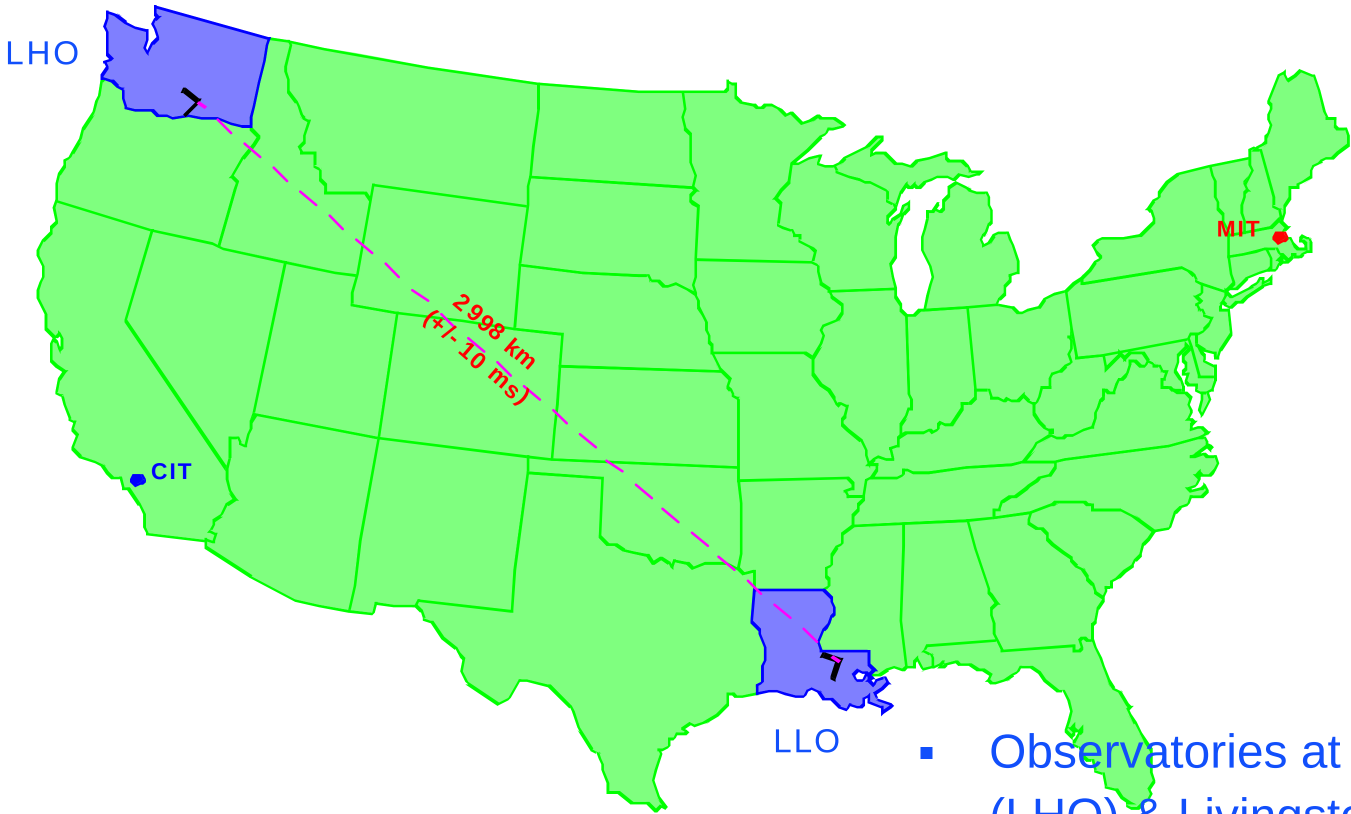
LIGO Commissioning Status

Reported on behalf of LIGO colleagues by

Fred Raab,

LIGO Hanford Observatory

The Four Corners of the LIGO Laboratory



- Observatories at Hanford, WA (LHO) & Livingston, LA (LLO)
- Support Facilities @ Caltech & MIT campuses

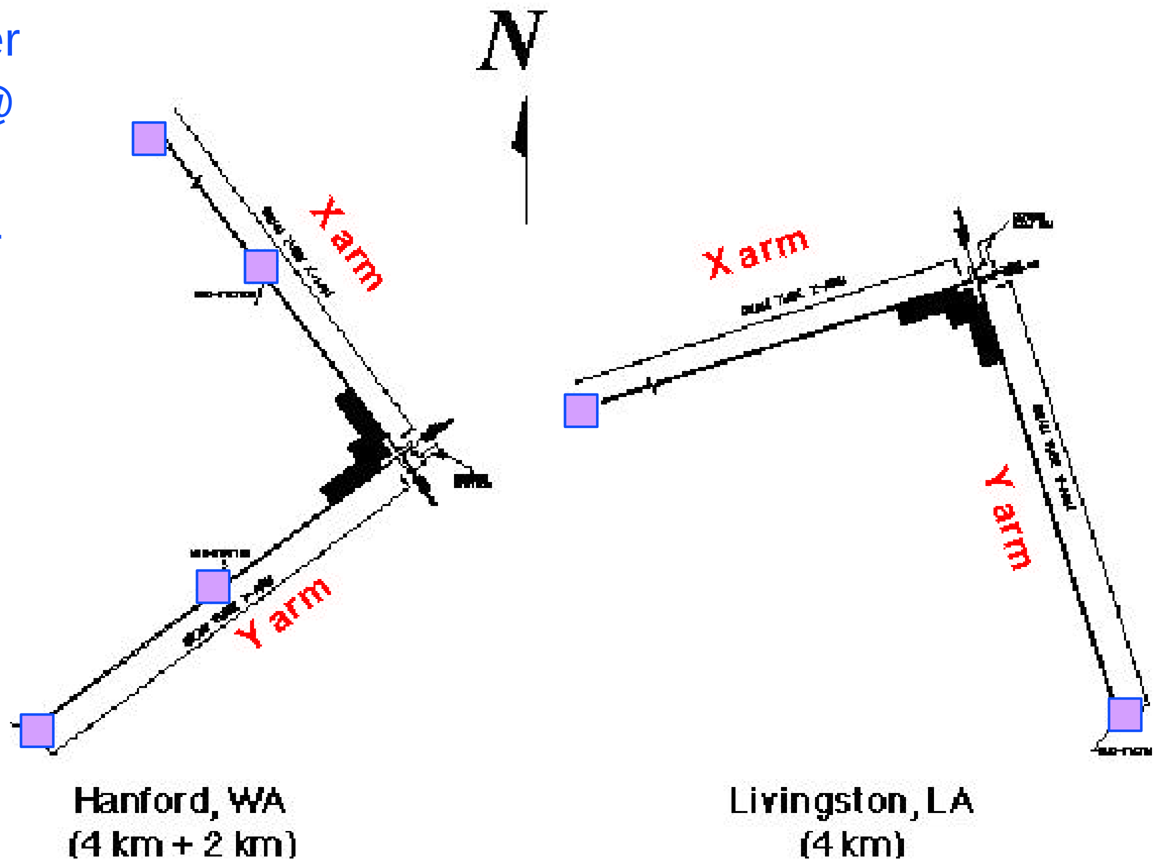
Aerial Views of LIGO Facilities

LIGO Hanford Observatory
(LHO)

LIGO Livingston Observatory
(LLO)

Configuration of LIGO Observatories

- 2-km & 4-km laser interferometers @ Hanford
- Single 4-km laser interferometer @ Livingston



LIGO Laboratory & Science Collaboration

- LIGO Laboratory (Caltech/MIT) runs observatories and research/support facilities at Caltech/MIT
- LIGO Science Collaboration is the body that defines and pursues LIGO science goals
  - » >300 members worldwide (including LIGO Lab personnel)
  - » Includes GEO600 members & data sharing
  - » Working groups in detector technology advancement, detector characterization and astrophysical analyses
  - » Memoranda of understanding define duties and access to LIGO data

Chronology of Detector Installation & Commissioning

- 7/98 Begin LHO detector installation
- 2/99 Begin LLO detector installation
- 6/99 Lock first mode cleaner
- 11/99 Laser spot on first end mirror
- 12/99 First lock of a 2-km Fabry-Perot arm
- 4/00 Engineering Run 1 (E1)
- 6/00 Brush Fire burns 500 km^2 of land surrounding LHO
- 10/00 Recombined LHO-2km interferometer in E2 run
- 10/00 First lock of LHO-2km power-recycled interferometer
- 2/01 Nisqually earthquake damages LHO interferometers
- 4/01 Recombined 4-km interferometer at LLO
- 5/01 Earthquake repairs completed at LHO
- 6/01 Last LIGO-1 mirror installed
- 12/01 Power recycling achieved for LLO-4km
- 1/2002 E7: First triple coincidence run; first on-site data analysis
- 1/2002 Power recycling achieved for LHO-4km

Observatory Facilities

- Hanford and Livingston Lab facilities available starting 1997-8
- 16 km beam tube with 1.2-m diameter
- Beam-tube foundations in plane ~ 1 cm
- Turbo roughing with ion pumps for steady state

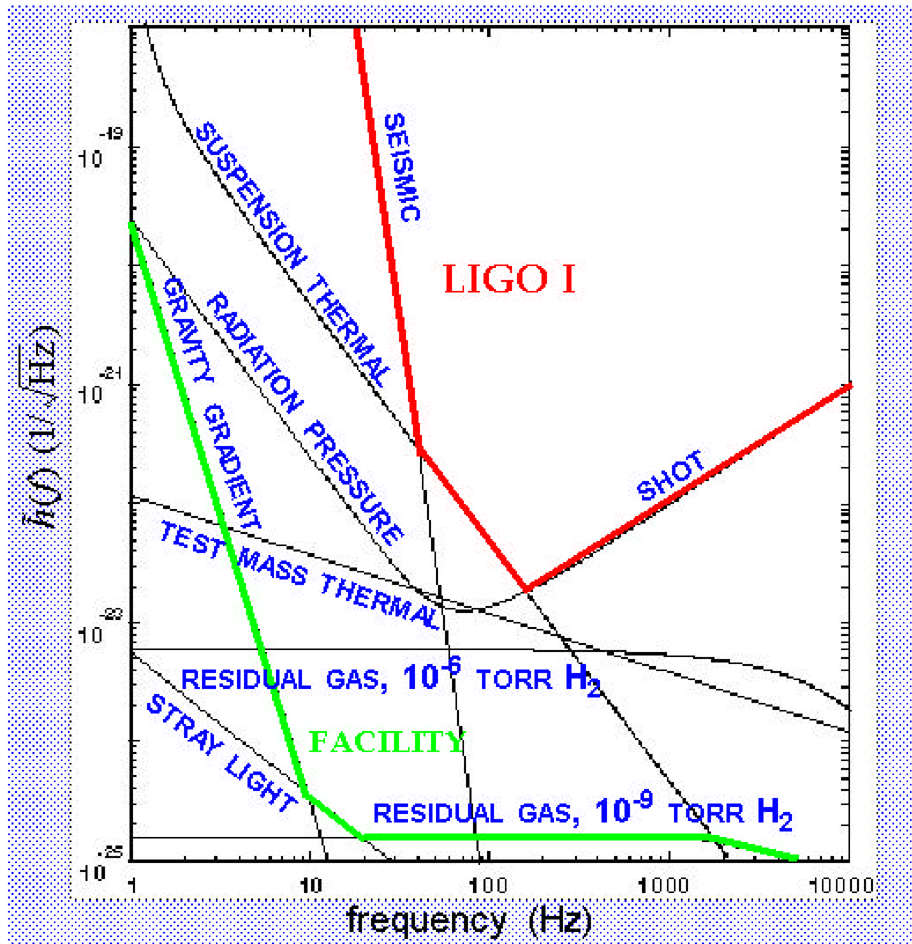
- Large experimental halls compatible with Class-3000 environment; portable enclosures around open chambers compatible with Class-100
- Some support buildings/laboratories still under construction

