LIGO Detector Performance

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NSF Review of the LIGO Laboratory
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LIGO Interferometer Optical Scheme

•Michelson interferometer with Fabry-Perot arm cavities

•Arm cavity storage time

$$\tau \sim 1/2\pi f_{GW}$$

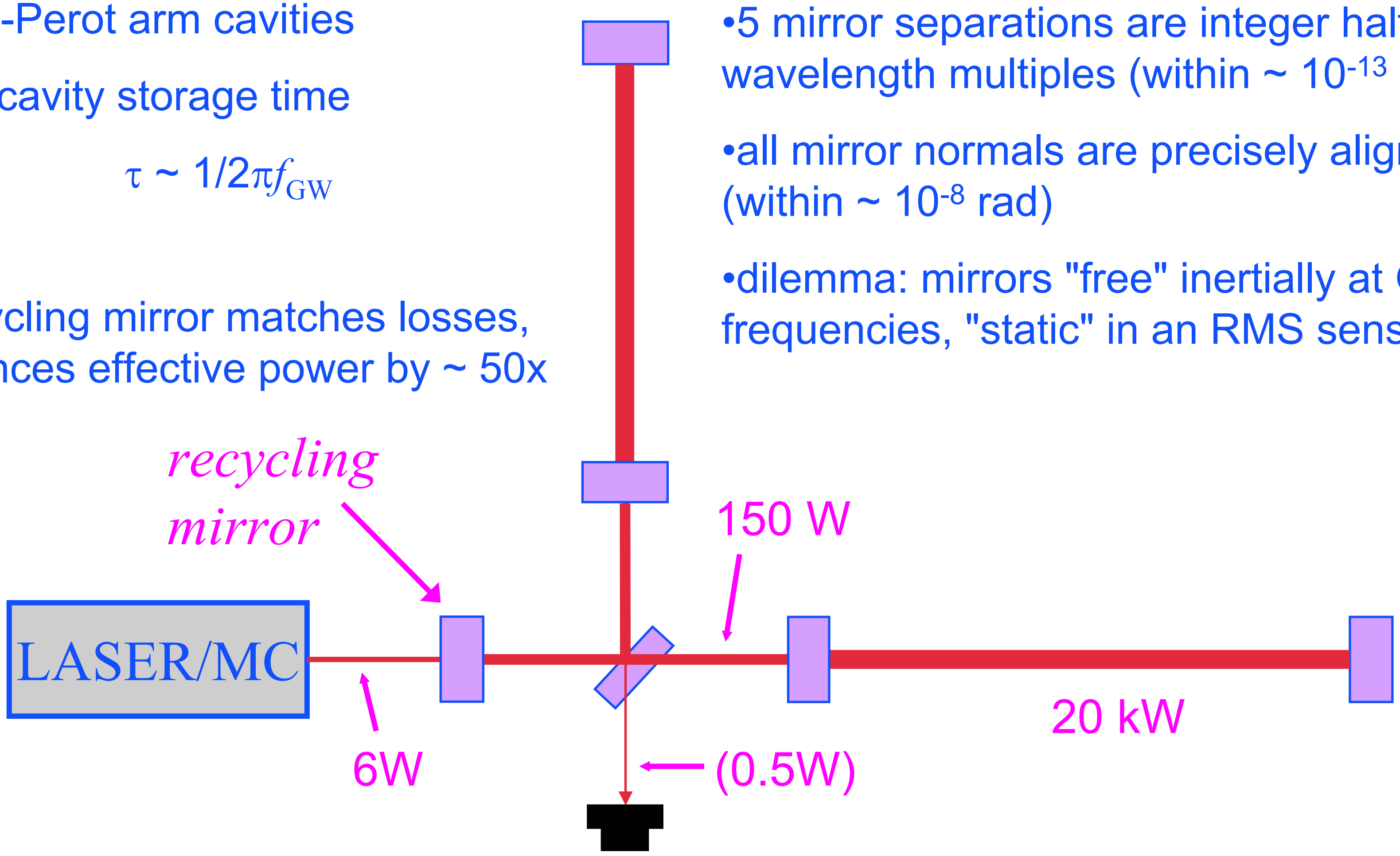
•Recycling mirror matches losses, enhances effective power by ~ 50x

Price to pay: linear readout only if

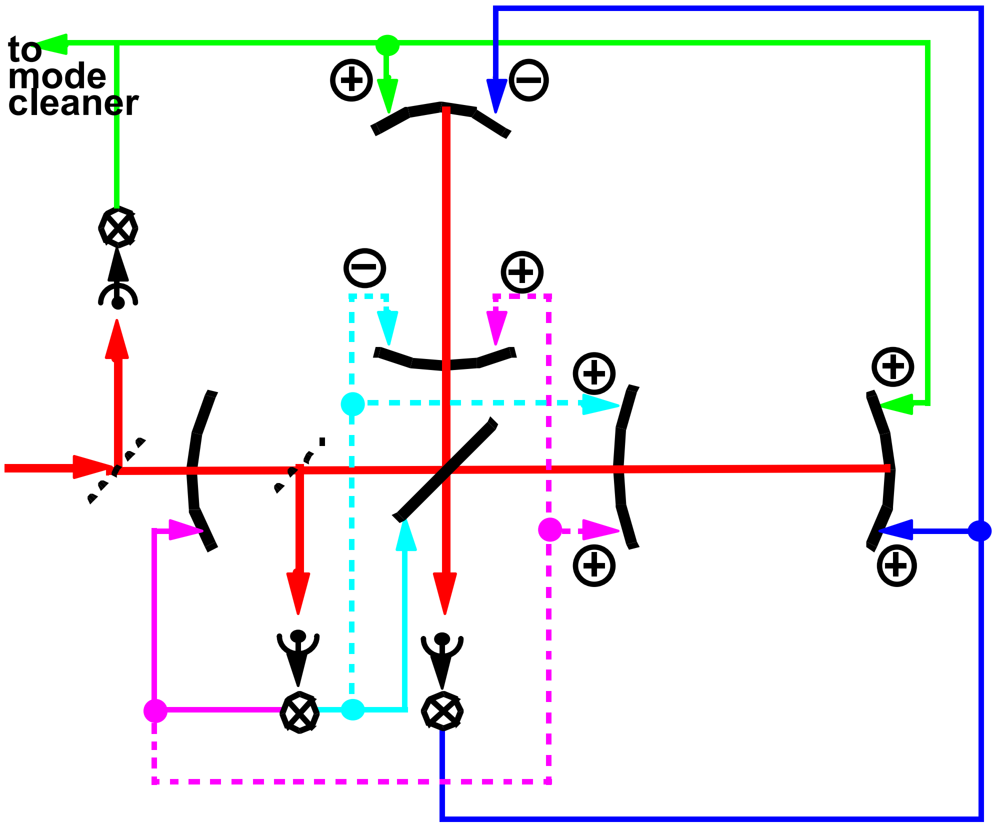
•5 mirror separations are integer half-wavelength multiples (within ~ 10^{-13} m)

•all mirror normals are precisely aligned (within ~ 10^{-8} rad)

•dilemma: mirrors "free" inertially at GW frequencies, "static" in an RMS sense



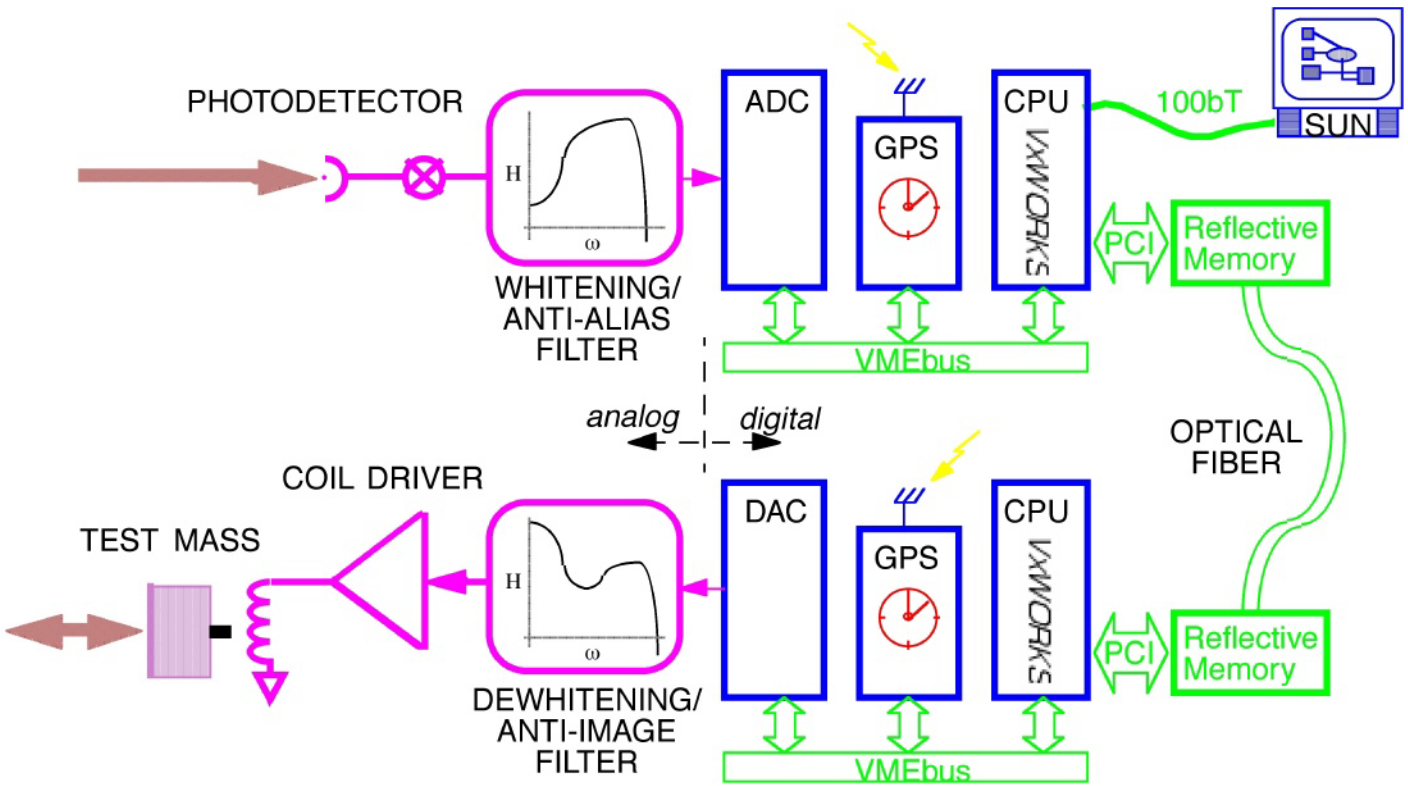
Feedback Control Systems



example: cavity length sensing & control topology

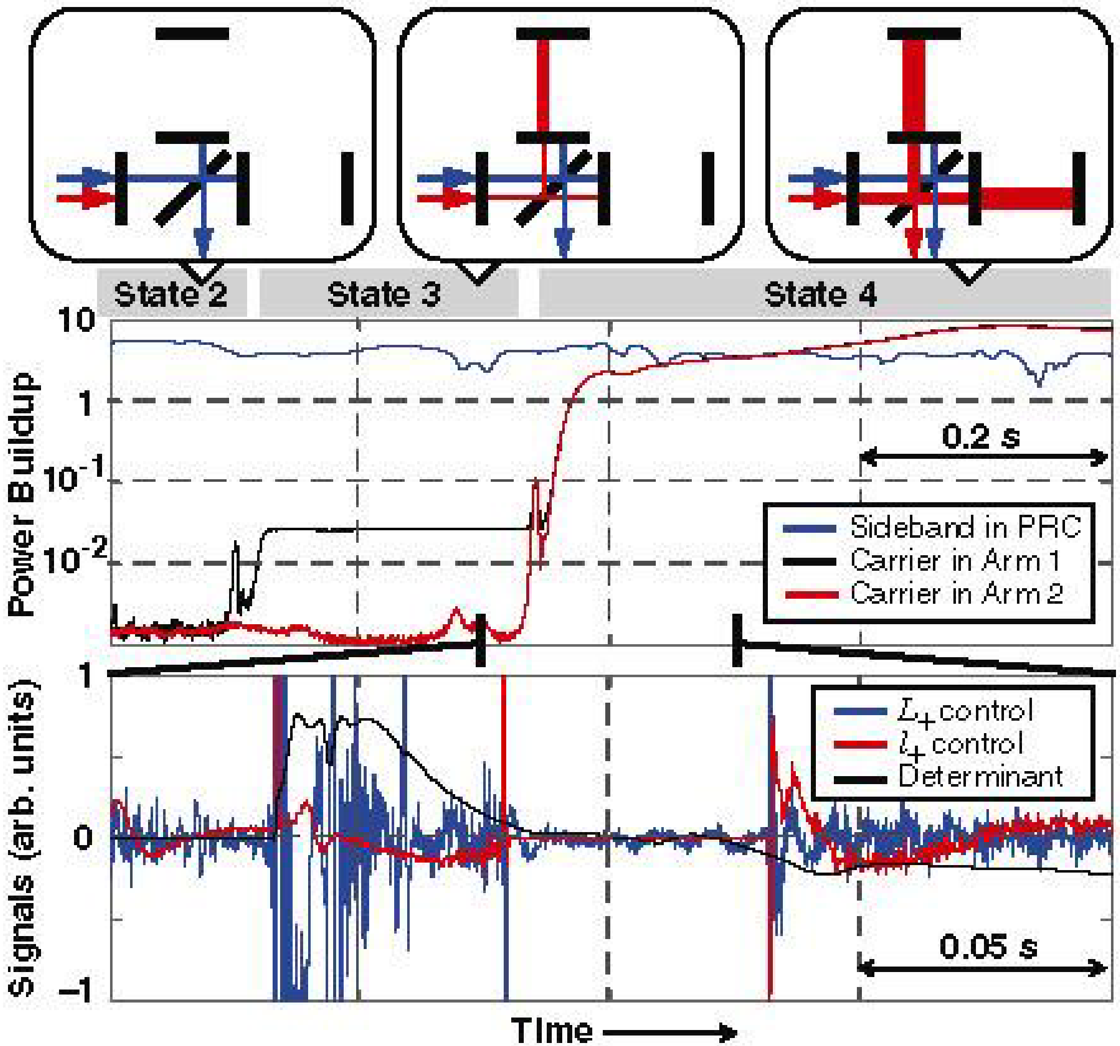
- Array of sensors detects mirror separations, angles
- Signal processing derives stabilizing forces for each mirror, filters noise
- 5 main length loops shown; total ~ 25 degrees of freedom
- Operating points held to about 0.001 Å, .01 µrad RMS
- Typ. loop bandwidths from ~ few Hz (angles) to > 10 kHz (laser wavelength)

