Static Fatigue in Fused Silica Fibres

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On behalf of the Glasgow SUS Team

ET Symposium May 2025

ET-0281A-25

Introduction

- Key Concepts for improving thermal noise in Suspensions
- Thermal noise performance → Glasgow heavy suspension prototype
- Fracture properties of Fused Silica
- Testing hang times of fibres for high stresses
- Future work

Core Concepts to Improve Suspension Performance

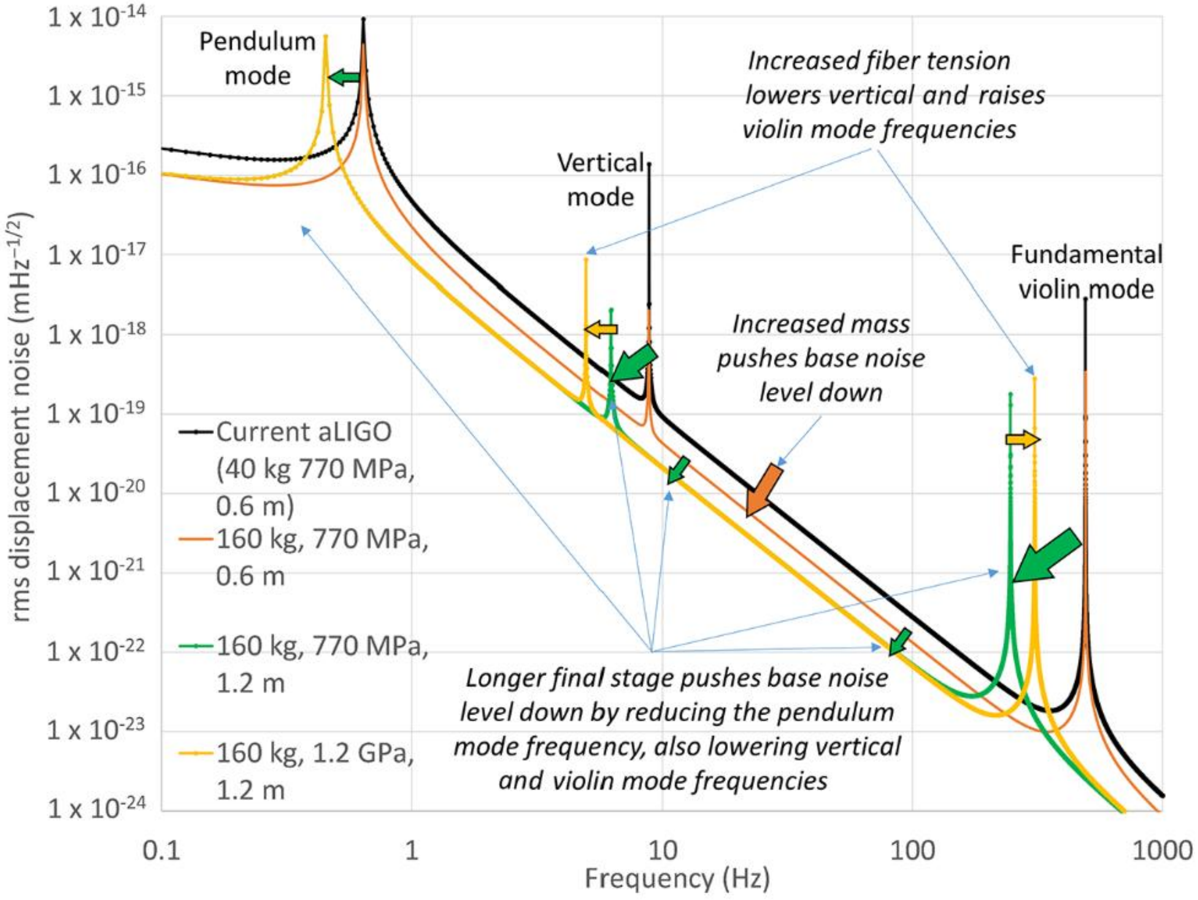
- Increasing the mass → Lowers the base noise:
  - ET-HF Design: 200 kg

$$x(\omega) \propto \frac{1}{\sqrt{m}}$$

- Increasing the length → Pushes all resonant modes to lower frequencies
  - ET-HF Design: 0.6 m

$$f_{violin} \propto \frac{\sqrt{\sigma}}{l} \qquad f_{pendulum} \propto \frac{1}{\sqrt{l}} \qquad f_{vert} \propto \frac{1}{\sqrt{l\sigma}}$$

- Increasing stress → Increases the separation between vertical and violin modes
  - ET-HF Design: 770 MPa



