Monolithic Suspensions for Advanced Detectors

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on behalf of the Suspensions Working Group

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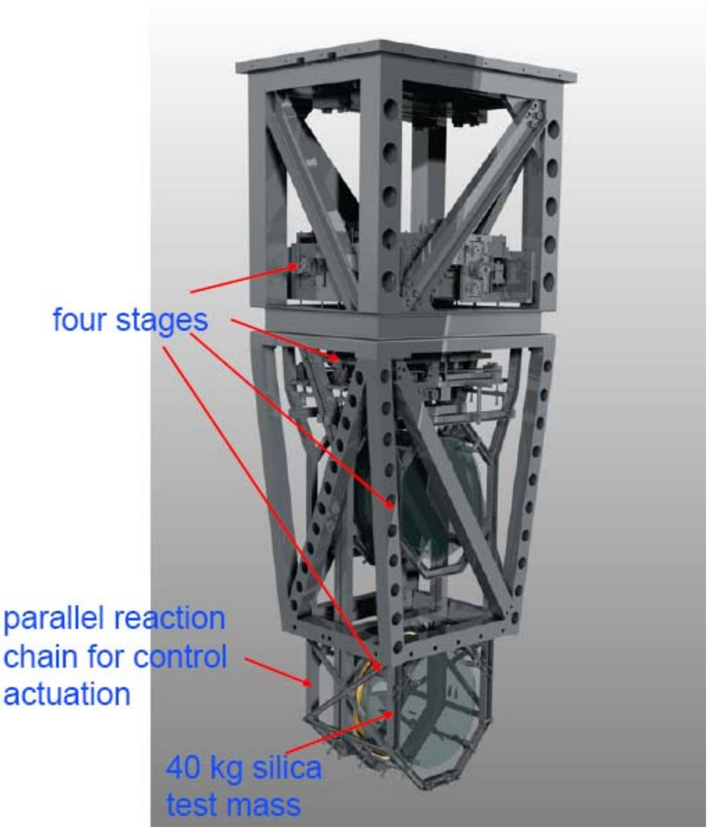
Overview of the presentation

- Advanced LIGO update (ear design and production, laser pulled fibres, laser welding)
- Test hangs in Glasgow and LASTI
- Suspension requirements for 3rd generation detectors
- Thermal noise and fibre geometry with silicon
- Summary

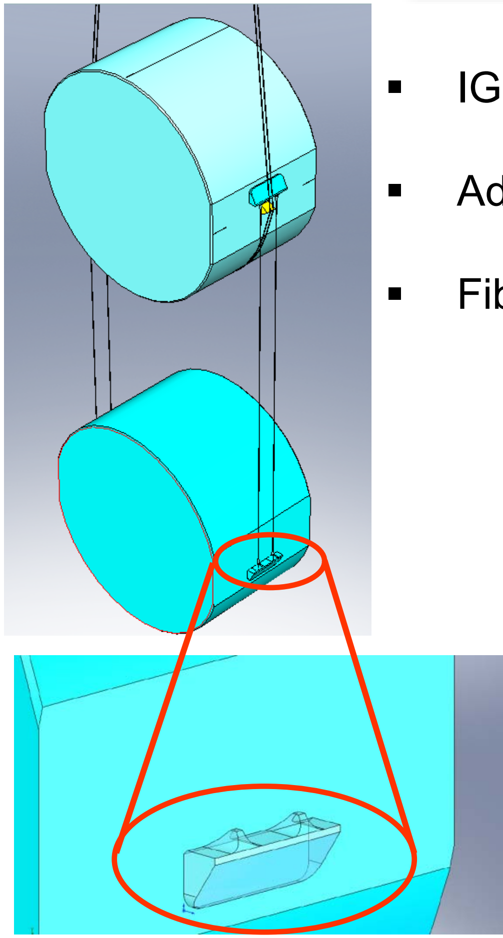
Suspension for Advanced LIGO

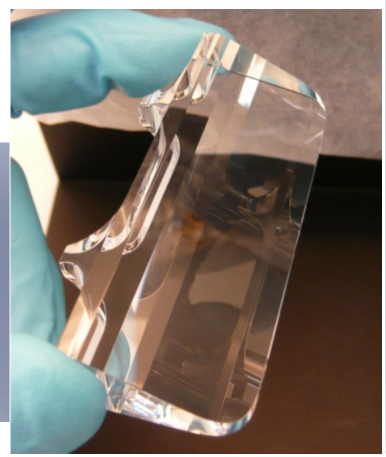
- Seismic isolation: use quadruple pendulum with 3 stages of maraging steel blades
- Thermal noise reduction: monolithic fused silica suspension as final stage
- Control noise minimisation: apply damping at top mass (for 6 degrees of freedom) and use quiet reaction pendulum for global control actuation in a hierarchical way
- Coil/magnet actuation at top 3 stages
- Electrostatic drive at test mass

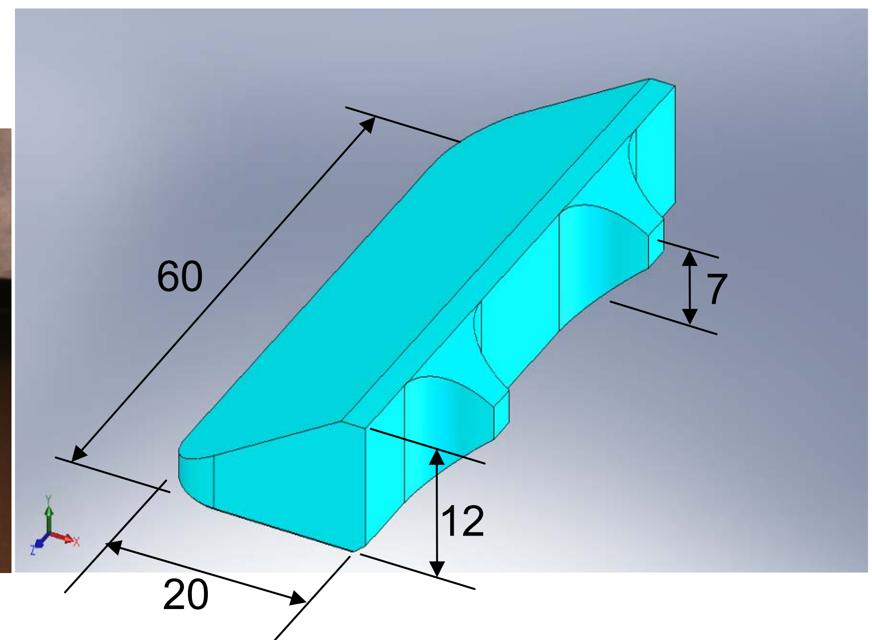


Ear design and production

- IGR (SUPA, University of Glasgow) providing monolithic suspension
- Advanced LIGO: 40kg test mass suspended by 4 silica fibres
- Fibres are butt welded onto silica ears bonded to the test mass







