THE LIGO INTERFEROMETERS
How they work and how well they work

Rainer Weiss MIT
for the
LIGO SCIENTIFIC COLLABORATION

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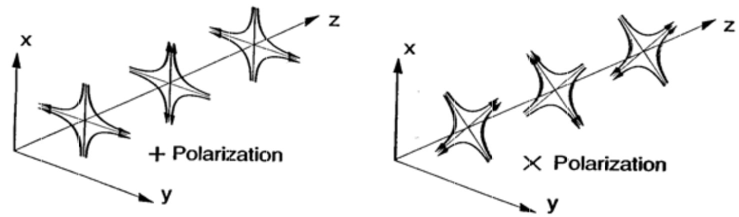
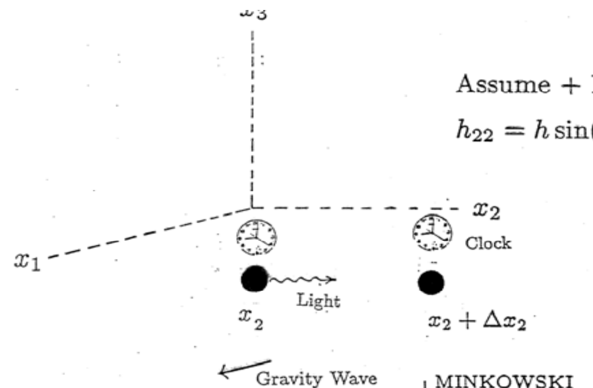
LIGO-G030024-00-D

Basic principles





Assume + Polarization

$h_{22} = h \sin(kx_1 - \omega t)$

MINKOWSKI

$$\Delta s^2 = 0 = c^2 \Delta t^2 - \left(1 + h \sin(kx_1 - \omega t)\right) \Delta x_2^2$$

LIGHT RAY

Let $\Delta t \ll \frac{1}{\omega}$ $\quad h \ll 1$

$$c \Delta t \cong \left(1 + \frac{h}{2} \sin(kx_1 - \omega t)\right) \Delta x_2$$

INFERRED DISTANCE BETWEEN POINTS

$$\frac{\delta(c \Delta t)}{\Delta x_2} = \frac{h}{2} \sin(kx_1 - \omega t)$$

Time Dependent Strain

$$\frac{\Delta l}{l} = \frac{h}{2}$$

The Measurable Quantity

Plane waves in the far field

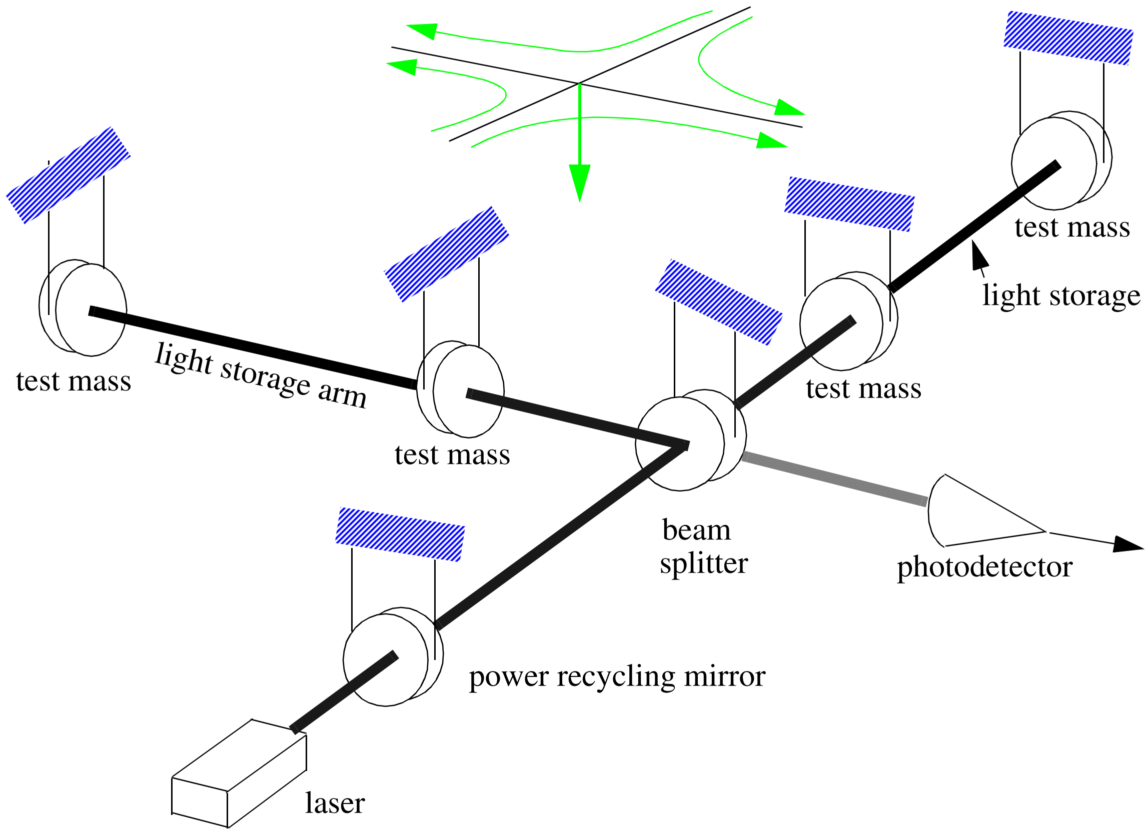
A “gedanken” experiment for the detection

Measurement challenge

- Needed technology development to measure:

