Bonding as an assembly technique in upgrades to aLIGO and detectors like ET and KAGRA

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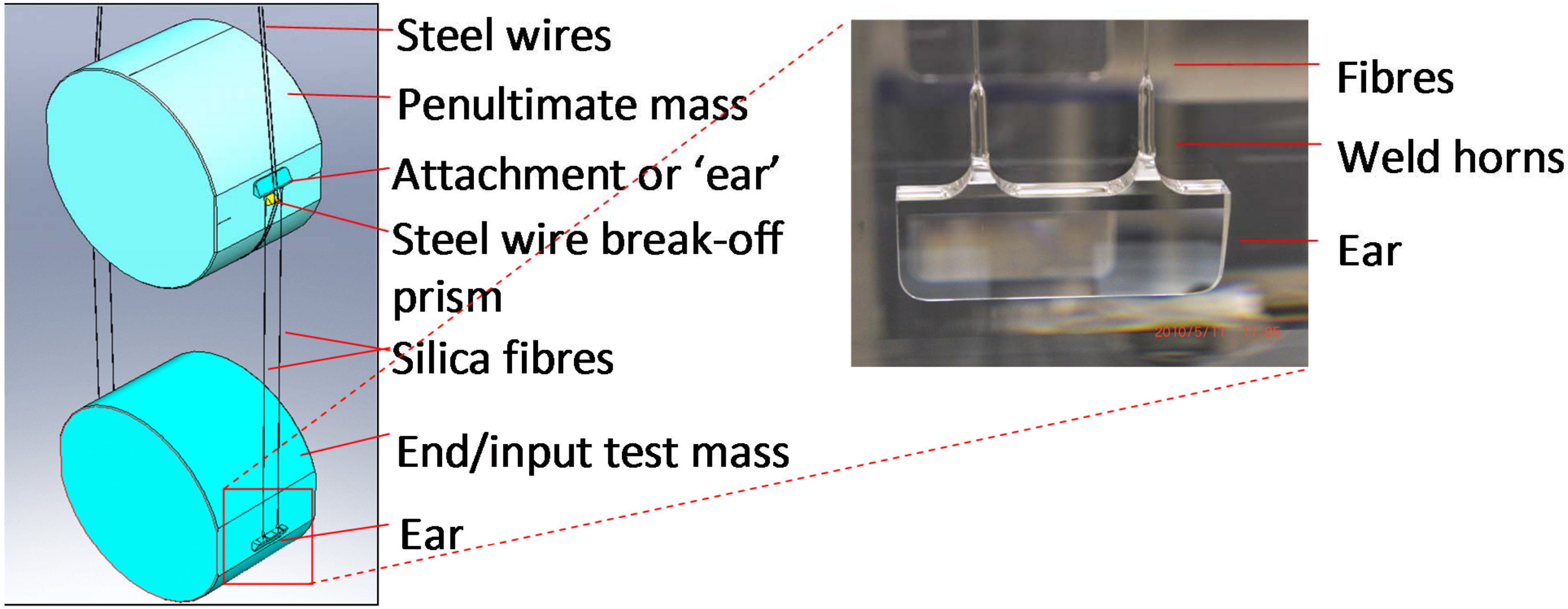
Introduction

- GEO600, aLIGO, and advanced VIRGO have quasi-monolithic test mass suspensions in fused silica which show superior thermal noise performance at room temperature
- Hydroxide catalysis bonding is used in all to attach some form of interface piece to the mirror to allow attachment of the fibres (which are welded)



- We are now talking about upgrades to detectors at room temperature (A+ and ET-HF) and various cryogenic temperatures (Voyager, ET-LF, KAGRA)

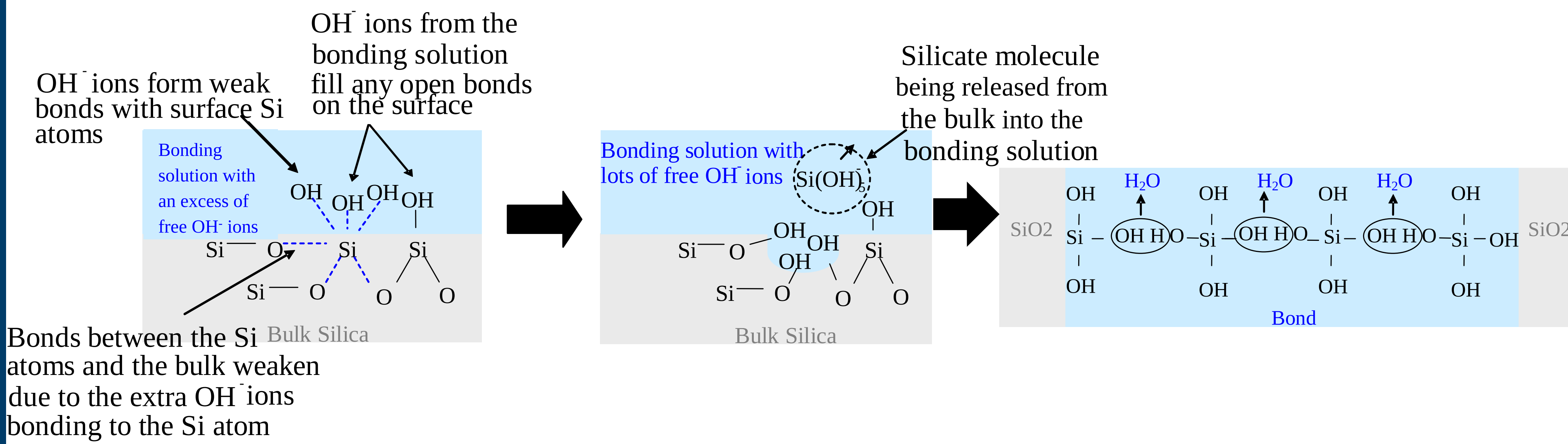
This method can create strong, durable bonds.

