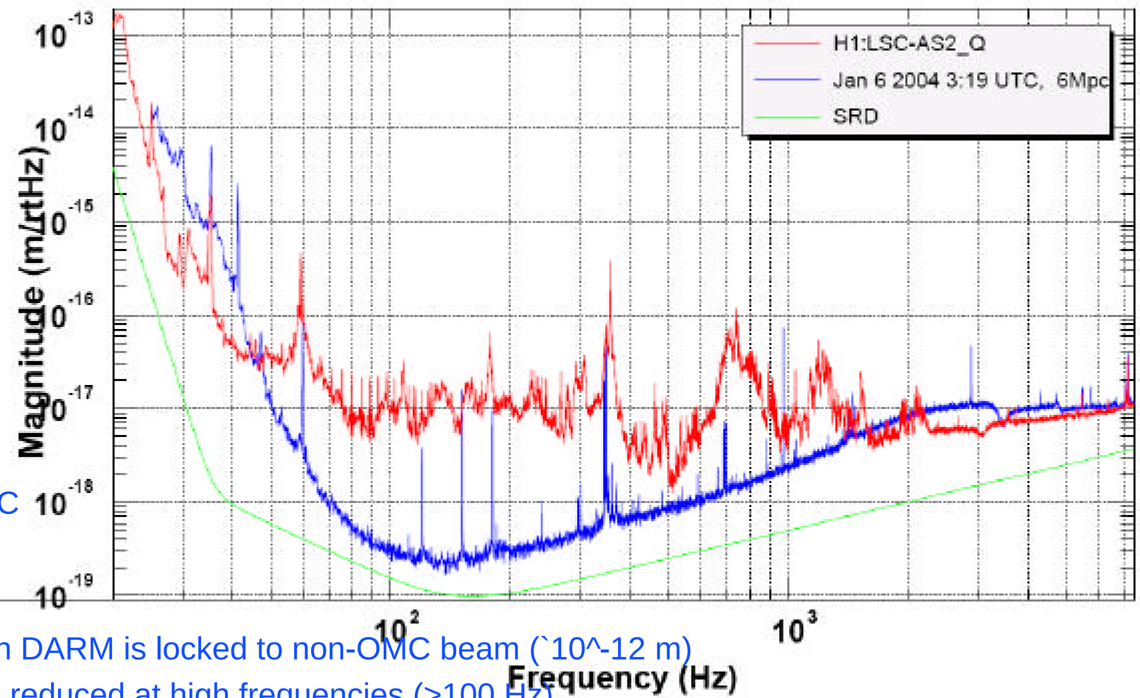
- Reduction of AS_I signal
  - Power in orthogonal phase limits the amount of power per AS port photodetector & AS_I servo is noisy
  - Produced by alignment fluctuations: $TEM_{01/10}$ modes would be removed by an OMC
- Improvement in shot noise sensitivity
  - Reduction of noise-producing (higher-order mode) power
- Potential saturation at $2f_m$ at higher power

Output Mode Cleaner (OMC) (2)

- GEO output mode cleaner a good fit for initial testing
  - On loan from GEO for several months
  - Finesse is ~40
  - Transmission:
    - Michelson bright fringe: 70% (30% reflected)
    - Full IFO dark port: T/(R+T) = 23%



Output Mode Cleaner (OMC) (3)



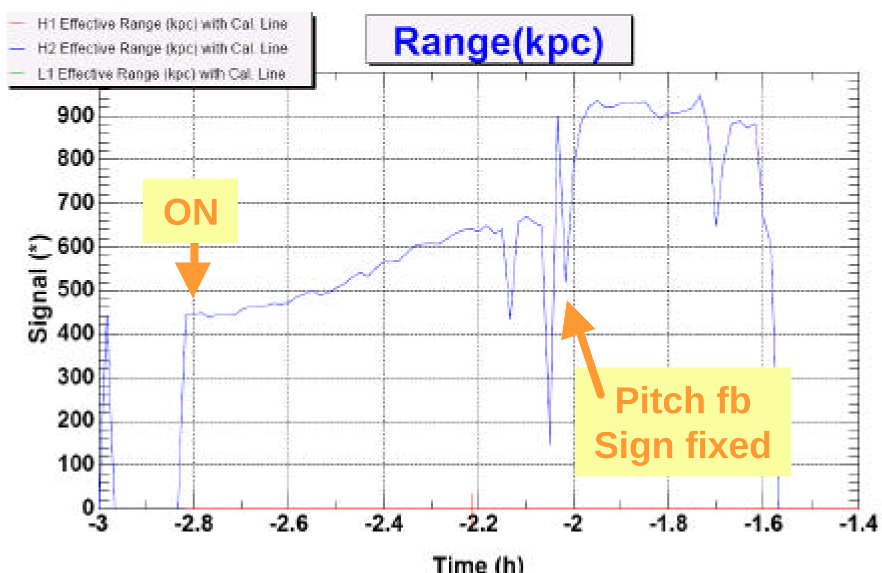
- Installation and testing on H1
  - Began mid-April & continues
  - AS port spectrum:
    - Carrier is ~50% of total before OMC
    - Carrier is ~2% of total after OMC
  - Locked OMC using AS_I signal
    - Observe offset in OMC signal when DARM is locked to non-OMC beam (`10^-12 m)
    - Laser amplitude noise sensitivity is reduced at high frequencies (>100 Hz)
    - AS_I signal reduced by a factor of 7 with the OMC
  - Noise observations:
    - Noise of post-PMC signal > pre-OMC signal
    - Extremely sensitive to tapping mounts or any added acoustic energy (in vacuum or not, suspended or not)
  - Next?
    - Continue to understand noise source/sensitivity
    - Unlikely to reduce noise by factor of ~1000
    - Pursue vacuum & seismically isolated optical train thru OMC
    - Pursue multiple RFPDs on the AS port

Alignment Control

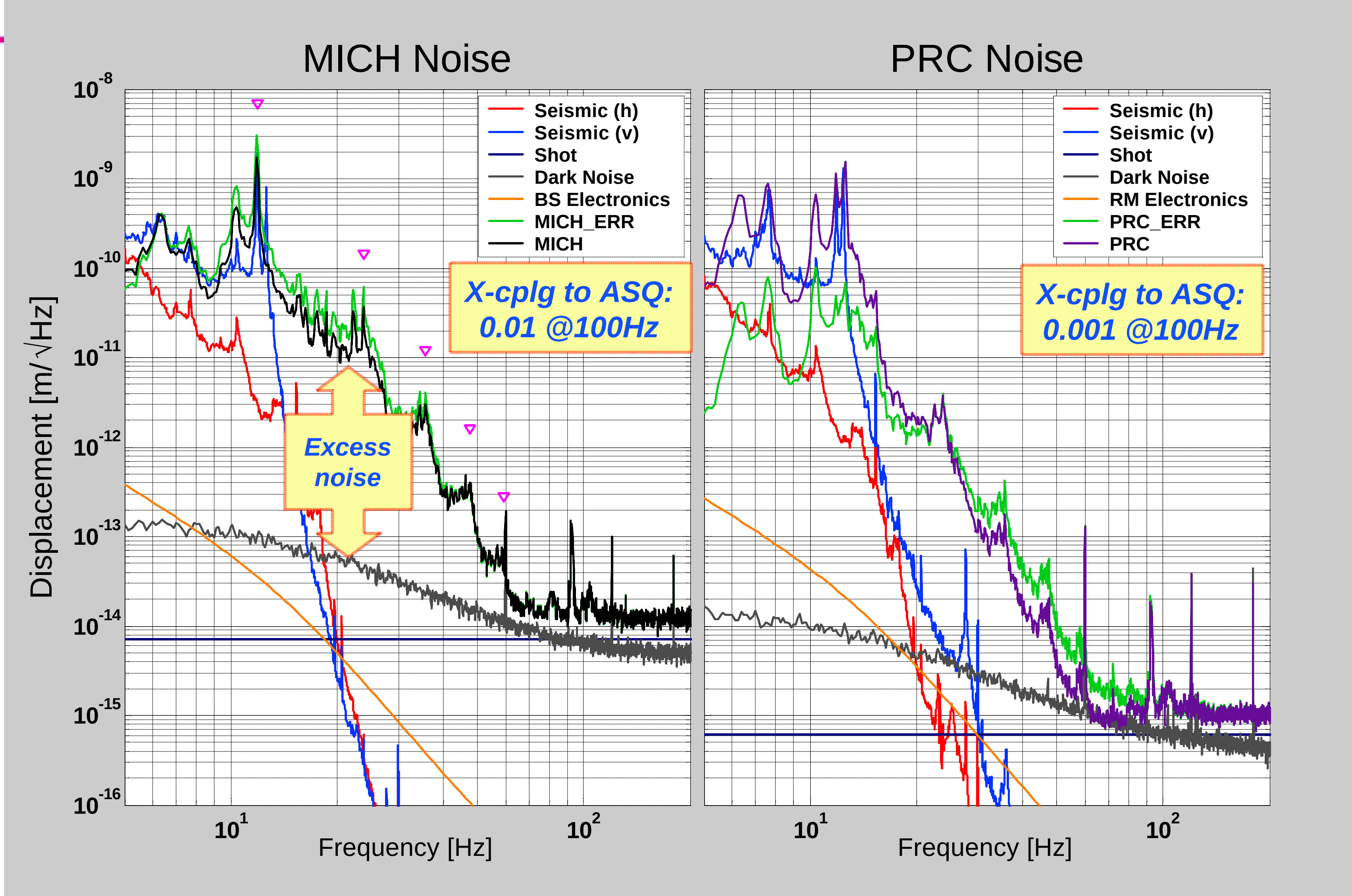
- Continued incremental progress on WFS/QPDs …
  - Goals:
    - Sufficient gain/bandwidth to reduce power fluctuations to ~1%
    - Turn off optical lever angular control: too noisy
    - Manage WFS/QPD noise coupling to AS_Q
  - Status, H1 (post-S3 progress)
    - Bandwidth now at 2.2 Hz for all but one WFS: effect not fully characterized
    - Some noise reductions made, still an active issue
    - Initial alignment steps now fully automated
    - Controls software upgrade: sensor input matrix; compensate radiation torques; compensate for optical gain change; not yet fully characterized
    - WFS feedback to mode cleaner mirrors; not yet fully characterized

