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Suspensions

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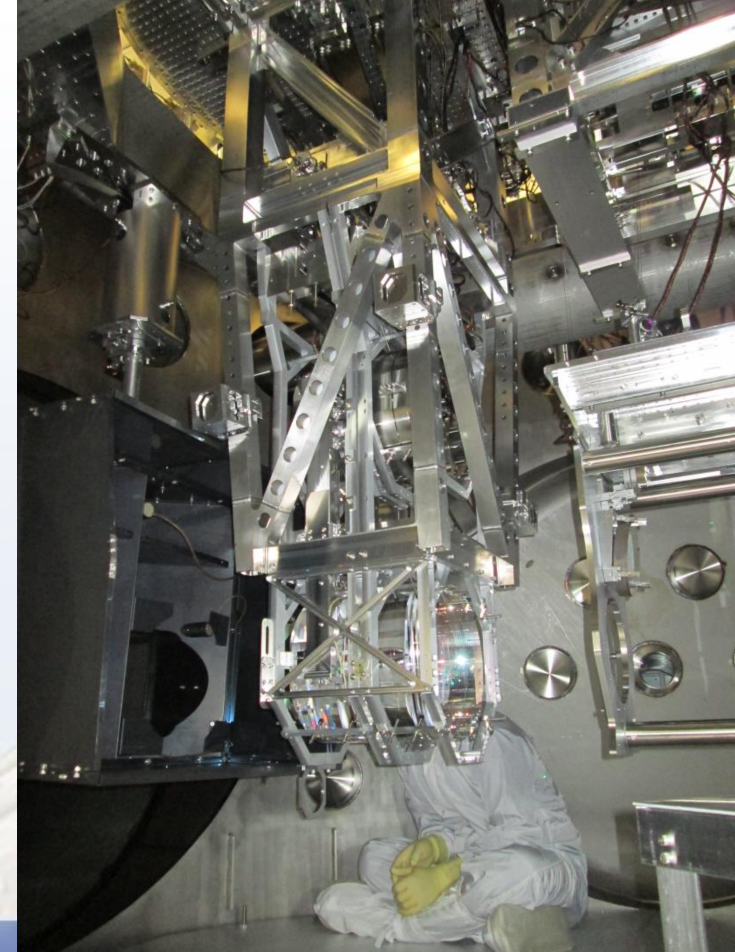

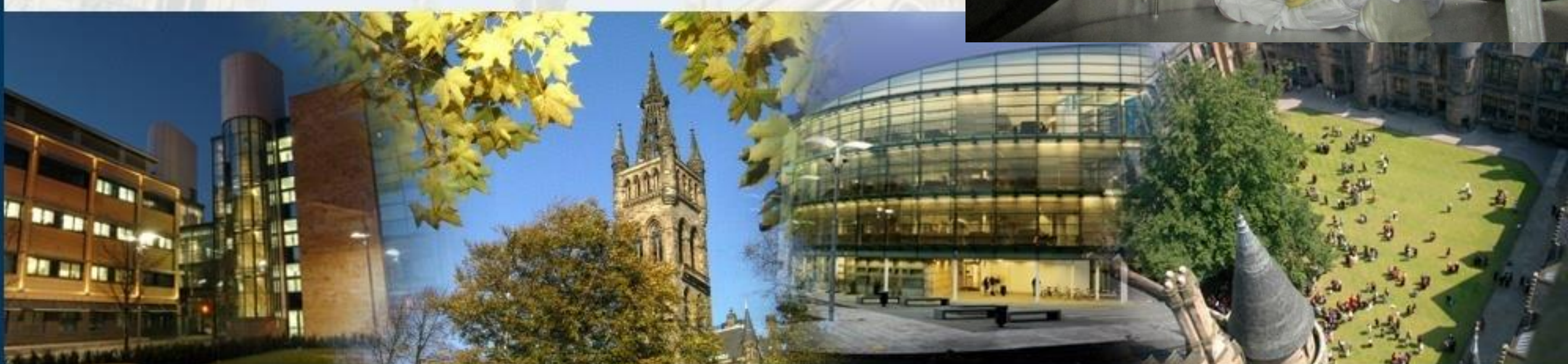

LIGO India Meeting, IUCAA, August 2016

A Team Effort

The Advanced LIGO Suspensions Team consists of more than sixty scientists, mechanical engineers, electronic engineers, designers, technicians and students from eight institutions.

USA

- **LIGO Caltech**: Jay Copti, Philip Croxton, Todd Etzel, Kate Gushwa, Jay Heefner, Alastair Heptonstall, Kristen Holtz, Tim McDonald, Gary McIntyre, Margot Phelps, Norna Robertson, Calum Torrie
- **LIGO Hanford Observatory:** Jeff Bartlett, Mark Barton, Betsy Bland, Doug Cook, Jeff Garcia, Jesse Garner, Gerardo Moreno, Gerardo Moreno Jnr., Jason Oberling, Andres Ramirez, Travis Sadecki, David Stone, Vern Sandberg
- **LIGO Livingston Observatory:** Carl Adams, Anna Aitken, Joe Betzwiezer, Derek Bridges, Virginia Brocato, Anamaria Effler (LSU) , Robert Giglio, Matt Heintze, Ed Merilh, Mike Meyer, Ralph Moffatt, Bobby Moore, Terry Pitre, Janeen Romie, Danny Sellers, Gary Traylor, Gene Winton
- **LIGO MIT:** Sam Barnum, Michael Hillard, Jeff Kissel, Rich Mittleman, Brett Shapiro

UK

- **University of Glasgow:** Angus Bell, Nicola Beveridge, Alan Cumming, Liam Cunningham, Giles Hammond, Jim Hough, Russell Jones, Rahul Kumar, Sheila Rowan, Ken Strain, Marielle Van Veggel
- **Rutherford Appleton Laboratory (RAL):** Justin Greenhalgh, Tim Hayler, Joe O'Dell, Ian Wilmut
- **University of Birmingham:** Stuart Aston (now LLO), Ludovico Carbone, Ron Cutler, Alberto Vecchio
- **Strathclyde University:** Nick Lockerbie, Kirill Tokmakov

Overview

- aLIGO suspensions and requirements
- Suspension construction/testing
- Lessons learned
- Suspension upgrades to aLIGO
- Thoughts for LIGO India
- …….
- Extra slides for discussion

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. baffles

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

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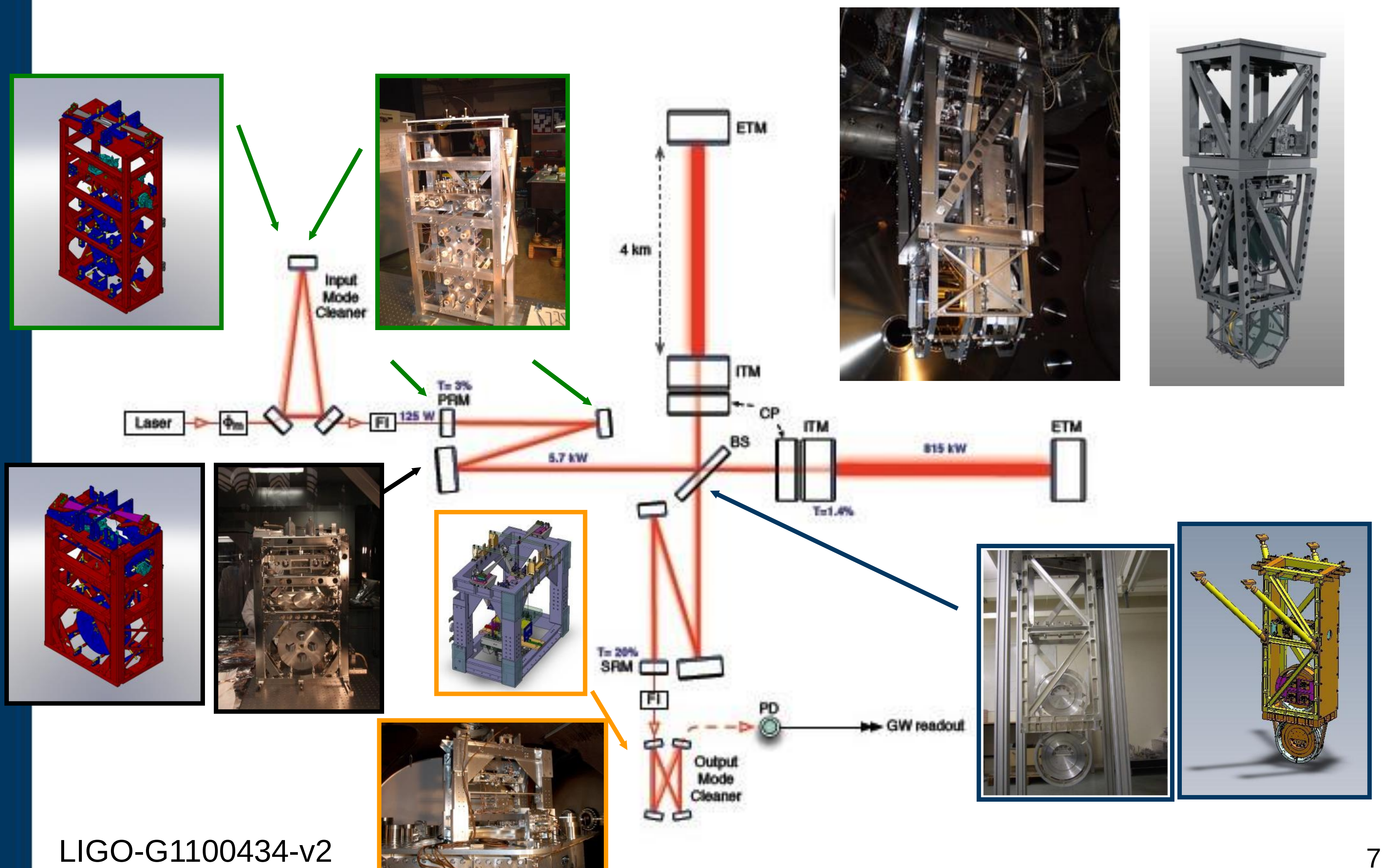
Requirements: Other Masses

In general, requirements are relaxed by two or more orders of magnitude compared to the test masses (End Test Mass/ETM, Input Test Mass/ITM)

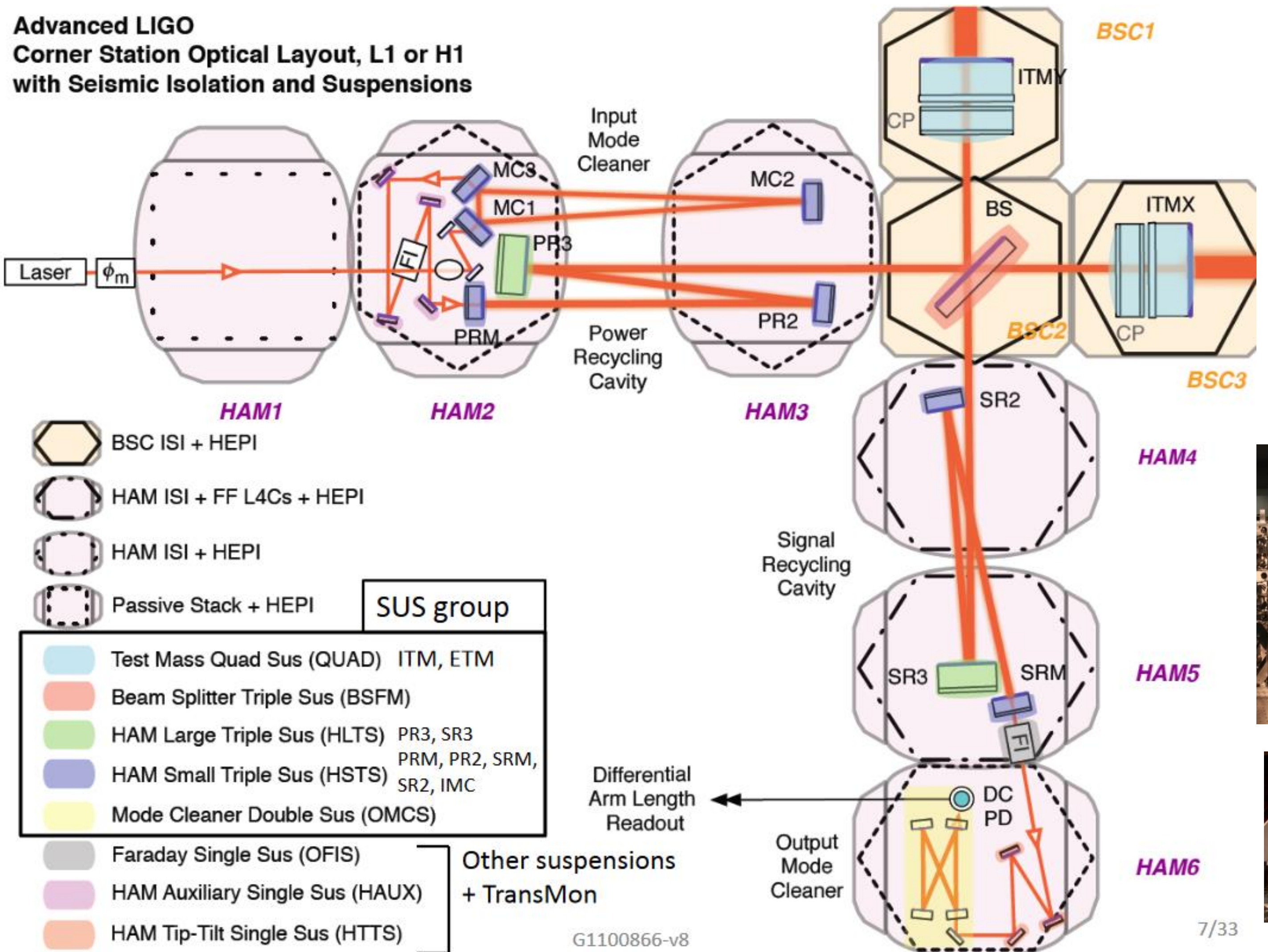
- Beamsplitter/Folding Mirror triple suspension (BS/FM):
  - 6.4×10^{-18} m/√Hz at 10 Hz
- HAM large triple suspension (HLTS):
  - 1×10^{-17} m/√Hz at 10 Hz
- HAM small triple suspension (HSTS):
  - 1×10^{-17} m/√Hz at 10 Hz when used in recycling cavities
  - 3×10^{-15} m/ √ Hz at 10 Hz when used in input modecleaner
- Output modecleaner double suspension (OMC SUS):
  - 10^{-13} m/ √ Hz at 10 Hz

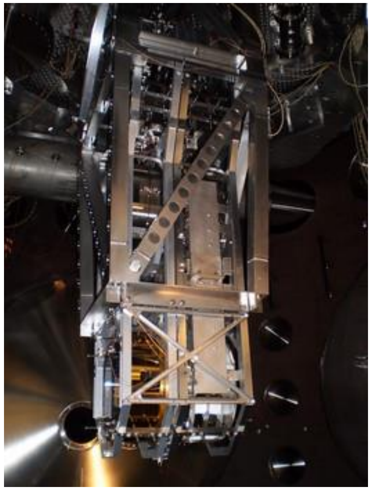
- BS/FM seismic noise is product of suspension transfer function and residual noise on the two-stage BSC-ISI seismic platform
- HLTS, HSTS and OMC seismic noise is product of suspension transfer function and residual noise on the one-stage HAM-ISI seismic platform
- The HLTS and HSTS requirements assume equal contributions from the 3 mirrors in the recycling cavities.

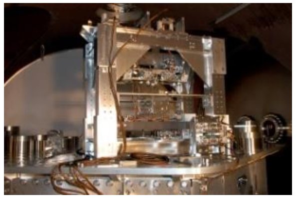
Suspensions in aLIGO



Suspension Inventory

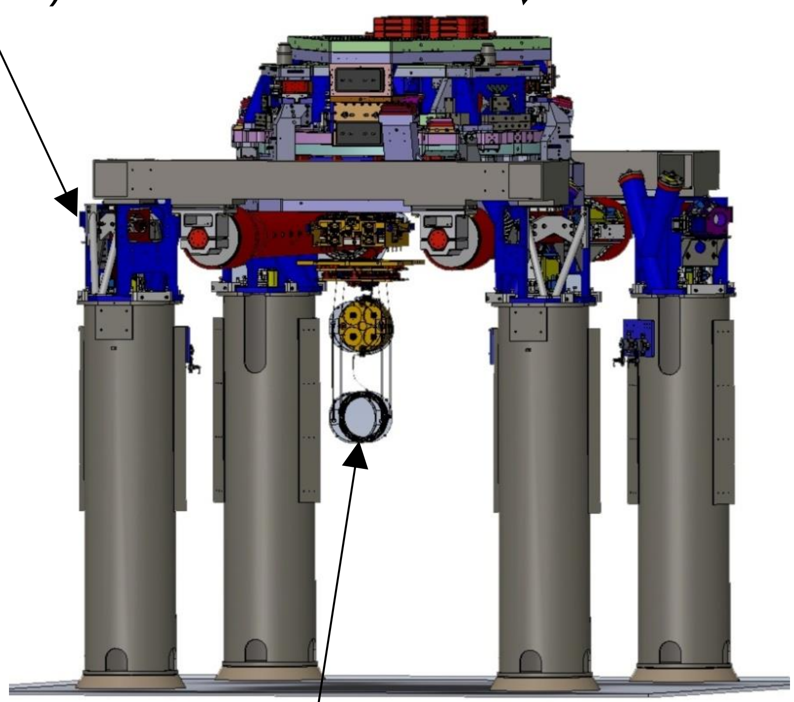




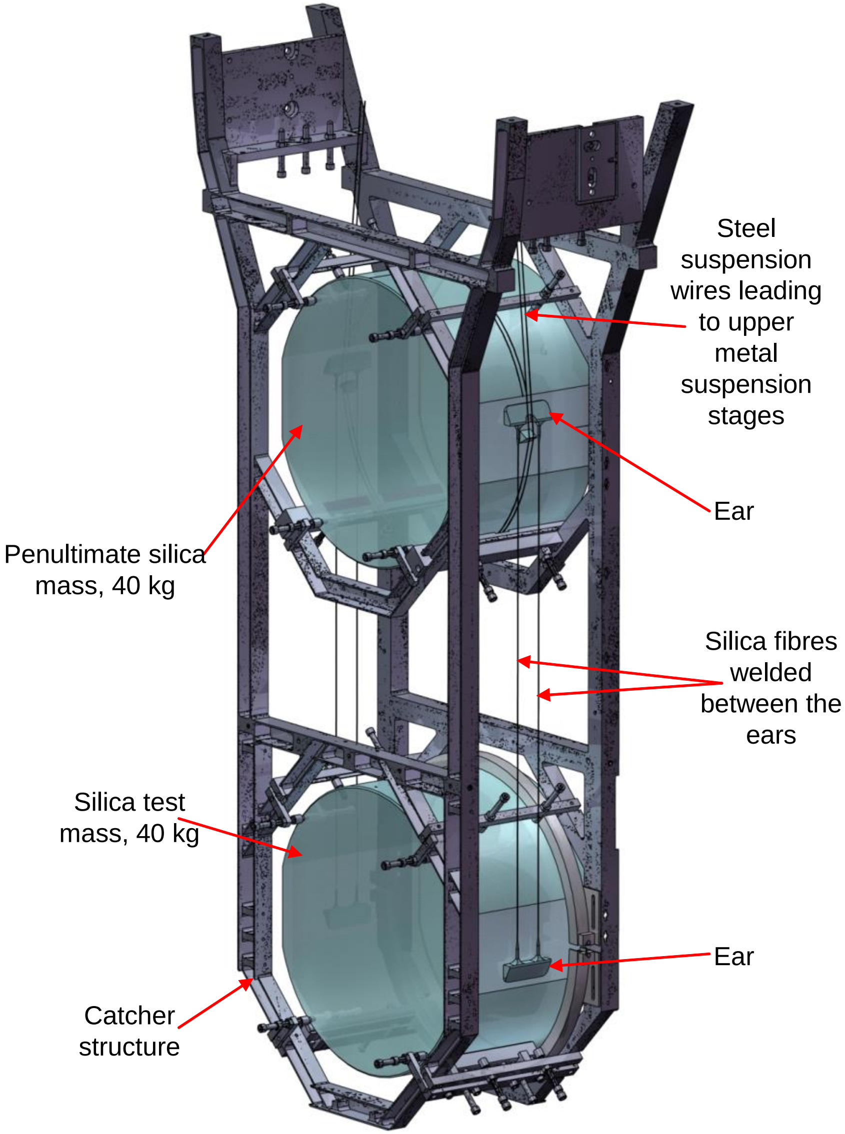


aLIGO ISI/SUS

- 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



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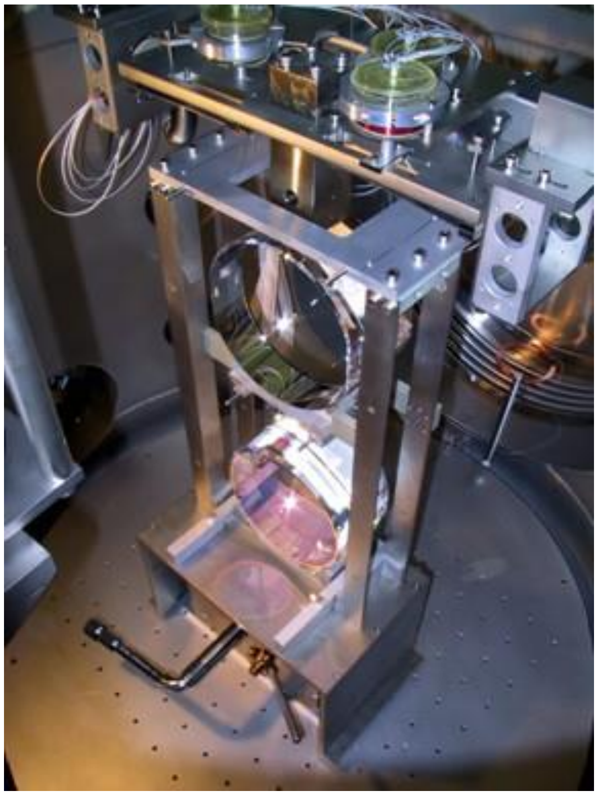
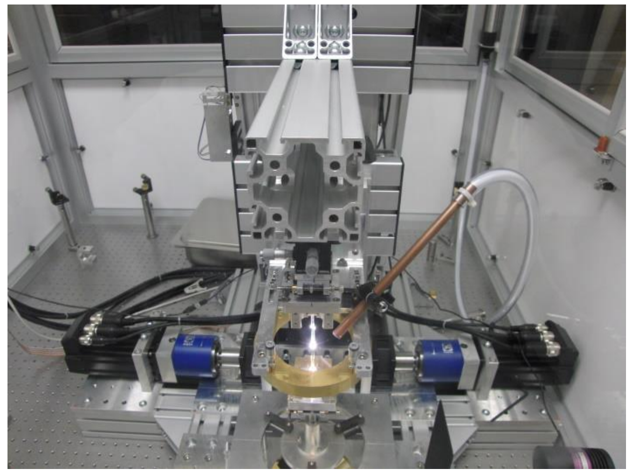
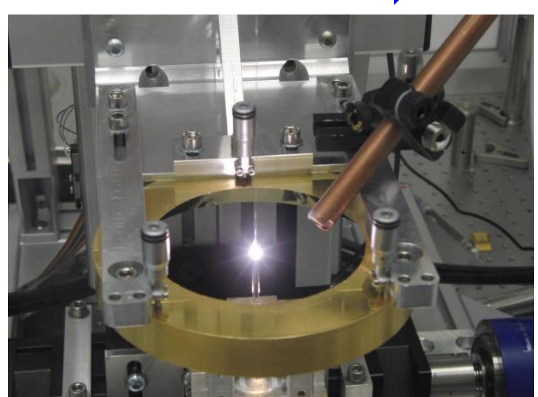
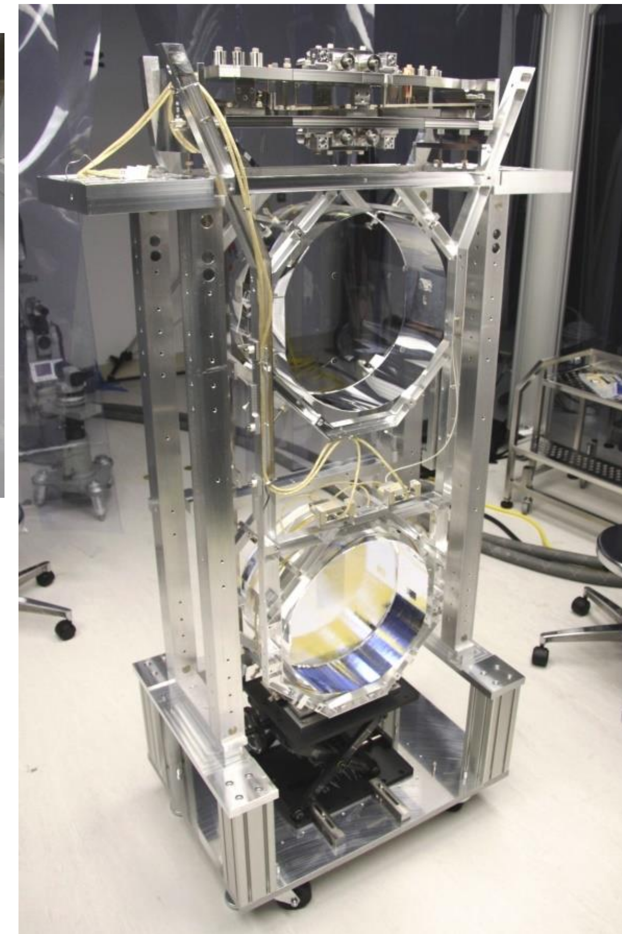
Monolithic Suspensions

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









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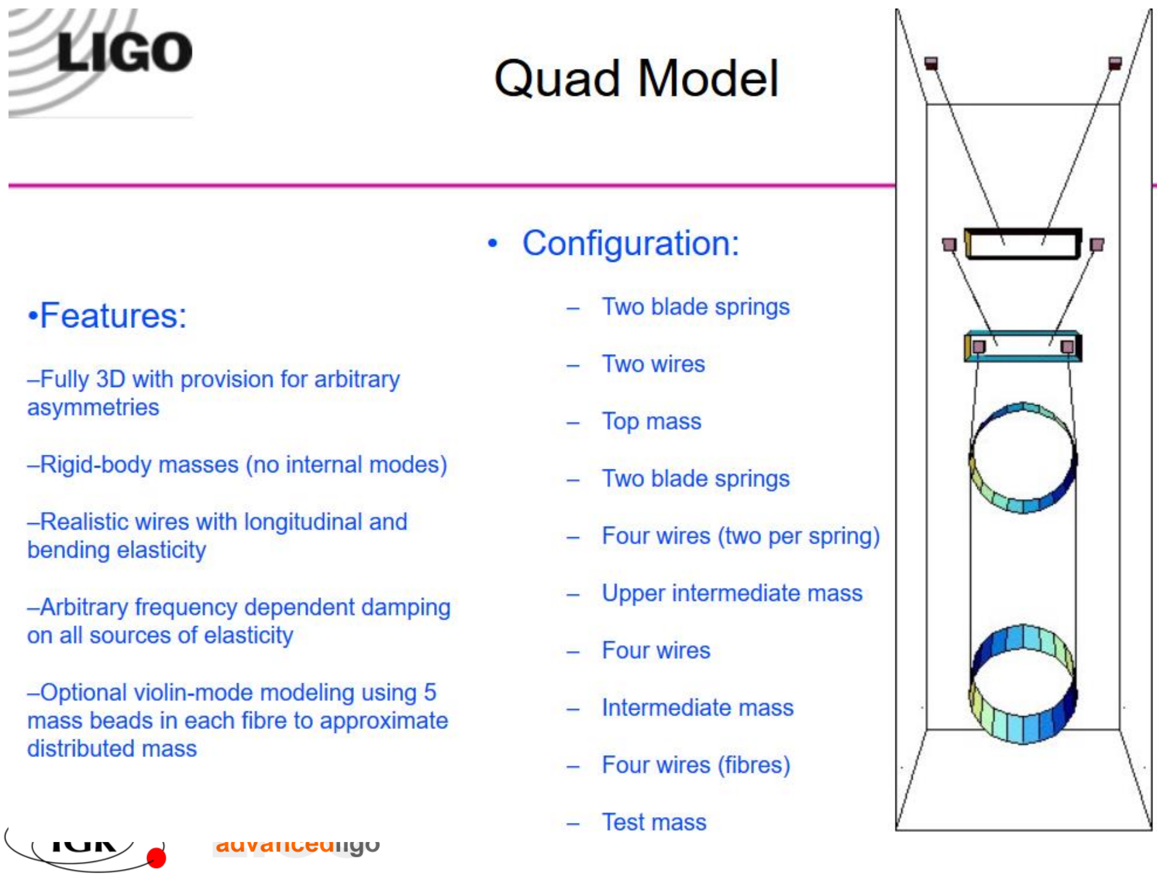
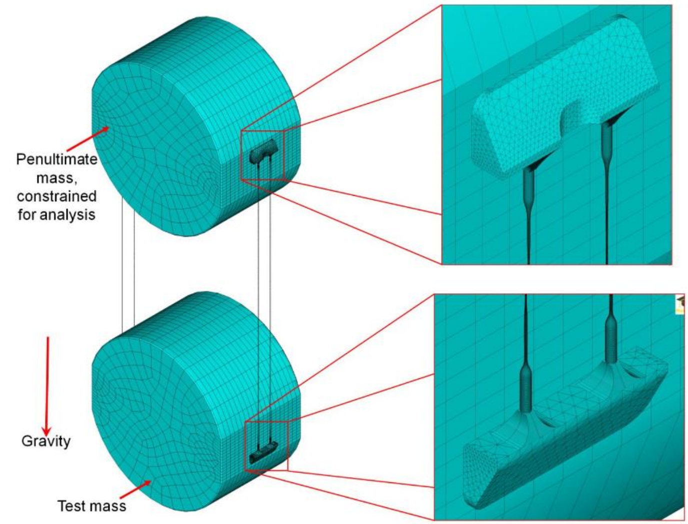
Suspension Models