Chemistry of bonding between silica surfaces:

Hydration and Etching

Polymerisation

Dehydration



See Giles' talk (G1500598)

- Which suspensions are we thinking about?

At room temperature:

Name detector	ET-HF[1]	A+[2]
TM material	silica	silica
Mass TM [kg]	211	80
Diameter [mm]	500	430*
Thickness [mm]	463	253*
Beam radius [mm]	90	75**
Temperature TM [K]	293	293

[1] ET design document (ET-0106C-10)
[2] LIGO-G1500404
*Aspect ratio the same as for aLIGO
** Chosen to keep clipping losses the same as for aLIGO (G1500404 says beam radius 80/94 mm)

See Giles' talk (G1500598)

At cryogenic temperatures:

Name detector	ET-LF[1] (option 1)	ET-LF[1] (option 2)	Voyager[3] (option 1)	Voyager[3] (option 2)
TM material	silicon	sapphire	silicon (with silicon ribbons)	silicon (with silica fibres)
Mass TM [kg]	211	211	143	143
Diameter [mm]	500	500	560	560
Thickness [mm]	463	340	250	250
Beam radius [mm]	90	90	81	81
Temperature TM [K]	10	10	123	123

[1] ET design document (ET-0106C-10)
[3] L1500077 (derived from blue team design)
[4] Yamamoto, ET meeting 2014

Feasibility study: how?

- Can we bond sapphire and silicon using hydroxide catalysis bonding?
  - Yes, we can
  - Silicon surfaces must be oxidised to facilitate reliable bonding.
  - Chemistry is different for sapphire: aluminate chains.
- Are there other jointing techniques that may be suitable?
  - Indium bonding but only under compression and if suspension is not baked out.
- What is the strength of bonds in conditions that would occur in cryogenic suspension assembly and operation?

Feasibility study: how? Cont’d

- What stresses could occur in the bonds that would occur in cryogenic suspension assembly and operation?
  - ➢ Stress under the load of the suspension (mostly shear, some peel)
  - ➢ Stresses due to thermal expansion differences between the two parts bonded, if the thermal expansion of these parts doesn’t match (Voyager (option 2), KAGRA, ET-LF (option 2), or a potential silicon/sapphire suspension)
- What is the thermal conductivity of these bonds?
- What is the thermal noise arising from bonds in cryogenic mirror suspensions?

Bond strength: what do we know?

Silicon

- In Glasgow we bond with sodium silicate solution
- Potassium hydroxide is also possible (Dari et al., CQG, 2010)
- Using a wet thermal oxide layer, we need 50 nm oxide layer to get reliably strong bonds (Beveridge et al., CQG, 2011)
- Strengths tested at R.T. and at 77 K
- Ion beam sputtered oxide layer is an excellent and probably more practical alternative (Beveridge et al., CQG, 2013)
- Average strength values in 20 – 40 MPa (depending on type of material, crystal orientation, temperature of test.
- Strength at 77 K higher than at R.T.
- Recent thermal cycling tests (3,10 and 20 times down to ~8 K) of <100>-<100> silicon (2 sets tested), suggest that the average stays constant (see my poster G1500837). We are developing techniques to assess the quality of bonds during the bonding procedure to ensure only high quality bonds are accepted.

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Bond strength: what do we know?

Sapphire

- M-M sapphire can be bonded with sodium silicate solution (65 MPa), potassium hydroxide (>10 MPa), sodium hydroxide (>10 MPa) and sodium aluminate (>10 MPa). These were tensile tests. (Douglas et al., CQG, 2014)
- C-A (25 MPa), C-M (32 MPa) and C-C (50 MPa) bonds tested at 8 K. These were torsional shear tests. (Haughian et al., CQG, 2015)
- Sapphire doesn't break very often when a bond is broken and can be rebonded (be it with some loss of strength).
- Thermal cycling (M-M) suggests a drop in average strength (still > 5 MPa) experiments (K. Yamamoto, ET meeting 2014, Lyon). Not enough statistics though. Torsional shear tests.
- Curing time (C-C) at room temperature is not yet understood. Four weeks curing gives high strength (as with silica). However, 8 and 12 weeks curing seem to indicate a slight drop (See my poster G1500837). Research ongoing to understand curing better. Tensile tests.
- Very recent have shown that when directly comparing C-C sapphire, to A-A and M-M doesn't show a significant difference in strength. Though fracture behaviour is different (see my poster G1500837)

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Bond strength: questions remaining?

