Suspending the Test Masses of Gravitational Wave Detectors

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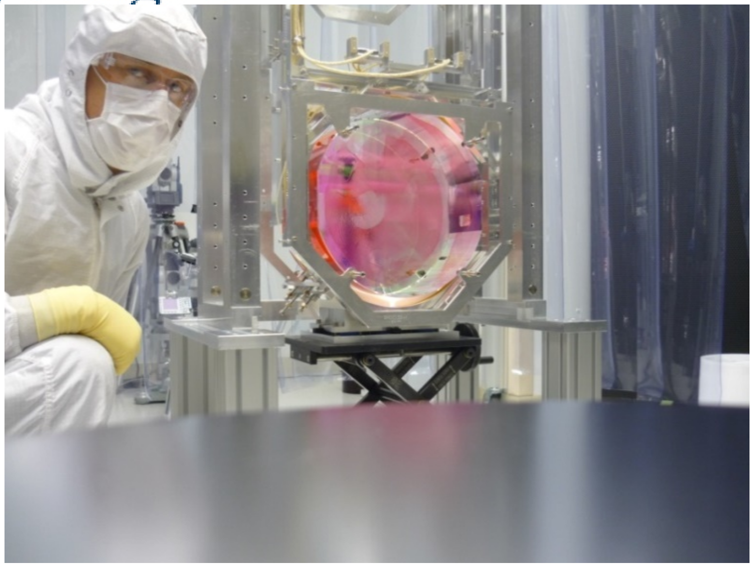
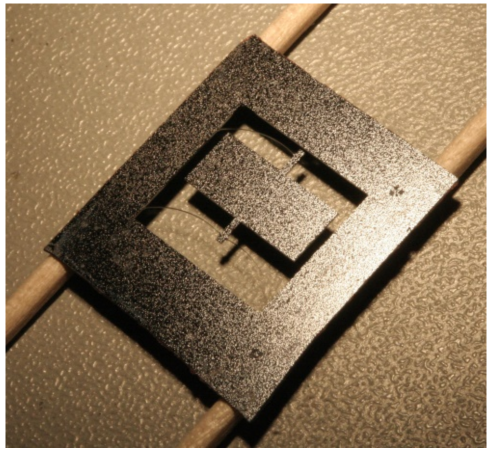
Overview

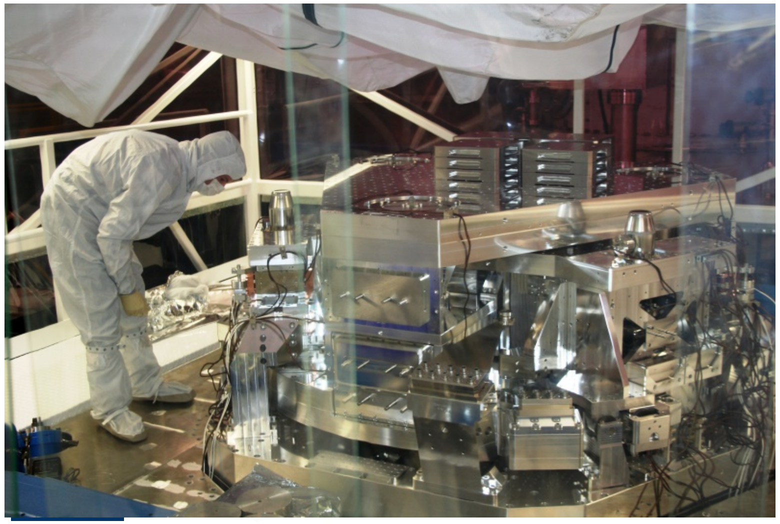
- aLIGO suspensions and requirements
- Seismic noise & thermal noise
- Suspension construction
- Dissipation dilution
- Noise model of suspensions
- Warm and cold upgrades to aLIGO
- Summary

About Myself



- Precision measurements of gravity; axion searches and Casimir force (PhD, postdoc)
- Suspension for Advanced gravitational wave detectors; silica, silicon, sapphire (now)
- MEMS gravimeters for gravity imaging (now)

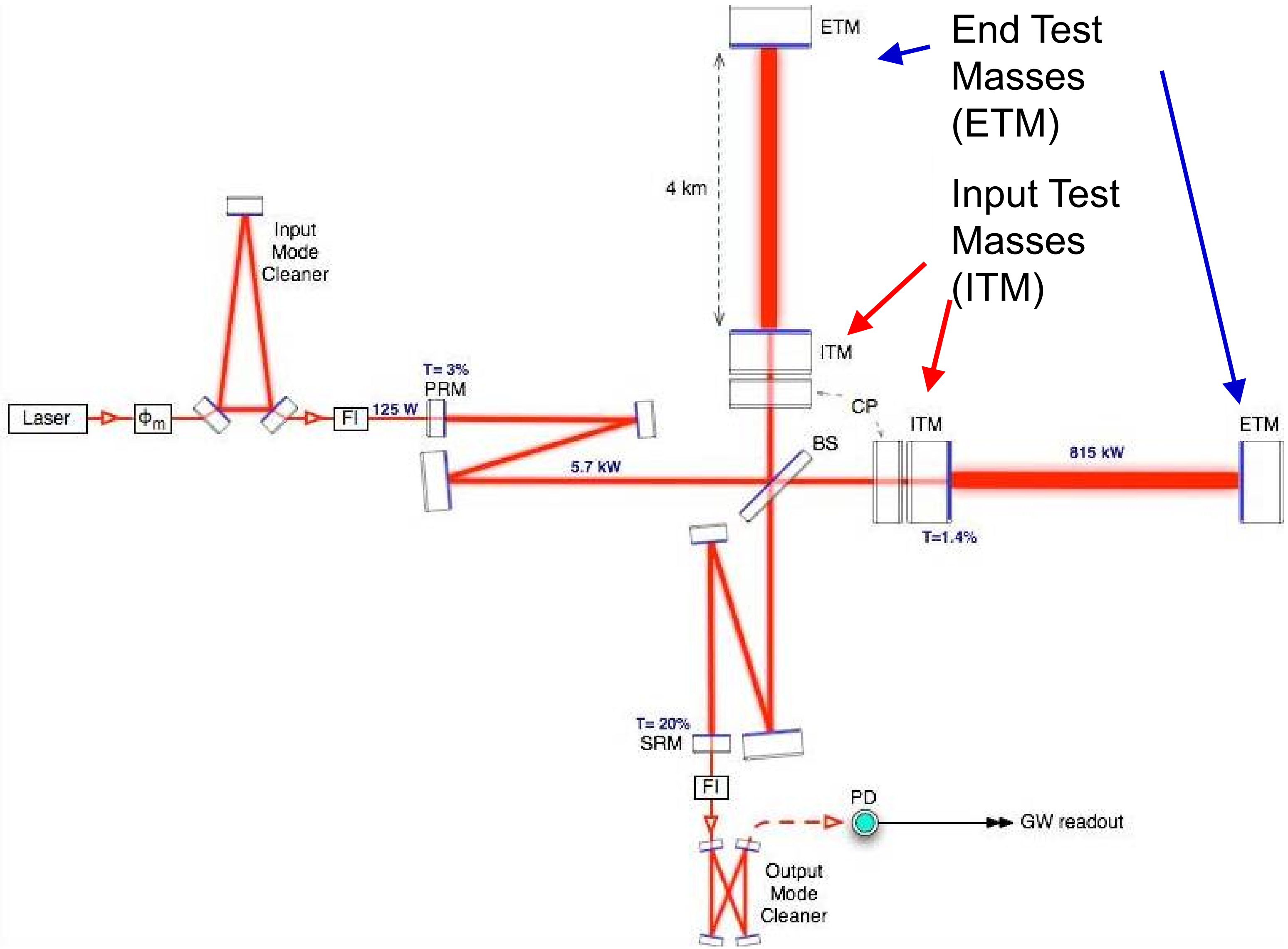




- aLIGO ISI (postdoc)

QUANTIC

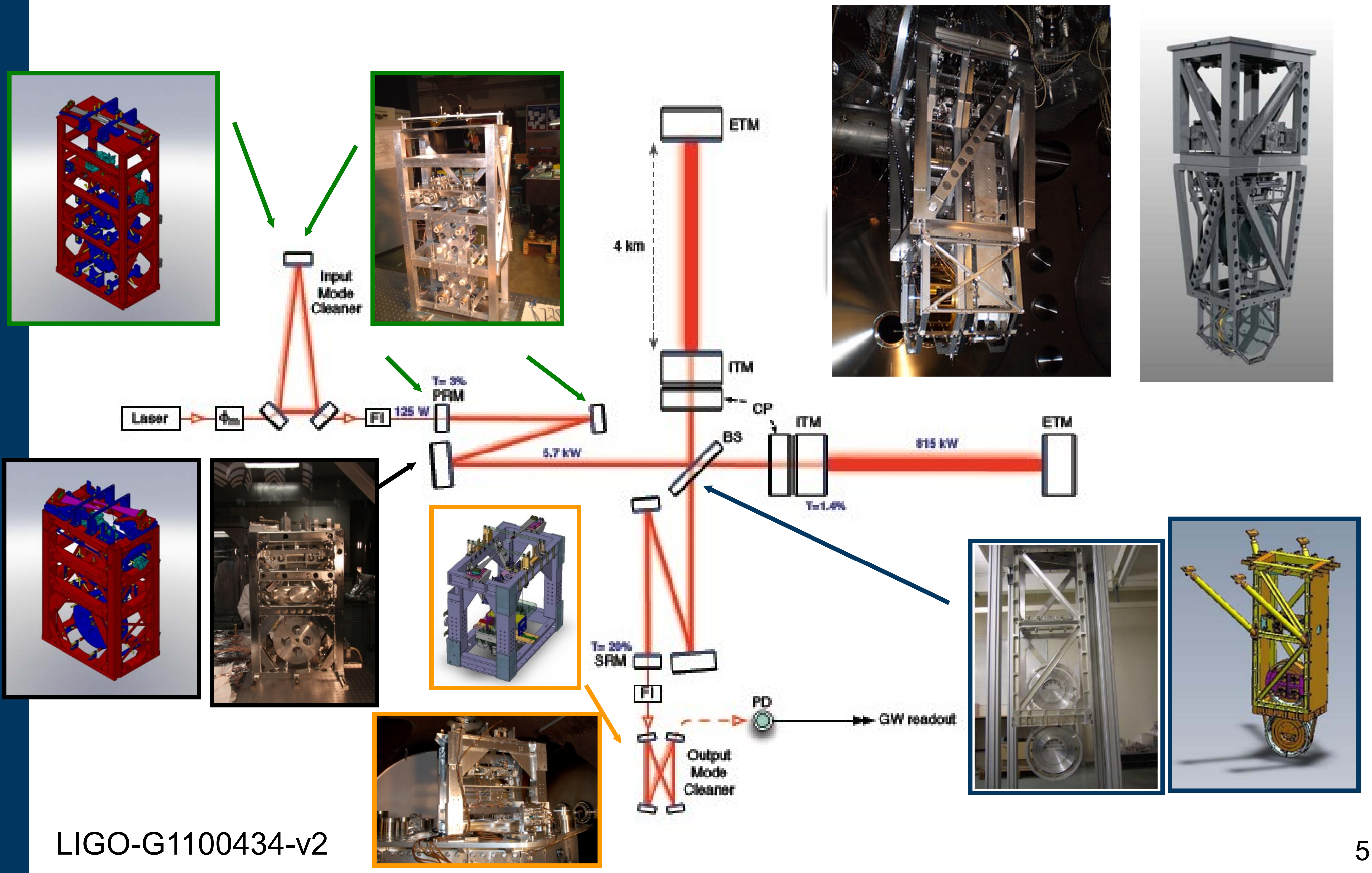
aLIGO Layout and Core Optics



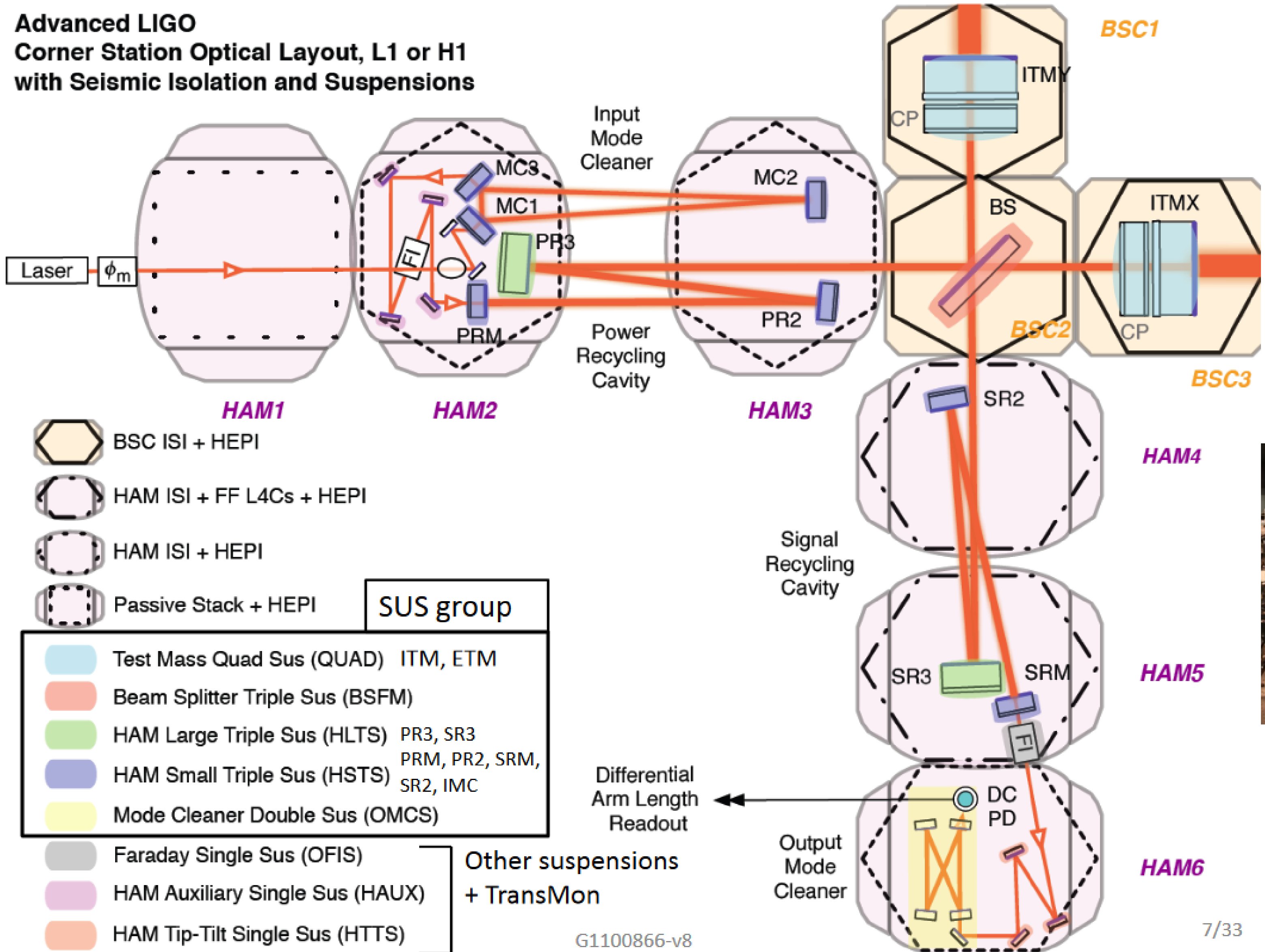
End Test Masses (ETM)

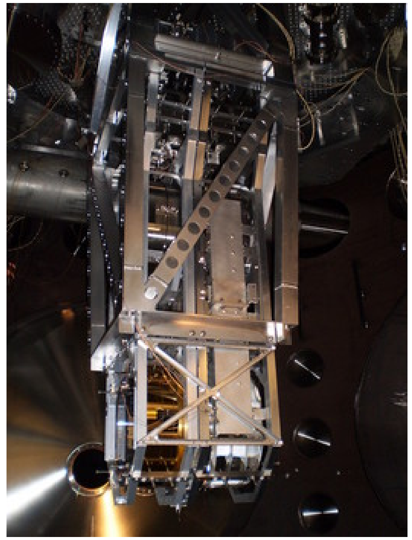
Input Test Masses (ITM)

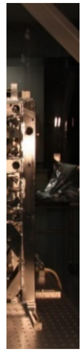
Suspensions in aLIGO

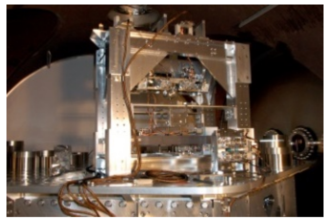


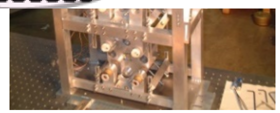
Suspension Inventory











Suspension System Functions

- Support the optics to minimise the effects of
  - thermal noise in the suspension
  - seismic noise acting at the support point
- Provide damping of low frequency suspension resonances (local control), and
- Provide means to maintain interferometer arm lengths (global control)
  - while not compromising low thermal noise of mirror
  - and not introducing noise through control loops
- Provide interface with seismic isolation system and core optics system
- Support optic so that it is constrained against damage from earthquakes
- Accommodate a thermal compensation scheme and other systems as required e.g. acoustic mode dampers, baffles, alignment fiducials, ancilliary tooling, vibration absorbers

Requirements:Test Masses

- Top-Level Requirements:

Requirement	Value
Suspension Thermal Noise	10^{-19} m/√ Hz at 10 Hz (longitudinal) 10^{-16} m/√ Hz at 10 Hz (vertical)*#
Residual Seismic Noise	10^{-19} m/√ Hz at 10 Hz (assumes seismic platform noise 2×10^{-13} m/√ Hz)
Pitch and Yaw Noise	10^{-17} rad/√ Hz at 10 Hz (assumes beam centering to 1 mm)
Technical Noise Sources (e.g. electronic noise, thermal noise from bonds)	1/10 of longitudinal thermal noise for each source (since noise terms add in quadrature, each increases total by 0.5%)

*assumes 10^{-3} coupling vert. to long.

