Current LIGO Commissioning Activities

LIGO Seminar, Caltech

August 1, 2003

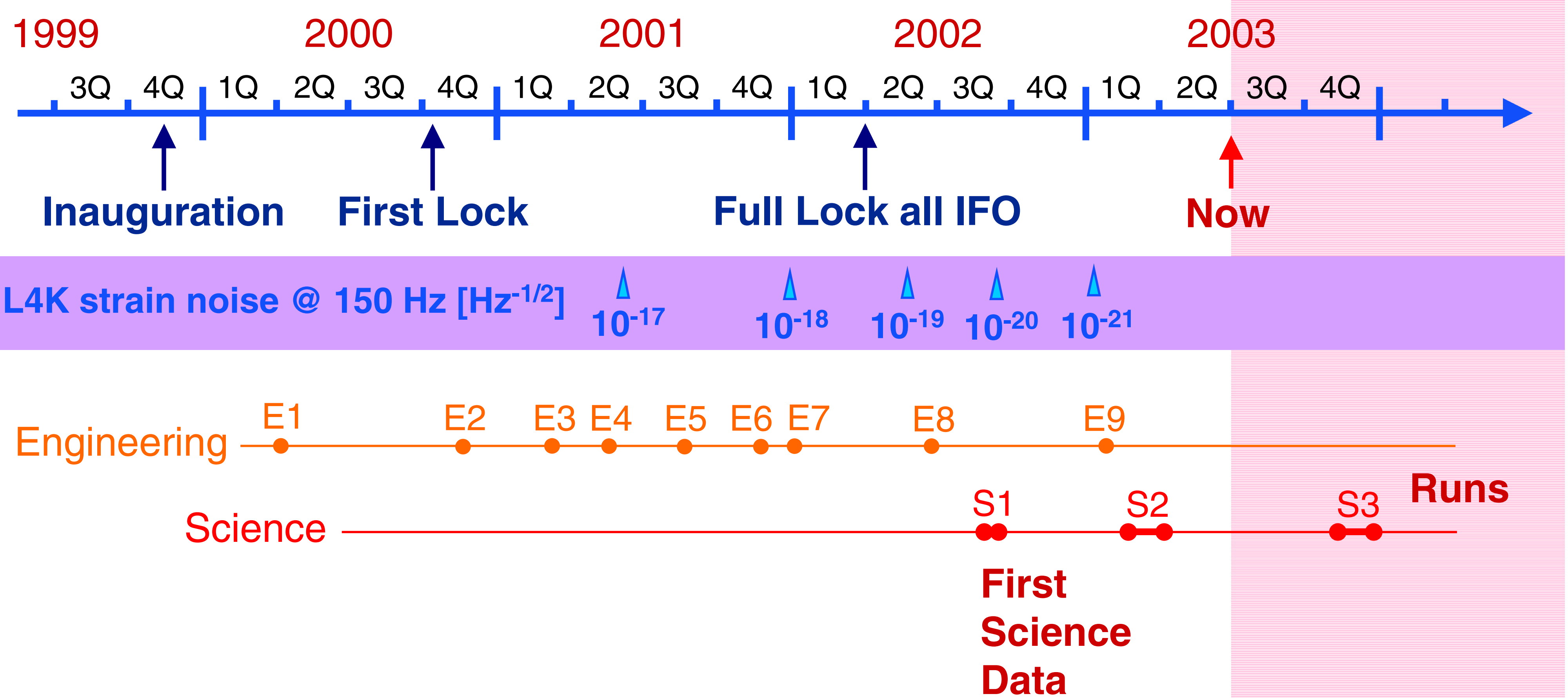
Daniel Sigg, LIGO Hanford Observatory

Aerial View of the LIGO Sites

LIGO Hanford Observatory

LIGO Livingston Observatory

Time Line

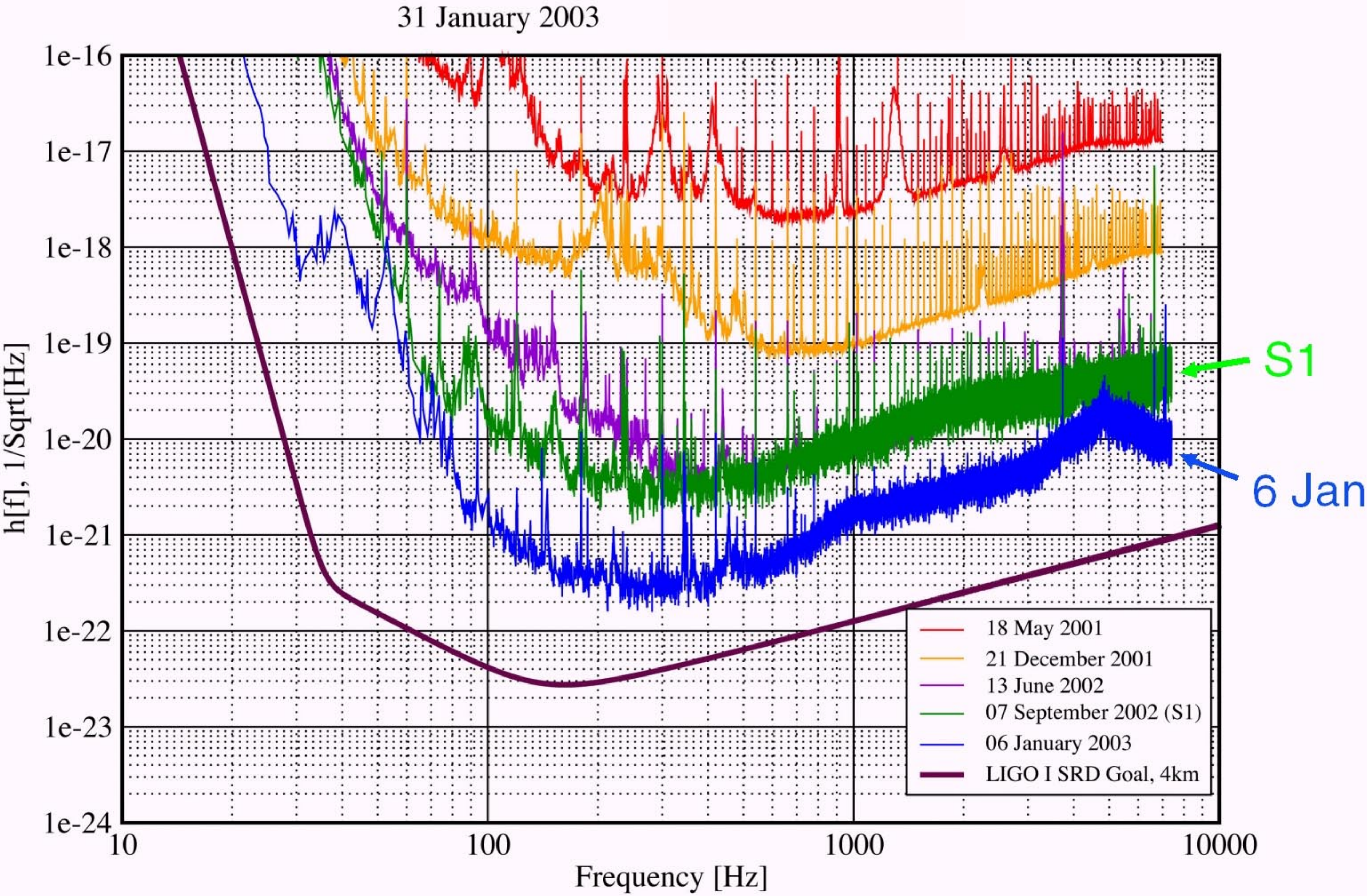


1999
2000
2001
2002
2003
3Q 4Q 1Q 2Q 3Q 4Q 1Q 2Q 3Q 4Q 1Q 2Q 3Q 4Q 1Q 2Q 3Q 4Q
Inauguration
First Lock
Full Lock all IFO
Now
L4K strain noise @ 150 Hz [Hz^-1/2]
10^-17
10^-18
10^-19
10^-20
10^-21
Engineering
E1
E2
E3
E4
E5
E6
E7
E8
E9
Science
S1
S2
S3
Runs
First Science Data

Major Achievements in the Last 2 Years

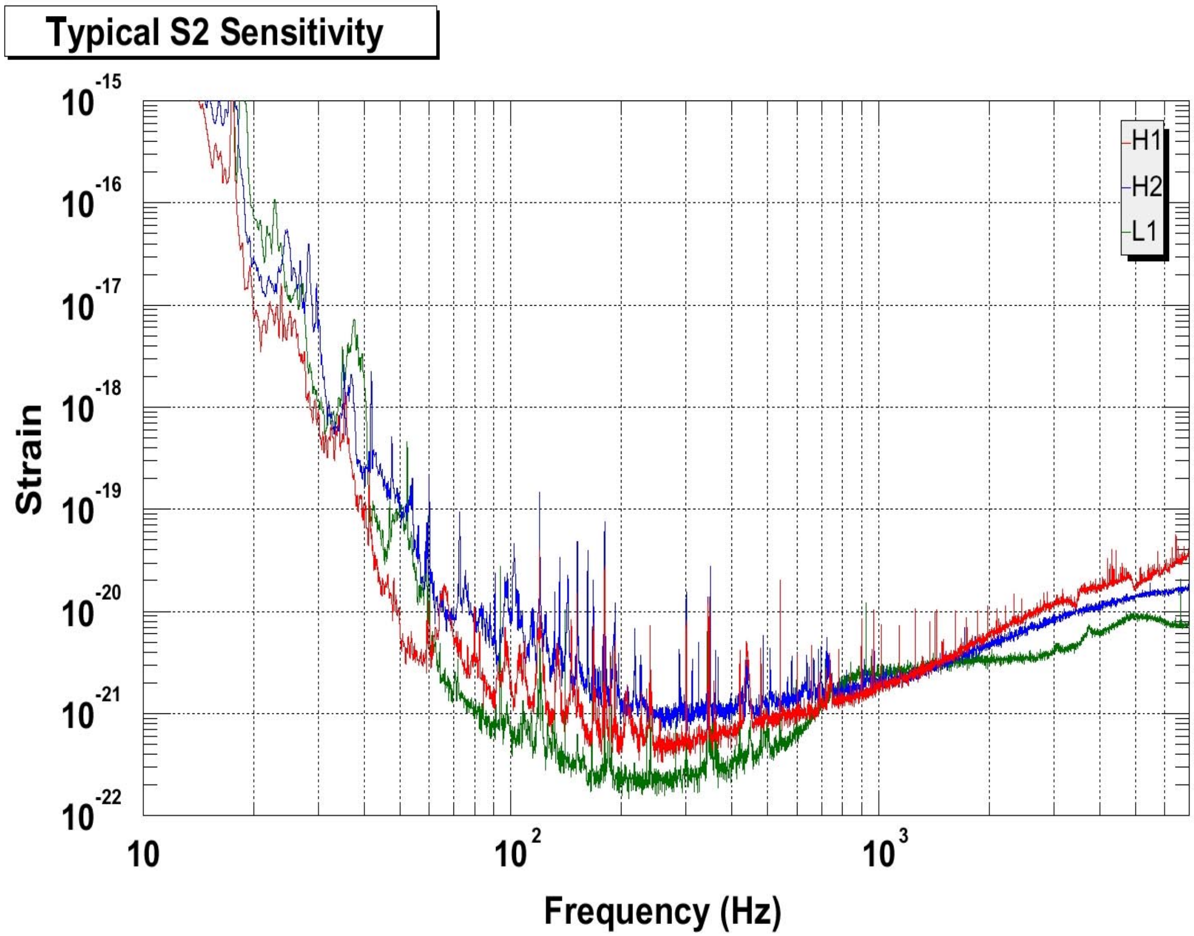
- Four orders of magnitude improvement in sensitivity (at 150Hz)
- All 3 interferometers operate routinely in power-recycled mode
  - Kilowatts in the arm cavities
  - Common mode control to the laser
  - Auto-alignment system / Optical levers for local damping
  - Great improvements in digital controls
    - Digital suspension controller
- First science data