$$h = \Delta L / L < 10^{-21}$$

$$\Delta L < 4 \times 10^{-18} \text{ meters}$$


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

FRINGE SENSING

wavelength 1×10^{-6} m

$$h = \frac{x}{L} \sim \frac{\lambda}{L b \sqrt{\dot{N} \tau}}$$

arm length = 4000 m

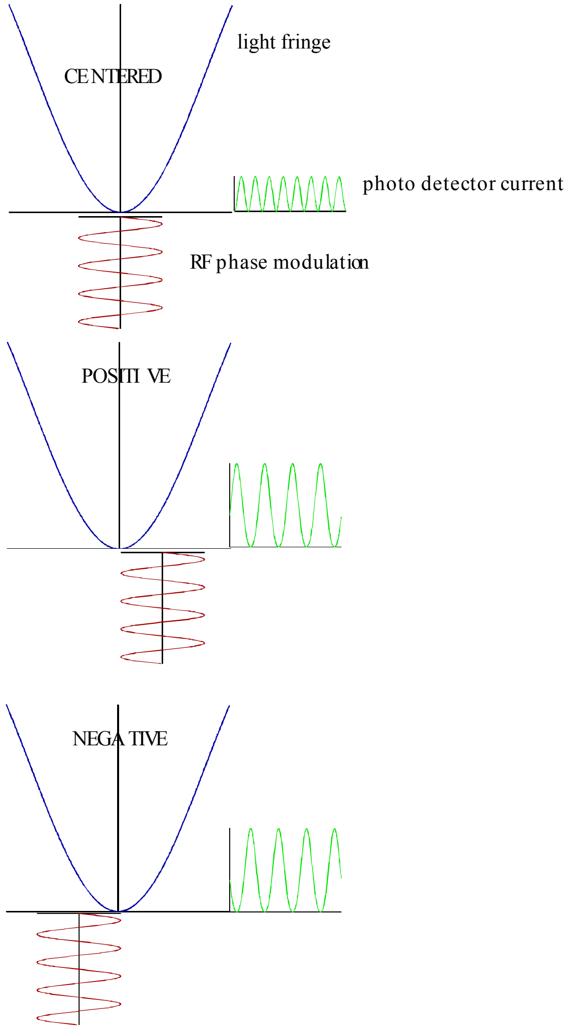
integration time

equivalent # of passes = 100

number of quanta/second at the beam splitter

300 watts at beam splitter = 10^{21} identical photons/sec

$h = 6 \times 10^{-22}$ integration time 10^{-2} sec



PENDULUM THERMAL NOISE

Pendulum Brownian motion

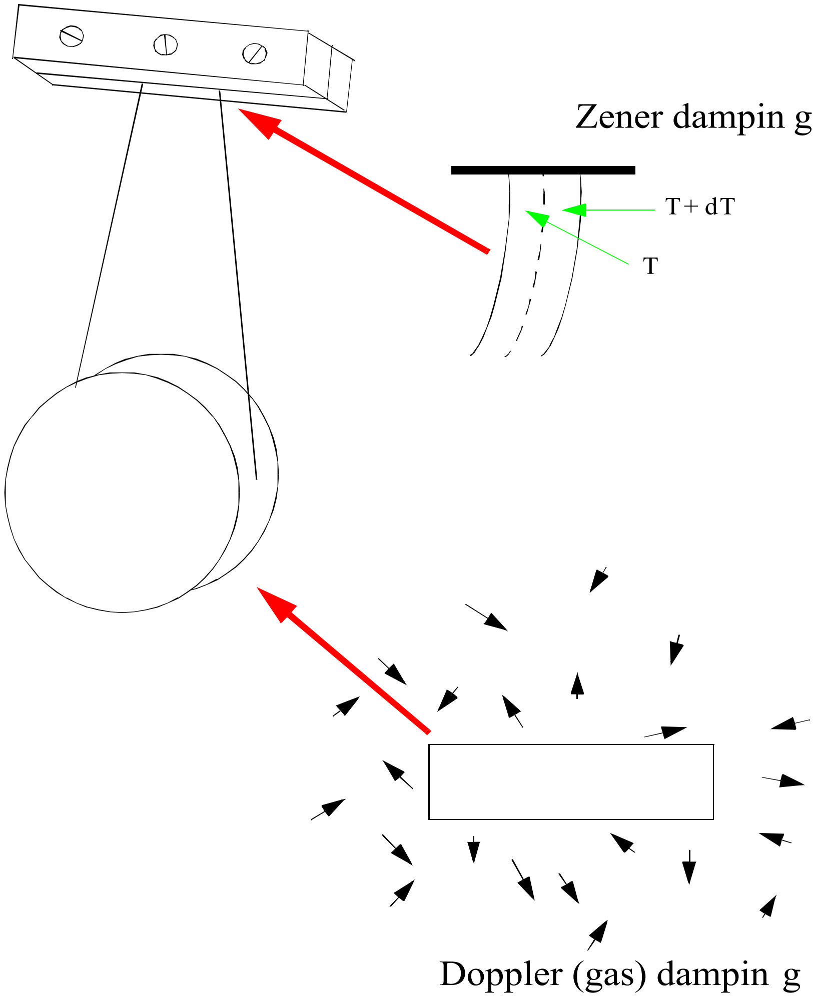
Dissipation leads to fluctuations

Tc = coherence or damping time
= Q x period of oscillator

Exchange with surroundings:

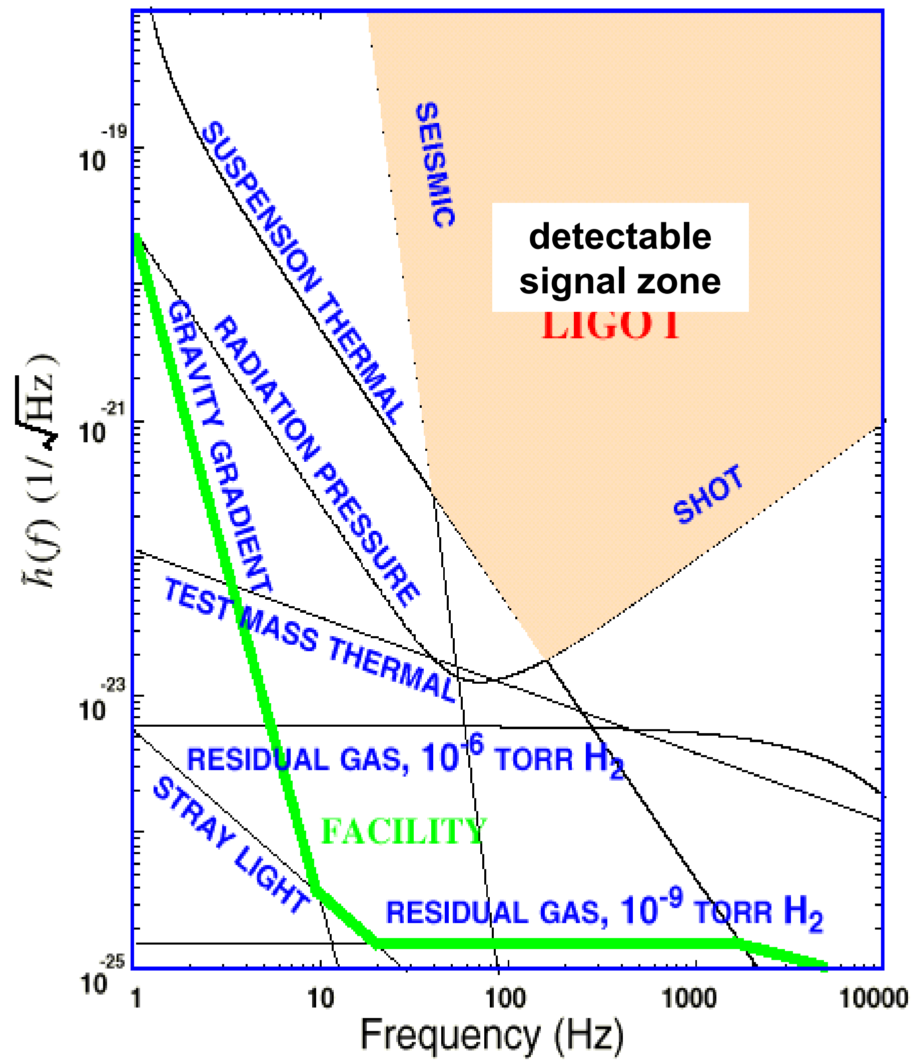
$$E(\text{thermal}) = \frac{kT\ t}{Tc}$$

Large Tc => smaller fluctuations

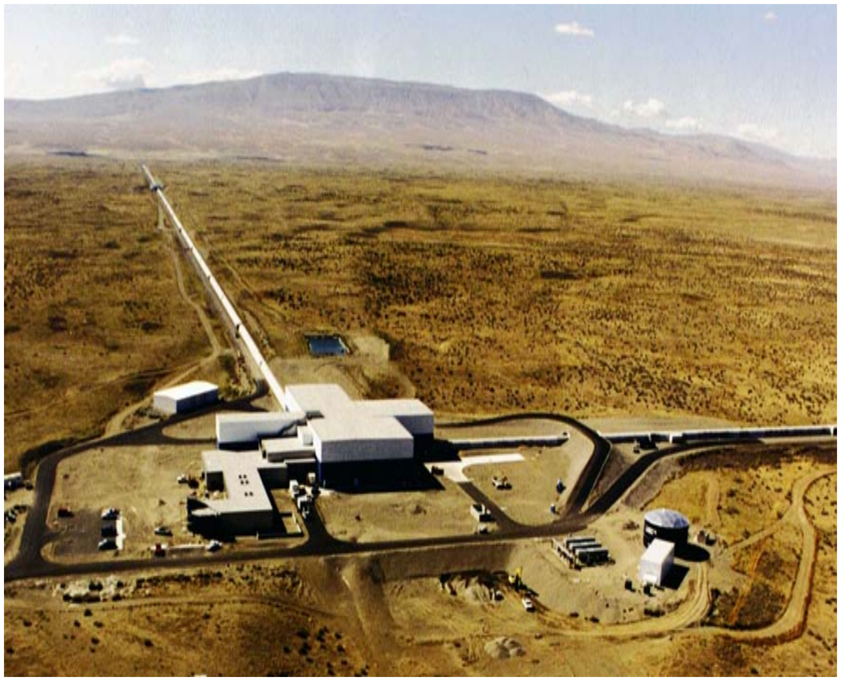


Interferometers: design noise

- Sensing and stochastic force noise
- Calculated "fundamental" limits determined design goal
  - **seismic** at low frequencies
  - **thermal** at mid frequencies
  - **shot noise** at high frequencies
- Other "technical" noise not allowed above 1/10 of these
- Facility limits much lower to allow improvement as technology matures