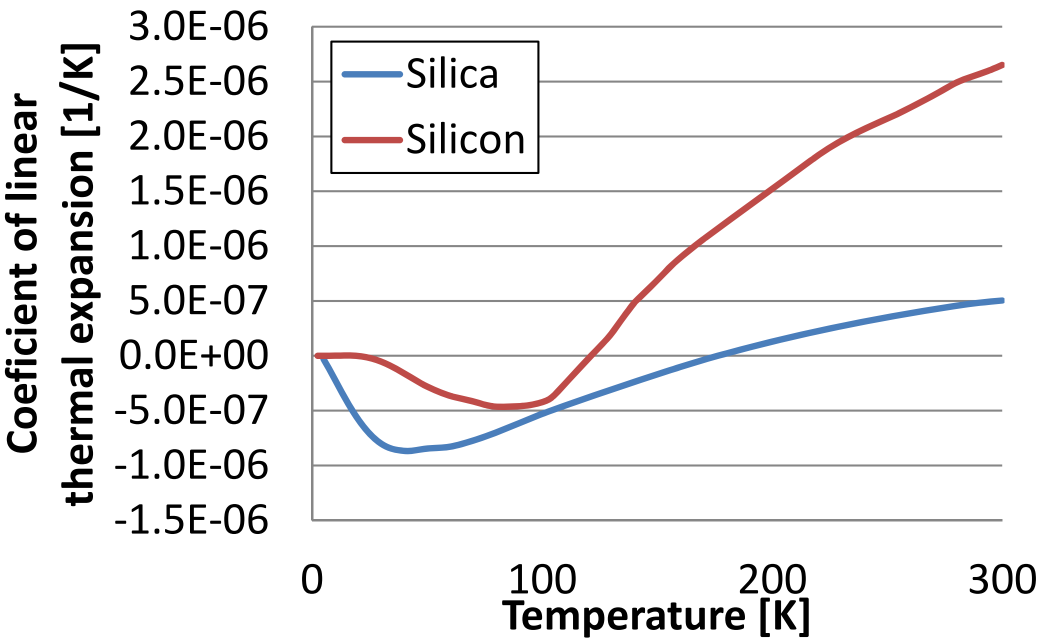
Silicon

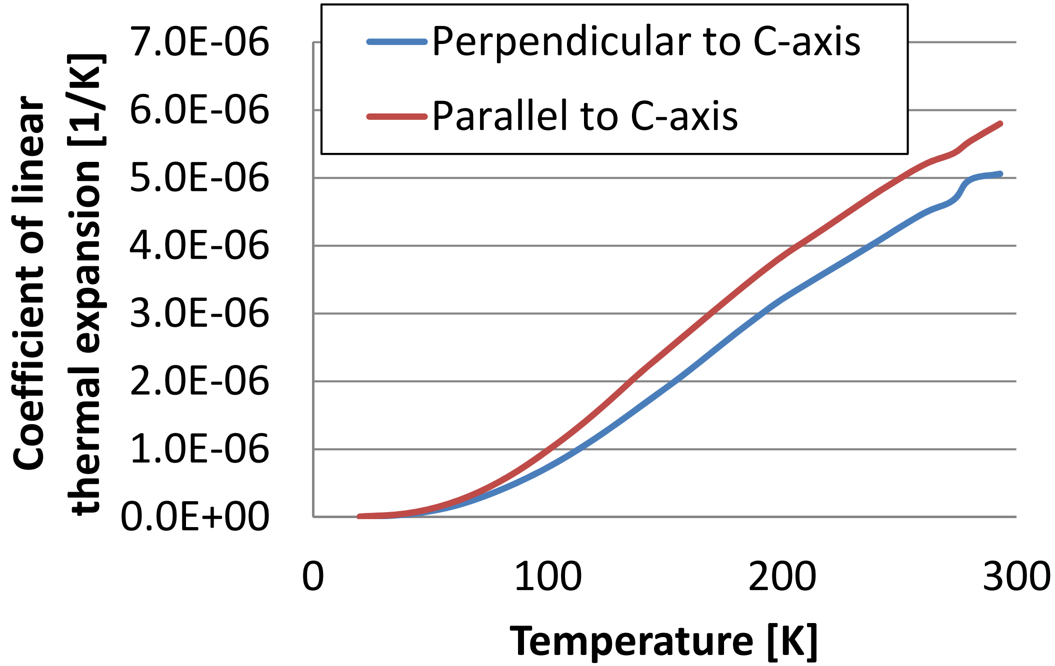
- What is the minimum oxide layer thickness for ion-beam sputtered coatings?
- What is causing difference in strength: crystal orientation or purity? Why?
- Can strength/mechanical loss be improved through heat/vacuum treatment?
- What is the curing time?
- How can we best to assess bond quality?