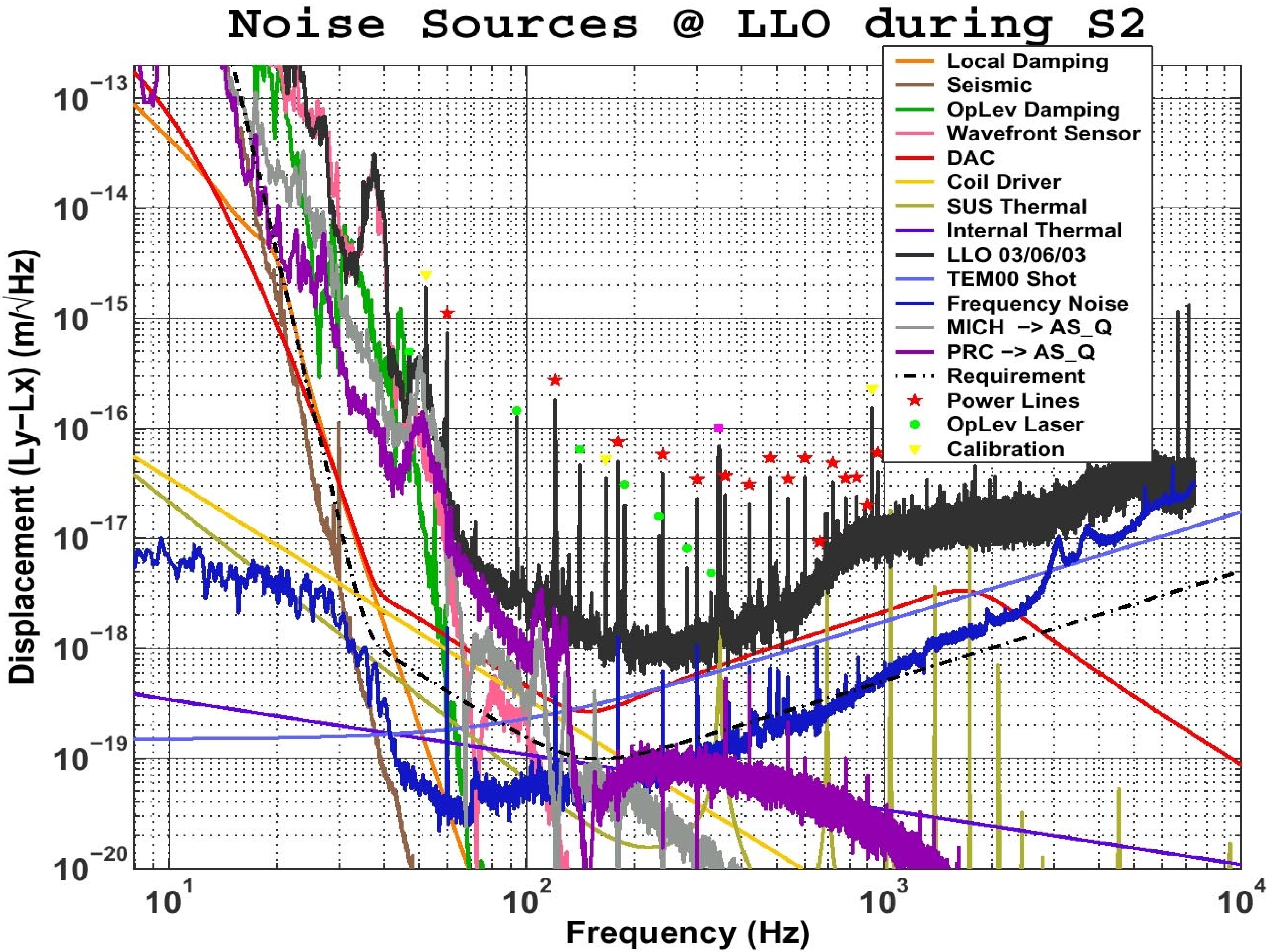
Strain Sensitivity for the LLO 4km Interferometer



2nd Science Run

- Inspiral Sensitivity
  - L1: ~900 kpc
  - H1: ~350 kpc
  - H2: ~200 kpc
- Duty cycle
  - L1: 37%
  - H1: 74%
  - H2: 58%
  - Triple: 22%




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}

Goals for Next Science Runs

- Low frequency noise
  - Reduce acoustic couplings (S3)
  - Reduce noise from auxiliary degrees-of-freedom (S3)
- High frequency noise
  - More light to reduce shot noise (S3)
  - Thermal compensation to make recycling cavity stable (S4)
- Duty cycle
  - Full alignment control (S3)
  - Develop seismic pre-isolator for LLO (S4)

List of Tasks (1)

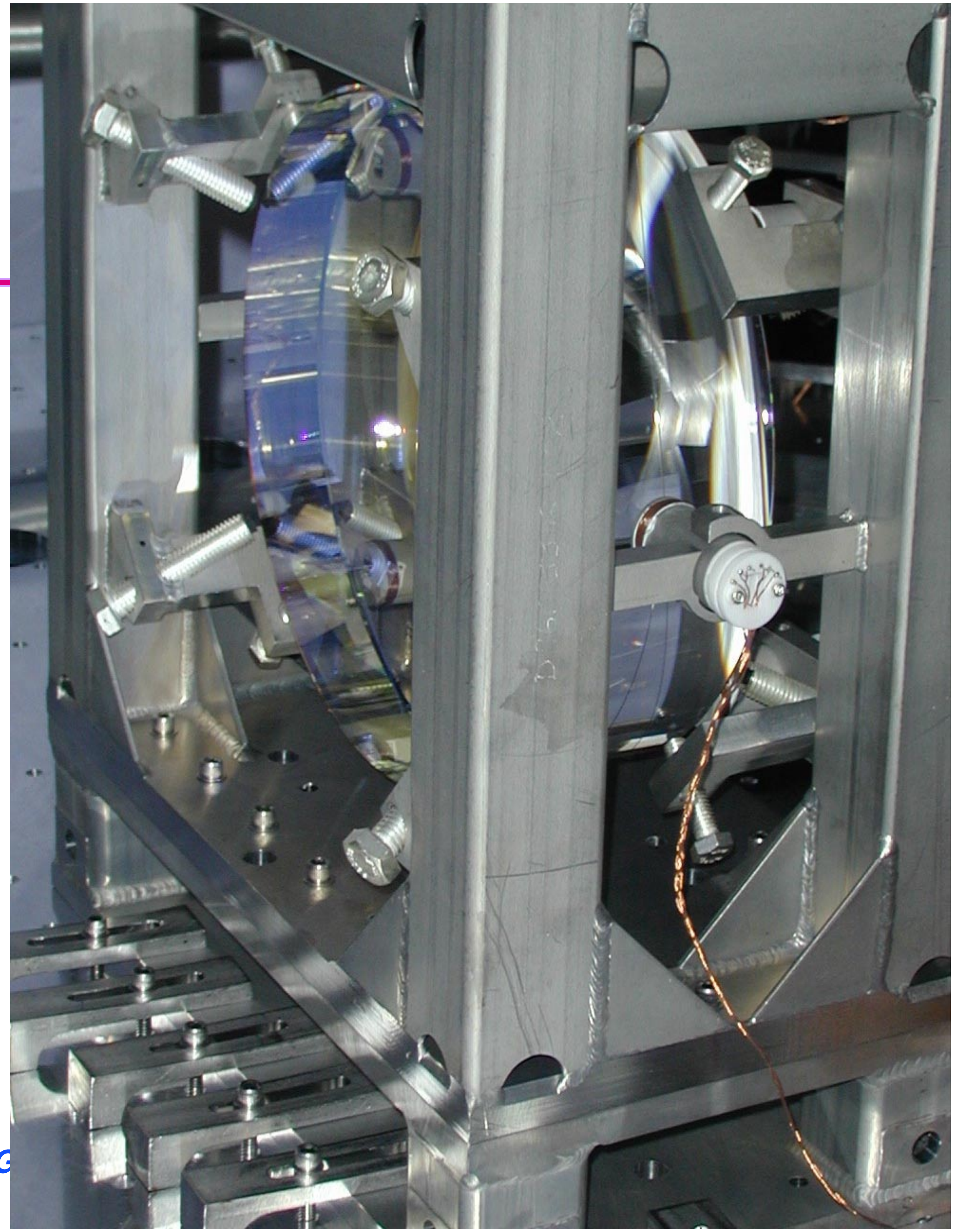
- Investigate thermal lensing
- Optical gain increase of LSC photodiodes
- Reduce acoustic coupling
- Improve shot noise sensitivity
- Finish auto-alignment system
- Initial Alignment (WFS5)
- Seismic retrofit at LLO
- 2K ITMX replacement
- Fix Schnupp asymmetry
- Fix LLO recycling cavity length

List of Tasks (2)

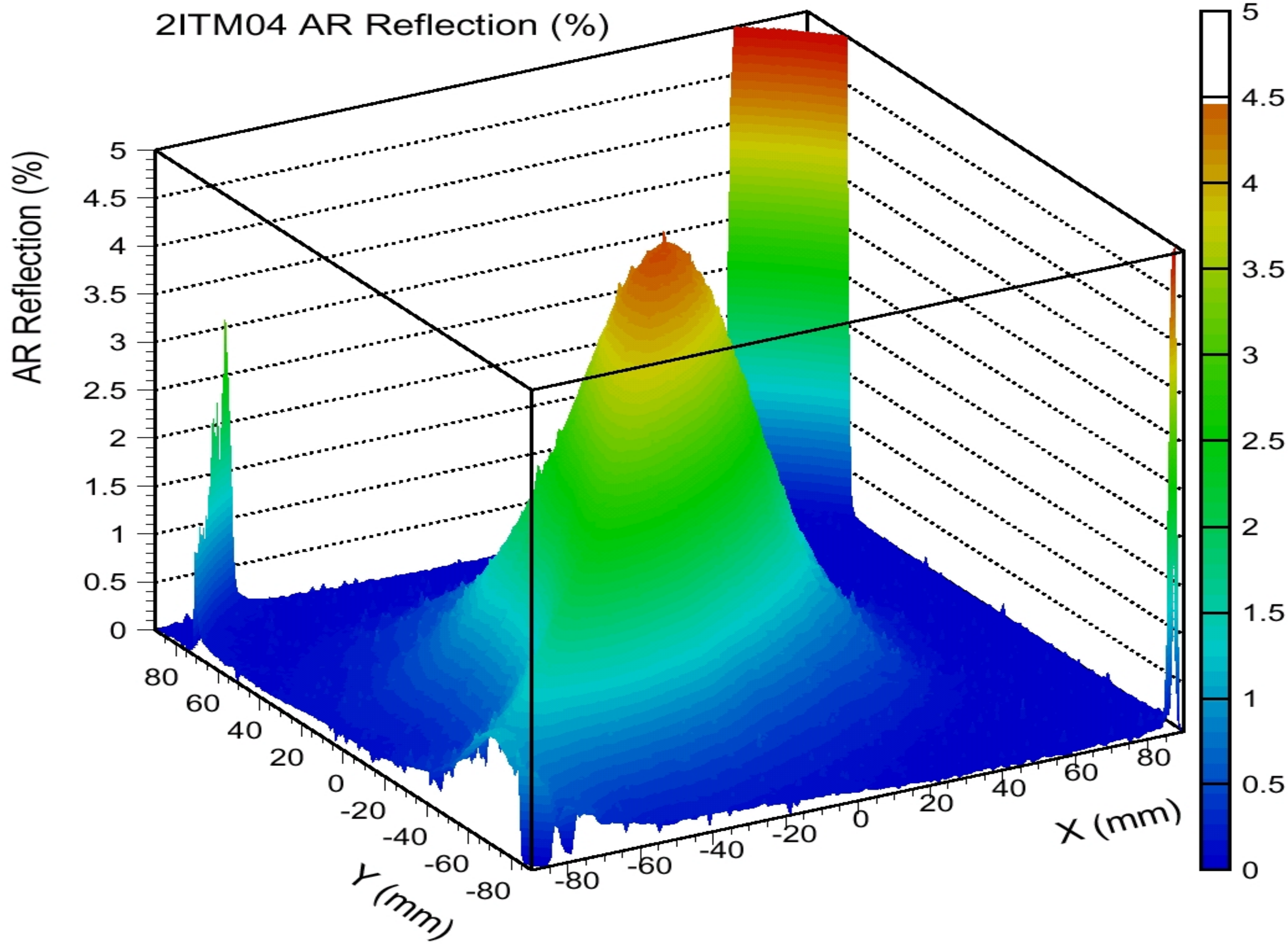
- Tune laser, replace lossy pre-mode cleaner
- Install remote power dial
- Improve laser power stabilization
- Finish ν stabilization servos
- Reduced quadrature signal (ASI servo)
- Digital IO alignment system
- Add more length sensing channels
- RFI cleanup: linear power supplies
- Install atomic clocks for timing diagnostics
- Photon calibrator

Optics

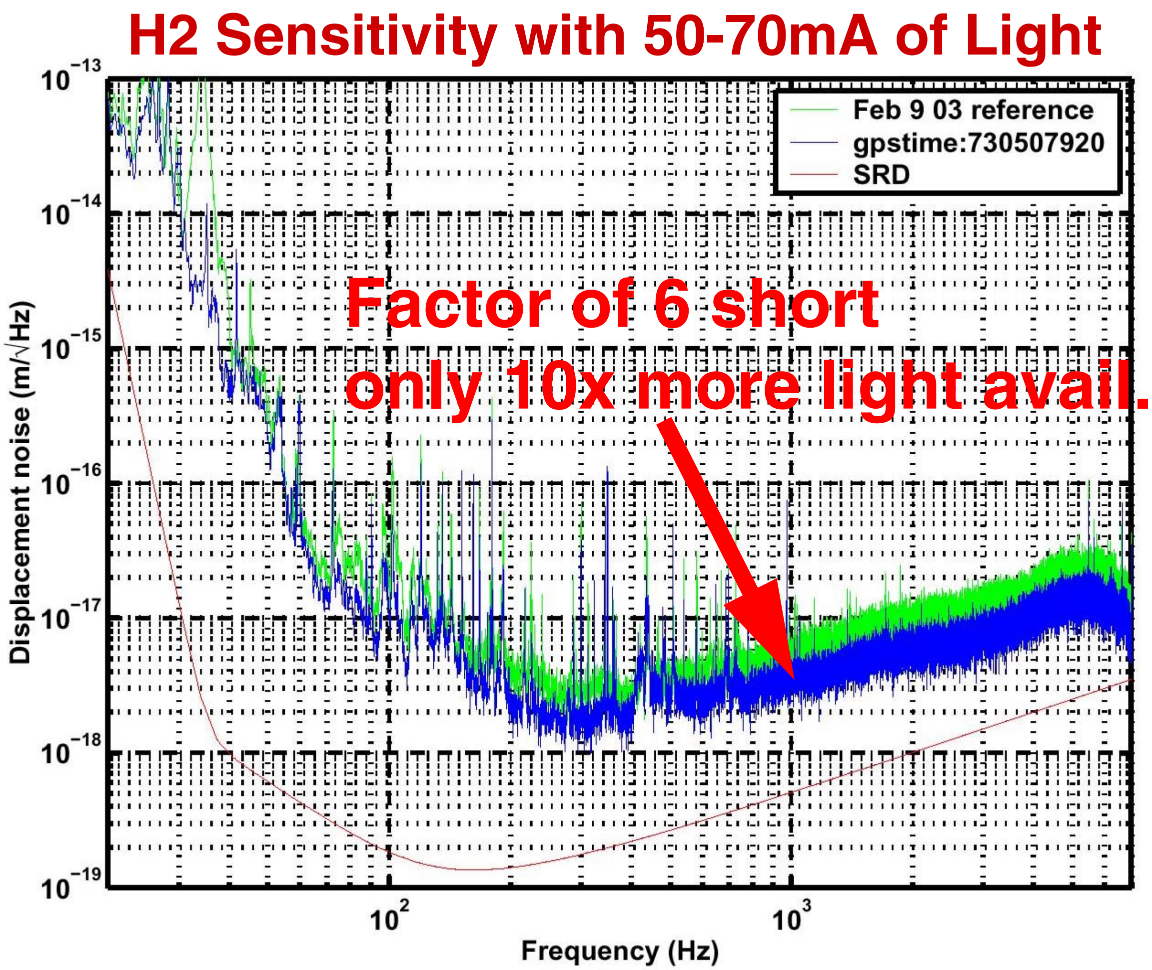
- Optics quality is (almost all) good
- Recycling gain meets or exceeds goals
  - L1: Gain of 45- 50 seen
  - H1: Gain of 40-45
  - H2: Cause of low recycling gain (20) found and fixed
- Contrast defect meets or exceeds goals
  - L1: $P_{as}/ P_{bs} = 3 \times 10^{-5}$
  - H1: $P_{as}/ P_{bs} = 6 \times 10^{-4}$