Control signal processing architecture



Guided Lock Acquisition

- Fast sensors monitor circulating powers, RF sidebands in cavities
- Sequencing code digitally switches feedback state at proper transition times
- Loop gains are actively scaled (*every sample*) to match instantaneous carrier & sideband buildups
- Designed by Matt Evans (PhD thesis)

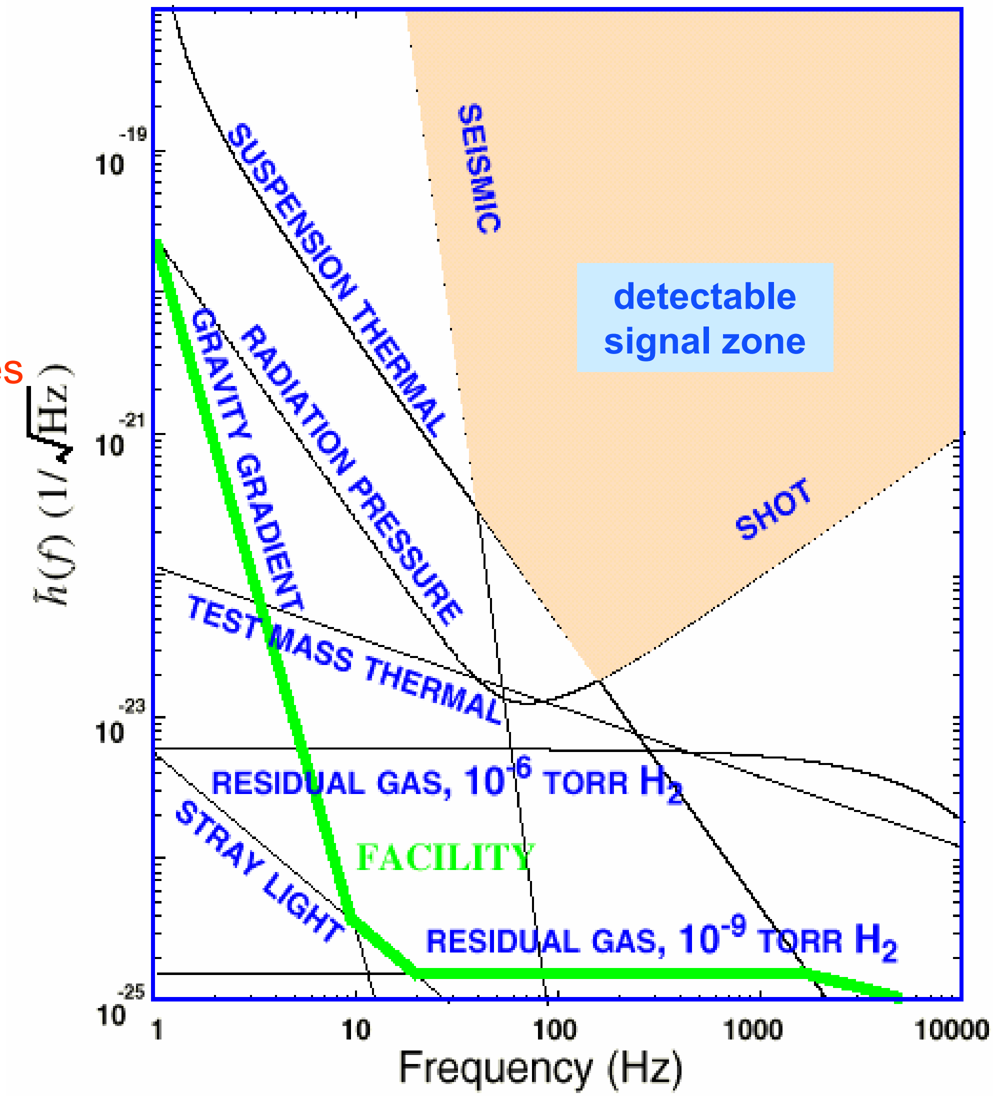


Interferometers: design noise budget

- "Fundamental" limits (with then-current technology) determined design goals
  - **seismic** at low frequencies
  - **thermal** at mid frequencies
  - **shot noise** at high frequencies
- Facility limits much lower to allow improvement as technology matures
- Other "technical" noise not allowed above 1/10 of these (by design, anyway...)

BUT

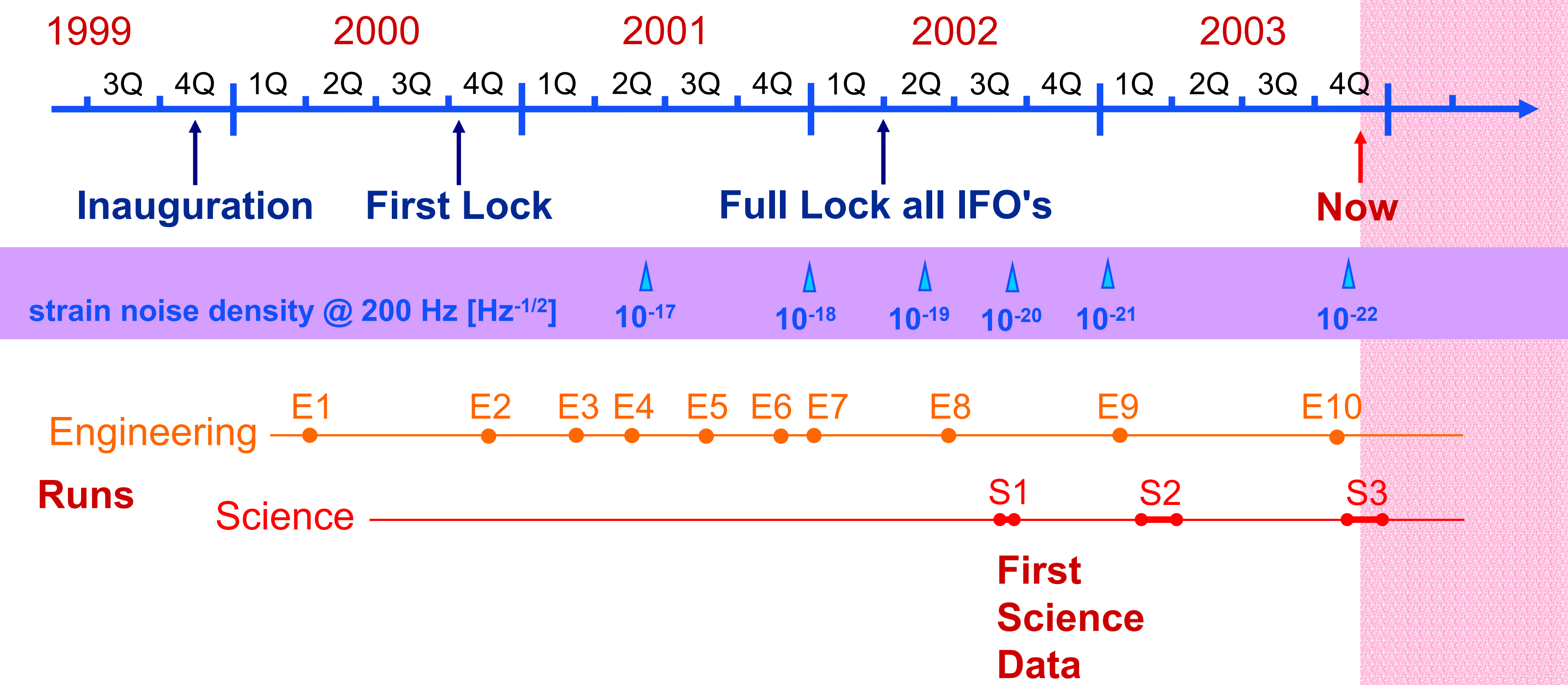
- Didn't start out near design sensitivity



Commissioning & Observing Strategy

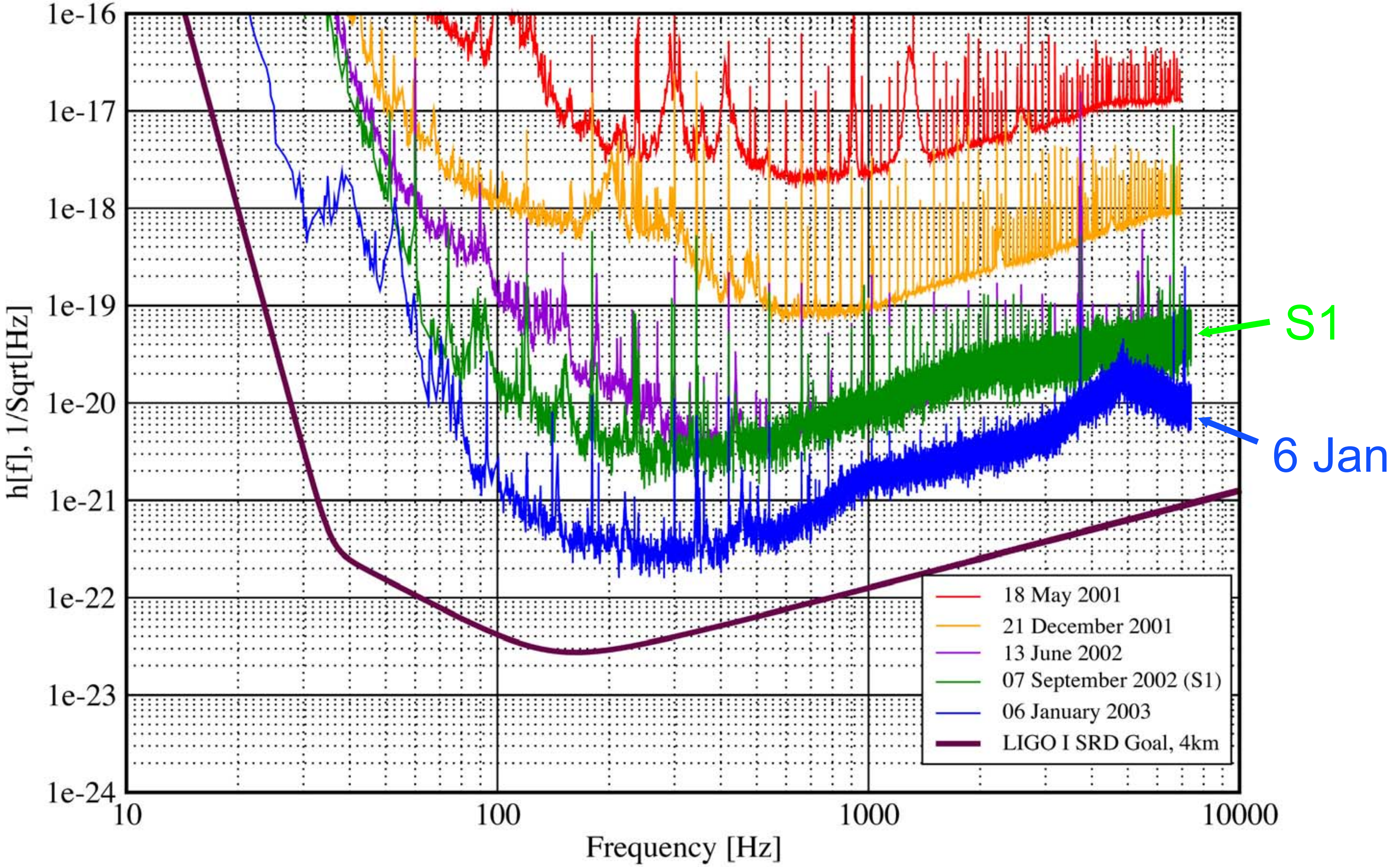
- 3 interferometers at once: challenges & opportunities
  - Shortage of people (perpetually) & hardware (at least initially), BUT...
  - Can still "try out" proposed improvements & iterate designs on one machine at a time
  - Can run investigations on several phenomena at once without interference
- Installation and early commissioning staggered, specific roles for each:
  - First interferometer, LHO 2km: 'Pathfinder' – move quickly, identify problems, move on
  - LLO 4km (L1) interferometer: systematic characterization, problem resolution
  - LHO 4km (H1) interferometer: wait for updated/revised systems at the start
- Strategy has matured & evolved over the last 2 years
  - H1 implemented new digital suspension controls while others did noise studies
  - L1needed to adapt control systems for higher local seismic velocities
  - Beginning to focus on stability and robustness for long-term operations
  - Higher investment in periodically synchronizing all 3 machines to latest revisions
- Interferometers are now **comparable in sensitivity**
  - Noise and stability improvements "leap-frog," with rapid propagation after debugging
  - Expert site operators & staff provide continuity, support, local knowledge
- Interferometer operation (Engineering & Science runs) alternate with commissioning & upgrades
- Scheduling includes GEO, TAMA, ALLEGRO

