Thermal Noise Sources Relevant to Interferometric Gravitational Wave Detection

Shanti Rao
Caltech

Thanks to

Caltech

Ken Libbrecht, Eric Black, Luca Matone

LIGO

Jordan Camp, Jay Heefner, Rich Abbott, Paul Russell

TAMA

Seiji Kawamura

Funded by the NSF/LIGO R&D

GWDs are large interferometers...

Photo from LHO web site

LIGO Hanford Observatory

with large mirrors...

LIGO-G000103-00-M

...held by small wires

Thermal Noise Sources Relevant to Interferometric Gravitational Wave Detection

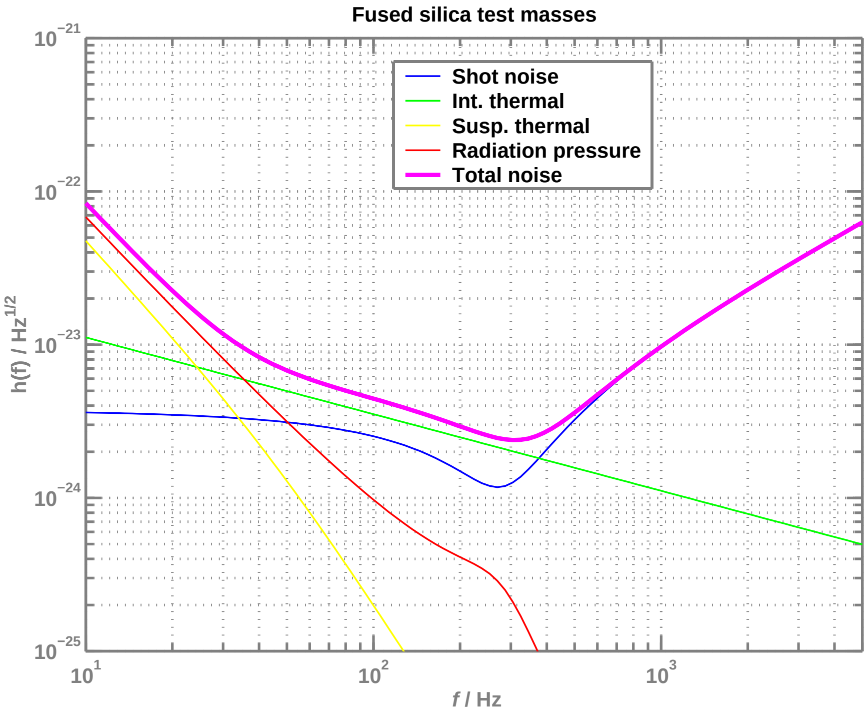
Noise sources

Thermoelastic damping

Brownian motion

Photothermal noise

Other thermal noise?



Plot from LIGO II web site

Motivation

Limits event rate in GWDs

Hard to measure in the LIGO spectrum

Models not adequately verified at LIGO levels

Stragety

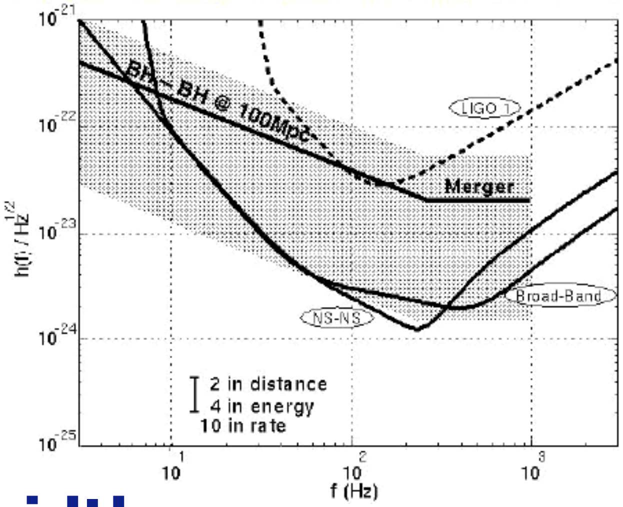
Isolate and measure noise sources

Brownian motion

Currently believed to be the dominant thermal noise source for LIGO I

Fluctuation – dissipation theorem

$\propto (\phi\, k_B T / \omega\, r_0)^{1/2}$



LIGO-G000025-00-M, Kip Thorne

Limits LIGO I over a narrow bandwidth

Largest thermal noise contribution for fused silica
Limits LIGO I sensitivity
Broadband measurement needed to characterize noise

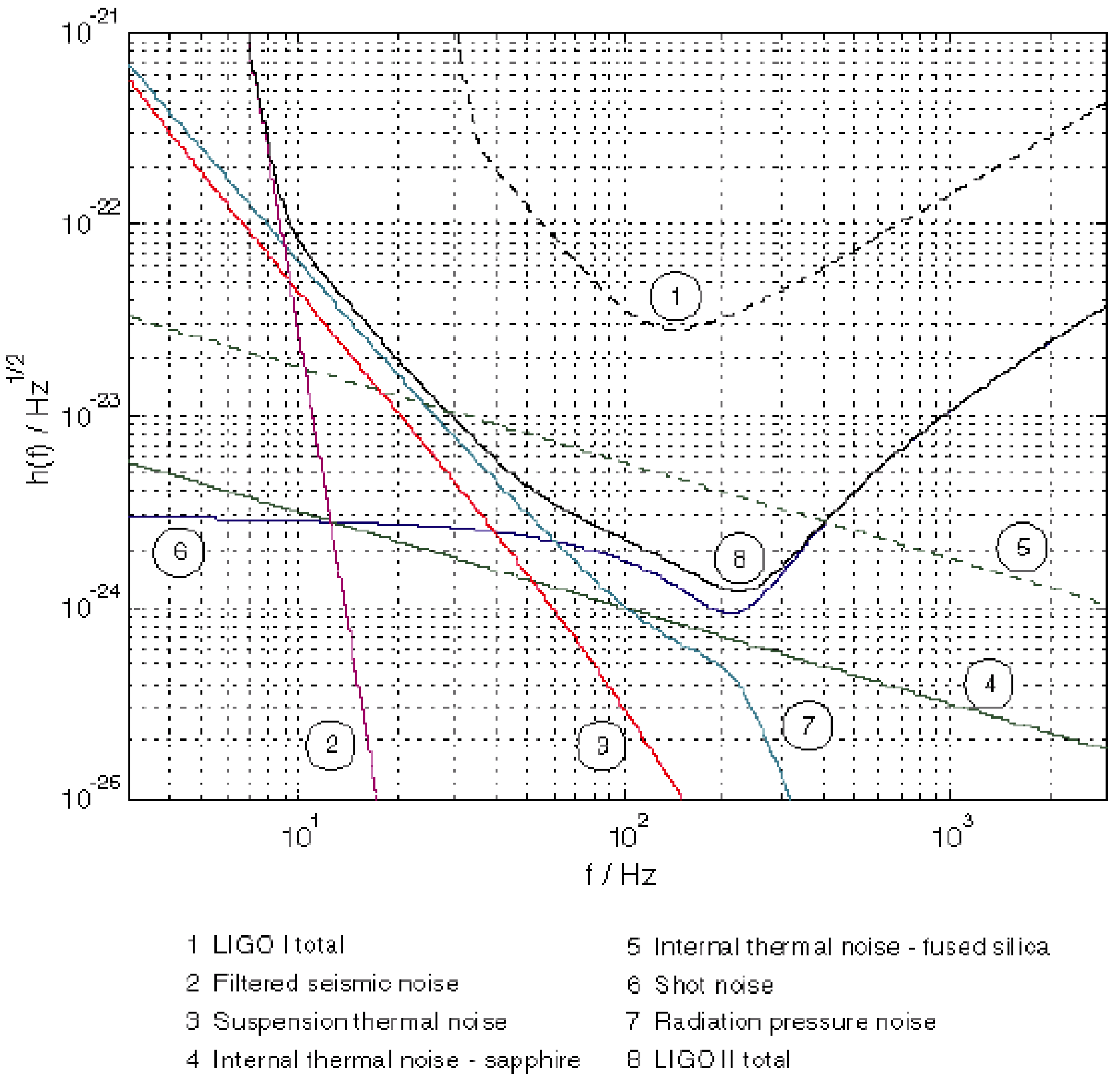
Model validation

Maybe $\phi(\omega)$ isn't constant

Non-Gaussian tails in distribution?

Model not adequately verified at LIGO levels

LIGO Brownian Motion



(Neglects Thermoelastic Damping)

Thermoelastic Damping

The "Sapphire Killer"

Newly predicted type of thermal noise

Fluctuations arise from thermal expansion dissipation

$\propto (\alpha^2 k_B T^2 / \omega^2 r_0^3)^{1/2}$

(Braginsky et al, 1999)

Bigger in sapphire than in fused silica

Large thermal noise contribution in sapphire

Depends strongly on thermal properties of the material

Model validation

Non-Gaussian tails in distribution?

Model not adequately verified at LIGO levels

Photothermal Noise

Newly predicted noise source

Laser heats mirror surface, causing thermal expansion

$\propto (h\nu P/ \omega^2 r_0{}^4)^{1/2}$

(Braginsky et al, 1999)

Bad for delay line IFOs

Dependent on spot size and coating losses

Photothermal noise is high in materials that have high conductivity, like Si and GaAs.

Bad for cryogenic IFOs

Chilling a mirror lowers thermal noise, but not photothermal noise.

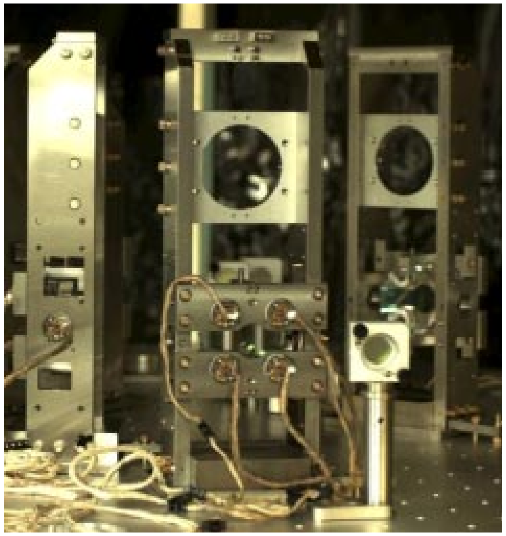
Thermal Noise Interferometer (TNI)

Current: Characterize advanced detectors

- Measure noise sources
- Measure non-thermal noise
- Verify design specifications

Future: Physics of fundamental noise sources

- Reach (and exceed) the SQL
- QND experiments
- Squeezed light



The TNI uses LIGO-like mirrors and suspensions

Sensitivity to Thermal Noise

Bandwidth and sensitivity

Short length (~1 cm)
High finesse cavities
No power recycling
No optical recombination
Two independent cavities
Relax laser stability requirements