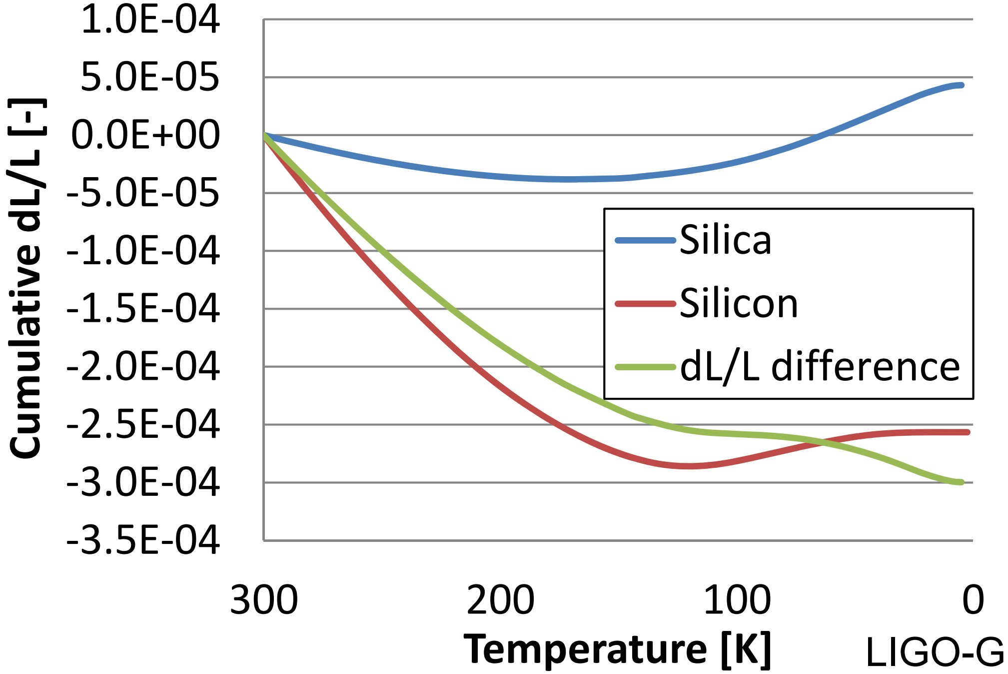
Sapphire

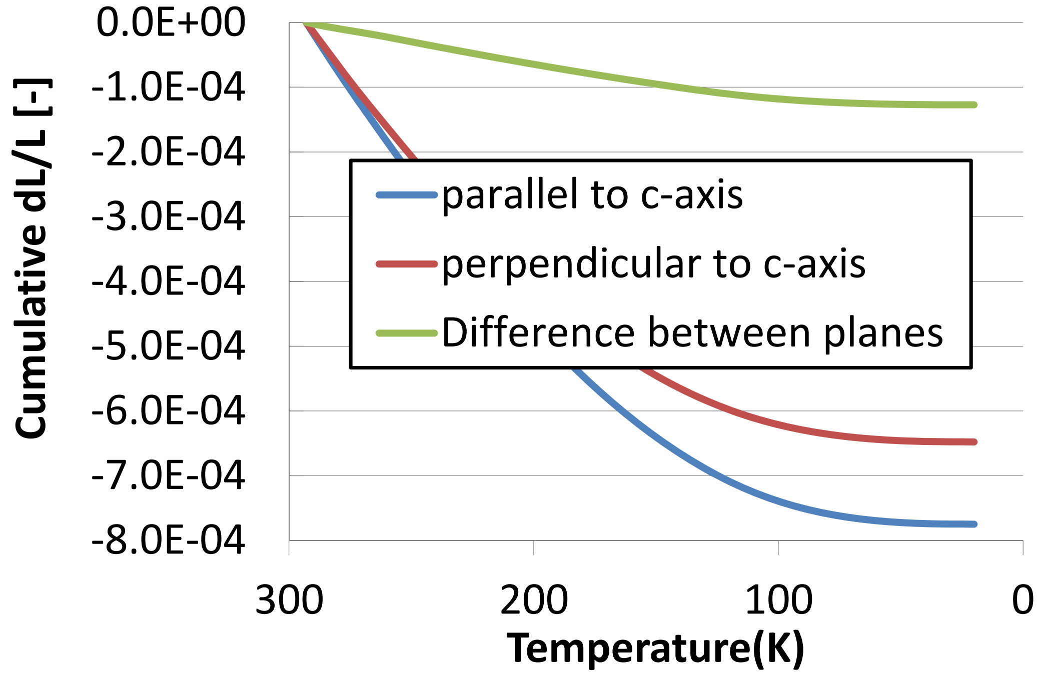
- Influence of thermal expansion differences between different crystal orientations on bond strength when bonding e.g. c-a plane or c-m plane?
- Influence of polishing process/surface damage on strength.
- Literature study suggests surface reactivity higher for mechanically polished surfaces a.o.t. pristine surfaces
- Can strength/mechanical loss be improved through heat/vacuum treatment?
- Bond strength of sapphire not polished or cut on specific crystal plane?

