The LIGO-I Gravitational-wave Detectors

Stan Whitcomb

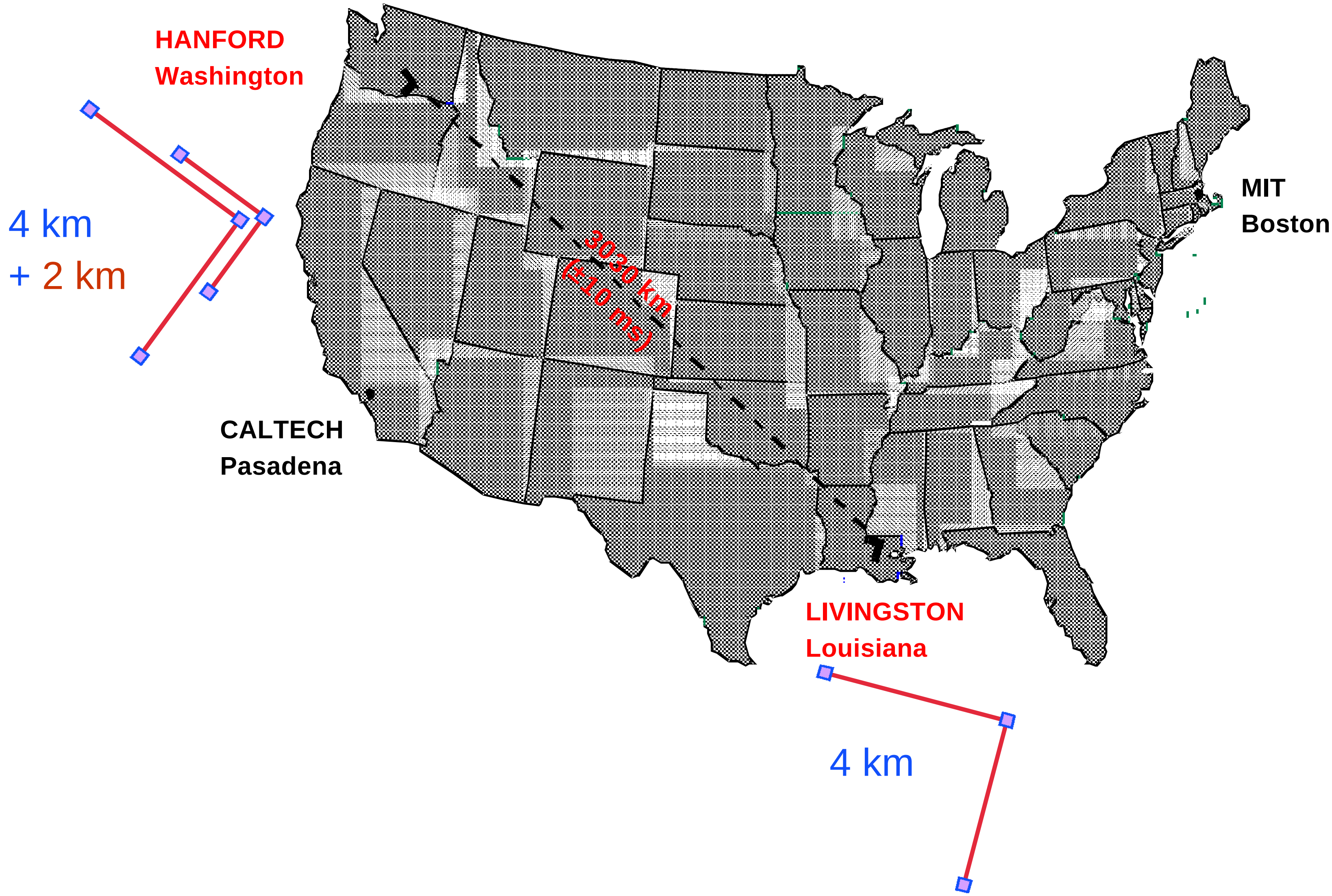
CaJAGWR Seminar

February 16, 2001

Outline of Talk

- Initial Performance Goals
- Detector Overview
  - What do the parts look like?
  - How does it work?
- Status
  - Installation and Commissioning
- Near-term Future

LIGO Observatories

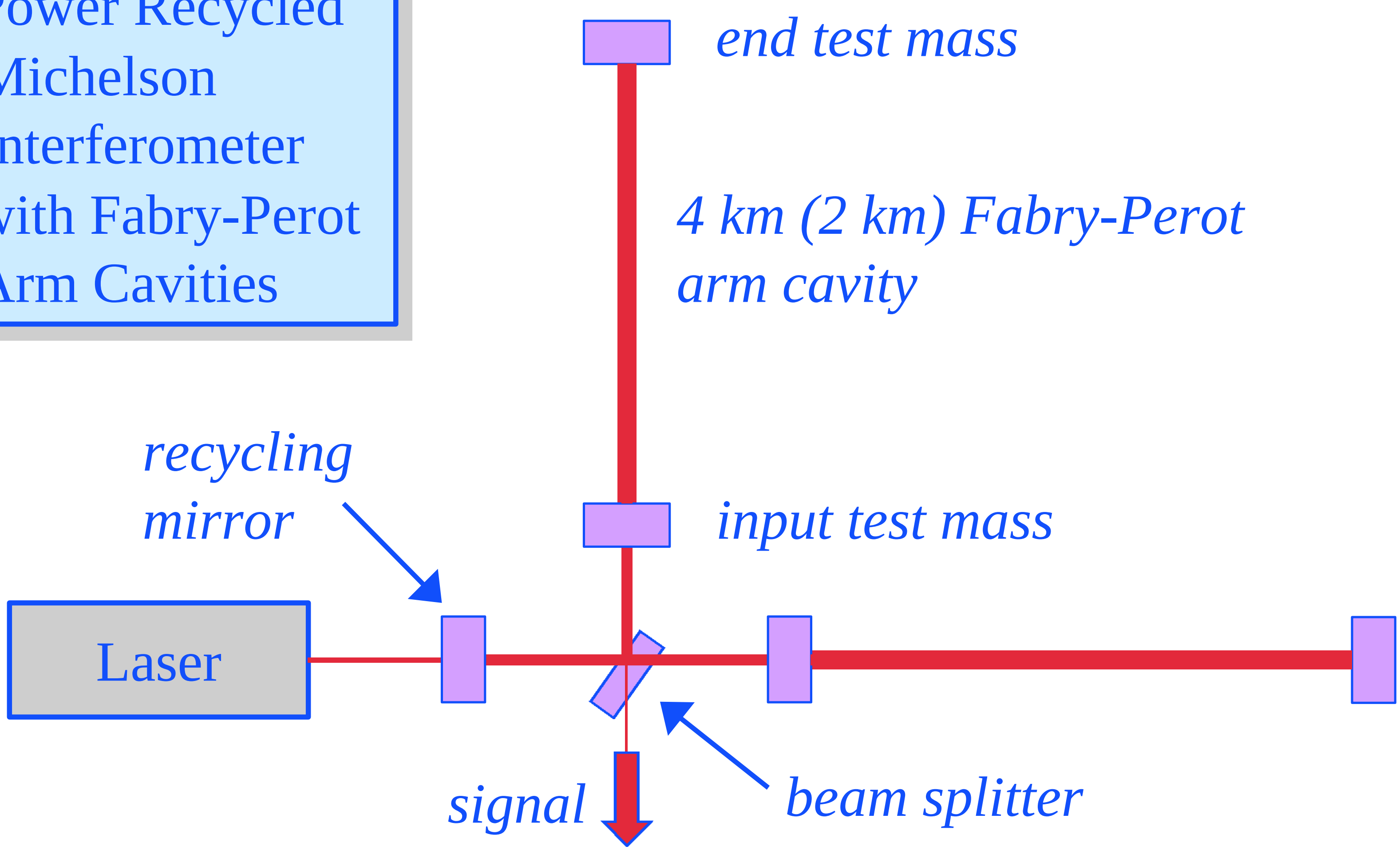


Initial LIGO Detector Status

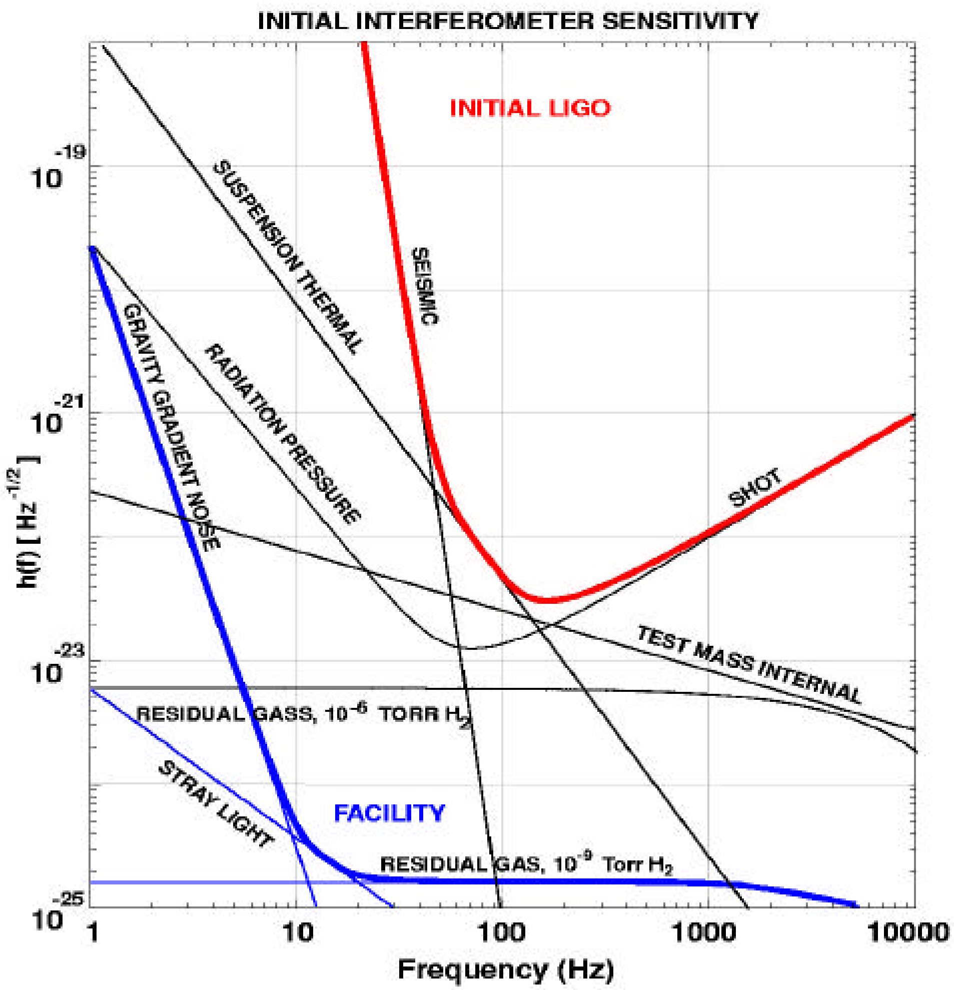
- Construction project - Finished
  - » Facilities, including beam tubes complete at both sites
- Detector installation
  - » Washington 2k interferometer complete
  - » Louisiana 4k interferometer complete
  - » Washington 4k interferometer in progress
- Interferometer commissioning
  - » Washington 2k full interferometer functioning
  - » Louisiana 4k individual arms being tested
- First astrophysical data run - 2002

Initial LIGO Interferometers

Power Recycled Michelson Interferometer with Fabry-Perot Arm Cavities



Initial LIGO Sensitivity Goal



- Strain sensitivity <3x10^{-23} 1/Hz$^{1/2}$

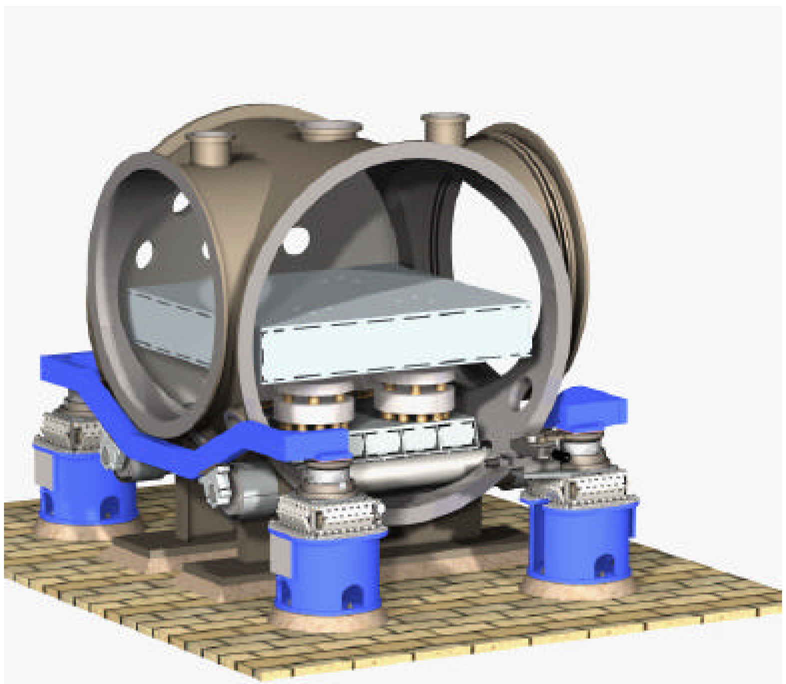
  at 200 Hz
- Sensing Noise
  - » Photon Shot Noise
  - » Residual Gas
- Displacement Noise
  - » Seismic motion
  - » Thermal Noise
  - » Radiation Pressure

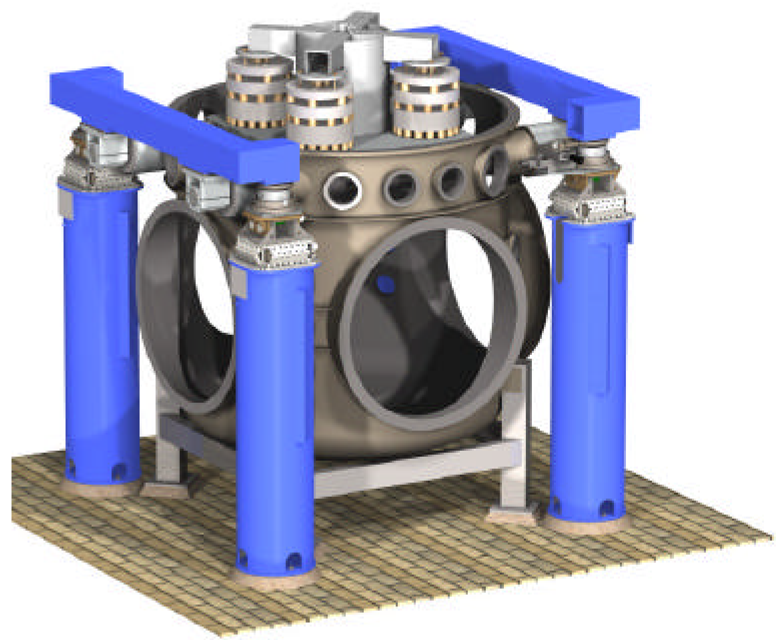
Vibration Isolation Systems

» Reduce in-band seismic motion by 4 - 6 orders of magnitude

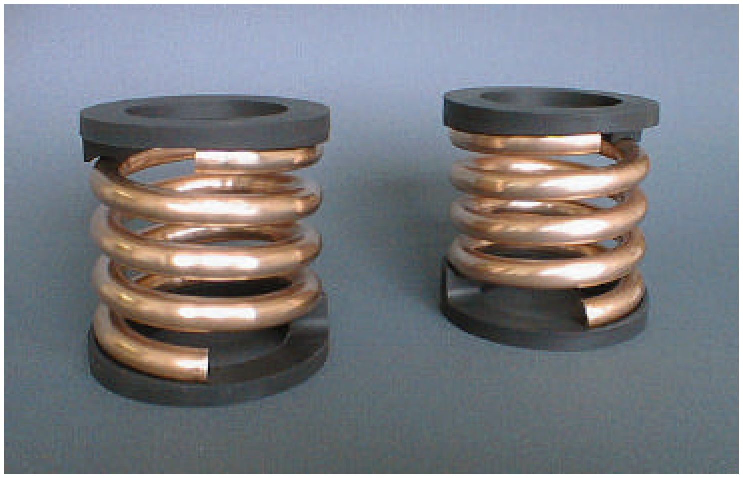
» Large range actuation for initial alignment and drift compensation

» Quiet actuation to correct for Earth tides and microseism at 0.15 Hz during observation