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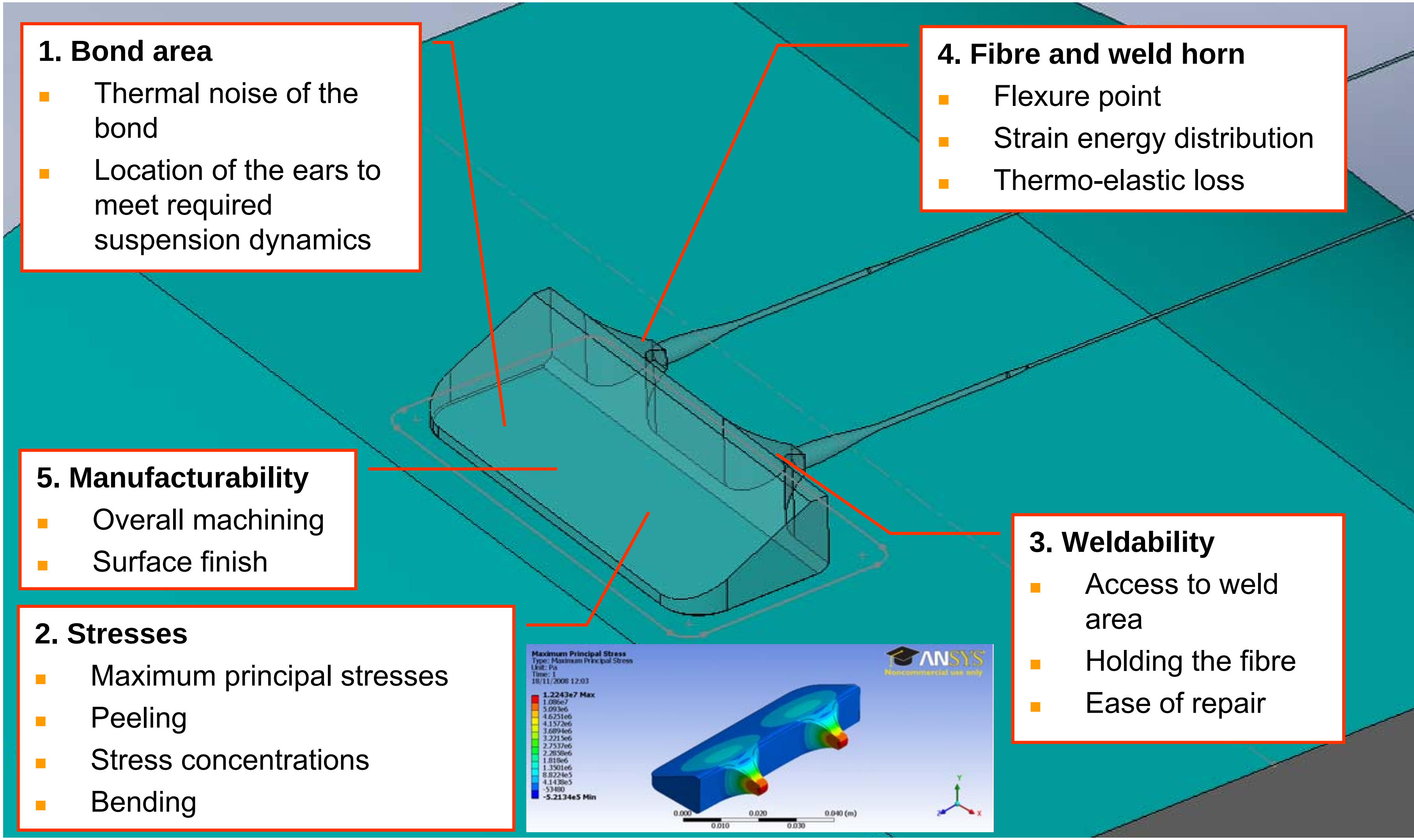
Design considerations (Adv LIGO + ET)



1. Bond area
- Thermal noise of the bond
- Location of the ears to meet required suspension dynamics

4. Fibre and weld horn
- Flexure point
- Strain energy distribution
- Thermo-elastic loss

5. Manufacturability
- Overall machining
- Surface finish

3. Weldability
- Access to weld area
- Holding the fibre
- Ease of repair

2. Stresses
- Maximum principal stresses
- Peeling
- Stress concentrations
- Bending

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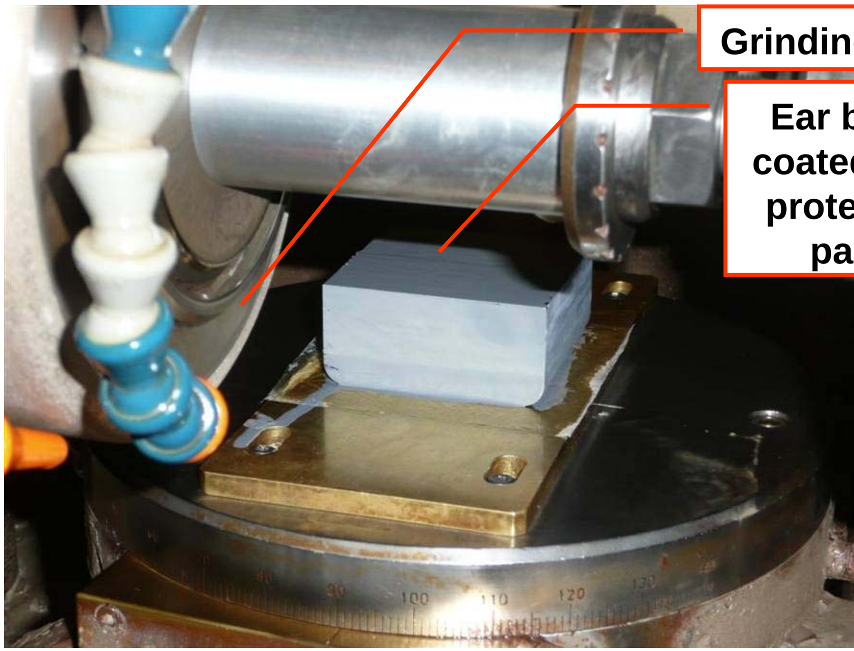
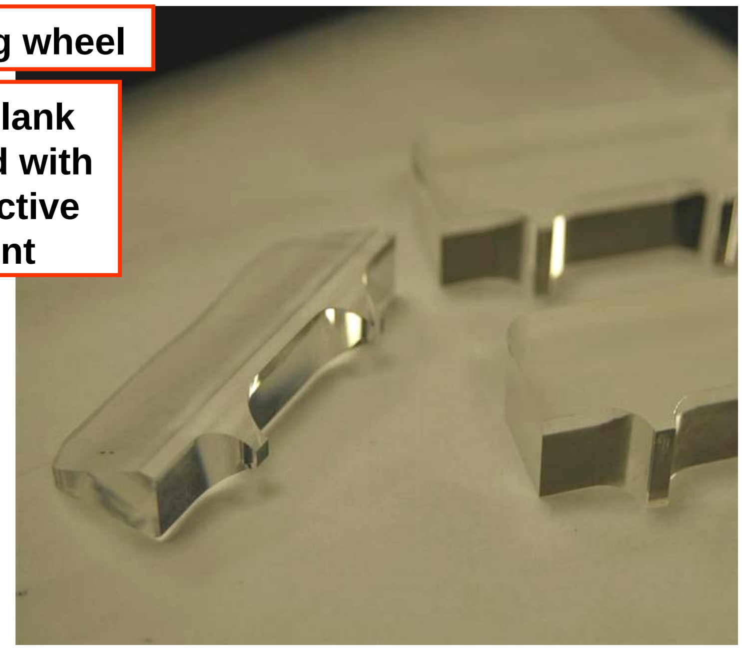
Ear redesign and production (Adv LIGO)