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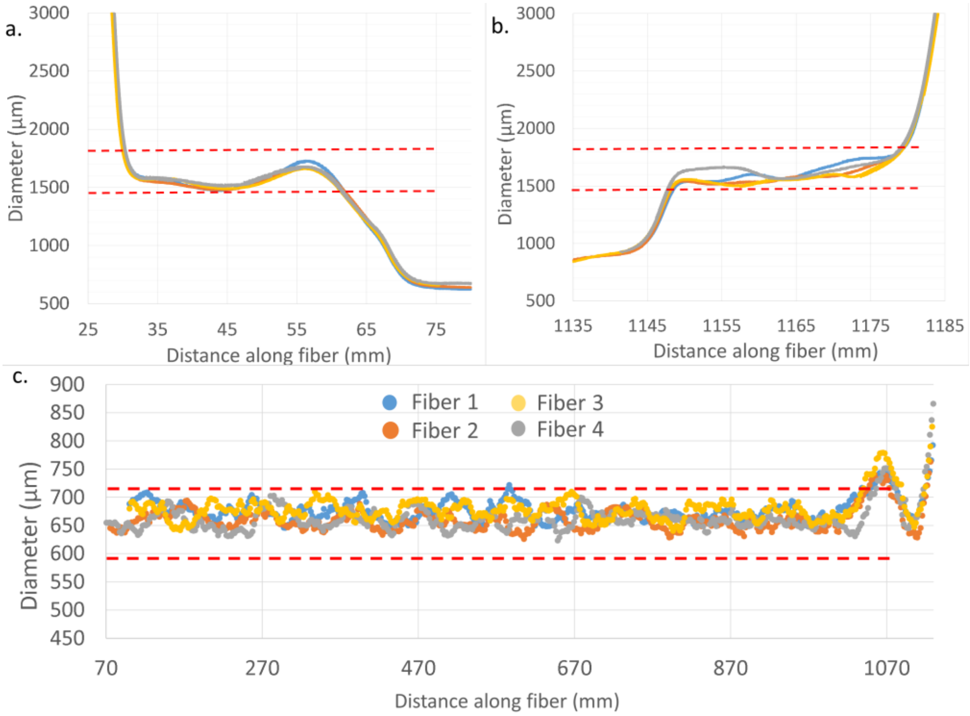
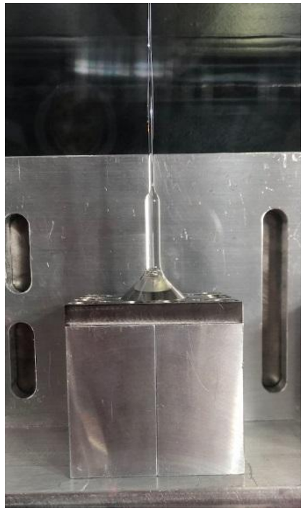
Conceptual Design and Noise Budget of Einstein Telescope : https://apps.et-gw.eu/tds/?r=19401

Glasgow Prototype Suspension

- Glasgow Large scale prototype:
  - High stress fibres → 1.2 GPa
  - Longer fibres → 1.2 m
  - Larger Mass → 160 kg and heavier
  - Welding larger diameter stock → 5 mm





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PHYSICAL REVIEW APPLIED

Highlights Recent Subjects Accepted Collections Authors

Large-scale Monolithic Fused-Silica Mirror Suspension for Third-Generation Gravitational-Wave Detectors

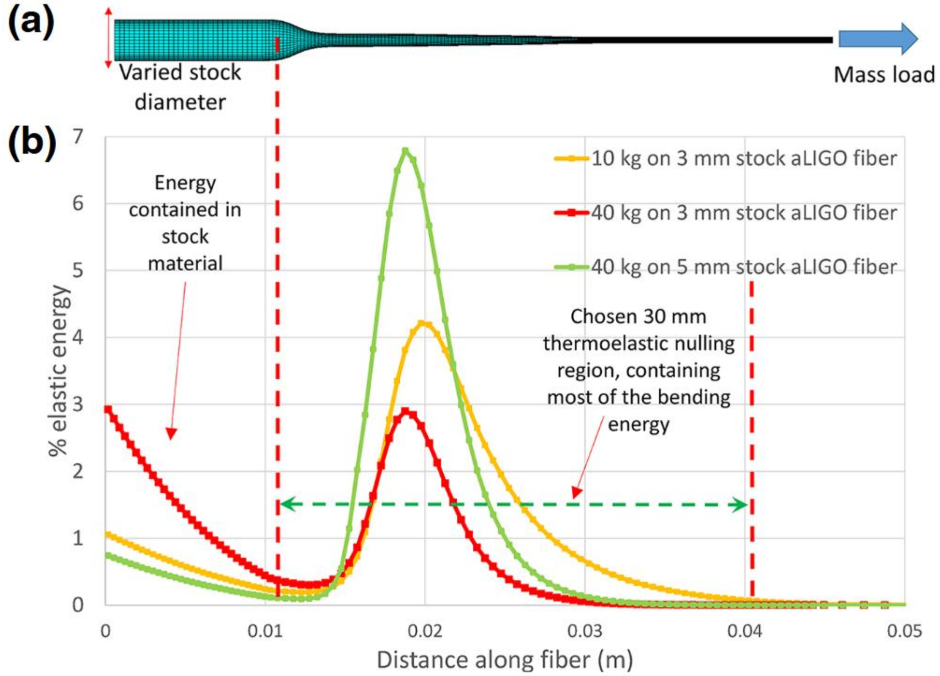
A. V. Cumming, R. Jones, G. D. Hammond, J. Hough, I. W. Martin, and S. Rowan

