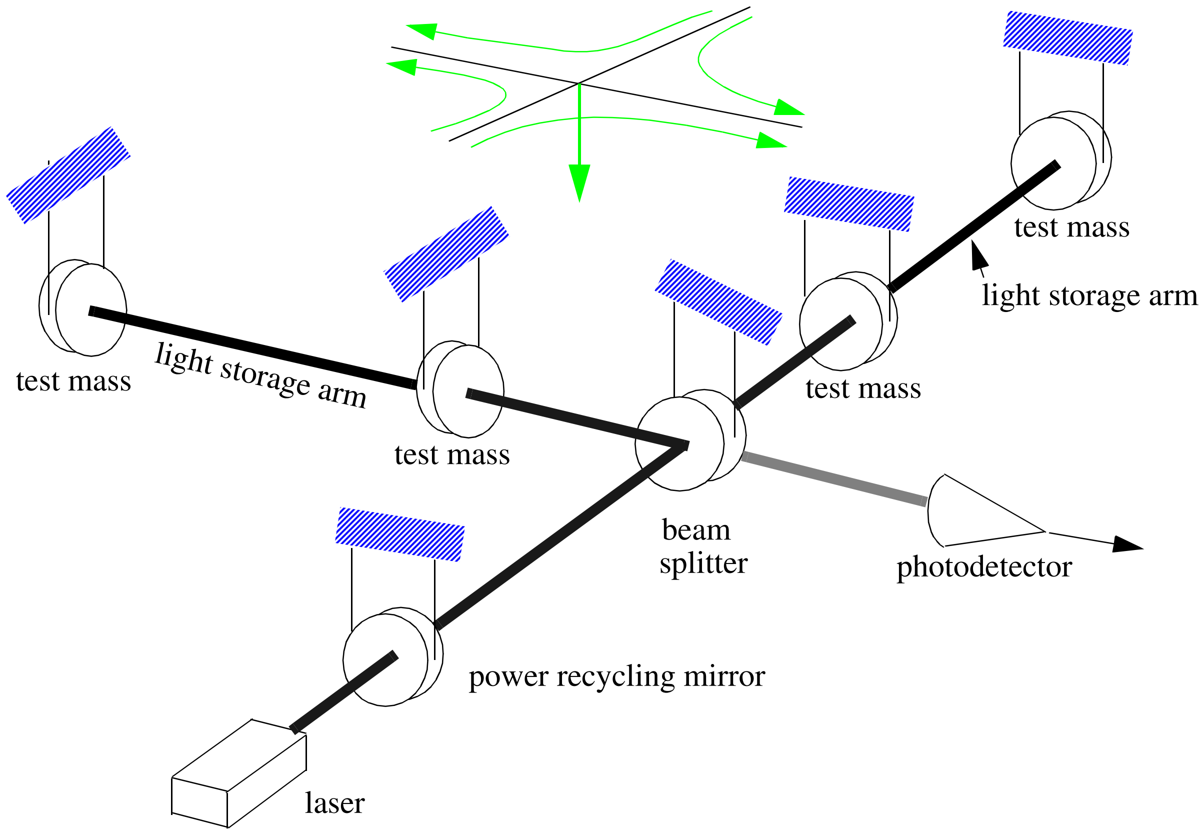
DETECTOR COMMISSIONING AND SEISMIC NOISE REMEDIATION

Rainer Weiss for Peter Fritschel and Dennis Coyne

PAC Meeting

December 5, 2002


test mass
light storage arm
test mass
test mass
test mass
light storage arm
beam
splitter
photodetector
power recycling mirror
laser

LIGO COMMISSIONING

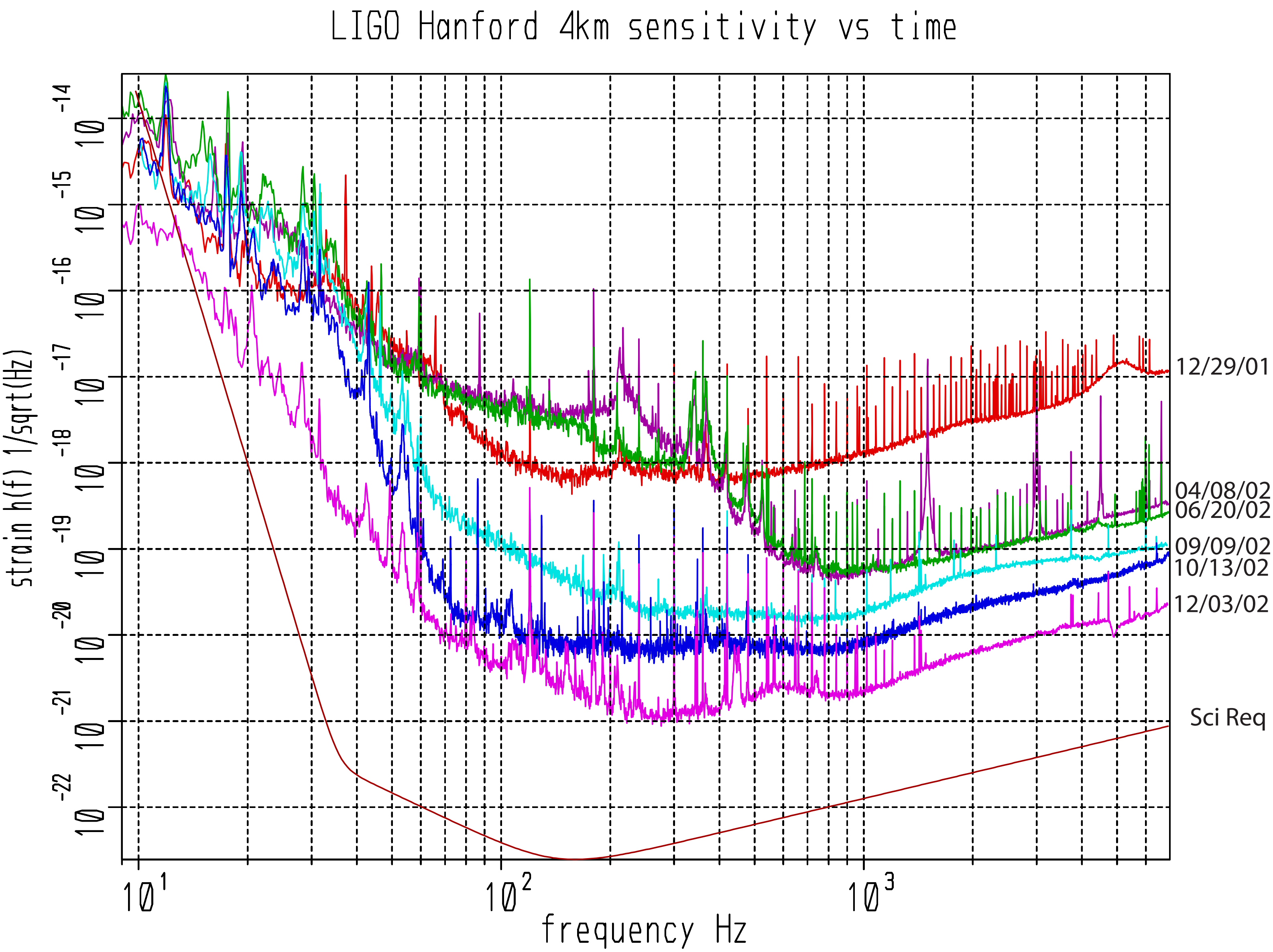
- Primary functions of the commissioning
  - » After installation bring the interferometer, data acquisition and environmental monitoring system into operation
  - » Improve the ability to hold lock and make it more robust
  - » Reduce the noise in the interferometer
  - » Determine correlations between interferometer and environment
  - » Test the data acquisition system, diagnostic software and archiving
  - » Train operators to acquire, run and diagnose the interferometer
  - » Maintain technical communication between the Laboratory sites
  - » Couple modeling with the diagnostic measurements