- Mathematica: transfer functions, SS matrices, thermal noise, all suspensions (QUAD, HLTS, HSTS)
- https://labcit.ligo.caltech.edu/~e2e/SUSmodels/





- FEA: thermal noise, details of lower stage

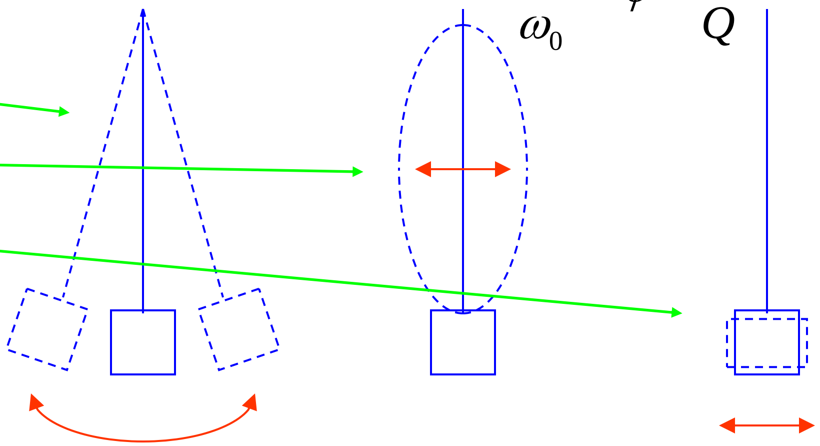
Thermal Noise

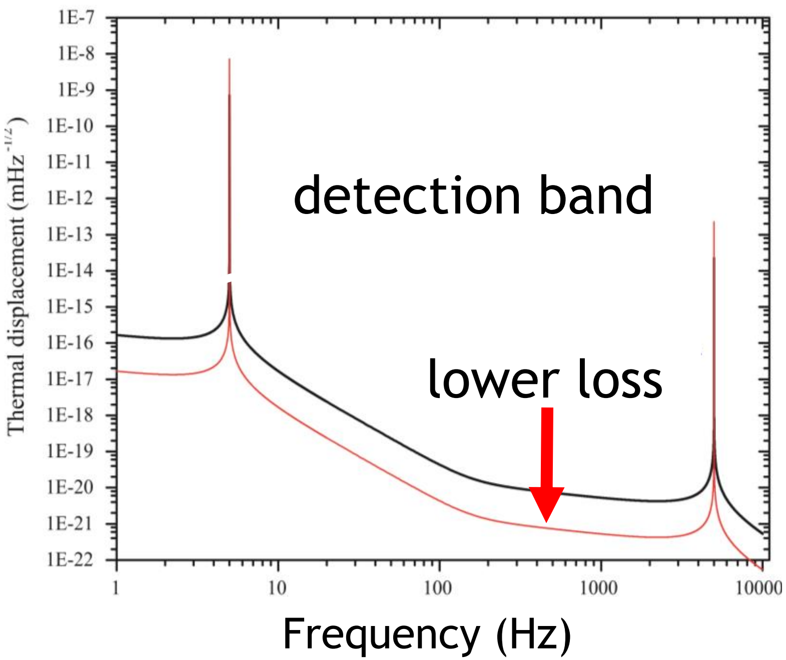
$$\frac{\Delta\omega}{\omega_0} = \phi = \frac{1}{Q}$$

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





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

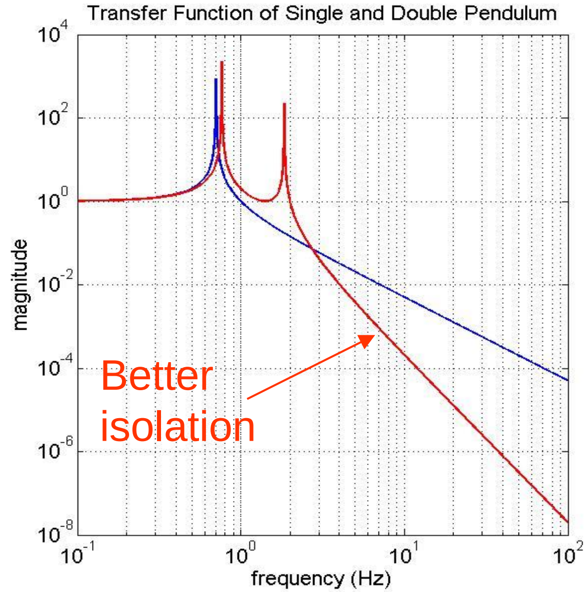
– many orders of magnitude above target noise level

Solution - multiple stages of isolation

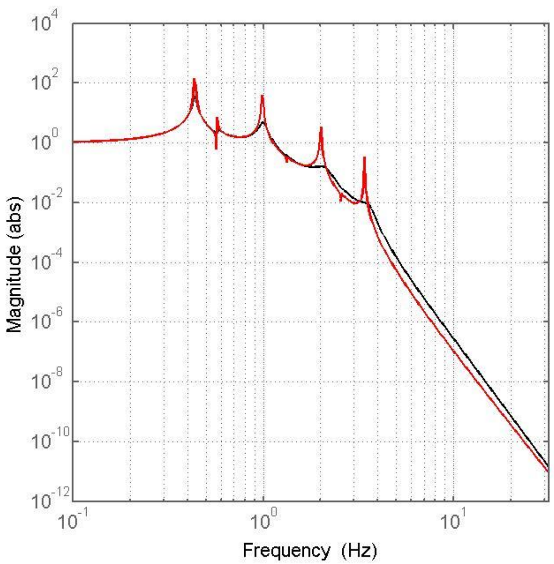
Isolation required in vertical direction as well as horizontal due to cross-coupling

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 double over single pendulum, same overall length
- Initial LIGO used a single stage wire suspension



- Quadruple pendulum transfer function: predicted longitudinal isolation ~ 3 x 10^{-7} at 10 Hz

Seismic Noise

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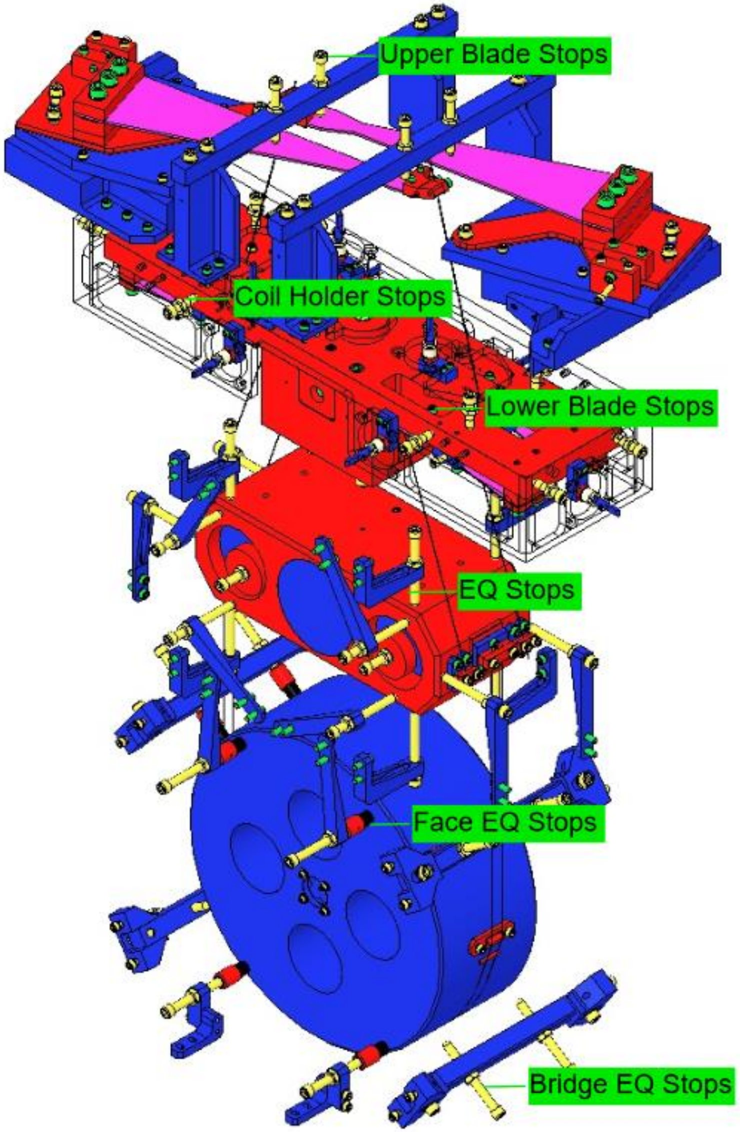

HLTS model

Origins 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

aLIGO Quadruple Suspension

We will look at the QUAD, but same concepts apply for the triples/doubles (except no reaction chain and fewer isolation stages)

- **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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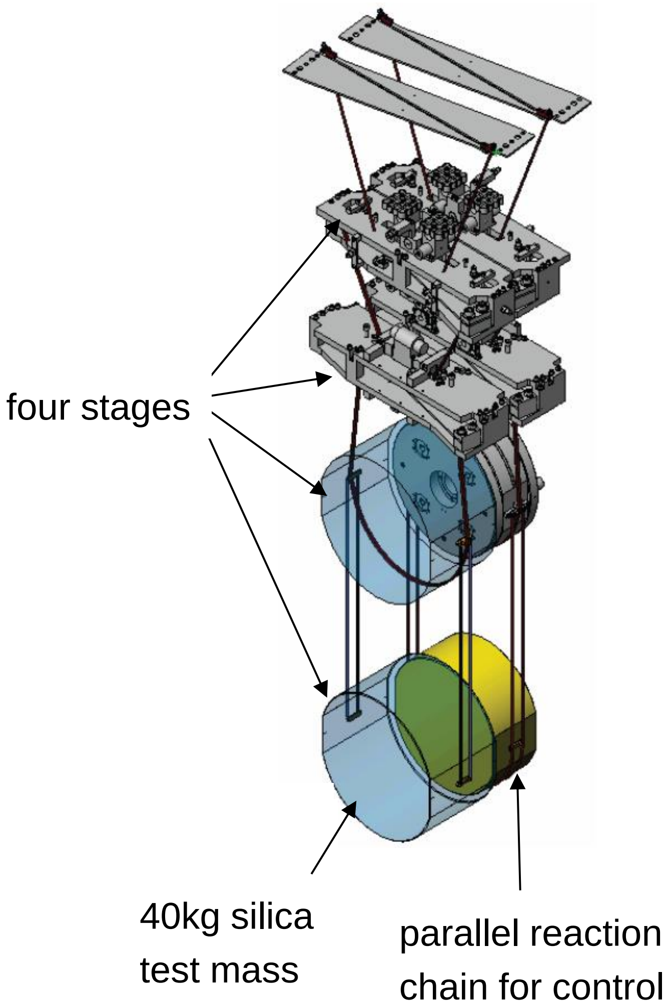
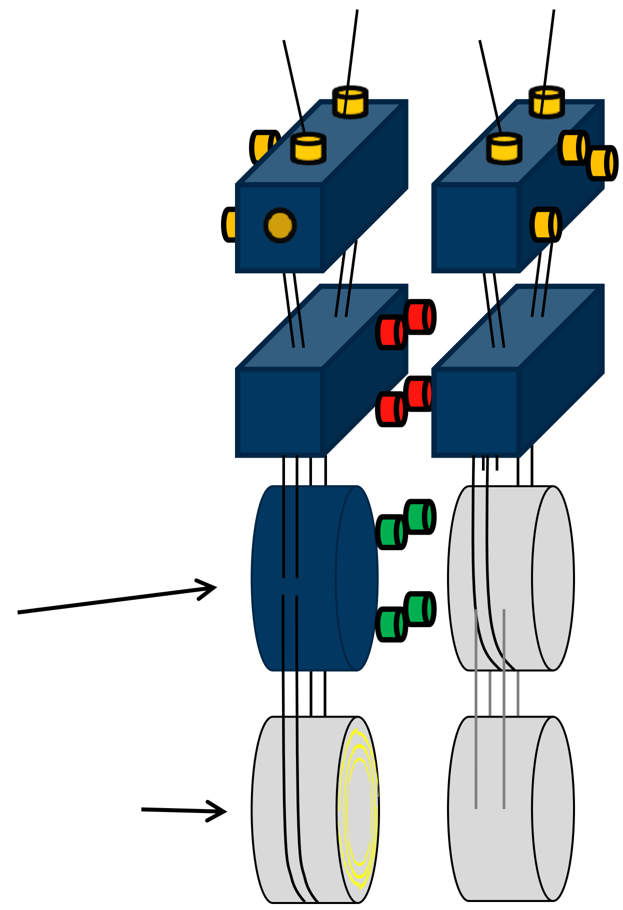


Local and Global Control

- 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

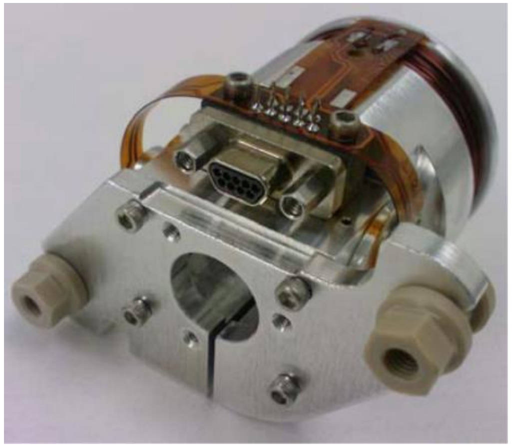
- Reaction Chain
- Main (test) Chain

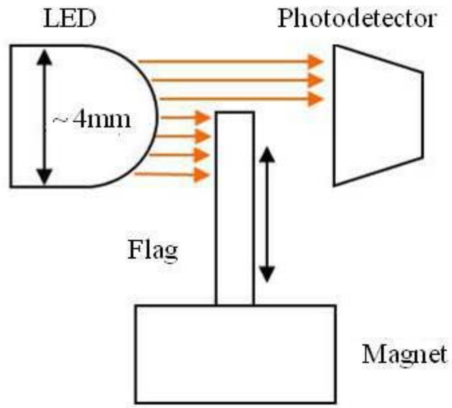


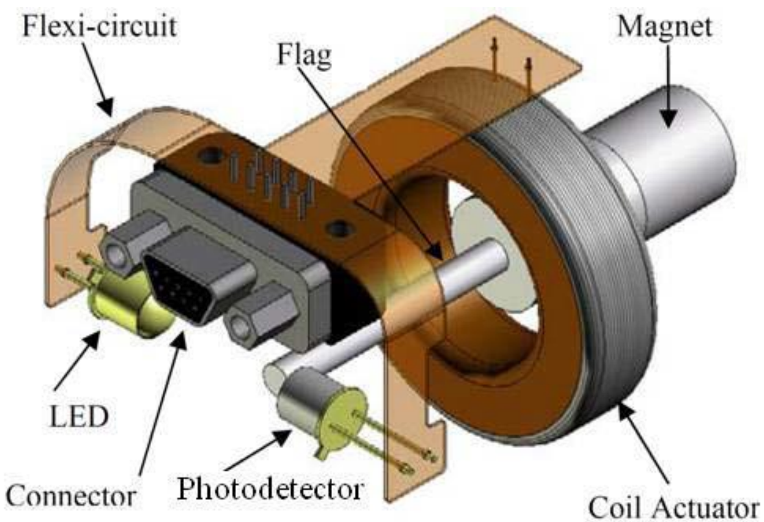
•*BOSEM = Birmingham Optical Sensor/Electromagnetic Actuator

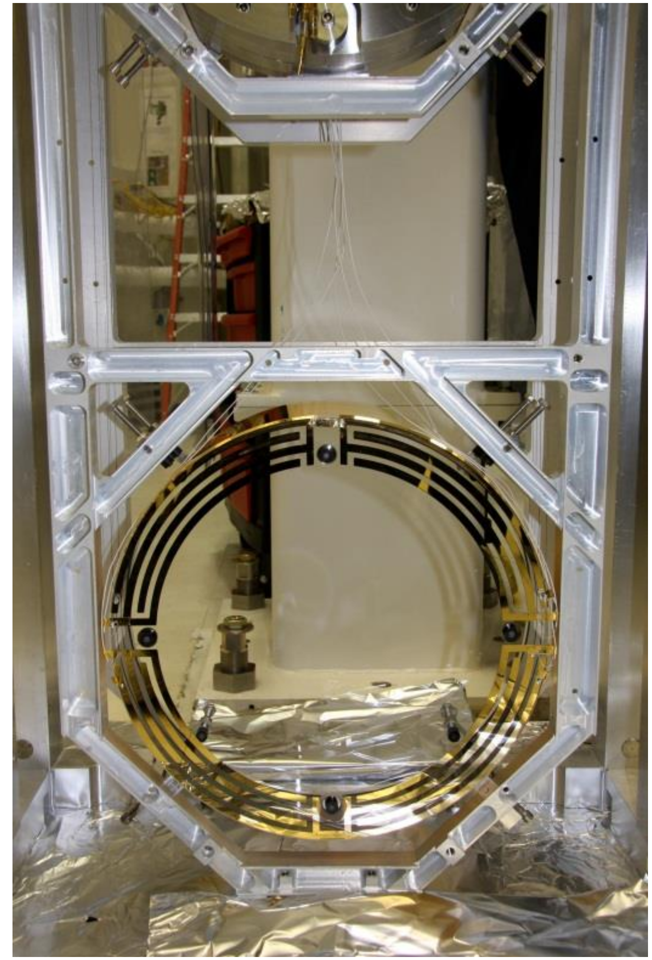
•*AOSEM = ALIGO OSEM = modified initial LIGO OSEM

Sensors/Actuators



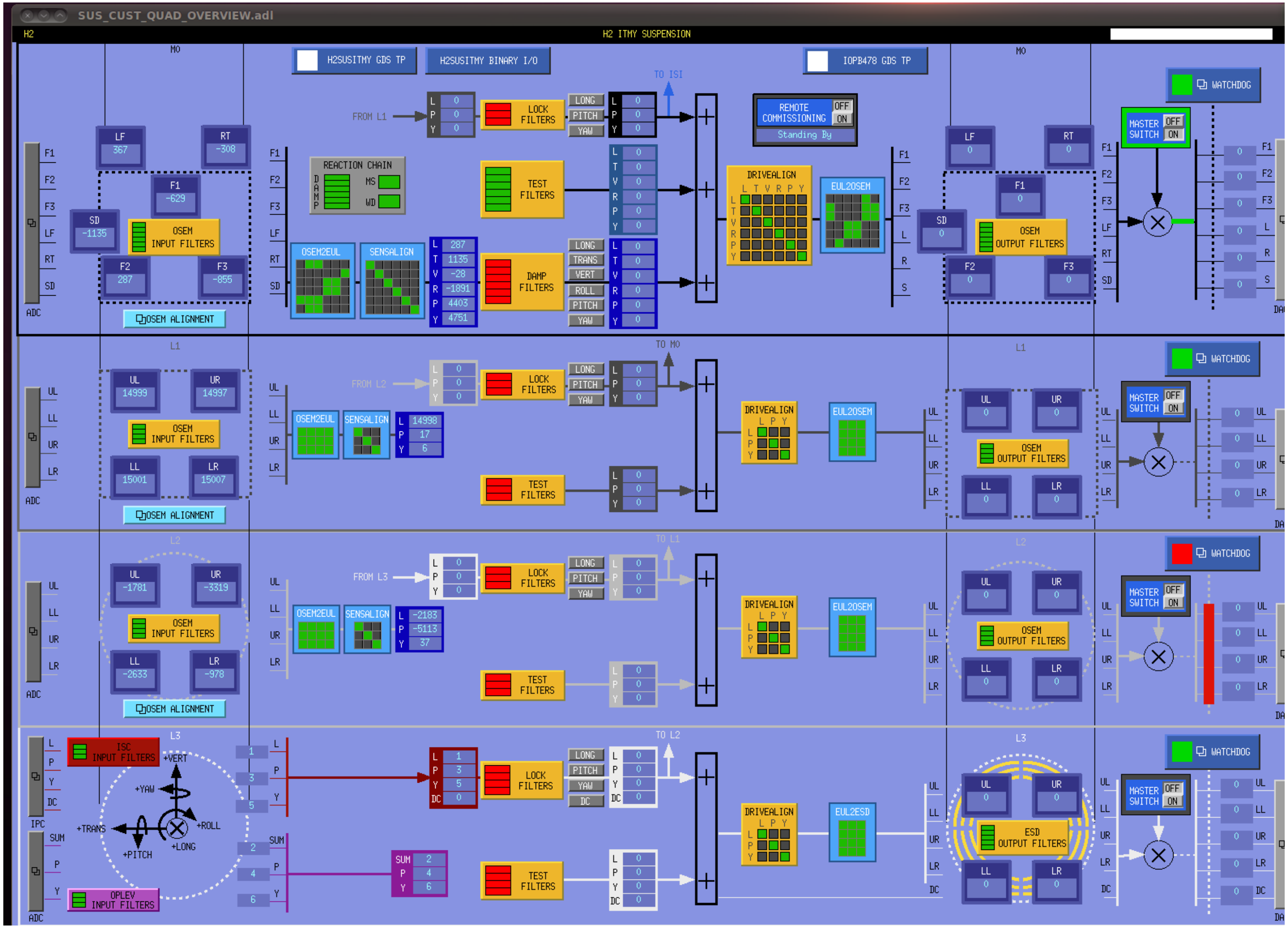




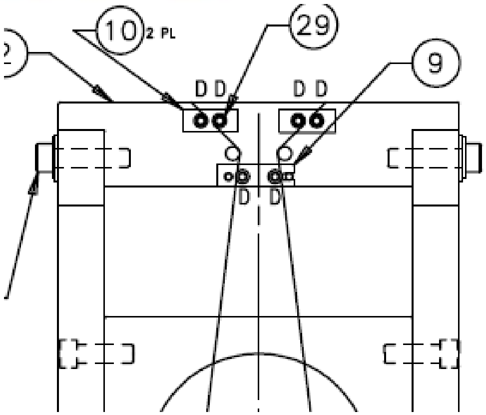


aLIGO ESD

Similar Control Structure to ISI



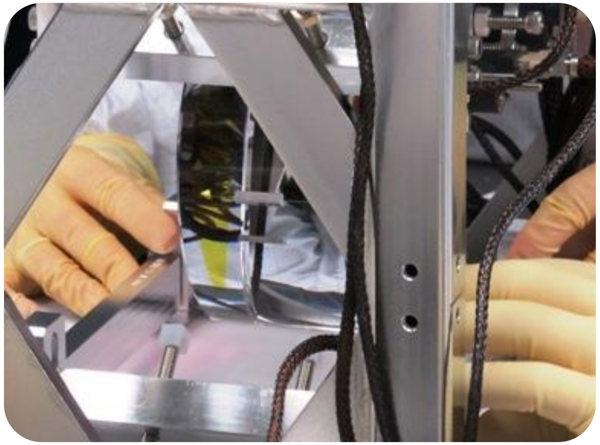
Suspension Construction (all)



- Drawings, installation routines

- Fabrication metal parts

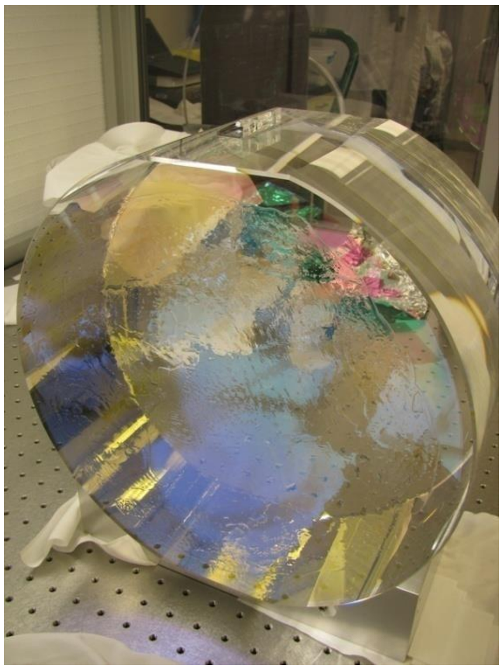
- Metal build

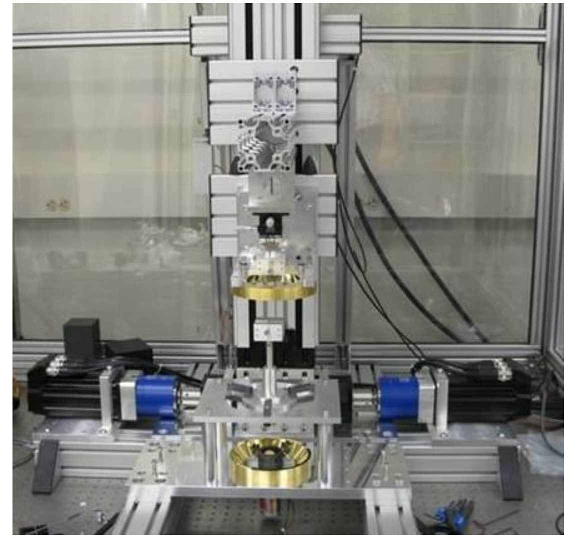


- Cabling

Suspension Construction (QUADs)

