Instrument Science update from Glasgow Group:

ET Symposium 2024 Maastricht

Bryan Barr, Mark Barton, Angus Bell, Alan Cumming, Jennifer Docherty, Victoria Graham, Giles Hammond, Karen Haughian, Margot Hennig, James Hough, Russell Jones, Ross Johnston, Gregoire Lacaille, Iain Martin, Mariela Masso Reid, Graeme McGhee, Peter Murray, Ardiana Nela, Sheila Rowan, Thejas Seetharamu, **Andrew Spencer***, Karl Toland, Stephen Webster

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Institute for Gravitational Research

University of Glasgow

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The Glasgow ET Instrument Science Group

A WORLD TOP 100 UNIVERSITY

- 6 Academic Staff
- 11 Postdoctoral Researchers
- 6 Postdoctoral Students

- **UK ‘Next Gen GW’ Grant**
- **Glasgow Suspensions Group**
  - Heavy Silica Suspensions
  - Bonding R&D
  - Cryogenic Suspension Materials
- **Glasgow Coatings Group**
  - Coatings & Substrates
- **Cryogenic Glasgow Interferometer Facility**
  - Cryogenic Suspension Demonstration
  - Longer Wavelength Laser Systems
  - Cryogenic Cavity Control and Operation
  - Facility Commissioning

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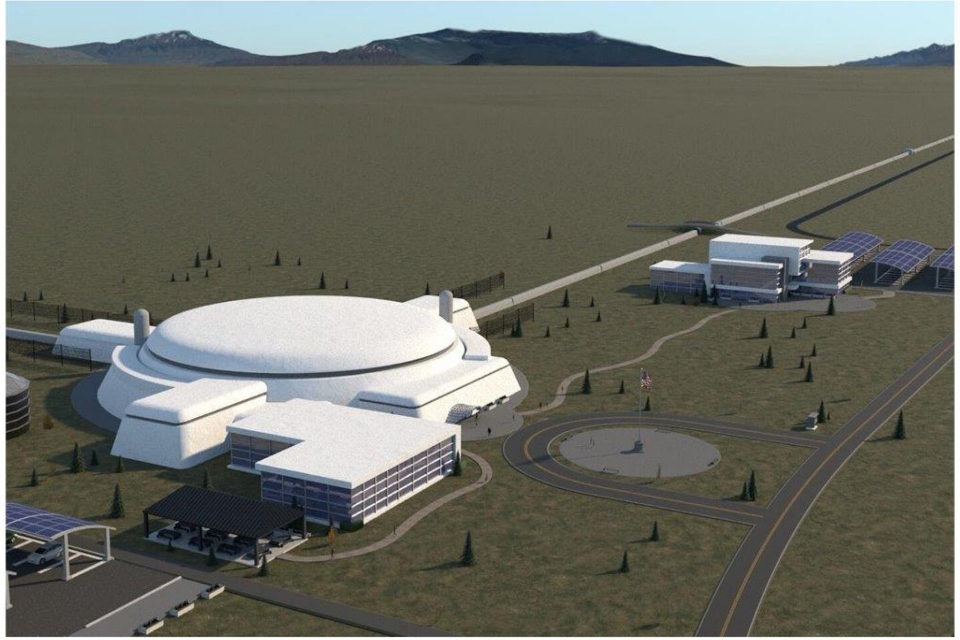
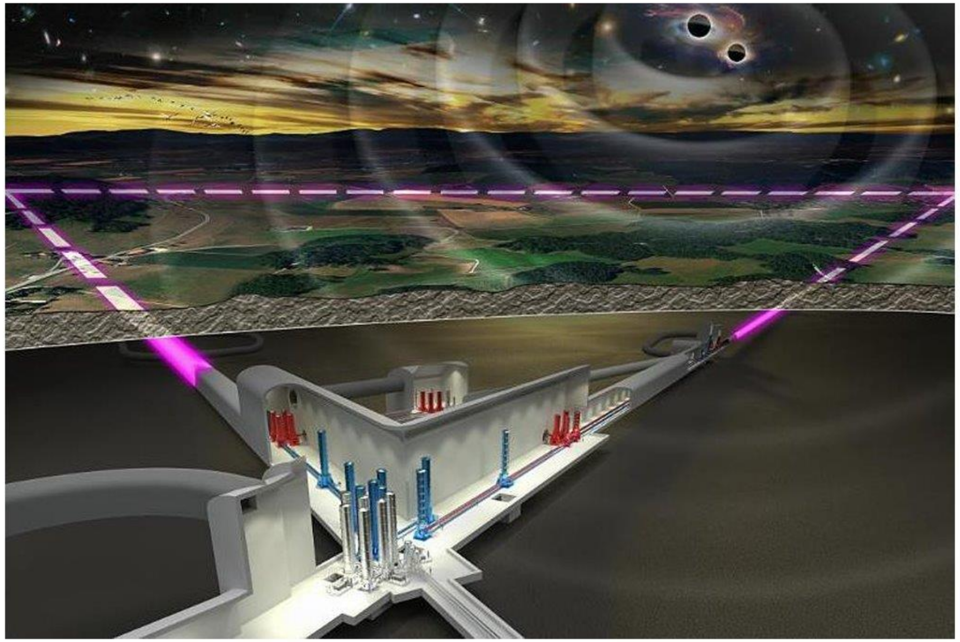
UK 'Next Gen GW' Grant

"Next-gen GW" - The next-generation gravitational-wave observatory infrastructure

An award by the UK Science and Technology Facilities Council (2023 – 2026)

University of Birmingham, Cardiff University, University of Glasgow, University of Portsmouth, University of Southampton, University of Strathclyde, University of the West of Scotland.





Artist's impression of Cosmic Explorer (left) the Einstein Telescope (right)

UK 'Next Gen GW' Grant

Prof Sheila Rowan (*PI*) Dr Angus Bell, (*Project Manager*) Prof Giles Hammond, Dr Iain Martin, Dr John Veitch and Dr Stephen Webster

University of Glasgow

Prof Alberto Vecchio (*Deputy PI*) , Dr Denis Martynov, Dr Geraint Pratten, Dr Patricia Schmidt and Dr Teng Zhang

University of Birmingham

Prof Stephen Fairhurst, Prof Katherine Dooley, Prof Hartmut Grote, Prof Mark Hannam, Dr Keiko Kokeyama, and Dr Vivien Raymond

Cardiff University

Dr Andrew Lundgren

University of Portsmouth

Prof Nils Andersson

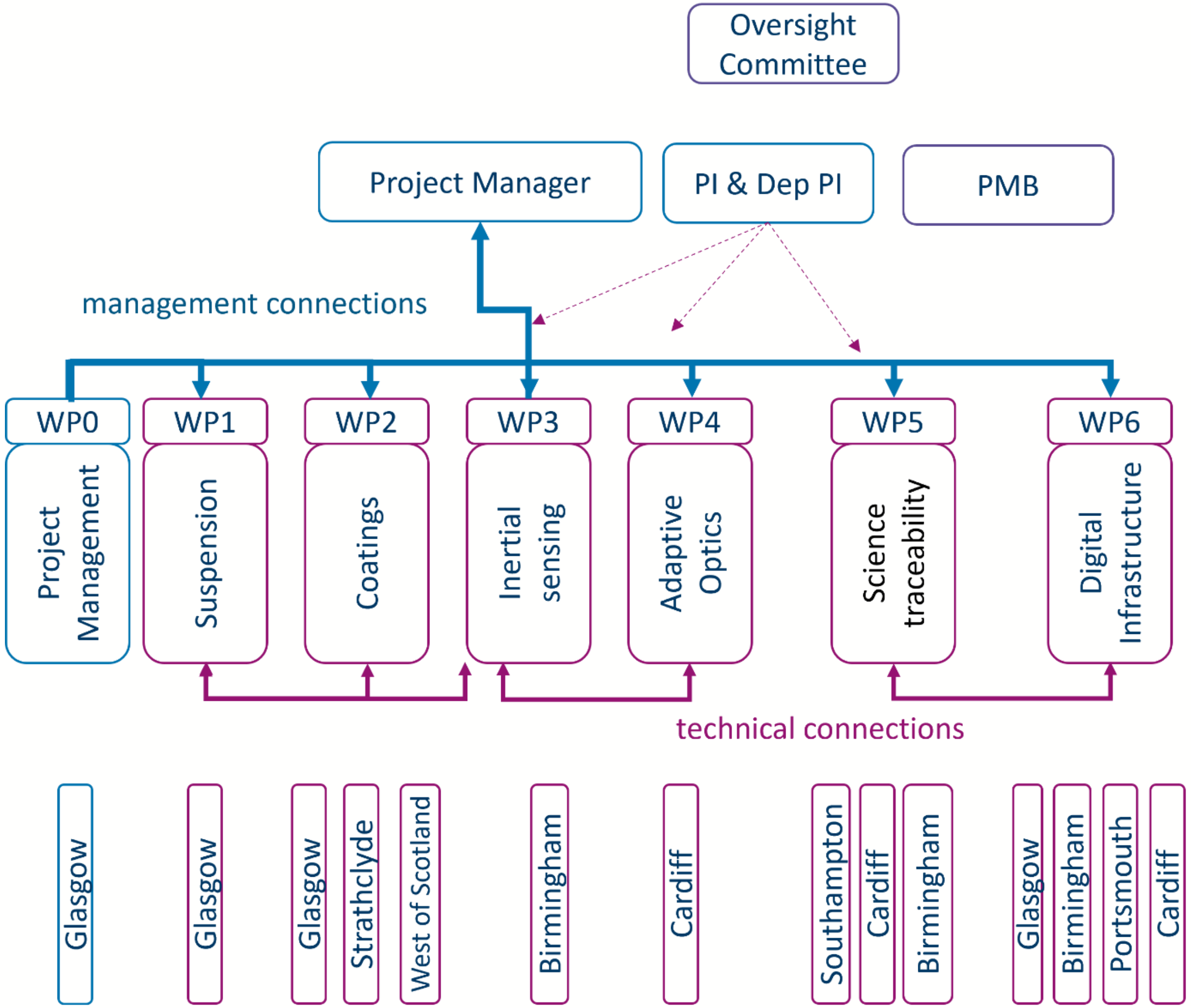
University of Southampton

Prof Stuart Reid, Dr Mariana Fazio

University of Strathclyde

Prof Des Gibson

University of the West of Scotland



Objectives

Contacts:

- Angus Bell (PM)
- Sheila Rowan (PI)
- Alberto Vecchio (Deputy PI)

WP1 Suspensions:

develop a conceptual design for the suspensions systems for the heavier masses in next generation observatories

WP2 Mirror coatings:

develop characterisation and optimisation strategies for development of coatings of greater than 600mm diameter

WP3 Inertial control:

develop and validate aspects of inertial sensing and control contribute to the conceptual design of a robust interferometer

WP4 Interferometer sensing and controls:

sensing and control scheme for interferometers of extended baselines

WP5 Science traceability matrix:

quantify the impact of detailed design decisions on science deliverables

WP6 Digital infrastructure:

design and prototype digital infrastructures for real-time operation in the signal-rich era

Work in close alignment with our international colleagues in the CE and ET projects to deliver these goals.

Developing and de-risking technologies to provide input to meet the requirements of the conceptual design reviews for CE and the ET technical design studies

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Heavy Silica Suspensions

Contacts:

- Giles Hammond
- Alan Cumming
- Karl Toland

Summary: Investigation of options for heavier mass (100-400kg), higher stress (1.2-2GPa) quasi-monolithic fused silica test-mass suspension for next generation detectors.