LIGO Observatory Facilities



LIGO Hanford Observatory [LHO]

26 km north of Richland, WA

2 km + 4 km interferometers in same vacuum envelope

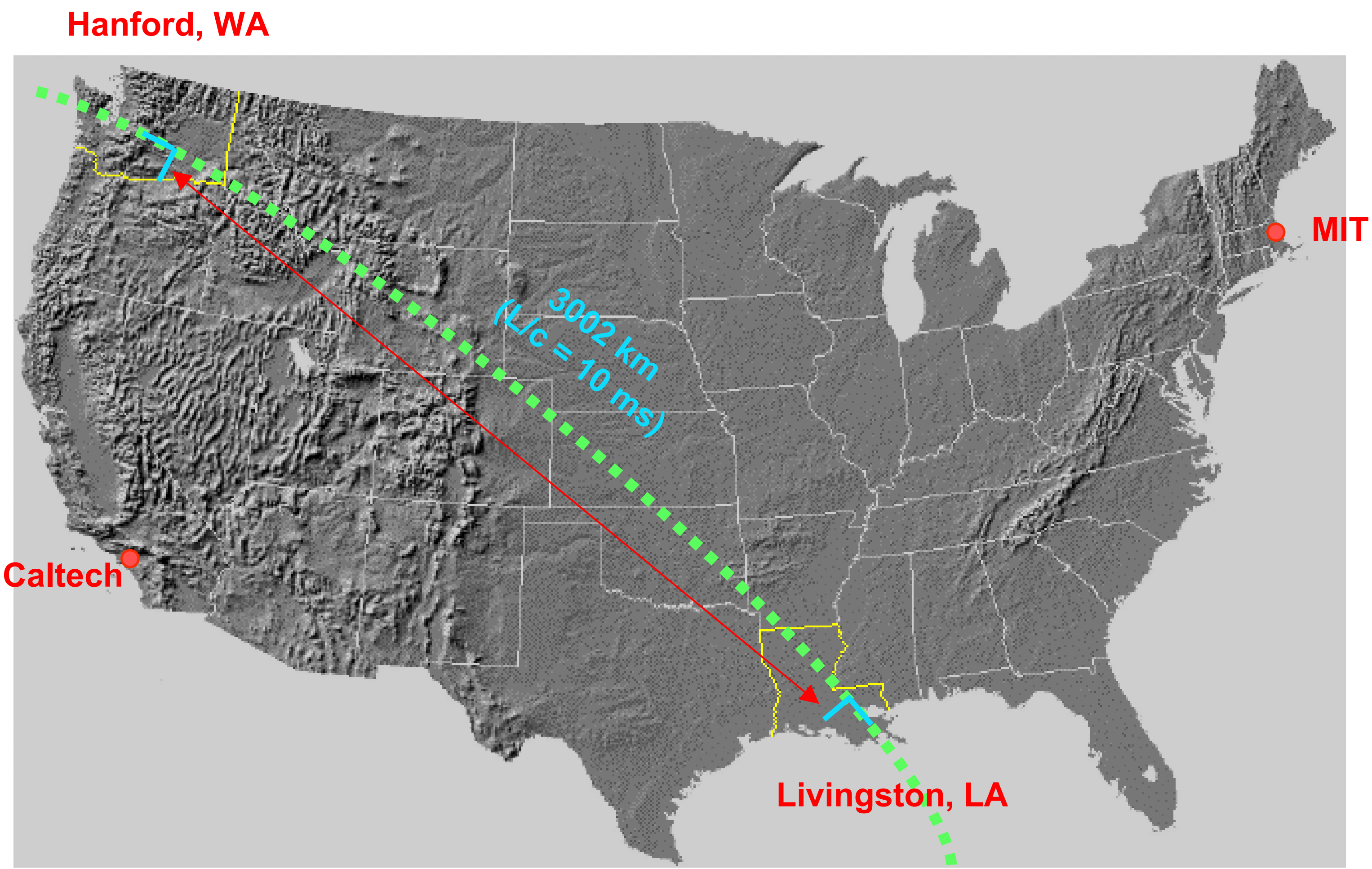
LIGO Livingston Observatory [LLO]

42 km east of Baton Rouge, LA

Single 4 km interferometer

The LIGO Laboratory Sites

Interferometers are aligned along the great circle connecting the sites



Beam Tubes and Enclosures

Precast concrete enclosure

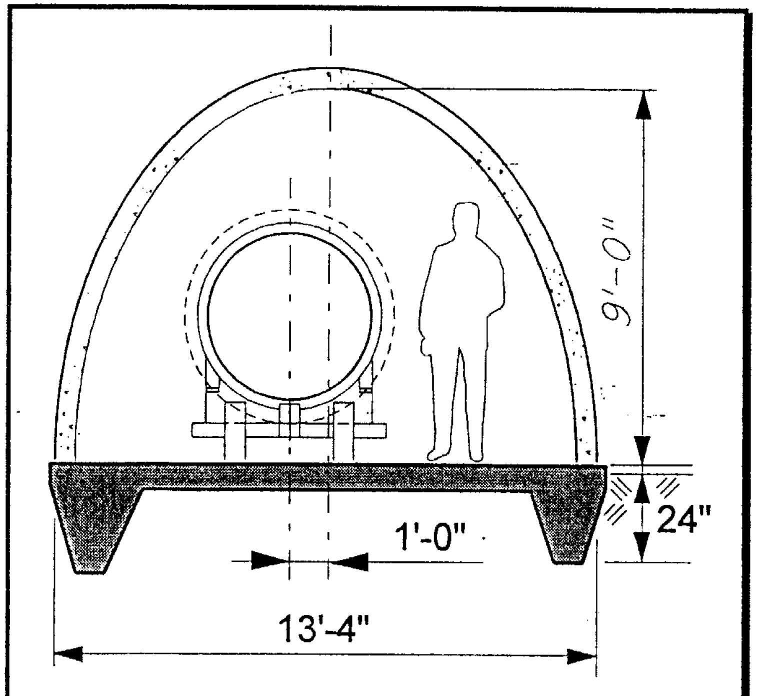


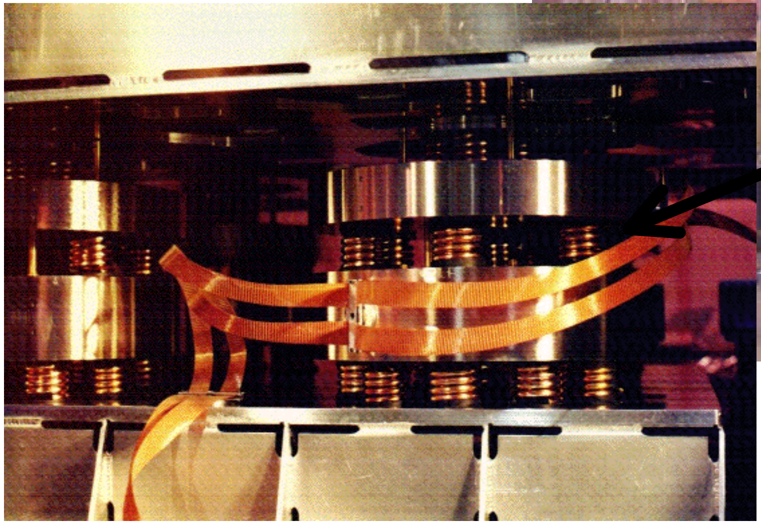
Figure 2.1-1 -- Cross Section of Design Baseline at Hanford