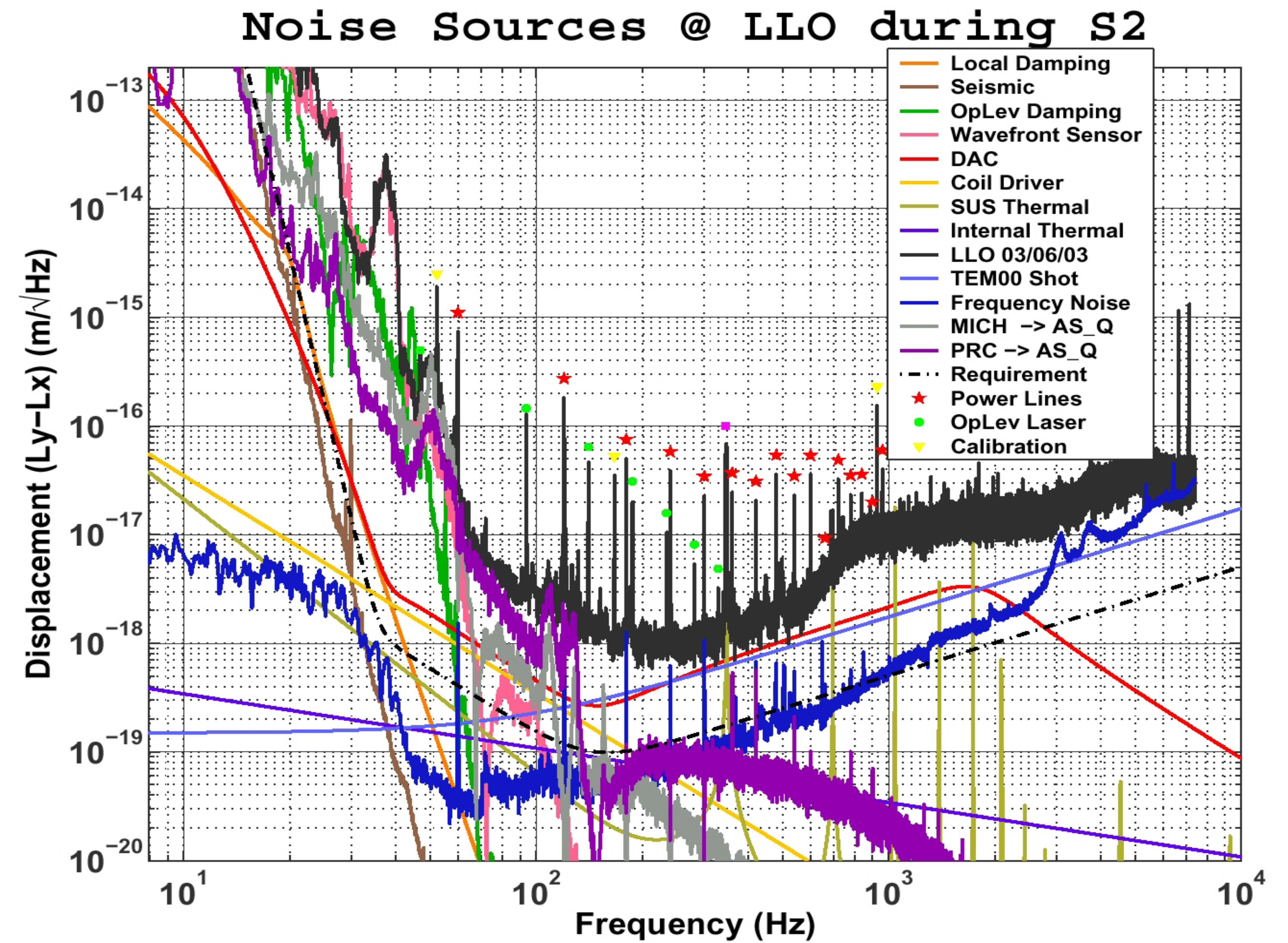
Time Line


1999
2000
2001
2002
2003
3Q 4Q 1Q 2Q 3Q 4Q 1Q 2Q 3Q 4Q 1Q 2Q 3Q 4Q 1Q 2Q 3Q 4Q
Inauguration
First Lock
Full Lock all IFO's
Now
strain noise density @ 200 Hz [Hz$^{-1/2}$]
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
Engineering
E1 E2 E3 E4 E5 E6 E7 E8 E9 E10
Runs
Science
S1 S2 S3
First Science Data

Strain Sensitivity for the LLO 4km Interferometer

31 January 2003 LIGO-G030014-00-E



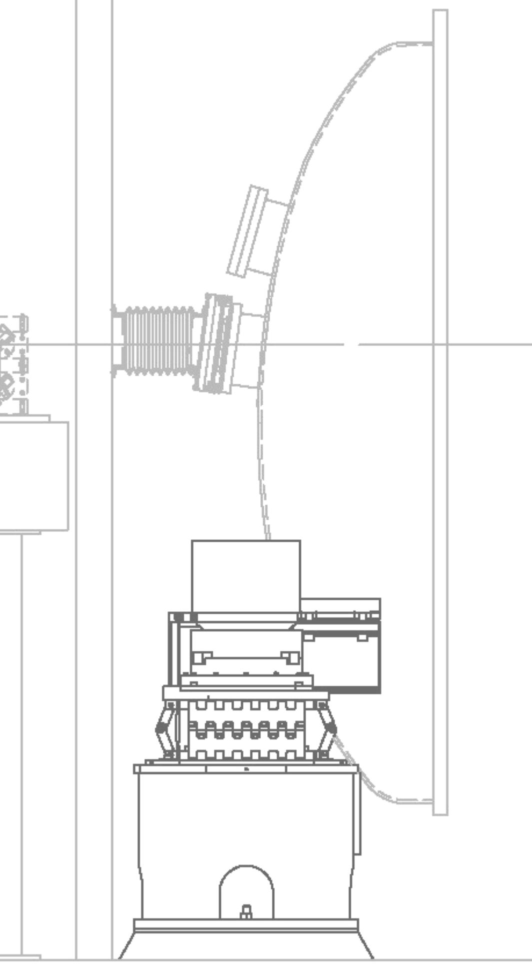

Noise Sources @ LLO during S2
Local Damping
Seismic
OpLev Damping
Wavefront Sensor
DAC
Coil Driver
SUS Thermal
Internal Thermal
LLO 03/06/03
TEM00 Shot
Frequency Noise
MICH -> AS_Q
PRC -> AS_Q
Requirement
Power Lines
OpLev Laser
Calibration
Displacement (Ly-Lx) (m/√Hz)
Frequency (Hz)
10^-13
10^-14
10^-15
10^-16
10^-17
10^-18
10^-19
10^-20
10^1
10^2
10^3
10^4

Major upgrades between S2 and S3

- Increased effective laser power
  - Now detecting full AS port power on each IFO (multiple PD's)
  - Also increased input power – beginning to see expected thermal lensing
  - Still factor of 3-5 to go in input power
- Mitigated acoustic coupling at detection ports
  - Combination of improved acoustic isolation; reduction of acoustic sources; reduction of physical coupling mechanisms
- Continued implementation of wavefront sensor (WFS) alignment
  - Propagated enhanced S2-era stability of H1 to other two machines
  - (full high-bandwidth implementation remains for post-S3)
- Fixed accumulated in-vacuum problems
  - Adjusted optic separations (~ 2 cm) on H1 and L1
  - Bad AR coating on one H2 test mass (replaced w/spare)
  - Installed baffles to prevent laser-cutting our suspensions wires
  - Very time-consuming due to degassing cycle
- Major upgrade to realtime feedback controls code
  - Adaptive gains to accommodate power up & thermal lens onset

Acoustic Mitigation

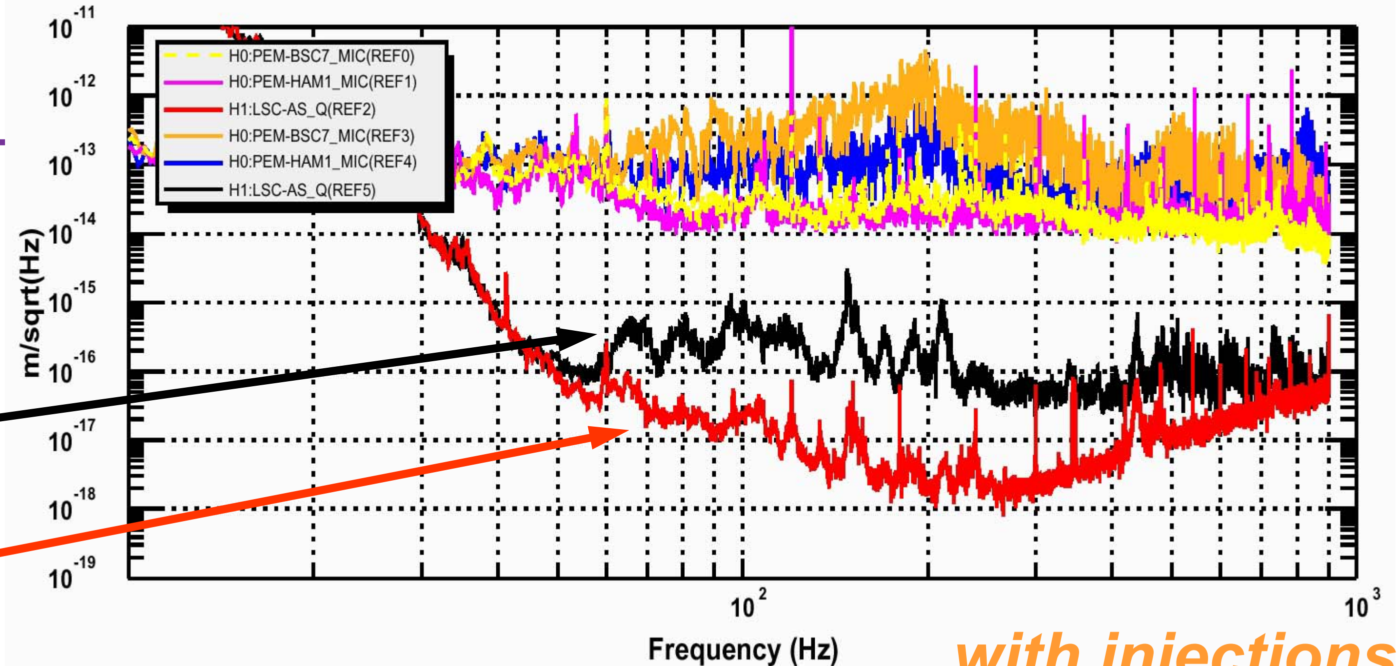
- Primary sources:
  - Building HVAC
  - Electronics cooling fans
- Installed acoustic enclosures on dark ports
- Removed microphonic optics
  - opened to 2” clear aperture at critical locations
  - EO shutters removed at ISCT4 and ISCT1
  - stiffened & damped beam delivery periscopes
- Results:
  - ~10x from optics rework ~10x from acoustic enclosure)
  - *No acoustic peaks* left in S3 spectra
  - H1 - H2 correlations substantially reduced !