Topics in scope of investigation:

- Review of different jointing concepts ('ears' and 'anchors')
- Welding for large test masses
- High stress silica fibre production and hanging demonstrations
- Fibre stress corrosion study

Silica Suspensions:
Study of ‘ears’ and ‘anchors’

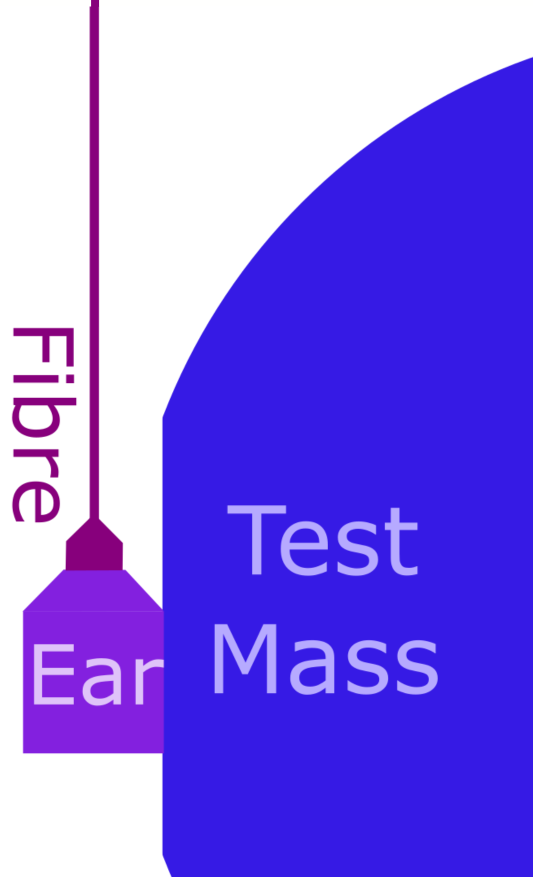
Anchor Concept:

- **Fibre** to **Anchor** join: **Weld**
- **Fibre Anchor** to **Ear** join: *Sodium Silicate* **Bond**
- **Ear** to **Test Mass** join: **HC Bond**

Ear Concept:

- **Fibre** to **Ear** join: **Weld**
- **Ear** to **Test Mass** join: **HC Bond**

**Not to scale. Mock geometries only for demonstration*
***HC = Hydroxy Catalysis*

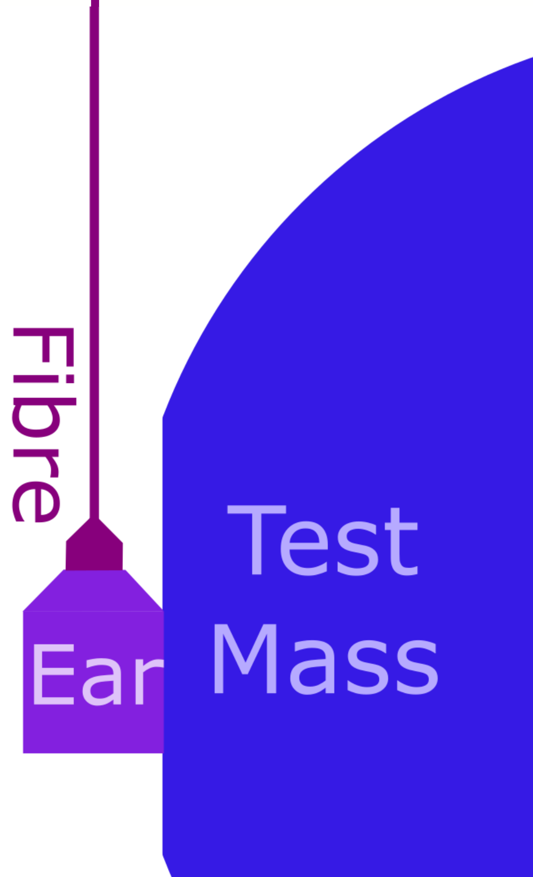


Silica Suspensions:
Study of ‘ears’ and ‘anchors’

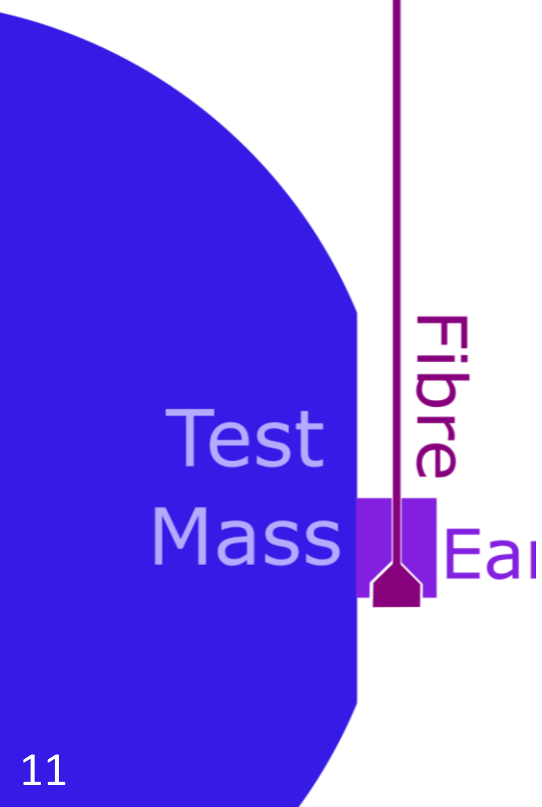
Factors considered in review study:

- Repairability and mass reusability
- Assembly procedure (in situ or not)
- Violin mode tuning and pitch correction
- Skill required for assembly
- Thermal noise and bond loss
- Upper mass join (monolithic or silica-metal)

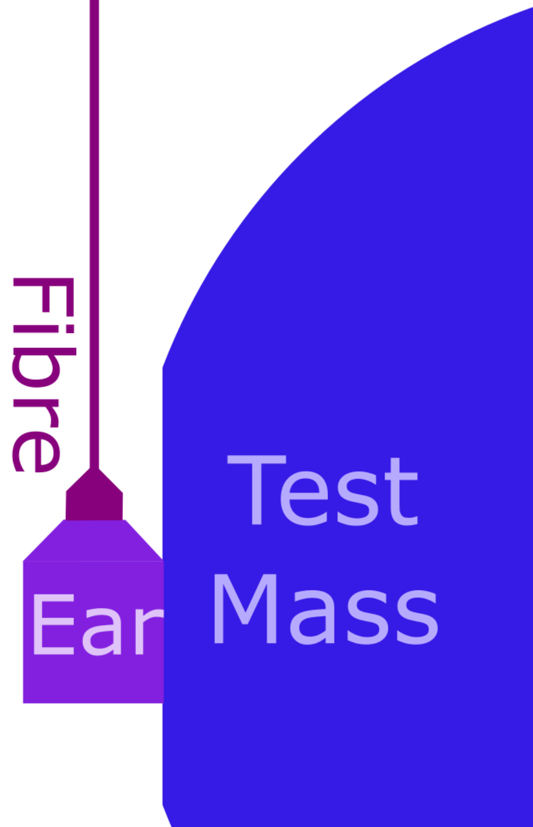
Purpose: Utilising experience from advanced detectors to form combined solution for next generation detectors.



Silica Suspensions:
Study of 'ears' and 'anchors'



	aVirgo Anchor concept (as currently deployed)	GEO/aLIGO Ear concept
Repairability, mass reusability	✗ No ability to re-weld a broken fibre. Evidence of significant (write-off-level) damage on failures. ✓ Ability to remove fibres/anchor.	✓ Proven repeatedly in aLIGO to reuse masses. ✗ Fibres need to be broken to remove and repair.
In situ welding	✗ Not possible	✓ Proven repeatedly in aLIGO
Violin Mode tuning	! Set by fibre geometry/length, not subsequently adjustable	✓ Reducing spread in fibre tensions via fibre de-stress weld procedure
Setting static pitch/pitch correction	! Reliant on current repeatability in length of fibres ±(0.2mm), and pairing/fibre choice	✓ Set using de-stress procedure, and subsequently
Skill necessary for welding staff	✓ Simpler concept, easier to weld & teach	! Skills need to be taught, practiced, and subsequently maintained
Thermal noise	! More questionable/risky – doubling the number of bonds in the system. Violin mode Q's in Virgo do not show thermal noise performance	✓ Concept proven in aLIGO from agreement between model and violin mode Q's
Bond/Weld parameters	✓ HC Bond and weld losses understood and proven. ? Anchor bond parameters unknown, modelling ongoing, noise very dependent on bond/geometry parameters	✓ HC Bond and weld losses understood and proven.

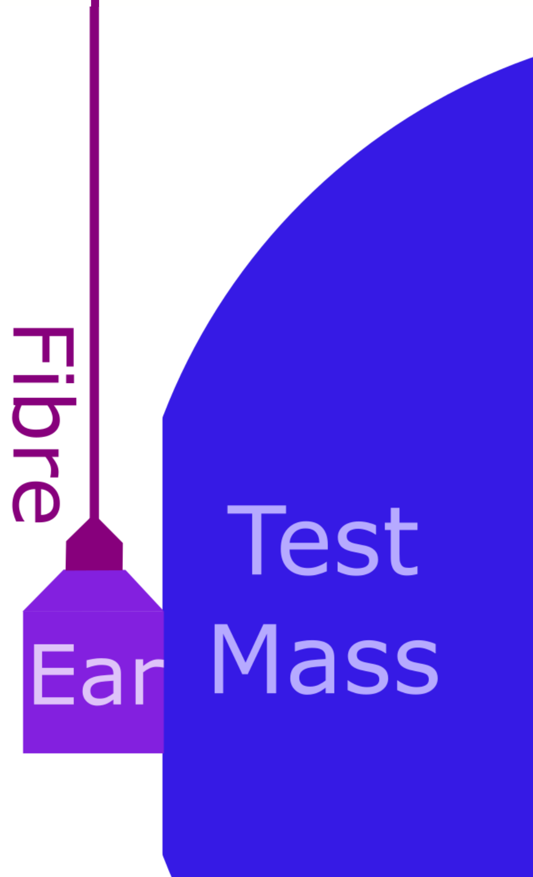


Silica Suspensions:
Study of ‘ears’ and ‘anchors’

Purpose: Utilising experience from advanced detectors to form combined solution for next generation detectors.

Outcome: Ear solution with one weld and one HC bond. Known reliability and thermal noise performance. Replicated de-stressing procedure. Improved welding setup

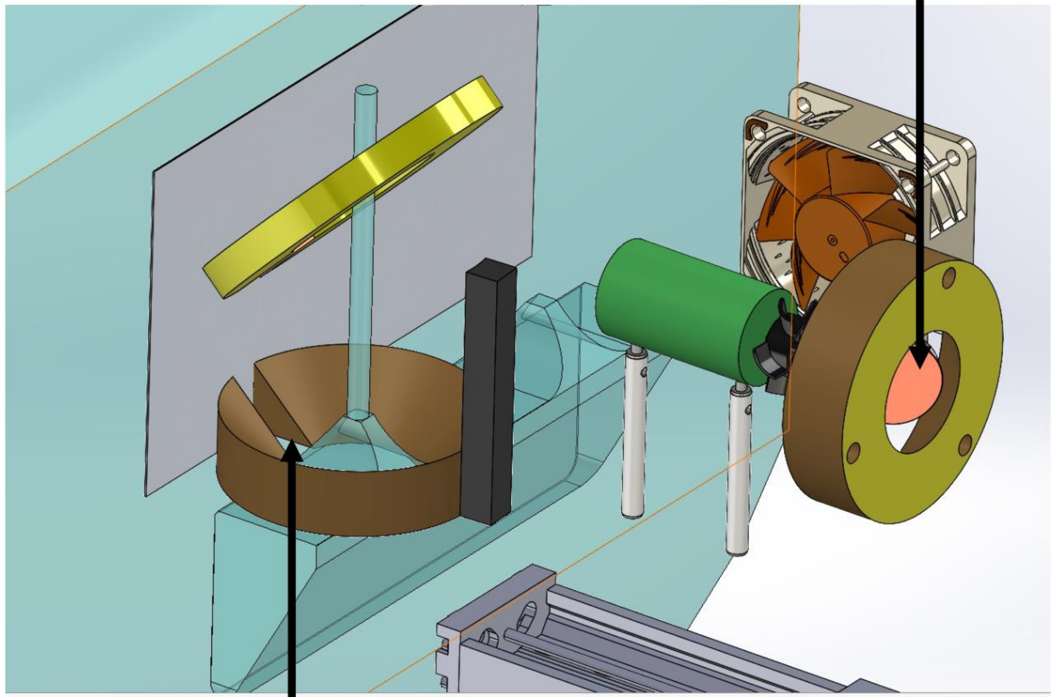
Recommendation for ET-HF: Use outputs of this study *or* undertake a similar review study and decision-making process.



Silica Suspensions:
Welding for large test masses

- Risk mitigation into the development of technologies for next generation heavy suspension systems (up to 400 kg masses), relevant for ET-HF.
- Developing a **new welding technique** based on the conical mirror configuration used for pulling silica fibres to decrease the time and effort required to weld fibre to test mass.
- **Ear redesign** to accommodate new welding procedure for proof-of-concept testing.
- **Hanging test** in new big vacuum system of PUM and ETM suspension for up to 400 kg. Also potential to explore in-situ welding within the chamber.