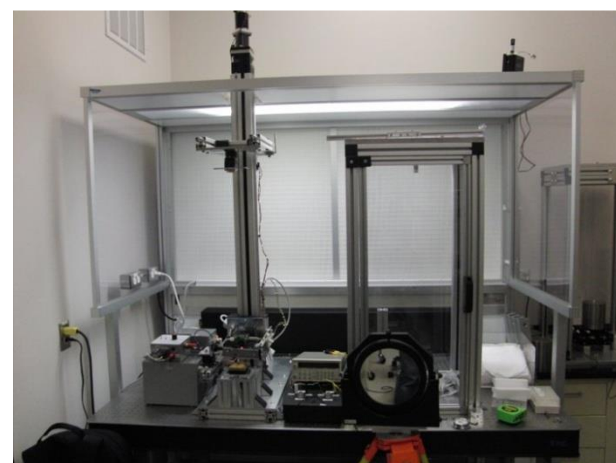
Hydroxide catalysis bonding of the ears



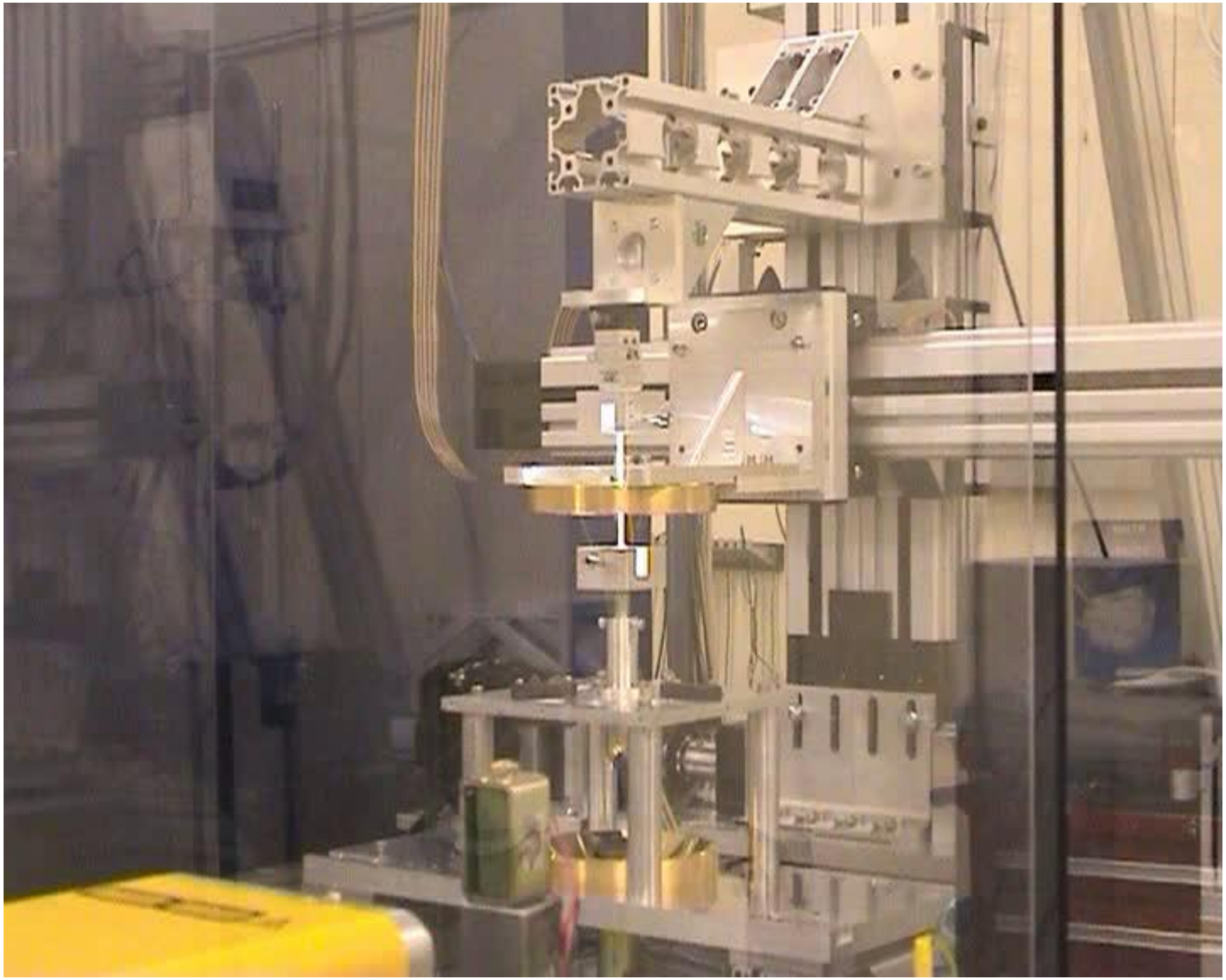


- Fibre pulling with CO_2 laser

- Fibre profiling for importing into Finite Element Analysis



Laser Pulling



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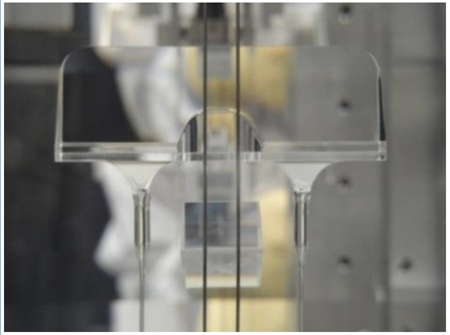
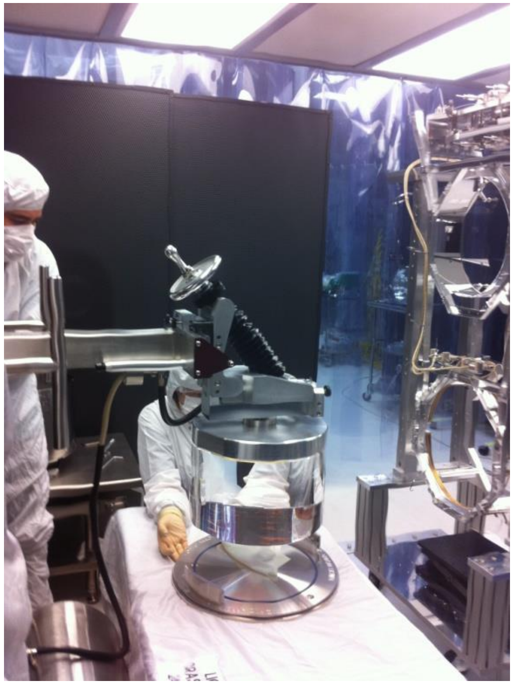
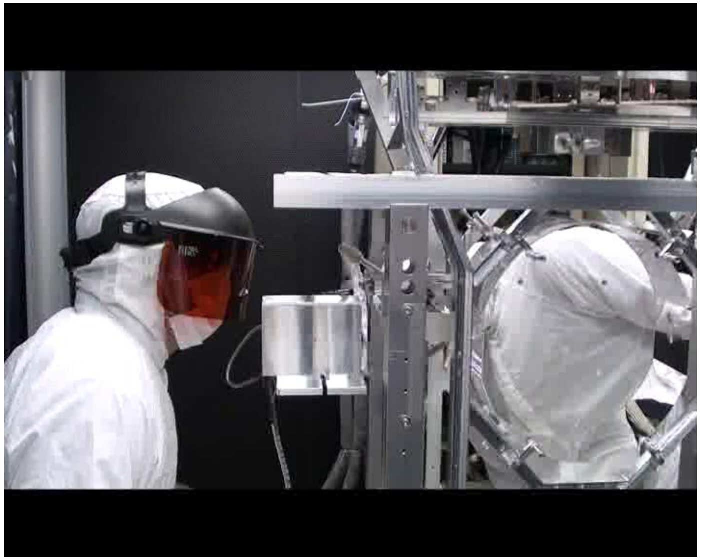
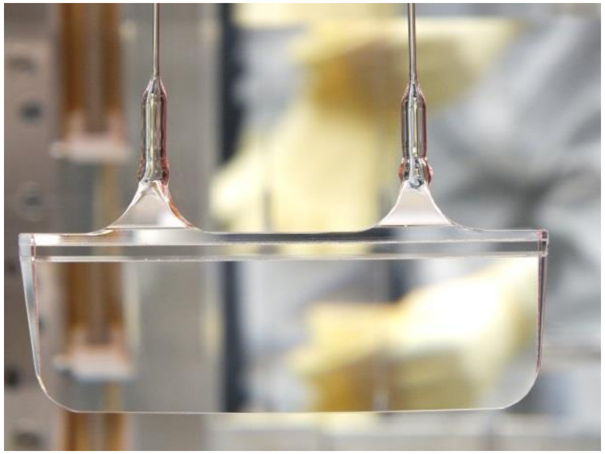
Monolithic Suspension Construction









- Alignment with:
  - autocollimator (±10urad)
  - scale (±0.1mm)

- Weld 8 fibres at penultimate and test masses
- De-stress welds (to set pitch angle)
- Hang

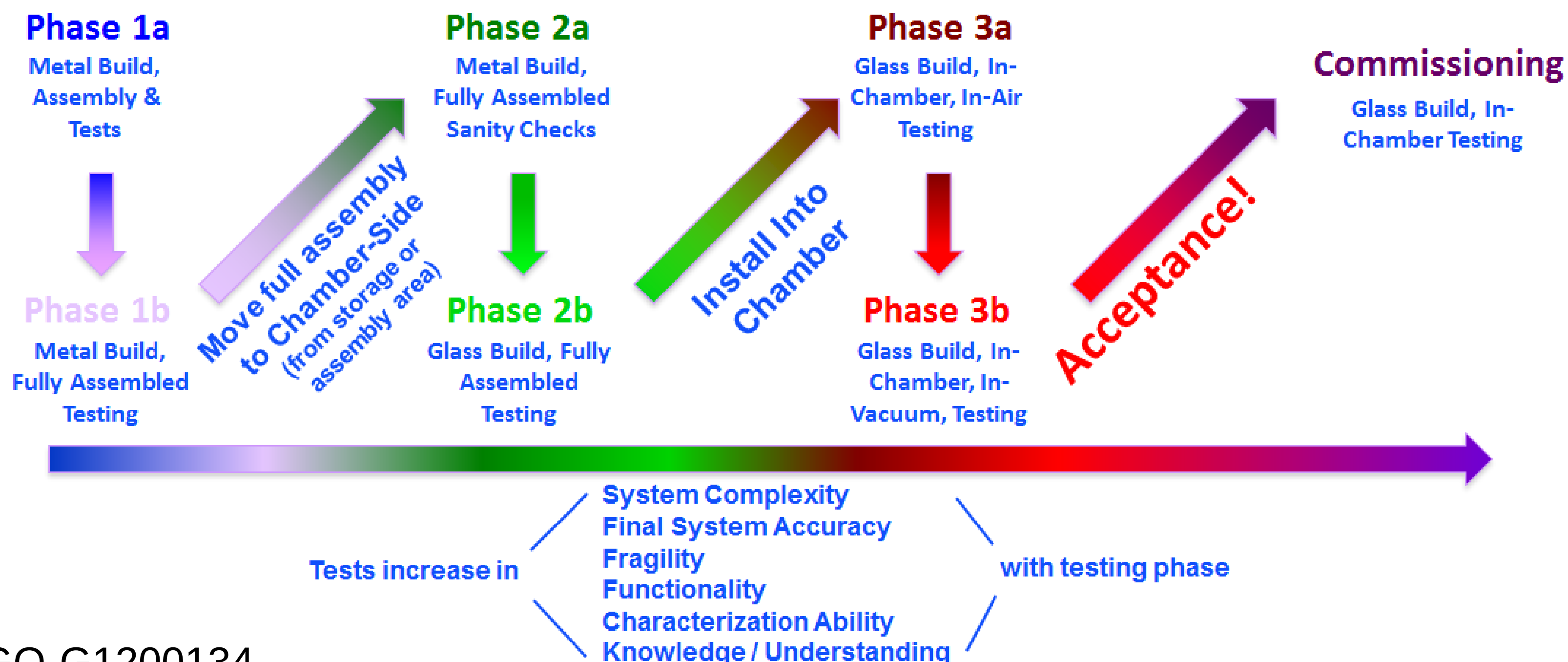
Suspension testing

- Learn as much as you can about the system(s), as early as possible
- In aLIGO, “**assembly**” and “**testing**” were heavily integrated
- Test “procedures” must fluid and flexible to account for development / new understanding / surrounding changes (schedule and infrastructure)

Driving Principles:

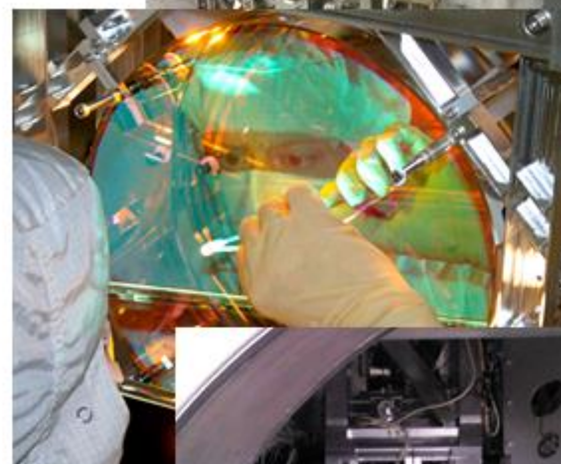
- Learn as much as you can, as early as possible
- “Assembly” and “Testing” are synonomous
- Test simple cases first

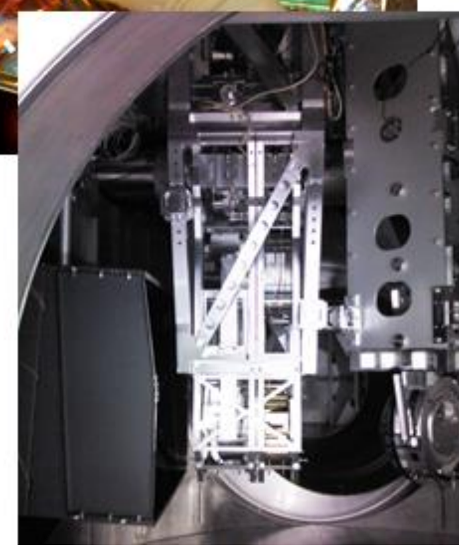
⇒ All lead naturally to a **phased approach** to assembly and testing:



LIGO

Testing and Commissioning
A Phased Approach





- **Phase 1** Sub Assy and Upper Stage Mechanical Characterization
  - Pretest and sanity check sub-assemblies
  - Test mechanical assembly / alignment / suspension of upper stages
  - Test sensors, actuators, and cabling of upper stages with test electronics
  - Test ability to control from TOP stage

- **Phase 2** Semi-final Configuration, Pre-install Characterization
  - Test Glass assembly / alignment / suspension of all stages
  - Checkout sensors, actuators, and cabling of all stages
  - Test final digital and analog electronics
  - Test lower stage actuators

- **Phase 3** Final, As-installed Characterization
  - Test as installed alignment / suspension of all stages
  - Test system interactions
  - Final checkout of sensors, actuators, and cabling

Testing Logs

DCC

Home Reserve Number Search Recent Changes Topics Events Public Help

aLIGO SUS QUAD Testing and Commissioning Documentation

Document #:
LIGO-E1000495-x0 (Public)
LIGO-E1000495-x0 (Private)
Document type:
E - Engineering documents
Submitted by:
Derek Bridges
Updated by:
Betsy Weaver
Document Created:
01 Oct 2010, 11:13
Contents Revised:
01 Oct 2010, 11:13
Metadata Revised:
13 Jan 2016, 10:23

Watch Document

Abstract:
This is a compilation of documents related to testing and commissioning of the Quad Suspensions for Advanced LIGO.

Files in Document:
None

Topics:
- Commissioning
- Subsystem Test
- Assembly
- Suspensions

Authors:
- Derek Bridges
- Mark Barton
- Robert Lane

Keywords:
SUS quad testing commissioning

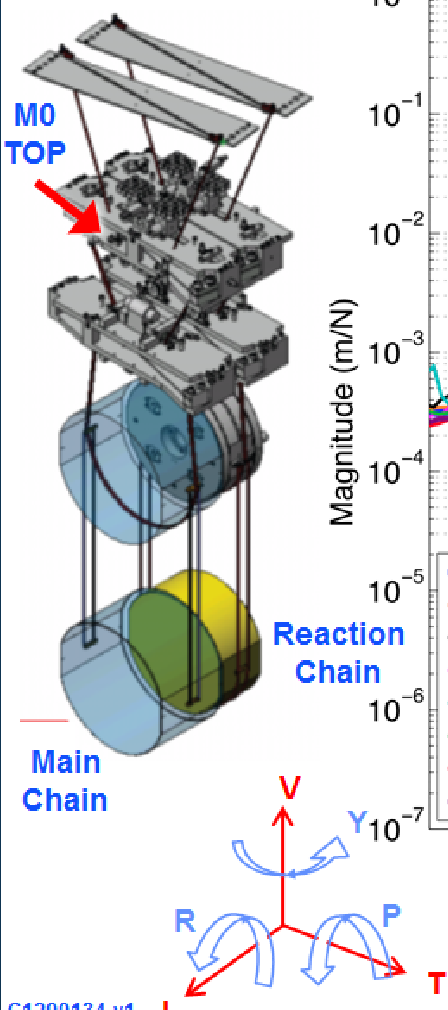
Notes and Changes:
An "Electronics Testing Reports" branch has been added for test results and reports that are not specific to a particular Quad.

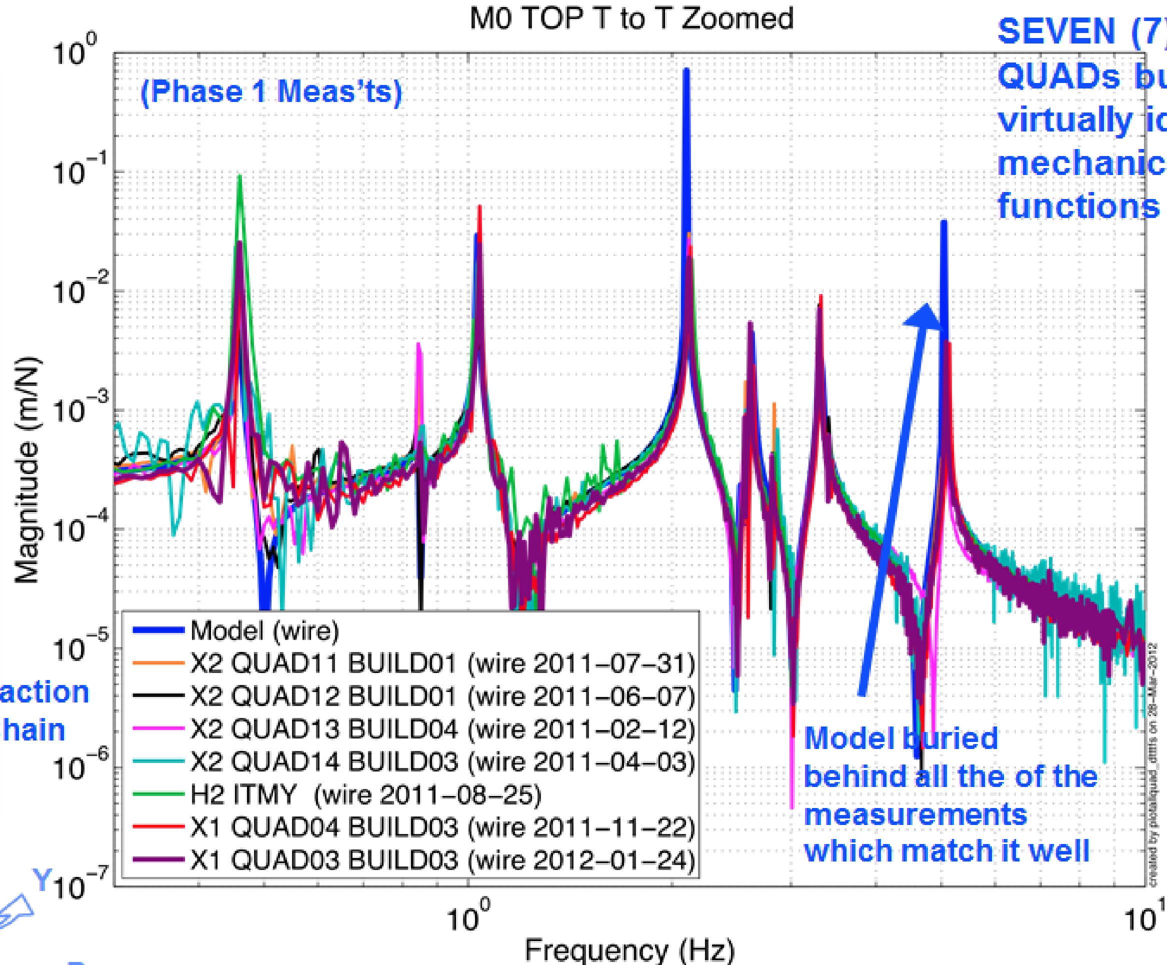
To find info on predicted resonances for the quad suspensions, go to the SUS Operations Manual at
https://awiki.ligo-wa.caltech.edu/aLIGO/Suspensions/OpsManual
and look in the "Table of Contents" under "Resonances".

Related Documents:
- LIGO-G1100769: QUAD Testing Outline, Phase 2B
- LIGO-E1101049: aLIGO SUS Quad Suspension Fibre Test Reports
- LIGO-F1000008: Quad Suspension Assembly Process Traveler Template
- LIGO-E1000516: aLIGO SUS Quad Suspension Assembly Process Travelers
- LIGO-E1000617: Quad Suspension Controls Arrangement Poster
- LIGO-E1000167: Advanced LIGO Quad Suspension Glass Mass Preparation Procedure
- LIGO-E1000366: QUAD Monolithic Fiber Pulling/Welding Procedure (Approved)
- LIGO-E1000277: Preparation of an end or input penultimate mass (ETM-PM/ITM-PM) (Hydroxide-Catalysis Bonding of ears and gluing prisms and magnet flags)
- LIGO-E1000278: Preparation of an end or input test mass (ETM/ITM) (Hydroxide-Catalysis Bonding of ears)
- LIGO-F1000013: Ear quality control sheets
- LIGO-G1100693: Ideal Order/Contents of aLIGO QUAD Testing / Commissioning
- LIGO-G1200070: Ideal Order/Contents of aLIGO Triple SUS Testing / Commissioning
- LIGO-E1000617: Quad Suspension Controls Arrangement Poster
- LIGO-E1200343: OSEM Chart

Referenced by:
- LIGO-E1200902: aLIGO BSC Test Procedures (associated with install)
- LIGO-D0901346-v12: Advanced LIGO Quadruple Suspension Assembly
- LIGO-G1200070-v2: Ideal Order/Contents of aLIGO Triple SUS Testing / Commissioning
- LIGO-E1200482: aLIGO, SUS

Examples of Testing

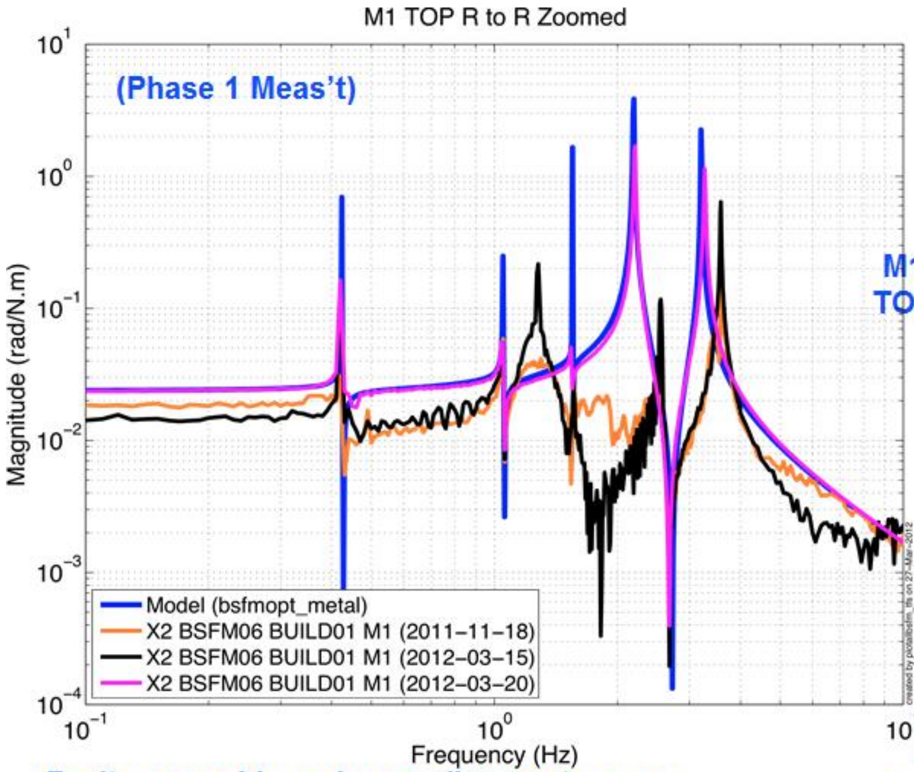




SEVEN (7) phase 1 tested QUADs built, all with virtually identical TOP stage mechanical transfer functions

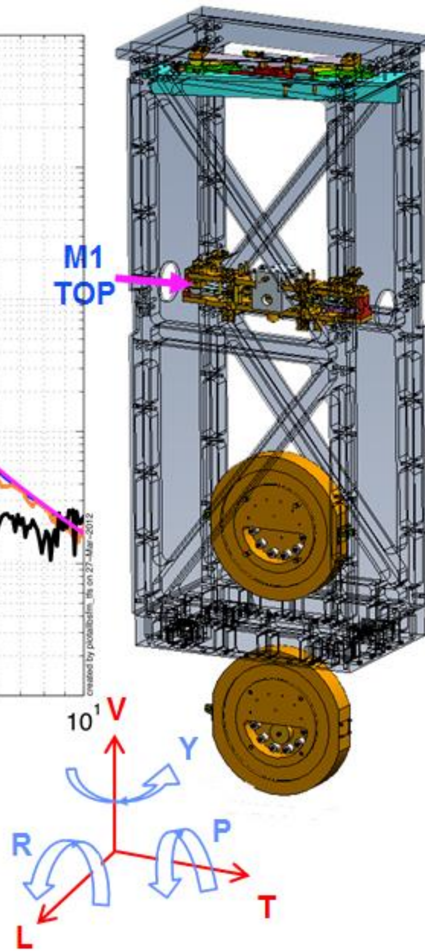
- Reproducable "plant" means control system design is a one-time, one-size fits all, i.e. easier
- Model matching measurements mean we have a complete understanding of the mechanics – makes it very useful to predict motion of stages that can't be measured locally

Examples of Testing

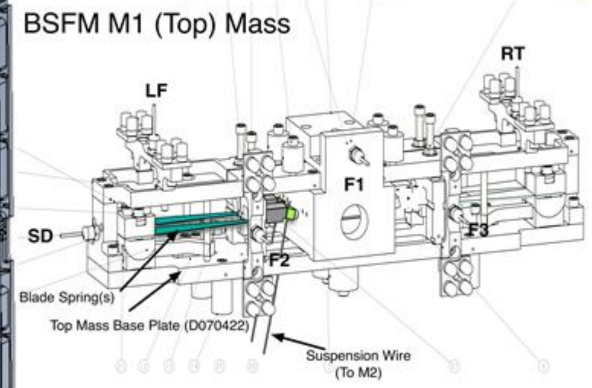


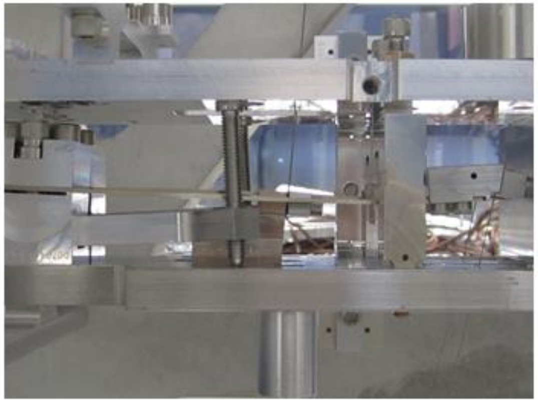
Faulty assembly and poor alignment cause fixed mechanical parts (the cage, sensors, EQ stops) to interfere with the suspended elements