Stress due to thermal expansion differences









Stress due to thermal expansion differences

Using Chen, W. W. (1979, March). Thermal Stress in Bonded Joints. *IBM J. RES. DEVELOP., 23*(2), 179-188, an estimation was made of shear stress occurring in bonds between silica and silicon; and sapphire of perpendicular crystal orientations.

Assumptions Chen:

- Substrates and bond linear elastic
- 2D calculation; only shear, no bending

Assumption specific calculation:

- aLIGO size ear and test mass
- HCB bond thickness: 100 nm
- Indium bond thickness: 1 µm

$$\tau = \frac{\Delta\left(\frac{dL}{L}\right)_{300-70K} G_{bond}}{\beta_{2D} t_{bond}\left(C_1 + C_2\right)} I_1\left(\beta_{2D} x\right)$$

$$\beta_{2D} = \sqrt{\frac{G_{bond}}{t_{bond}}\left(\frac{1-\nu_1^2}{E_1 t_1} + \frac{1-\nu_2^2}{E_2 t_2}\right)}$$

$$C_1 = -\frac{2}{1+\nu_1}\left(\frac{1-\nu_1}{\beta_{2D} R} I_1\left(\beta_{2D} l\right) - I_0\left(\beta_{2D} l\right)\right)$$

$$C_2 = -\frac{2}{1+\nu_2}\left(\frac{1-\nu_2}{\beta_{2D} R} I_1\left(\beta_{2D} l\right) - I_0\left(\beta_{2D} l\right)\right)$$

Stress due to thermal expansion differences

The stresses calculated are very high:

- factor >10 above the strength of HCB bonds (16 and 30 MPa)
- factor >100 above the strength of an indium bond (a few MPa in tensile load).
- factor > 1 above the strength of substrate material (the tensile strength of sapphire is ~400 MPa, of silicon ~150 MPa and silica ~60 MPa),

Damage could potentially occur to both the bonds and the substrate materials for Voyager (option 2), KAGRA and ET-LF (option 2)

	Calculated shear stress in bond [MPa]
HCB silica ear –silicon test mass	805
HCB c-sapphire ear – m-sapphire test mass	865
Indium bond silica ear - silicon test mass	290
Indium bond c-sapphire ear – m-sapphire test mass	312

FIRST ESTIMATE!!!

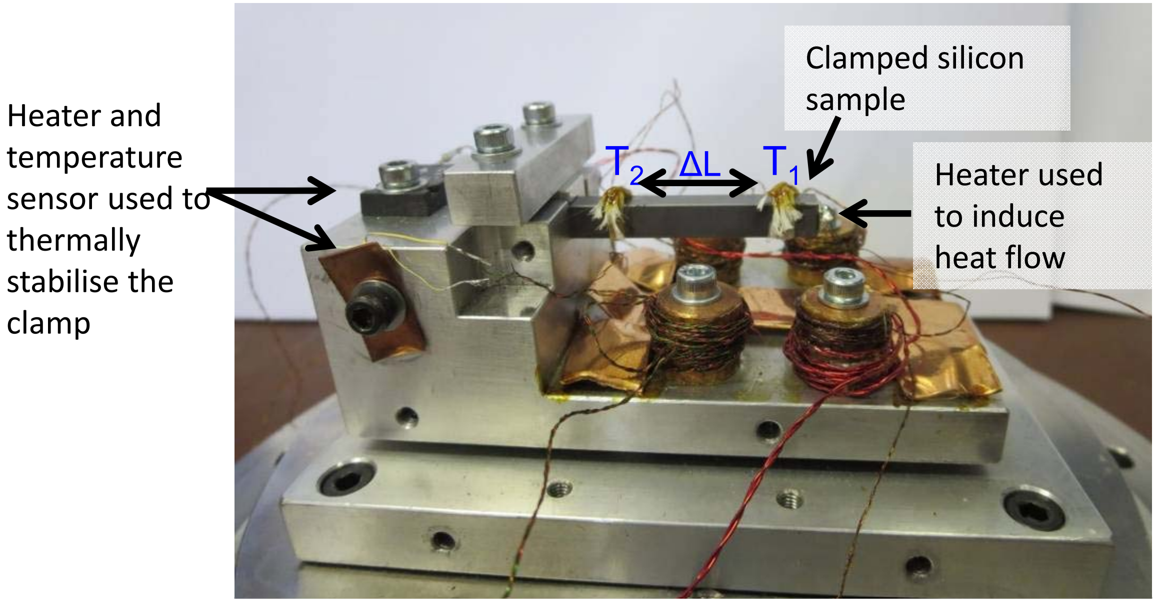
Further investigation through FEA and strength tests ongoing

