NOISE in GW detectors

- After ~ 40 years of effort, no one has detected a GW!
- Why? Noise levels in detectors exceed expected signal; *insufficient sensitivity*
- Want to detect GW strain *h*; can express detector noise in terms of equivalent *h* sensitivity
- Most of the effort in GW detection has gone into *understanding and reducing noise* to the fundamental quantum limit (and beyond!)
- We are the beneficiaries of that pioneering and frustrating work: on the threshold of doing what sounds almost impossibly hard!

NOISE SOURCES IN THE DETECTOR

- Noise $\Rightarrow$ signals which appear in detector as GWs but are imposters
- Three categories:
- Displacement noise $\Rightarrow$ moves mirrors (path length changes)

$\delta x = L\,\delta h$, so to achieve $h \approx 10^{-21}/\sqrt{Hz}$ with $L = 4$km,

$\Rightarrow \delta x \approx 10^{-18}\ m/\sqrt{Hz}$

(*cf*: diameter of proton is 10^{-15} m)

- Phase noise $\Rightarrow$ changes the phase of the light:

$\delta\phi = 4\pi\, NL\, \delta h / \lambda$, with $N \approx 100$ and $\lambda \approx 1.064\ \mu$m,

$\Rightarrow \delta\varphi \approx 10^{-10}\ rad/\sqrt{Hz}$

- Technical or instrumental noise (laser, electronics, EMF pickup, *etc*)

must engineer IFO to keep this *below* the fundamental noise!

Sensing limits

Photon shot noise:

$$E_{APD} = P_{APD}\tau_{\text{int}} = N_{photon}(h_{Pl}c/\lambda)$$

uncertainty in intensity due to counting statistics:

$$\Rightarrow \delta P_{APD} = \sqrt{P_{APD}h_{Pl}c/\lambda\tau_{\text{int}}}$$

can solve for equivalent strain:

$$h_{shot} = \frac{\delta L}{L} = \frac{1}{L}\sqrt{\frac{h_{Pl}c\lambda}{2\pi T(f)P_{laser}}}$$

Note: scaling with $1/\sqrt{P_{laser}}$; gives requirement for laser power

Radiation Pressure

quantum limited intensity fluctuations anti-correlated in two arms

photons exert a time varying force, spectral density

results in opposite displacements of *each* of the masses; strain

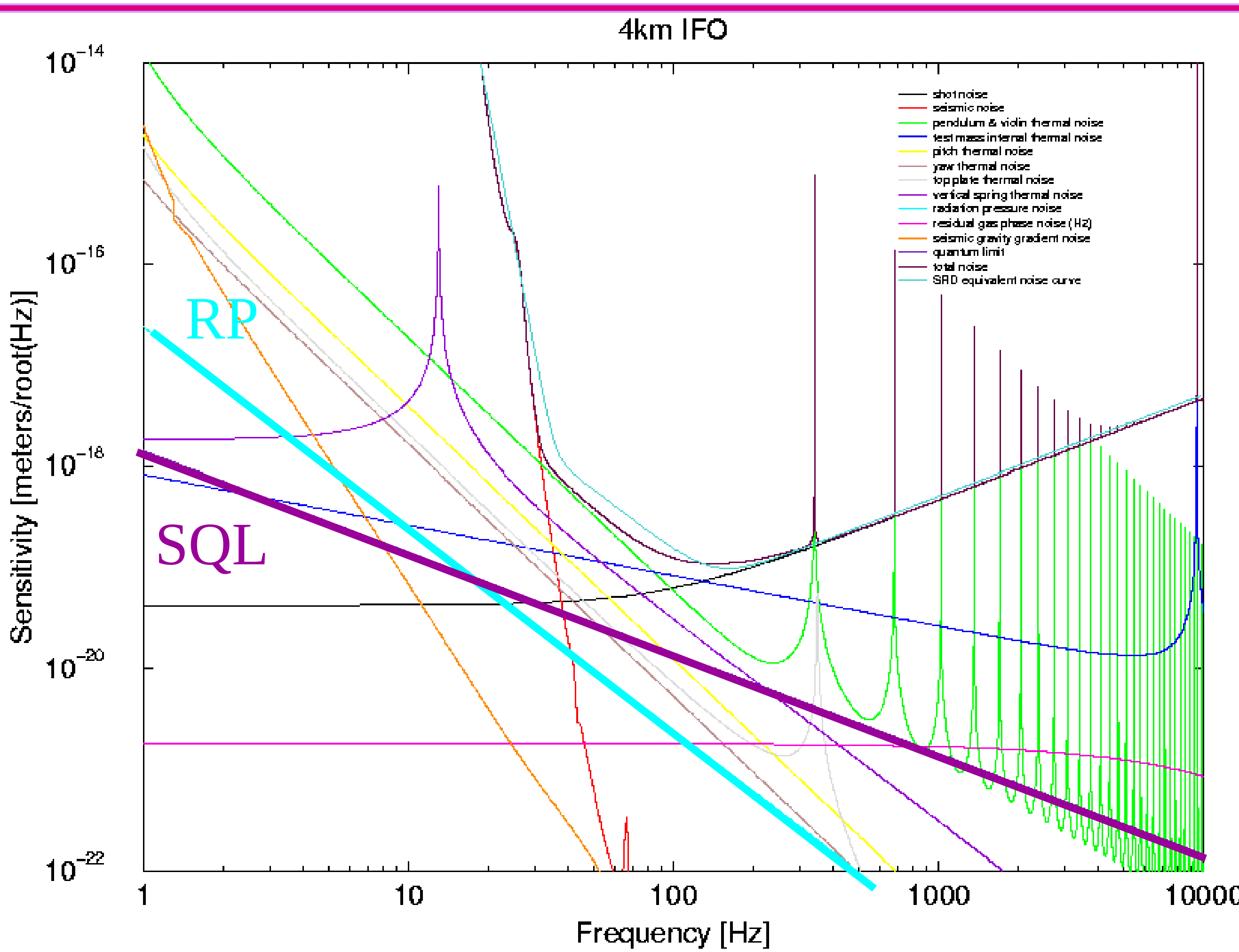
$$h_{rp} = \frac{\delta L}{L} = \frac{2}{L}\frac{1}{mf^2}\sqrt{\frac{h_{Pl}T(f)P_{laser}}{8\pi^3 c\lambda}}$$

NOTE: scaling with $\sqrt{P_{laser}}$, scaling with the arm length

Total optical readout, or quantum noise:

quadrature sum $h_q = \left(h_{shot}^2 + h_{rp}^2\right)^{1/2}$; can be optimized

Optical readout noise



Optical readout noise:

$$h_{ro}(f) = \sqrt{h_{shot}^2(f) + h_{rp}^2(f)}$$

Optimize h_{ro} wrt P_{laser} at each point in f; Locus of points is the Standard Quantum Limit, Obtainable from Heisenberg Uncertainty

$$h_{SQL} = \frac{1}{\pi f L}\sqrt{\frac{\hbar}{m}}$$

Thermal displacement noise

Mechanical systems excited by the thermal environment

results in physical motions of the tests masses

$$x_{rms} = \sqrt{\left\langle (\delta x)^2 \right\rangle} = \sqrt{k_B T / k_{spring}}$$

Each normal mode of vibration has $k_B T$ of energy; for a SHO,

An extended object has many normal modes at discrete frequencies;

each will experience thermal excitation.

Dissipation causes the energy, and fluctuations in position, to spread over a range of frequencies, according to Fluctuation-Dissipation theorem:

$$\tilde{x}(f) = \frac{1}{\pi f}\sqrt{\frac{k_B T}{\Re(Z(f))}}$$

, $\Re(Z)$ is the real (lossy) impedance

e.g., damping term in an oscillator: $m\ddot{x} = F_{ext} - \Re(Z)\dot{x} - k_{spring}x$

•viscous damping: $\Re(Z) = b$ = constant. Recall, at a definite f, $\dot{x} = i2\pi f\, x$

•internal friction: $F = -kx \quad \Rightarrow \quad F = -k(1 + i\phi(f))x$

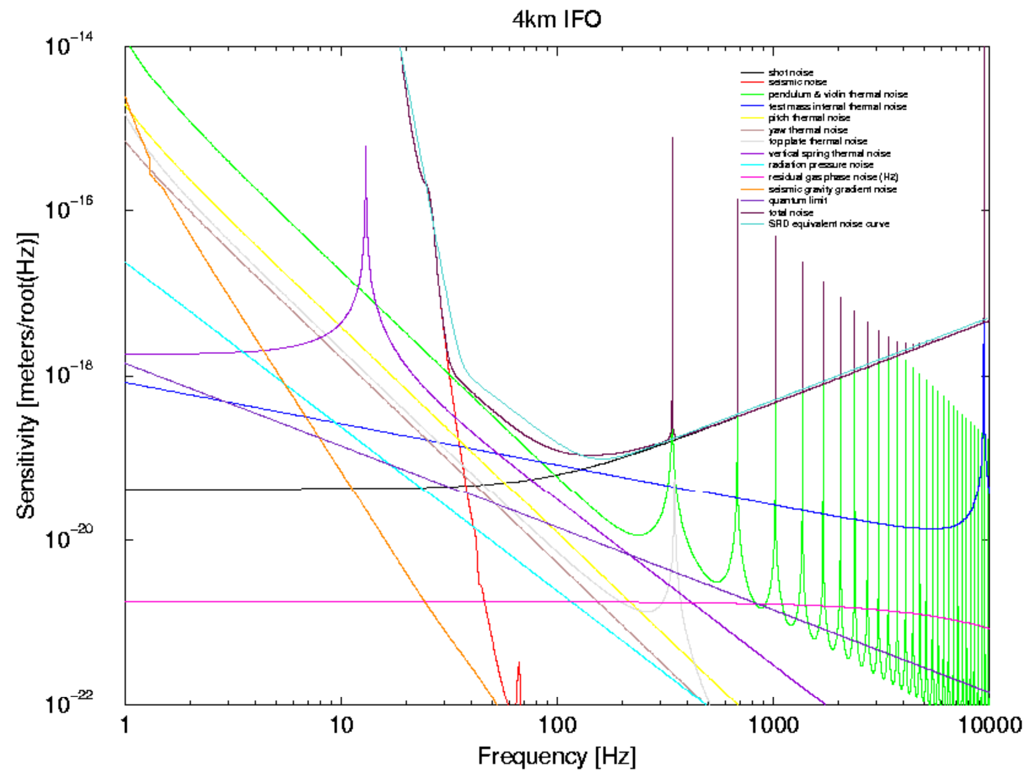
$\phi(f)$ is often a constant, = 1/Q

Minimize thermal motion $\Rightarrow$ materials and techniques for very low loss (high Q)

Thermal displacement noise

Sum of many normal modes, Each with loss $\phi_n(f)$:

$$x^2_{thermal} = \frac{4kT}{2\pi f}\sum_n \frac{\phi_n(f)}{m_n(2\pi f_n)^2}\left\{\frac{1}{\left(1-(f/f_n)^2\right)^2+\phi_n{}^2(f)}\right\}$$