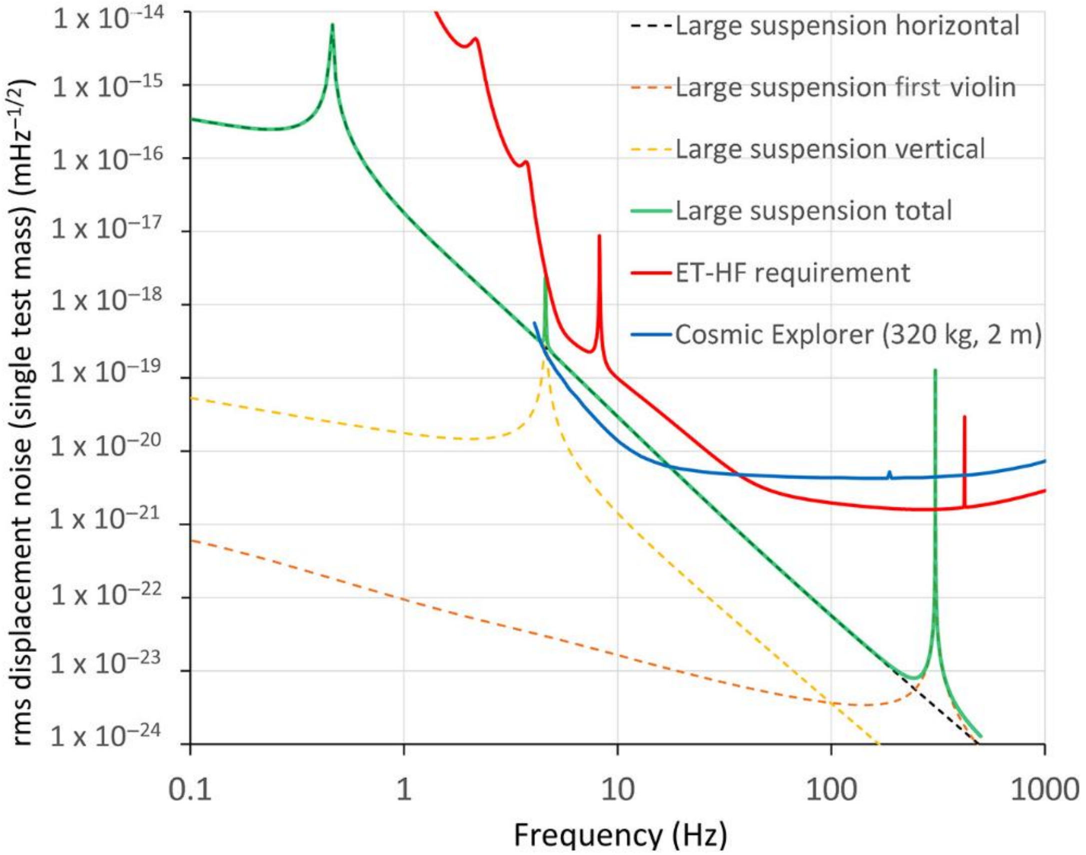
Phys. Rev. Applied **17**, 024044 – Published 16 February 2022

Glasgow Prototype Suspension

- FEA done on real fibres:
  - Assumed Adv. LIGO style ears (in-situ welding, low noise)
  - Base noise satisfies ET-HF requirement
  - Vertical and Roll modes below 20 Hz (crossover point for HF and LF)

$$f_{roll} \approx \sqrt{2} f_{vert}$$





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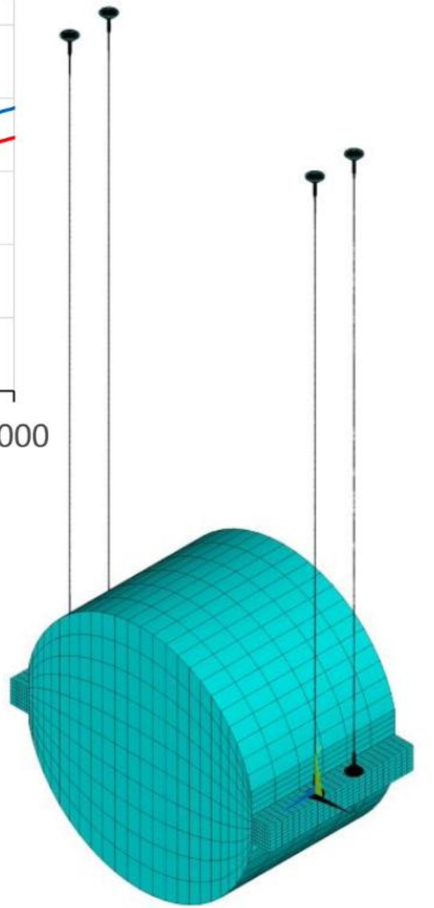
- Scaling mass 160kg → 200kg should give 1.12x improvement (first order extrapolation)
- Increasing stock diameter should provide further improvement
- **Increasing the stress will help push violin modes to higher frequencies**