Beam centering

- Transmission QPDs hold the beam position fixed at the ETMs
  - Need to independently find the right spot (w/in 1mm of center)
- WFS control all mirror angles: only DOF left is the beam position in the corner
- New servo:
  - Capture image of beam scatter from BS face
  - Image processing to determine position of beam center
  - Slow feedback to input telescope to fix BS beam position



Auxiliary degrees-of-freedom: small coupling, but very noisy

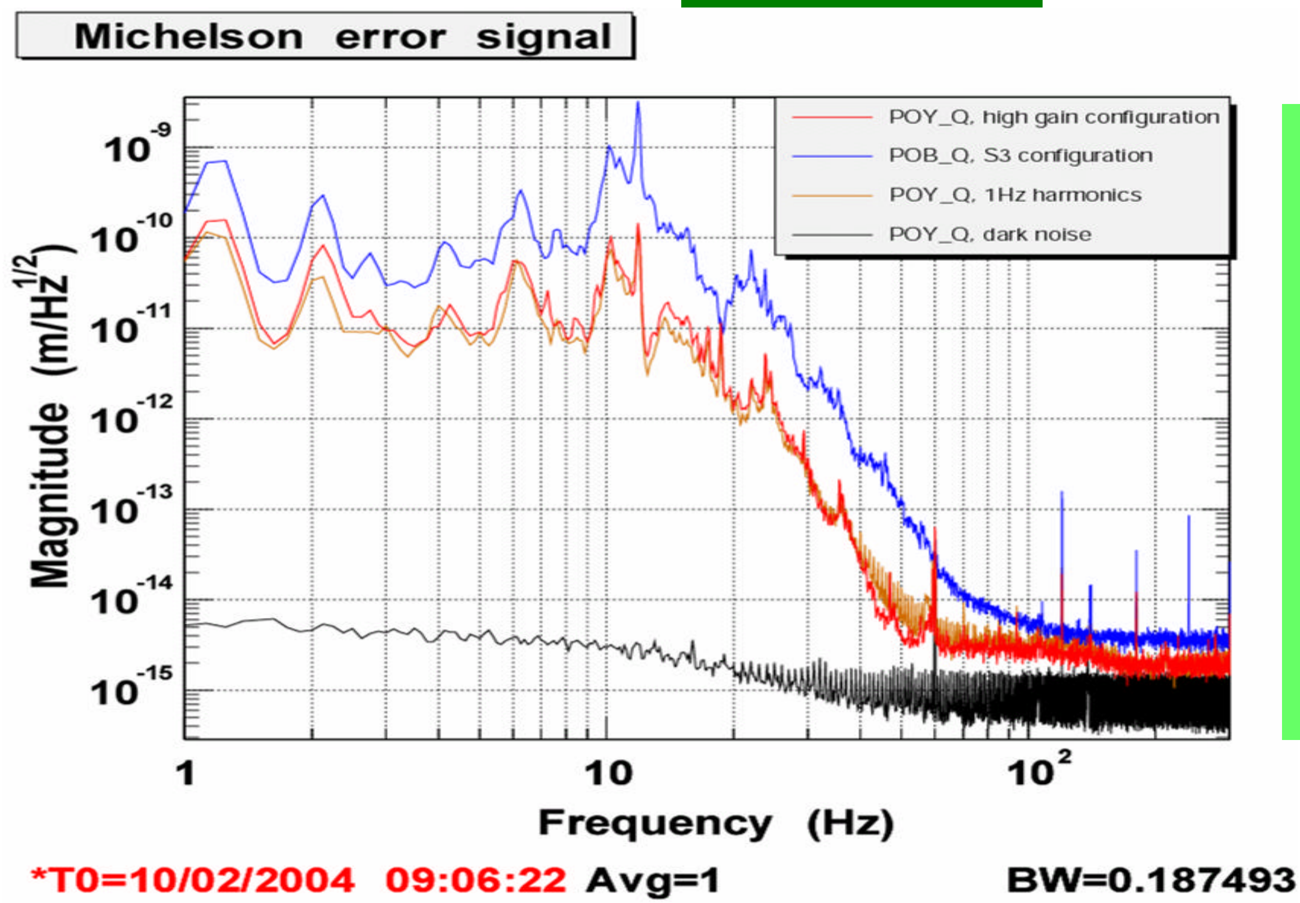


Excess noise: optical gain modulation

- *Signal (sideband field)·(length deviation)*

Intermodulation

Reduce these by increasing loop gain



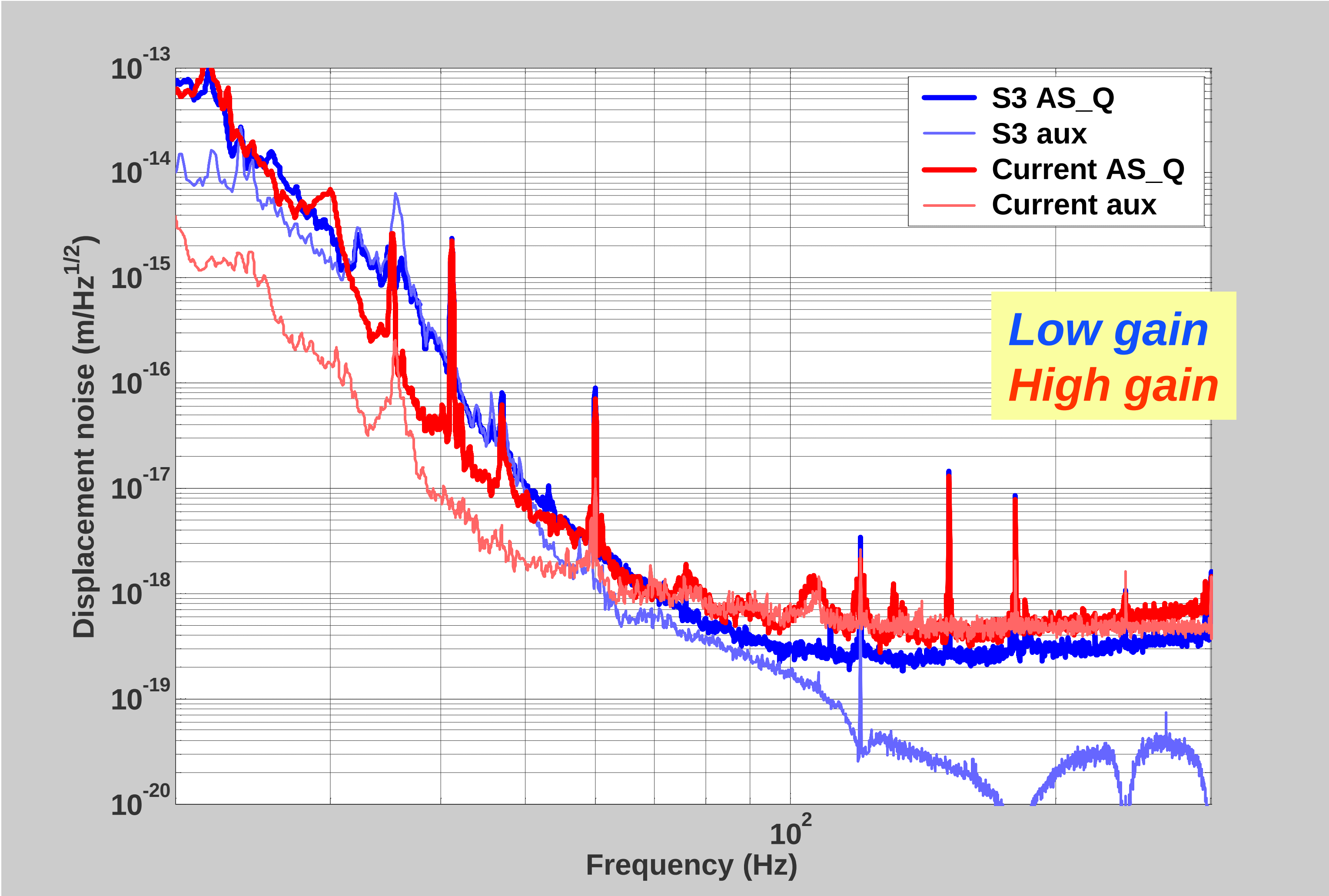
Effect of increasing the MICH bandwidth from 10Hz to 50Hz:

> 10x lower noise at 40Hz

> able to detect higher power pick-off beam for reduced shot noise

Similar noise reduction for PRC, and for the WFS error signals

Impact on noise

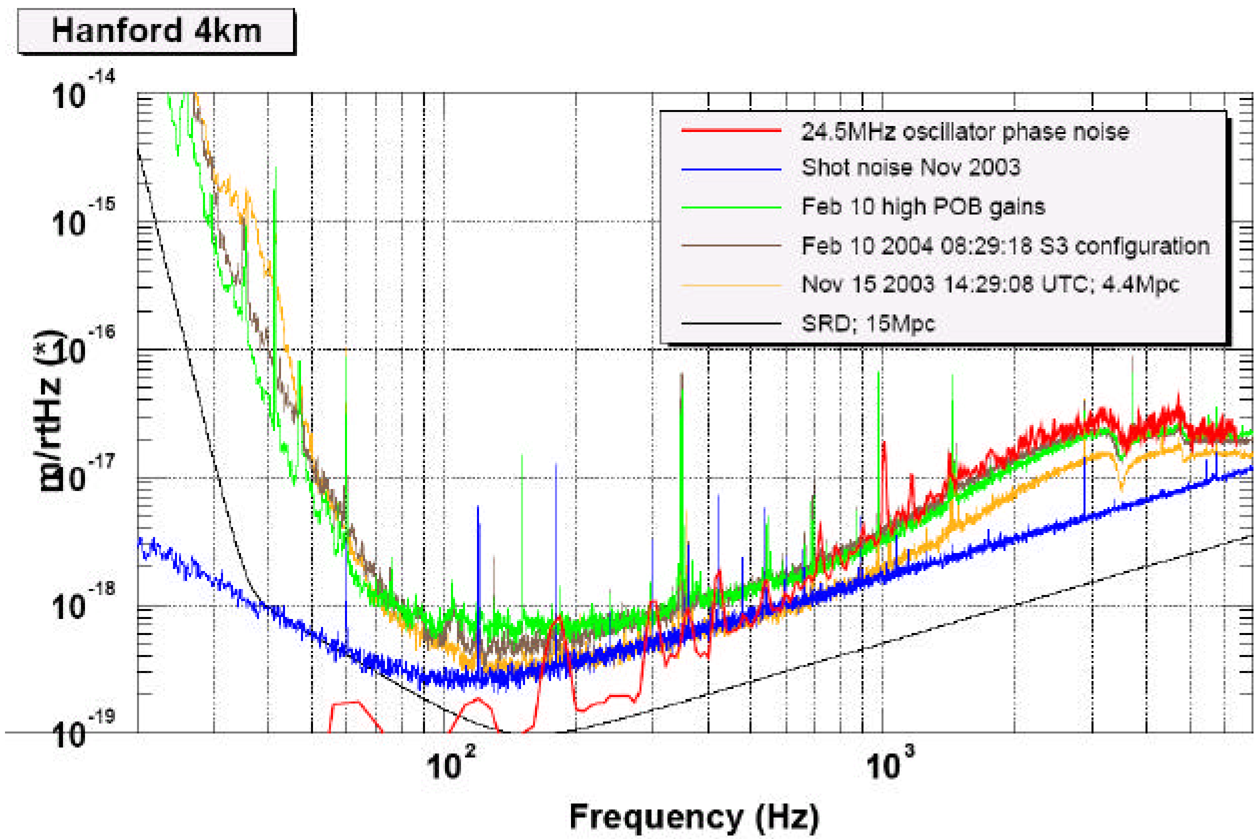


High-f noise bump: mystery solved

RF Oscillator phase noise

Mechanism: possibly coupling through the DC AS_I signal

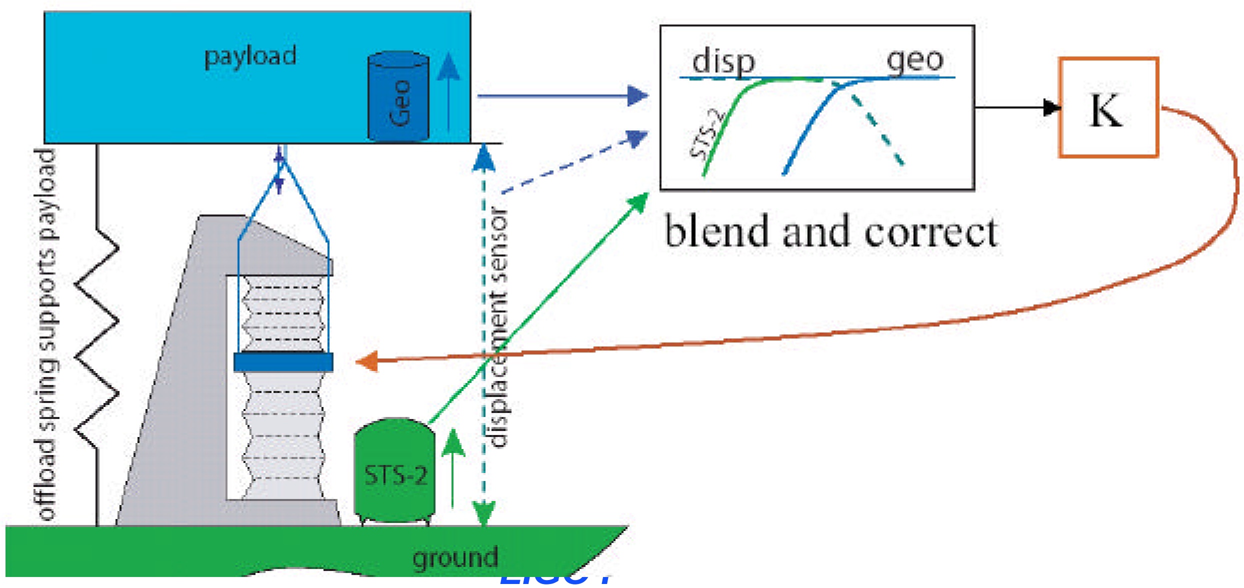
- Modulation phase noise appears on demodulation signal (LO) too
- True at low frequencies, but perhaps mode cleaner pole shifts phase of modulation fields – doesn't cancel out at higher frequencies?
  - Pass LO through an electronic filter to equalize paths – failed to work; coupling path not understood
- Solution:
  - Low phase noise crystal oscillator – received new osc. – being characterized



Hydraulic External Pre-Isolator (HEPI)

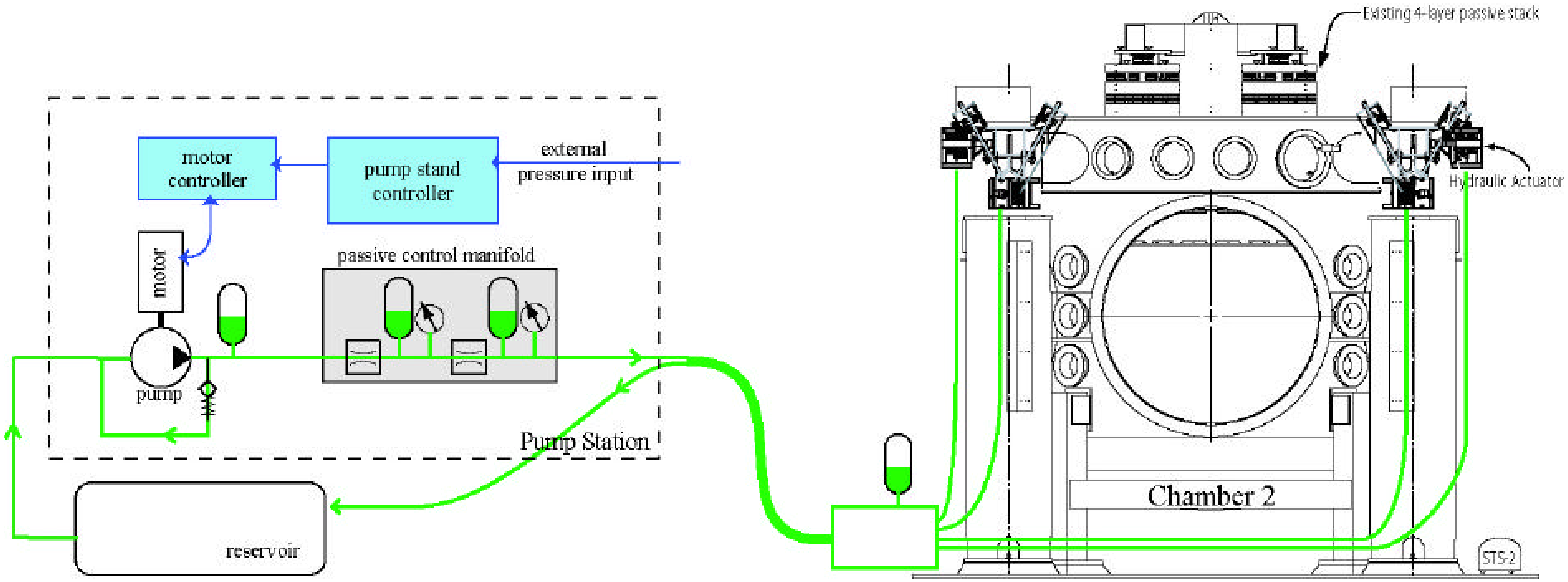
- Stanford's proposed Adv. LIGO approach for the first stage of active isolation and high range, position/alignment control was accelerated & adapted for use in initial LIGO

  - At each tank corner pier, there is a sensor/actuator set, vertical and horizontal.
  - Each DOF controlled with respect to HEPI displacement sensors and geophones.
  - Displacement sensor corrected for floor motion as measured by Streckeisen STS-2., in x, y, z DOF's.

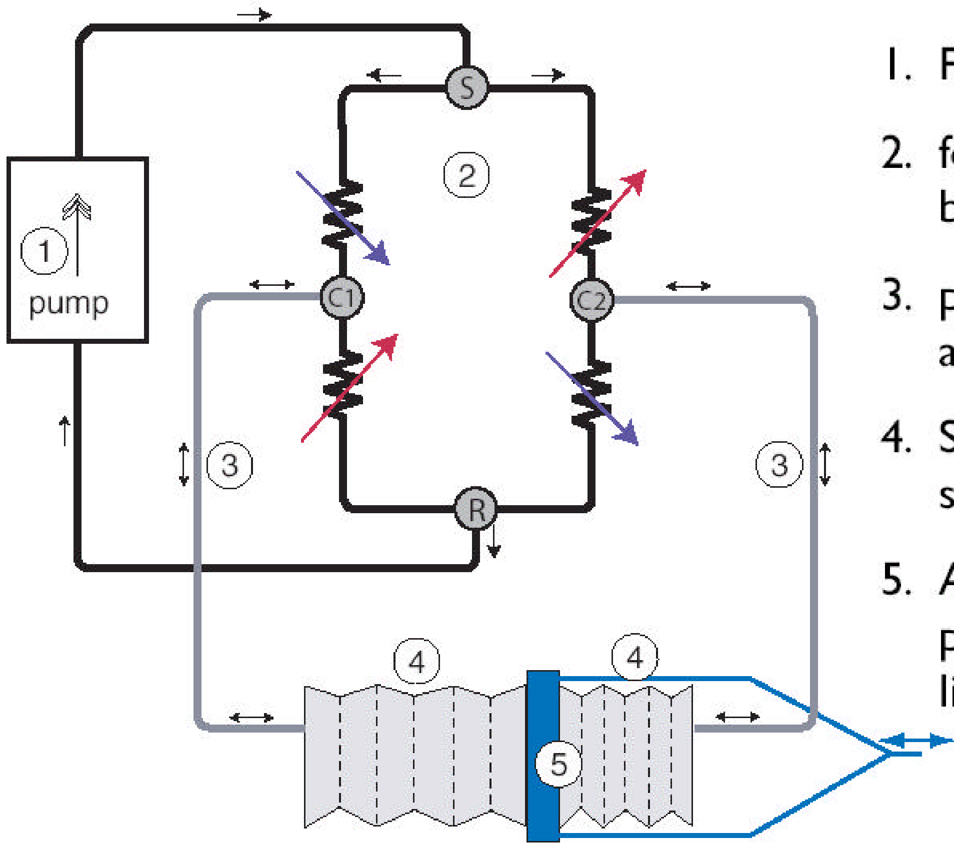


HEPI

- Pressure regulation point is at the load manifold
- In the corner station the output of 3 pump stations are ganged together
- High bandwidth pressure regulation was found to be unnecessary



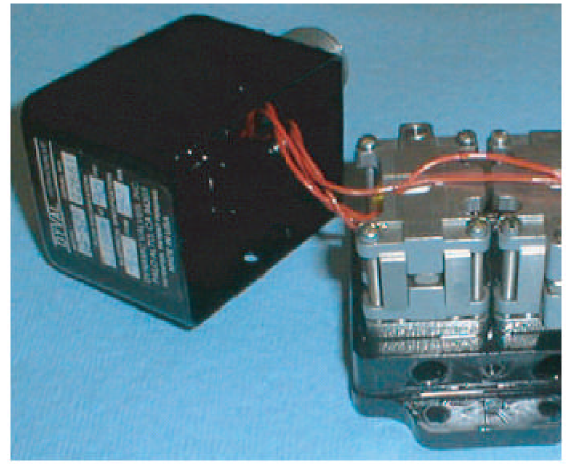
Hydraulic Bridge Actuation



1. Pressure-stabilized pump.
2. four-valve flow-resistance bridge.
3. pipes connect bridge to actuator.
4. Stiction-free bellows on each side of actuated plate.
5. Actuated plate connected to payload through 1-DOF linkage.