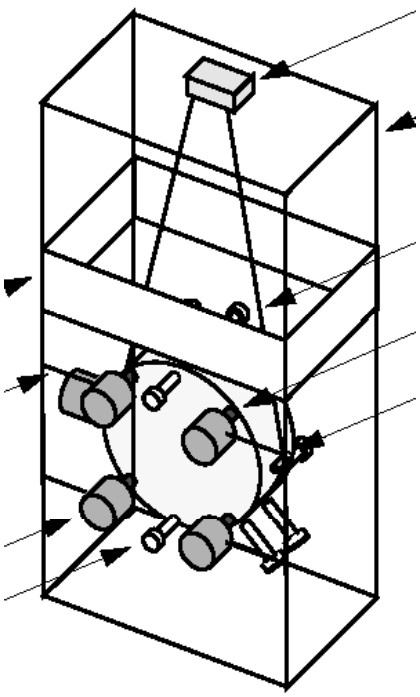


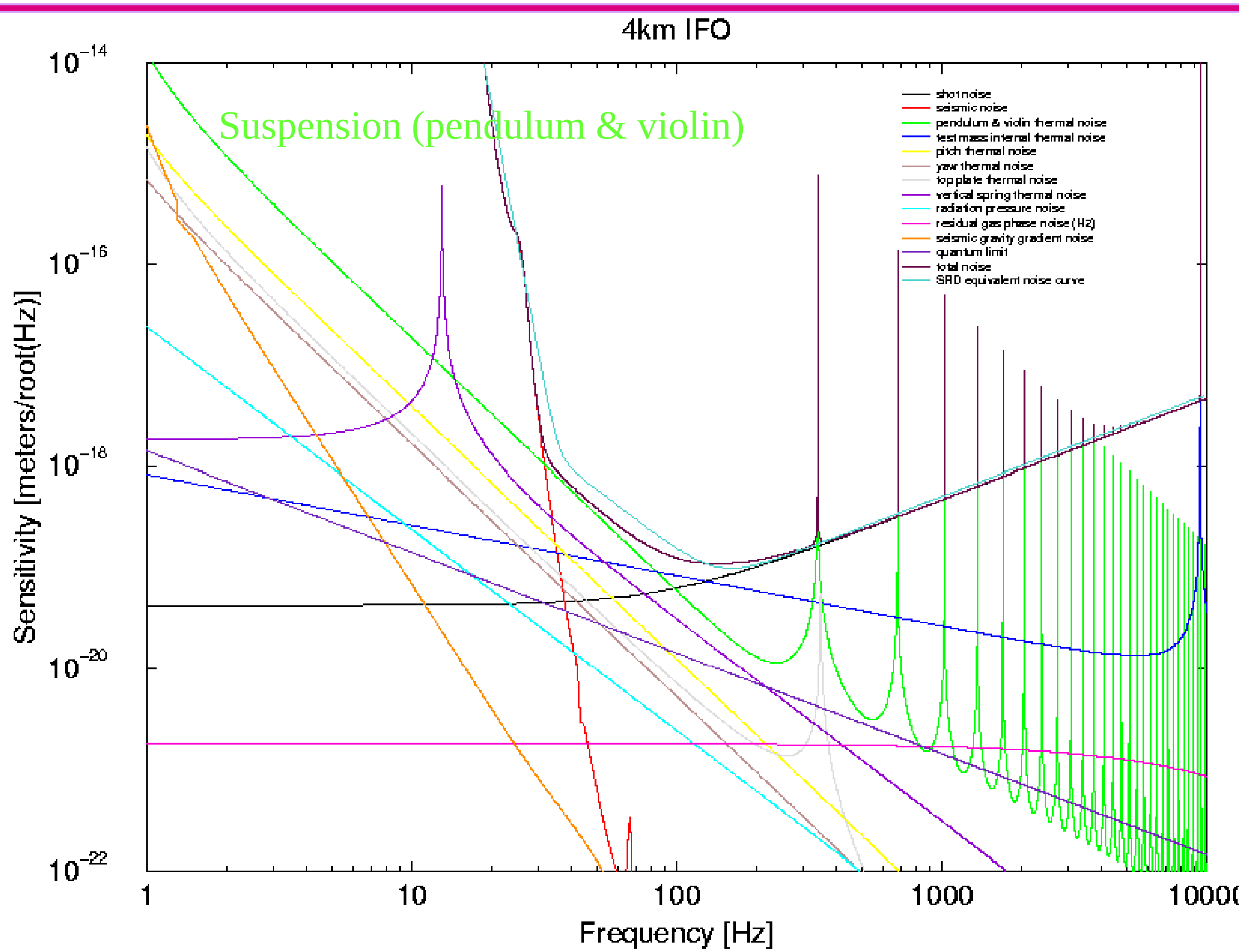
Equivalent strain (noise):

$$h_{thermal}(f) = \frac{2}{L}\sqrt{x^2_{thermal}}$$

Suspension thermal noise

Suspension wires vibrate (violin modes, stretch/bounce modes), kick the test mass around, introducing a harmonic series of noise lines

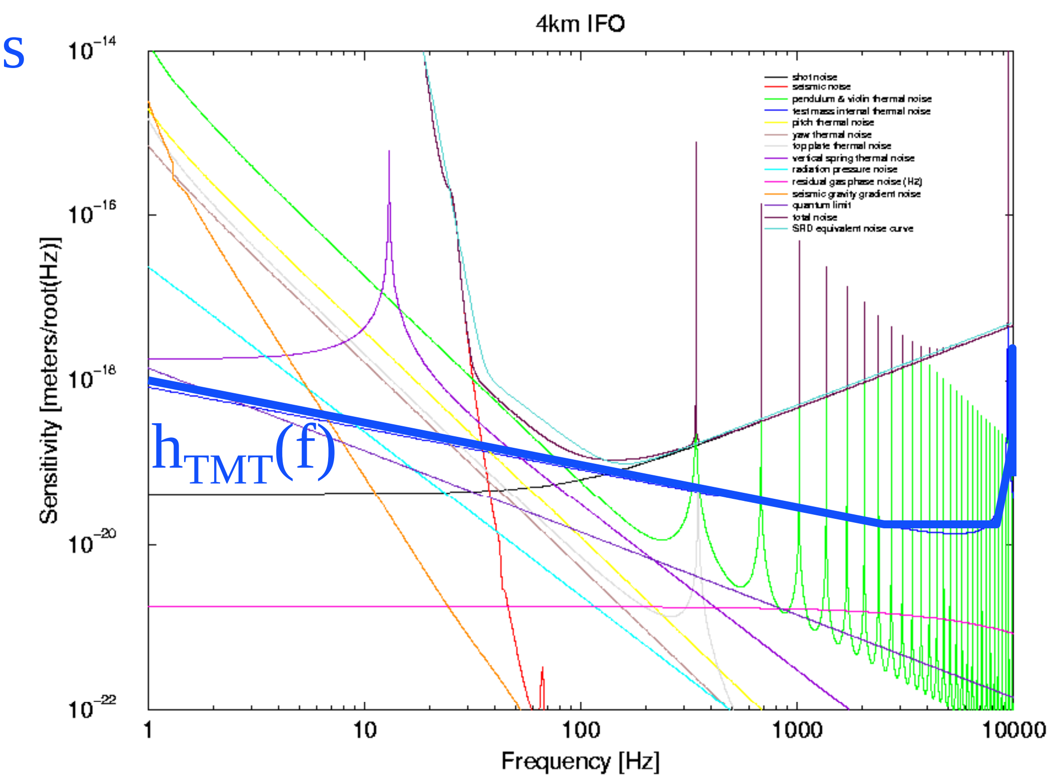




Test mass internal thermal noise

$$x_{TMT}^2 = \frac{4kT}{2\pi f} \sum_n \frac{\phi_n(f)}{m_n (2\pi f_n)^2} \left\{ \frac{1}{\left(1-(f/f_n)^2\right)^2 + \phi_n{}^2(f)} \right\}$$

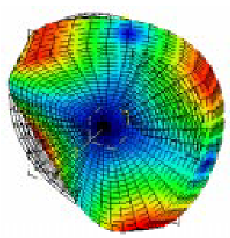
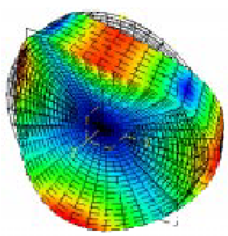
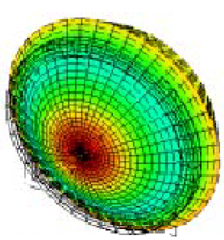
Test masses have normal modes
Above the LIGO band

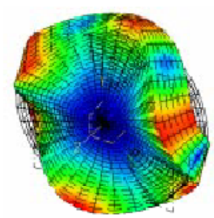
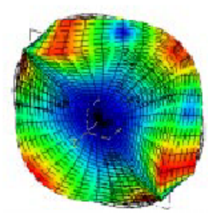
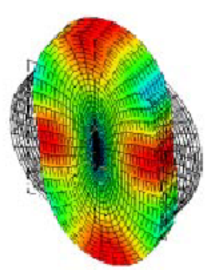


Equivalent strain:

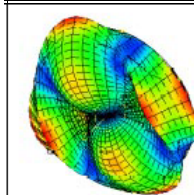
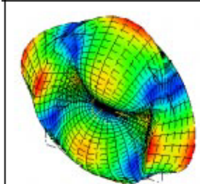
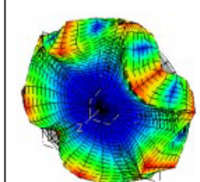
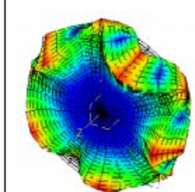
$$h_{TMT}(f) = \frac{2}{L}\sqrt{x_{TMT}^2}$$

Vibrational modes of test masses

Mode Shape	Frequency (Hz)
	3785
	3785
	5578

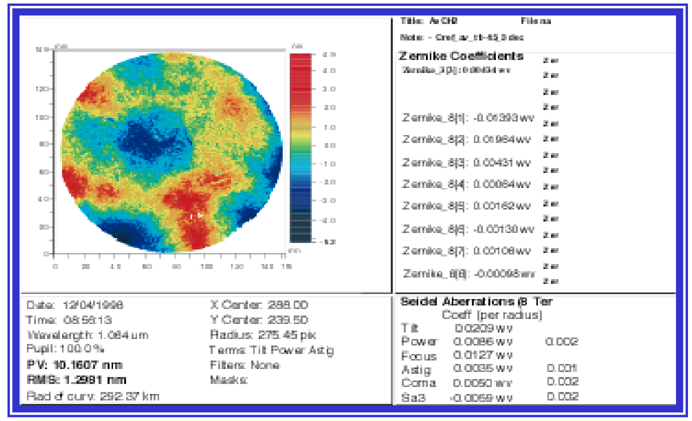
Mode Shape	Frequency (Hz)
	7975
	7975
	11259

• • •

Mode Shape	Frequency (Hz)
	17388
	17388
	17958
	17958

This is for beam splitter. Test masses have no resonances below ~8KHz (?).

