# MAD workshop report on crystalline Test Mass suspension

F. Travasso on behalf of ET-Test Mass Suspension WP…and many others

*ET Annual Meeting – Opatija– 12/11/2025*

# …a young but very proficient collaboration

EINSTEIN TELESCOPE

**List of previous meetings**
- ISB Workshop – L'Aquila – October 2022
- Silicon Workshop – Maastricht – April 2023
- TMS-CO Workshop – Glasgow – October 2023
- MAD 2024 – Warsaw – November 2024
- MAD 2025 – Berlin – October 2025 (IKZ)

**MAD25 Participation**

Organized at IKZ, the workshop was a mix of researchers and industry professionals

44 in person attendees

~20 remote attendees

ikz

**MAD25 Organisers**

Iryna Buchovska

Robert Menzel

**Scientific Committee**

Alex Amato

Iryna Buchovska

Elisabetta Cesarini

Margot Henning

Robert Menzel,

Luca Naticchioni

Andrew Spencer

Flavio Travasso

# MAD Workshop timetable

**Monday 6 October 2025**

10:00-12:00
IKZ Lab tour

12:30-17:00
Substrates

**Tuesday 7 October 2025**

9:00-12:00
Suspension

12:30-16:00
Coatings

**Cooling away the absorption - Silicon mirror developmen...**
*Janis Woehler*

**Development of a Silicon Suspension System for the Ein**
*Maike Kühler*

**Advancing electrochemical micromachining technology f...**
*Dr Muhammad Hazak Arshad*

**Towards Reliable Bonding of Sapphire and Silicon II**
*Alexey Kuzmichev*

## Meeting page

https://indico.ego-gw.it/event/905/

## Minutes of the workshop

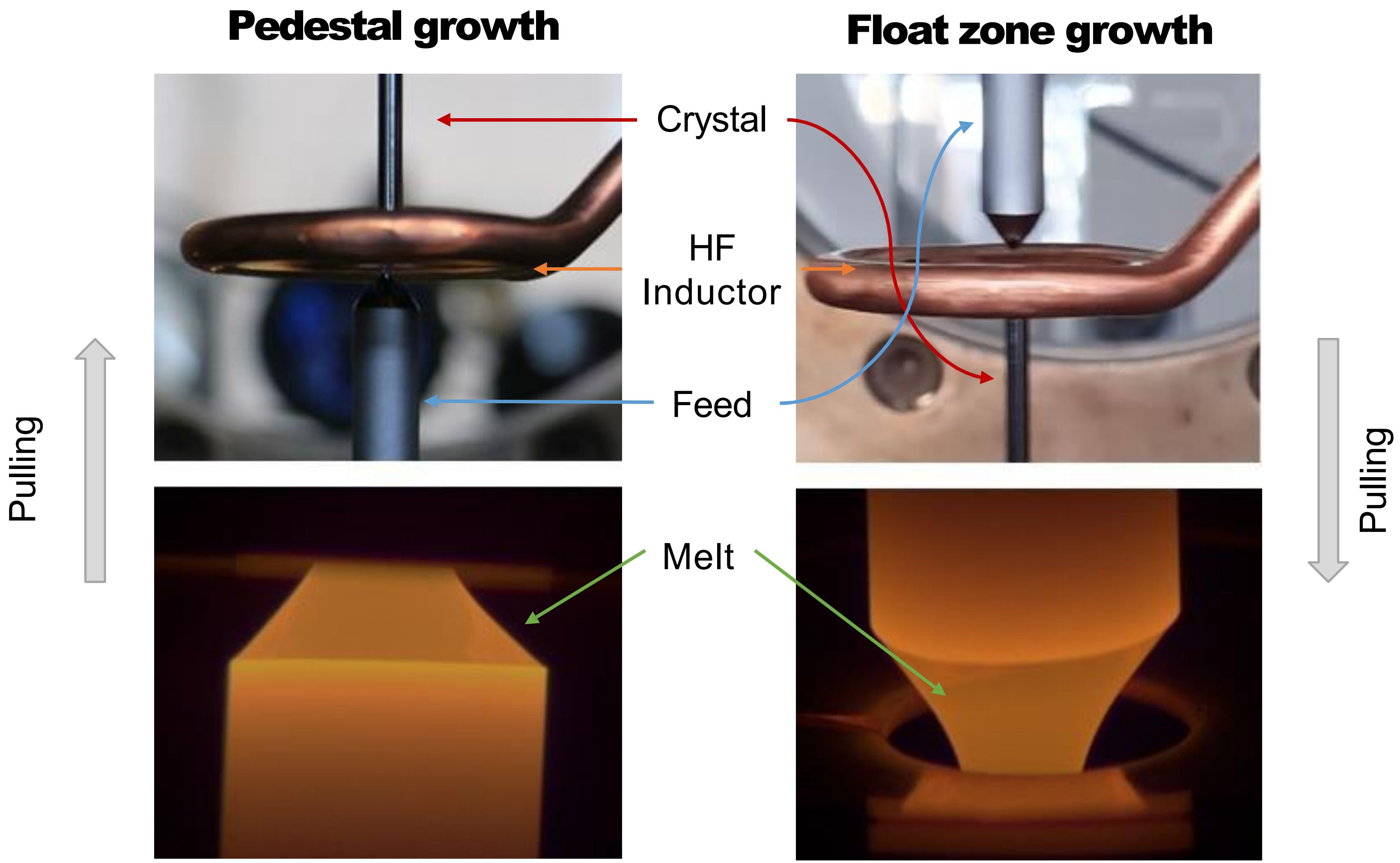
https://apps.et-gw.eu/tds/ql/?c=18189

| Time | Contribution | Speaker | Room | Slot |
|---|---|---|---|---|
| 09:00 | Introduction on Suspension Research | *Andrew Spencer* | *Max-Born-Saal* | 09:00 - 09:15 |
| | Float zone silicon fibers for suspension application in Einstein Telescope | *Dr Iryna Buchovska* | *Max-Born-Saal* | 09:15 - 09:30 |
| | ET-FIBER: Monocrystalline Silicon Fibre Development for Cryogenic Test Mass Suspensions | *Mr Gilles Magain et al.* | *Max-Born-Saal* | 09:30 - 09:45 |
| | Cautions for a correct evaluation of breaking strength measurements | *Flavio Travasso* | *Max-Born-Saal* | 09:45 - 10:00 |
| 10:00 | Precision Mechanical Loss Measurement & Noise Characterisation: E-TEST Cryogenic Prototype | *Hemendra Singh* | *Max-Born-Saal* | 10:00 - 10:15 |
| | Coffee Break | | *Max-Born-Saal* | 10:15 - 10:45 |
| | Mechanical Dissipation in Maraging Steel at Room Temperature and Very Low Frequency | *Matteo Baratti* | *Max-Born-Saal* | 10:45 - 11:00 |
| 11:00 | Sapphire-Based Suspension at ARC-ETCRYO Laboratory: Ongoing Test Campaigns | *Dr Emanuele Tofani et al.* | *Max-Born-Saal* | 11:00 - 11:15 |
| | Sapphire fibre suspensions for KAGRA and ET with low loss jointing techniques | *Jennifer Docherty* | *Max-Born-Saal* | 11:15 - 11:30 |
| | MAD25: Session 2. Suspensions: Discussion | | *Max-Born-Saal* | 11:30 - 12:00 |

# Float Zone silicon fibers for suspension application in Einstein Telescope

I. Buchovska[1], B. Scalise[1], M. Scheffler[1], F. M. Kiessling[1], K. Schindler[1], I. Tsiapkinis[1], R. Menzel[1], A. Nela[2], G. Lacaille[2], K. Haughian[2], K. Toland[2], A. Spencer[2]

[1] Leibniz-Institut für Kristallzüchtung (IKZ)
[2] University of Glasgow



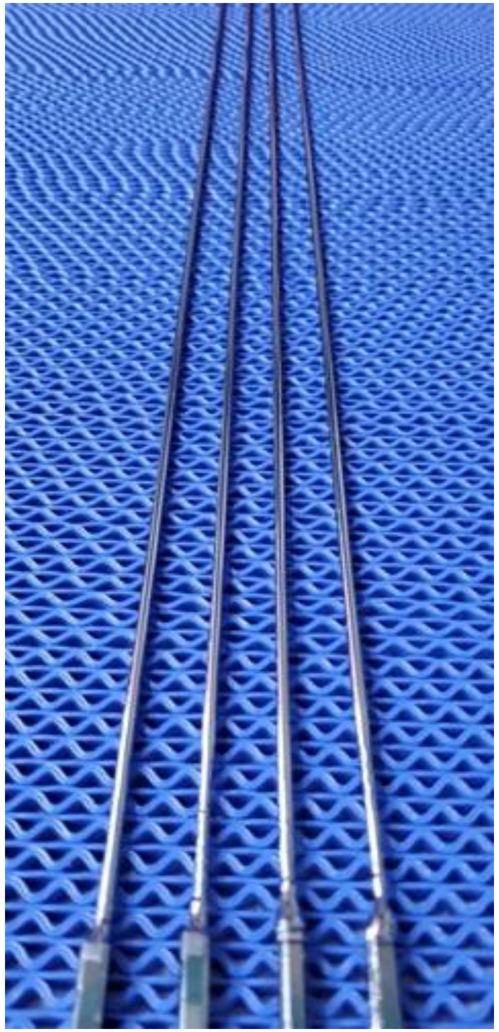

Bundesministerium
für Bildung
und Forschung

This work was funded by the BMBF, Grant Number 05A23BC1, 07/2023 – 06/2026

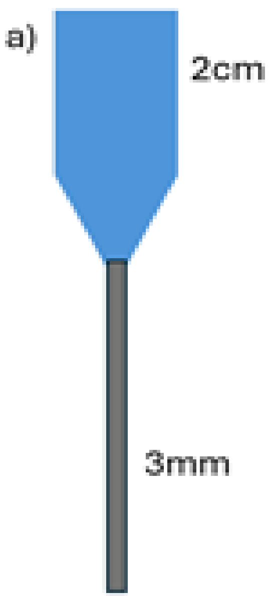
“Verbundprojekt 05A23BC1 – 3G-GWD:
Gravitationswellen-Teleskop der dritten Generation. Teilprojekt 4”

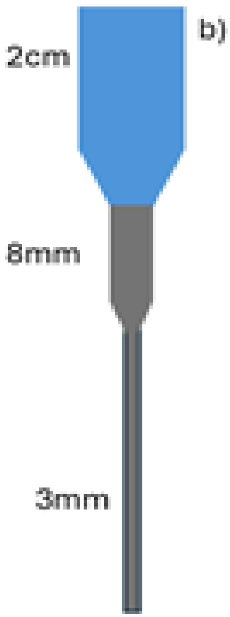
# IKZ Production

## Long fibers with heads



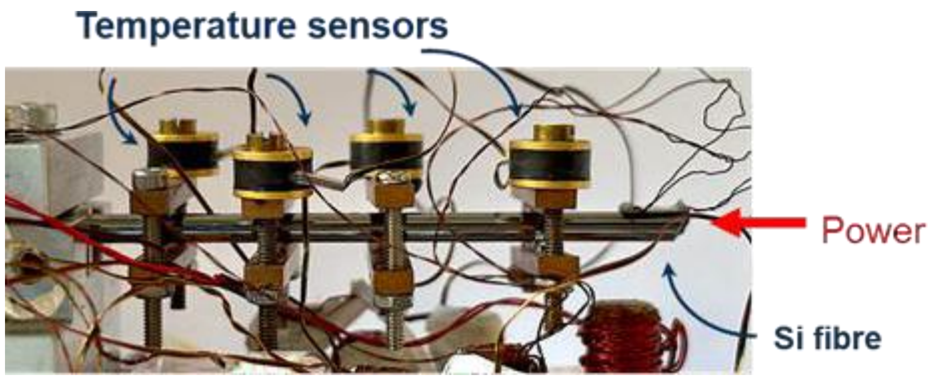
## Welding

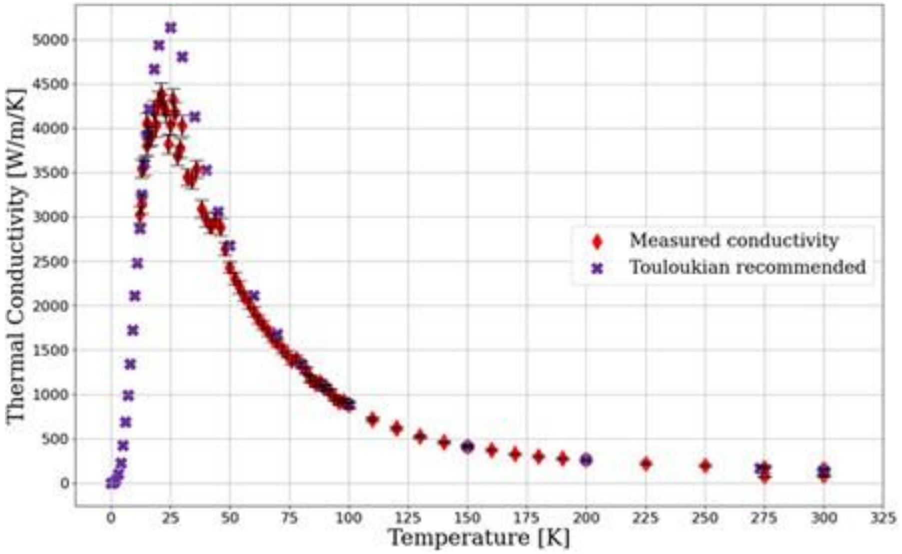



# Thermal conductivity ⌀ 3 mm fiber

- Measured thermal conductivity of ⌀ 3mm uniform control sample
- Results within the recommended Touloukian curve [2]
- Growth process preserves the high thermal conductivity of silicon
- Diameter for heat extraction limited case for ET:
  1375 μm (at 15-20K)