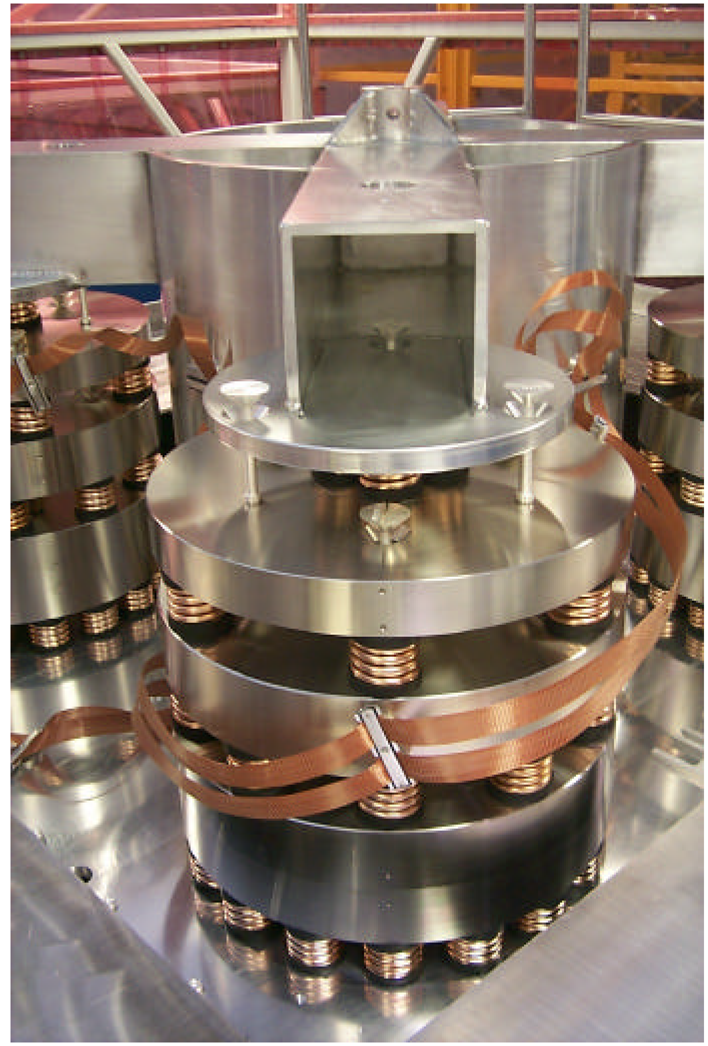




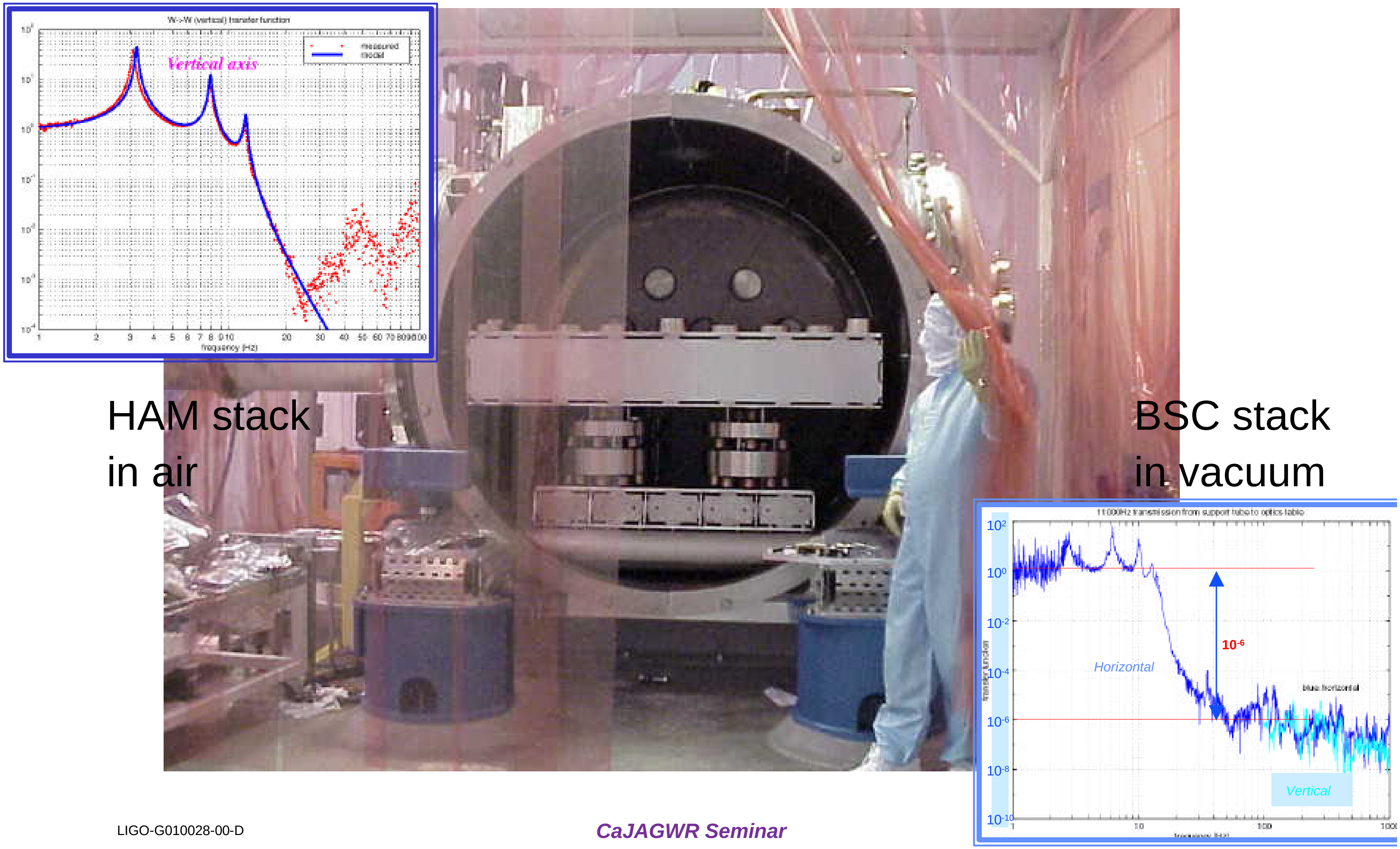
Seismic Isolation – Springs and Masses



damped spring
cross section



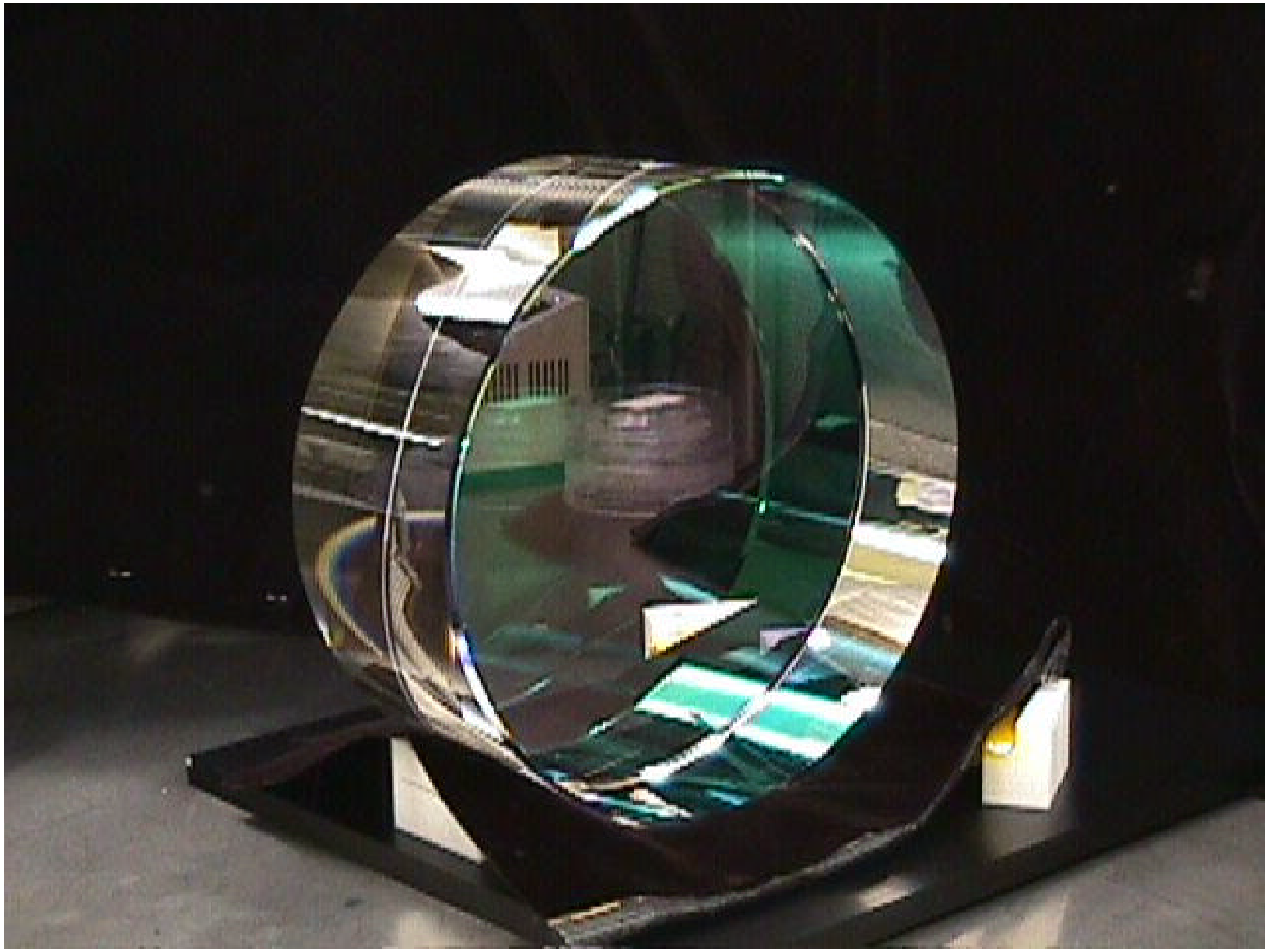
Seismic System Performance



HAM stack
in air

BSC stack
in vacuum

Core Optics

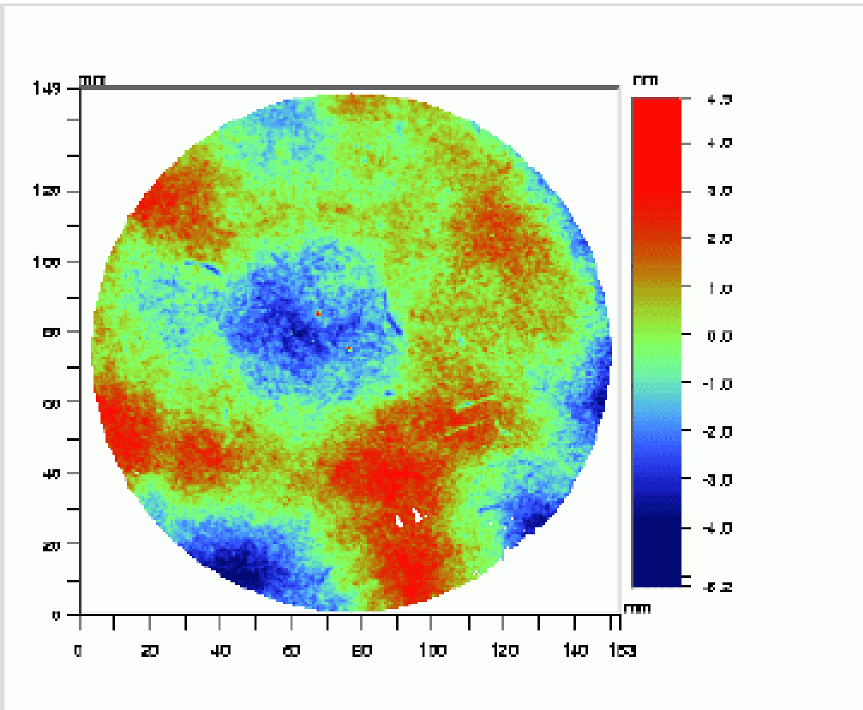


Core Optics Requirements

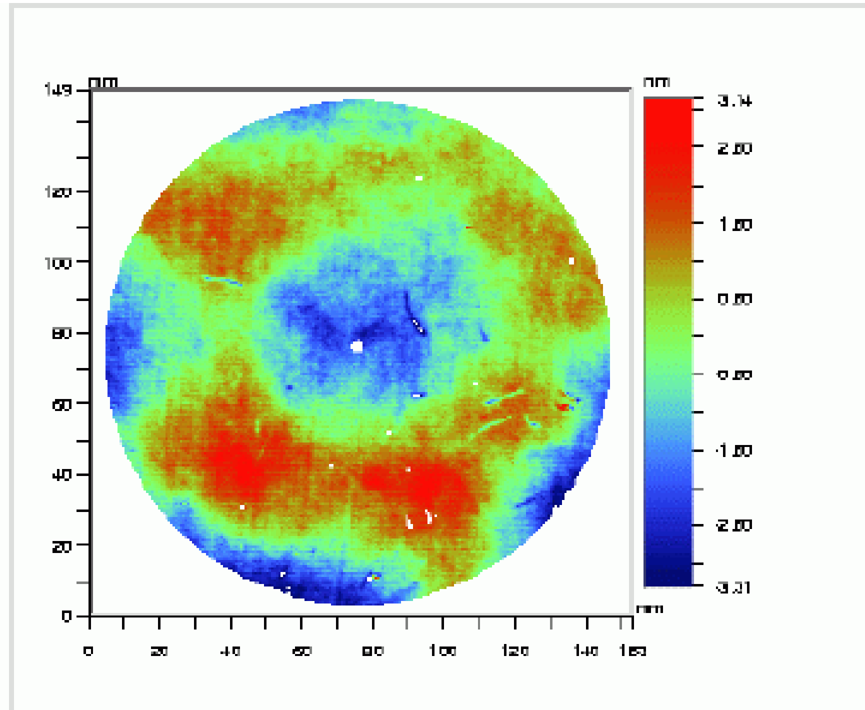
- Substrates
  - 25 cm Diameter, 10 cm thick
  - Homogeneity < 5 x 10^{-7}
  - Internal mode Q's > 2 x 10^{6}
- Polishing
  - Surface uniformity < 1 nm rms
  - ROC matched < 3%
- Coating
  - Scatter < 50 ppm
  - Absorption < 2 ppm
  - Uniformity <10^{-3}
- Successful production eventually involved 6 companies, NIST and the LIGO Lab

Core Optic Metrology

- Current state of the art: 0.2 nm repeatability

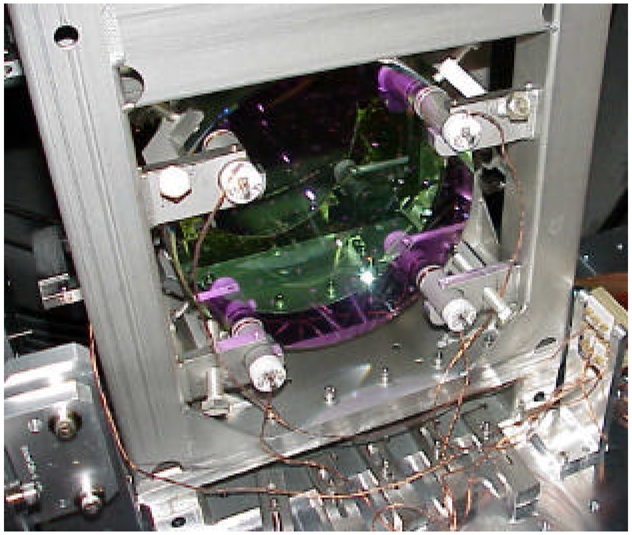


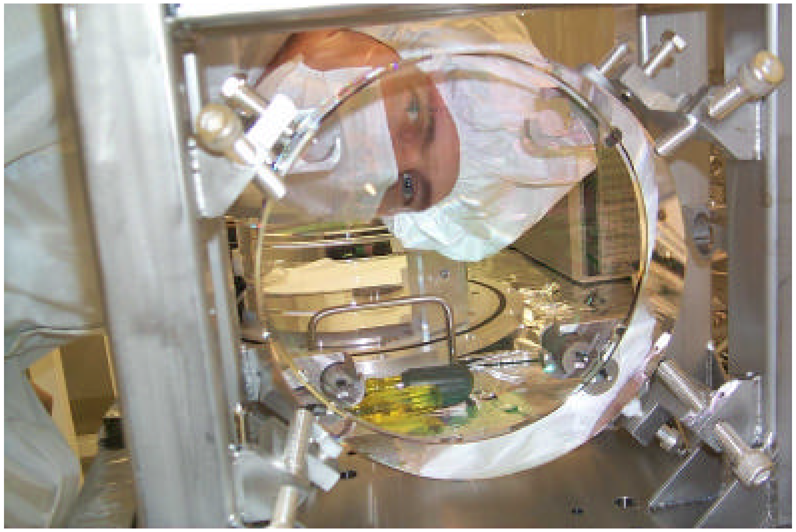
LIGO data (1.2 nm rms)