Noise from imperfect Optics



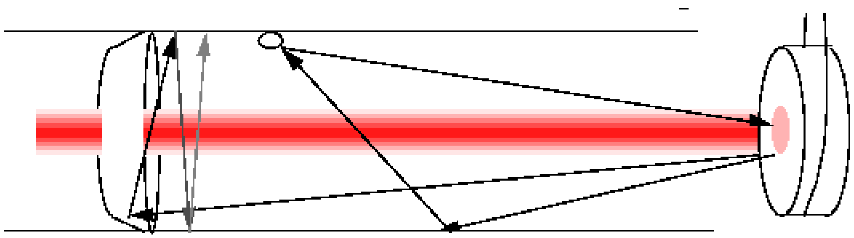
Highly efficient optical system:

~50 ppm lost per round-trip

- optics are 25 cm diameter, 10 cm thick fused silica cylinders
- light beam ~10 cm diameter; 1ppm scattered, ~1ppm absorbed

Constraints on optical surface due to noise requirements:

- minimize scatter (power loss ⇒ phase noise)
- minimize absorption (thermal distortions, lensing ⇒ phase noise)
- minimize scattering out of beam, onto tube, back into beam (phase noise)
- minimize wavefront distortions (*contrast defect* at dark port ⇒ phase noise)



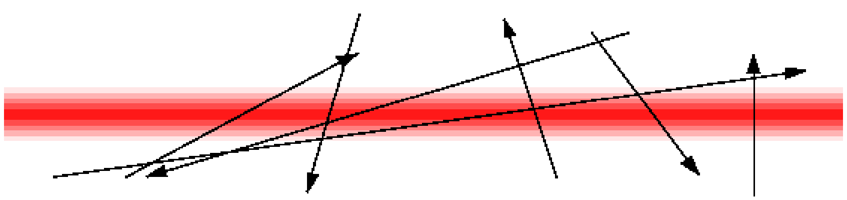
Results

- **λ/800** over central 10 cm (~1 nm rms); fine scale `superpolish‘
- Sophisticated *baffling*

Residual gas in beam tube

Light must travel 4 km without attenuation or degradation

- refractive index fluctuations in gas cause variations in optical path, phase noise
- residual gas scatters light out of, then back into, beam; phase noise
- Residual gas pressure fluctuations buffet mirror; displacement noise
- Contamination: low-loss optics can not tolerate surface 'dirt';
  High circulating powers of ~10-50 kW burns dirt onto optic surface



requirement for vacuum in 4 km tubes:

- H_2 at 10^{-6} torr initial, 10^{-9} torr ultimate
- H_2O at 10^{-7} torr initial, 10^{-10} ultimate
- Hydro-, flourocarbons < 10^{-10} torr
- vacuum system, 1.22 m diameter, ~10,000 m^3
- strict control on in-vacuum components, cleaning

Seismic displacement noise

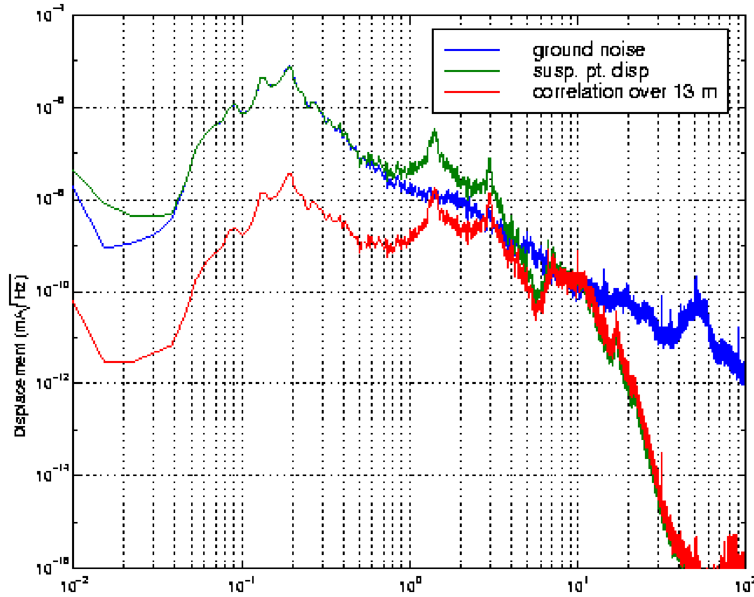
Motion of the earth

•driven by wind, volcanic/seismic activity, ocean tides, humans

•requires *e.g.*, roughly 10^9 attenuation at 100 Hz

•~300 micron tidal motion, microseismic peak at 0.16 Hz.

• At low frequencies, motion is correlated over two mirrors



Approaches to limiting seismic noise

•careful site selection

- •far from ocean, significant human activity, seismic activity

•active control systems (only microseismic peak for now)

- •seismometers, regression, feedback to test masses

•simple damped harmonic oscillators in series

- •`stacks', constrained layer springs and SS masses

•one or more low-loss pendulums for final suspension

- •gives $1/f^2$ for each pendulum

Seismic Isolation Systems

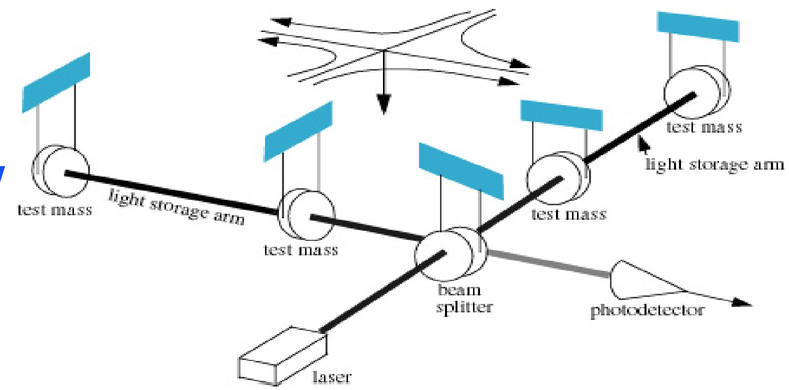
Support Tube Installation

Stack Installation

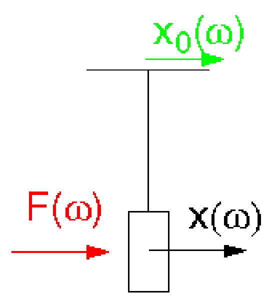
Coarse Actuation System

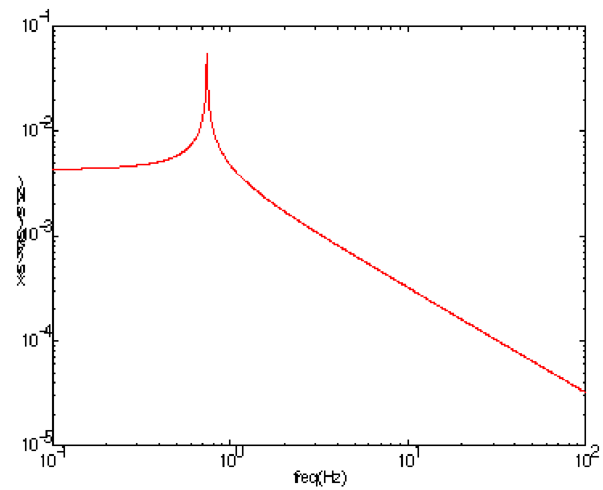
Suspended test masses

- To respond to the GW, test masses must be "free falling"
- On Earth, test masses must be supported against DC gravity field
- The Earth, and the lab, is vibrating like mad at low frequencies (seismic, thermal, acoustic, electrical);
  - can't simply bolt the masses to the table (as in typical ifo's in physics labs)
- So, IFO is insensitive to low frequency GW's
- Test masses are suspended on a pendulum resting on a seismic isolation stack
  - "fixed" against gravity at low frequencies, but
  - "free" to move at frequencies above ~ 100 Hz



"Free" mass: pendulum at $f >> f_0$





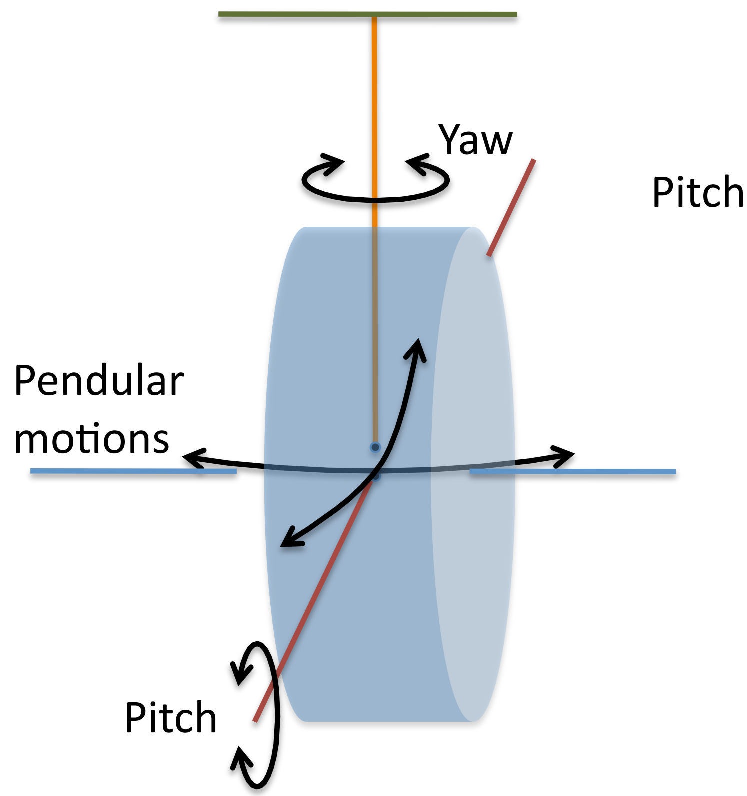
Seismic Isolation

The Target:

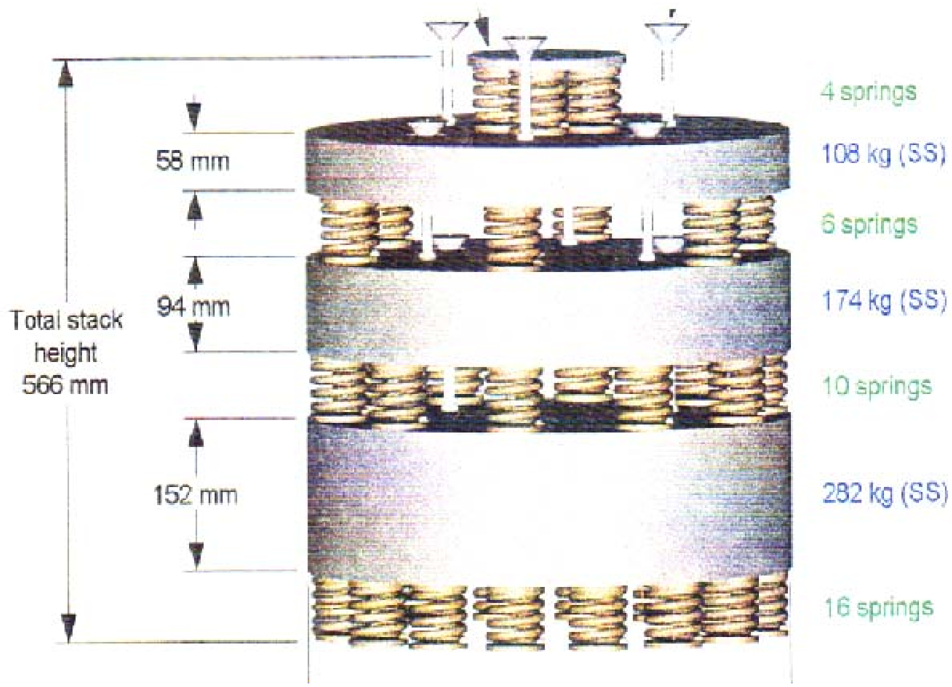
Relative distance between mirrors

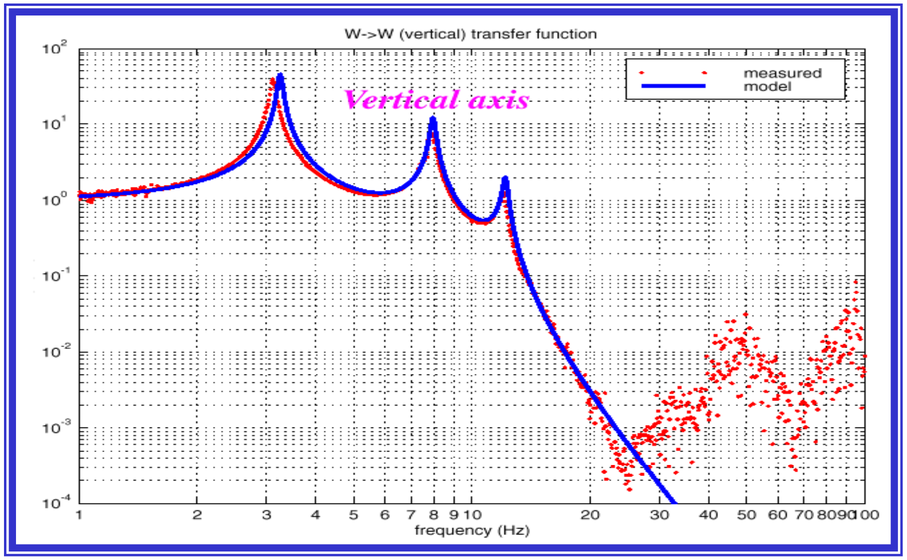
Degrees of freedom

Pendular motion	2
Pitch and Yaw motion	2
Torsional motion	1
Vertical motion	1

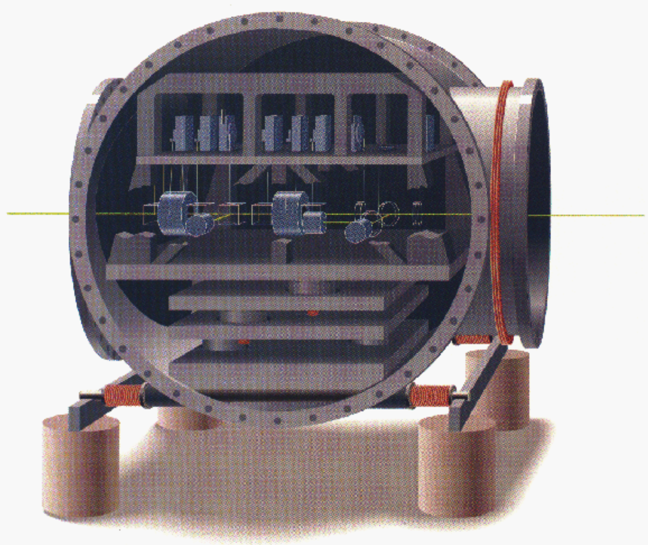


Seismic isolation stacks





LIGO Vacuum Chambers



HAM Chambers

BSC Chambers

Seismic Isolation Systems

Support Tube Installation

Stack Installation

Coarse Actuation System

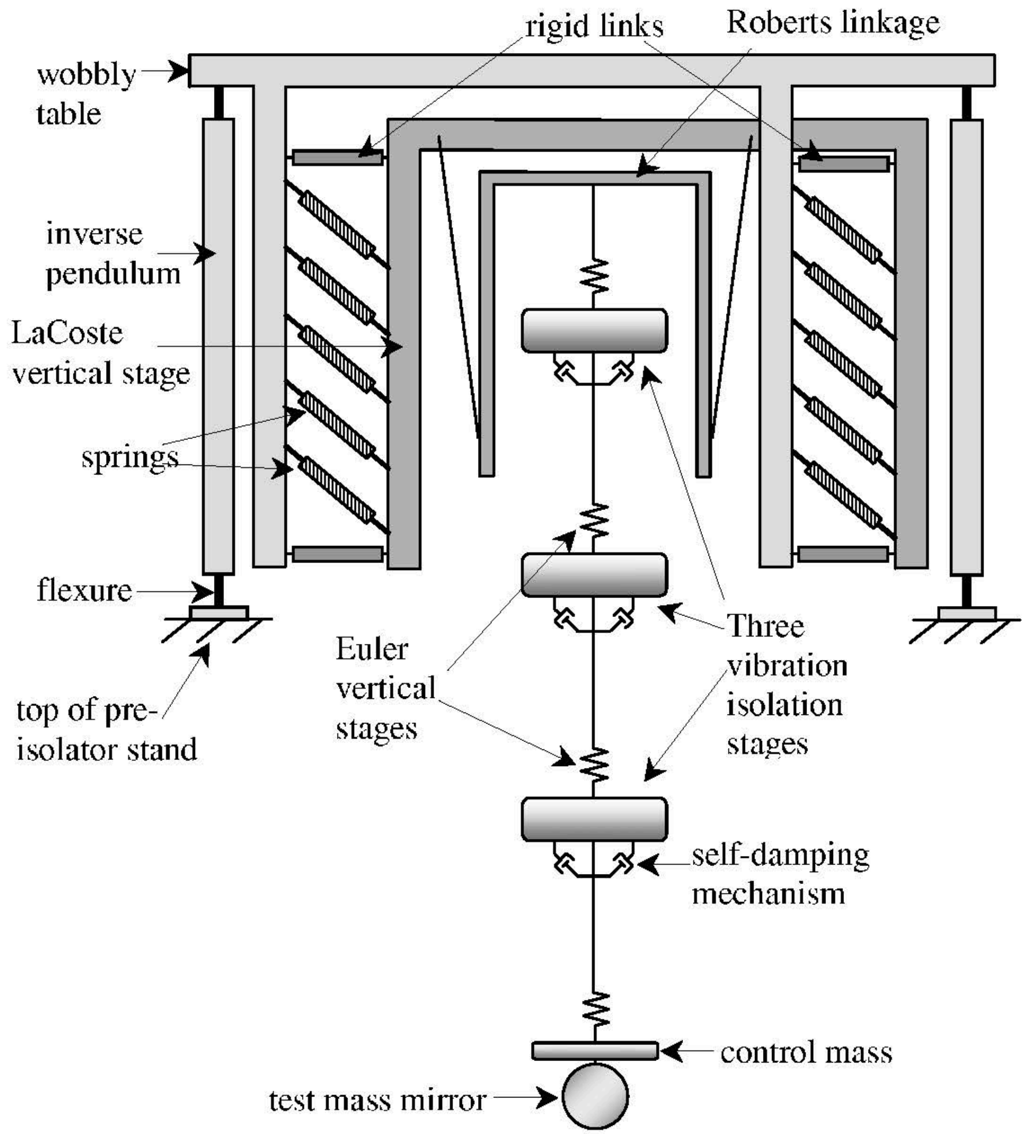


Fig. 1.10: *The schematic of the entire AIGO vibration isolator chain showing the main components of the pre-isolator stages, the three Euler vertical stages, the four pendulum stages, and the test mass stage.*

Geometric Anti-Spring

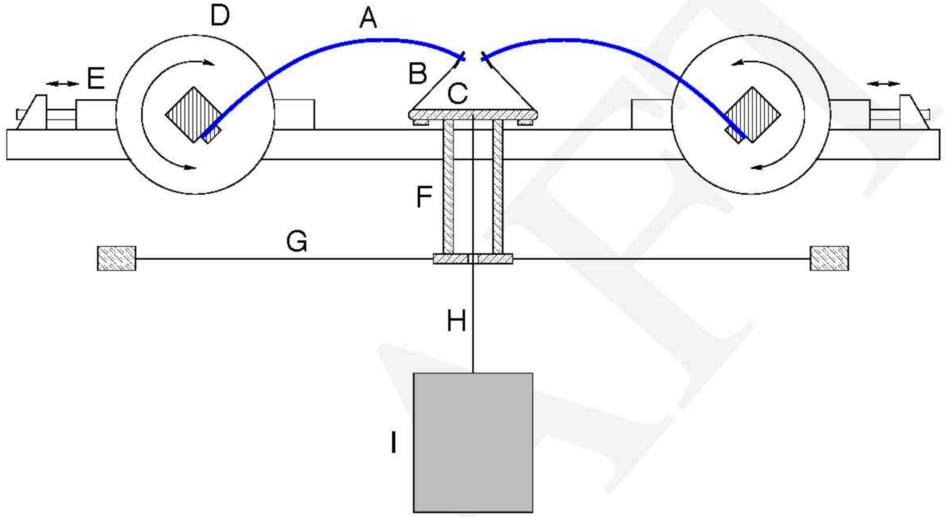


Figure 4: Cut view of the setup for the experimental tests. A: stressed blade, B: link wire, C: load disk, D: angular movement of the blade base, E: radial movement of the blade base, F: anti-tilt tower, G: anti-tilt centering wires, H: suspension wire (or rod), I: load.

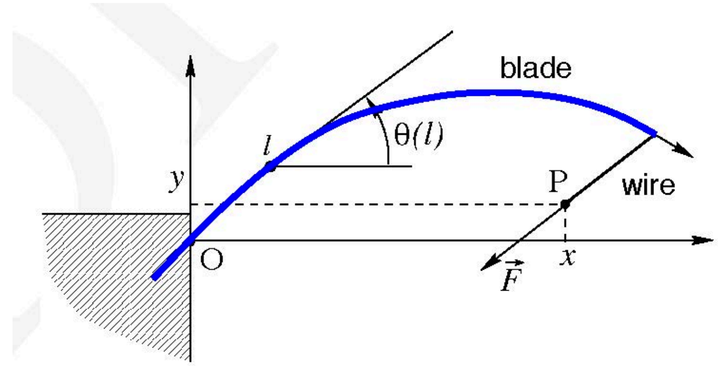


Figure 1: blade reference frame.

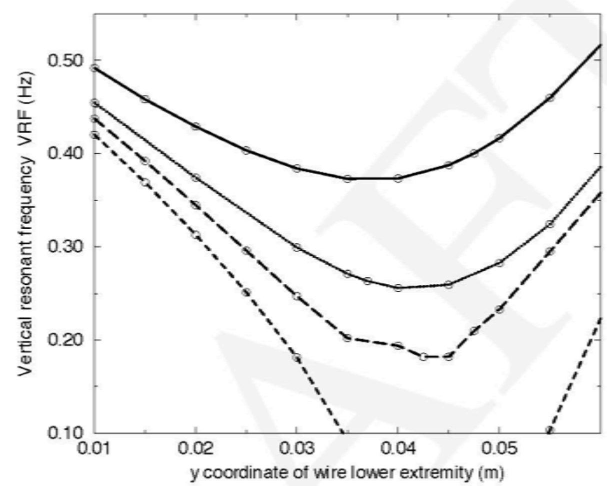


Figure 2: Vertical resonant frequency versus payload vertical position (y in fig.1). Each curve corresponds to a different x coordinate as defined fig.1. The scatter of some points is due to numerical precision errors. The effect of these errors is more visible at low frequencies, where spring and anti-spring add up to a smaller number.

