Sapphire suspensions for KAGRA and ET with low loss jointing techniques

MAD Workshop Berlin 2025

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Institute for Gravitational Research
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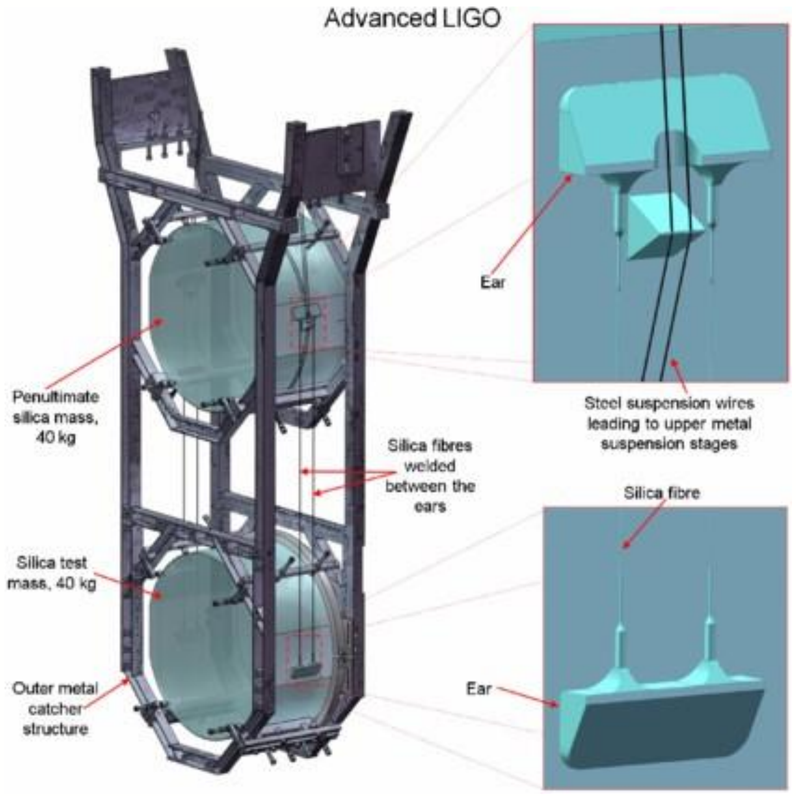
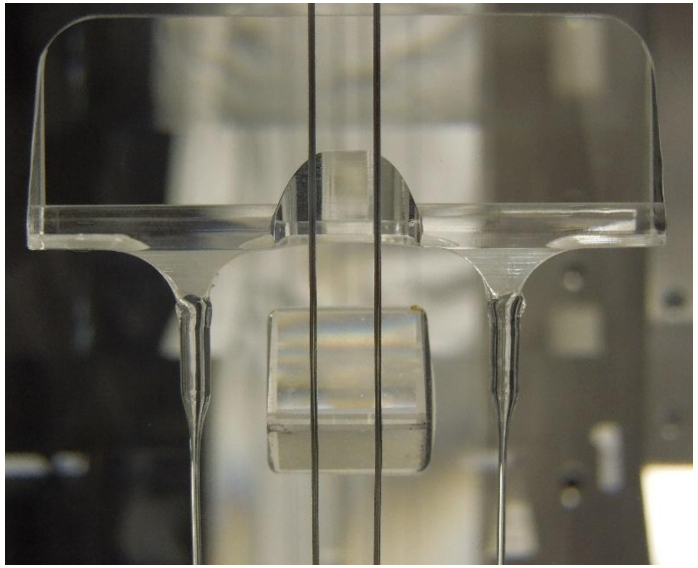
Recap: Laser welding of fused silica in aLIGO

[1]





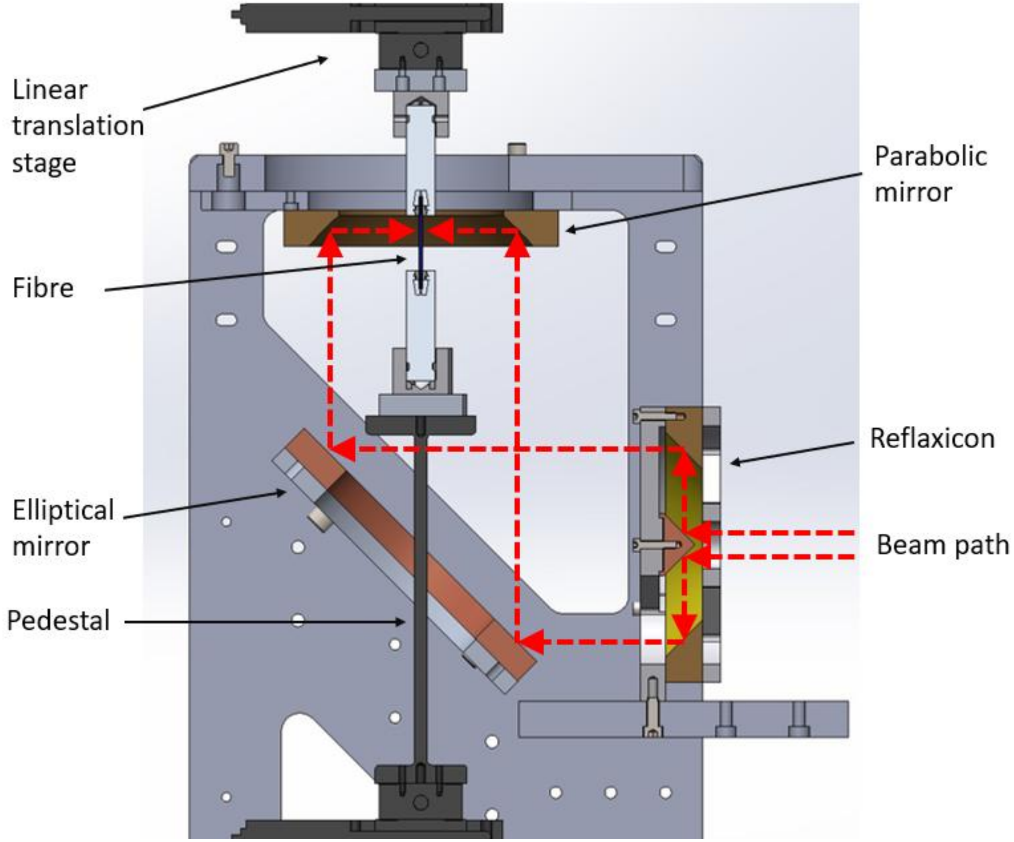
Advantages:
- Demonstrated use in aLIGO
- **Low thermal noise**
- Allows for violin mode tuning and pitch correction [1]
- No need for bond at high stress area, near the bending region of the fibre
- Can replace broken fibres without damaging ear

Highest Q measured in aLIGO: up to 2 billion [2]

[1] A.V. Cumming et al. “Design and development of the advanced LIGO monolithic fused silica suspension”. Classical and Quantum Gravity 29.3 (2012)
[2] A.V. Cumming et al. “Lowest observed surface and weld losses in fused silica fibres for gravitational wave detectors”. Classical and Quantum Gravity 37.19 (2020)

Previous work on sapphire fibre growth

Research conducted by Dr. Jack Callaghan [3]