Fracture Mechanics in Glass

- Intrinsic strength of fused silica is estimated to be around ~14 GPa; in reality, fibre strengths are around ~4-5 GPa.
- Stresses near the crack tip can be characterised using the Stress Intensity Factor - $\boldsymbol{K \propto \sigma_\infty \sqrt{a}}$
- There exists a value for which crack is self propagating ($\boldsymbol{K_c}$) generally referred to as the fracture toughness of the material
- There are mechanisms that allow ‘subcritical’ crack growth
- Hang time should correspond to the time required for crack to reach a_c

$$K_c \propto \sigma_\infty \sqrt{a_c}$$

B. A. Proctor, I. Whitney and J. W. Johnson “The Strength of Fused Silica”

*T.L. Anderson, “Fracture Mechanics Fundamentals and Applications”

Sub-critical Crack Growth in Fused Silica

- Cracks can grow at lower rates below the critical value using other mechanisms
- Region I – Stress enhanced corrosion
  - Although various chemical kinetics models are under debate, the underlying cause is well established.*
  - The crack growth rate (v) is generally modelled as:

$$v = v_0 \exp\left(\frac{-E^* + bK}{RT}\right)$$

E* refers to the activation energy for water-silica reaction under zero stress*

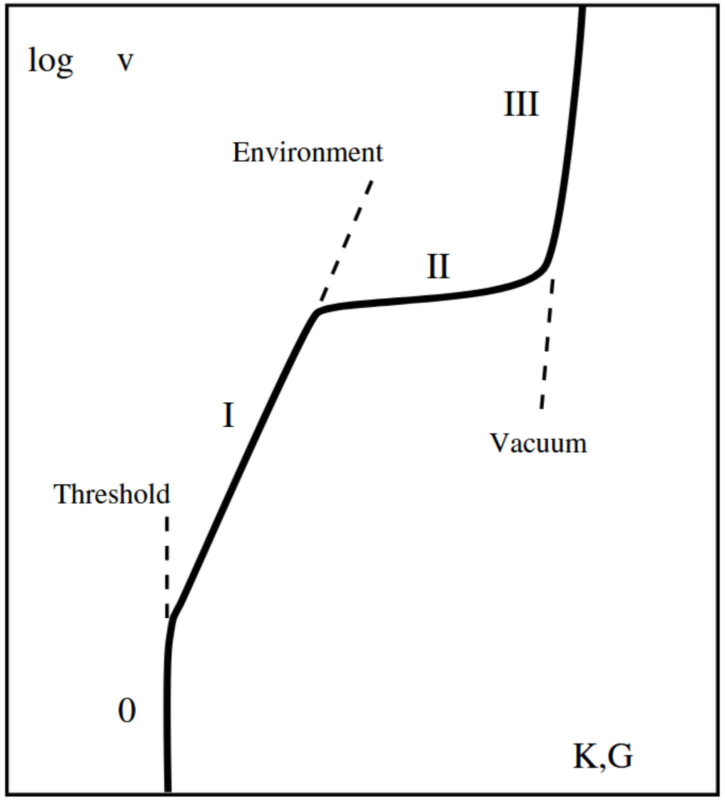


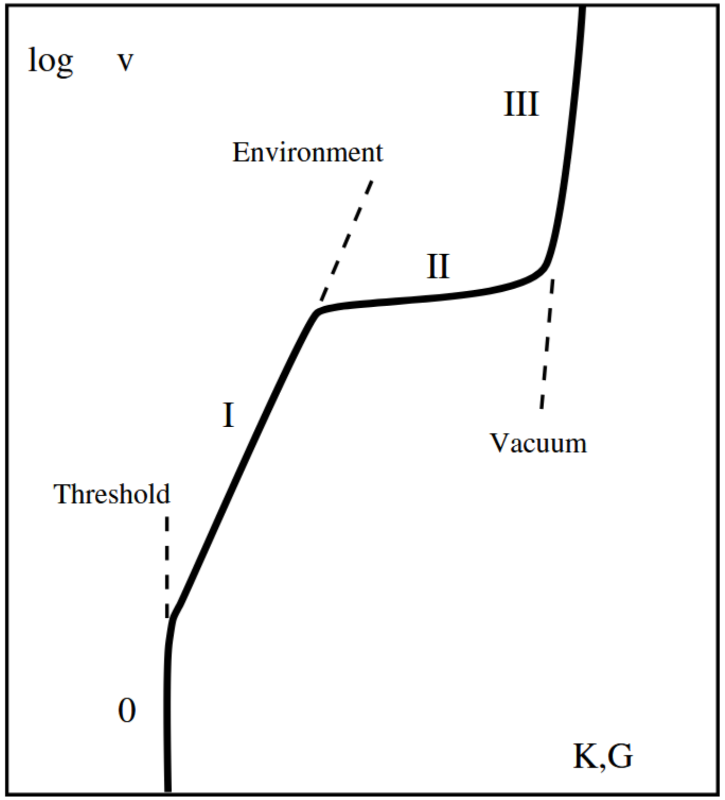
Figure 4. Typical $v(K)$ or $v(G)$ diagram for subcritical crack propagation in glass.

