Overview of Crystalline Suspension Fibre Research

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4th ET Annual Meeting: Croatia November 2025

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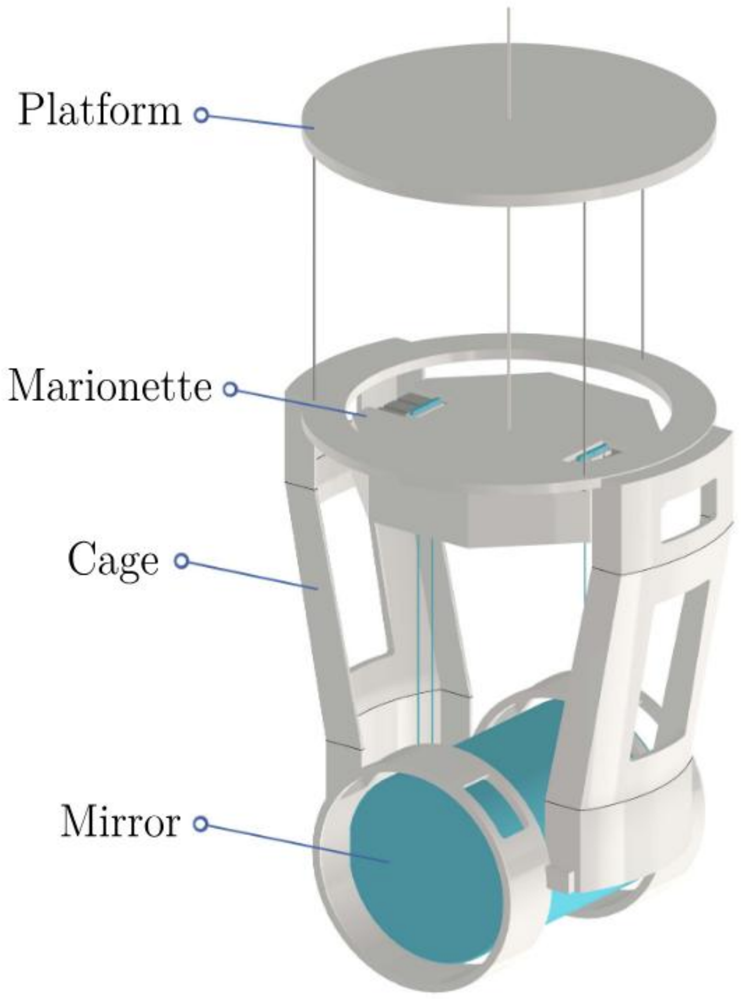
Crystalline suspensions in ET-LF

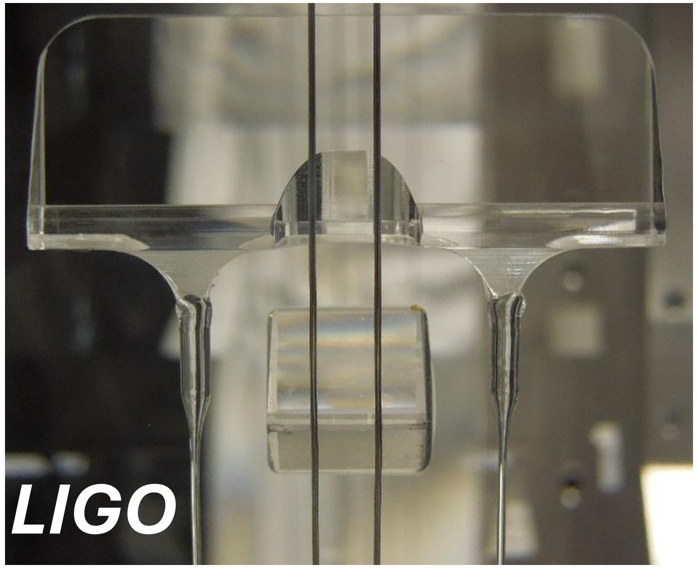


X. Koroveshi et al. Phys. Rev. D 108, 123009 – Published 7 December, 2023

- Baseline design parameters:
  - Mass: 211 kg
  - Fibre length: 1.2 m
  - Fibre diameter: 3 mm
  - Fibre material: silicon
  - Mirror material: silicon

- Silicon is currently the baseline design material, but sapphire is being explored as a potential alternative

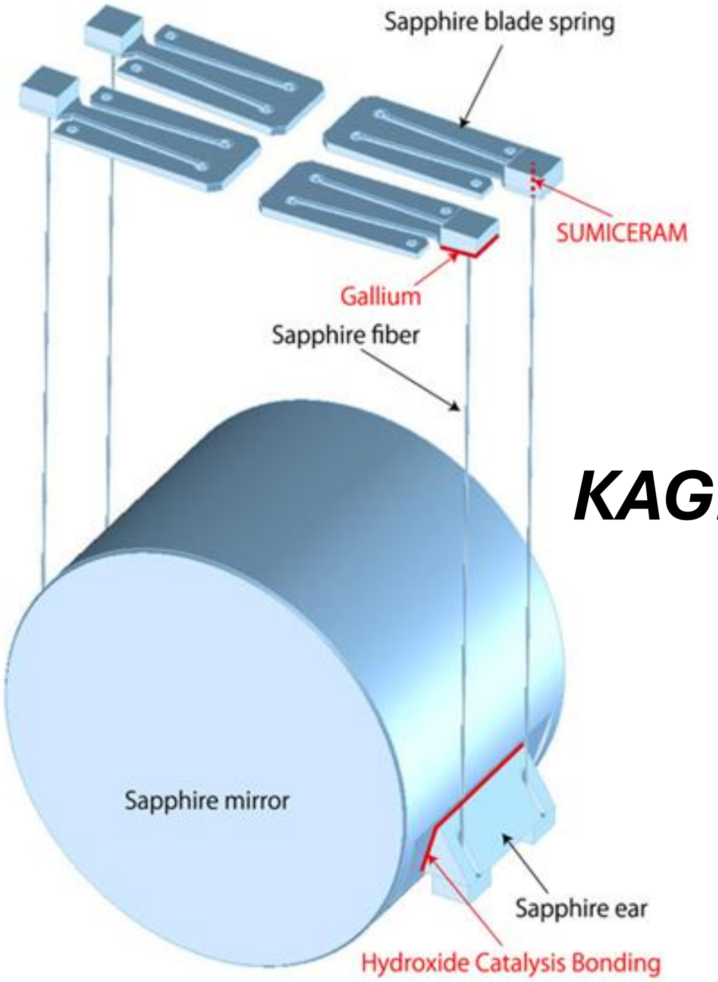
Jointing methods



- In LIGO, Virgo, and KAGRA side prisms are **hydroxy-catalysis** bonded to test masses
- Silica fibres can then be welded directly to these ears (LIGO), or to anchors (Virgo)