Center of Percussion

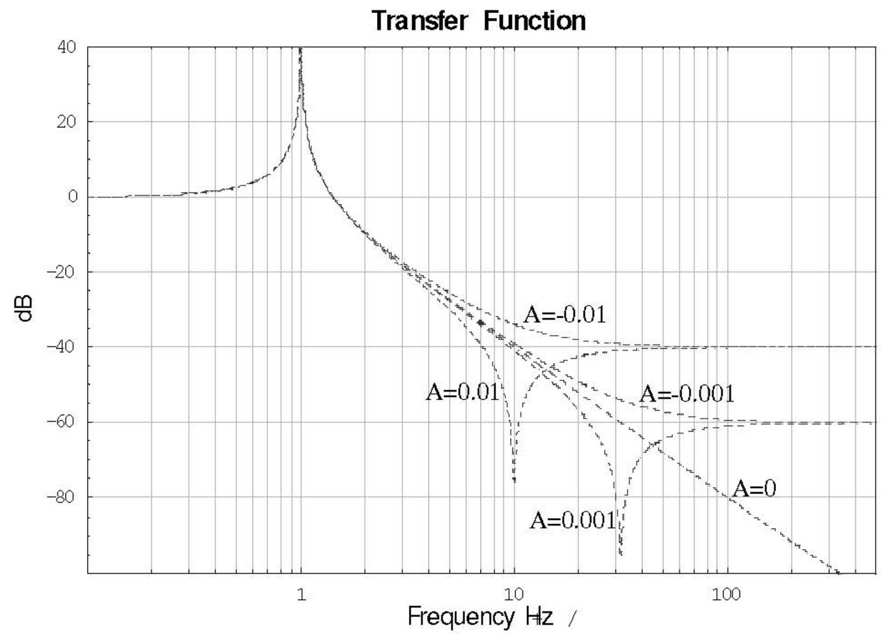


Fig. 1.9: *Transfer functions of resonant frequency of 1 Hz showing the center of percussion effect.*

Transfer Function

$$\frac{X_2}{X_1} = \sqrt{\frac{(1 - A(\frac{2\pi f}{f_{res}})^2)^2 + (\frac{f}{f_{res}^2 Q})^2}{(1 - (\frac{2\pi f}{f_{res}})^2)^2 + (\frac{f}{f_{res}^2 Q})^2}}$$

where

$$A = 1 - \frac{3l_p}{l}$$

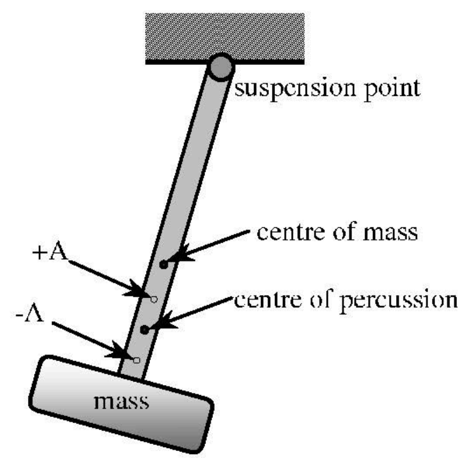


Fig. 1.8: *Diagram of a simple pendulum illustrating the concept of the center of percussion effect. The transfer function isolation floor depends on the position of measurement point A.*

Euler Springs

Close relative of
Geometric Anti-springs

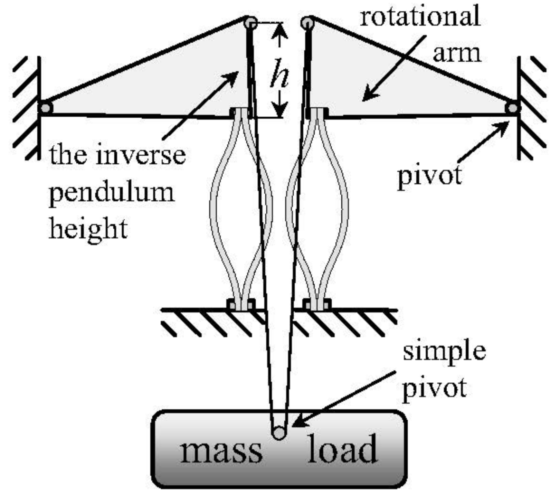
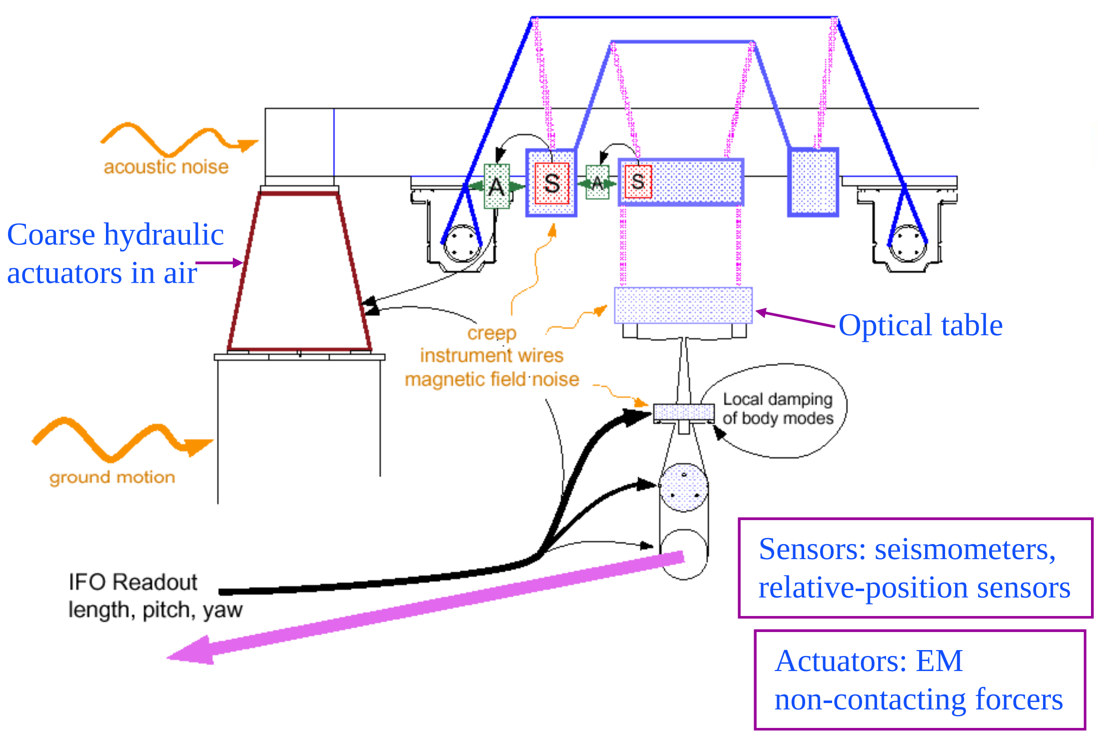
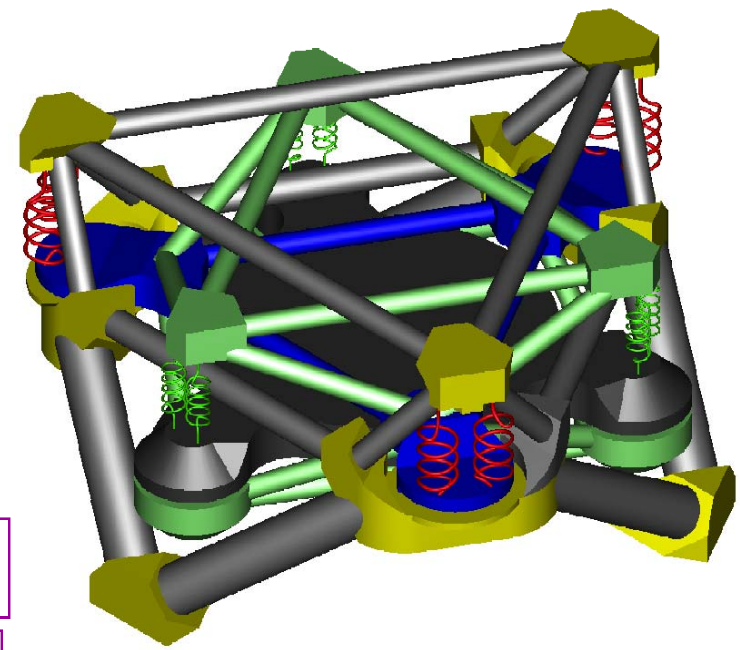


Fig. 3.8: *Diagram of the Euler system consisting of two pairs of Euler springs and an inverse pendulum of height h in the rotational arms [49].*

Active control of SEI system

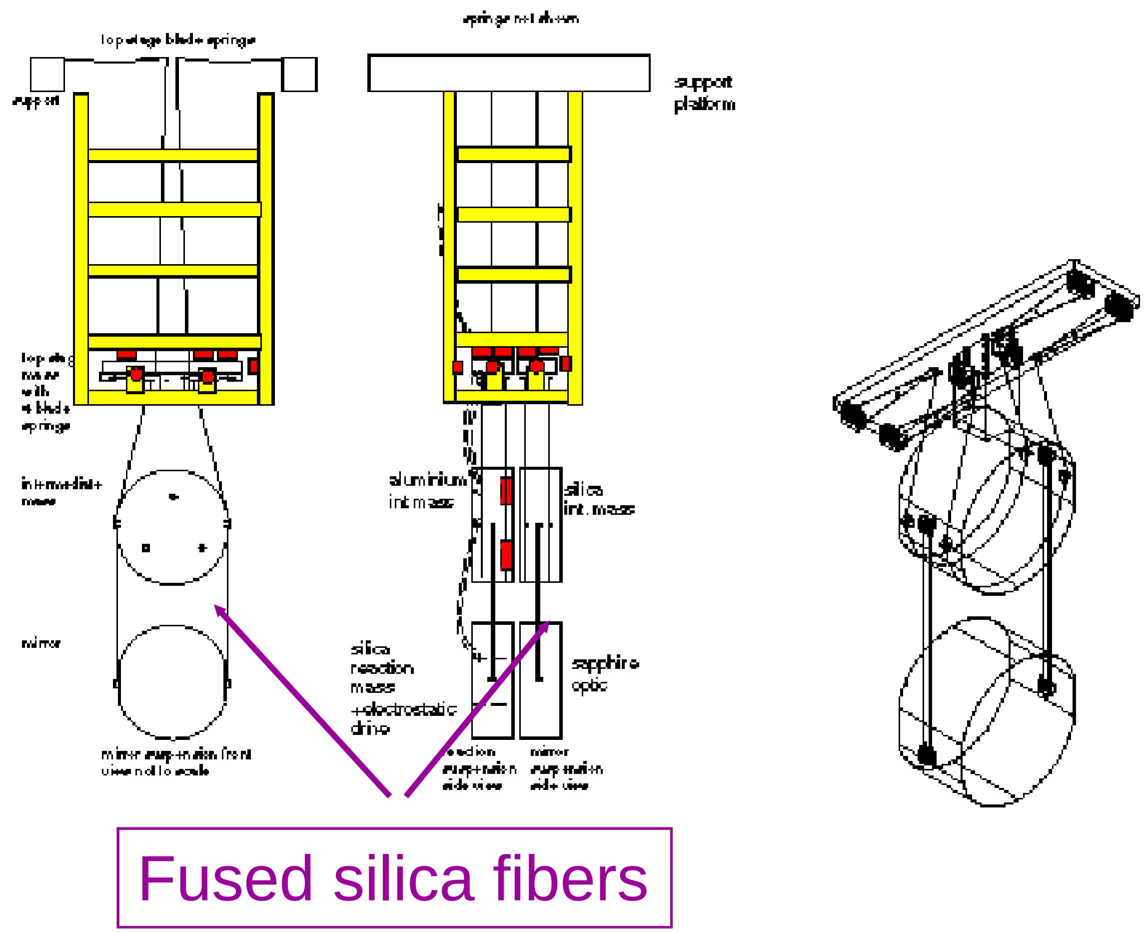




Two active stages: cages, masses, springs, S/A pairs.
All DOF under active control.