Stress-corrosion mechanisms in silicate glasses, Matteo Ciccotti

*Y.S. Shiue, M.J. Matthewson "Apparent activation energy of fused silica optical fibers in static fatigue in aqueous environments"

Sub-critical Crack Growth in Fused Silica

- Cracks can grow at lower rates below the critical value using other mechanisms
- Region II – Mechanism still under debate, transport kinetics, water diffusion being a few



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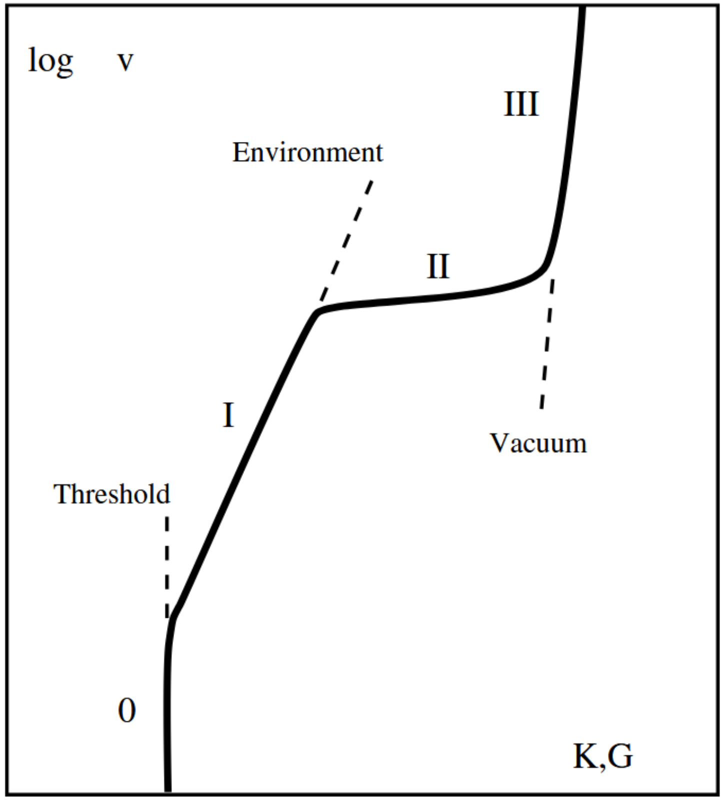
Sub-critical Crack Growth in Fused Silica

- Cracks can grow at lower rates below the critical value using other mechanisms
- Region III –