F. Travasso (2018) Journal of Physics: Conference Series. 957. 012012. 10.1088/1742-6596/957/1/012012.

- In KAGRA, sapphire fibres are attached to nail end blocks using '**sumiceram**', and then these nail ends are inserted to the ears and bonded to the blade springs using **gallium**



KAGRA

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

Essential fibre requirements

Mechanical loss

- To meet thermal noise requirements, materials must be high quality crystals with low mechanical loss at cryogenic temperatures
- Fibres must be fabricated to specific geometries with high surface quality

Thermal Conductivity

- High thermal conductivity required to extract heat from test mass
- Highly dependent on crystal quality and surface
- Sets a diameter requirement

Tensile Strength

- To reliably support the test mass load (within a safety factor of 3-6)
- Allow for use of thin fibres as this reduces thermal noise via dissipation dilution
- Sets a diameter requirement

Essential jointing requirements

Mechanical loss

- Must maintain low loss through material and/or optimisation of bending energy

Thermal Conductivity

- Maintain sufficient thermal conductivity

Tensile Strength

- Sufficient in tensile and shear

Alignment

- Must be able to adjust static pitch and hanging position

Repairability

- For test mass swaps and conserving the test mass/ ear components

Feasibility

- Can be practically implemented and maintained
- Training of personnel

The challenge

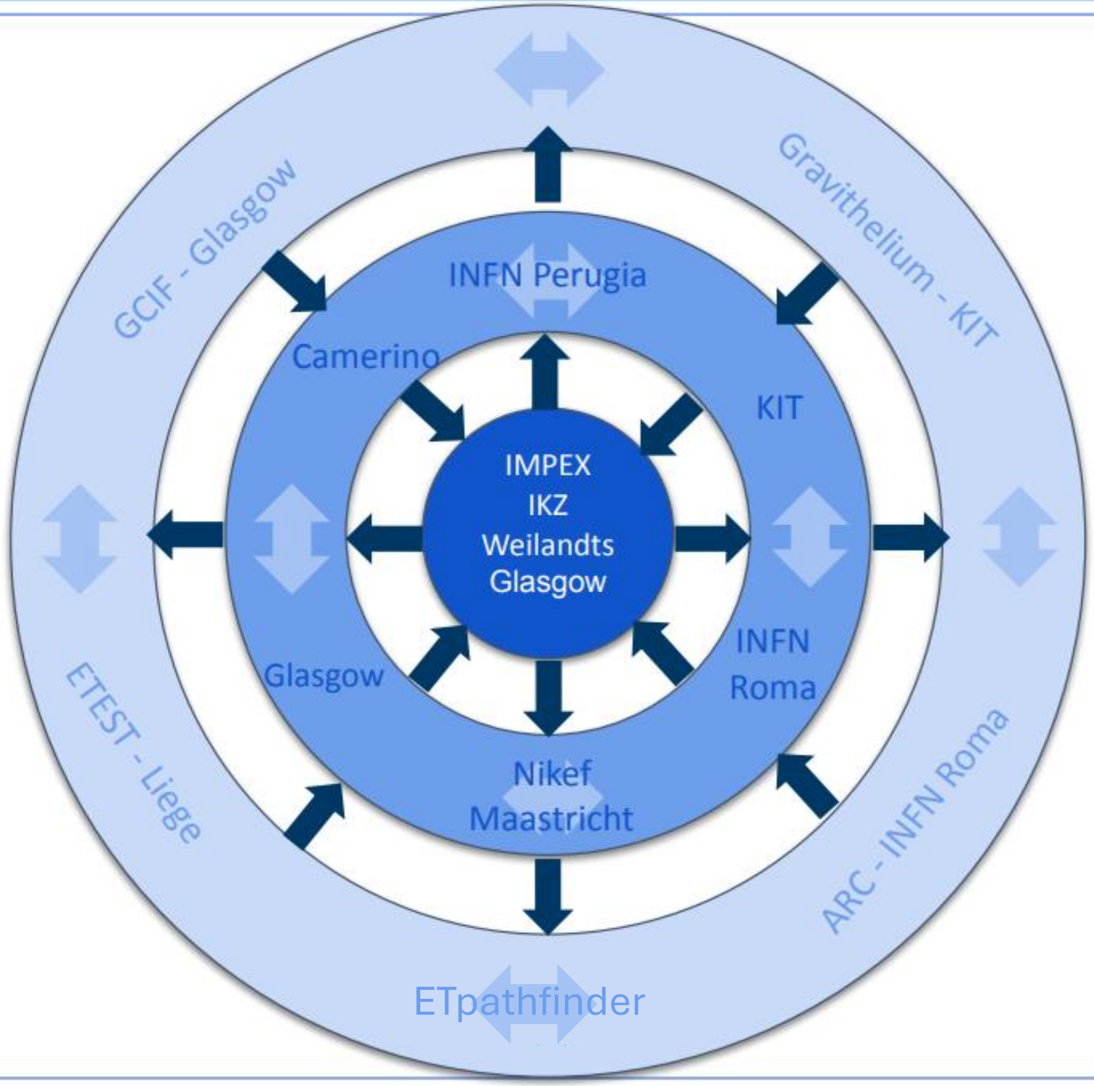
- We must produce high quality fibres by **crystal growth** or **machining**
- Updated characterisation of **specific fibre geometries**
- Develop **reliable** jointing techniques: welding and/or chemical bonding
- **Prototype testing** of different approaches
- Improved accuracy of **thermal noise models** using measured parameters

A Collaborative Approach

Production

Characterisation

Prototype Demonstration



IMPEX
IKZ
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ETpathfinder - Maastricht
ETEST -Liege
GCIF -Glasgow
CAOS - Perugia

Image credit: A. Spencer

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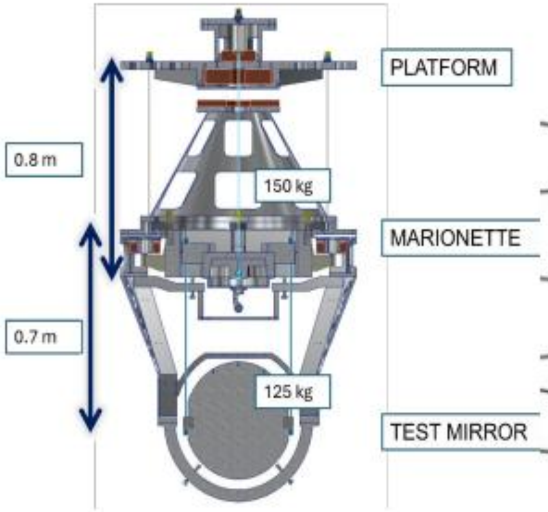
UNIVERSITÀ DI ROMA