Rotating mirror to sweep the beam around conical mirror to create cylindrical beam



Gap in mirrors to allow for installation around weld area

Mirrors to be operated via motorised stages

Silica Suspensions: Stress Corrosion

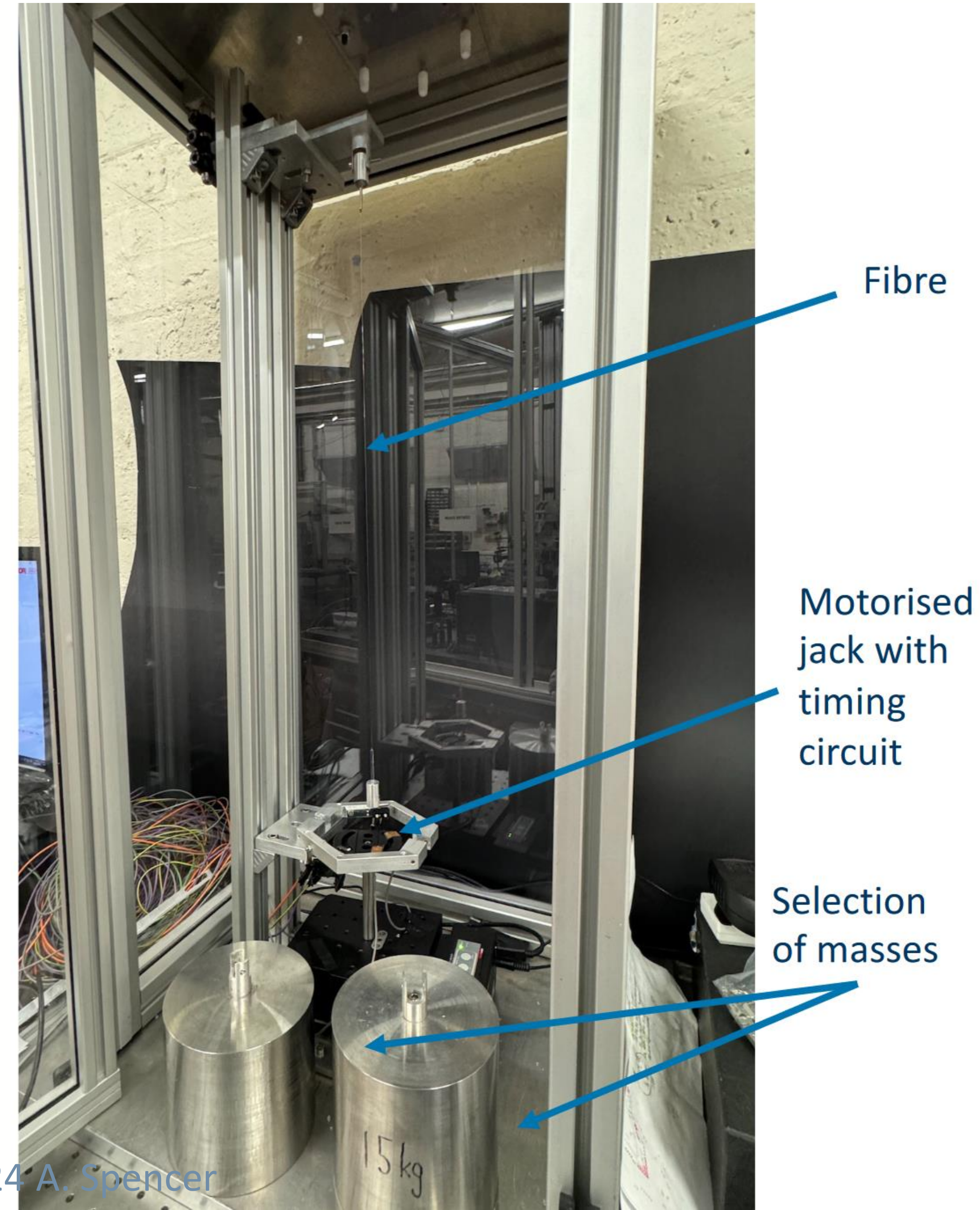
Contacts:

- Karl Toland

Replicate various "real-life" scenarios for both in-air and in-vacuum:

- Short term storage
- Long term storage
- Under tension mimic opening and closing of chamber without replacing fibres (alternating same fibre within an in-air and in-vacuum environment).

Want to build on the dataset to increase statistics to further build confidence in increasing applied stress on fibres.



Bonding R&D

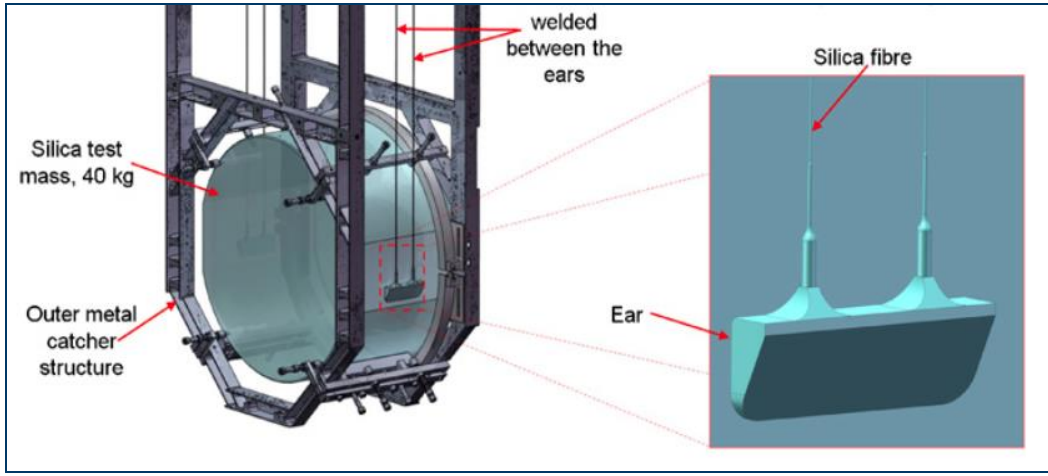
Contacts:

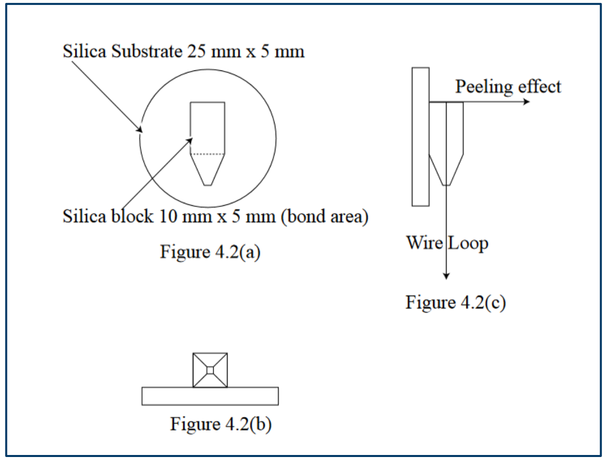
- Gregoire Lacaille
- Karen Haughian

Finite Elements Analysis (FEA) review of bond strength testing setups.

- Study combining information from FEA, analytical calculations and benchtop experiments.
- Looking at safety factors and possibility to reduce bond area in future suspensions.

- Various setups for strength testing are being analysed with homogenous model parameters so that they can be reliably compared to each other.





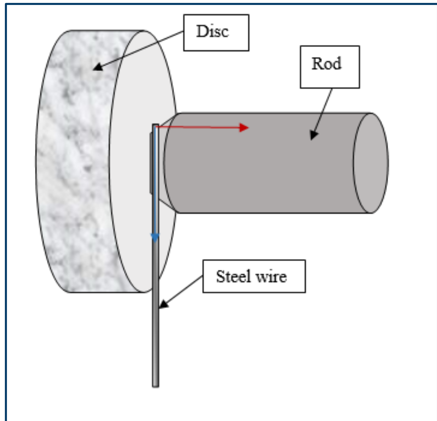


Figure 10. Shows the setup used in the experiment.

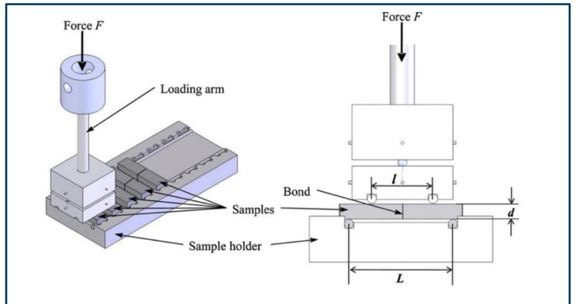
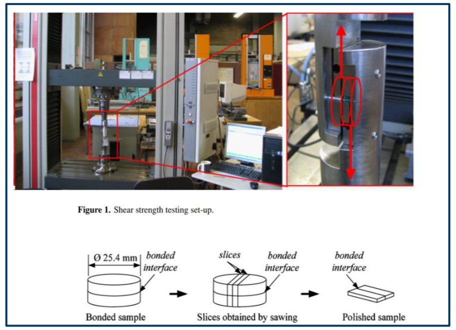
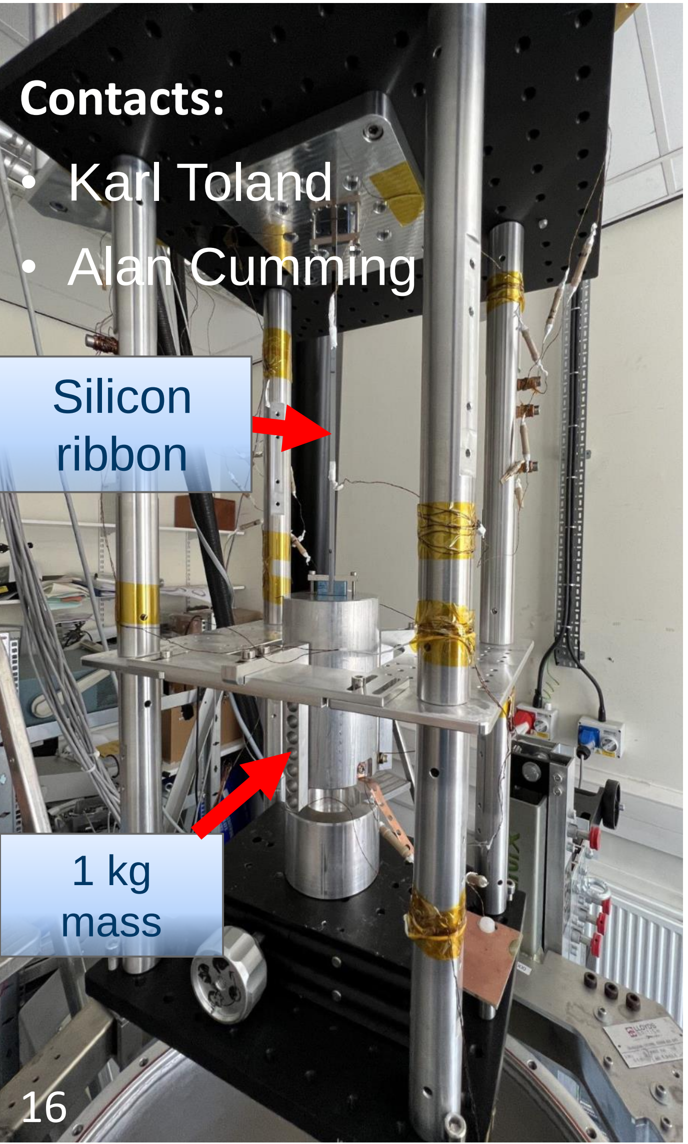


Figure 3. Three-dimensional and detail CAD images of the bending strength set-up.



Crystalline Suspensions: Silicon Suspension Demo



Contacts:

- Karl Toland
- Alan Cumming

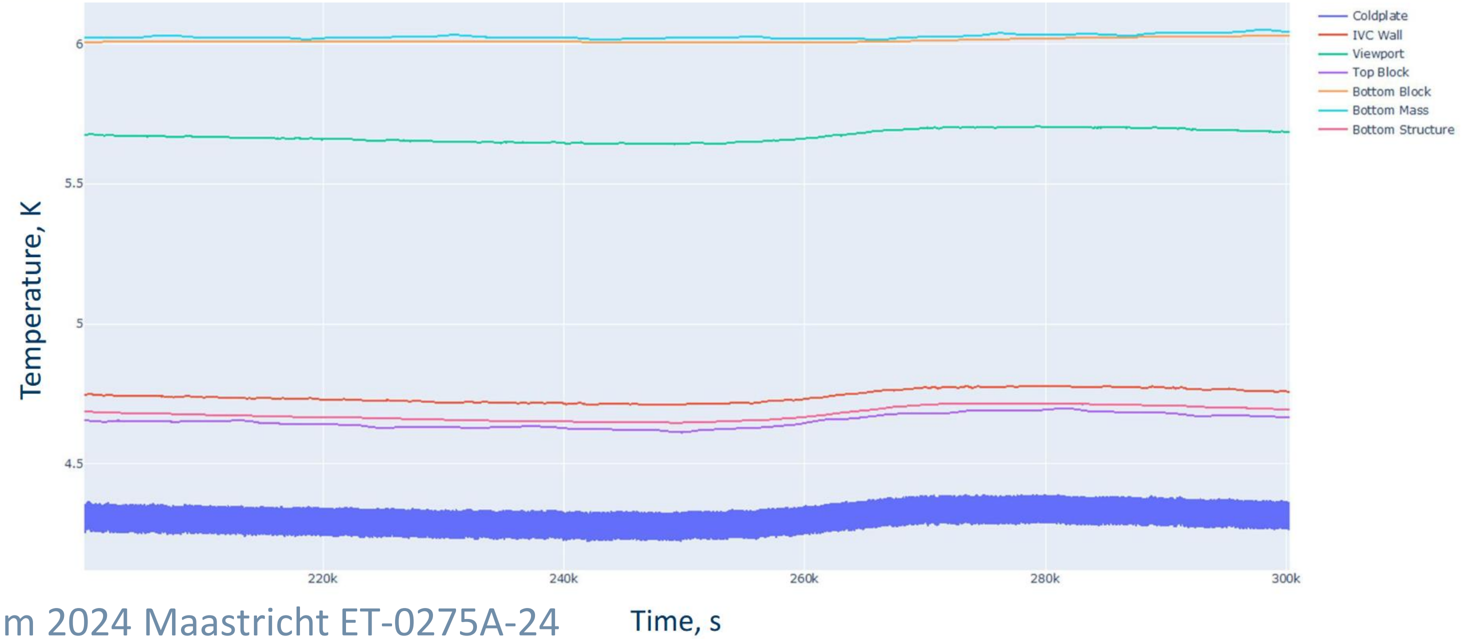
Proof-of-concept for silicon monolithic suspension.