2 ITMX Anti-Reflective Coating



High Power Operations

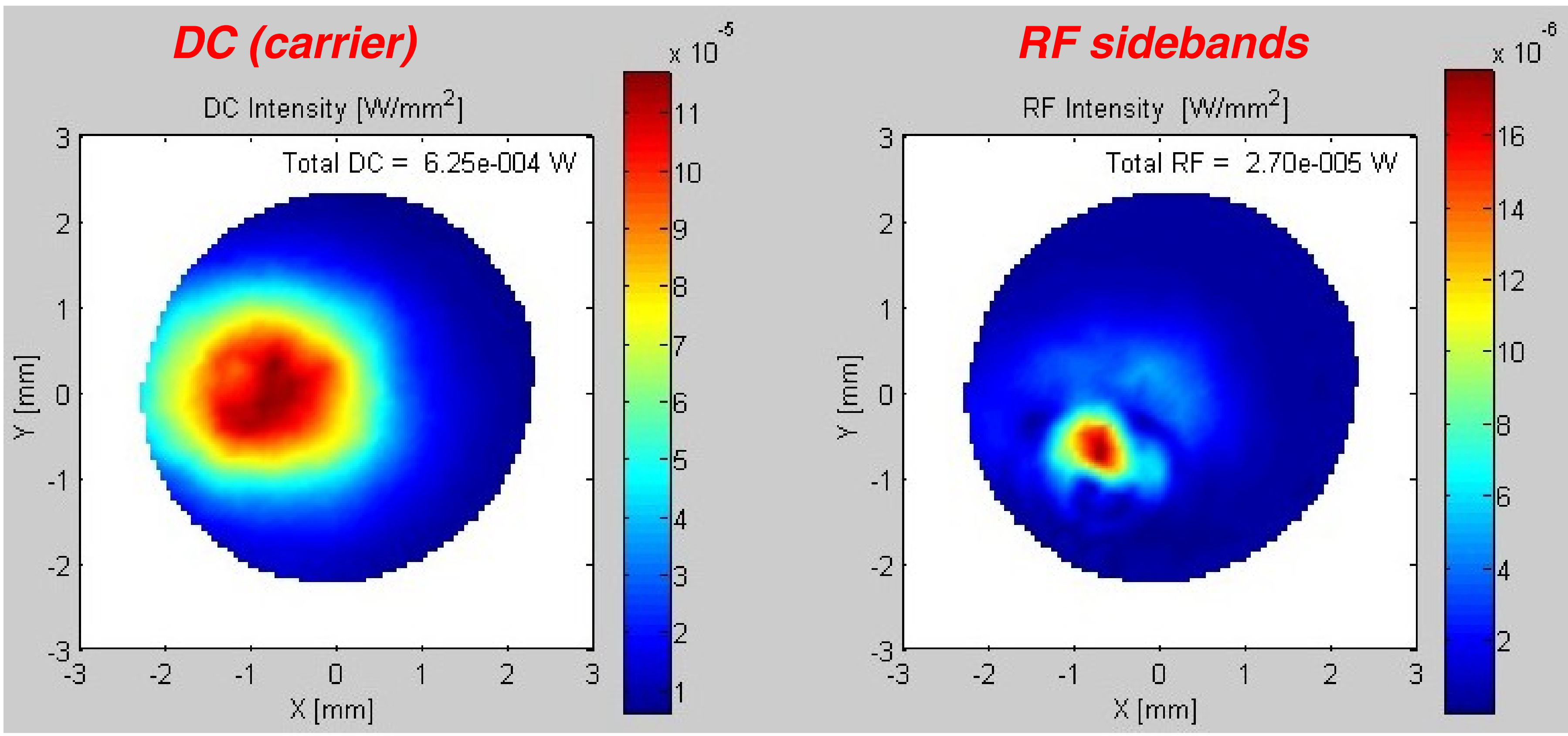


- Dynamic range problem: 1000x
- Signal in wrong quadrature dominant!
- Use multiple detectors at anti-symmetric port
- Need protection for photodetectors
- Need protection for suspension wires!

Recycling Cavity Degeneracy

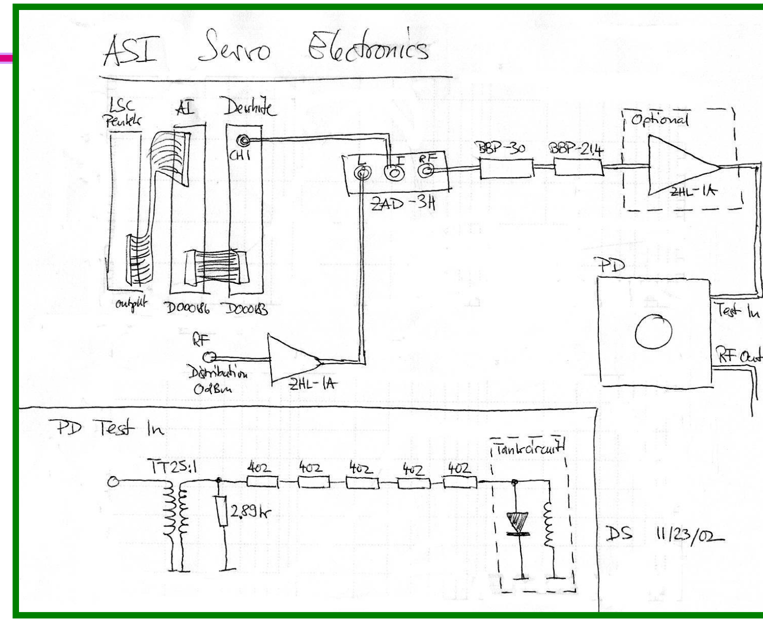
- RF sideband efficiency is very low
  - H1 efficiency: ~6% (anti-symmetric port relative to input)
  - lack of ITM thermal lens makes $g_1 \cdot g_2 > 1$ (unstable resonator)

Bad mode overlap!

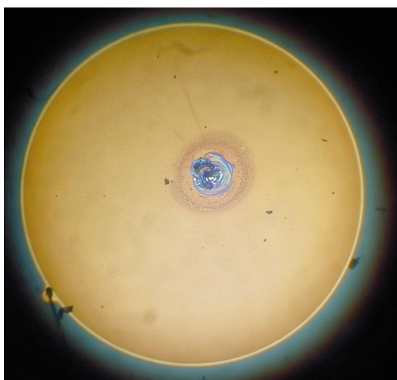


Optical Gain Increase for LSC Photodiodes

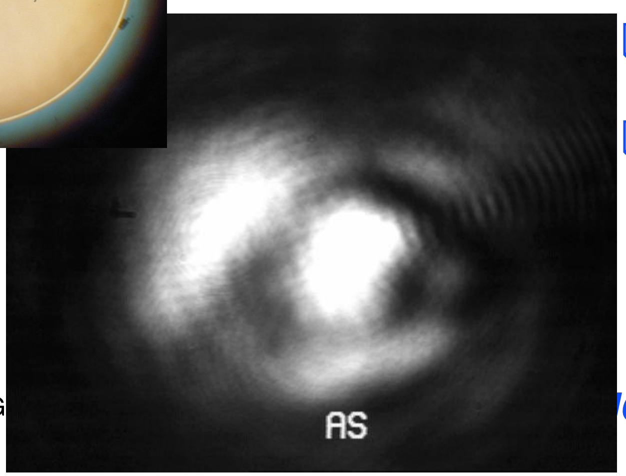
- Dynamic range problem: 1000x
  - Locking ~100 μA / running ~100 mA
  - Separate PDs for locking (low power) and running (high power)
  - Remote dial for laser power



ASI Servo

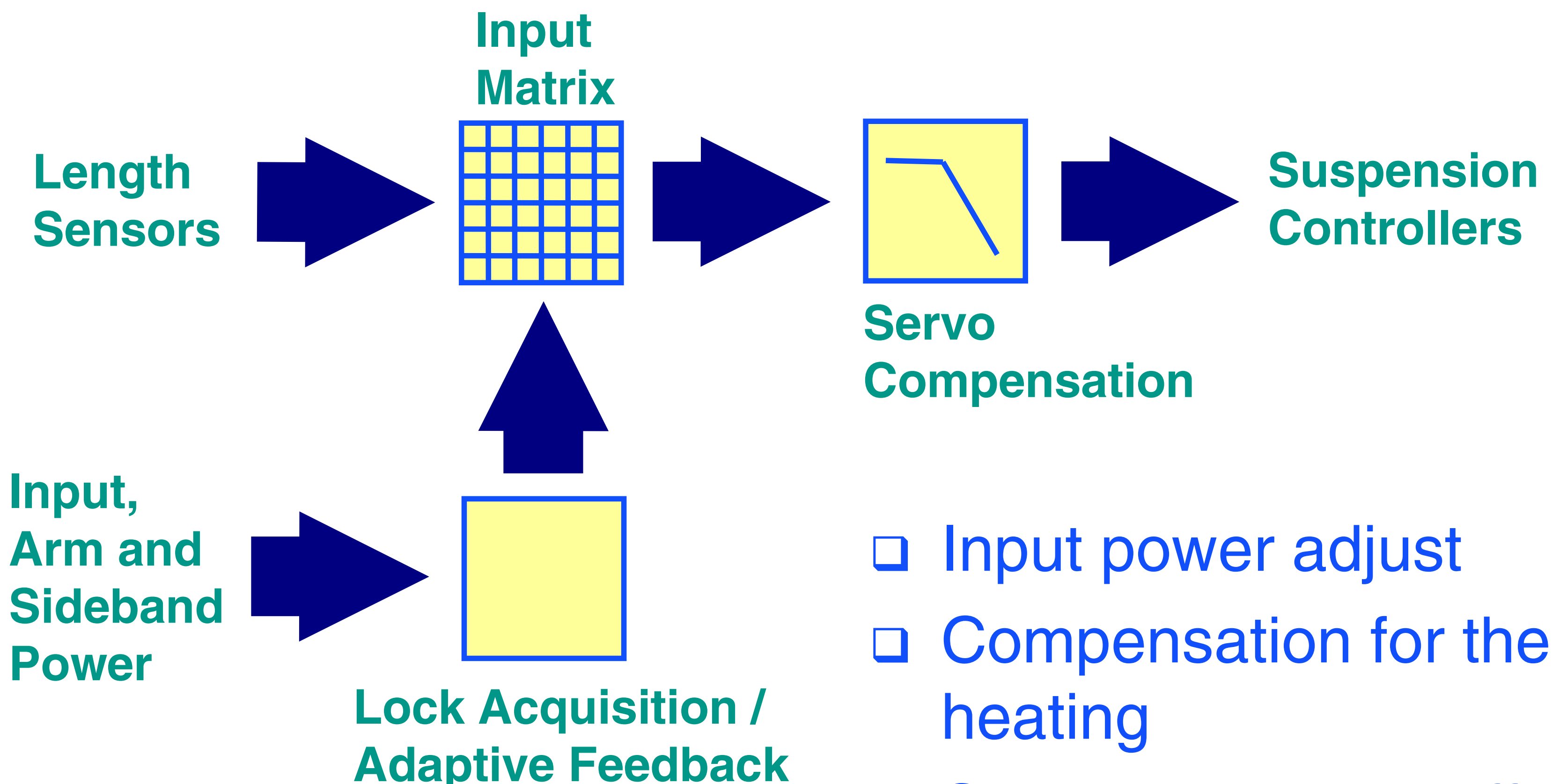


AS Port



- **AS quadrature signal dominant!**
- Multiple AS port detectors
  - H1: P_{AS} = 500-600 mW ⇨ 4 detectors
  - L1: P_{AS} = ~20-30 mW ⇨ 1 detector