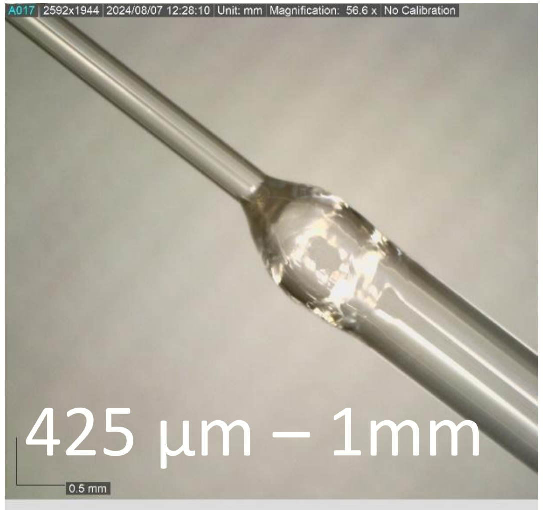


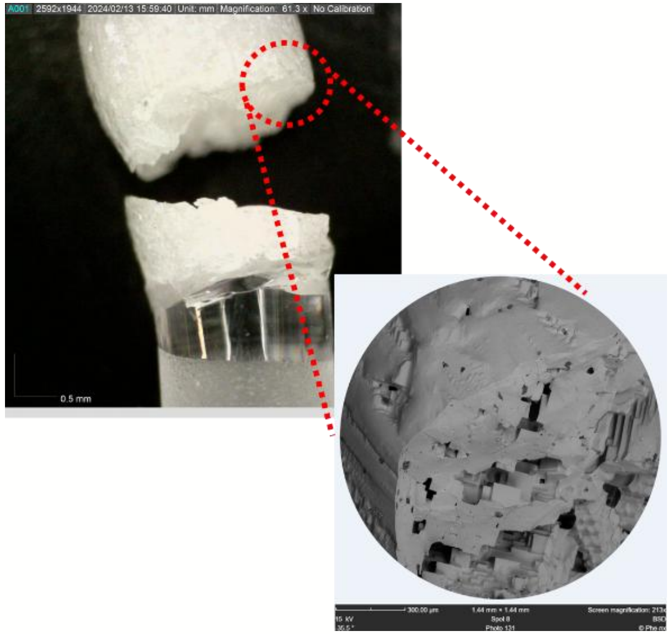
- Laser heated pedestal growth method used to produce sapphire fibres
- 1 mm in diameter, 350 mm long
- Peak strength of 792 MPa (unbroken)
- Low diameter variation and good surface quality
- Further research to continue

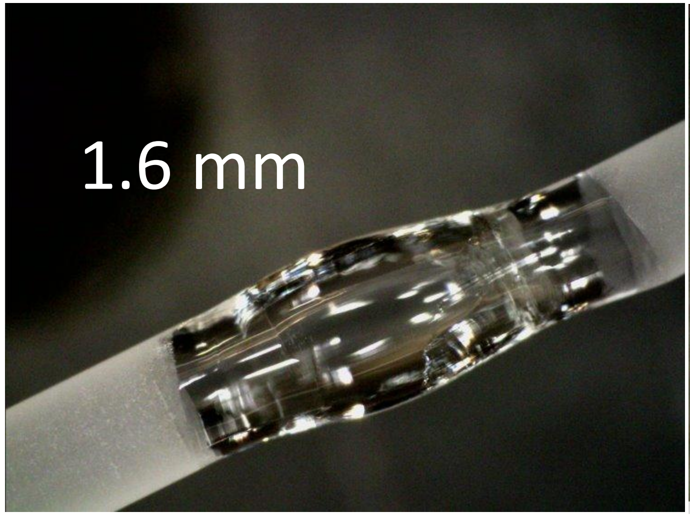
[3] J. Callaghan. "Development of crystalline suspension fibres for next generation gravitational wave detectors." PhD thesis, University of Glasgow, Aug 2024

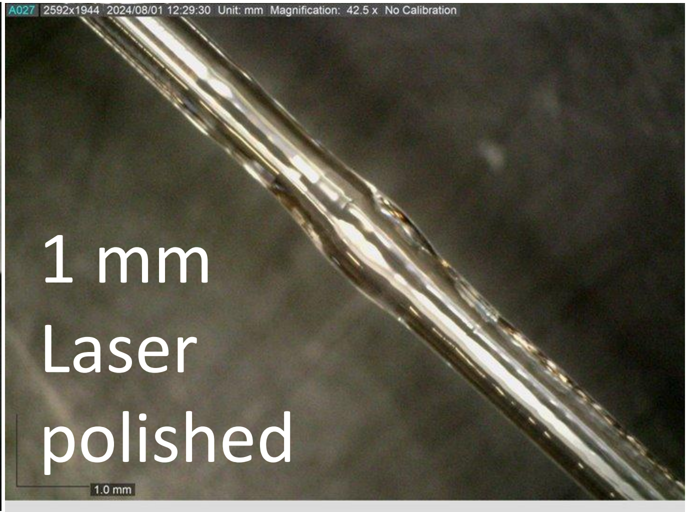
Sapphire welds

- 100+ welds in total completed
- Smallest diameter: 425 µm
- Largest diameter: 1.6 mm
- Investigated surface quality
- Ability to repair/reweld repeatedly