Measurements direct the search for problems, confirm fixes

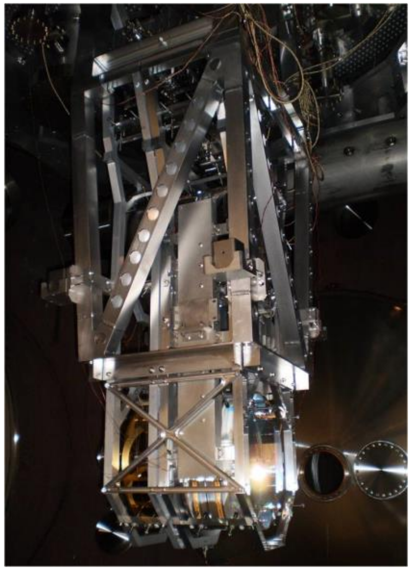


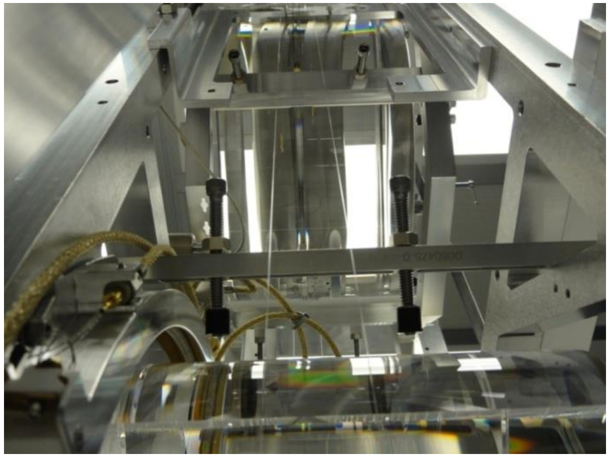
Rubbing, rubbing, rubbing

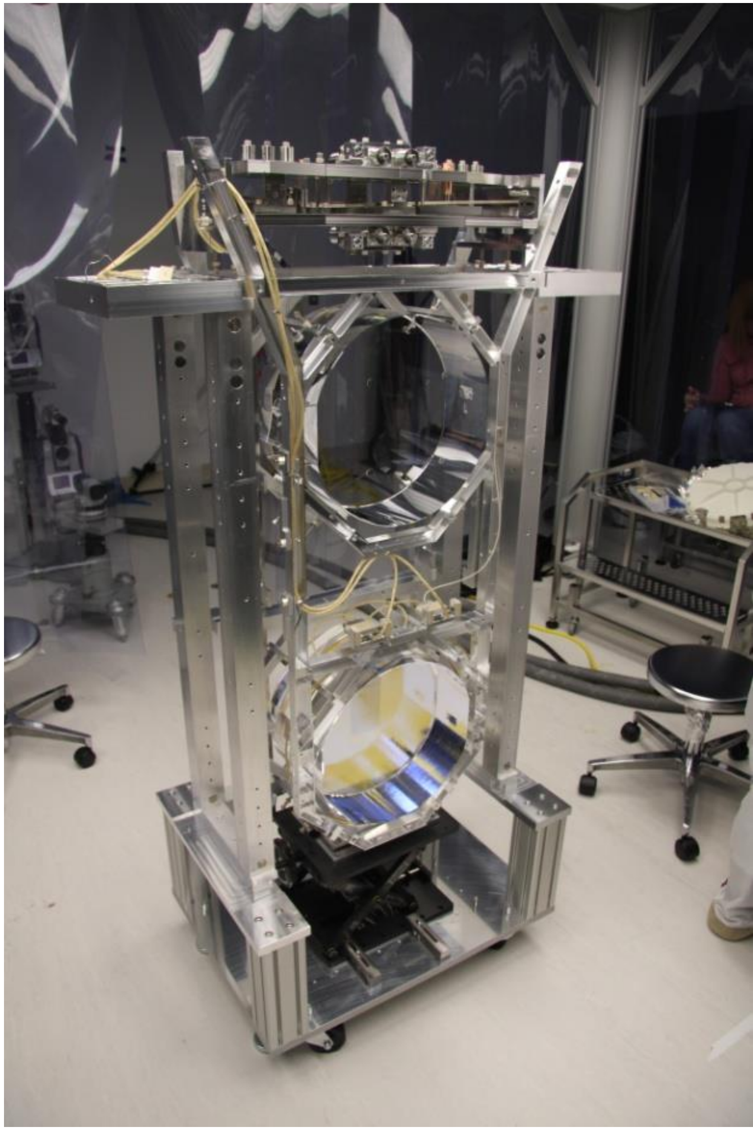




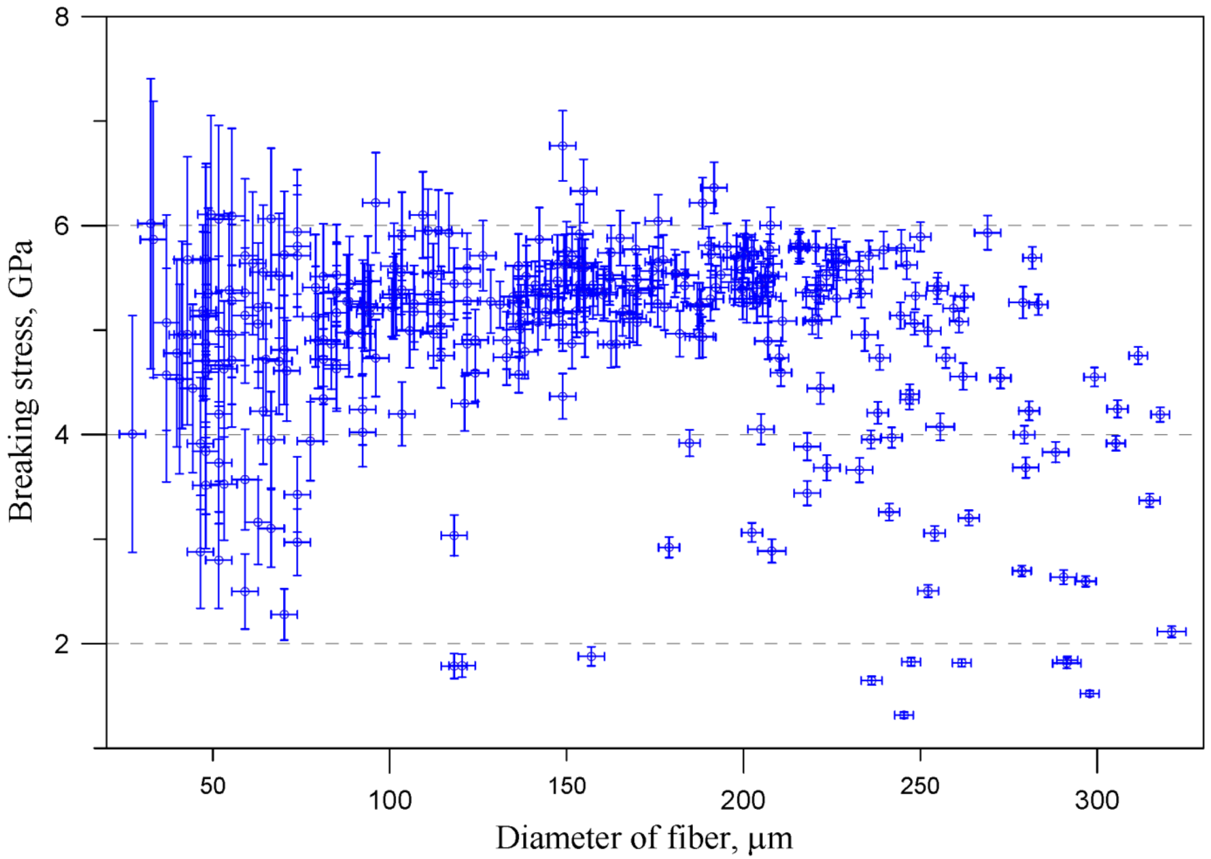
aLIGO Suspensions

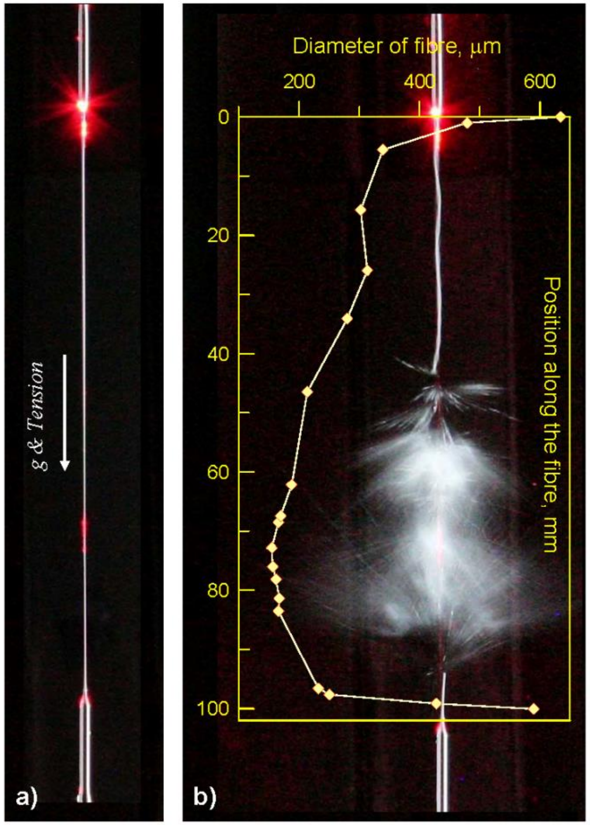






Fused Silica

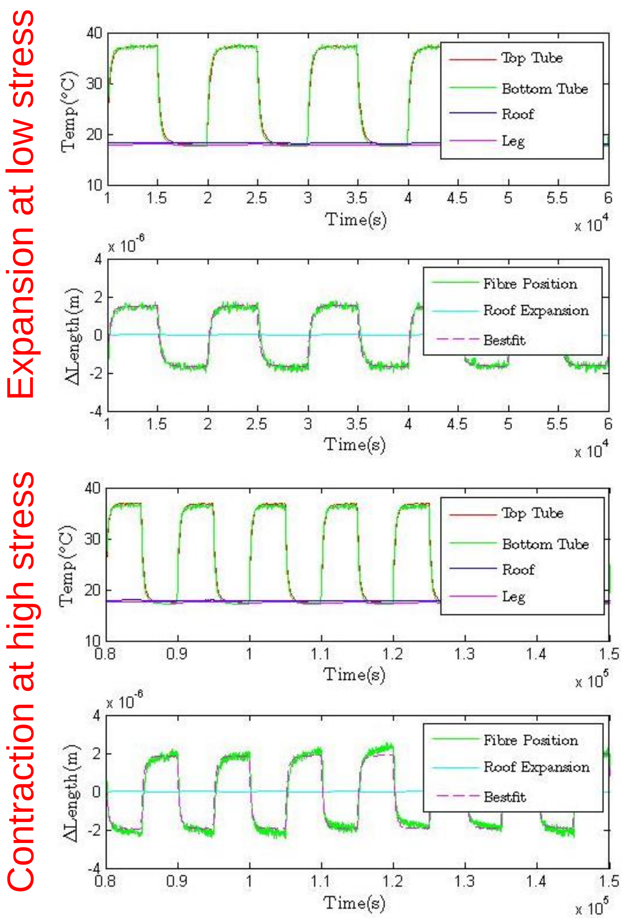


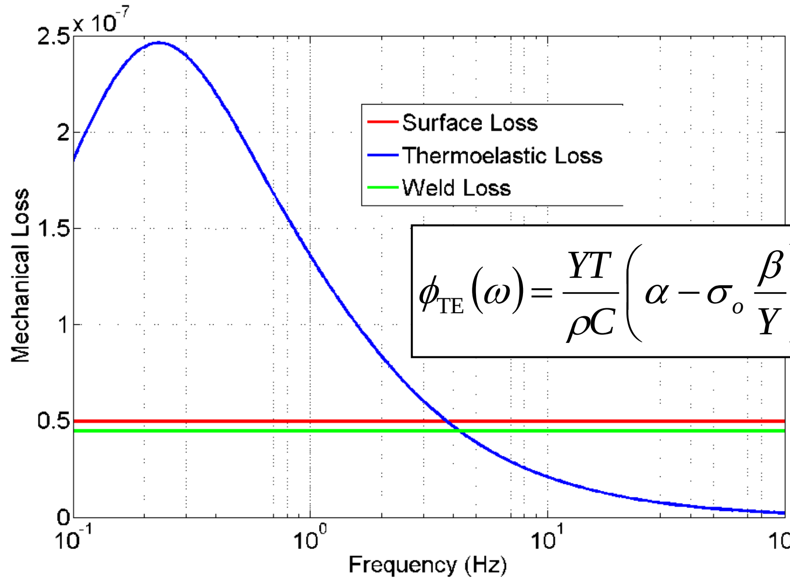


- aLIGO fibres operate with a safety factor of ≈7 (@800MPa)

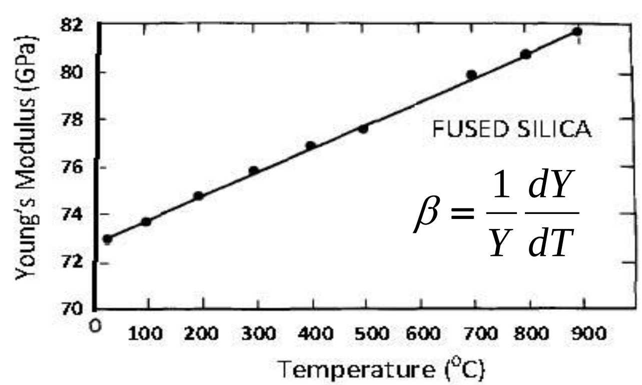
Suspension Thermal Noise

- 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





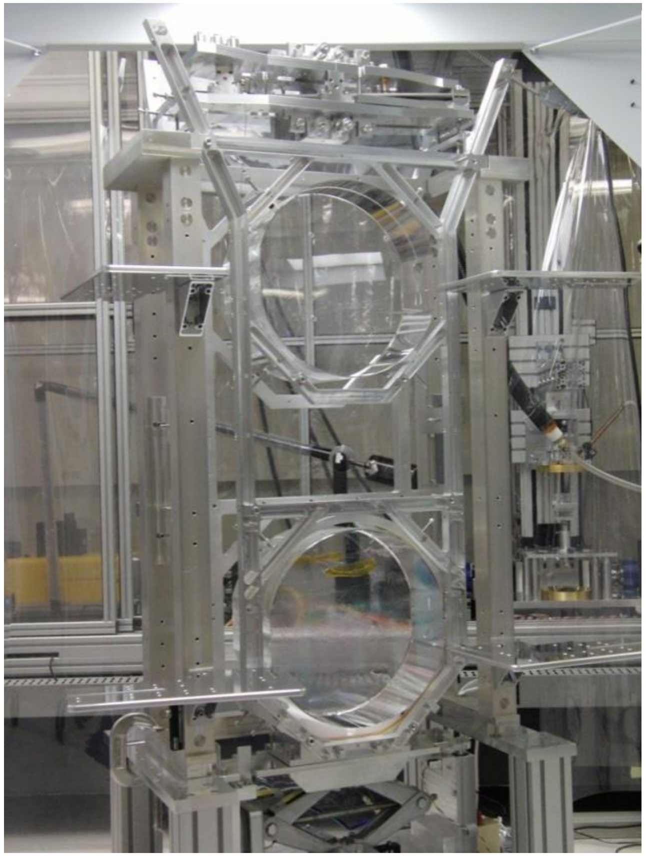
$$\phi_{\mathrm{TE}}(\omega) = \frac{YT}{\rho C}\left(\alpha - \sigma_o \frac{\beta}{Y}\right)^2 \left(\frac{\omega\tau}{1+(\omega\tau)^2}\right)$$

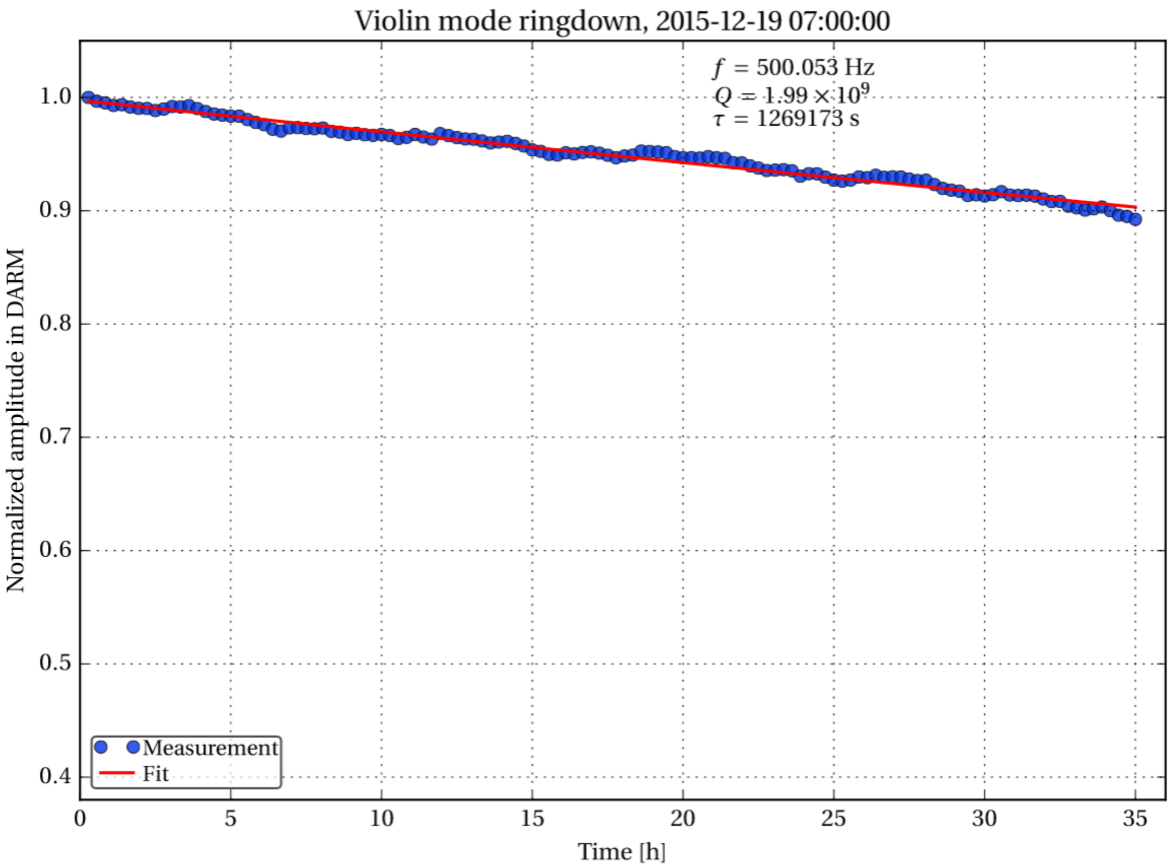


$$\beta = \frac{1}{Y}\frac{dY}{dT}$$

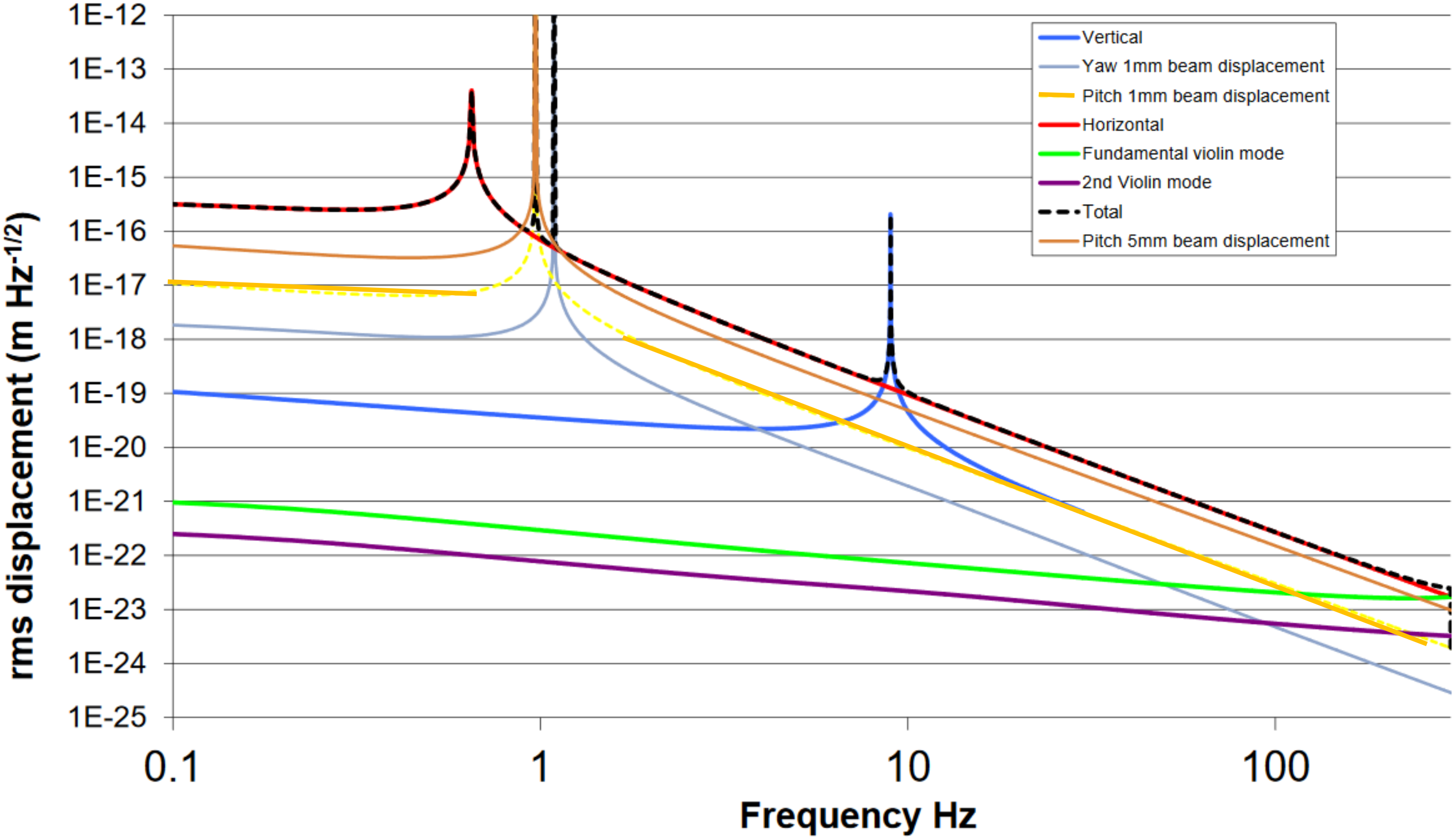
aLIGO Suspension Thermal Noise

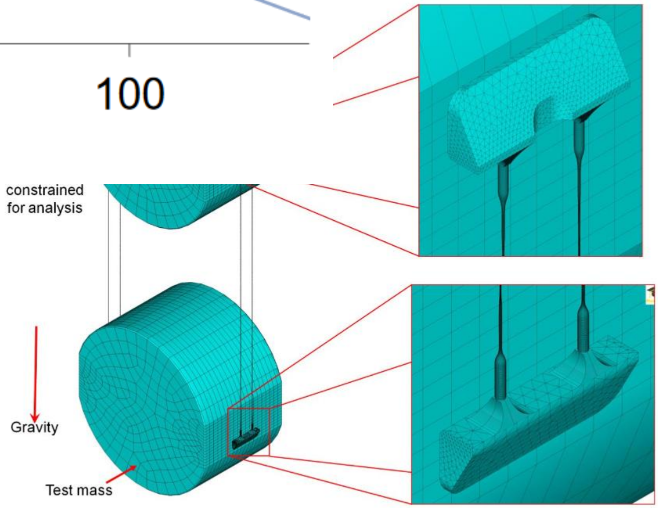
- Violin modes show extremely high quality factor
- Ring down over several days





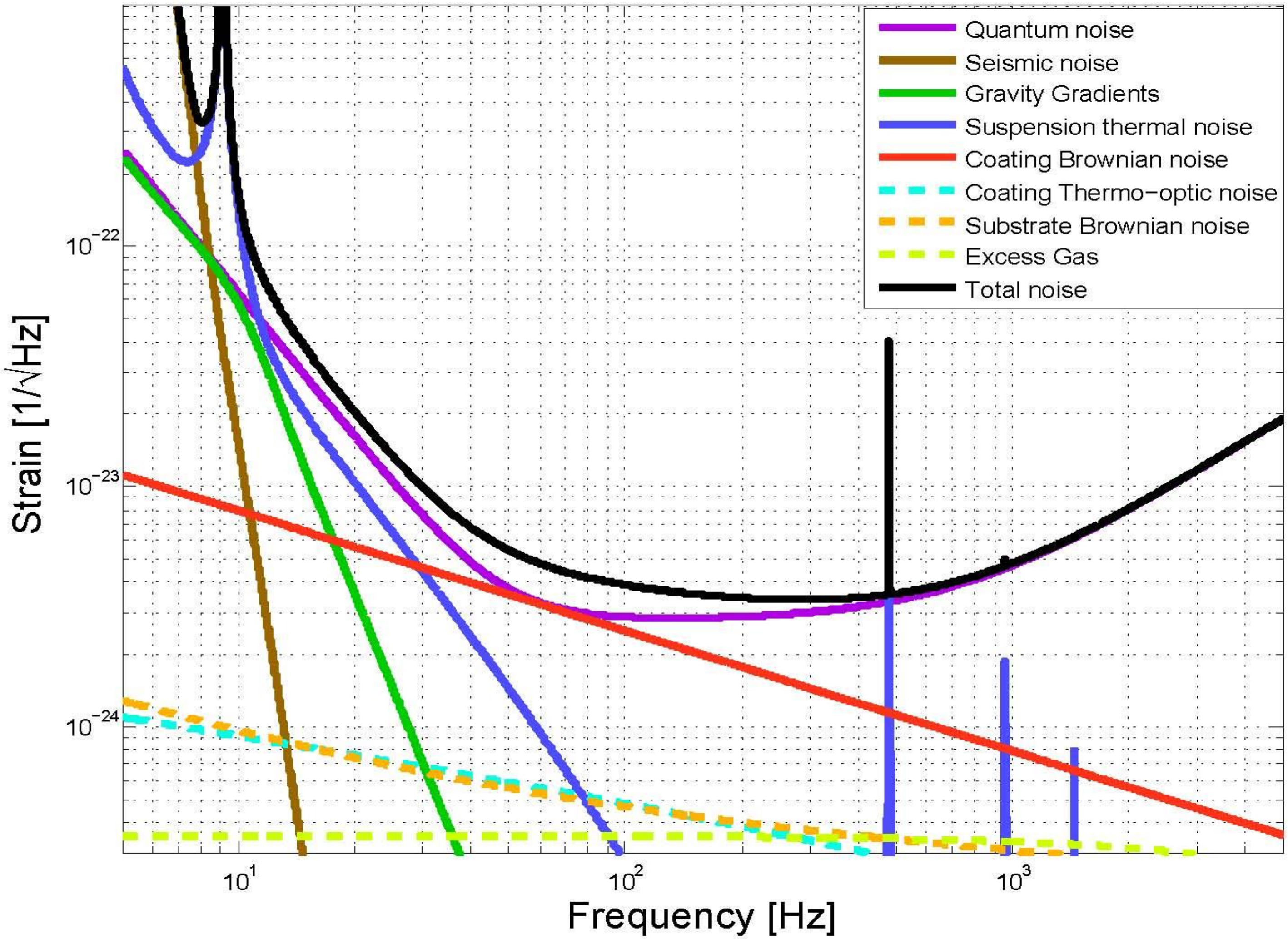
aLIGO Suspension Thermal Noise





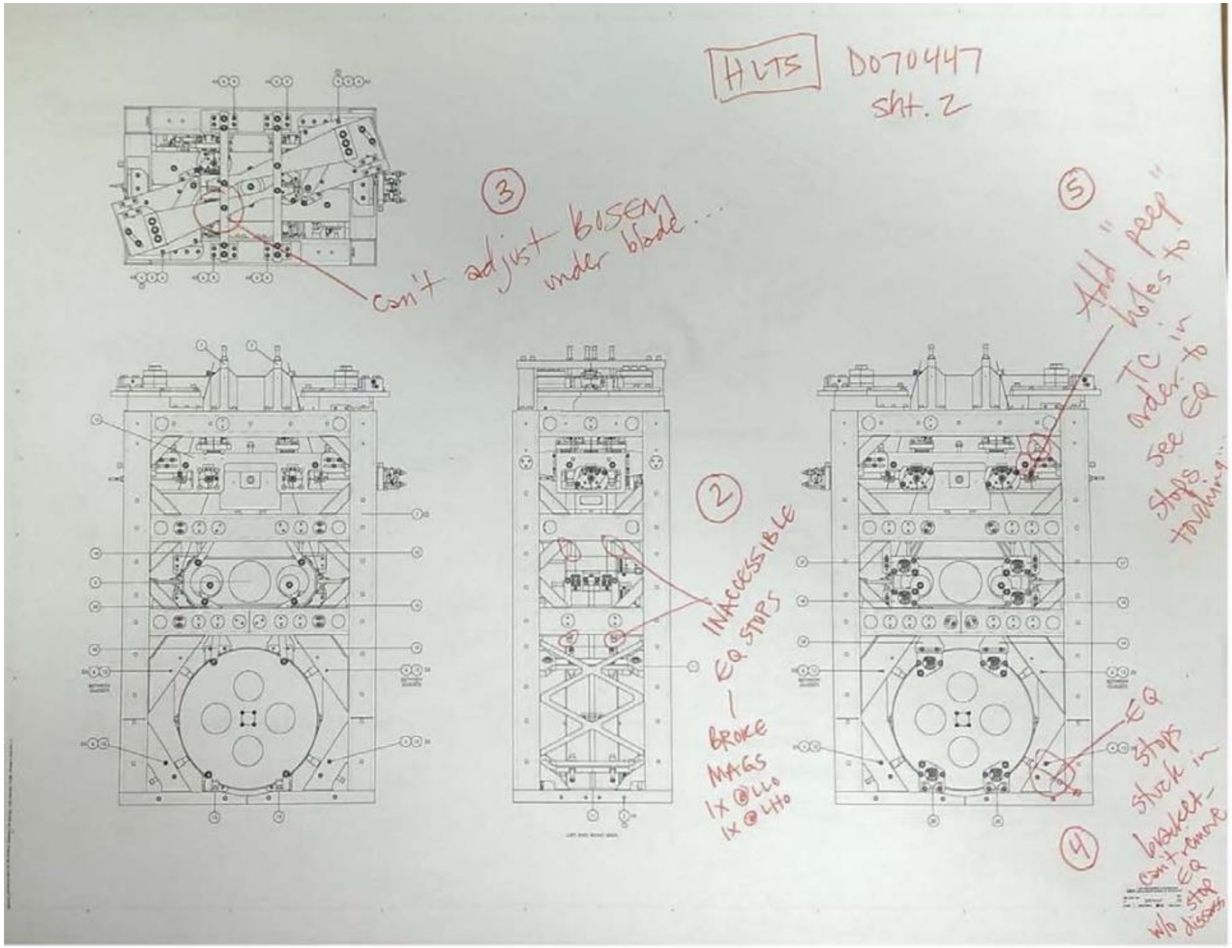
- FEA models to estimate final stage thermal noise
- Mathematica models to predict the transmissibility of all stages/transfer functions

aLIGO Sensitivity



Lessons Learned

- Suspensions are complicated, comprise multiple build varieties, and attention to detail is important
- Good documentation is essential (plus modifications/redlining)