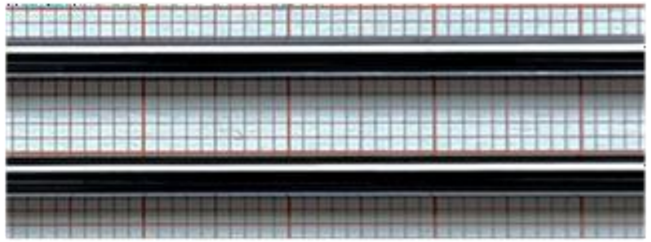

*[2] Y. S. Touloukian et al. "Thermophysical properties of matter - the TPRC data series (1970); Volume1*

# Results on ⌀ 1 mm Si-fiber growth

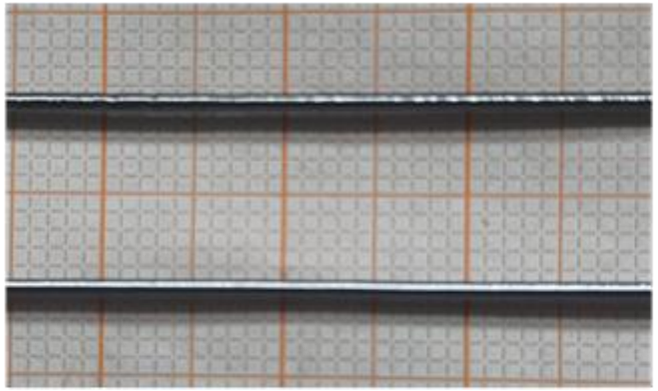
Nikhef ETPATHFINDER

- Si-fiber diameter: 1 mm
- Diameter variation: +/- 0.1 mm
- Length: up to 80 cm
- Further development for stable and reproducible process is ongoing

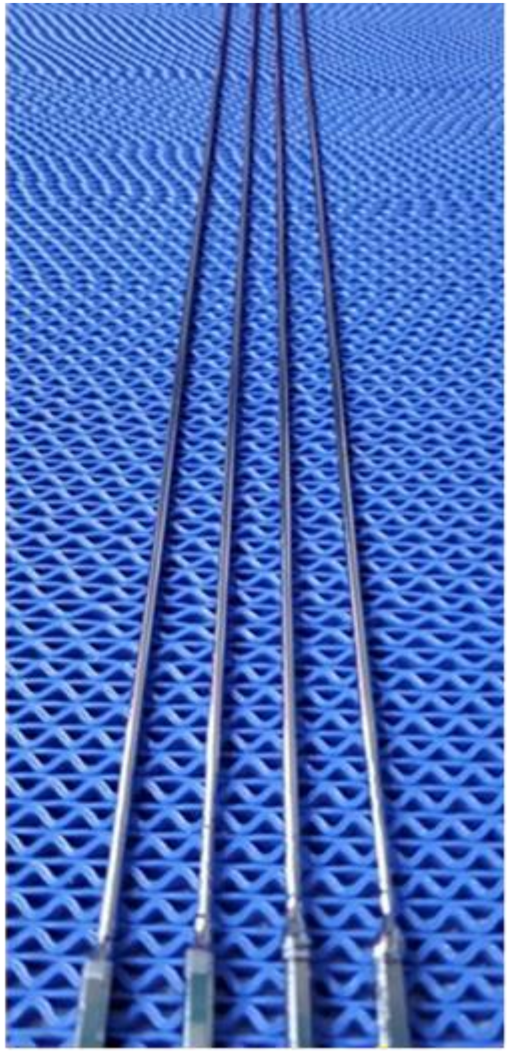
Ø 3 mm



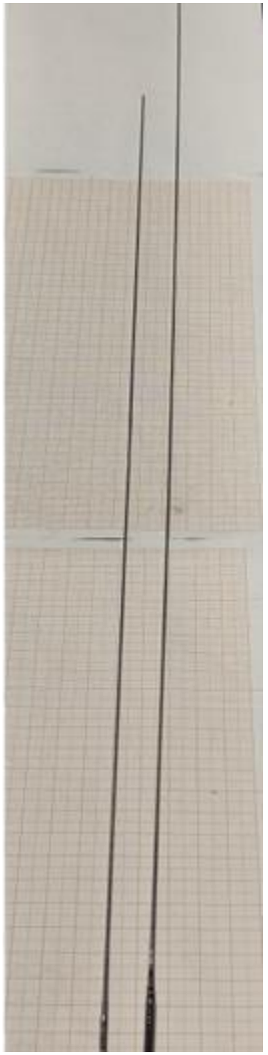
Ø 1 mm



Ø 3 mm



Ø 1 mm



❖ Max-Born-Str. 2 ❖ 12489 Berlin ❖ Germany ❖ info@ikz-berlin.de ❖ www.ikz-berlin.de ❖

# Cautions for a correct evaluation of breaking strength measurements

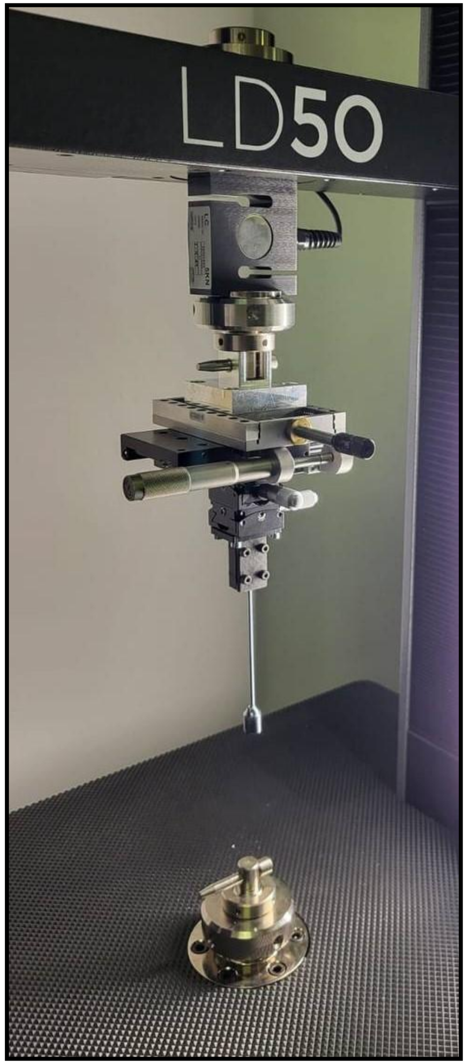
M. A. Dicorato, A. Nela, A. Spencer, F. Travasso

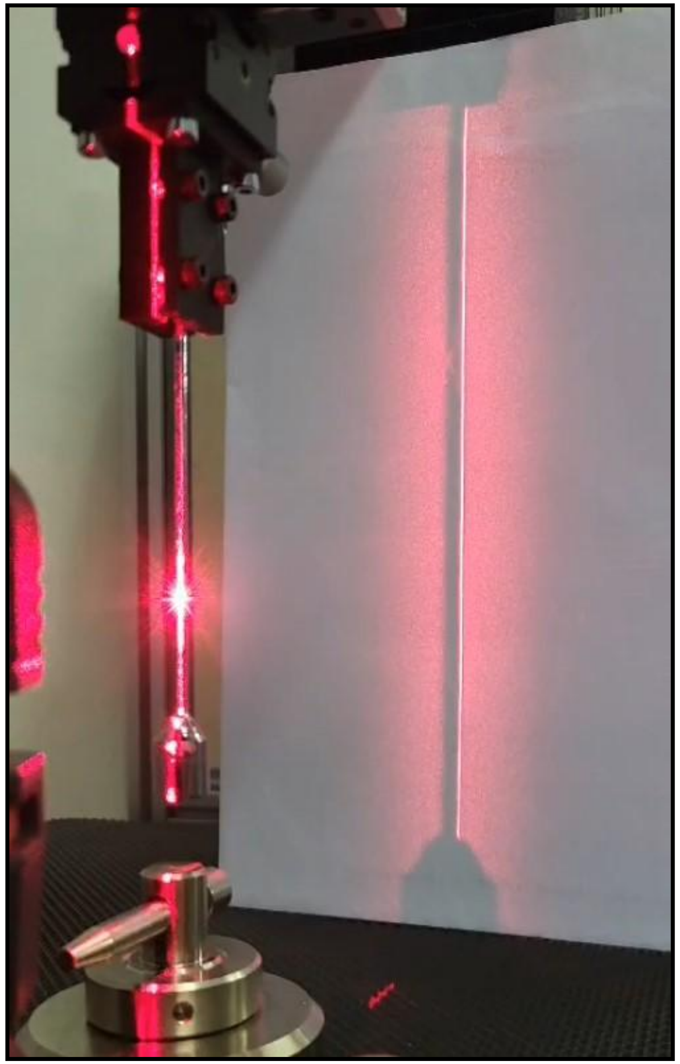
# Clamping method

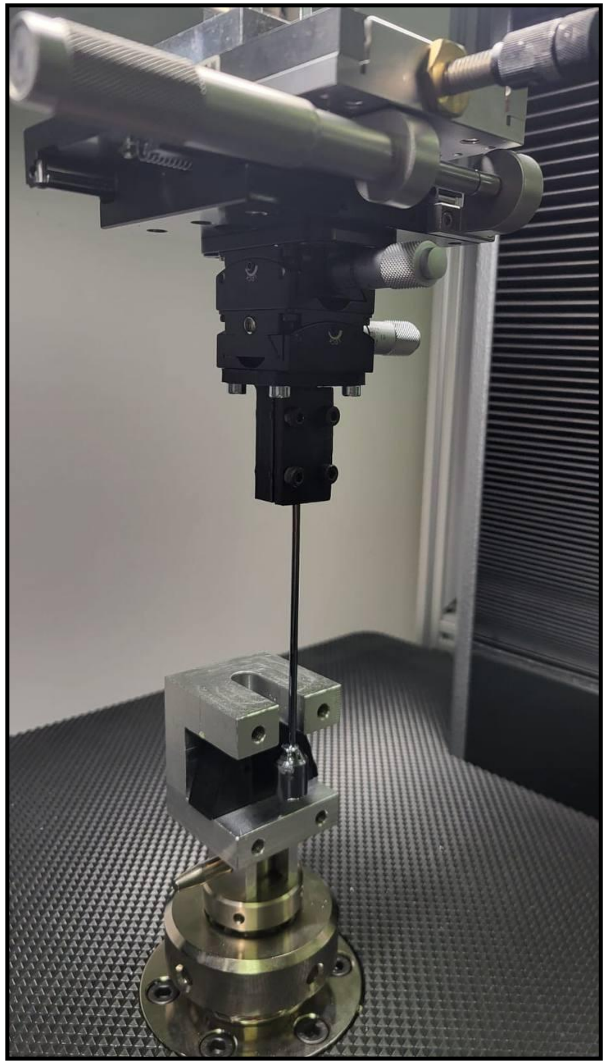
1. Temporary fixation of the seed to the micrometric alignment system

2. **Vertical fiber alignment**, checking fiber position with laser level

3. Positioning the lower clamp so that it embraces the fiber head, without touching the fiber body, and **injecting the epoxy resin** into the 3D-head housing