Grinding weld horns



1st ear production status showing two stages

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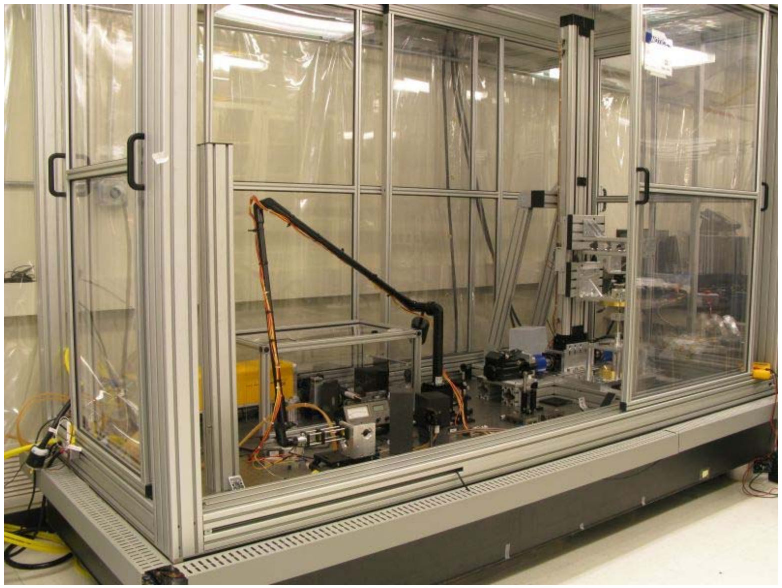
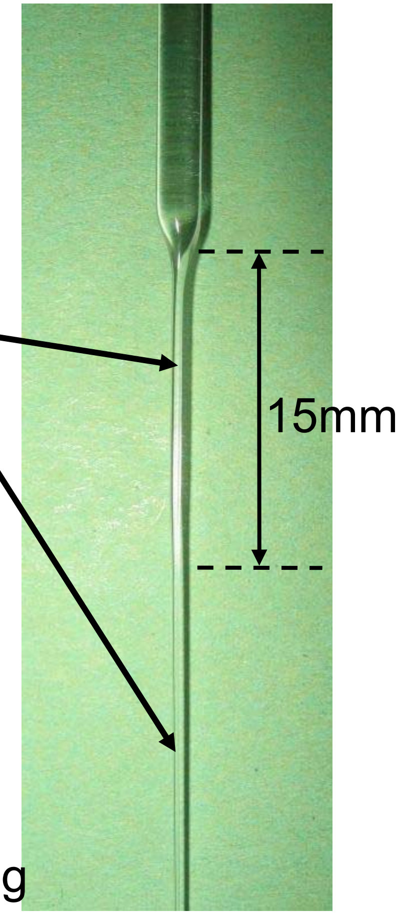
Laser pulled fibres (Adv LIGO)



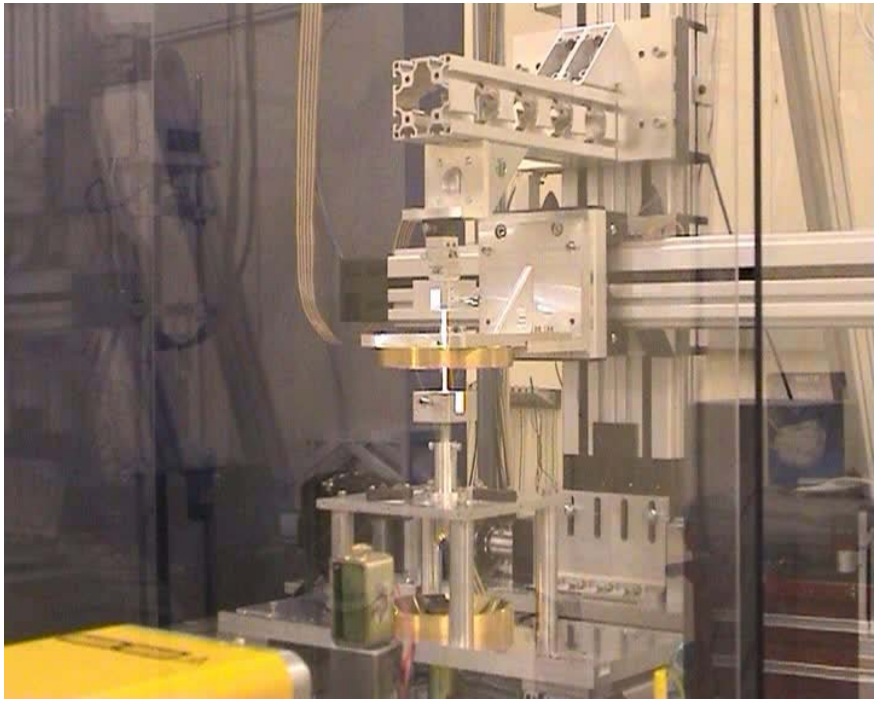
Advanced LIGO fibre geometry

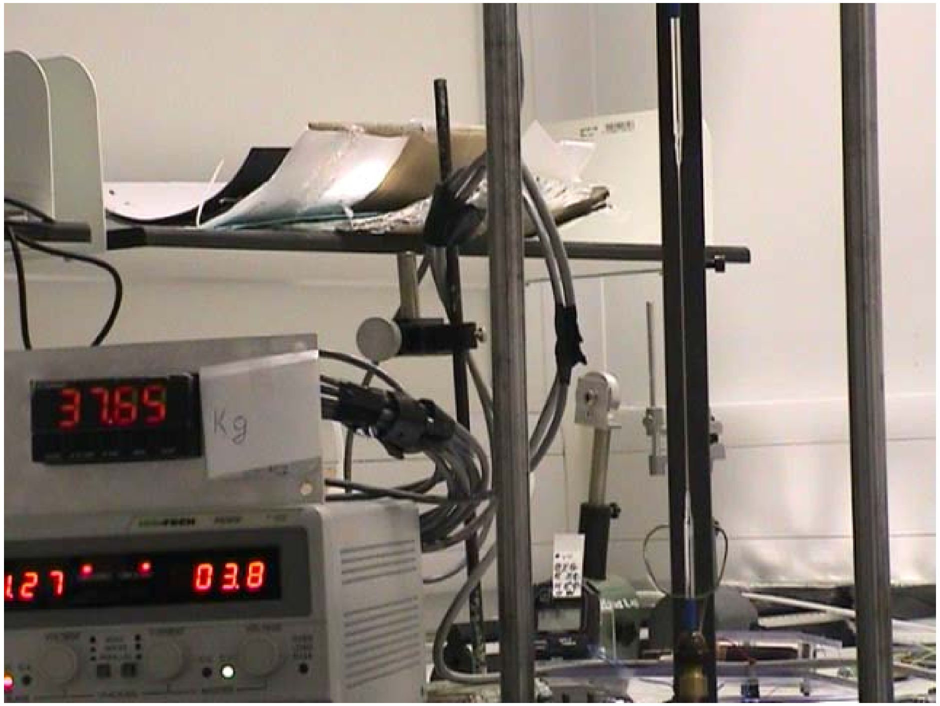
- 60cm long
- 0.8mm diameter neck
- 0.4mm diameter body



- Pulling machine is capable of pulling reproducible fibres
- Recipe for fibres developed in collaboration with Glasgow/LASTI
- Fibres are stored in racks within a low humidity enclosure
- Strong fibres (>5GPa) are possible with high power+laser polishing

Laser pulled fibres (Adv LIGO)