CSIRO data (1.1 nm rms)

Core Optics Suspension and Control

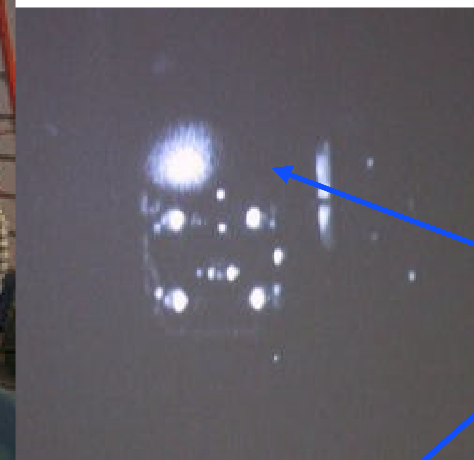




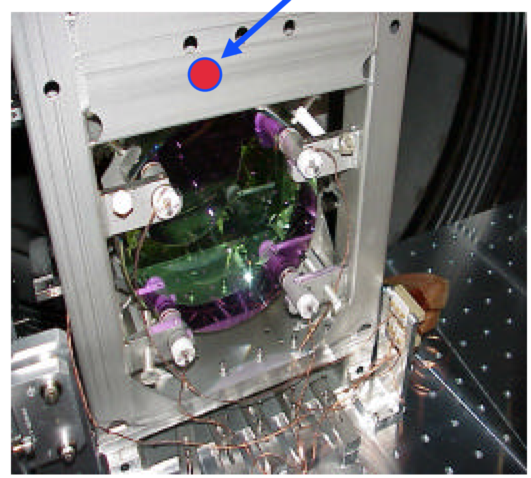
Core Optics Installation and Alignment

Initial Alignment Requirement:
100 microradians (50 goal)

Confirmation of Initial Alignment



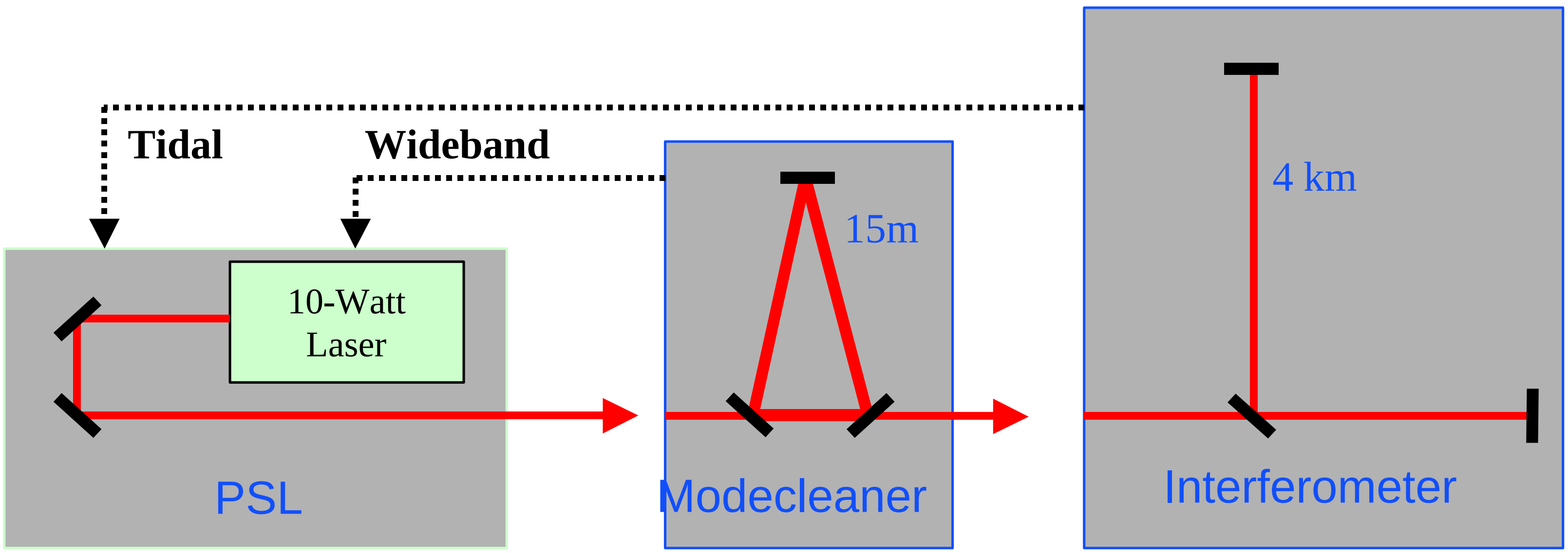
beam
spot



- Opening gate valves revealed alignment “dead reckoned” from corner station was within 100 micro radians
- First 8 optics!

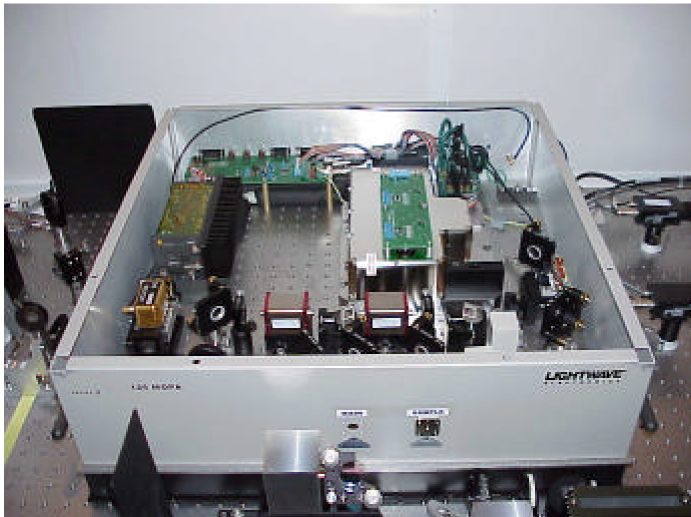
Pre-stabilized Laser

- Deliver pre-stabilized laser light to the 15-m mode cleaner
  - **Frequency fluctuations**
  - **In-band power fluctuations**
  - **Power fluctuations at 25 MHz**
- Provide actuator inputs for further stabilization
  - **Wideband**
  - **Tidal**

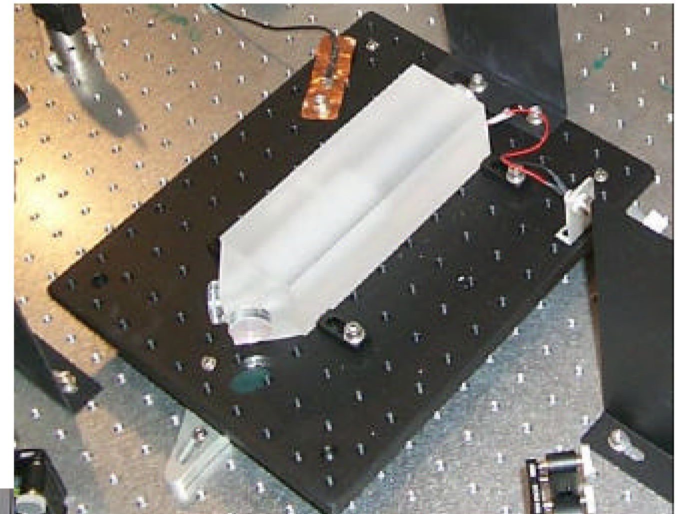


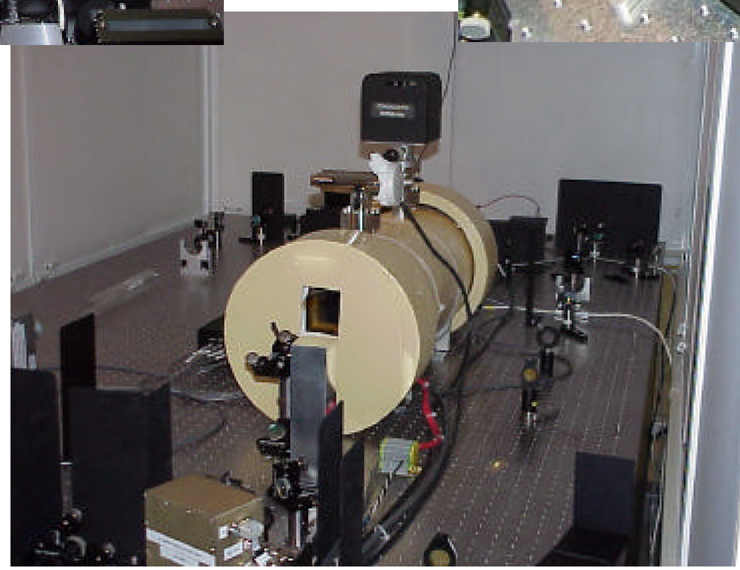
10^{-1} Hz/Hz$^{1/2}$ 10^{-4} Hz/ Hz$^{1/2}$ 10^{-7} Hz/ Hz$^{1/2}$

Washington 2k Pre-stabilized Laser



Custom-built
10 W Nd:YAG
Laser

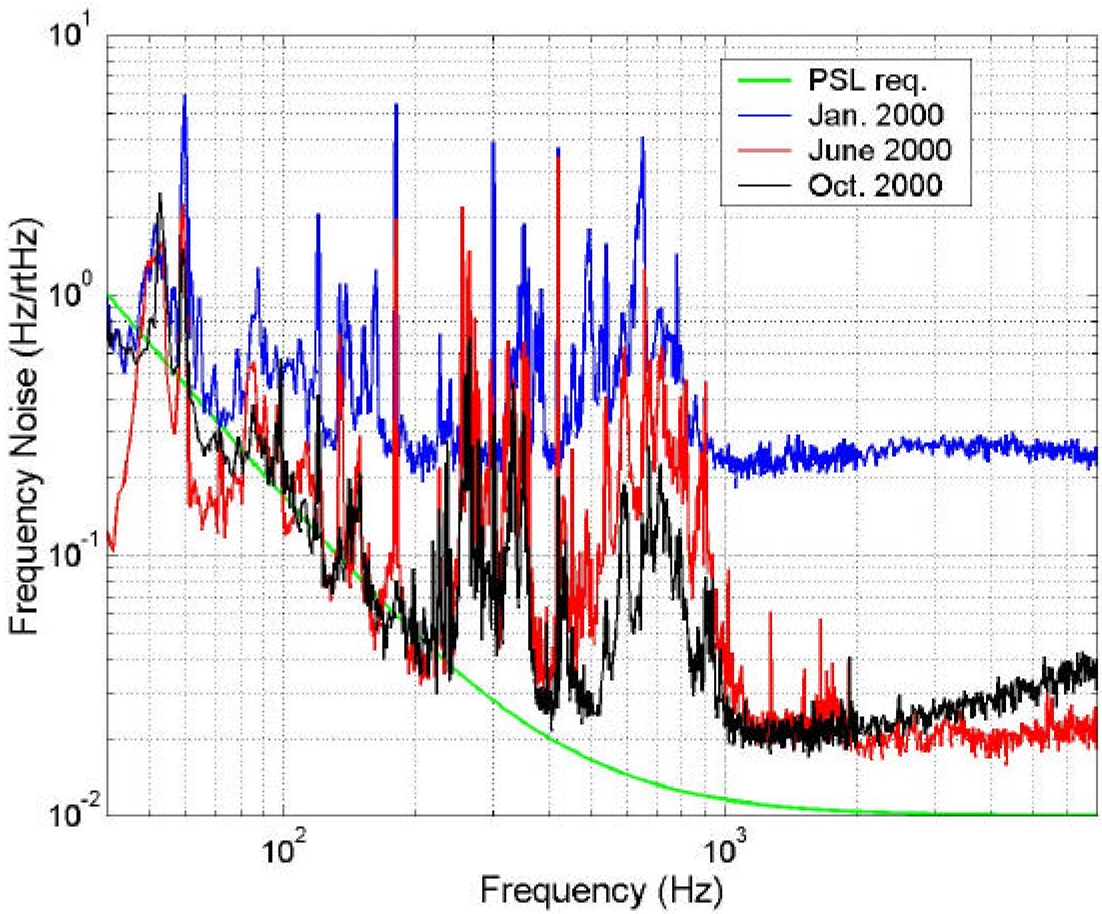




Stabilization cavities
for frequency
and beam shape

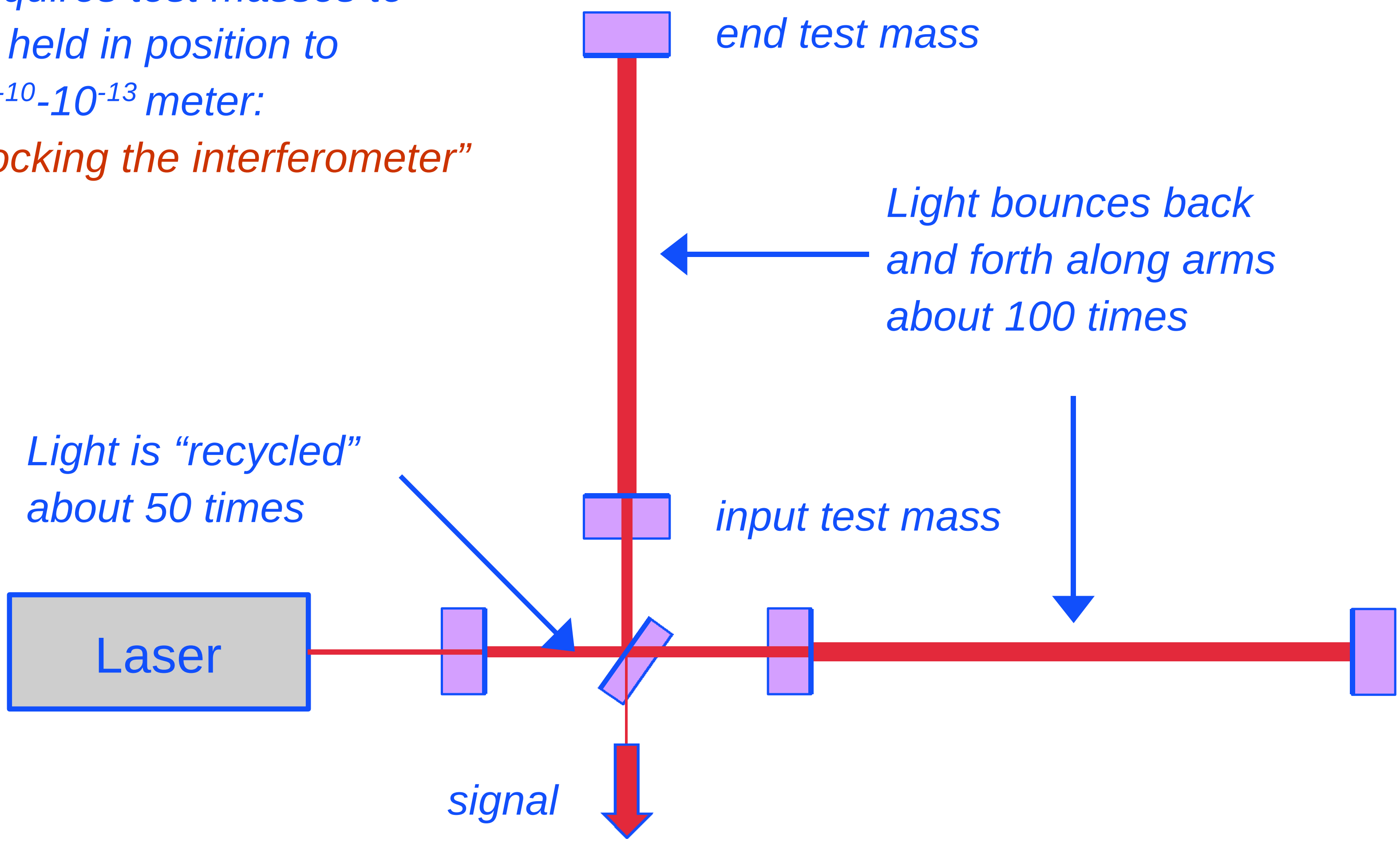
WA 2k Pre-stabilized Laser Performance

- > 20,000 hours continuous operation
- Frequency lock very robust
- TEM_{00} power >8 W delivered to input optics
- Non-TEM_{00} power < 10%
- Improvement in noise performance
  - » electronics
  - » acoustics
  - » vibrations