Beam Tube Bakeout

- Method: Insulate tube and drive ~2000 amps from end to end

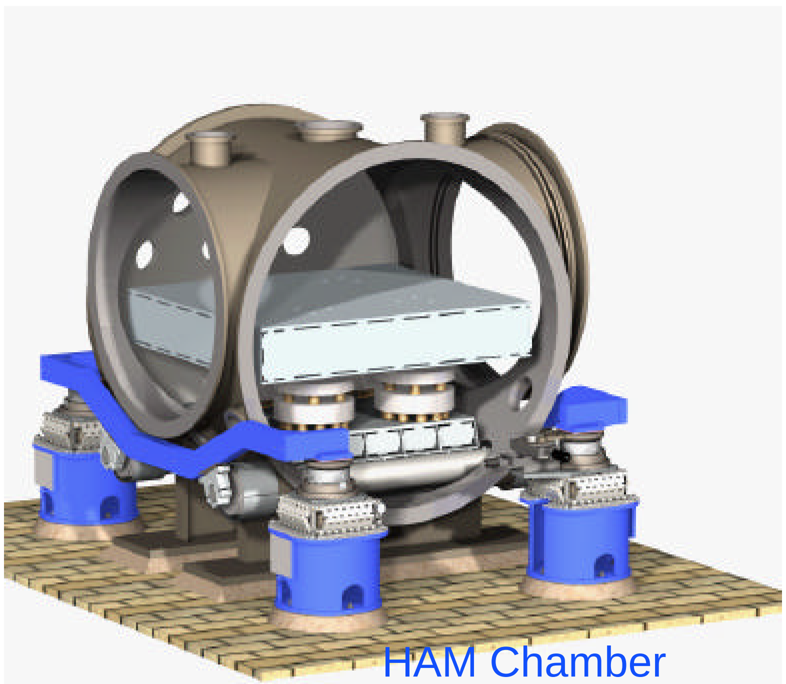
LIGO I Detector Being Commissioned

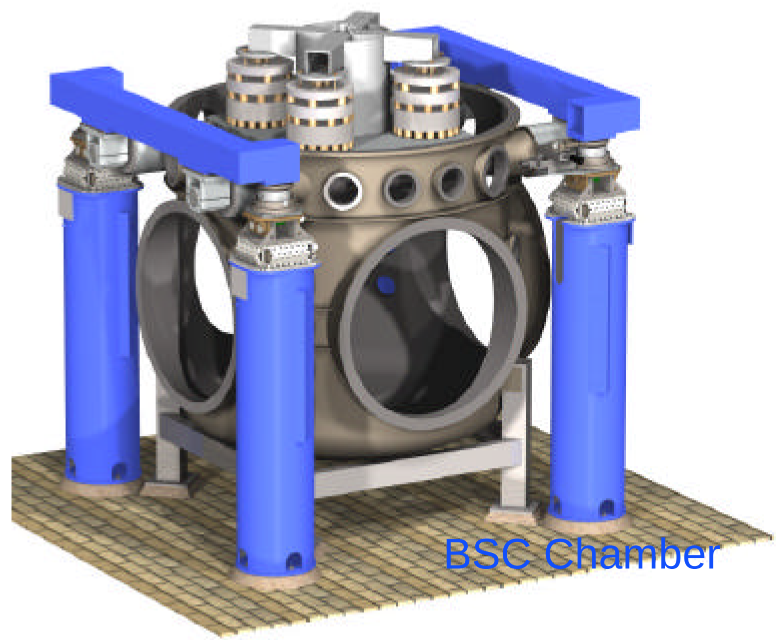
- LIGO I has evolved from design principles successfully demonstrated in 40-m & phase noise interferometer test beds
- Design effort sought to optimize reliability (up time) and data accessibility
- Facilities and vacuum system designs provide an environment suitable for the most aggressive detector specifications imaginable in future.



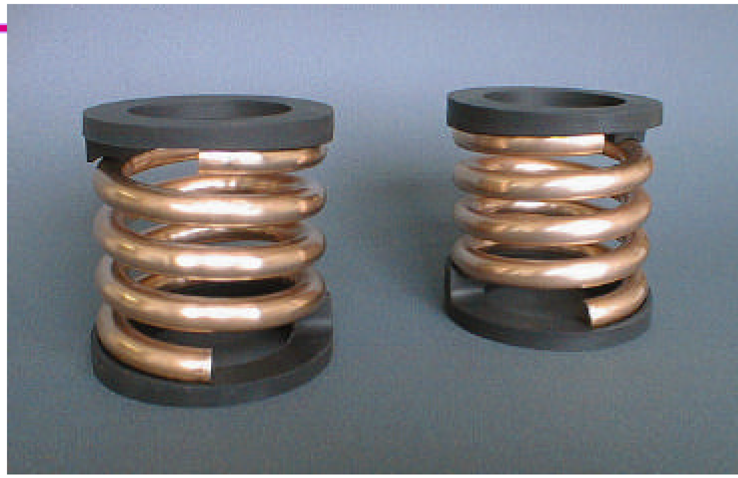
Vibration Isolation Systems

» Reduce in-band seismic motion by 4 - 6 orders of magnitude
» Little or no attenuation below 10Hz
» 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