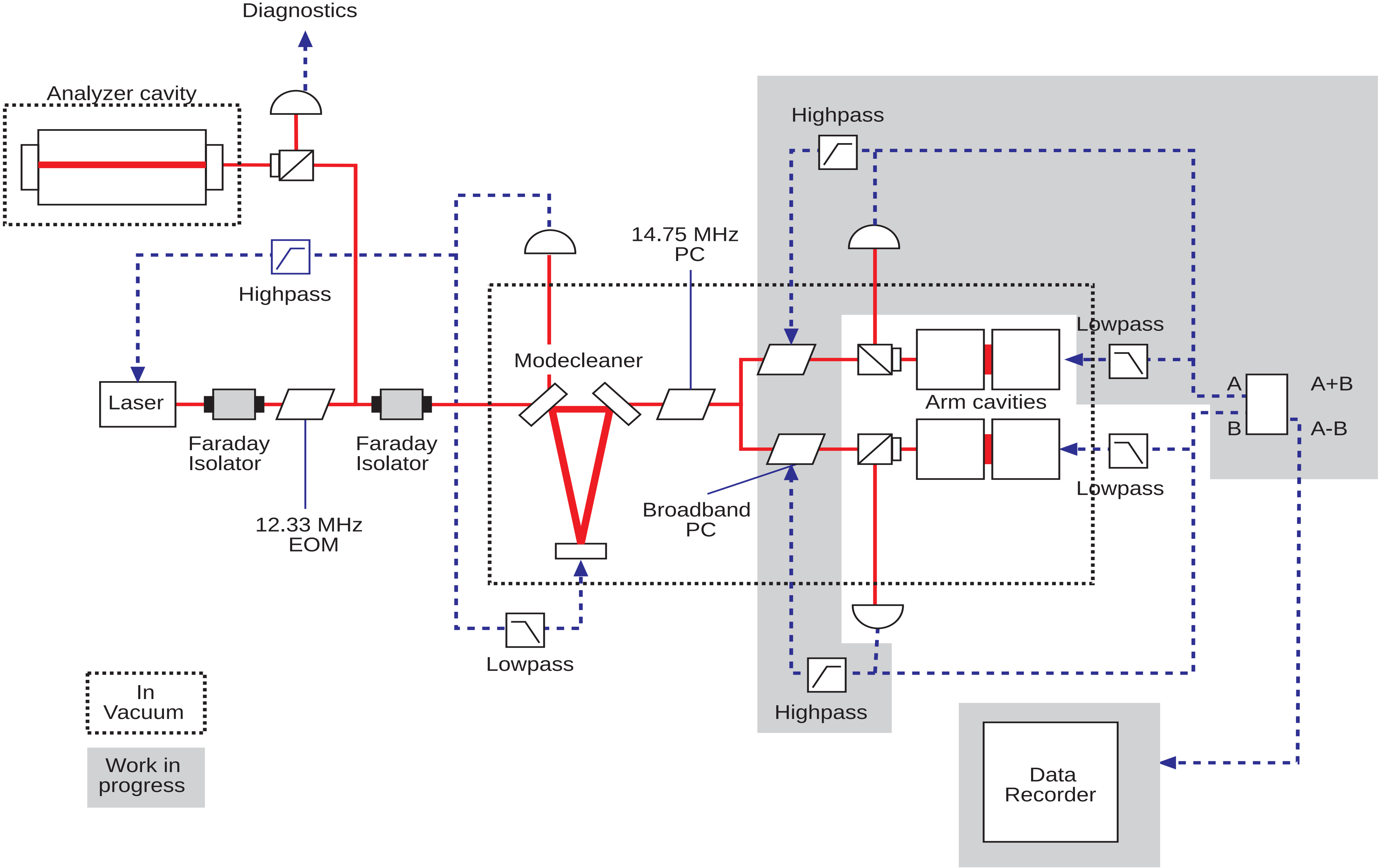
Common support

Common mode noise rejection
Reduce seismic noise
Reduce suspension recoil thermal noise

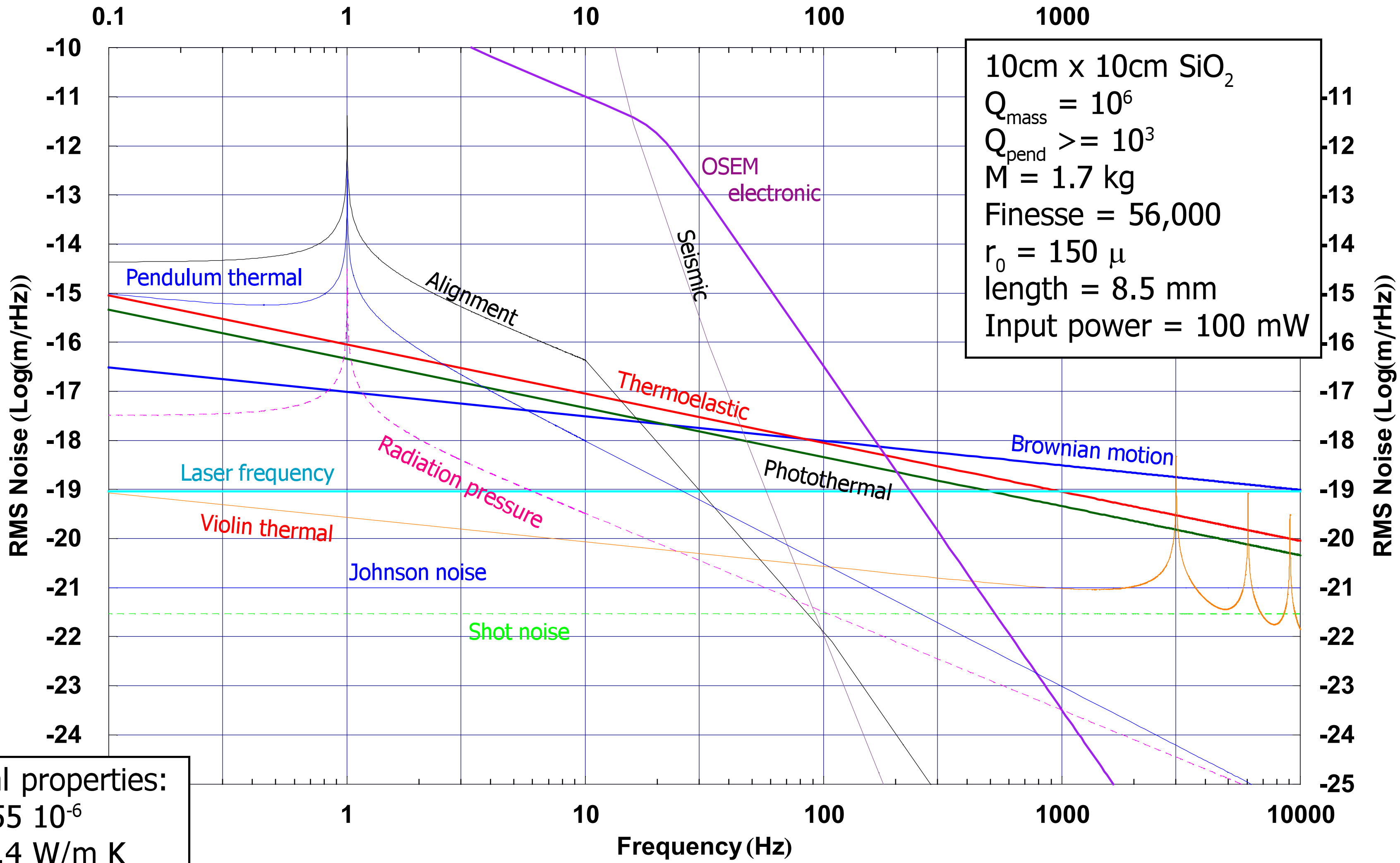
Small spot size increases thermal noise

Easier to characterize noise
But not with LIGO’s sensitivity

TNI Equipment



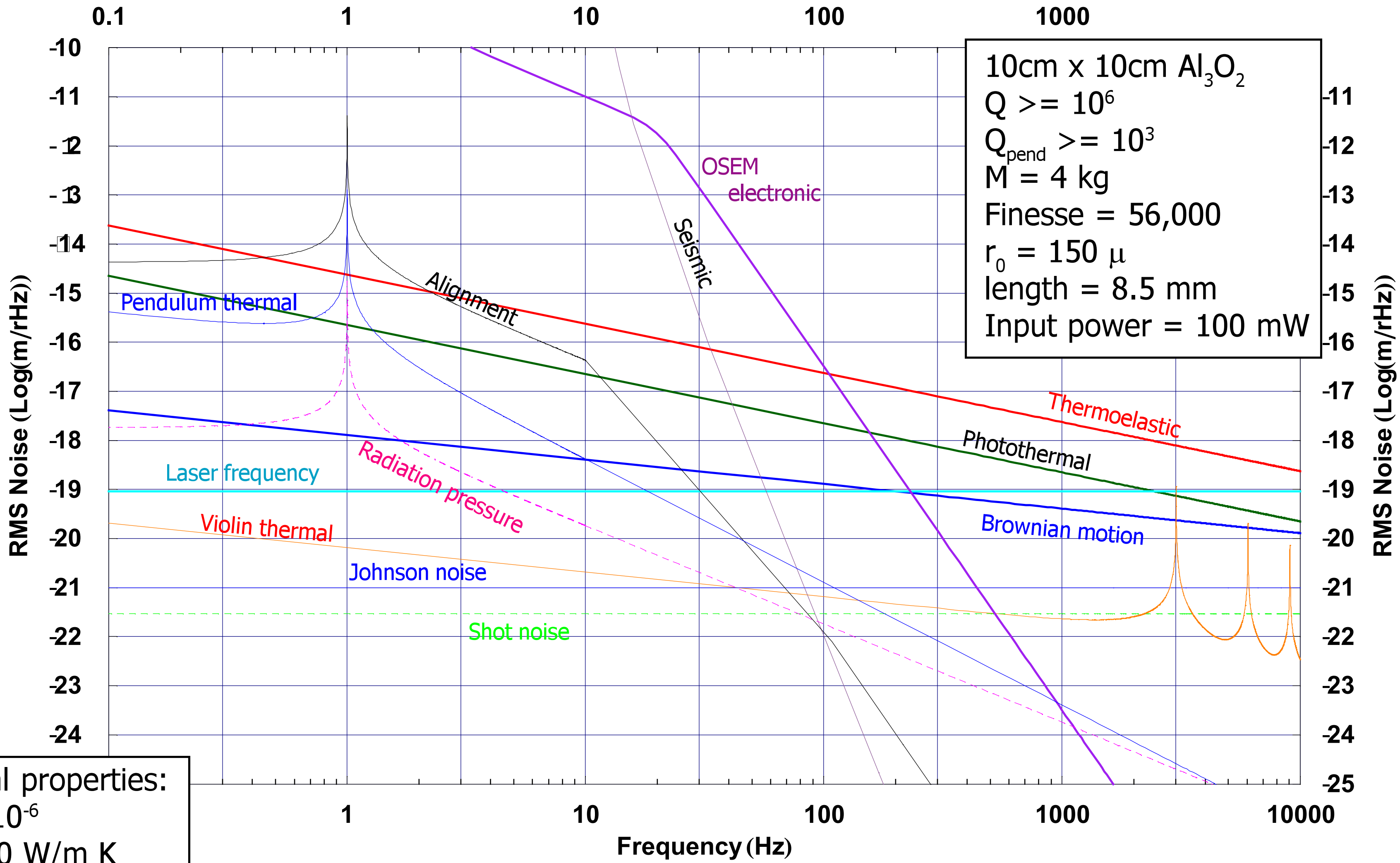
TNI Expected Spectrum - Fused Silica



10cm x 10cm SiO_2
$Q_{mass} = 10^6$
$Q_{pend} >= 10^3$
M = 1.7 kg
Finesse = 56,000
$r_0 = 150\ \mu$
length = 8.5 mm
Input power = 100 mW