Adaptive Feedback Control for Power Increase

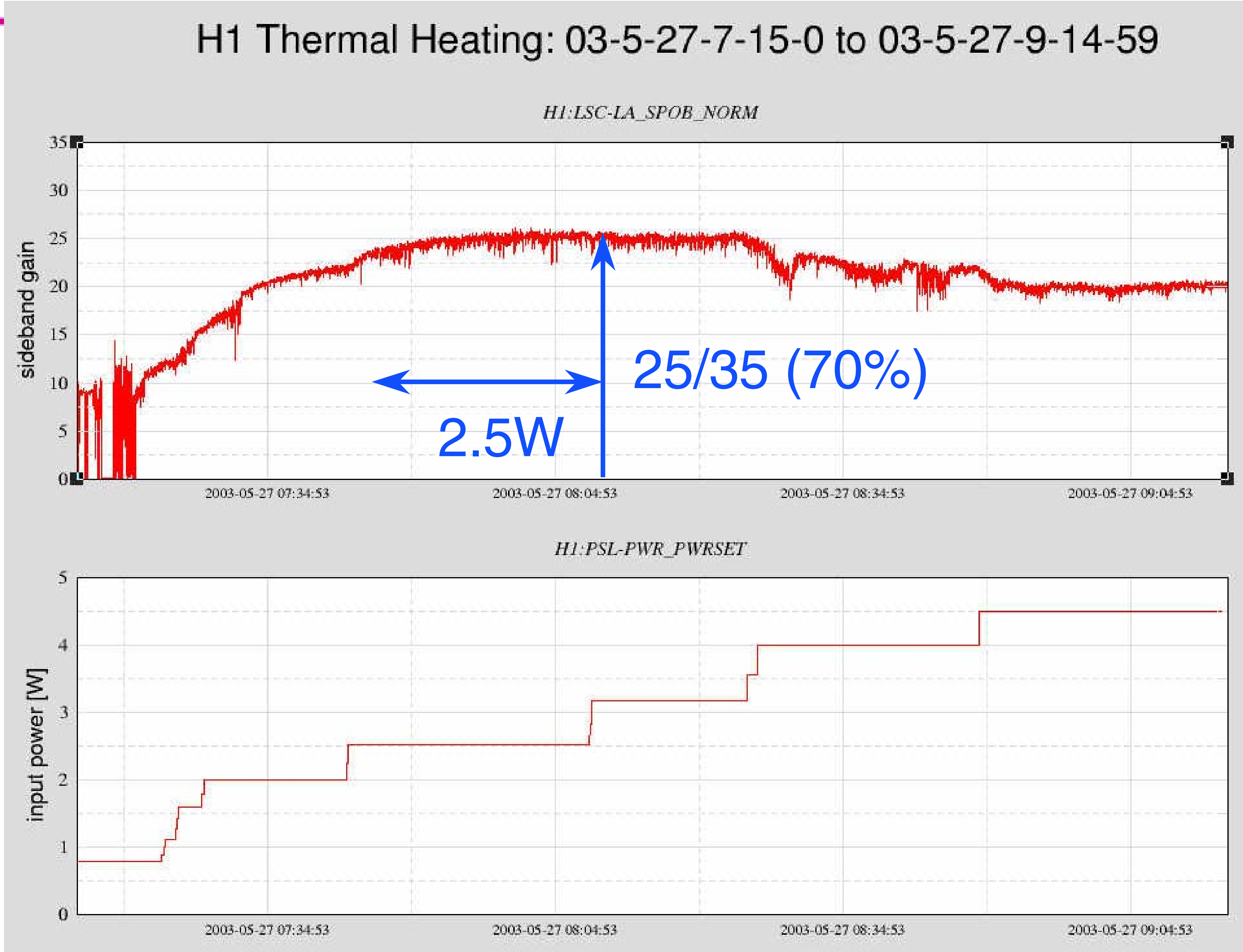


- Input power adjust
- Compensation for thermal heating
- Spatial overlap coefficients

Thermal Lensing

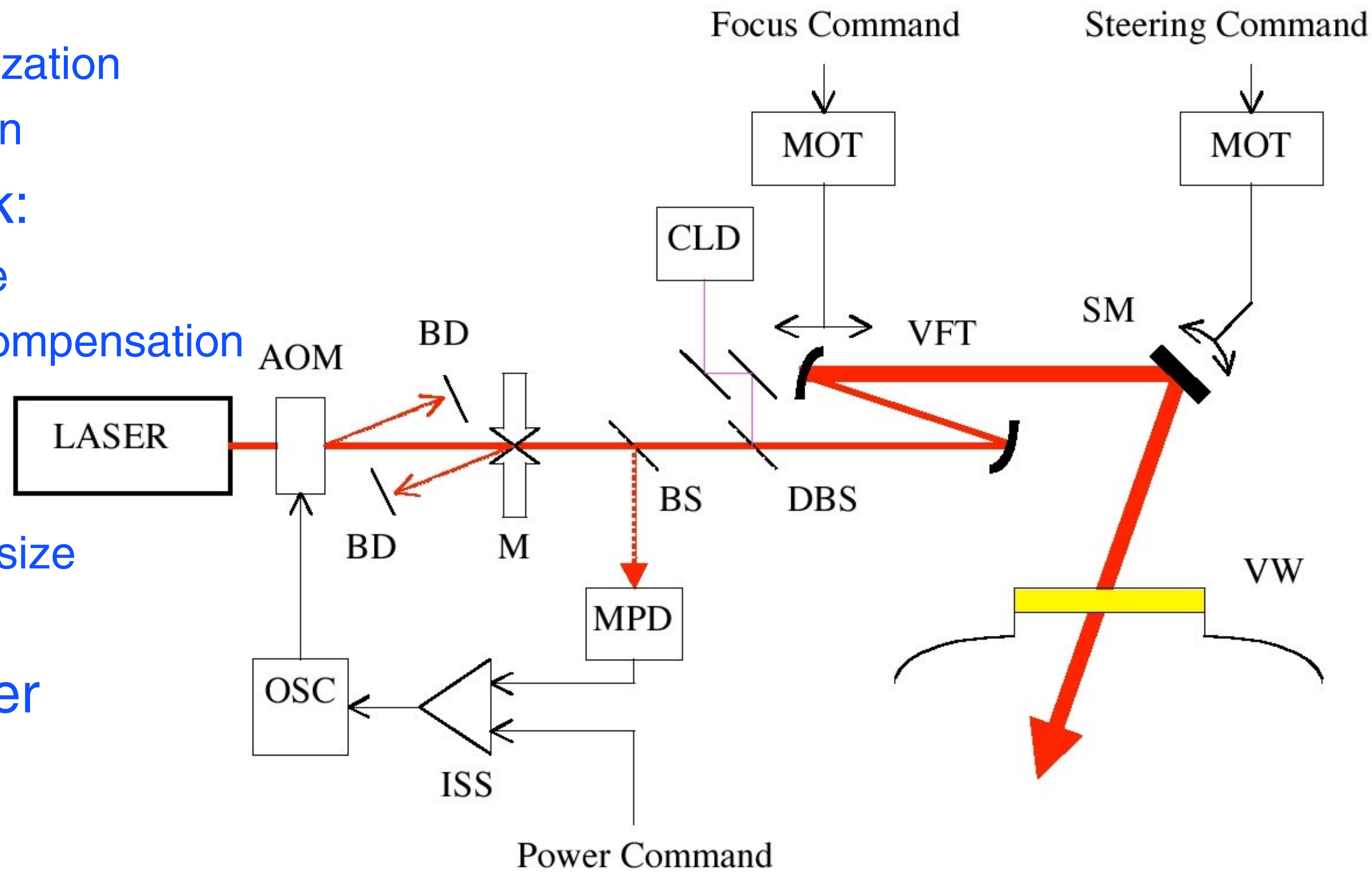
No mode overlap improvements seen at AS port!?

H2/L1: Thermal Compensation



Thermal Compensator Proposal

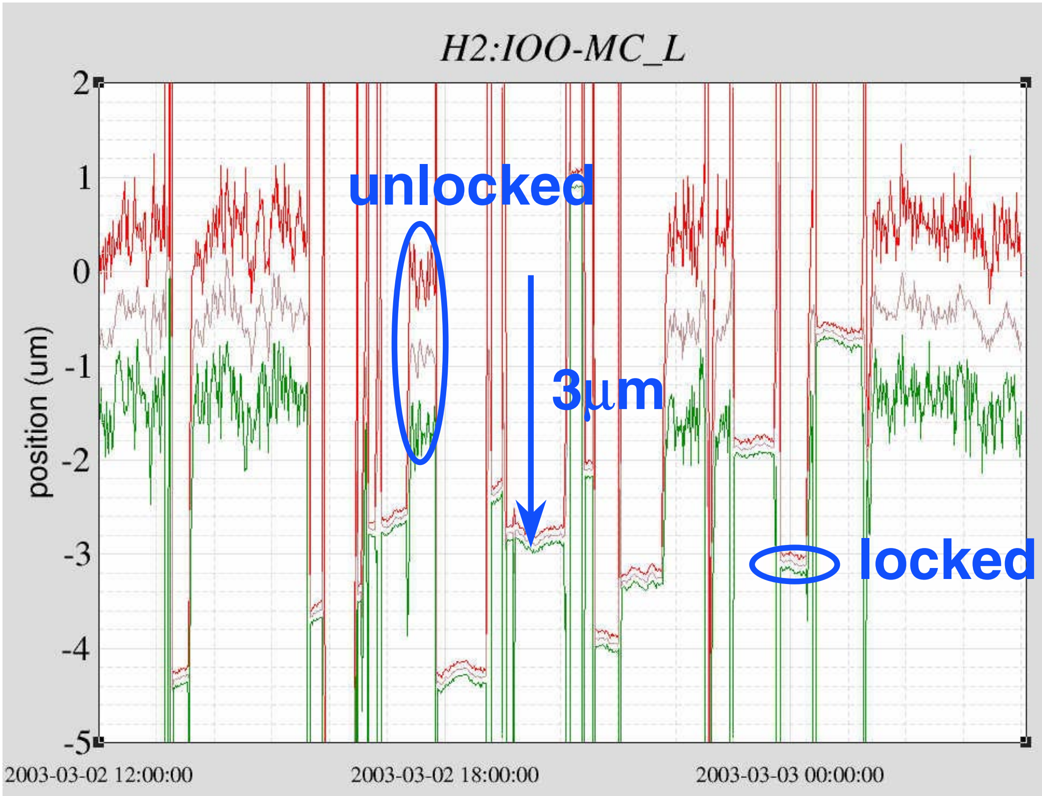
- Laser: 10-30W CW TEM_{00} CO_2 (10.6μm)
- Ge AOM:
  - Intensity stabilization
  - Power selection
- Reflective mask:
  - Intensity profile
  - Astigmatism compensation
- Relay optics:
  - Adjust focus
  - Adjust pattern size
  - Adjust position
- Visible pilot laser

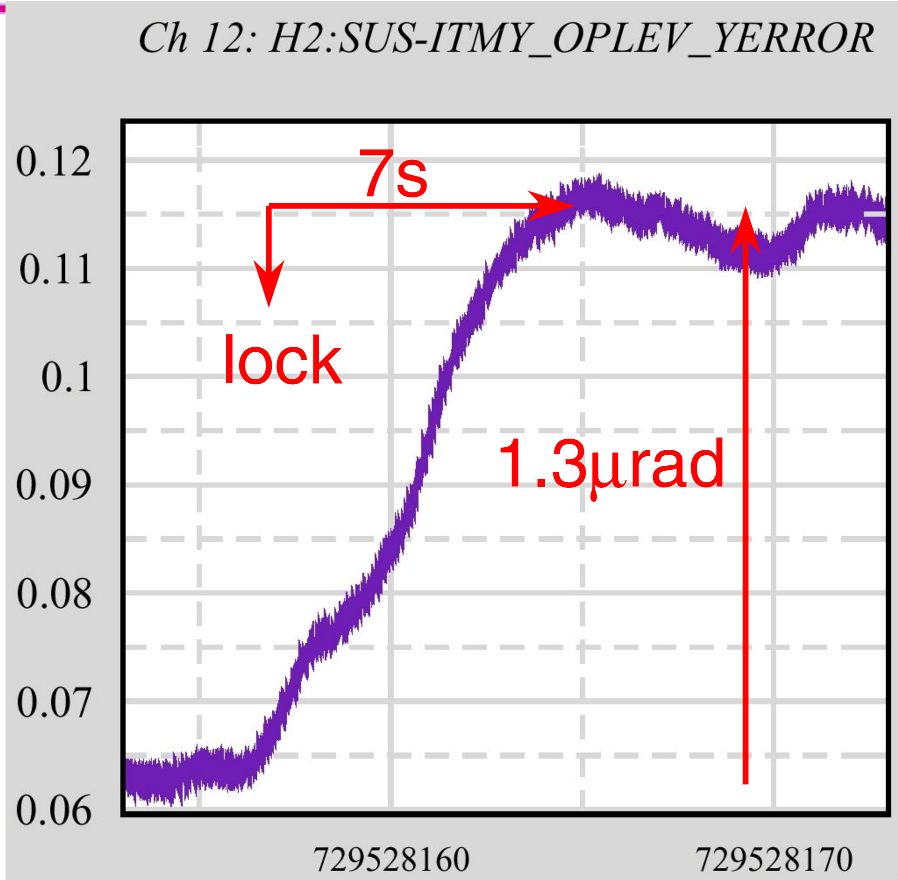


Radiation Pressure

- Not a small effect!