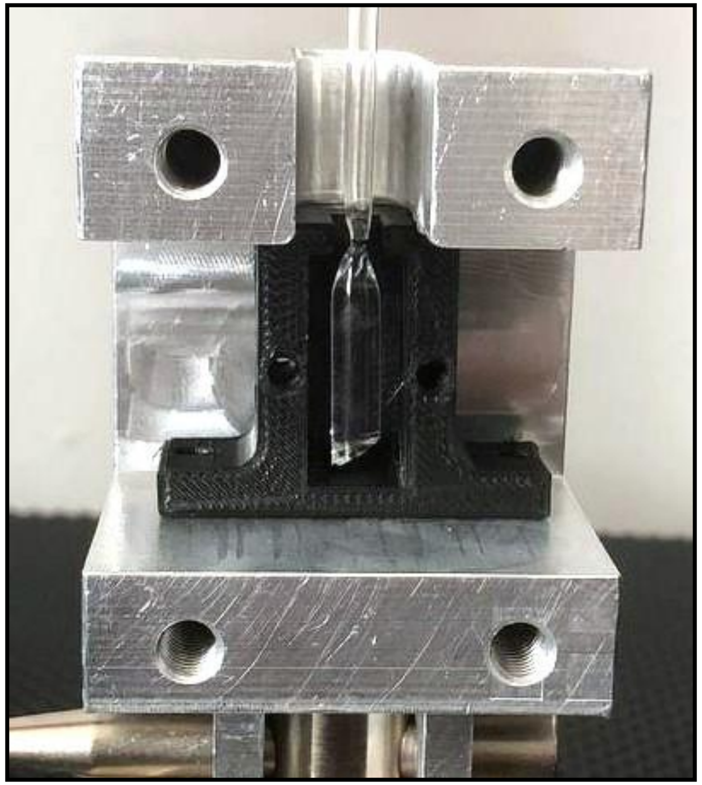


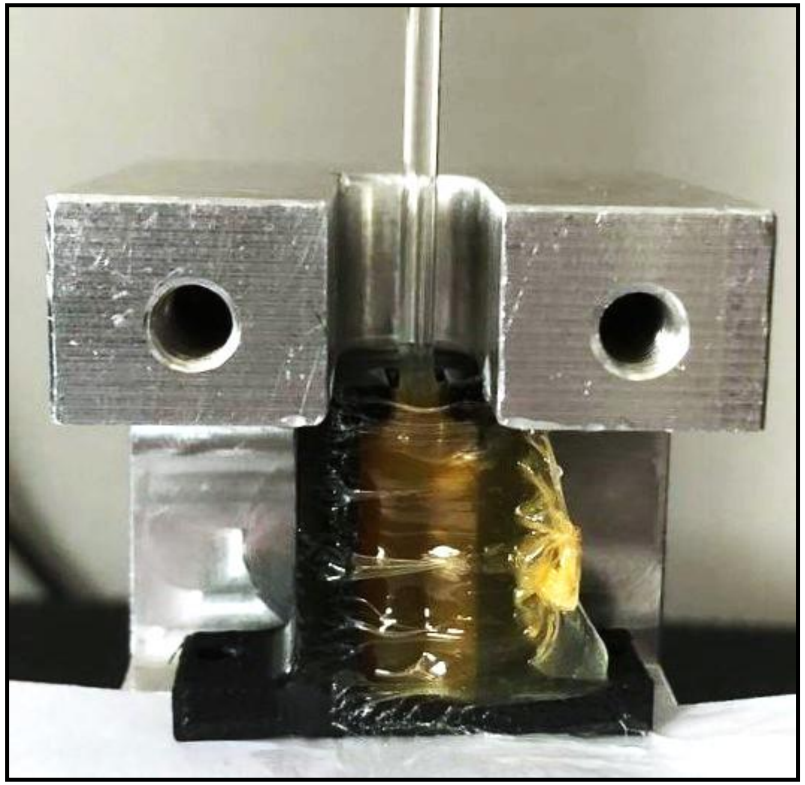


# Clamping method

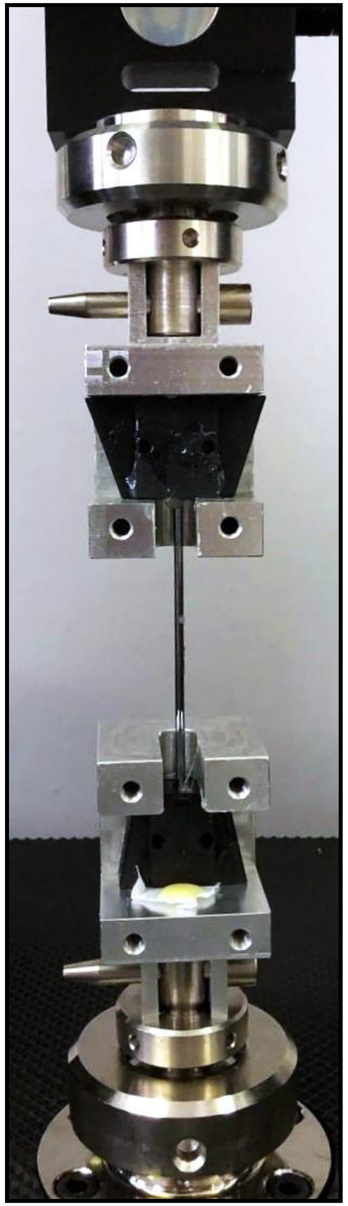
3. Positioning the lower clamp



4. Waiting for the resin to cure



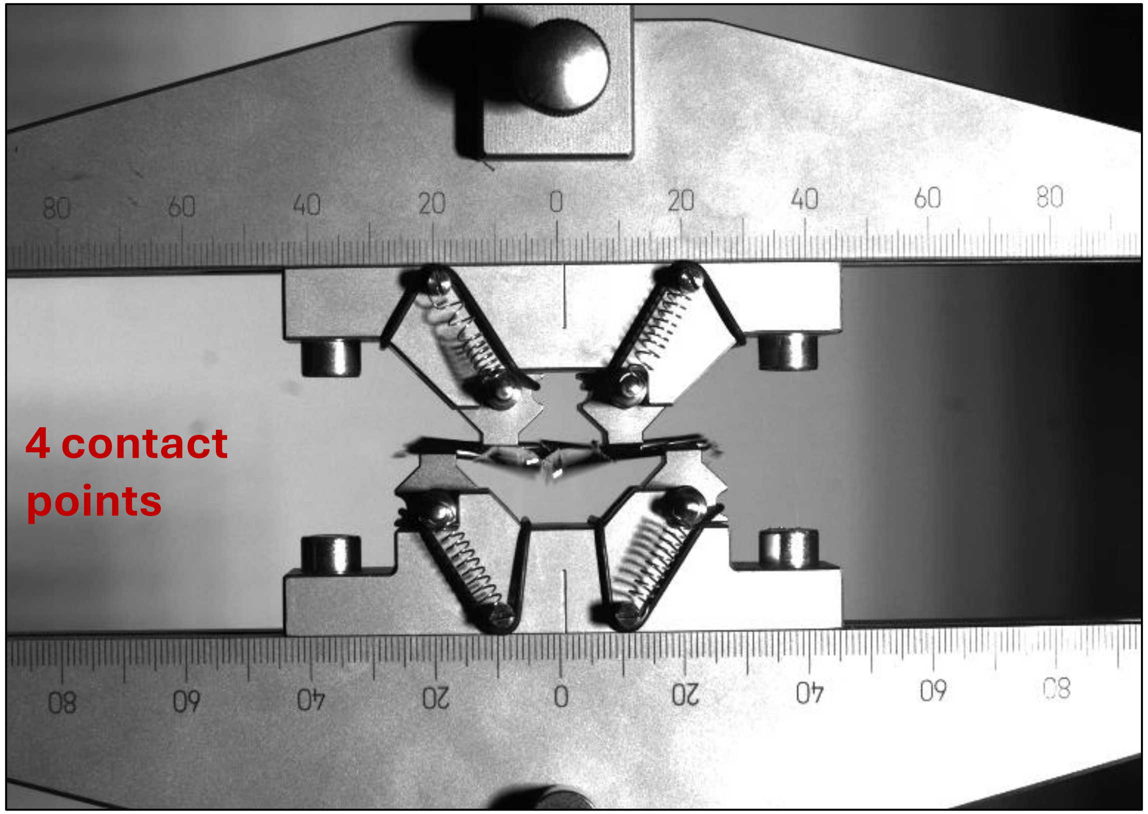
5. Repeating the procedure to glue the seed

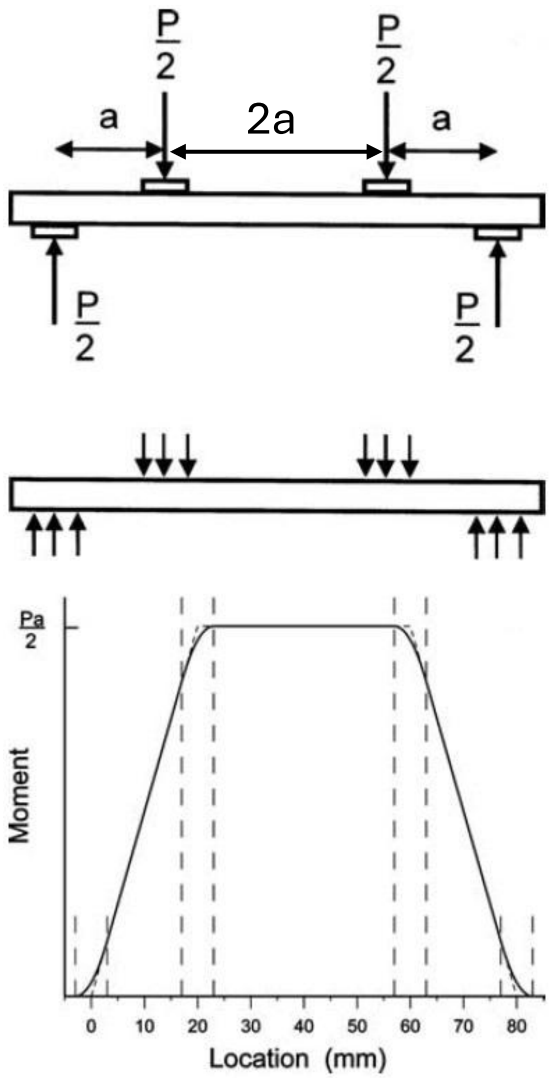


# 4-point bending method

Maximum stress on a line at the bottom of the rod within the two inner loading points

$$\sigma_{max} = \frac{16Pa}{\pi D^3} \qquad a = 10 \text{ mm} \quad D = 3 \text{ mm}$$

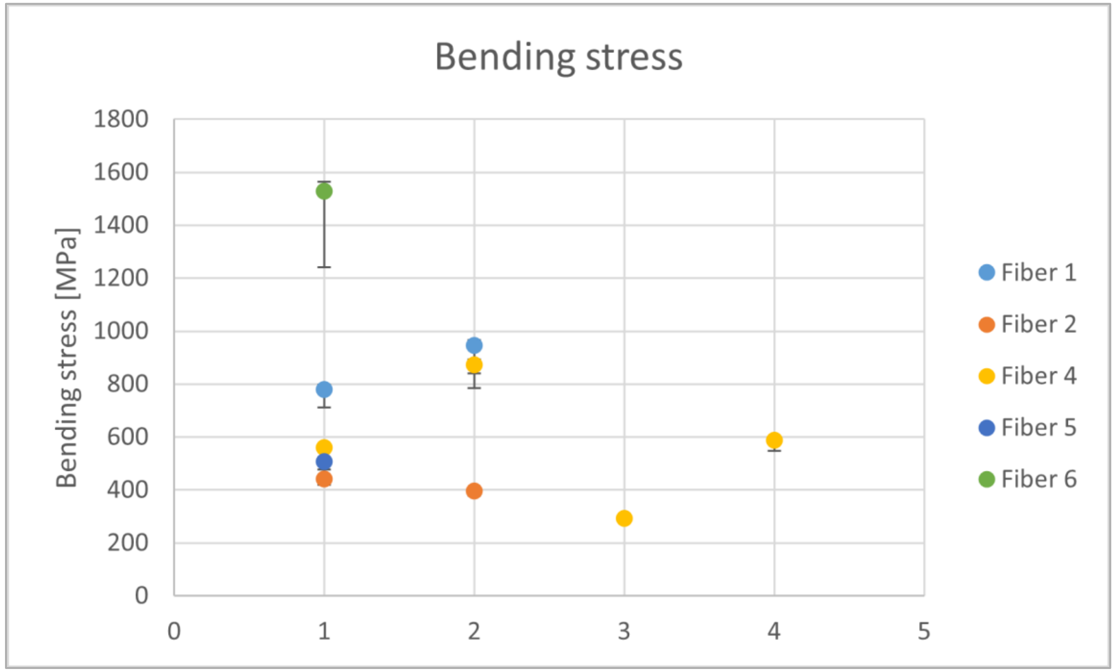


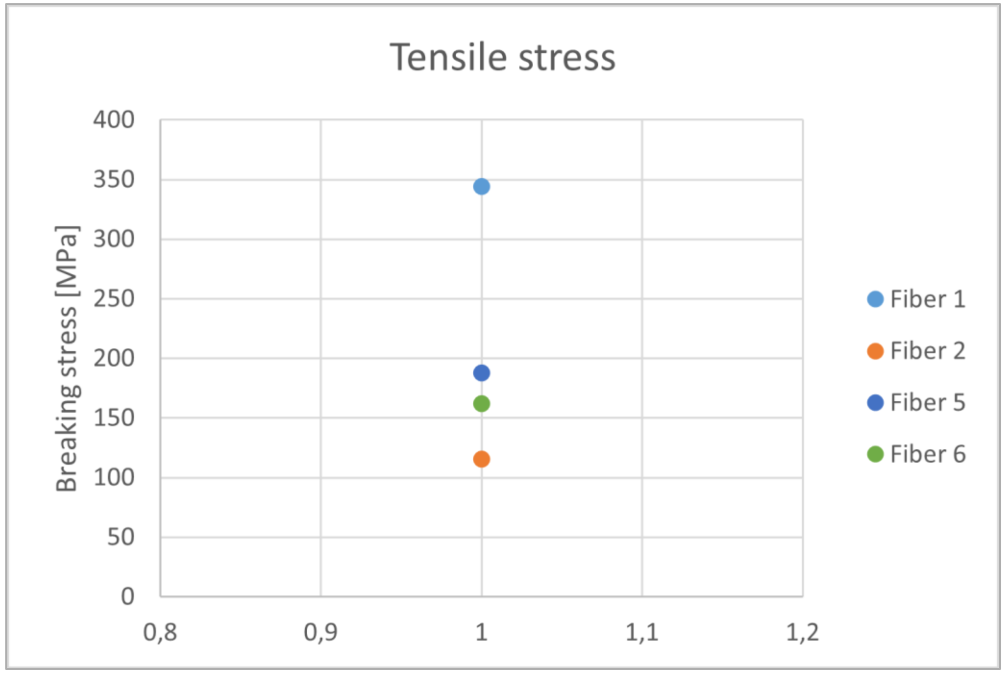




Quinn et al., Journal of Testing and Evaluation, 2009

**Bending system designed and optimized for cylindrical rods 3 mm thick and 5 cm long, according to the American Society for Testing and Materials standard ASTM C1684-18 2023**