Physical properties:
$\alpha = 0.55\ 10^{-6}$
$\lambda^* = 1.4$ W/m K
$\rho = 2.2$ g/cm^3
C = 670 J/kg K
E = 72 GPa

TNI Expected Spectrum - Sapphire

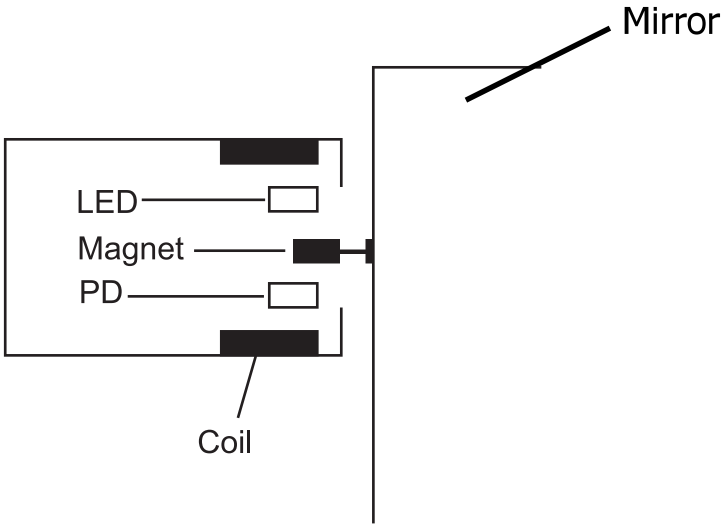


10cm x 10cm Al_3O_2
Q >= 10^6
Q_{pend} >= 10^3
M = 4 kg
Finesse = 56,000
r_0 = 150 μ
length = 8.5 mm
Input power = 100 mW

Physical properties:
α = 5 10^{-6}
λ^* = 40 W/m K
ρ = 4 g/cm^3
C = 790 J/kg K
E = 400 GPa

Low Frequency Limts

Magnet Sensor/Actuator (OSEM)



Photodiode noise limits low frequency sensitivity

TNI Progress

Facility

Cleanroom and workspaces

Vacuum chamber and pumps: pressure $\leq 10^{-6}$ torr

Suspended optics

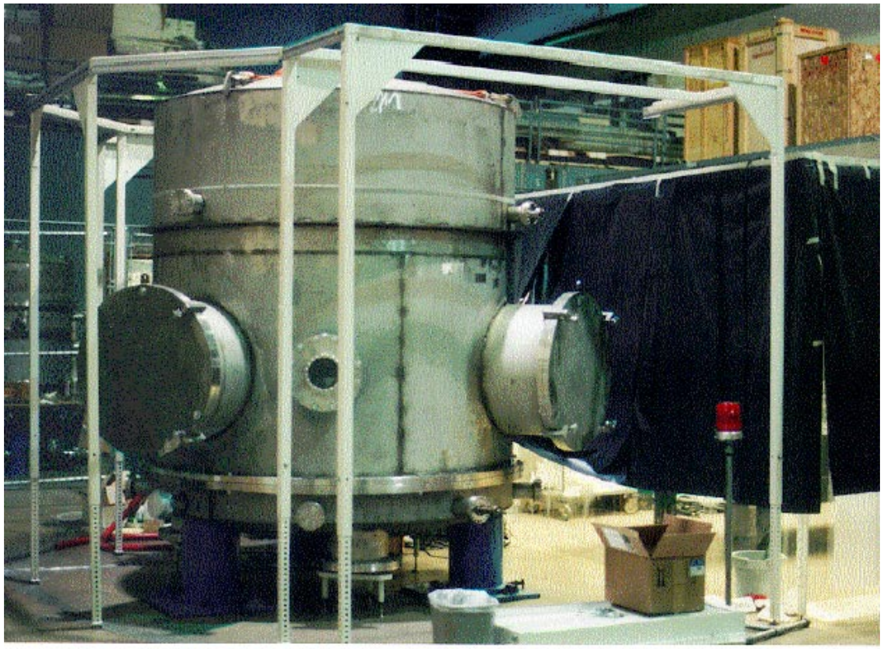


Photo by Ken Libbrecht

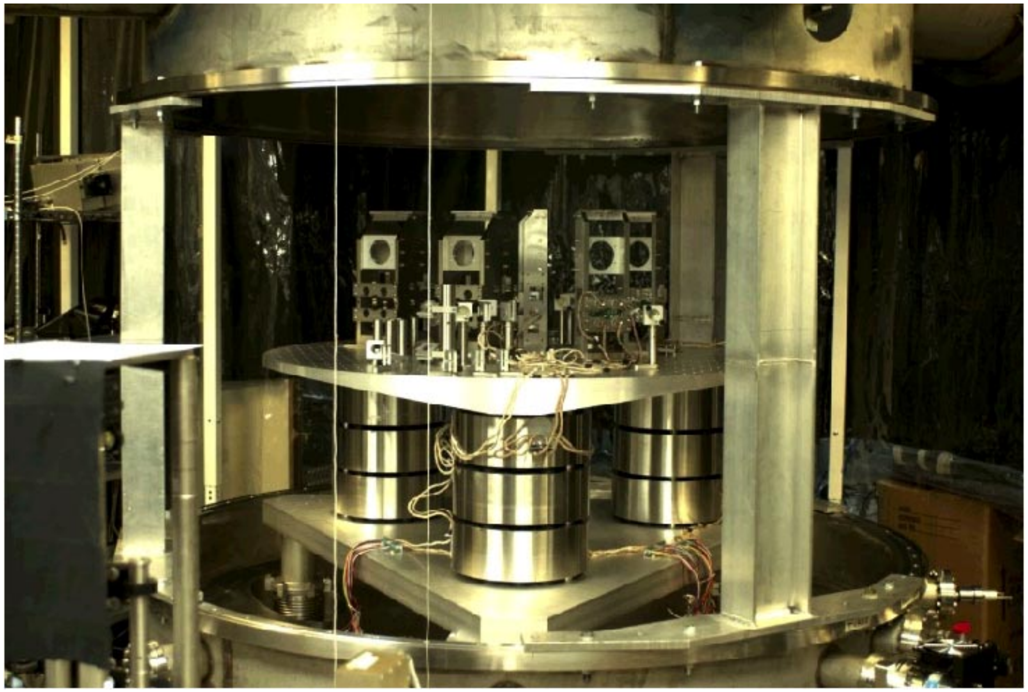


Photo by Ken Libbrecht

TNI Progress

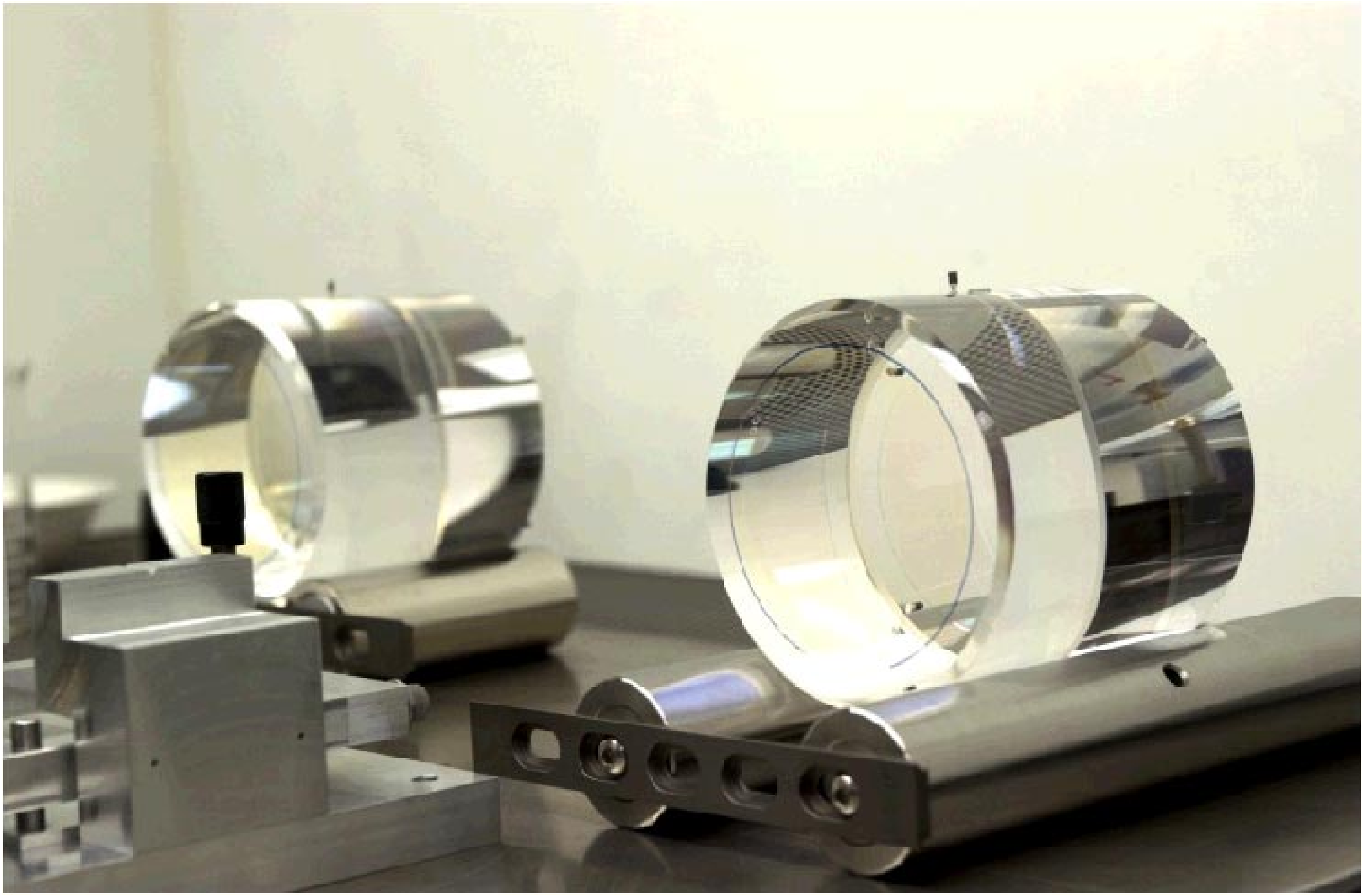


Photo by Ken Libbrecht

Magnets and guide rods are the same as for LIGO

TNI Progress

Laser & Modecleaner

Pre-Stabilized Laser (PSL): $f_{RMS} \cong 100$ mHz/$\sqrt{\text{Hz}}$

Modecleaner locked: $f_{RMS} \leq 30$ mHz/$\sqrt{\text{Hz}}$

Suspension hardware and electronics: $x_{RMS} \leq 10^{-8}$ m/$\sqrt{\text{Hz}}$ at DC