Mode cleaner length shift (2kW)

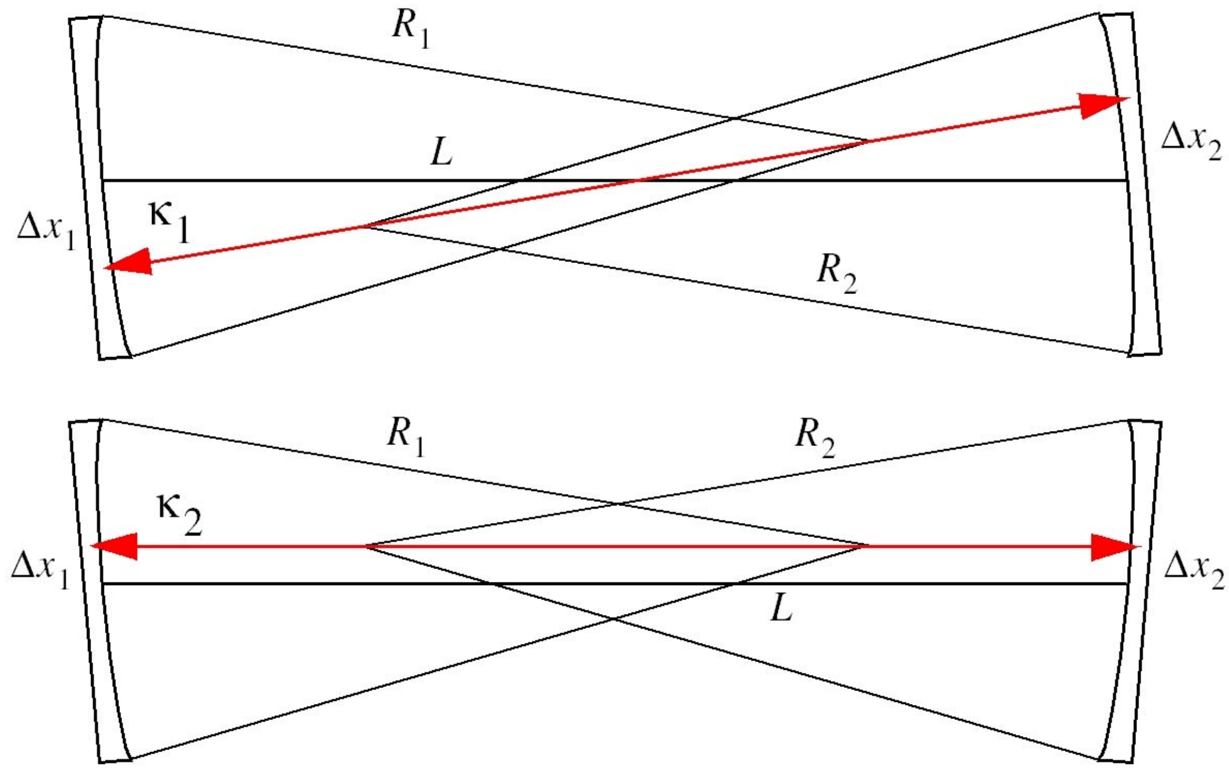




Arm cavity angular shift
2cm de-centering at 5kW

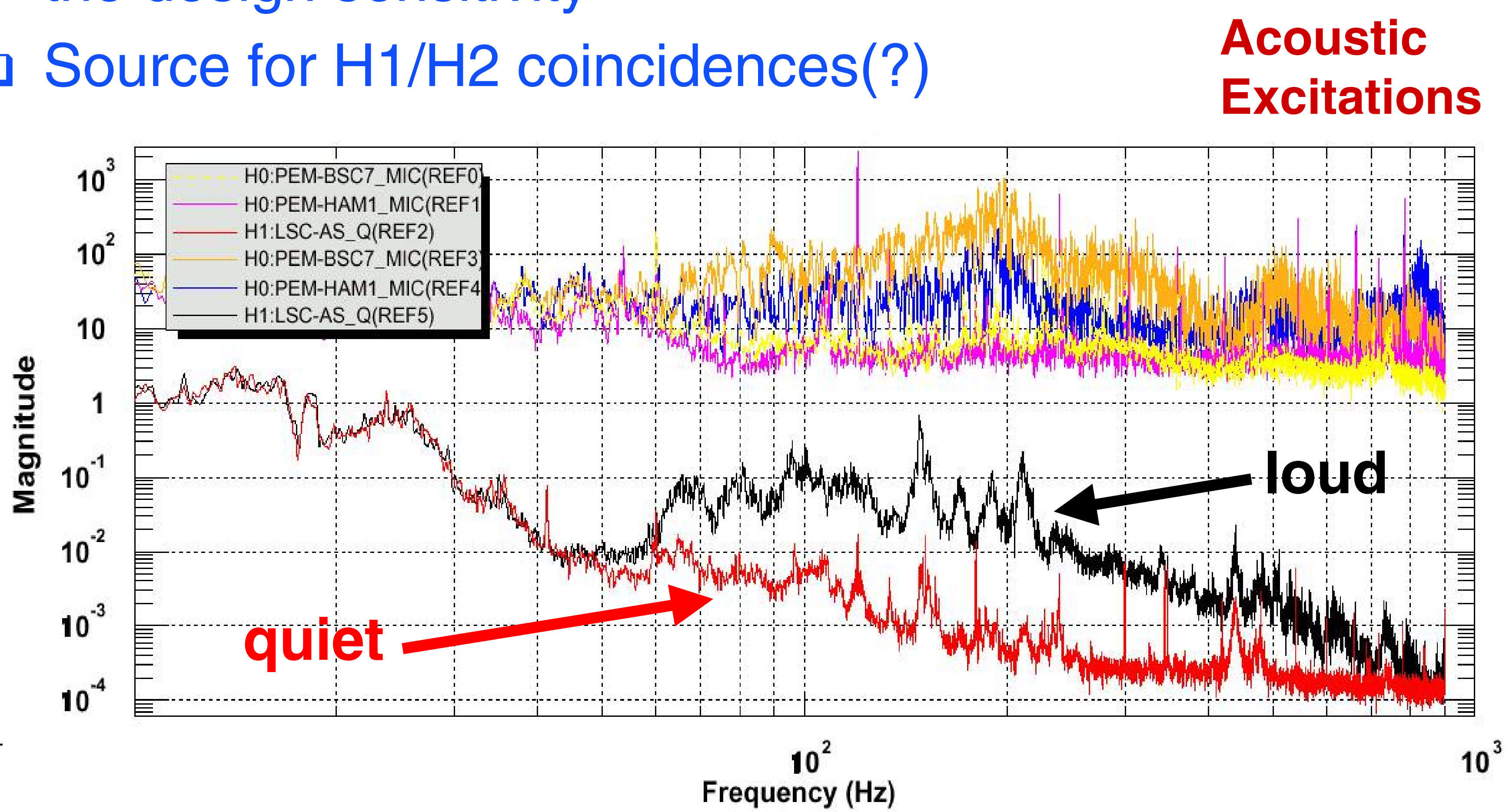
Alignment Instabilities in High Power Optical Cavities

- Misaligned cavity & de-centered beams
  - Torque depends on alignment
- Purely geometrical
  - Misalignment displaces beams on optics
  - Torque depends on alignment



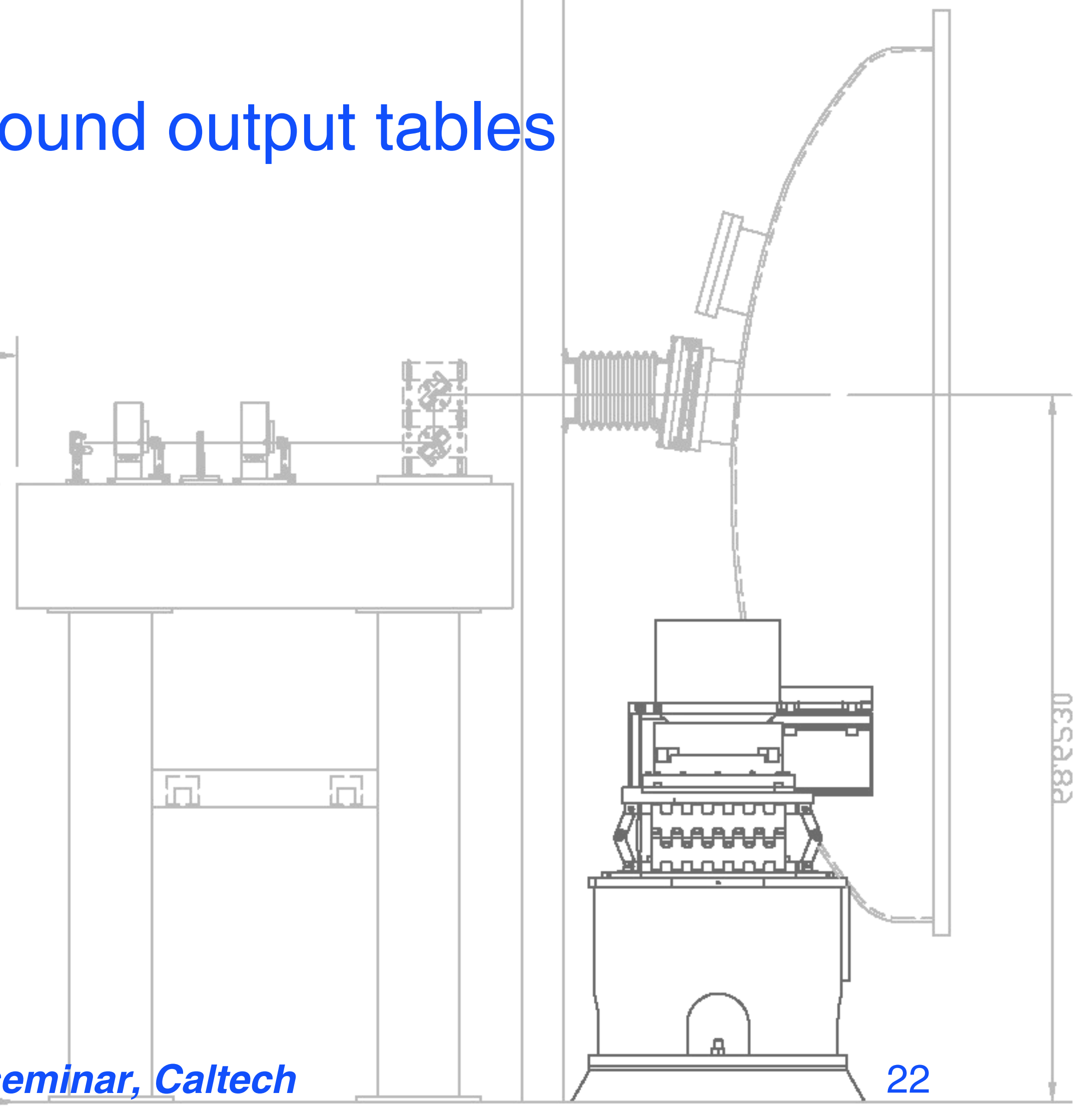
Acoustic Noise Coupling

- Peaks occur in 80-1000 Hz band, at a level 10-100x the design sensitivity
- Source for H1/H2 coincidences(?)



Acoustic Mitigation

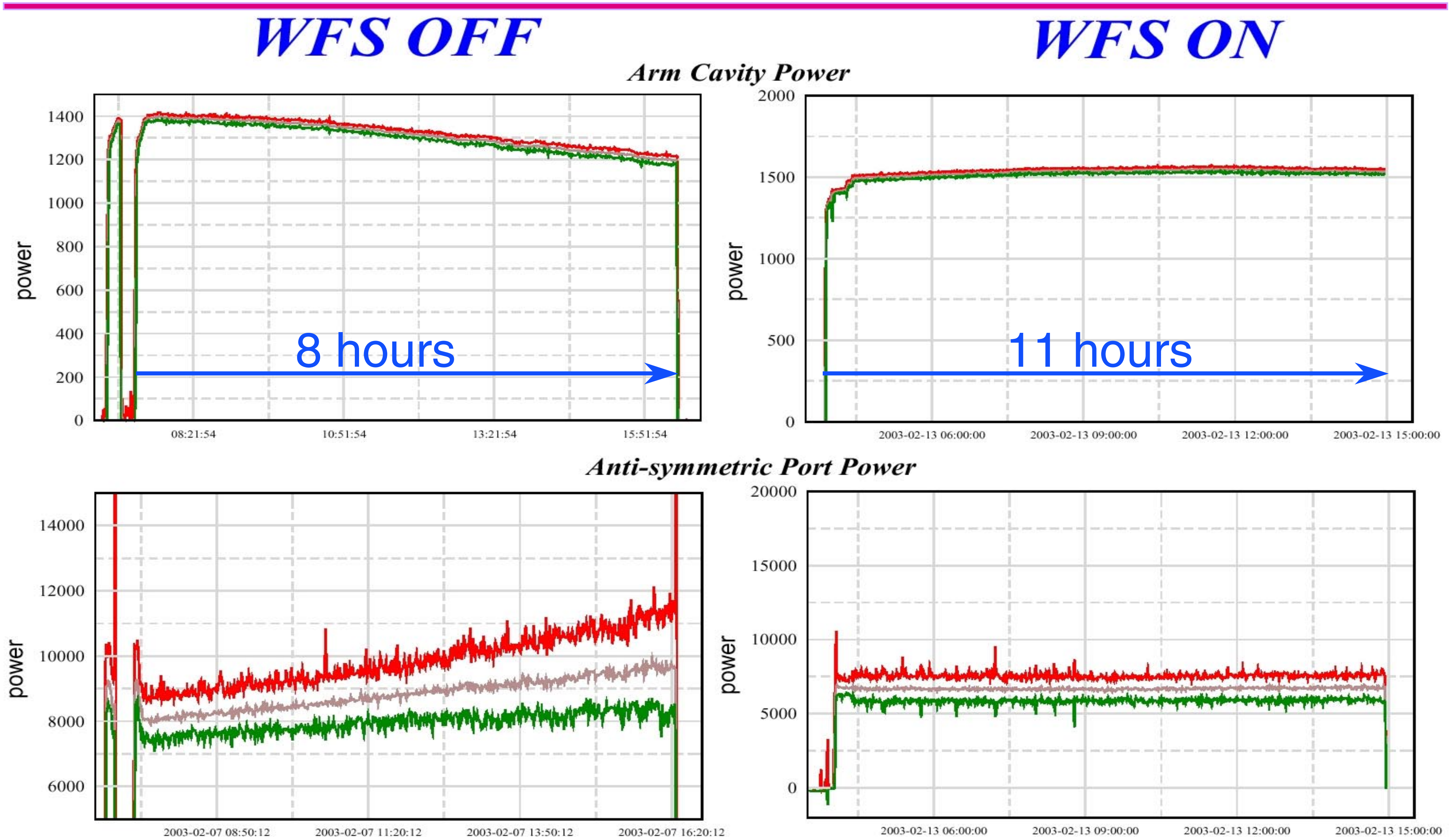
- Acoustic enclosures around output tables
- Reduce couplings
  - Float optics tables
  - Simplify beam path
  - New stiffer periscope
- Reduce source
  - Muffle fan noise at electronics crates
  - Racks on isolation legs
  - Move racks
  - Reduce HVAC noise
  - Insulate mechanical room



Output Mode Cleaner(?)