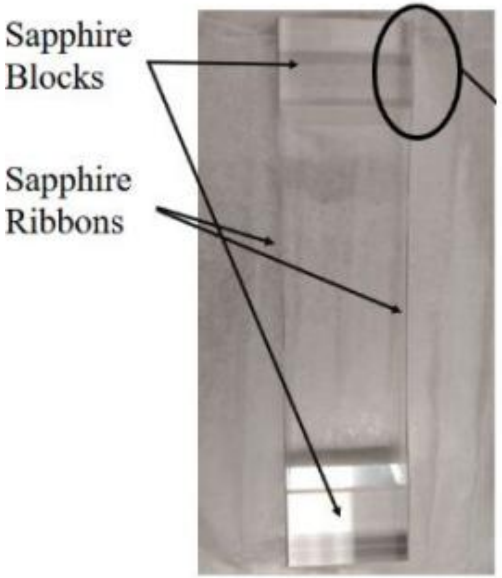
E-TEST Einstein Telescope EMR Site & Technology

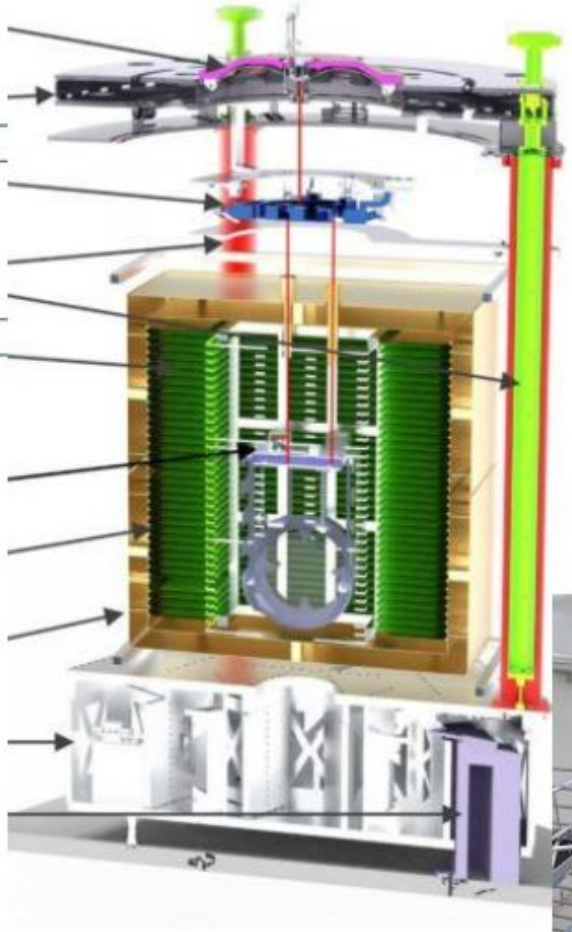
KIT
Karlsruher Institut für Technologie

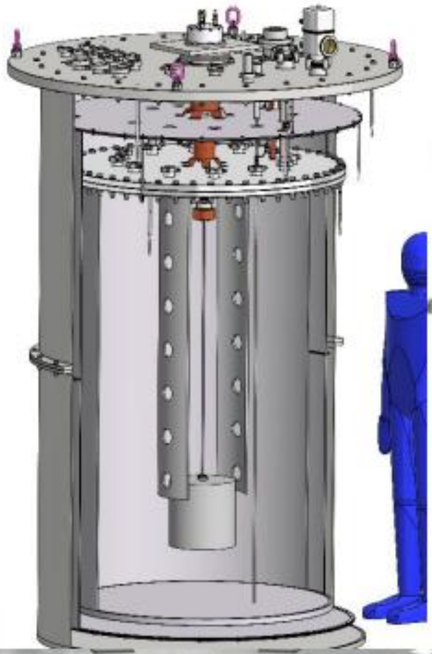
ETPATHFINDER

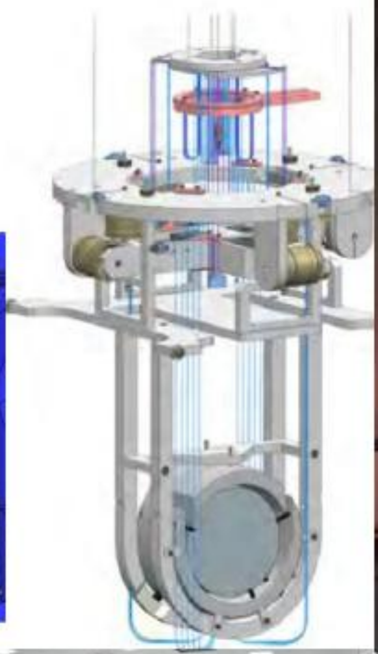
University of Glasgow

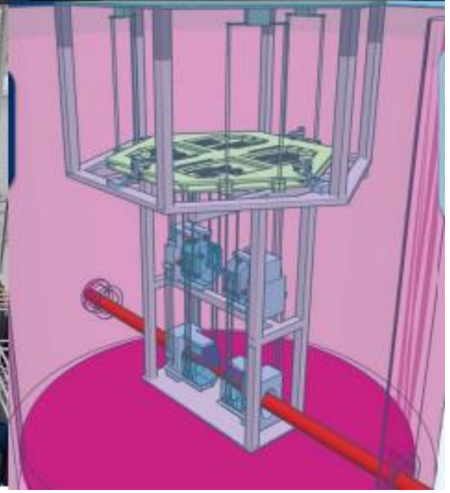








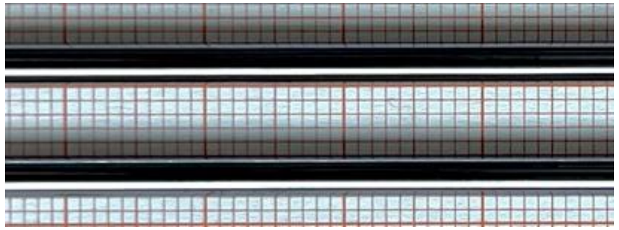


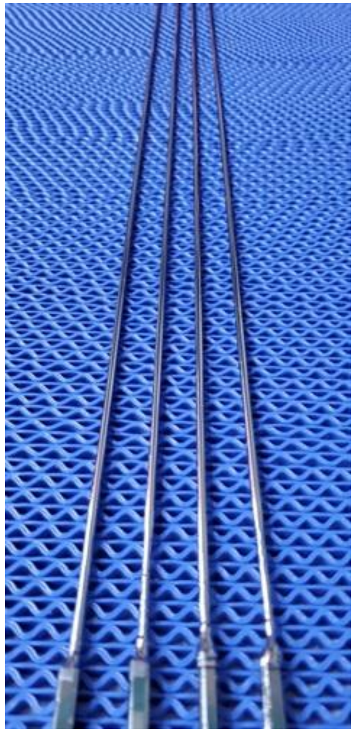


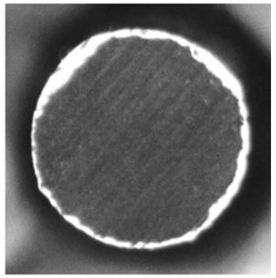
Some Recent Silicon Fibre R&D

Si-fibers for ET suspensions by Float Zone method

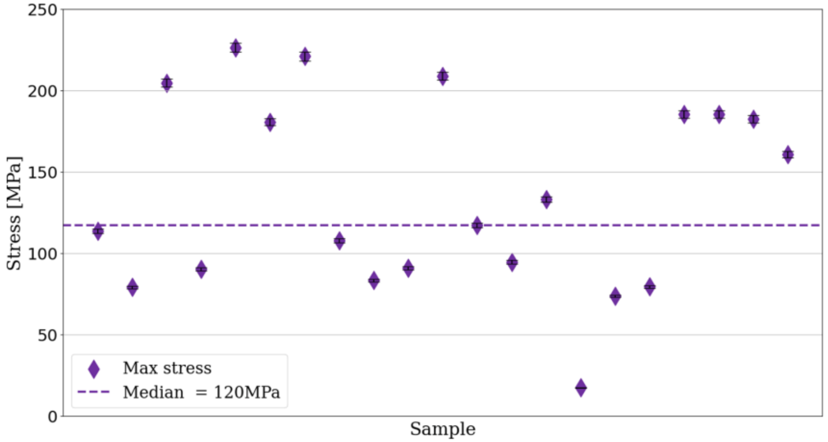
- Si-fiber diameter: 3 mm
- Diameter variation: < 0.1 mm
- Length: up to 1.5 m
- Dislocation-free structure
- No surface defects