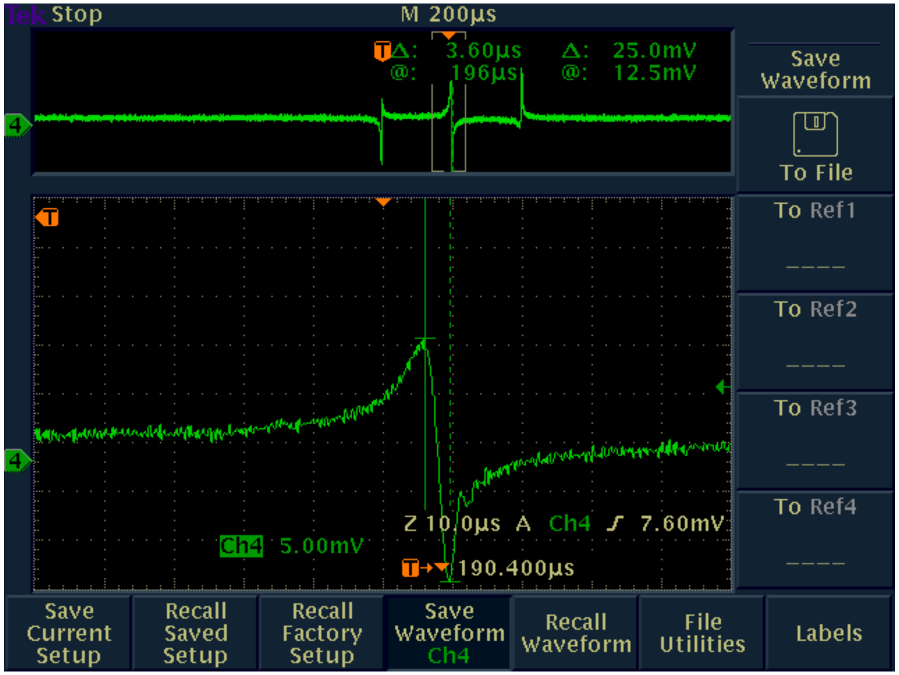
Arm cavities

Fused silica optics

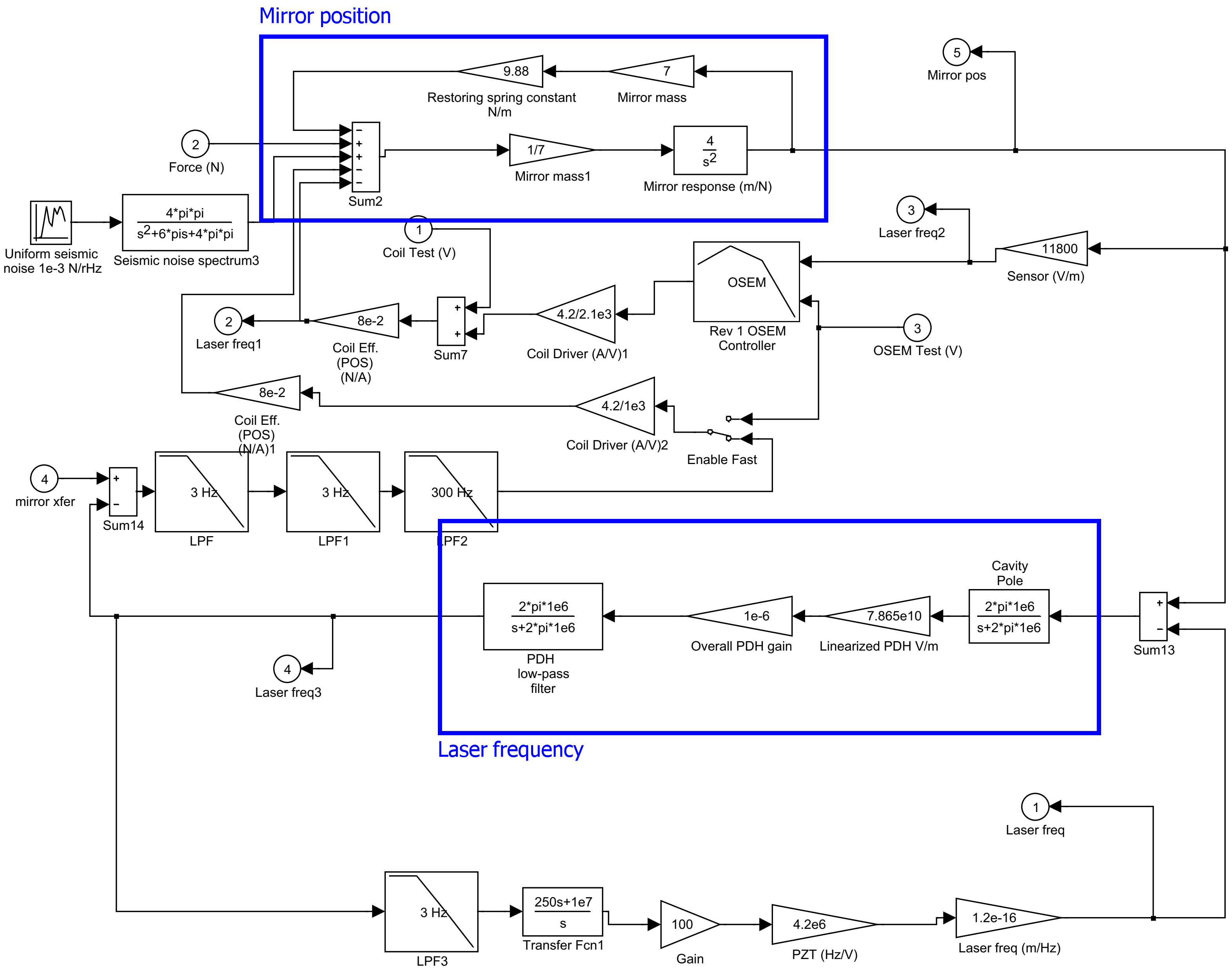
Suspension hardware and electronics: $x_{RMS} \leq 10^{-9}$ m/$\sqrt{\text{Hz}}$ at DC

One arm and laser locked to each other (without MC)

Finesse $\cong$ 60,000



Arm Cavity Model



Thesis

1. Finish construction

Verify laser noise and calibrate instrument

2. Brownian motion measurement

Measure thermal noise in fused silica from 200 Hz to 10 kHz

Look for non-Gaussian noise

3. Thermoelastic noise measurement

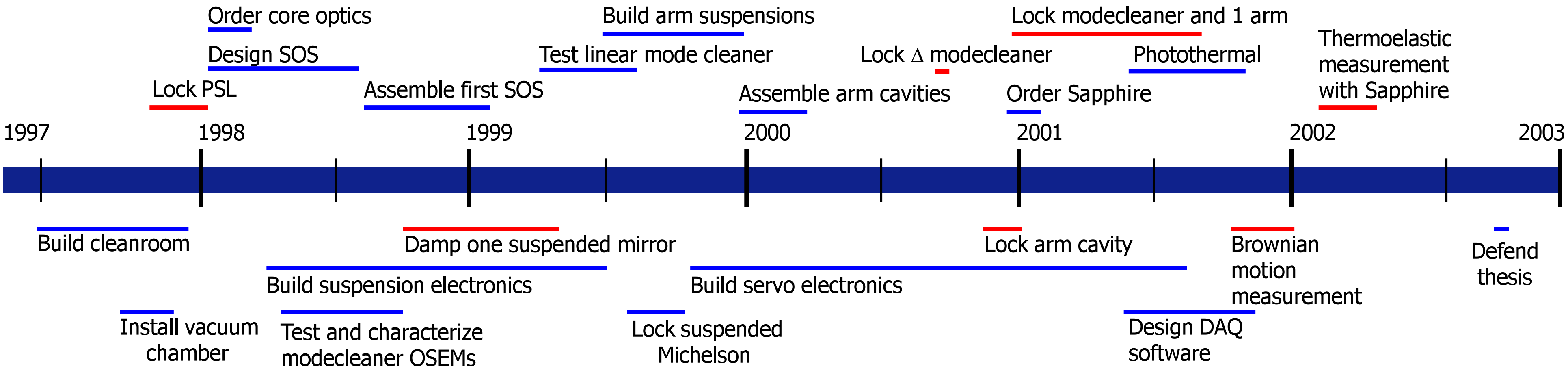
Upgrade TNI to sapphire mirrors

Requires minimal changes to TNI equipment and procedures

Photothermal measurement

Runs in parallel with the TNI

TNI Timeline



Order core optics

Design SOS

Lock PSL

Assemble first SOS

Build arm suspensions

Test linear mode cleaner

Assemble arm cavities

Lock Δ modecleaner

Lock modecleaner and 1 arm

Photothermal

Order Sapphire

Thermoelastic measurement with Sapphire

1997 1998 1999 2000 2001 2002 2003

Build cleanroom

Install vacuum chamber

Build suspension electronics

Test and characterize modecleaner OSEMs

Damp one suspended mirror

Lock suspended Michelson

Build servo electronics

Lock arm cavity

Design DAQ software

Brownian motion measurement

Defend thesis

Fused Silica Measurement

Noise similar to LIGO I

1. Lock the modecleaner and laser
2. Lock one arm
    - Use a broadband Pockel's Cell (BBPC) at high frequency
    - Actuate directly on one mirror at low frequency
3. Lock two arms to the laser
4. Measure noise, expect $x(\omega) \propto f^{-1/2}$
5. Look for non-Gaussian noise

Sapphire Measurement

Noise similar to LIGO II

1. Replace arm cavity test masses with Sapphire
2. Lock IFOs
3. Measure noise, expect $x(\omega) \propto f^{-1}$

Minimal equipment changes, and no new procedures

Thicker suspension wires

Boost OSEM gain by 2

$Q_{min} = 10^6$

Glue magnets and guide rods to Sapphire mirrors

Single point failure modes

Equipment failure – a few weeks

- Laser dies
- Pump breaks
- Seismic noise increases
- Shadow sensor LEDs burn out

Major problems – a few months

- Beam jitter
  - The Hanford PSL group has promised to help us reduce
- Arm cavity servo
  - Garry Sanders has promised support from CDS
  - Use models to design servos
- Scattered light
  - TNI has less of a problem than LIGO
  - New LIGO sensor-actuators are already in the schedule