  - Very sharp increase in velocities.
  - Speculated to be independent of environment
  - $v=AK^n$, n=1600 in vacuum as opposed to 40 in humid air (30% RH)*



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Stress-corrosion mechanisms in silicate glasses, Matteo Ciccotti

*"Role of structural relaxations in the fracture of vitreous silica", Terry A. Michalske,

Static fatigue in fused Silica Fibres

- The spread for in vacuum results from Proctor el al’s data is very large.
- More hang time tests of fibres at high stresses are required to accurately gauge their reliability

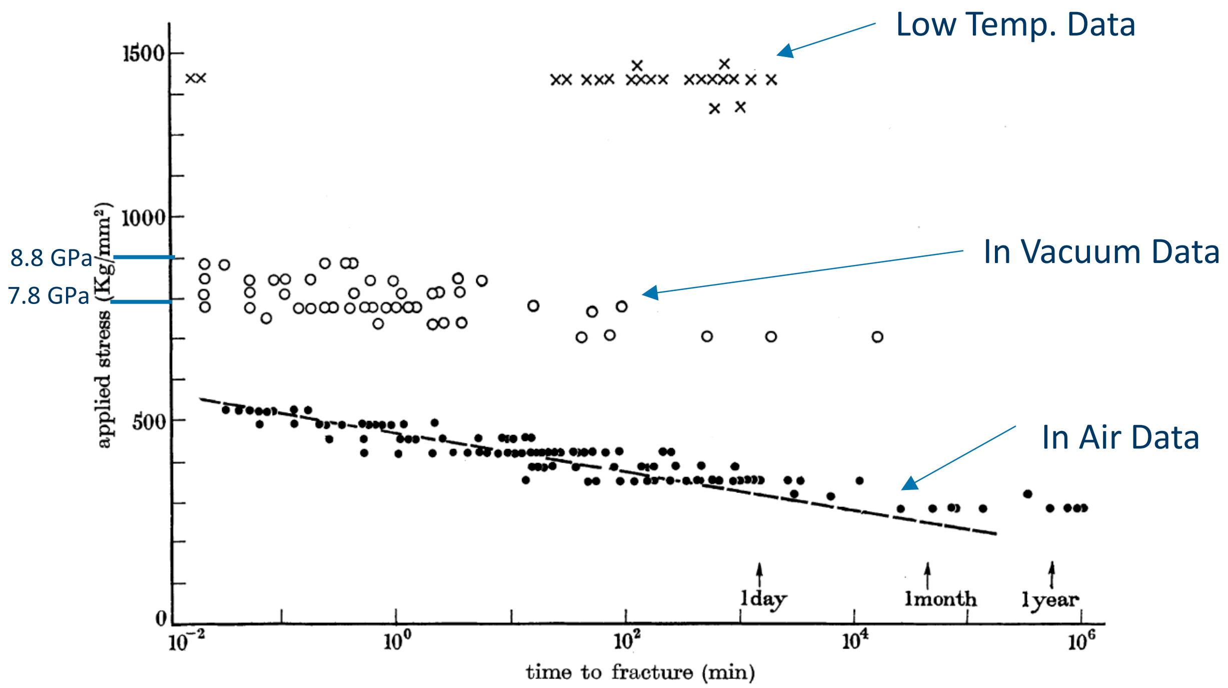
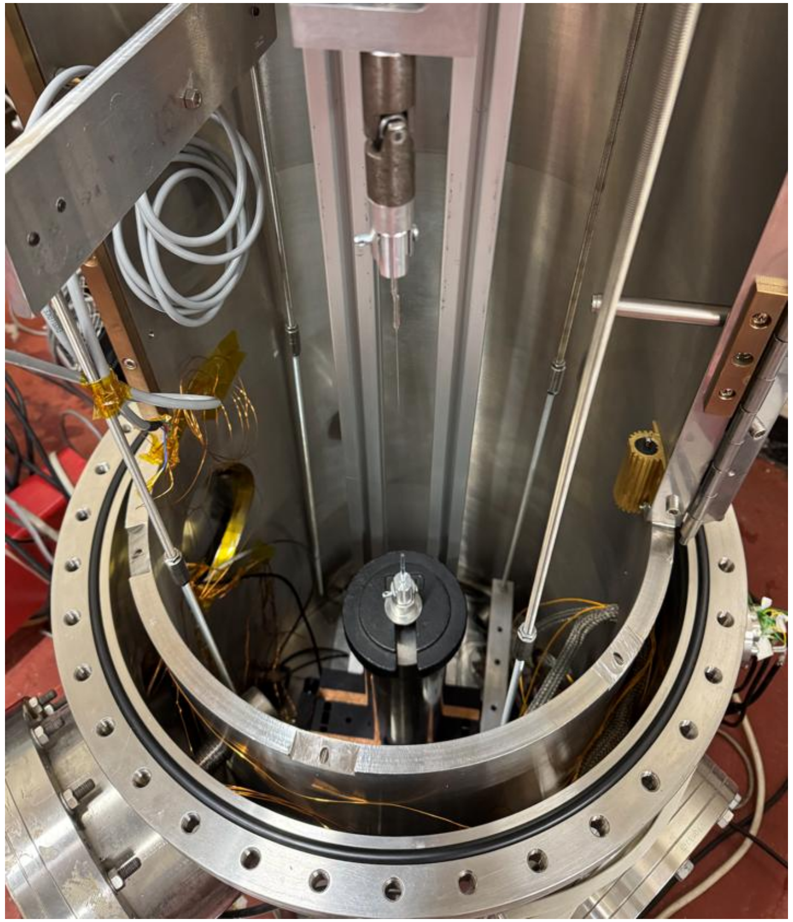