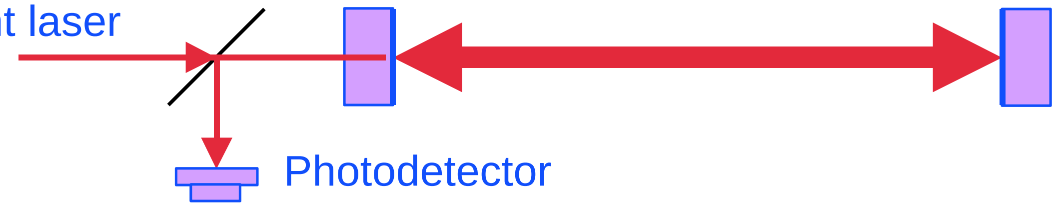
LIGO Interferometers

Requires test masses to be held in position to 10^{-10}-10^{-13} meter:
"Locking the interferometer"



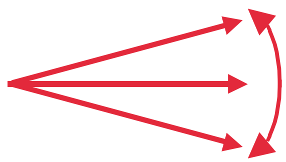
Reflection Locking a Single Cavity

- "Pound-Drever-Hall locking"



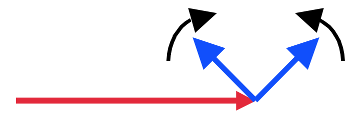
Phase Modulation

$$E_{opt}(t) = \mathrm{Re}(E_{LF}(t)e^{i(w-w_c)t})$$

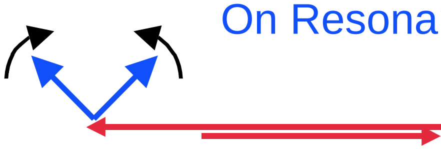


Decomposition into

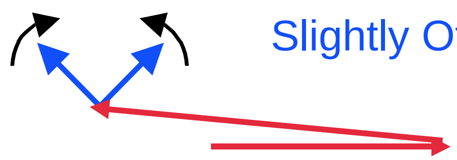
carrier and sidebands



On Resonance



Slightly Off Resonance



$$\frac{dV}{dL} \propto E_c E_{sb}$$

Carrier Resonance Conditions

Resonate carrier in arms

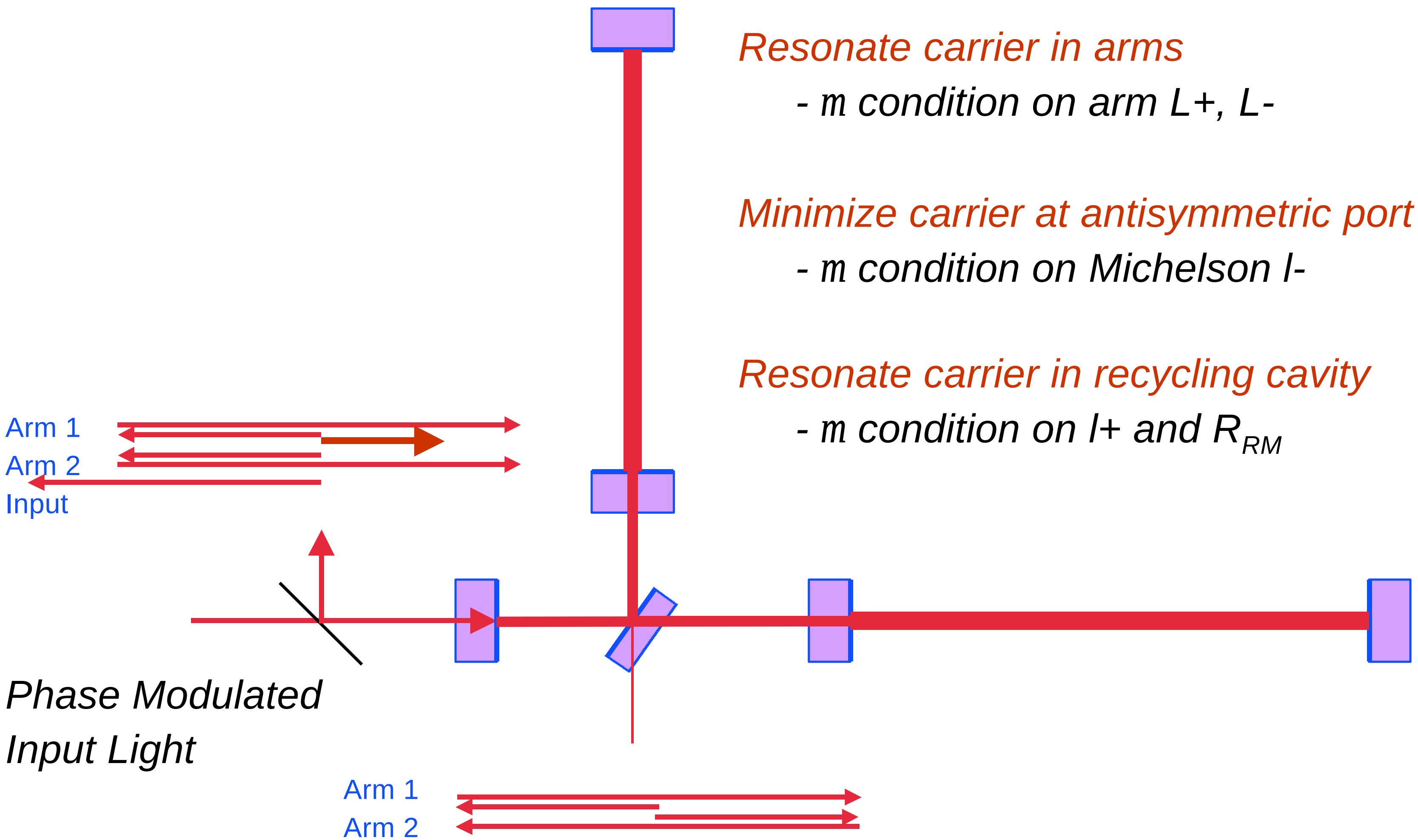
- *m condition on arm L+, L-*

Minimize carrier at antisymmetric port

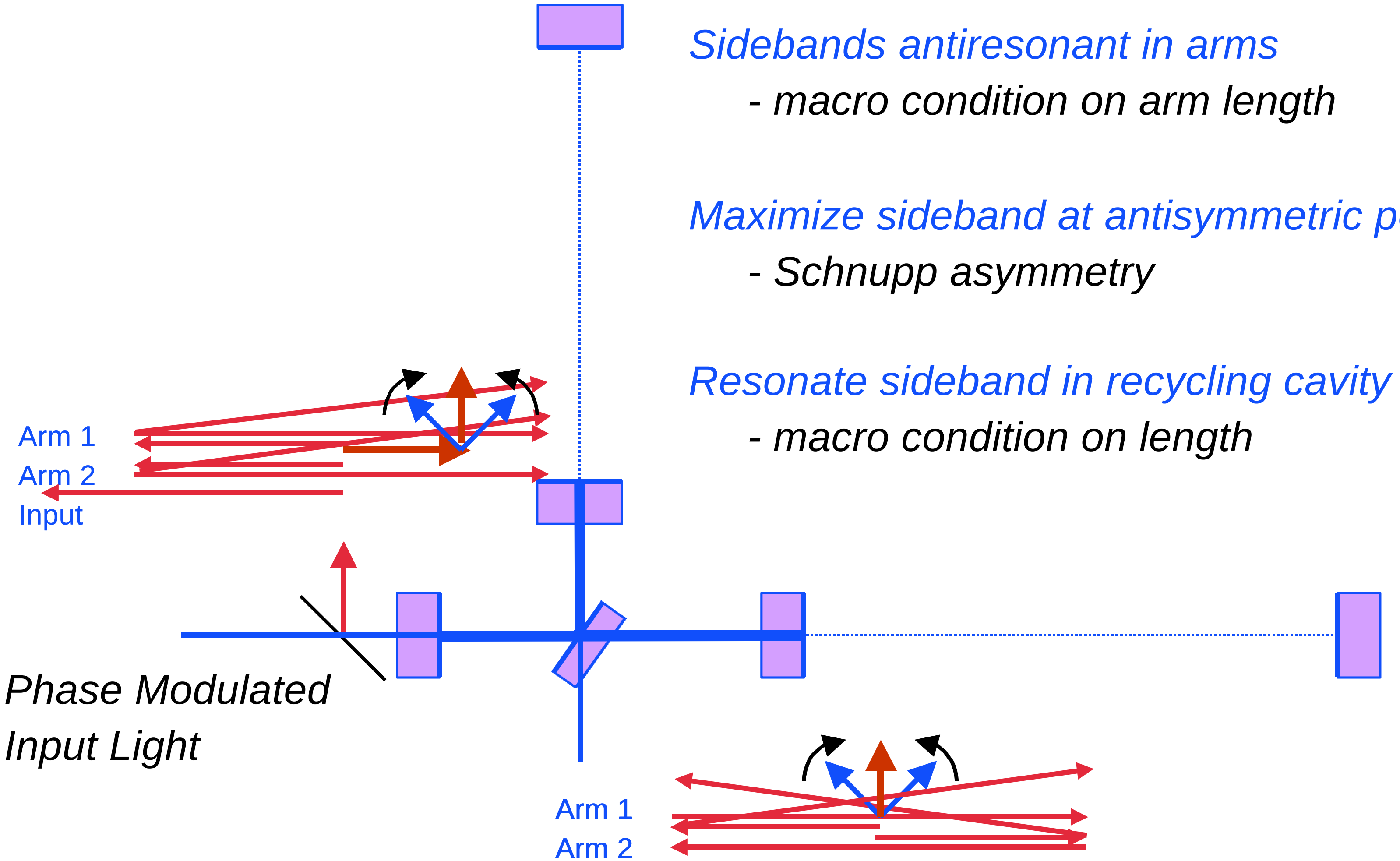
- *m condition on Michelson l-*

Resonate carrier in recycling cavity

- *m condition on l+ and R_{RM}*



Sideband Resonance Conditions

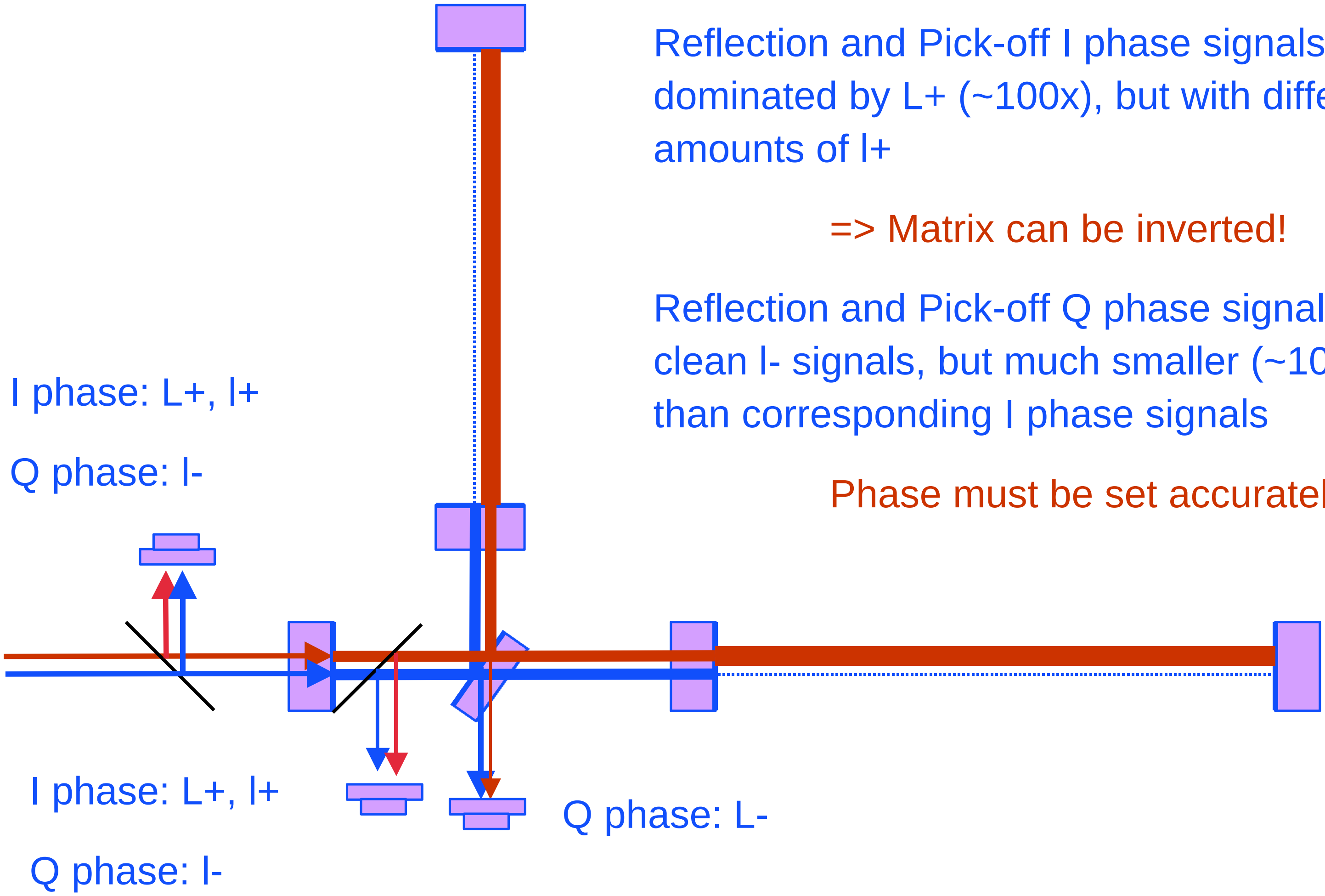


Sidebands antiresonant in arms
- *macro condition on arm length*

Maximize sideband at antisymmetric port
- *Schnupp asymmetry*

Resonate sideband in recycling cavity
- *macro condition on length*

In-lock Sensing Points



Reflection and Pick-off I phase signals both dominated by L+ (~100x), but with different amounts of l+

=> Matrix can be inverted!