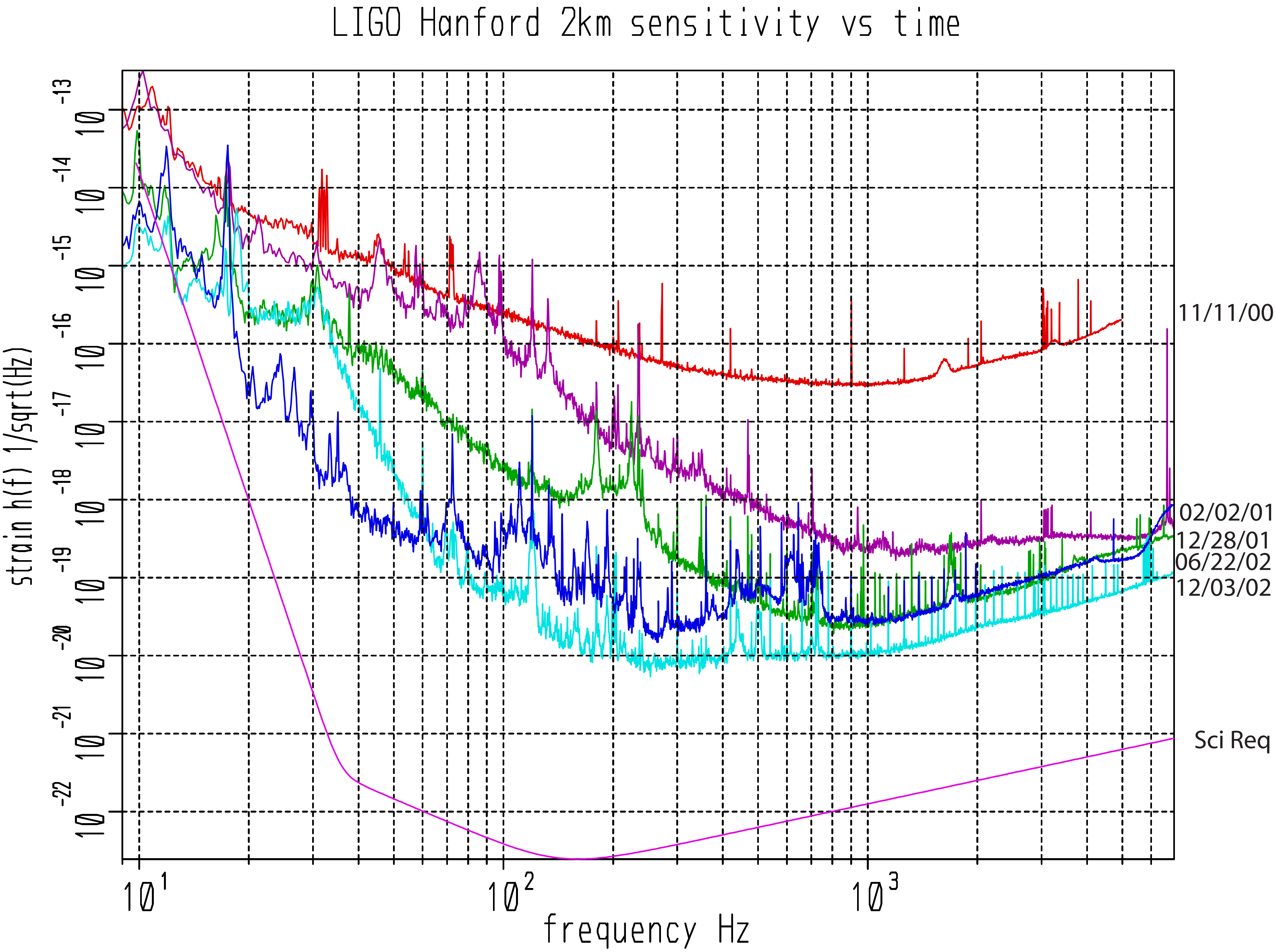
LIGO COMMISSIONING

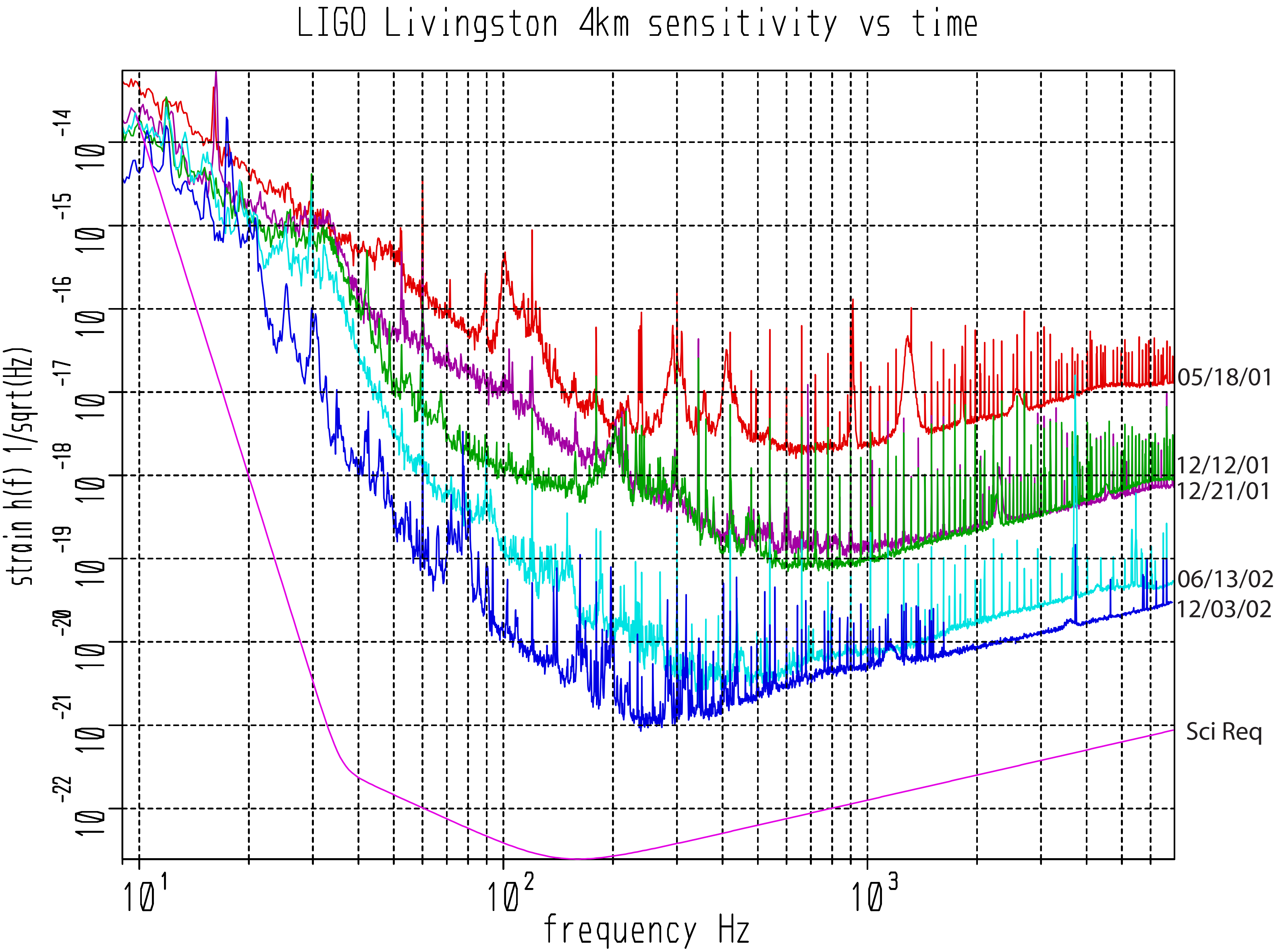
- Commissioning strategy
  - » Progression: Hanford 2km->Livingston 4km -> Hanford 4km
  - » Operate and test all in vacuum sub-systems as soon as possible after pumpdown – reduce water load on beamtubes and risk of contamination
  - » Operate interferometers even if sub-systems are incomplete -shakedown
  - » Assess the limiting noise terms and Iterate

LIGO COMMISSIONING

- Sub-systems
  - » Length and angle sensing and control
    - – Control longitudinal degrees of freedom
    - – Longitudinal and angular damping – OSEMS
    - – Optical lever monitor and active angular damping
    - – Wavefront sensors for final alignment
  - » Light frequency and amplitude control
    - – nested frequency control loops:pre mode cleaner, reference cavity,
    - – common mode of the interferometer – laser to follow common mode
    - – Intensity stabilization:around the laser, around mode cleaner
  - » Light geometric control
    - – Mode cleaner alignment and damping
    - – Mode matching telescope stability and damping
    - – Control of parasitic interferometers and scattered paths
  - » Environment control : reduction in control dynamic range
    - – Tidal servo common and differential mode
    - – Microseismic feed forward system
    - – Seismic noise reduction using external PZT controllers (Livingston)

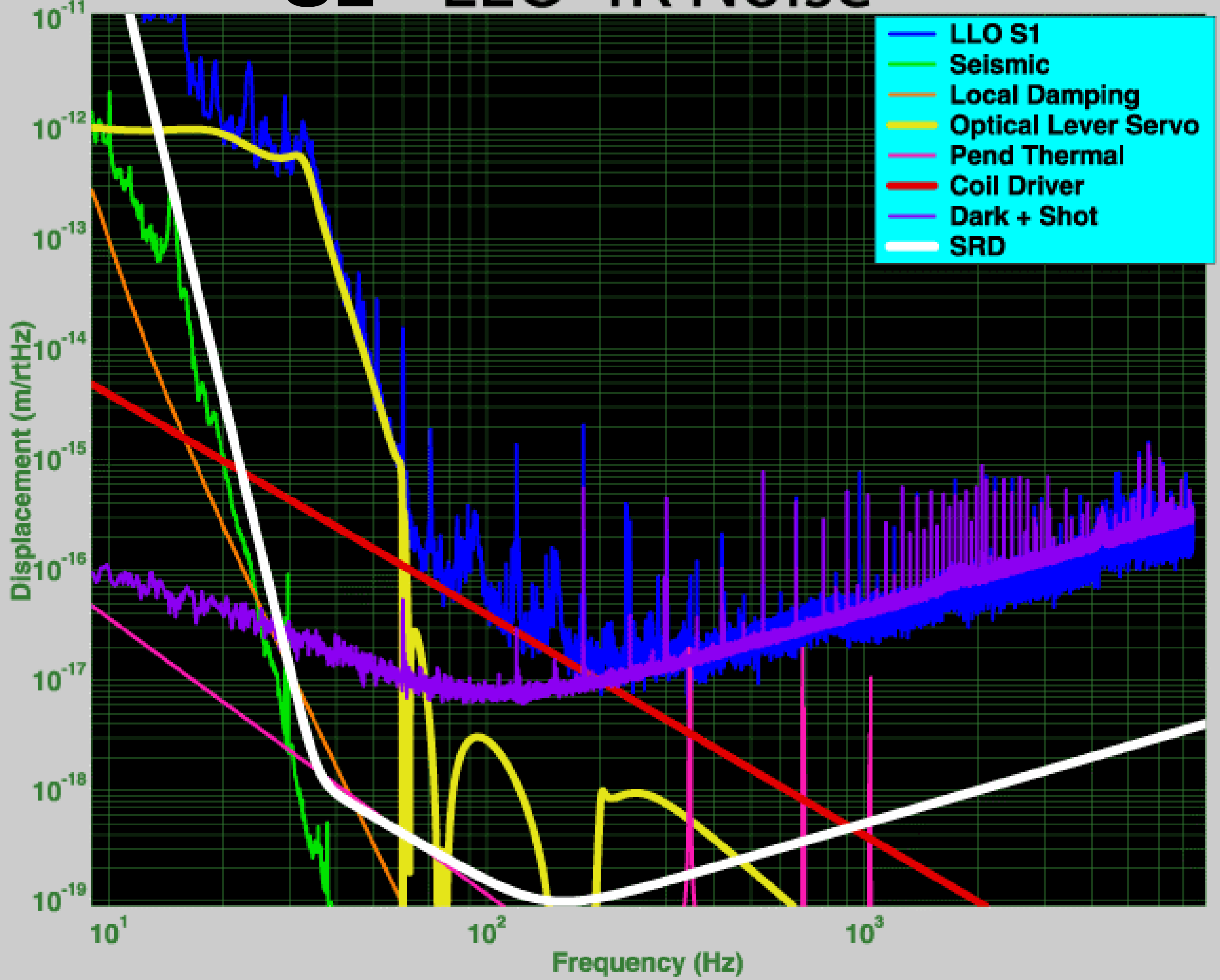

LIGO Hanford 4km sensitivity vs time
strain h(f) 1/sqrt(Hz)
frequency Hz
12/29/01
04/08/02
06/20/02
09/09/02
10/13/02
12/03/02
Sci Req