Displacement Spectra

with acoustic injections at ISCT4

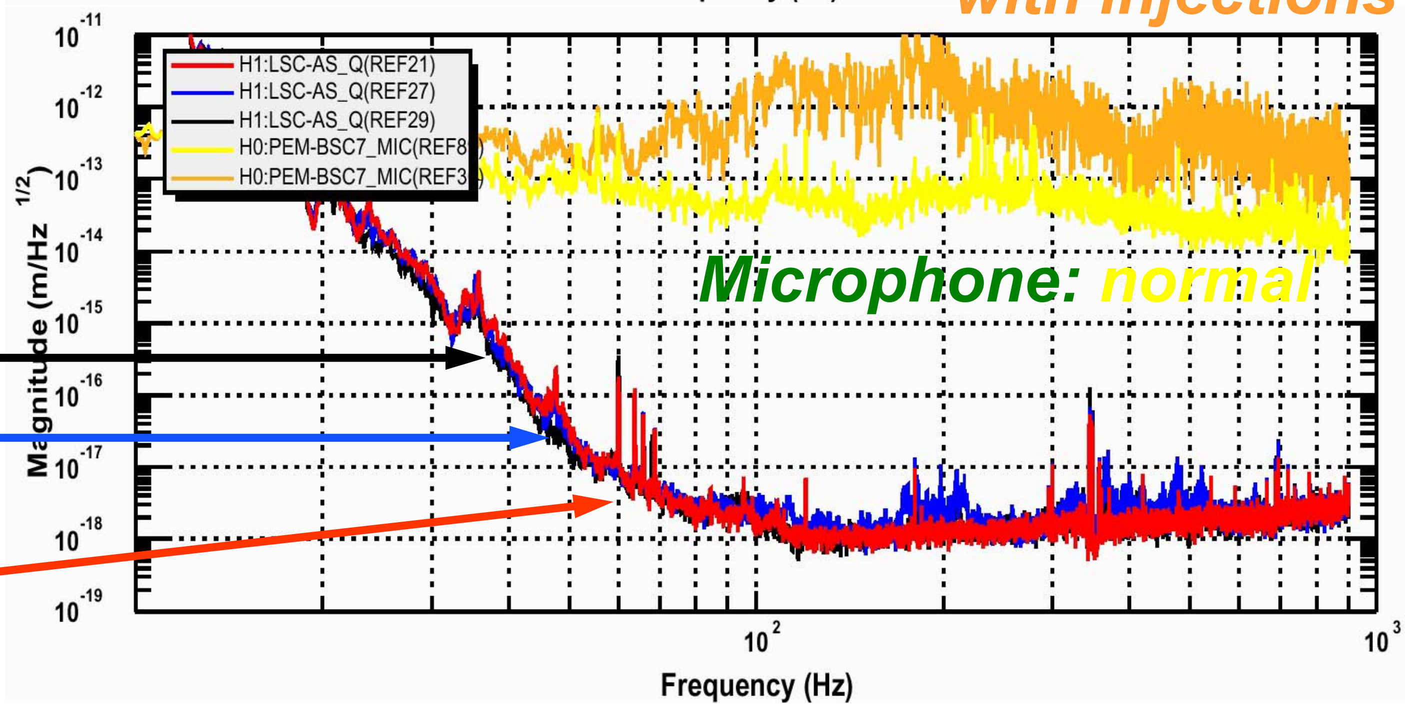
S2



with injections

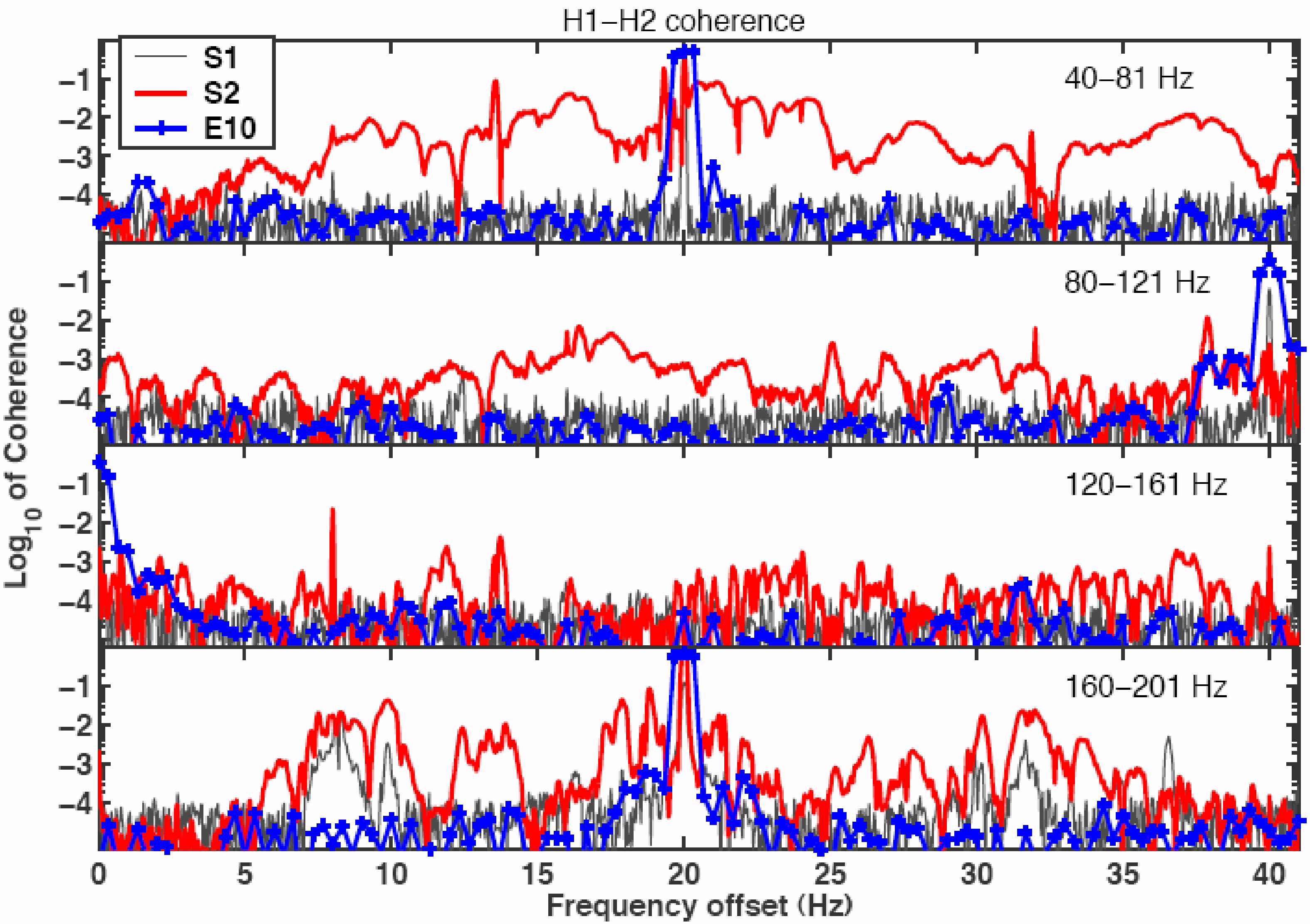
with acoustic injections at ISCT4 and ISCT1