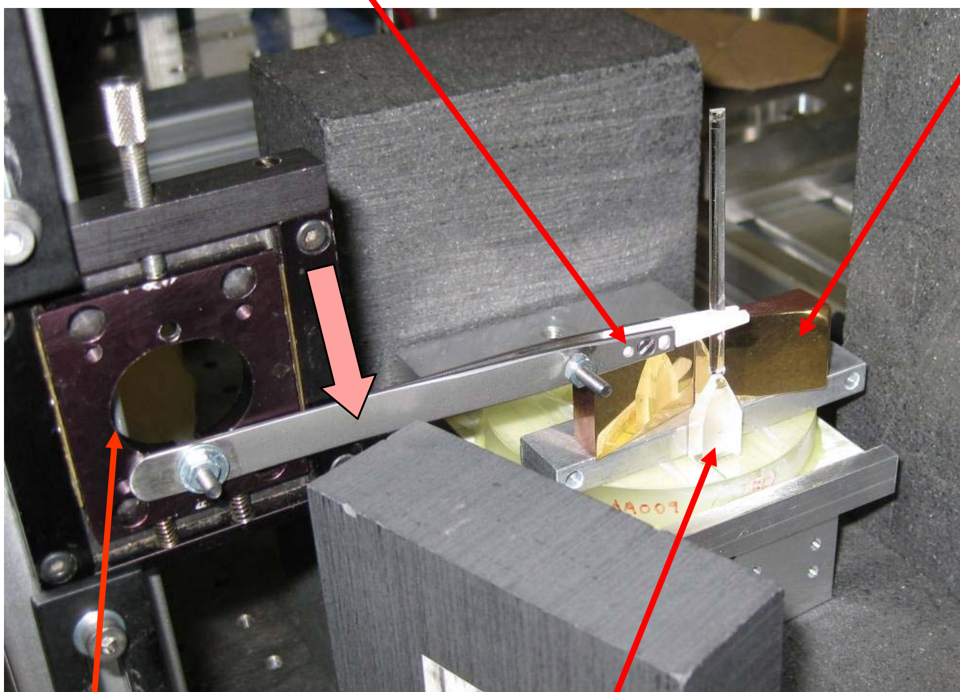
0.35mm diameter fibre

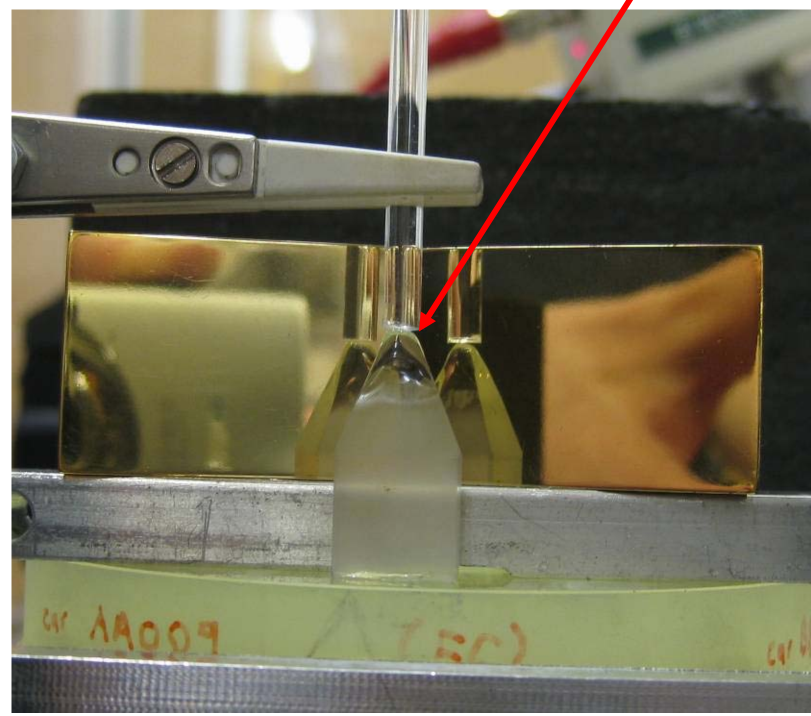
Laser welding (Adv LIGO)

Zirconia tipped tweezers

Gold coated mirror

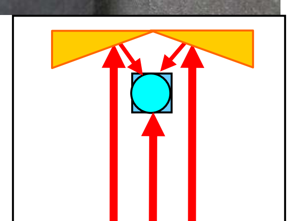
Back side accessible via mirror reflection





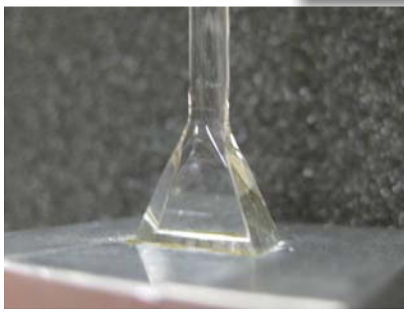
Translation stage to move stock down

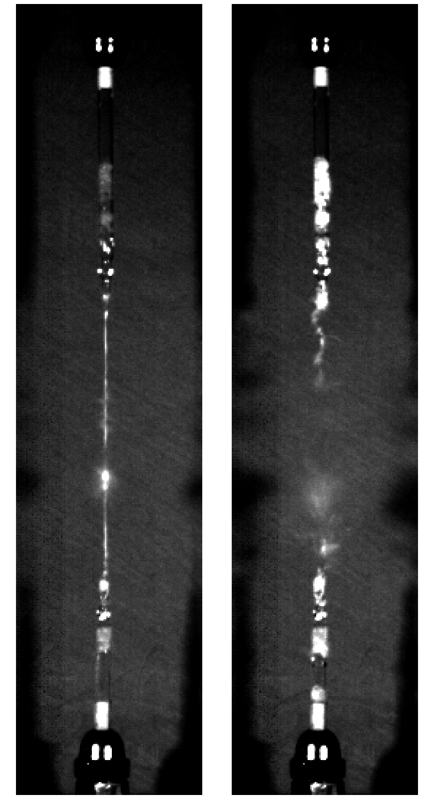
test ear



Laser view

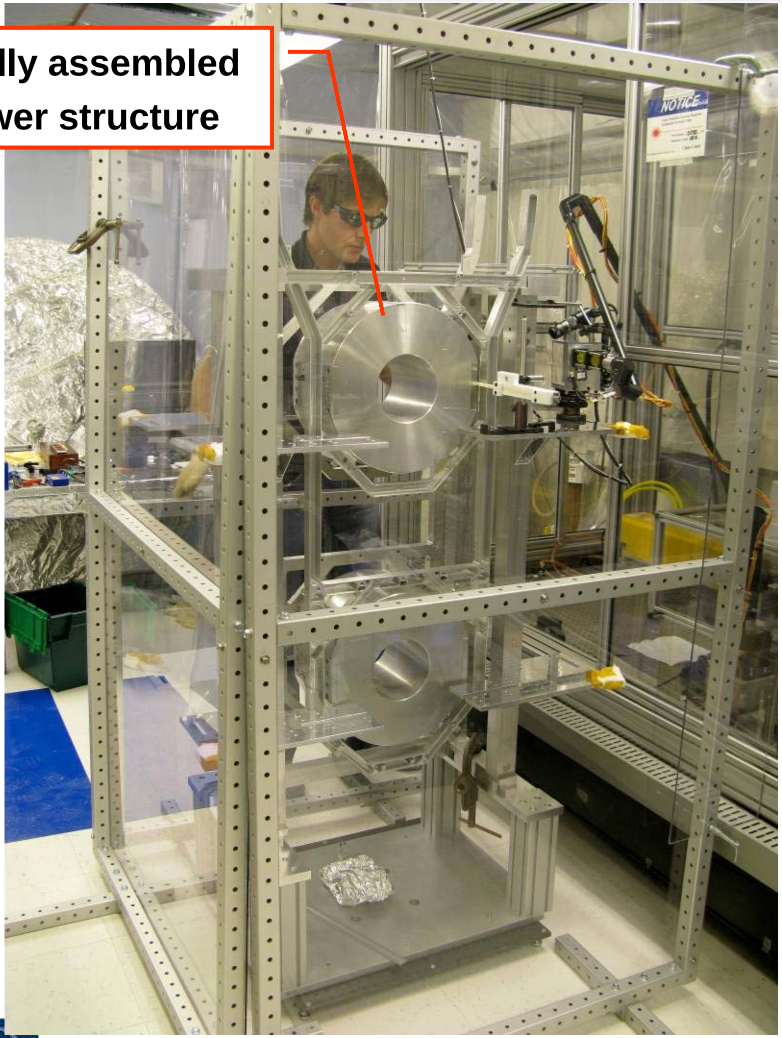
Laser welding (Adv LIGO)