Reflection and Pick-off Q phase signals are clean l- signals, but much smaller (~100x) than corresponding I phase signals

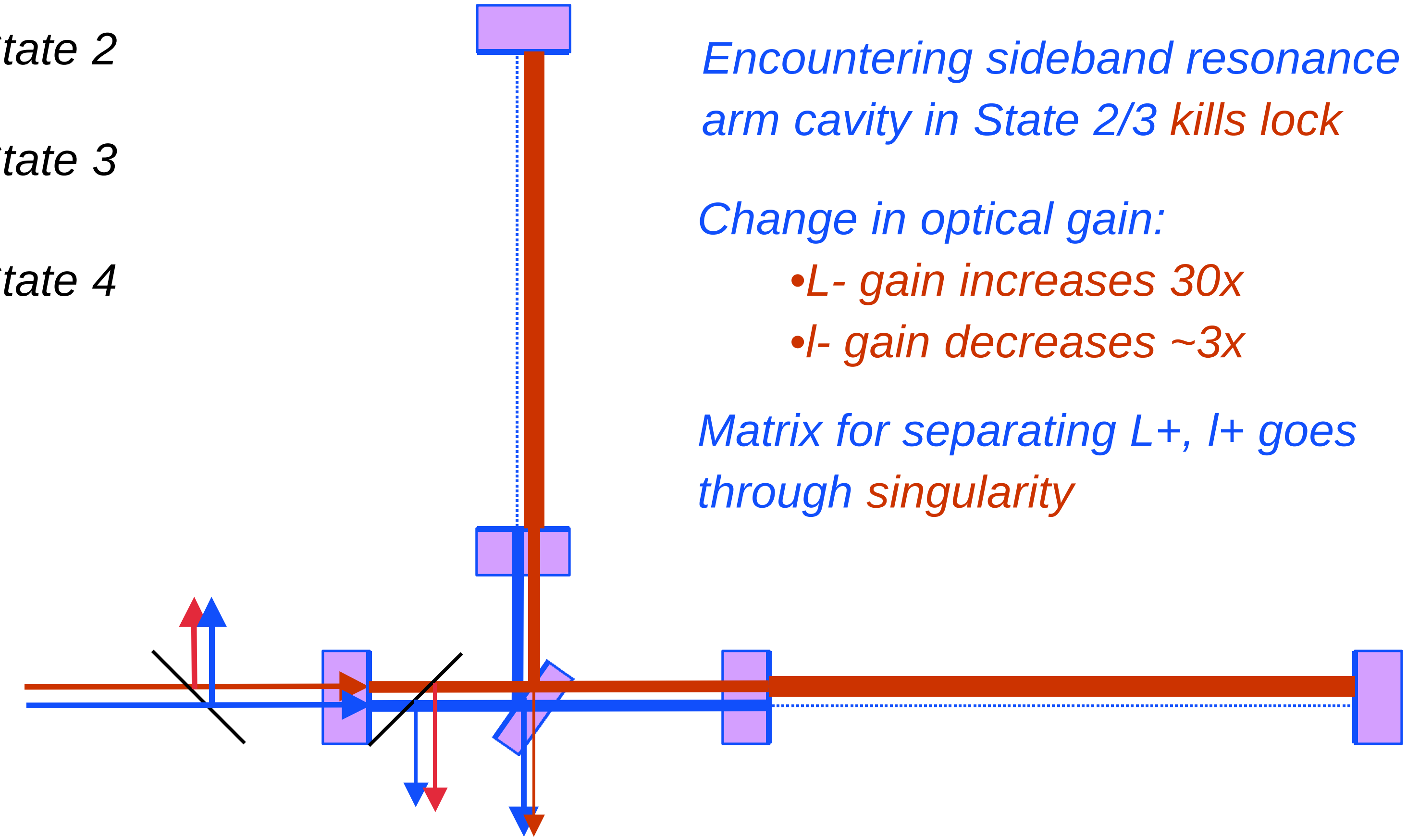
Phase must be set accurately

Lock Acquisition Sequence

State 2

State 3

State 4

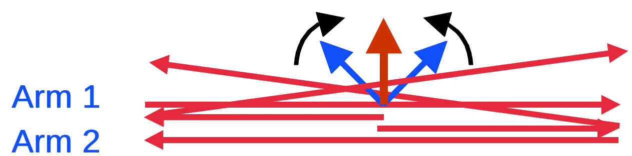


Encountering sideband resonance in arm cavity in State 2/3 kills lock

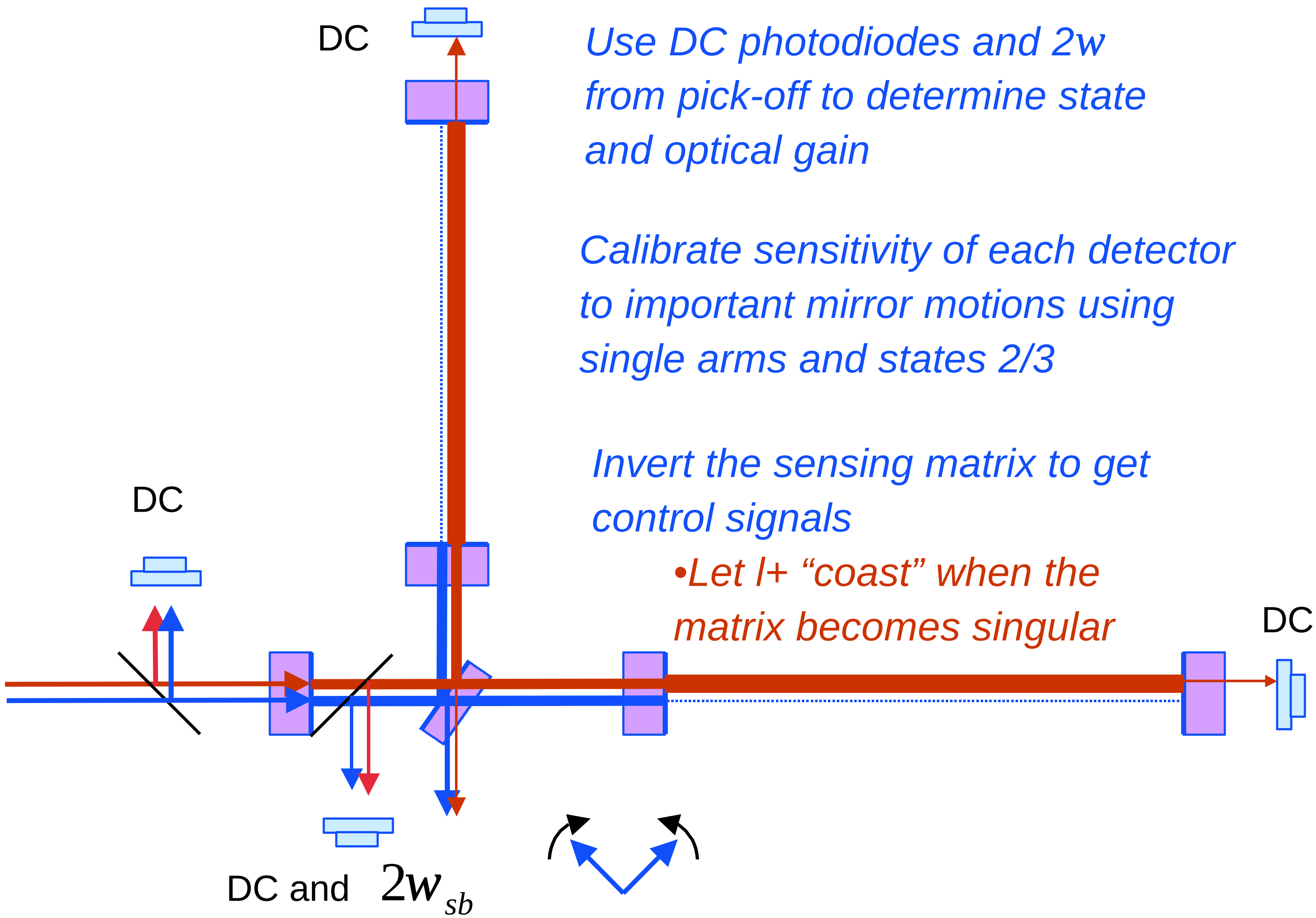
Change in optical gain:

- *L- gain increases 30x*
- *l- gain decreases ~3x*

Matrix for separating L+, l+ goes through singularity



Matt's "Lock Acquisition Program"



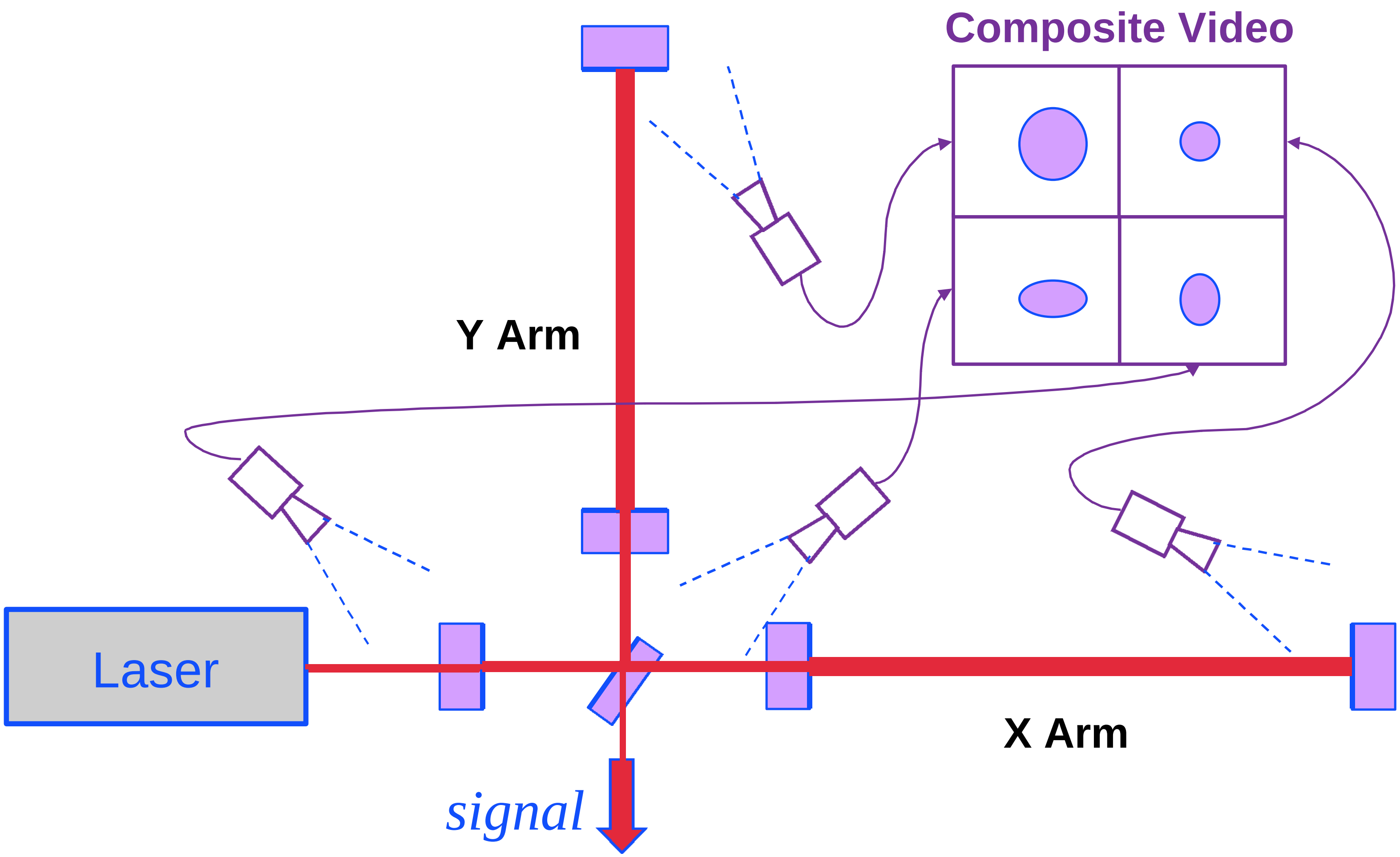
Use DC photodiodes and 2w from pick-off to determine state and optical gain

Calibrate sensitivity of each detector to important mirror motions using single arms and states 2/3

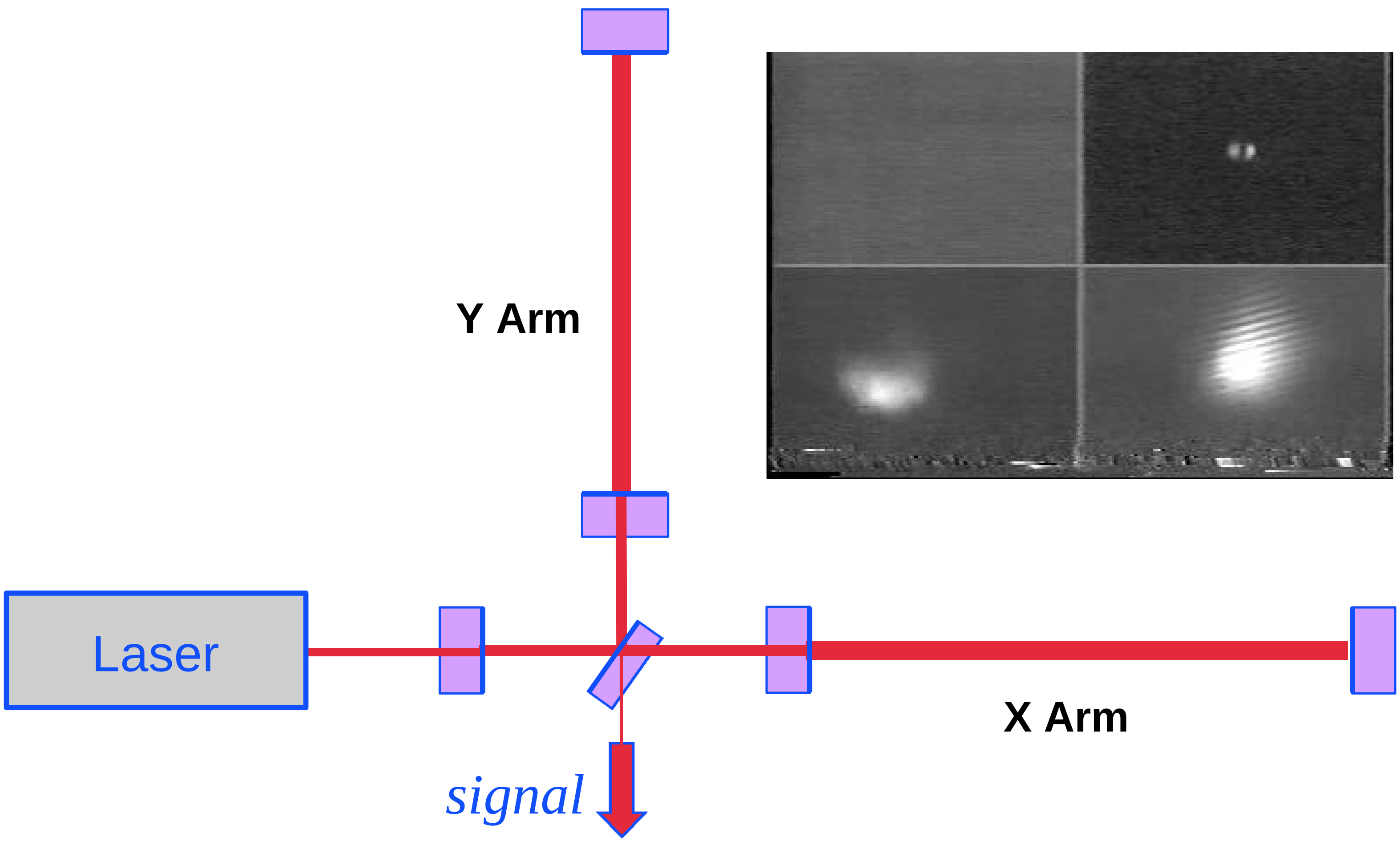
Invert the sensing matrix to get control signals