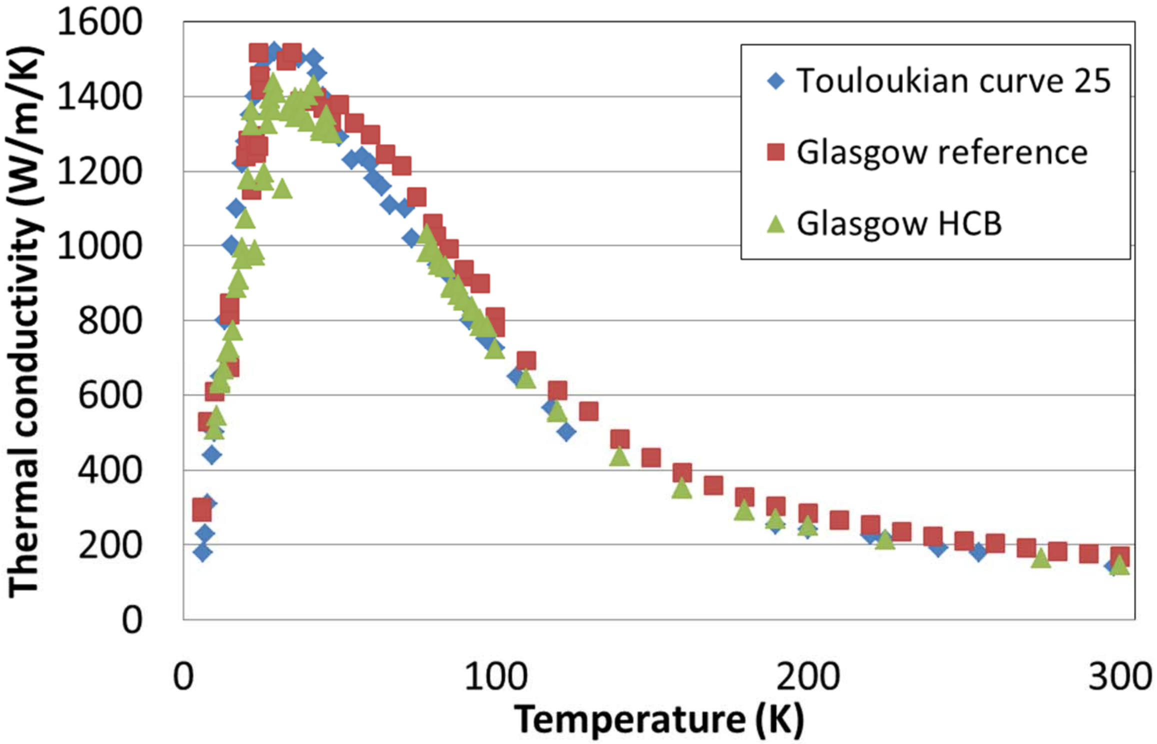
Thermal conductivity

- Thermal conductivity has now been measured of:

1. Silicon-silicon HCB bonded cylinders (∅25 mm x 76 mm) down to 30 K (Lorenzini, ET meeting Jena, 2010)
2. Silicon-silicon HCB bonded samples (5x5x40 mm) down to 8 K (see my poster G1500637)
3. Sapphire-sapphire HCB bonded samples (Poster C. Schwarz, D. Chen, ET meeting 2014, Lyon).
4. Sapphire-sapphire indium bonded sample

Results suggest drop in thermal conductivity is very small.