Lessons Learned

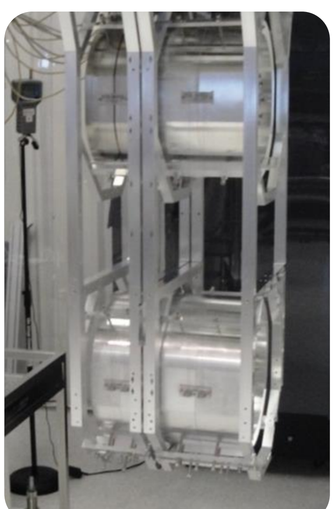
- Suspensions are complicated, comprise multiple build varieties, and attention to detail is important
- Good documentation is essential (plus modifications/redlining)
- A well integrated assembly/testing programme is essential
- Lots of interactions between teams: SUS/ISI/SYS
  - Layout drawings
  - cables, tooling, interferences
  - Quality Assurance/Quality Control
  - Contamination Control
- Need good interactions with the site/sites
  - Ownership of hardware
  - Preparation of work space and tooling
  - Organization and coordination
- From work on GEO/aLIGO there is lots of expertise on fused silica/bonding
- Good links with UK/US SUS activities were essential, including training of staff

Lessons Learned

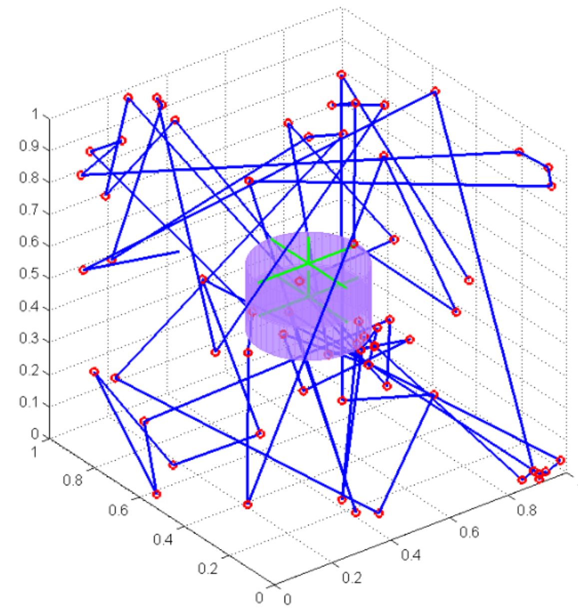
- Prior lesson that needed to be re-learned with wire loops

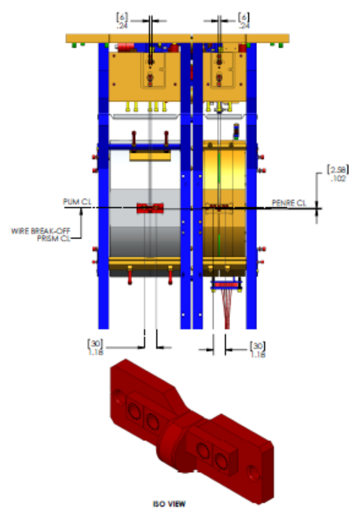
Prototype: Tested wire loop

Production: Dummy wire segments



- Squeeze film gas damping => extend gap/redesign reaction mass





Production: Re-invented the loop

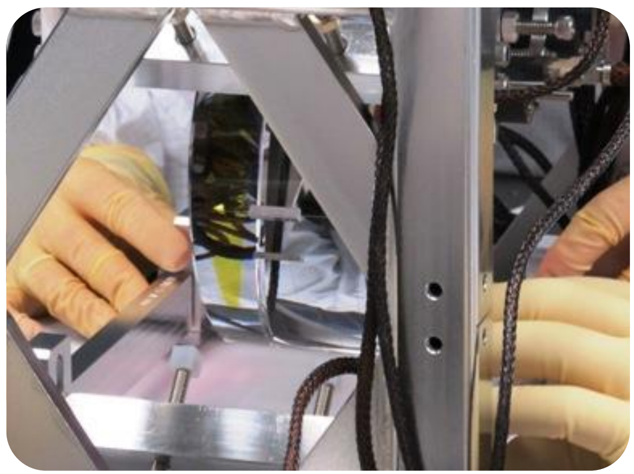
LIGO G1301002

Lessons Learned

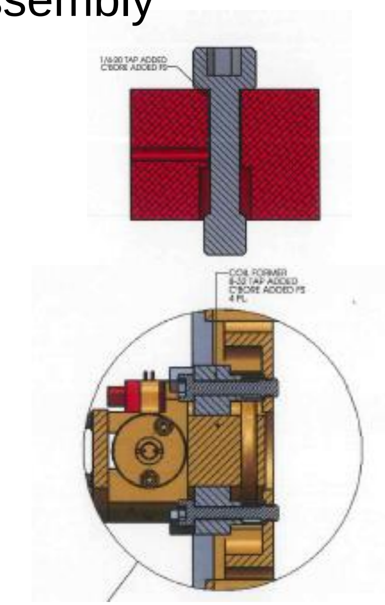
LIGO G1301002

- Optic handling within the suspension needed work

- EQ stops
- Transport
- Shielding/Face guards



- Captive screws: damage mitigation and ease of assembly



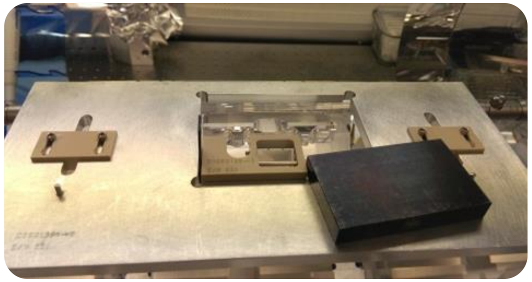
- Magnetic materials

Lessons Learned

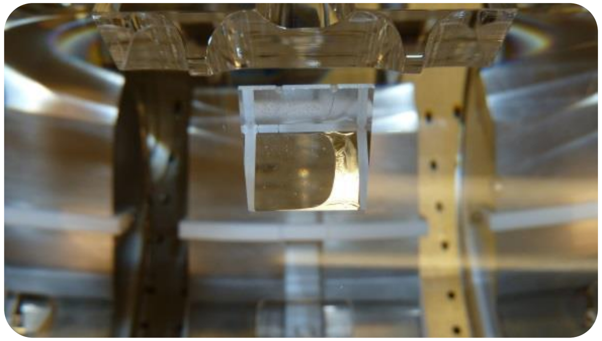
- Work space – cleanroom
- Cleanroom needs to be completely moved to crane into chamber.

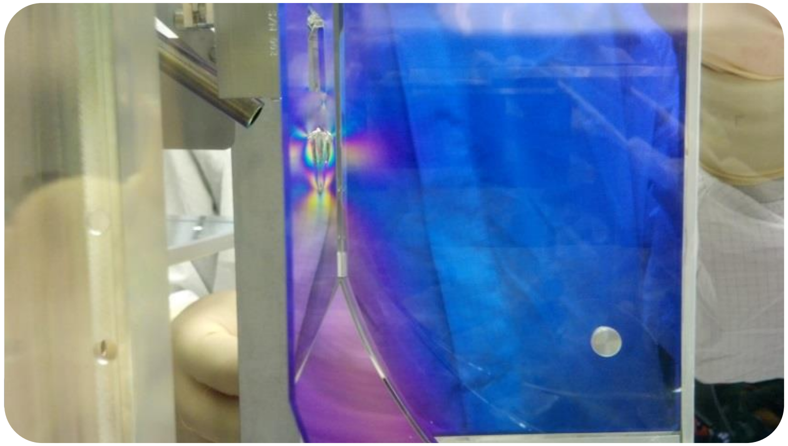
Lessons Learned

Gluing



- Don’t underestimate the smallest of jobs; EP30-2 – the “replacement product”
- Required 13 gluing configurations with 6 procedures, and counting!
- Failures due to lifting, curing, handling
- Glue removal

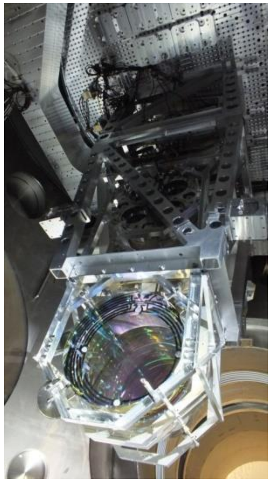




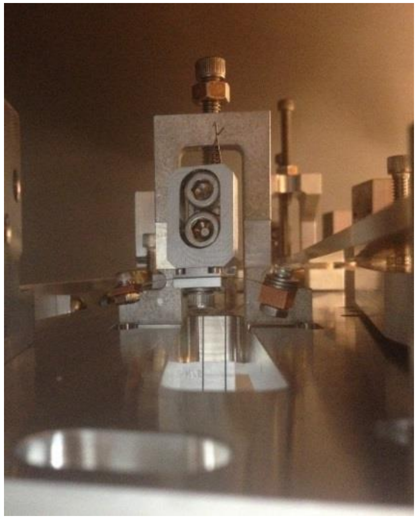
Lessons Learned

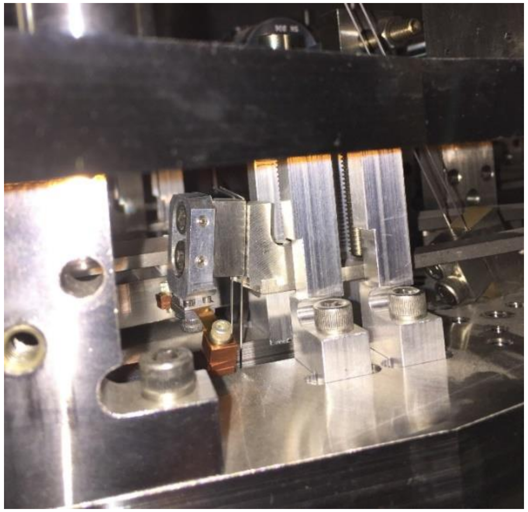
Bounce/Roll mode dampers

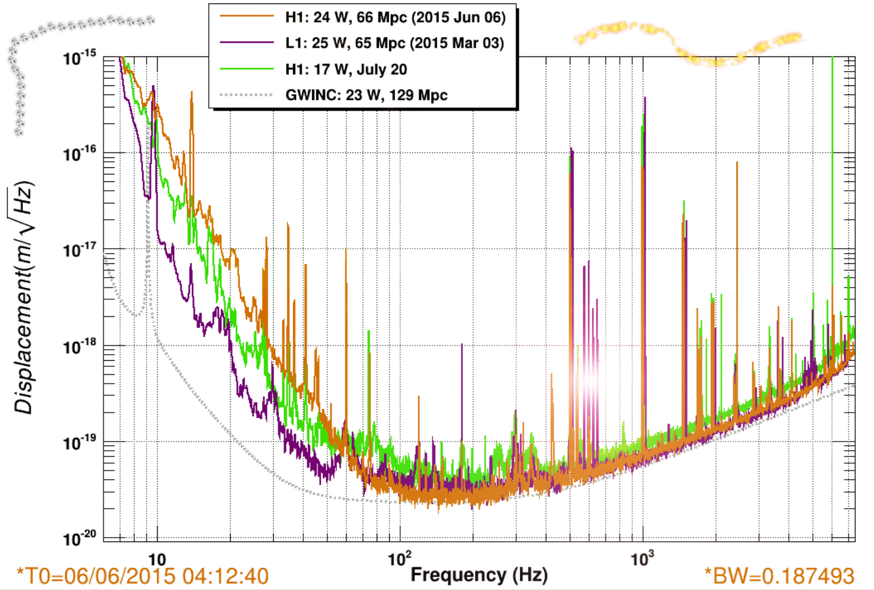
LIGO G1600371



- The highest modes at ~9.7Hz/13.8Hz (bounce/roll) have Q's of 10^5
- Damping strategies using PUM feedback have been applied
- Bounce and Roll mode dampers currently being installed

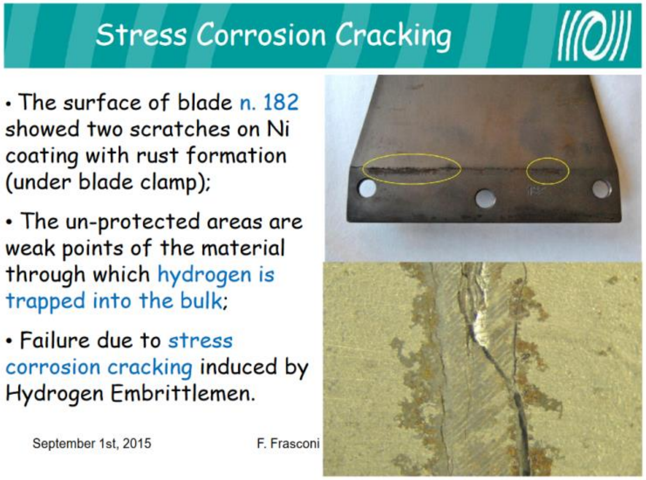






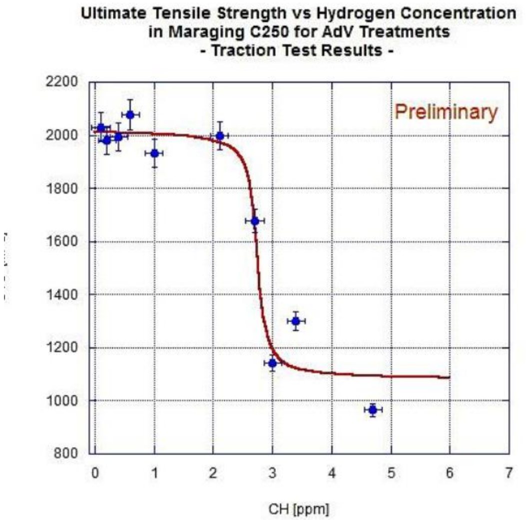
Current Considerations

- VIRGO have identified some seismic/suspension issues



LIGO G1501168

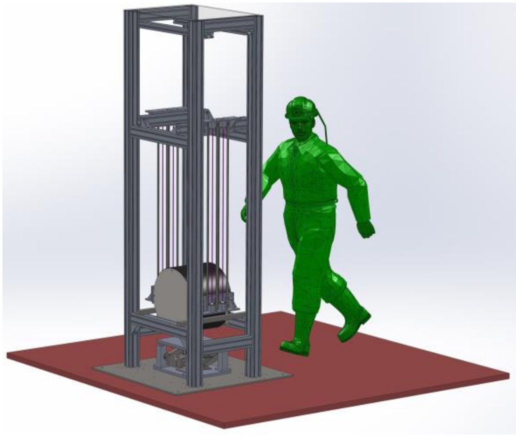
- Maraging steel spring breaks due to hydrogen embrittlement
  - high stress to get low frequency passive isolation (x2 higher than aLIGO)
  - protective coatings are important
- Fused silica suspension fibres
  - There have been some fibre breakages in VIRGO
  - Glasgow/SUS/VIRGO working together, fibres look strong so mechanism is focusing on joint at the ear/test mass

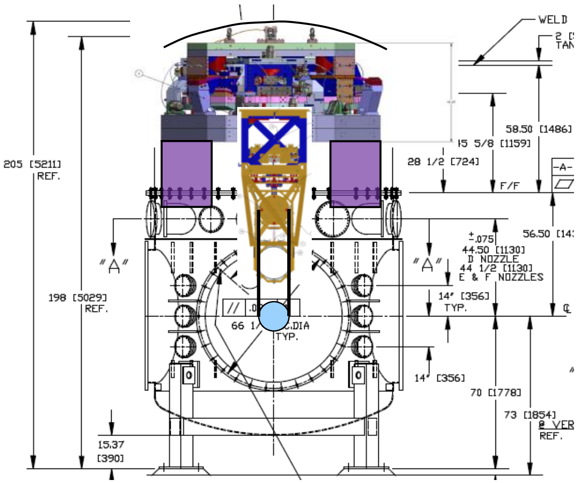


LIGO G1600683

Possible Upgrade Scenarios

- Currently looking at several various warm upgrade scenarios for the lower stage
- Fused silica
- 40 kg test mass
- 60 cm suspension length
- 1.2GPa stress in fibres (bounce/roll @ 7Hz/10Hz)
- Fused silica
- 80 kg – (160-400) kg test masses
- (120-200) cm suspension lengths
- 1.2GPa – 1.5GPa stress in fibres





Upgrade to the aLIGO Puller

- Installed suspensions are working well (296 fibre years over GEO/aLIGO)
- Robust noise models enable us to predict future performance
- R&D in Glasgow to upgrade fibre pulling facilities (2m long, 160kg test mass, 5mm stock)

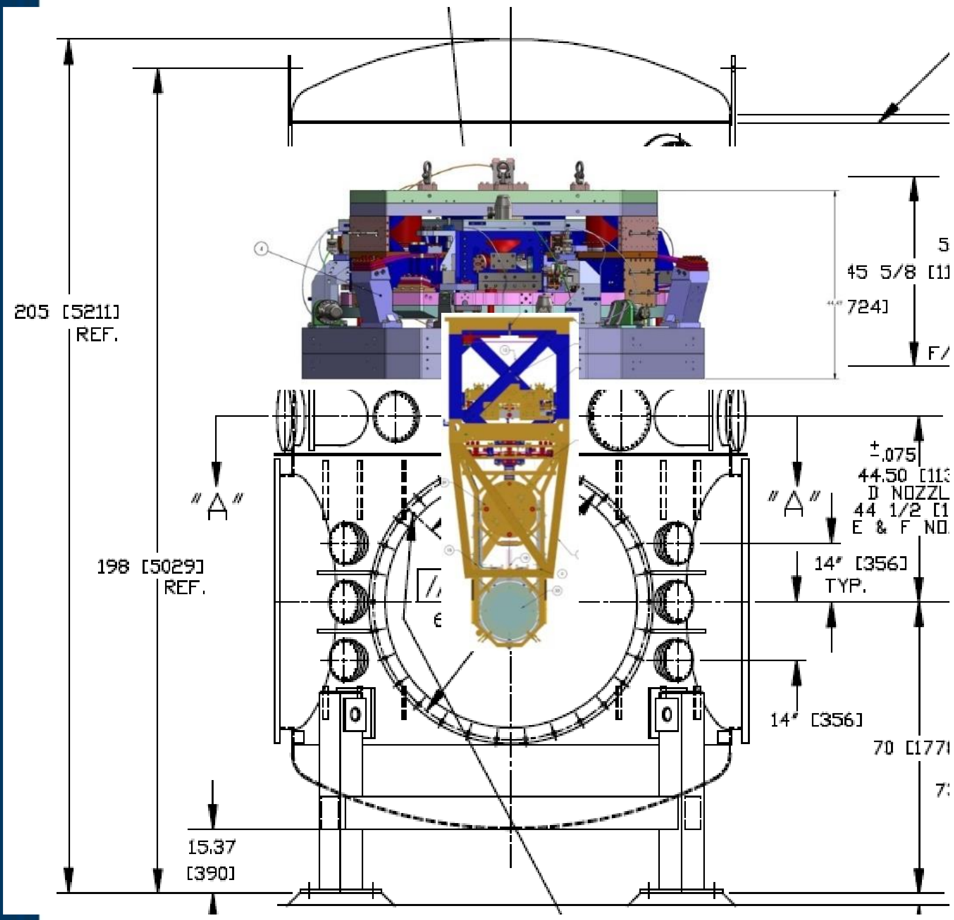
Laser power control via camera video feed

How Much Stress

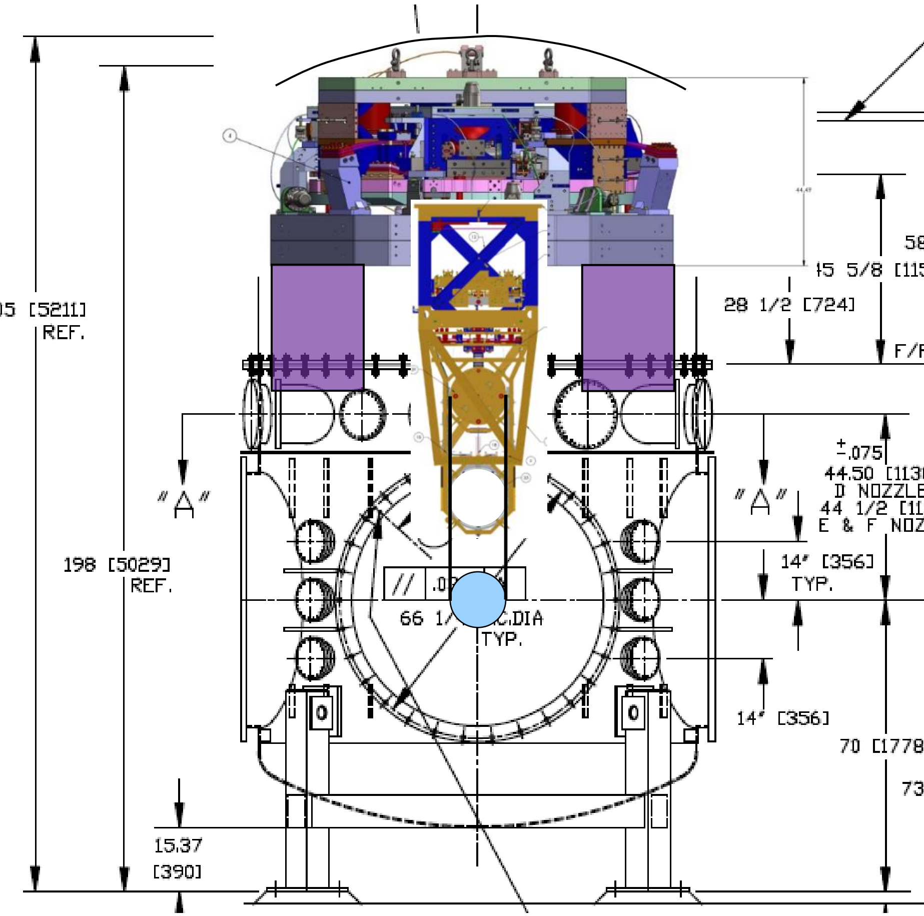
- aLIGO utilises 780MPa in the thin section to push violin modes to 500Hz and the bounce mode to 9.5Hz
- Strong fibres have breaking stress of >4GPa, a safety factor of >5
- In aLIGO, thinning fibres has the benefit of lowering bounce mode out of band, and increasing violin mode frequencies

Diameter (μm)	Stress (MPa)	Bounce (Hz)	1st violin (Hz)
400	780	9	520
320	1200	7	650
300	1600	6.3	750

Warm Upgrades: Suspensions



aLIGO (0.6 m final stage)

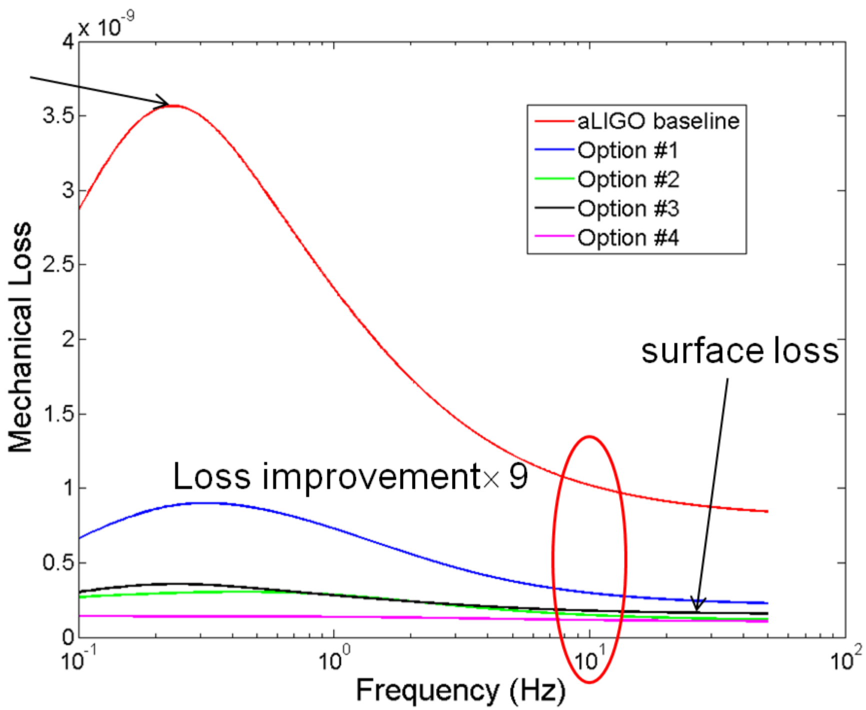


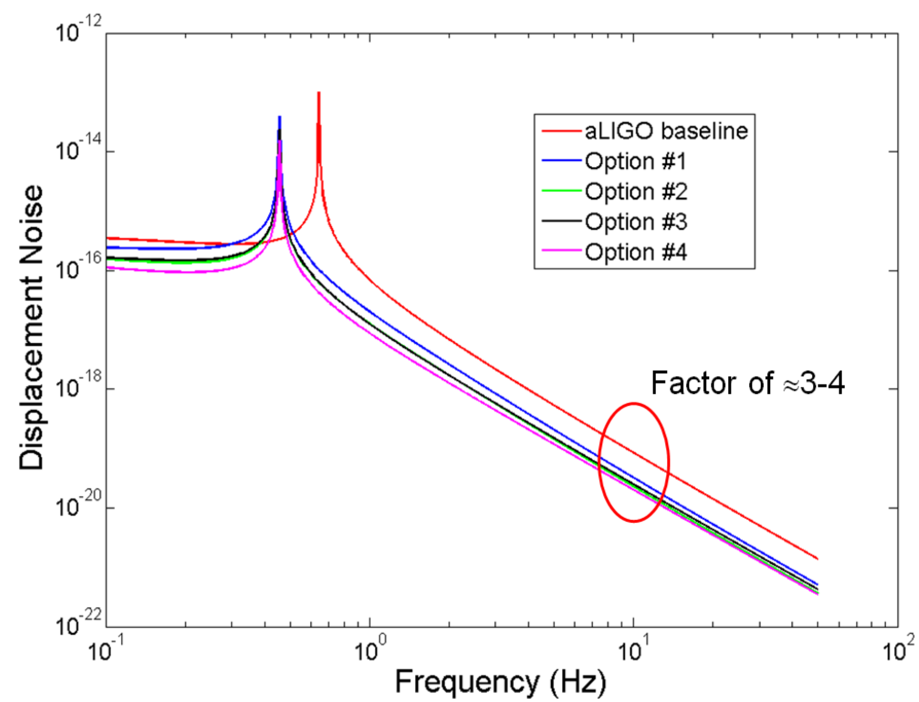
LIGO-3 (≈1.2 m final stage)

$$D \approx \frac{2L}{\xi}\sqrt{\frac{T}{YI}}$$

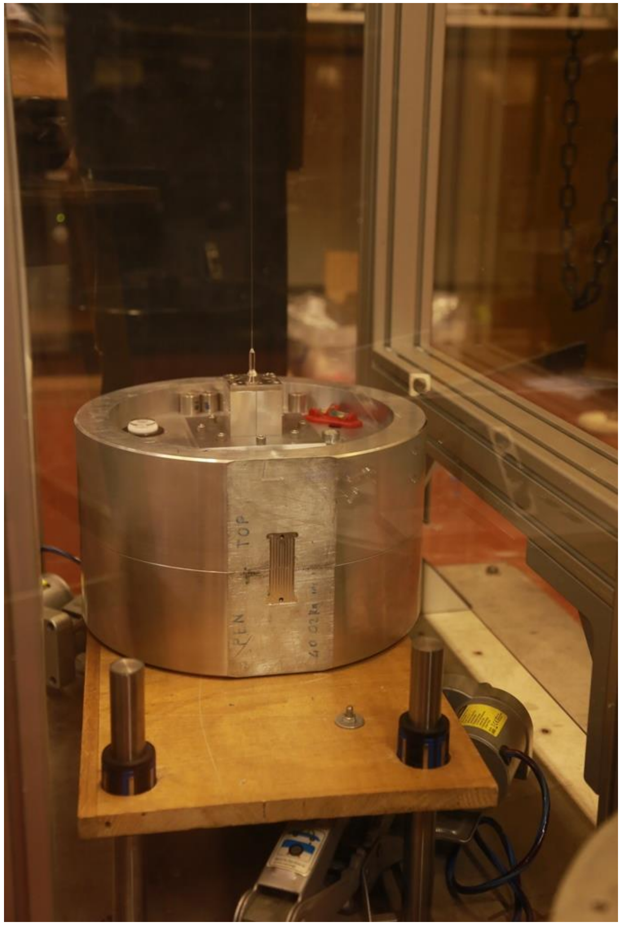
Sensitivity Gain

Option	L (m)	ϕ_{stock} (mm)	Stock length (mm)	Neck length (mm)	$\phi_{surface}$
aLIGO	0.6	3	11	7	6×10^{-12}
Option #1	1.2	3	5	5	3×10^{-12}
Option #2	1.2	5	5	5	3×10^{-12}
Option #3	1.2	3	5	2	3×10^{-12}
Option #4	1.2	5	5	2	3×10^{-12}





Current R&D



- 40kg on 0.8mm diameter fibre

- LHO test suspension, hanging in air for >1 year @ 1.2GPa

Thoughts for LIGO India

- There are a wide variety of suspension configurations to be built and each have their own challenges
- There is a huge experience of aLIGO team members on all aspects
- Good documentation/assembly/testing is essential
- Many lessons have been learned, which will help LIGO India

- **Challenges/opportunities:**

- How to keep the knowledge fresh until LIGO India is ready for installation (e.g. so we don’t have to relearn things currently known, but forgotten)
- Training of staff/SUS team members: collaboration opportunities
- Upgrade opportunities? May require some redesign but will ensure LIGO India is the latest model
- Developing fused silica technology
- Shipping/handling/storage

Thoughts for LIGO India

- Cleanliness is important

"Known" Particulate Samples

Document #:
LIGO-T1300165-v5
Document type:
T - Technical notes
Submitted by:
Kaitlin Gushwa ✉
Updated by:
Calum Torrie ✉
Document Created:
26 Feb 2013, 12:26
Contents Revised:
22 May 2013, 13:47
Metadata Revised:
22 Jan 2014, 16:36

Watch Document

Abstract:
Collection of known particulate samples:
1. Glove print
2. glove piece
3. Alpha 10 wipe
4. Contec wipe
5. Berkshire wipe
6. Skin particulates
7. cut section of over-temperature bake teflon cable (not clean)
8. C3 suit (old)
9. C3 cover (HAM2)
10. Al foil (new)
11. ameristat bag (new)
12. cleaned & baked teflon quadrapuss cable
13. Human sweat and saliva
14. site cleanroom curtain
15. site concrete floor dust
16. Teflon
17. cotton glove liner
18. New C3 bunnysuit
19. well used foil
20. jeans
21. saliva
22. sweat
23. eyebrow hair
24. viton
25. face skin
26. Kapton tape and Kapton from in-vacuum cable
27. PEEK mesh and PEEK clamp scraping

Notes on these samples: These SEM samples were created from known sources in order to build up a library of standards to compare the samples from each site to.