- Reproducible process with low fiber-to-fiber variation







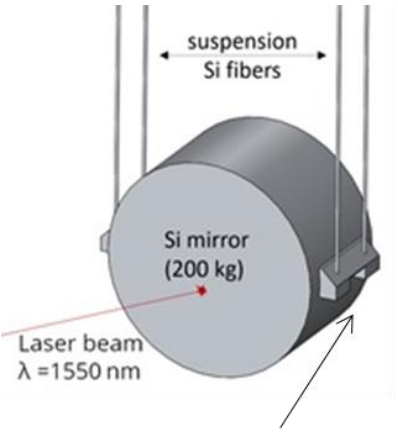
- High median breaking stress of **120MPa** corresponding to **4.4 mm diameter** (SF 3.5) for ET baseline requirements
- However, large variation between individual samples



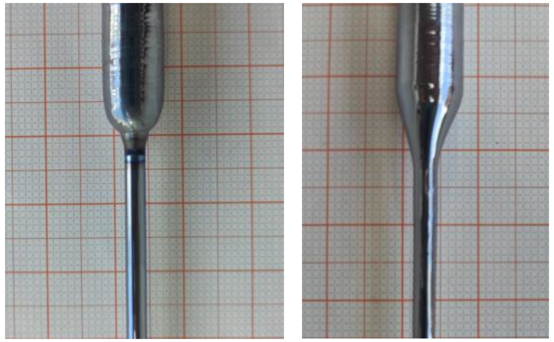
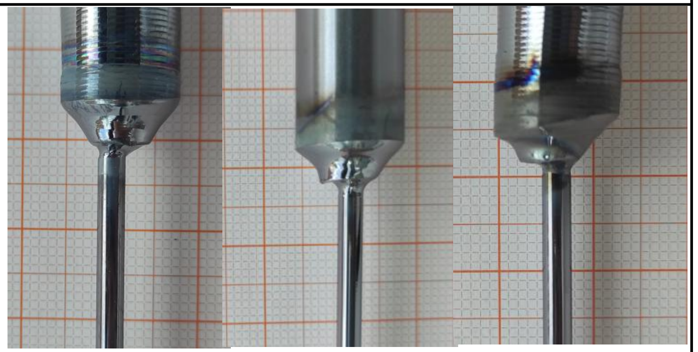
Research for improvement:

- Growth parameters and conditions
- Sample handling after growth
- Measurement procedure

FZ-Si fibers with tailored profile for mirror attachment

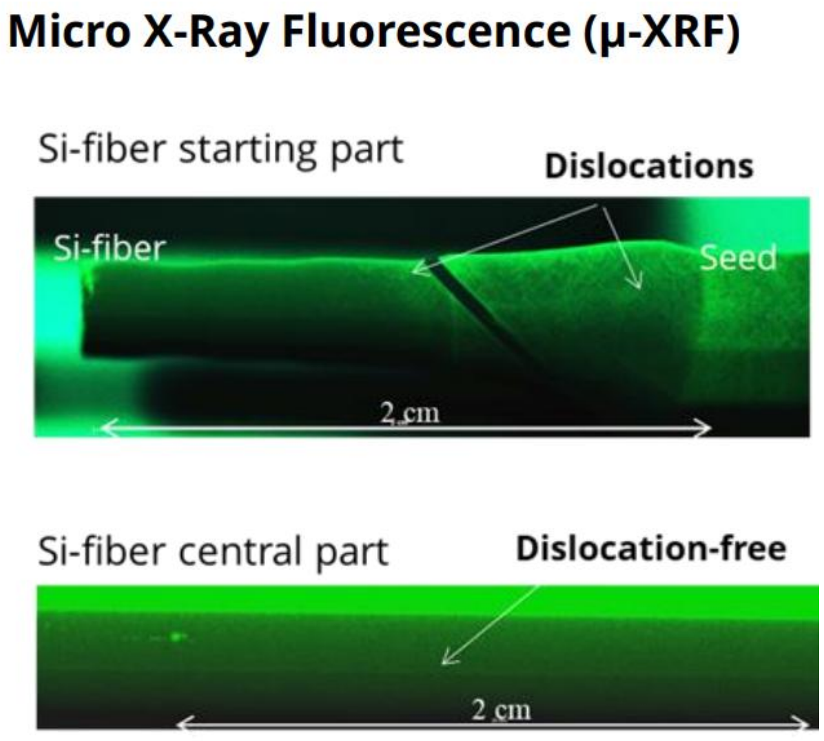


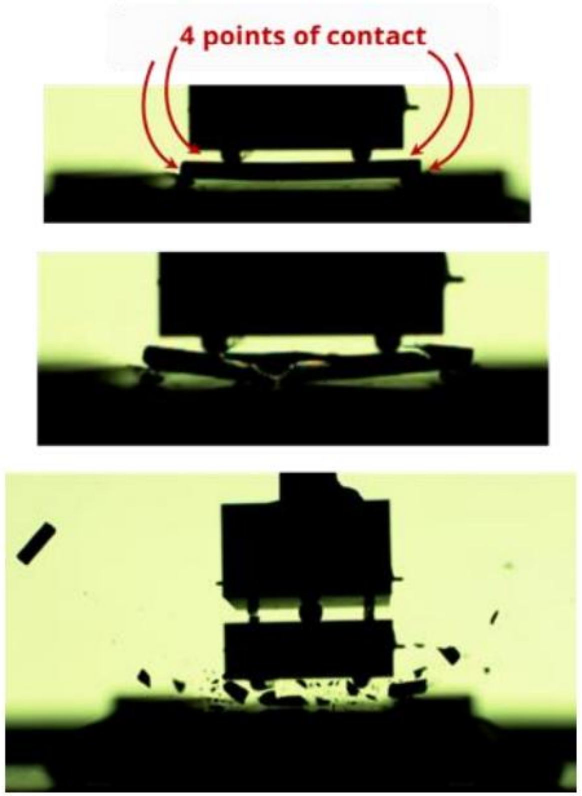
- Enlarged endings (heads) for further attachment
- Fibers + heads grown/welded **in the same FZ furnace**
- Utilizing **the same FZ growth setup**

