Hydroxide catalysis bonding for aLIGO, eaLIGO and beyond

Mariëlle van Veggel

on behalf of the team at the Institute for Gravitational Research, Glasgow

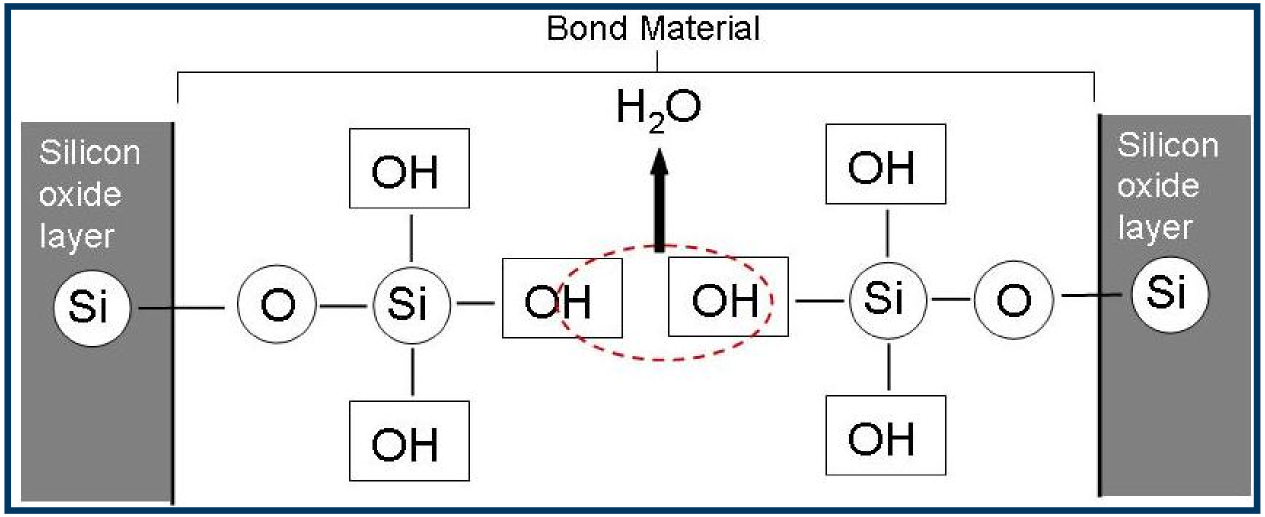
LIGO-G1100166-v3

Overview of the presentation

- Introduction to hydroxide catalysis bonding
- How is hydroxide catalysis bonding currently used in aLIGO?
- How can we improve the performance of hydroxide catalysis bonds for eaLIGO?
- Hydroxide catalysis bonding in detectors beyond eaLIGO
- Conclusions

Hydroxide-Catalysis Bonding

- Achieves bonding if a silicate-like network can be created between the surfaces
  - Silica based materials
    - E.g. silica, Zerodur, fused silica, ULE glass and granite
  - Alkaline bonding solution
    - E.g. sodium hydroxide (NaOH), potassium hydroxide (KOH) or sodium silicate (Na_2SiO_3) dissolved in water.



Hydroxide-Catalysis Bonding

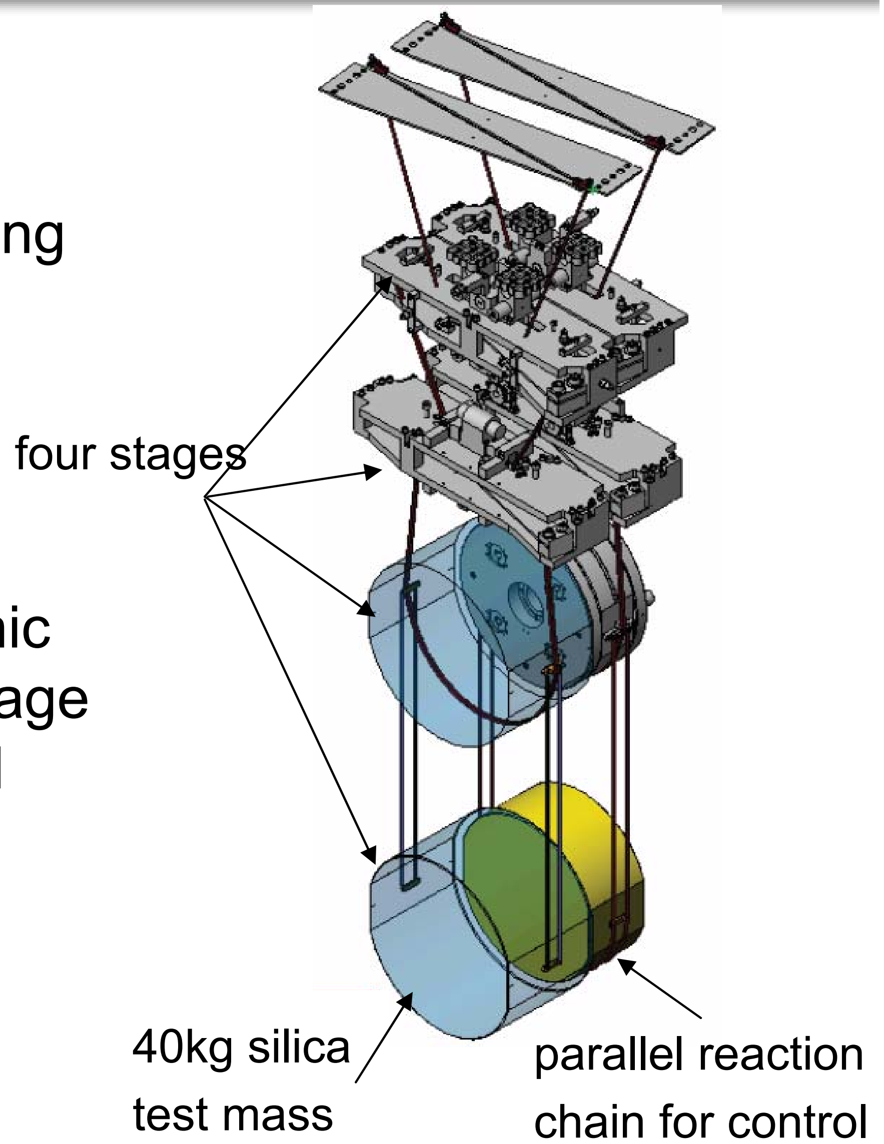
- High strength, thermally conductive and low loss bonds
- Joints optical components without mechanical fasteners
  - Accommodates requirements for precise alignment
- Launched in Gravity Probe B (patented by Gwo)
  - Able to withstand launch forces
  - Suitable at cryogenic temperatures