# Bending vs tensile results




**Considerations**

- Stresses in bending are higher than those in tensile
- High variability in general
- Fiber 4: very different values (maybe heterogeneity in the defects)
- Dominant error at high strength: Contact point tangency shift
- The bending and tensile data are consistent for fibers 2,5, and 1

**Future work**

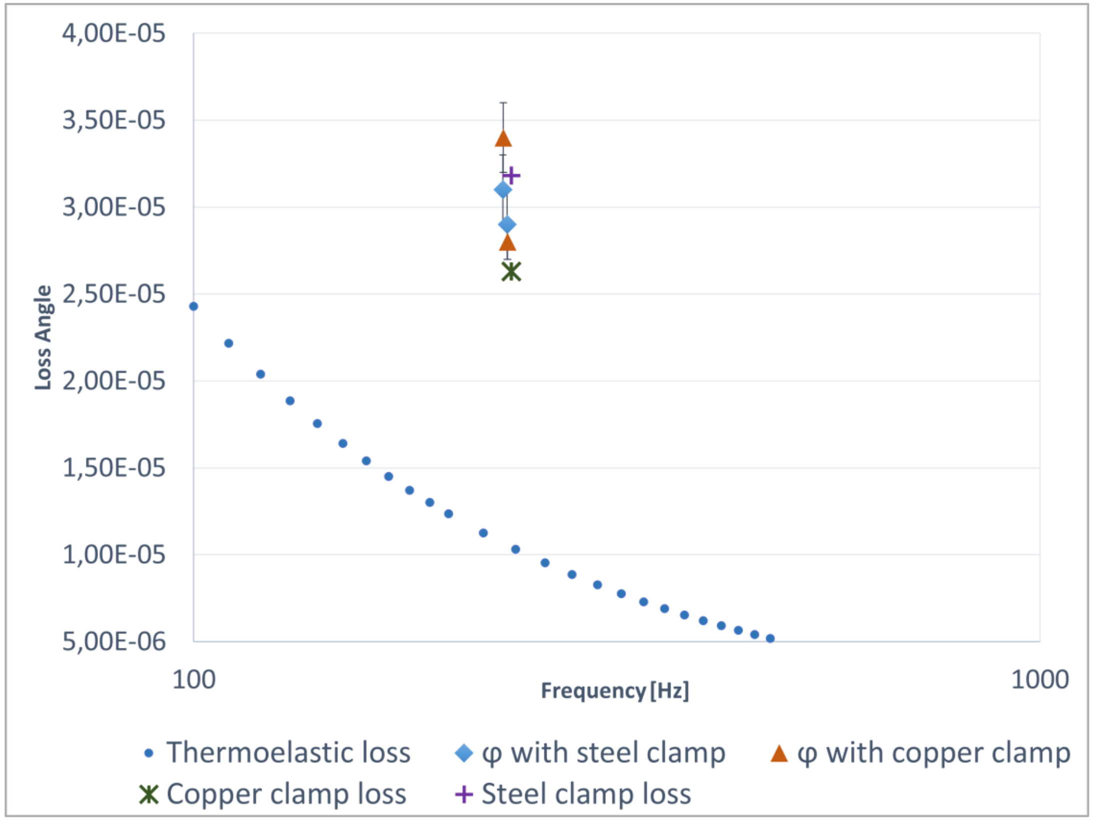
- Reduce the cradle size and the roller size to reduce the dominant error
- Increase the number of tested samples to improve the statistics

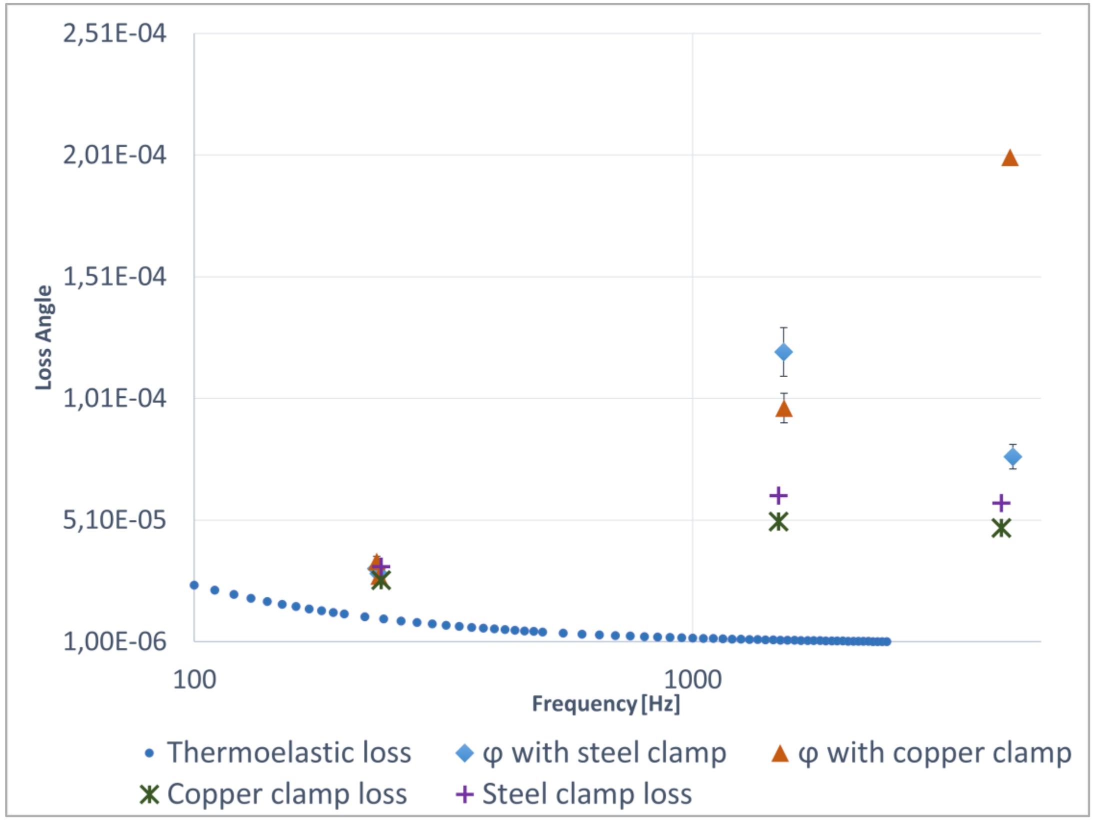
# Clamps

**Steel clamp**
Thickness: 4,5 cm
E = 200 GPa
$\rho = 7850$ kg/m$^3$
$\nu = 0{,}3$

**Copper clamp**
Thickness: 5,3 cm
E = 128 GPa
$\rho = 8960$ kg/m$^3$
$\nu = 0{,}34$

# Results




**Considerations**

- Clamp is probably the dominant source of dissipation
- Measured loss-angle too high with respect the expected value for silicon at room temperature ($10^{-8}$)

**Future work**

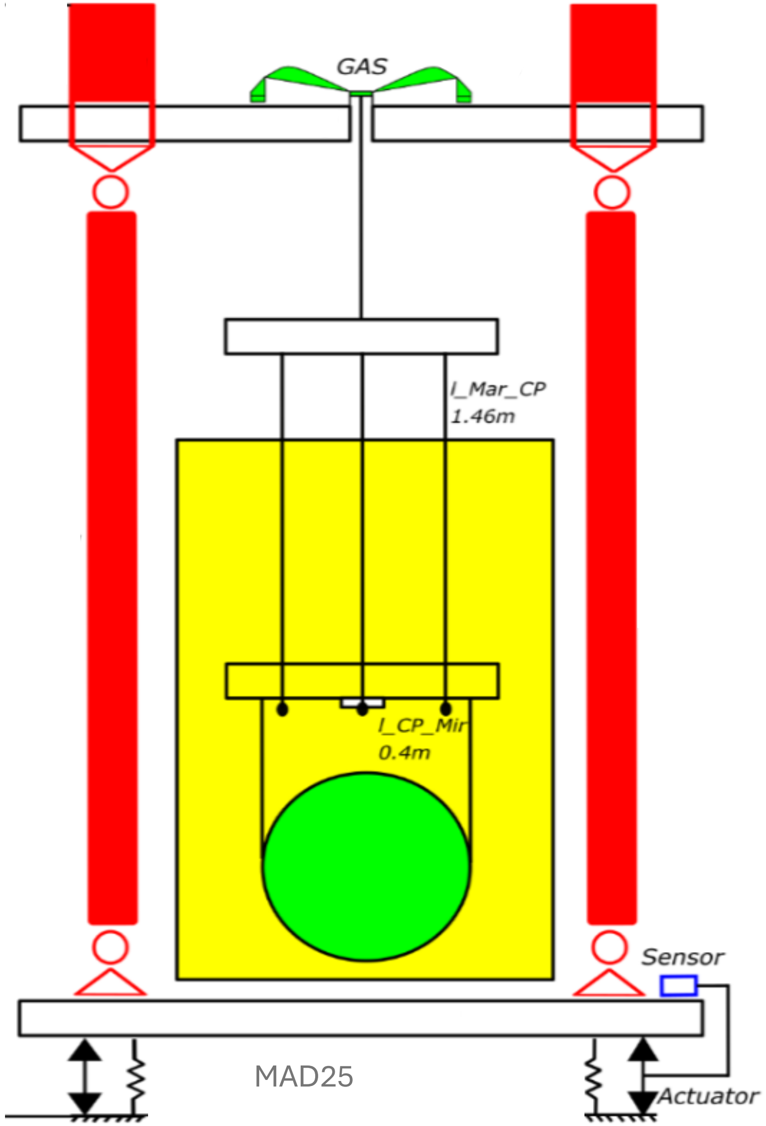
- Increase clamp thickness
- Cryogenic measurements
- Copper clamp with inserts

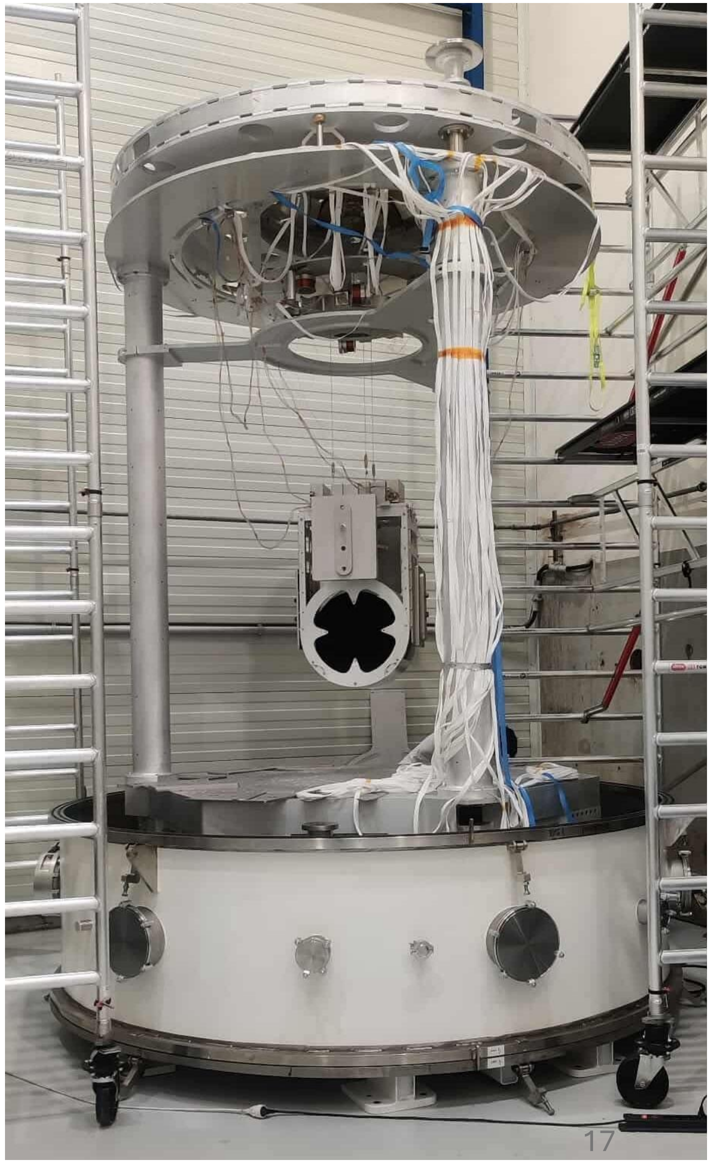
# MAD25 : The ETFIBER Project

Gilles Magain

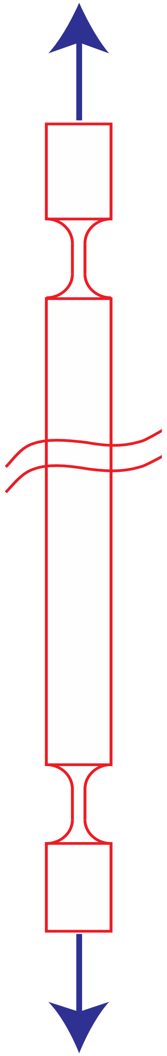
# ETEST Prototype

- Test of advanced seismic isolation
- Low seismic noise below 10 Hz
- The goal is to isolate the test mass
- The isolated mass will ultimately be a 100 kg silicon mirror design to operate at cryogenic temperatures (20K)