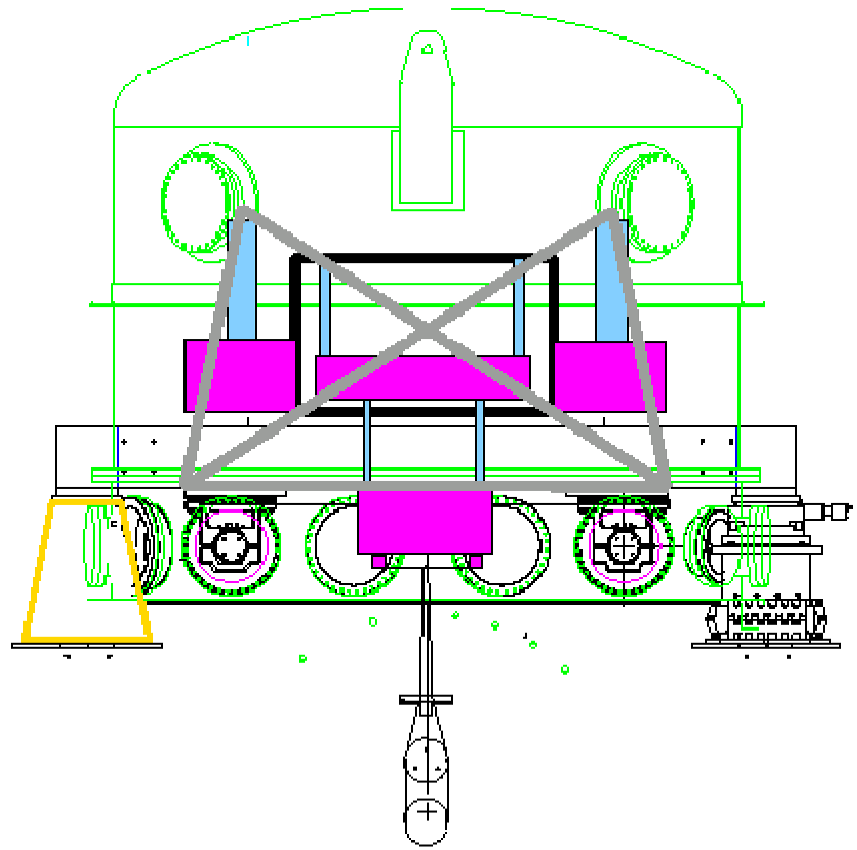
GEO multiple pendulum design

- 3 or 4 pendulum stages; each provides $1 / f^2$ filtering for $f > f_0$
- Top stage has 6 OSEMs for 6-dof control (“marionetta”), relative to support cage.
- Normal modes of the multiple pendulum (~24) must not have nodes at the top, so they can be controlled from the top.
- Blade springs at the very top provide tuned vertical isolation.
- Lower stages must control w.r.t. stage above it; so the actuators must push against a “reaction mass” which is as quiet as the stage above it
- lowest stage (test mass optic) is attached to stage above it with fused silica fibers.



LIGO II Active seismic isolation and multiple pendulum suspension

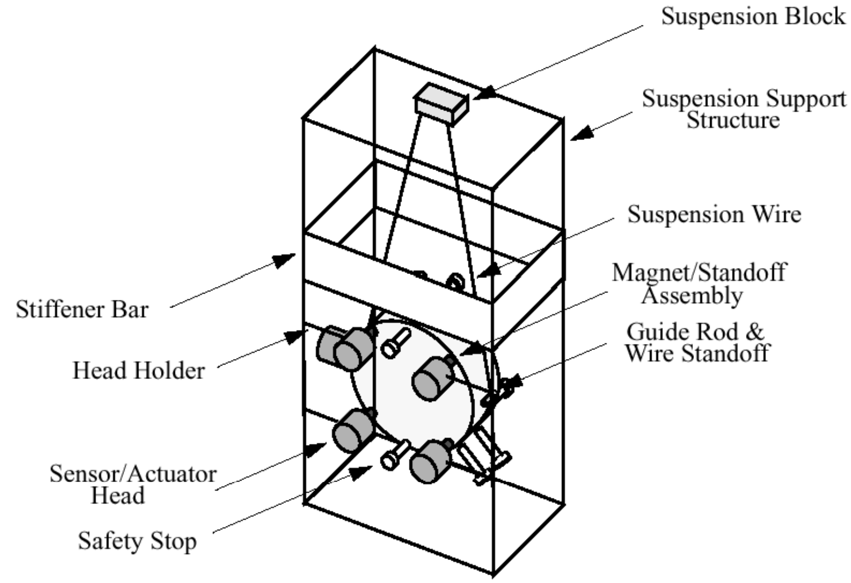
- Must support LIGO test mass optic at the beamline.
- Must fit inside existing vacuum chambers, and be fully vacuum compatible.
- Must provide full control system.
- Must satisfy specs:



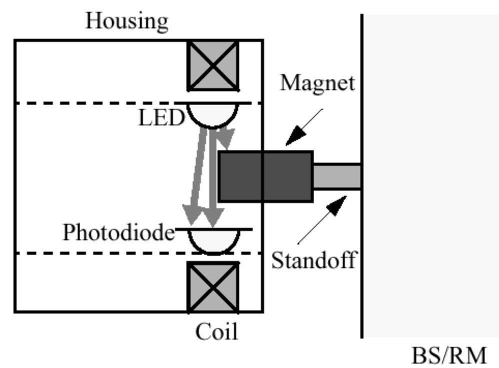
Optics Payload, (Chamber type)	Optic Axis (X-direction)				Y & Z directions		Pitch, Yaw
	Freq. (Hz)	Noise (m/√Hz)	*Motion* (m rms)	Velocity (m/s)	Noise (m/√Hz)	*Motion* (m rms)	*Motion* (rad rms)
ITM, ETM, BS, FM (BSC)	10	10^{-19}	10^{-14}	10^{-9}	10^{-16}	10^{-11}	10^{-96}
RM, SRM (HAM)	10	10^{-17}	10^{-13}	10^{-8}	10^{-14}	10^{-10}	10^{-96}
MC (HAM)	10	$3x10^{-18}$	10^{-12}	10^{-7}	$3x10^{-15}$	10^{-9}	10^{-96}
Ancillary Optics (HAM, BSC)	10						

Mirror control

- Seismic isolation system, and pendulum, keep the mirror motion to a minimum.
- Now the mirrors are not being kicked around by the environment (at high frequencies) – “free” masses!
- But, being free, they may not be where you need them to be to keep the laser resonant in the cavities.
- Instead, they’re swinging back and forth at the pendulum frequency (~ 0.8 Hz).
- Need active control system to keep mirrors at set points (at/near DC), to keep F-P cavities resonant, without injecting noise at high frequencies
- ⇒ Carefully designed feedback servo loops

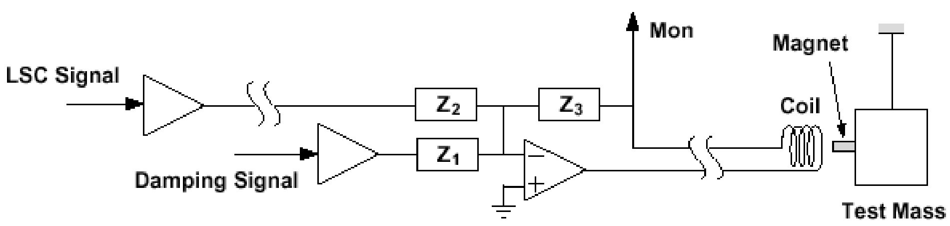


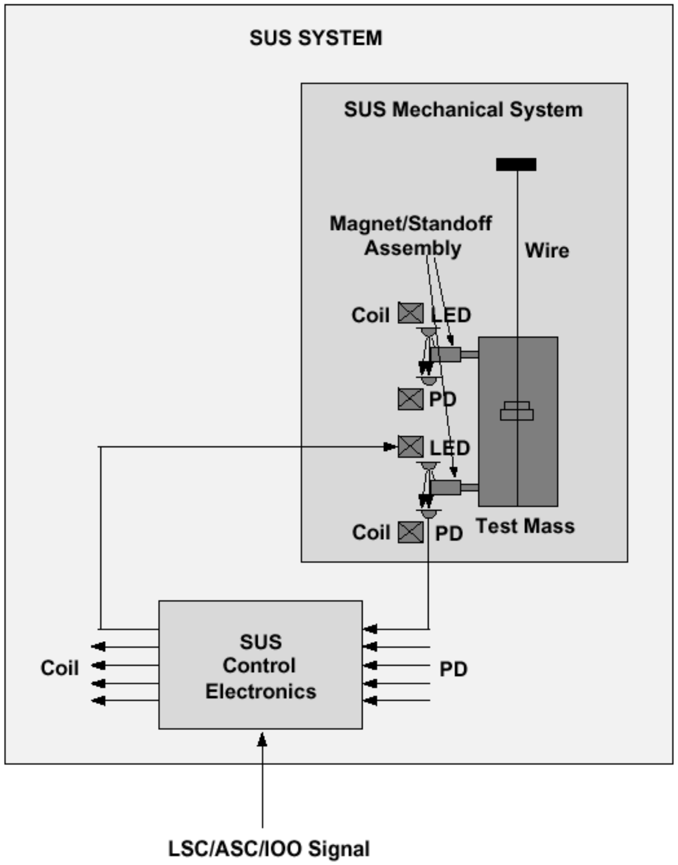
sensor/actuator head (OSEM)



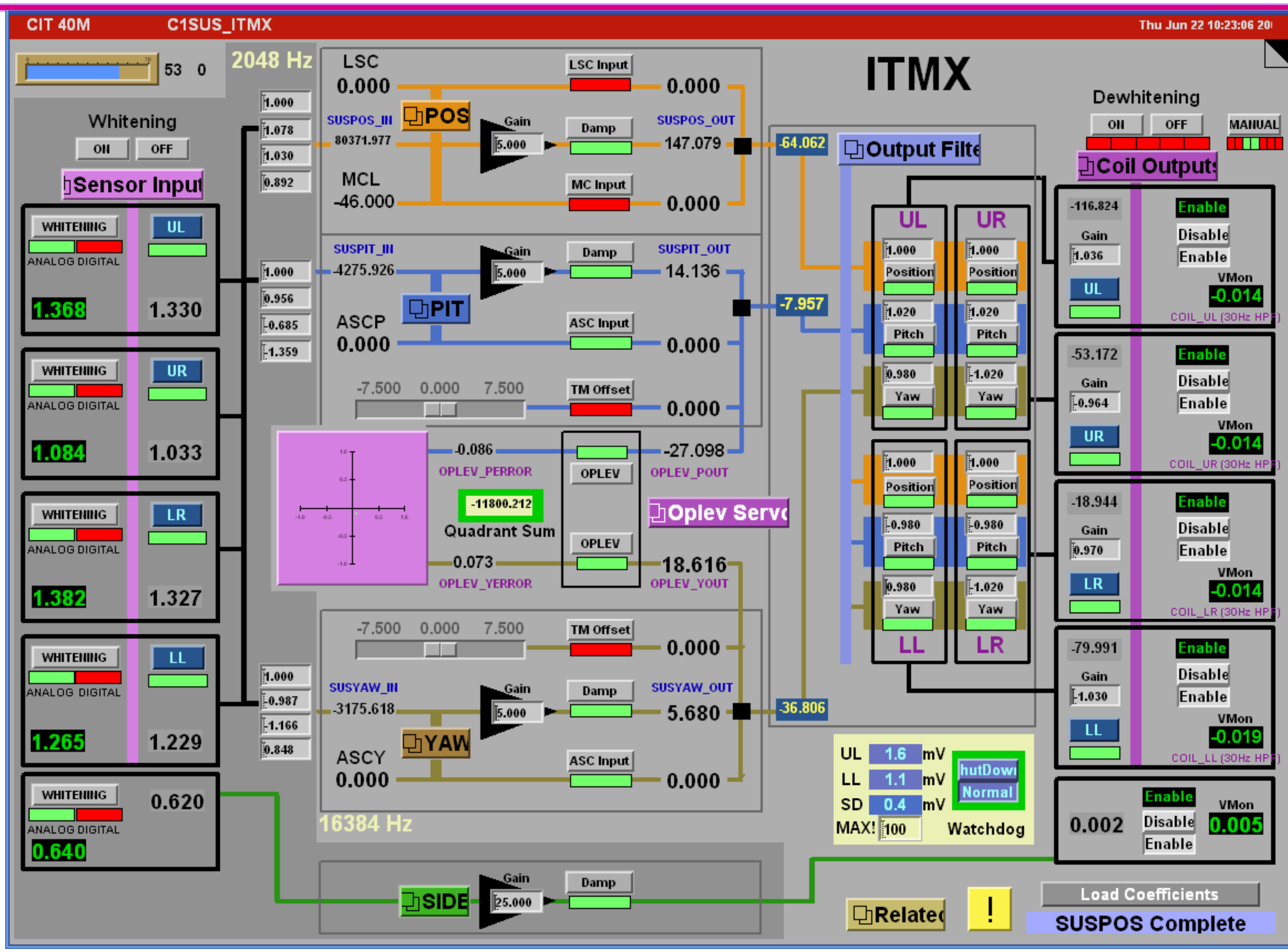
Suspension control system

- Each suspension controller handles one suspension (5 OSEMs)
- Local velocity damping
- Input from LSC and ASC to fix absolute position, pitch, yaw of mirror to keep cavity in resonance