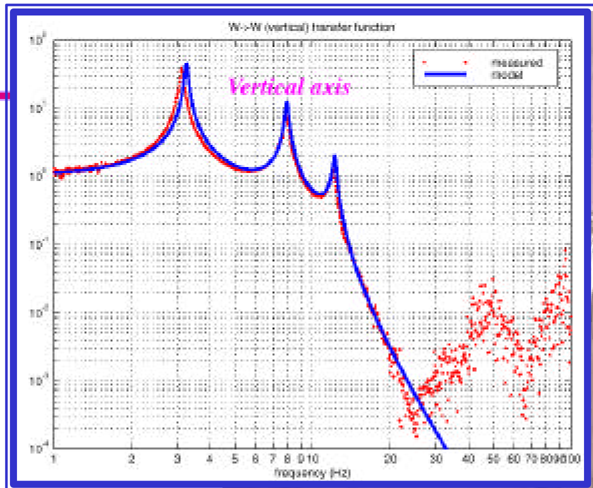

BSC Chamber

Seismic Isolation – Springs and Masses

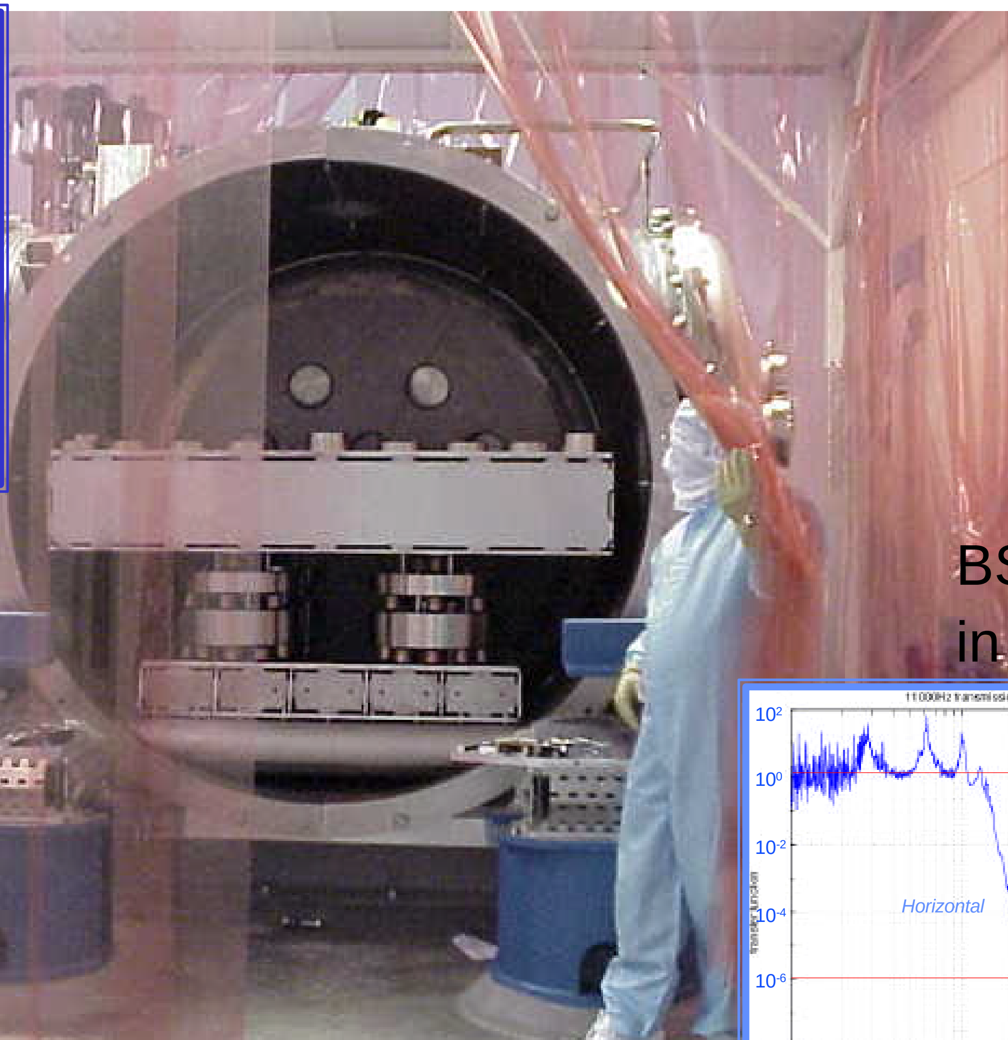


damped spring
cross section

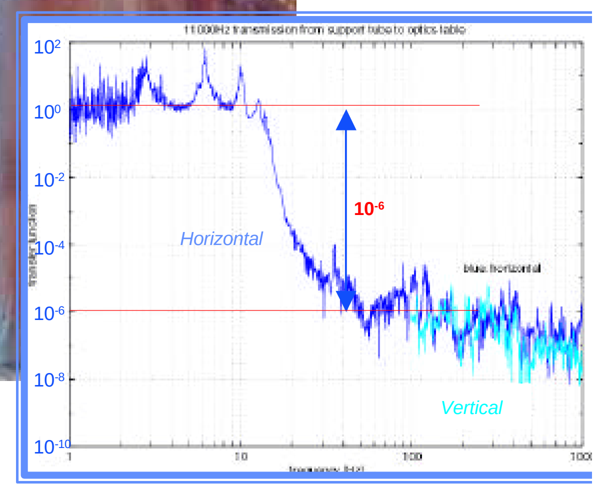
Seismic System Performance



HAM stack
in air

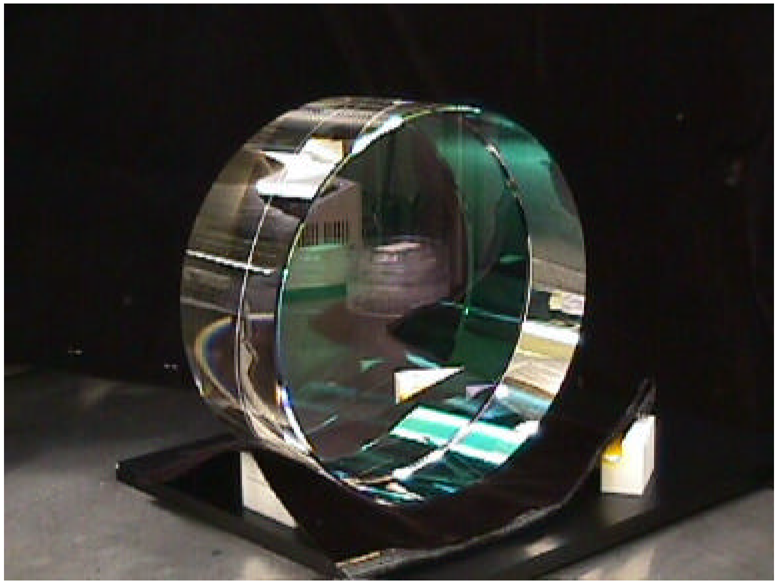


BSC stack
in vacuum

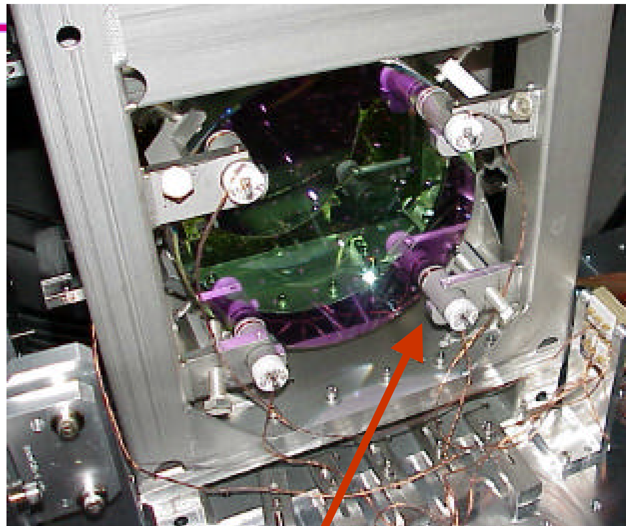


Core Optics

- Substrates: SiO_2
  - » 25 cm Diameter, 10 cm thick
  - » Homogeneity < 5 x 10^{-7}
  - » Internal mode Q's > 2 x 10^{6}
- Polishing
  - » Surface uniformity < 1 nm rms
  - » Radii of curvature matched < 3%
- Coating
  - » Scatter < 50 ppm
  - » Absorption < 2 ppm
  - » Uniformity <10^{-3}
- Production involved 6 companies, NIST, and LIGO

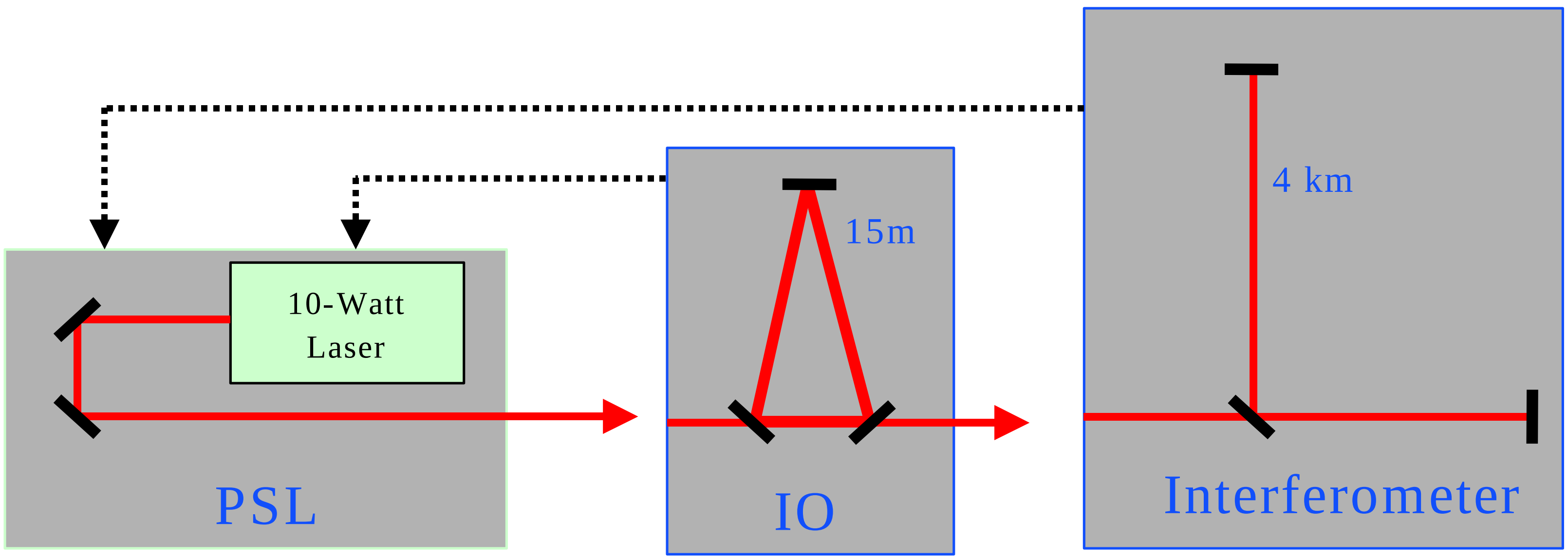


Core Optics Suspension and Control

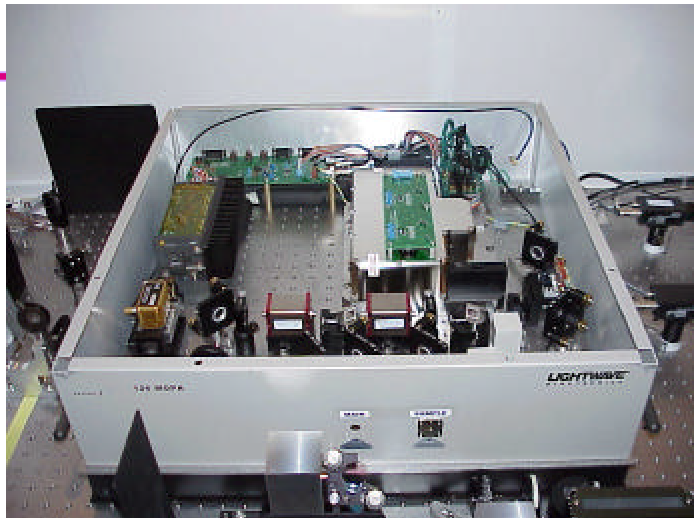


- Optics suspended as simple pendulums
- Local sensors/actuators for damping and control

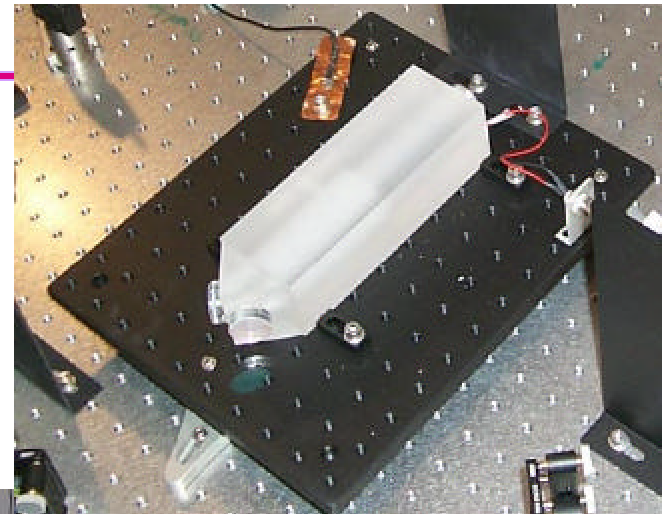
Frequency Stabilization of the Light Employs Three Stages



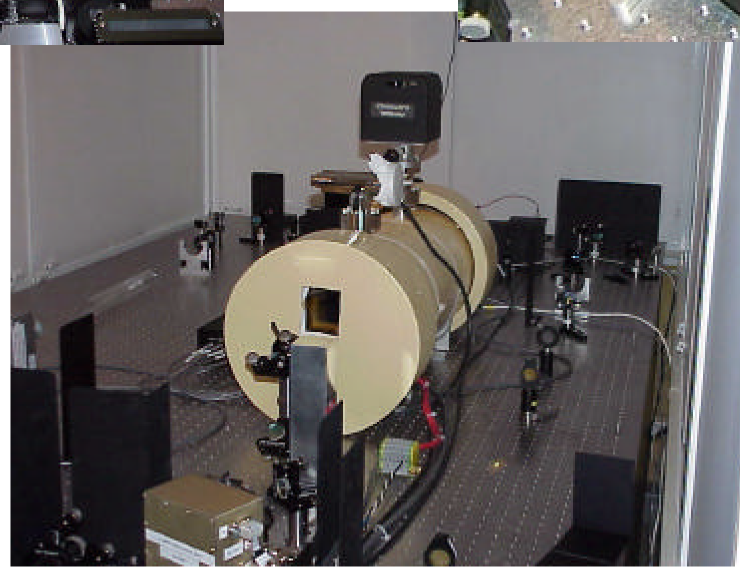
Pre-stabilized Laser (PSL)