- Small fixed spacer triangular cavity
  - Thermally controlled
  - In vacuum on seismic isolation
- Advantages:
  - Reduces light level (higher order modes are filtered out)
  - Solves acoustic coupling problem
  - Reduces fringe offsets coming from higher order modes
  - Reduces back scattering problems
  - Most likely reduces quadrature signal problem
- Disadvantages:
  - Fairly huge effort!
  - Photodetectors not readily accessible, must be vacuum compatible
  - Thermal control slow to acquire

Auto-Alignment System

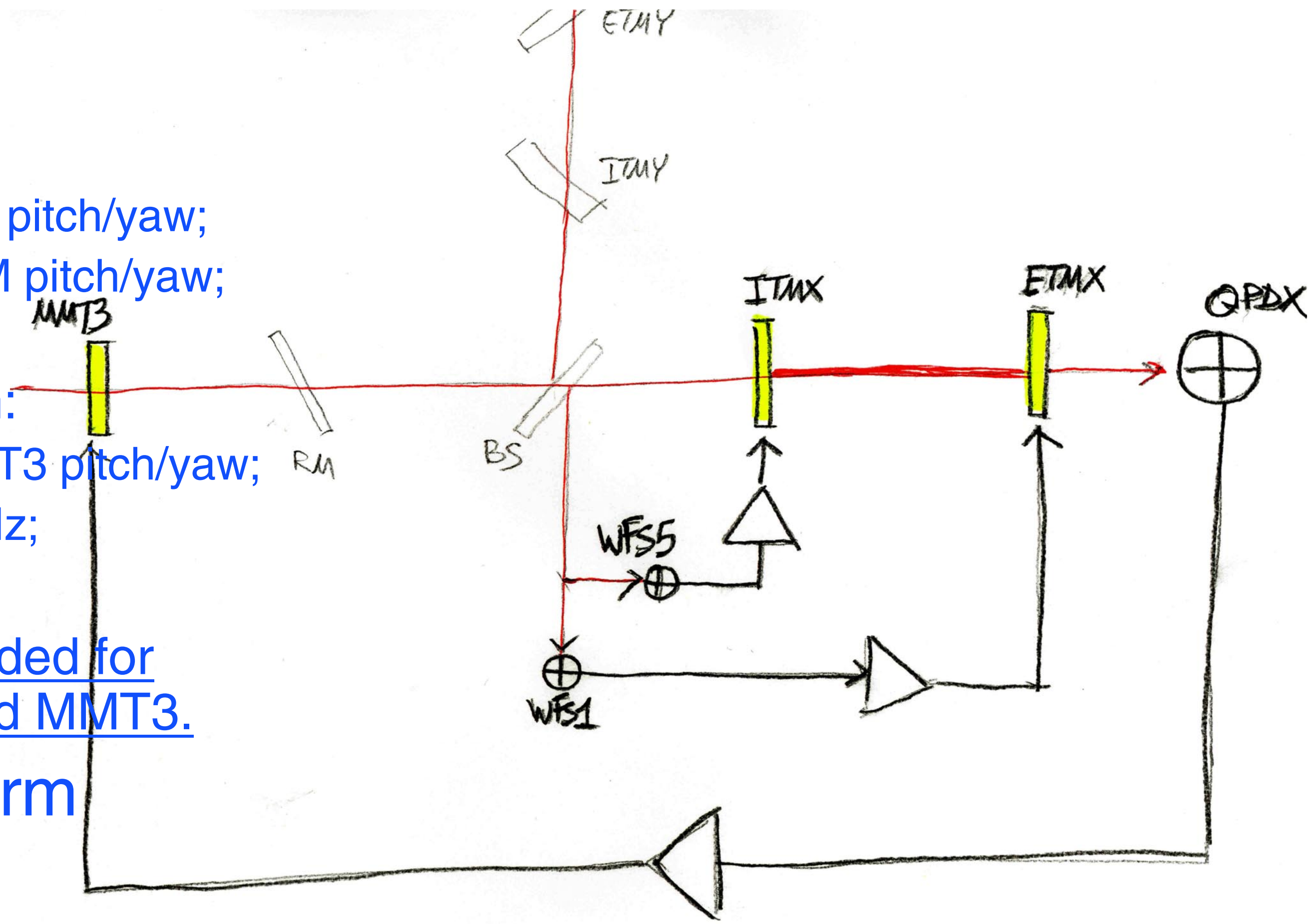


Initial Alignment Using Wavefront Sensors

Step 1:

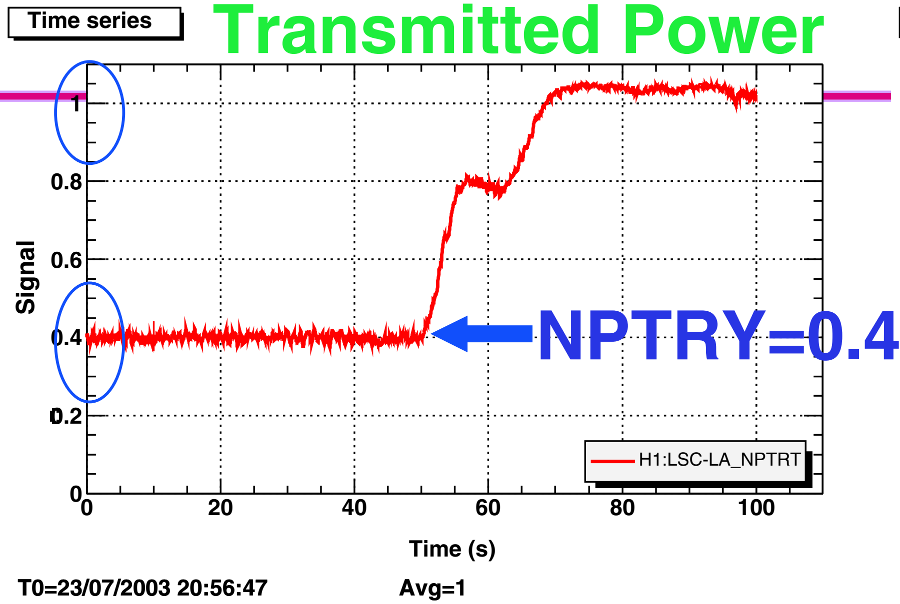
1. Lock X-Arm;
2. Lock cavity axis:
   - WFS5 -> ITM pitch/yaw;
   - WFS1 -> ETM pitch/yaw;
   - UGF ~1Hz;
3. Lock input beam:
   - QPDX -> MMT3 pitch/yaw;
   - UGF ~100mHz;
4. WFS relief;
5. TM biases recorded for ETMX, ITMX and MMT3.