1kg metal mass suspended from silicon ribbon with HC bonds between ribbon and top and bottom silicon attachment blocks.

Suspensions cooled down to 4K and survived multiple thermal cycles.

Heat Extraction

Measured heat extraction shows 2.5K ‘excess’ thermal gradient. Currently under investigation along with thermal conductivity study of silicon ribbons.

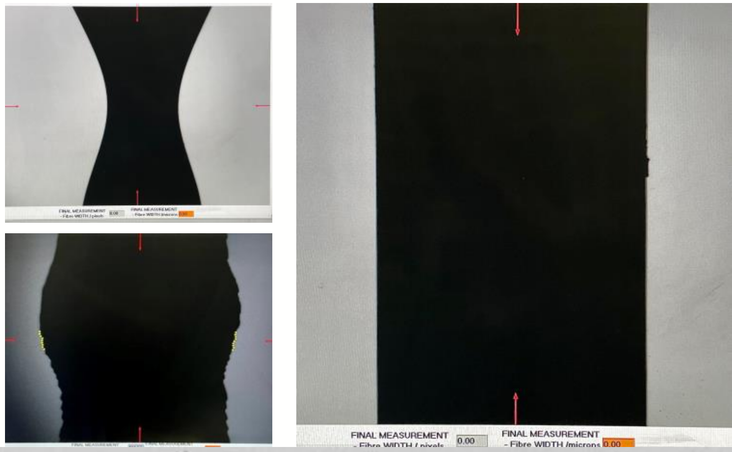


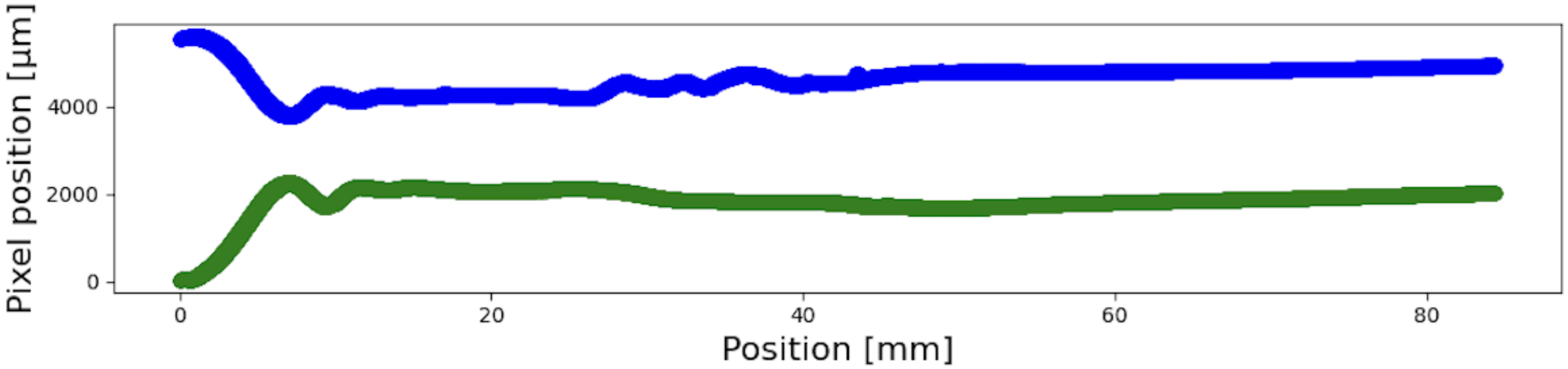
Crystalline Suspensions:
Silicon Fibre Characterisation

Contacts:

- Ardiana Nela
- Karl Toland

Characterisation of 3mm diameter silicon fibres of 65cm-116cm length, produced by float zone crystal growth by IKZ Berlin. (5 highly uniform, 6 non-uniform).





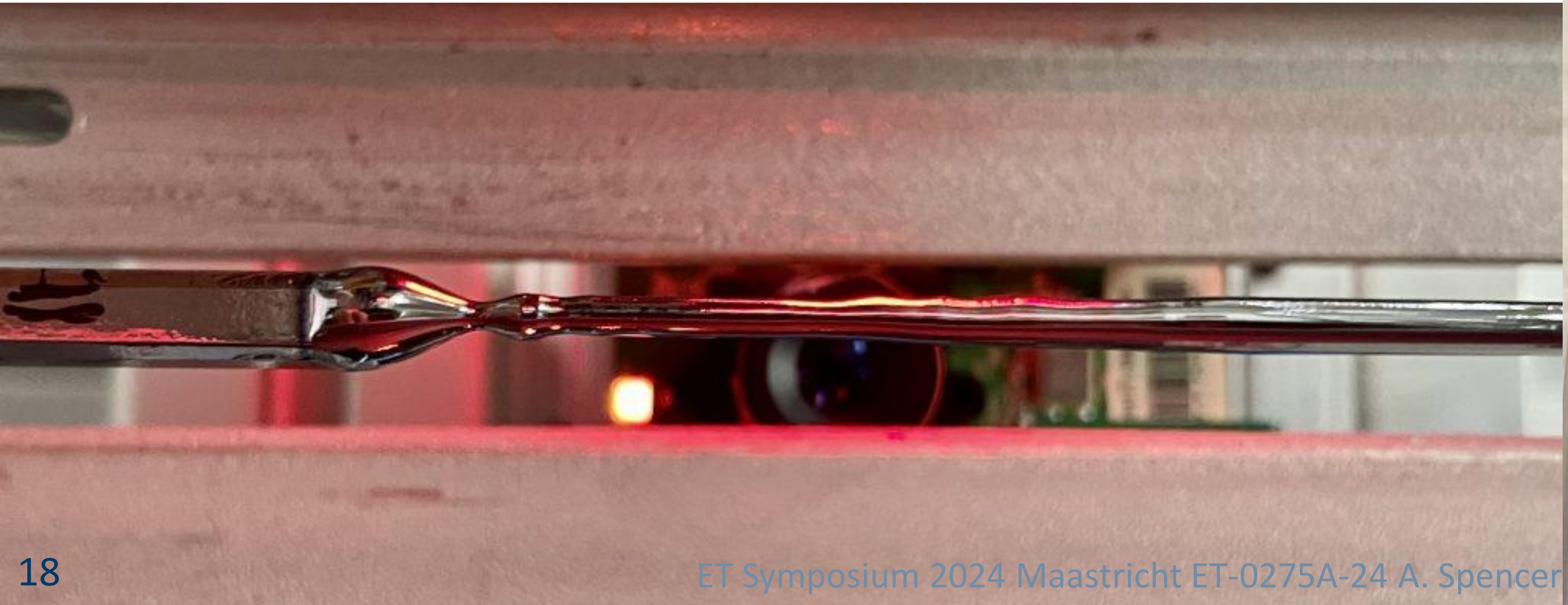
Crystalline Suspensions: Silicon Fibre Characterisation

Contacts:

- Ardiana Nela
- Karl Toland

Fibres have been profiled and next will be characterised for:

- Breaking strength
- Crystalography (X-ray diffraction)
- Thermal Conductivity



Crystalline Suspensions: Sapphire Welding

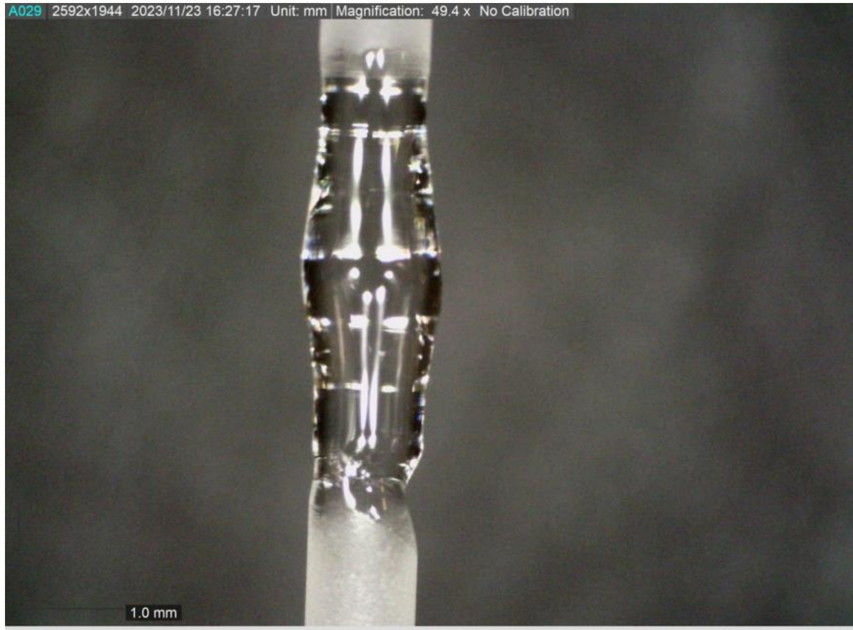
Contacts:

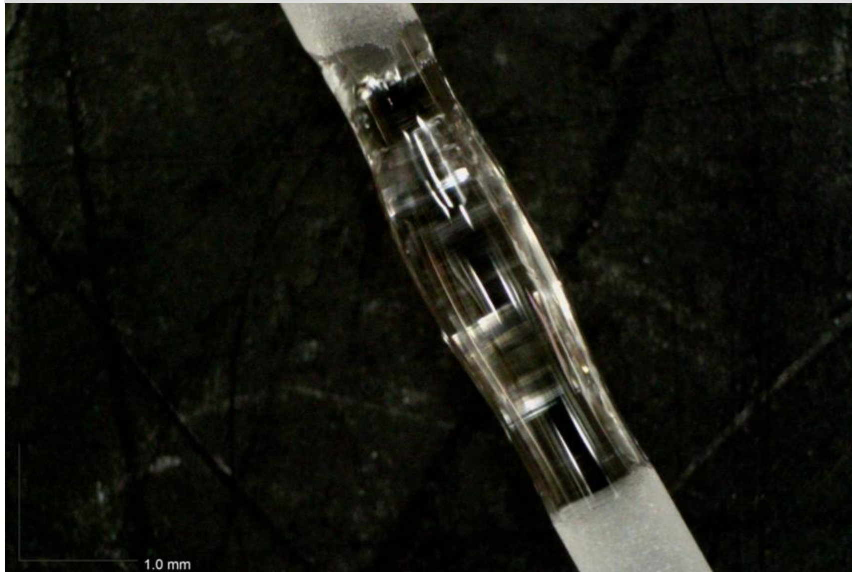
- Jennifer Docherty
- Alan Cumming

Successfully welded sapphire to sapphire of varying millimetre diameters. Welds have shown a consistent high optical quality with no obvious cracks or deformations.