#except for highest bounce mode peak

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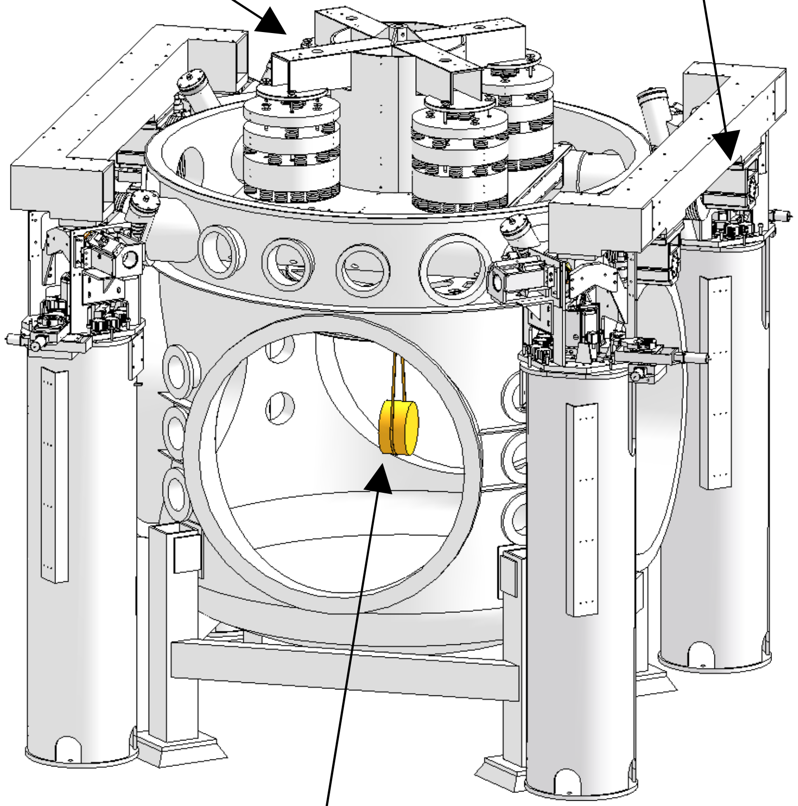
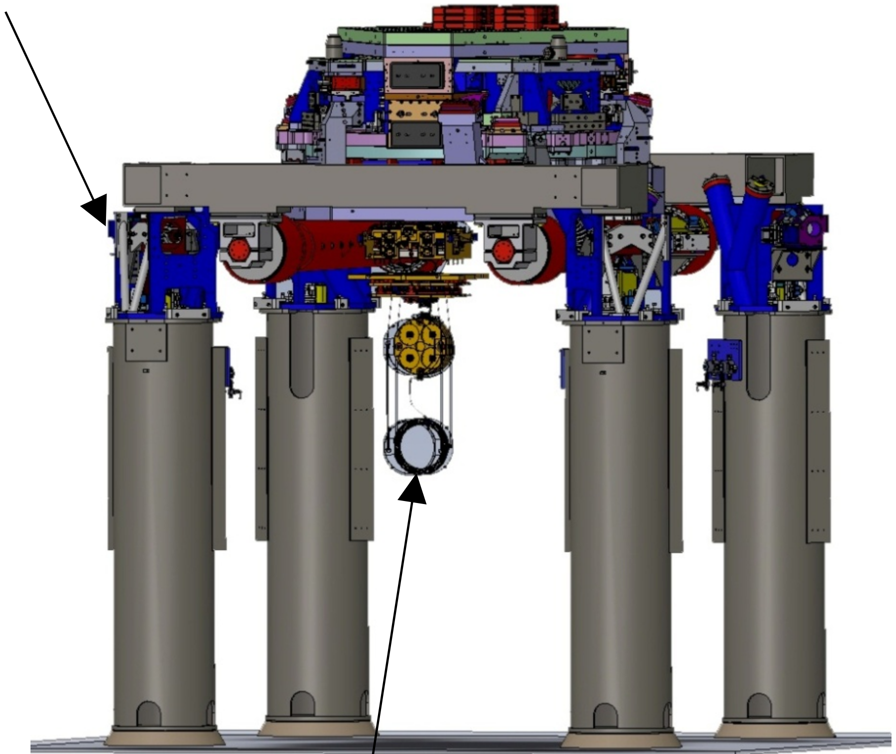
Initial LIGO and aLIGO

- 4 layer passive isolation stack
- coarse & fine actuators



- single pendulum on steel wire

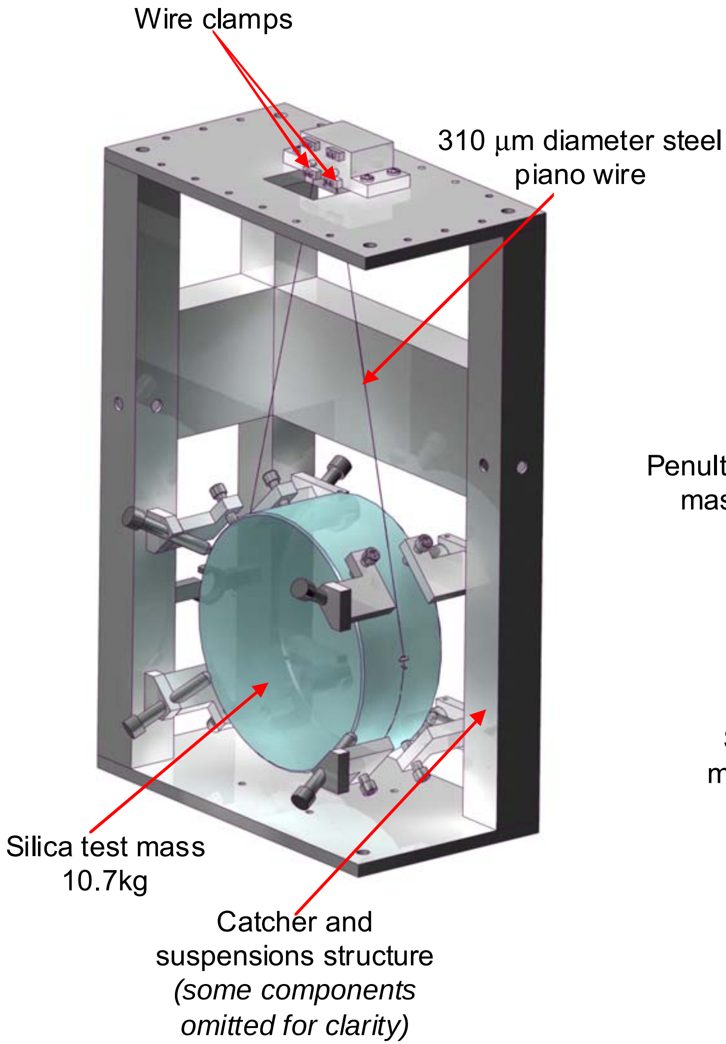
- hydraulic external pre-isolator (HEPI) (one stage of isolation)
- active isolation platform (2 stages of isolation)



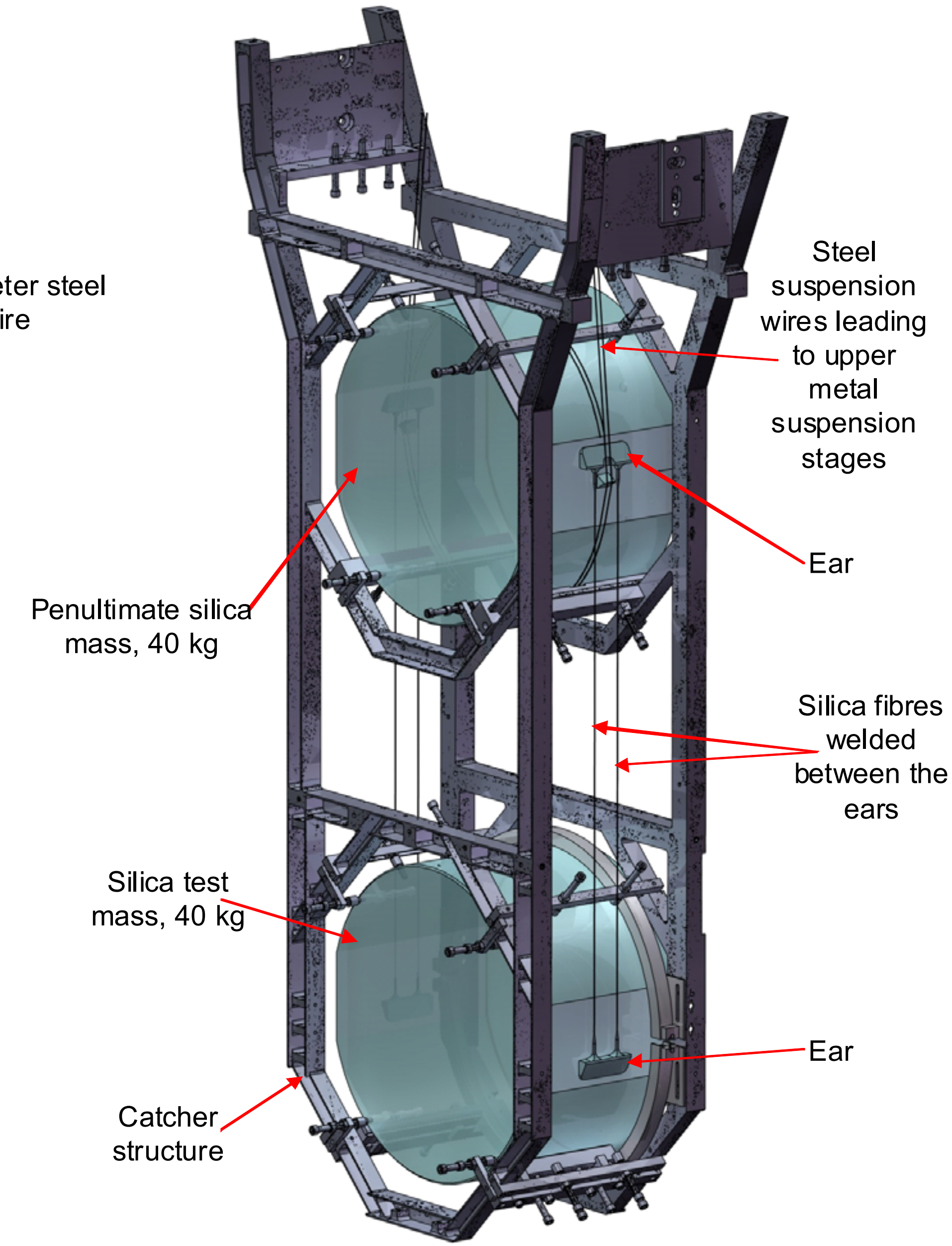
- quadruple pendulum (four stages of isolation) with monolithic silica final stage

Initial LIGO and aLIGO

LIGO



Advanced LIGO



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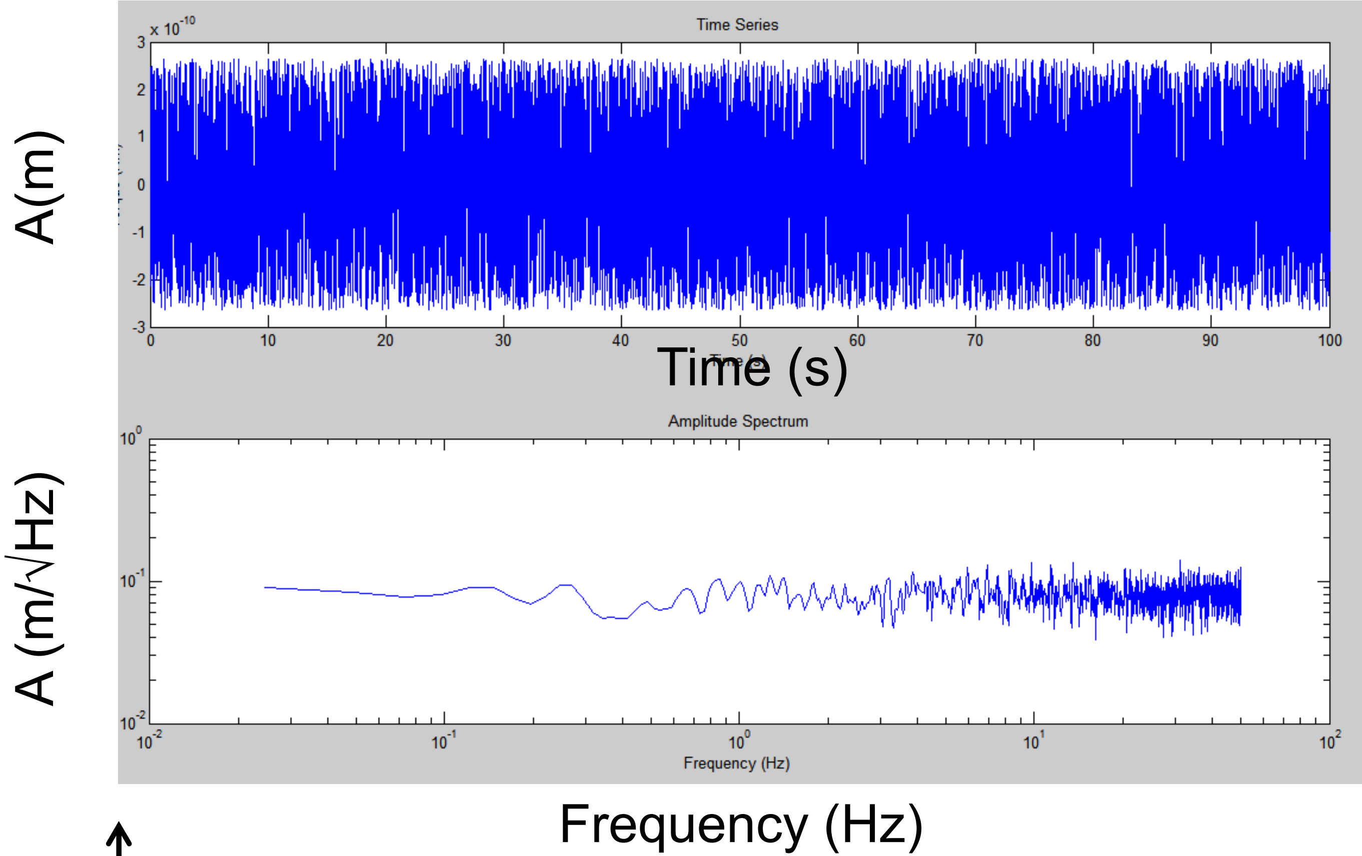
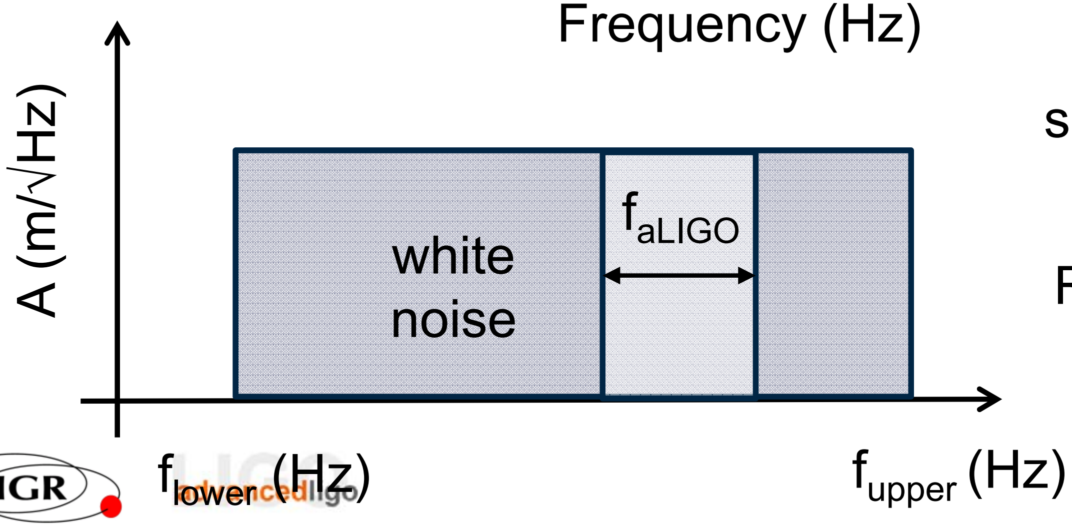
ASD and RMS



Time series : Random noise

FFT: Random noise



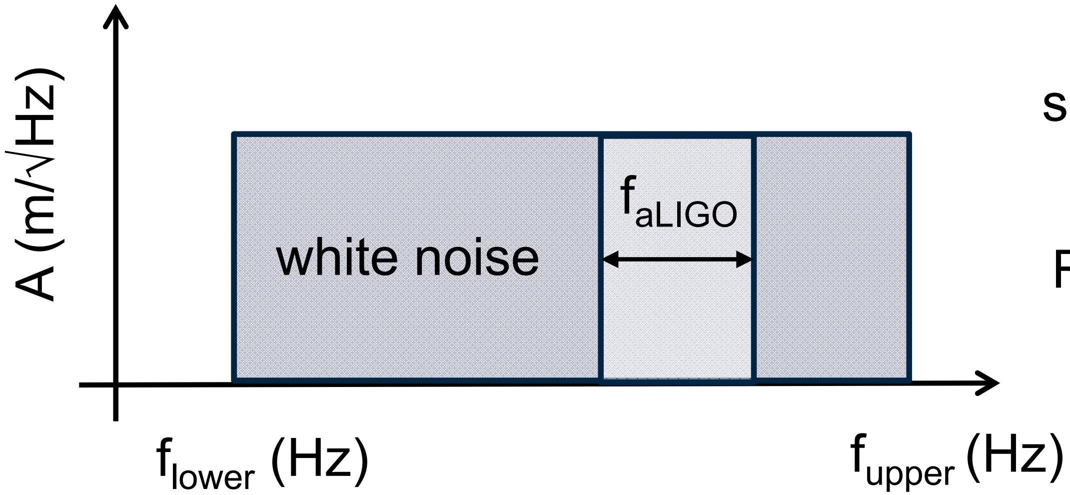
spectral density=A m/√Hz

$$\text{RMS}=\sqrt{\int_{f_{lower}}^{f_{upper}} A^2 df} = \sqrt{A^2\left[f_{upper}-f_{lower}\right]}\ \text{m}$$

IGR advancedligo

Seismic Noise in aLIGO

- There are two characteristic features that cause large motions over small frequency bands.
- Earth tides at ≈10^{-5}Hz (diurnal and semi-diurnal variation)
- Microseismic peak at ≈0.16 Hz
- These are below the operating bandwidth for Advanced LIGO=> why the problem?
- Root Mean Square (RMS) motion of the test masses is important (m_{rms}) as well as the noise, or spectral density, at a particular frequency (m/√Hz)

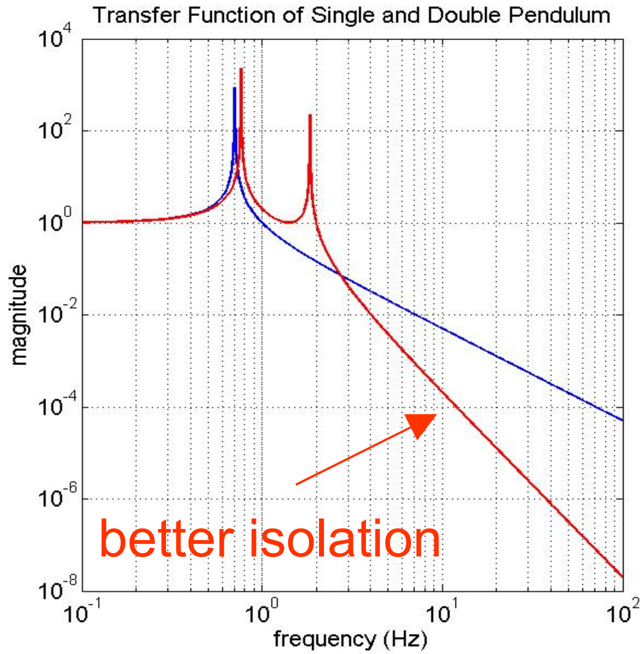


spectral density=A m/√Hz

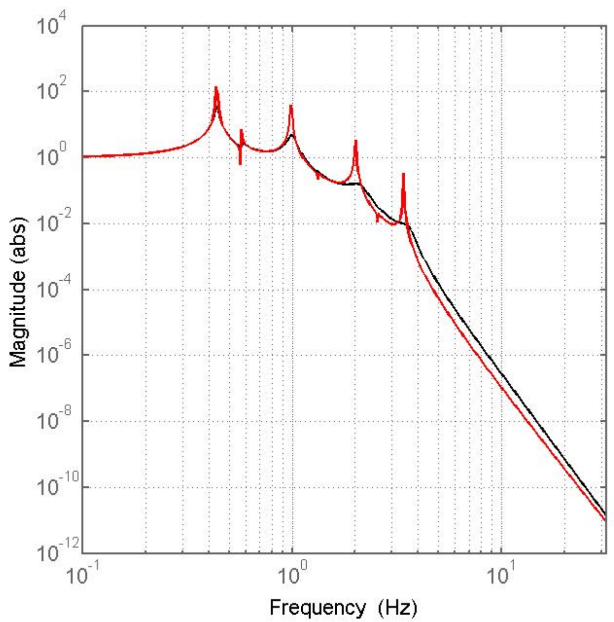
$$\text{RMS}=\sqrt{\int_{f_{lower}}^{f_{upper}} A^2 df} = \sqrt{A^2\left[f_{upper} - f_{lower}\right]}\ \text{m}$$