LIGO Hanford 2km sensitivity vs time
strain h(f) 1/sqrt(Hz)
frequency Hz
11/11/00
02/02/01
12/28/01
06/22/02
12/03/02
Sci Req



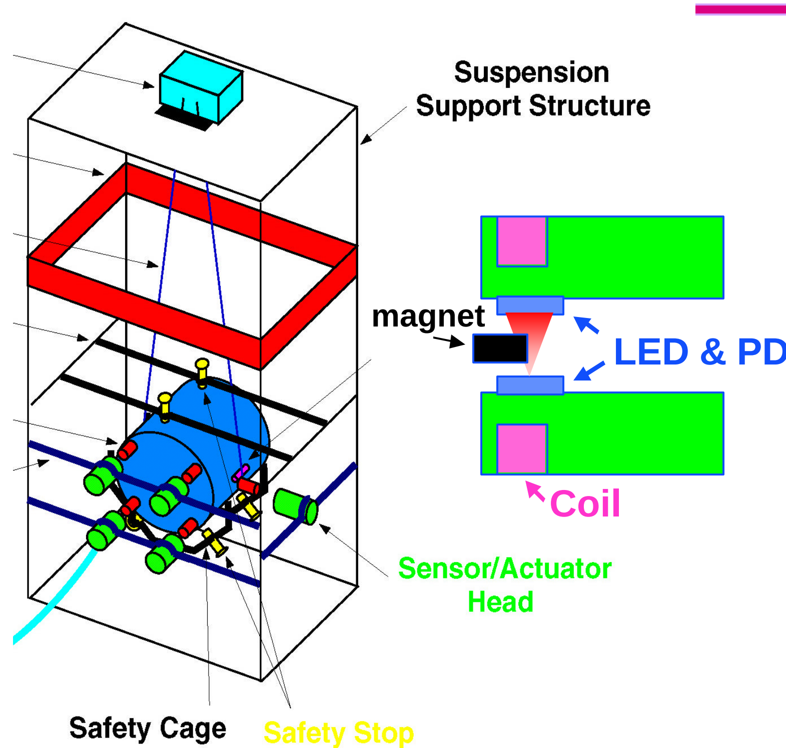
LIGO Livingston 4km sensitivity vs time
strain h(f) 1/sqrt(Hz)
frequency Hz
10^1
10^2
10^3
10^-14
10^-15
10^-16
10^-17
10^-18
10^-19
10^-20
10^-21
10^-22
05/18/01
12/12/01
12/21/01
06/13/02
12/03/02
Sci Req

S1 LLO 4K Noise



Completed design modifications & additions

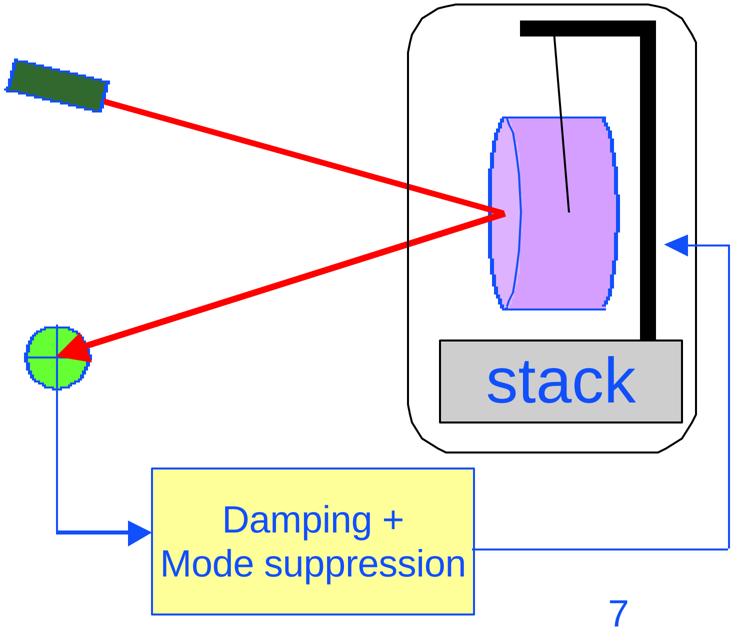
- New suspension local sensors
  - Initial sensors picked up scattered laser light, prevented high power operations
  - New sensors developed in parallel with low power commissioning, now installed on all interferometers and tested at full power



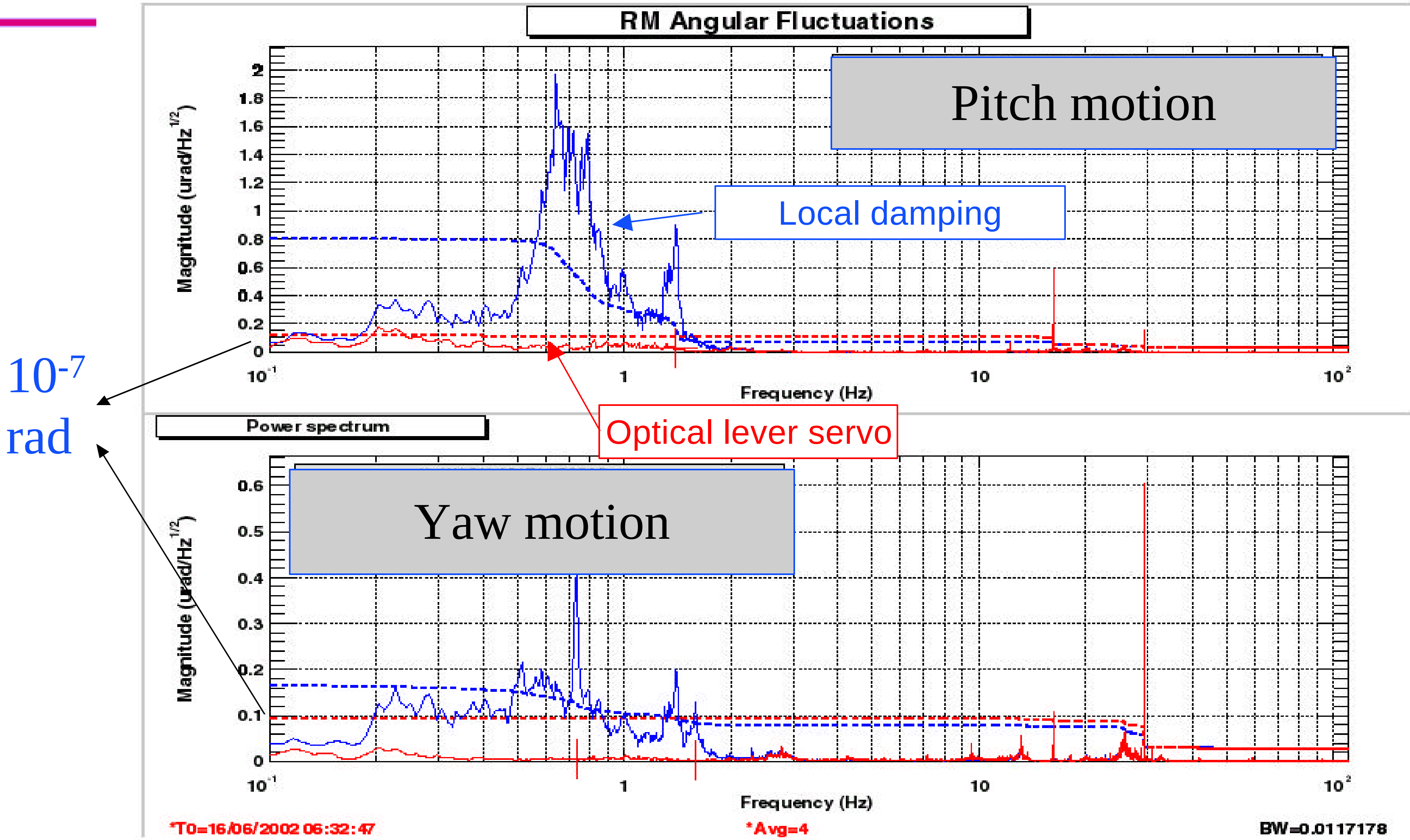
- Suspended optic angular stabilization using optical levers
- Seismic noise attenuation at LLO
- New suspension controls
- Enhancements of real-time digital control systems