See talk Norna Robertson G1100176

aLIGO
Quadruple suspension

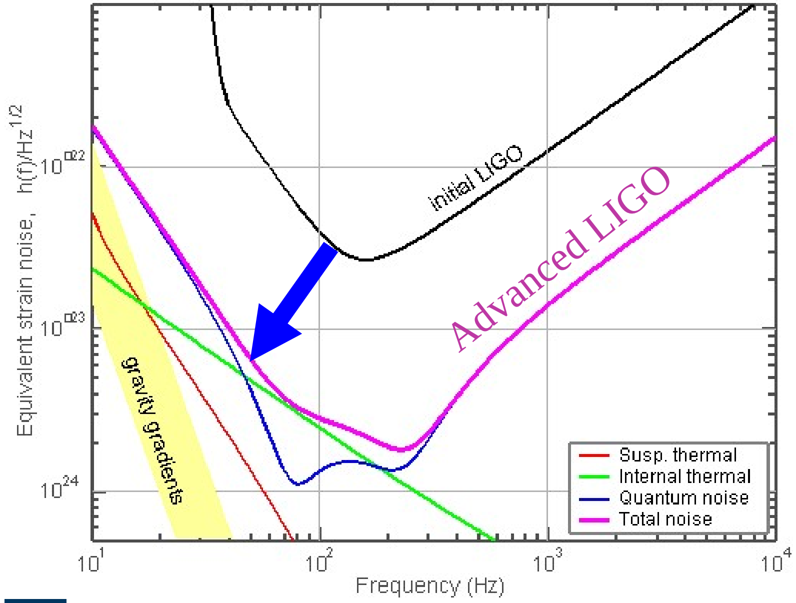
- Seismic isolation: use quadruple pendulum with 3 stages of maraging steel blades for enhanced vertical isolation

- Thermal noise reduction: monolithic fused silica suspension as final stage - low pendulum thermal noise and preservation of high mirror quality factor
  - *silica fibre loss angle ~ $3 \cdot 10^{-7}$,*
  - *c.f. steel ~$2 \cdot 10^{-4}$*