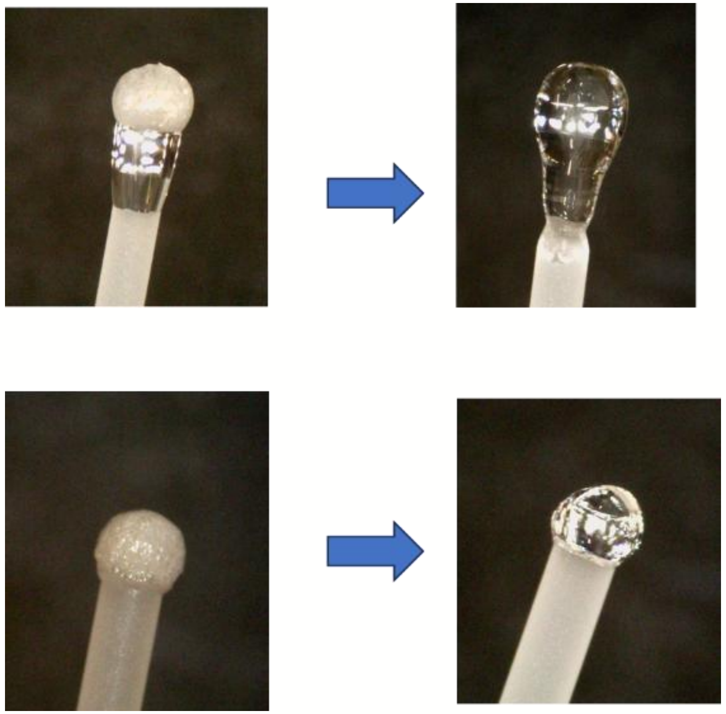






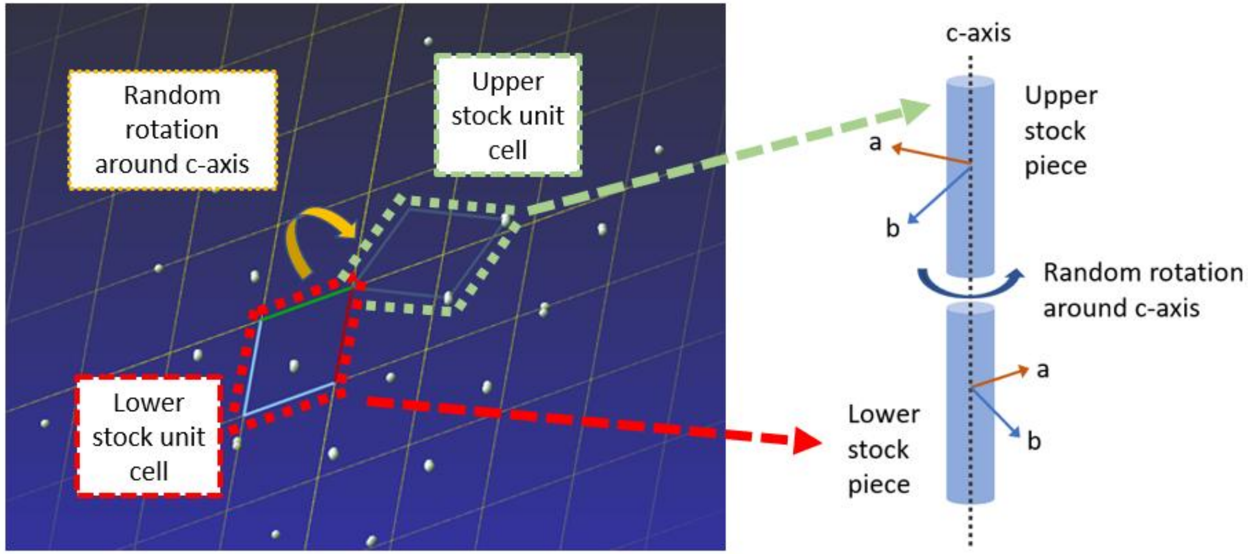


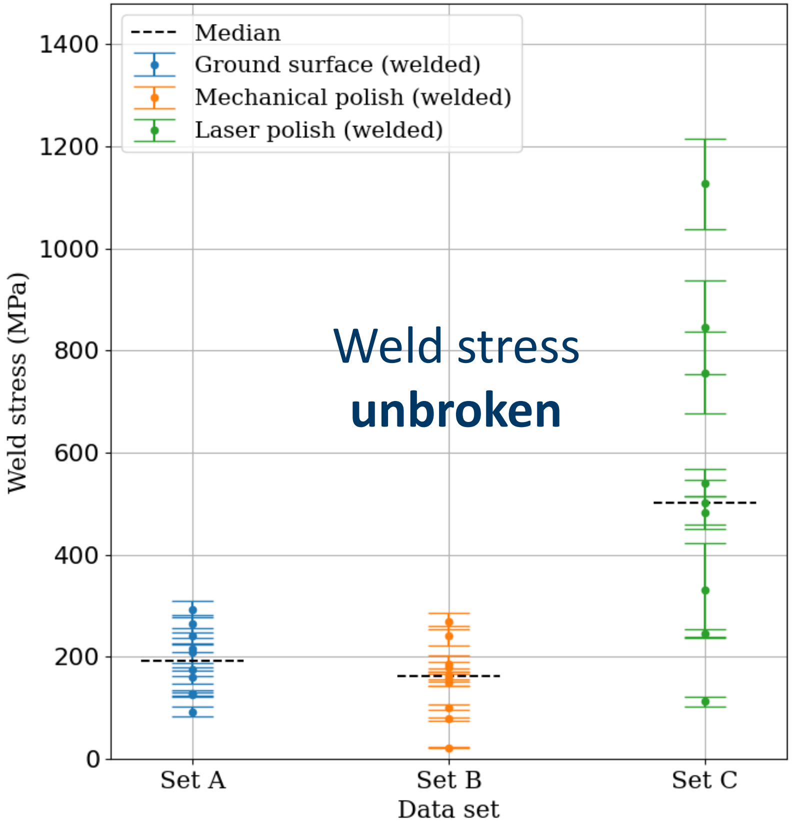
Managing cool down rate is essential



Crystallography and tensile strength

- In both welded samples and grown fibres, it was shown that the c-axis orientation was maintained in the joint region, with an arbitrary rotation of the a and b axes
- Crystalline weld region limited to **≤200 µm**





- Maximum stress observed in a laser polished and welded sample: **1.1 GPa, unbroken**
- Laser polishing shown to increase tensile strength up to three times when compared to ground and mechanically polished samples

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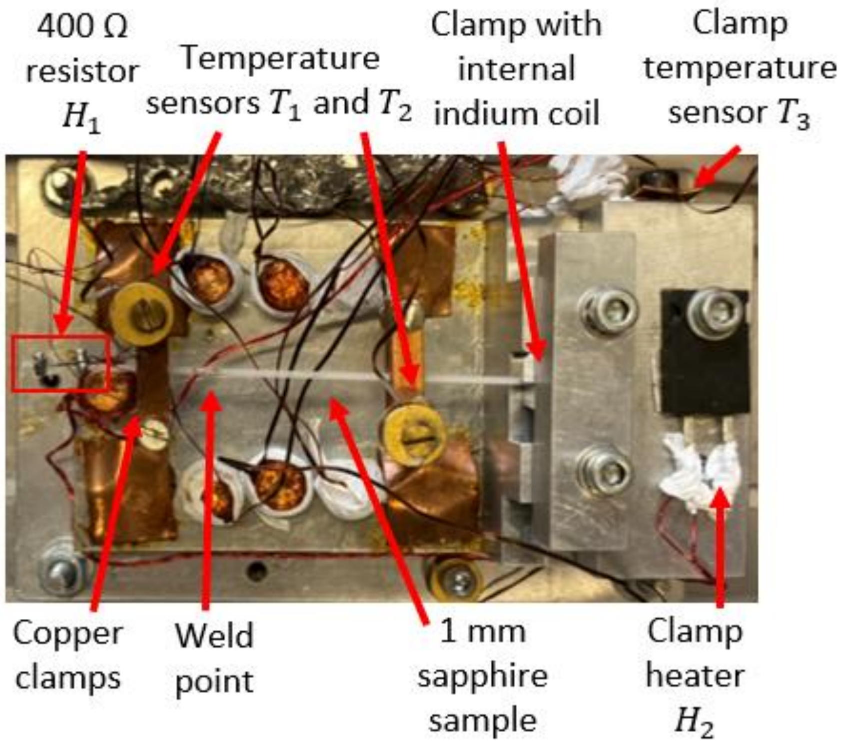
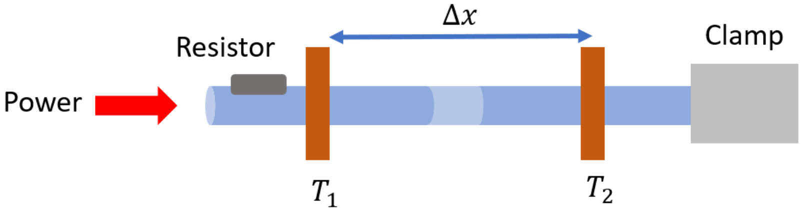
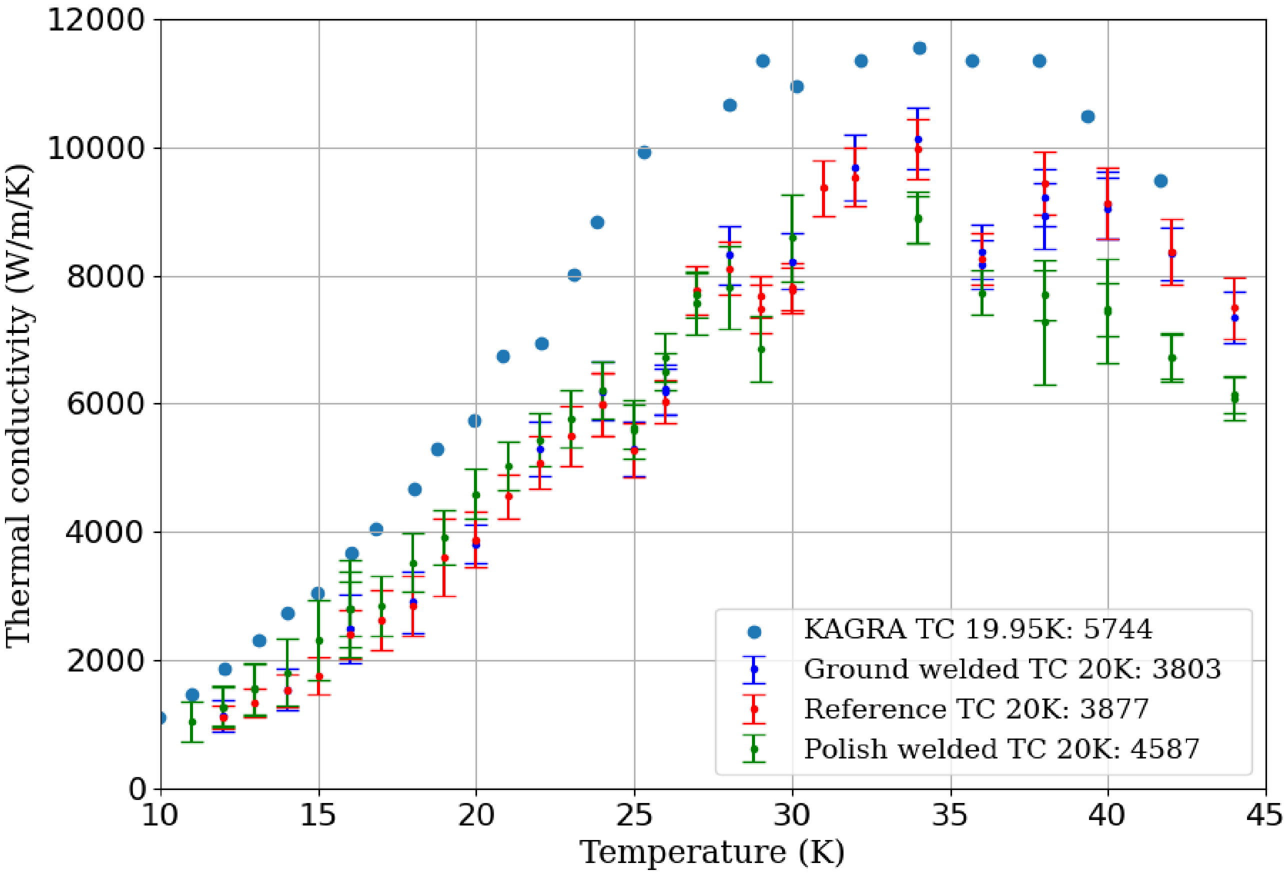
Thermal conductivity