Seismic Noise

- Seismic noise limits sensitivity at low frequencies - "seismic wall"
- Typical seismic noise at quiet site at 10 Hz is ~ few x 10^{-10} m/√Hz
  - many orders of magnitude above target noise level
- Isolation required in vertical direction as well as horizontal due to cross-coupling
- Two-stage internal isolation platform has target noise level of 2 x 10^{-13} m/√Hz at 10 Hz.
- require 4 more stages, i.e. quadruple pendulum, to meet target of 10^{-19} m/√ Hz



- Advantage of a double over single pendulum, same overall length



- Quad pendulum transfer function: predicted isolation ≈ 3 x 10^{-7} at 10 Hz

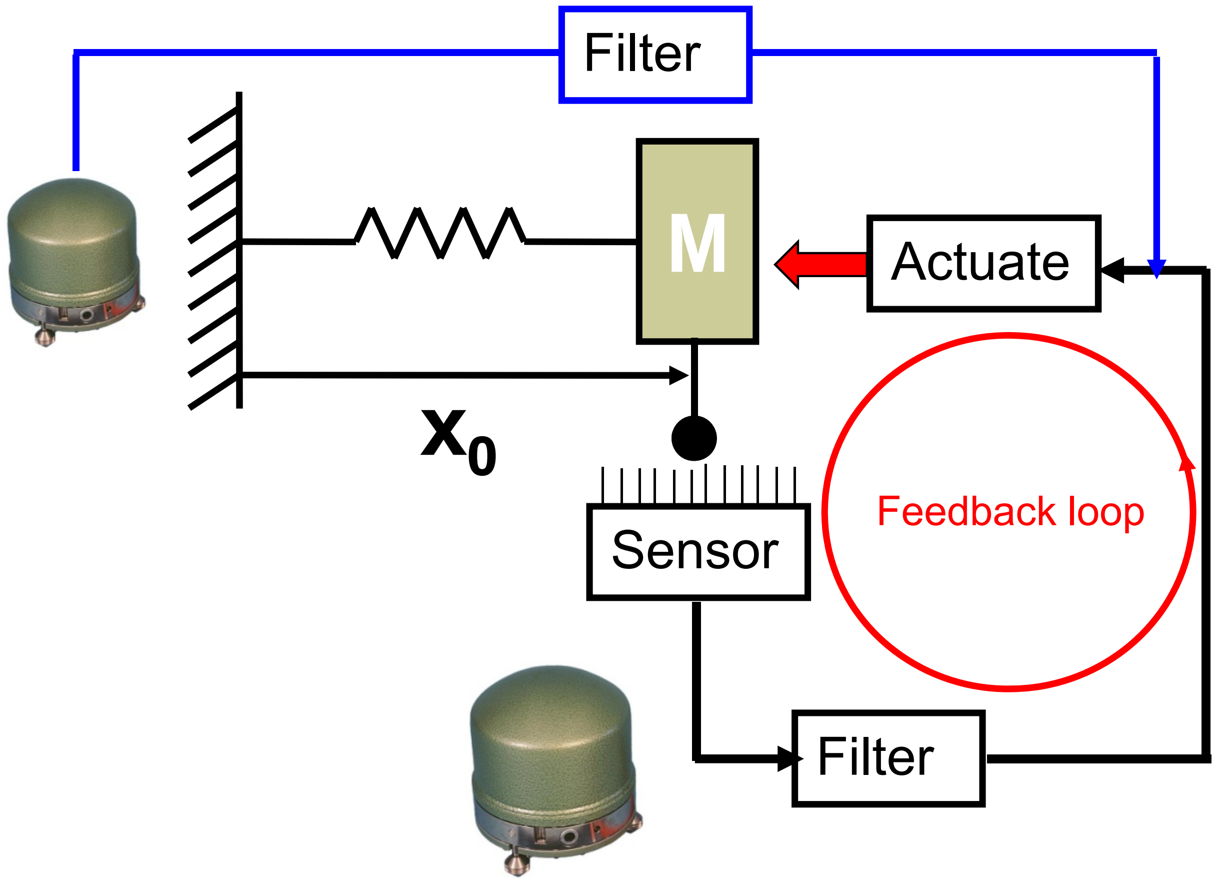
$$\frac{x_{mass}}{x_{ground}} = \left(\frac{f}{f_0}\right)^{-2n}$$

cedligo

Active Seismic Isolation

- Sense motion with seismometers and actuate to drive their output to zero

- Advanced LIGO: Passive isolation above 10Hz, Active isolation from 100mHz-10Hz



Feedback: velocity damping, integral control

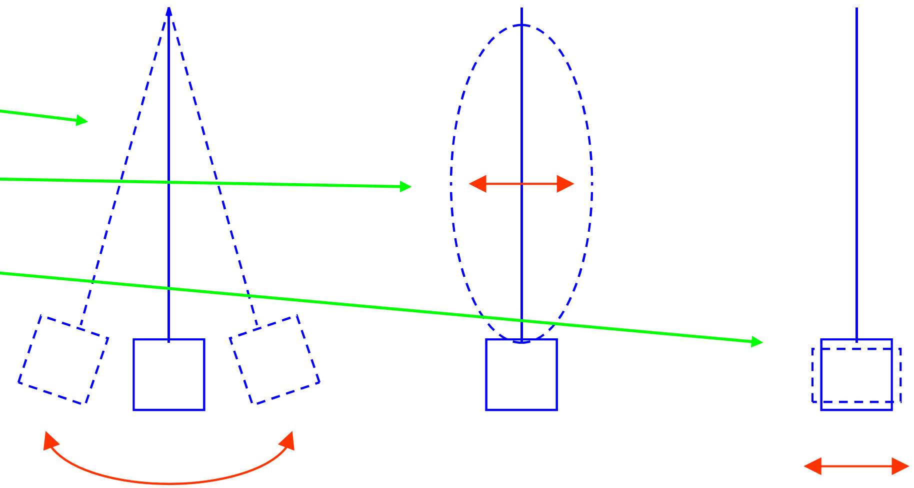
Feedforward: measure ground and predict motion

BSC Seismic Isolation

Thermal Noise

Thermally excited vibrations of

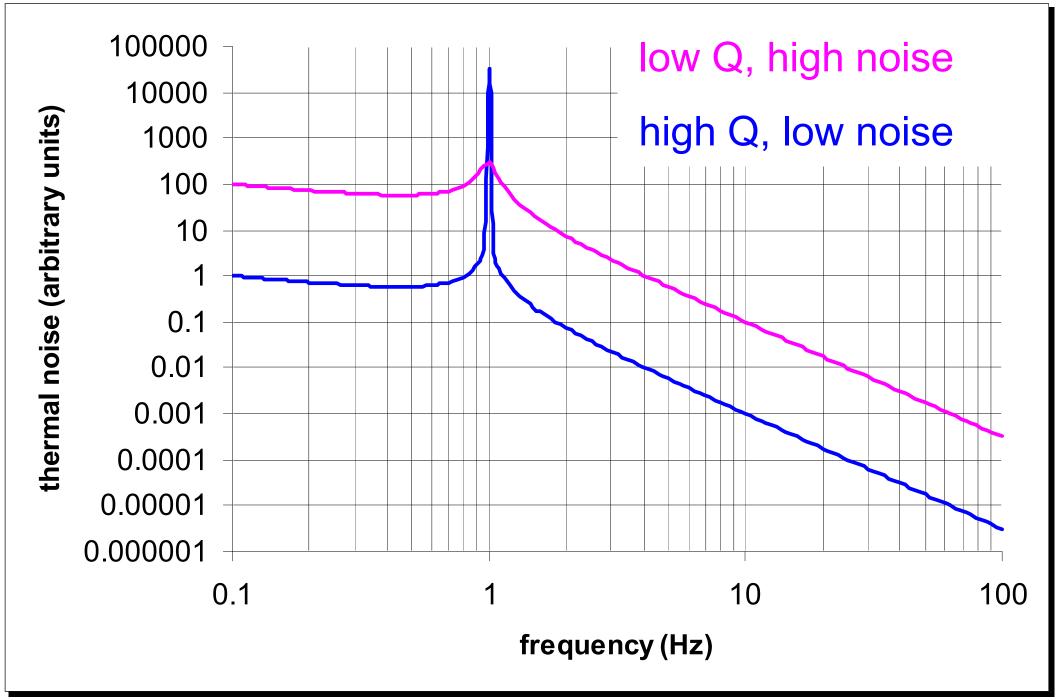
- suspension pendulum modes
- suspension violin modes
- mirror substrates + coatings



Use fluctuation-dissipation theorem to estimate magnitude of motion

To minimise:

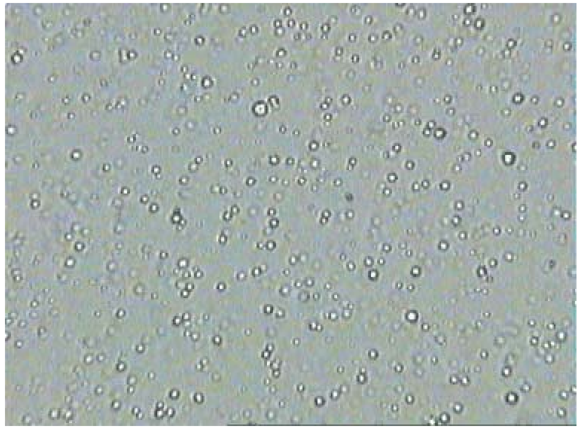
- use low loss (high quality factor) materials for mirror and final stage of suspension (fused silica)
- use thin, long fibres to reduce effect of losses from bending
- use low loss bonding technique: hydroxide-catalysis bonding
- reduce thermal noise from upper stages by careful design of break-off/attachment points



Origin of Thermal Noise

- Thermal noise is the statistical movement of particles driven by thermal energy
- The most common example is Brownian motion with $k_B T$ energy per degree of freedom distributed equally over the kinetic and potential energy
- A general theoretical description of fluctuations was developed by Callen, Welton & Greene (1950)
- A strong correlation between the loss in a system (dissipation) and its thermal noise was shown: Fluctuation-Dissipation theorem

$$S(\omega) = 4 k_B T \Re[Z(\omega)]$$

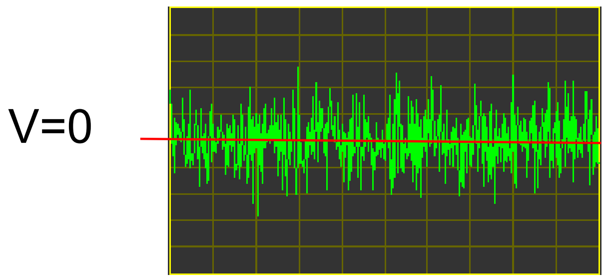


Brownian motion observed in fat droplets suspended in milk

- Both thermal energy and the dissipation in a system determine its thermal noise.
- example: Johnson Voltage noise

$$\langle V \rangle = 0$$

$$\langle V^2 \rangle = 4 k_B T R \Delta f$$



The Fluctuation-Dissipation Theorem

$$F(\omega) = -k(1 + i\phi(\omega))x$$

- If the resonant modes of the suspended mirror system in a gravitational wave detector are modelled as harmonic oscillators with internal damping, the equation of motion can be written as

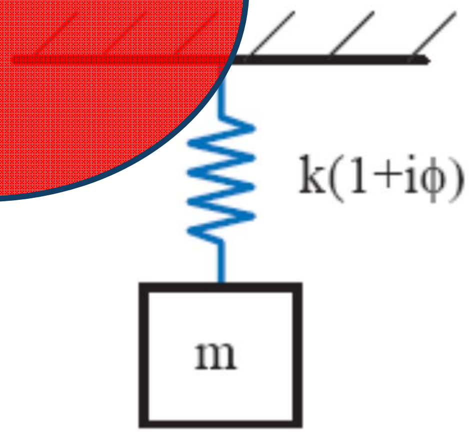
$$F(\omega) = m\ddot{x} + k(1 + i\phi(\omega))x$$

Homework: go through this derivation

- Using the standard relating the acceleration and displacement to the velocity of a harmonic oscillator $x \propto e^{i\omega t}$, $v = i\omega x$, $\ddot{x} = i\omega v$

$$F(\omega) = i\omega m v - i\frac{k}{\omega}(1 + i\phi(\omega))v$$

- The impedance Z can then be calculated



$$Z(\omega) = \frac{F(\omega)}{v}$$

$$= i\omega m - i\frac{k}{\omega}(1 + i\phi(\omega))$$

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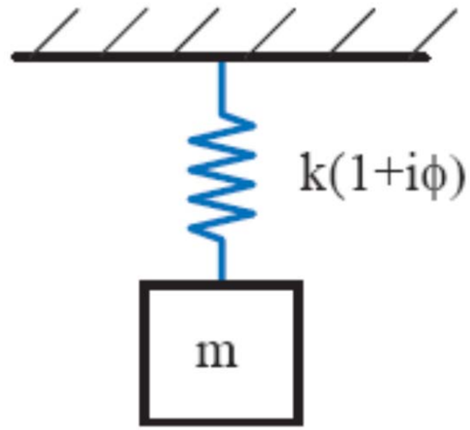


$$Z(\omega) = \frac{F(\omega)}{v}$$

$$= i\omega m - i\frac{k}{\omega}(1 + i\phi(\omega))$$

The Fluctuation-Dissipation Theorem

- The impedance Z can be simplified to $Z(\omega) = i\left(\omega m - \dfrac{k}{\omega}\right) + \phi(\omega)\dfrac{k}{\omega}$

- This expression can be inverted to give the admittance

$$Y(\omega) = \frac{\omega}{i\left(\omega^2 m - k\right) + \phi(\omega)k}$$

- Then rationalise the denominator by multiplying by numerator and denominator by the complex conjugate $\boldsymbol{k\phi(\omega) - i\left(\omega^2 m - k\right)}$ gives

$$Y(\omega) = \frac{\phi(\omega)k\omega - i\omega\left(\omega^2 m - k\right)}{\left(\omega^2 m - k\right)^2 + \left(\phi(\omega)k\right)^2}$$

The Fluctuation-Dissipation Theorem

- Can now calculate the power spectral density of displacement thermal noise of an oscillator with mass *m* at temperature *T* associated with a resonant mode of frequency w_0

$$S_x(\omega) = \frac{4kT}{\omega^2}\Re\left[Z^{-1}(\omega)\right] = \frac{4kT}{\omega^2}\Re\left[Y(\omega)\right]$$

- where $\boldsymbol{\omega_0^2 = {}^{k}/_{m}}$ and $\boldsymbol{\phi(\omega)}$ is the mechanical dissipation of the oscillator

$$S_x(\omega) = \frac{4kT}{\omega}\left[\frac{\phi(\omega)k}{\left(\omega^2 m - k\right)^2 + \left(\phi(\omega)k\right)^2}\right]$$

$$S_x(\omega) = \frac{4kT}{m\omega}\left[\frac{\phi(\omega)\omega_0^2}{\left(\omega^2 - \omega_0^2\right)^2 + \phi^2(\omega)\omega_0^4}\right]$$

Origin of Thermal Noise

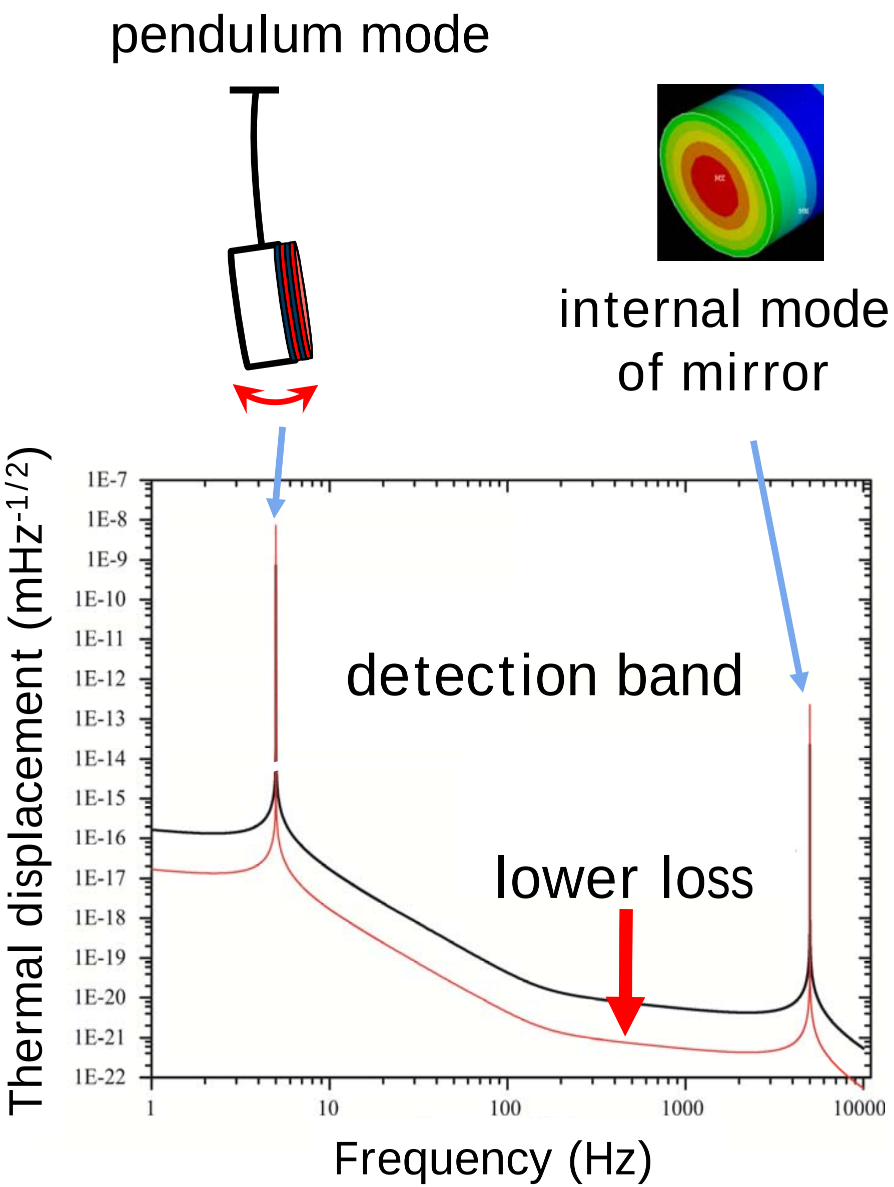
- Thermal noise of the optical materials and suspension elements manifests as statistical fluctuations of the front surface which is sensed by the laser beam:
  - coatings and suspensions are important areas of R&D.
- The fluctuation of the surface can be produced by two possible mechanisms:
  - Brownian motion of the surface – Brownian thermal noise
  - statistical temperature fluctuations within the test mass cause local changes of the surface position (thermal expansion) – Thermoelastic noise
- The origin is the thermal energy that is stored in the atoms of the system so improvements require:
  - ultra pure materials with low mechanical loss
  - lower temperature