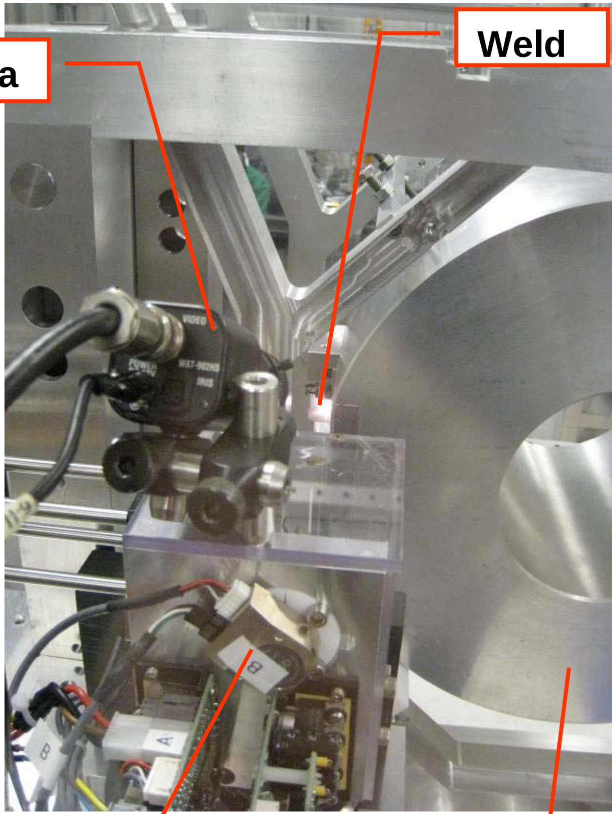




Samples with welds have supported loads up to 93 kg (eventually breaking in the stock, not the weld)

Preparing for test hangs in the UK and US





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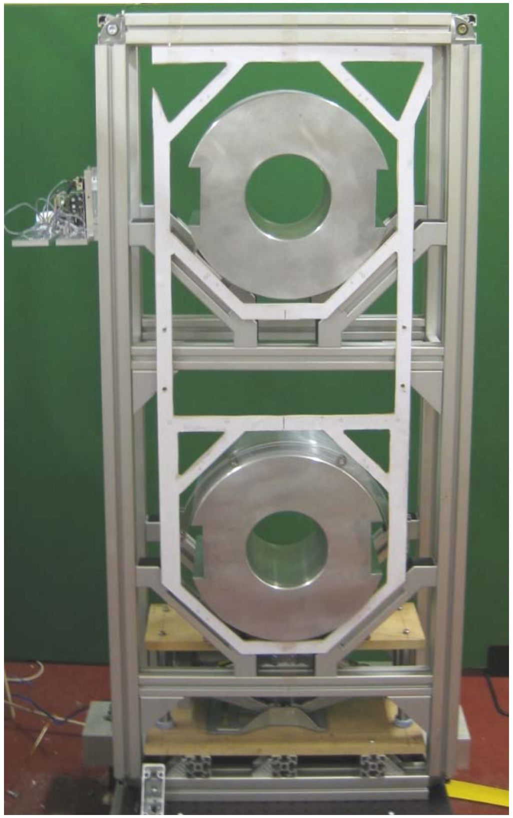
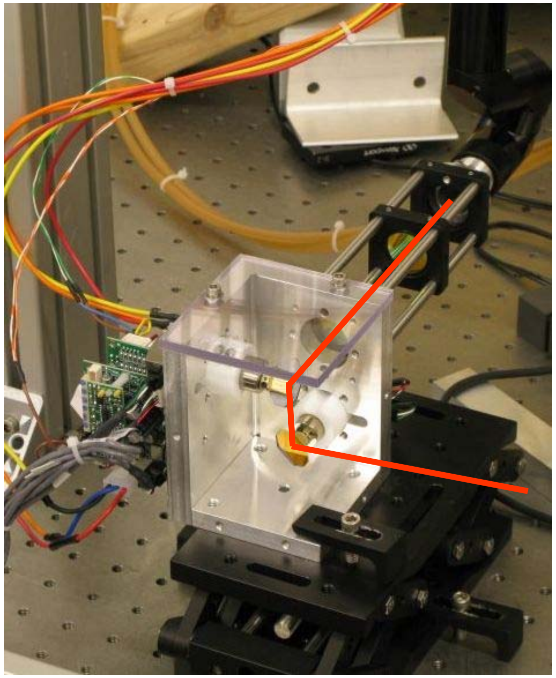
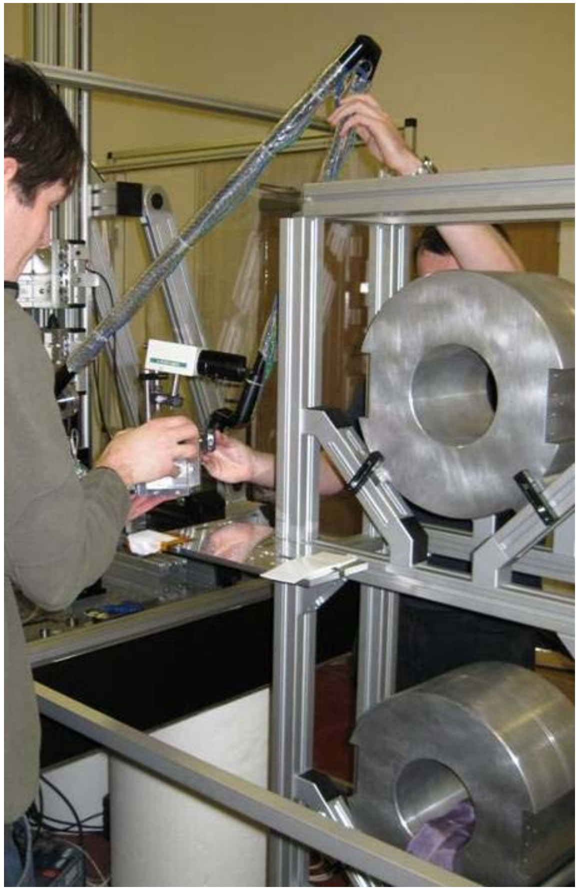
Preparing for test hangs in the UK and US



Mock-up lower structure



Mirror galvanometers



Articulated arm

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Requirements for 3rd Generation Detectors

- Operation down to ≈1Hz => improved seismic isolation
- Lower thermal noise => cryogenic temperature + low loss materials
- Higher laser power => heavier test mass
- Ability to remove up to 1W at cryogenic temperatures

Parameter	LIGO	Advanced LIGO	ET
Mirror Mass	10kg	40kg	150kg (see R. Nawrodt's talk)
Cut off frequency	f> 50Hz	f>10Hz	f>1Hz
Mirror suspension	Single pendulum	Quadruple pendulum	5 stages (10m)
Monolithic stage	--	60cm	1m

Thermal noise and fibre geometry (Adv LIGO)

- The baseline design for Advanced LIGO is a circular cross section dumbbell fibre

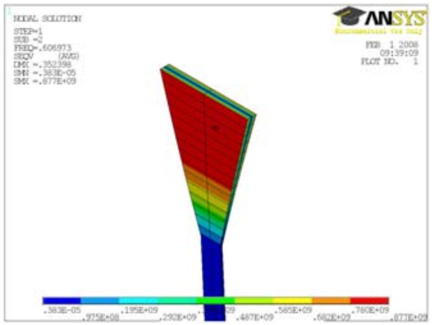
$$\phi_{total} = \frac{1}{D}\left[\phi_{bulk} + \frac{E_{surface}}{E_{bulk}}\phi_{surface} + \frac{YT}{c_v}\left(\frac{f\tau}{1+(f\tau)^2}\right)\left(\alpha - \left[\frac{1}{Y}\frac{dY}{dT}\right]\frac{\sigma_0}{Y}\right)^2\right]$$