Research undertaken with Dr. Karen Haughian and Dr. Mariela Masso Reid





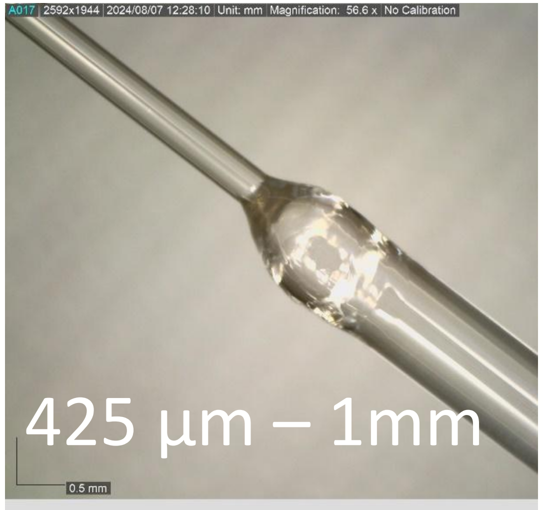


- Measurements of three samples down to 13 K using steady state method
- No appreciable difference between welded and unwelded sample
- Difference to KAGRA curve thought to be due to purity levels in base sapphire

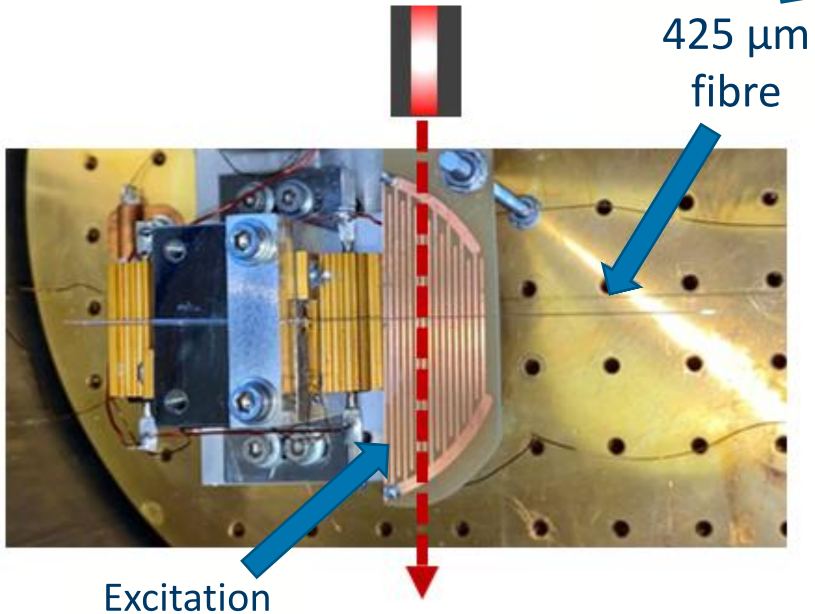
Mechanical loss

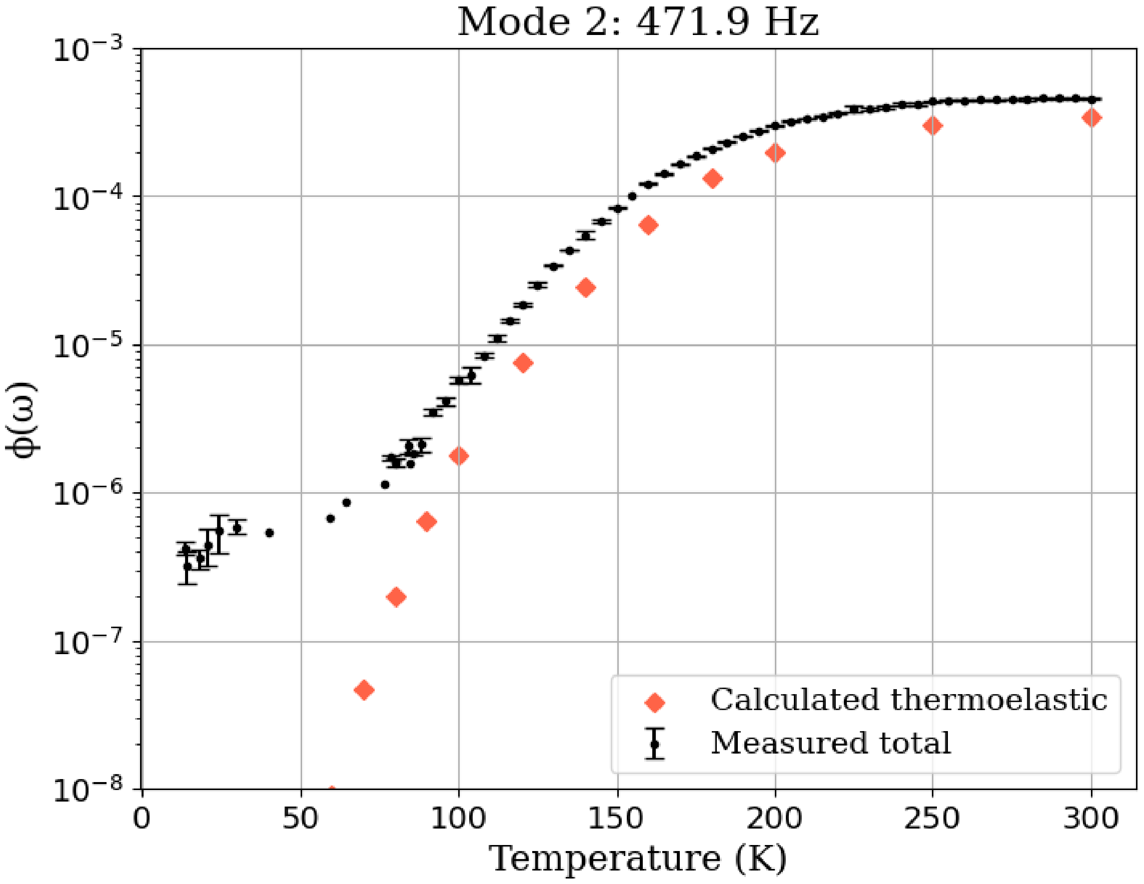
Research undertaken with Dr. Peter Murray, Dr. Iain Martin and Dr. Alan Cumming

- Measured down to 13 K for six resonant modes
- Using welded 425 μm fibre to 1 mm rod