Custom-built
10 W Nd:YAG Laser,
joint development with
Lightwave Electronics
(now commercial product)



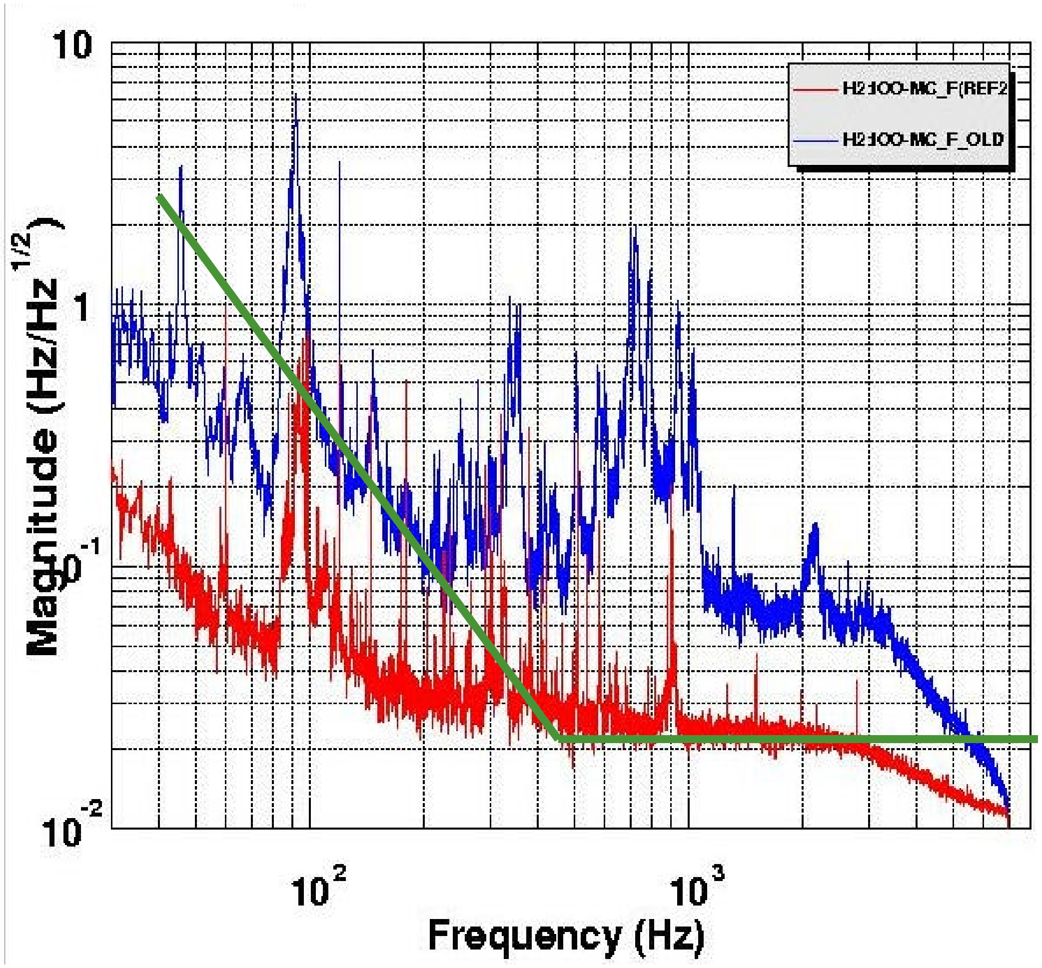
Cavity for
defining beam geometry,
joint development with
Stanford



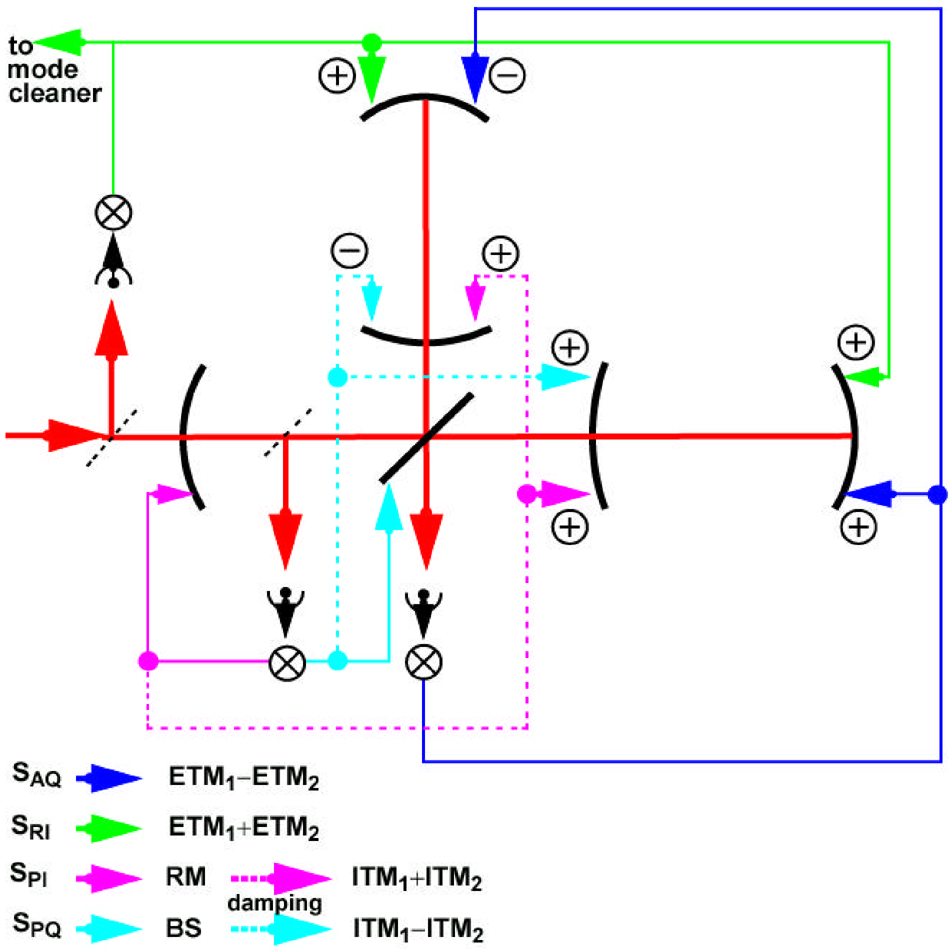
Frequency reference
cavity (inside oven)

Continued improvement in PSL Frequency Noise

- Simplification of beam path external to vacuum system eliminated peaks due to vibrations
- Broadband noise better than spec in 40-200 Hz region