- *Let l+ "coast" when the matrix becomes singular*

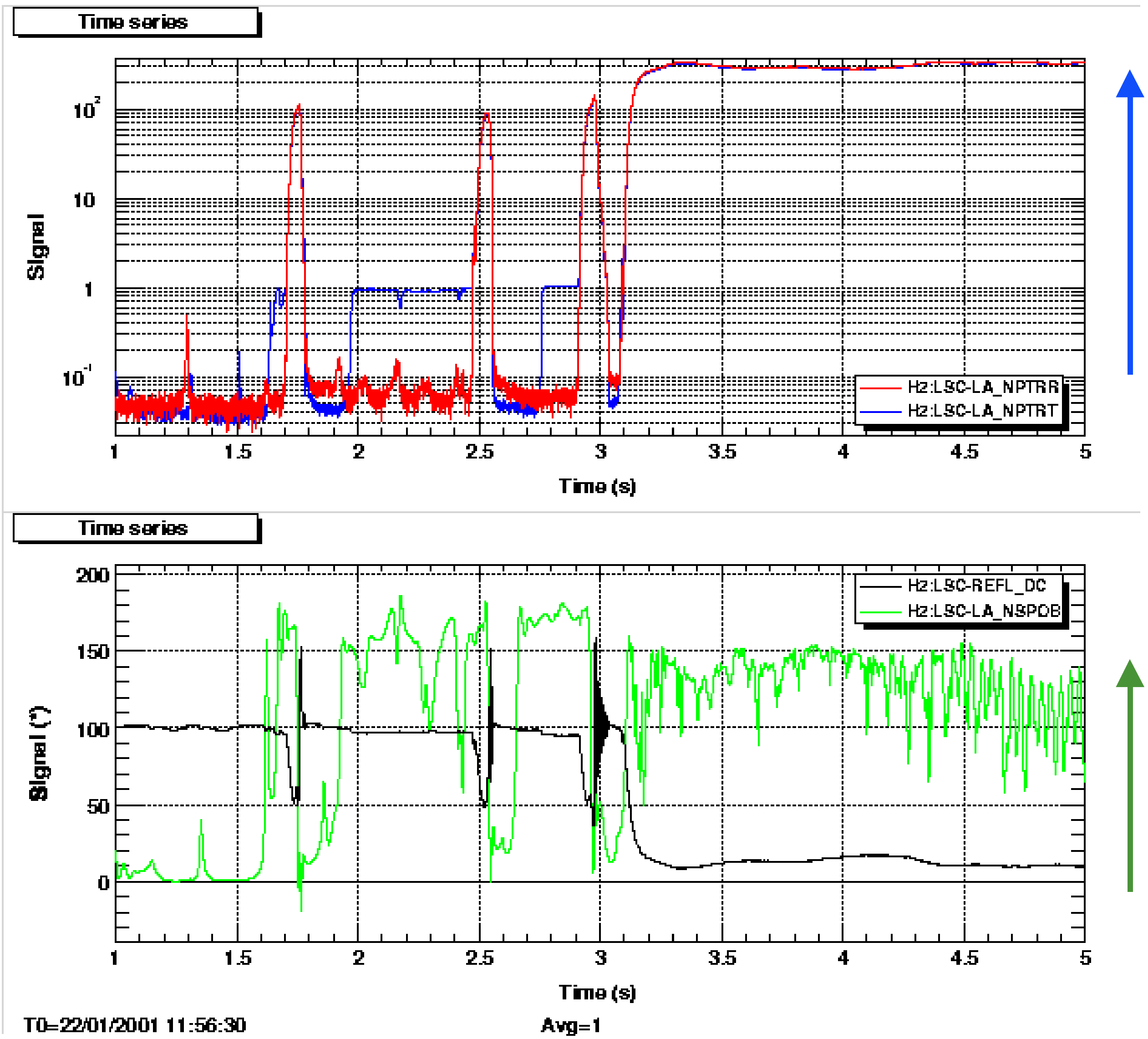
Steps to Locking an Interferometer



Watching the Interferometer Lock



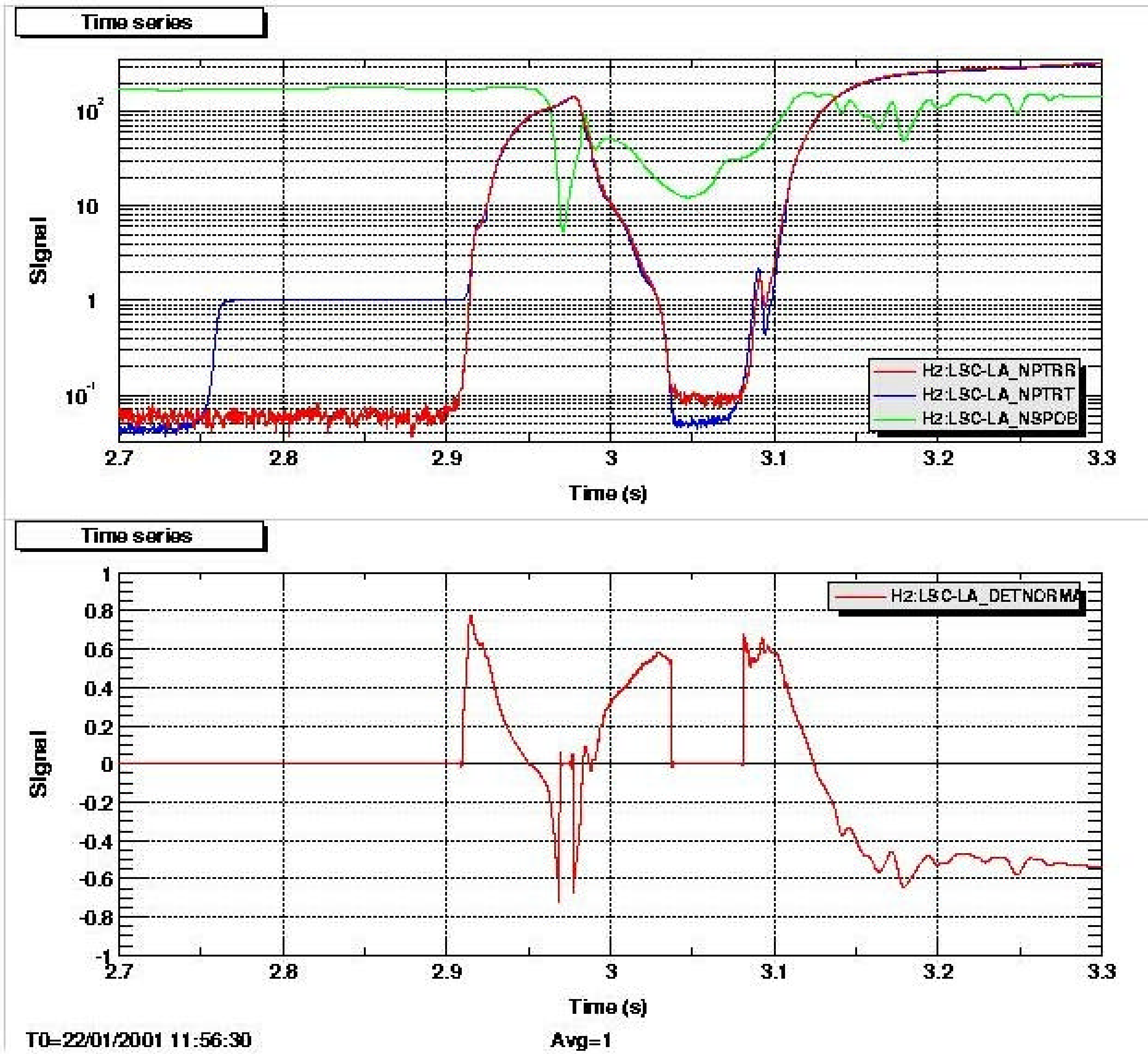
Lock Acquisition Example



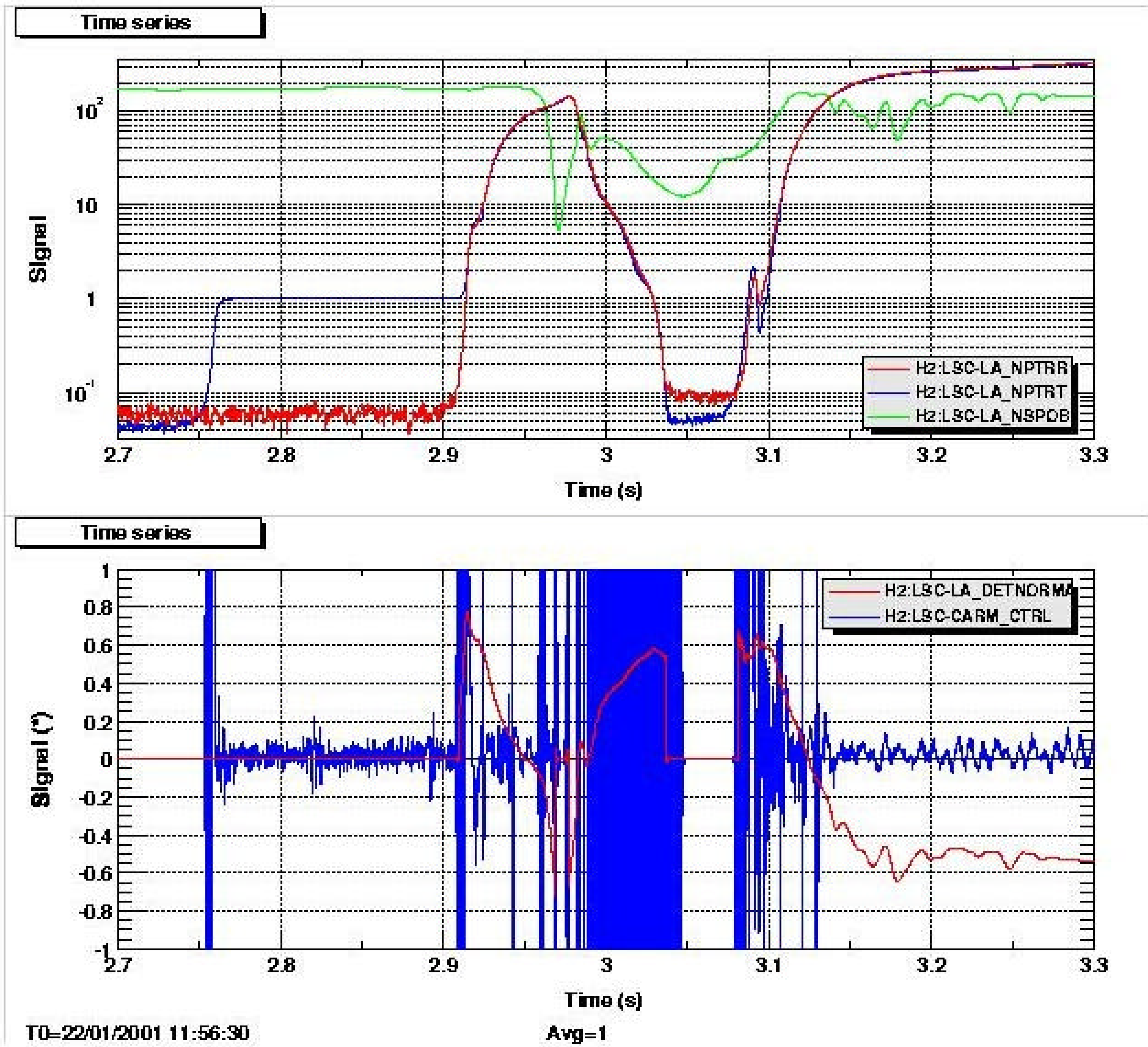
Carrier Recycling Gain ~10

Sideband Recycling Gain ~5

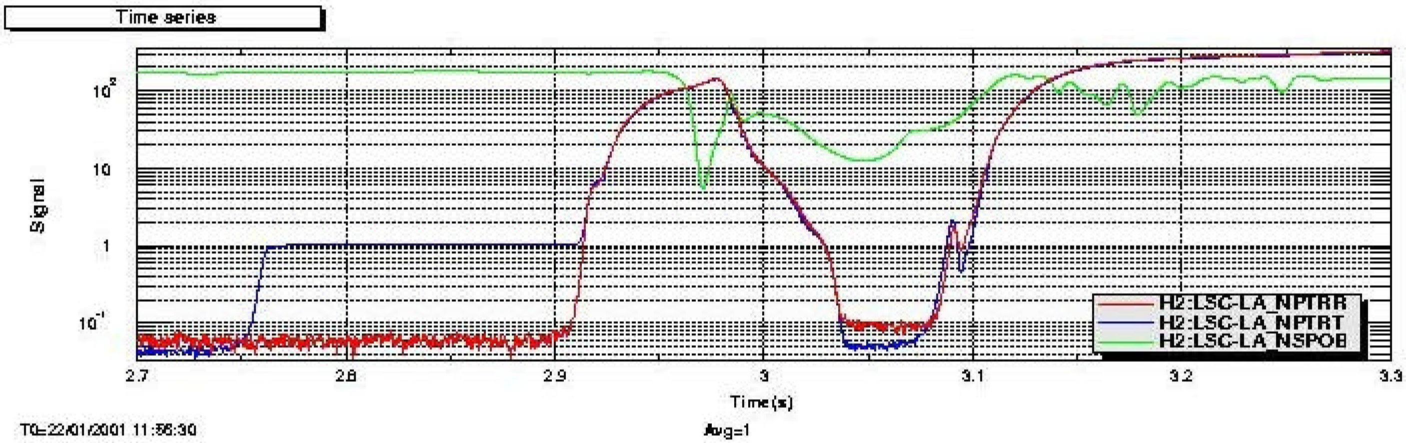
Closeup of Lock Acquisition

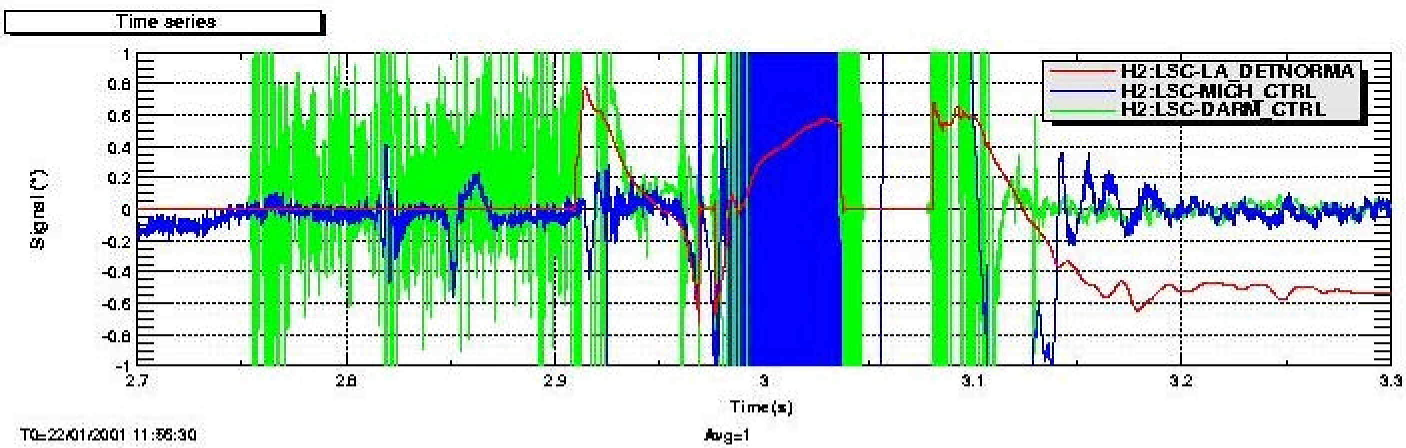


Common Mode Control Signals