Mechanical Loss

- Thermal energy ($k_B T$) drives resonant modes
- Width of resonance related to mechanical loss of material, ϕ:
- Mechanical loss is energy dissipation by internal friction in material

$$\frac{\Delta\omega}{\omega_0} = \phi = \frac{1}{Q}$$

- Lower loss material → lower off - resonance thermal noise
- Use of fused silica (ϕ <10^{-7}) mirror substrates and suspension fibres in room temperature GWDs



aLIGO Quadruple Suspension

- The input test masses (ITM) and end test masses (ETM) of Advanced LIGO will be suspended via a quadruple pendulum system

- **Seismic isolation:** use quadruple pendulum with 3 stages of maraging steel blades for horizontal/vertical isolation

- **Thermal noise reduction:** monolithic fused silica suspension as final stage

- **Control noise minimisation:** use quiet reaction pendulum for global control of test mass position

- **Actuation:** Coil/magnet actuation at top 3 stages, electrostatic drive at test mass

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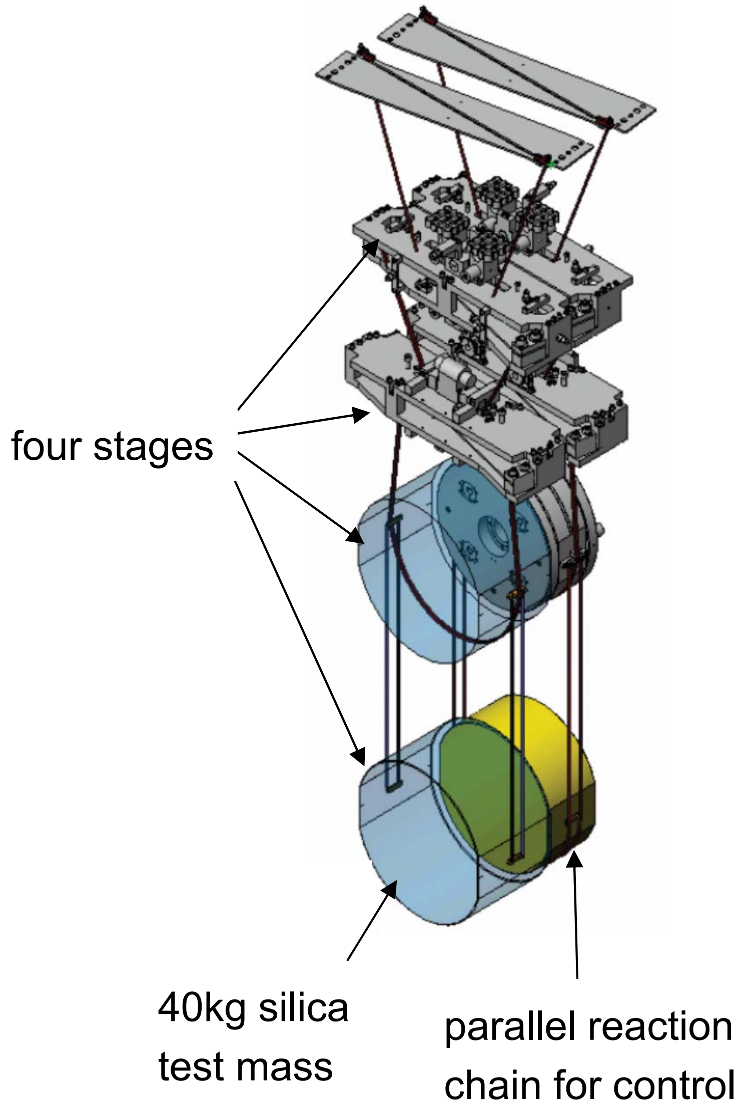
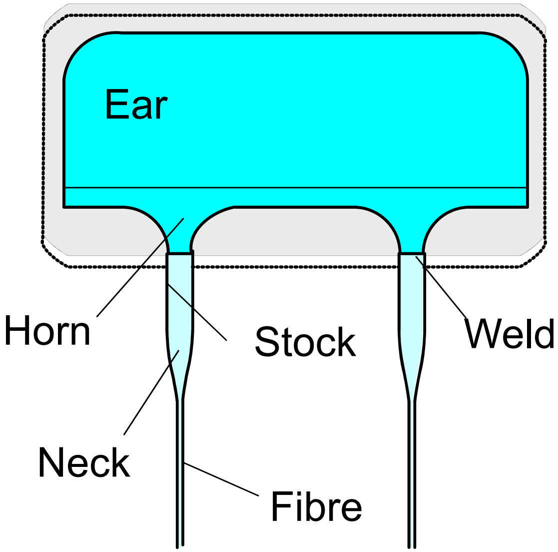
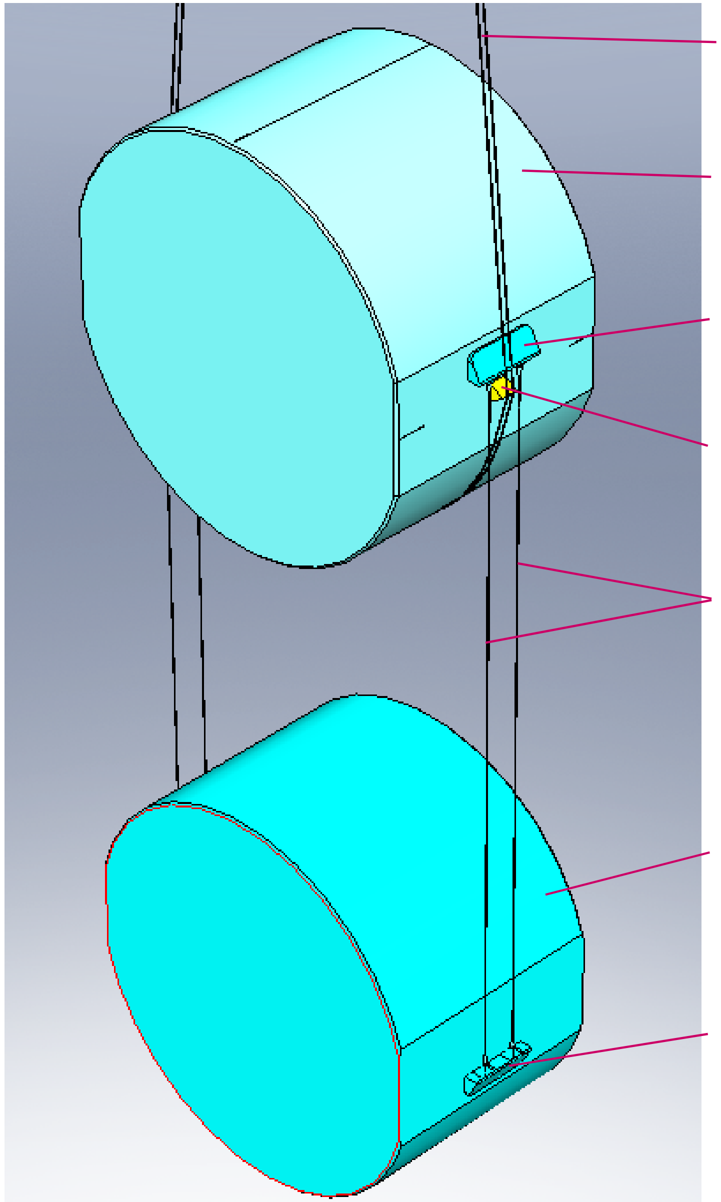


aLIGO Monolithic Stage

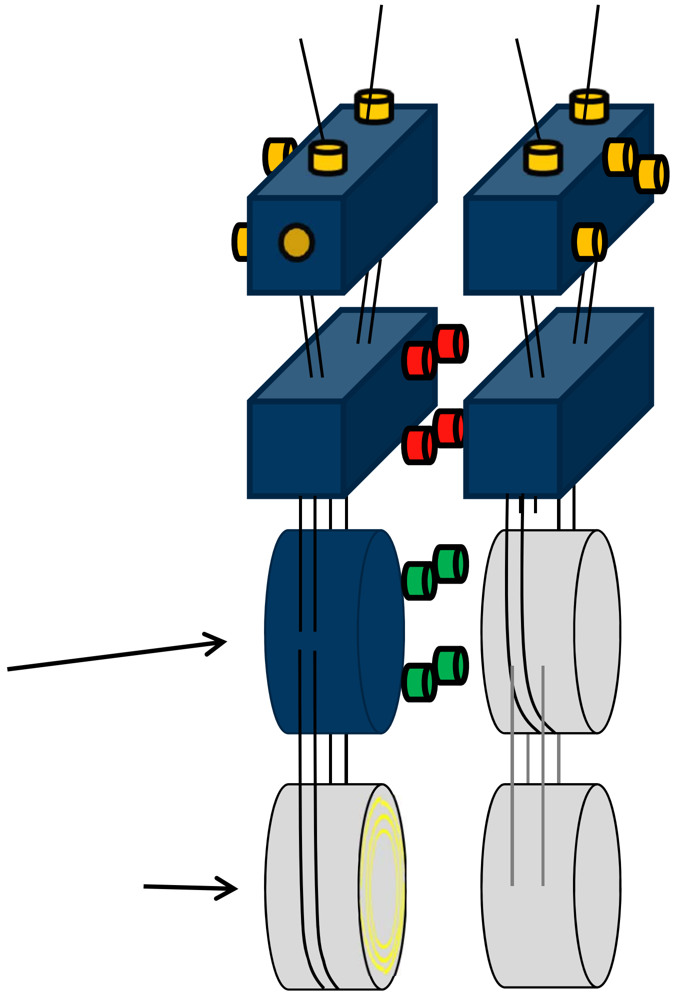




Local and Global Control

- Local control: damping at top mass, separately for each chain, using BOSEMs (next slide) with 10mm x 10mm NdFe magnets
- Global control (length and angular) at all four levels
  - BOSEMs with 10mm x 10mm NdFe magnets at top mass
  - BOSEMs with 10mm x 10mm SmCo magnets acting between chains at upper intermediate mass
  - AOSEMs** with 2mm x 6mm SmCo magnets acting between chains at penultimate mass
  - Electrostatic drive (ESD) using gold pattern on reaction mass/compensator plate at test mass level

- Reaction Chain
- Main (test) Chain

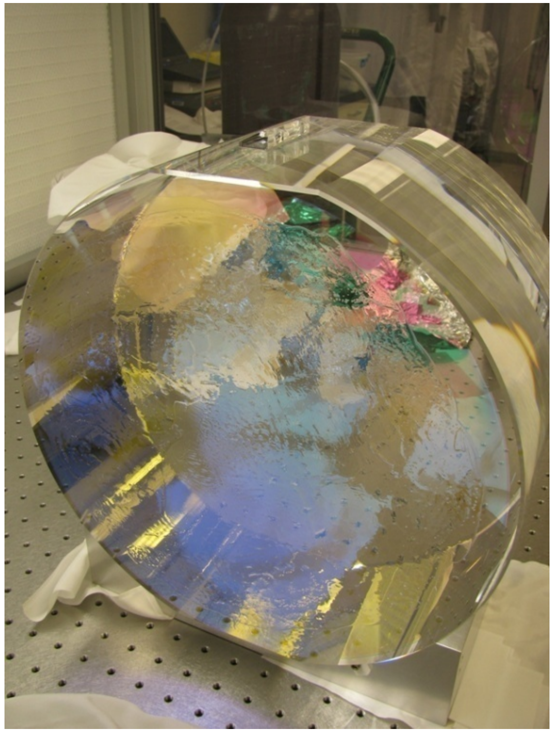


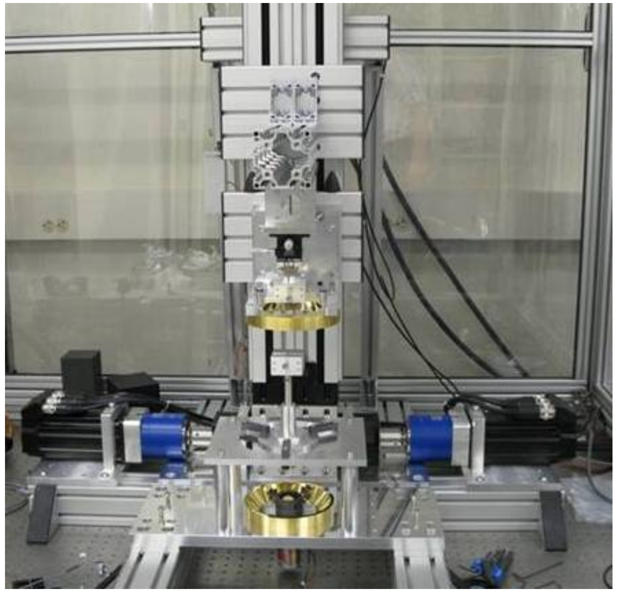
•*BOSEM = Birmingham Optical Sensor/Electromagnetic Actuator