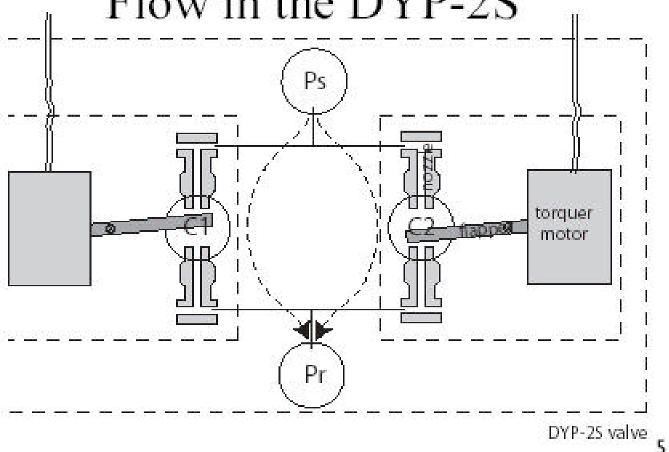
Valve Modification

- Hardham, Lantz, DeBra designed new nozzles for valve, to allow laminar flow and large linear bridge response.
- New nozzles procured, but need to be installed and adjusted by hand.



Parker DYP-2S valve

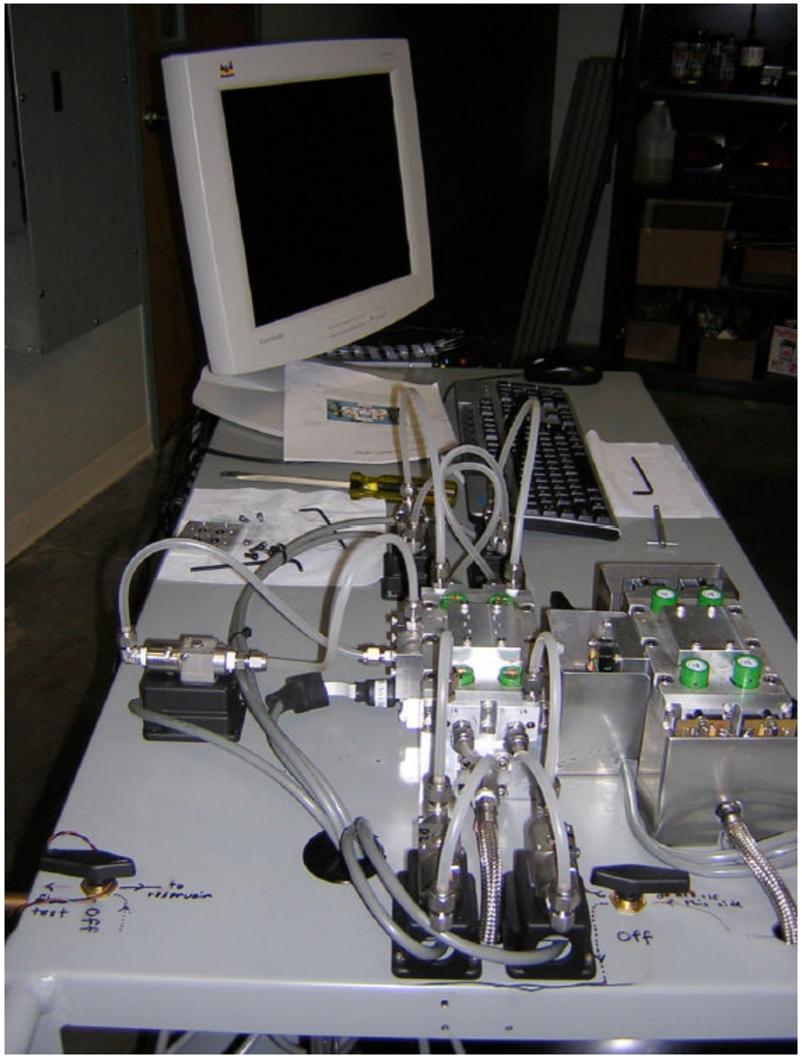
Flow in the DYP-2S



The new nozzle

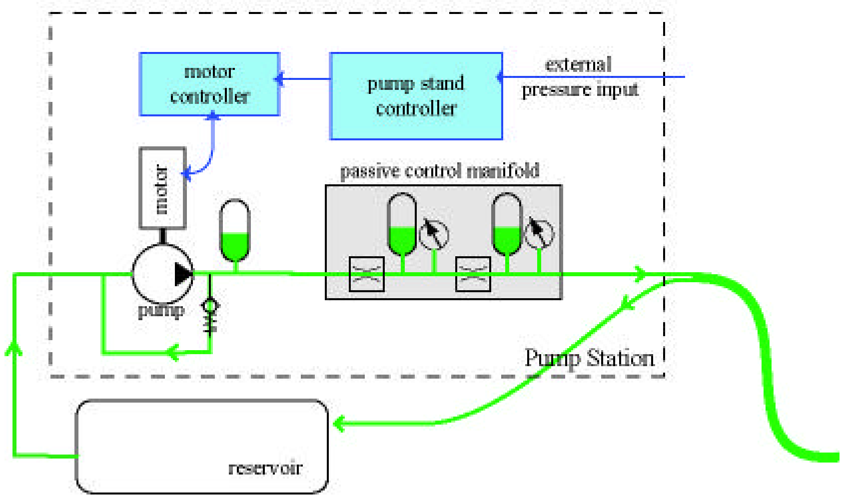
Valve Calibration Stand

- Purpose:
  - Check function
  - Check for leaks
  - Set orifice position
  - Check linearity & hysteresis
- All 96 valves checked
  - ~20 returned to manufacturer under warranty (Parker) for leaks or non-linearity
  - 2 of 16 valves on systems tests show low authority and nonlinearity, not observed on test stand
    - Under investigation



Pump Station

- All 7 test stands completed
  - 1 for each end station
  - 3 for the corner station
  - 1 replacement for LASTI prototype
  - 1 spare at LLO
- Reliability
  - The LASTI pump station has been running ~continuously for ~14 months
  - The 2 pump stations at the end buildings have been running continuously for several months
  - Stanford is performing forensics on a LASTI servo-valve exposed to the hydraulic fluid for ~1 yr and looking at long term compatibility, corrosion

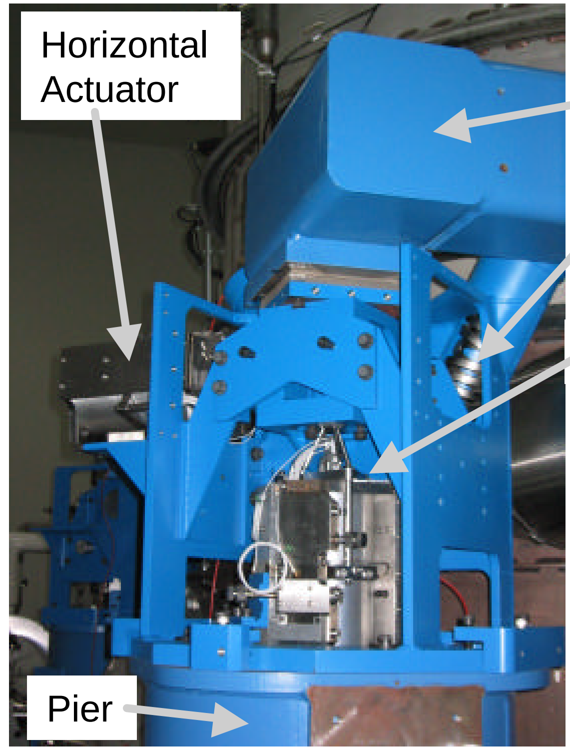


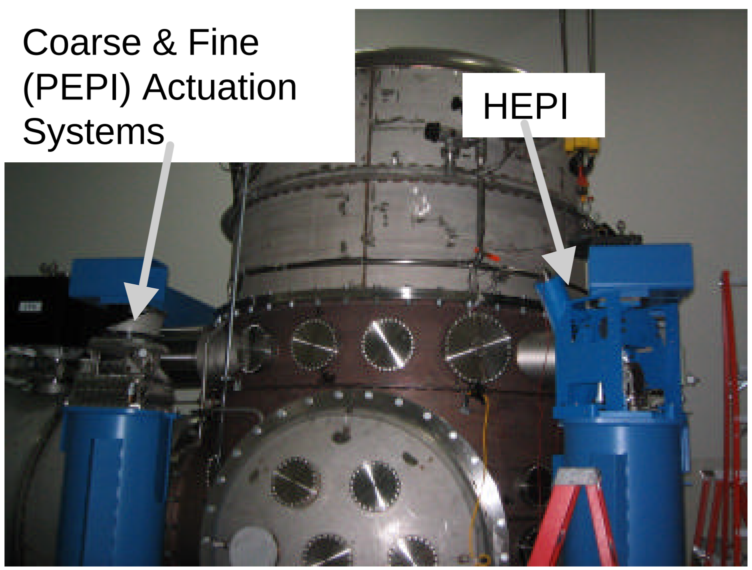
Mass Production

- All part fabrication completed
- All Assembly & Test in-house
  - Essentially completed