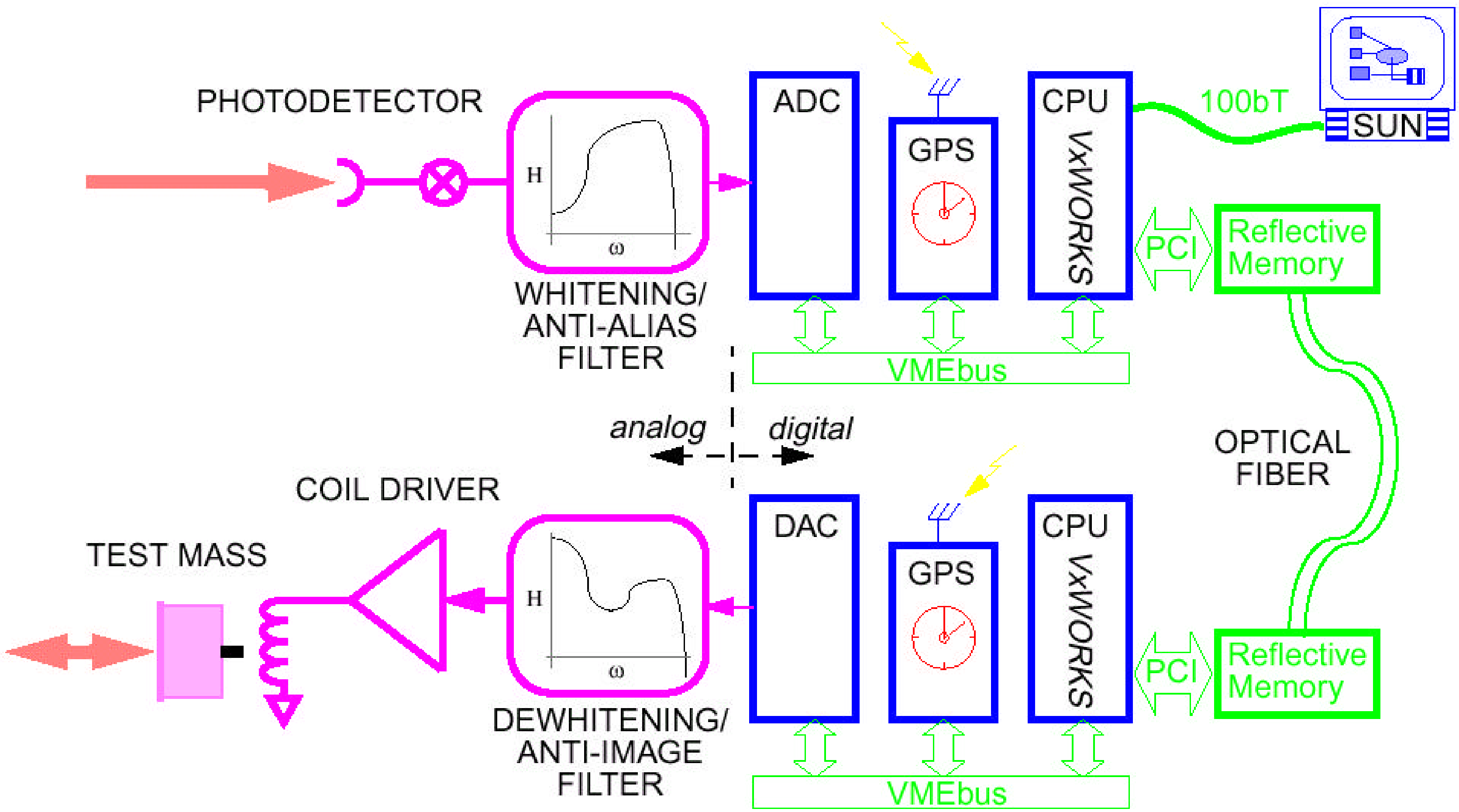


Interferometer Control System



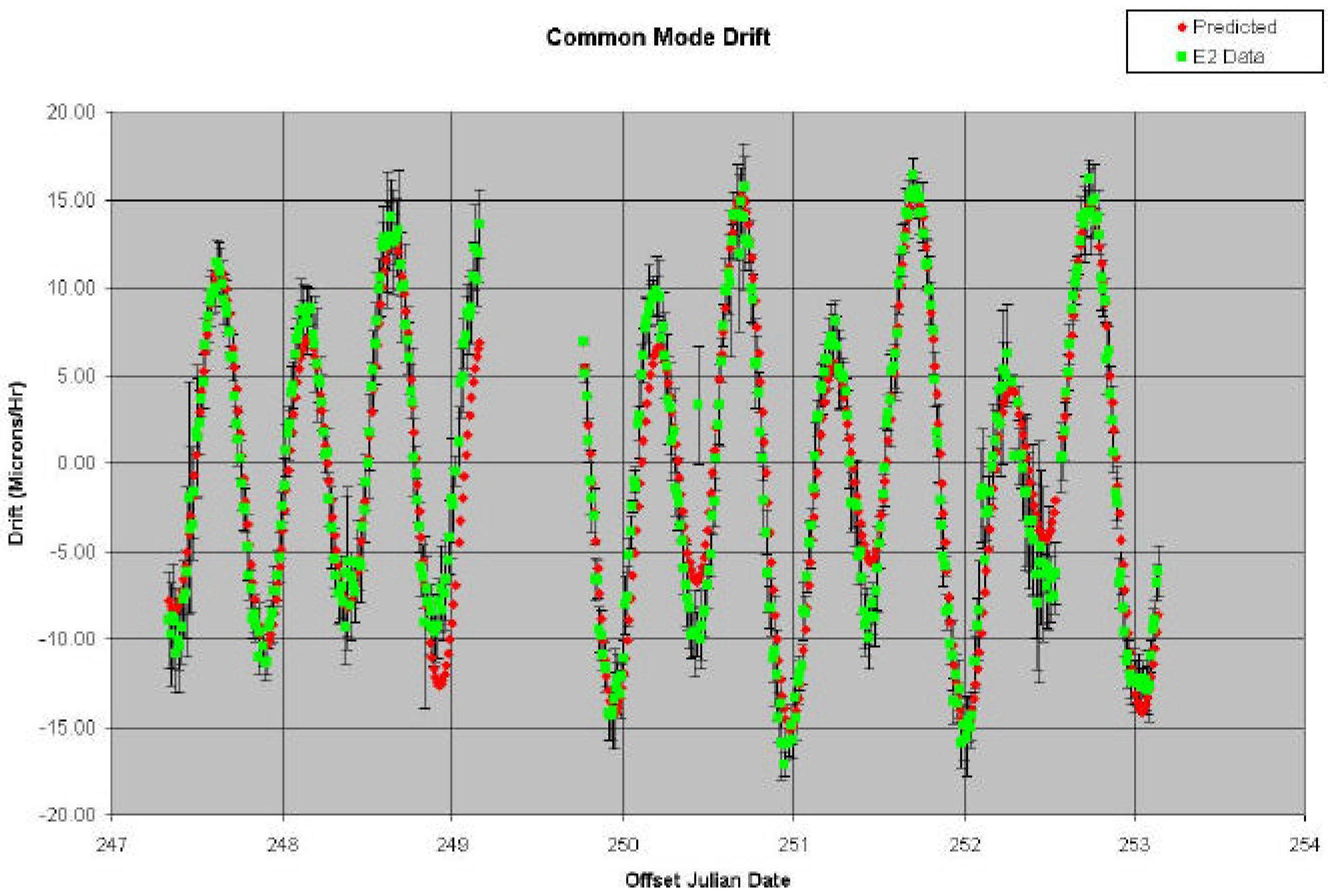
- Multiple Input / Multiple Output
- Three tightly coupled cavities
- Ill-conditioned (off-diagonal) plant matrix
- Highly nonlinear response over most of phase space
- Transition to stable, linear regime takes plant through singularity
- Employs adaptive control system that evaluates plant evolution and reconfigures feedback paths and gains during lock acquisition
- But it works!

Digital Interferometer Sensing & Control System



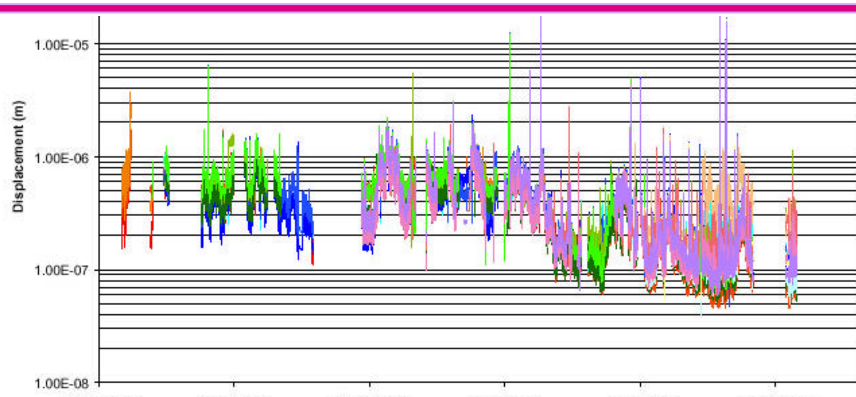
Earth Tide: Largest Source of Interferometer Drift

- Actuation in end/mid- stations and on laser reference cavity
- Simple model in feed-forward removes ~80%
- Feed-back removes ~20%
- Analysis of feed-back gives non-modeled tidal and temperature effects



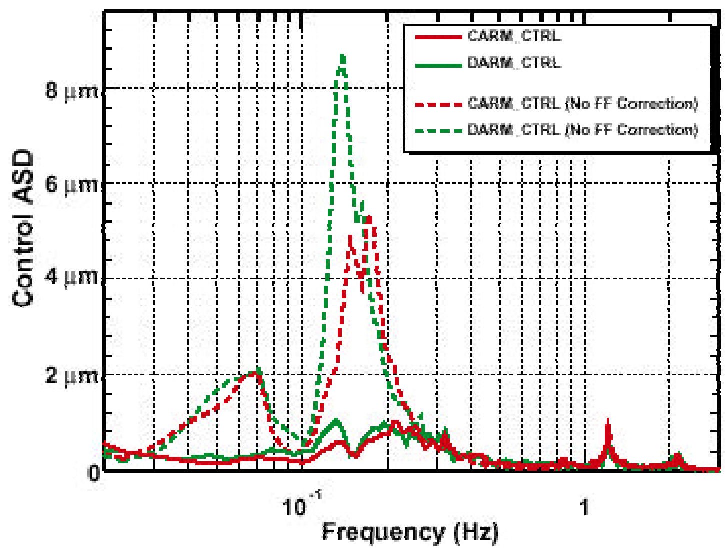
Microseism

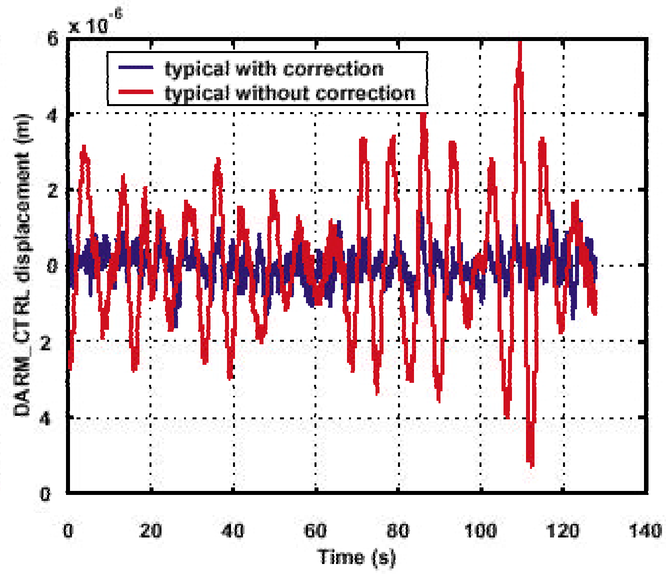
Microseism at 0.12 Hz dominates ground velocity



Trended data (courtesy of Gladstone High School) shows large variability of microseism

Reduction by feed-forward derived from seismometers





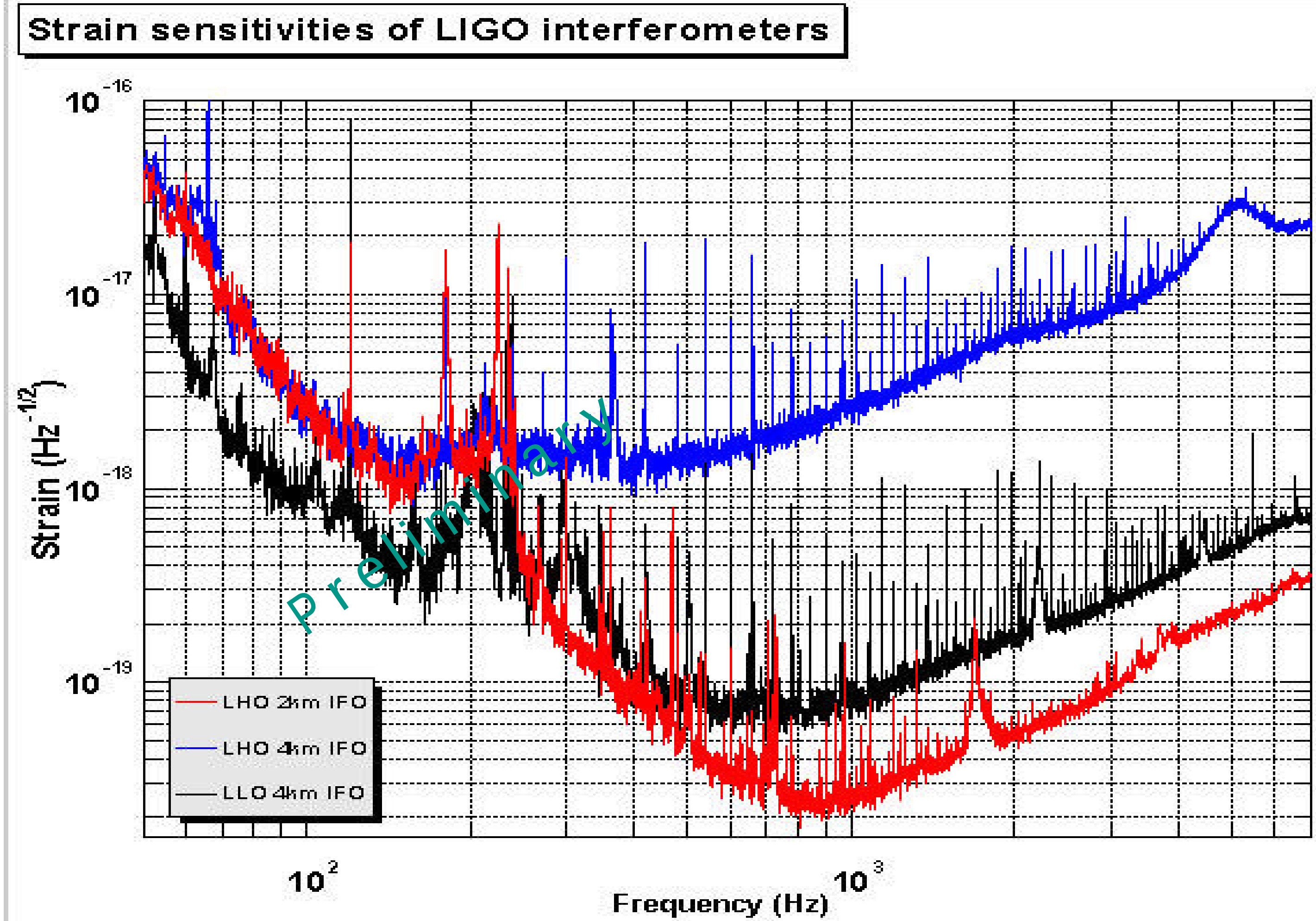
Engineering Run 7 (E7) 28Dec01 – 14Jan02