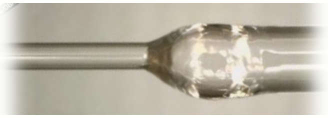


Lowest measured loss average: $\mathbf{3.2\times 10^{-7}}$





Extracting a weld loss estimate

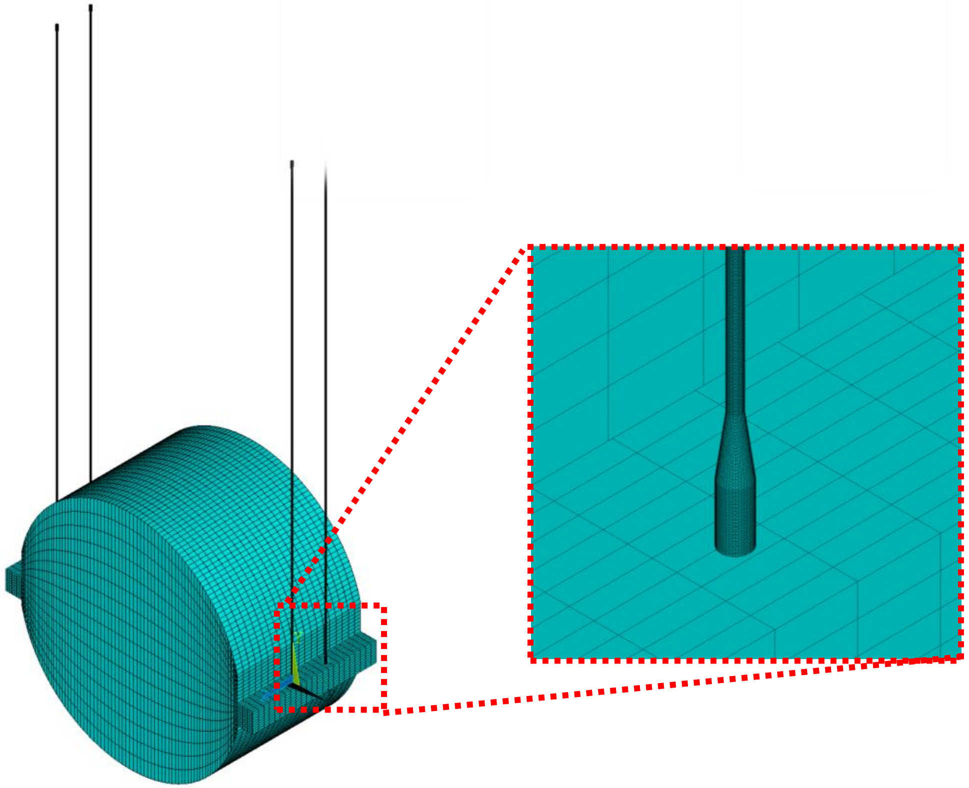


- Decoupling weld loss and surface loss is challenging, as seen in previous study on fused silica violin modes in aLIGO [2]
- Using FEA, we determined the bending energy in the weld of the measured sample
- We extracted the weld to surface loss ratio in aLIGO as 1:18, and (initially) assume this is the case is sapphire, providing:

$$E_1\emptyset_{surface} + E_2\emptyset_{weld} = \emptyset_{min}$$

And $\emptyset_{weld} = 18\emptyset_{surface}$

- From this we obtain an h$\emptyset_s$ of $\mathbf{1.5\times 10^{-11}}$, and a $\emptyset_{weld}$ of $\mathbf{5.1\times 10^{-6}}$
- This was then implemented in an FEA model of a hypothetical ET-LF suspension to determine the bending energy in the weld to be 0.12% of total system, if welding to a 5 mm diameter stock end



Thermal extraction

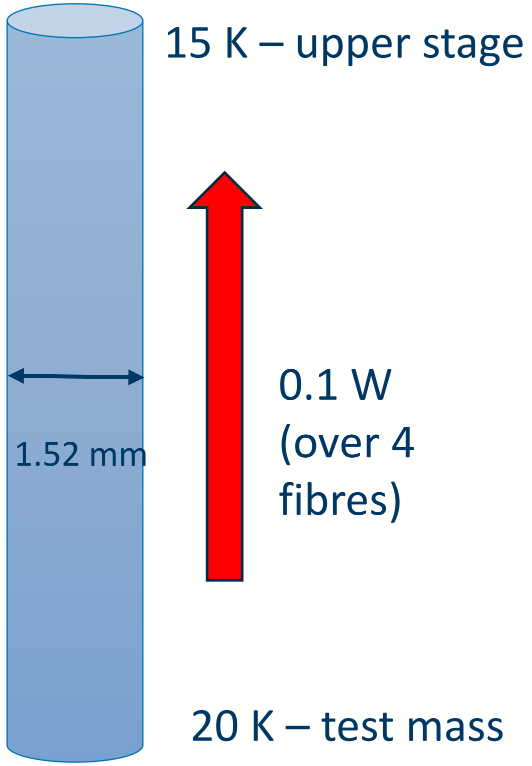
$$A_{\text{fibre}} = \frac{HL}{4\int_{T_1}^{T_2} \kappa(T)dT}$$

- Fibres must have sufficient thermal conductivity to extract heat from test mass

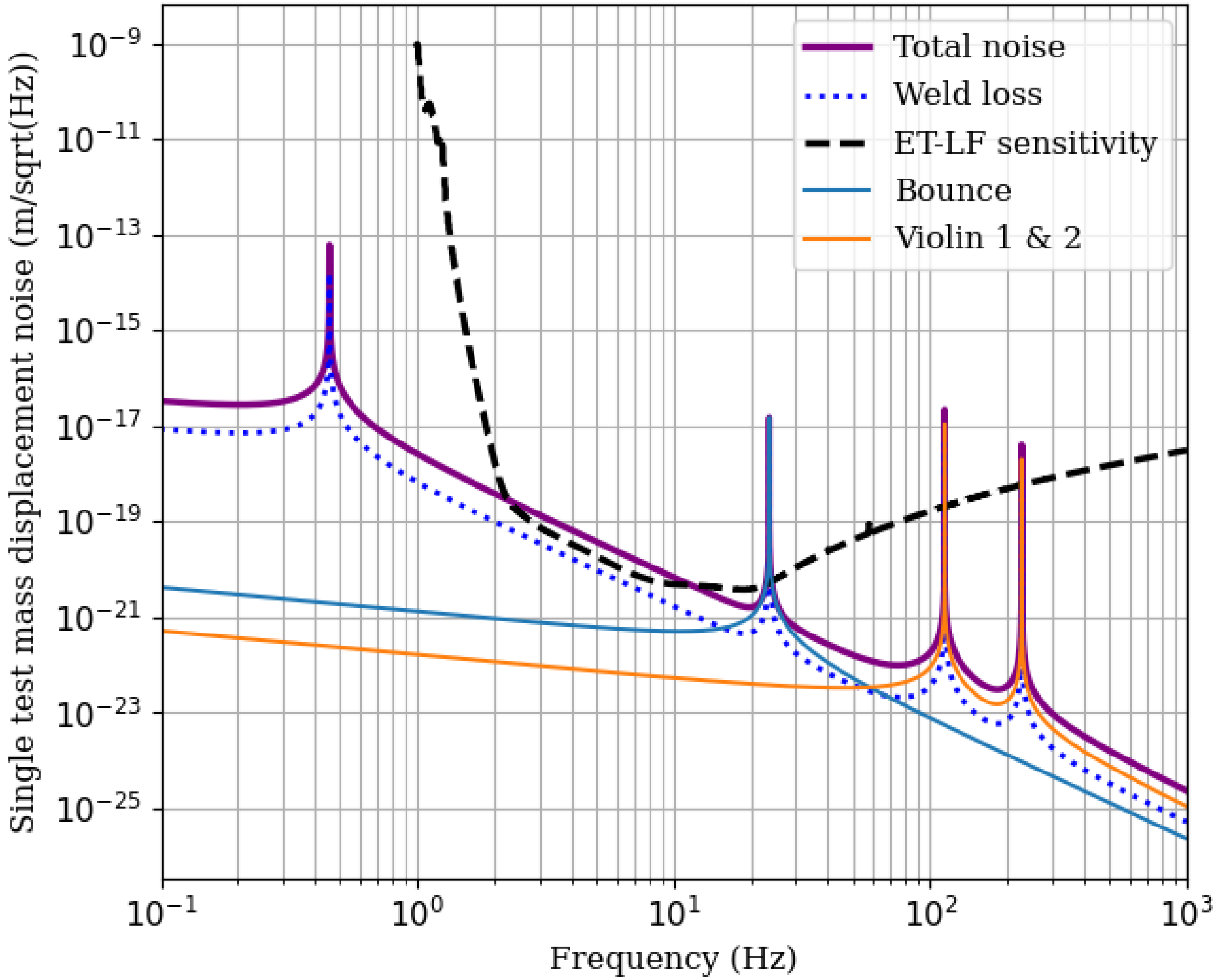
- This provides a limit on diameter

- In ET, we assume a 15-20 K temperature gradient along the fibre, and a heat flow of 0.1 W (from laser and environmental sources) to be extractedd by the 4 fibres