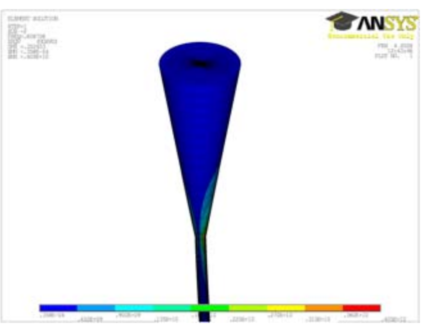
dilution — bulk + surface loss — non-linear thermoelastic loss

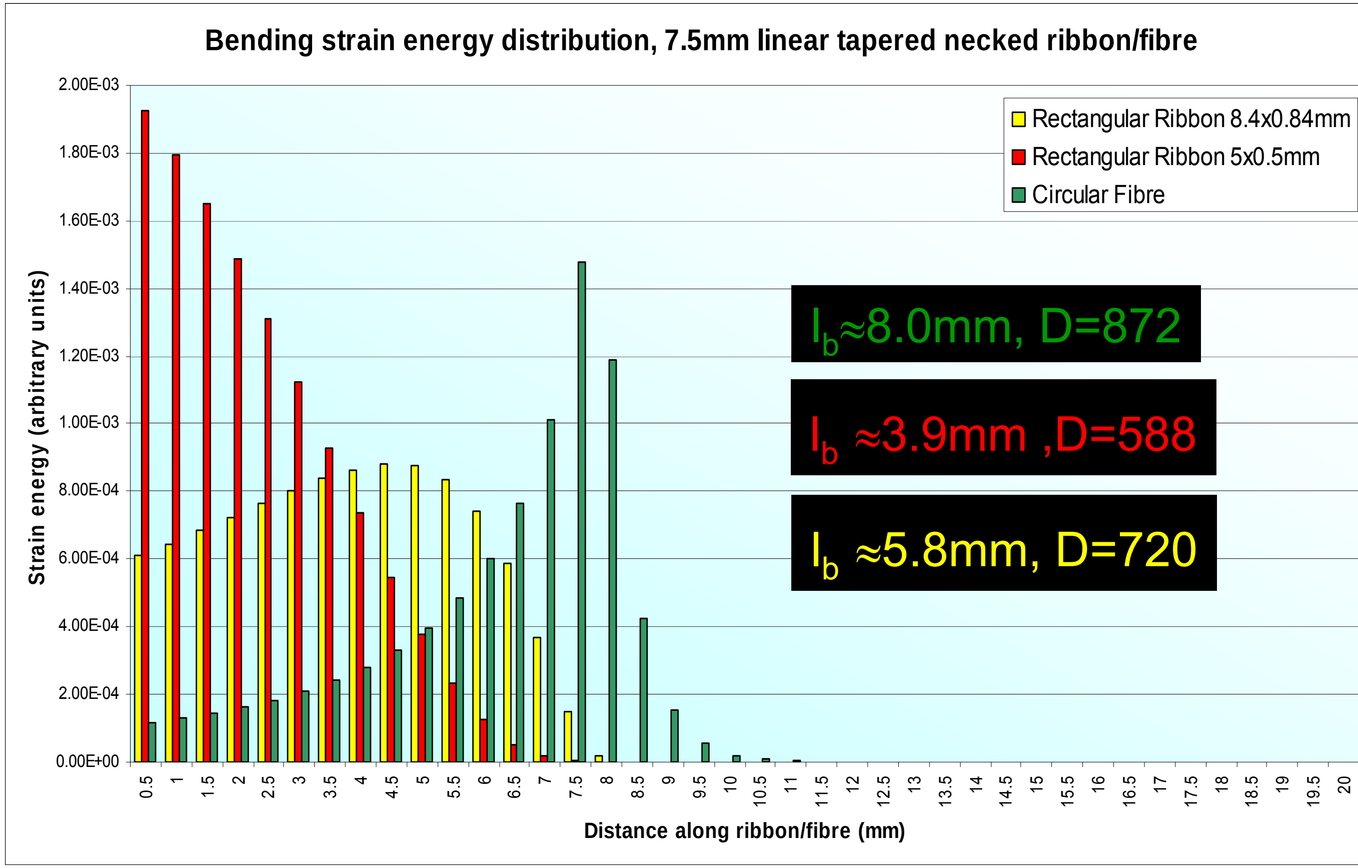
- The strain energy distribution in the neck region is an important factor when trying to assess the real performance of a particular geometry (i.e. dilution factors)

G. Cagnoli and P.A. Willems, Phys. Rev. B, 2002
P.A. Willems, T020003-00
A.M. Gretarsson et al., Phys. Rev. A, 2000
M.Barton et al., T080091-00-K

Thermal noise and fibre geometry (Adv LIGO)

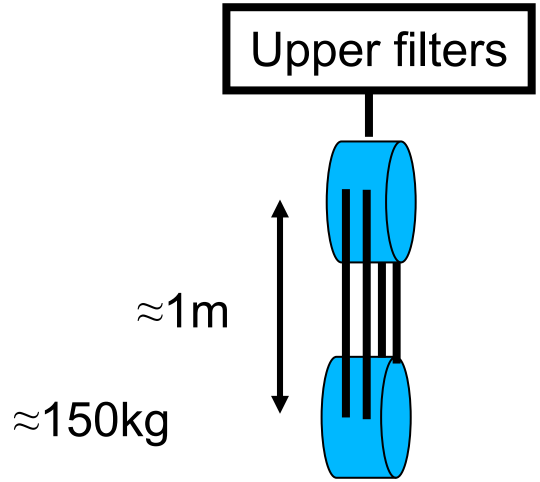


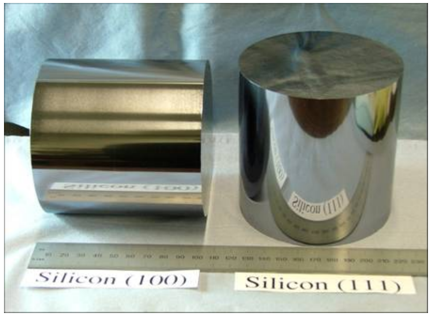




Thermal noise and fibre geometry (ET)