- Engineering runs test partially integrated and commissioned machines under “operational” conditions to identify needed improvements
- E7 was first engineering run to include all 3 interferometers in coincidence and tested on-line data analysis at Hanford and Livingston
- E7 data sets will be analyzed jointly with data sets from GEO600 and Allegro
- E7 analysis will exercise full range of astrophysical data-analysis software

E7 Interferometer Configurations

- H1: 4-km interferometer at Hanford; recombined configuration; digital suspension controllers; tidal compensation; 1-W laser power
- H2: 2-km interferometer at Hanford; full power-recycling configuration; differential-mode wave-front control; analog suspension controllers; tidal compensation ; 1-W laser power
- L1: 4-km interferometer at Livingston; recombined configuration; analog suspension controllers; microseism compensation ; 1-W laser power

Preliminary Noise Equivalent Strain Spectra for E7



E7 Analysis Working Groups

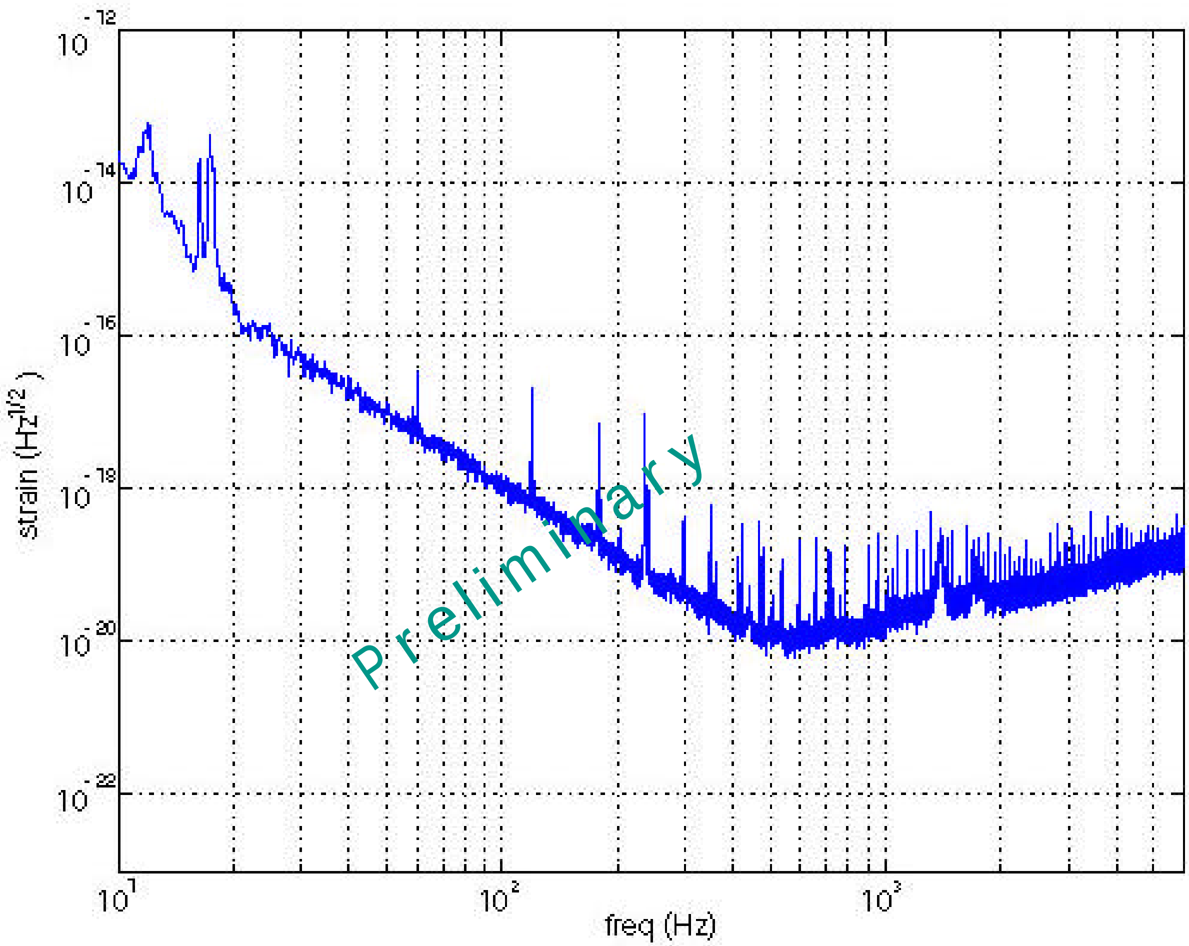
- Data from E7 is being analyzed by LSC working groups for:
  - » Detector Characterization
  - » Binary Inspirals
  - » Bursts
  - » Periodic Sources
  - » Stochastic Background
- This exercise will test analysis methodology for 1st Science Run S1 this summer and feed back results into detector commissioning and code-writing effort

Progress since 14Jan02

- Common-mode feedback from arms to laser frequency is now engaged on Hanford 2-km interferometer
  - » Improved control of laser frequency noise
  - » Establishes gain hierarchy to get better-conditioned control system
- Power-recycling works on Hanford 4-km interferometer
  - » Important validation of digital suspension controllers
- Laser power increased to 6 W for Hanford 2-km interferometer; tuning up under new operating conditions

Hanford 2km interferometer improvements after E7

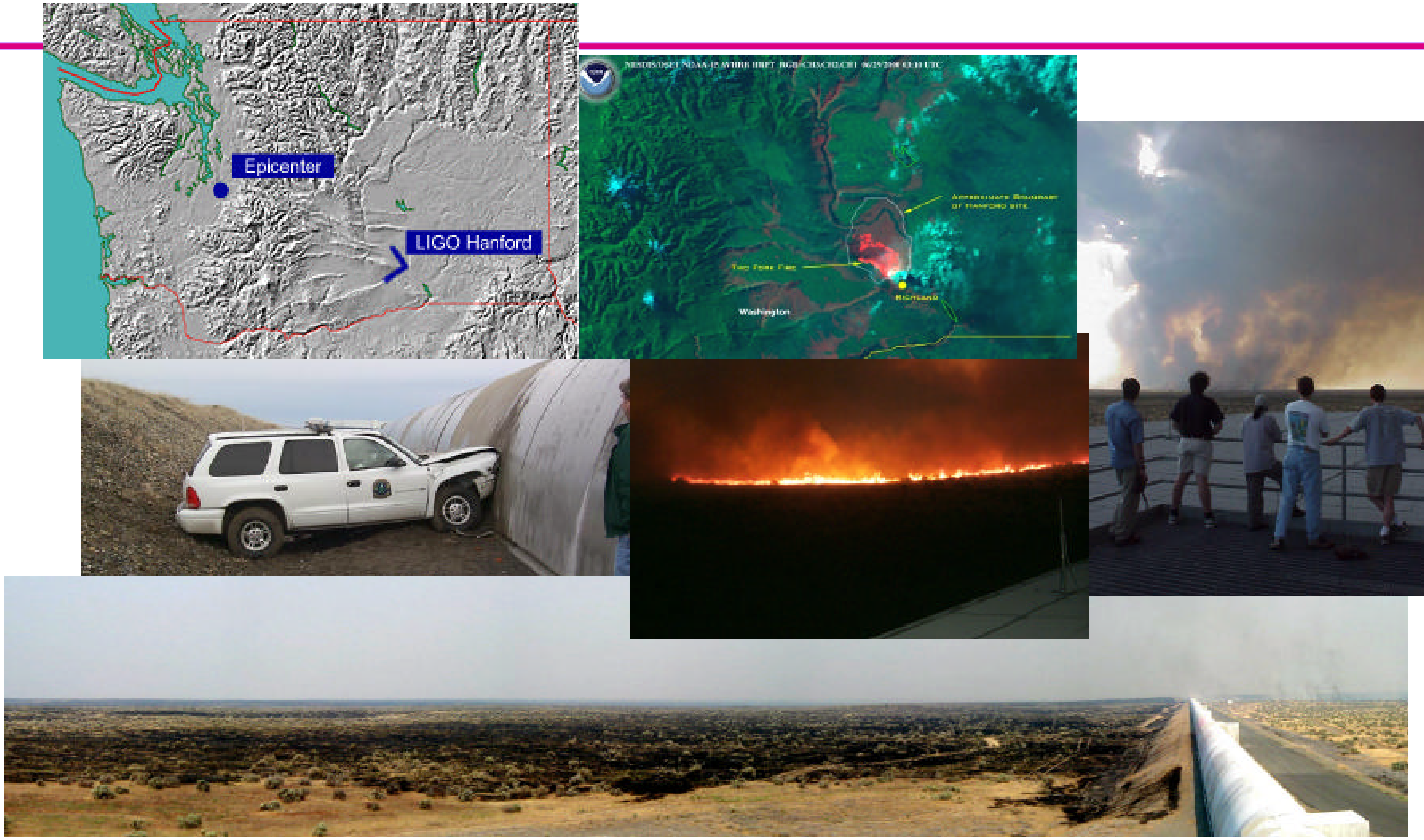
- Closed feedback loop from arms to laser frequency
- Reallocation of gains within length control servo system
- laser power 1 W



Summary

- First coincidence run completed
- On-line analysis systems tested at LHO and LLO
- First end-to-end test of complete data analysis ongoing
- Power-recycling demonstrated on all interferometers
- All interferometers still need many control loops to be closed and then tuned
- Working to increase immunity to high seismic noise periods (especially important at LLO)

Despite a few difficulties, science runs will start in 2002.