Ongoing characterisation of:

- Strength
- Thermal conductivity measurements
- X-ray diffraction analysis
- Mechanical loss measurements





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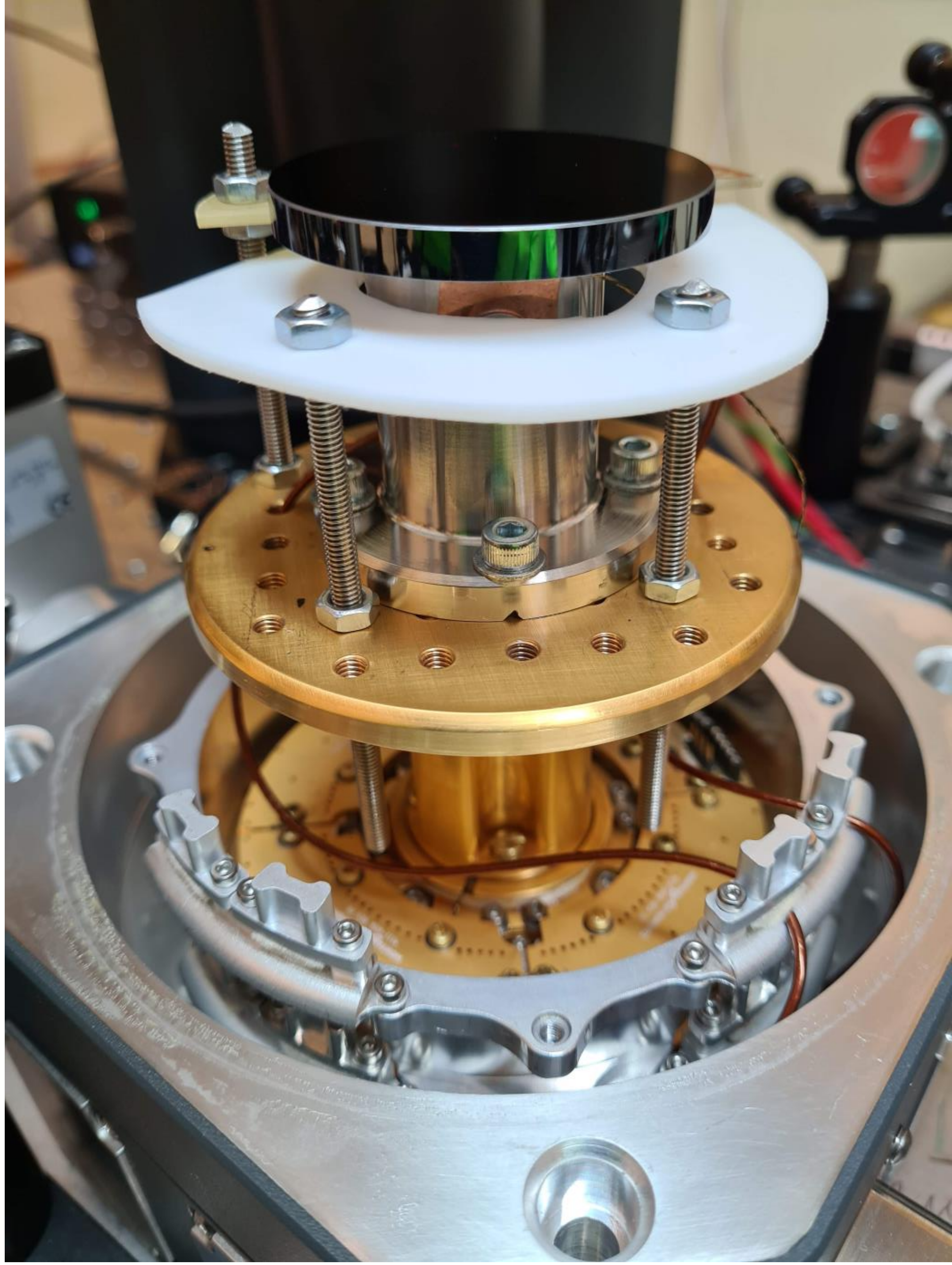
Glasgow – Coatings and Optics update

Contacts:

- Iain Martin
- Peter Murray
- Margot Hennig
- Graeme McGhee
- Ross Johnston

- Cryogenic mechanical loss of silicon substrates, multimaterial and nanolayered coatings (capability to measure both discs and cantilever-type samples)
- Room temperature mechanical loss of coatings relevant for ET-HF e.g. titania mixed silica and titania mixed germania coatings
- Absorption of coatings at 1064, 1550 and 2000 nm as a function of post-deposition heat treatment
- Calorimetry for cryogenic studies of the absorption of silicon



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Cryogenic Glasgow Interferometer Facility

The Glasgow Cryogenic Interferometry Facility brings together the IGR instrumentation sub-groups

- Interferometry
- Suspensions
- Bonding
- Coatings

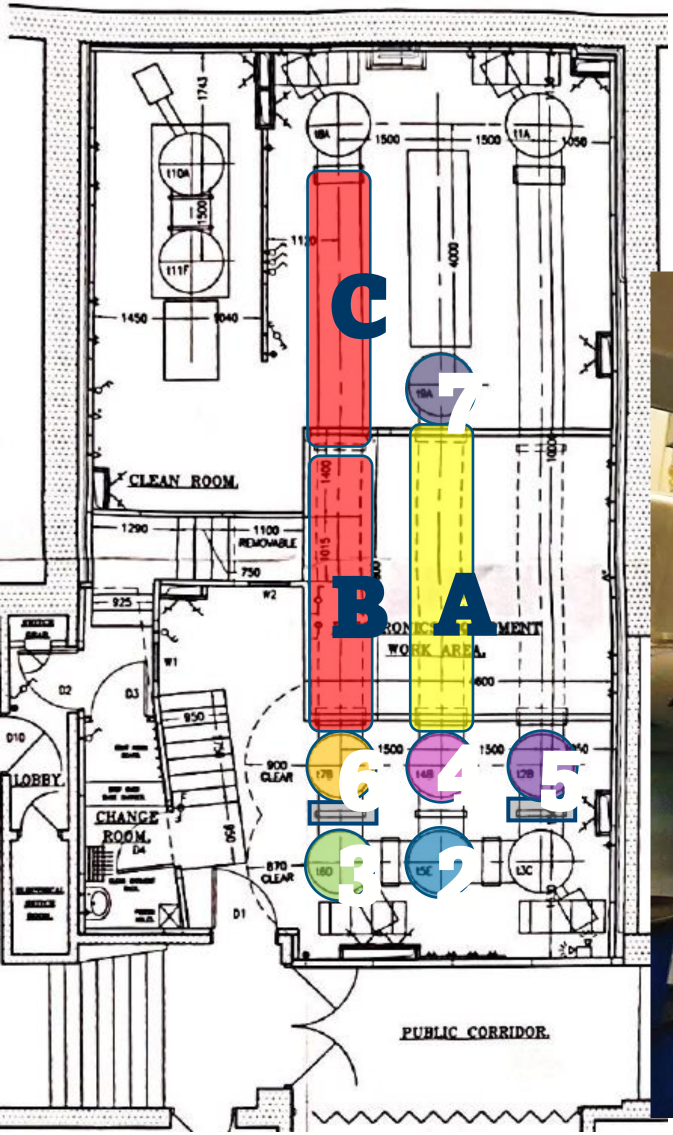
and ISB work packages primarily:

- Test-Mass Suspension
- Core Optics
- Lasers

Research Themes

- Monolithic Suspensions
- Silicon and Sapphire Bonding
- Cryogenic Coatings and Substrates
- Cryogenic Sensors and Actuators
- Cavity Control
- Long Wavelength Laser Stabilisation

Cryogenic Glasgow Interferometer Facility: Commissioning



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Cryogenic Glasgow Interferometer Facility: Commissioning

Cryogenic Glasgow Interferometer Facility: Facility Commissioning

Contacts:

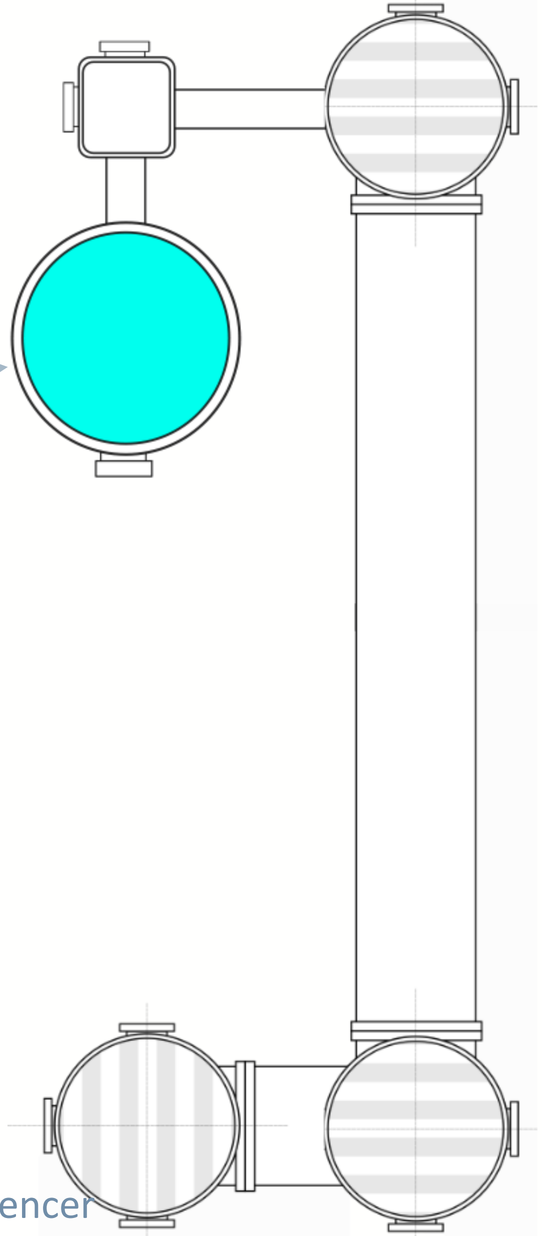
- Andrew Spencer
- Bryan Barr
- Victoria Graham
- Thejas Seetharmu
- Ardiana Nela

Infrastructure work:

1. Removal of vacuum infrastructure
2. Installation of new large volume cryostat

Room temperature

Cryogenic temperature (4-7K)



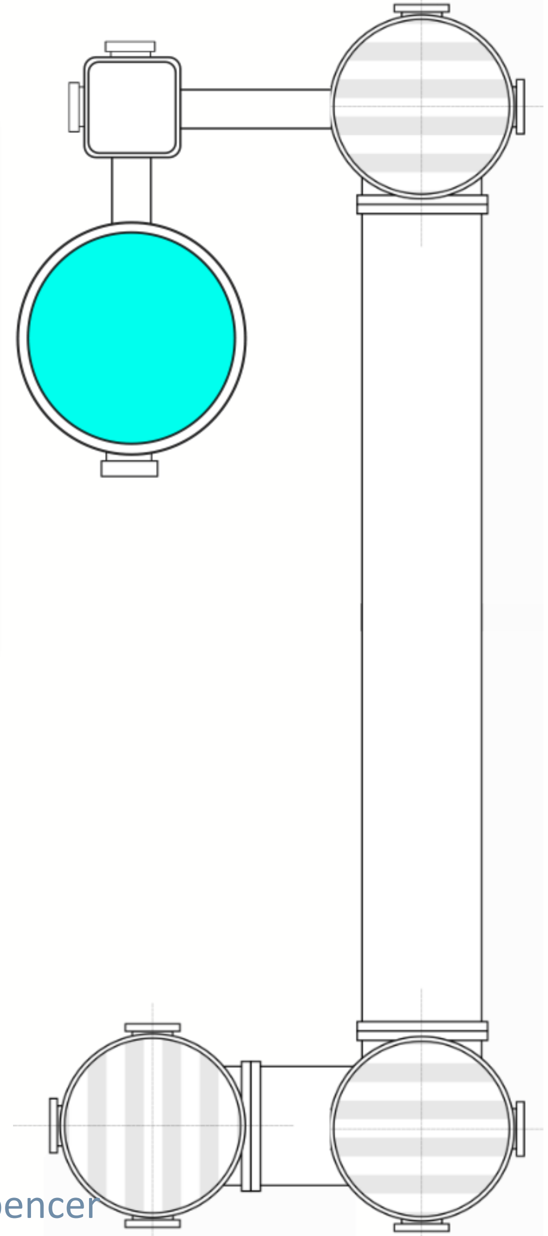
Cryogenic Glasgow Interferometer Facility: Facility Commissioning

Contacts:

- Andrew Spencer
- Bryan Barr
- Victoria Graham
- Thejas Seetharmu
- Ardiana Nela

Cryostat :

- Manufactured by Leiden Cryogenics
- Closed cycle pulsed-tube helium cooling (Cryomech) of payload down to 7K (phase 1, phase 2: 4K)
- Space for two 1kg triple suspension and reaction chains
- Inner chamber roughly 1m tall, 1m diameter.