Installation

- Replacing the fine & coarse actuation systems on all BSC chambers – the coarse actuation and piers on all HAM chambers

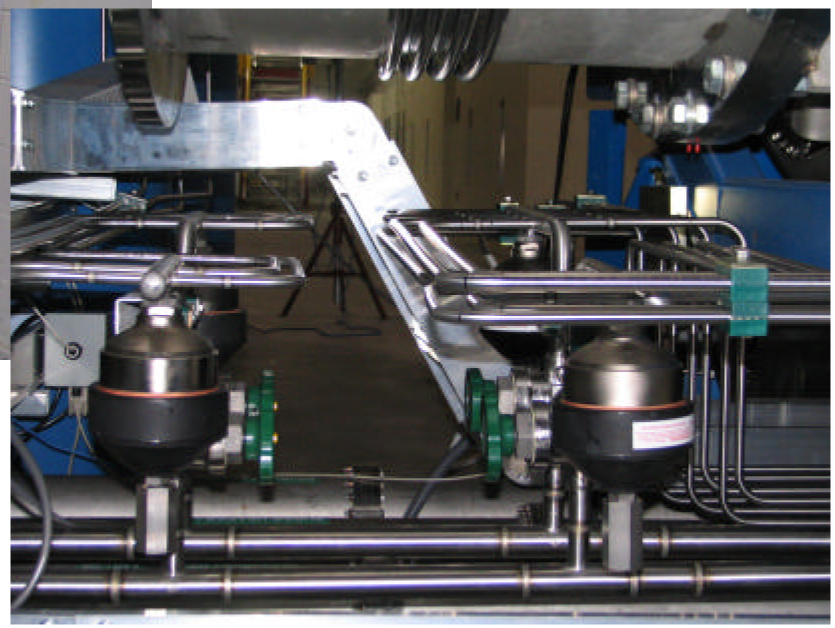




Installation (2)

- Payload is instrumented & freely suspended:
  - 12 dial gauges at the support tube/crossbeam connections
  - 2 optical lever signals (where available)
  - SUS OSEM shadow sensors
- Each corner is supported from directly above the spring attachment point
  - Load is transferred with a worm gear drive and load cell such that the load is never more that +/- 0.15 mm from initial posiiton
- After all 4 mechanical assemblies are in place on each of the 4 piers, the springs tension is adjusted (read out by load cells) and the payload returned to the initial position & alignment
- Have locked the X-arm after HEPI mechanical installation

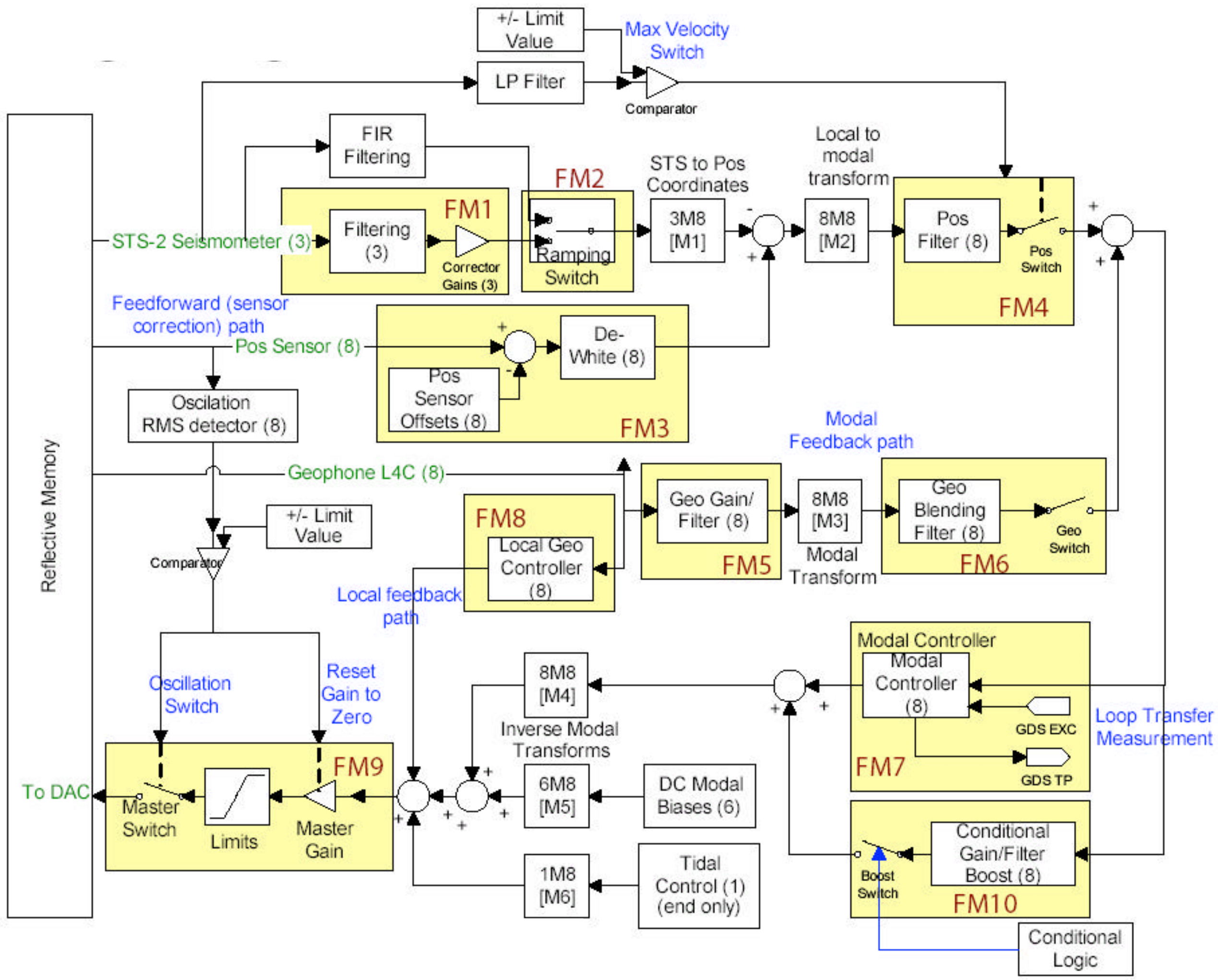
Piping



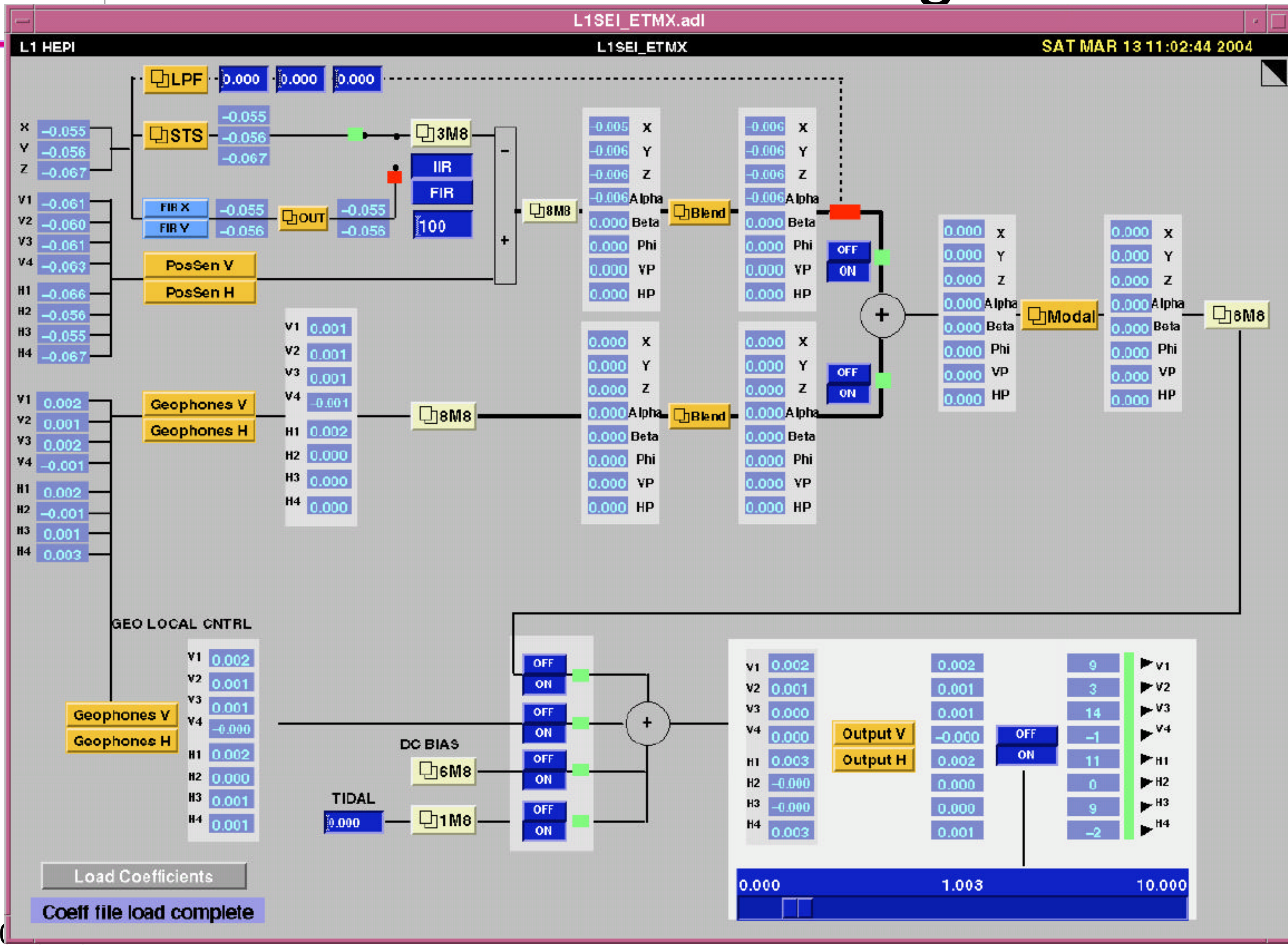
- Piping is stainless steel, food grade, seamless, welded
- Installation to be completed 6/4
- Testing to be completed 6/11