•*AOSEM = ALIGO OSEM = modified initial LIGO OSEM

Monolithic Suspension Construction

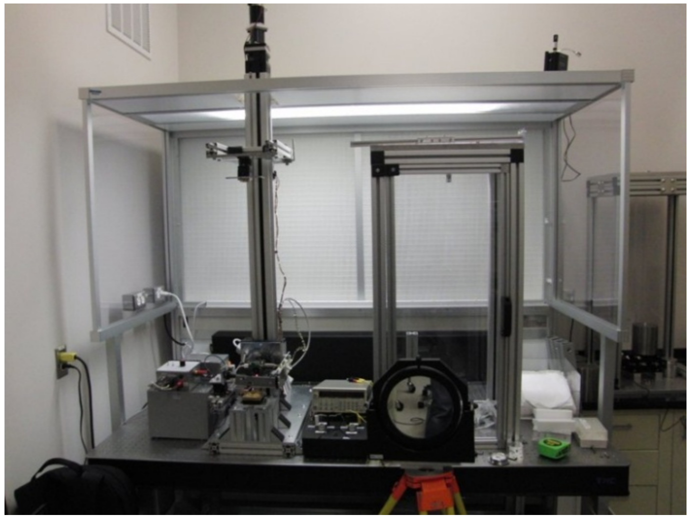
Hydroxide catalysis bonding of the ears



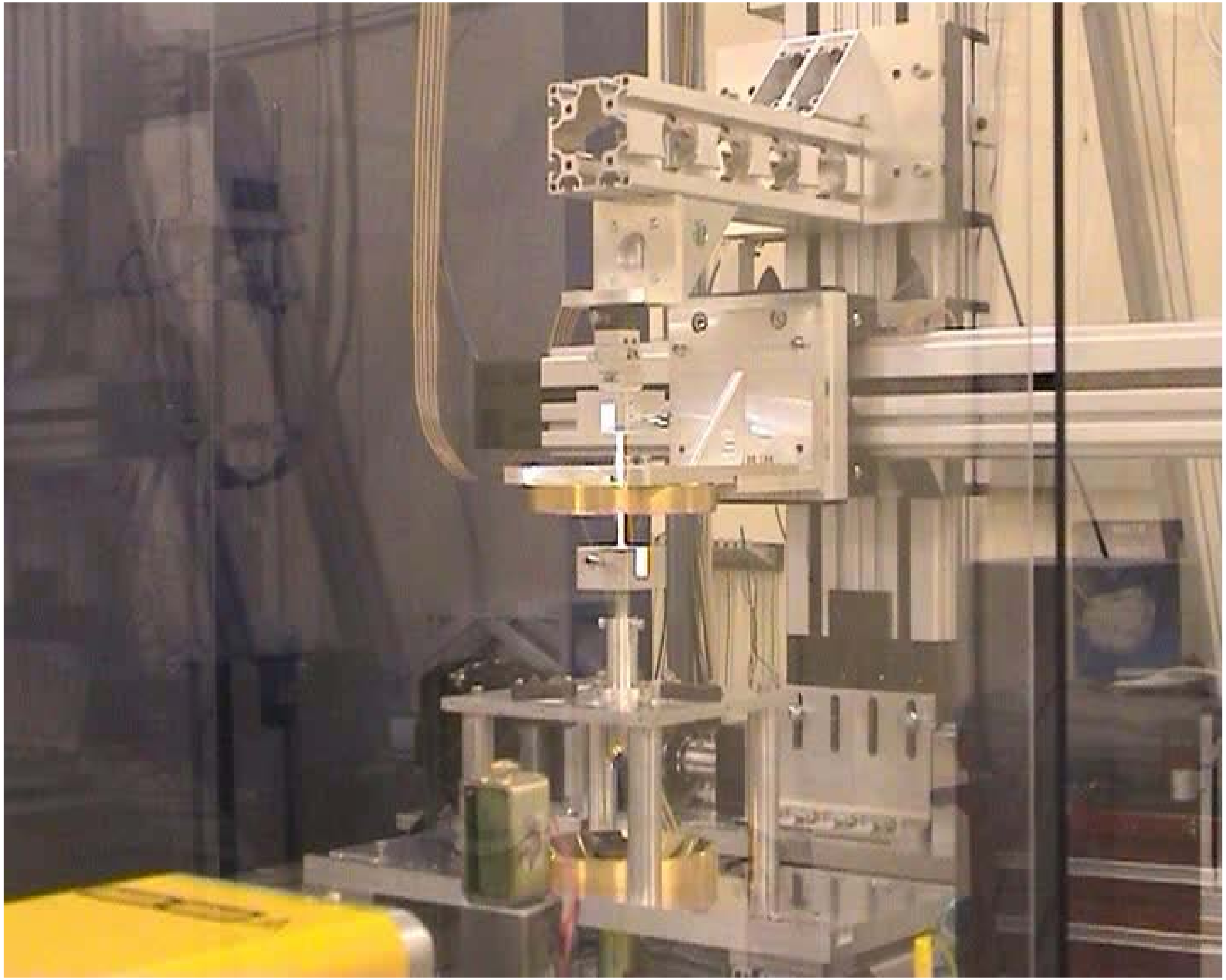


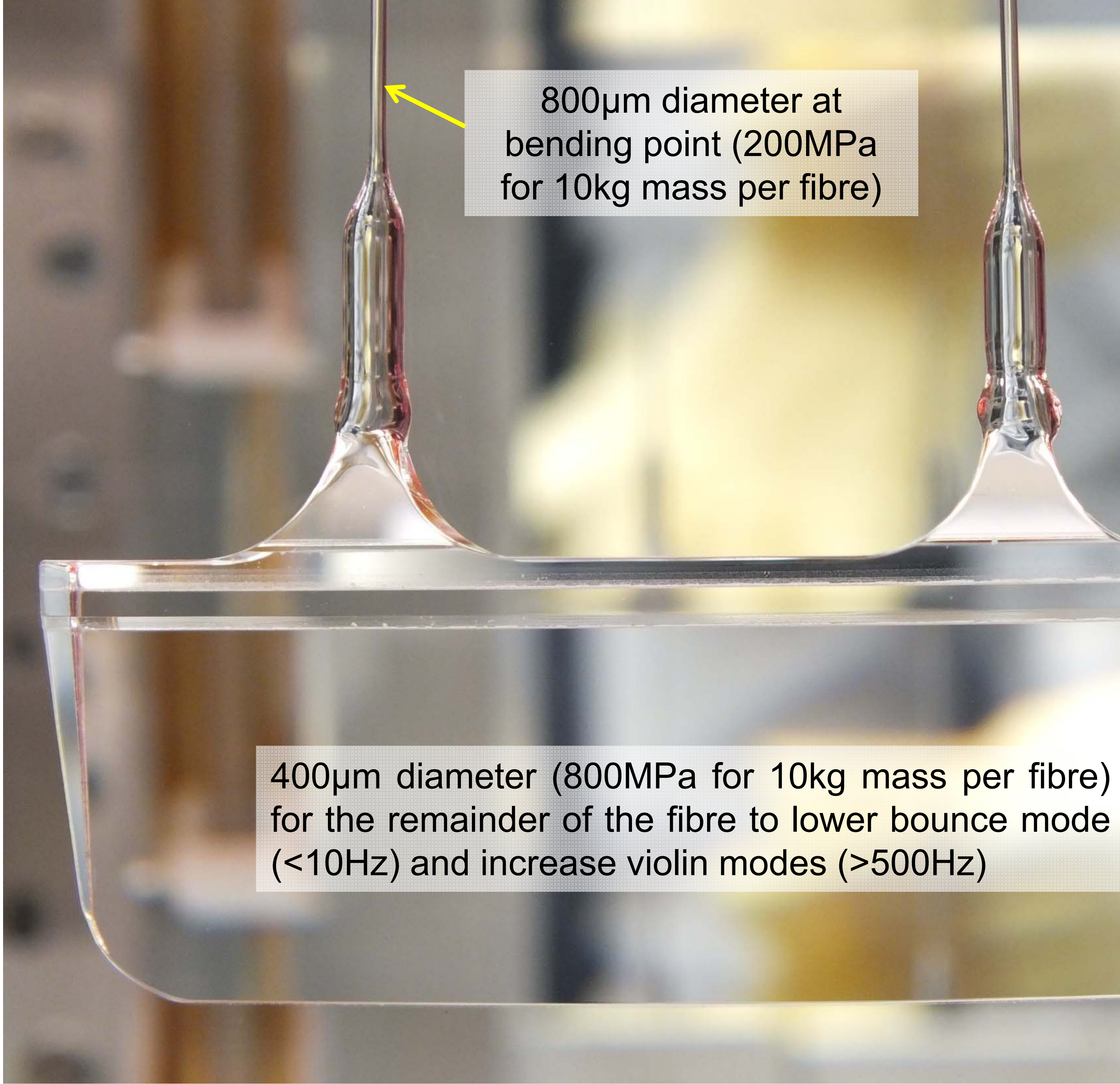
- Fibre pulling with CO_2 laser

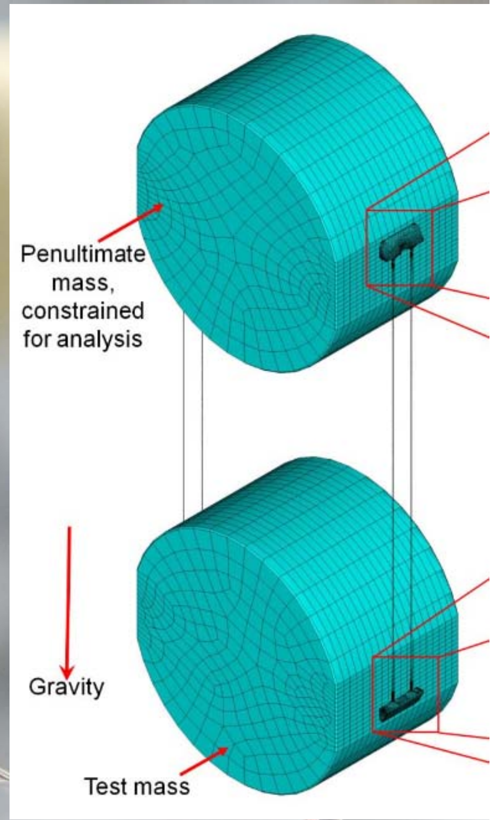
- Fibre profiling for importing into Finite Element Analysis



Laser Pulling

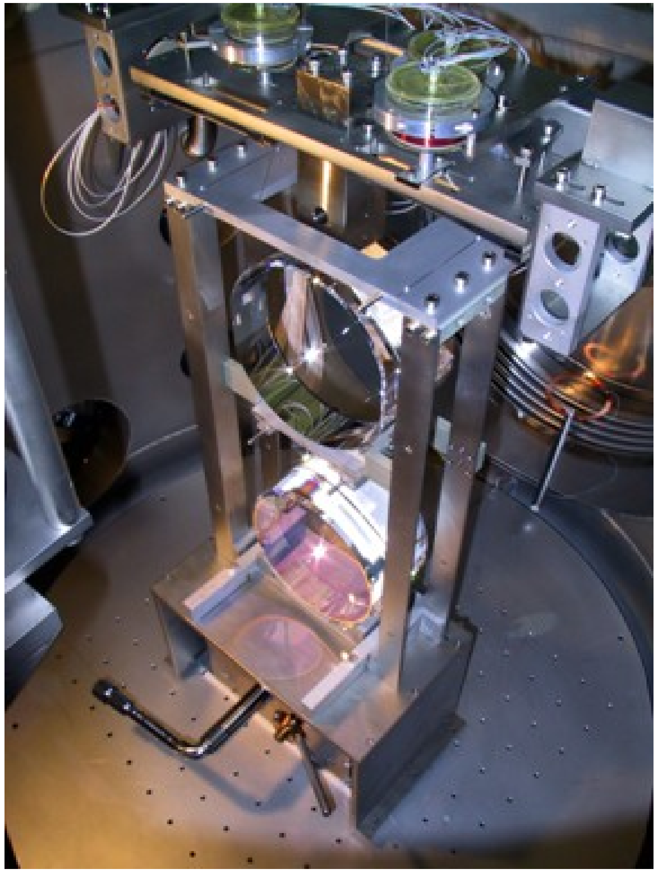


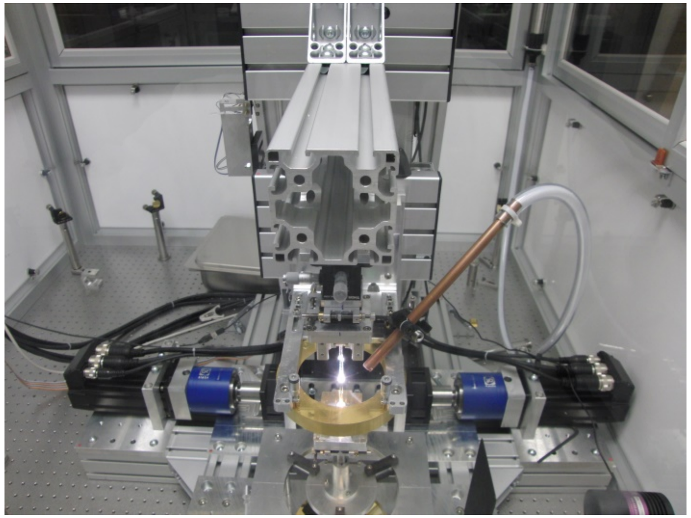

800µm diameter at bending point (200MPa for 10kg mass per fibre)
400µm diameter (800MPa for 10kg mass per fibre) for the remainder of the fibre to lower bounce mode (<10Hz) and increase violin modes (>500Hz)

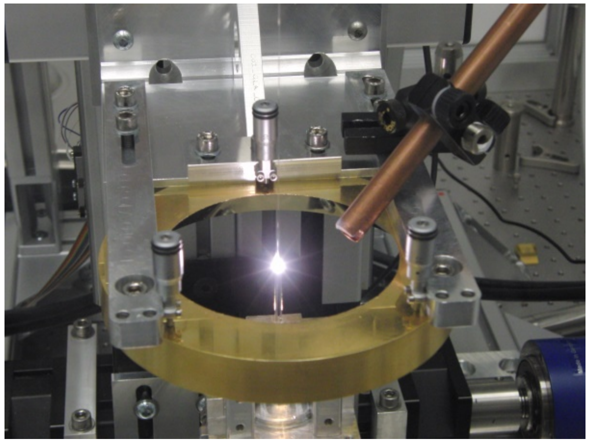

Penultimate mass, constrained for analysis
Gravity
Test mass

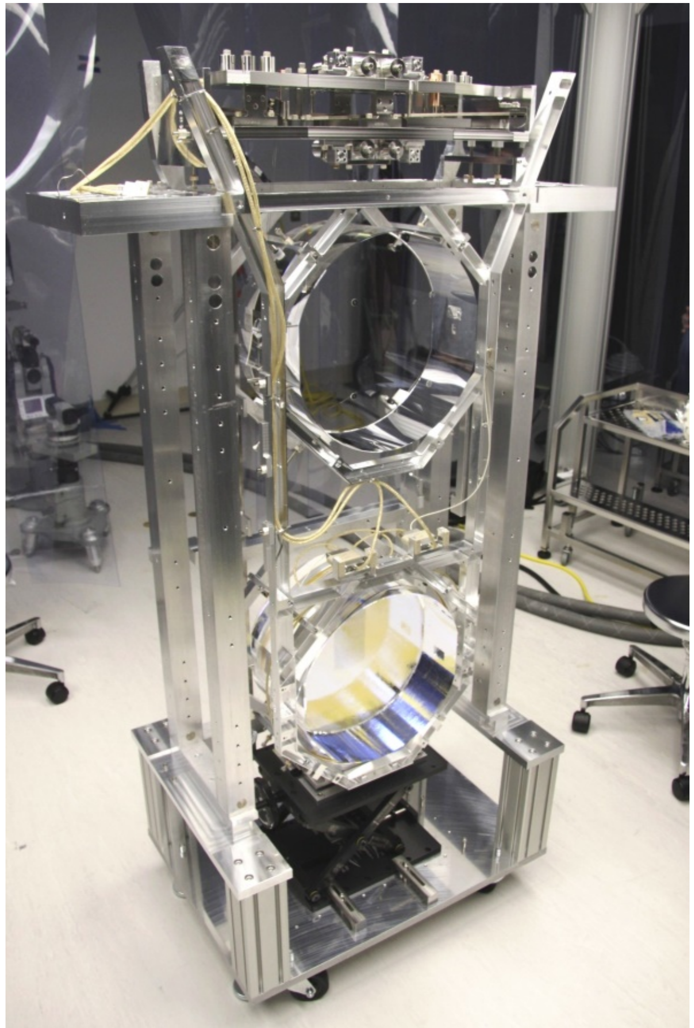
Monolithic Suspensions

- Monolithic suspensions & signal recycling pioneered in GEO-600 → upscaled to aLIGO









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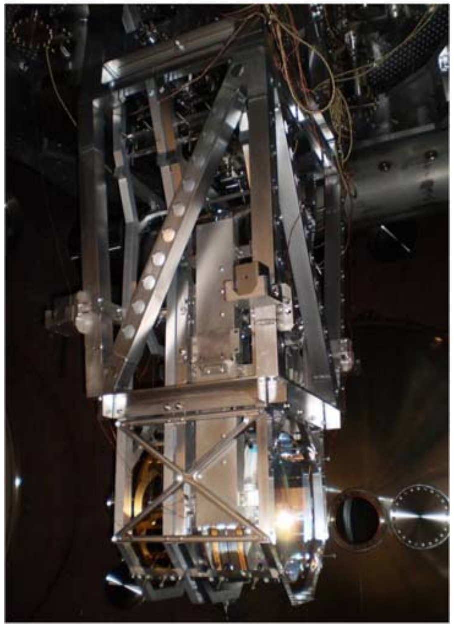
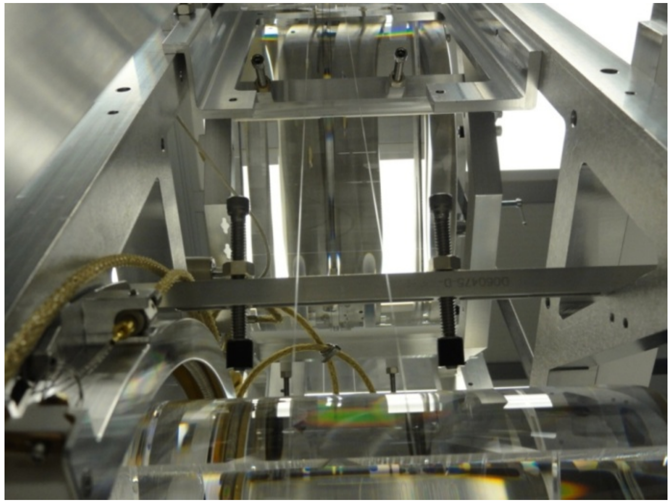
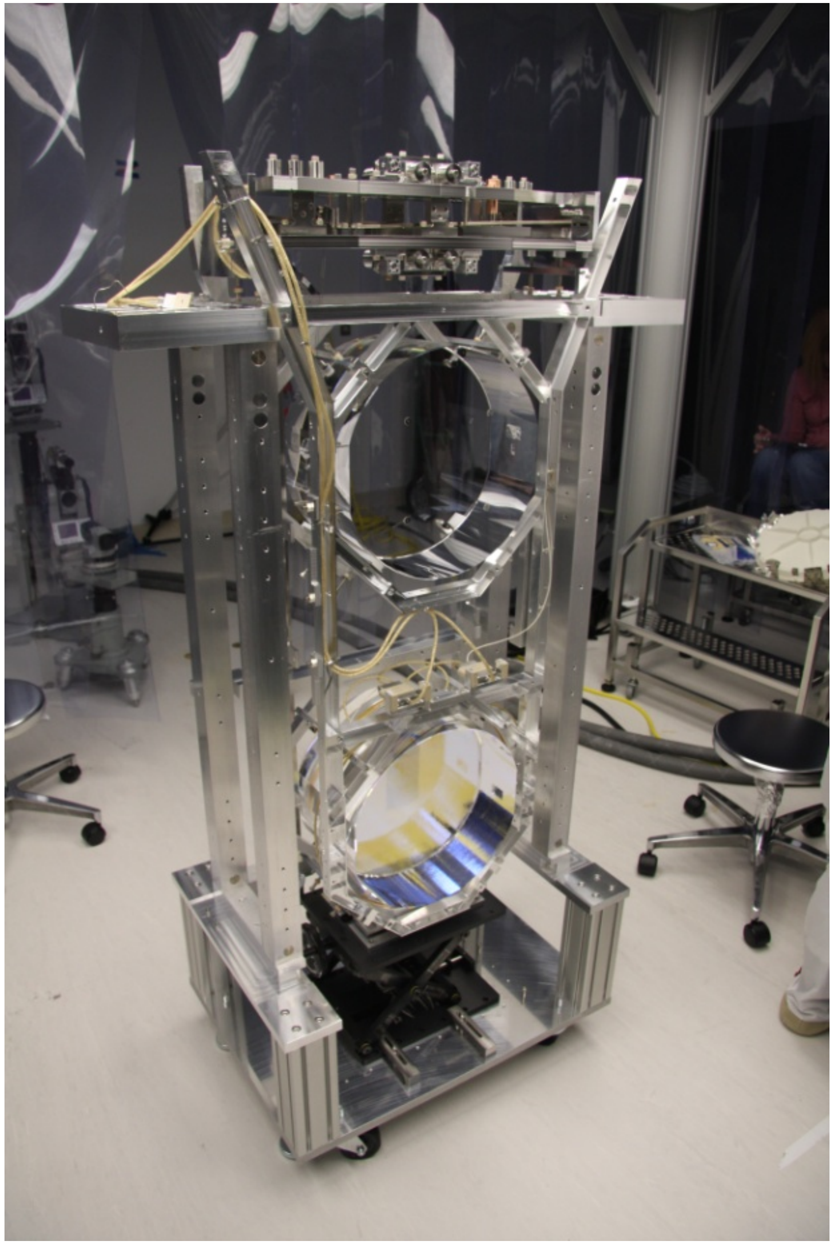
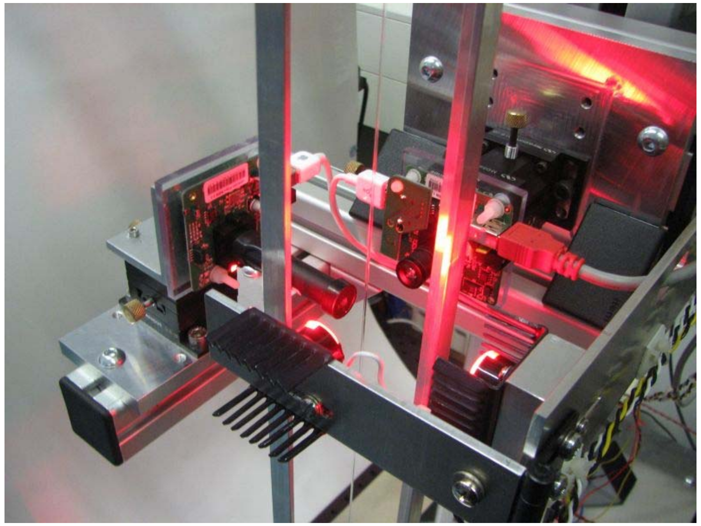
aLIGO Suspensions

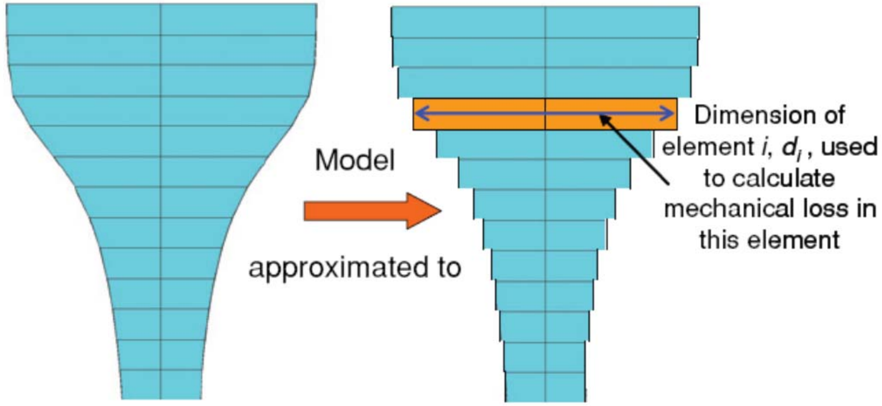






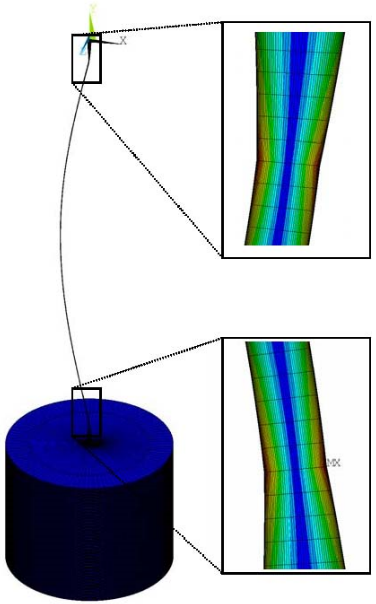
Suspension Thermal Noise (Dilution)