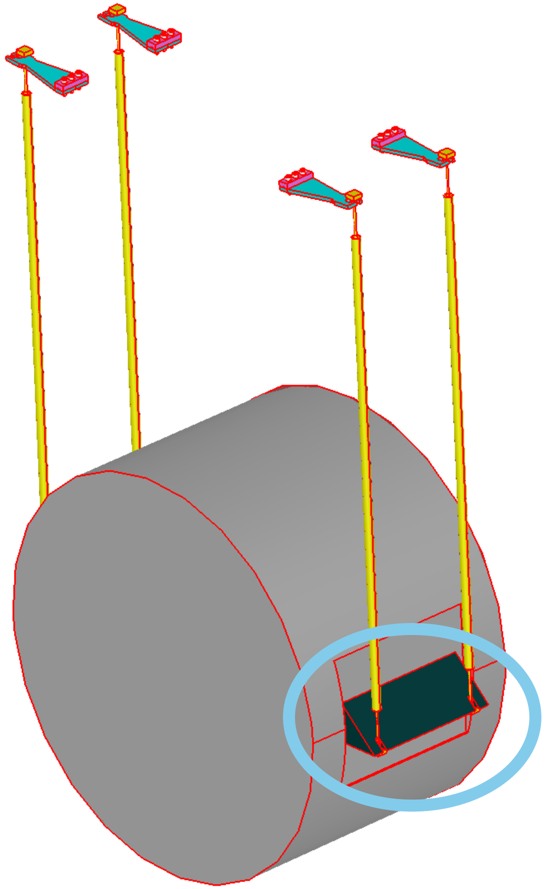



# Tension design

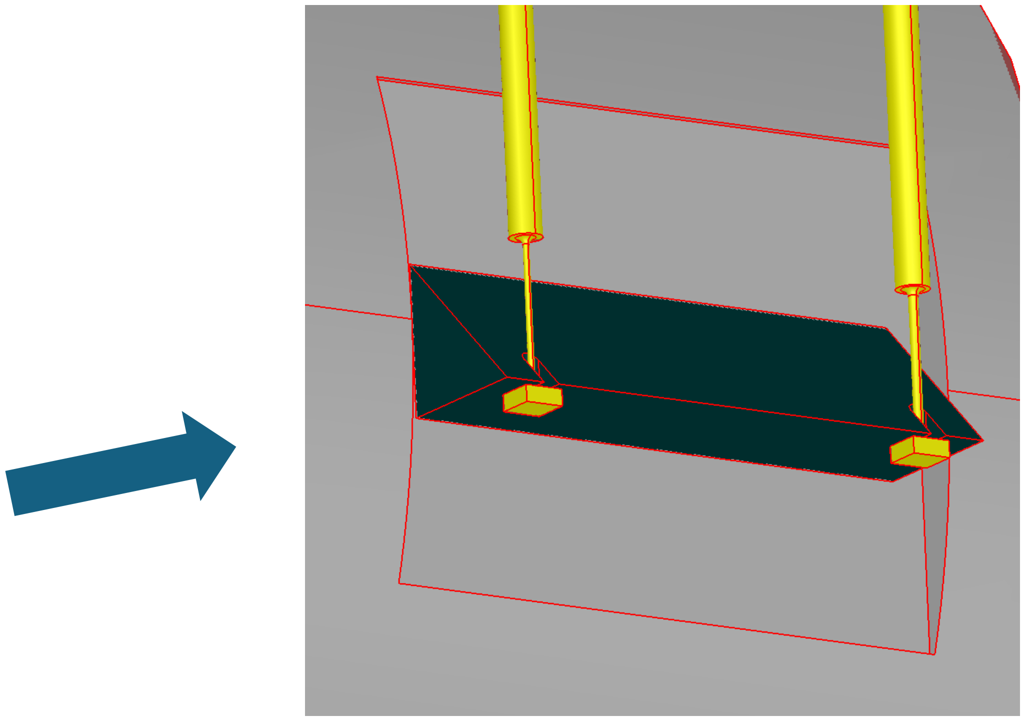


Thinning to gain flexibility :

- Smaller diameter close to the yield point
- Effective stiffness not as low as wanted.

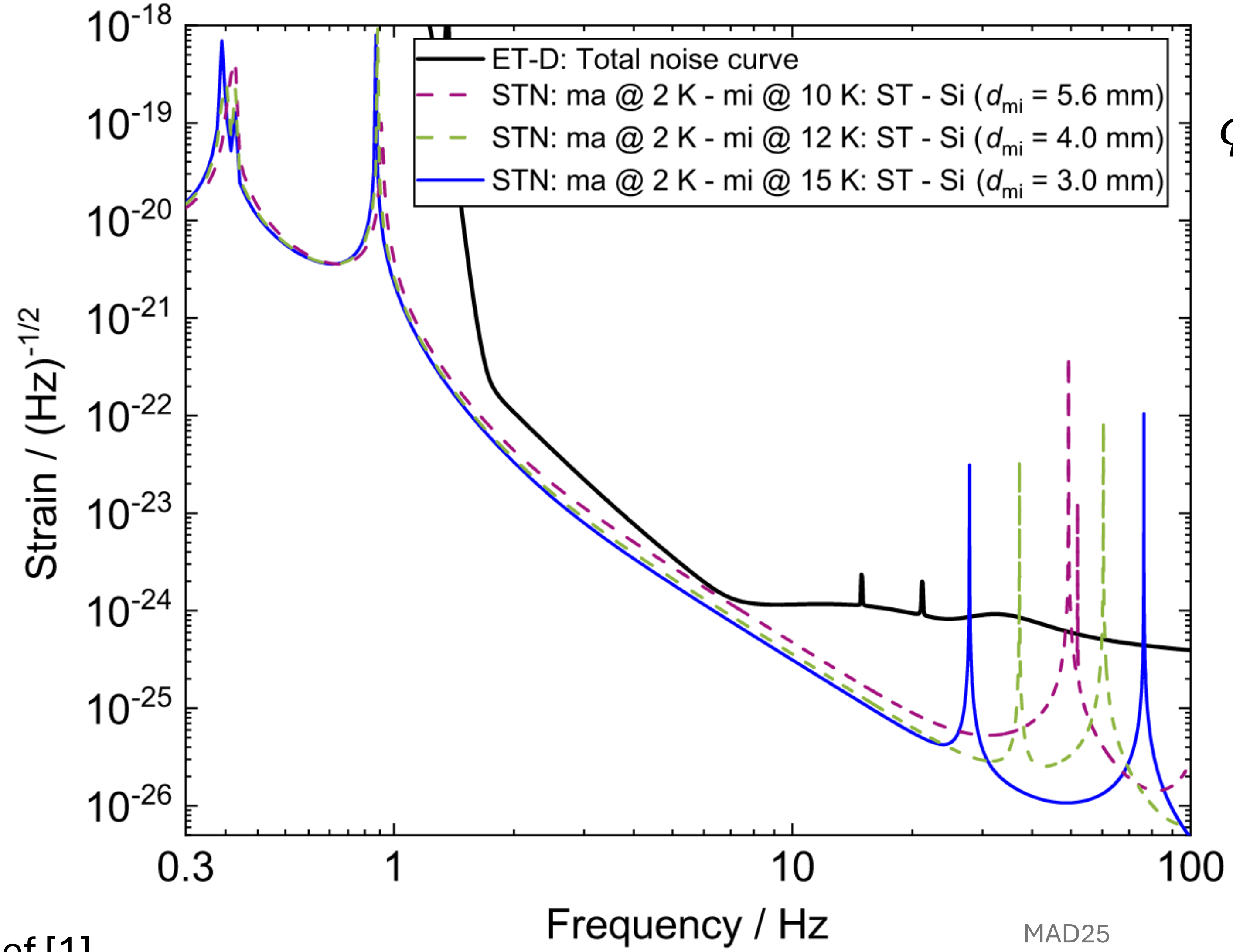


Hydroxide catalysis bonding (HCB)



Ref [2]

# Thermal noise VS Sensitivity




Ref [1]

$$\phi_p(\omega) = \phi_w(\omega)\frac{n\sqrt{TEI}}{2mgl}$$

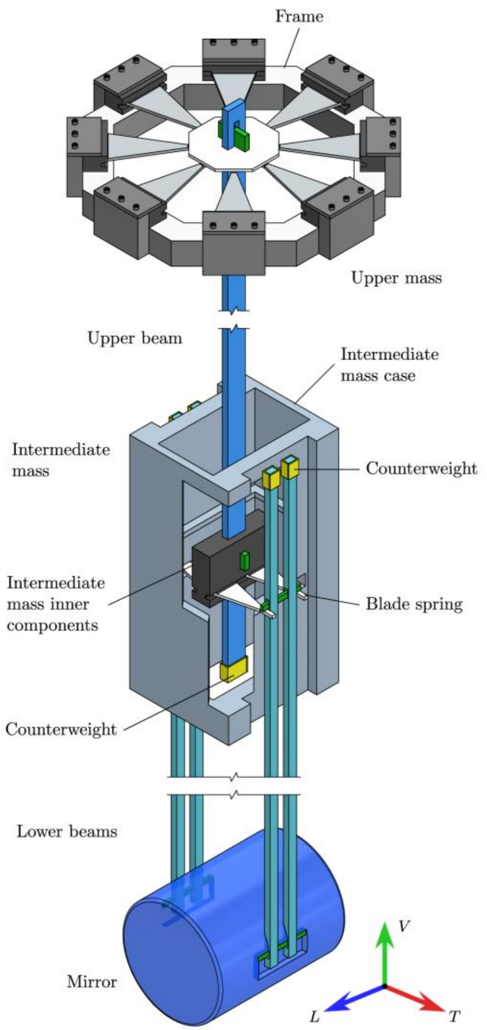
Ref [4]

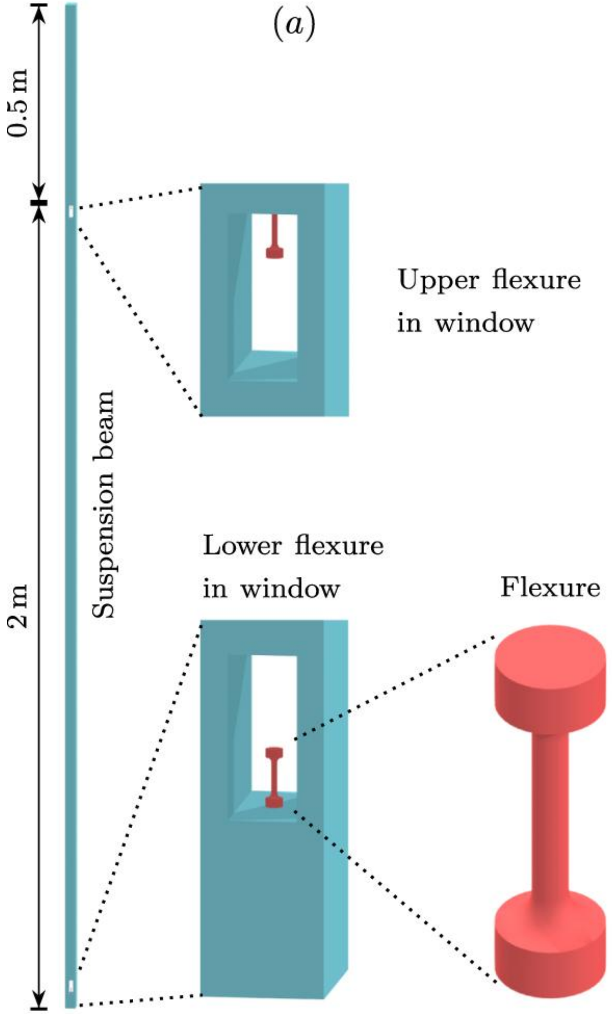
$$I = \pi\frac{d^4}{64}$$

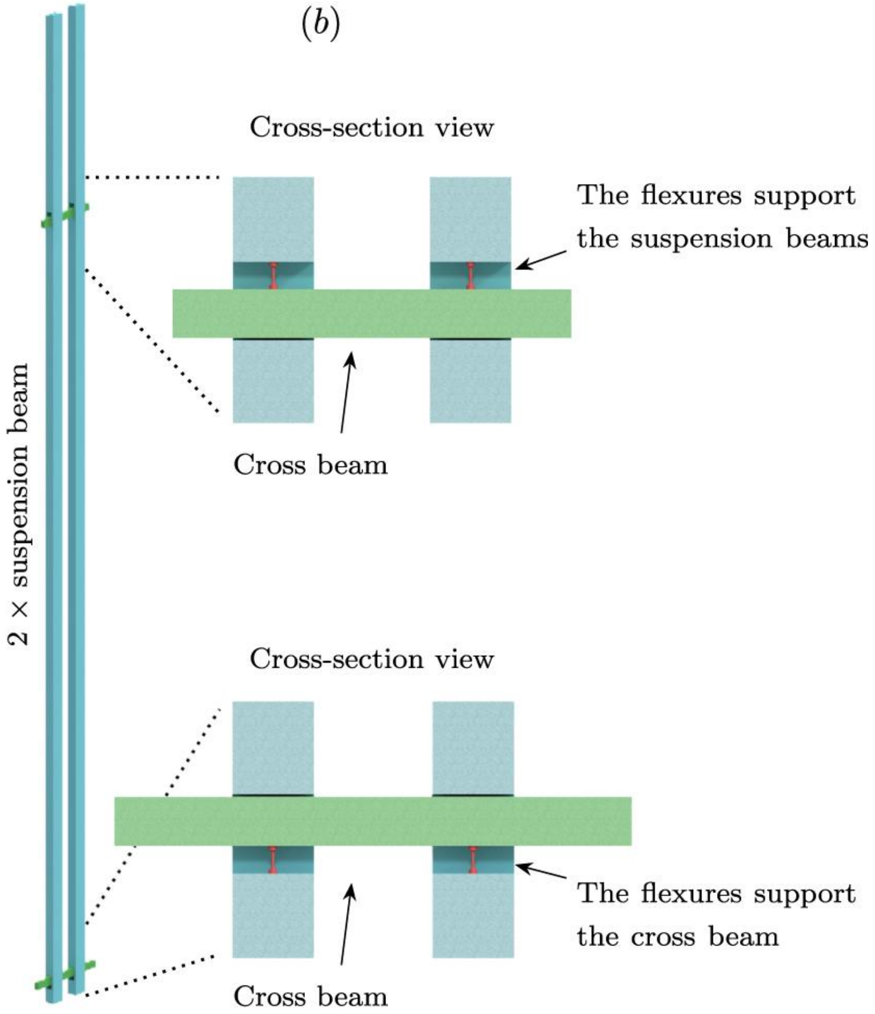
The loss angle is proportional to $d^2$

The thermal noise is just below the sensitivity.