Design Control Diagram

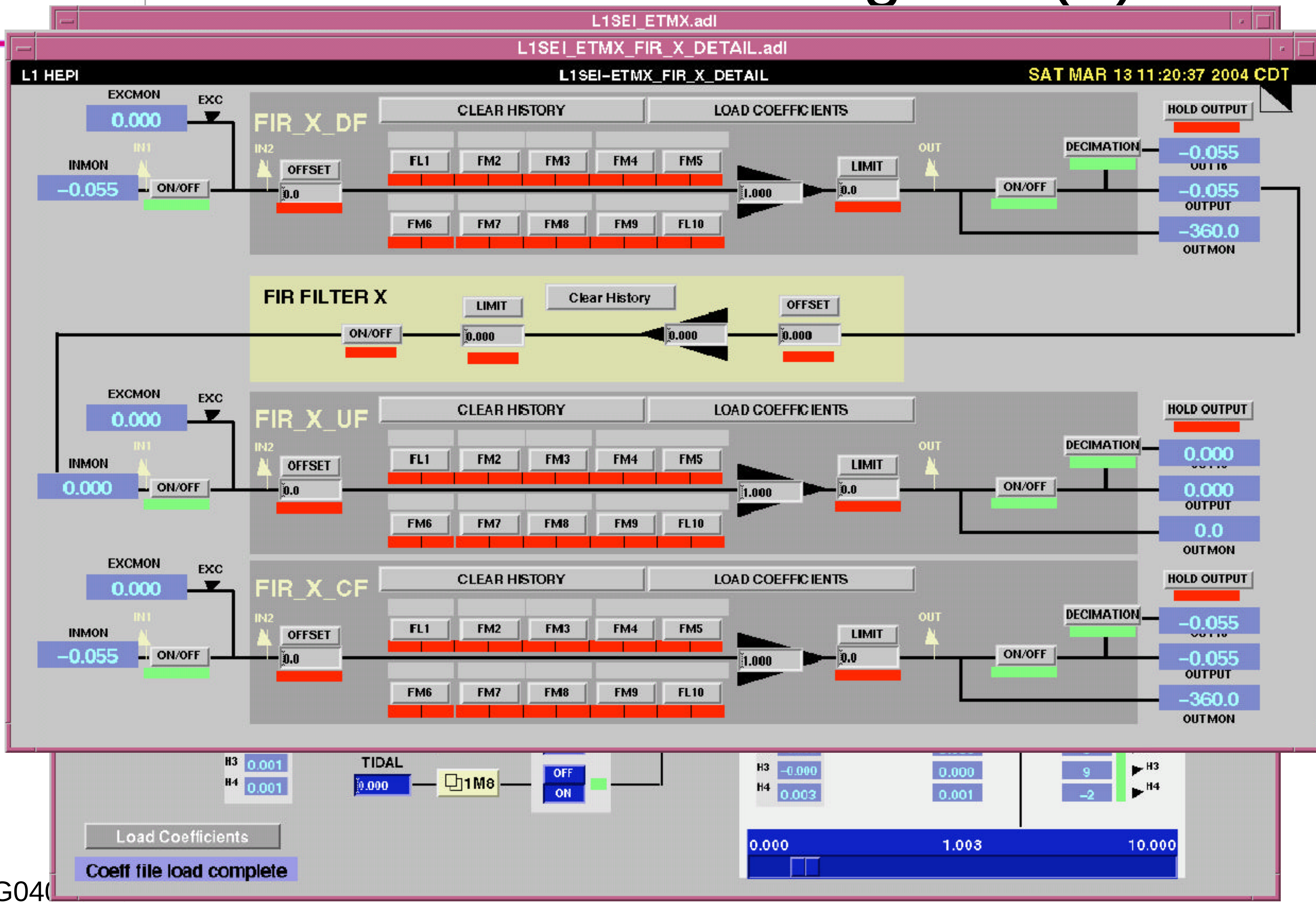
- Modal and/or local feedback plus feedforward (sensor correction) control
- Watchdogs are in place & verified to work



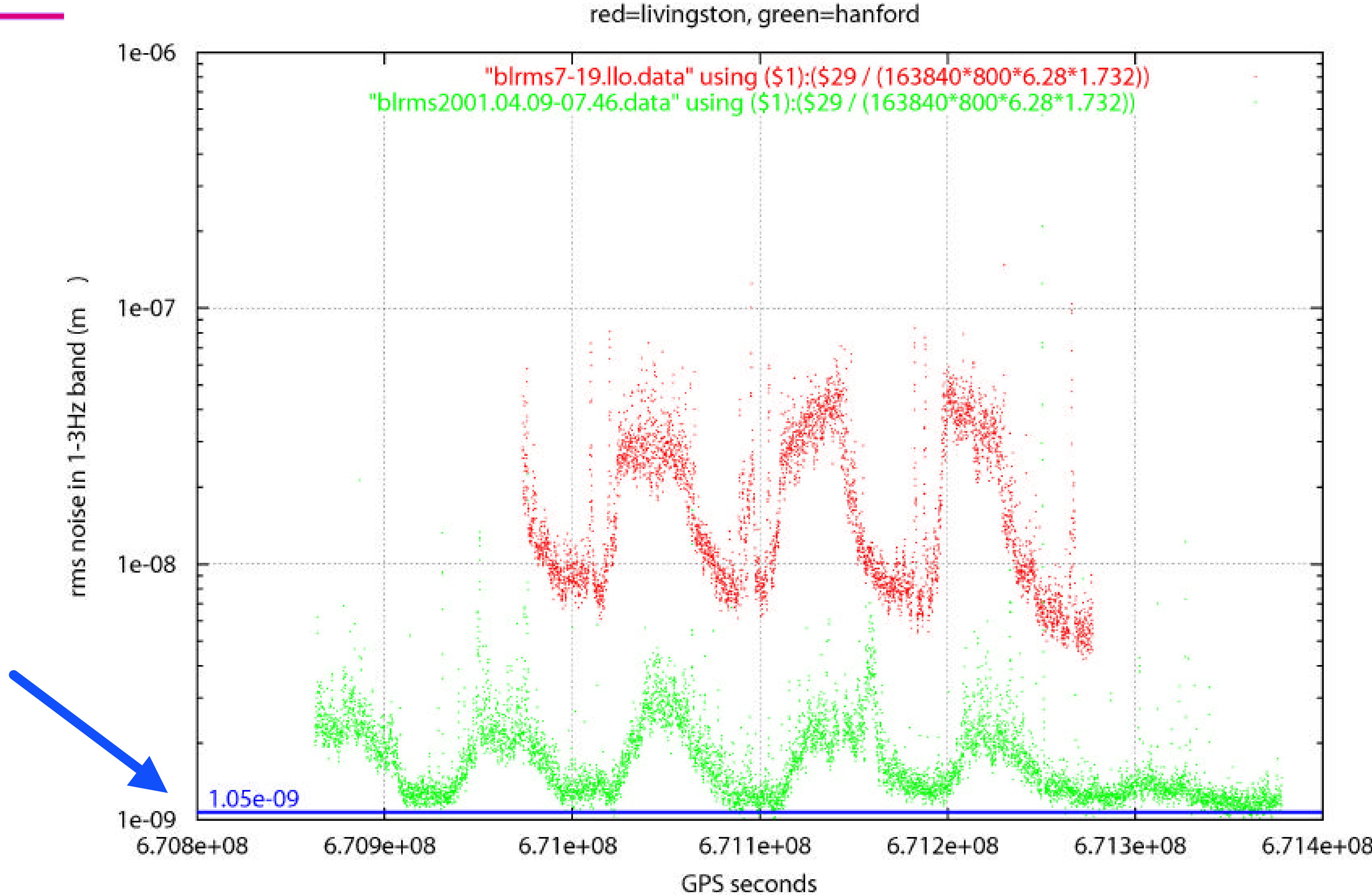
EPICS Control Diagram



EPICS Control Diagram (2)