• Profile fused silica fibre

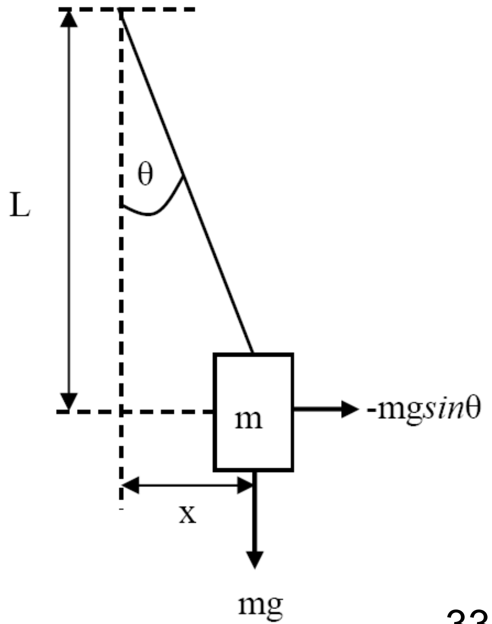
• Extract elastic strain energy and modal frequencies from ANSYS



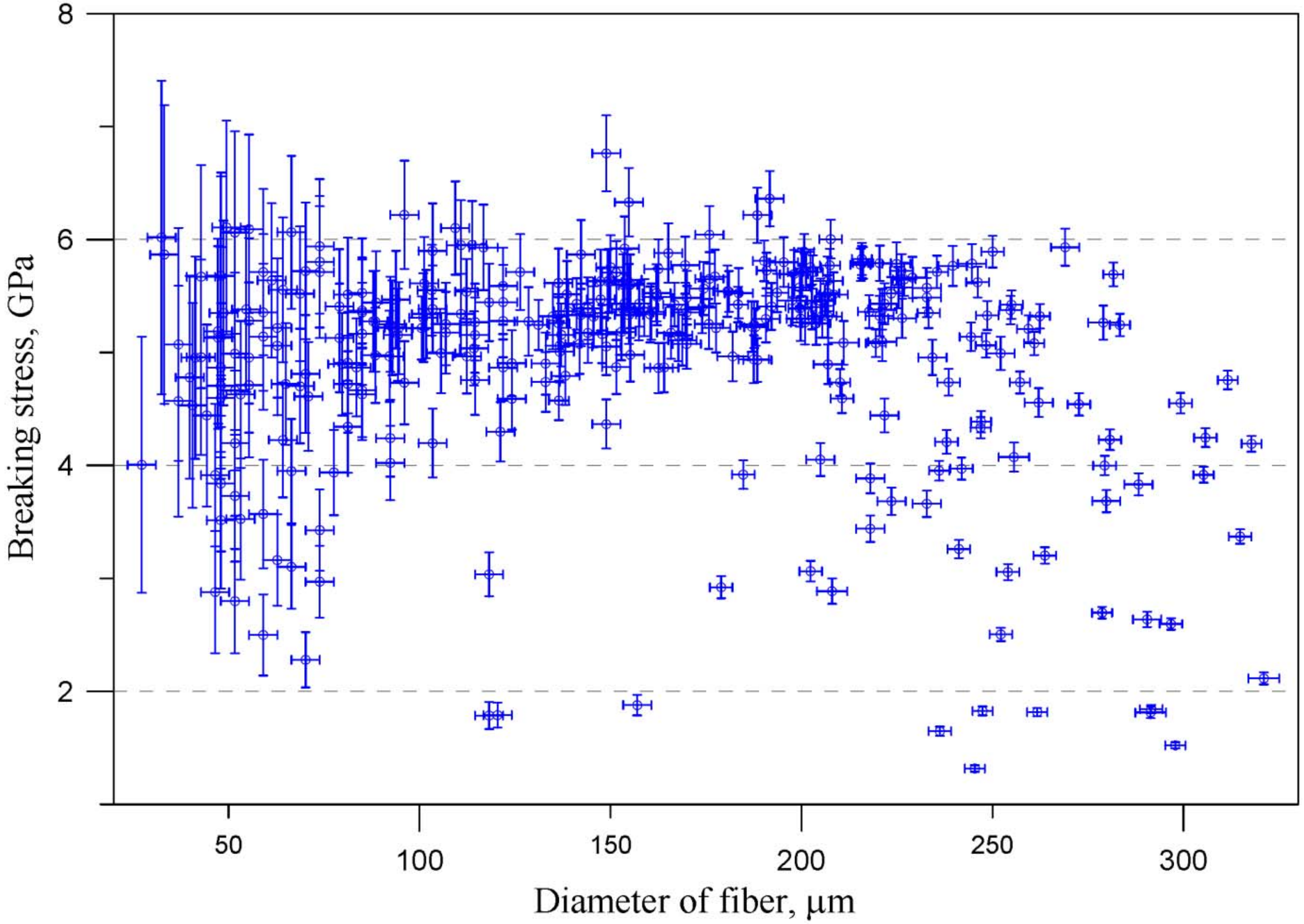
• Loaded suspension fibres the majority of energy in gravity ⇒ dilute loss due to elastic energy

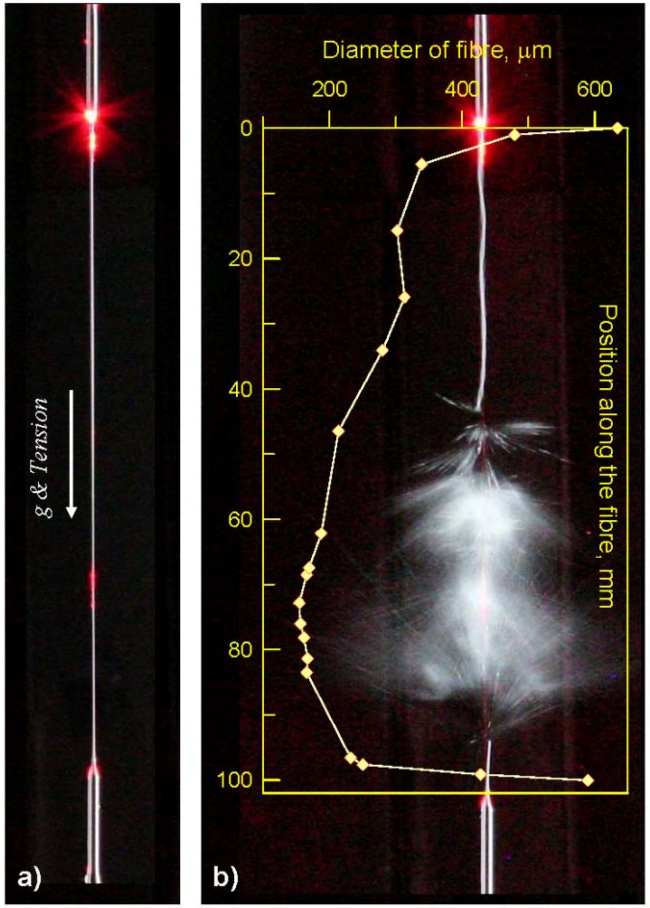
$$D = \frac{E_{\text{total}}}{E_{\text{elastic}}} \approx \frac{k_{\text{gravity}}}{k_{\text{fibre}}} \approx \frac{2L}{\xi}\sqrt{\frac{T}{YI}}$$

• ξ=2 (bending top/bottom)



Fibre Strength





Fused Silica

- Fused silica is a remarkable material: high strength, low mechanical loss, can be welded and drawn into fibres

$$Y = \frac{\sigma}{\varepsilon}$$

- With 10kg on a 400 μm diameter, 60 cm long fibre:

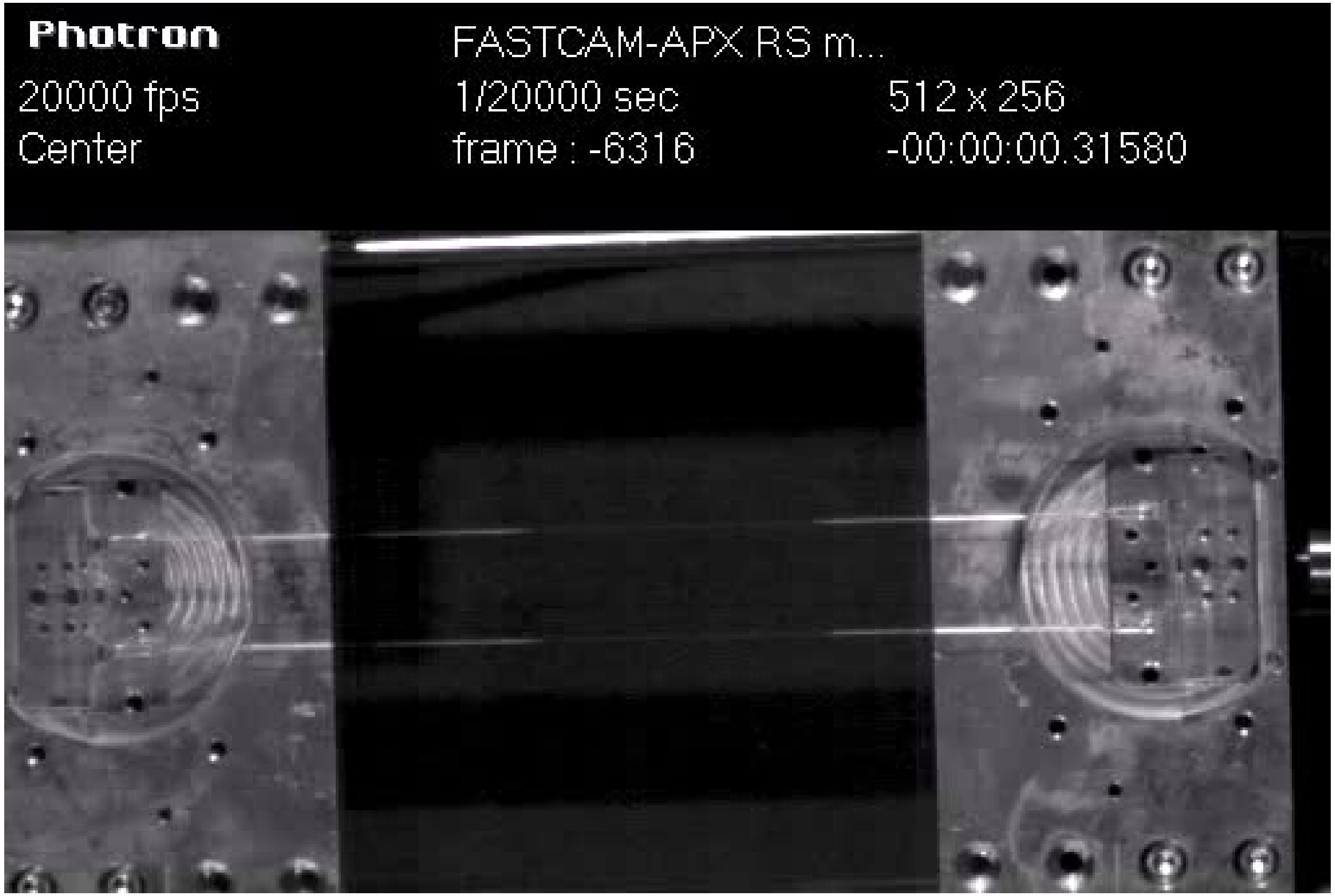
$$\sigma = 10 \times 9.81 / \pi \times \left(400 \times 10^{-6}\right)^2 = 780 MPa$$

- and the extension is

$$\Delta L = \varepsilon \times L = \left[\frac{\sigma}{Y}\right] \times L = \left[\frac{780 \times 10^6}{72 \times 10^9}\right] \times 0.6 = 6mm$$

- The strain is 1% at this load !!!

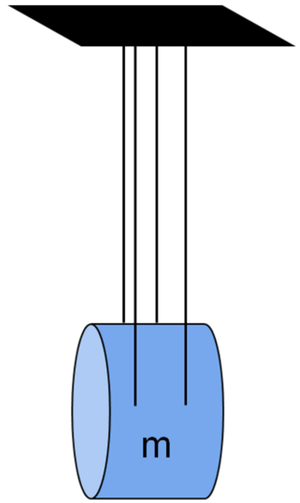
Fused Silica



- Explosive fracture at 4 GPa (strain of 6%, extension of 11mm for a 20cm long fibre)
- aLIGO fibres operate with a safety factor of $\approx$7

Fibre Geometry

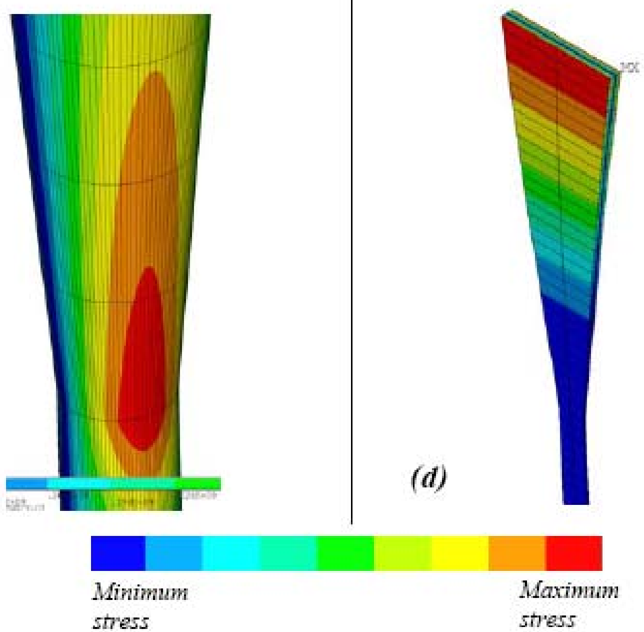
- The fibre geometry defines the dilution of the suspension and can be approximated analytically as $D \approx \frac{2L}{\xi}\sqrt{\frac{T}{YI}}$
- Fibres are not infinitely stiff attachments and thus the analytical dilution values are modified with FE analysis (D_{cyl}=75)

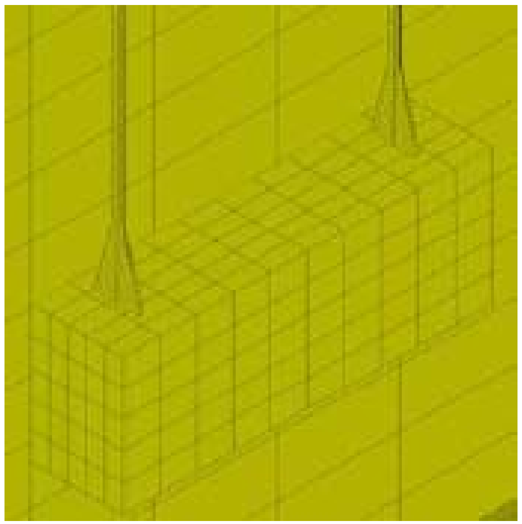


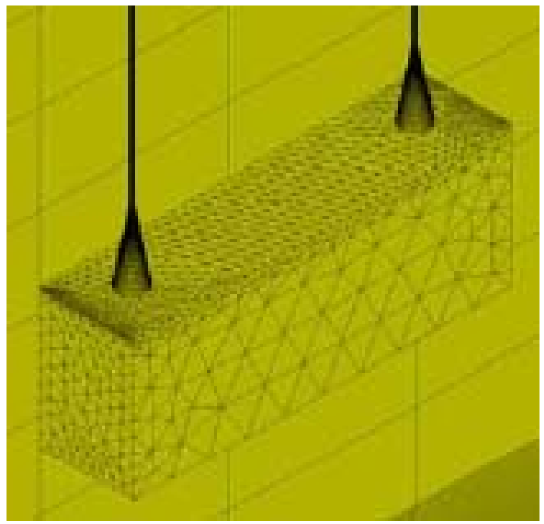
Geometry	D (Analytic)	D (FEA)	Dimensions
Cylindrical	112	75	ϕ 0.8mm
Rectangular	480	-	0.1mm×1mm

$$I_{cyl} = \pi R^4 / 4$$

$$I_{rec} = wt^3 / 12$$

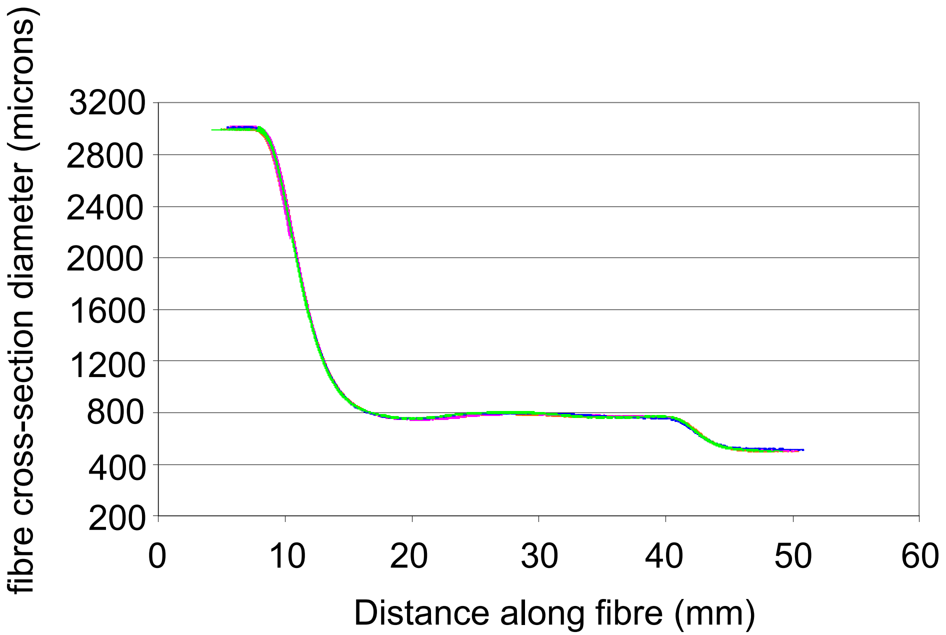


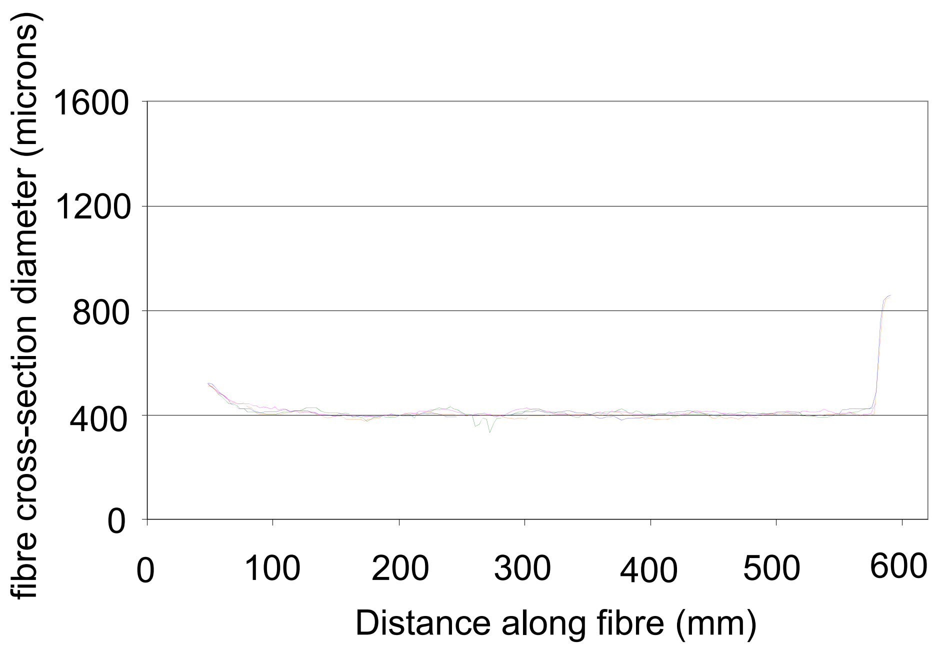


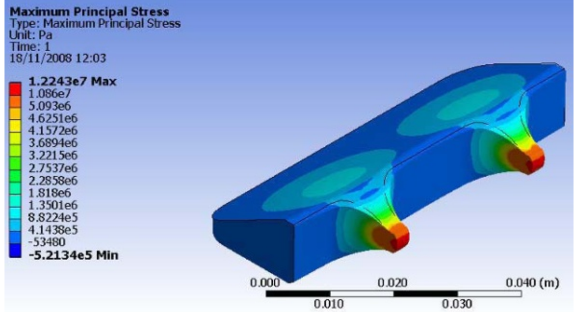


Fibre Profile

- Fibre stock is 3 mm diameter
  - Ease of welding and handling, stiff connection
- Short 800 μm diameter section
  - Bending takes place close to the attachment point (modal frequencies)
  - Reduces thermoelastic noise
- 400 μm diameter over the majority of the fibre length
  - Violin mode ≈510Hz, vertical mode ≈9Hz