Viewable by:
- LSC
- Authors

Modifiable by:
- LIGO_Lab
- Authors

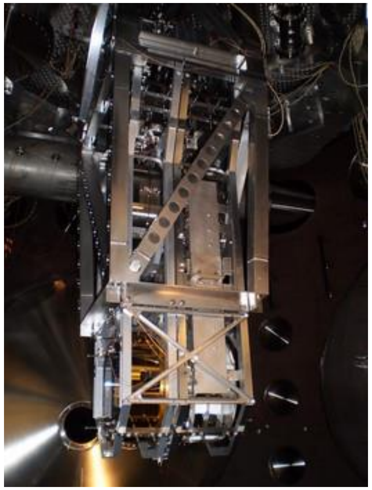
Other Versions:
LIGO-T1300165-v4
11 Jun 2013, 12:08

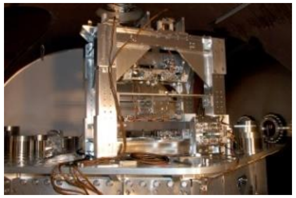
Extra Discussion Slides

1. Thermal noise estimates
2. Warm upgrades
3. Cold upgrades

Suspension Inventory

- Two Input Test Mass (ITM) suspensions
- Two End Test Mass (ETM) suspensions
- One Beamsplitter (BS) suspension
- Seven HAM Small Triple Suspensions (HSTS)
- Two HAM Large Triple Suspensions (HLTS)
- One, Output Mode Cleaner (OMC) Suspension
- SUS electronics racks
- Spare suspension components/parts
- Spare SUS electronics

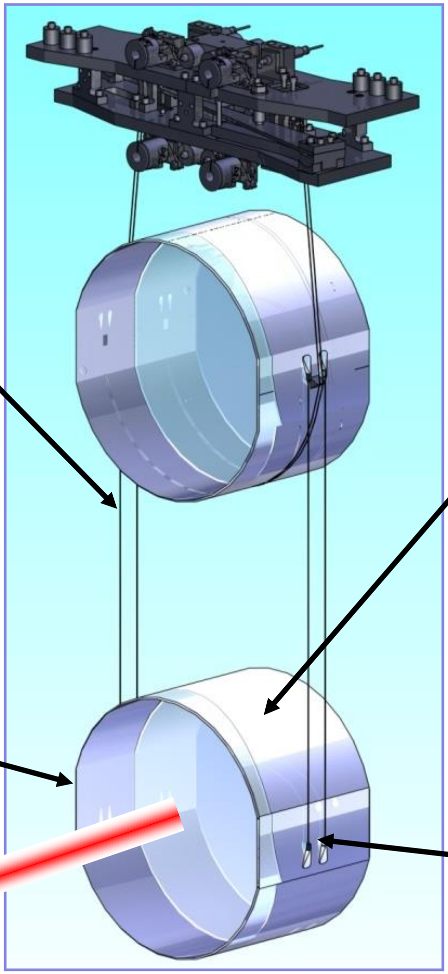


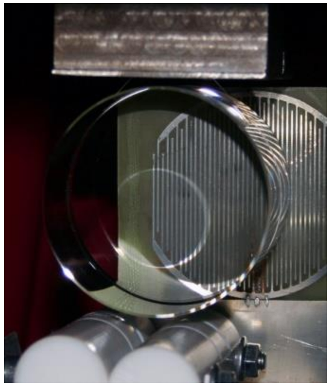


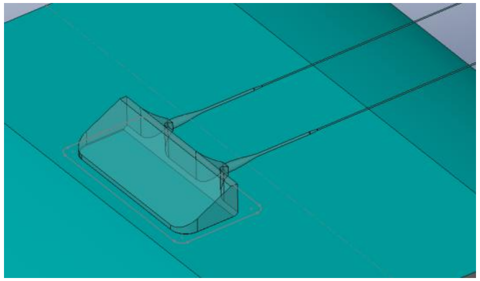
Thermal Noise Sources

- Suspension thermal noise

(pendulum, vertical and violin modes of suspension fibres)

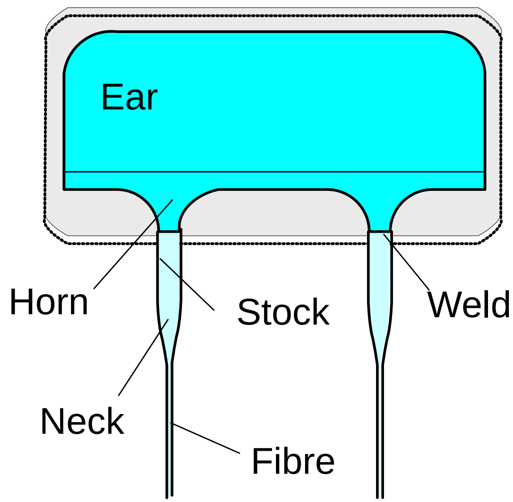


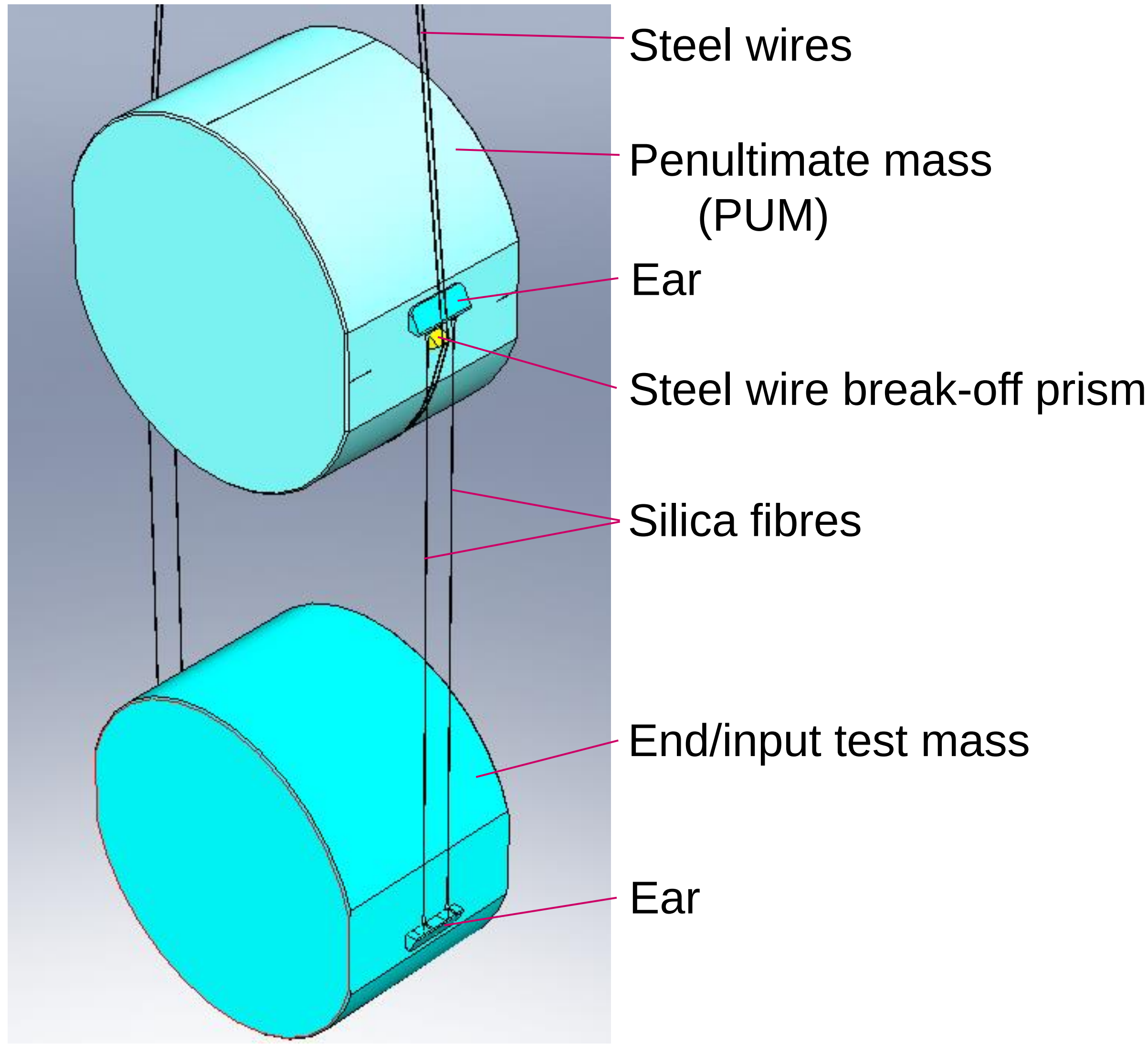




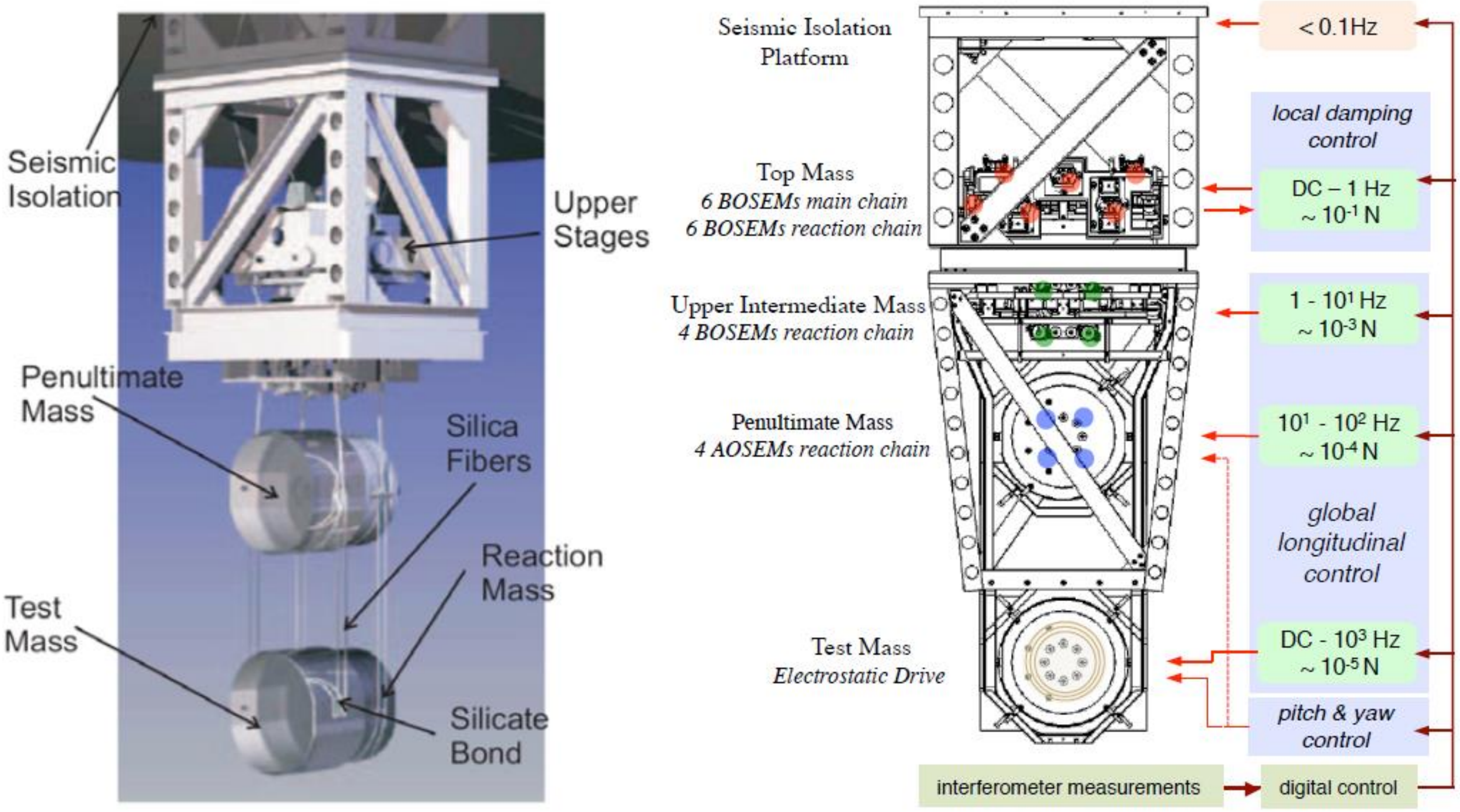
- Substrate thermal noise
- Mirror coating thermal noise
- Bond thermal noise from mirror-fibre interfaces

aLIGO Monolithic Stage



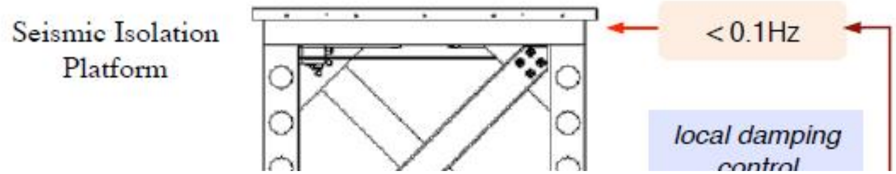


QUAD Control Forces

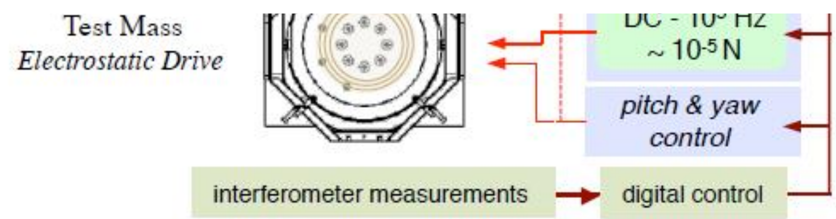


LIGO P1100208

QUAD Control Forces



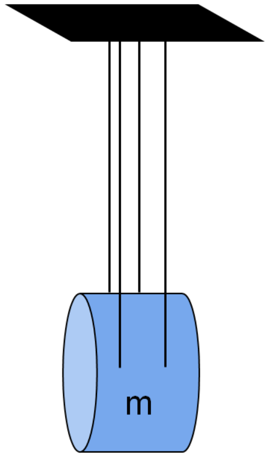
Coil-driver	Q-TOP	UIM	PUM
dynamic range	$\pm$ 200mA (continuous)	$2\,\mathrm{mA_{rms}} < 1\,\mathrm{Hz}$ $16\,\mu\mathrm{A_{rms}}$ @ $100\,\mathrm{Hz}$	$16\,\mathrm{mA_{rms}}$ (200 - 5000 Hz)
noise @ 1 Hz	$1\,\mathrm{nA\,Hz^{-1/2}}$	$0.5\,\mathrm{nA\,Hz^{-1/2}}$	$20\,\mathrm{nA\,Hz^{-1/2}}$
noise @ 10 Hz	$73\,\mathrm{pA\,Hz^{-1/2}}$	$3\,\mathrm{pA\,Hz^{-1/2}}$	$4\,\mathrm{pA\,Hz^{-1/2}}$
noise @ 100 Hz	$1000\,\mathrm{nA\,Hz^{-1/2}}$	$200\,\mathrm{nA\,Hz^{-1/2}}$	$5\,\mathrm{nA\,Hz^{-1/2}}$
noise @ 1000 Hz	$1000\,\mathrm{nA\,Hz^{-1/2}}$	$1000\,\mathrm{nA\,Hz^{-1/2}}$	$1000\,\mathrm{nA\,Hz^{-1/2}}$
actuation strength	$1.7\,\mathrm{N\,A^{-1}}$	$1.7\,\mathrm{N\,A^{-1}}$	$0.03\,\mathrm{N\,A^{-1}}$
max force noise @ 10 Hz	$40\,\mathrm{pN\,Hz^{-1/2}}$	$8\,\mathrm{pN\,Hz^{-1/2}}$	$0.1\,\mathrm{pN\,Hz^{-1/2}}$



LIGO P1100208

Suspension Thermal Noise (Dilution)

- 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)



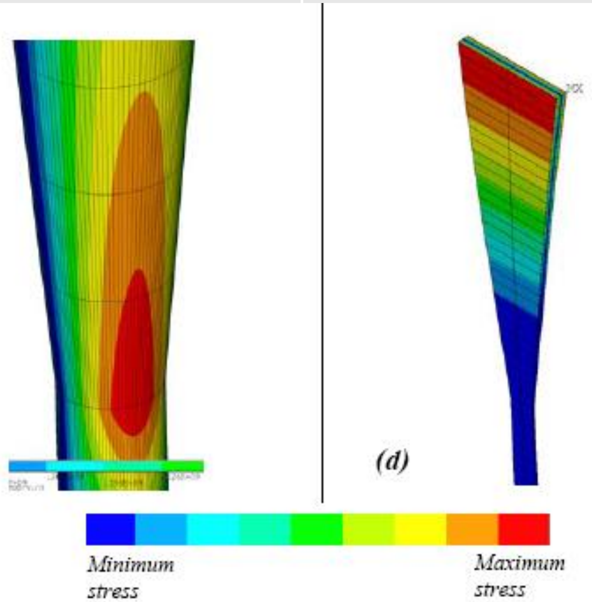
n=4

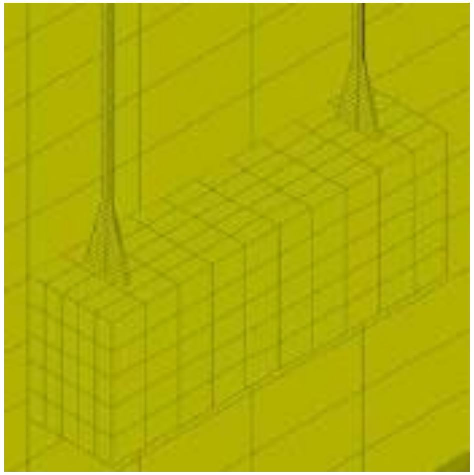
T=mg/4

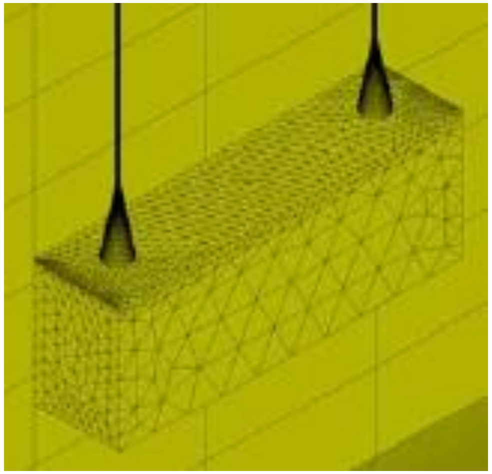
$$I_{cyl} = \pi R^4 / 4$$

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

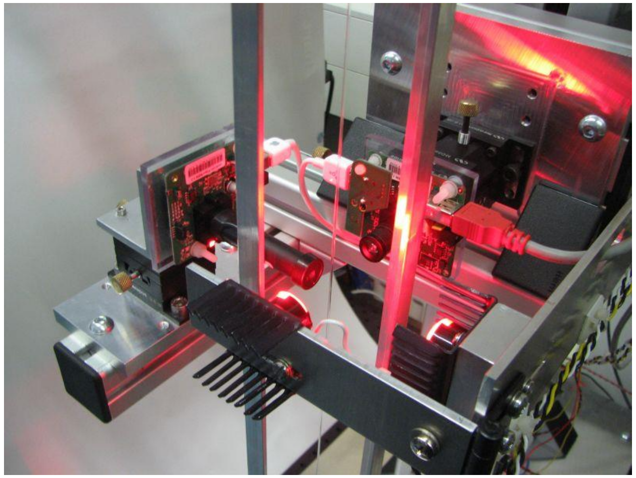
Geometry	D (Analytic)	D (FEA)	Dimensions
Cylindrical	112	75	ϕ 0.8mm
Rectangular	480	-	0.1mm×1mm



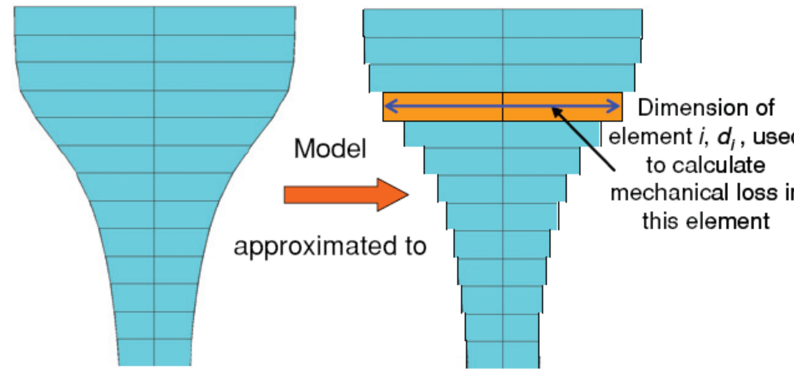




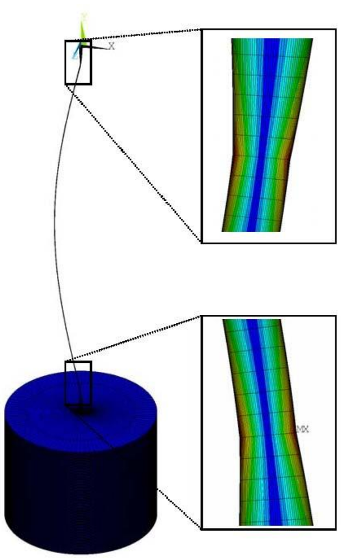
Suspension Thermal Noise (Dilution)



- Profile fused silica fibre



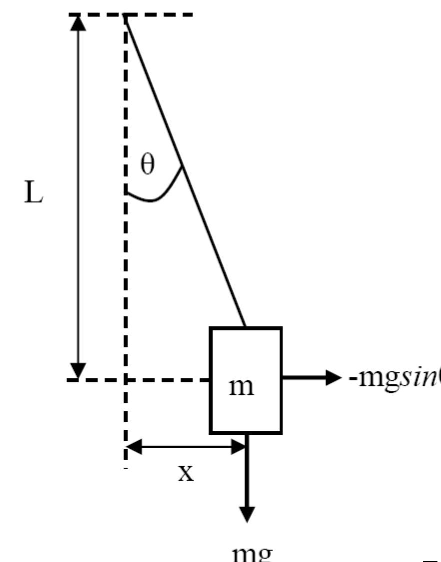
- Extract elastic strain energy and modal frequencies from ANSYS



- Loaded suspension fibres the majority of energy in gravity $\Rightarrow$ dilute loss due to elastic energy

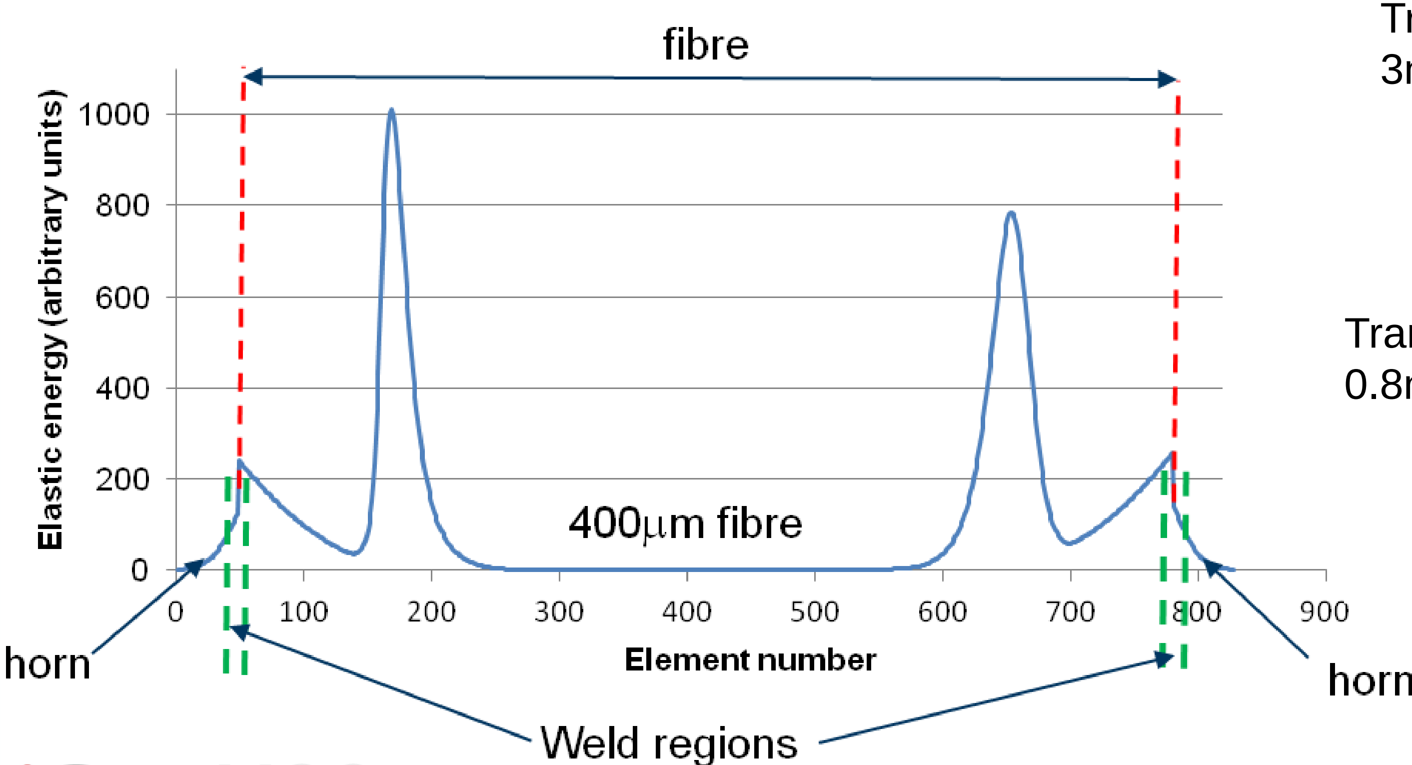
$$D = \frac{E_{\text{total}}}{E_{\text{elastic}}} \approx \frac{k_{\text{gravity}}}{k_{\text{fibre}}} \approx \frac{2L}{\xi}\sqrt{\frac{T}{YI}}$$