Digital suspension controls



Ideas

- Cascaded Pendulums
- Long period pendulums
  - Inverted pendulums
  - Anti Springs

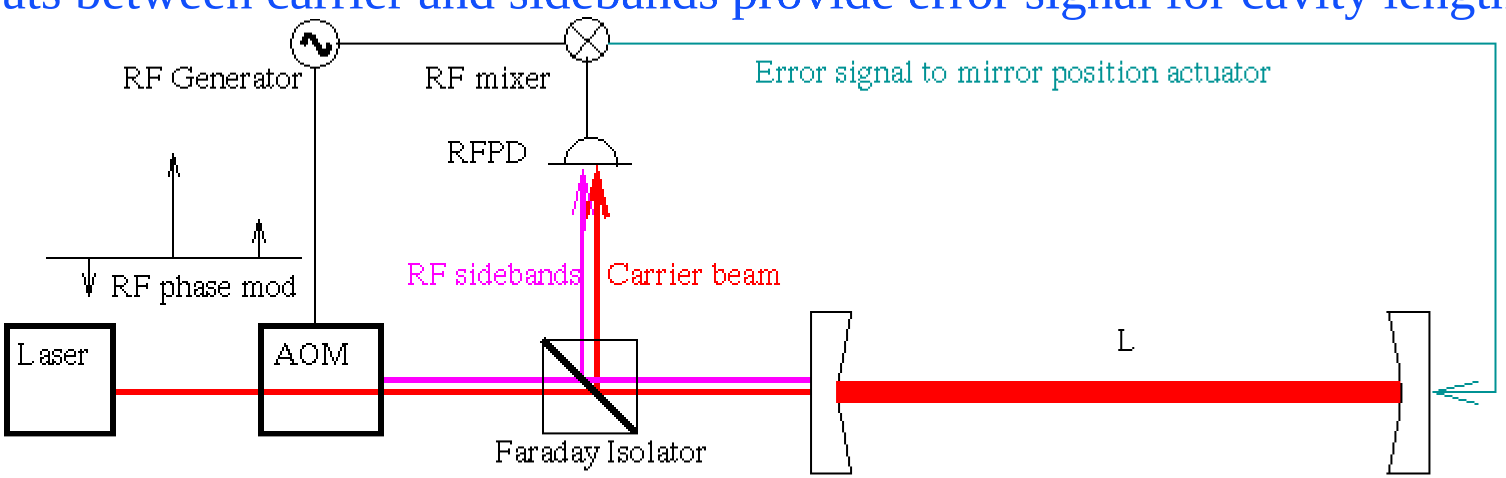
- Self Damped Pendulums
- Active damping
  - Damping in specific bands
  - Adaptive seismic feed-forward
  - Sensors : Shadow sensors, capacitive sensors, PDH length signal
  - Actuators: Voice coils, capacitive forces
  - Controls: Digital filters with analog signal conditioners

- High Q suspension wires and Optics
- Actuation from a suspended reaction mass

Cavity control

Pound-Drever (reflection) locking used to control lengths of all the optical cavities in LIGO

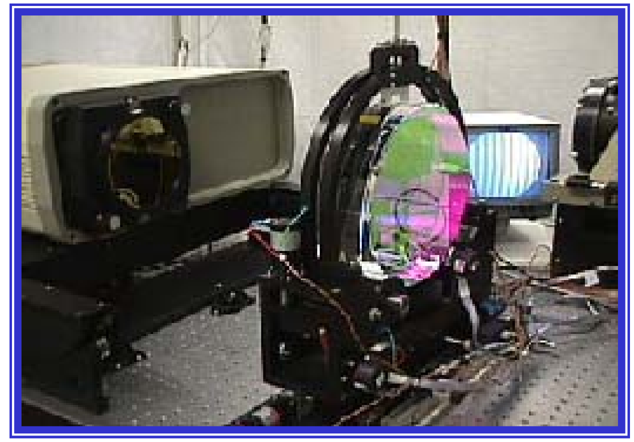
- Phase modulate incoming laser light, producing RF sidebands
- Carrier is resonant in cavity, sidebands are not
- Beats between carrier and sidebands provide error signal for cavity length

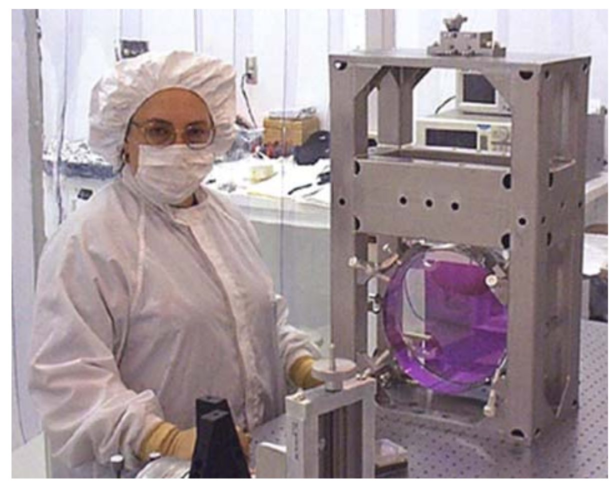


LIGO Optics

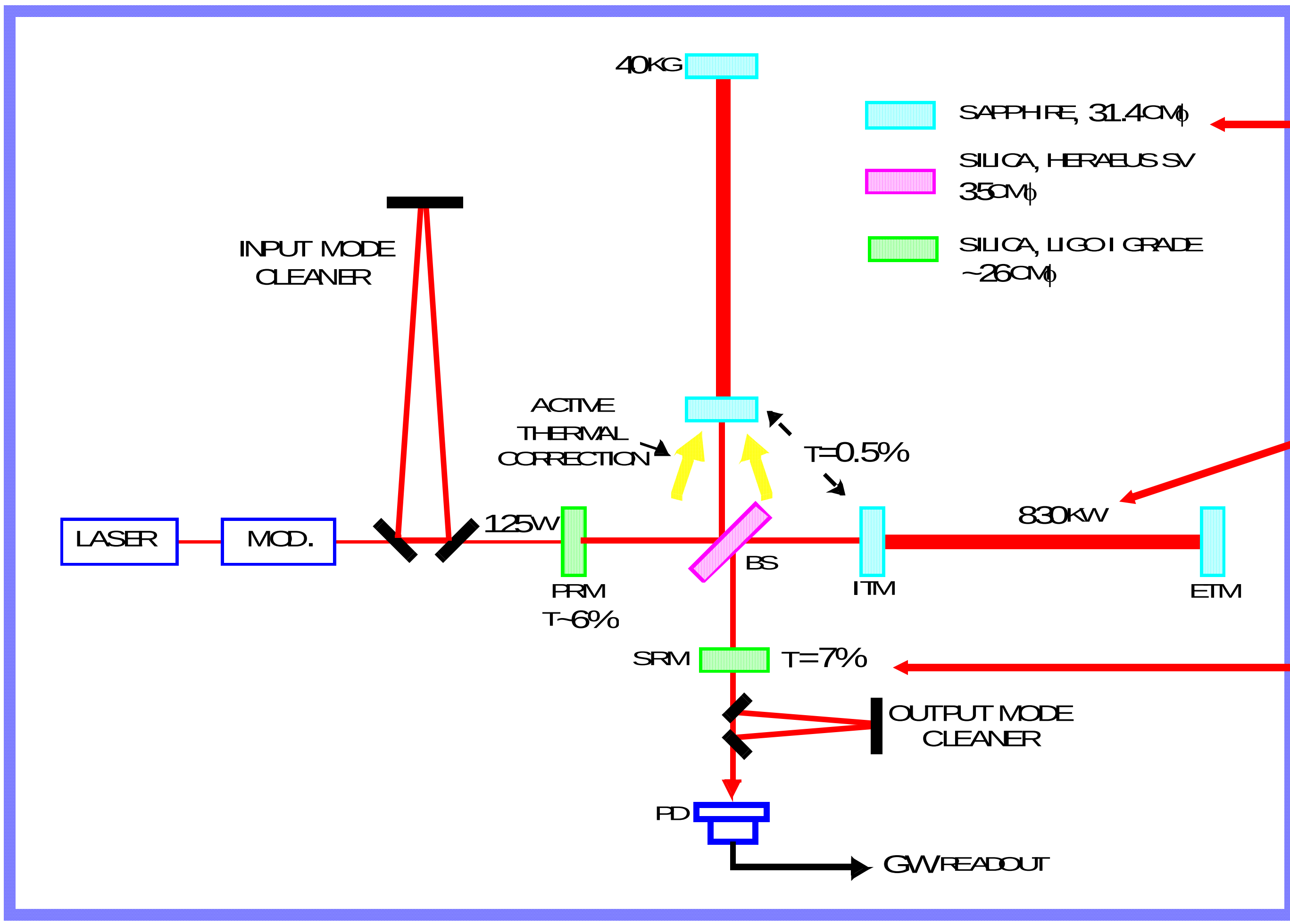
mirrors, coating and polishing

- SUPERmirrors:
  - » High uniformity fused silica quartz
  - » reflectivity as high as 99.999%
  - » losses < 1 ppm in coating, 10 ppm in substrate
  - » polished with mircoroughness < $\lambda/1800 \approx 0.5$ nm
  - » and ROC within spec.
  - ≈ ($\delta R/R < 5\%$, except for BS)
- Suspensions: hang 10kg optic by a single loop of wire, and hold it steady with feedback system





LIGO II Optics



High-Q optics

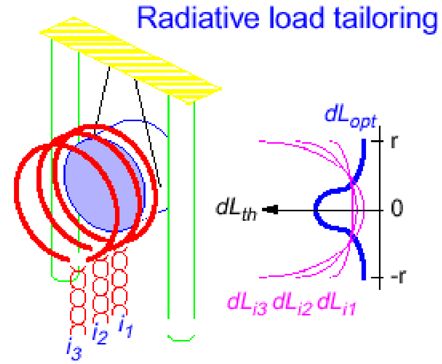
High stored power

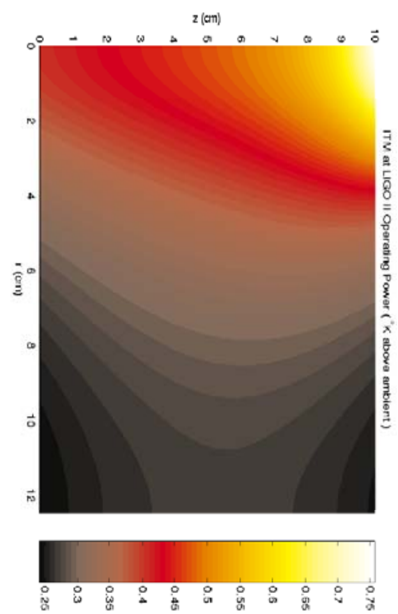
Signal recycling

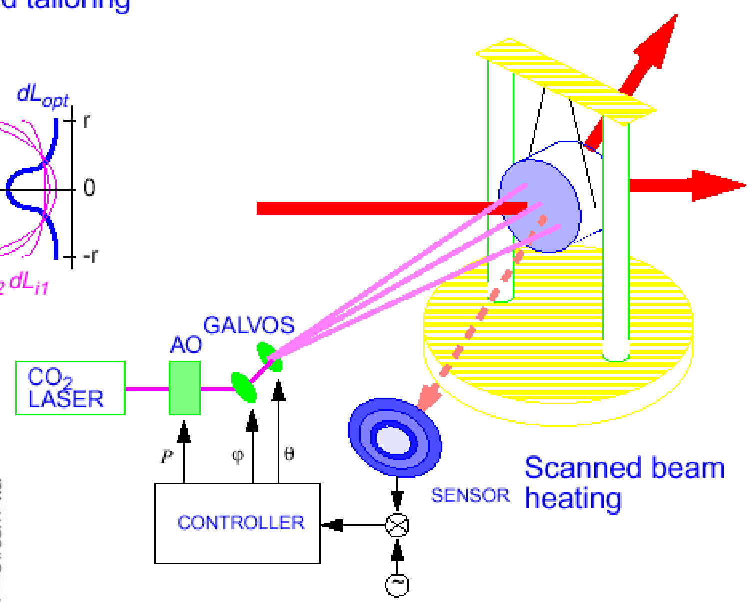
Thermal compensation (de-lensing) methods

- Beam heating at center of optic distorts the optic due to thermal expansion, changing ROC, index of refraction, etc.