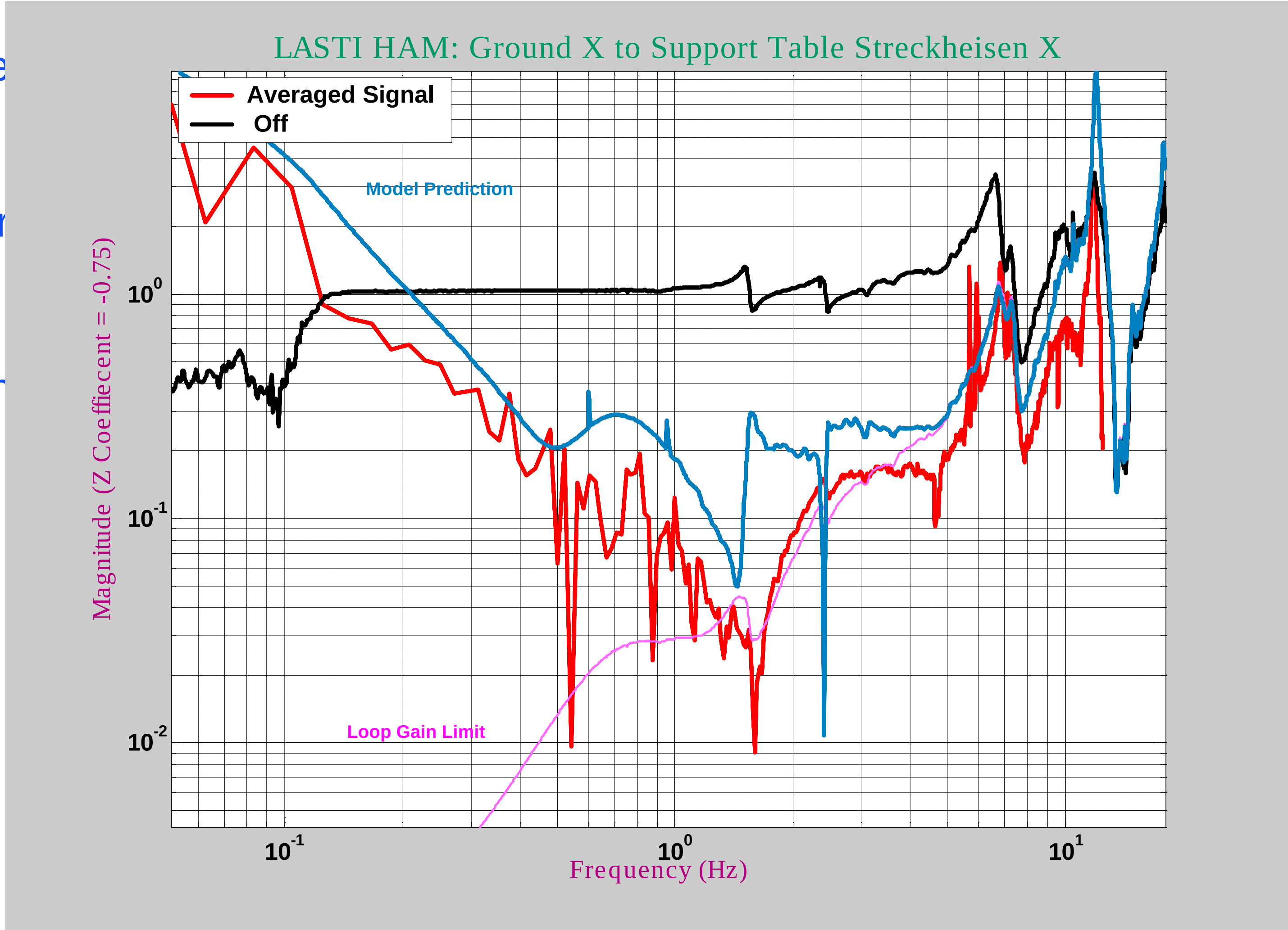


Daily variability – and requirement



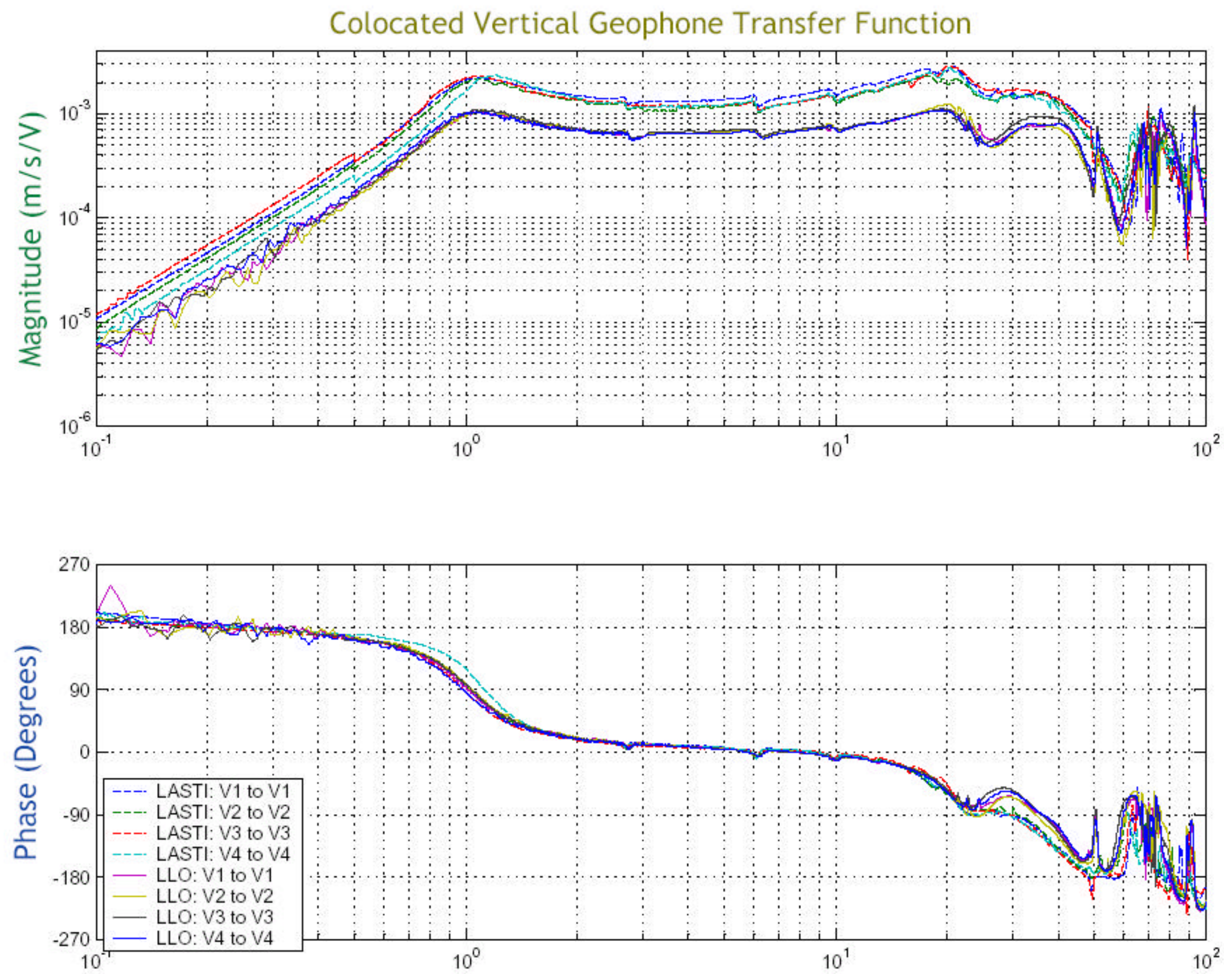
Seismic isolation performance

- Best performance data from LASTI, on a HAM chamber – similar results for a BSC
- Expect first LLO isolation results in ~1 week (witness on support table, plus OSEMs on ETMx)

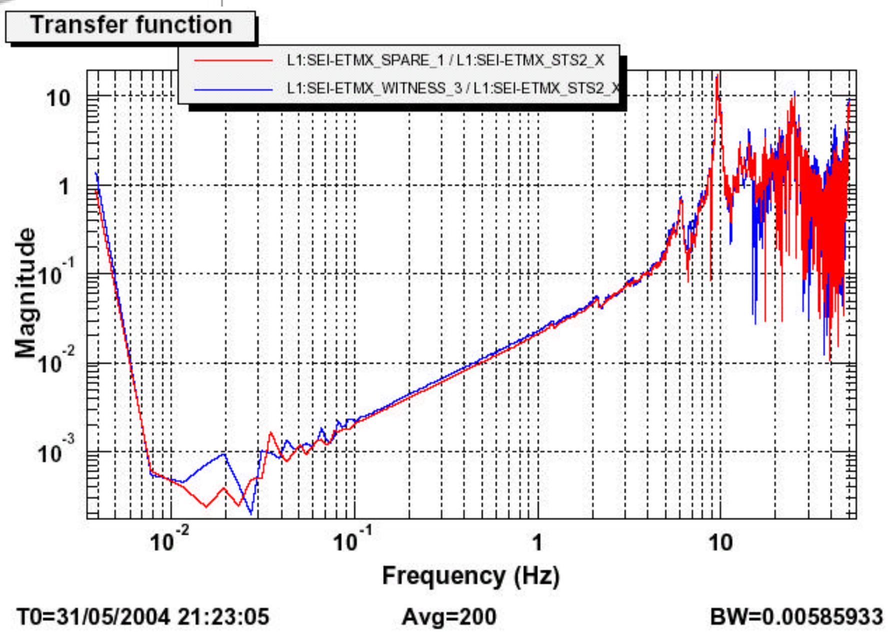


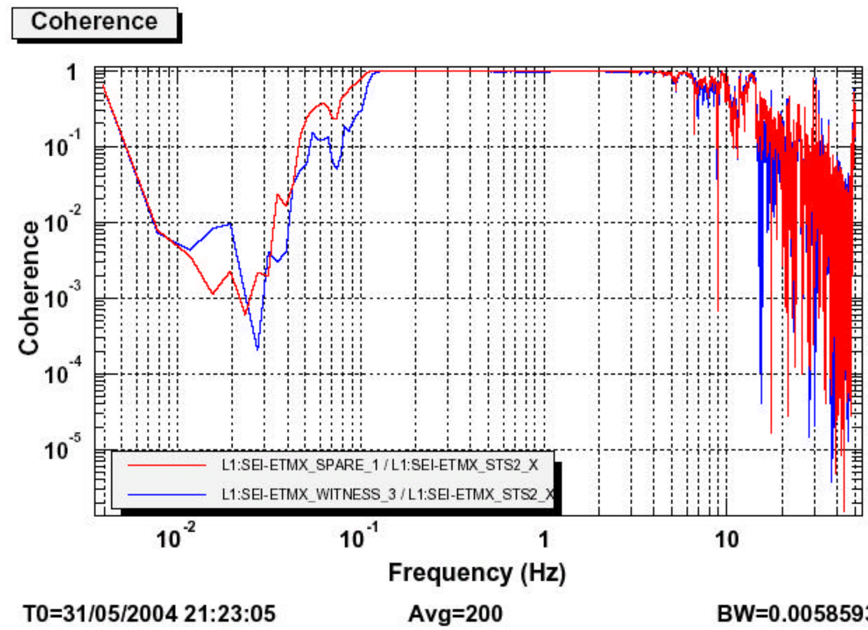
HEPI ETMX Transfer Functions

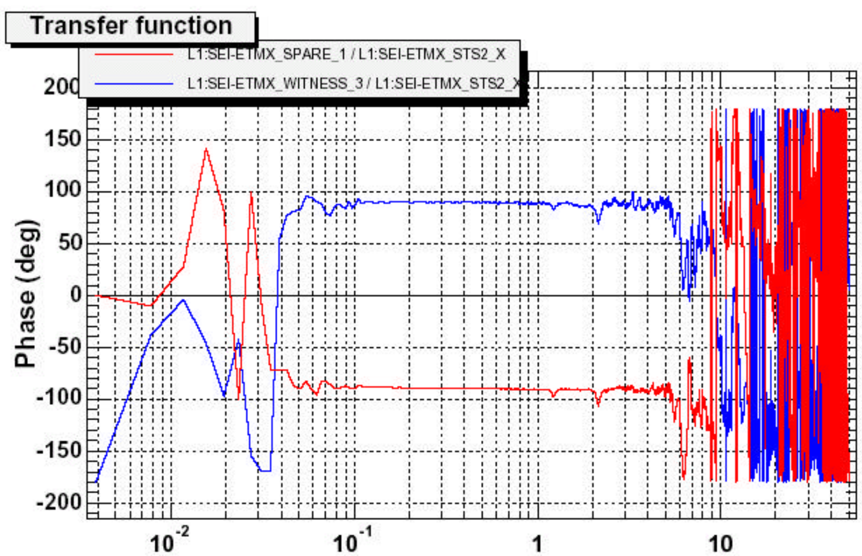
- LLO ETMX and LASTI BSC transfer functions are similar
- Supports upper unity gain of ~10 to 25 Hz
- Isolation at vertical bounce mode (16 Hz) may be possible with a resonant gain stage