Beam Tube Bakeout Results

Postbake measurements of module X1 at Hanford

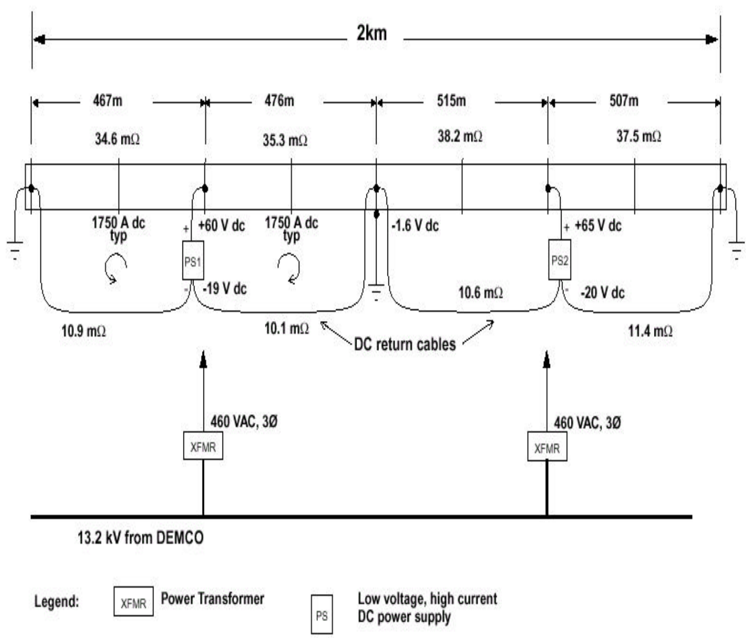
March 11-12, 1999

Table 1: Results from gas model solution of 16.9 hour postbake accumulation ending March 12, 1999 at 10:00AM .

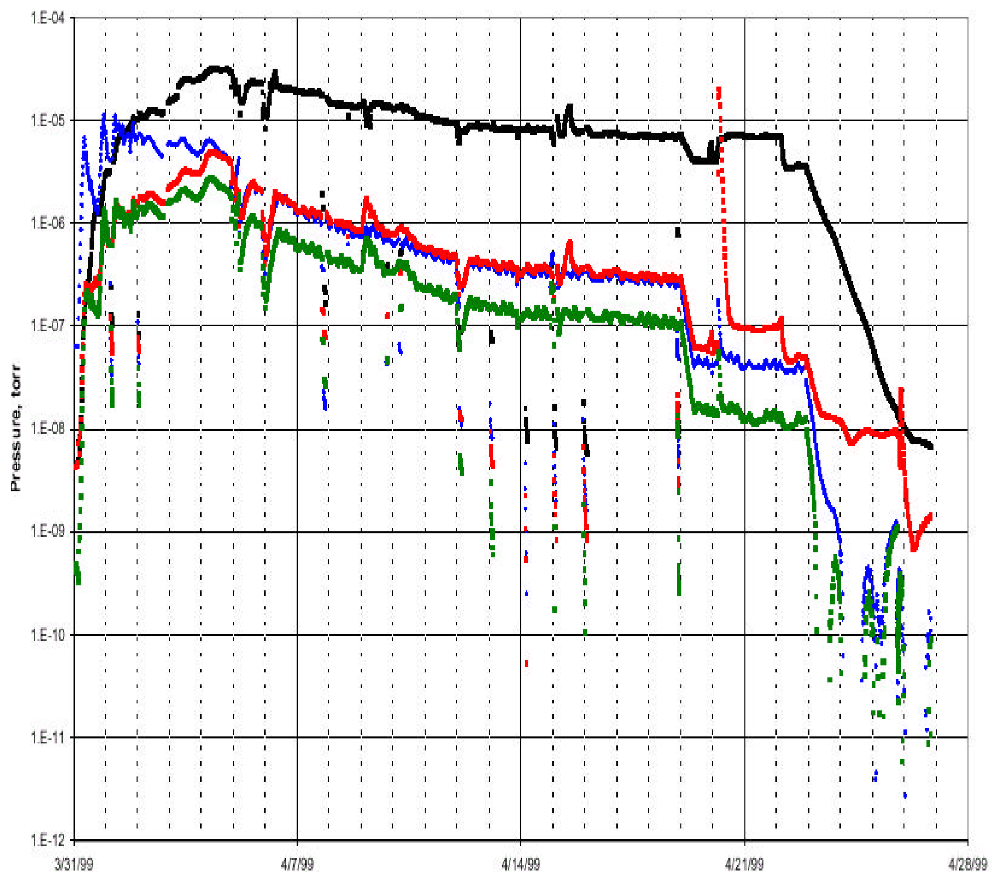
molecule	Outgassing rate @ 10C	pressure@ 10C	outgassing rate @ 23C	pressure@ 23C
	torr liters/sec/cm^2	torr	torr liters/sec/cm^2	torr
H_2	1.6×10^{-14}	1.0×10^{-9}	5.2×10^{-14}	3.4×10^{-9}
CH_4	$< 2 \times 10^{-20}$	$< 3.4 \times 10^{-13}$	$< 8.8 \times 10^{-20}$	$< 1.5 \times 10^{-12}$
H_2O	$< 3 \times 10^{-19}$	$< 5.2 \times 10^{-13}$	$< 1.3 \times 10^{-18}$	$< 2.3 \times 10^{-12}$
N_2	$< 9 \times 10^{-19}$ **	$< 1.5 \times 10^{-13}$		
CO	$< 1.3 \times 10^{-18}$	$< 1.7 \times 10^{-13}$	$< 5.7 \times 10^{-18}$	$< 7 \times 10^{-13}$
O_2	$< 1.2 \times 10^{-20}$	$< 2.3 \times 10^{-14}$		
A	$< 2.5 \times 10^{-20}$	$< 3.6 \times 10^{-14}$		
CO_2	$< 6.5 \times 10^{-20}$	$< 1.2 \times 10^{-13}$	$< 2.9 \times 10^{-19}$	$< 5.2 \times 10^{-13}$

Beam Tube Bakeout

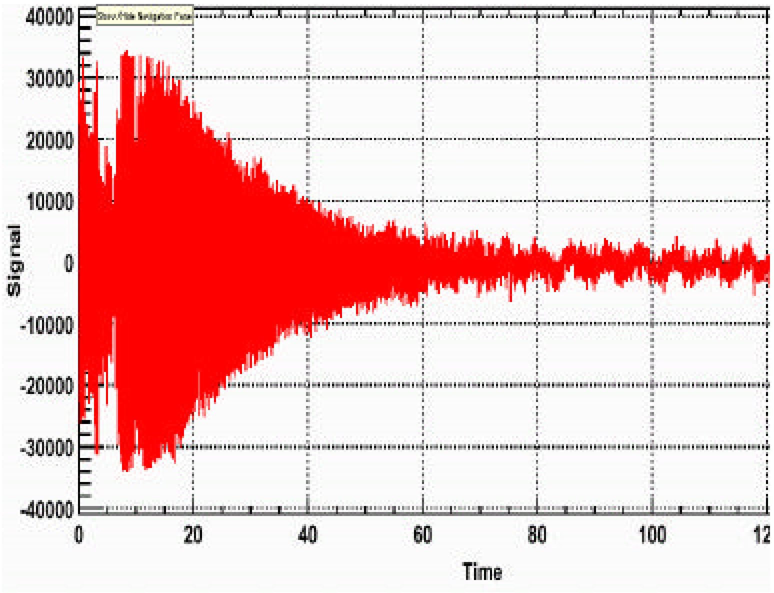
BEAM TUBE BAKEOUT ELECTRICAL HEATING POWER



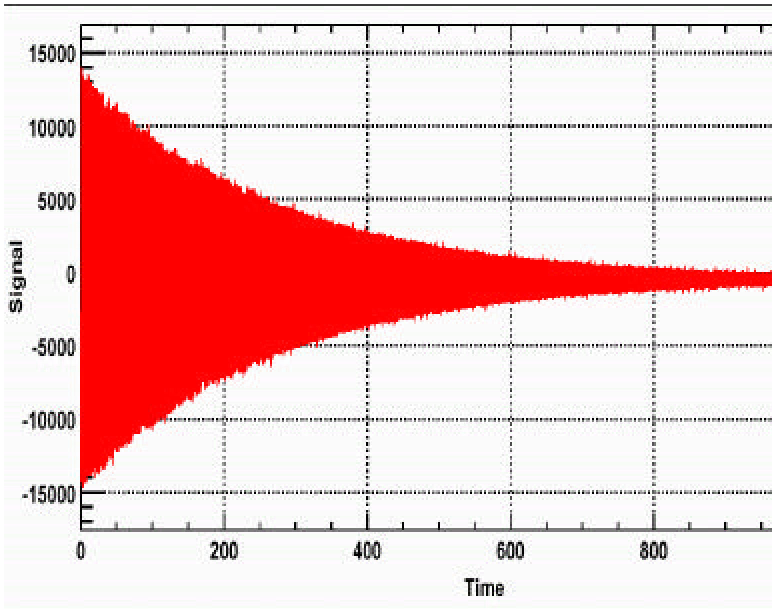
HX2 RGA PRESSURE, AMU 2 (blk), AMU 18 (blu), AMU 28 (red), AMU 44 (green)