- Using our measured thermal conductivities from the laser polished sample, the required diameter in ET was found to be **1.52 mm**, higher than the strength limited case (1.3 mm diameter: using stress of 1.1 GPa and s.f of 3)



Suspension thermal noise modelling in ET



- Includes measured loss, with estimated decoupling
- Model of 1.52 mm diameter fibres with 5 mm stock ends compared to current ET-LF design curve [4]
- Total noise is already approaching design curve without fully optimising weld loss

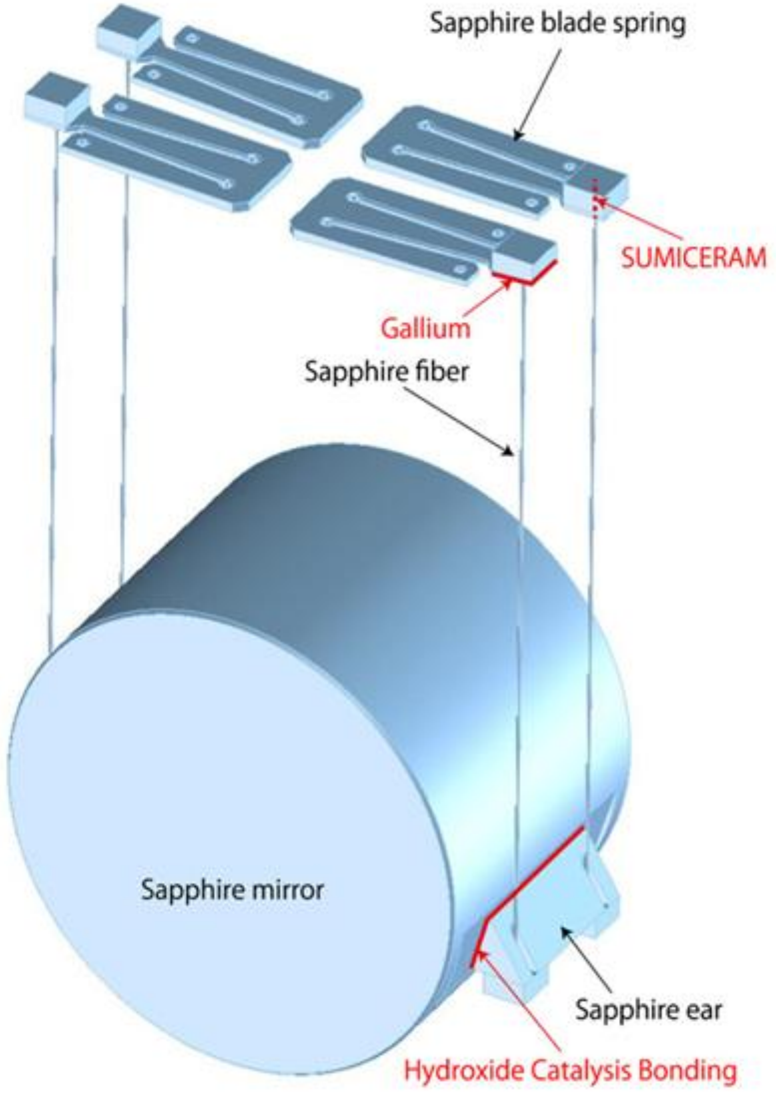
[4] https://apps.et-gw.eu/tds/?r=19401

Larger diameter welds: 1 mm – 3mm

- Next stage of sapphire welding work is attaching fibres to larger masses
- Challenges with cracking, laser alignment, and limitations of laser power
- Trials of welding 1 mm stock to 3 mm stock as an intermediate step
- Heat reduction rate critical, especially at low powers (<30%)

KAGRA Suspensions

- 4 x sapphire fibres of 1.6 mm diameter and 350 mm length
- Attached to 20 x 20 x 10 mm nail heads using SUMICERAM alumina bonding agent
- Nail heads bonded to blade springs using gallium bonding



[5]

[5] T. Ushiba et al. “Cryogenic suspension design for a kilometer-scale gravitational wave detector”. In: Classical and Quantum Gravity 38.8 (2021), p. 085013.

KAGRA fibre investigation

- Collaborating with KAGRA to improve the Q of their sapphire suspensions
- KAGRA suspension FEA model in progress
- Development of laser polishing and welding 1.6 mm KAGRA fibres ongoing with Munetake Otsuka, visitor from University of Tokyo
- Investigating: Ansys simulations, surface quality, Q contributions, implementing welding and polishing

Conclusion

- Sapphire welding found to be repeatable, repairable and a promising concept for cryogenic detectors
- Characterisation found no appreciable difference on thermal conductivity or strength
- Collaboration with KAGRA
- Future work will look at joining fibres to larger ear-like masses, and working towards a demonstration of a hanging mass in our 10 m cryogenic prototype
- **Publication in preparation, available on LIGO DCC: P2500357, ET TDS: ET-0451A-25**

	aLIGO silica welding	**Glasgow sapphire welding**
Demonstrated	In aLIGO	In lab repeatedly
Thermal noise	Ultra-low demonstrated by violin mode measured Qs	• Initial weld loss approaching required level, with further investigation to come • Weld size at most **200 µm**
HC bonding	Eliminates need for extra bond region	Could eliminate need for extra bond region
Repairability	Ability to repair	Ability to repair
Violin mode/pitch tuning	Proven in aLIGO	Believed to be possible, investigation ongoing

Thank you for you listening

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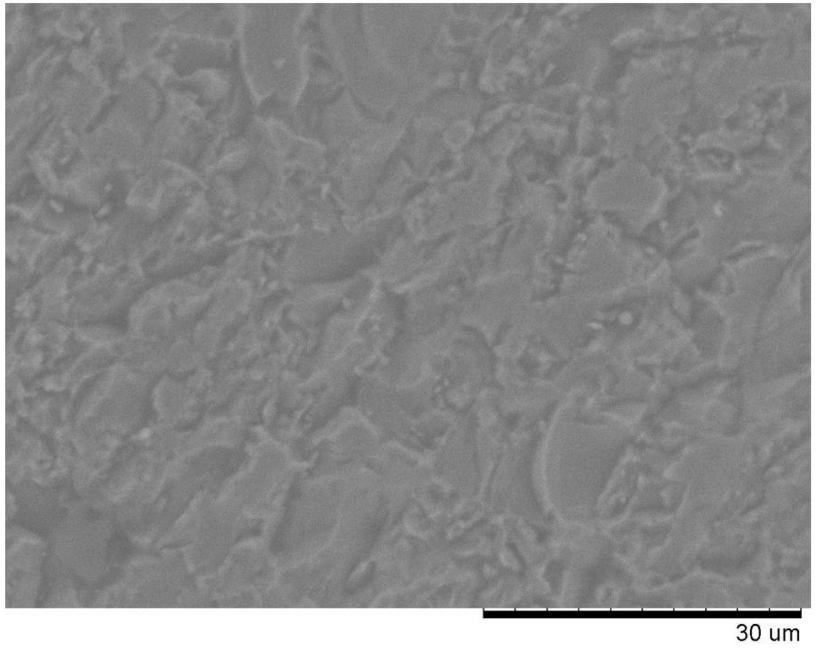
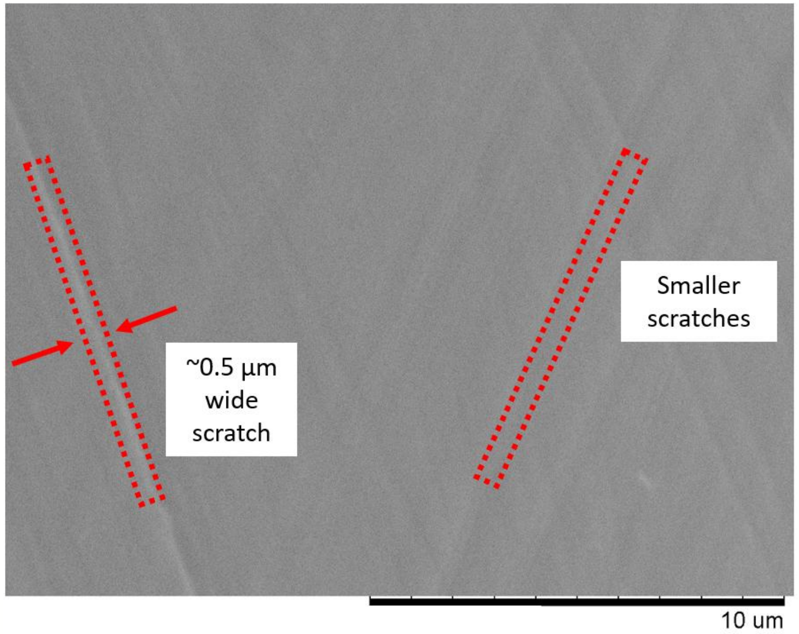
Extra Slides