Photothermal Effect

Laser power fluctuations drive thermal expansion

For shot noise $\propto (h\,\nu\,P)^{1/2}$

For direct modulation $\propto P$

Advanced GWDs

Coating losses

Laser power

Laser intensity noise

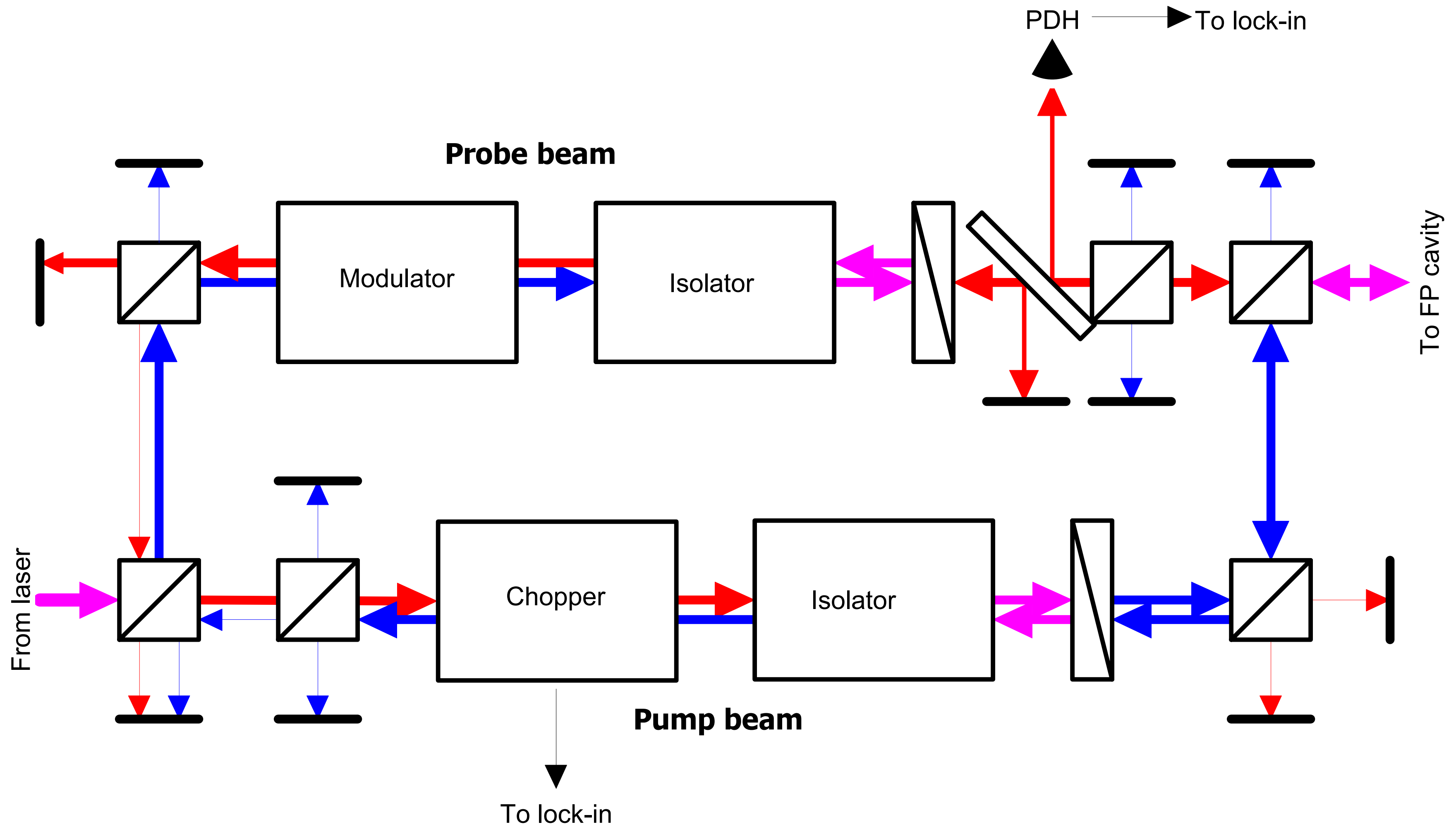
Depends on material properties

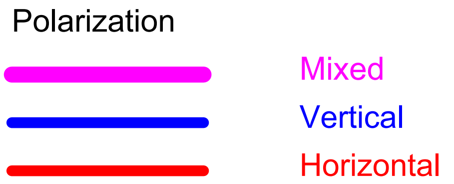
Lowest in Fused Silica

Low in Sapphire

Highest in Aluminum

Photothermal Effect



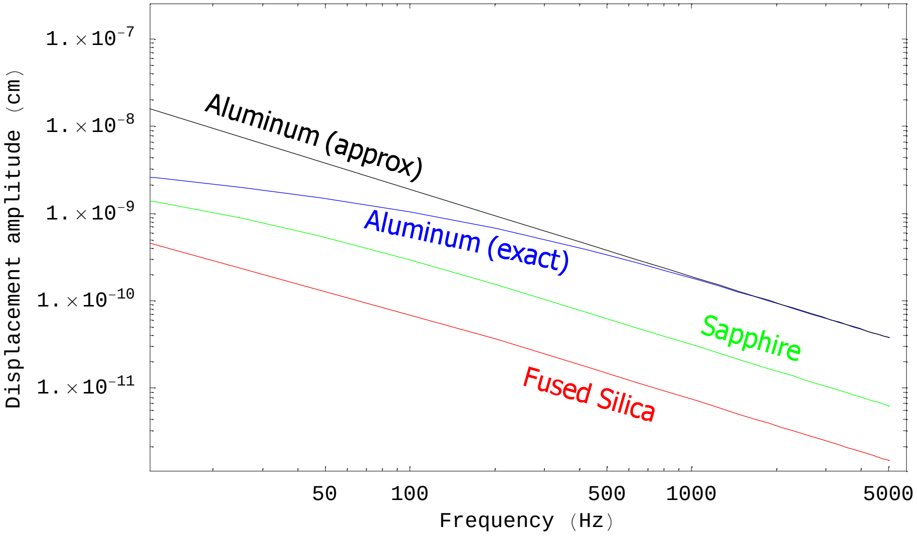


Photothermal Effect

Frequency dependent!

$$f(\omega) = \frac{P\alpha}{\rho C}\,\frac{e^{\frac{i\omega r^2}{2a}}}{8\pi a}\left(\mathrm{EI}\left[-\frac{i\omega r^2}{2a}\right] + i\,\pi\right)$$

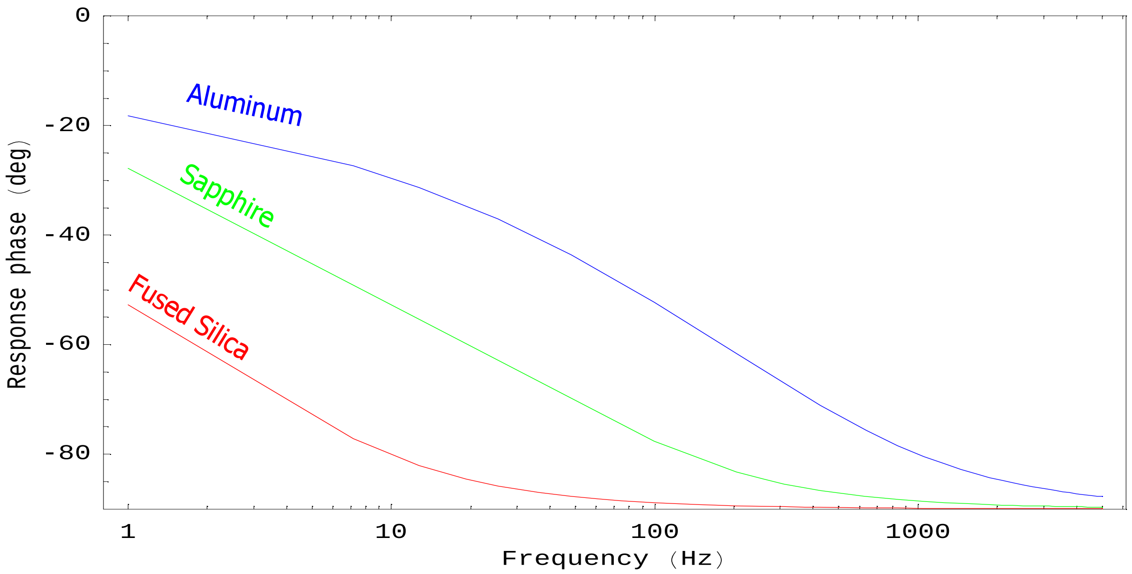
$$\text{Where } \mathrm{EI}(z) = -\int_{-z}^{\infty} e^{-t}/t\,dt$$



(DOC# T000004-00-R)

Test coatings

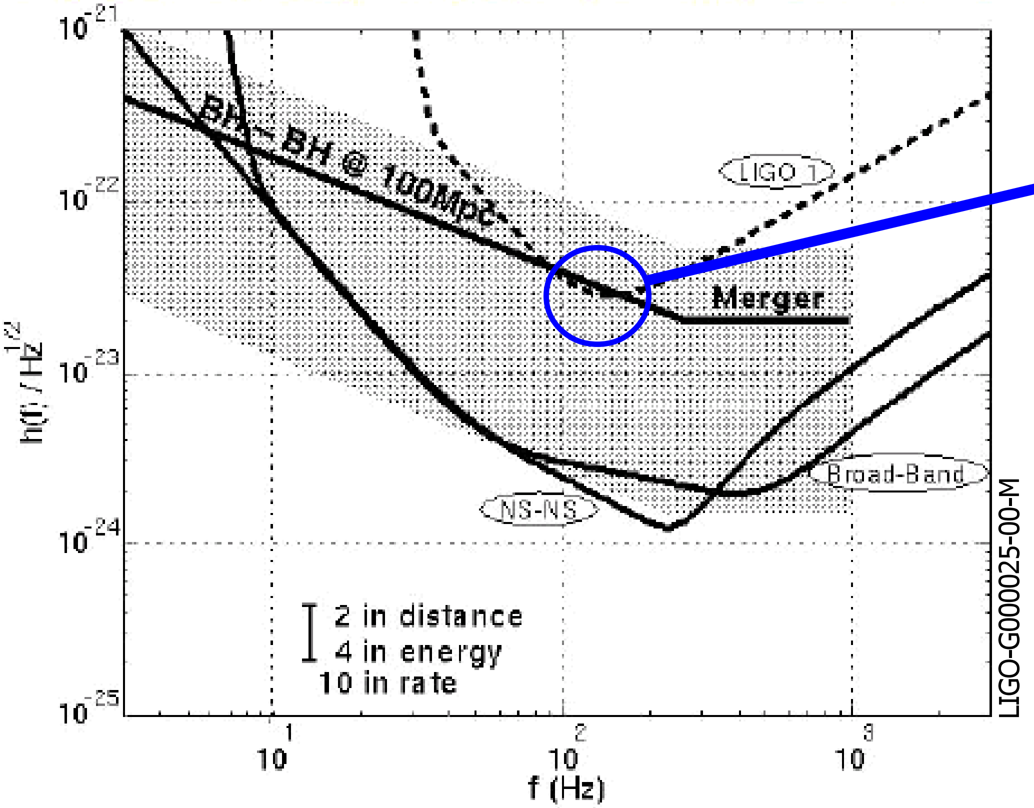
Compare phase response of coated (SiO_2, Al_2O_3) and uncoated (metal) mirrors



Thermal Noise Affects Event Rate

Rates Highly Uncertain. Optimistic estimates:

» LIGO-I: 100 Mpc, ~1/year. LIGO-II: z=0.5, ~1/hour



Thermal Noise

Limits event rate

Hard to measure with LIGO

Verify model

We need to understand thermal noise!