FIGURE 14. Static fatigue of silica fibres at room temperature in air and *in vacuo*, and at liquid nitrogen temperature *in vacuo*. ●, In air at room temperature; ○, *in vacuo* at room temperature; ×, *in vacuo* at −196 °C; ——, line giving values of *n*, *k*, quoted in text.

B. A. Proctor, I. Whitney and J. W. Johnson “The Strength of Fused Silica”

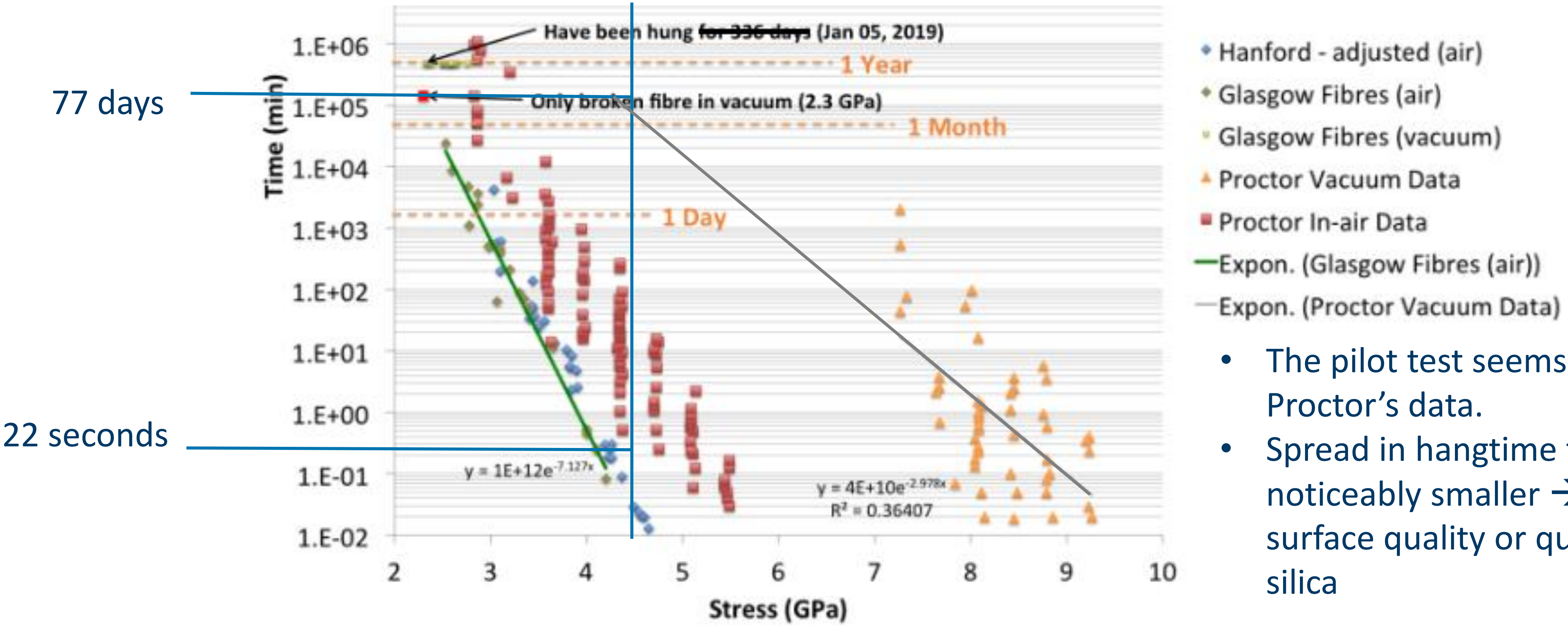
Hang Time of Fibres

- Pilot test results:
  - Fibres were hung at 4.4GPa in air and in vacuum
  - In air hang-time: 22s
  - In vacuum hang-time: over 77 days (broken intentionally)
  - Fibre was kept in vacuum for 12 hours prior to being loaded



Hang Time of Fibres

- A comparison of hang times :

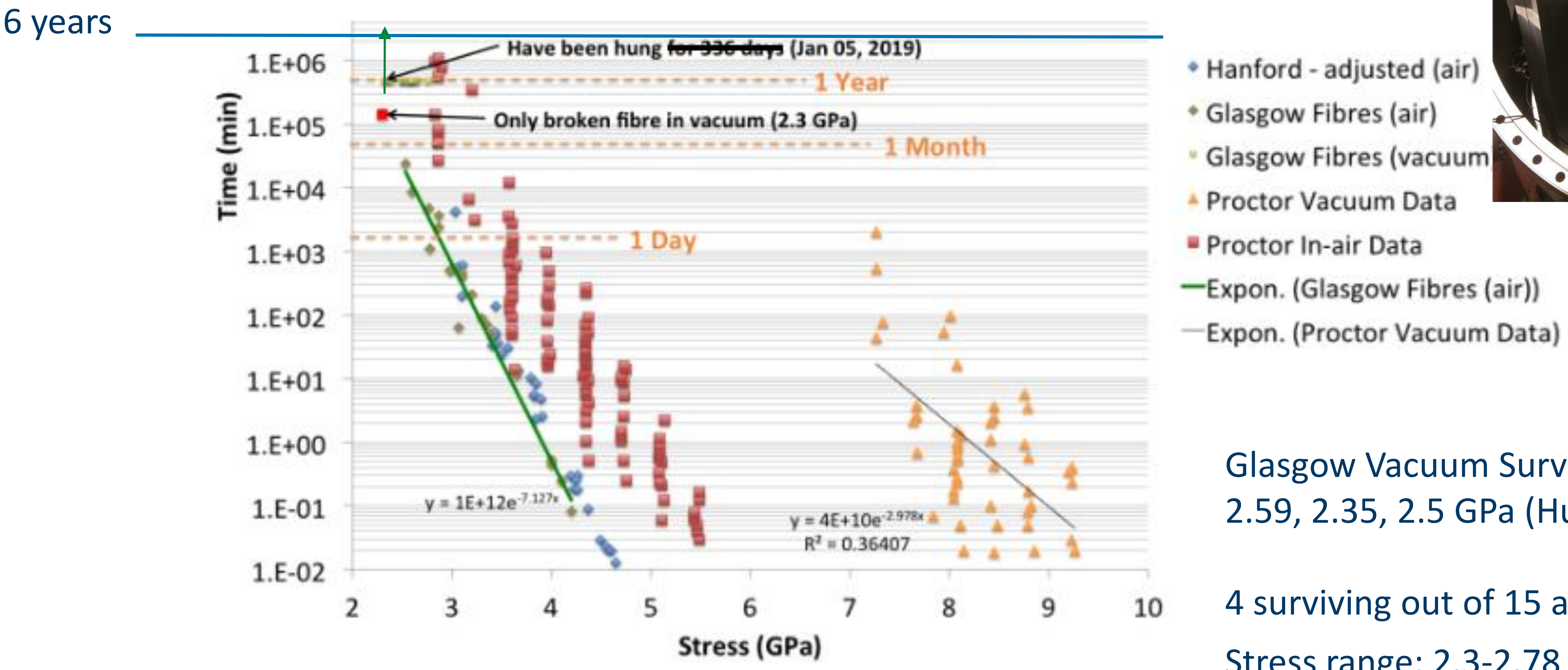


- The pilot test seems to agree with Proctor’s data.
- Spread in hangtime for LIGO fibres is noticeably smaller → Could be surface quality or quality of fused silica

Suspension upgrades for future gravitational wave detectors Lee, Kyung Ha. https://theses.gla.ac.uk/40954/

Hang Time of Fibres

- A comparison of hang times :



Glasgow Vacuum Surviving fibres: 2.57, 2.59, 2.35, 2.5 GPa (Hung in Jan 2019)