S3



Microphone: normal

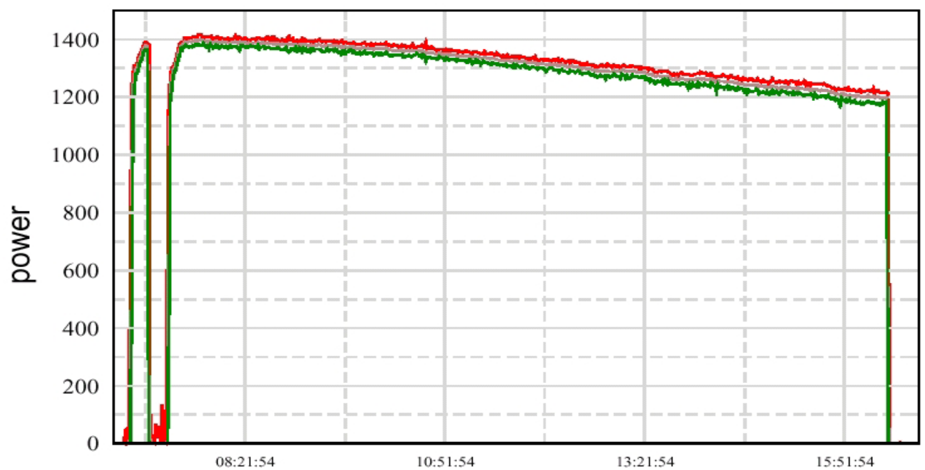
H1-H2 Correlations Reduced

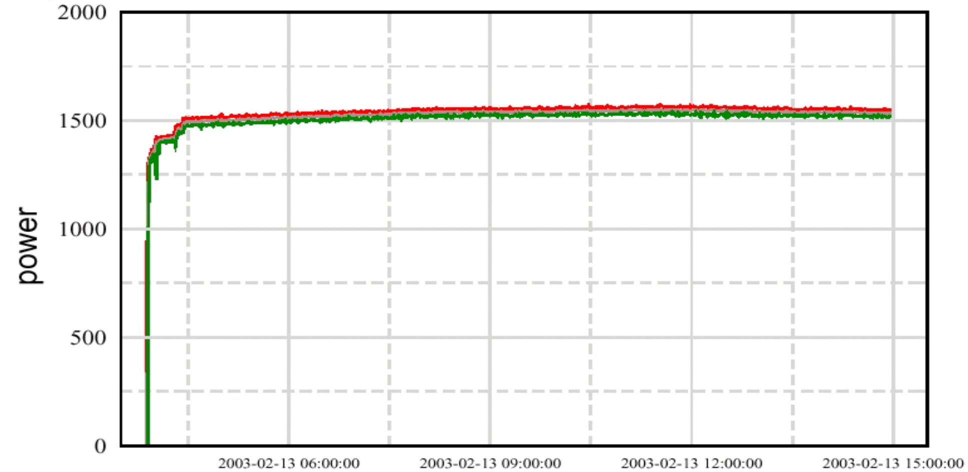


WFS Alignment System

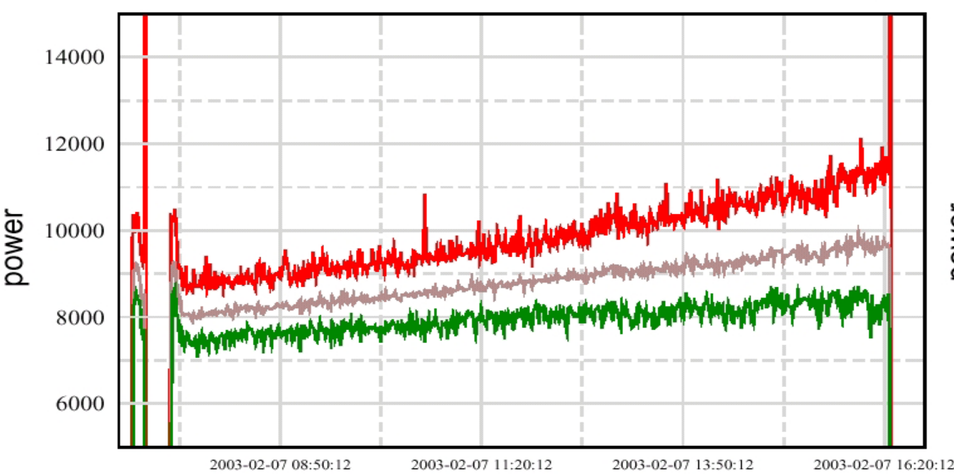
WFS OFF | **WFS ON**

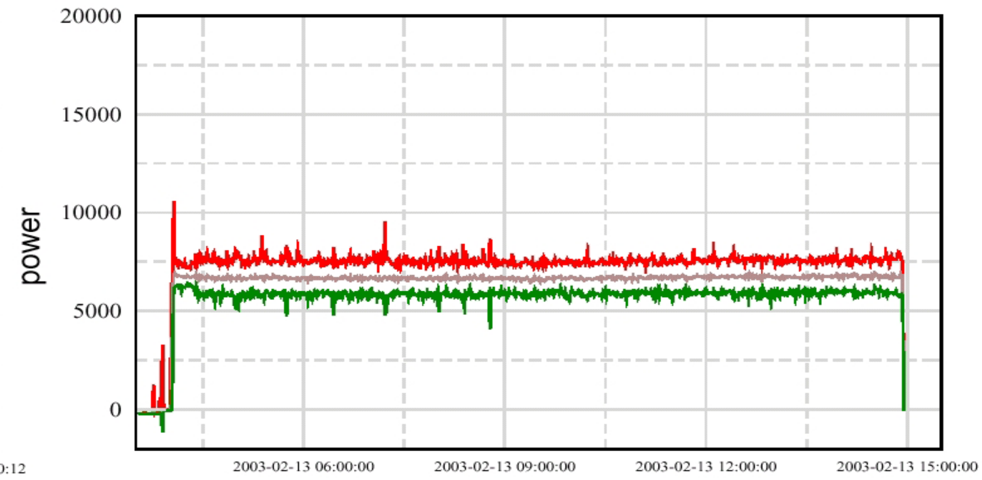
Arm Cavity Power



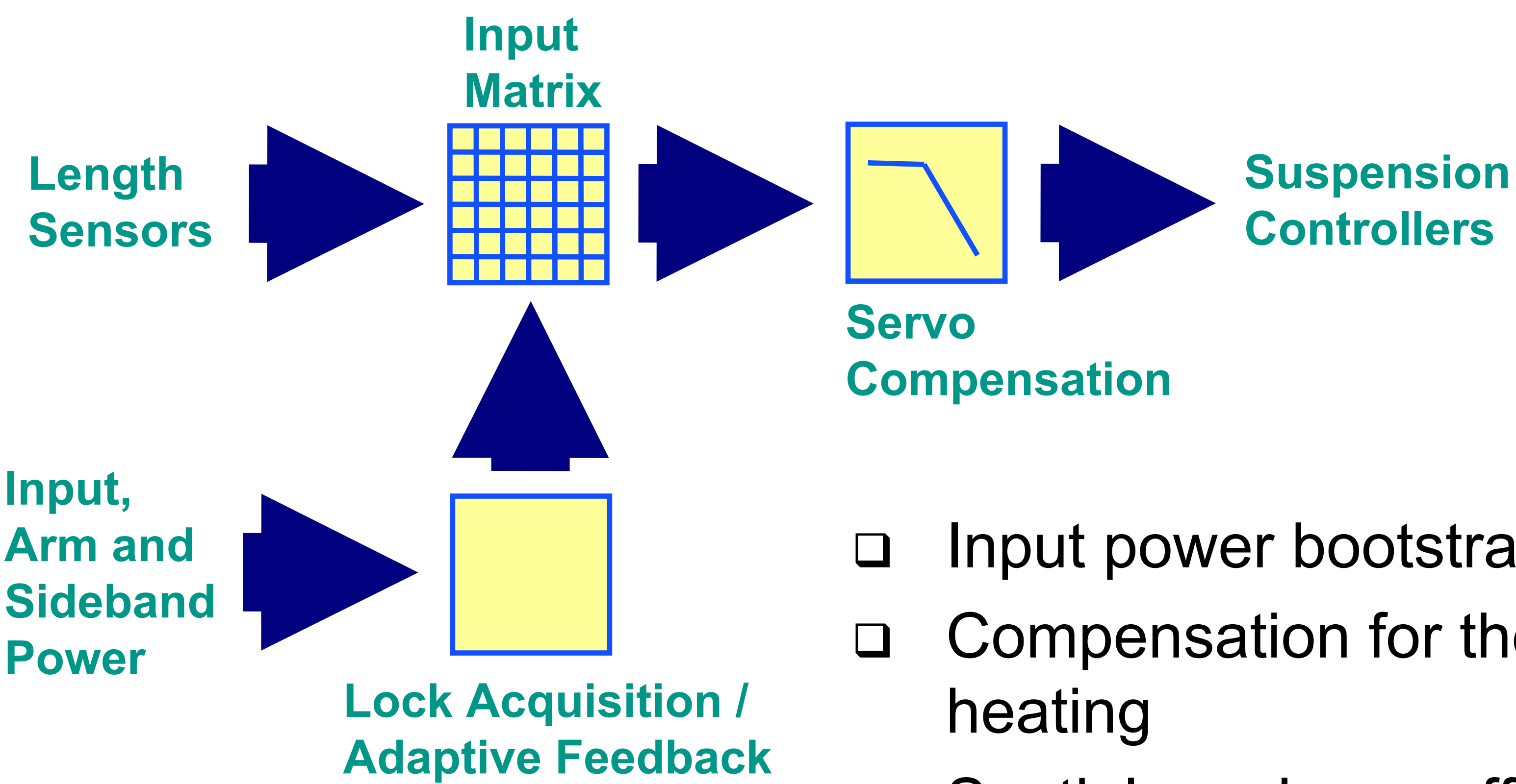


Anti-symmetric Port Power



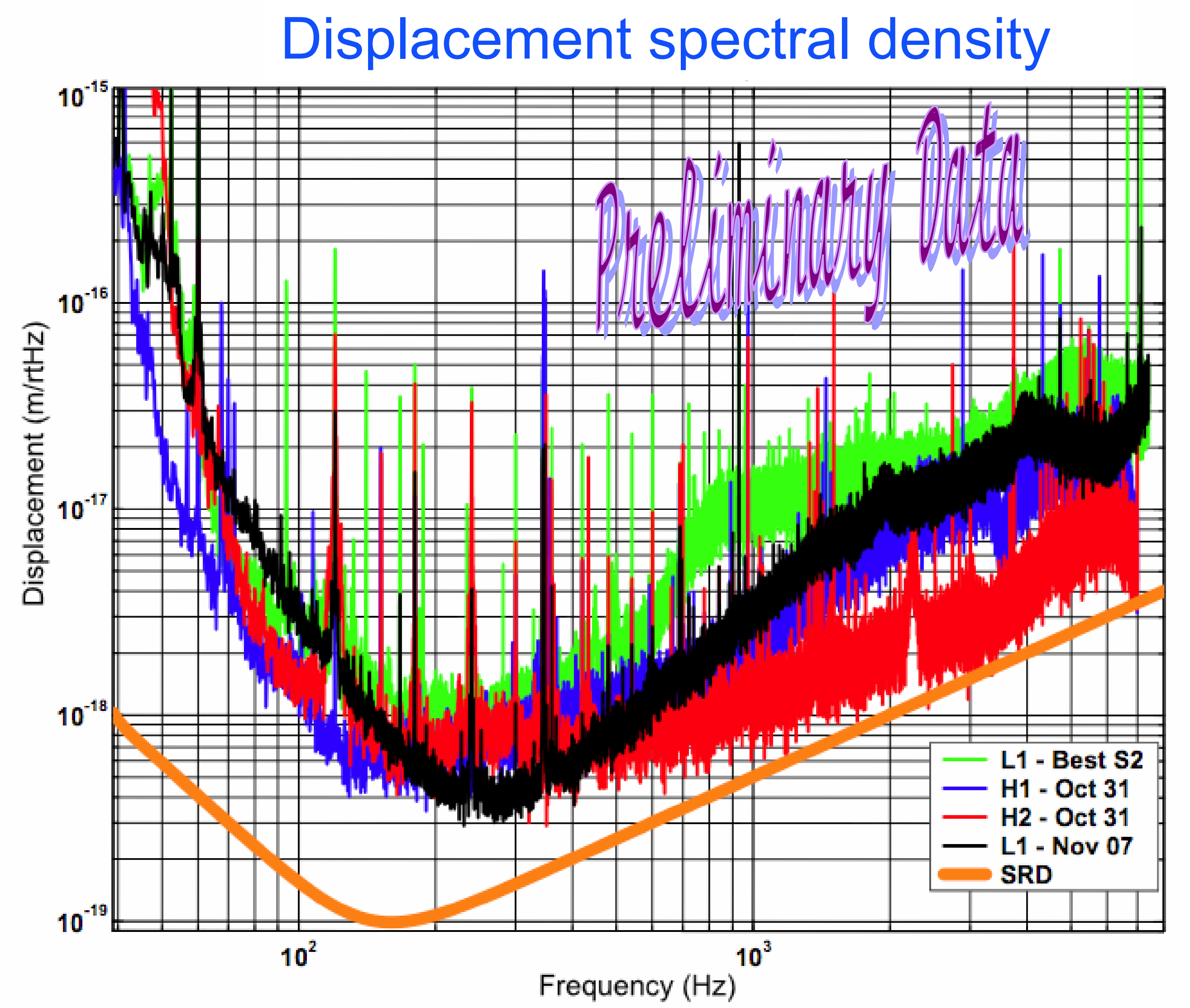


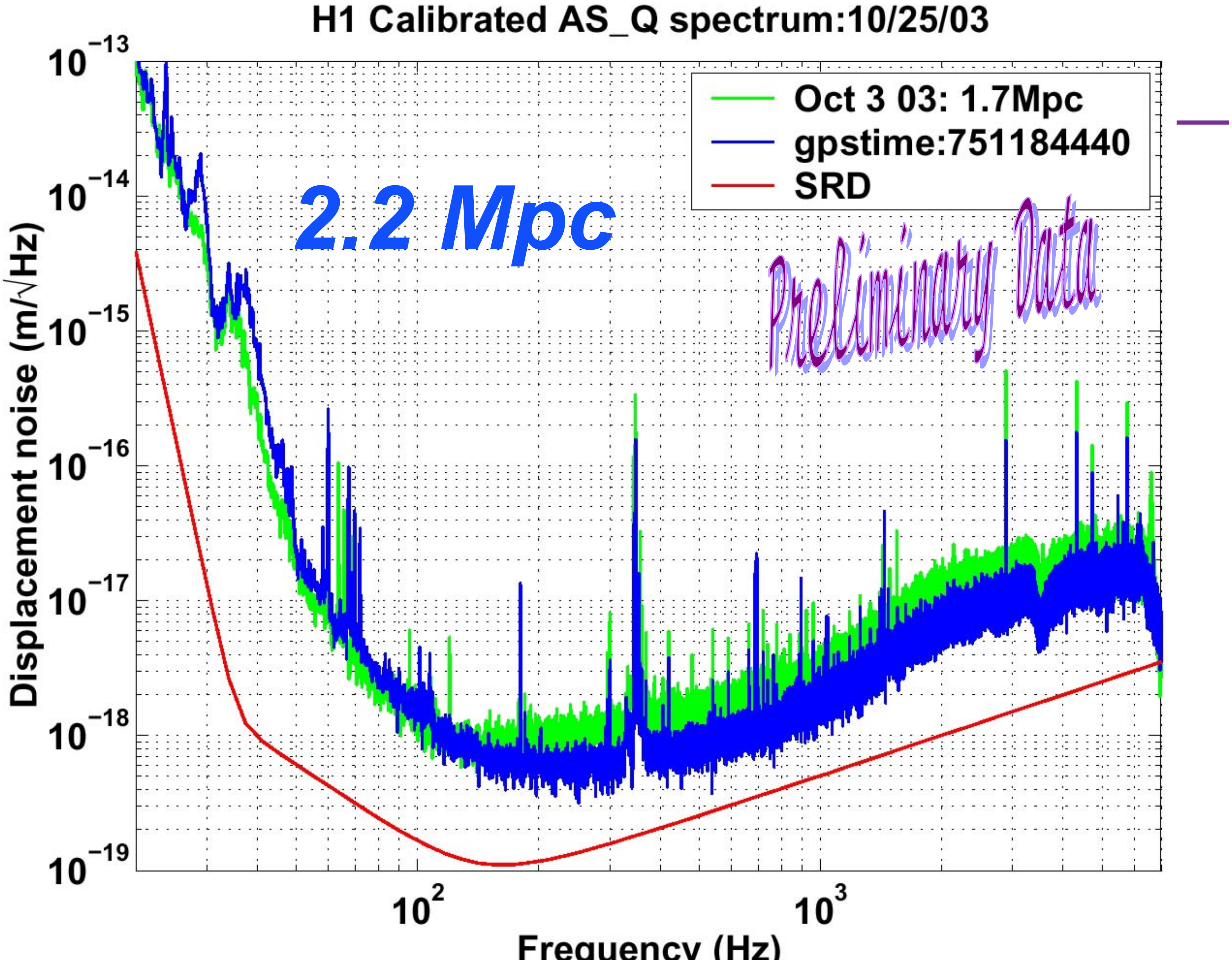
Adaptive Feedback Tracking



- Input power bootstrapping
- Compensation for thermal heating
- Spatial overlap coefficients

Start of S3: All 3 LIGO Interferometers at Extragalactic Sensitivity



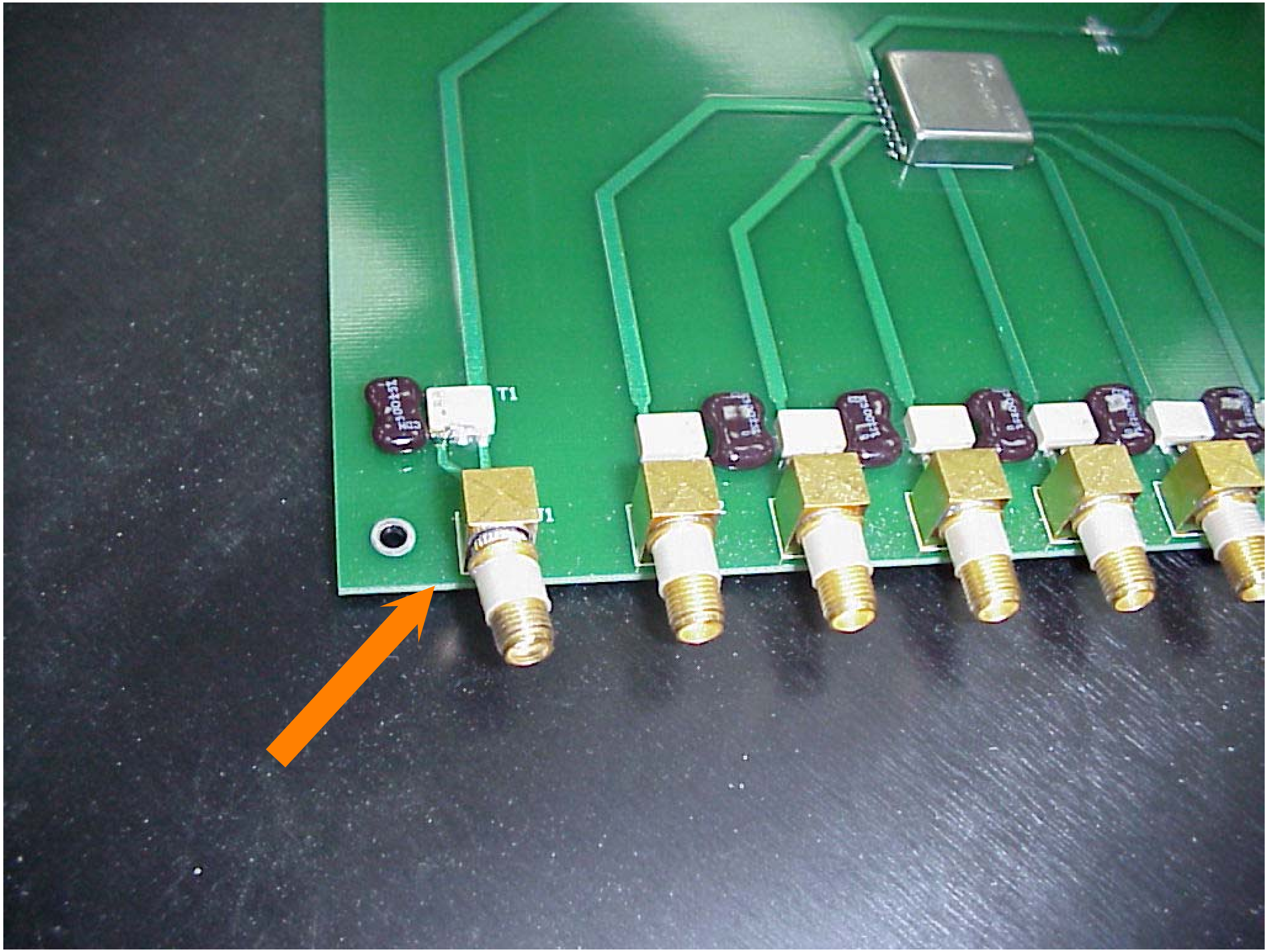

H1 Calibrated AS_Q spectrum:10/25/03
Oct 3 03: 1.7Mpc
gpstime:751184440
SRD
2.2 Mpc
Preliminary Data
Displacement noise (m/√Hz)
Frequency (Hz)
10^-13
10^-14
10^-15
10^-16
10^-17
10^-18
10^-19
10^2
10^3