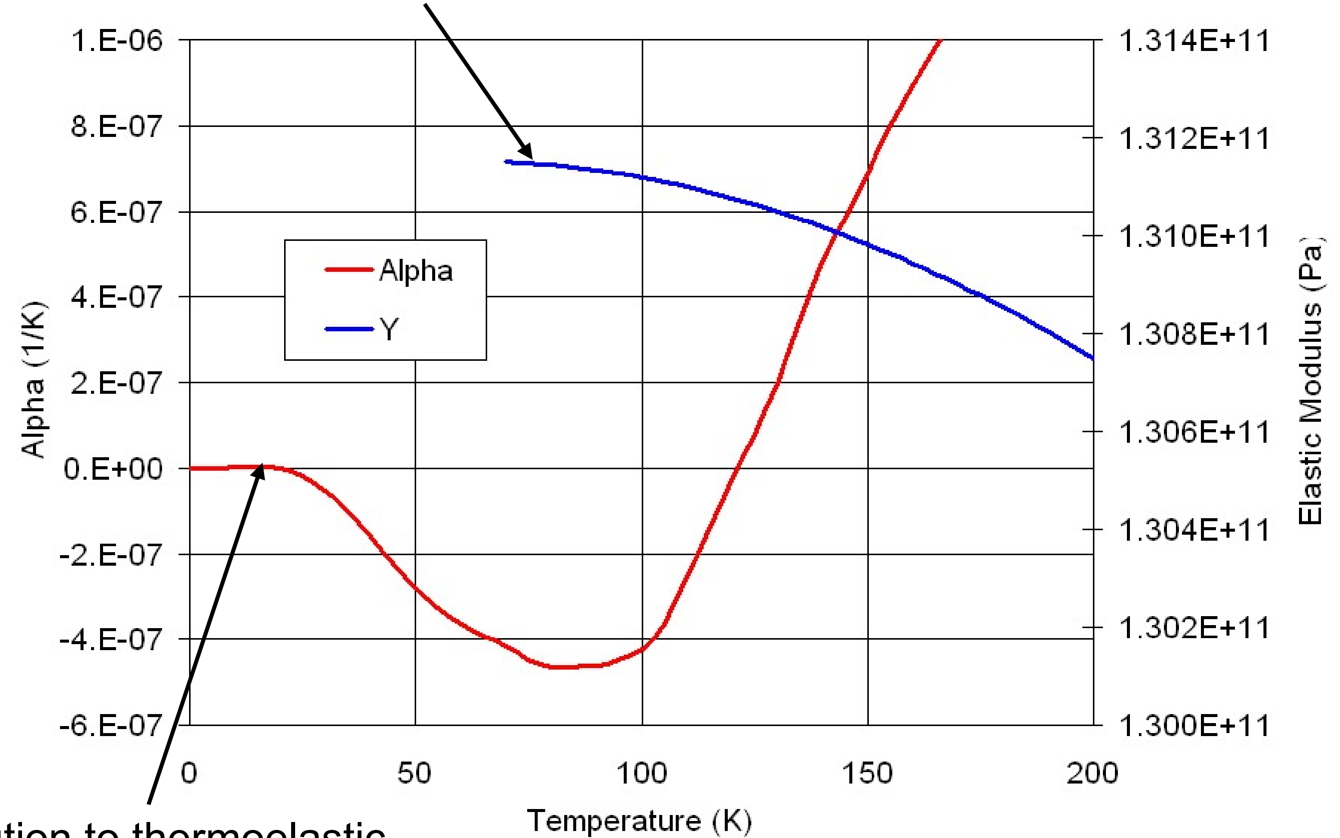
- Silicon seems a promising material for 3rd generation detectors
- Silicon has a zero in its coefficient of thermal expansion (α) at $\approx$18K and $\approx$123K=> can choose operating point such that thermoelastic contribution is nulled
- Another possibility for the fibres is sapphire (as used in LCGT)





Silicon properties

data needed on the elastic modulus of silicon below 77K (dY/dT→0)



small contribution to thermoelastic noise below ≈20K due to small α and dY/dT

C.A. Swenson, J.Phys. Chem. Ref. Data, 12m 179, (1983)

Silicon Suspensions

- The observed variability in breaking stress is approximately 0.2GPa-6GPa in bulk silicon (K. Peterson, Transactions IEEE, 70, 5, 1982).
- Assume 4 fibres carry 150kg => d$\approx$1mm gives 0.5GPa (with safety factor of $\times$3 requires 1.5GPa)
- At low temperature, thermoelastic peak will be at high frequency (short time constant due to low specific heat and high thermal conductivity)
- Lets choose 120K as the operating point initially (will also look at 20K, but need some data for Y at these temperatures)
- Non-linear thermoelastic loss can be nulled by thickening fibre ends (like Adv LIGO)

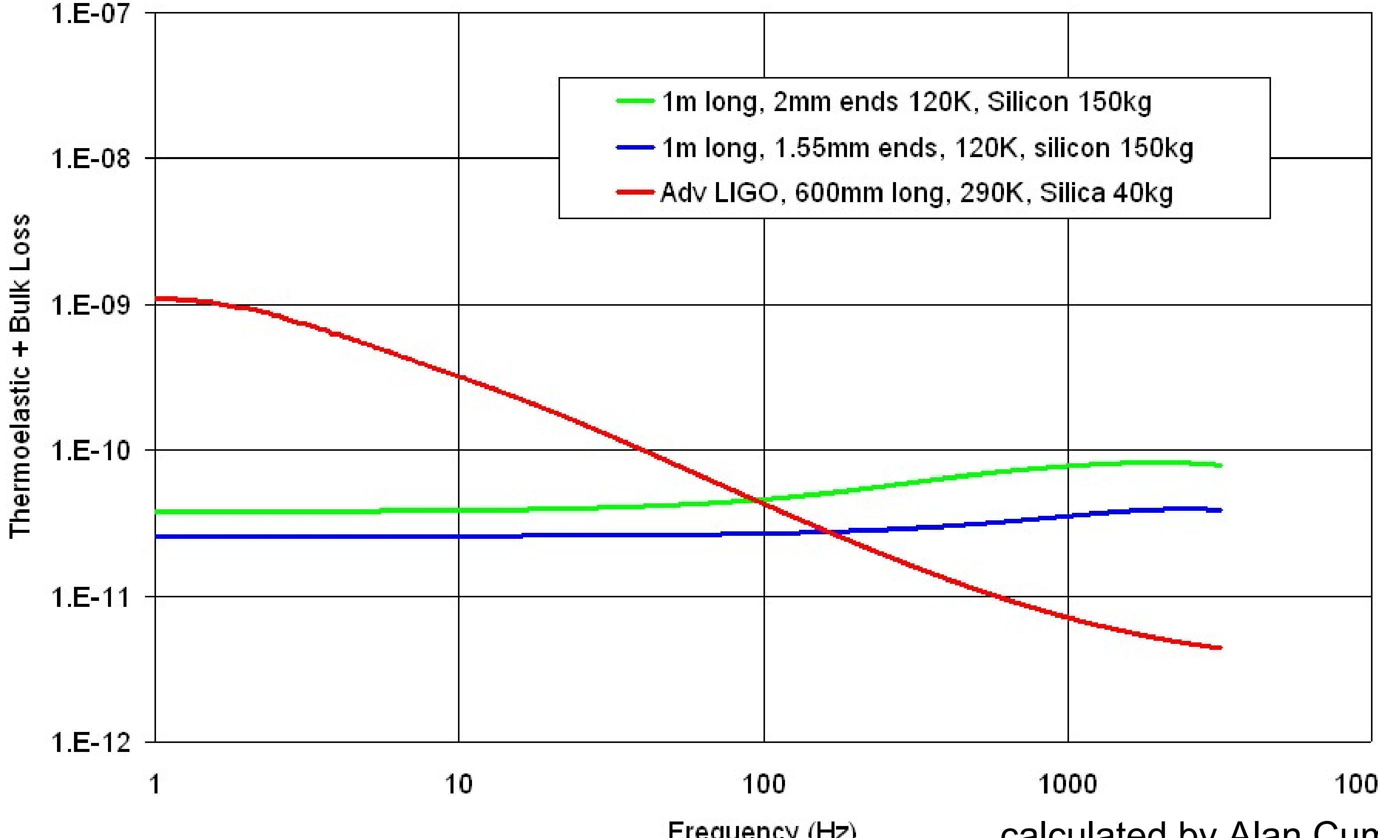
Silicon Suspensions (Preliminary calculation)

- Model the suspension in ANSYS and determine the distribution of strain energy in the fibre (to determine the dilution).

modelled by Alan Cumming, IGR

Silicon Suspensions (Preliminary calculation)