4 surviving out of 15 after 6 years

Stress range: 2.3-2.78 GPa

Suspension upgrades for future gravitational wave detectors Lee, Kyung Ha. https://theses.gla.ac.uk/40954/

Avenues for Improving Hang-Times

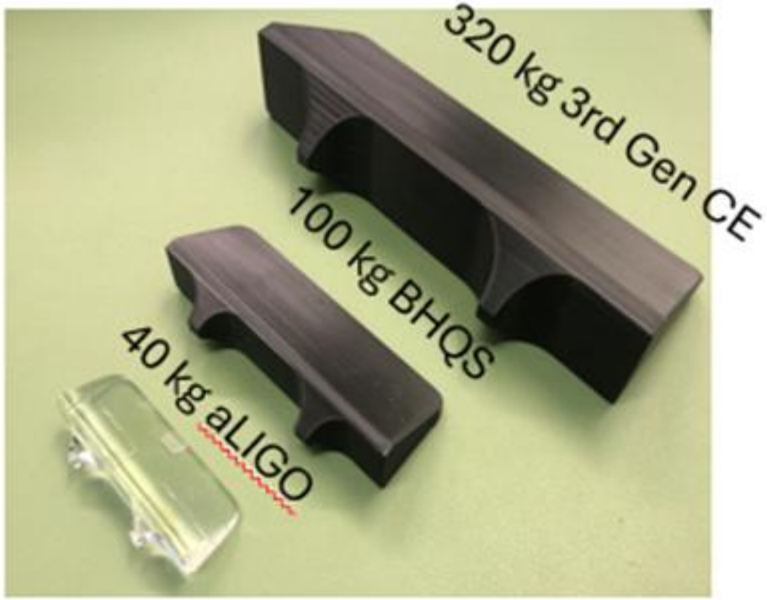
- Load Fibres in vacuum
- Compressive stresses on the surface may reduce crack propagation
  - Heraeus and AEI group – Composite fibres with different viscosities of surface and core resulting in compressive stresses on the surface after cooling under stress*.
  - Heat treating fibre surface and cooling under stress (can reach tensile stresses up to ~7–8 GPa in air as opposed to the usual 5.5 GPa)**

*https://dcc.ligo.org/LIGO-T2400384 - "Composite Suspension Fibres for Increased Tensile Load" Juliane von Wrangel et al

**"An Overview of the Strengthening of Glass Fibers by Surface Stress Relaxation" Peter J. Lezzi* and Minoru Tomozawa

Plans for Future Tests

- More data for in vacuum hang times at higher stresses with current fibres.
- Estimating change in moisture content in vacuum over time. By using spectrometry and/or by measuring the violin mode Q
- Imaging fibres before and after hangs and investigate possible causes of failure.
- Study crack propagation in fibres using smaller samples
- Look at residual thermal stresses in fibres using polarimetry
- Currently working on modelling thermal noise in composite fibres
- Prototyping future suspension – with various ear geometries and masses 160kg up to 440kg (under UK NextGen Award) for Next Gen Detectors



Conclusions

- Recent protype of a large-scale suspension at Glasgow showcased performance acceptable for ET-HF requirements
  - This assumed LIGO style ears were used
- There is benefit in increasing the fibre stresses to push the violin modes to higher frequencies.
- We may be able to achieve much higher stresses in vacuum and the Glasgow group is investigating this. - Make more generic
  - Fibre hang-time tests
  - Avenues to increase fibre strength without affecting thermal noise performance.

Questions

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Extrapolating Hang Times to Lower Stresses

- Approximate to a simple exponential expression: $t_h = B\sigma_\infty{}^{-m}$
- Or use a fracture mechanics based approach and Parameter Estimation:
  - Important assumptions made:
    - The crack growth rate obeys the form: $\dot{a} = AK^n$
    - Stress Intensity factor relates to global stress as: $K = C\sigma_\infty\sqrt{a}$
    - Weakest link theory: It takes only one crack to reach the critical length for failure of the fibre.
    - We can write:

$$t_h = \left(\frac{(a_c)^{1-n/2} - (a_i)^{1-n/2}}{1 - n/2}\right)\frac{1}{A(C\sigma_\infty)^n}$$

    - Where $a_c = \left(\frac{K_c}{C\sigma_\infty}\right)^2$

Similar approach used by PRAISE for crack growth with dynamic loading:
"Probabilistic failure analysis of nuclear piping with empirical study of Taiwan's BWR plants" Jang-Shyong You, Wen Fang Wu

Challenges in Extrapolating to Lower Stresses

- Uncertainty in breaking stress
  - Bounds are known but hard to determine error distribution
- Uncertainty in measured Hang-Time of fibres
  - Only lower bound known in certain cases
- Broad range and possible multimodal distribution of crack parameter values

$$t_h = \left(\frac{\left(\frac{K_c}{C\sigma_\infty}\right)^{2-n} - (a_i)^{1-n/2}}{1 - n/2} \right) \frac{1}{A(C\sigma_\infty)^n}$$

- Crack growth-rate parameters – Expected to have a single value given consistent environment
- Crack shape parameters – May have a multimodal distribution
- Measured Parameters – Hard to determine error distributions