# The compressive design




Ref [3]

# Use of Si Isotope

Flexures have short length, but they set the limit of suspension thermal conductivity due to their small diameter

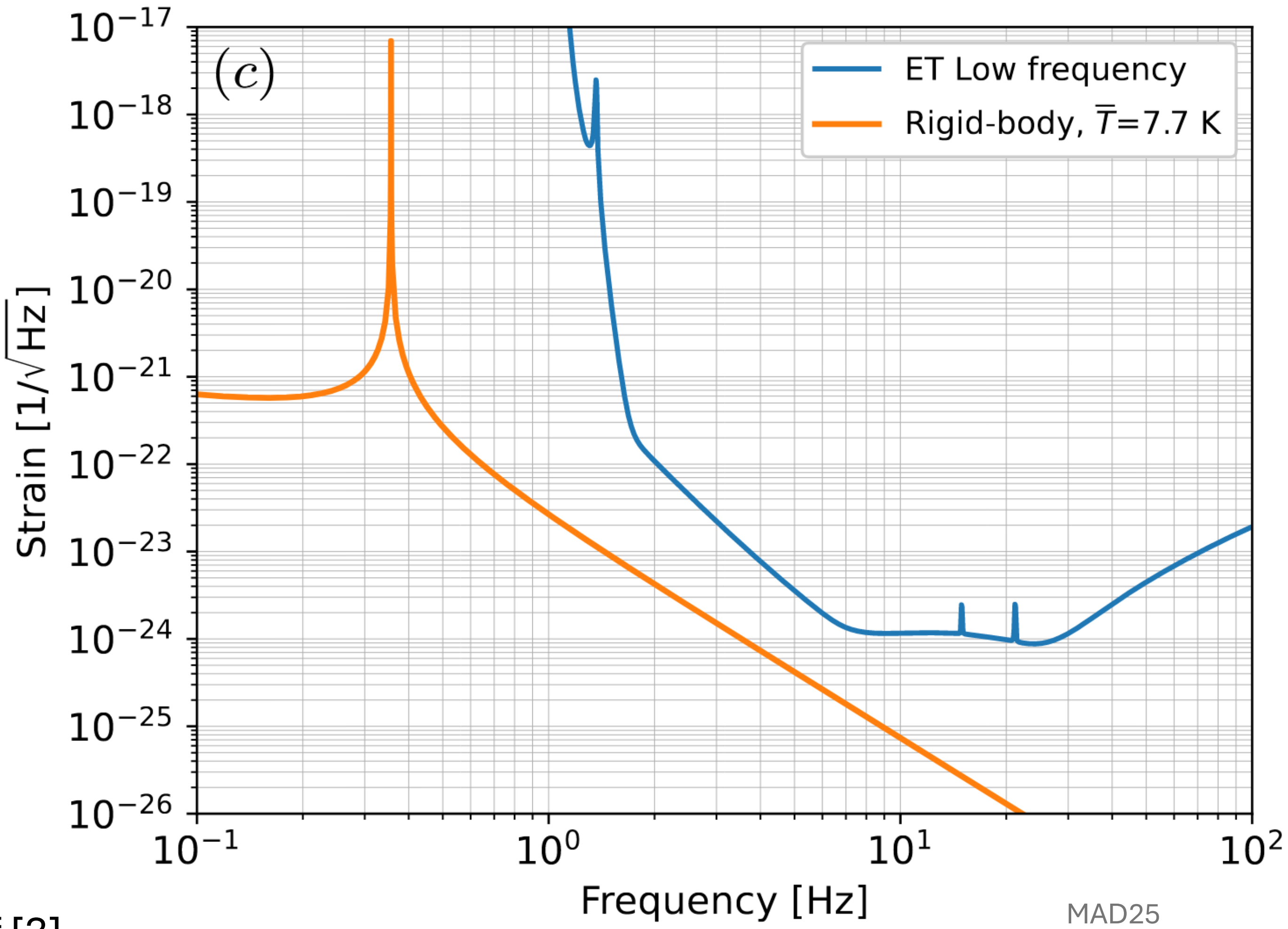
Use of isotopically pure Silicon $^{28}Si$ → better in conductivity due to absence of $^{29}Si$ and $^{30}Si$ which scatter the heat carrying phonons and then reduce mean free path.

This isotope has a better conductivity below 100K with peaks of 10 orders of difference at 20K.

Ref [3]

# Performance and Comparison

## The Compressive solution



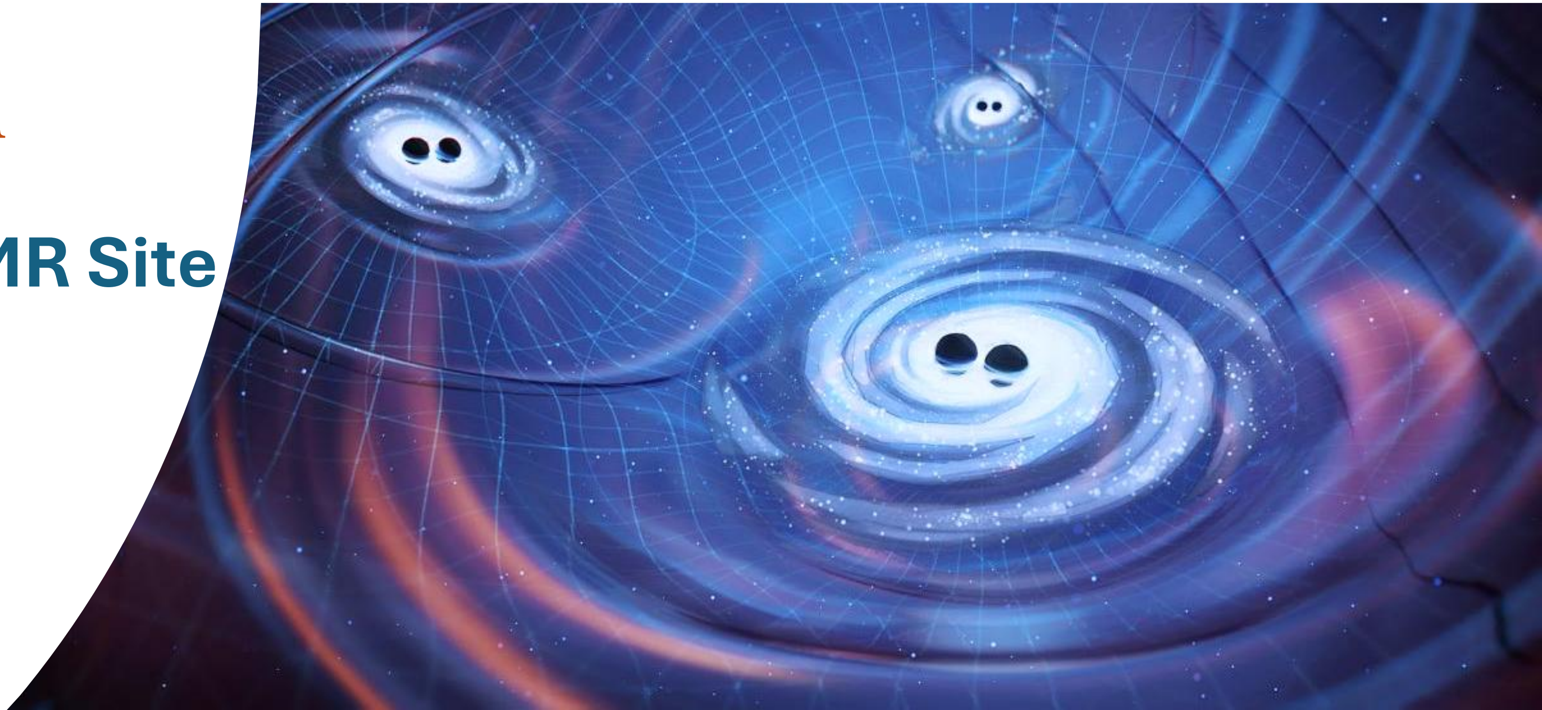

| Pro | Cons |
|---|---|
| Better performances | Centre of percussion effect and beam resonance |
| Easy mounting or disassembling | No recoil mass -> New control solutions must be developed |
| Good heat extraction thanks to large cross sections | We have to use isotope for flexure to obtain those results |

Ref [3]

MAD 2025

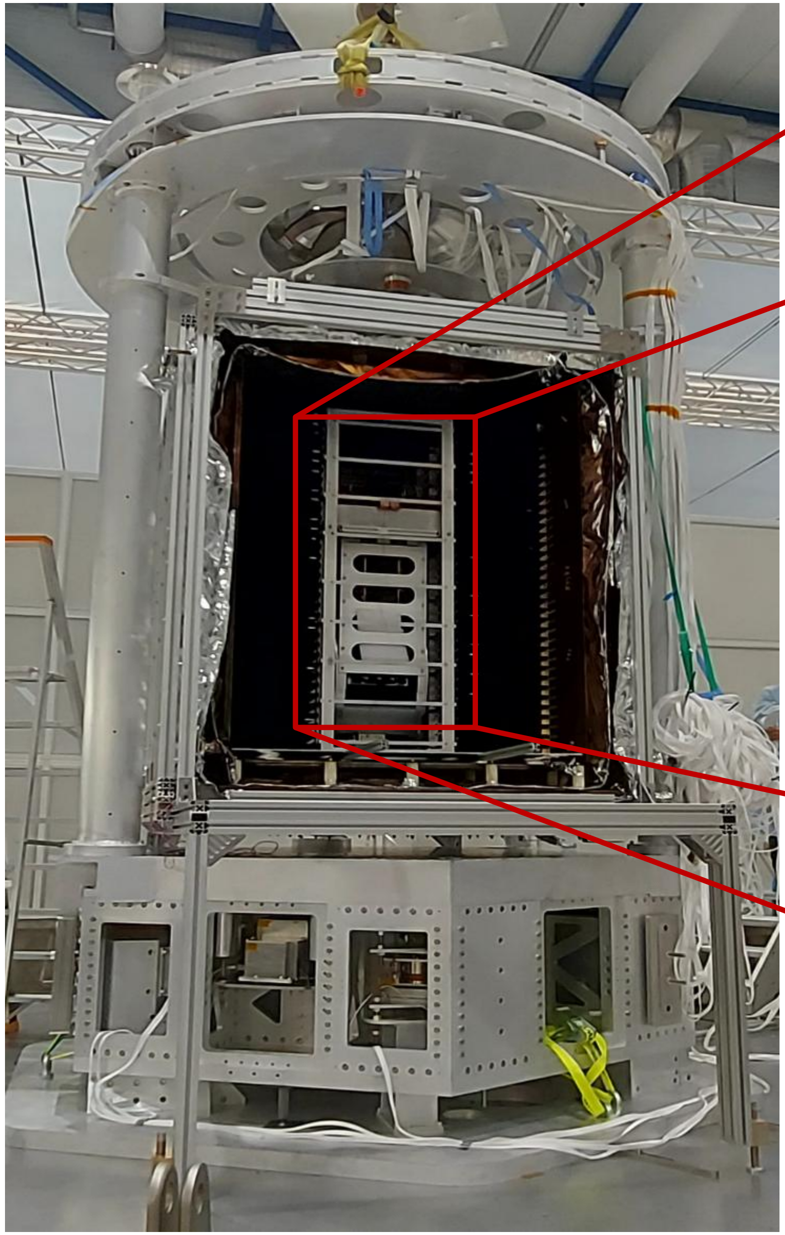
# Precision Measurement of Mechanical Loss & Thermal Noise Characterisation