Summary Science Run Metrics

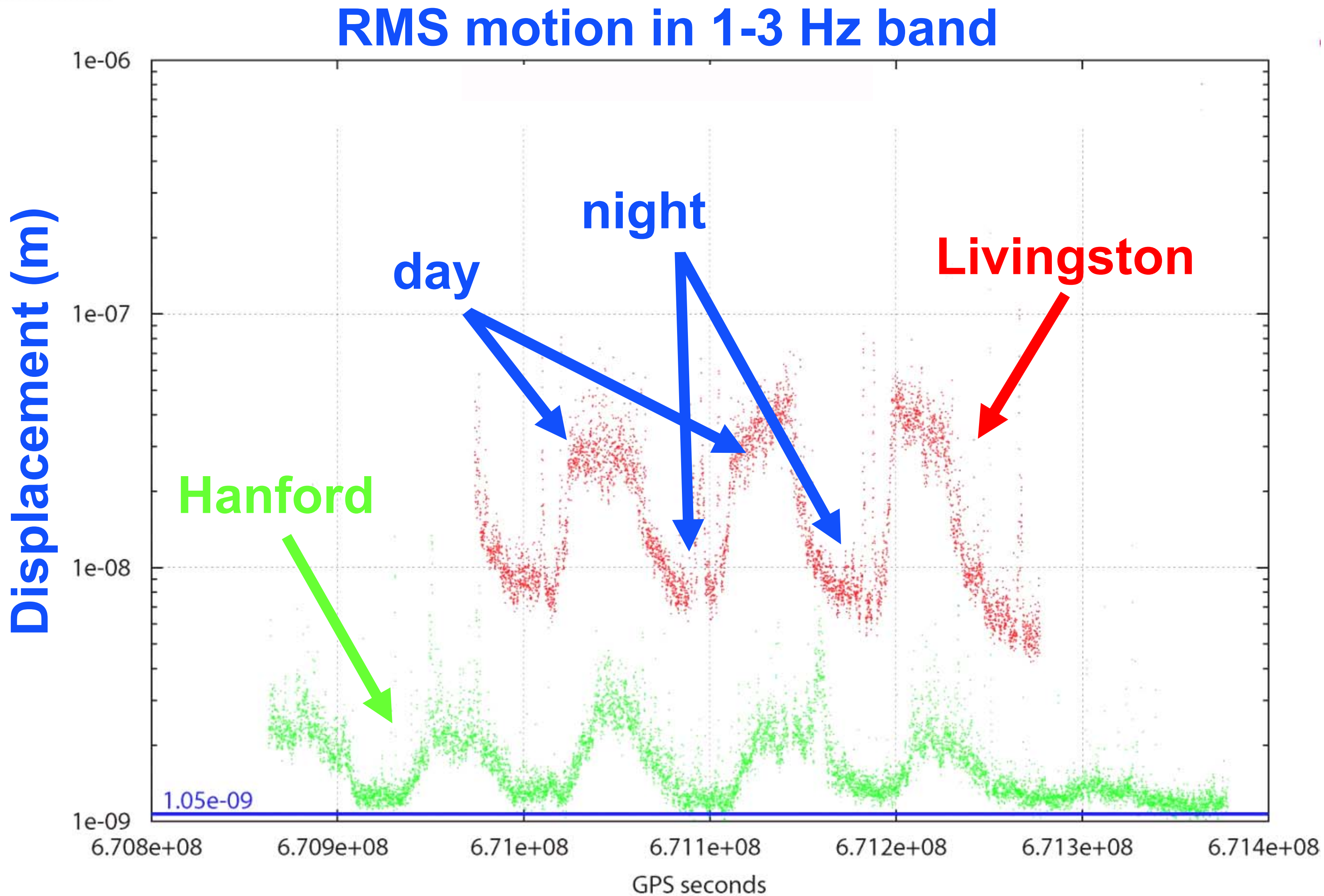
RUN ⇒	GOAL ("SRD")		S1		S2		S3*	
IFO ⇓	*BNS RANGE (kpc)*	*DUTY FACTOR*	*BNS RANGE (kpc)*	*DUTY FACTOR*	*BNS RANGE (kpc)*	*DUTY FACTOR*	*BNS RANGE (kpc)*	*DUTY FACTOR*
L1	14,000	90%						
H1	14,000	90%						
H2	7,000	90%						
3-way		75%						

***PRELIMINARY**--RUN IN PROGRESS*

L1 got a slow start...



Daily Variability of Seismic Noise



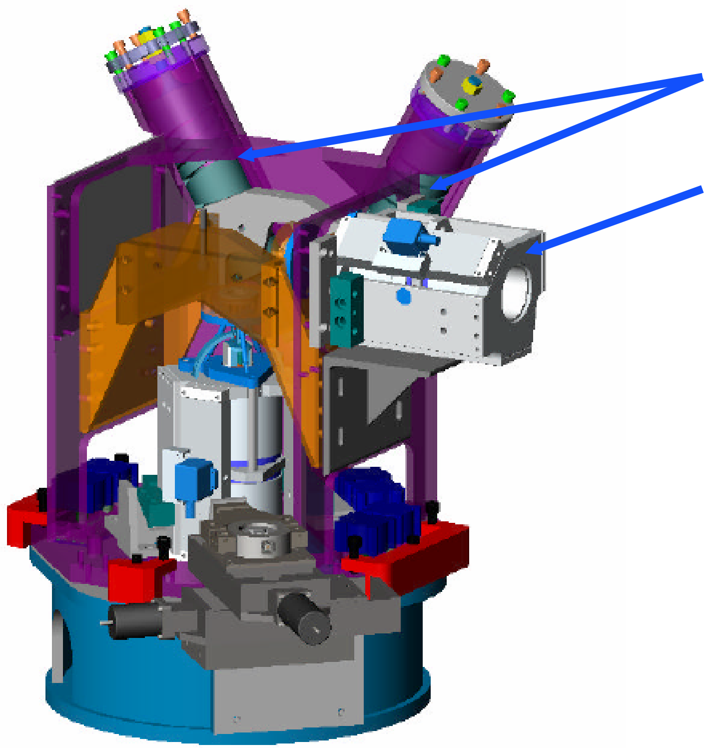
What Next? From S3 to S4 +

- Stability & uptime
  - Seismic retrofit at LLO ⇒ L1
  - Adapt WFS controls for radiation pressure torques
  - WFS bandwidth upgrade (wean off optical levers)
  - Possible wind noise mitigation for LHO
- Sensitivity
  - Thermal compensation system (TCS) ⇒ H1 test
  - Higher *effective* laser power (power & sideband overlap)
    - Laser & input optics efficiency improvement
    - Output mode cleaner (OMC) [possibly]
  - Finish acoustic mitigation
    - Enclosures for other output ports
    - Relocate electronics racks remotely ⇒ L1 test
  - Electronics cleanup: EMC upgrade ⇒ L1 test
  - Custom low-noise DAC's, other electronics upgrades

Seismic Environment at LLO

- Spiky impulsive seismic noise in 1-3 Hz band
  - Related to human activity – mostly lumber industry
  - Dominant frequencies accidentally coincide with isolator resonances
  - Impedes IFO locking during weekdays
- Large & variable microseism
  - Ocean waves excite double frequency (DF) surface waves on land
    - Fraction to several microns RMS; frequency: ~ 0.15 - 0.25 Hz
    - Wavelength ~ kilometers ➔ L1 arm length change several microns
- Strategy for recovering full-time duty at LLO
  - Active Hydraulic External Pre-Isolator system
    - 6 D.O.F active stabilization of seismic supports (External Pre-Isolator)
  - Prototype demonstrated at Stanford and MIT
  - Now in full production for January installation start at LLO

Hydraulic External Pre-Isolators (HEPI)

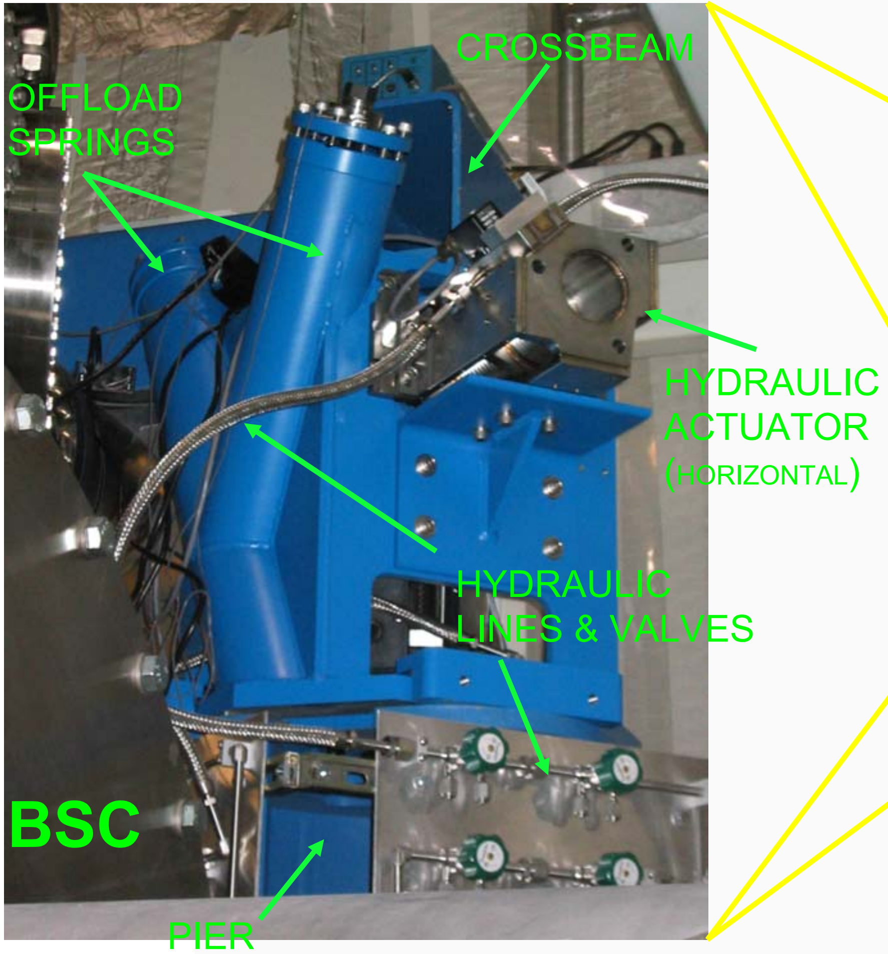


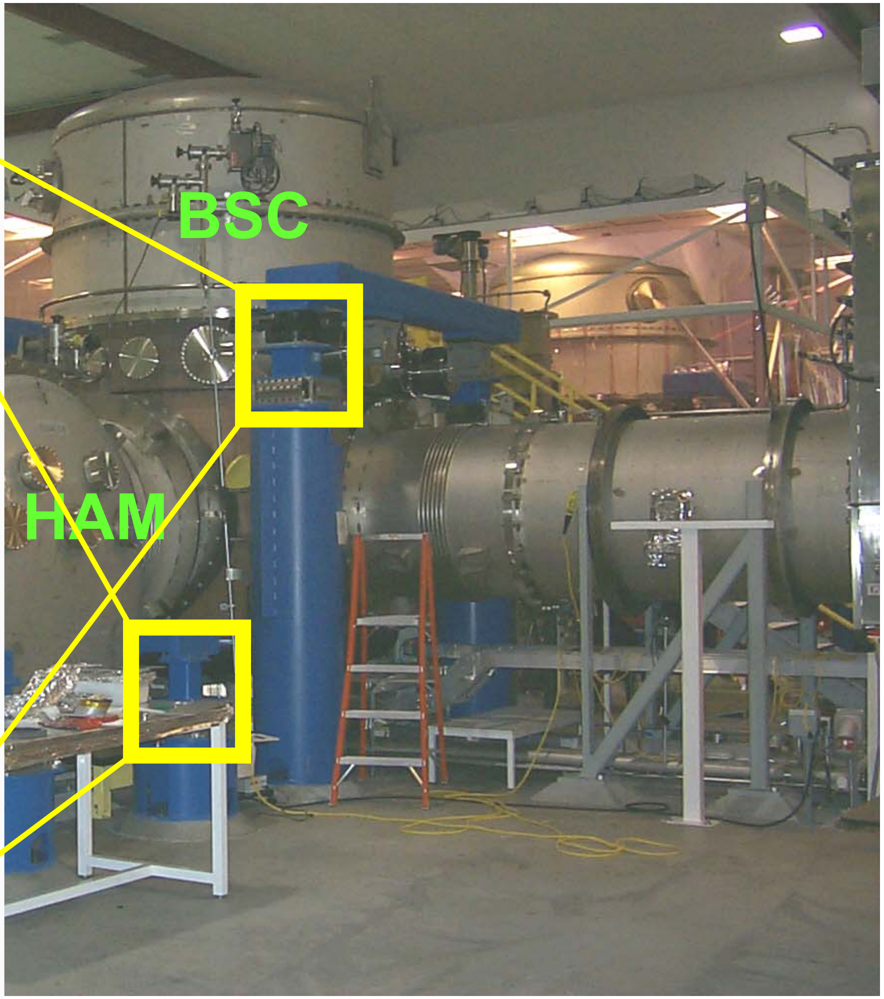
K. Mason, MIT

- Static load is supported by precision coil springs
- Bellows hydraulic pistons apply force without sliding friction, moving seals
- Laminar-flow differential valves control forces
- Working fluid is glycol/water formula (soluble, nonflammable)
- Stabilized “power supply” is remote hydraulic pump with “RC” filtering & pressure feedback control
- Fits in space now used for adjusters in existing system