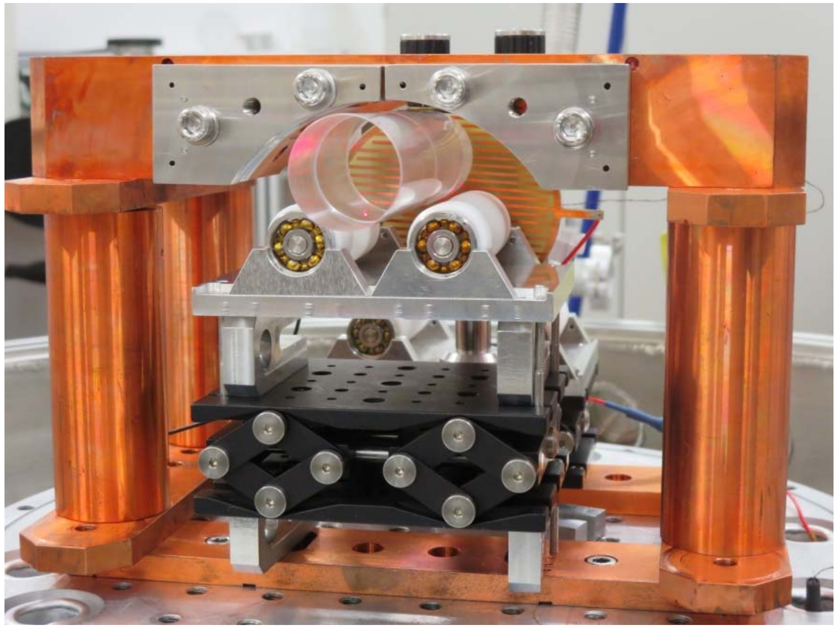


Bond mechanical loss, overview

- Silica-silica HCB bond made with sodium silicate solution @ R.T. Bond loss: 0.11 ± 0.02 (Cunningham, CQG, 2010)
- Silica-silica HCB bond (same as above) after 3 years and after heat treatment 150 °C for 48 hours. Bond loss: 0.06 ± 0.01 (Haughian, thesis, 2012)
- Silicon-silicon HCB bond made with sodium silicate solution @ R.T. Not an ideal bond (offset). Bond loss: 0.27-0.52 (Haughian, thesis, 2012)
- Sapphire-sapphire HCB made with sodium silicate solution a.f.o. temperature
  - Bond loss @ R.T. 0.03± 0.01
  - Bond loss @ 20 K $(3 - 7)\cdot 10^{-4} \pm 1\cdot 10^{-4}$

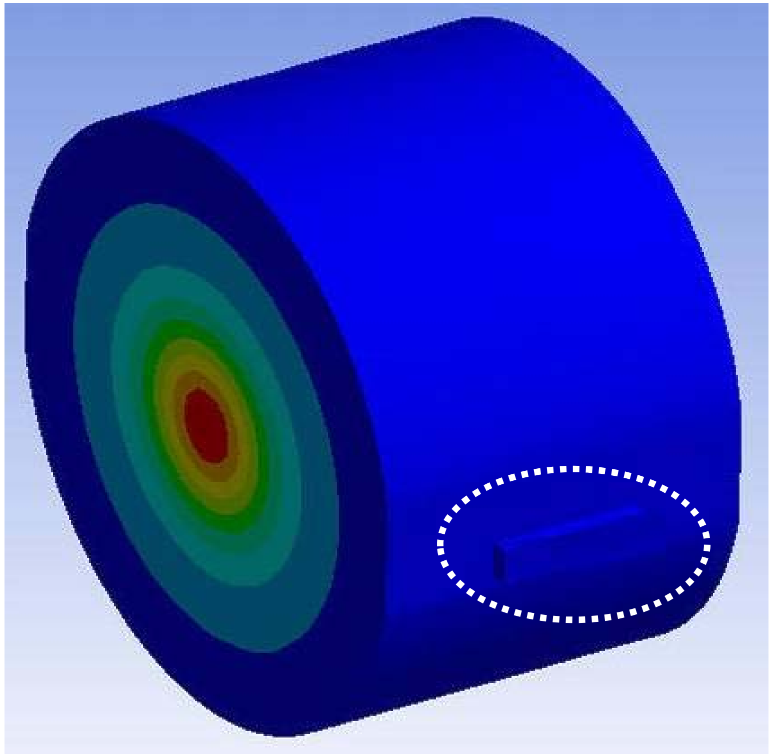
  (see my poster G1500637)
- Sapphire-sapphire indium bond
  - Bond loss @ 20 K $(2 – 3)\cdot 10^{-3}$

  (Talk K. Yamamoto, ET meeting 2014, Lyon).