Stability improvements: reduction of angular fluctuations

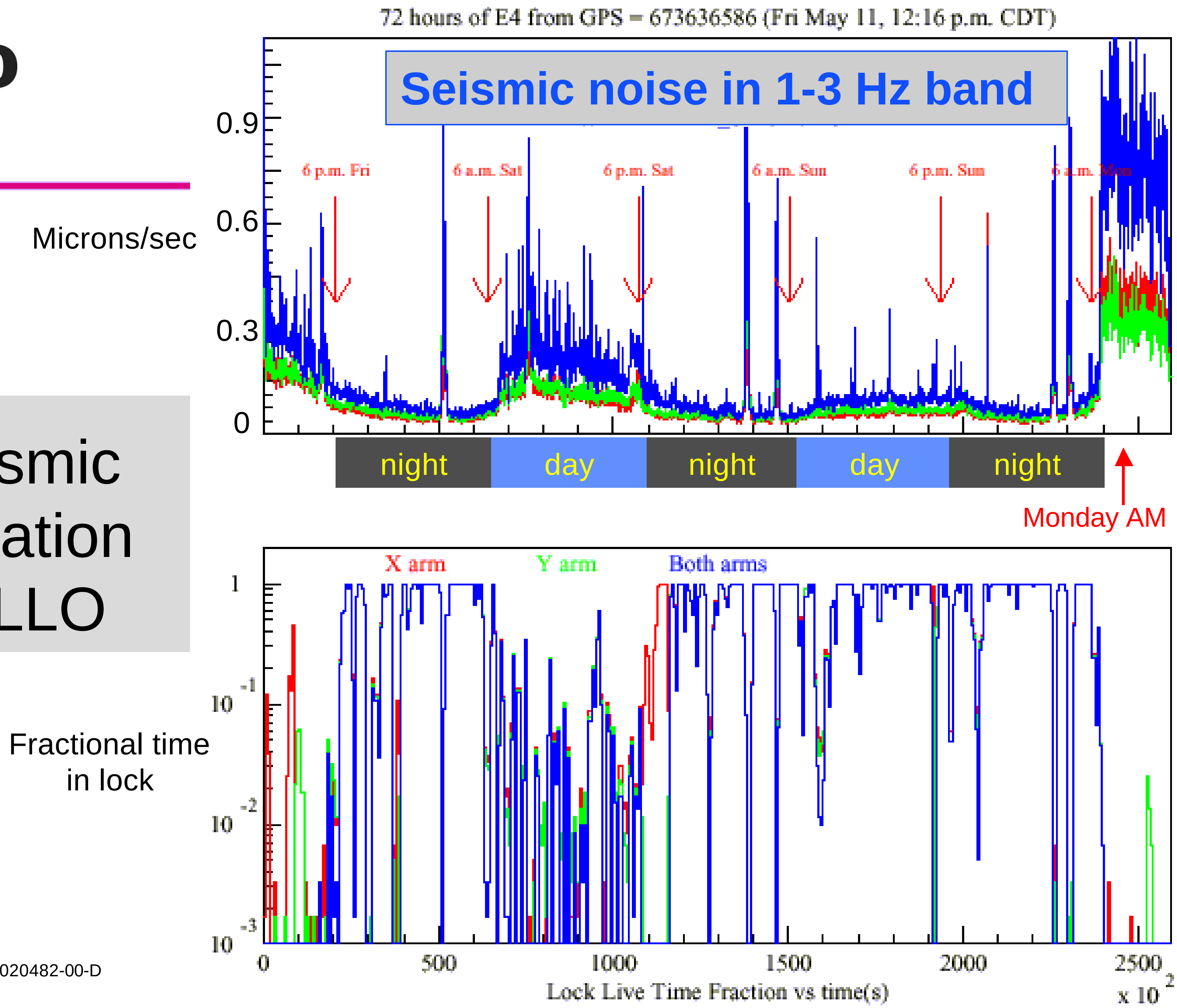
- Angular fluctuations of core optics lead to difficulty in locking and large power fluctuations when locked
  - Fluctuations dominated by low-frequency isolation stack and pendulum modes
  - Suspension local sensors damp the pendulum modes, but have limited ability to reduce the rms motion
- Optical lever sensors:
  - initially meant as an alignment reference and to provide long term alignment information
  - they turn out to be much more stable than the suspended optic in the ~0.5-10 Hz band
  - wrap a servo around them to the suspended optic, with resonant gain peaks at the lowest modes
  - tradeoff: increased noise in GW band



Optical lever servo results



Seismic Situation at LLO



Seismic Situation at LLO (2)

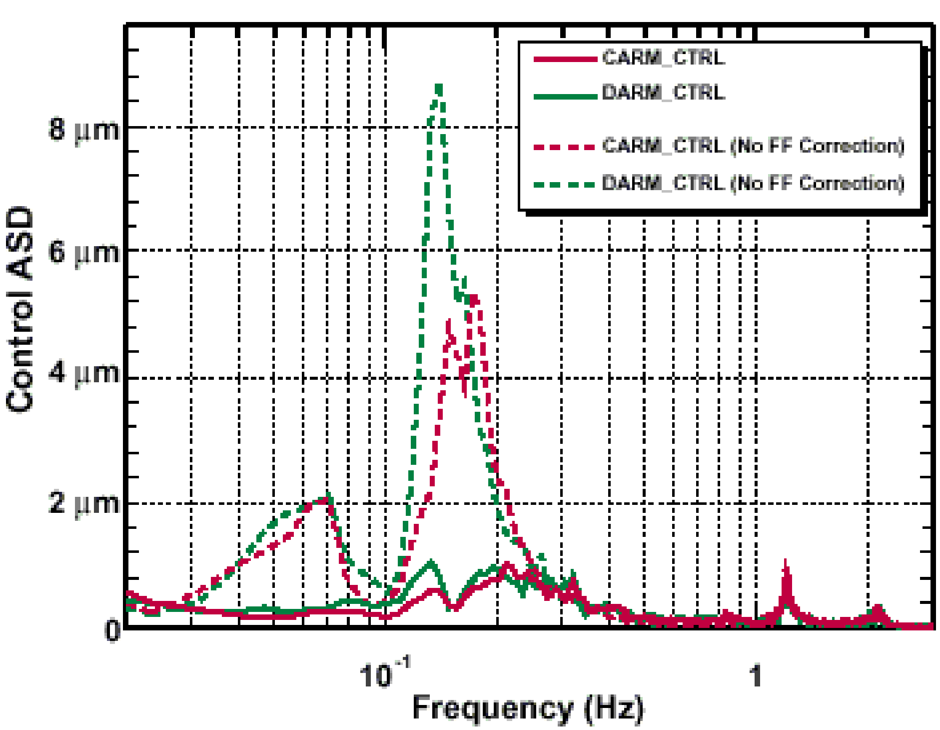
- Spiky seismic noise 1-3 Hz band
  - Related to human activity – mostly lumber industry, but also trains, highway traffic … most likely to grow with time
  - Coincident with stack resonances
  - Precludes IFO locking during weekdays
- Dealing with the noise
  - Short term: Coil drivers with extended range
    - Increase maximum current to the coils, needed to acquire lock
    - Cannot reach ultimate LIGO noise floor
  - Long term: active external compensation system
    - 2 D.O.F. feedback stabilization of test mass supports (next talk)
    - 6 D.O.F. feedback stabilization of all suspended optic supports (next talk)
    - Feed forward reduction of microseism

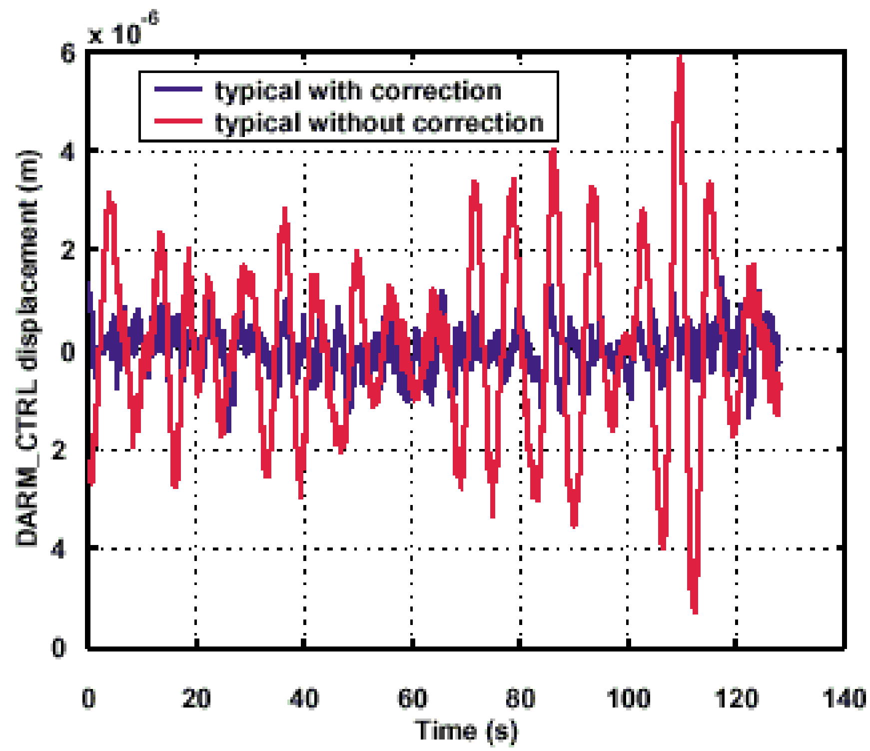
µSeismic Feed-forward System (LLO)

- Standing ocean gravity waves driven by storms excite double frequency (DF) surface waves that traverse large distances on land
  - Amplitude: from fractions to several microns; frequency: ~0.15 Hz
  - Wavelength: several kilometers ➔ LIGO arm length changes of several microns
- Seismic design provides an external fine actuation system (FAS)
  - Single DOF flexure design, ±90 µm range for each end (or mid) station BSC payload
  - Principally intended for tracking tidal arm stretching
- Streckeisen STS-2 seismometer signals collected from each building
  - filtered to produce arm length correction signals that are applied to the FAS, largely removing the microseism independently of global interferometer servos
  - Filters are derived using system-identification tools, & represent a compromise between high performance at the microseism and minimal added noise elsewhere.

Noise Reduction during E6

- E6 was during a period of very high microseism, allowing a good test.
- Test mass RMS (0.03 - 0.5 Hz) reduced by 85% , so that this spectral band no longer dominates the control signal.





LHO 4k: Development ground for new suspension controls

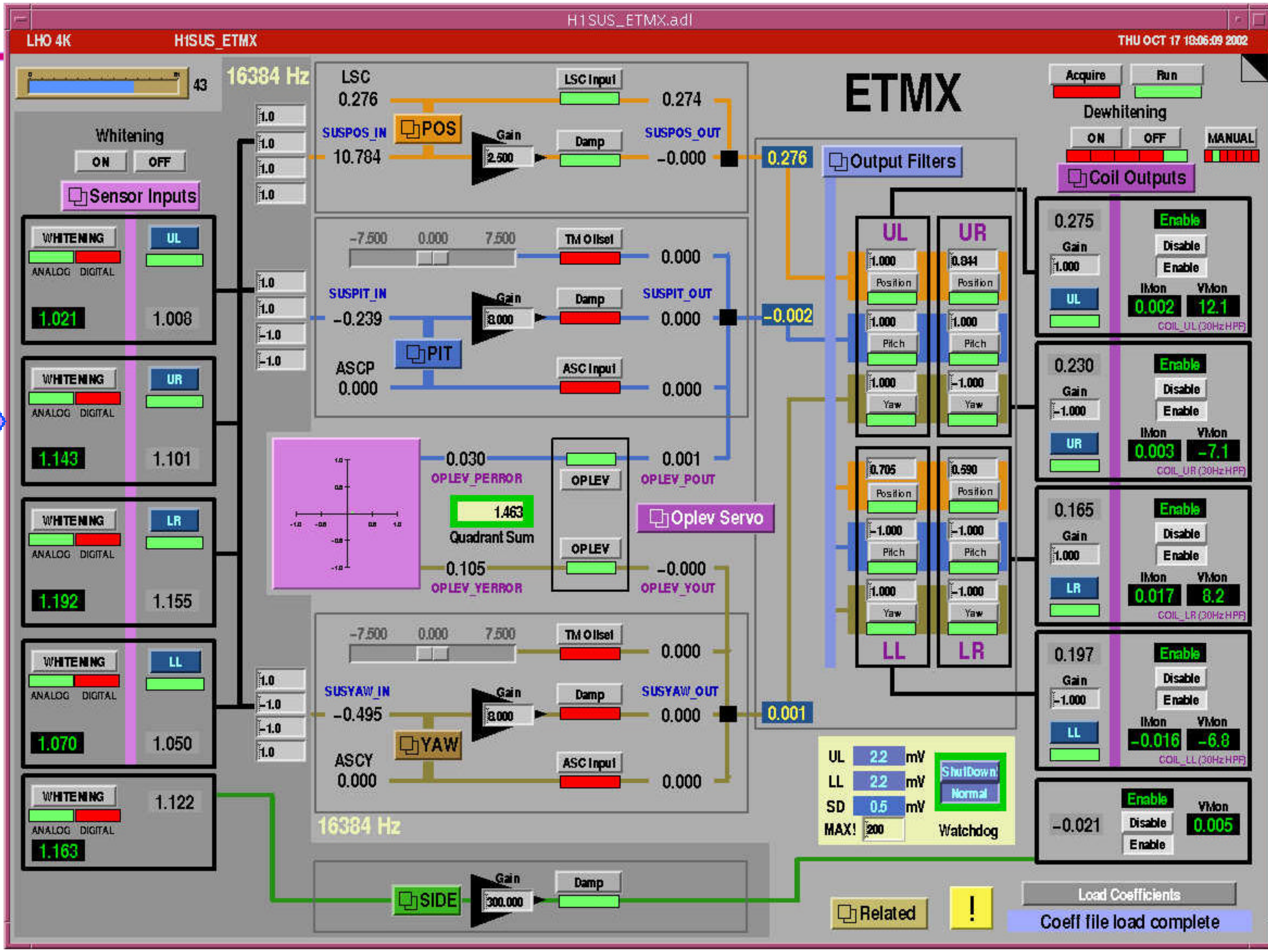
- **Why a new suspension controls system?**
  - Coil driver design limitation:

Acquisition currents: 100 – 300 ma	Alignment currents: 10 – 30 ma	In-lock length control: ~3 ma

    – Coil driver design made it impractical to reduce longitudinal control range after lock ⇒ couldn't achieve the noise benefits of a smaller range
  - Local sensing & damping electronics, and coil drivers (including LSC & ASC input conditioning) made all on one board
    – Made changes very difficult to implement; more modularity desired
- **Moved to a system with a digital processing core & more modular analog components**
  - Much easier to implement & change digital filtering; low freq filters don't require big C's
  - Suspension signals digitally integrated w/ global length and alignment controls
  - Alignment bias currents are generated and fed in, well filtered, independently of the feedback signals

Digital Controls screen example

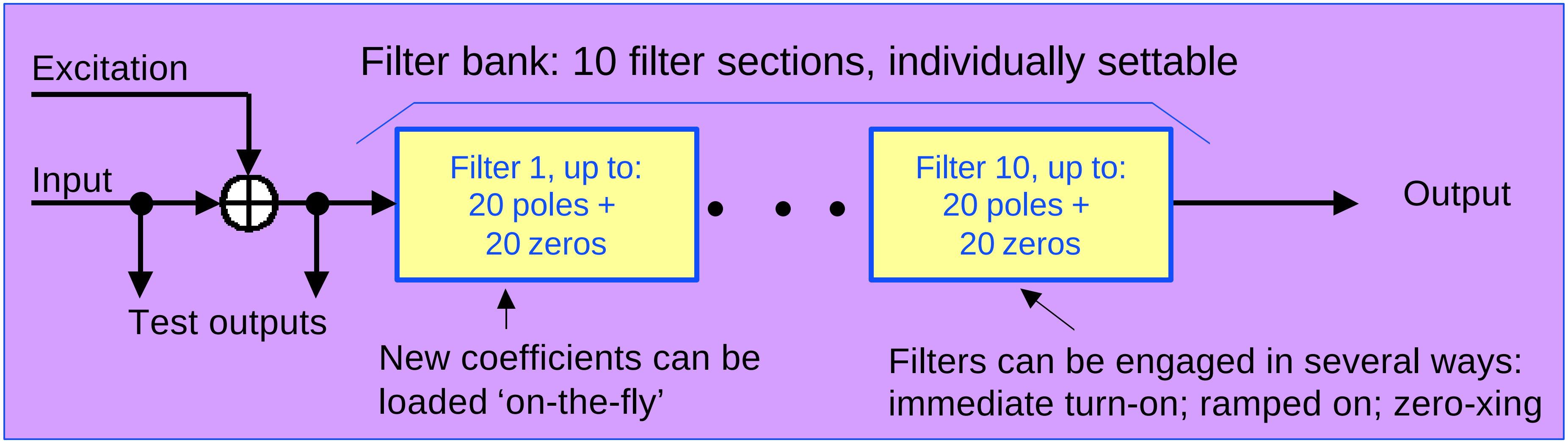
Analog In



Analog Out

Real-time digital filtering

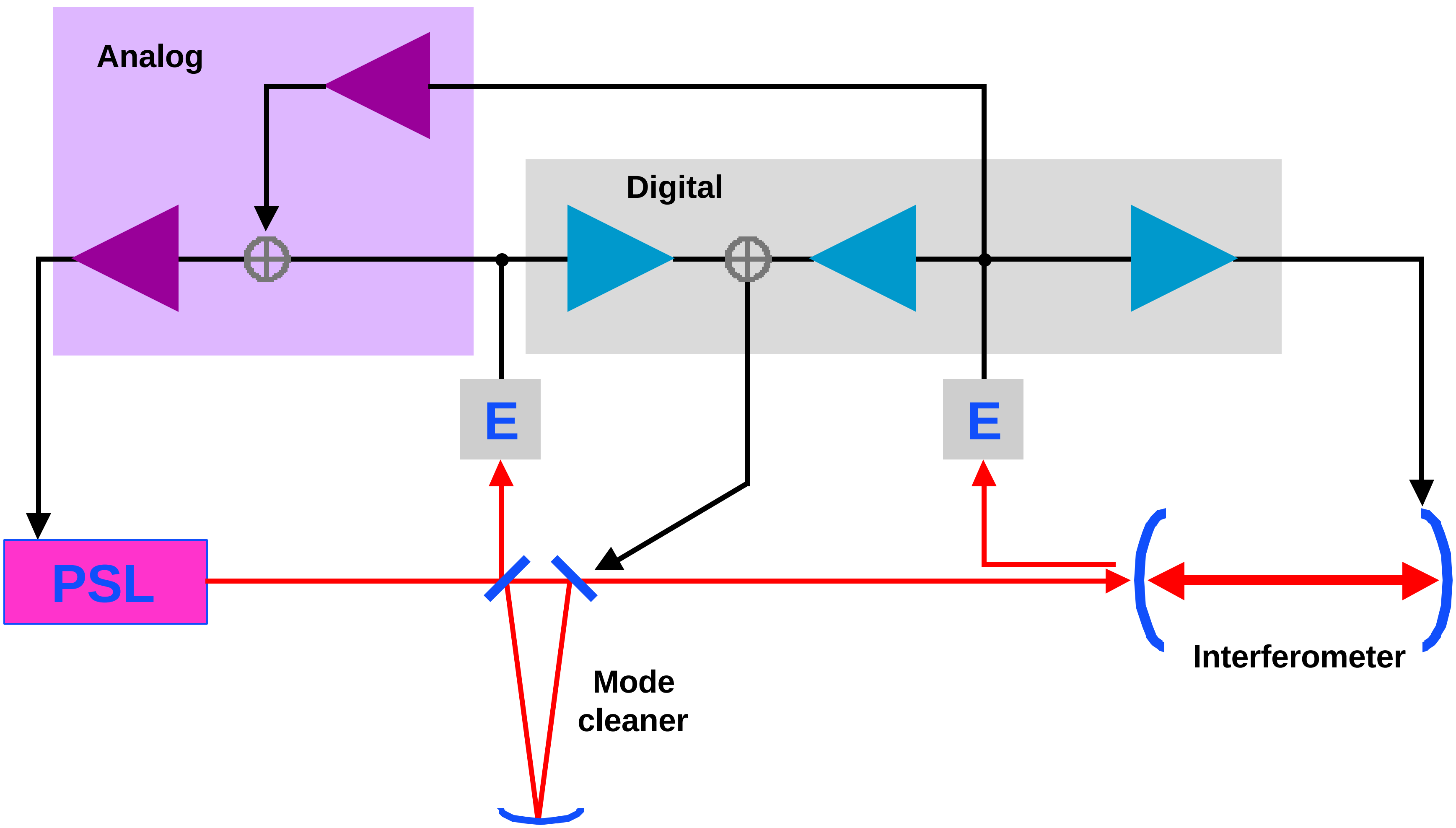
- Servos based on digital filtering a crucial part of improvements
  - Can suppress features that account for rms fluctuations (typically f < 10 Hz)
  - Can filter out noise coupled into the gravity wave band
- Recent real-time code enhancements have made it much easier to implement complex digital filters
  - Reductions in processing & I/O time allow us to do more
  - All digital feedback systems (LSC, ASC, DSC) now use a new 'generic filter module'