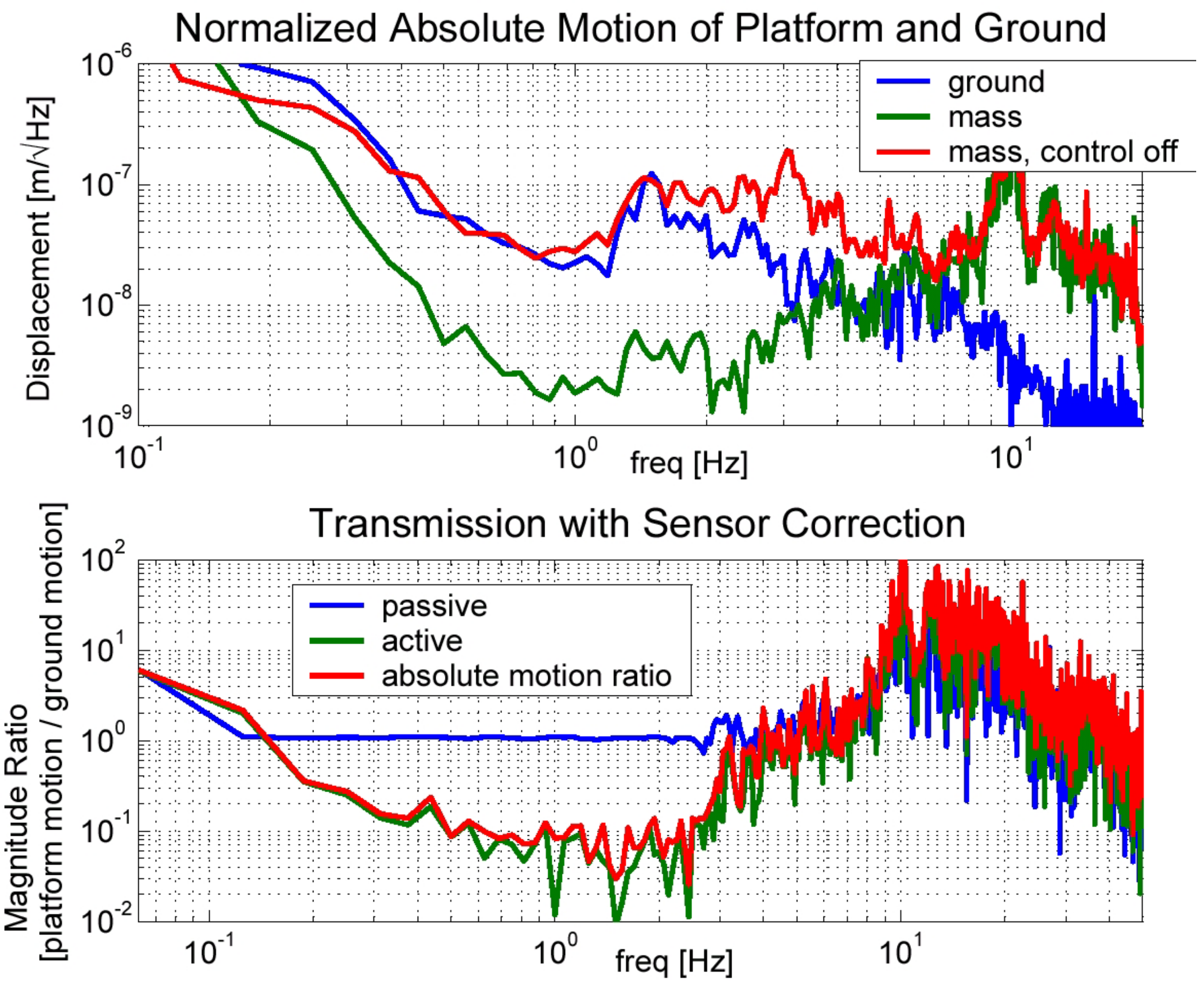
Active Seismic Isolation

Hydraulic External Pre-Isolator (HEPI)





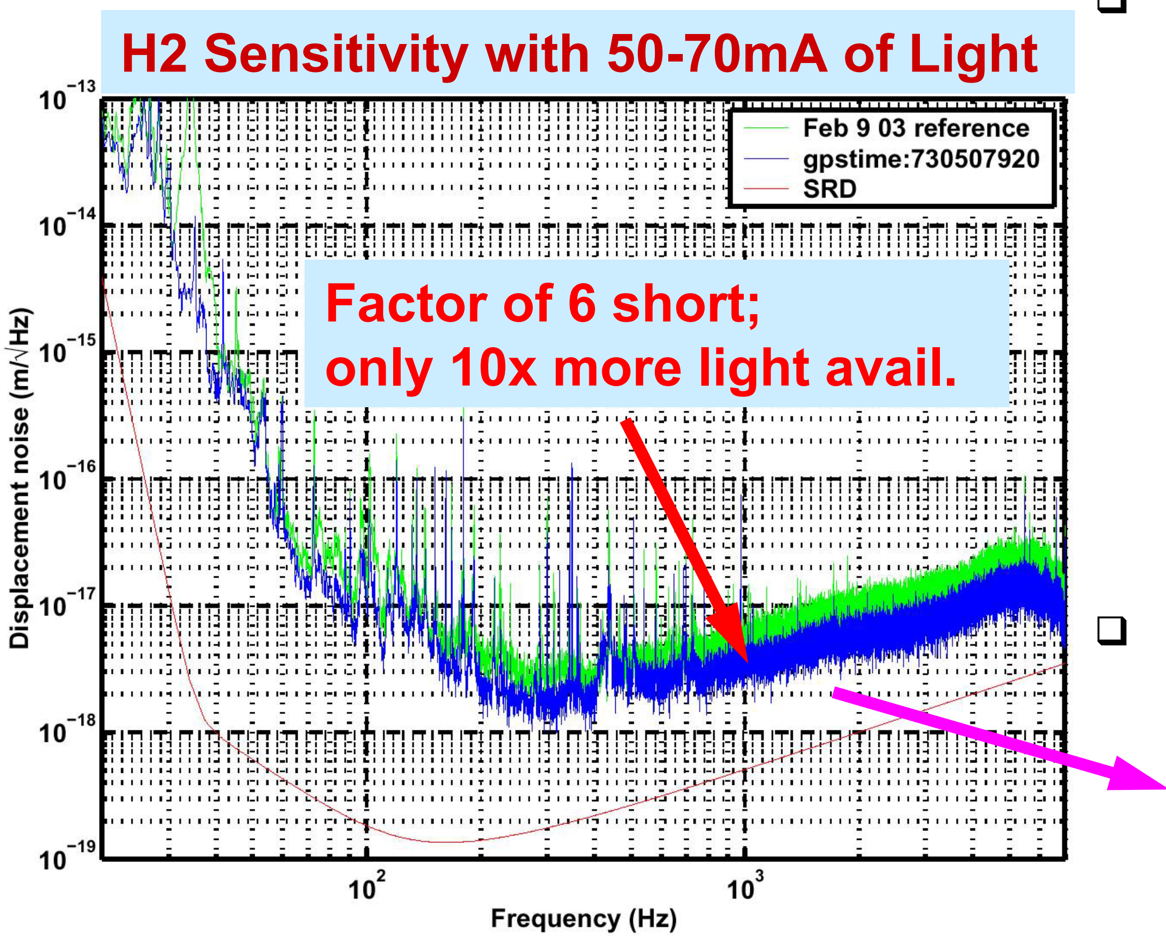
HEPI Preliminary Results



HEPI prototype performance on MIT testbed:

- Residual motion 2e-9 m/√Hz at critical frequencies
- Robust and fault tolerant
- Leak-free & clean
- Meets immediate LLO requirements
- *Exceeds* advanced LIGO requirements

High Power Operation

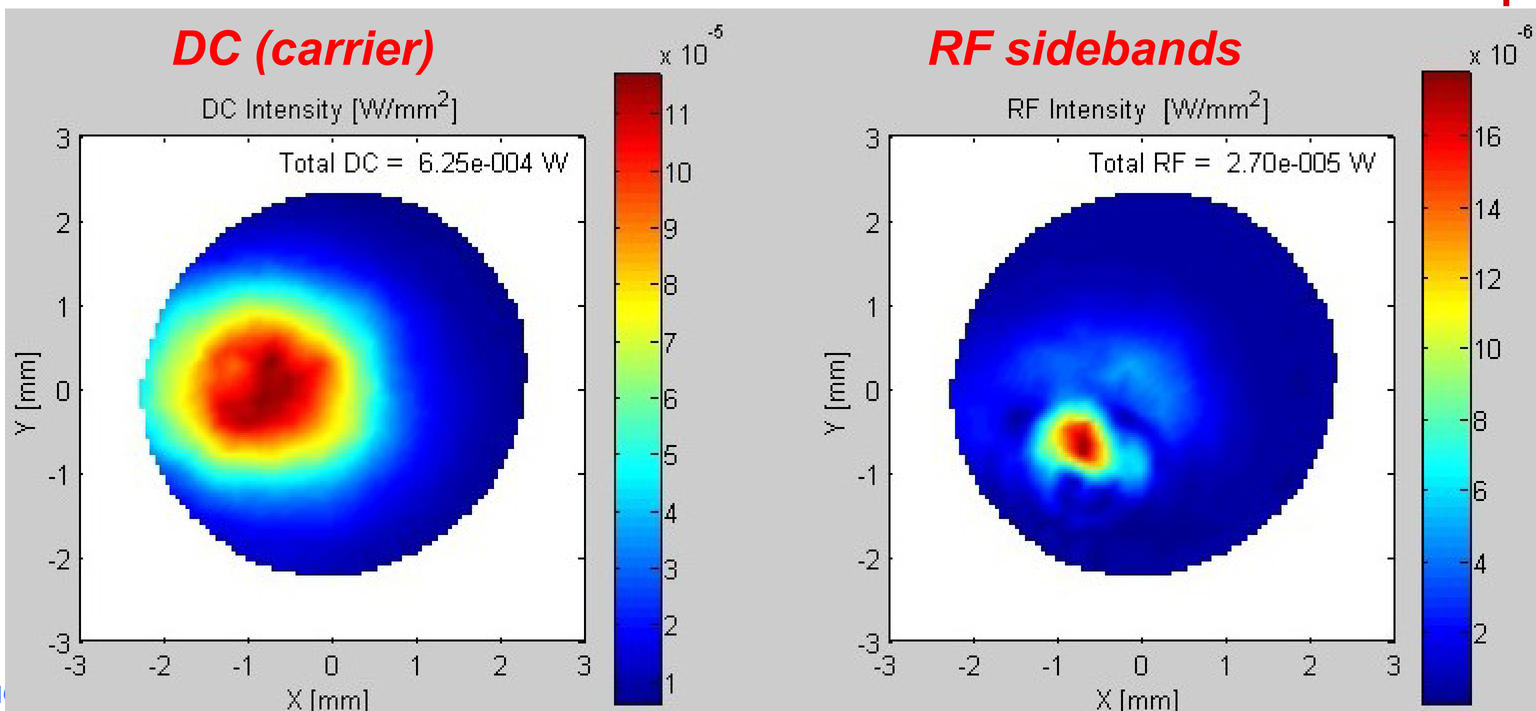


- Power improvements:
  - Locking dynamic range 1000:1 (run/acquire PD's)
  - Huge signal in wrong quadrature (?!) (I servo)
  - Blend multiple detectors at anti-symmetric port
  - Protect photodetectors on lock loss (fast shutters)
  - Protect suspension wires on misalignment (baffles, watchdogs)
- Open Issues:
  - Laser output & beam delivery efficiency
  - Sideband coupling & sideband/carrier overlap inadequate

Recycling Cavity Degeneracy

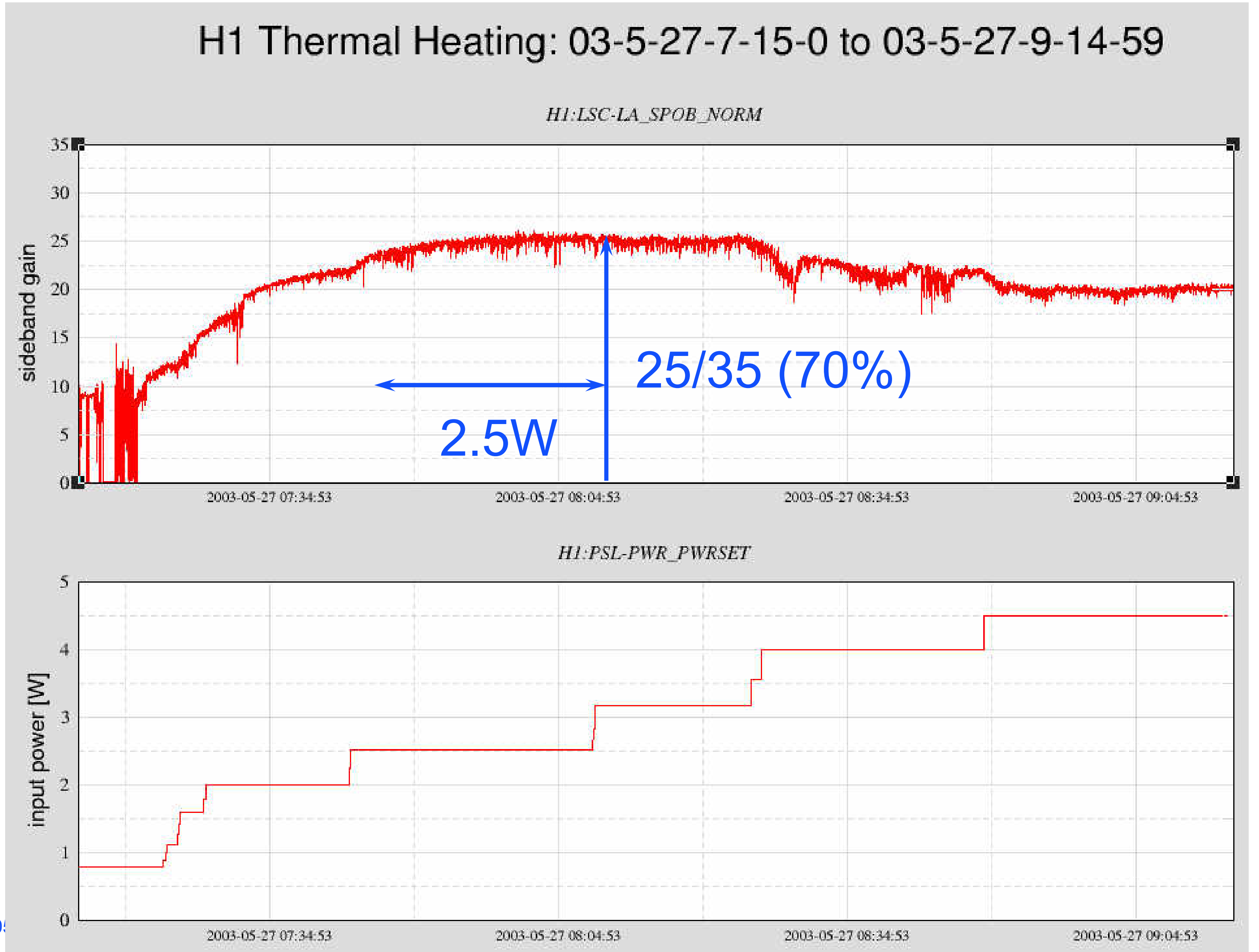
- 'Frontal modulation' scheme depends on efficient coupling
  - Local oscillator field generated at laser, coupled into recycling cavity (not co-resonant in arm cavities)
  - Recycling cavity is **nearly degenerate** ($ROC_{[cold]}$ ~ 15 km, length ~ 9 m)
  - Original "point design" depends on specific, balanced **thermal lensing**
- RF sideband efficiency found to be very low
  - H1 efficiency: ~6% (anti-symmetric port relative to input)
  - incorrect/insufficient ITM thermal lens makes $g_1 \cdot g_2 > 1$ (unstable resonator)

⇒Bad mode overlap!