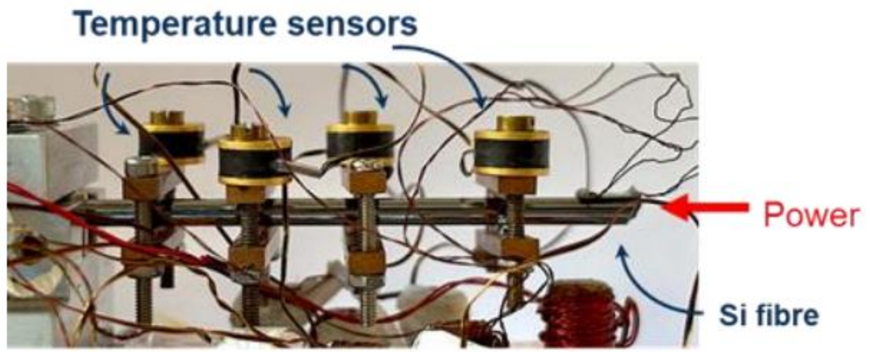
As-grown heads	Welded heads
	
Fiber + head grown within the same process	Fiber + head grown separately and welded afterwards
Dislocation-free	Massive dislocations in welded area
Transition area is symmetric, shape can be customized (smooth or sharp)	Shape and size of transition area is arbitrary
High shape reproducibility	Low shape reproducibility
Head size is limited (maximum Ø 8 mm head for Ø 3 mm fiber)	No restriction for head size
Improvement requires development of a **new growth setup** (coil, support etc.)	Improvement requires **major FZ-furnace modification** (preheating system, power control etc.)

IKZ Silicon Characterisation

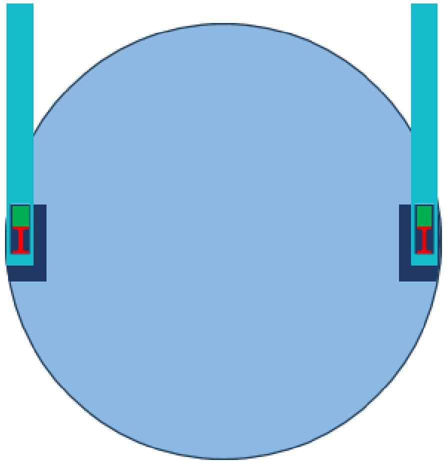
- **Thermal conductivity:** high conductivity maintained
- **Tensile strength:** along-axis measurements median of 120 MPa, 4-pt bending measurements median of 365 MPa
- Very low **diameter variation,** less than 1%
- High **surface quality**
- **Monocrystalline** along length

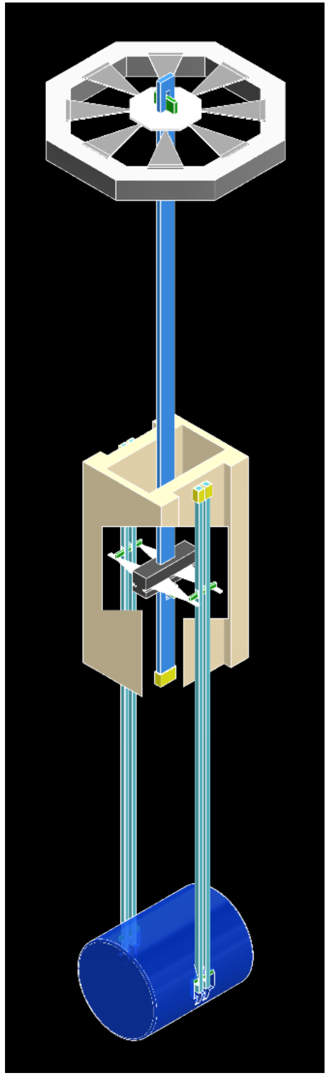






Status of silicon TM suspension system

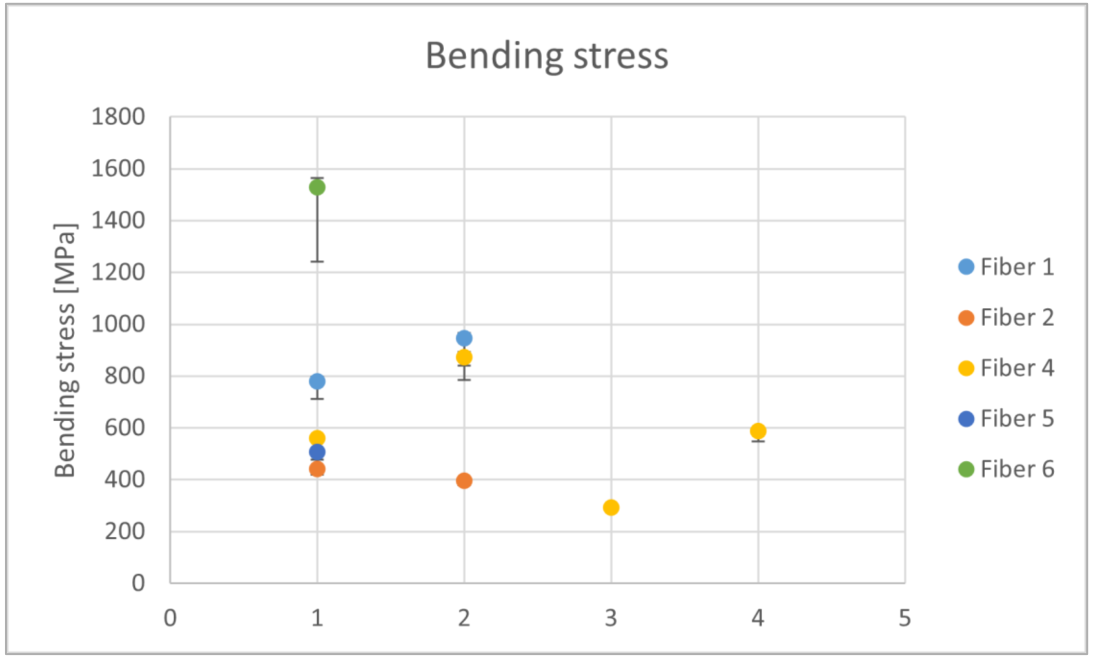




General design

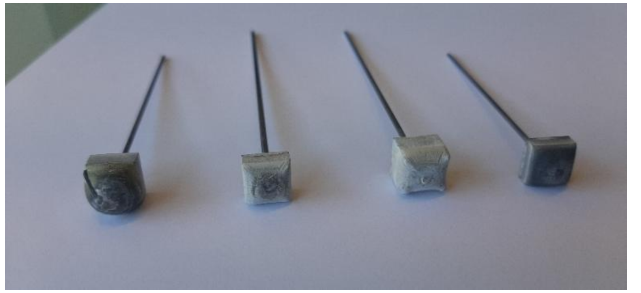
- **Compression**
  - Design and simulation ready (*Guadalajara, CalState, Salerno, Glasgow*)
  - Silicon joins under production thanks to the ET-Fiber project (*UMPT-ULiege*)