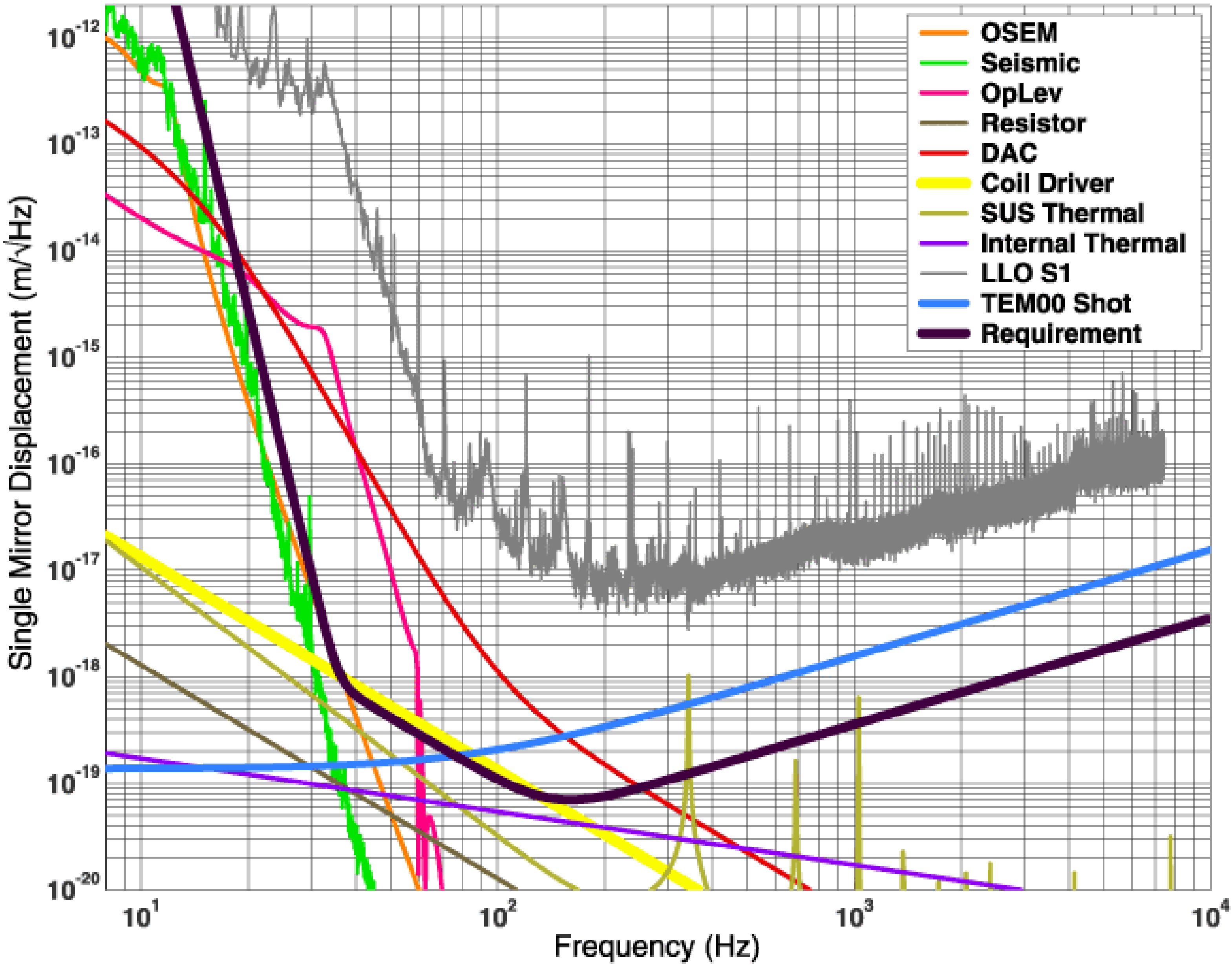
Noise reduction: interferometer frequency stabilization

- Feedback loop from the ‘common mode’ error signal – error between the average arm length and the laser frequency – to the laser frequency
  - Provides the final level of frequency stabilization, after the prestabilization and mode cleaner stages
  - Ultimately, need a stability of 3×10^{-7} Hz/rtHz at 150 Hz
  - Lock is acquired with feedback only to the end mirrors …
  - the tricky operation is then to transfer the common mode feedback signal to the laser frequency, with multiple feedback paths
- Status
  - Operational on all 3 ifo’s during S1
    - Removed all coherence between common and differential D.O.F.
  - Frequency coupling measured on LHO 2k: 300:1 rejection ratio! (100 Hz)

Frequency stabilization feedback configuration



Estimated Noise limits for S2



Ongoing subsystem integration

- Laser power stabilization servo
  - First stage operational, achieving a relative intensity noise of ~$10^{-7}/Hz^{1/2}$
  - Second stage of stabilization in the works ⇨ $10^{-8}/Hz^{1/2}$
- Wave-front sensor (WFS) based alignment system
  - Optical lever servos reduce the fluctuations, but they don't find the right alignment point
  - Wave-front sensors are referenced to the cavity axes, indicating the optimal alignment point for 10 degrees-of-freedom
  - Being interferometric sensors, they have lower sensing noise than the optical levers ⇨ *reduce low-frequency noise*
  - Single sensors have functioned so far to align the end test masses, full system is being commissioned

Summary: what works

- Initial alignment: surveying good to ~25 μradians
  - No searching for beams!
- Lasers: 2+ yrs of continuous operation
  - Prestabilized frequency noise meets requirement
- Seismic isolation stacks: isolate as designed
- Suspensions: thermal excitation of wire resonances observed
- Core optics quality
  - power recycling gains of ~40
  - Internal mode quality factors as expected (~10^6)
- Interferometer lock acquisition: acquisition times within few minutes
- Global diagnostics system: now an indispensable tool
- Digital control systems:
  - Critical to noise & stability improvements
  - Can deal with dynamic range limitations

Summary: major accomplishments

- First Science Run completed with good sensitivity and uptime
- Systems integration is nearing completion
- Significant noise improvements on all interferometers over the last year
- Stability improvements: optical lever stabilization, external preisolation
- Seismic isolation fine actuators used successfully to:
  - Compensate for tidal stretching of the arms
  - Compensate for the microseismic arm fluctuations
  - Attenuate ground noise at LLO
- Suspensions:
  - Mechanical robustness improved
  - New improved control electronics implemented
- Operator training
  - operators now an integral part of day-to-day commissioning

Summary: future plans

- Plans for near term
  - Recover full operation of LLO and LHO 2k interferometers following suspension controls upgrade
  - Full wavefront sensor alignment control
    - Enable power increase at detection port
  - Begin effort to improve the electronics infrastructure, EMI/RFI environment
  - Focus on robustness & stability
    - Planning a longer stabilization period – ‘configuration freeze’ – prior to second science run (S2)
    - Need to increase duty cycle from ~60% to >90%
  - Noise hunting …

SEISMIC NOISE REMEDIATION

Slides come from presentation made by Dennis Coyne
at the November 2002 NSF Review

Issue

- 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

- Retrofit design
  - » Original design included expansion capability for active control
  - » No commercially available systems with acceptable performance
  - » Accelerate the existing advanced LIGO R&D effort for an active pre-isolator
    - – An LSC effort scientifically led by Joe Giaime (LSU) and Brian Lantz (Stanford)
    - – Digital servo controls (flexibility & graceful degradation under failure)
    - – Two alternative actuator designs
  - » Install without disturbing in-situ optics alignment
  - » BSC & HAM chambers
  - » Prove performance with full scale prototypes at LASTI
- Active Isolation with the Fine Actuation Systems (FAS) on Test Mass chambers
  - » Use of the FAS actuator for active control is known as PEPI: Piezo-electric External Pre-Isolation
  - » PEPI is an interim solution for LLO; installed for S1
  - » PEPI is the planned solution for LHO
- Number of retrofit systems:
  - » All chambers with suspended optics at LLO (8 systems)
  - » Addition of PEPI systems to Test Mass and Mode Cleaner chambers at LHO (6 systems per interferometer)

External Pre-Isolator performance requirements

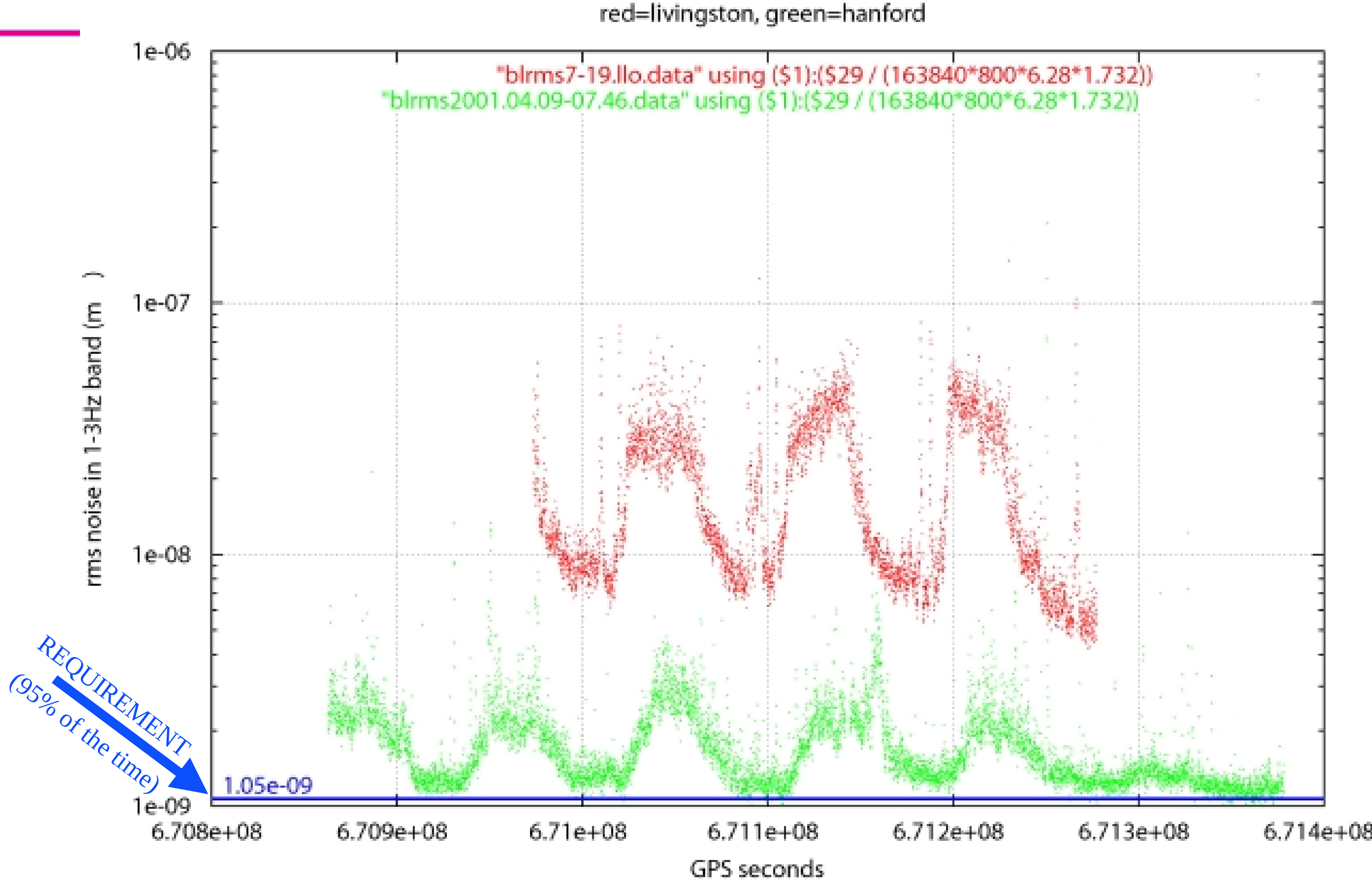
Basic tenets:

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 95% of the time
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

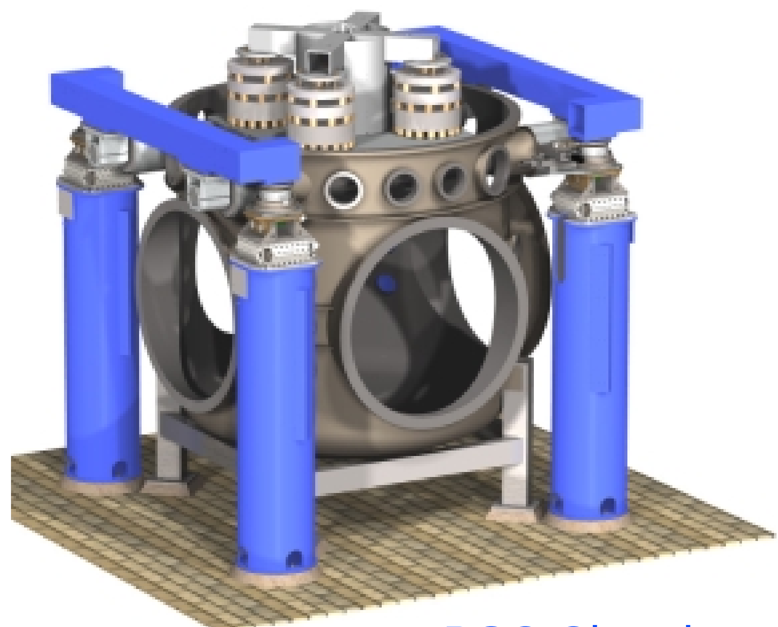
Daily variability – and requirement



Initial Vibration Isolation Systems

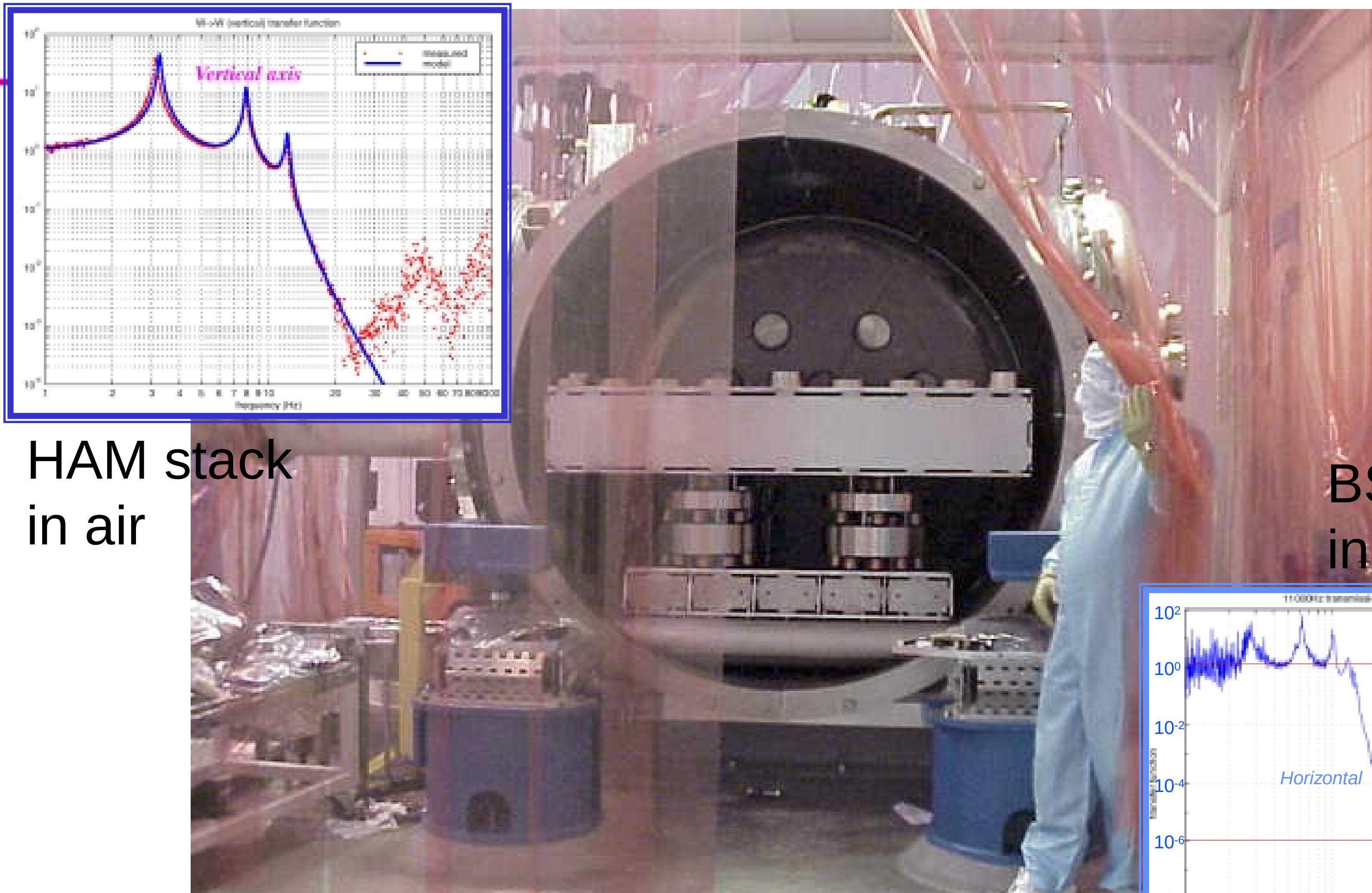
» Reduce in-band seismic motion by 4 - 6 orders of magnitude
» Little or no attenuation below 10Hz; amplification at stack mode resonances
» Large range actuation for initial alignment and drift compensation
» Quiet actuation to correct for Earth tides and microseism at 0.15 Hz during observation