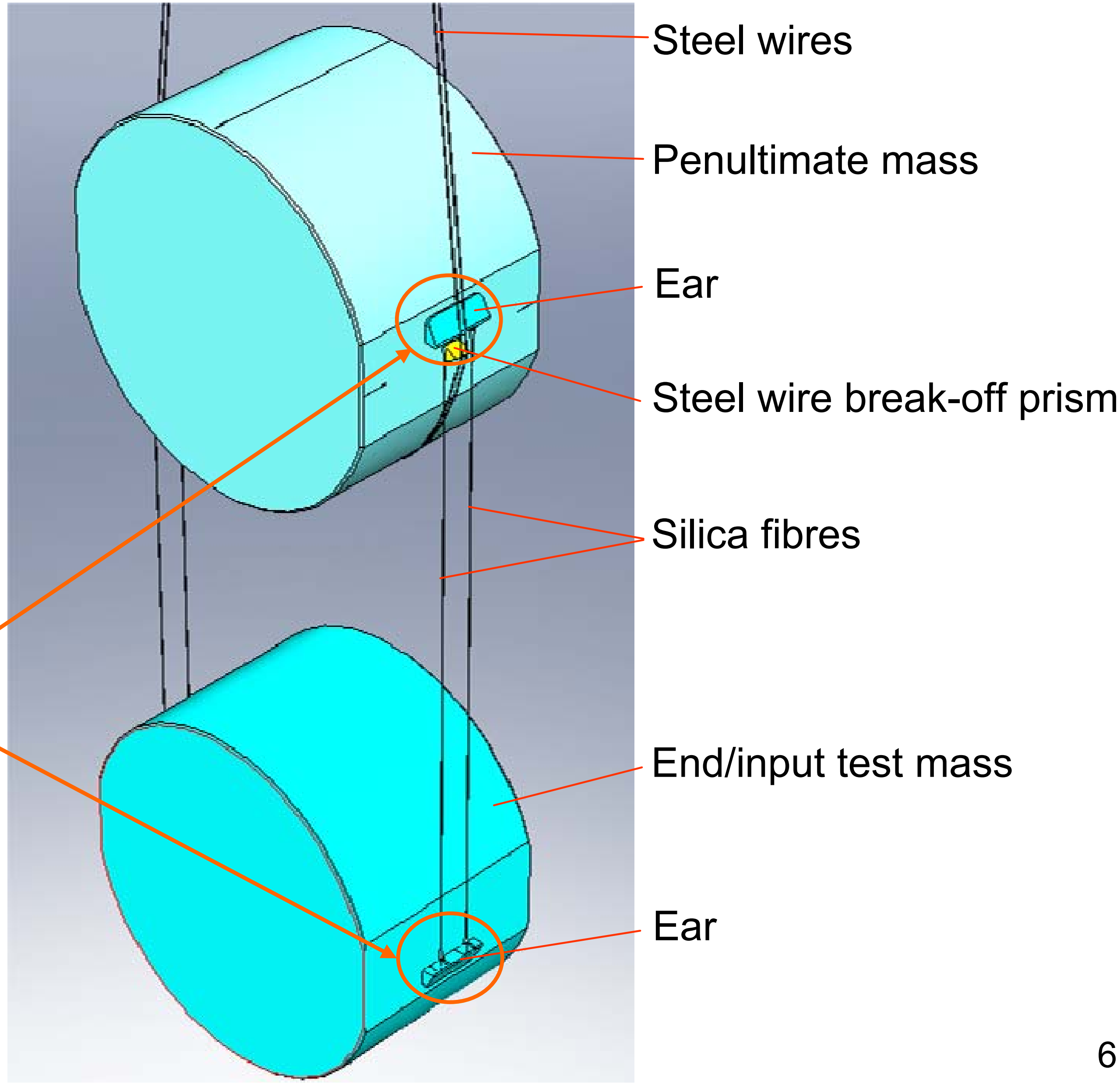


aLIGO

Monolithic final stage of the quad suspension



The ears are hydroxide catalysis bonded to the sides of the masses

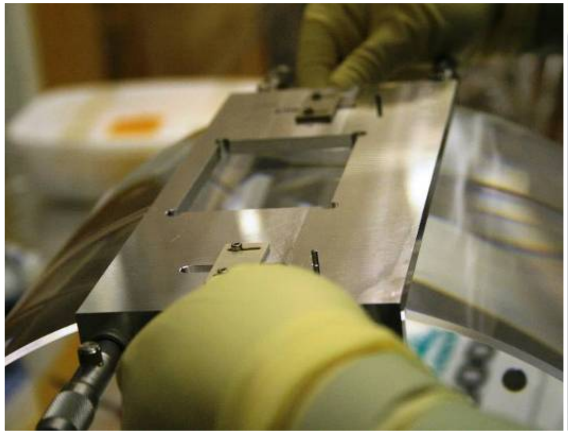


aLIGO

Monolithic suspension procedure

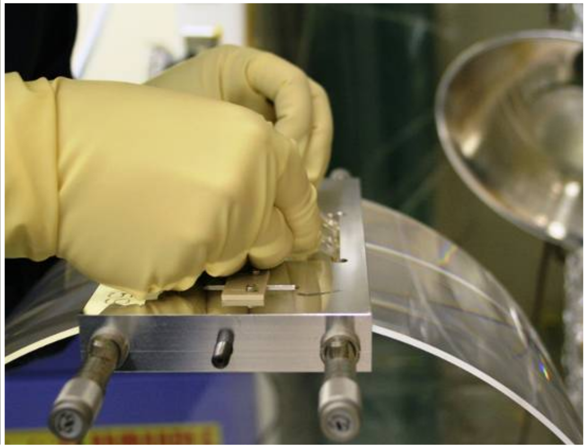
3 main stages

- Preparing masses by hydroxide catalysis bonding of the ears to:
  - the test mass and
  - the penultimate mass
- Manufacturing and testing of the fibres
- Installation of fibres using laser welding



Placing bonding jig

Applying bonding solution



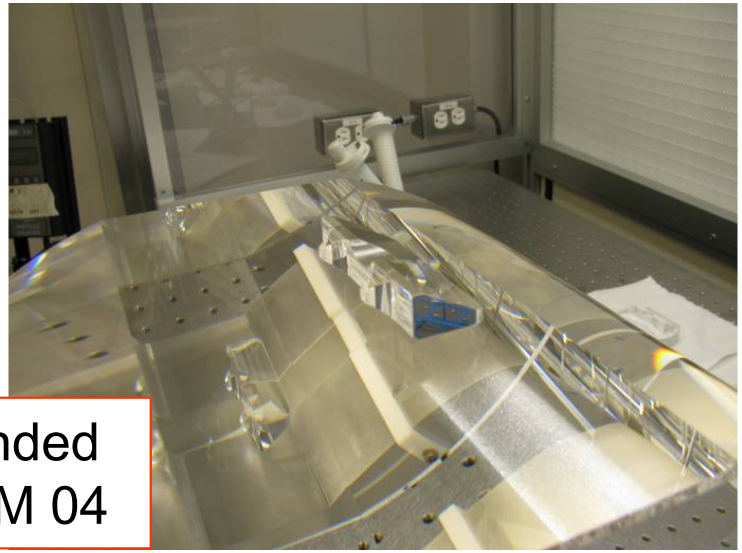
Putting down ear

aLIGO

Current status with the preparation of masses

Tasks	Status
Bonding ears to penultimate masses	Ears bonded successfully to ITM PUM 04, ITM PUM 01, ETM PUM 03 and ETM PUM 04
Glueing prisms and earthquake stops to penultimate masses	Prisms and earthquake stops successfully glued to ITM PUM 04
Bonding ears to test masses	ITM (for single arm test) pencilled in for May 2011, ETM for June 2011

Gerardo Moreno bonding an ear to ITM PUM 04 at LHO



An ear bonded to ITM PUM 04

Hydroxide catalysis bonding for eaLIGO

R&D for the reduction of bond thermal noise

- Factors that influence bond thermal noise:
  - Bond surface area and thickness
  - Geometry of ear
  - Bond mechanical loss
  - Bond density and Young's modulus

- Estimated bond thermal noise in a quadruple suspension for aLIGO (Cunningham, L, et al., Physics Letters A 374 (2010) 3993–3998)
  - Upper limit for bond loss 0.11 ± 0.02
  - 5.4×10^{-22} m/√Hz at 100 Hz with a 61 nm thick bond (< 10% of the total thermal noise budget of 7×10^{-21} m/√Hz)

- Questions to answer:
  - How can we improve strength?
  - What is the Young's modulus and density of bonds?
  - How can we reduce the mechanical loss of bonds?

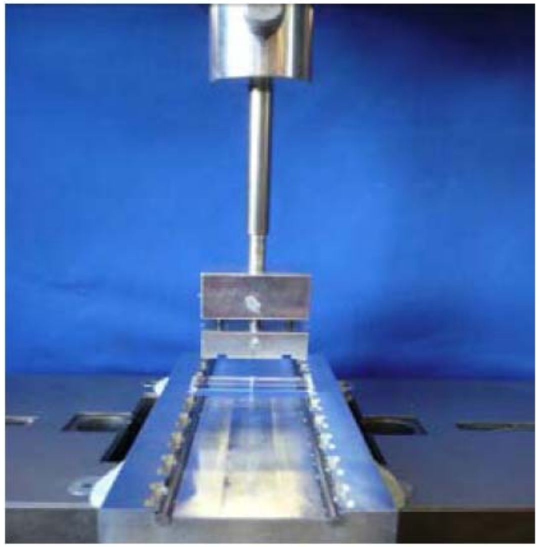
Hydroxide catalysis bonding for eaLIGO

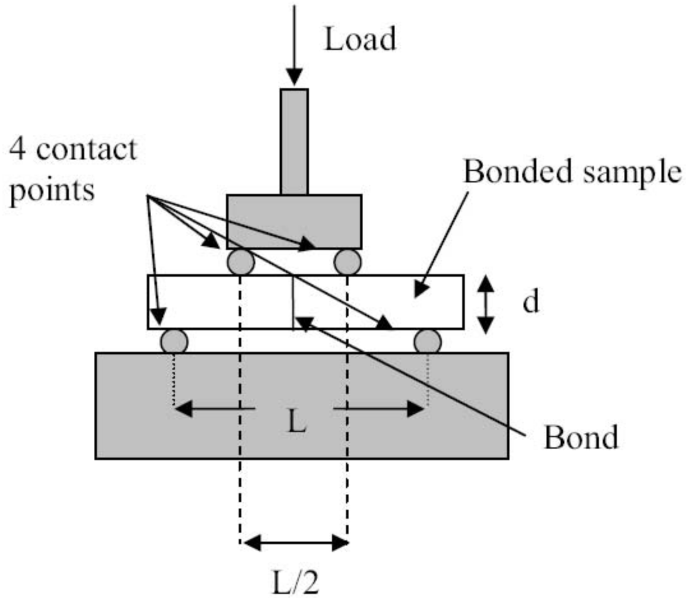
Further improvements to bond strength

- Bend strength tests by Karen Haughian

  (4-point bend strength according to ASTM C1161):