## E-TEST: Einstein Telescope EMR Site



**Hemendra Singh**
Precision Mechatronics Laboratory - ULiege
https://www.pml.uliege.be

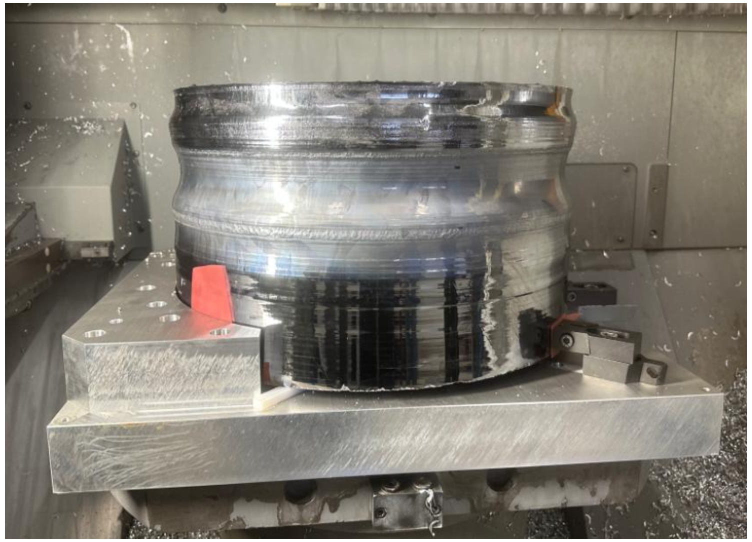
# 2. TEST MASS (First Run:2023)

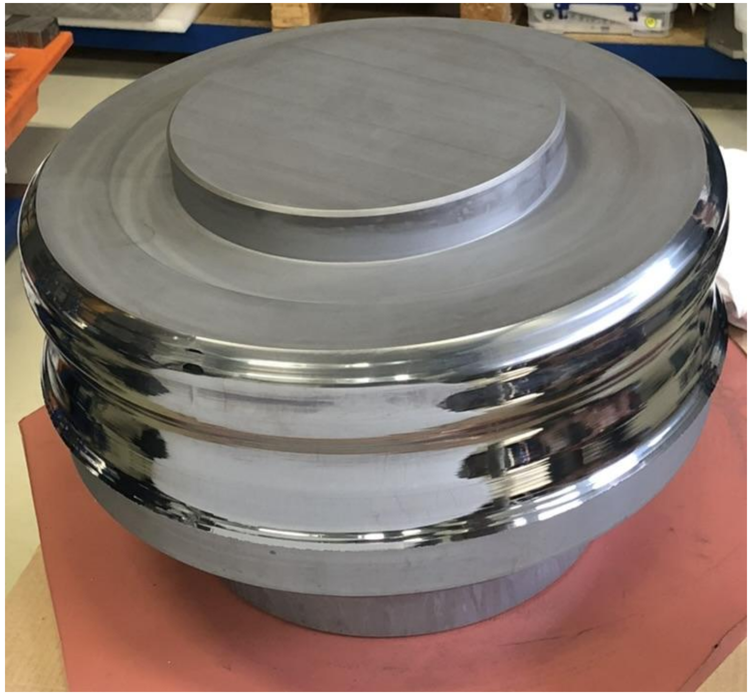


2023: 1st Run: Dummy Test mass

- **CuCrZr Suspensions**
- **Aluminium ears attached to TM**
- **Black painted finish**

# 2. TEST MASS (Second Run:2025)





- Monocrystaline (Silicon)
  Magnetic Czochralski Process
- Diameter: 45 cm
- Mass:  90 kg

**Additionally,**

1. Mid-tier mass, Cylindrical,
   Ø4.27 cm, 3 cm, ~100 g
2. Intermediate mass, Cylindrical,
   Ø10 cm, 10 cm, ~1.83 kg

**Meeting specific minimum Requirements** such as
Roughness <2 nm RMS, Flatness λ/4,
Parallelism <30 μrad, ROC ∞ (Flat) etc.

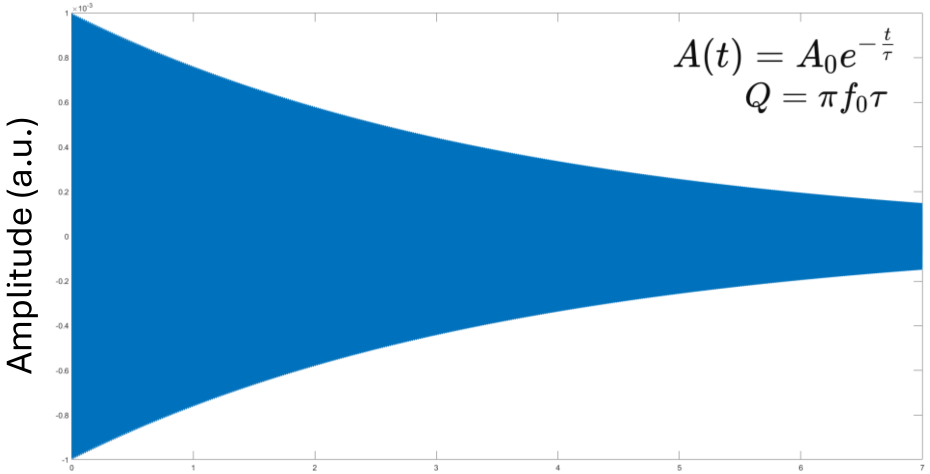
*Ref:SINGLE CRYSTAL Silicon database(ET_docs)*

- Diameter: 45 cm
- Thickness ~ 17 cm

# 3. Mechanical Loss Measurement

**Traditional Q- Measurement Method**

**Monocrystalline Si @ cryo** → ultra-high **Q**, long ring-down!




**E-TEST**

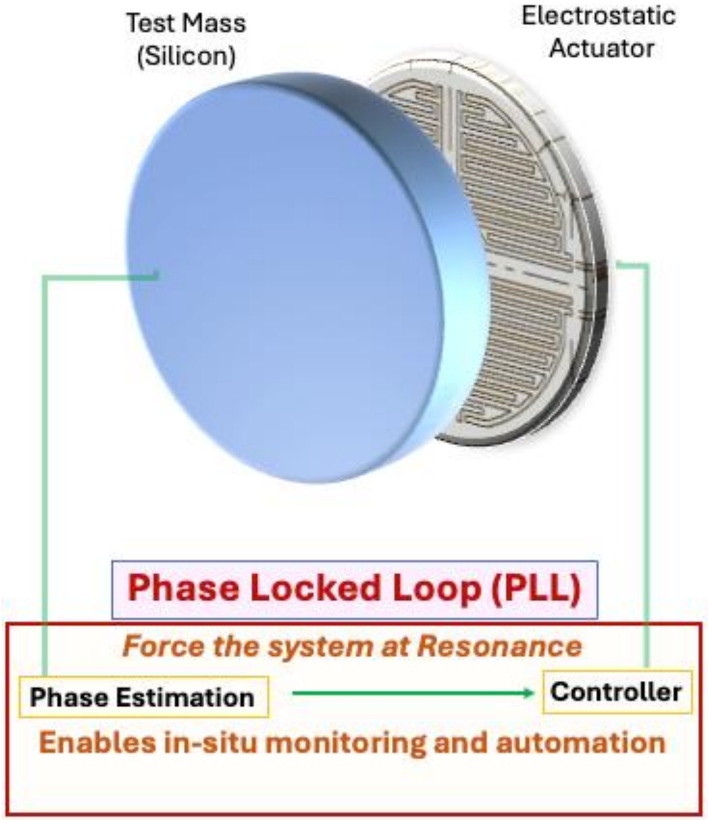
Decay Period

**High Q-Factor Silicon Resonator Setup**

- Non- Contact Cool Down and **Actuation (@resonant frequency)** of the Test Mass (Si)
- **Minimal damping, Lower Thermal Noise!!**

***Why PLL?***

- **Ring-down too slow** for **Silicon**
- Faster, **Real-time tracking of Resonance, Continuous measurement**, no waiting for decay.




## Challenges: Non-Contact Method

- Development of **ESD** approach and analysis of **Eddy current** generation, unpredictable **electric fringe interactions** due to **semiconducting** properties
- Integration with Phase-Locked Loop (**PLL**)
- **Compatibility** with **cryogenic** operation

**Q v/s Temp relationship !!**

*Ref: PLL: Nic Smith et al., ESD: John Miller Thesis, LIGO-T1700446, Challenges :* LIGO-T1400226/010

**@François Winand**
francois.winand@uliege.be

# Temperature Measurement (Non- contact Method)

**ΔT** → **Thermo-optic Coefficient**

Thermo-Elastic **α (dL/dT)**

Thermo-Refractive **β (dn/dT)**

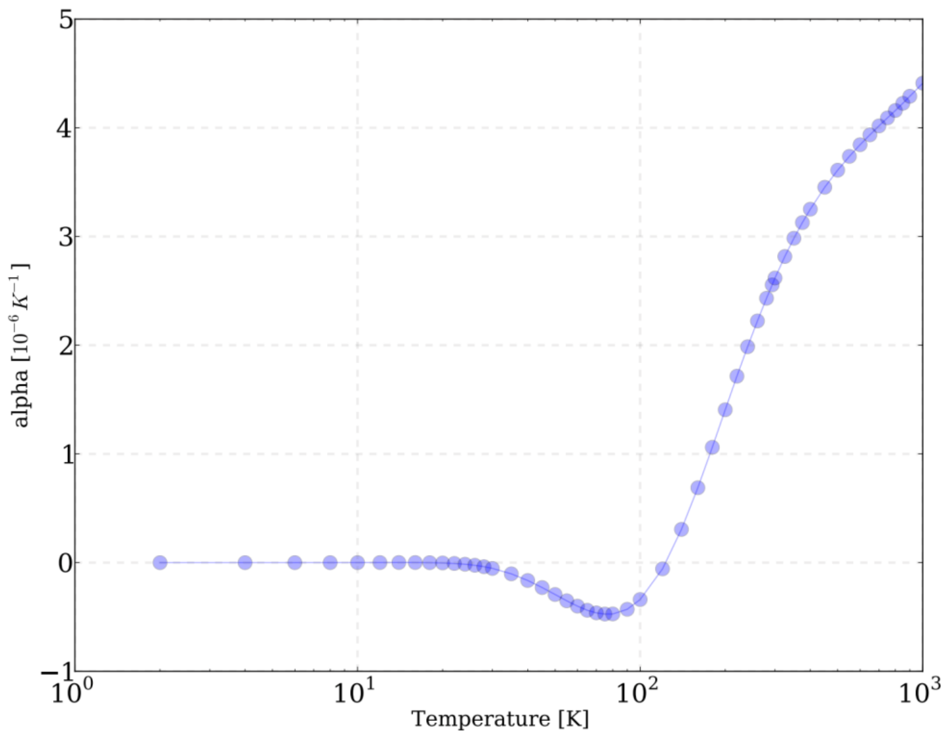



Fig: CTE of Si as function of T

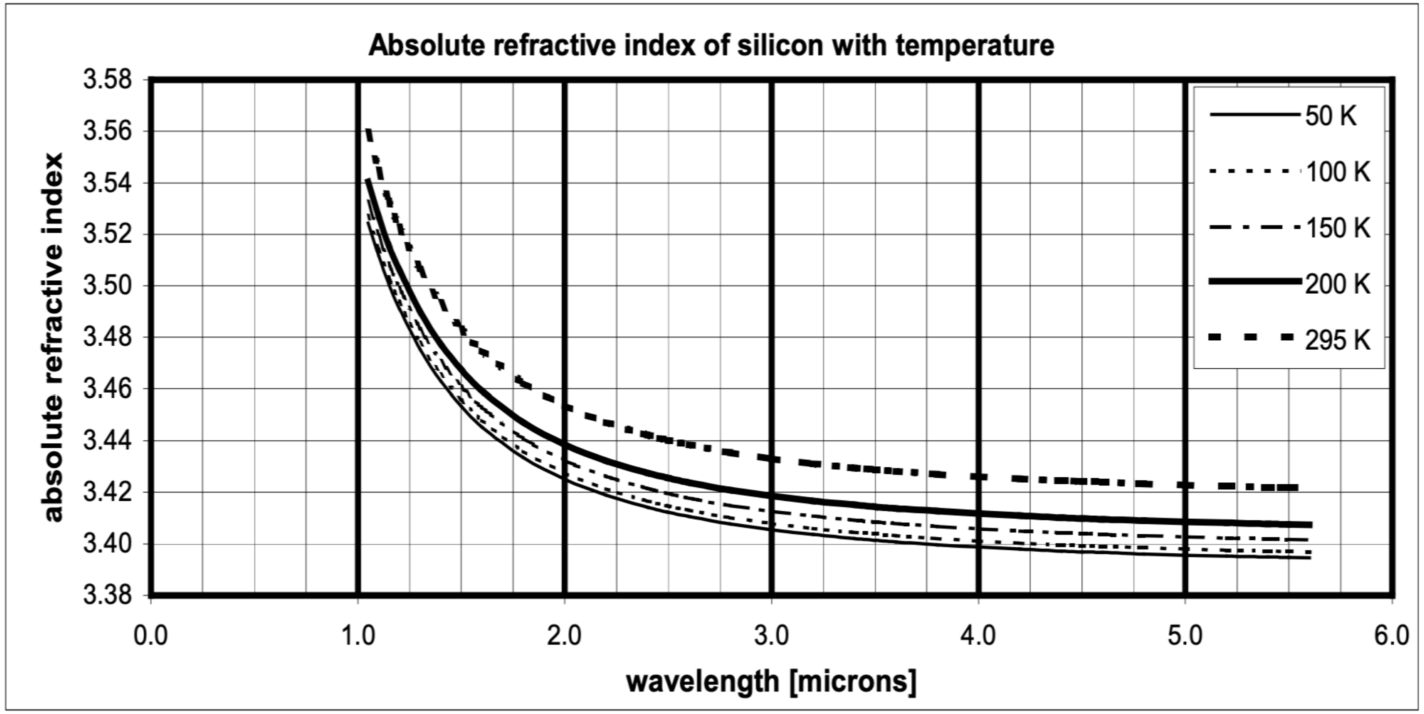



Fig: Measured absolute refractive Index of Silicon
as a function of wavelength for selected Temperature



Ref: J. Komma et al. , CTE Silicon: Yu. M. kozlovskii et al. LIGO-T1400226, NIST Swenson etc.