HAM Chamber



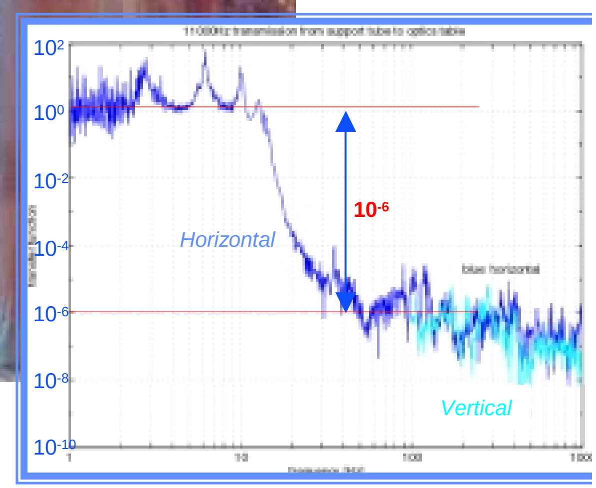
BSC Chamber

Seismic System Performance

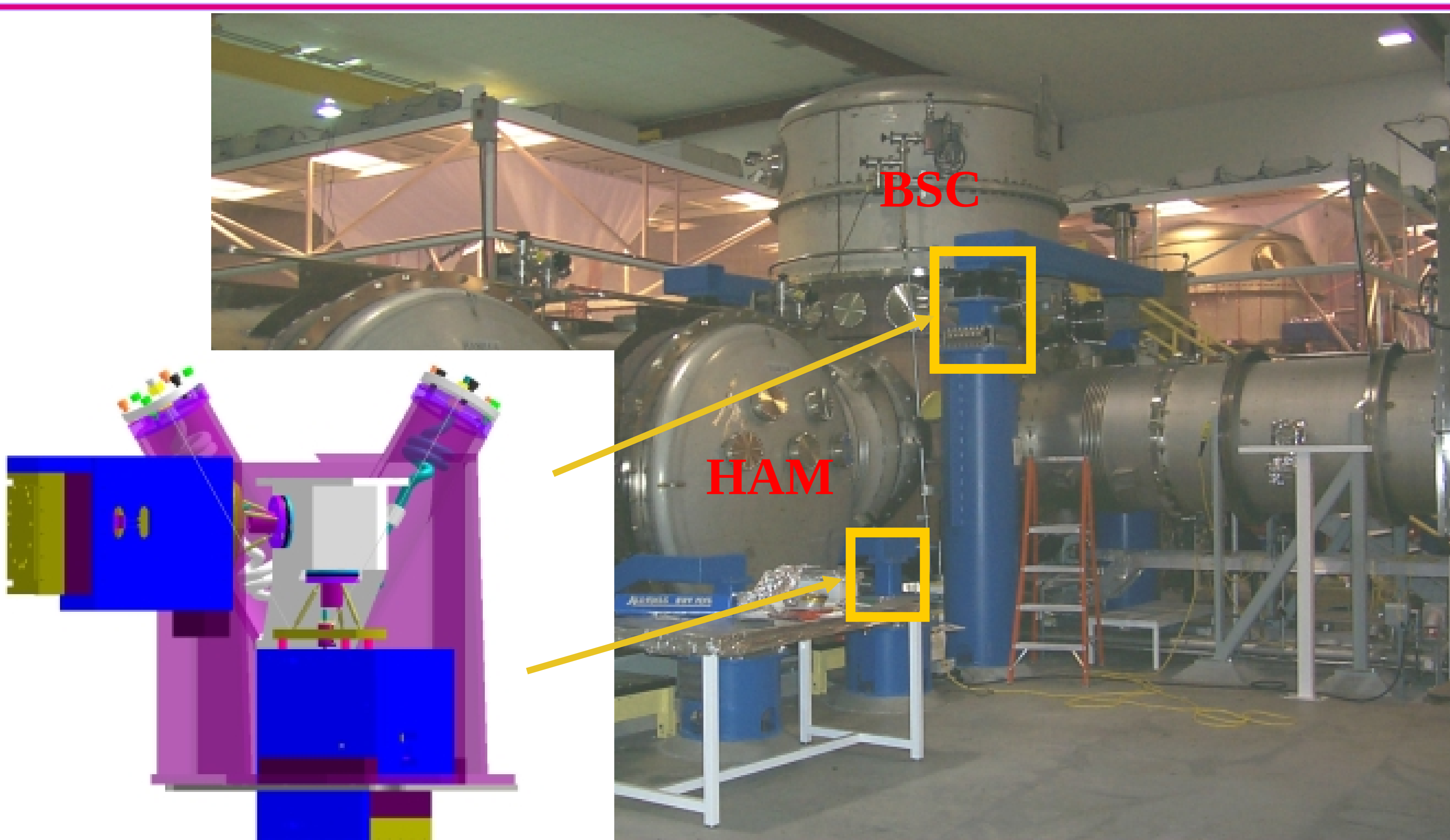


HAM stack
in air

BSC stack
in vacuum

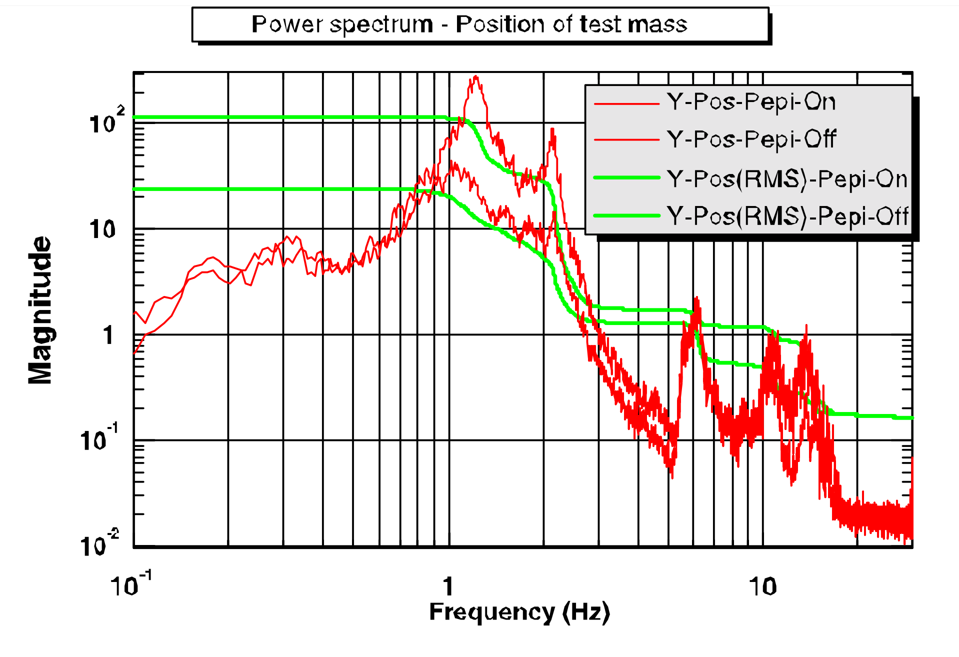


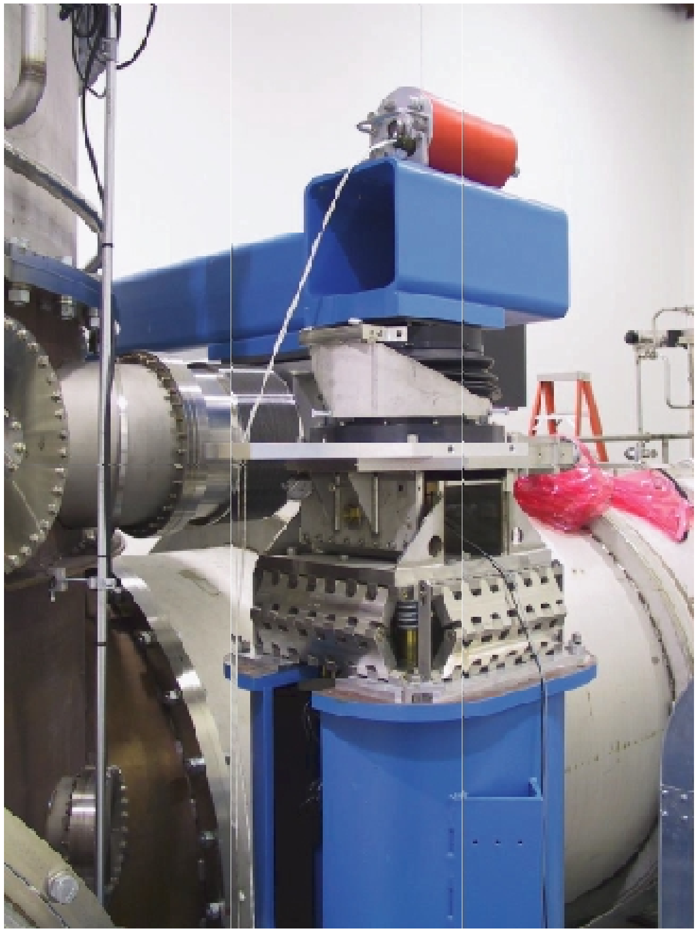
Planned Initial Detector Modifications



Piezo-electric External Pre-Isolator (PEPI)

- Single (longitudinal) degree of freedom isolation
- Employs Fine Actuation System on End Test Mass Chambers (also used for Tidal and Microseismic control)
- Added to Input Test Masses at LLO for the S1 Run
- Baseline approach for LHO for S3

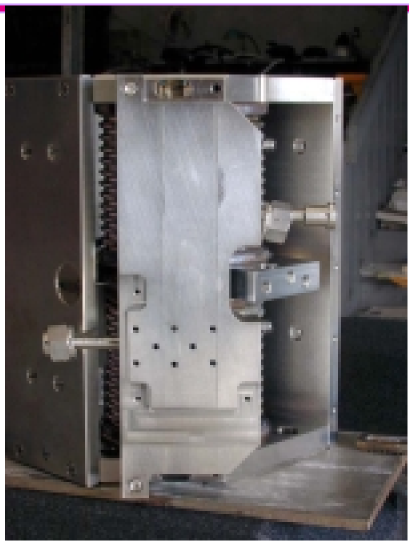


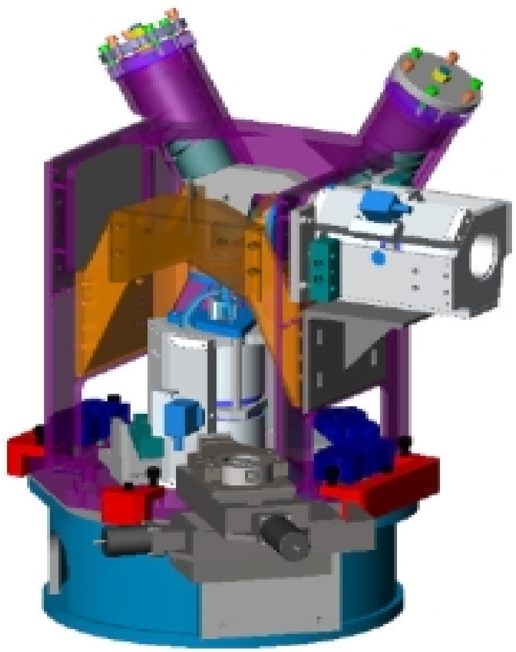


Actuators for an External Pre-Isolation (EPI) System

- Large range (300 microns p-p) required for tidal & microseismic correction
  - » Goal of 1 mm for coarse positioning/alignment
  - » Piezo-electric actuation may not be suitable
- Quiet Hydraulic Actuators
  - » Hydraulic Wheatstone bridge
  - » Used for precision diamond turning vibration isolation
  - » High range, high stiffness, high bandwidth, high velocity
  - » Developmental system (not commercially available)
- Electro-magnetic actuators
  - » Different actuator (force instead of displacement)
  - » Increased robustness of EPI solution – a second path
  - » Familiar technology (in contrast to quiet hydraulics)
  - » Reduced risk of contamination
  - » Less complexity in power supply
  - » Same performance requirements, mechanical superstructure, sensors
  - » Concern regarding EM coupling to the magnets on the suspended optics

Hydraulic External Pre-Isolators (HEPI)

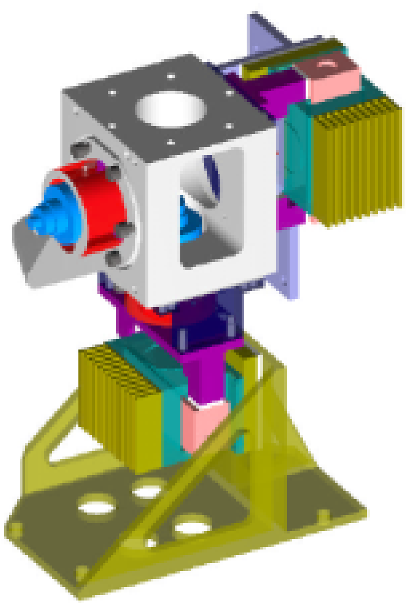




- Working fluid is high-viscosity fluid (glycerin/ethanol or mineral oil)
- Bellows hydraulic pistons apply force without sliding friction, moving seals
- Laminar-flow differential valves control forces
- Stabilized “power supply” is remote hydraulic pump with fluid-equivalent “RC” pressure filtering
- Technology adapted from precision machine tool applications

MEPI Installed on HAM at LASTI

- Alternative to the developmental hydraulic actuator
- Uses commercially available voice-coil actuator
- 'Pin-compatible' mechanically
- Simpler electronics
- 'Soft' mechanical back impedance



Status & Decision Points

- MEPI
  - » Installed at LASTI & under Test
  - » Interaction of HAM structural support modes with the control system may limit performance, add control complexity or cause us to consider structural modifications/additions
  - » Initial MEPI/HAM Chamber results are promising; Hope to demonstrate control to required performance in the next 2 months
- HEPI
  - » 3rd generation hydraulic actuator in test on the Stanford test stand
  - » Pump station tests at CIT have demonstrated pressure noise performance requirements
  - » Installation at LASTI to start in 2 weeks
  - » Compliance of the BSC pier may likewise limit gain-bandwidth and performance
  - » Initial test results are expected by early December
- Design Review & Long-Lead Procurement Review, Jan, 2003
  - » After prototype installation & some preliminary experience will decide whether to go forward with the hydraulic actuator or the electro-magnetic actuator
  - » Commissioning will continue to improve performance and transition from dSpace to VME based controllers
- Installation start at LLO, April, 2003
  - » Following the S2 run