Sample set	Temperature treatment	Average strength [MPa]
8 samples	R.T. only	18.0 +/- 2.8
8 samples	R.T. for 4 weeks then 150ºC for 48 hrs	20.0 +/- 2.9



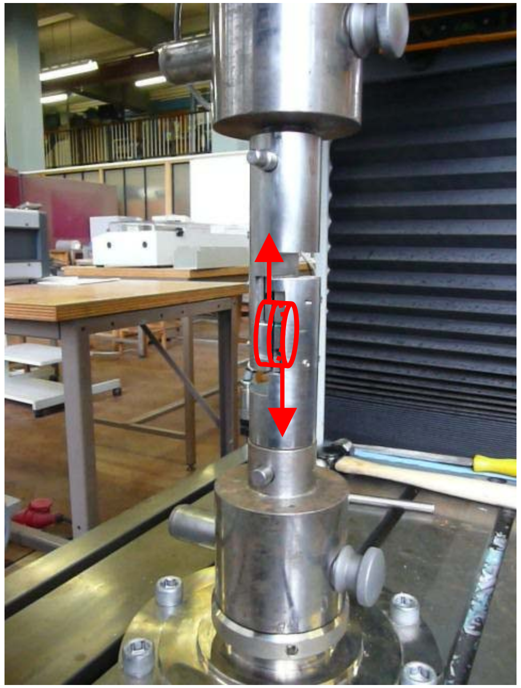


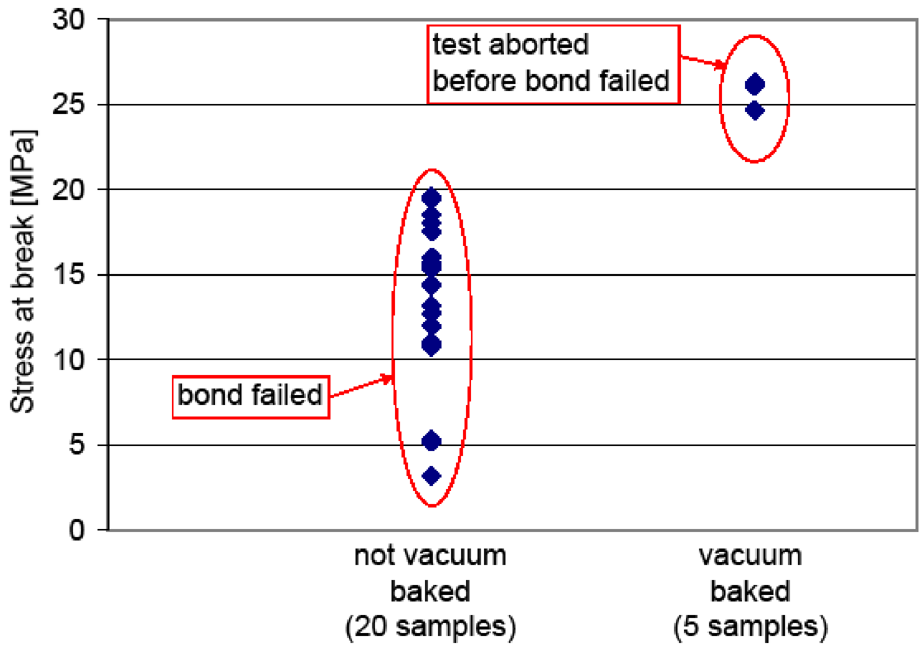
Hydroxide catalysis bonding for eaLIGO

Further improvements to bond strength

- Shear strength tests by Mariëlle van Veggel:

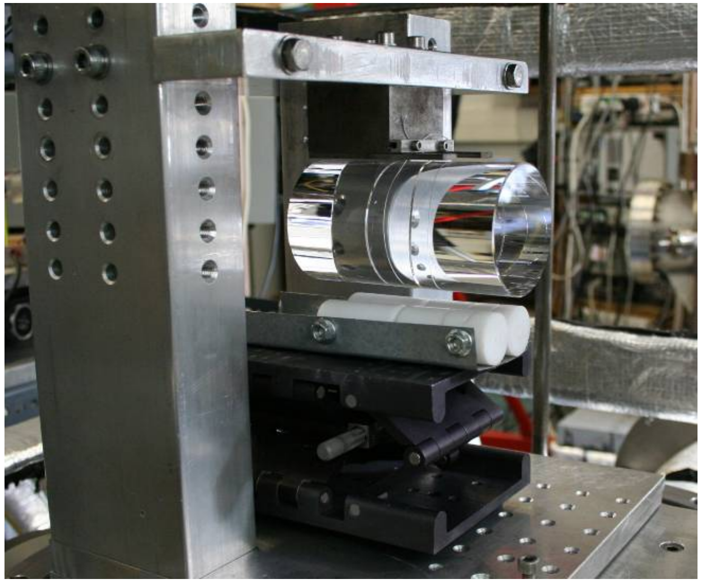
Sample set	Temperature treatment	Average strength [MPa]
5 samples	R.T. for 3 month then 120ºC in vacuum for 48 hrs	>25.0
20 samples	R.T. only	15.8 +/- 6.4