Cryogenic Glasgow Interferometer Facility: Facility Commissioning

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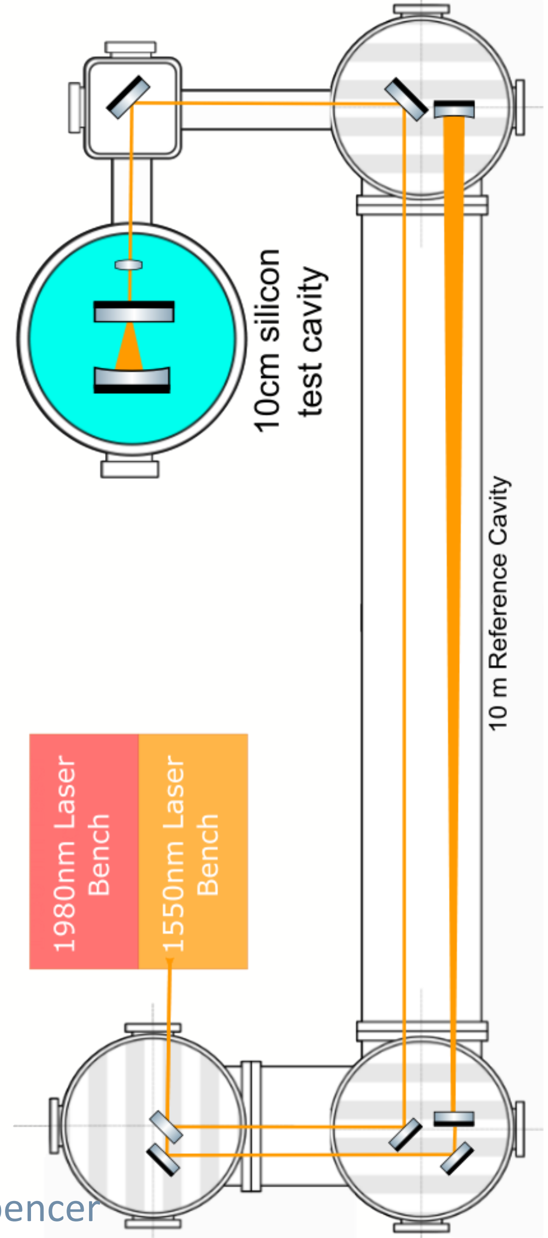
- Ardiana Nela

Suspension:
1kg Silicon (float zone) mirror mass and Penultimate mass
Silicon or Sapphire suspension elements (ears, fibres)
Controls:
Cryo-shadow sensors
ESD actuation
Lasers:
5W 1550nm Laser
200mW 1980nm Laser
ISS and 2-stage FSS (10cm refcav, 10m 'IMC')



Cryogenic Glasgow Interferometer Facility: Prototype crystalline cryogenic suspended cavity

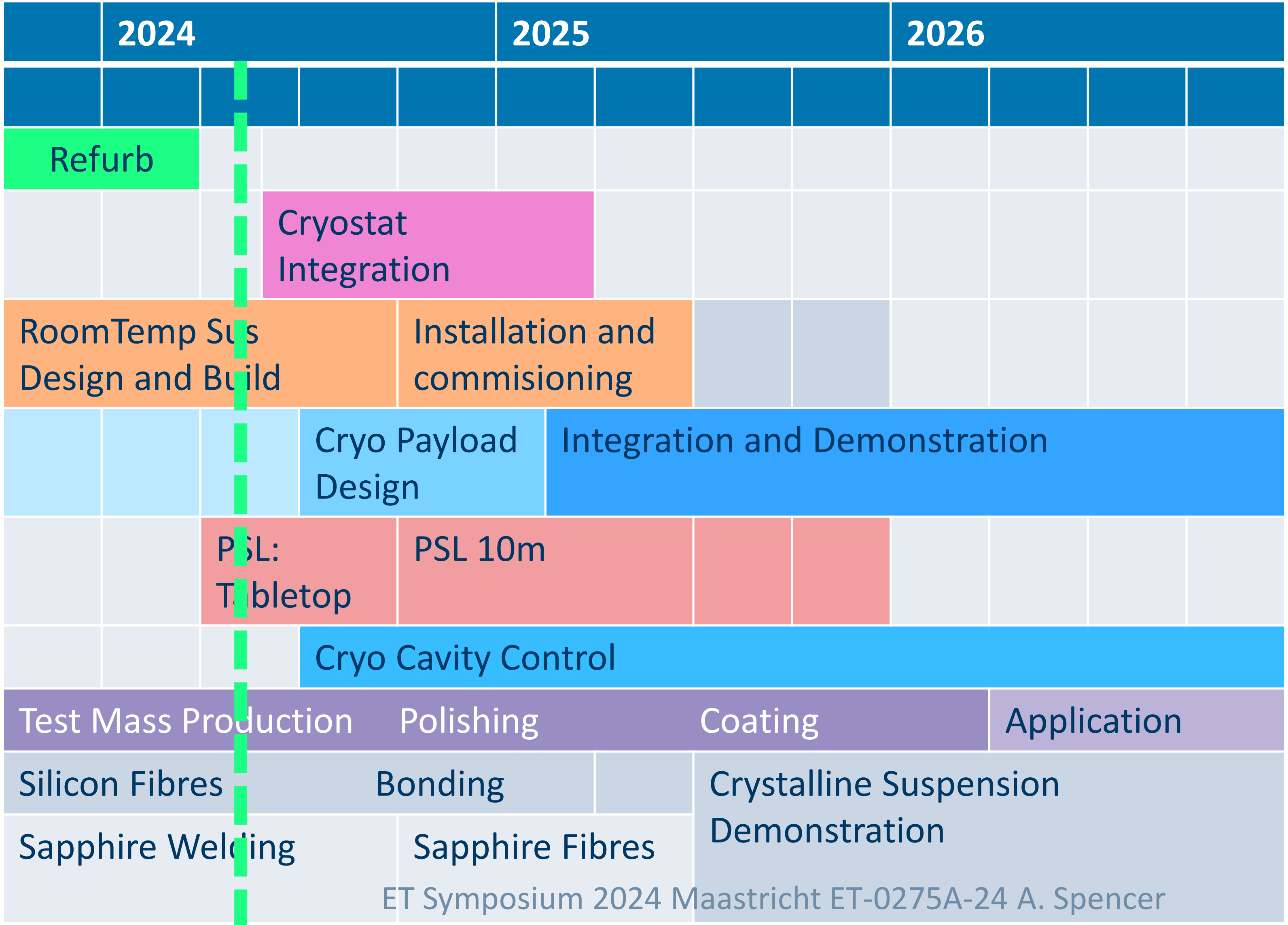
Research Themes

- Monolithic Crystalline Suspensions
- Silicon and Sapphire Bonding
- Cryogenic Coatings and Substrates
- Cryogenic Sensors and Actuators
- Cavity Actuation and Control
- Long Wavelength Laser Stabilisation

Research Goals:

- Demonstrations of cryogenic monolithic suspension system.
- Demonstration of heat extraction from a triple suspension system.
- Demonstration of control and locking of a suspended cryogenic cavity.
- 1550nm and 1980nm PSL concepts.
- Demonstration of coating technology.
- Direct coating thermal noise measurement.

Glasgow Interferometer Facility Timeline



Cryogenic Glasgow Interferometer Facility: Facility Commissioning

Most of that vacuum hardware is now in The Netherlands to be used by the ETPathfinder project.

UKRI Funding contribution to ET through 'Next Gen GW' Grant.

IGR research groups contributing R&D to ET ISB in the areas of:

- ET-HF heavy fused silica suspensions
- ET-LF cryogenic crystalline suspensions
- ET-HF + LF coatings and substrates
- Laser, suspensions and interfermetric control
- Prototype Facility

Contact: *andrew.spencer@glasgow.ac.uk
Institute for Gravitational Research
University of Glasgow
https://www.gla.ac.uk/schools/physics/research/groups/igr/

Thank-you very much for your attention

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Bonus Slides

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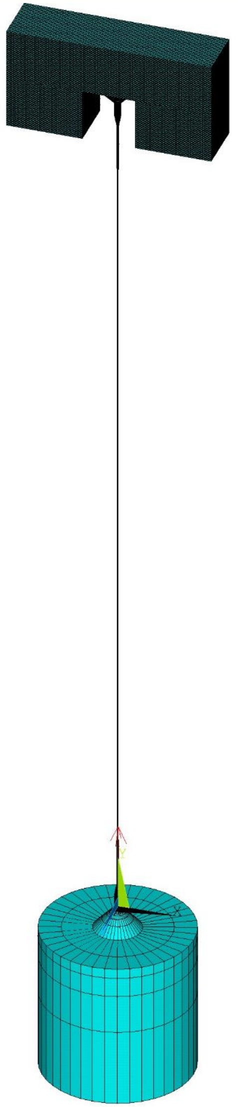
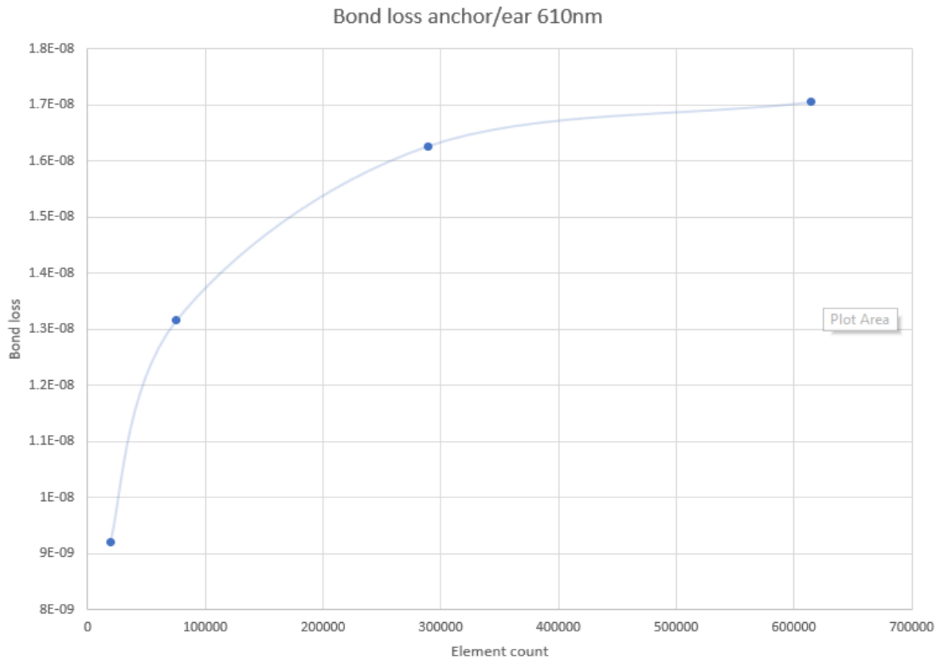
Silica Suspensions: Study of ‘ears’ and ‘anchors’

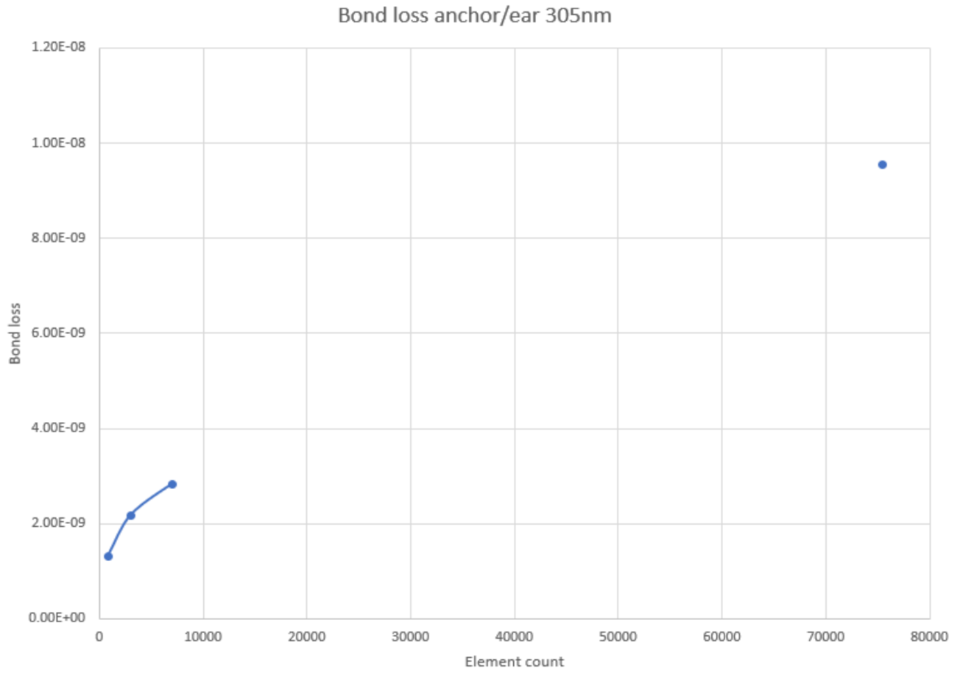
Modelling of TN anchor systems currently ongoing.

Large but extremely thin bond areas proving to be extremely difficult to model – this is at the absolute limits of the FEA – continues to be a challenge to get to converged final solutions.

Ear solution is understood with FEA modelling.