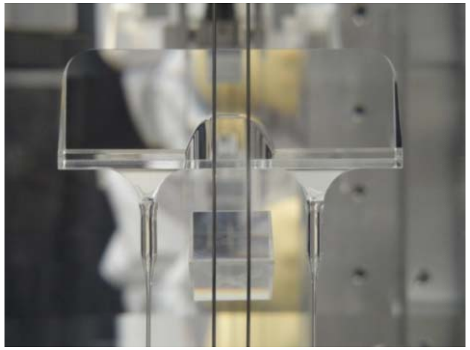


Suspension Thermal Noise

- Use the following loss terms to model the welds, ear horns and fibres

$\phi_{\text{bulk}} = 1.2\times10^{-11} f^{0.77}$	$\phi_{\text{TE}}(\omega) = \frac{YT}{\rho C}\left(\alpha - \sigma_o \frac{\beta}{Y}\right)^2 \left(\frac{\omega\tau}{1+(\omega\tau)^2}\right)$
$\phi_{\text{surface}} \approx \frac{8h\phi_s}{d}$	$\phi_{\text{weld}}(\omega) = 5.8\times10^{-7}$

$$\phi_i(\omega) = \left(\phi_{\text{bulk,i}}(\omega) + \phi_{\text{TE,i}}(\omega) + \phi_{\text{surface,i}}(\omega) + \phi_{\text{weld,i}}(\omega)\right)$$



$$\phi_{total}(\omega) = \frac{1}{D}\left[\frac{E_1}{E_{\text{elastic}}}\phi_1(\omega) + \frac{E_2}{E_{\text{elastic}}}\phi_2(\omega) + \ldots + \frac{E_{\text{n}}}{E_{\text{elastic}}}\phi_{\text{n}}(\omega)\right]$$

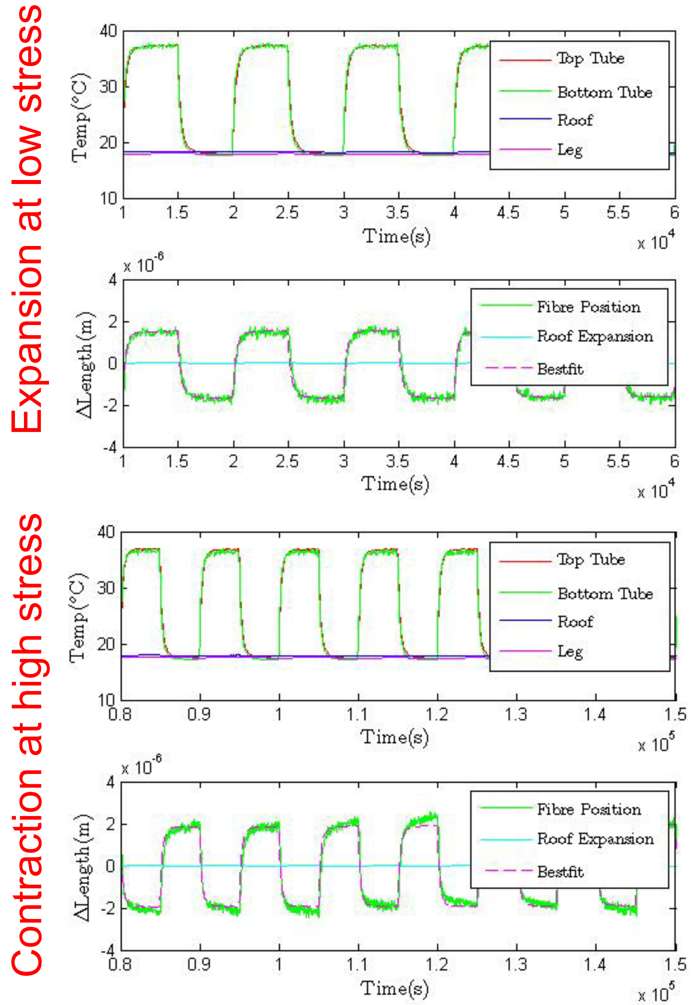
$$S_x(\omega) = \frac{4k_BT}{m\omega}\left(\frac{\omega_o^{\,2}\phi_{total}(\omega)}{\omega_o^{\,4}\phi_{total}^{\,2}(\omega) + \left(\omega_o^{\,2} - \omega^2\right)^2}\right)$$

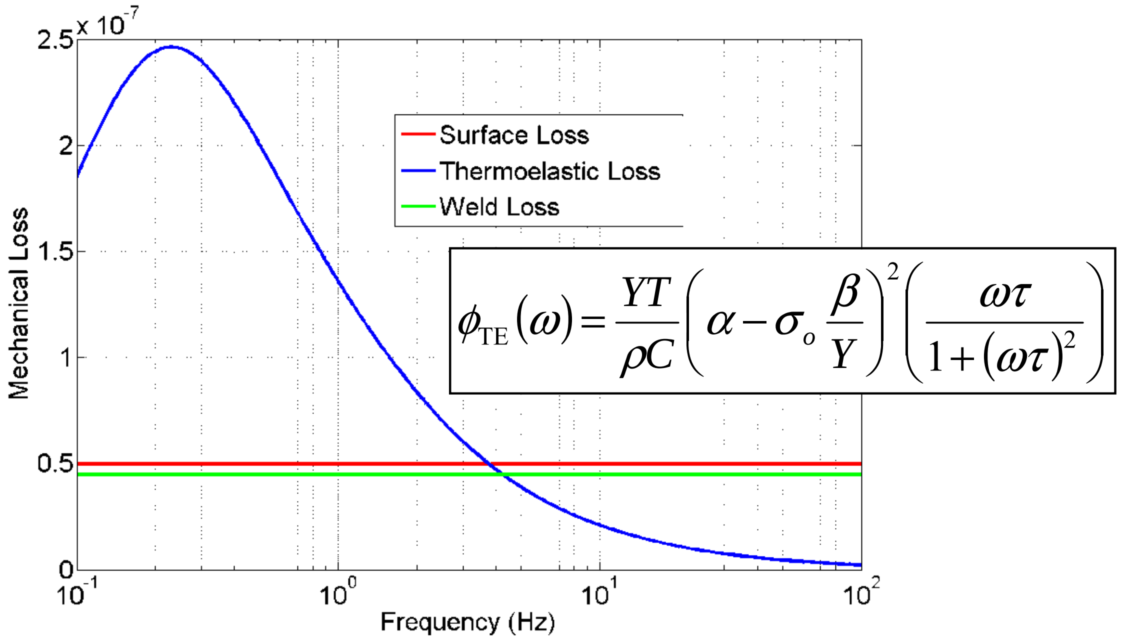
- Surface loss: dislocations, un-terminated dangling bonds and micro-cracks on the pristine silica surface
- Thermoelastic loss: heat flow across the fibre due to expansion/contraction leads to dissipation.
- Bulk loss: strained Si-O-Si bonds have two stable minima which can redistribute under thermal fluctuations.

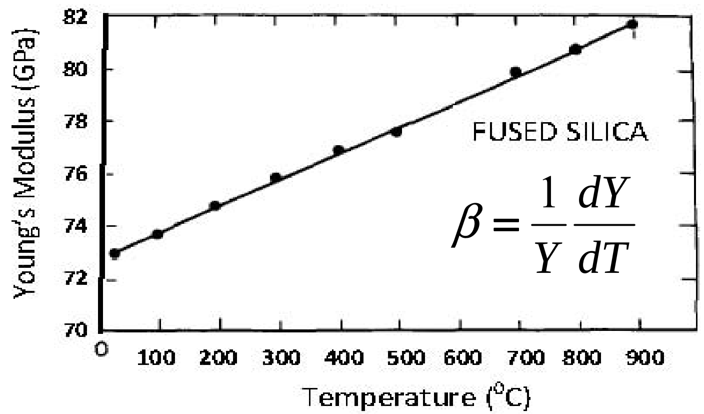
A.M. Gretarsson et al., Phys. Rev. A, 2000
G. Cagnoli and P.A. Willems, Phys. Rev. B, 2002
P.A. Willems, T020003-00
M.Barton et al., T080091-00-K
A. Heptonstall et al., Phys. Lett. A, 354, 2006
A. Heptonstall et al., Class. Quant. Grav, 035013, 2010

Suspension Thermal Noise

- aLIGO utilises thermoelastic cancellation to meet the noise requirement of 10^{-19} m/√Hz at 10Hz.
- Fused silica has a Young's modulus which increases with temperature

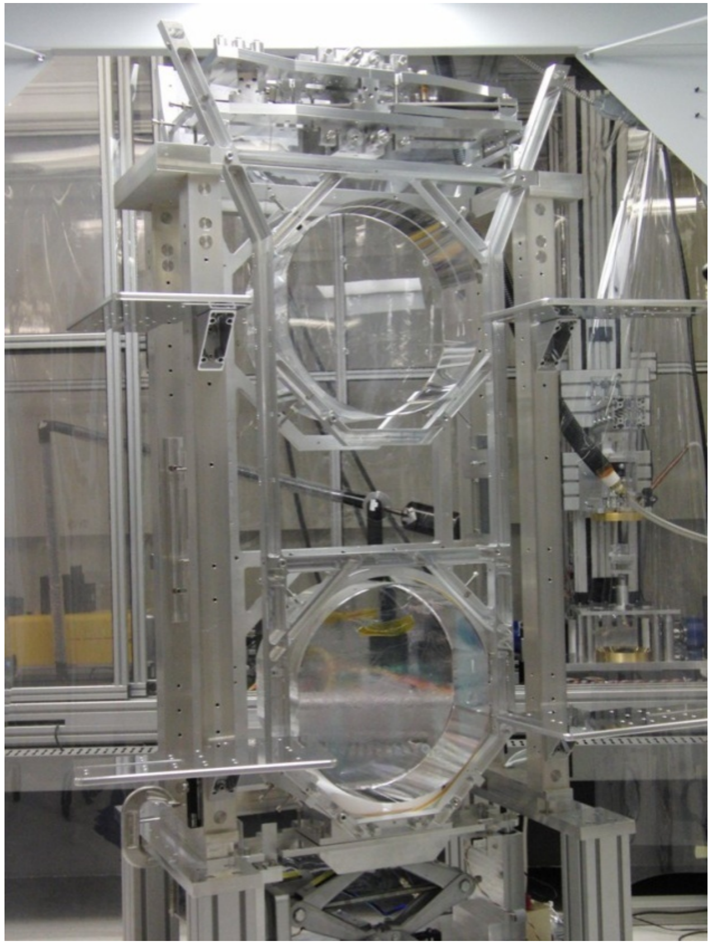


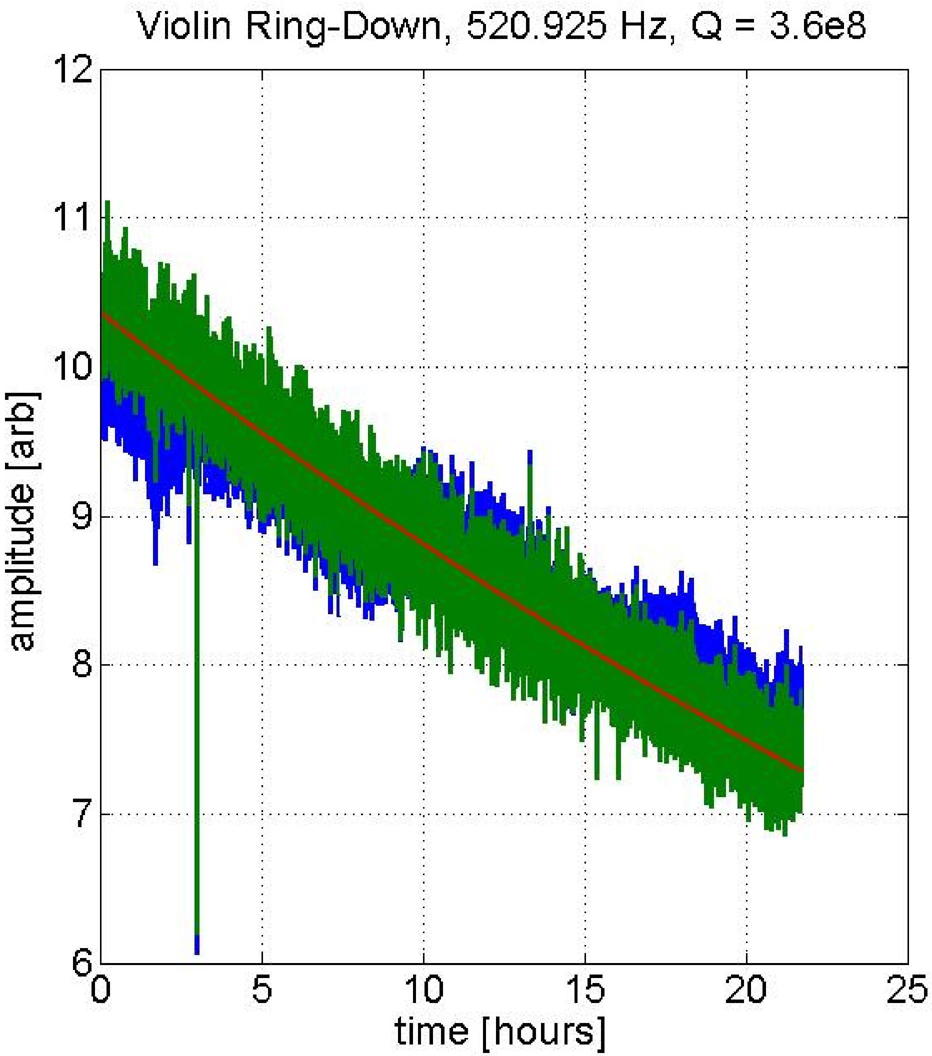




aLIGO Suspension Thermal Noise

- ANSYS predictions of violin mode quality factors are in good agreement (≈15%) with ringdown measurements at the LIGO Advanced Systems Test Interferometer (LASTI) at MIT where the first monolithic suspension was installed.





Ringdown Time to 1/e

- Violin frequency $c=\sqrt{\frac{T}{\mu}}$ with tension *T* and mass per unit length μ

$$T = mg/4 = 98.1N$$

$$\mu = \pi \times r^2 \times \rho = \pi \times \left(200\times10^{-6}\right)^2 \times 2202 = 0.000277 kg/m$$

$$c = \sqrt{\frac{98.1}{0.000277}} = 595 m/s$$

$$f = \frac{c}{\lambda} = \frac{c}{2L} = \frac{595}{2\times0.6} = 496 Hz$$

$$Q = \pi N_{1/e} \Rightarrow 3.6\times10^8 = \pi N_{1/e}$$

$$N_{1/e} = 3.6\times10^8 = 1.1\times10^8$$

$$\tau_{1/e} = \frac{1.1\times10^8}{f} = \frac{1.1\times10^8}{496} = 2.7 days$$

Useful Equations

$$x^2_{thermal} = \frac{4k_B T\omega_0^2\phi}{\omega m\left(\left(\omega_0^2-\omega^2\right)^2+\left(\phi\omega_0^2\right)^2\right)}$$

Thermal displacement noise

$$S_x(\omega) = \frac{4k_B T}{\omega^2}\Re\left[\frac{1}{Z(\omega)}\right]$$

Fluctuation Dissipation theorem

$$\frac{\Delta\omega}{\omega_0} = \phi = \frac{1}{Q}$$

Quality factor

$$D = \frac{E_{\text{total}}}{E_{\text{elastic}}} \approx \frac{k_{\text{gravity}}}{k_{\text{fibre}}} \approx 2L\sqrt{\frac{T}{YI}}$$

Dissipation dilution (in horizontal direction)

$$\phi_{\text{surface}} \approx \frac{8h\phi_s}{d}$$

$$\phi_{\text{TE}}(\omega) = \frac{YT}{\rho C}\left(\alpha - \sigma_o\frac{\beta}{Y}\right)^2\left(\frac{\omega\tau}{1+(\omega\tau)^2}\right)$$

$$\phi_{\text{weld}}(\omega) = 5.8\times10^{-7}$$

$$\tau_{circular} = \frac{\rho C d^2}{4.32\pi\kappa}$$

Dominant fibre loss terms (thermoelastic is minimised with appropriate fibre stress)