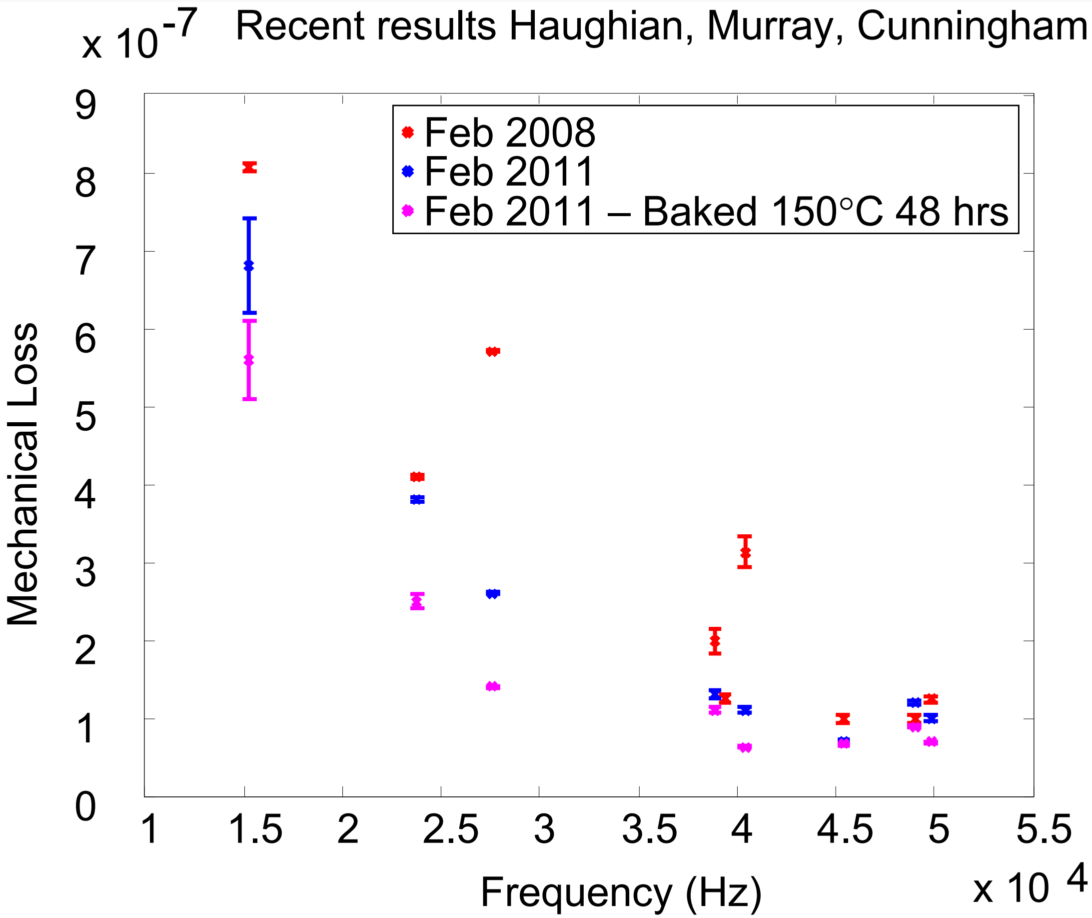
Hydroxide catalysis bonding for eaLIGO

Improving bond loss



∅76 mm x 120 mm

Suprasil 311 cylinder



Assuming substrate loss is frequency dependent and bond loss is not.

$$\phi_{total} \cong \phi_{substrate} + \left(\frac{E_{bond}}{E_{total}}\right)\phi_{bond} \cong \phi_{substrate} + \left(C\frac{Y_{substrate}}{Y_{bond}}\right)\phi_{bond}$$

Hydroxide catalysis bonding for eaLIGO

Improving bond loss

- Assuming the bond loss has changed and the Young's modulus remains constant at 7.9 GPa

Age bond	Temperature treatment	Average loss over 8 modes	Thermal noise aLIGO TM [m/√Hz]
5 months	Room temperature only	0.11 ± 0.02	$5.4 \cdot 10^{-22}$
3 years	Room temperature only	0.08 ± 0.02	$4.6 \cdot 10^{-22}$
3 years	Room temperature for 3 years then 48 hrs at 150 ºC	0.06 ± 0.02	$4.0 \cdot 10^{-22}$

Fluctuation dissipation theorem using Levin's approach:

$$\text{Thermal noise} \sim \sqrt{S_x(f)} \sim \sqrt{W_{diss}} \sim \sqrt{\phi_{bond}}$$

Hydroxide catalysis bonding for eaLIGO

Improving bond loss

- Assuming the Young's modulus has changed and the average bond loss value remains constant at 0.11

Age bond	Temperature treatment	Young's modulus [GPa]	Thermal noise aLIGO TM [m/√Hz]
5 months	Room temperature only	7.9 ± 1.4	$5.4 \cdot 10^{-22}$
3 years	Room temperature only	11.2 ± 1.4	$4.6 \cdot 10^{-22}$
3 years	Room temperature for 3 years then 48 hrs at 150 ºC	14.9 ± 1.4	$4.0 \cdot 10^{-22}$

Fluctuation dissipation theorem using Levin's approach:

$$\text{Thermal noise} \sim \sqrt{S_x(f)} \sim \sqrt{W_{diss}} \sim \sqrt{U_{strain}} \sim \sqrt{\frac{1}{Y_{bond}}}$$

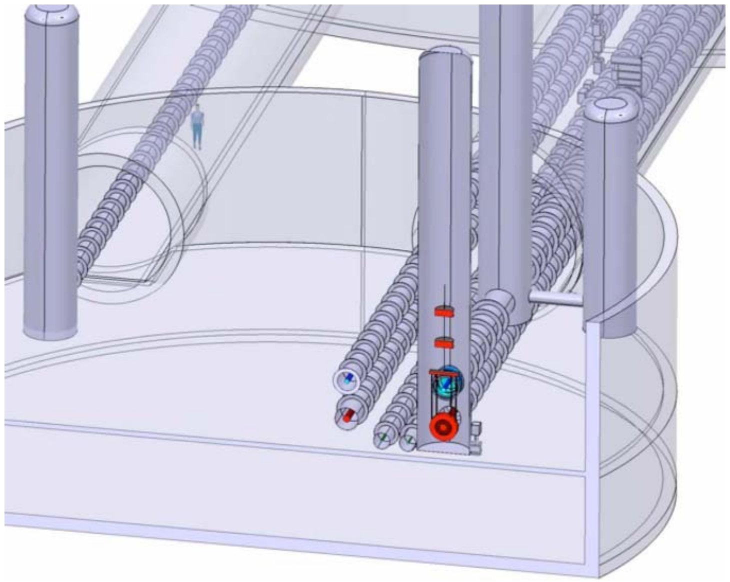
See talk Stuart Reid G1100345

Beyond eaLIGO

Yet more sensitive detectors

- Example: the Einstein Telescope preliminary design study has converged to proposing one facility with:
  - a LF cryogenic interferometer with silicon final stages
  - a HF room temperature interferometer with silica final stages