Extra slides: surface quality SEM images

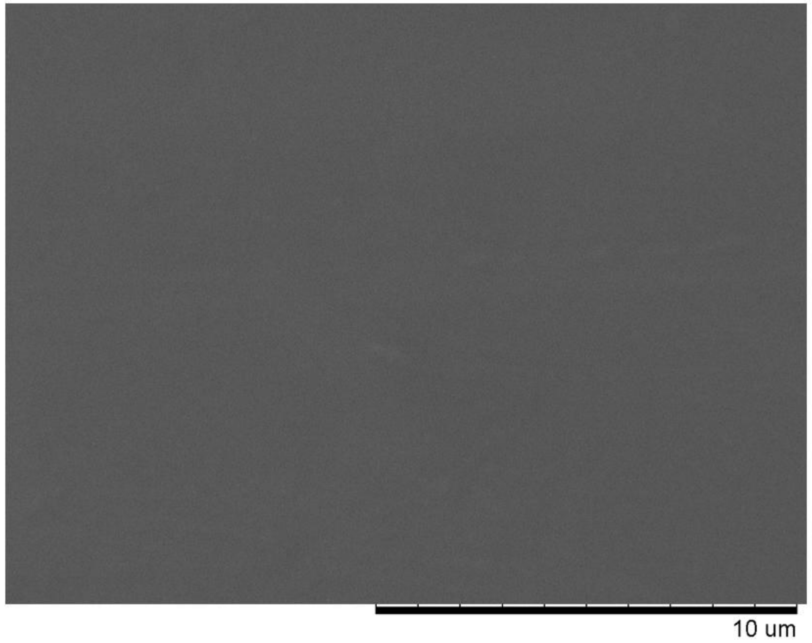
Ground surface



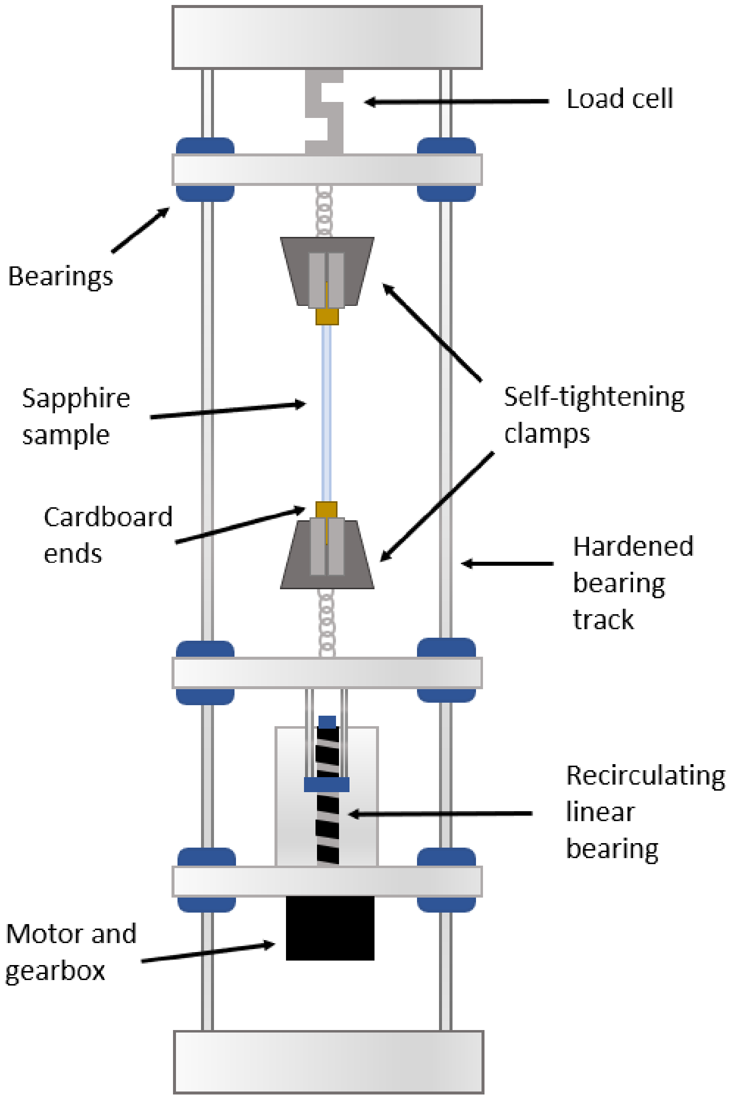
Mechanical polish



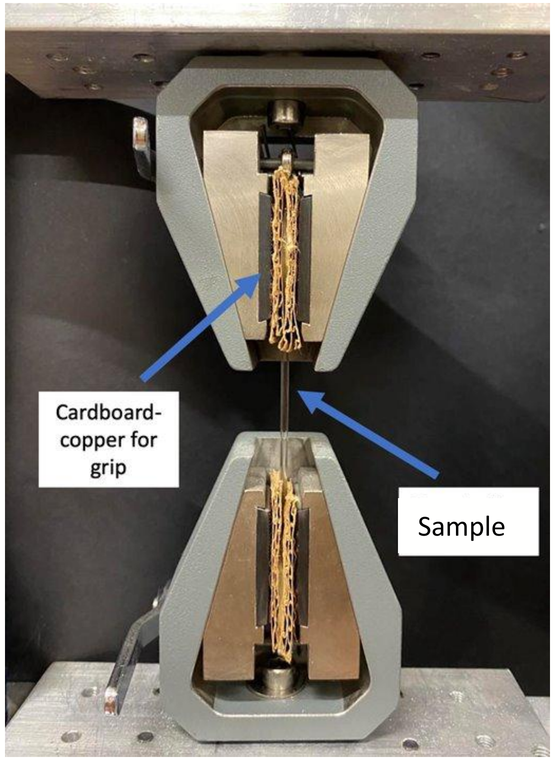
Laser polish



Strength testing



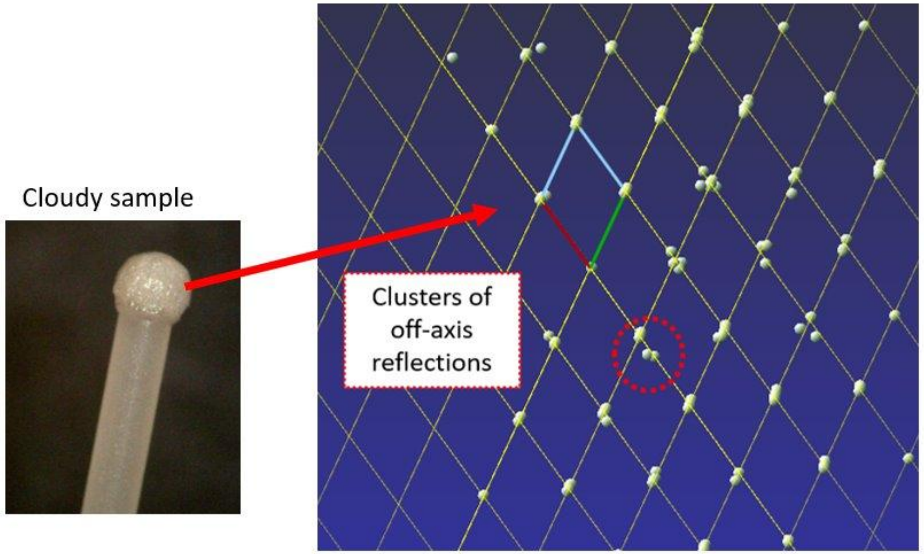
- Using the strength tester at Glasgow [10]
- Highest maximum stress in weld observed: **1.1 GPa (unbroken)**
- Literature value of ultimate tensile stress is 400 MPa [4]
- Laser polished samples significantly stronger than ground and mechanically polished samples
- No welds were broken