Thermal Noise Sources Relevant to Interferometric Gravitational Wave Detection

Measure noise sources

Sapphire (thermoelastic noise) – LIGO II

Fused Silica (Brownian motion) – LIGO I

Photothermal noise – Advanced GWD proposals

Progress report

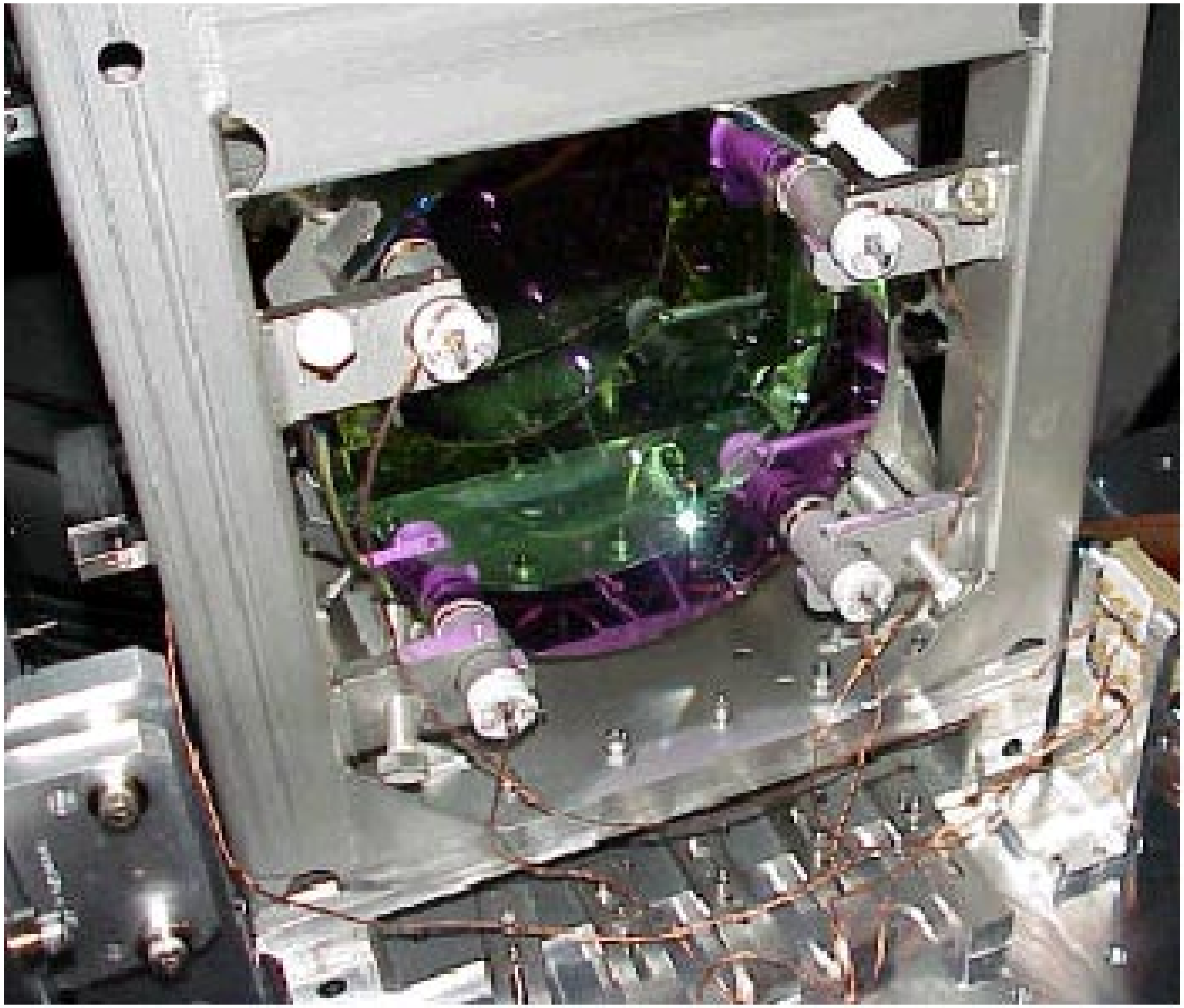
Prestabilized laser – frequency noise $\cong$ 100 mHz/$\sqrt{\text{Hz}}$

Triangular mode cleaner – finesse $\cong$ 5,000, $\nu \cong$ 30 mHz/$\sqrt{\text{Hz}}$

Test cavity – finesse $\cong$ 60,000

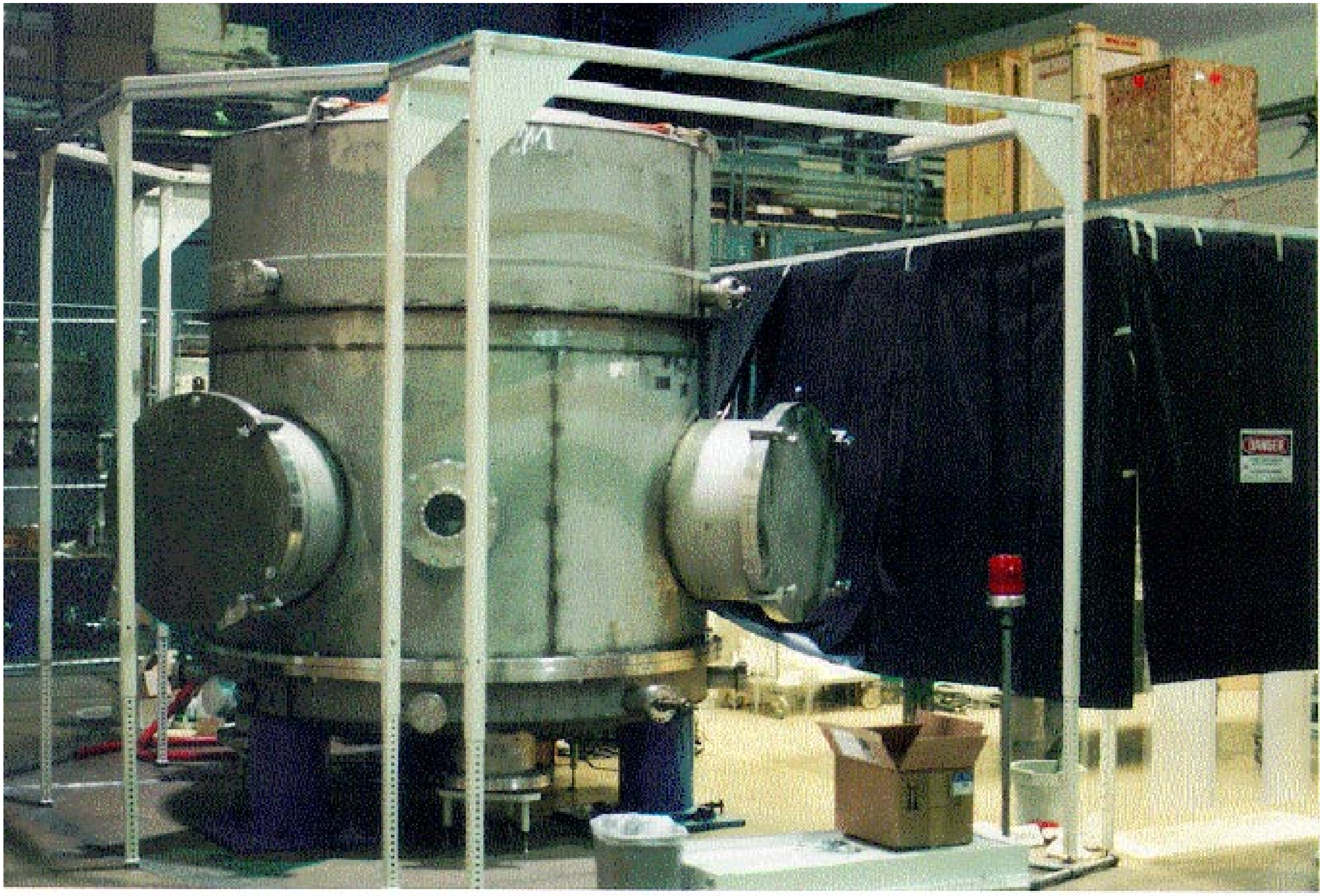
Completion in Spring 2002

Extra pictures



LIGO-G000306-00-M

Lab Facility



…before clean-room cover around vacuum chamber

Photo by Ken Libbrecht

Inside the Vacuum Chamber

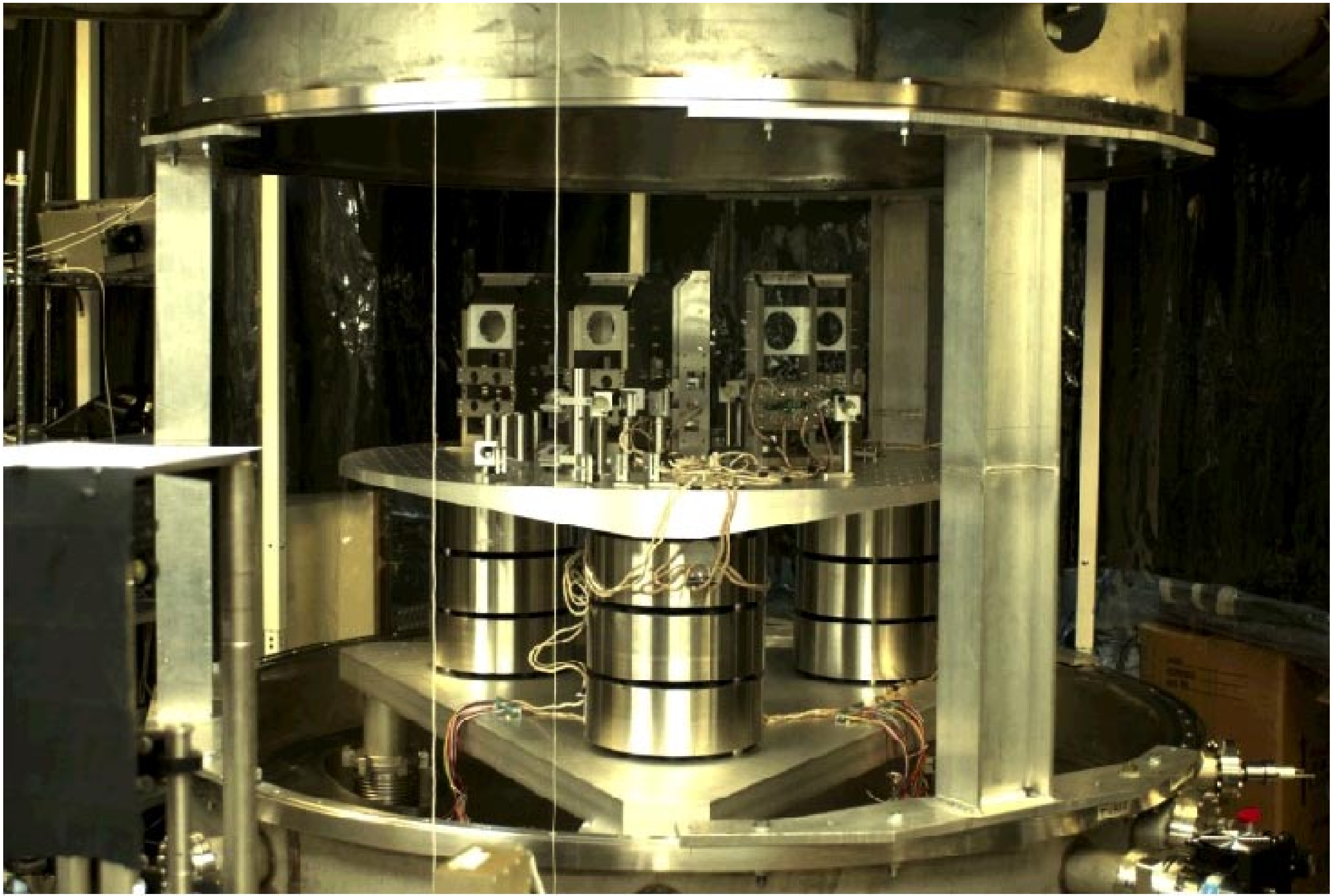


Photo by Ken Libbrecht

Thermal Noise Sources

Brownian motion

$$S_B(\omega) = \frac{4\ \mathrm{kB}\ T\ (1 - \sigma^2)\ \phi\mathrm{mass}}{\omega\ \mathrm{Sqrt}[2\ \pi]\ \mathrm{YoungM}\ \mathrm{SpotSize}}$$