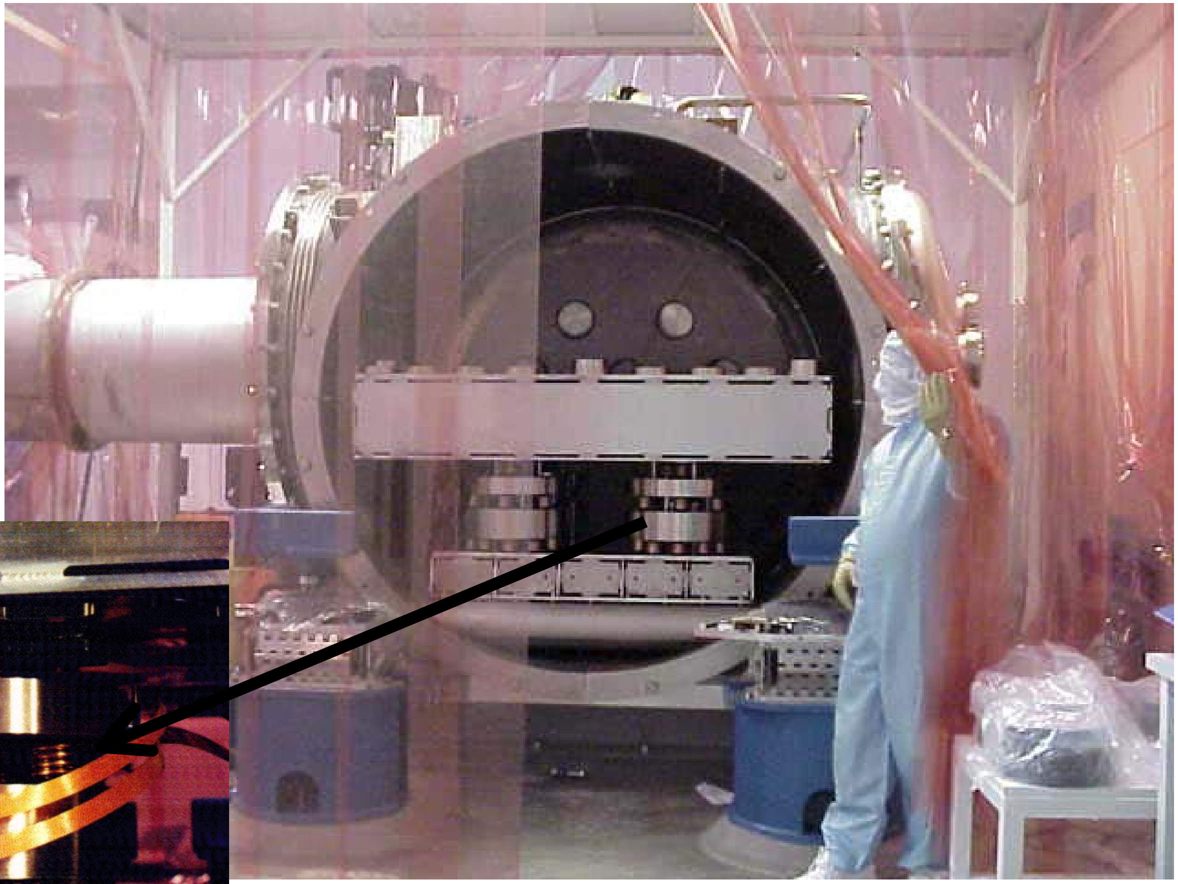
- **Beam Tube**
  - **1.2m diam; 3 mm stainless**
  - **special low-hydrogen steel process**
  - **65 ft spiral weld sections**
  - **50 km of weld (NO LEAKS!)**
  - **In situ 160 C bakeout**
  - **20,000 m^3 @ 10^{-8} to 10^{-9} torr**

Vacuum Equipment

Seismic Isolation System

Tubular coil springs with internal constrained-layer damping, layered with reaction masses