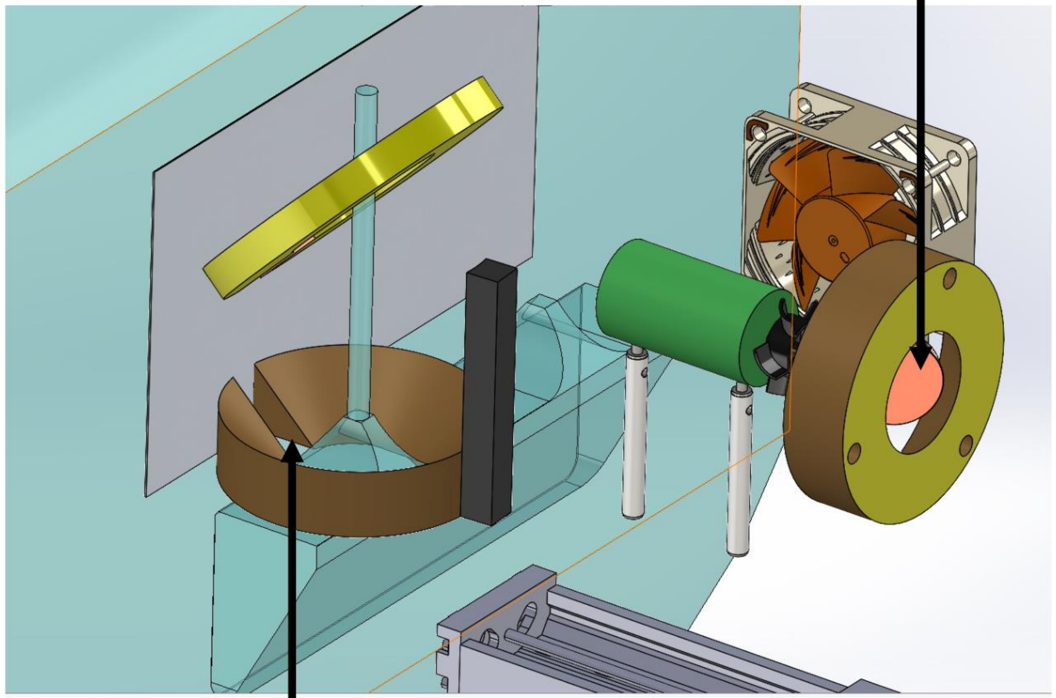




Silica Suspensions: Welding for large test masses

- Risk mitigation into the development of technologies for next generation heavy suspension systems (up to 400 kg masses), relevant for ET-HF.
- Developing a new welding technique based on the conical mirror configuration used for pulling silica fibres to decrease the time and effort required to weld fibre to test mass.
- Ear redesign to accommodate new welding procedure for proof-of-concept testing.
- Purchasing ~2.7 m inner height vacuum chamber to allow for PUM and ETM suspension for up to 400 kg. Also potential to explore in-situ welding within the chamber.

Rotating mirror to sweep the beam around conical mirror to create cylindrical beam



Mirrors to be operated via motorised stages

Gap in mirrors to allow for installation around weld area

Silica Suspensions: Stress Corrosion

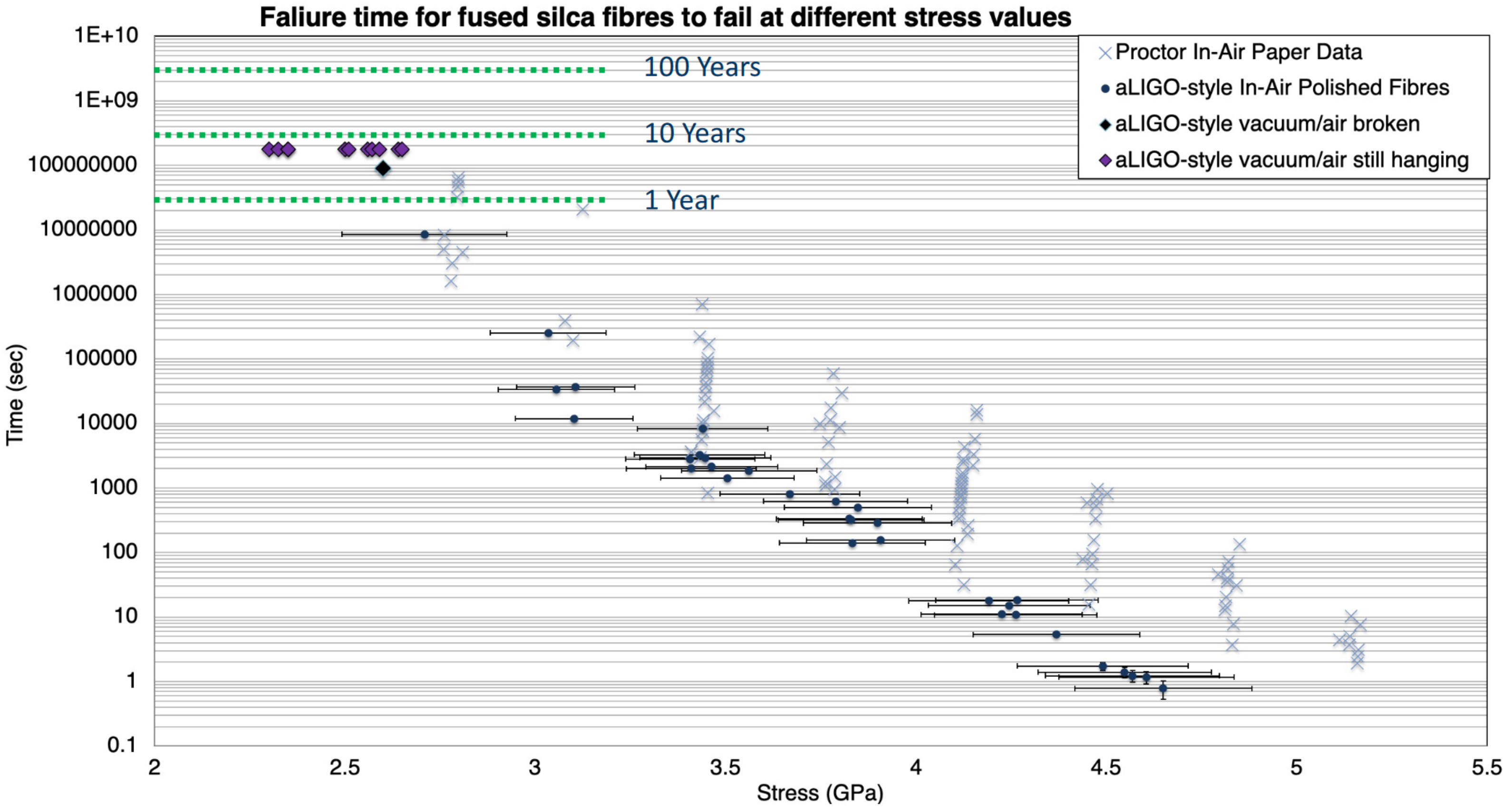
Another aspect of Next Generation work is related to the applied stress to fibres in suspensions.

• Previous work [2-4] conducted on fibre stress corrosion looked at a stress range of 2.5-5 GPa.

• This data set was conducted in-air.

• Want to build on the dataset to increase statistics to further build confidence in increasing applied stress on fibres.

• Historical data suggests that fibres would last longer in-vacuum. Want to conduct in-vacuum tests.



[2] K. Toland, Aspects of fused silica fibres for use in gravitational waves research, PhD Thesis, 2020

[3] K. H. Lee, Suspension upgrades for future gravitational wave detectors - PhD Thesis, 2019

[4] K. Toland, Fused Silica Fibre Research At Glasgow, LVC Meeting 2017, LIGO-G1701559

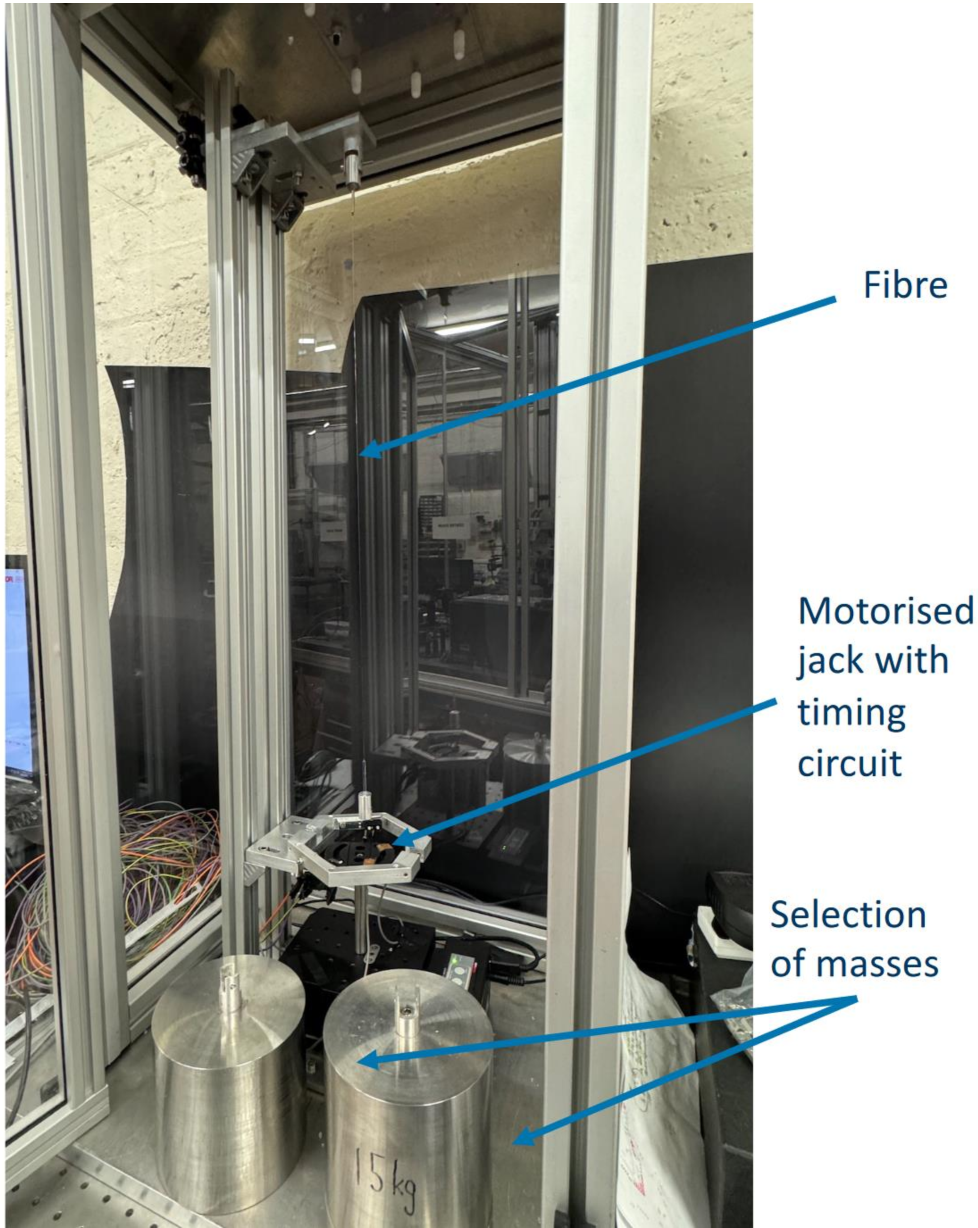
Silica Suspensions: Stress Corrosion

Replicate various “real-life” scenarios for both in-air and in-vacuum:

• Short term storage (fibre pulled, profiled, immediately tested). This is the same condition as previously tested.

• Long term storage (fibre pulled, stored away in a low-humidity cabinet for several months, then tested). New condition, mimicking storage of fibres before installation.

• Lower-stress (~3GPa) alternating same fibre within an in-air and in-vacuum environment to see if this accelerates the aging process. Mimics opening and closing of chamber without replacing fibres.



Bonding R&D

Contacts:

- Gregoire Lacaille
- Karen Haughian

Finite Elements Analysis (FEA) review of bond strength testing setups.

- Ear design has mostly been informed by FEA to assess stress level. There is no data for a bond breakage for an aLIGO bonded ear.
- The threshold stresses and safety factor are estimated through benchtop experiments and analytical calculations which are not easily compared to the mix loading in bonded ears.
- If there is a discrepancy between FEA and analytical studies, it is possible that the safety factor is underestimated.
- If bond thermal noise is limiting, using that margin on safety factor to decrease the bond area without compromising the assembly safety can be a valuable design tool.
- Various setup for strength testing are being analysed with homogenous model parameters so that they can be reliably compared to each other.