  $\Rightarrow$ higher power, bigger masses than aLIGO or VIRGO++



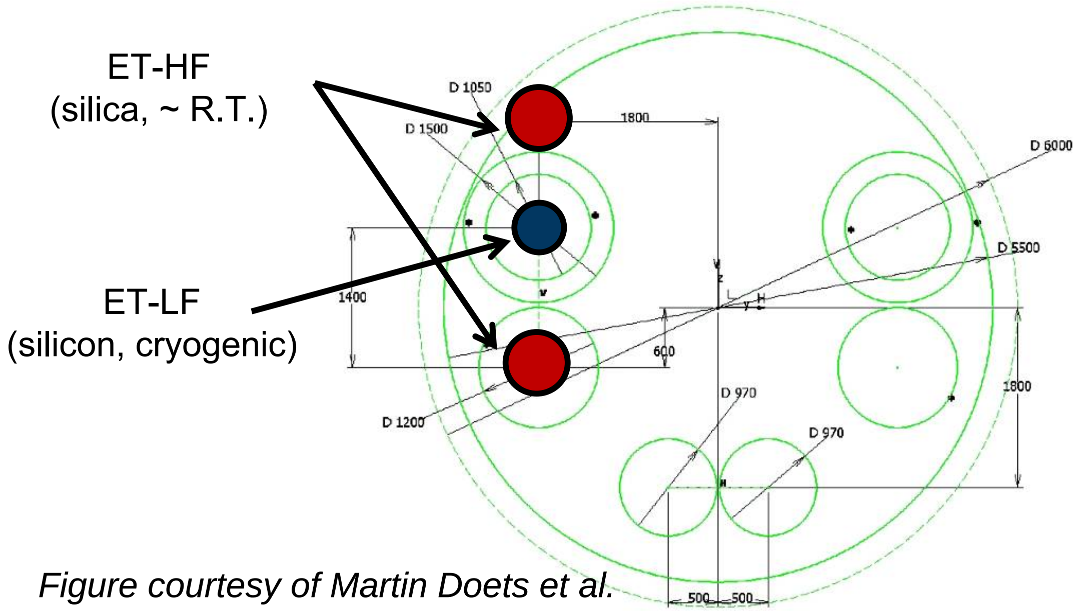


Figure courtesy of Martin Doets et al.

Beyond eaLIGO

Hydroxide catalysis bonding silicon to silicon

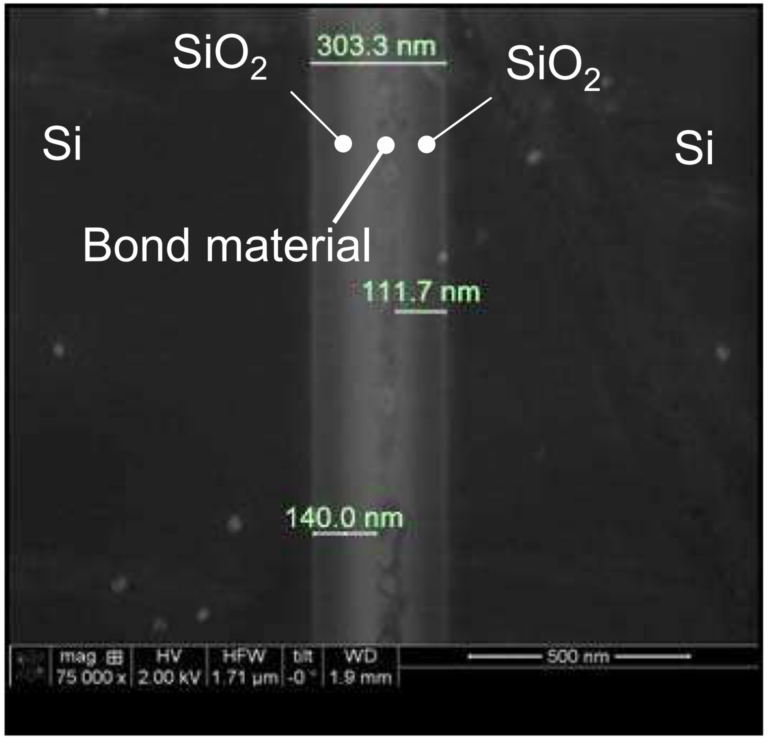
- Require to attach silicon suspensions to the silicon mirror test mass

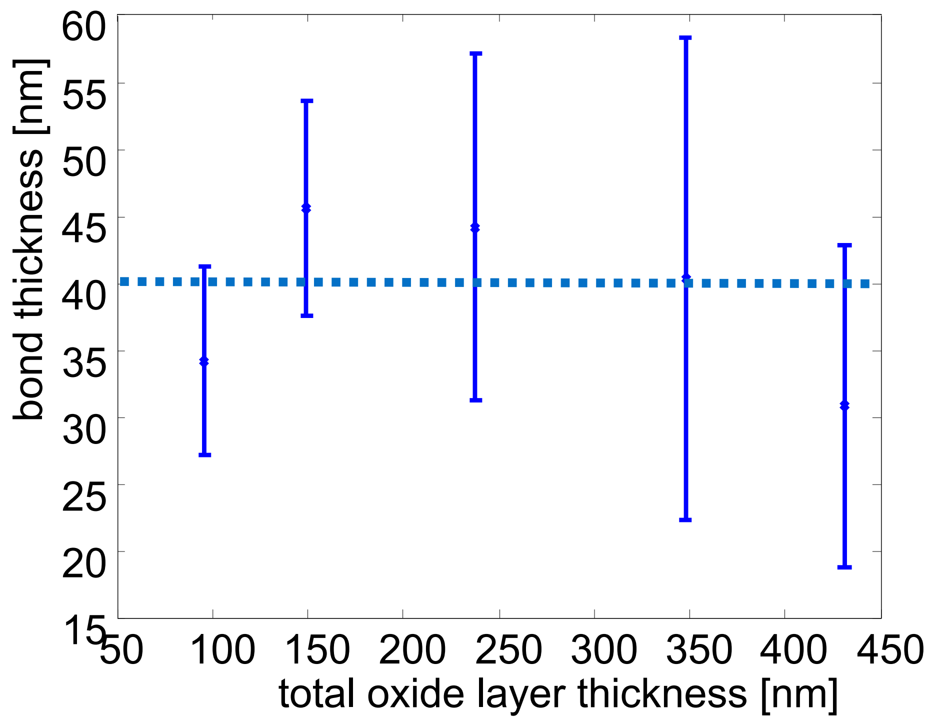
- We need to evaluate the use of silicate bonds for low-temperature silicon suspensions:
  - Bond thermo-mechanical properties
    - Thermal noise (mechanical loss + thickness)
    - Heat extraction (thermal conductivity + bond area)
  - Bond robustness
    - Mechanical strength
    - Temperature cycling effects/failures

Beyond eaLIGO

Si-Si mechanical loss and bond thickness

- Mechanical loss measurements of a first set of bonded silicon cylinders are currently ongoing
- Bond thickness measurements have been made with wet thermally oxidised silicon