- **Traction**
  - Cylindrical fibers (ϕ=3mm and ϕ =1mm) produced by IKZ with FZ showed the best result so far: it is mandatory to reduce the spread of the breaking strength
  - General design to be optimize (*position of the fibers, etc*) to reduce the coupling with controls



Heads

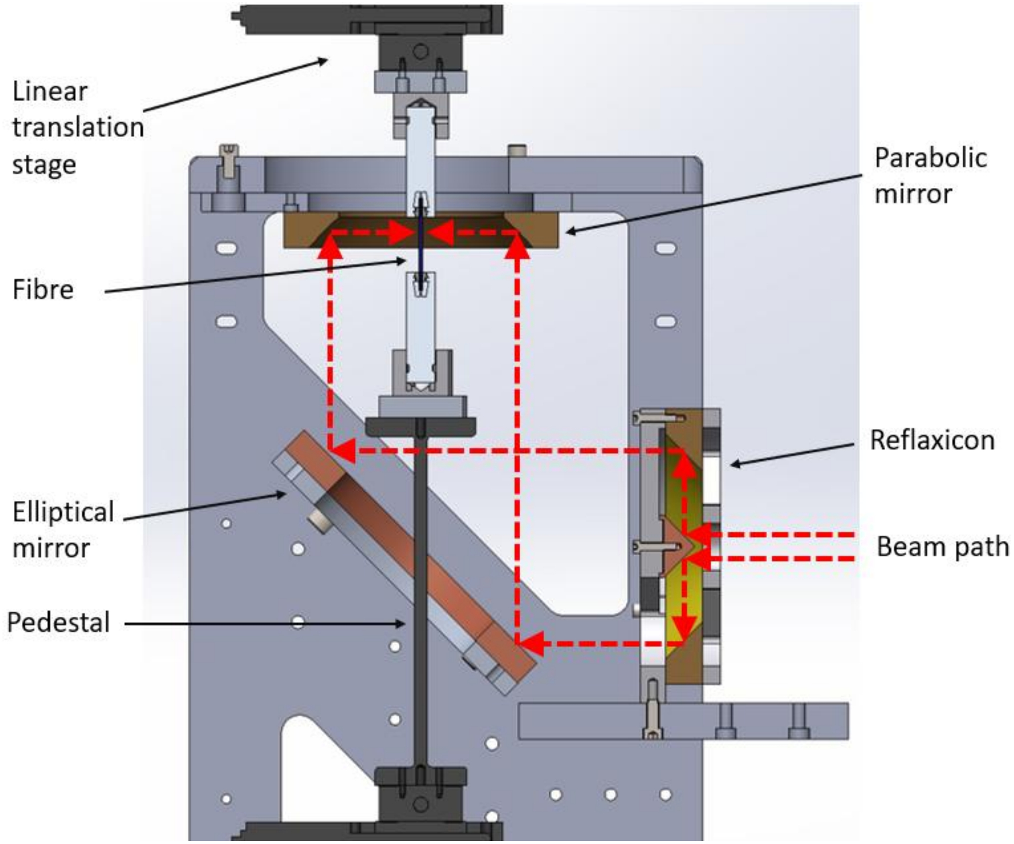
- **Welding**
  - IKZ success to weld 3mm-3mm, 8mm-8mm, 1mm-1mm, 1mm-cone, 3mm-cone) only on one side of the fiber *(see Iryna's poster)*
  - Impex tried to weld a fiber in a cube with a hole, but the method still need to be implemented



- **Glueing**
  - everything needs to be tested

Some Recent Sapphire Fibre R&D

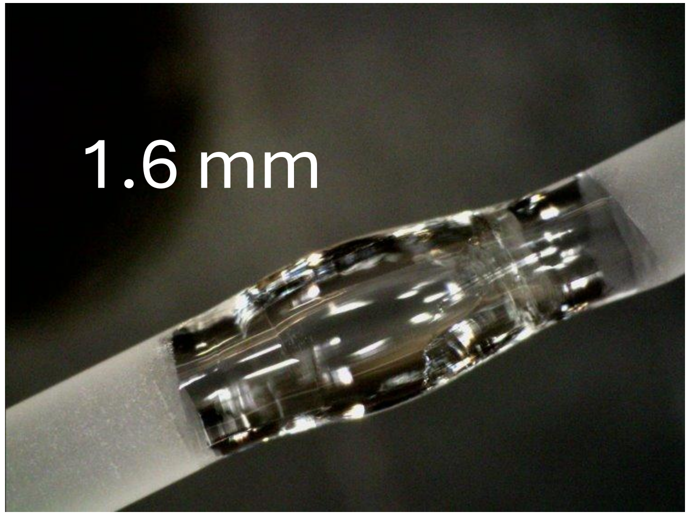
University of Glasgow: Sapphire fibre growth

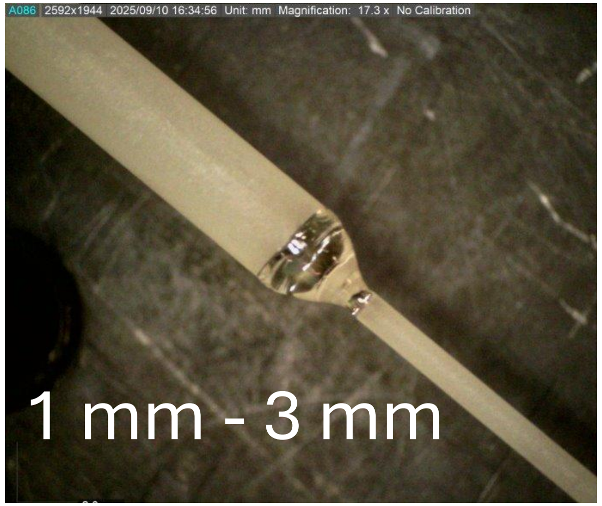


- Laser heated pedestal growth method used to produce sapphire fibres
- 1 mm in diameter, 350 mm long
- Peak strength of 792 MPa (unbroken)
- Low diameter variation and good surface quality
- Further research to continue

J. Callaghan. “Development of crystalline suspension fibres for next generation gravitational wave detectors.” PhD thesis, University of Glasgow, Aug 2024