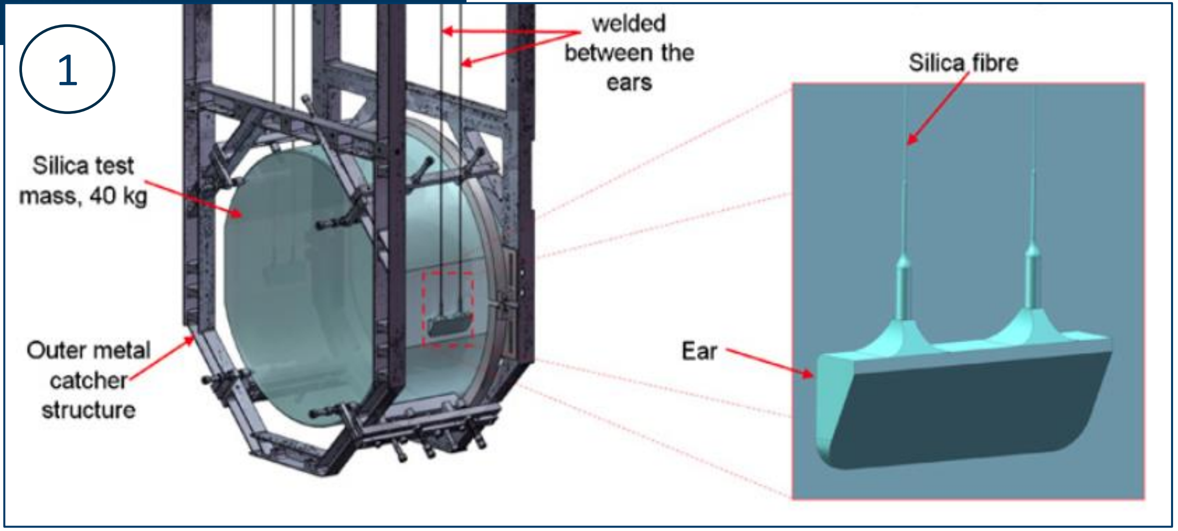
University of Glasgow

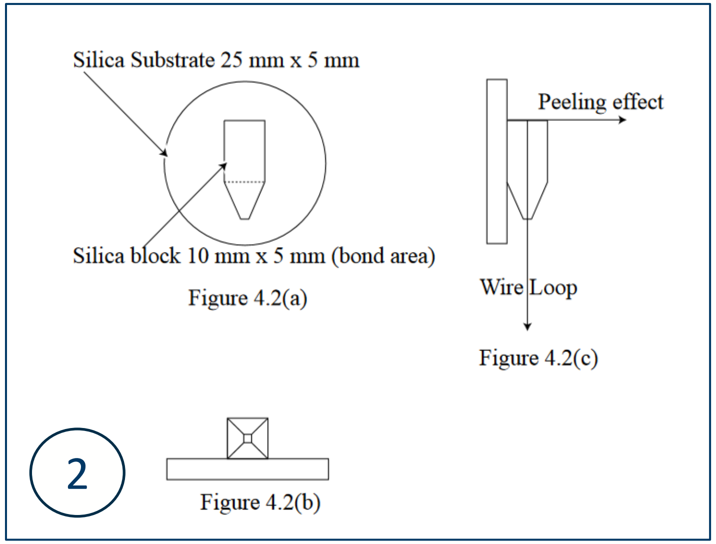
Bonding R&D

- Gregoire Lacaille
- Karen Haughian

		Main feature	Reference
1	aLIGO ear with 200N loading	Mixed loading, hard to assess analytically	https://dcc.ligo.org/public/0005/T0900447/004/T0900447-v4_Final_design_document_ETM_ITM_ears.pdf
2	GEO-like ear with wire loop	Wire offset from bond line for mixed loading	ProQuest Dissertations And Theses; Thesis (Ph.D.)--University of Glasgow (United Kingdom), 2005.; Publication Number: AAT 10906049; ISBN: 9780438163850; Source: Dissertation Abstracts International, Volume: 76-10C.; 277 p.
3	Rod on disc assembly with wire loop	Wire as close as possible to bond line to minimise peeling	Internal document
4	4-point bending	Standardised test for tensile (peeling) strength	N L Beveridge et al 2013 Class. Quantum Grav. 30 025003
5	Clamped discs in shear	Attempt at pure shear loading	A A van Veggel et al 2009 Class. Quantum Grav. 26 175007

Finite Elements Analysis (FEA) review of bond strength testing setups





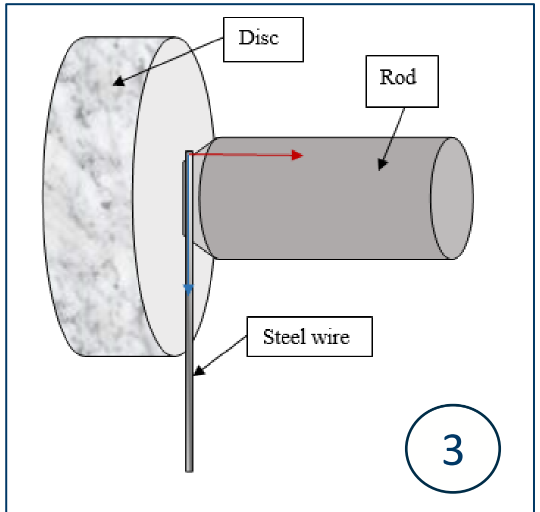


Figure 10. Shows the setup used in the experiment.

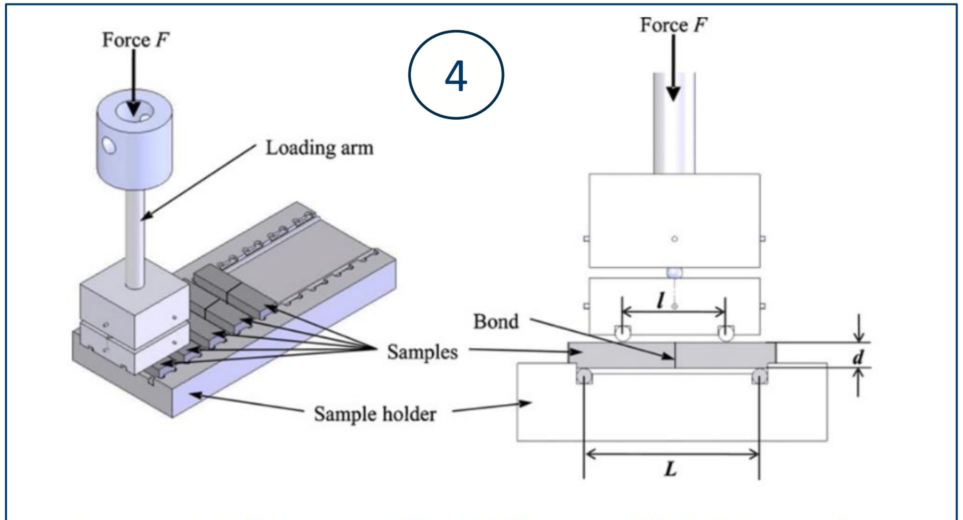


Figure 3. Three-dimensional and detail CAD images of the bending strength set-up.

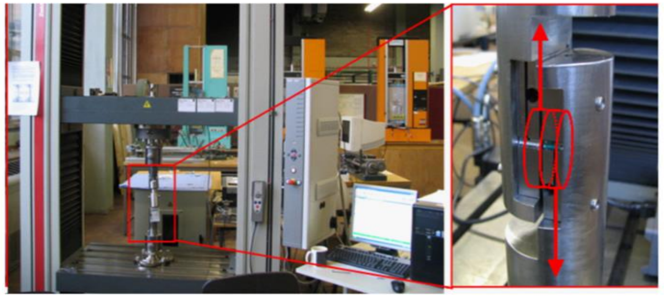
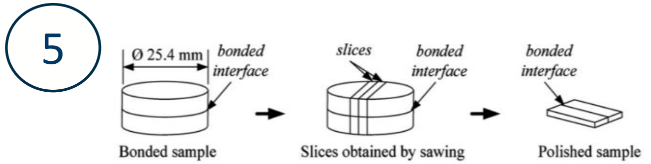


Figure 1. Shear strength testing set-up.



Finite Elements Analysis (FEA) review of bond strength testing setups

Safety factors

Equivalent stress: 1.5 MPa versus 9 MPa (ignoring dark blue that mostly comes from compression) **6**

Shear stress : 0.54 MPa versus 4.1 MPa **8**

Normal (peeling): 0.61 versus 10.7 MPa **17**

Assess safety of assemblies with decreased safety factors informed by both FEA and experiment for future ear designs

Work in progress-

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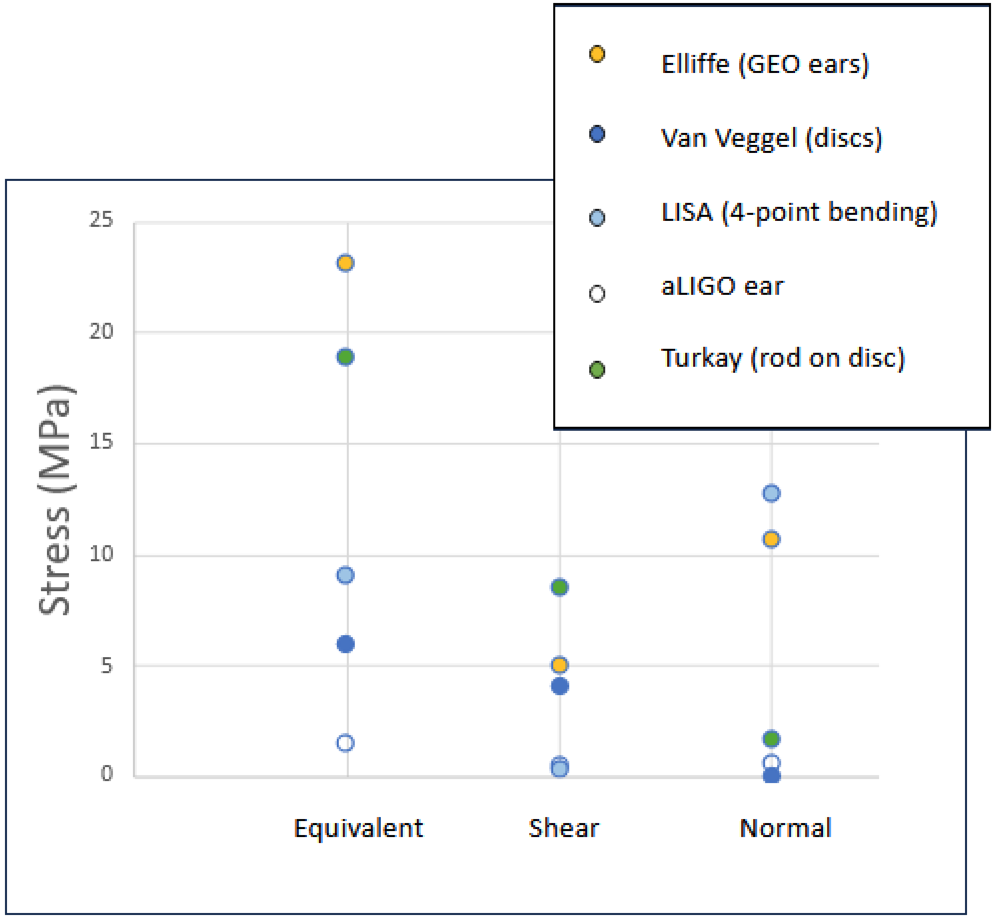
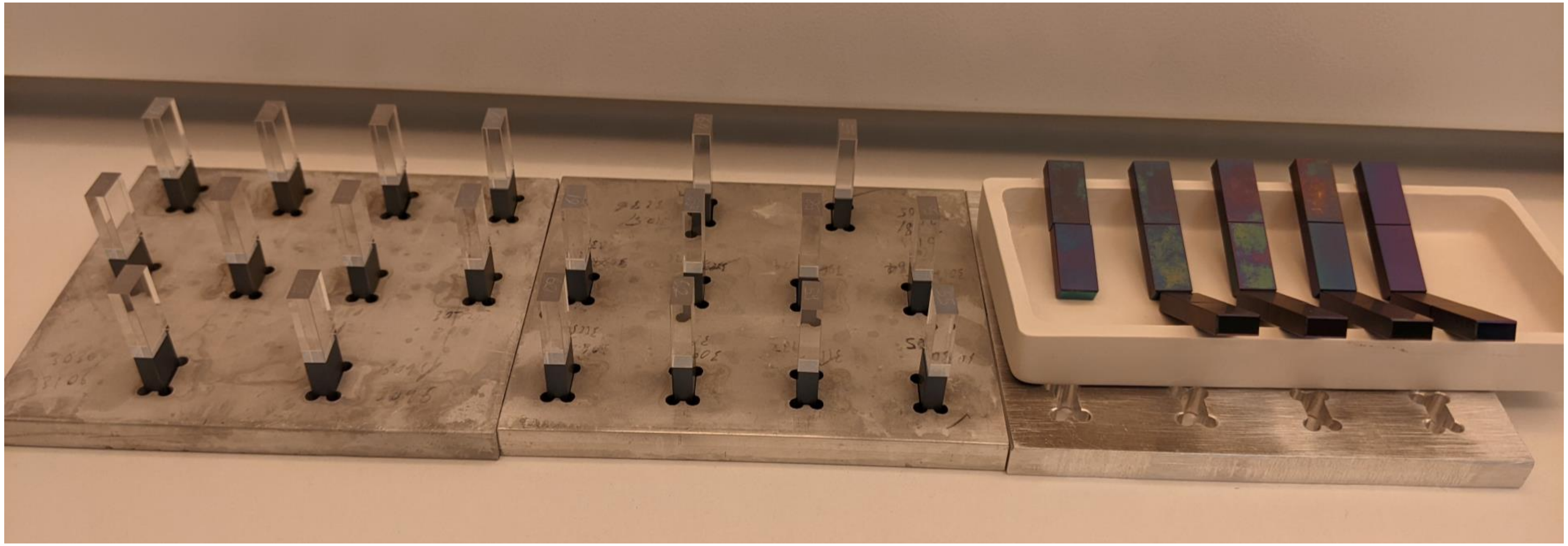


Stress in bonded interfaces at failure for various assemblies compared with the stress in the aLIGO ear bonded interface

Bonding R&D

Set of samples for 4-point bending testing:

- Silicon/Sapphire sodium silicate bonds after several thermal cycling down to 4K
- Direct bonded Silicon annealed to 1000C



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