- Step 2: other arm

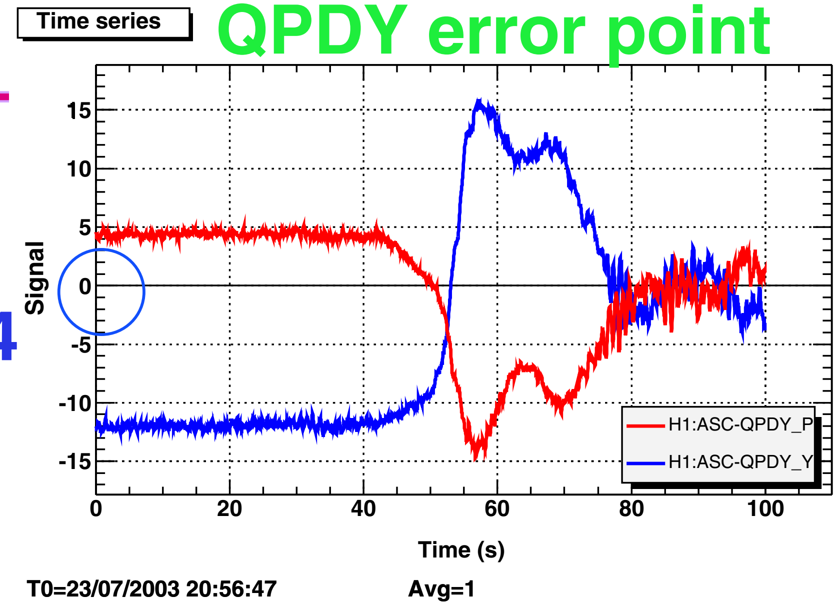


Initial Alignment: Results for Y Arm

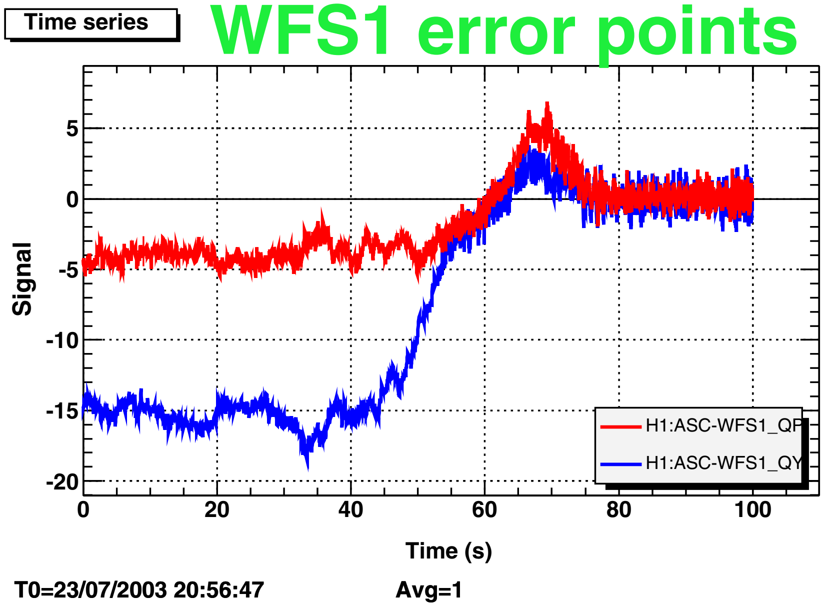
Transmitted Power



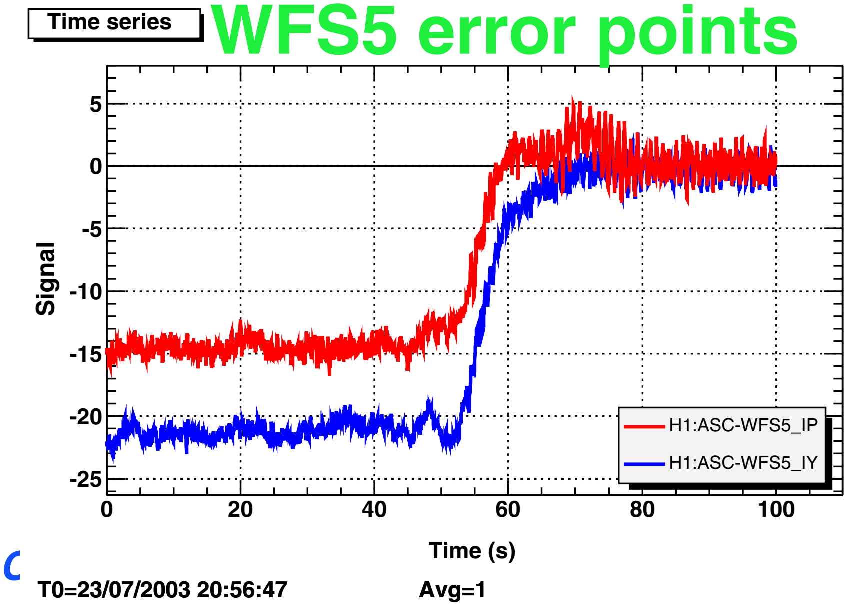
QPDY error point



WFS1 error points

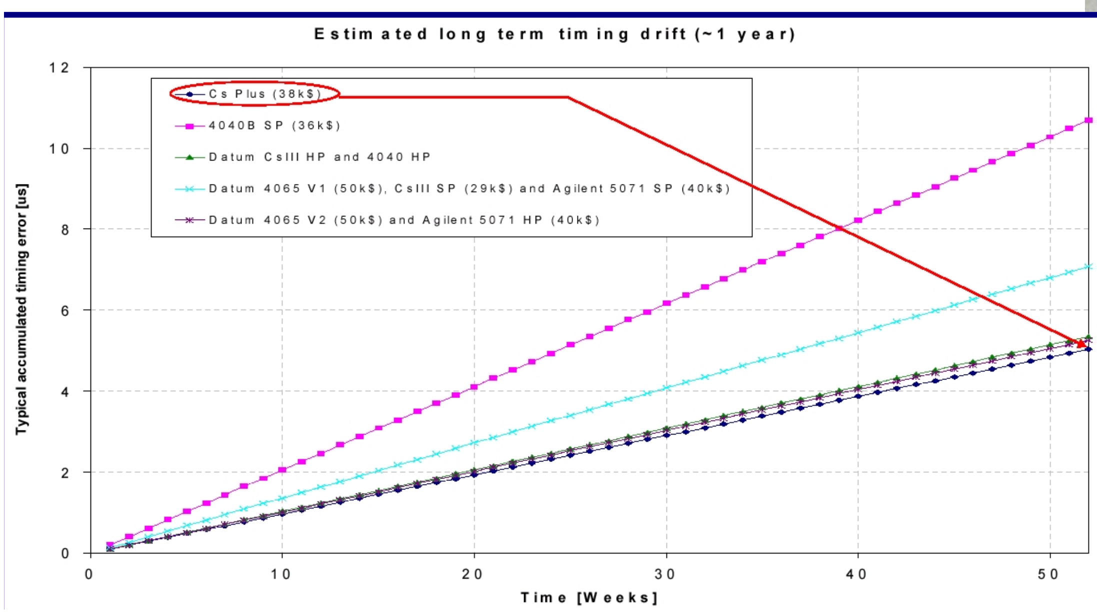


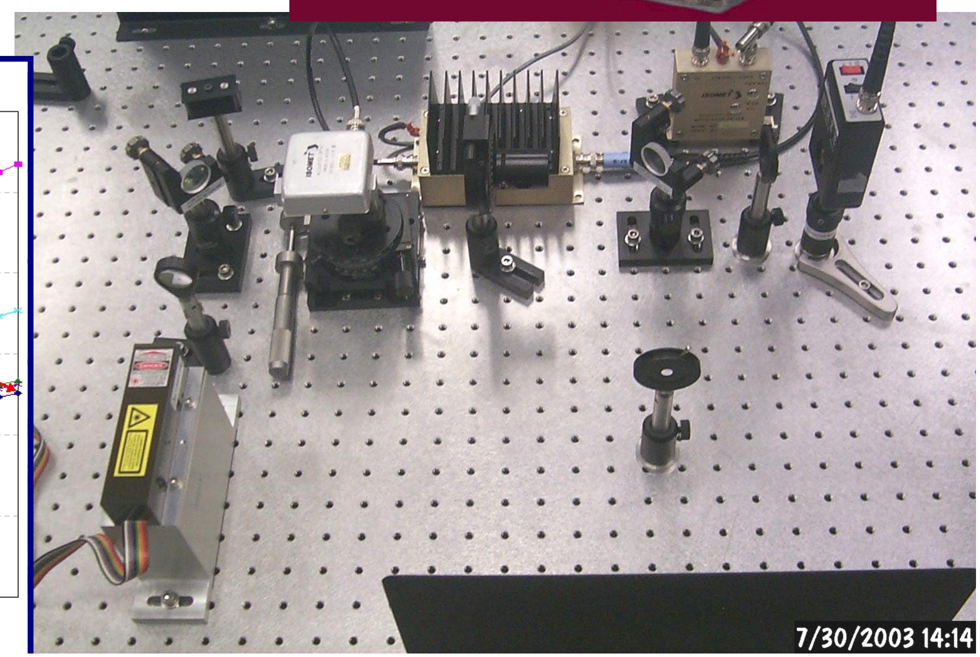
WFS5 error points



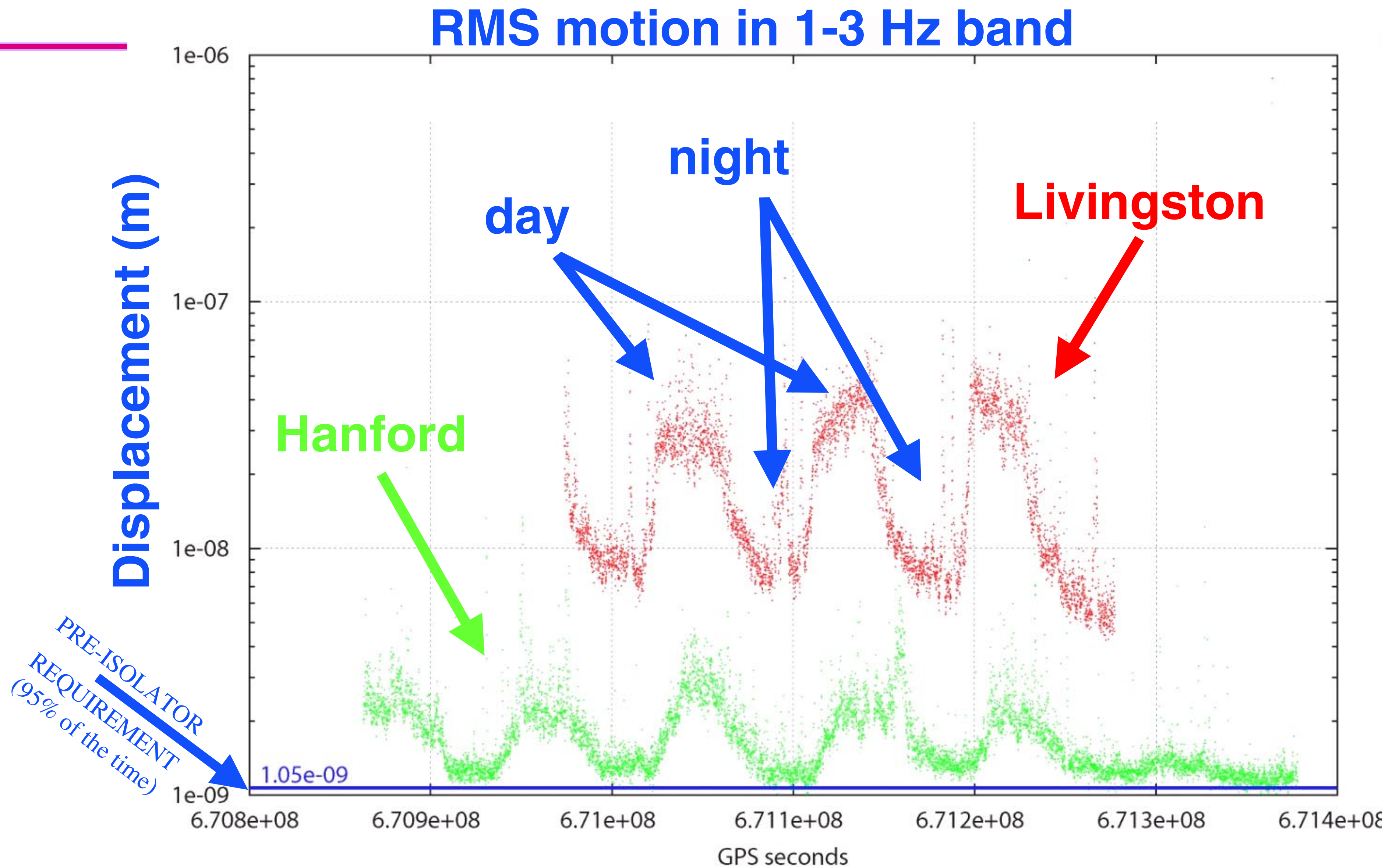
Atomic Clocks & Photon Calibrator

- Proposed system:
  - Central atomic clock
  - Timing distributed to all buildings over fiber
  - Check local GPS clocks
  - Portable rubidium clock
  - Required precision: 10 μs
  - Synchronize photon calibrator