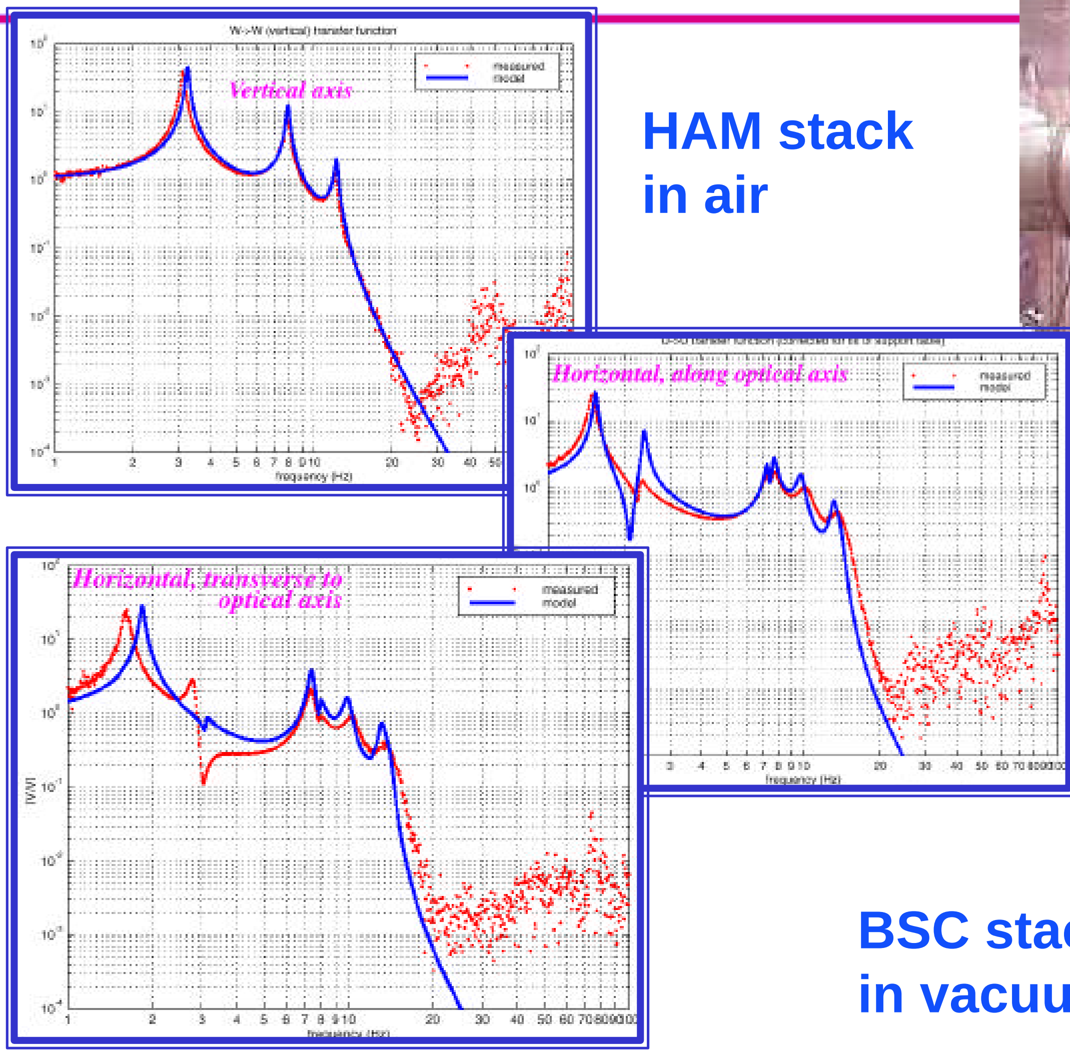




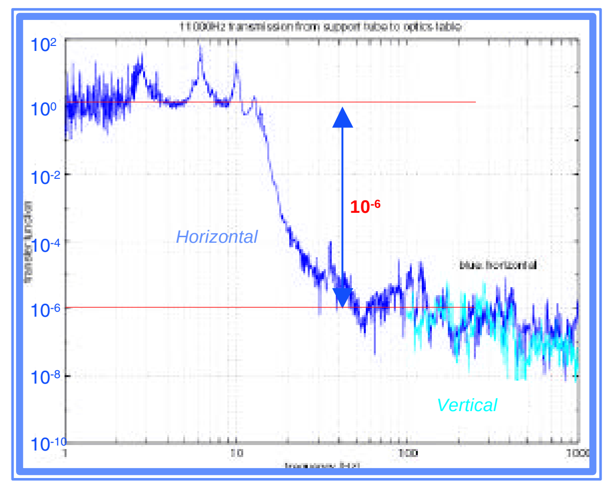
Isolation stack in chamber

Seismic Isolation

performance

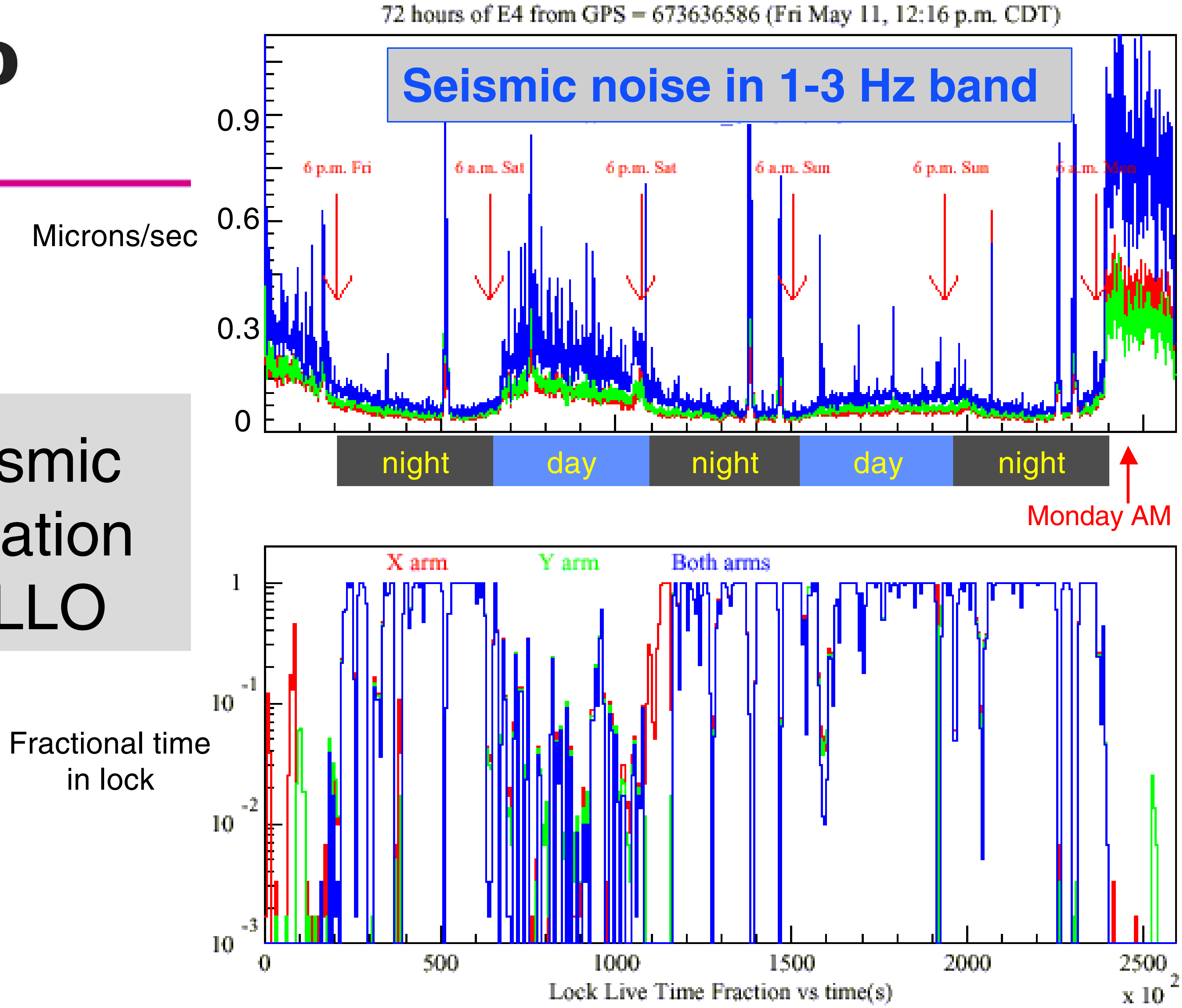


HAM stack in air

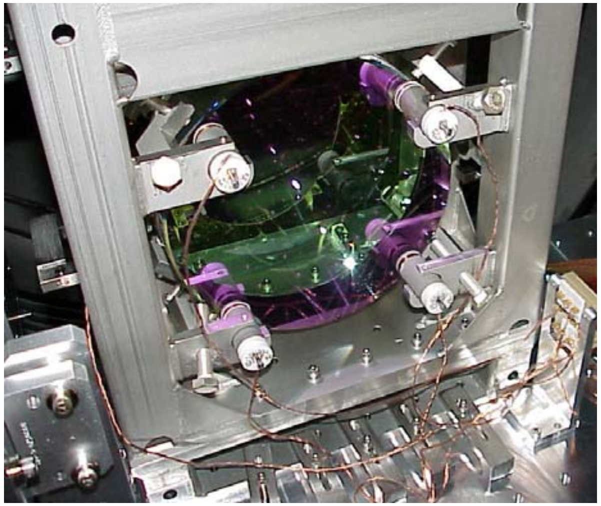


BSC stack in vacuum

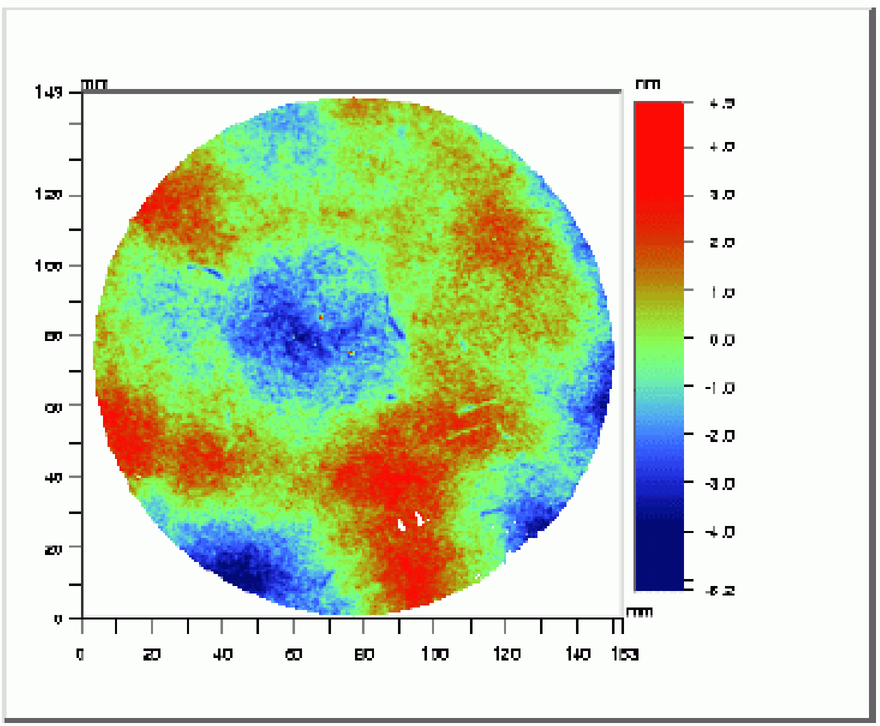
Seismic Situation at LLO



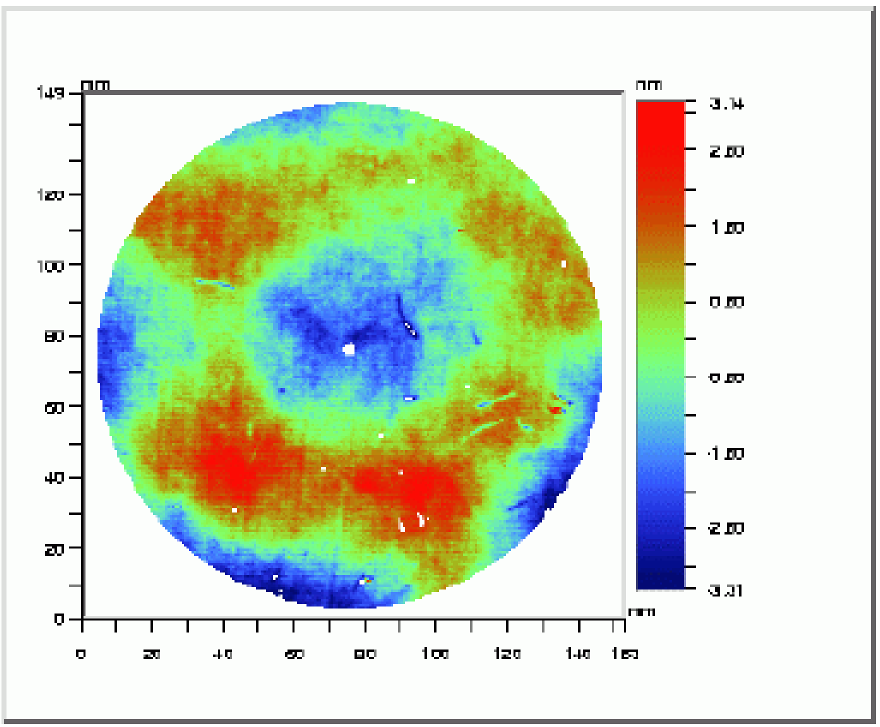
Installation and alignment