- ξ=2 (bending top/bottom)



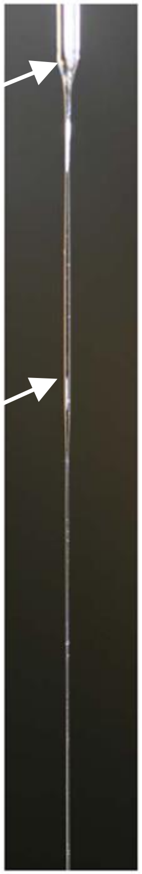
Fibre Geometry

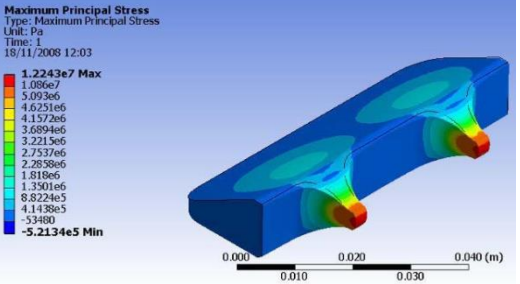
- Short, thick necks are best to minimise energy leakage up the stock and approximate an ideal attachment
- Cylindrical fibres can be made stiffer than rectangular fibres ⇒ aLIGO baseline uses cylindrical dumbbell fibres (ϕ3mm→ ϕ0.8mm→ ϕ0.4mm)
- For future detectors, the possibility of fabricating fibres from silicon wafers may allow rectangular fibres with short stiff necks



Transition from 3mm to 0.8mm

Transition from 0.8mm to 0.4mm



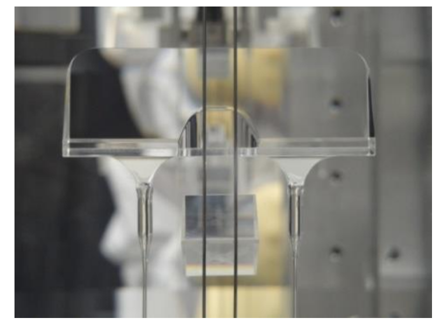


Suspension Thermal Noise

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

$\phi_{\text{bulk}} = 1.2\times 10^{-11} f^{\,0.77}$	$\phi_{\text{TE}}(\omega) = \dfrac{YT}{\rho C}\left(\alpha - \sigma_o \dfrac{\beta}{Y}\right)^2 \left(\dfrac{\omega\tau}{1+(\omega\tau)^2}\right)$
$\phi_{\text{surface}} \approx \dfrac{8h\phi_s}{d}$	$\phi_{\text{weld}}(\omega) = 5.8\times 10^{-7}$

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



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

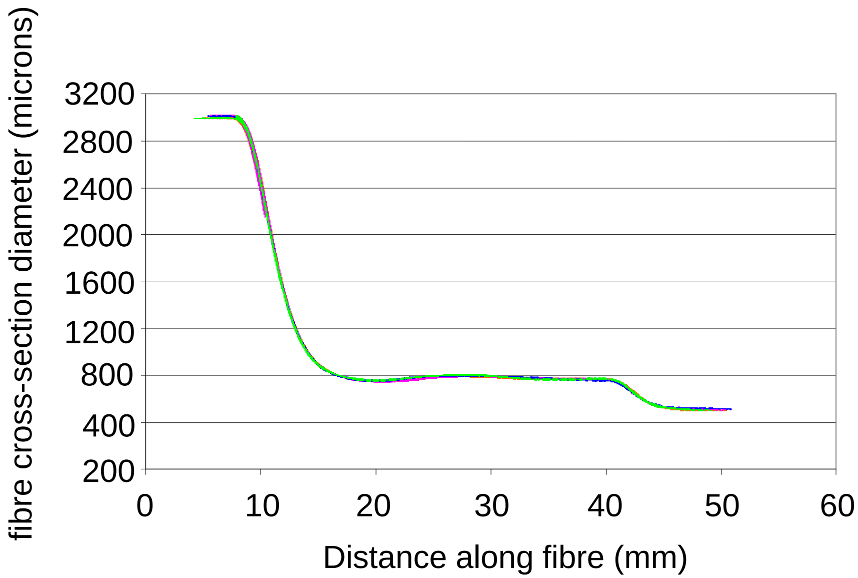
$$S_x(\omega) = \frac{4k_BT}{m\omega}\left(\frac{\omega_o{}^2\phi_{total}(\omega)}{\omega_o{}^4\phi_{total}{}^2(\omega) + \left(\omega_o{}^2 - \omega^2\right)^2}\right)$$

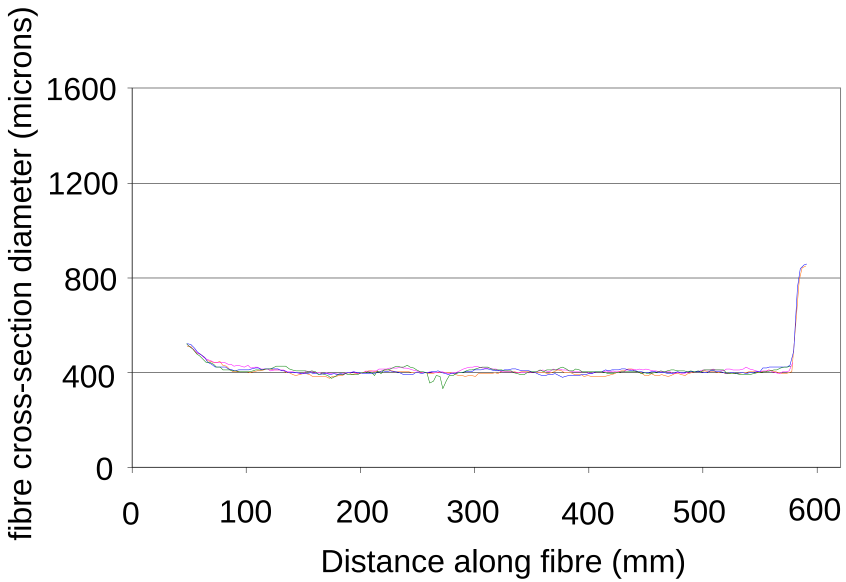
- Surface loss: dislocations, un-terminated dangling bonds and micro-cracks on the pristine silica surface
- Thermoelastic loss: heat flow across the fibre due to expansion/contraction leads to dissipation.
- Bulk loss: strained Si-O-Si bonds have two stable minima which can redistribute under thermal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

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





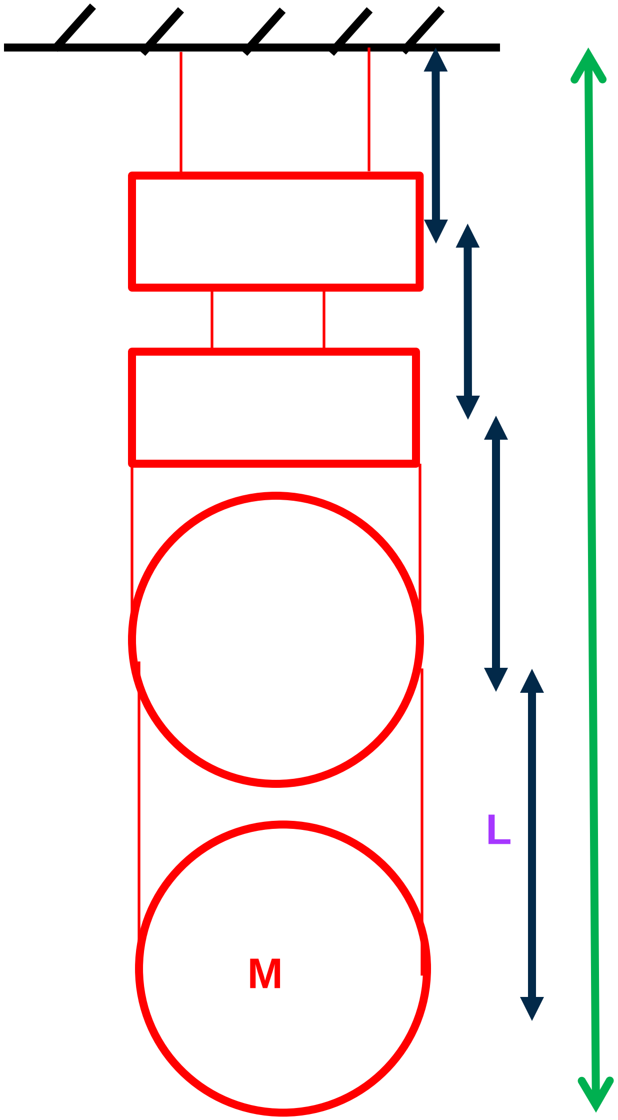
Assumptions for a New Quad

- Assume test mass is silica: (therefore not cryogenic)
  - *Producing a 400 kg silica mass is "just engineering".*
  - *Technology to grow crystalline masses (Si, sapphire) with the desired bulk properties to such sizes does not exist at present*
- Assume aspect ratio of mass is same as current design
- Assume overall length not limited to the maximum available in the current facilities
- Assume overall mass of the suspension is not limited by the current ISI (internal seismic isolation) design

Possible Suspension Design

- New test mass 400 kg:
  - 730 mm diam. (D) x 430 mm thick
- PUM = test mass (M), upper masses each 0.5 M
- **Overall mass (main chain) = 3M = 1200 kg**
- Final stage length, L >= D+0.1 = 0.83 m minimum, up to (say) 1.2 m
- Upper lengths; 0.5 L, 0.5 L, 0.75 L
- **Overall length to bottom of optic**

  = 2.75 L + D/2 = 2.4 m up to ~ 3.6 m



Compare to aLIGO design: final length 0.602 m, total mass 124 kg and total length 1.8 m

Total load on ISI for new design ~3 tonnes

(assume reaction chain mass is ~½ main chain mass, add support structure, telescope)

Approx. to scale for 2.4 m

Longitudinal/Vertical Isolation

- Long: Apply approx. relationship above resonances (T1300786 eqn.1, Brett Shapiro)

$$\frac{x_4}{x_g} \approx \frac{g^4}{(2\pi f)^8} \frac{1}{L_1 L_2 L_3 L_4} \frac{(m_1+m_2+m_3+m_4)(m_2+m_3+m_4)(m_3+m_4)m_4}{m_1 m_2 m_3 m_4}$$

  - Compare to aLIGO performance : new suspension is at least factor of ~3 better
  - Current isolation factor at f =10 Hz (assuming damping rolled off) ~ 10^{-7}
  - New suspension ~ 3 x 10^{-8} (for L_4 = 0.83 m), ~ 7 x 10^{-9} (for L_4 = 1.2 m)

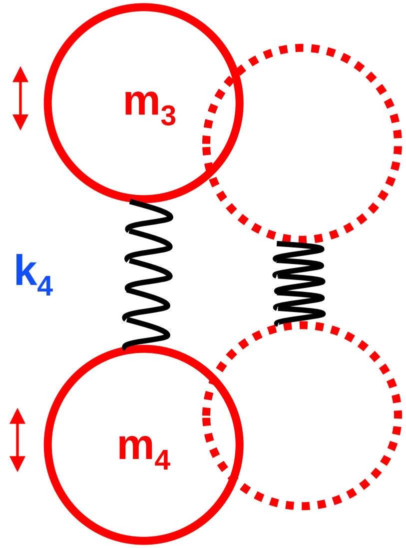
- Vert: apply T1300786 eqn.4 (where k_i = spring constants from top to bottom)

$$\frac{z_4}{z_g} \approx \frac{1}{(2\pi f)^8} \frac{1}{m_1 m_2 m_3 m_4} k_1 k_2 k_3 k_4$$

- Assume the *k/m* of three upper stages remain the same. Any change/improvement in vertical isolation comes from final stage. See next slide.

Final Stage Design

- Bounce frequency = $\frac{1}{2\pi}\sqrt{\left(\frac{2k_4}{m_4}\right)}$, where $m_3 = m_4$
- $k_4 = 4EA/L$, where E = Young's modulus of fibre, A = cross-sectional area, L = length, using 4 fibres
- Simply increase length, keeping A/m same (stress level constant). For minimum increase in length (to 0.83 m)
  - bounce frequency reduces from 9.7 Hz (aLIGO) to 8.3 Hz
  - vertical isolation improves by factor of ~1.4 from aLIGO
- Further reduction in frequency / increase in isolation:
  - Add in cantilever blades (not easy)
  - Raise stress level, e.g. by factor of 2, decreases k by 2
    - bounce frequency ~ 5.8 Hz
    - isolation improvement factor ~ 2.8
    - roll mode frequency ~ 8.2 Hz
    - violin mode frequency essentially unchanged ~ 500 Hz.
  - Increase length further to L_4 = 1.2 m
    - even lower bounce and roll freqs, and better isolation



Modelling Tools

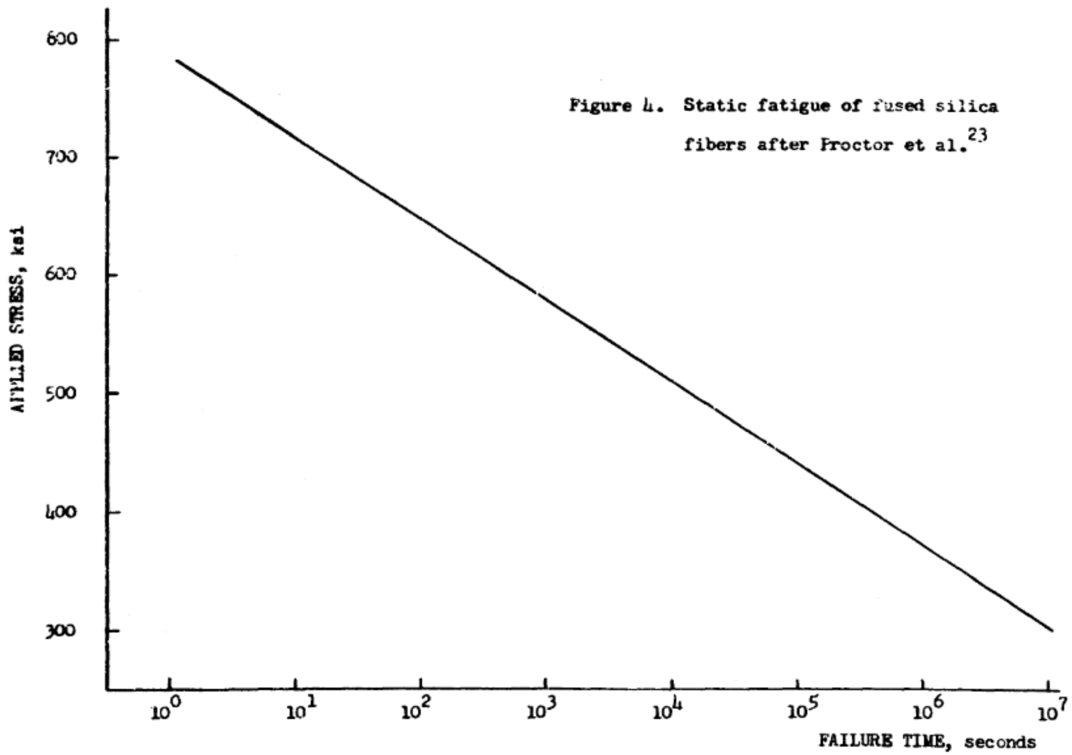
- We have been working on tools to model suspension thermal noise, coating thermal noise, radiation pressure noise.
- Allows upload of data files for noise sources => opportunity for bespoke codes
- Led by Manuel Marcano (2015 summer project) using wxPython (available at https://github.com/manuelmarcano22/aLIGO-wxPython);
- Suspension thermal noise
  - FEA dilution figures
  - horizontal, vertical and violin thermal noise
- Coating thermal noise
  - finite test mass correction (Somiya and Yamamoto, Phys. Rev. D 79, 102004, 2009
  - optimised aLIGO coatings (16×131nm Ta_2O_5 and 17×182nm SiO_2)
- Seismic Noise
  - uses DCC note by Shapiro et al. (T1300786) to estimate transmissibility (longitudinal and vertical)
  - uses BSC requirements for ISI seismic noise

How Much Stress

- Ultimate tensile stress in fused silica has been well studied (e.g. Proctor 1967)

4GPa

2GPa

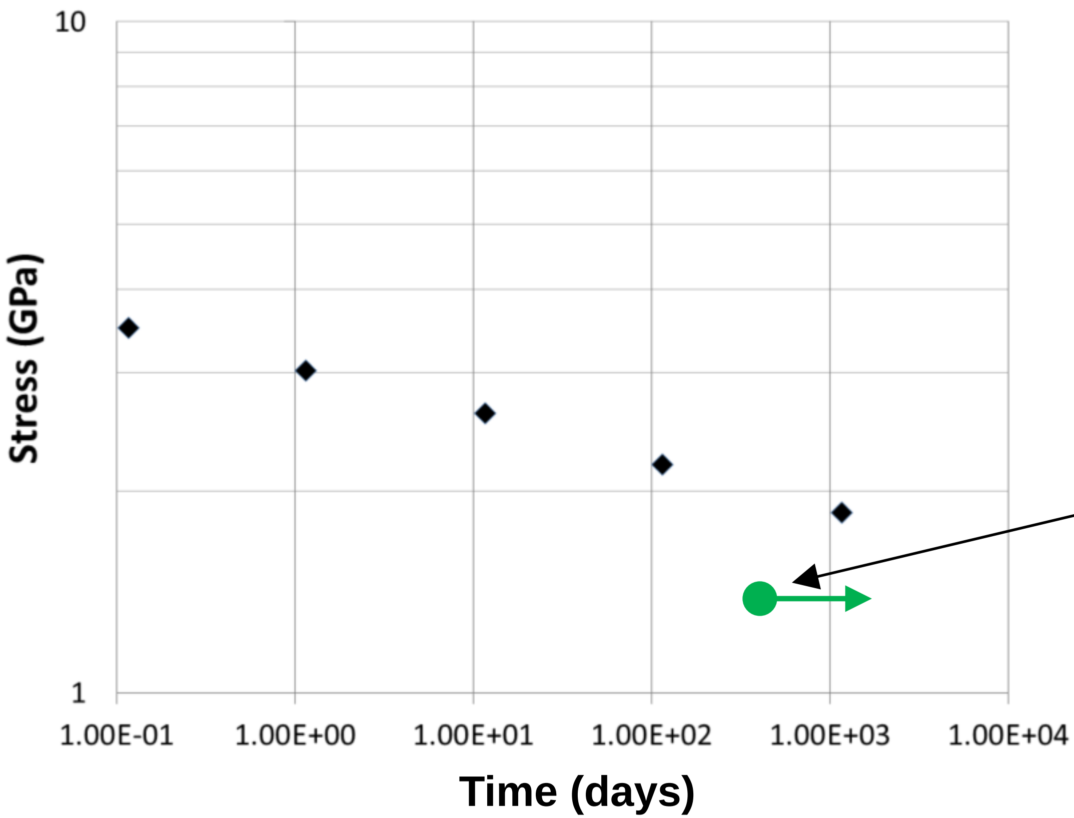


1 day

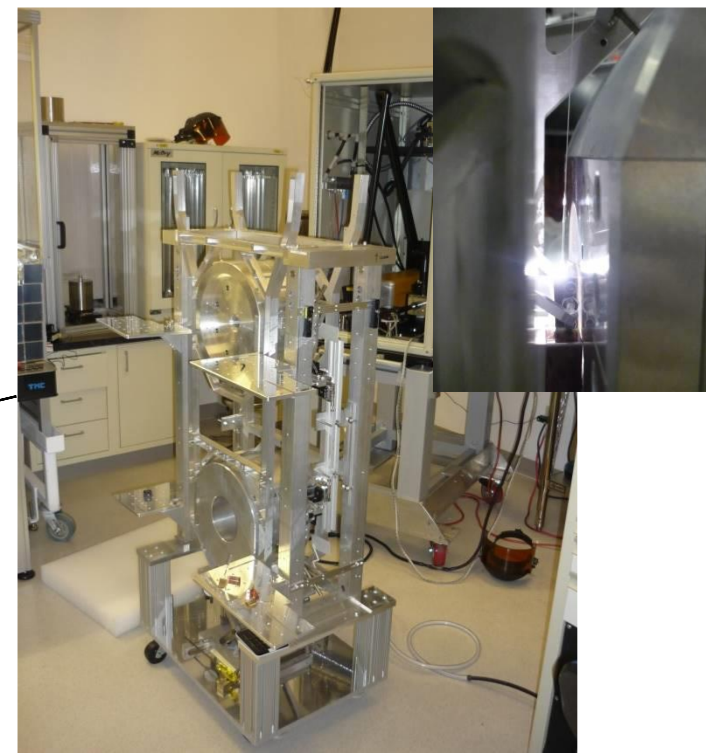
Proctor et al., Proceedings of The Royal Society A Mathematical Physical and Engineering Sciences, 297(1451), 534-5571967

How Much Stress

- There is margin for operating at higher stress and maintaining a robust suspension



- LHO test suspension, hanging in air for >1 year @ 1.2GPa. Still hanging



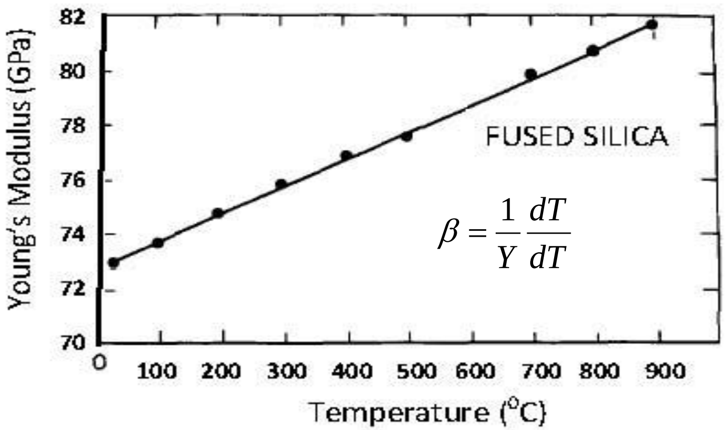
Heptonstall et al., Classical and Quantum Gravity, 31 (10). p. 105006, 2014

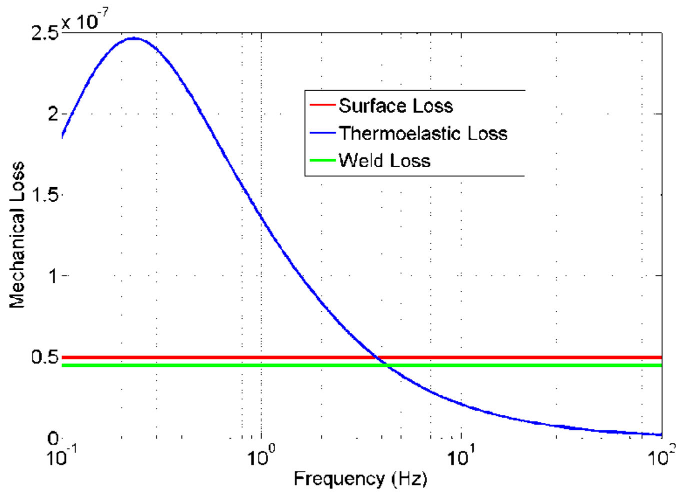
How Heavy can We Go

- aLIGO utilises thickened fibre ends (800μm) to cancel thermoelastic loss

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

- Dominant loss terms are then surface and weld, with roughly equal contribution

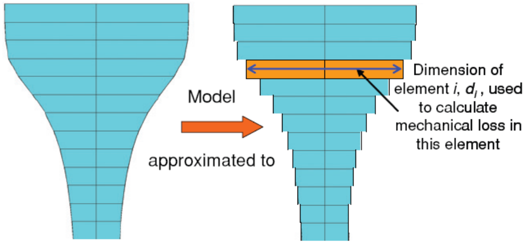


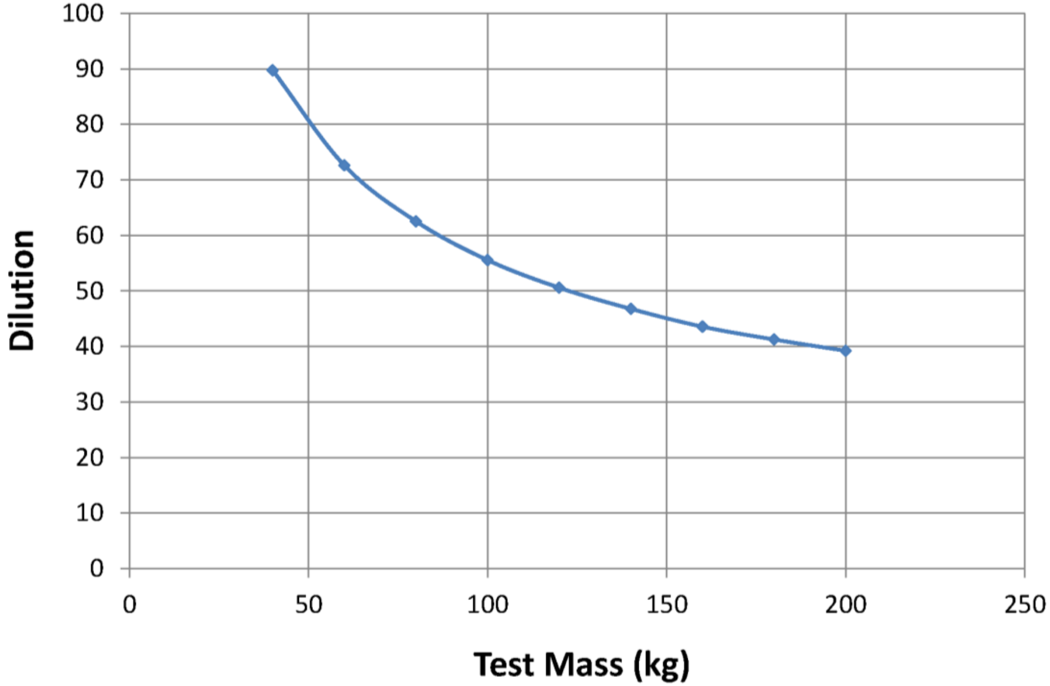


- Heavier mirrors require thickening of the fibres to maintain cancellation (≈190MPa); 1.8mm for 200kg and 2.6mm for 400kg
- This is not really a problem but will require thicker stock (e.g. 5mm)

How Heavy can We Go

- Dilution in the horizontal direction is important to realise the ultimate noise performance
- Even for aLIGO theoretical dilution is larger than FEA value, due to the non-rigid 3mm stock
- For heavier mirrors, the dilution flattens





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

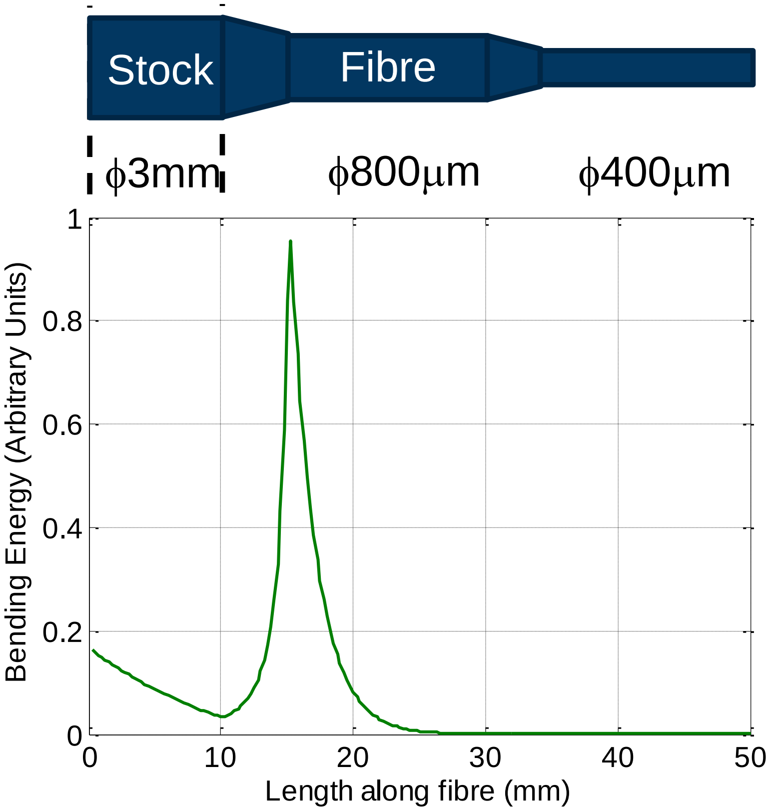
- Dilution values are for a 0.6 m suspension.