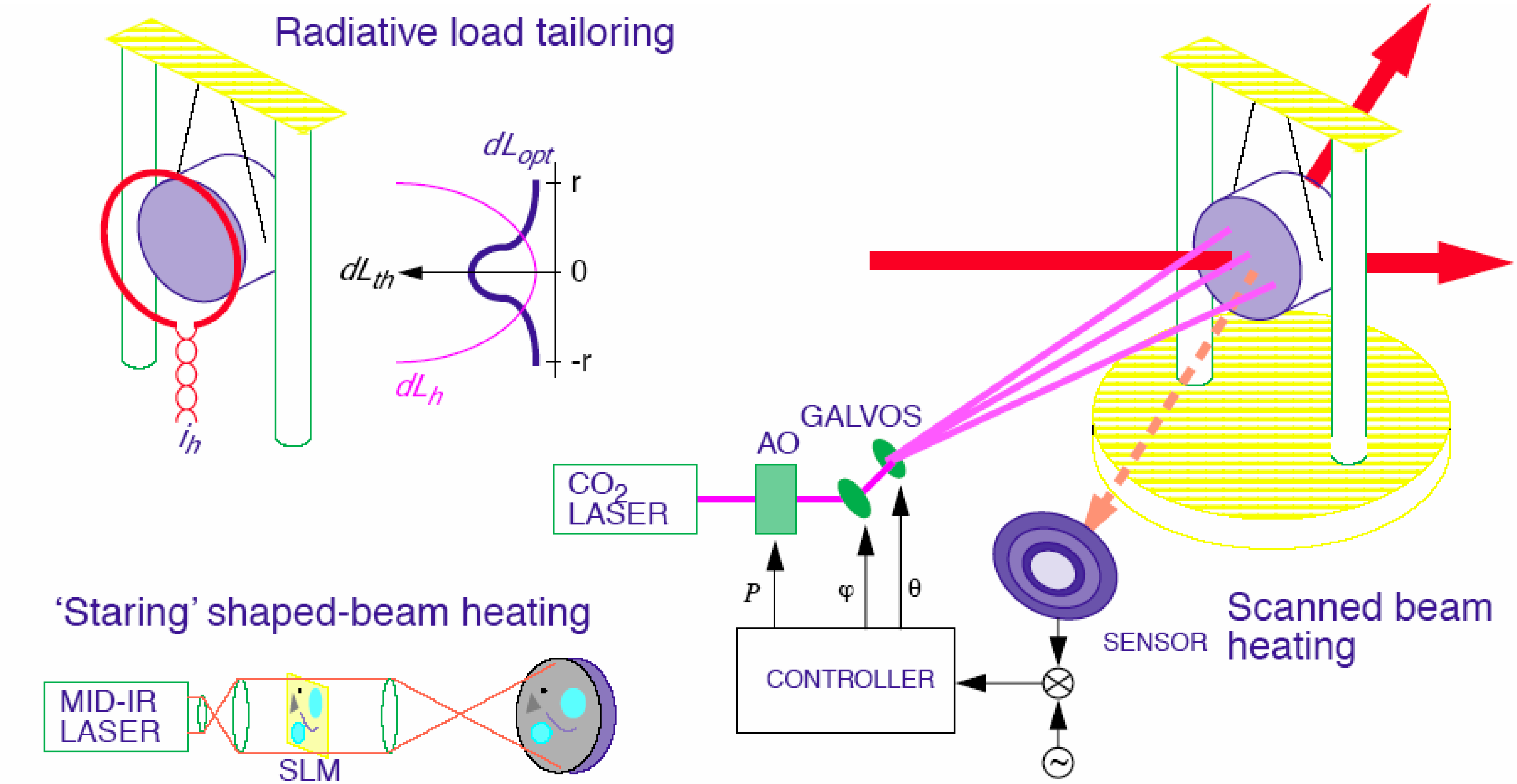


High Power Operations

Thermal Lensing

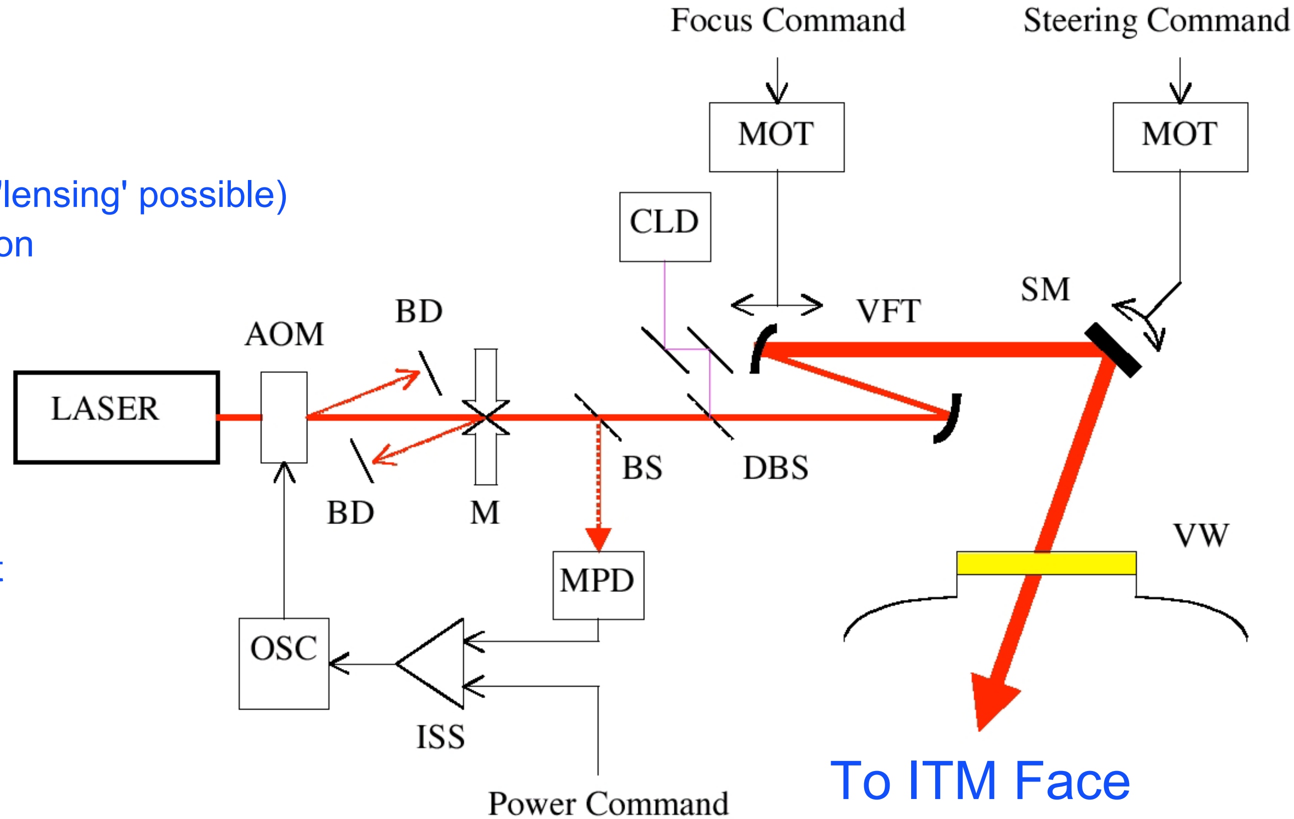


Thermal Compensation to the Rescue



Simplified LIGO I Thermal Compensator

- 10W CW TEM_{00} CO_2 Laser (10.6μm)
- Ge AOM:
  - Intensity stabilization
  - Power selection
- Reflective mask:
  - Intensity profile (+, - 'lensing' possible)
  - Astigmatism correction
- Relay optics:
  - Focus
  - Pattern size
  - Position
- Visible pilot laser
  - Steering & alignment

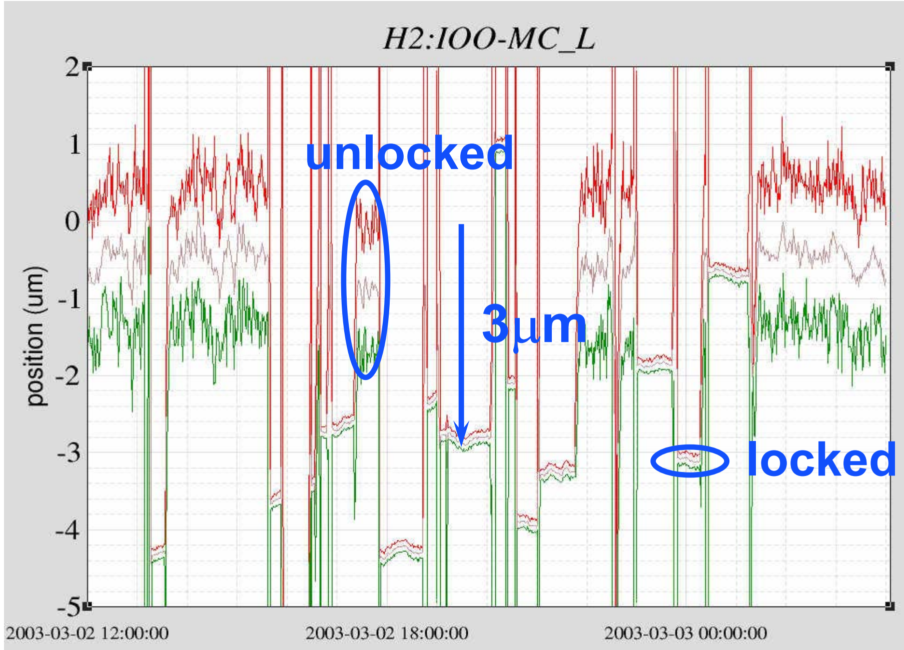


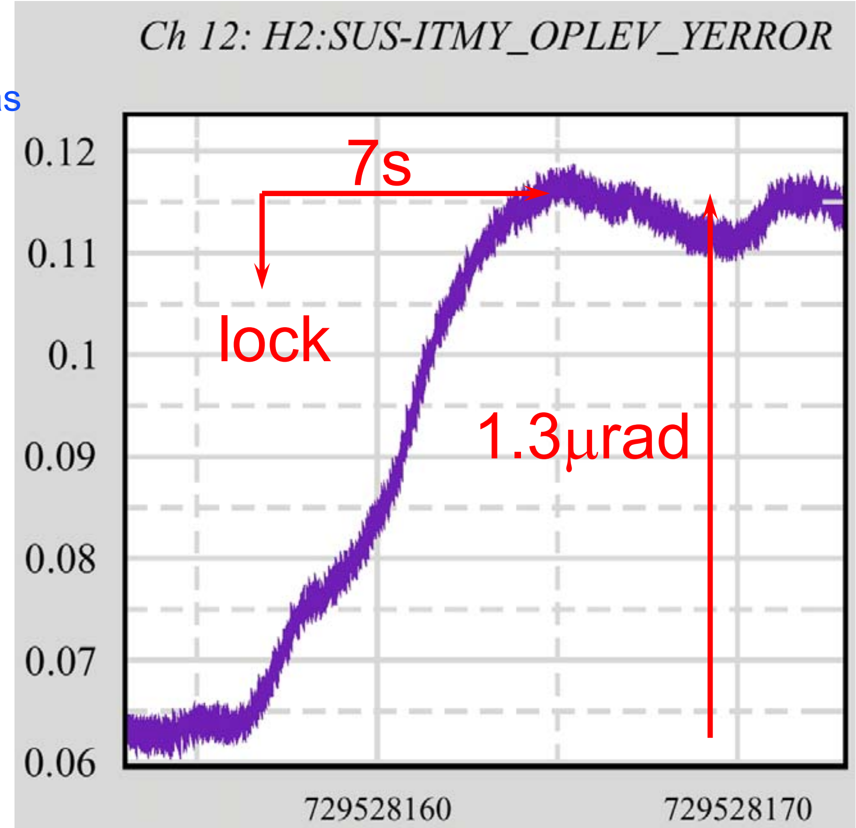
- *Design near complete; parts on order for January test on H1*

Effects of Radiation Pressure

- Not a small effect!
- Misaligned cavities & de-centered beams
  - Torque depends on alignment
- Strategy: modify controls
  - Powers and beam centroids already sensed
  - Enhanced alignment "Plant model " to include light as a dynamic mechanical component
  - Design calculations, code prototype under development

Mode cleaner length shift (2kW)





Arm cavity angular shift
2cm de-centering at 5kW

Summary

Over 4 decades sensitivity improvement since "first light"

Now within a decade of design sensitivity at 150 Hz

(of course, that's the longest mile!)

Tag-team commissioning strategy has helped turn burden of 3 concurrent machines into an advantage

Astrophysically interesting sensitivity on ALL 3 INSTRUMENTS

(and data rate's still ahead of analysis pipelines)

L1 Seismic Retrofit is crucial for improving uptime

Thermal Compensation, other high power upgrades to reduce noise

S4 run: longer duration, better uptime, and lower noise