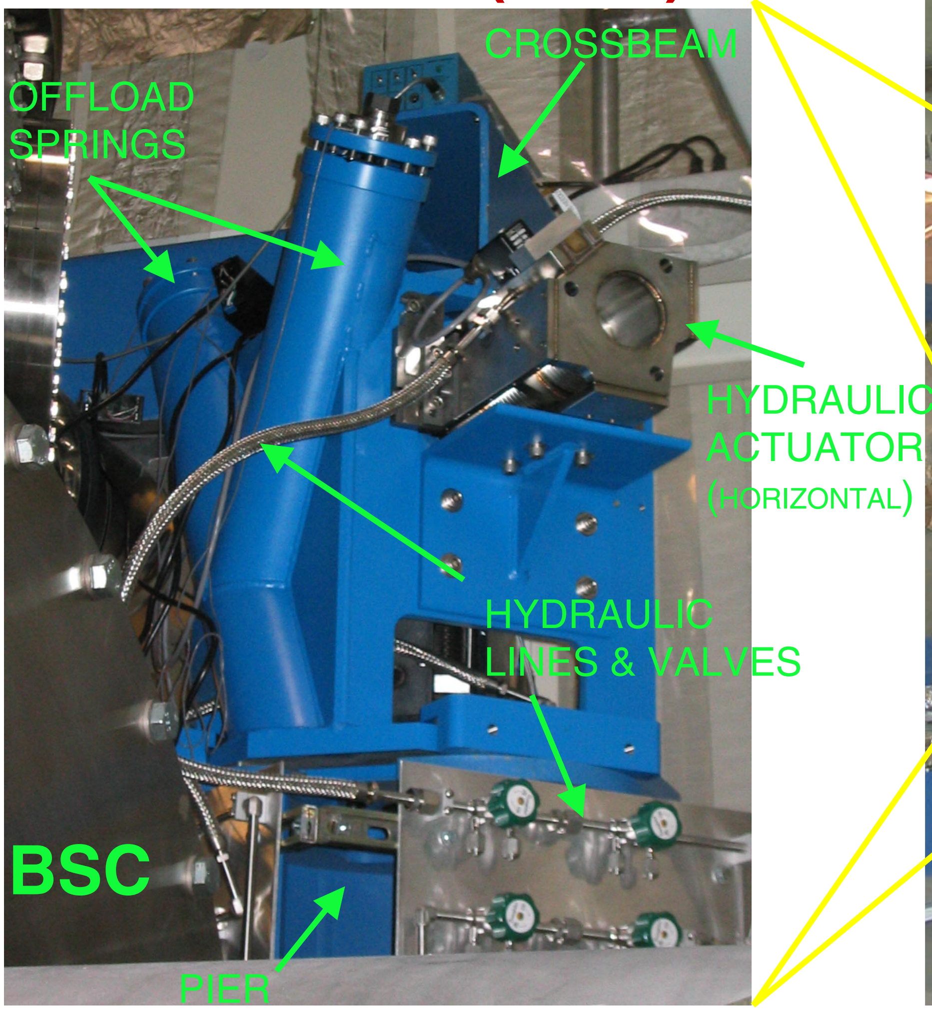


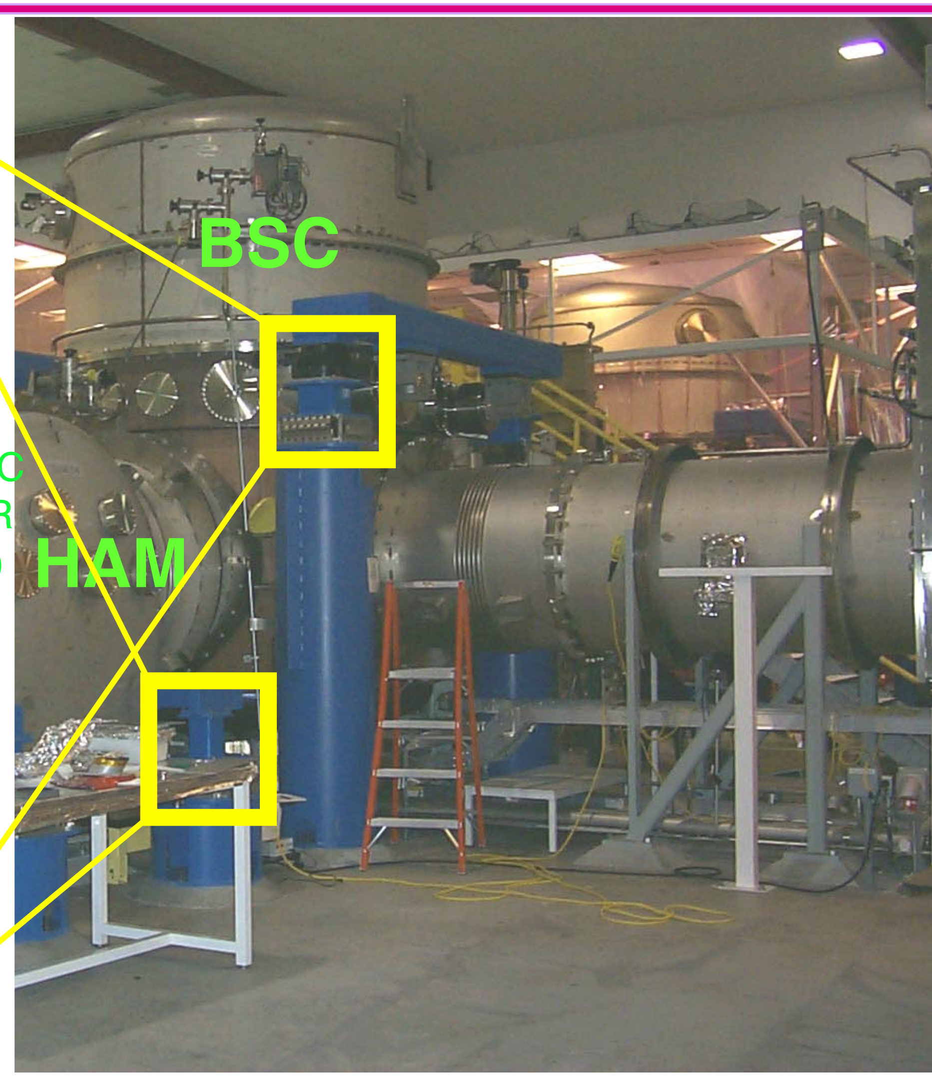
Daily Variability of Seismic Noise



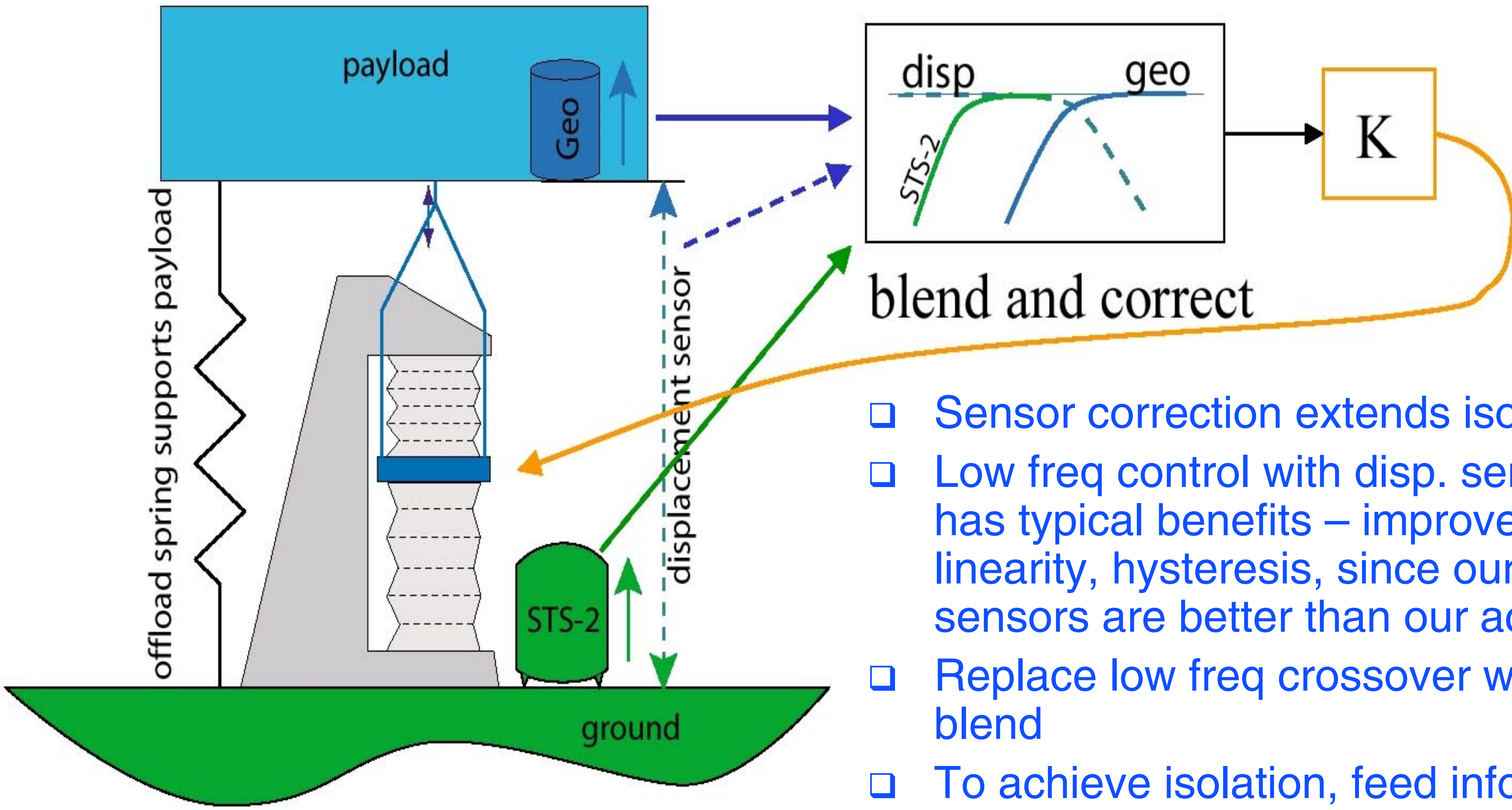
Active Seismic Isolation

Hydraulic External Pre-Isolator (HEPI)



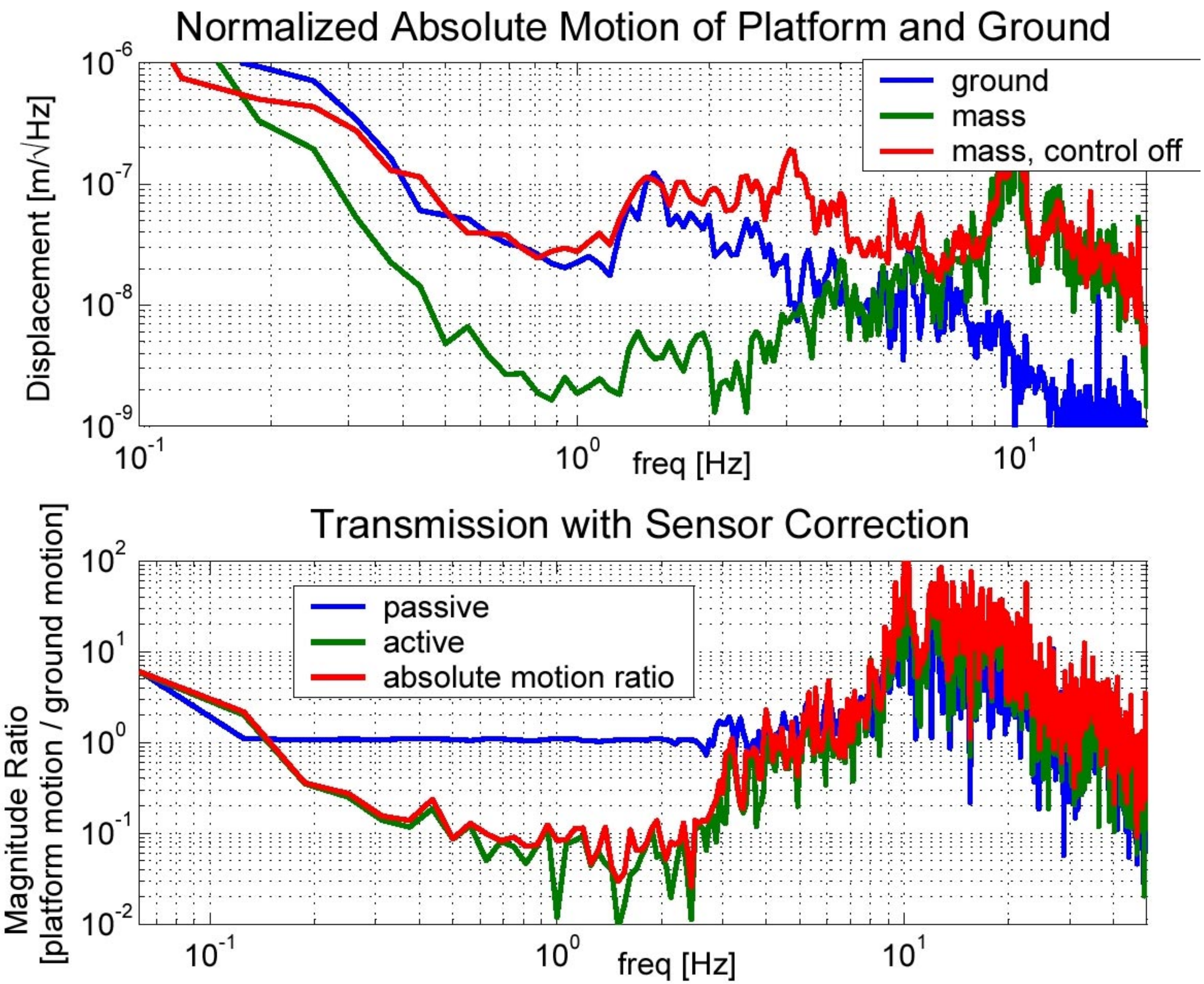


Active Seismic Isolation: How it Works



- Sensor correction extends isolation
- Low freq control with disp. sensor has typical benefits – improved linearity, hysteresis, since our sensors are better than our actuators
- Replace low freq crossover with blend
- To achieve isolation, feed information from STS-2 to correct the displacement sensor.

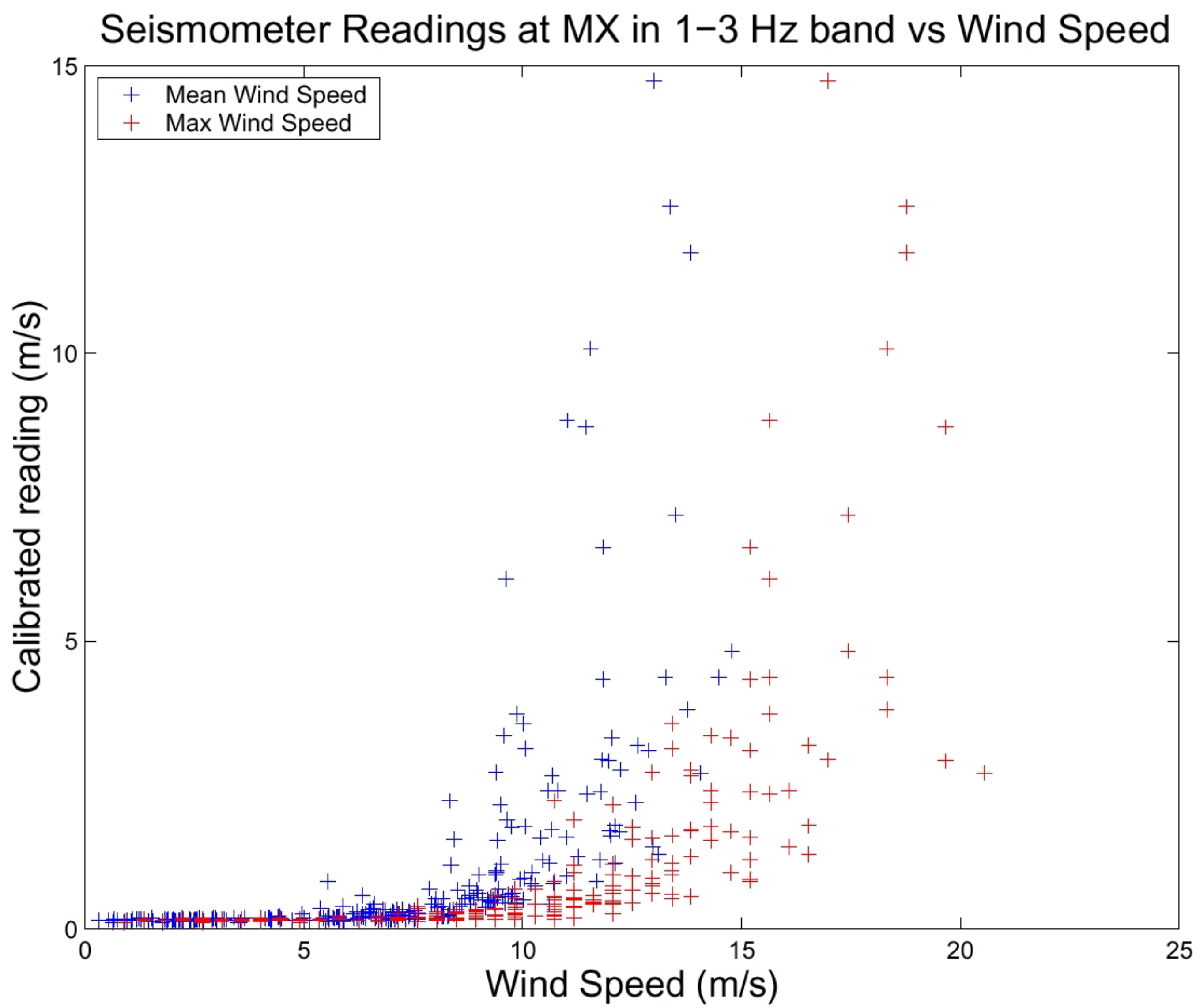
Active Seismic Isolation: Preliminary Results



Good performance:

- Motions of 2e-9 m/rtHz
- Match of trans&ratio indicates limits are loop gain and correction match.

- Strong threshold effect
- Benefits of active seismic pre-isolator unclear



Summary

Currently ongoing efforts:

- High power operations
- Acoustic mitigation
- Full alignment control
- Seismic pre-isolator development

S3 in November/December