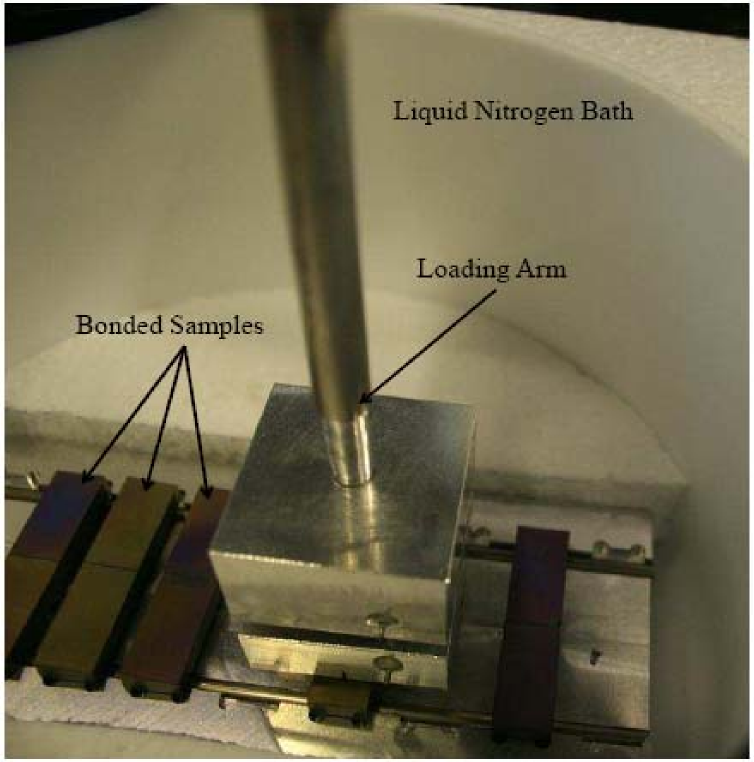


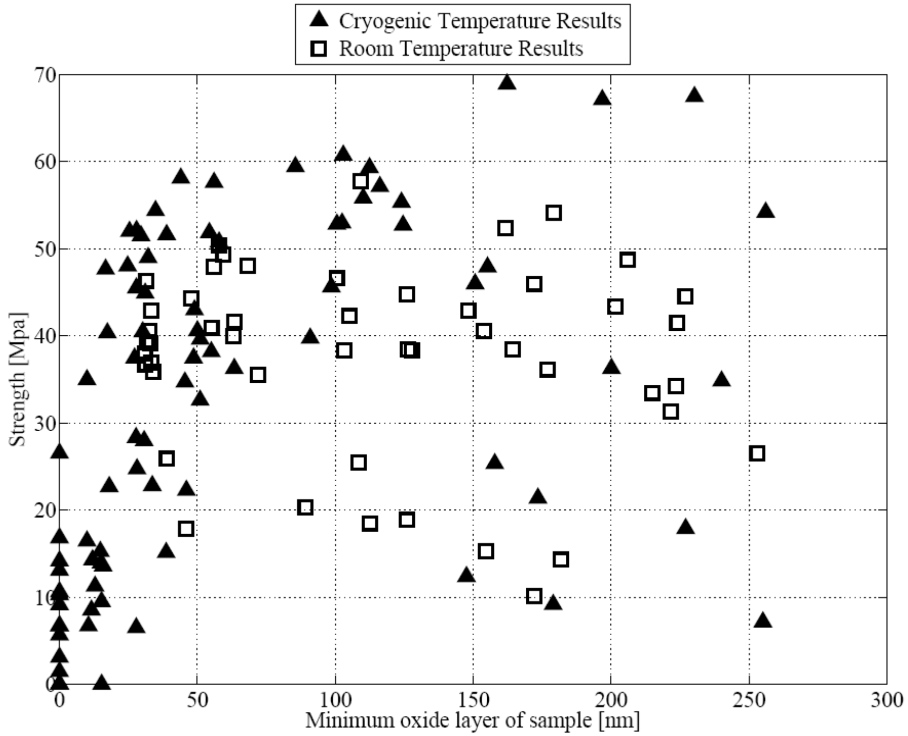
Rachel Montgomery, Peter Murray and Mariëlle van Veggel

Beyond eaLIGO

Bond robustness - strength

- Investigation of strength of Si-Si bonds at cryogenic temperature (4-point bend strength according to ASTM C1161)
  - No change in strength with reduction of temperature to 77 K
  - If the oxide layer thickness >50 nm (thermally grown in wet nitrogen) no correlation observed between it and strength