ITMx Internal Mode Ringdowns

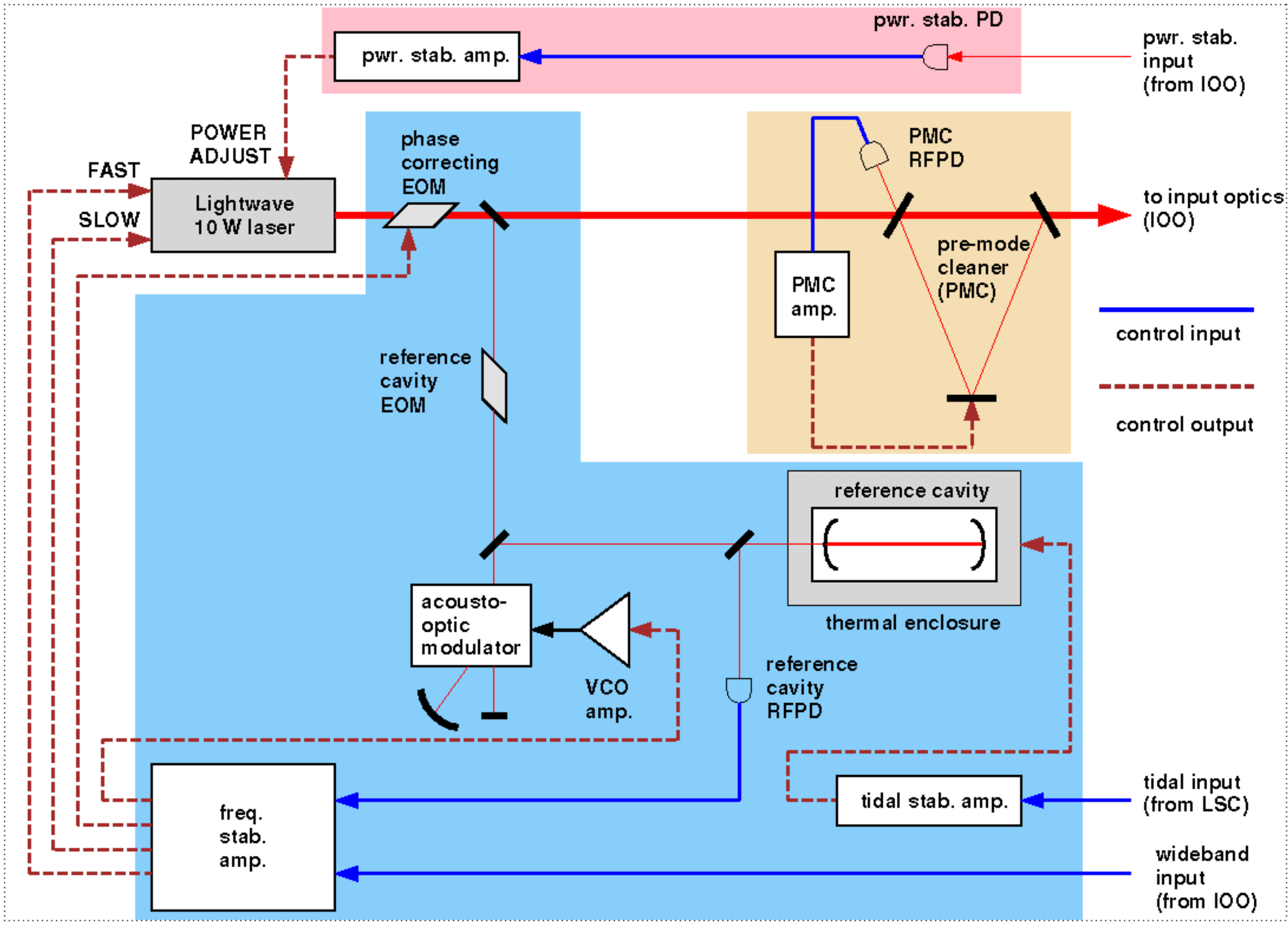


9.675 kHz; Q ~ 6e+5

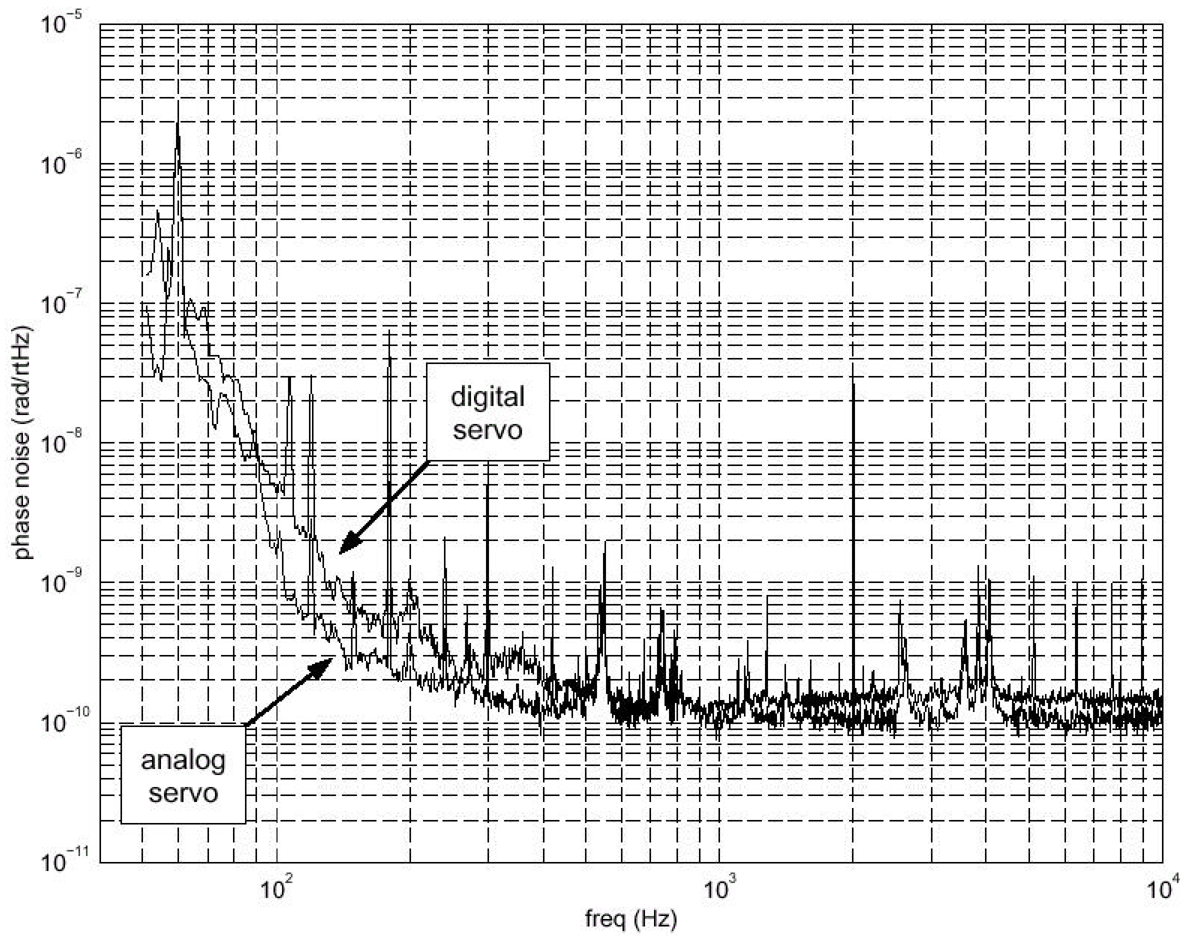


14.3737 kHz; Q = 1.2e+7

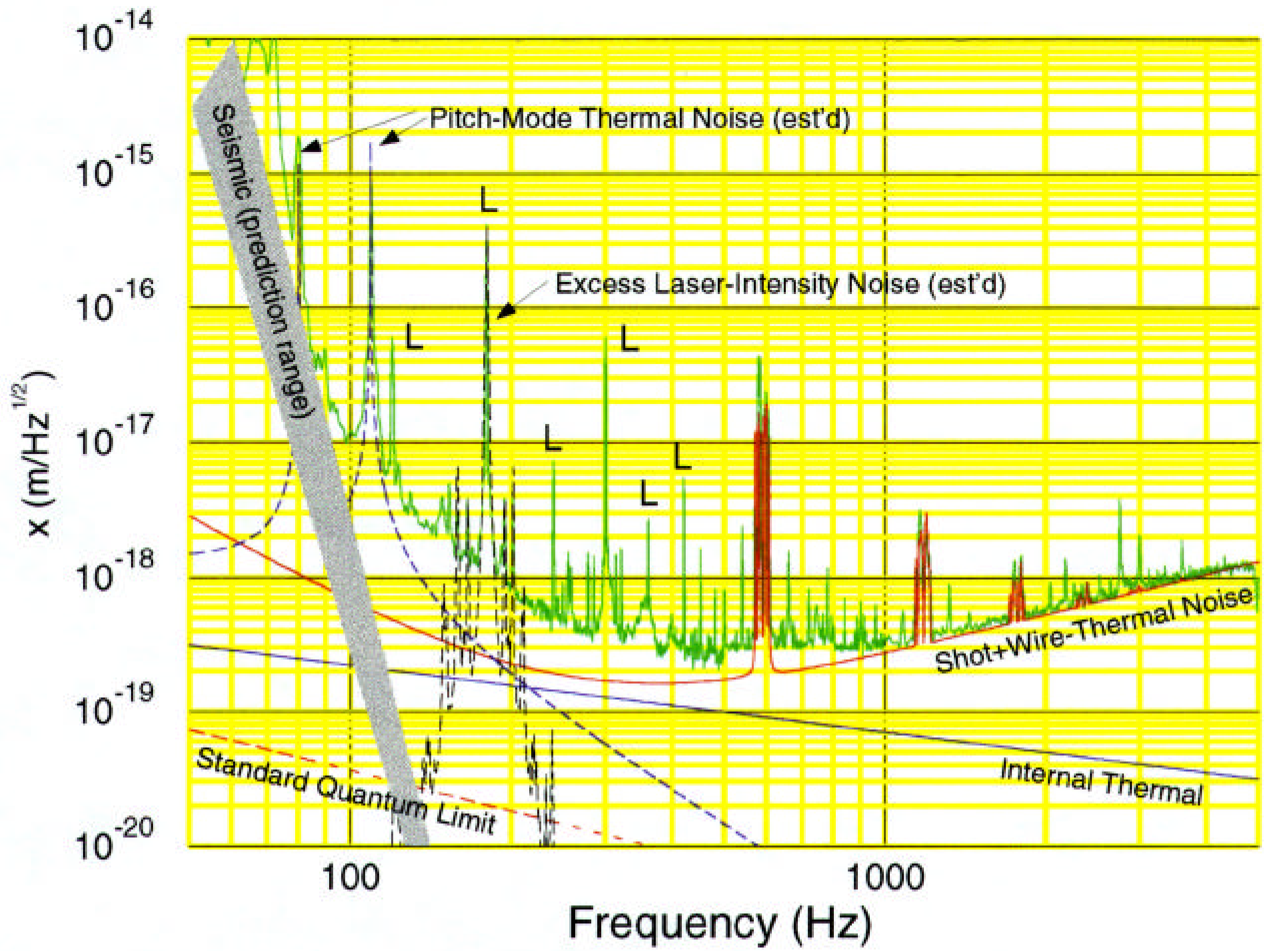
Pre-stabilized Laser Optical Layout



Digital Phase Control Test on Phase Noise Interferometer



Design for Low Background Spec'd From Prototype Operation



For Example:
Noise-Equivalent Displacement of 40-meter Interferometer (ca1994)

Earth Tide: Largest Source of Interferometer Drift