- Compensate by heating the optic from the circumference in, to give uniform and constant-in-time thermal loading as the IFO is operated.

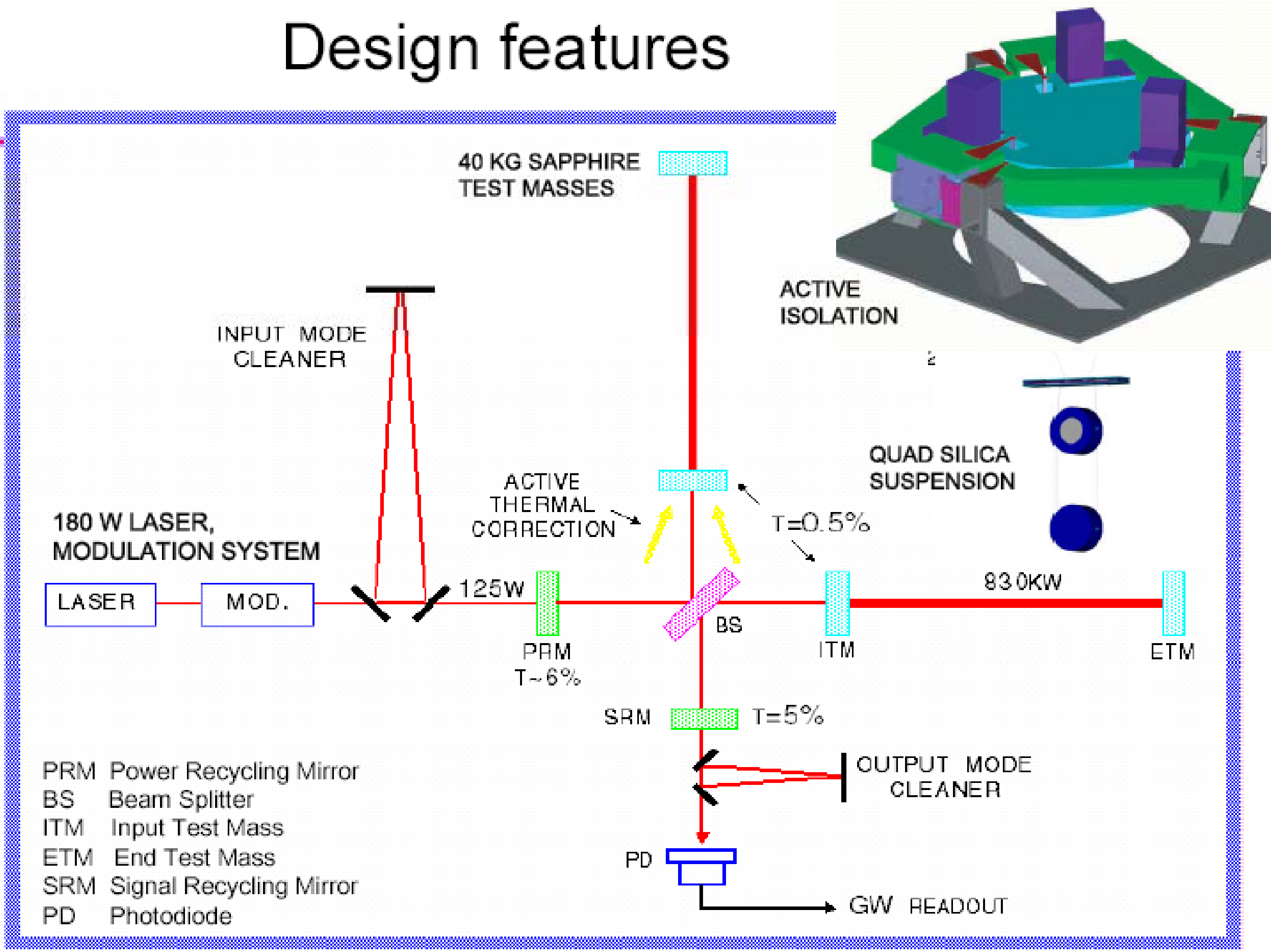






Advanced LIGO

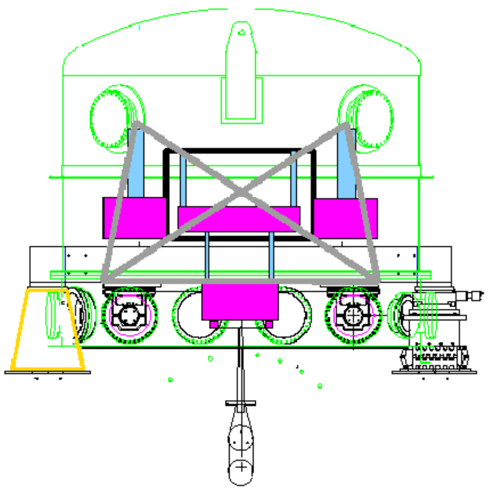
Design features

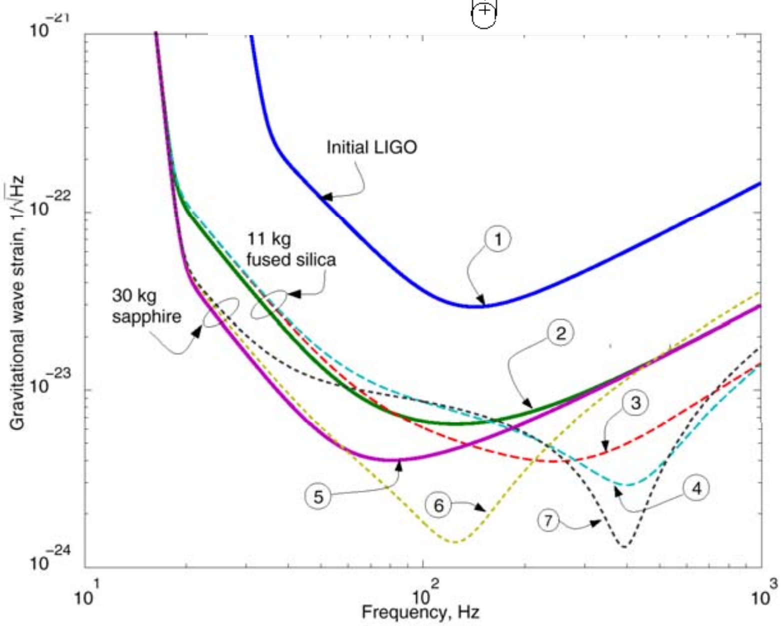


Advanced LIGO

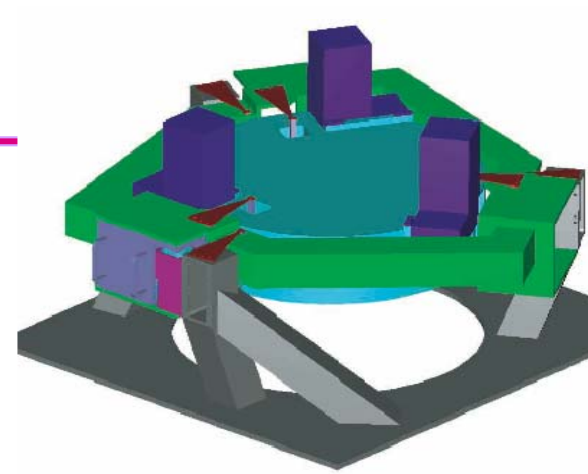
incremental improvements

- Reduce shot noise:
  higher power CW-laser: 12 watts ⇒120 watts
- Reduce shot noise: Advanced optical configuration: signal recycling mirror (7th suspended optic) to tune shot-noise response in frequency
- To handle thermal distortions due to beam heating: advanced mirror materials, coatings, thermal de-lensing compensation (heating mirror at edges)
- Reduce seismic noise: Active seismic isolation.
  Seismic wall moved from 40 Hz ⇒ ~ 10 Hz.
- Reduce seismic and suspension noise: Multiple pendulum suspensions to filter environmental noise in stages.
- Reduce suspension noise: Fused silica fibers, silica welds.
- Reduce test mass thermal noise: Last pendulum stage (test mass) is controlled via photonic and/or electrostatic forces (no magnets).
- Reduce test mass thermal noise:
  High-Q material (40 kg of single-crystal sapphire).

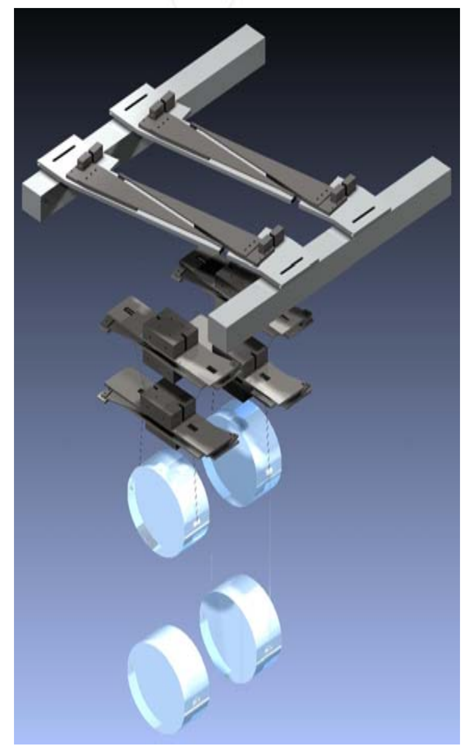




Advanced LIGO R&D



- Development of multiple pendulum suspensions with silica fibers
  - » Willems et al
- Development of advanced seismic isolation and suspension systems
  - » de Salvo et al
- Advanced interferometer techniques, detection of gravity at DC
  - » Drever et al
- Simulations of complex interferometer behavior
  - » Yamamoto et al
- Quantum-nondemolition optical techniques to reduce quantum readout noise
  - » Whitcomb et al



Signal recycling mirror to optimize sensitivity

- The signal mirror is NOT used to store the laser light; all it sees is light generated by the GW signal.

- The signal recycling cavity allows one to tune the response of the IFO to the signal, as a function of its frequency, independently of the light storage in the arms (the “reservoir” of light available to be converted into signal light.

- The frequency response of the IFO can be tuned to put the sensitivity where it is most needed (at high frequencies).

- Net result:
  - 2× sensitivity for CBI;
  - or ~ 10 × in event rate.