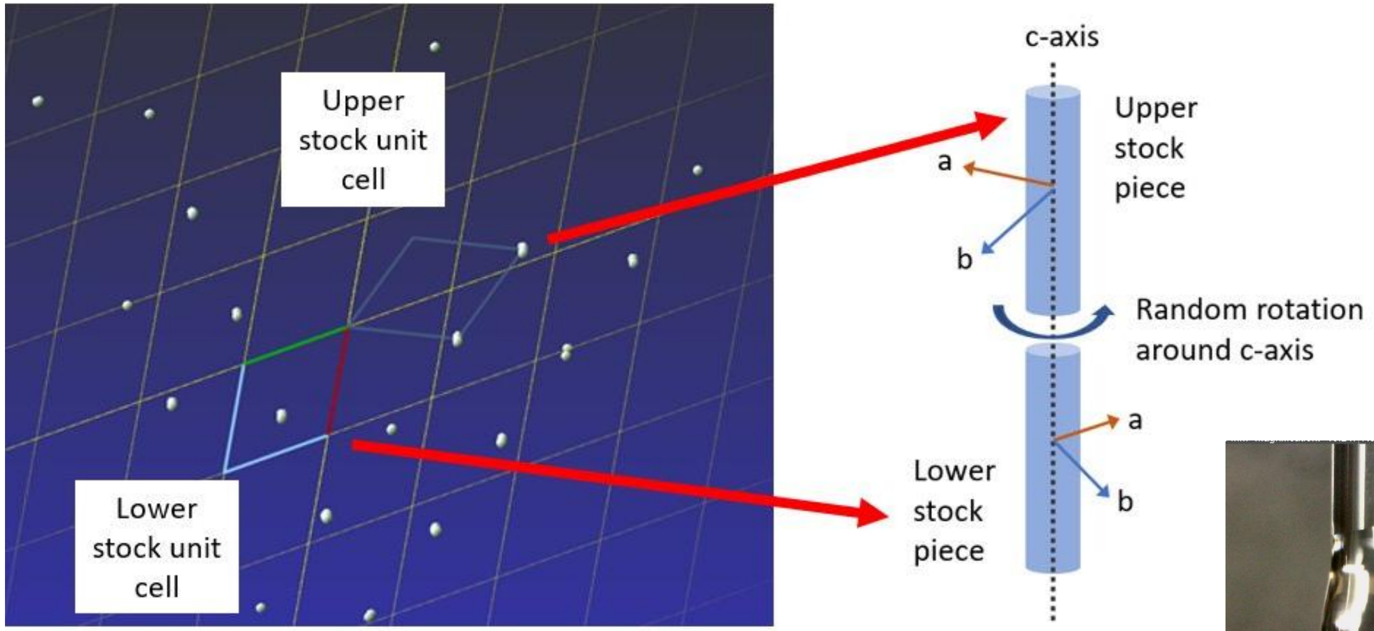
[10] R. Jones et al. "The Design of the IGR MKII Strength Testing Machine" https://dcc.ligo.org/LIGO-T1000345

Crystallography

Research supported by Dr. Claire Wilson and Dr. Sarah Dugmore (School of Chemistry)



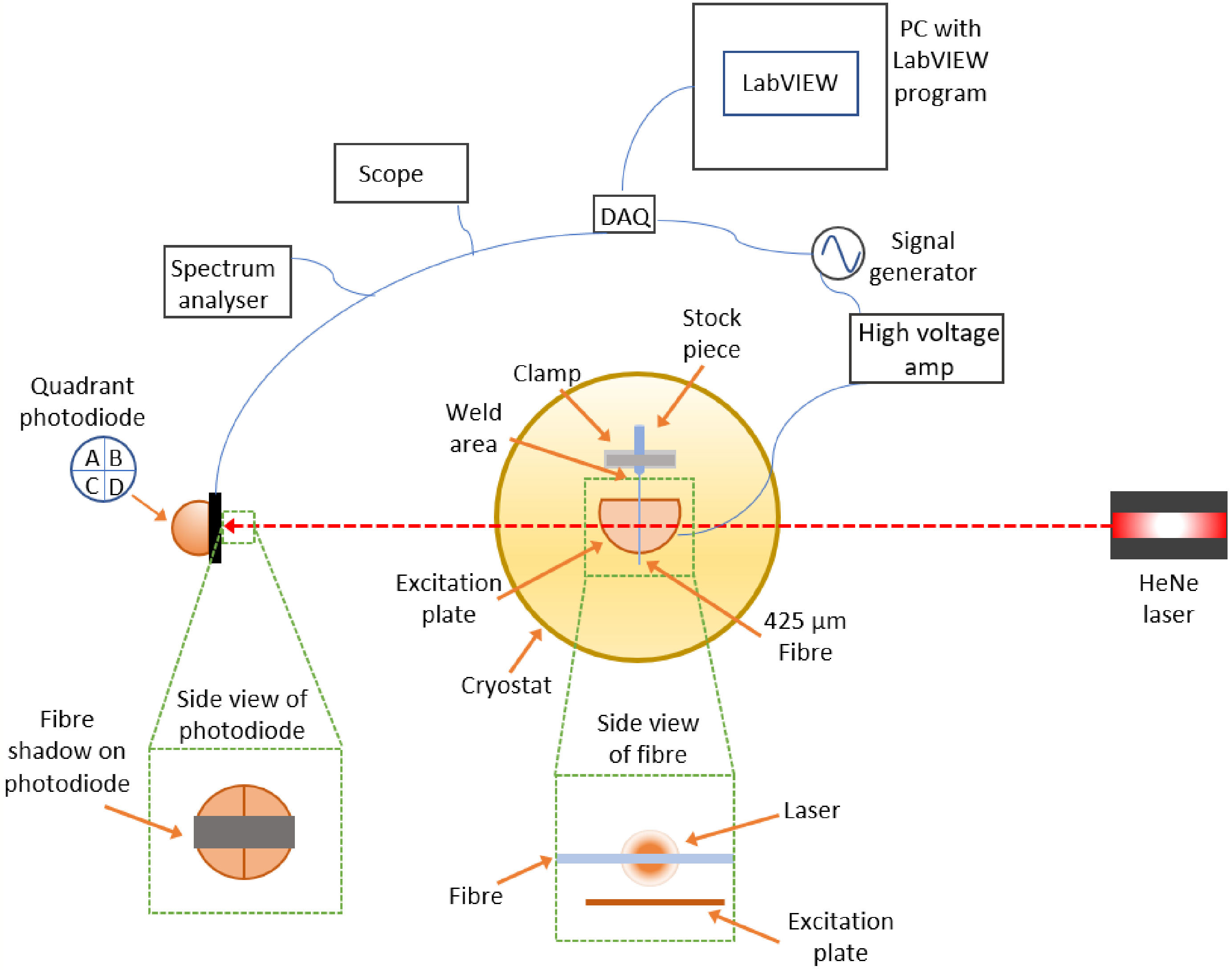
Cloudy material shown to be single crystalline with off-axis domains



Weld region ≤ 200 µm, ~10 x smaller than in aLIGO [8], promising for weld loss contribution

[8] A.V. Cumming et al. “Lowest observed surface and weld losses in fused silica fibres for gravitational wave detectors”. In: Classical and Quantum Gravity 37.19 (2020)

Measurements



Full thermal conductivity