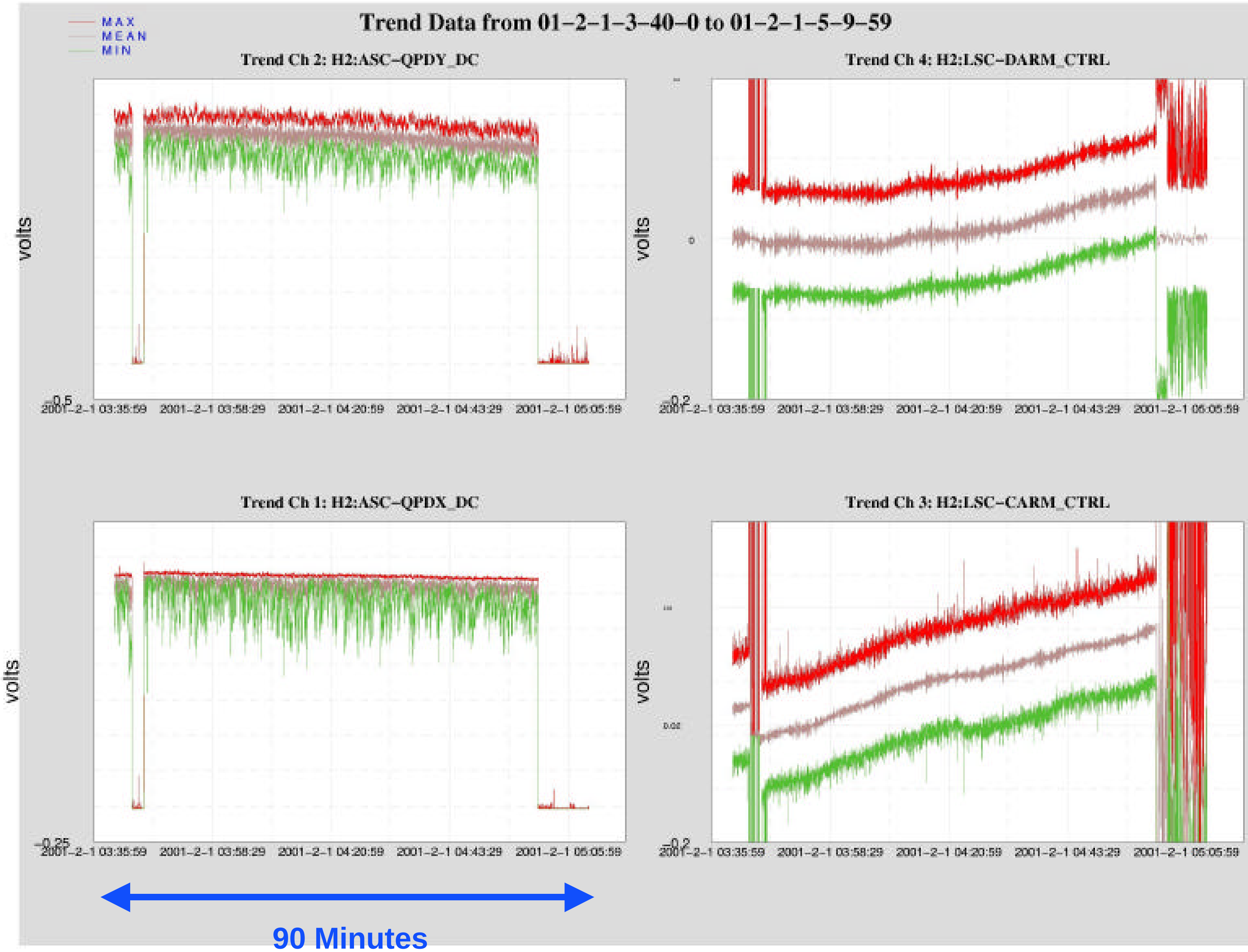


Differential Mode Control Signals



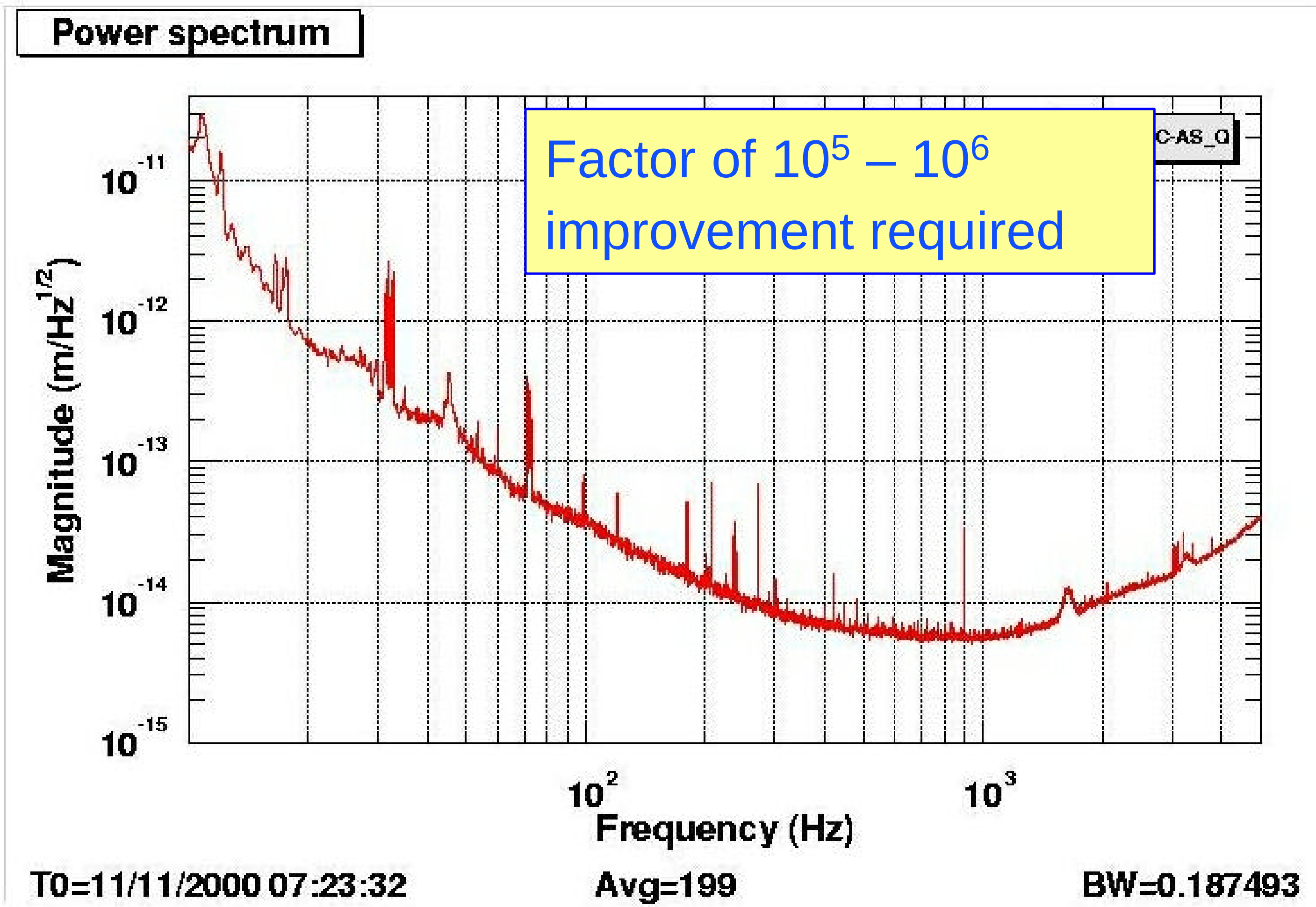


Full Interferometer Locking

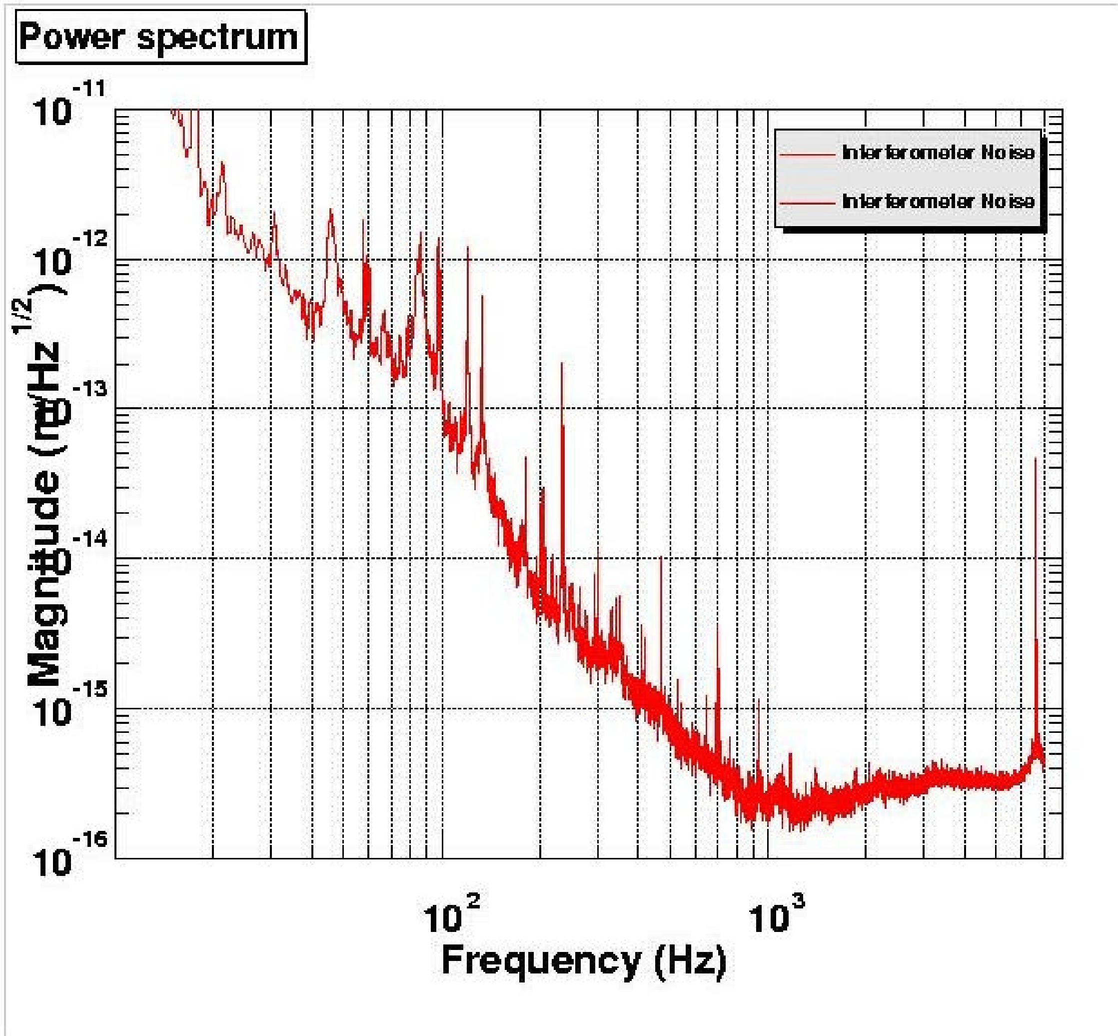


First Interferometer Noise Spectrum

Recombined Michelson with F-P Arms (no recycling) – November 2000



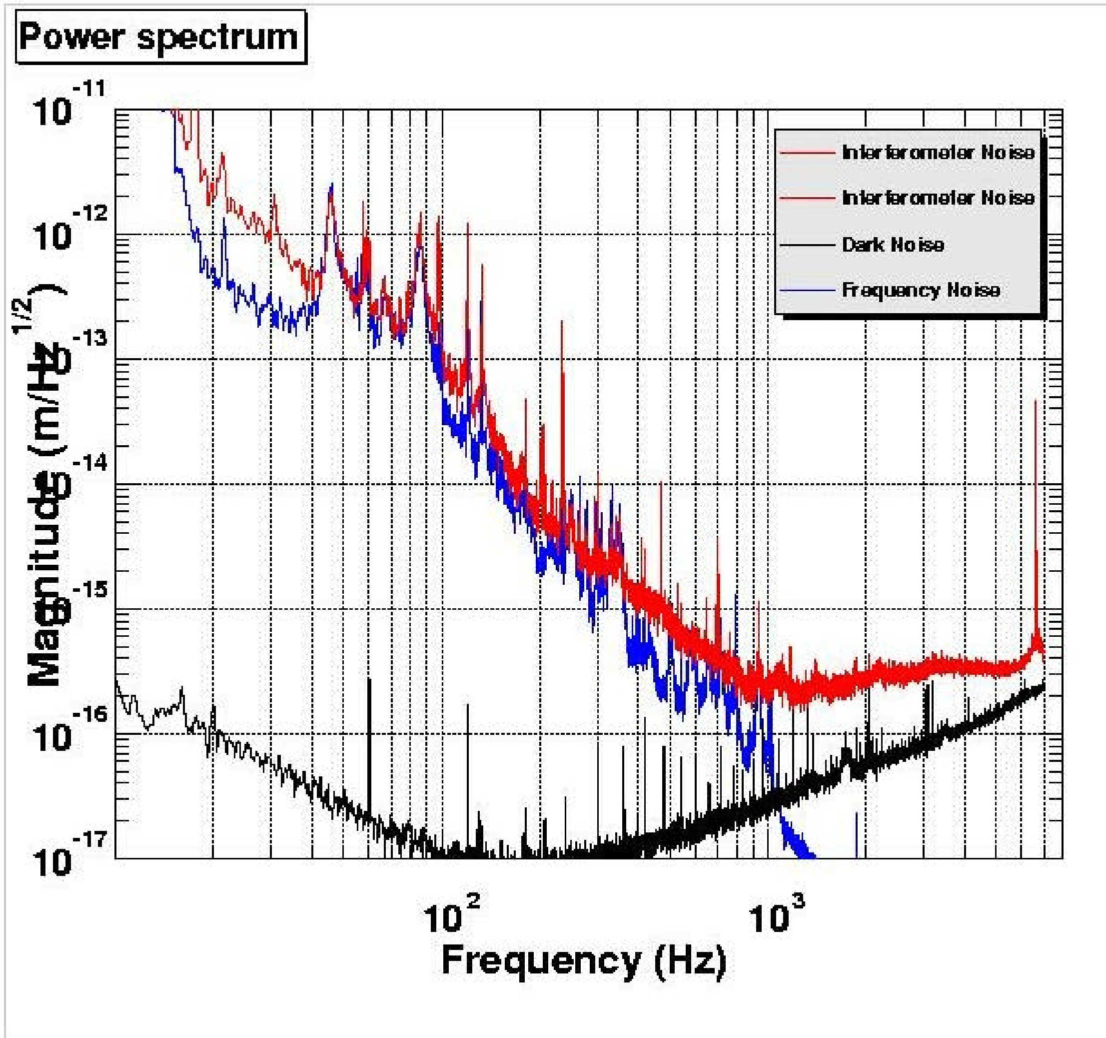
Improved Noise Spectrum



9 February 2001

- Recycling
- Reduction of electronics noise
- Partial implementation of alignment control