Warm Upgrades: Suspensions

- A variety of techniques will need to be used to further improve room temperature suspension thermal noise of aLIGO

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

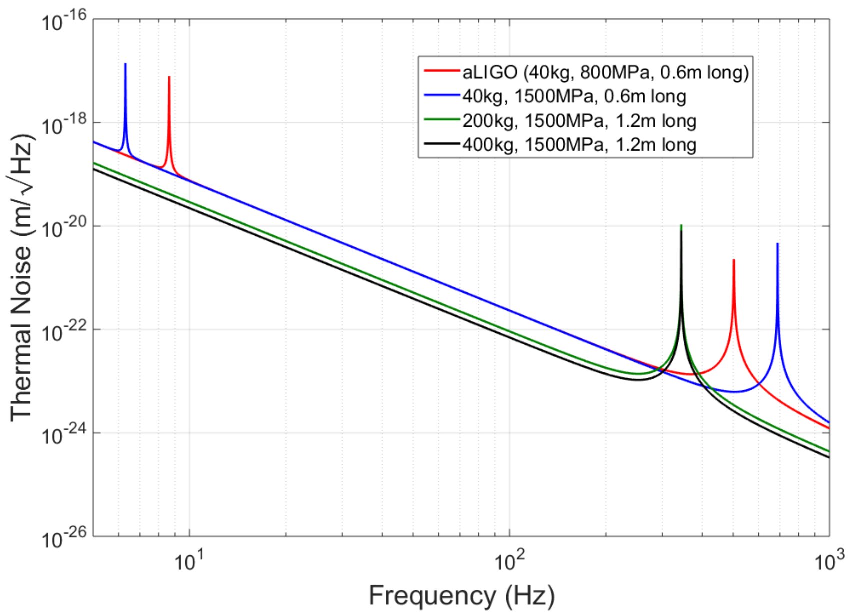
$$S_x(\omega)=\frac{4k_BT}{m\omega}\left(\frac{\omega_o^{\,2}\phi_{total}(\omega)}{\omega_o^{\,4}\phi_{total}^{\,2}(\omega)+\left(\omega_o^{\,2}-\omega^2\right)^2}\right)$$

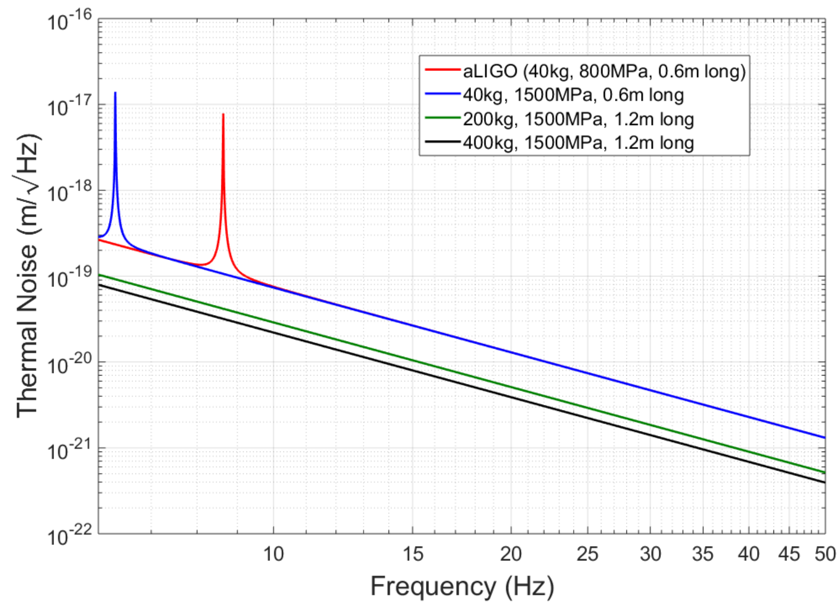


- Reduce surface loss and weld loss in suspension
- Longer suspensions to improve dilution
- Shorter fibre neck => reduce energy distribution up the neck
- Shorter stock length => reduce energy distribution up the neck
- Pull from thicker stock (3mm→5mm)

Performance

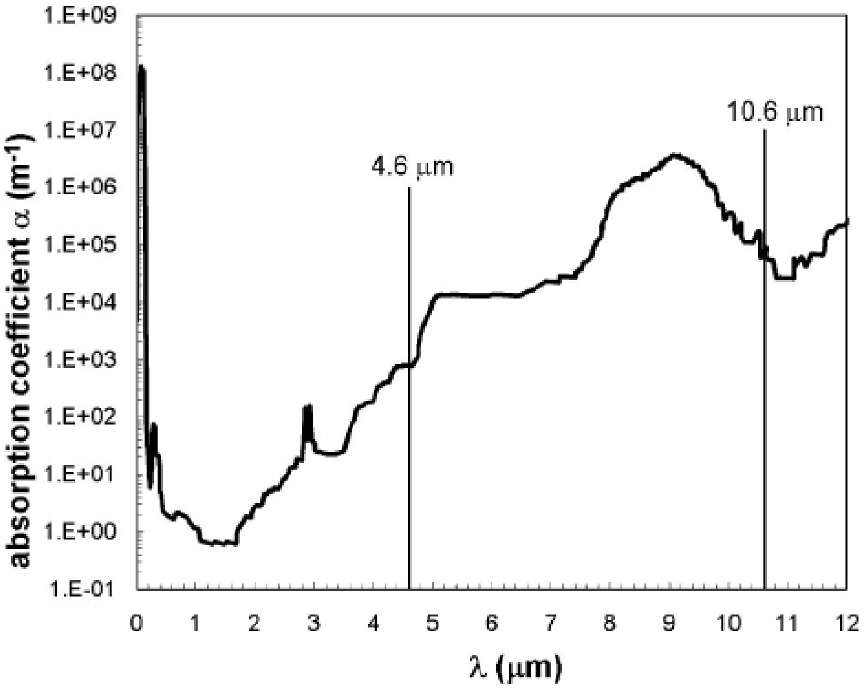
- Putting this all together, we can estimate the performance for; (i) aLIGO, (ii) a 1.2m long suspension, mirror=160kg, 1.5GPa stress (iii) a 1.2m long suspension, mirror=400kg, 1.5GPa stress

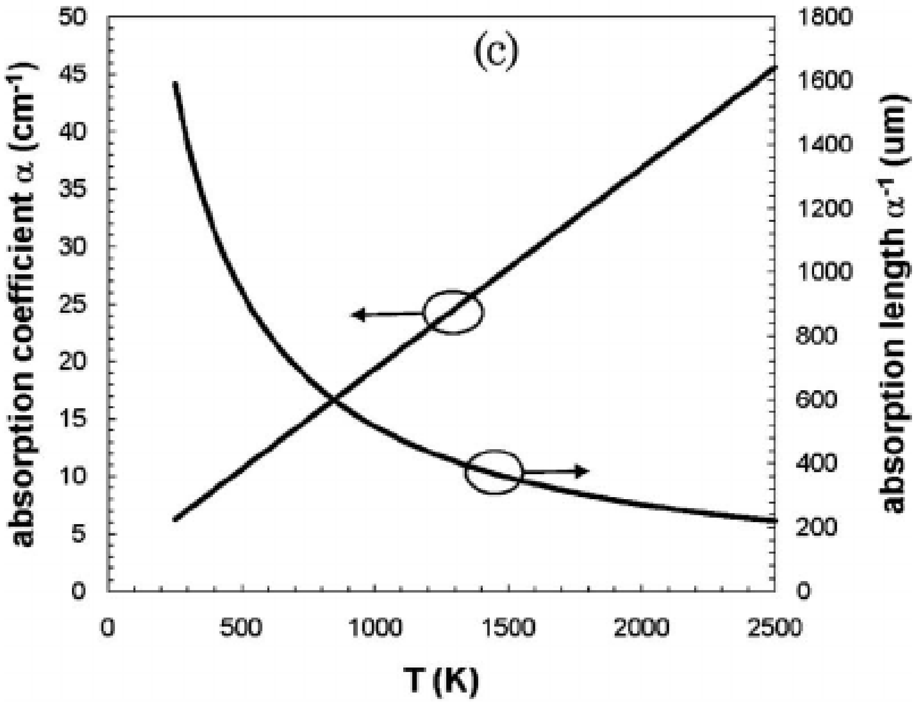




Alternative Fibre Pulling Laser

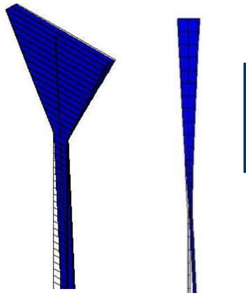
- CO_2 is a good choice for fibre pulling as high powers are available
- But absorption length is small, so most heat is deposited in outer layers and needs to be conducted inwards => inefficient and leads to vapour



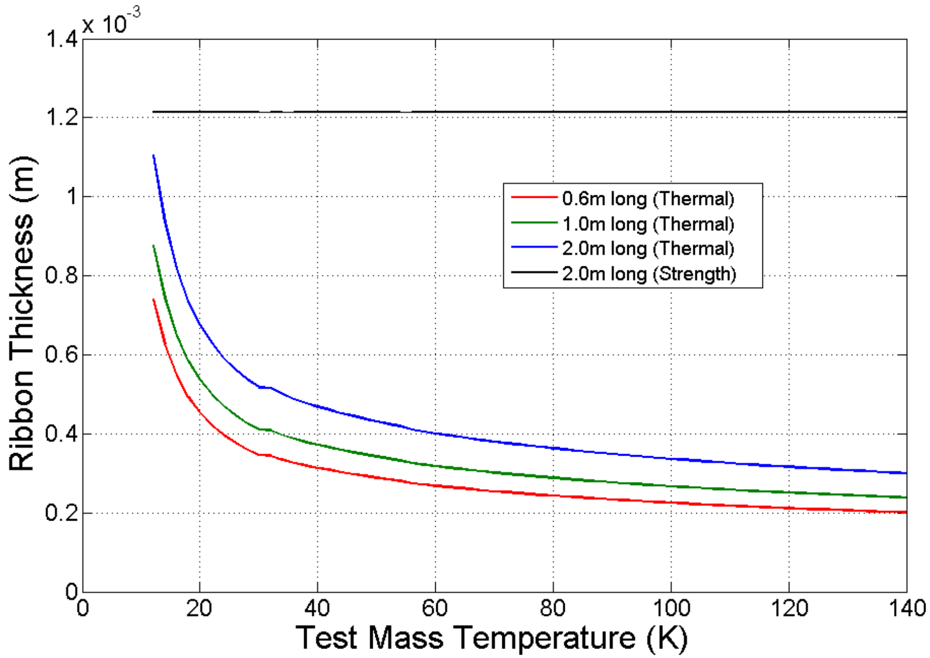


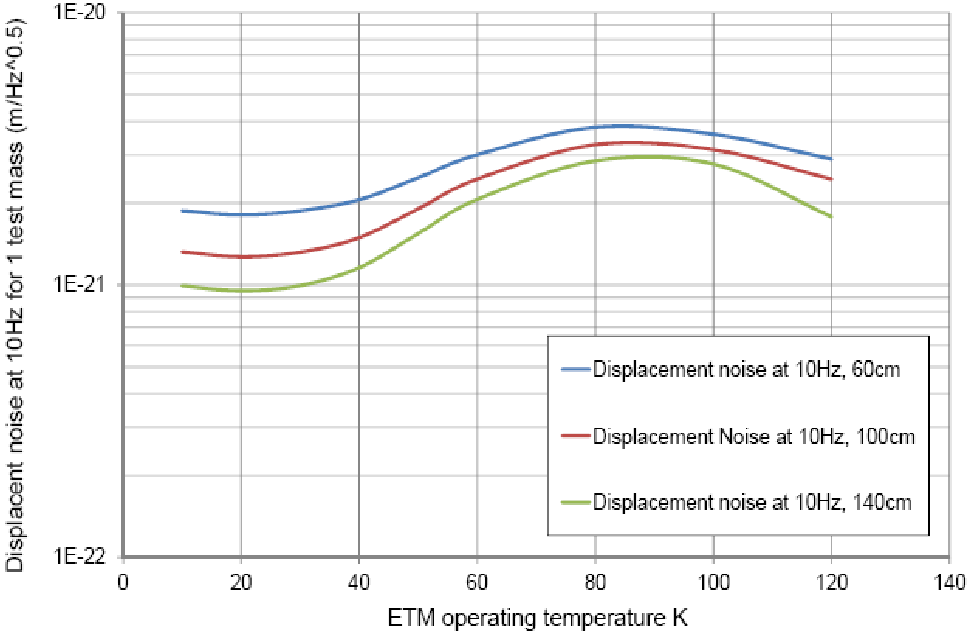
Yang et al., Applied Optics, 49(14), 2010

Cold Upgrades: Suspensions



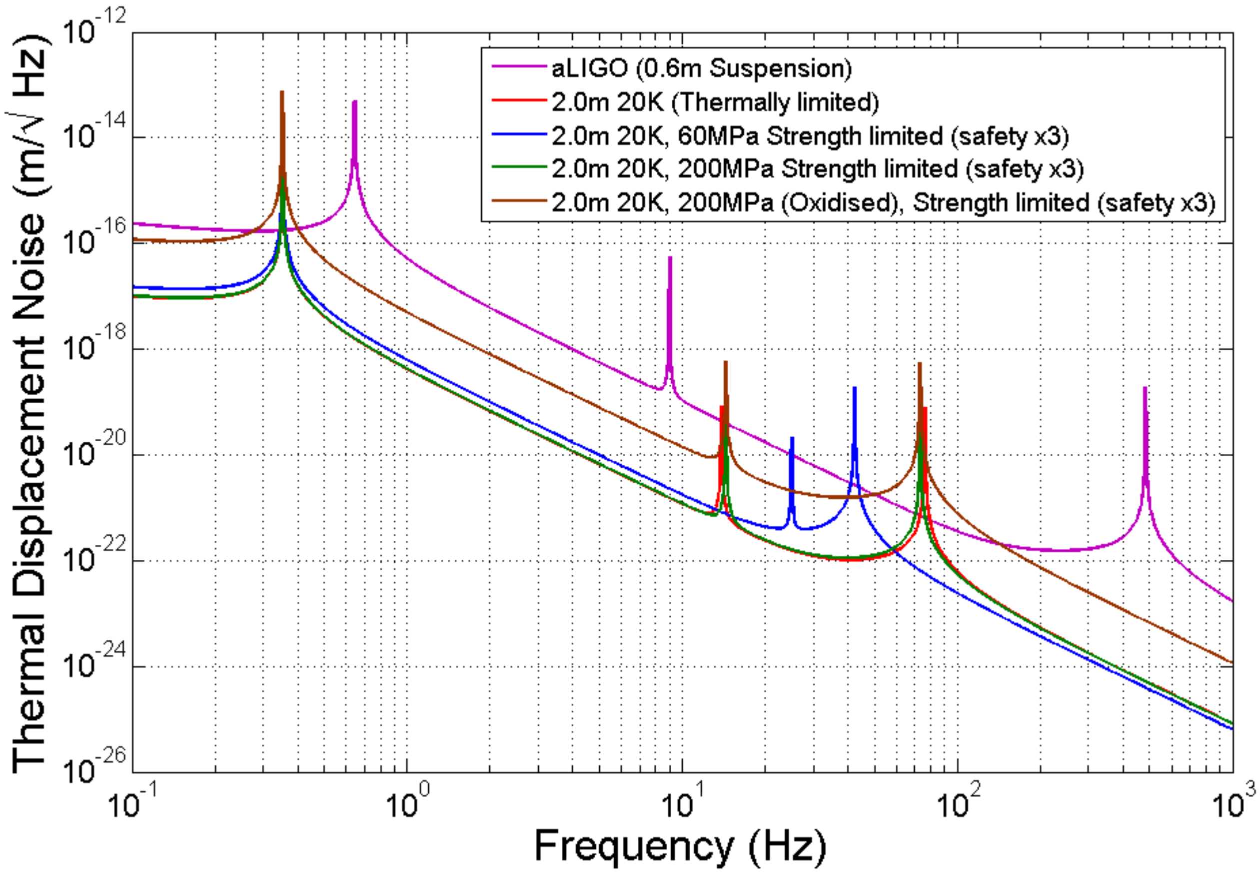
- Utilise crystalline materials such as silicon (ET baseline) or sapphire (KAGRA baseline)
- For low temperature (<100K) operation any heat input by the detector laser beam must be extracted via conduction up the suspension fibres. For T>100K radiative cooling is possible
- Model loss terms in a similar way to the fused silica but with suitable parameters which vary with temperature. Assume ribbon geometry to improve dilution.





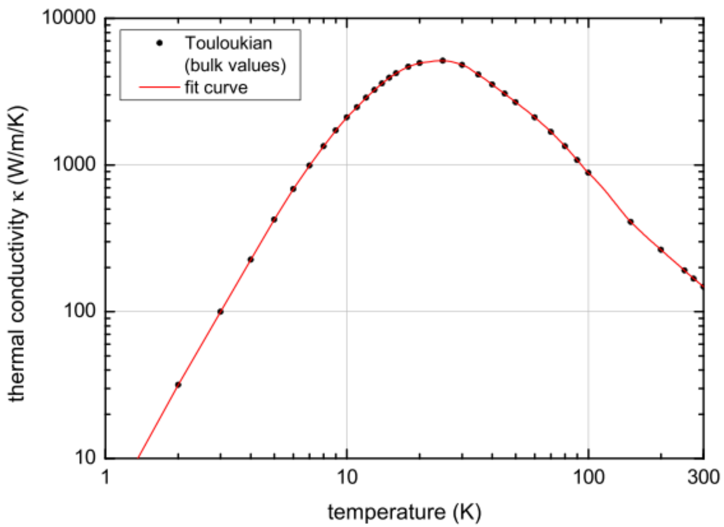
Cold Upgrades: Suspensions

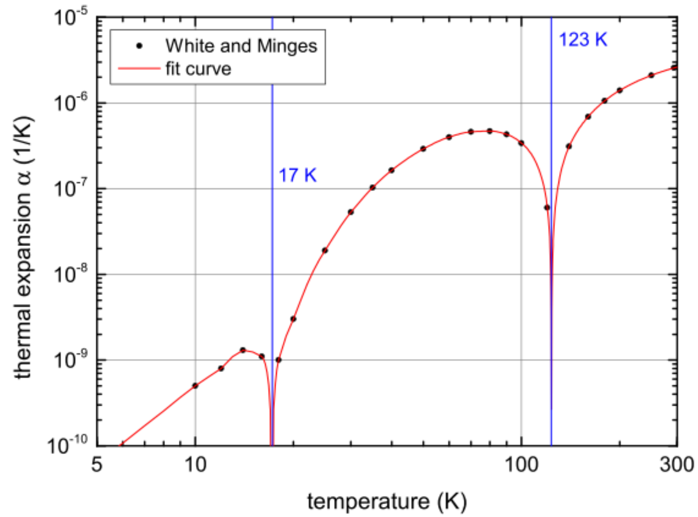
- Tensile strength tests of Silicon suggest values of 200MPa-300MPa for a variety of samples which have been mechanically polished, etched or oxidized (fused silica is 4GPa-5GPa)
- Thermal noise performance depends on whether thermal or strength limited



Cryogenic Technologies

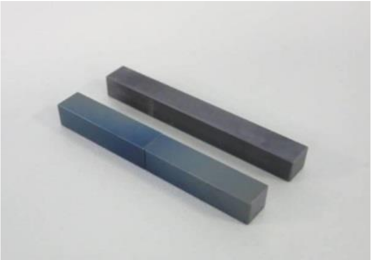
- Crystalline materials display high thermal conductivity and silicon has nulls in its thermal expansion at 123K and 17K (nulling thermoelastic noise)

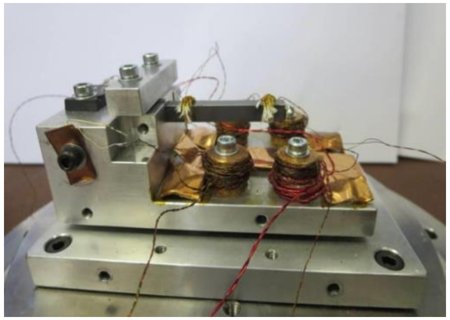


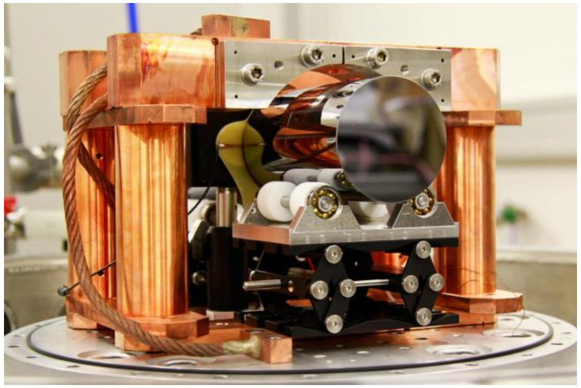


- Experimental programme to measure thermal conductivity, mechanical loss and techniques to bond (including robustness under thermal cycling)

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

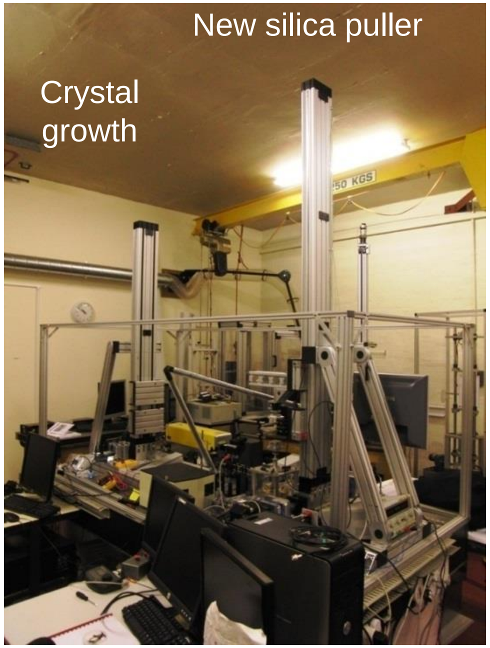




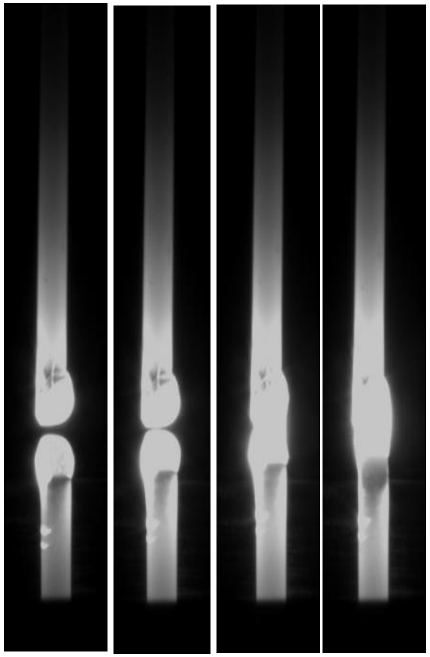


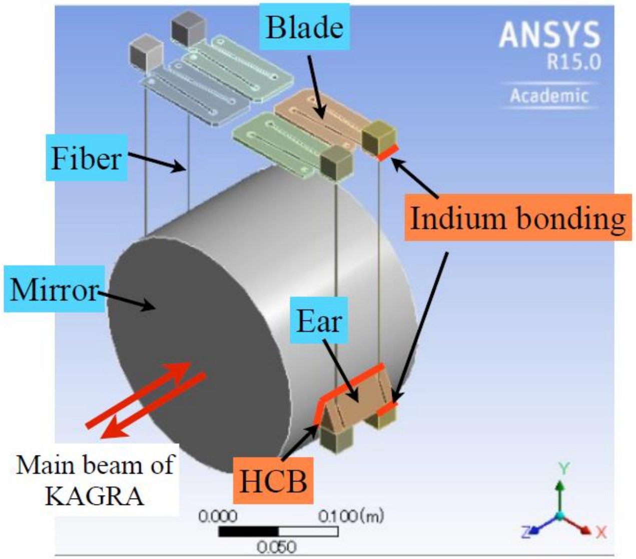
Cryogenic Technologies

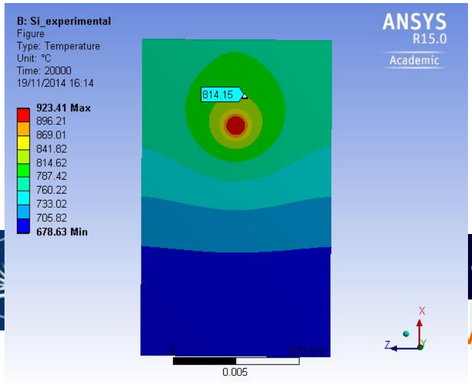
- Techniques to grow crystalline materials and provide reversible joints (e.g. indium bonding) are also current areas of research



Jointing sapphire with CO_2 laser



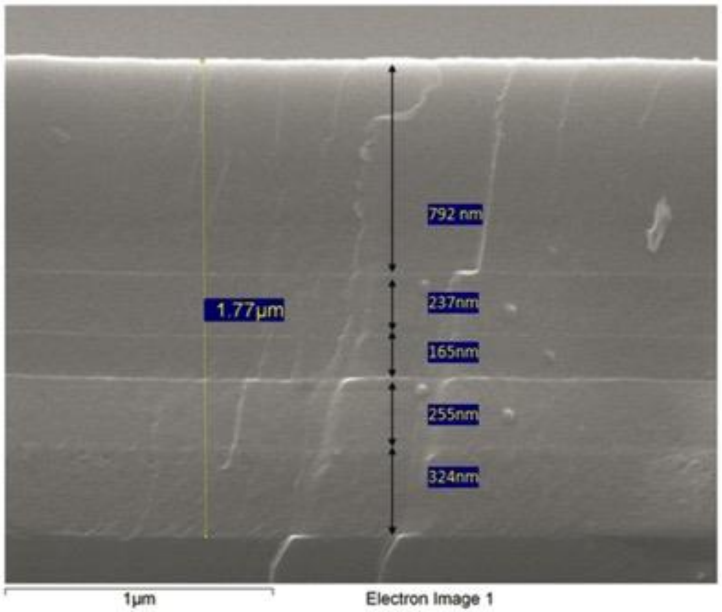




- Laser heated pedestal growth using CO_2 laser
- FLUENT thermal modelling

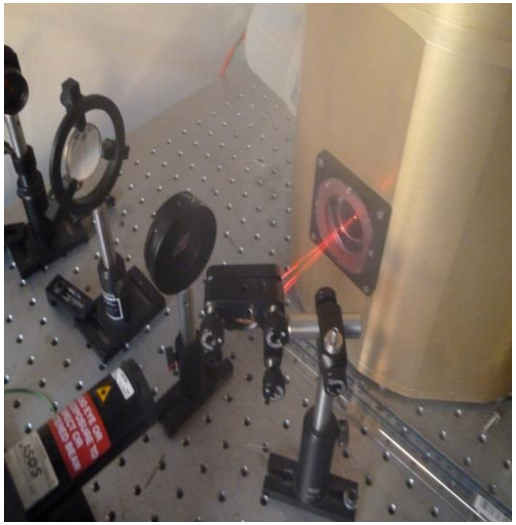
Cryogenic Technologies

- Working on DLC coatings for improved robustness during handling and for high emissivity cryogenic coatings (e.g. baffles and heat ducts)



- SEM cross-section of 5-layer modified DLC deposited on silicon

Small cryostat for coating mechanical loss measurements



Large cryogen-free cryostat for 1kg prototype silicon suspension