Ground to Support Platform Transfer Functions



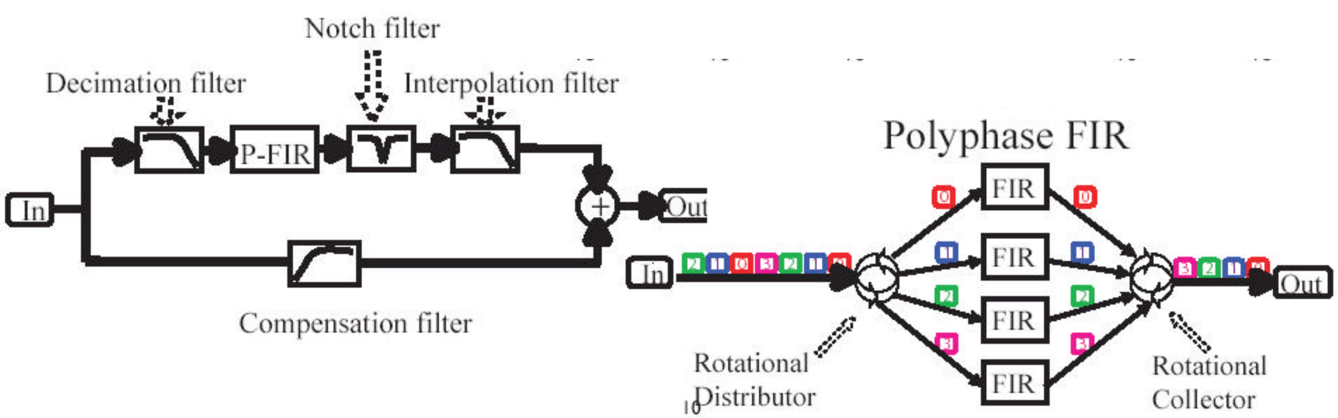




- ❑ High coherence from 0.1 to 7 Hz, so sensor correction will work fine
- ❑ Similar results in the other directions (Y, Z)

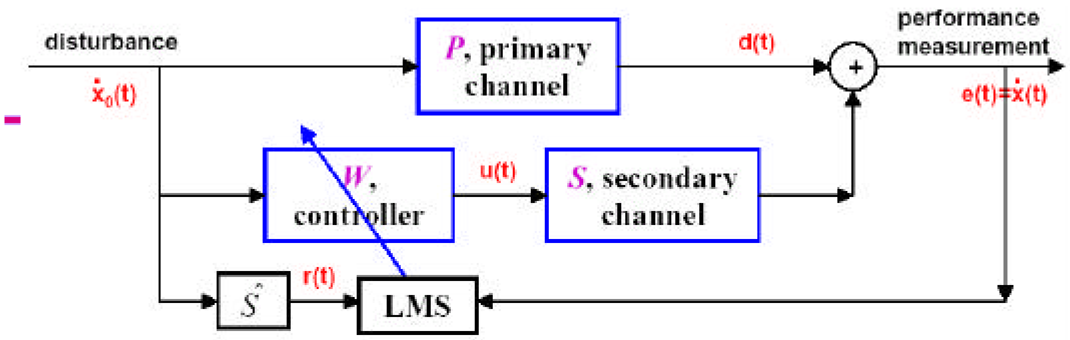
Continued HEPI R&D

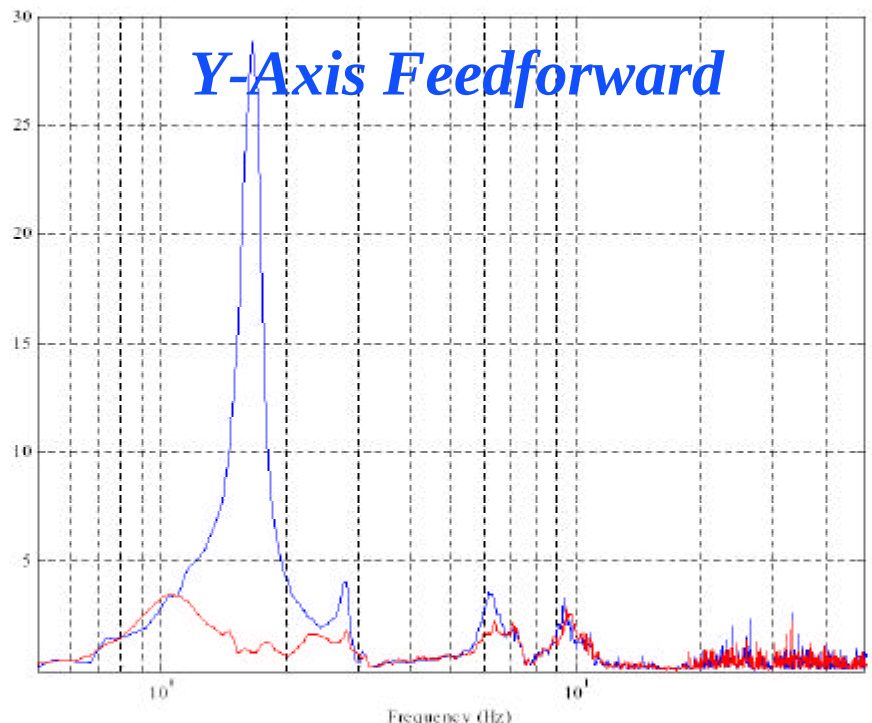
- LASTI HAM Testing/development:
  - Working on a LASTI HAM chamber
  - HAM stiffening beam found unnecessary
  - Verified SOS are OK on HAM table during excitation for system identification
  - Adapted GDS for HEPI Sys ID
- Stanford Efficient Polyphase FIR
  - Eliminates low-frequency noise and artifacts form sensor correction signal
  - Avoids excessive phase and amplitude mismatch in band
  - Computationally efficient
  - Incorporated into LIGO VME software

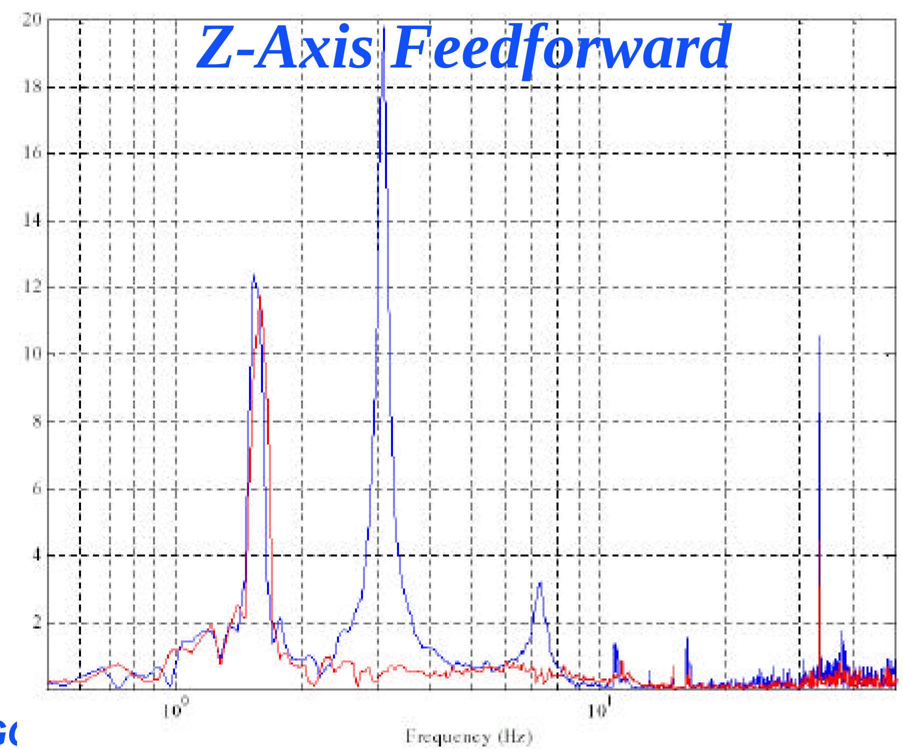


Continued HEPI R&D (2)

- LASTI Adaptive Feedforward Control
  - Combined SISO loops tried on HAM HEPI System
  - 1024 point FIR filter, 500 Hz sampling & innovation rate
  - Suppression of ~20x observed
  - Computationally prohibitive for MIMO control







Miscellaneous

- New low-noise D-A converters from Freq. Devices Inc.
  - 30-40 dB lower noise
  - Several installed on H1; Improved Anti-image filter being built to take full advantage
- New Faraday isolator for H2
  - Larger aperture to reduce clipping
  - Lower absorption for higher power operation
  - To be installed late-June/early-July
- Photon calibrators
  - Reproducing first-article: in place for S4
- Phase cameras on all interferometers
  - Introducing a reference field so that any field component can be mapped
- Dual ETM transmission photodetectors
  - To handle larger dynamic range with higher power
  - Installed and operating on H1
- Upgraded DAQ reflective memory network: higher capacity
- Micro-seismic feedforward system at LHO likely
- Improved design/electronics for ISS, FSS, RFPD, ASI-servo

Major Post-S3 Steps

First ~6 months after S3	
L1	▶ Thermal lens studies ▶ Seismic upgrade: HEPI installation & commiss. ▶ Electronics rack relocation ▶ Thermal comp.
H1	▶ Manage noise in auxiliary degrees-of-freedom ▶ Thermal compensation trial ▶ Wideband WFS control ▶ Laser power increase ▶ Output mode cleaner ▶ Duty cycle
H2	▶ Wideband WFS control