Known Contributors to Noise

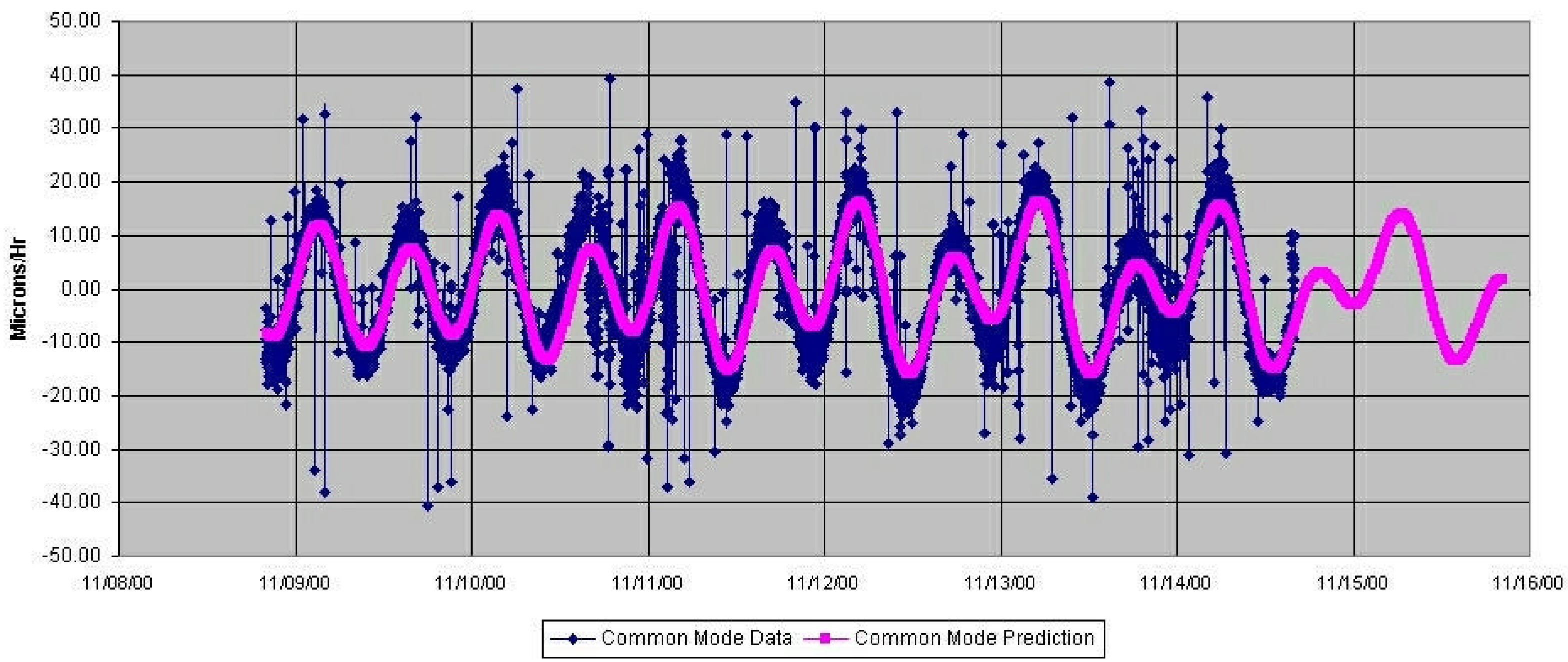


New servo to improve frequency stabilization installed last week

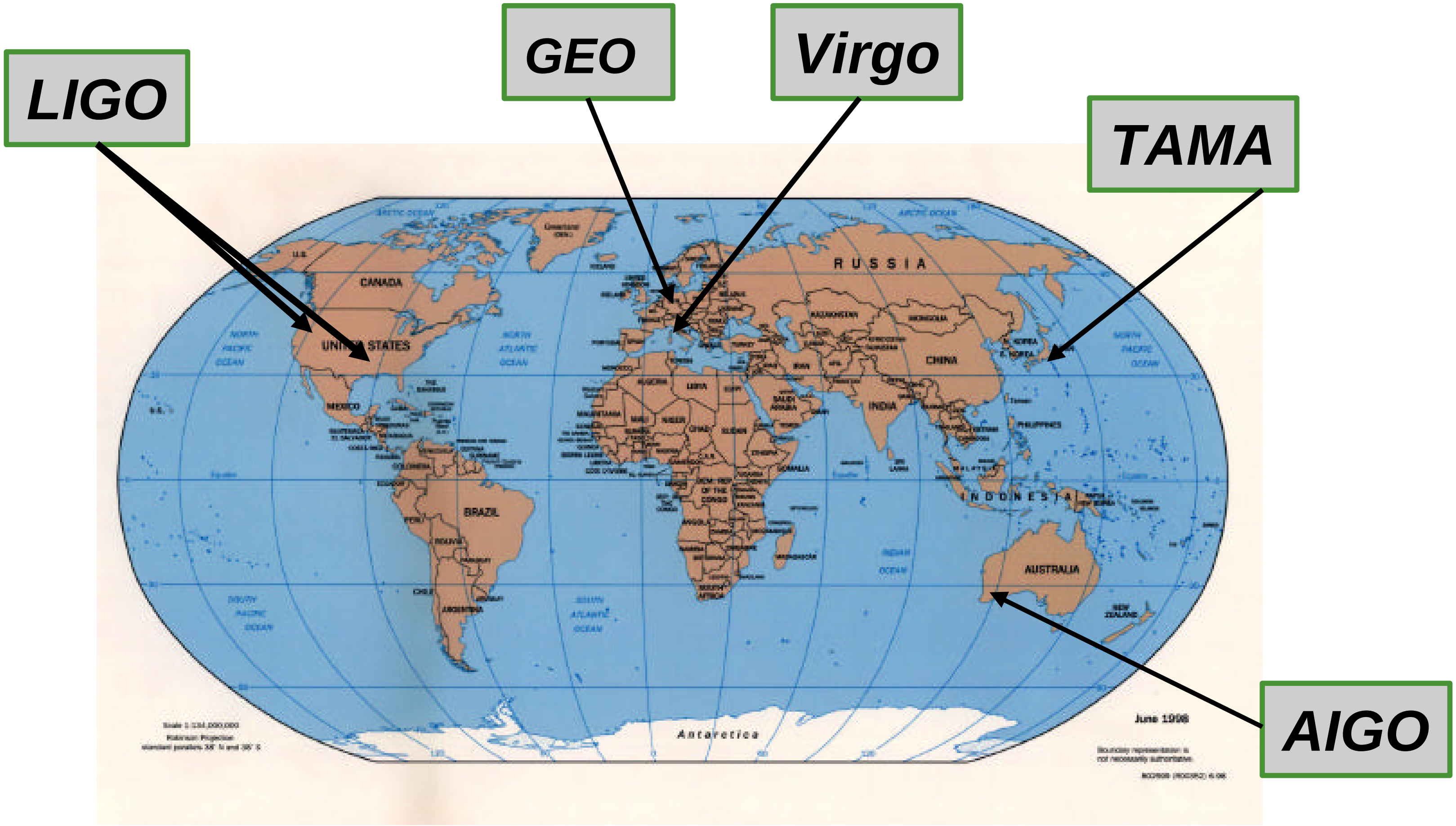
Testing underway

Example: Earthtide Investigation

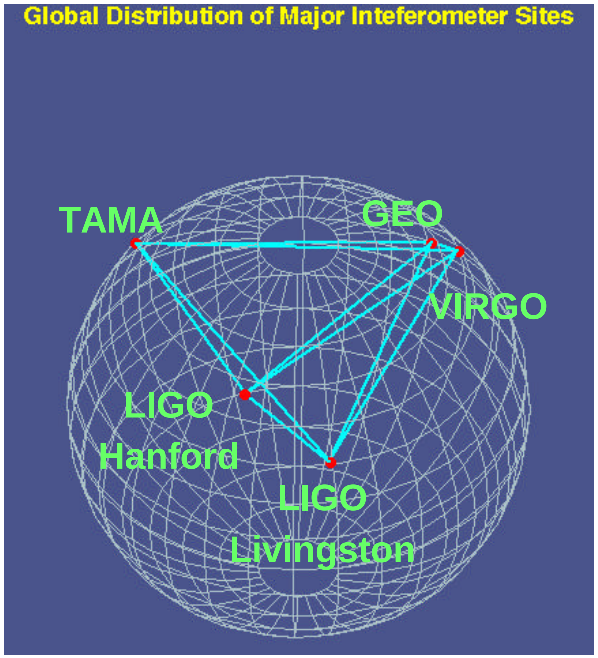
- One week continuous operation as recombined F-P Michelson (no recycling) -- November 2000
- ~200 microns P-to-P (main cause of loss of lock during run)
- Input to design of tidal actuator needed for continuous lock
- Common mode (both arms stretch together) and differential mode (arms stretch by different amounts)

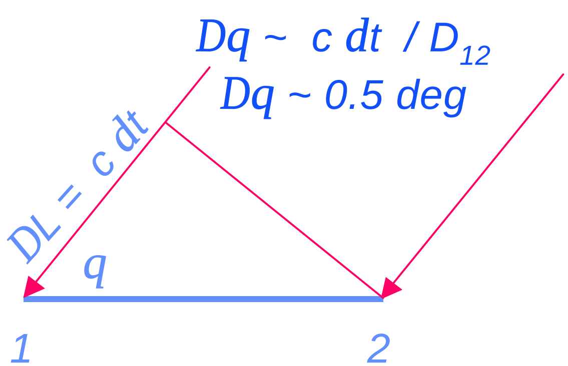


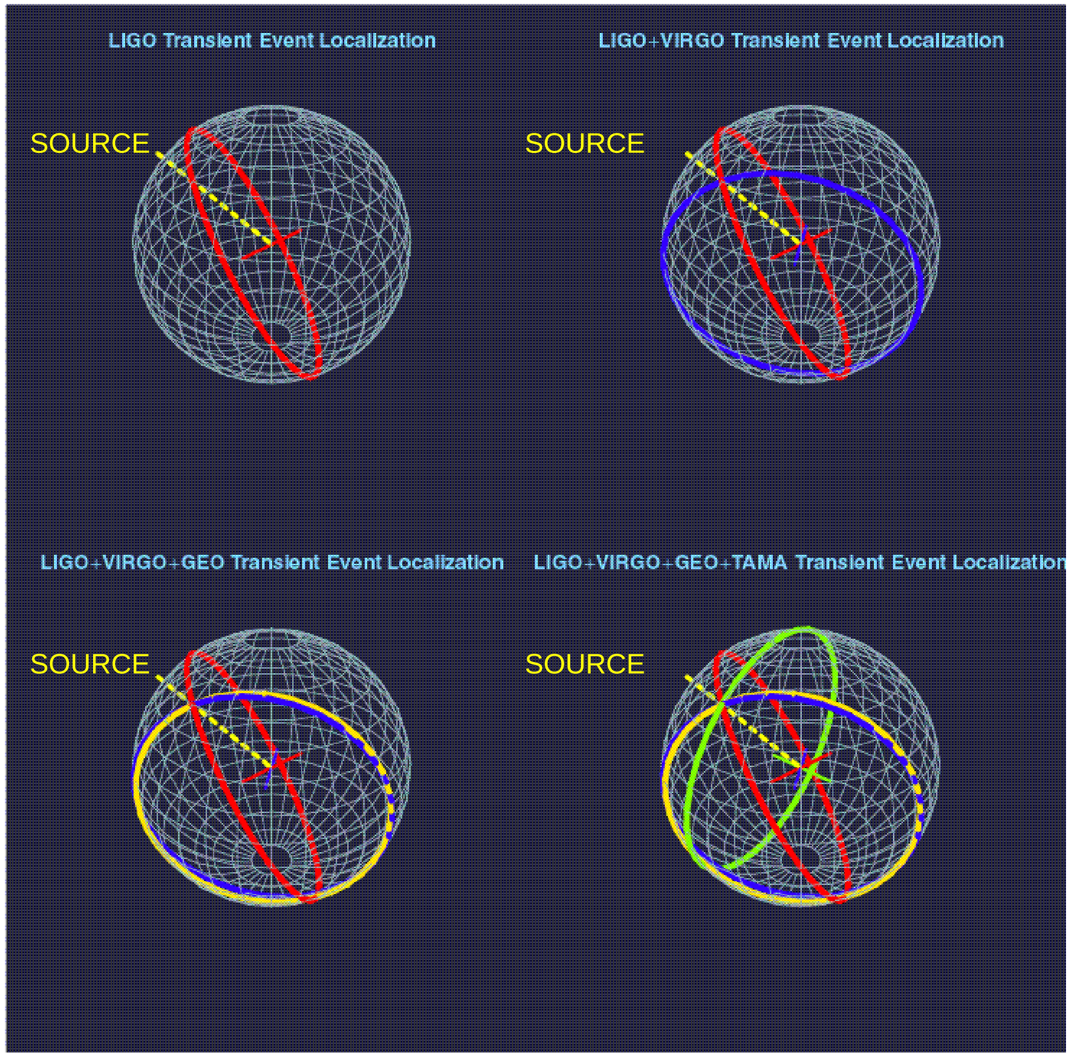
Global Network of GW Detectors



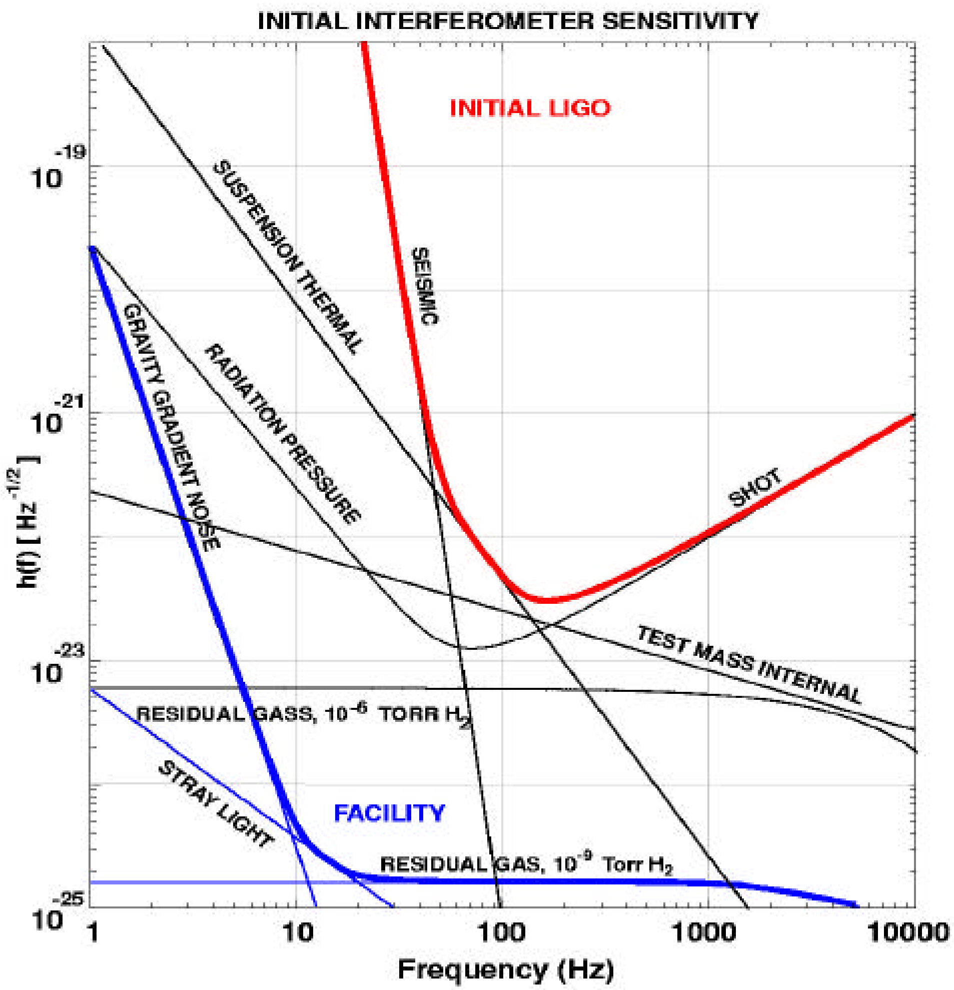
Event Localization with Array of Detectors







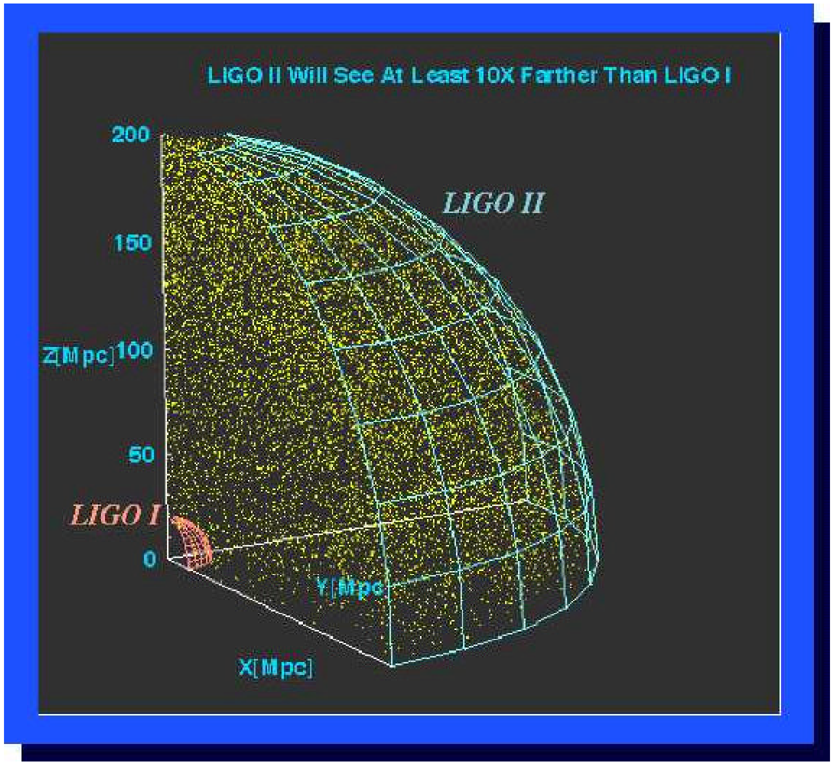
Initial LIGO Sensitivity Goal



- Facility limits more than 100 times lower than initial detector sensitivity
- Lots of room for future improvements

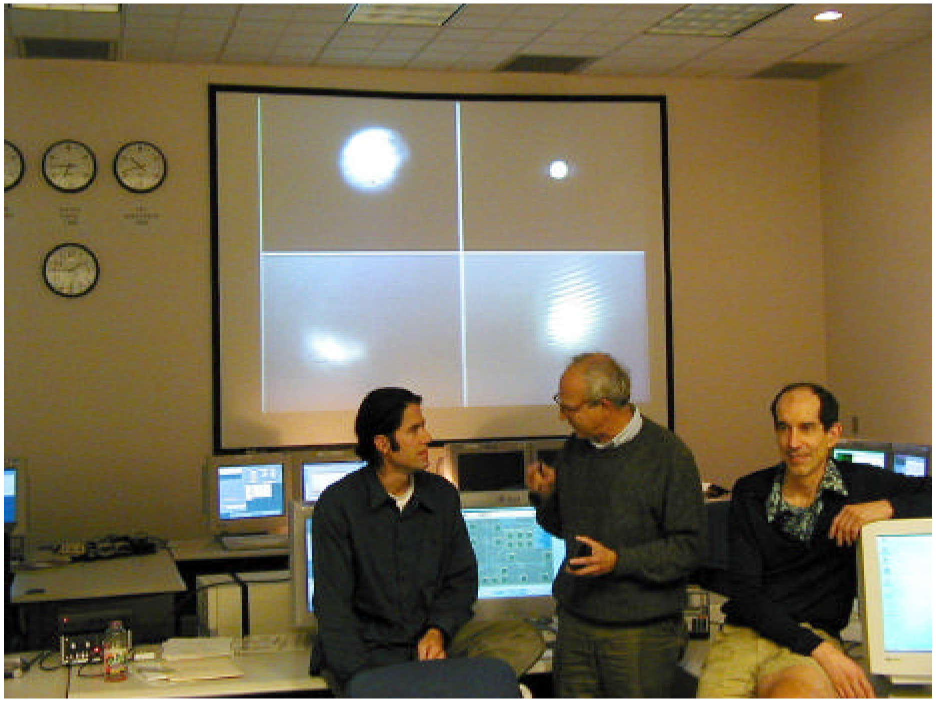
Advanced LIGO

- Now being designed by the LIGO Scientific Collaboration
- Goal:
  - » Quantum-noise-limited interferometer
  - » Factor of ten increase in sensitivity
  - » Factor of 1000 in event rate. One day > entire 2-year initial data run
- Schedule:
  - » Begin installation: 2006
  - » Begin data run: 2008



Where do we go from here?

- 2001
  - » Detector commissioning
  - » Engineering runs
  - » First coincidence operation
  - » Improve sensitivity/ reliability
  - » Initial data run ("upper limit run")
- 2002
  - » Begin Science Run
  - » Interspersed data taking and machine improvements
- Advanced LIGO R&D



First Lock in the Hanford Observatory control room