Other useful equations

$$f_{pendulum} = \frac{1}{2\pi}\sqrt{\frac{g}{L}}$$

$$f_{bounce} = \frac{1}{2\pi}\sqrt{\frac{YA}{mL}}$$

m=mass on 1 fibre

$$f_{free\_test\_mass} = \sqrt{2}\, f_{bounce}$$

$$I = \pi R^4/2$$

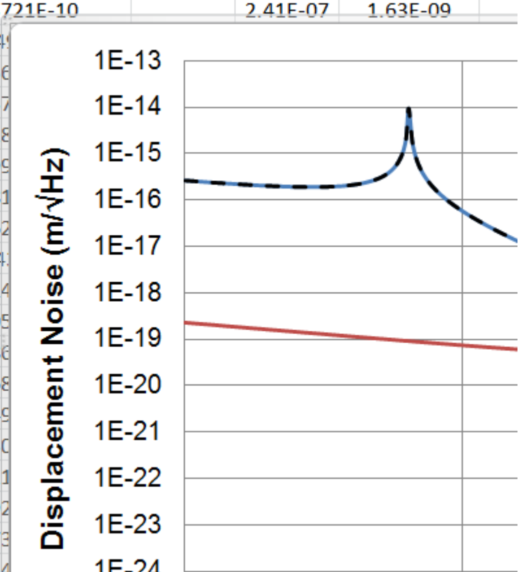
$$Y = \frac{\sigma}{\varepsilon}$$

$$\Delta L = \left[\frac{\sigma}{Y}\right]L$$

A Simple Model

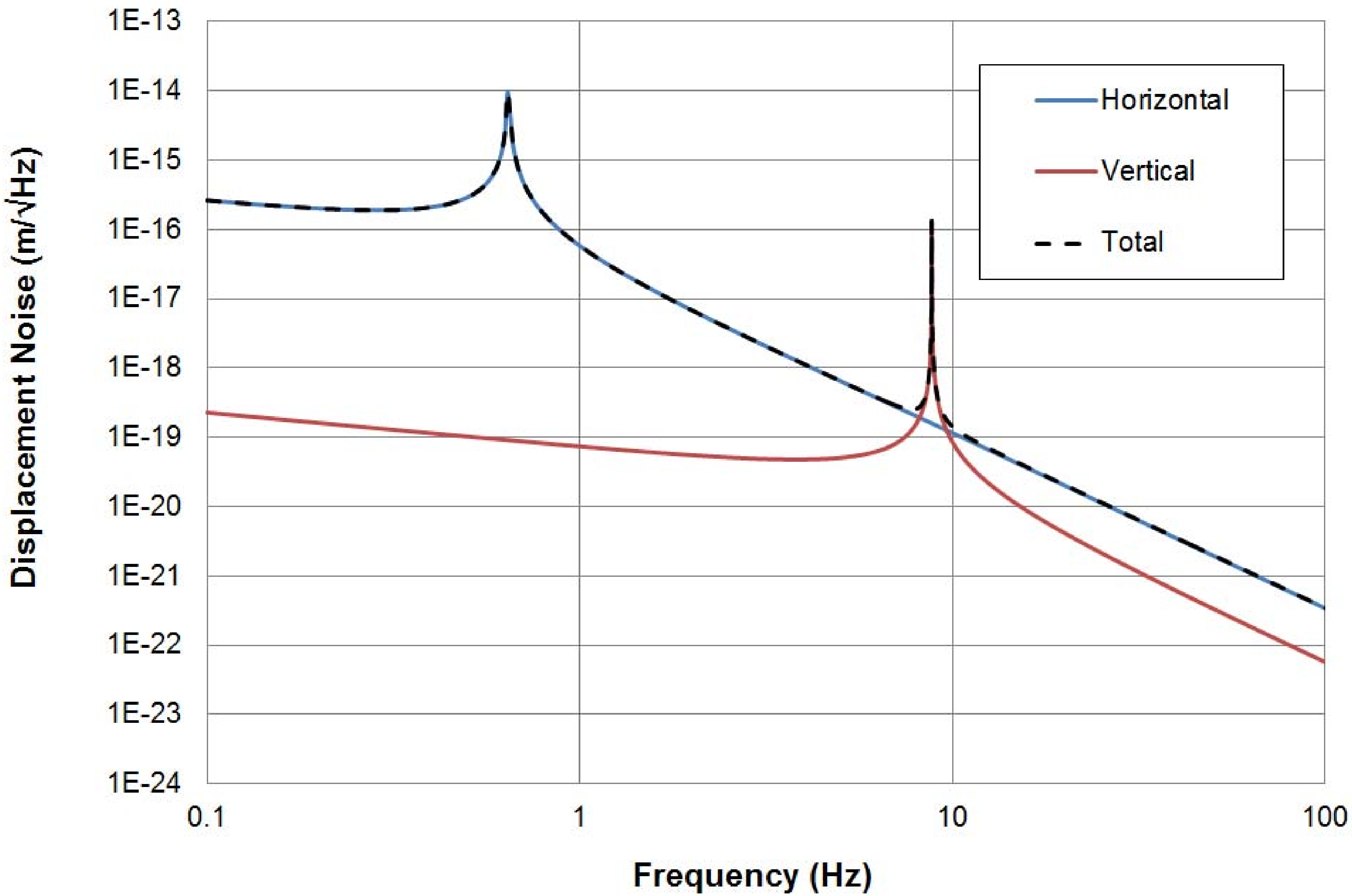
- Using the previous equations

A	B	C	D	E	F	G	H	I	J	K
mass	length	rthin	rend	fibre_area_thin	fibre_area_end	stress_thin	stress_end	T	Tension	I
40	0.6	2.00E-04	4.10E-04	1.26E-07	5.28E-07	7.81E+08	1.86E+08	300	98.1	2.21935E-14
C	K	alpha	beta	density	Y	h_phis	tau	1/tau		
740	1.4	3.00E-07	1.50E-04	2202	7.30E+10	6.00E-12	0.014416343	69.36572		
f_pendulum	f_bounce	f_violin	dilution	stretch	speed					
0.64354513	8.800875277	496.1804725	1.48E+02	0.006416342	595.416567					
w	f	pendulum	vertical	total		phi_surface	phi_thermoelastic		total loss	diluted loss
0.62831853	0.1	2.62724E-16	2.28E-19	2.62724E-16		2.40E-07	8.12487E-10		2.41E-07	1.63E-09
0.69115038	0.11	2.51849E-16	2.17E-19	2.51849E-16		2.40E-07	8.93721E-10		2.41E-07	1.63E-09
0.75398224	0.12	2.42555E-16	2.08E-19	2.42555E-16		2.40E-07	9.74			
0.81681409	0.13	2.34545E-16	2.00E-19	2.34545E-16		2.40E-07	1.056			
0.87964594	0.14	2.27598E-16	1.93E-19	2.27599E-16		2.40E-07	1.137			
0.9424778	0.15	2.21546E-16	1.86E-19	2.21547E-16		2.40E-07	1.218			
1.00530965	0.16	2.16259E-16	1.80E-19	2.16259E-16		2.40E-07	1.299			
1.0681415	0.17	2.11635E-16	1.75E-19	2.11635E-16		2.40E-07	1.381			
1.13097336	0.18	2.07593E-16	1.70E-19	2.07593E-16		2.40E-07	1.462			
1.19380521	0.19	2.04068E-16	1.66E-19	2.04068E-16		2.40E-07	1.54			
1.25663706	0.2	2.01008E-16	1.61E-19	2.01008E-16		2.40E-07	1.624			
1.31946891	0.21	1.9837E-16	1.58E-19	1.9837E-16		2.40E-07	1.705			
1.38230077	0.22	1.96121E-16	1.54E-19	1.96121E-16		2.40E-07	1.786			
1.44513262	0.23	1.94232E-16	1.51E-19	1.94232E-16		2.40E-07	1.868			
1.50796447	0.24	1.92681E-16	1.47E-19	1.92681E-16		2.40E-07	1.949			
1.57079633	0.25	1.91451E-16	1.45E-19	1.91451E-16		2.40E-07	2.030			
1.63362818	0.26	1.90528E-16	1.42E-19	1.90528E-16		2.40E-07	2.111			
1.69646003	0.27	1.89902E-16	1.39E-19	1.89902E-16		2.40E-07	2.192			
1.75929189	0.28	1.89566E-16	1.37E-19	1.89566E-16		2.40E-07	2.273			
1.82212374	0.29	1.89518E-16	1.34E-19	1.89518E-16		2.40E-07	2.354			

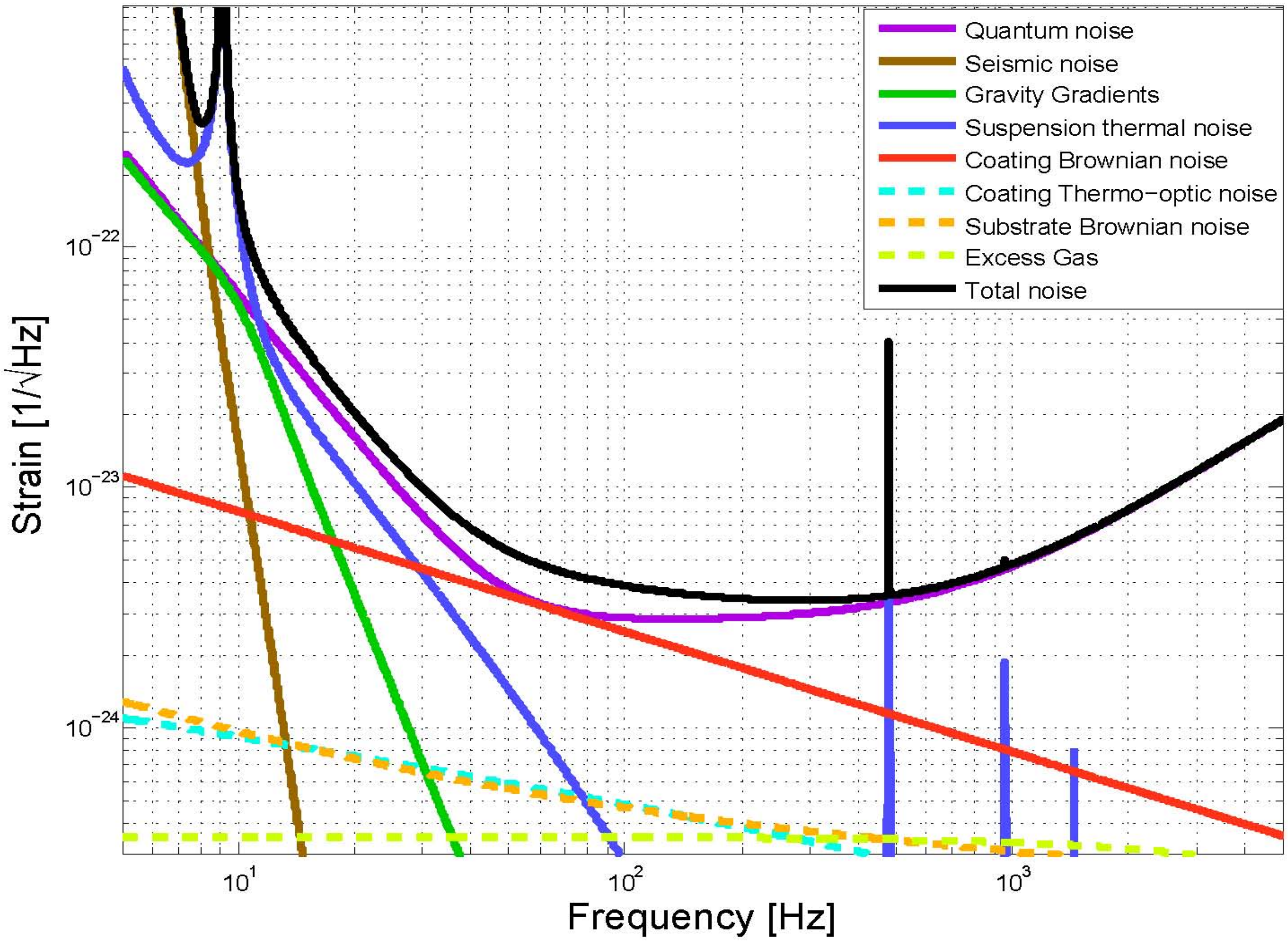


A Simple Model

- Using the previous equations

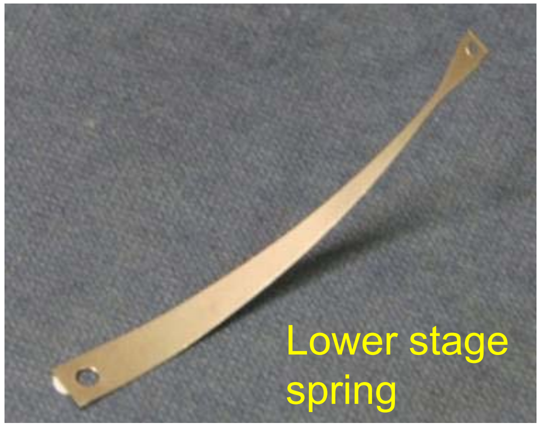


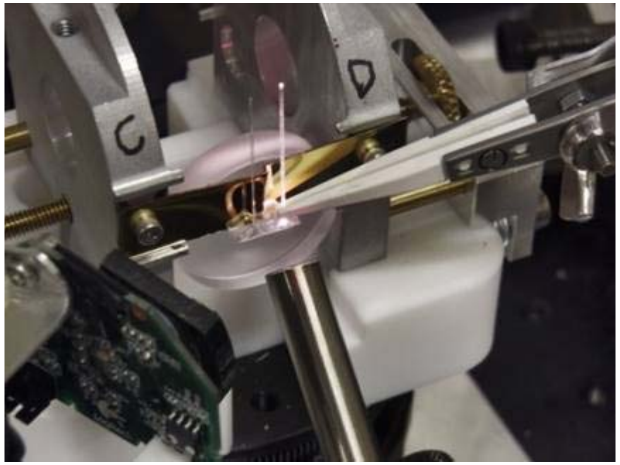
aLIGO Sensitivity



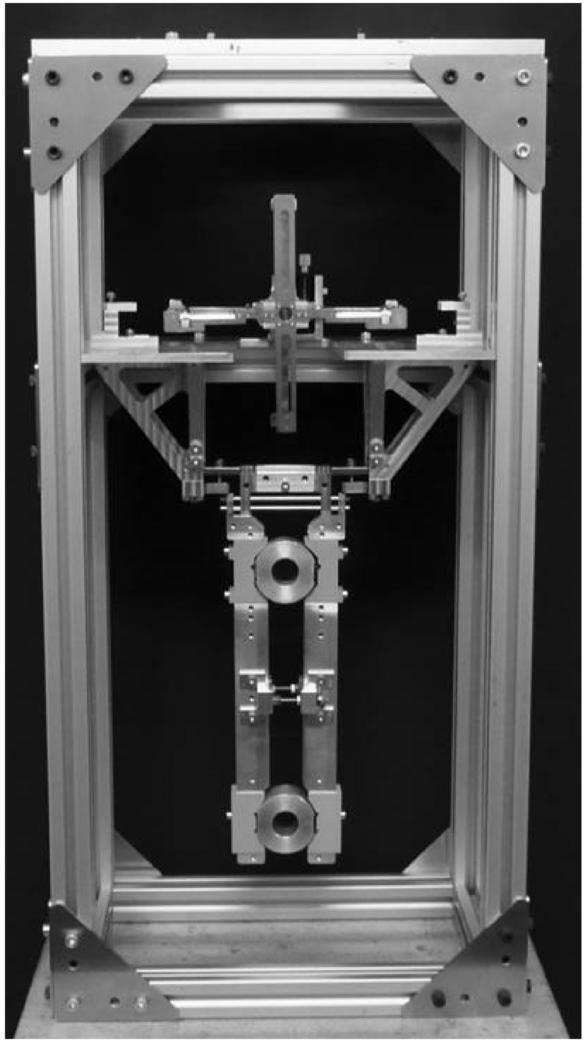
Thin Fibre Work

- Light suspensions (1g-100g) are being developed around the world for radiation pressure/SQL experiments (ICRR, MIT, Glasgow, AEI Hannover, Italy)
- Glasgow has developed triple suspensions for AEI



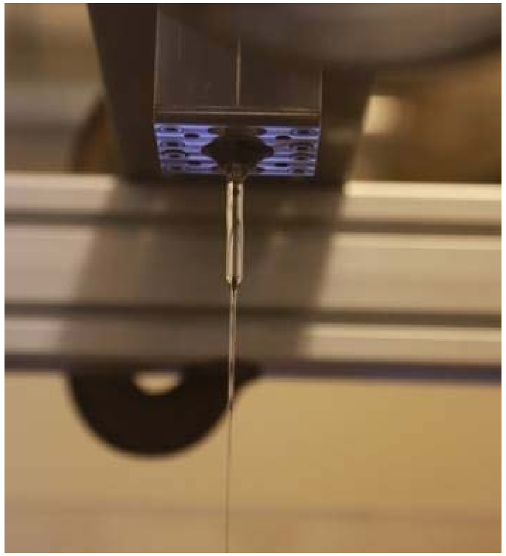


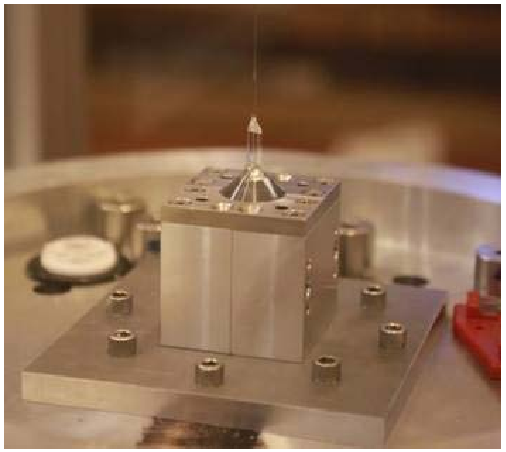
Welding



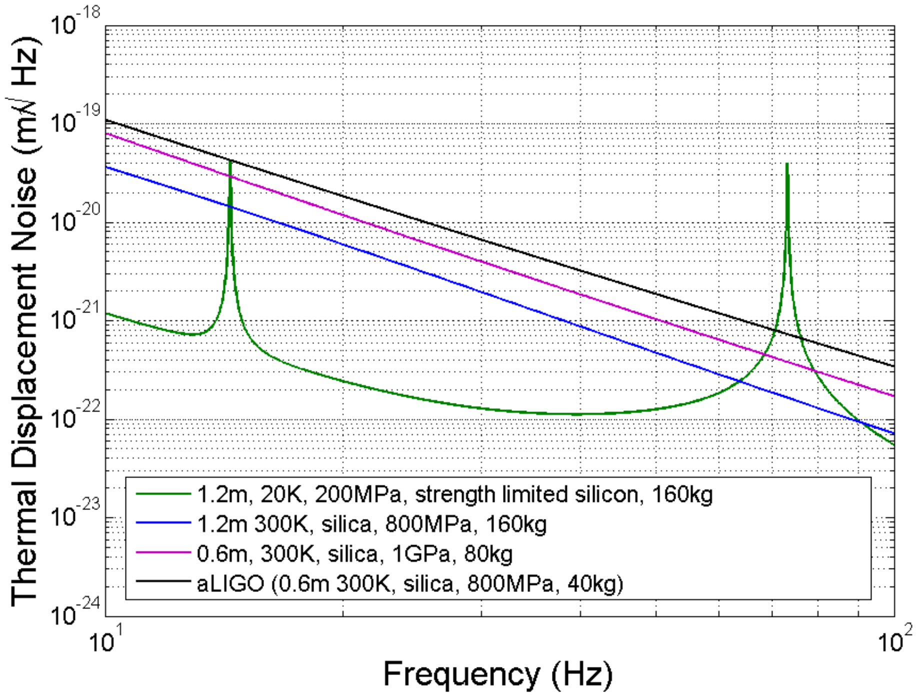
Heavy Suspensions

- We have already built up 2 single fibre 40kg tests (using 1200MPa fibre stress)
- Latest system been hanging since Dec 9th 2016
- 4 fibre (160kg) planned for late 2017





Cryogenic Suspensions



- Cryogenic suspensions operating at 120K/20K offer significant gains in sensitivity
- Silicon has a zero in its thermal expansion at these temperatures

Crystal growth machine (Glasgow)

KAGRA 23kg sapphire payload (R. Kumar)

- At 120K, use radiative cooling to remove heat
- At T<50K, need to use conduction through fibres

Summary

- Suspensions are a key component to provide:
  - Seismic isolation of the test masses
  - Low thermal noise operation
- aLIGO fused silica installation is a mature technology. This represents a well engineered robust design which is optimised for low thermal noise performance
- Good understanding of loss terms => high Q factors for violin modes
- Thin fibre work underway for suspending 100g/1g optics
- Further lowering thermal noise requires lower mechanical loss and/or low temperature operation
  - Heavy test masses and/or higher fibre stress
  - Cryogenic operation