Core Optic Metrology



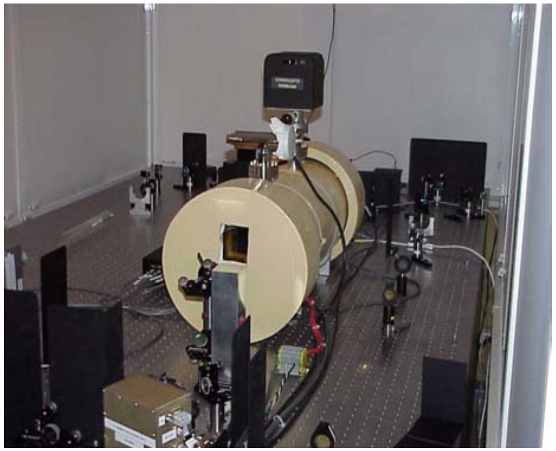
LIGO data (1.2 nm rms)

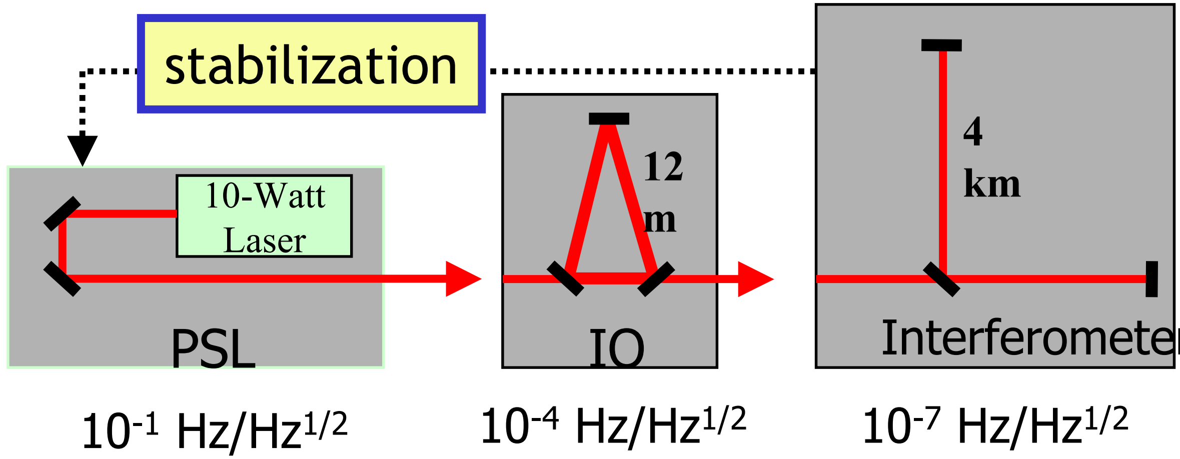


CSIRO data (1.1 nm rms)

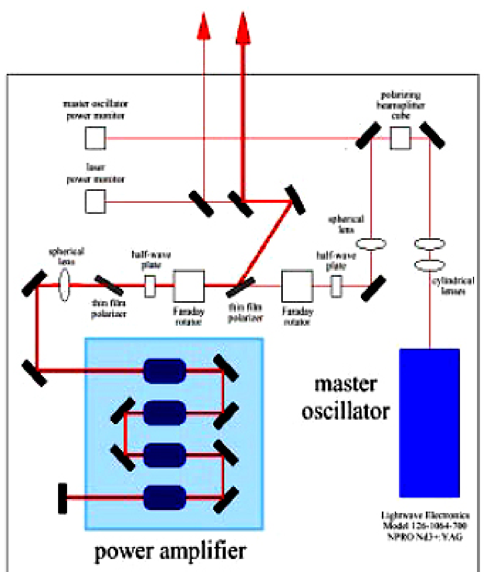
- ***Best mirrors are λ/6000 over the central 8 cm diameter***

LIGO Prestabilized Laser

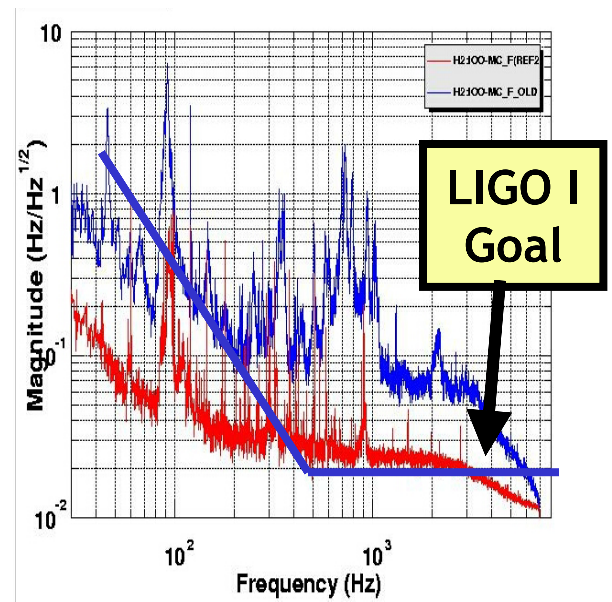




- Nd:YAG 1064 nm
- P > 8 W TEM_{00}
- Cascaded multi-loop frequency stabilization