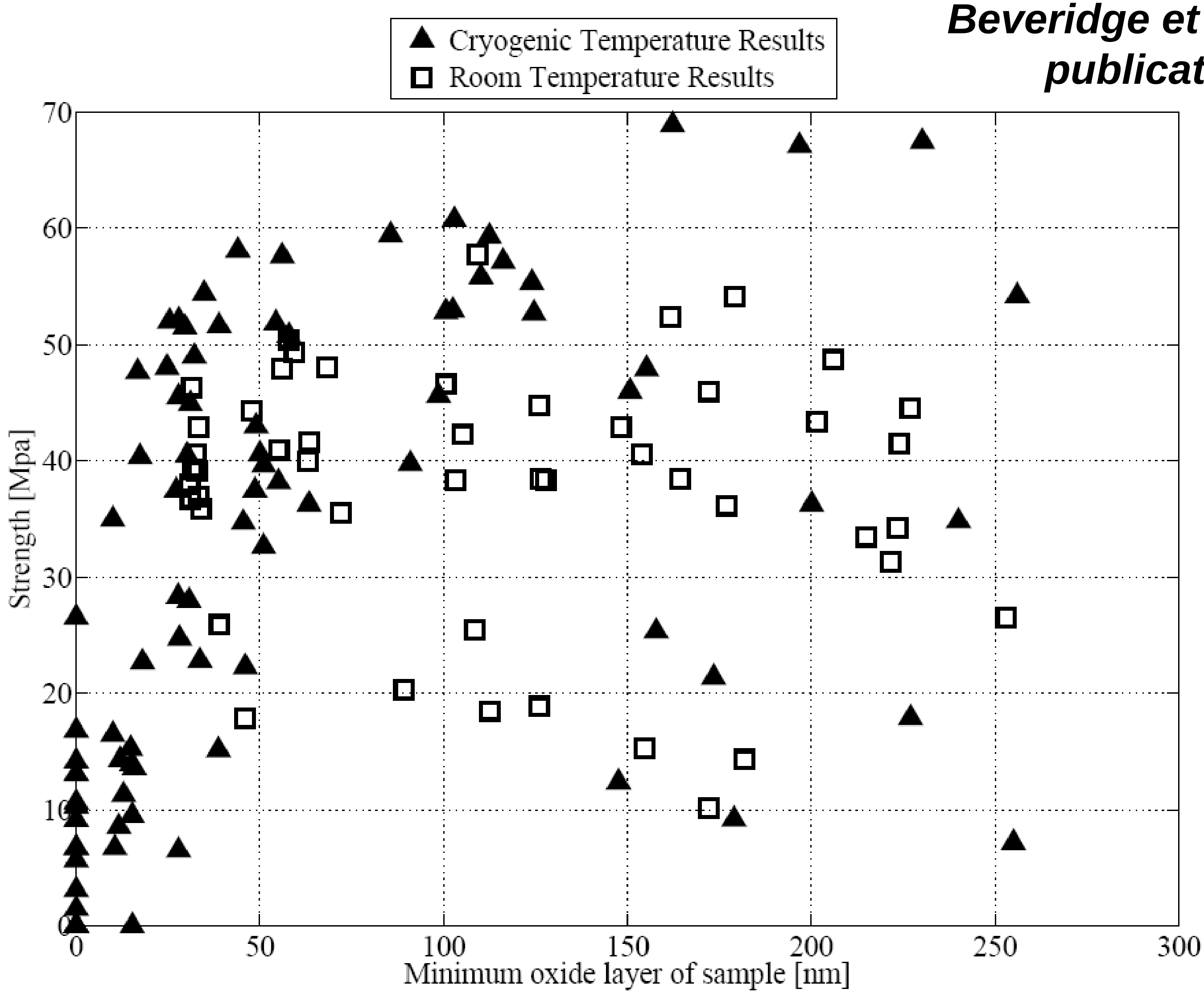




Beyond eaLIGO

Bond robustness - strength

Beveridge et al., accepted for publication in CQG 2011



Other results at room temperature:

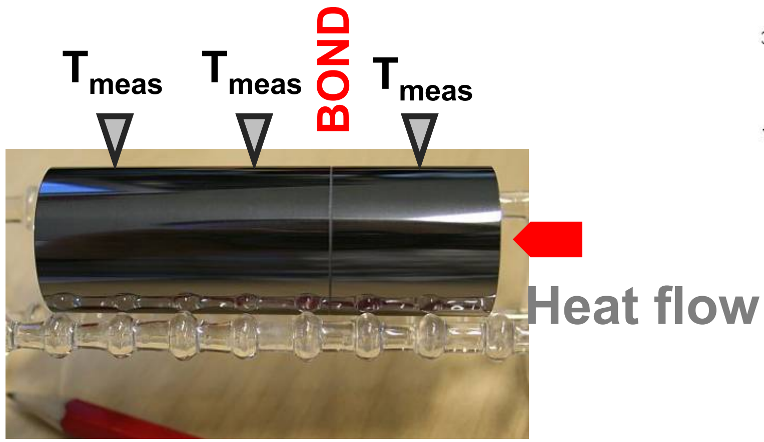
Van Veggel et al. CQG 26, 2009

Dari et al. CQG 27, 2010

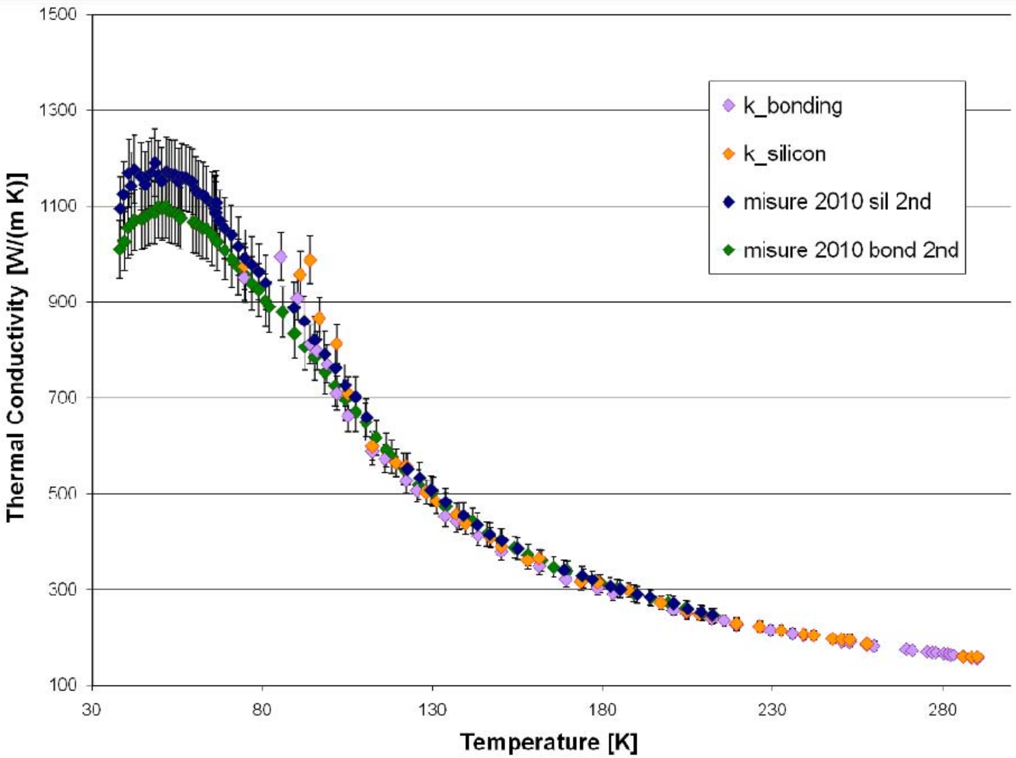
Beyond eaLIGO

Heat extraction – thermal conductivity

Thermal conductivity of bonded sample at low T peak similar to modelled pure silicon with thin (~700nm) glass-like layer



∅25 mm x 48 mm + 28 mm



Lorenzini et al., ET meeting, 1-3 March 2010, Friedrich-Schiller-Universität Jena.
http://www.et-gw.eu/
(Sample fabricated in Glasgow, measurements made in Florence)

Conclusions

- aLIGO - Hydroxide catalysis bonding for advanced LIGO are underway with the first penultimate masses bonded

- eaLIGO - Though the noise contribution of silica-silica hydroxide catalysis bonds is very small, room for improvement can be seen in heat treatment and or vacuum treatment and is under investigation

- Beyond eaLIGO - Hydroxide catalysis bonding of silicon to silicon in cryogenic detectors appears to be a viable solution with high strength at cryogenic temperatures and high thermal conductivity

Further research is ongoing in e.g. characterisation of mechanical loss of bonded silicon substrates and investigating the effect of the type of oxide on strength.