Fused Silica	$x(\omega) = 2.4\ 10^{-18}\ (f/100\ \mathrm{Hz})^{-1/2}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$
Sapphire	$x(\omega) = 3.2\ 10^{-19}\ (f/100\ \mathrm{Hz})^{-1/2}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$

Thermoelastic damping

$$S_{TE}(\omega) = \frac{8\ \alpha^2\ (1 + \sigma)^2}{\mathrm{Sqrt}[2\ \pi]}\ \frac{\mathrm{kB}\ T^2}{\rho\ \mathrm{HeatCap}}\ \frac{\mathrm{a2}}{\mathrm{SpotSize}^3}\ \frac{1}{\omega^2}$$

Fused Silica	$x(\omega) = 9.0\ 10^{-19}\ (f/100\ \mathrm{Hz})^{-1}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$
Sapphire	$x(\omega) = 2.4\ 10^{-17}\ (f/100\ \mathrm{Hz})^{-1}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$

Photothermal noise

$$S_{PT}(\omega) = 2\ \alpha^2\ (1 + \sigma)^2\ \frac{\mathrm{hbar}\ \ 2\ \pi\ c\ \mathrm{Absorption}\ \mathrm{Finesse}\ \mathrm{LaserP}}{\lambda\ (\rho\ \mathrm{HeatCap}\ \pi\ \mathrm{SpotSize}^2)^2}$$

Fused Silica	$x(\omega) = 4.6\ 10^{-19}\ (f/100\ \mathrm{Hz})^{-1}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$
Sapphire	$x(\omega) = 2.2\ 10^{-18}\ (f/100\ \mathrm{Hz})^{-1}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$

Fundamental Noise Sources

Pendulum thermal noise

$\phi_{wire} > 10^3$

Violin modes

Wires at 20% of breaking strength

$\nu_0 \cong 3$ kHz

Radiation pressure

Shot noise

Much lower than necessary

Seismic noise

Estimated at 1 nm at DC

Technical Noise Sources

Johnson Noise

Most of the TNI electronics has 50 Ω impedance

SQL

Shot noise – 3 10^{-22} m/√Hz for 1kHz bandwidth

Radiation pressure – equal to shot noise at 100 Hz

Laser Frequency

Specified to be less than 30 mHz/√Hz

OSEM

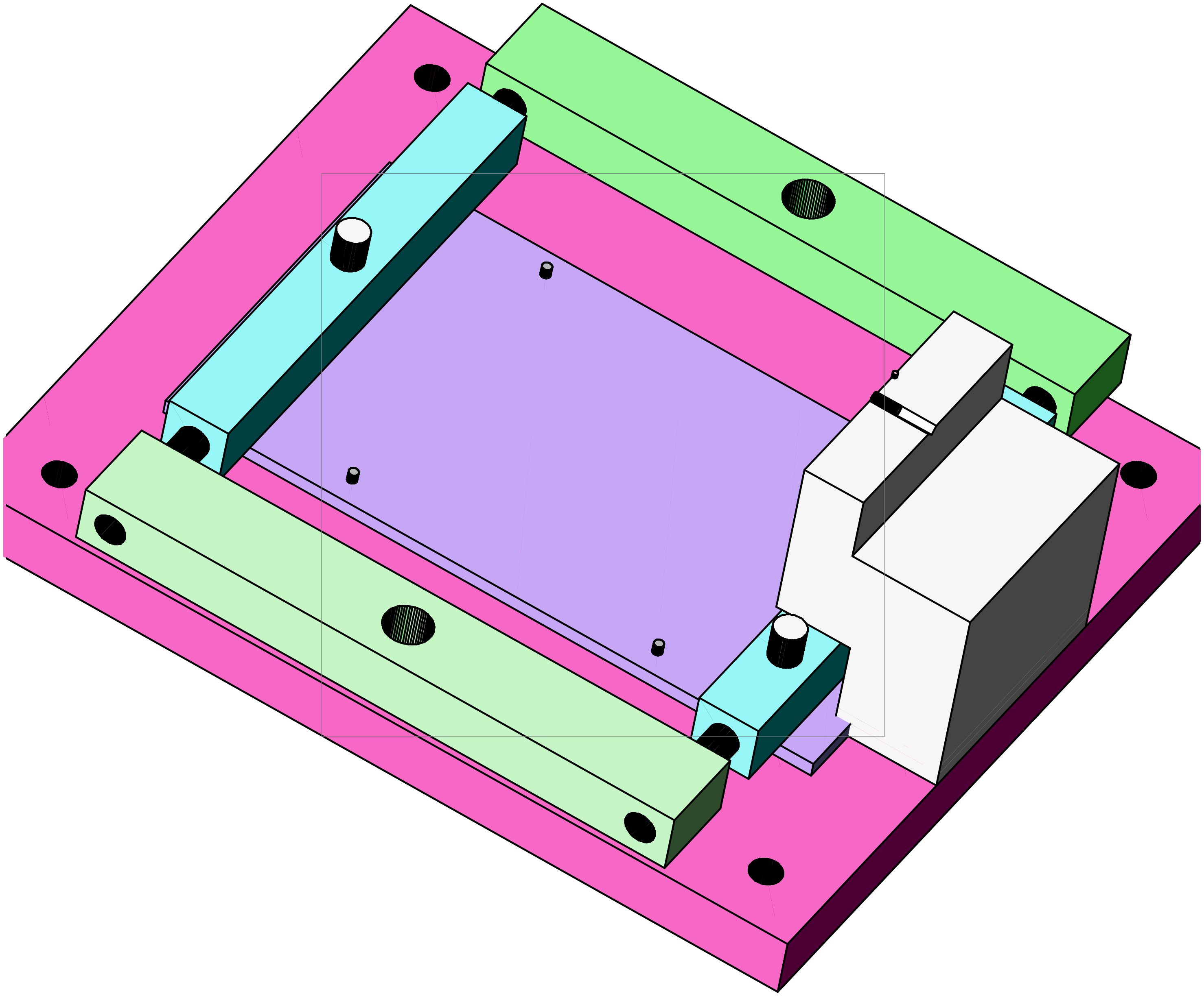
Shadow sensor dark current length noise is 10^{-9} m/rHz at DC

Aggressively filtered above 20 Hz

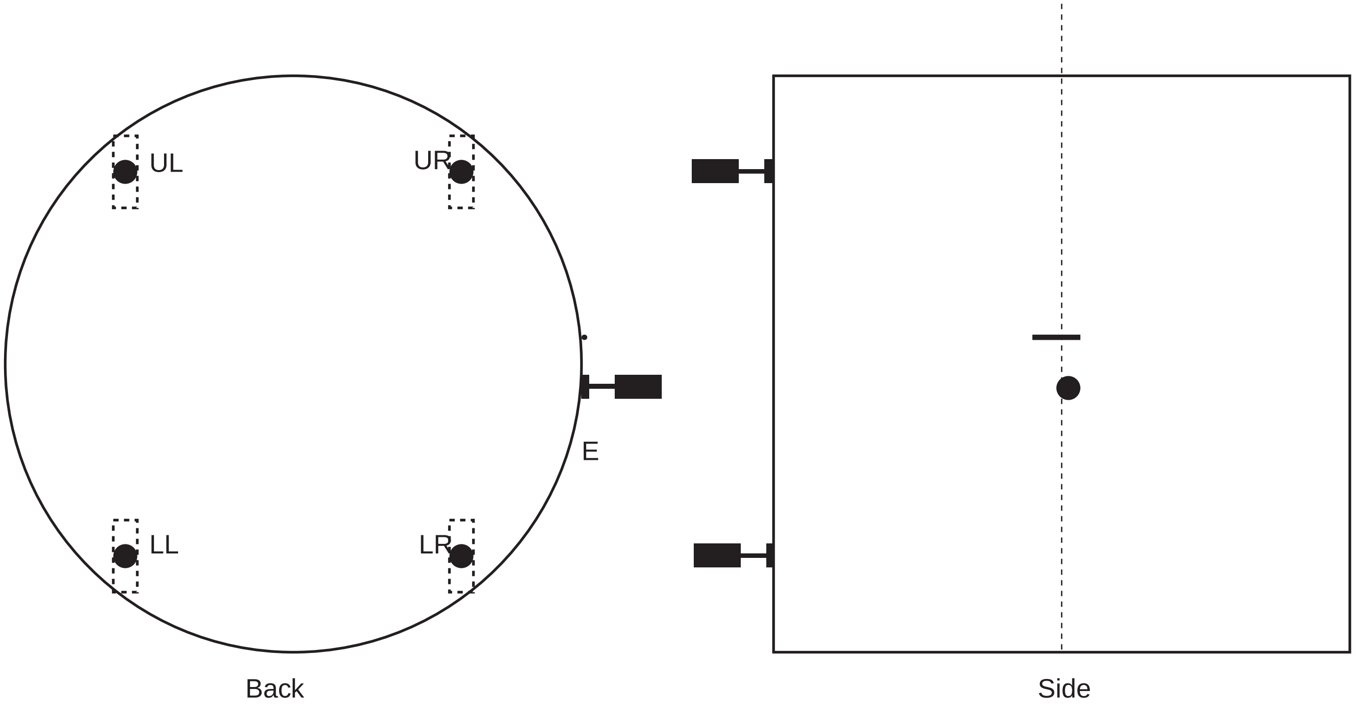
Alignment

OSEM electronics cross-couple 10% of photodiode length noise to alignment length noise