University of Glasgow: Sapphire Welding



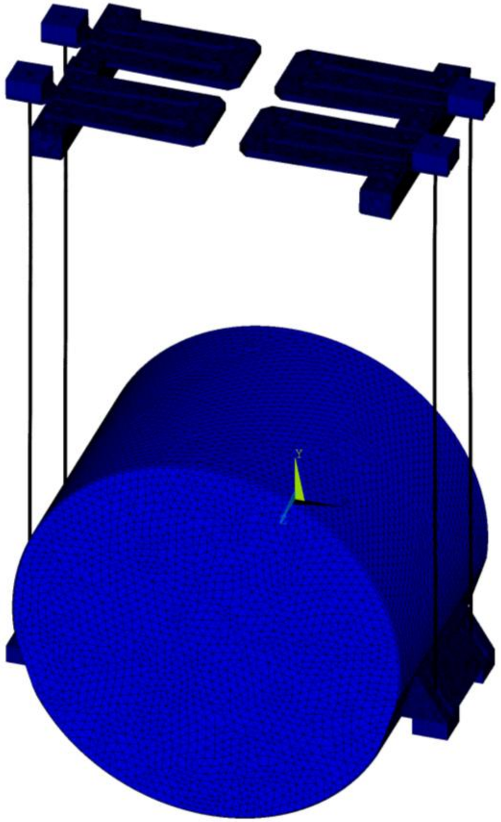


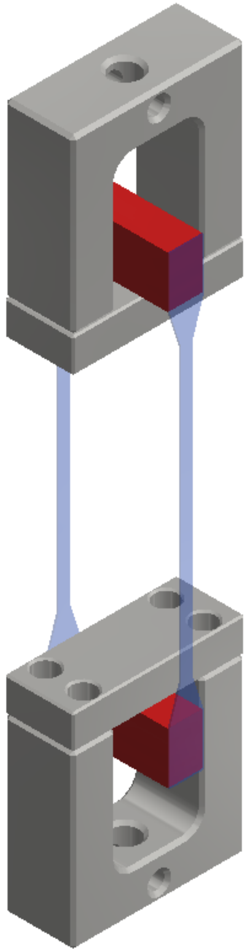
- Established a reliable and repeatable welding method used to produce over 100 welds
- Varying diameters achieved
- Maintain c-axis orientation with limited weld region ≤ 200 µm
- **Tensile strength**: 1.1 GPa minimum (unbroken)
- **Thermal conductivity:** no measured detriment
- **Weld loss:** preliminary investigation shows promising thermal noise model

Paper under peer review:
LIGO DCC: P2500357, ET TDS: ET-0451A-25

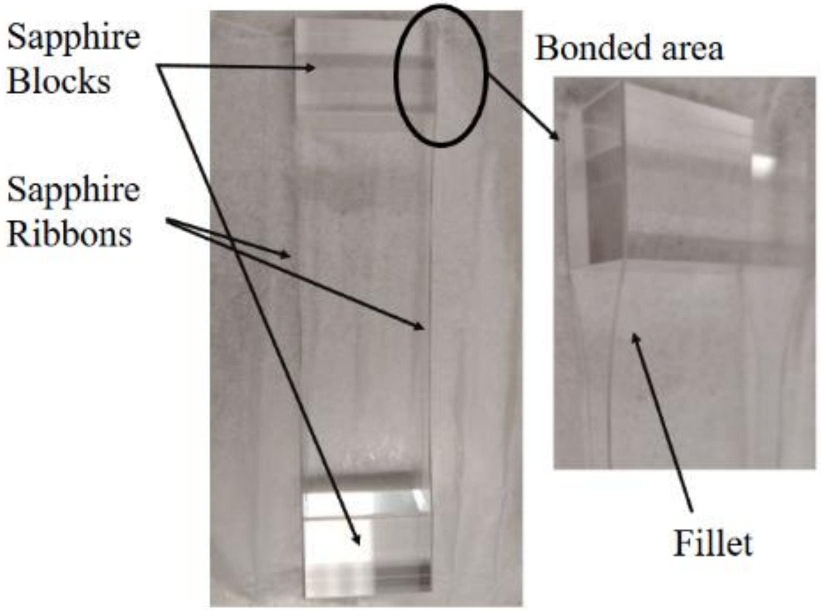
KAGRA + University of Glasgow

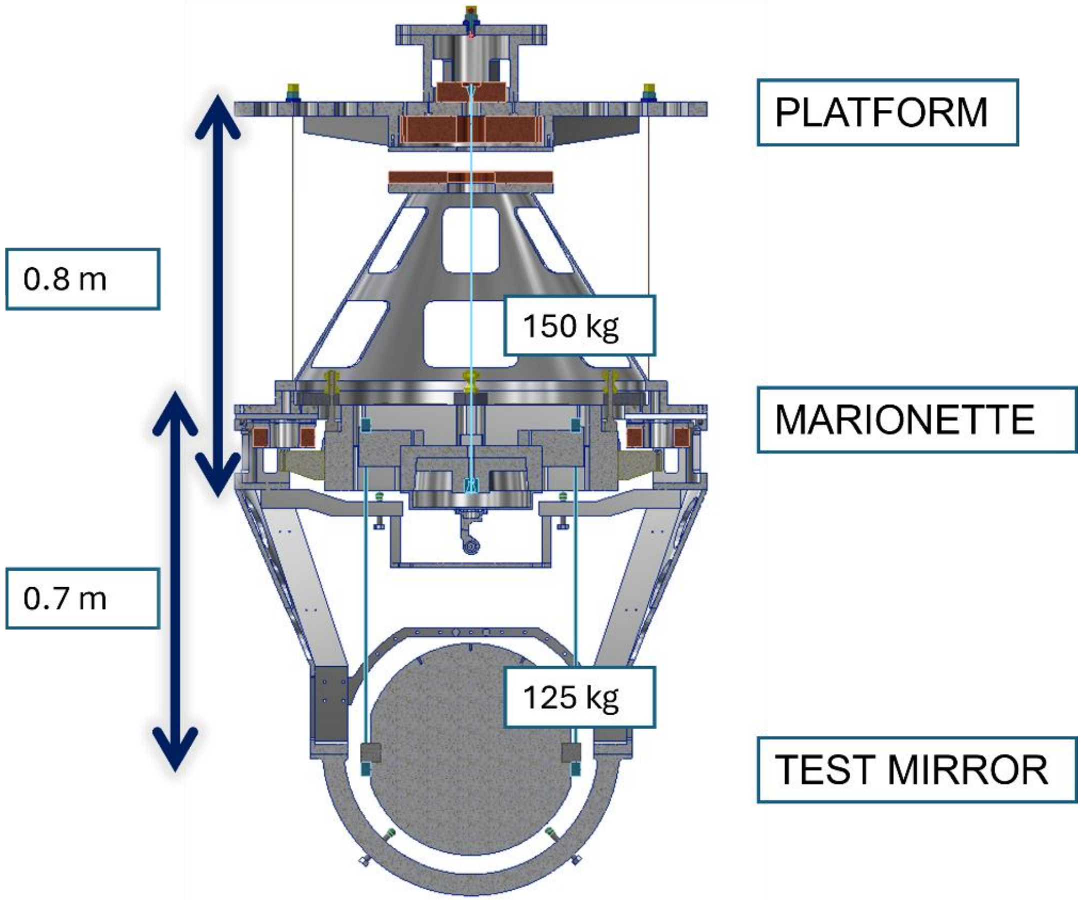
- Collaboration to determine cause of and solutions for low Q observed in KAGRA fibres
- FEA modelling of KAGRA suspension in progress
- Investigating welding and laser polishing of KAGRA fibres with visitor Munetake Otsuka, University of Tokyo