Lightwave Electronics MOPA

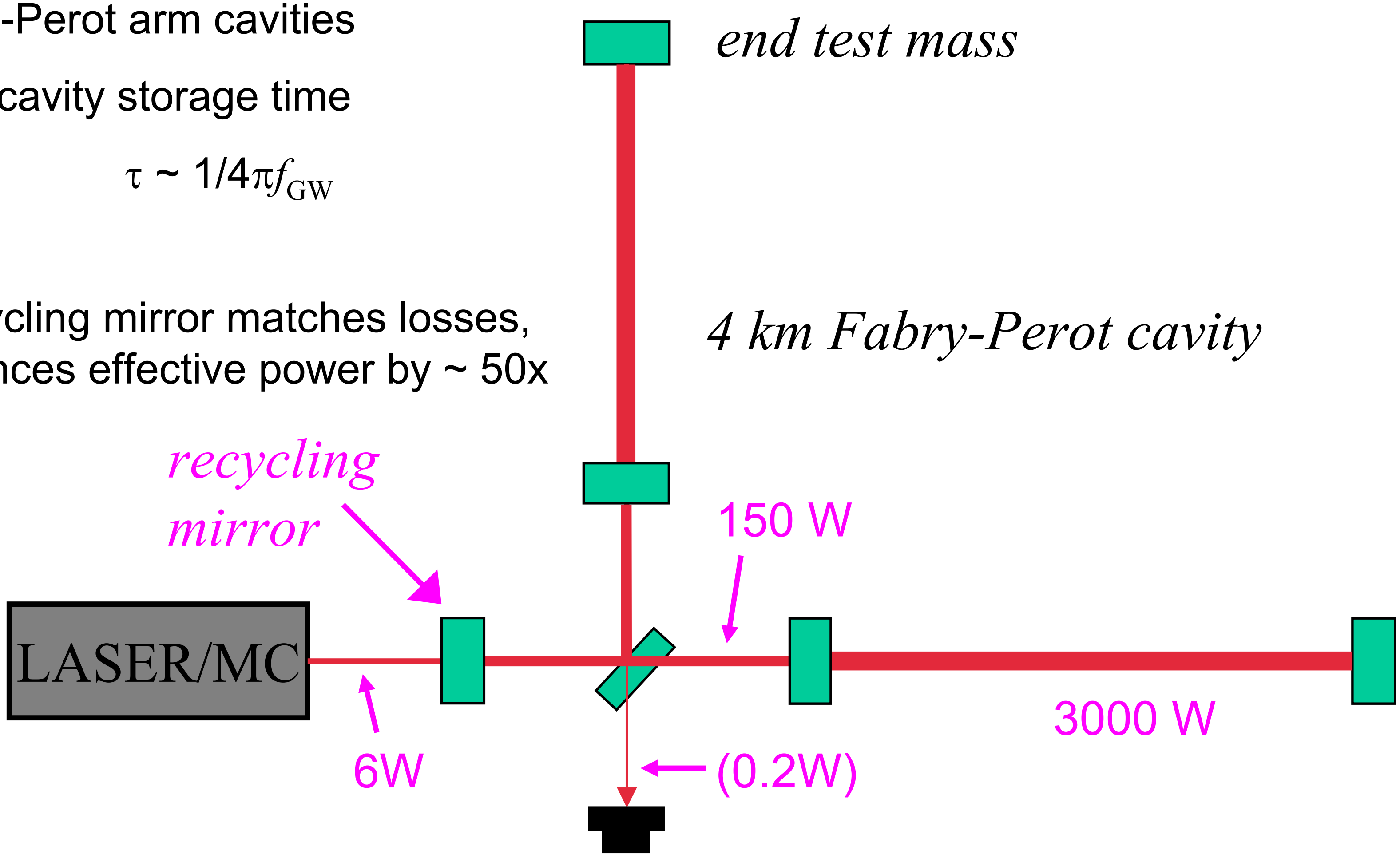


LIGO Interferometer Optical Scheme

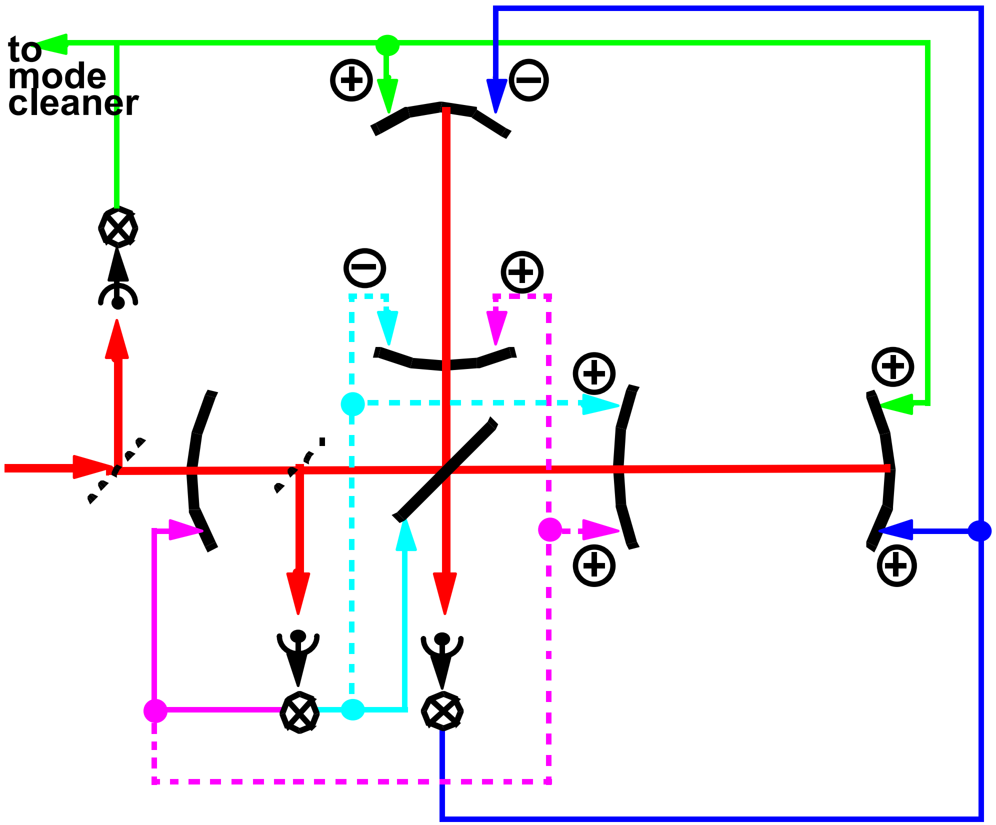
- Michelson interferometer with Fabry-Perot arm cavities
- Arm cavity storage time