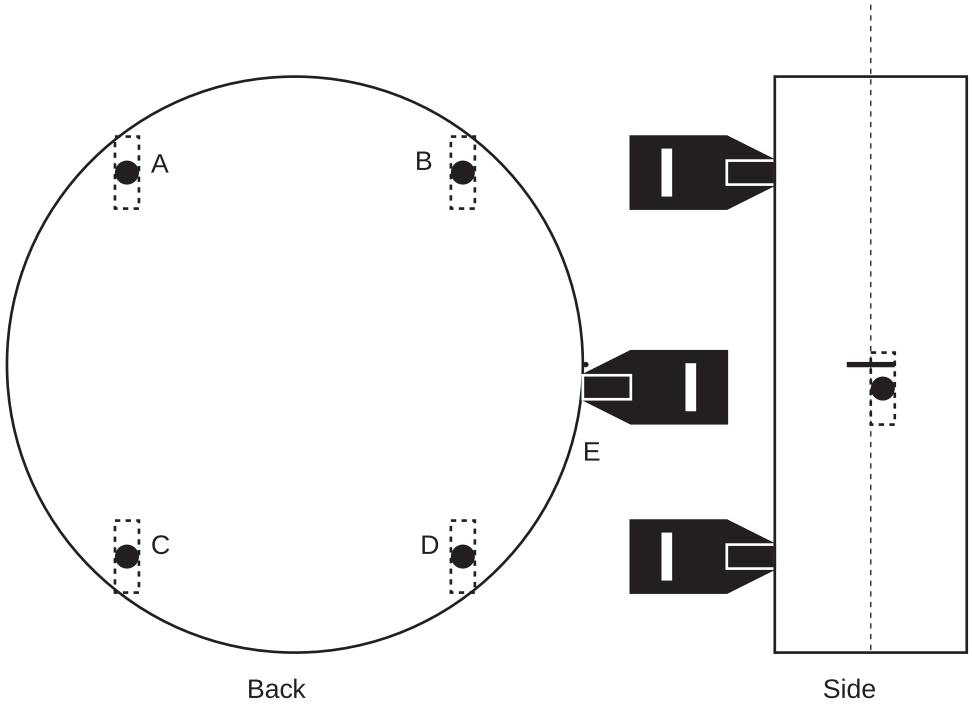
Cutting corners: magnet assembly jig



Arm cavity mirrors

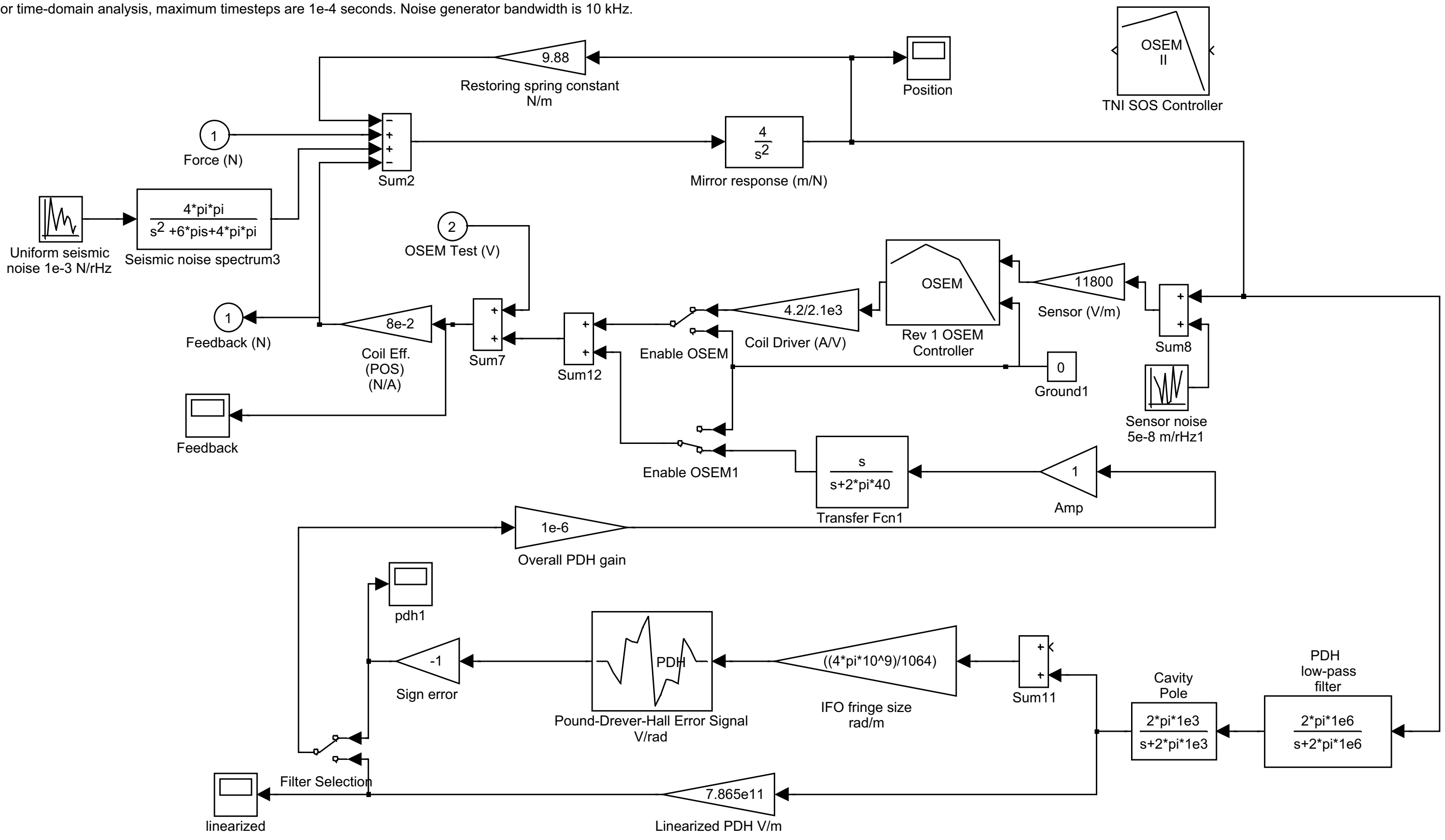


Modecleaner mirrors

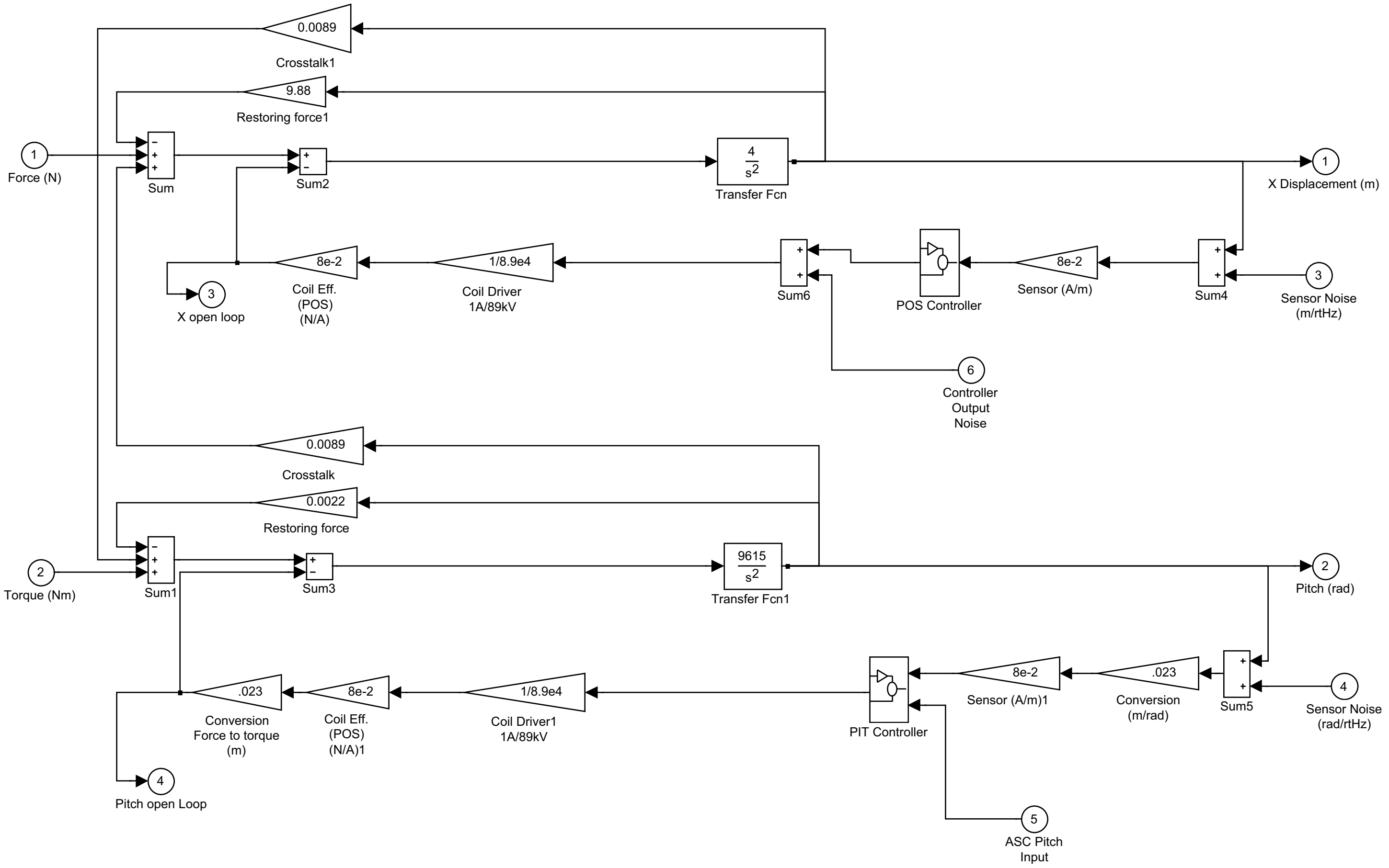


Modecleaner model

For time-domain analysis, maximum timesteps are 1e-4 seconds. Noise generator bandwidth is 10 kHz.



SOS Model


0.0089
Crosstalk1
9.88
Restoring force1
1
Force (N)
Sum
Sum2
4
$\frac{4}{s^2}$
Transfer Fcn
1
X Displacement (m)
8e-2
Coil Eff.
(POS)
(N/A)
1/8.9e4
Coil Driver
1A/89kV
Sum6
POS Controller
8e-2
Sensor (A/m)
Sum4
3
Sensor Noise
(m/rtHz)
3
X open loop
6
Controller
Output
Noise
0.0089
Crosstalk
0.0022
Restoring force
2
Torque (Nm)
Sum1
Sum3
$\frac{9615}{s^2}$
Transfer Fcn1
2
Pitch (rad)
.023
Conversion
Force to torque
(m)
8e-2
Coil Eff.
(POS)
(N/A)1
1/8.9e4
Coil Driver1
1A/89kV
PIT Controller
8e-2
Sensor (A/m)1
.023
Conversion
(m/rad)
Sum5
4
Sensor Noise
(rad/rtHz)
4
Pitch open Loop
5
ASC Pitch
Input

January 2001

Write a LIGO document describing the north arm cavity lock

February 2001

Fully characterize north arm lock, and write a LIGO document

Test the BBPC

Take laser from photothermal experiment and align optics

March 2001

Lock mode cleaner using mode cleaner servo electronics

Upgrade vacuum optics

Model the final servo electronics for the arm cavities and the BBPC

New laser arrives!

PCG meeting in Santa Barbara.

April 2001

Design arm cavity servo electronics

Analyze and repair arm cavity suspension controllers

Test BBPC servo

LSC meeting in LLO

Get quotes for grinding, polishing, and coating Sapphire

New Pockel's cells delivered — can now rebuild photothermal experiment

May 2001

Design arm cavity servo electronics

Analyze laser frequency noise with reference cavity

Repair arm cavity suspension controllers

Run photothermal experiment on Aluminum

June 2001

Test arm suspension controllers

Build and test arm cavity servo electronics

Sapphire blanks delivered — ship for grinding and polishing

July 2001

Test arm cavity servo (should result in fringe dragging)

Fix arm cavity servo electronics

Lock mode cleaner, and align transmitted beam to one arm

Design data acquisition software

August 2001

Photothermal experiment on sapphire

Sapphire optics ground — ship for coating

Design data acquisition software

Lock one arm cavity, modecleaner, and laser

Vacation

September 2001

Commission South arm cavity

Lock South arm cavity

If necessary, upgrade arm cavity sensor/actuators to new LEDs and photodiodes

Write data acquisition software

October - December 2001

Reduce noise and take data

Write a LIGO document before Christmas

January 2002

Repeat December's miracle, write a paper

Look for non-gaussian noise (continuous operation and data acquisition)

Order wire, standoffs, and guide rods for sapphire

Repeat photothermal measurement with Al, SiO2, Al2O3

February 2002

Rebuild arm cavities

Glue magnets and standoffs to sapphire mirrors

Inspect test cavity OSEMs

Install one sapphire arm cavity

Write a paper for the photothermal experiment

March - April 2002

Thermoelastic measurement with Sapphire

May 2002

Start writing thesis

Look for a job

September 2002

Defend thesis