Monolithic version

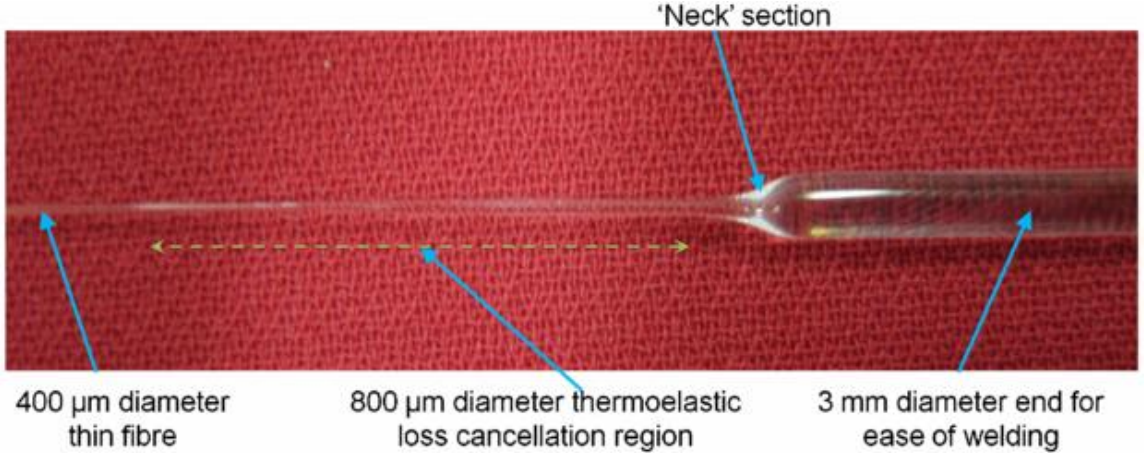




- Bonded ribbons to block and a monolithic sample from Impex
- Ongoing modelling, as well as mechanical loss and strength testing

Required: Updated Suspension Thermal Noise Models

Fibre shaping and Specific Geometries



A V Cumming et al 2012 Class. Quantum Grav. 29 035003

- Allows us to control location of bending energy, tune different resonant modes
- Fibre shaping demonstrated in silicon
- Fibre shape should be optimised to reduce dilution*

**A Cumming et al 2009 Class. Quantum Grav. 26 215012*

IKZ Silicon fibre shaping

Fibre shape affects:

- Thermal conductivity: heat extraction depends on diameter, thin fibres introduces boundary scattering
- Mechanical loss contributions: divert bending energy from higher loss regions
- Tensile strength: lower diameter, higher stress
- Thermal noise: **dissipation dilution** increase as fibre diameter decreases

Suspension Thermal Noise Modelling

From the fluctuation dissipation theorem, the suspension thermal noise for each resonant mode can be calculated:

Temperature

Resonant frequency of mode

$$x^2(\omega) = \frac{4k_B T}{\omega m} \times \frac{\omega_0^2 \varphi(\omega)}{\omega_0^4 \varphi(\omega)^2 + (\omega_0^2 - \omega^2)^2}$$

Mirror mass

Combined mechanical loss contributions for relevant mode

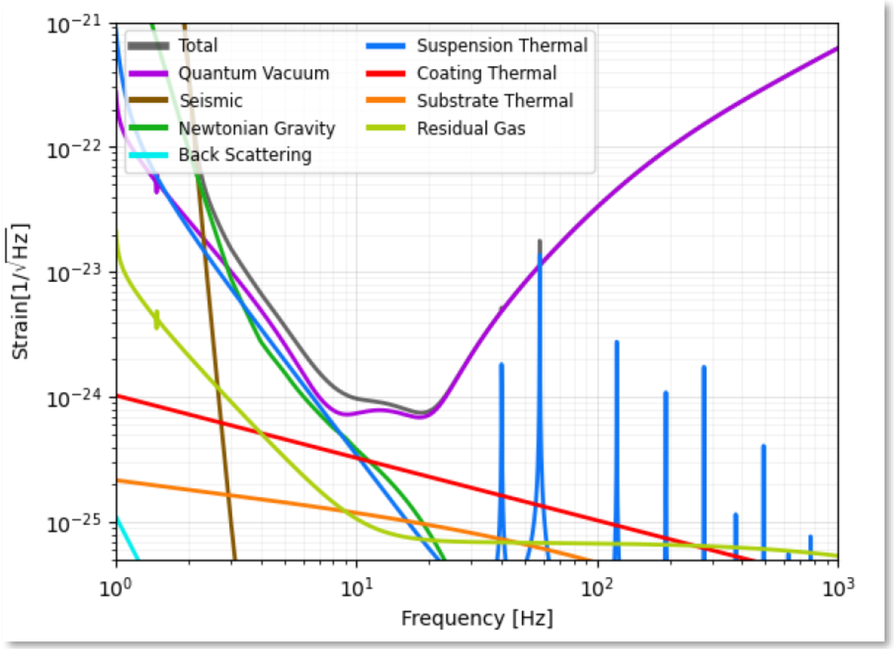
Suspension Thermal Noise Modelling

1. Measure conductivity, strength, loss
2. Model loss measurement in FEA, decouple loss terms
3. Model suspension in FEA
4. Calculate suspension thermal noise
5. Produce noise curve
6. Change select parameters
7. Repeat modelling and noise curves
8. **Find optimum suspension design**

Improved Thermal Noise Models

Measured for specific fibres:

- Mechanical loss (i.e surface, jointing)
- Thermal conductivity
- Tensile strength



Einstein Telescope Low Frequency detector noise budget 2025 https://apps.et-gw.eu/tds/ql/?c=16507

Models of different fibre profiles and parameters:

- Silicon or sapphire
- Machined or grown
- Bonded
- Welded

Conclusions

- There are now a number of promising solutions the challenges faced in ET-LF suspensions, with many teams actively working to develop these
- There is a lot of ongoing interesting work not included here, but is talk summarises the challenges and progress
- We are working to complete characterisation of jointing methods and specific fibre characteristics
- Updated thermal noise models of different scenarios are required to fin optimum suspension design

Thank you for your attention