$$\tau \sim 1/4\pi f_{GW}$$

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

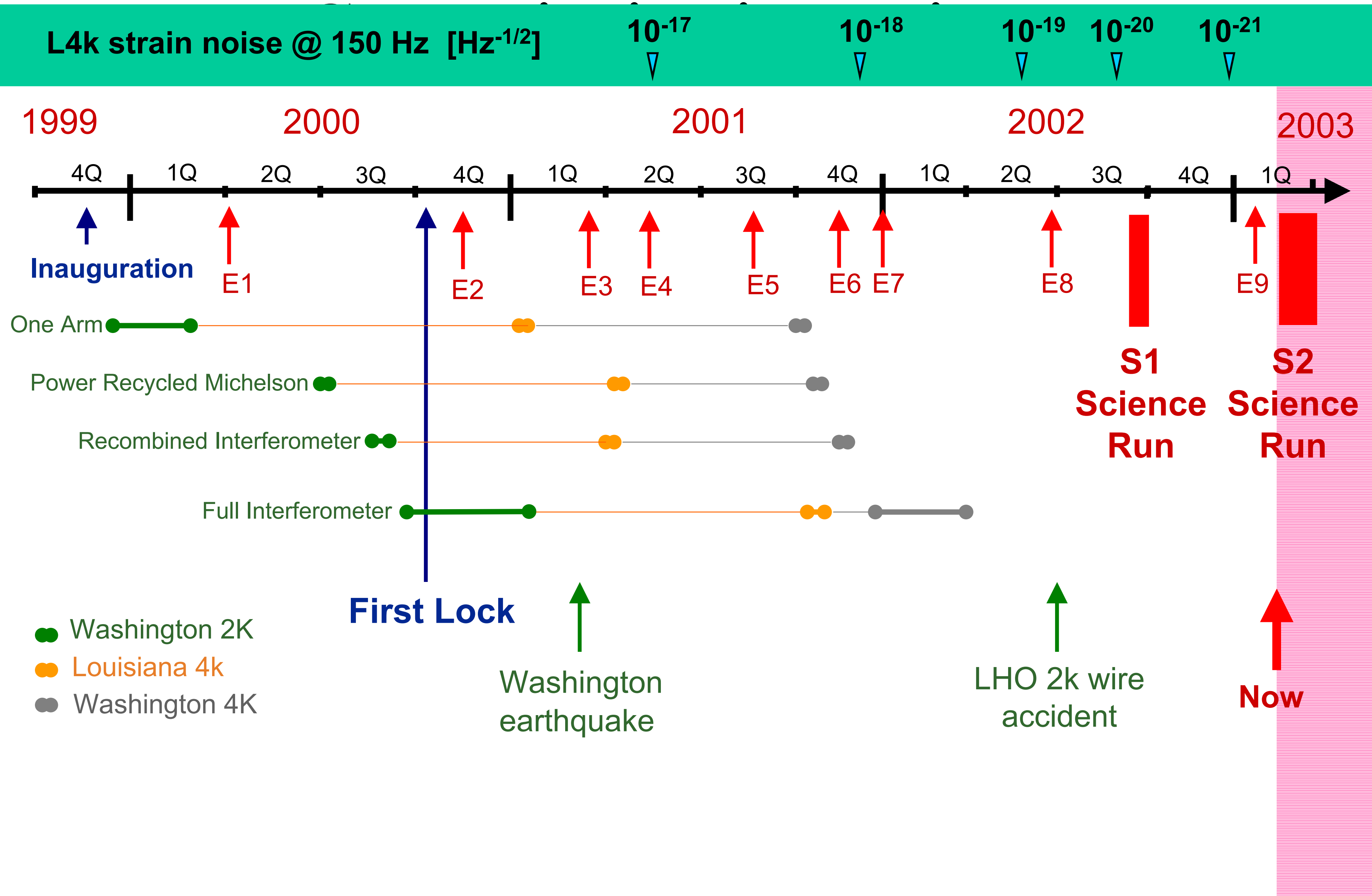


Feedback Control Systems



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)



L4k strain noise @ 150 Hz [Hz-1/2]
10-17
10-18
10-19
10-20
10-21
1999
2000
2001
2002
2003
4Q 1Q 2Q 3Q 4Q 1Q 2Q 3Q 4Q 1Q 2Q 3Q 4Q 1Q
Inauguration
E1
E2
E3
E4
E5
E6
E7
E8
E9
One Arm
Power Recycled Michelson
Recombined Interferometer
Full Interferometer
S1 Science Run
S2 Science Run
First Lock
Washington earthquake
LHO 2k wire accident
Now
Washington 2K
Louisiana 4k
Washington 4K

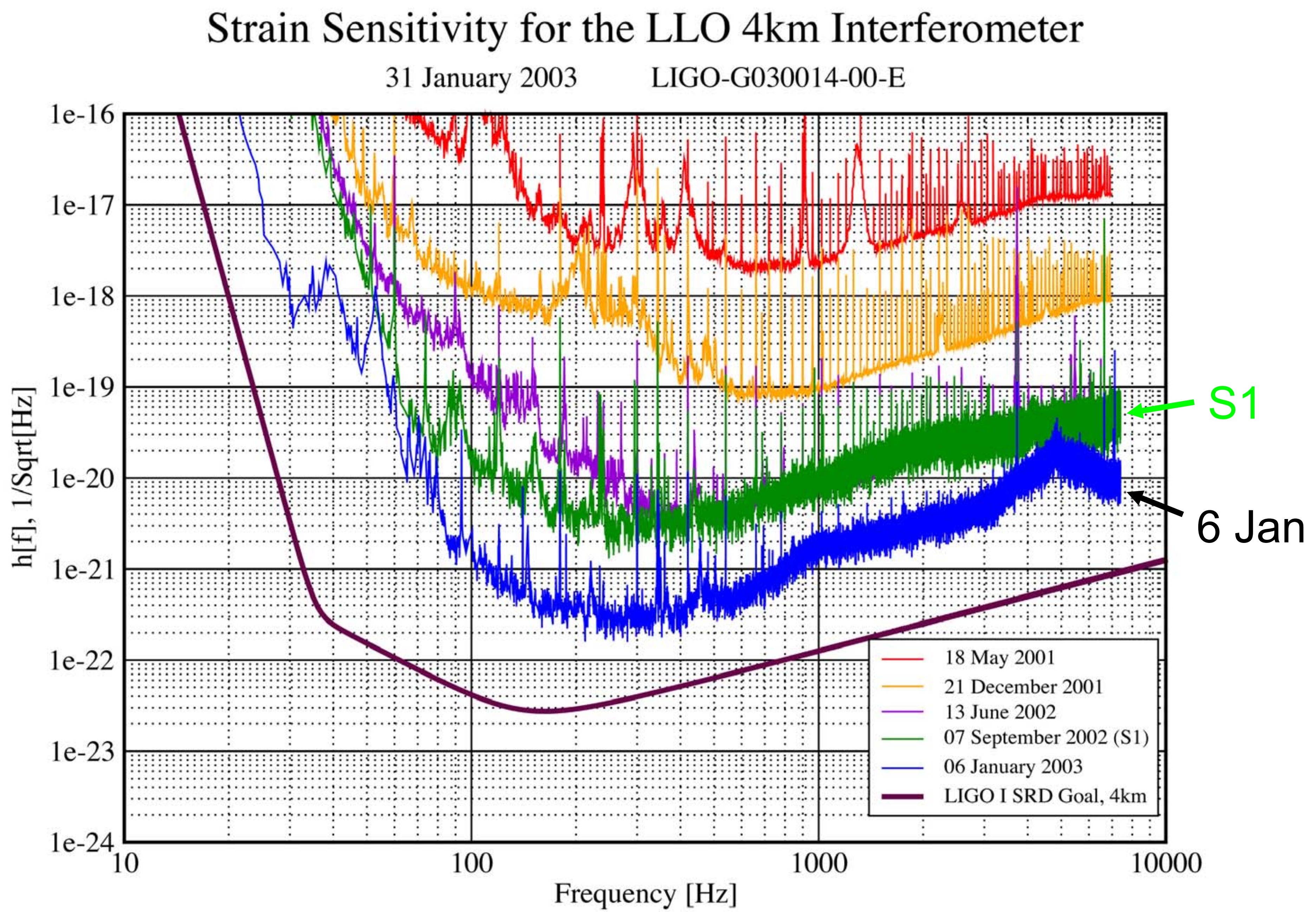

Strain Sensitivity for the LLO 4km Interferometer
31 January 2003
LIGO-G030014-00-E
h[f], 1/Sqrt[Hz]
1e-16
1e-17
1e-18
1e-19
1e-20
1e-21
1e-22
1e-23
1e-24
10
100
1000
10000
Frequency [Hz]
18 May 2001
21 December 2001
13 June 2002
07 September 2002 (S1)
06 January 2003
LIGO I SRD Goal, 4km
S1
6 Jan

Table 1: Initial detector parameters

Parameter	*Nominal Initial Interferometer*
Arm length	4000 m
Laser type @wavelength	Nd:YAG λ = 1064 nm
Input power at recycling cavity	6 W
Contrast defect 1-c	$< 3 \times 10^{-3}$
Mirror loss	$< 1 \times 10^{-4}$
Power recycling gain	30
Arm cavity storage time	880 μ sec
Cavity input mirror transmission	3×10^{-2}
Mirror mass	10.7 kg
Mirror diameter	25 cm
Mirror internal Q	1×10^{6}
Pendulum Q (structure damping)	1×10^{5}
Pendulum period (single)	1 sec
Seismic isolation system	T(100Hz) = -110dB