- Model suspension in ANSYS and predict distribution of strain energy in the fibre (to determine the dilution). **NO SURFACE LOSS YET**



calculated by Alan Cumming, IGR

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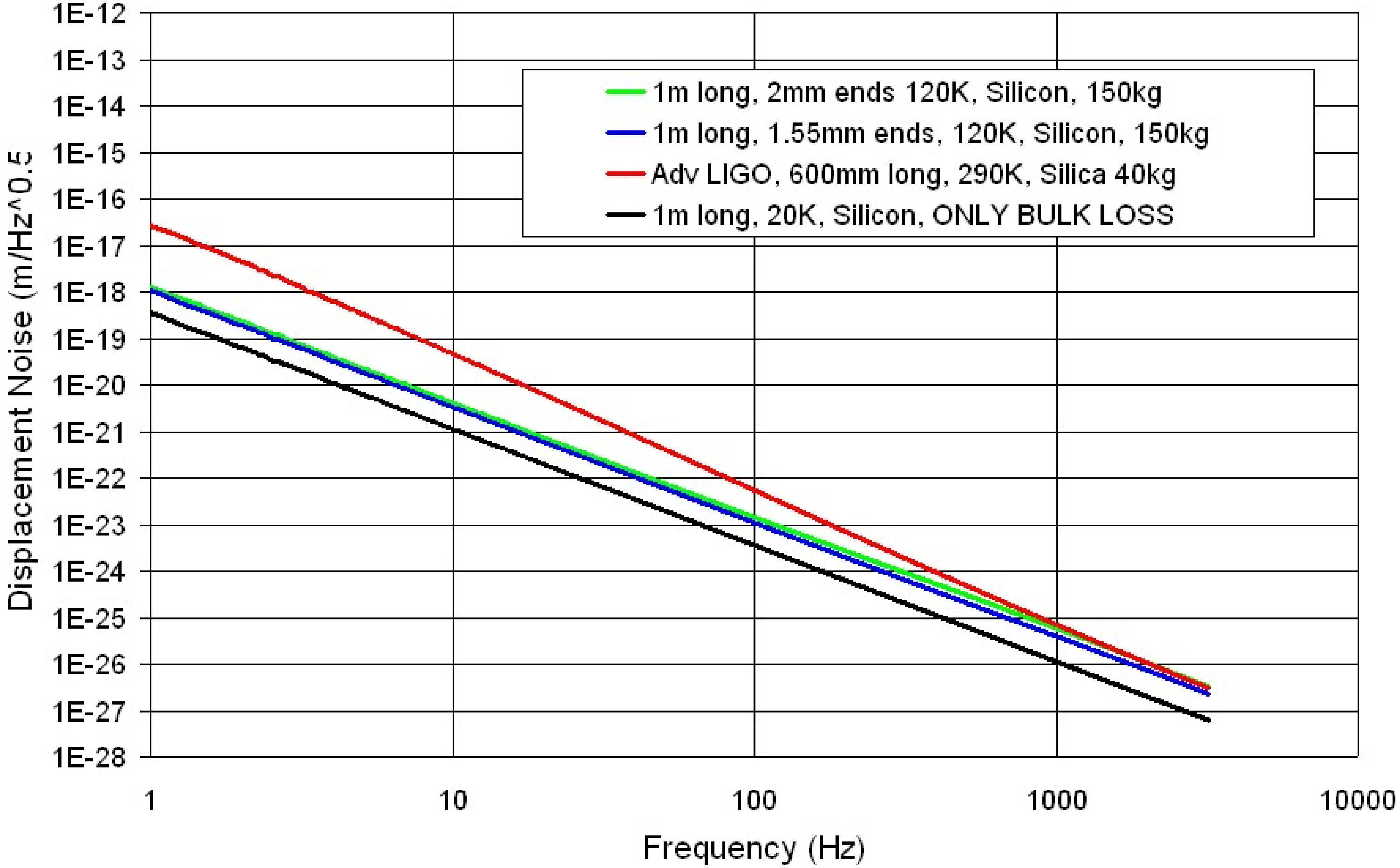
Silicon Suspensions (Preliminary calculation)

- NO SURFACE LOSS YET



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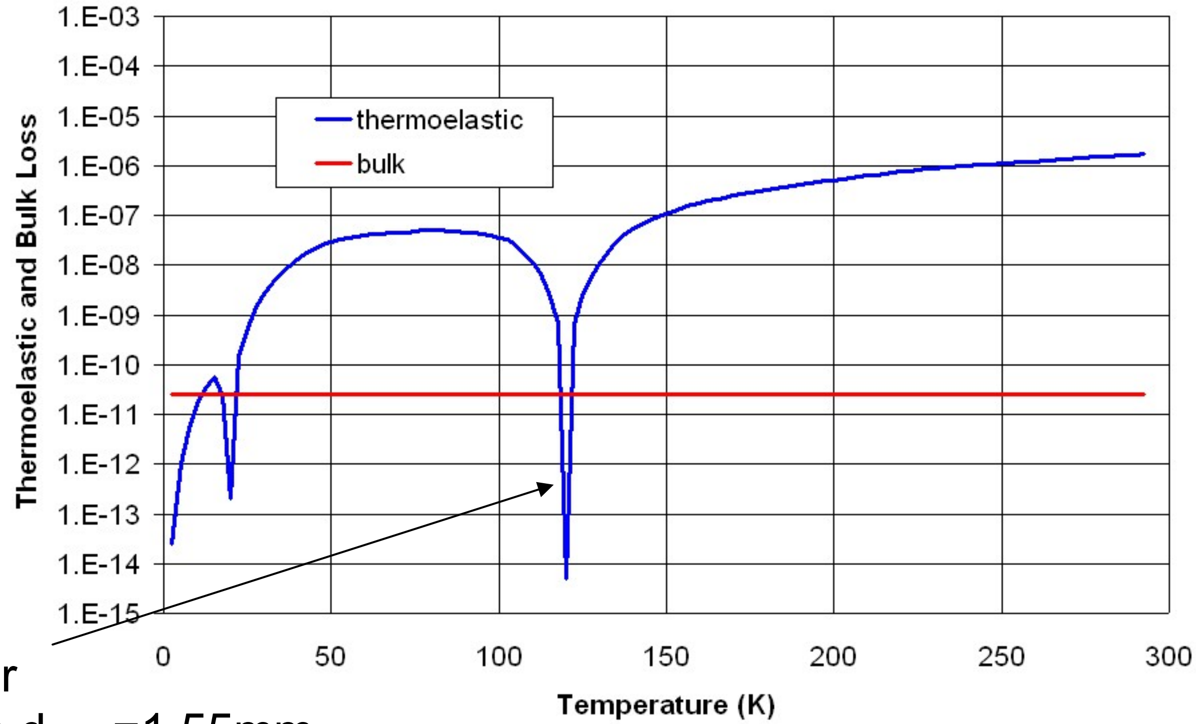
Thermal Noise

- It is also interesting to get an idea of the variation in the fibre thermoelastic loss as a function of temperature from knowledge of the material properties of Silicon



null with suitable choice of fibre diameter (just done at 123K with d_{thick}=1.55mm, can do this at 18K, but $dY/dT \rightarrow 0$)

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Summary

- The Advanced LIGO monolithic suspension utilises silica ear's welded to circular cross-section fibres. Design considerations address;

  thermal noise, manufacturability, weldability, strength

- Laser pulled fibres are strong and reproducible (d=0.4mm up to 70kg)

- Laser weld tests are strong and reproducible (up to 93kg)

- Fibre geometry is important for advanced detectors

- A silicon suspension could be feasible with 1mm diameter elements

- Operating at cryogenic temperatures can null/significantly reduce the thermoelastic contribution. Need to look at surface loss to in order to obtain the full picture.

- Heat extraction is an important driver (talk later this session) together with seismic/thermal noise performance