Thermal noise associated with HCBs or indium bonds between silicon and sapphire

Aim: some initial idea of levels of thermal noise



FE models of aLIGO size test mass with aLIGO size ears

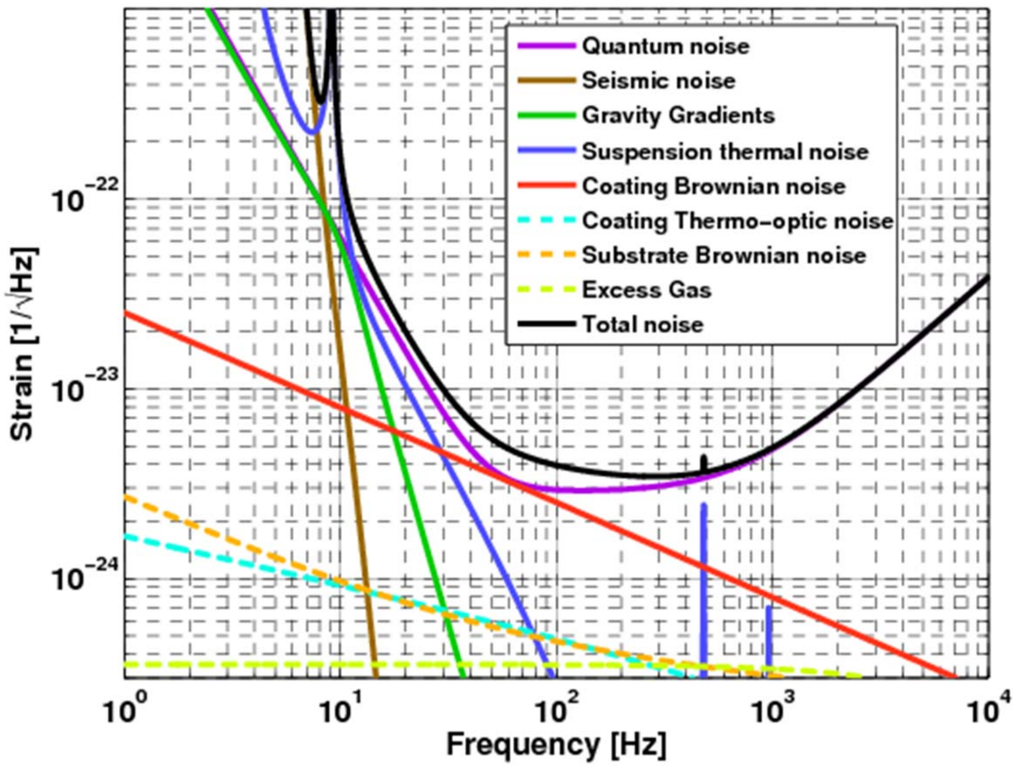
A Gaussian pressure wave is applied to front surface which causes deformation of the bond to calculate strain energy in the bond

Using Levin's method thermal noise associated with the strain energy at 100 Hz is calculated.

$$S_{\mathrm{x}}(f) = \frac{2 k_{\mathrm{B}} T W_{\mathrm{diss}}}{\pi^2 f^2 F_0^2}$$

$$W_{\mathrm{diss}} = 2\pi f \int_{\mathrm{vol}} \varepsilon(x, y, z)\, \phi(x, y, z)\, dV$$

Thermal noise associated with HCBs in aLIGO



Hild, S., Class.Quant.Grav. 29 (2012) 124006

In aLIGO thermal noise arising from bonds was to be 10% of the total thermal noise budget @ 100 Hz

Thermal noise budget @ 100 Hz is ~$2 \cdot 10^{-24}$ /√Hz ⇒

Bond thermal noise budget per test mass ~$2 \cdot 10^{-25}$ /√Hz ($7 \cdot 10^{-22}$ m/√Hz, (T010075-01,2009))

Calculated: $1.4 \cdot 10^{-25}$ /√Hz ($5.4 \cdot 10^{-22}$ m/√Hz)

assuming bond loss of 0.11 at 293 K

Assumptions for calculations following:

- bond thermal noise budget < 10% of overall thermal noise budget @ 100 Hz
- Ear size (where unknown): same ratios and average shear stress (0.17 MPa) as aLIGO.

Thermal noise from bonds for cryogenic

Name detector	A+[2]	ET-LF[1] (option 1)	ET-LF[1] (option 2)	Voyager[3] (option 1)	Voyager[3] (option 2)
TM material	Silica	silicon	sapphire	silicon (with silicon ribbons)	silicon (with silica fibres)
Temperature TM [K]	293	10	10	123	123
Bond area 1 ear [mm x mm]	39x118	45x136	45x136	52x157	52x157
Assumed bond thermal noise requirement [1/√Hz]	$1.5{\cdot}10^{-25}$	$4{\cdot}10^{-26}$	$4{\cdot}10^{-26}$	$3{\cdot}10^{-26}$	$3{\cdot}10^{-26}$
Bond loss [-]	$*1.1{\cdot}10^{-1}$	$**1.1{\cdot}10^{-1}$	$*7{\cdot}10^{-4}$	$**1.1{\cdot}10^{-1}$	$**1.1{\cdot}10^{-1}$
Calculated expected thermal noise (±15%) [1/√Hz]	$1.3{\cdot}10^{-25}$	$1.4{\cdot}10^{-26}$	$1.1{\cdot}10^{-27}$	$9.0{\cdot}10^{-26}$	$3.6{\cdot}10^{-26}$

* Measured value

** Assumed value (bond loss silica-silica bond @ R.T

Questions

Scientific questions

- Factors that influence strength of bonds?
- Could we bond mixed thermal expansion materials safely?
- What is mechanical loss of silicon-silicon bond down to cryogenic temperatures?
- What is the Young's modulus of bonds between these different materials?
- What is expected thermal noise for suspensions with two bonds?

Engineering questions

- Can we make suspensions like aLIGO/GEO600 -> do we need to go to aVIRGO/KAGRA type designs with a bond in shear and a bond in compression?
- Assess bond quality silicon-silicon bonds

Thank you for your attention!