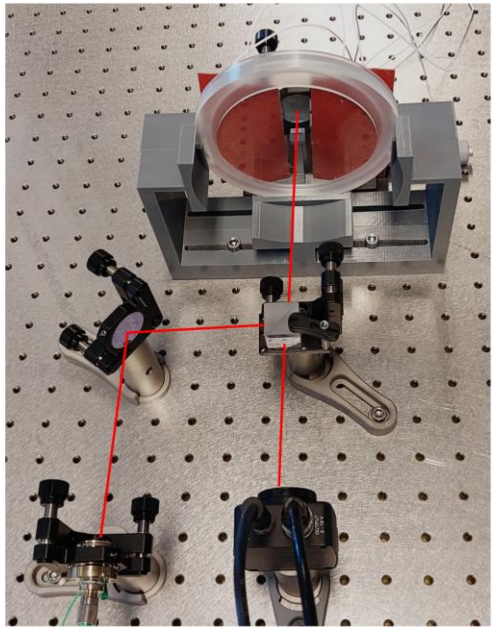
# Experimental Framework: Temperature Measurement

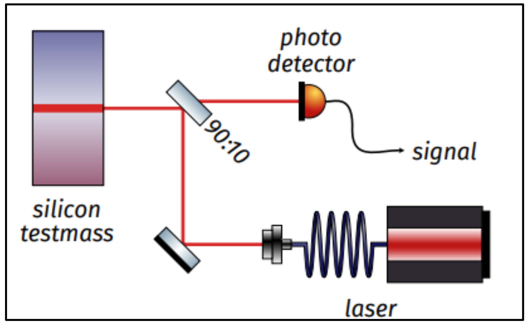
**Step 01**

**Step 02**

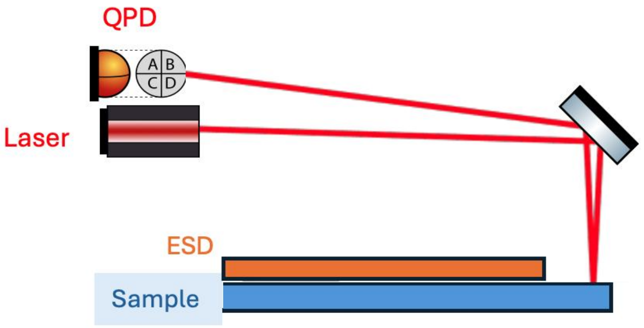
**Step 03**

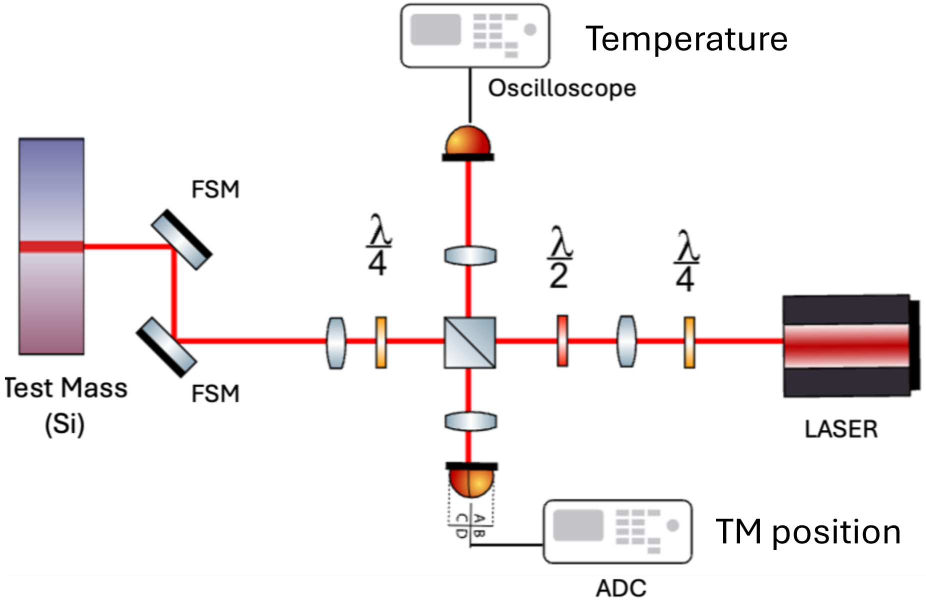
@Janis Wöhler






**OPL → ΔT → ΔL & Δn → Fringe shift**



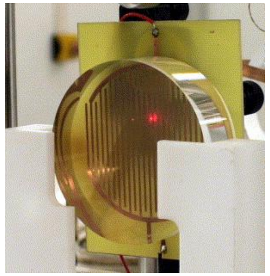

**Considerations:**

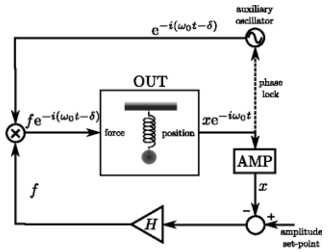
- Effects of ground motion
- LASER (Wavelengths: 1550 nm vs. 2000 nm)
- Scalability

Small (1 gm) → **100X** → Mid-tier (100 gm) → **18.3X** → Intermediate (1.83 kg) → Large **(E-TEST)**

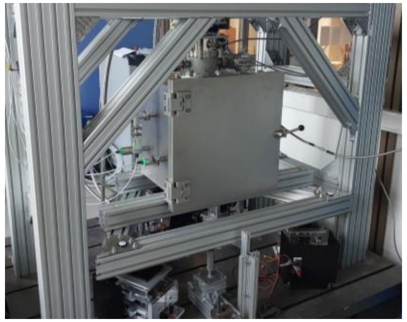
# Summary

## Quality Factor (Q) Measurement

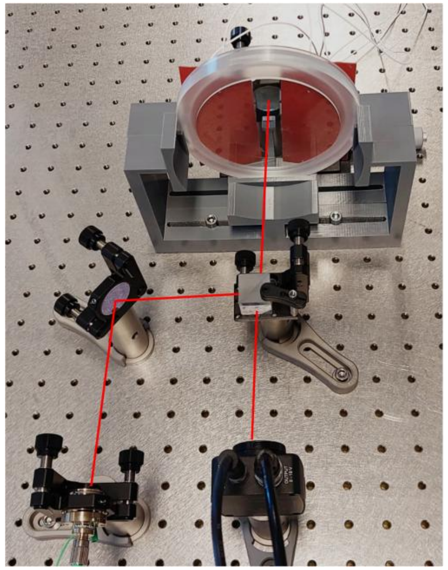





- ☑ Study AC, DC, and AC+DC Current effects
- Ongoing ❑ ESD designs: Duty Cycle impact on Fringe Generation
- Ongoing ❑ Fused silica & Silicon samples
- ❑ Apply Phase-Locked Loop
- ❑ Cryogenic testing



## Temperature Measurement



Ongoing

- ❑ Fringes → α & β (predict thermo-optic coefficients due to ΔOPL)
- ❑ Laser stabilization, Wavelength absorption & Thermal Gradient (1550 nm vs 2000 nm)
- ❑ Final Optical Setup

## Integration

- ❑ **Real-time Q vs T monitoring** → **E-TEST (2026)**

# Mechanical Dissipation in Maraging Steel at Room Temperature and Low Frequency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F. Peña Arellano(3)(6)(7), M. Razzano(1)(2)

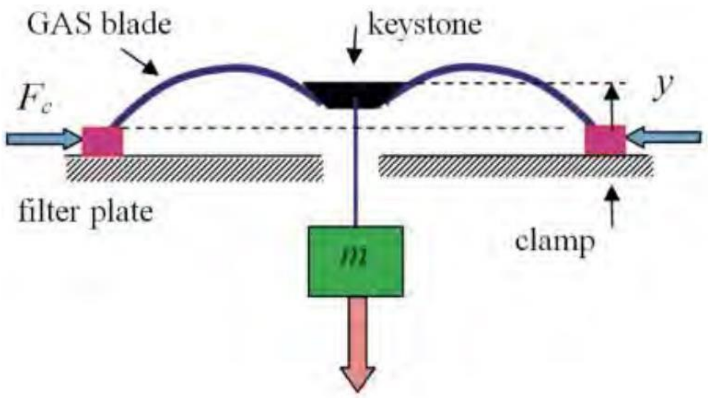
(1) INFN, Sezione di Pisa; (2) University of Pisa; (3) California State University; (4) University of Sannio; (5) INFN, Sezione di Napoli; (6) University of Guadalajara; (7) Institute for Cosmic Ray Research

# ET-LF Vertical Seismic Attenuation

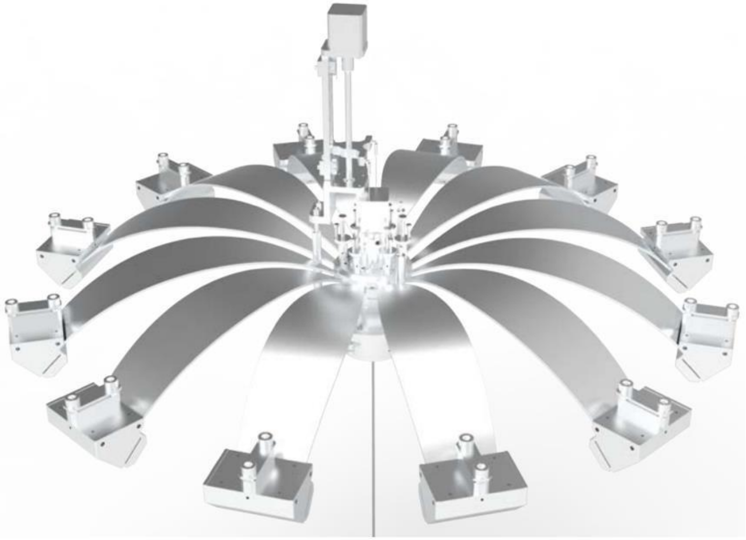
Geometric Anti Spring (GAS) filters to attenuate vertical seismic noise

- Used in Virgo and KAGRA detectors
- Components under high mechanical stress → Maraging steel
- Very effective attenuators, but generate their own thermal noise

Baars M., Nikhef (2023)



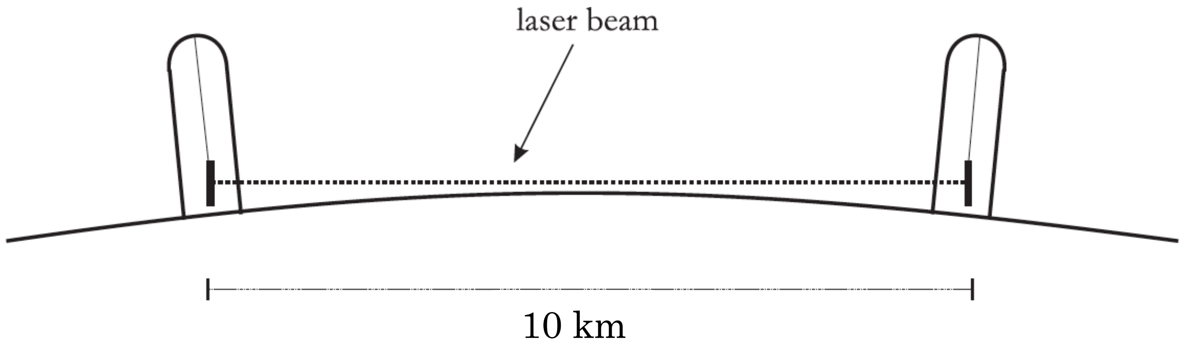

E-TEST Prototype Design Report (2022)



The vertical direction is not perpendicular to the interferometer direction due to Earth curvature

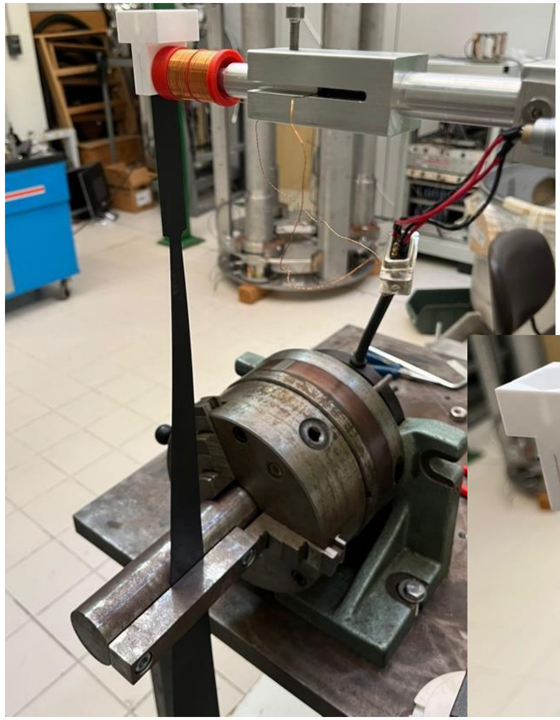
The minimum projection factor for four independent test masses is: $h = 1.57 \times 10^{-3}$

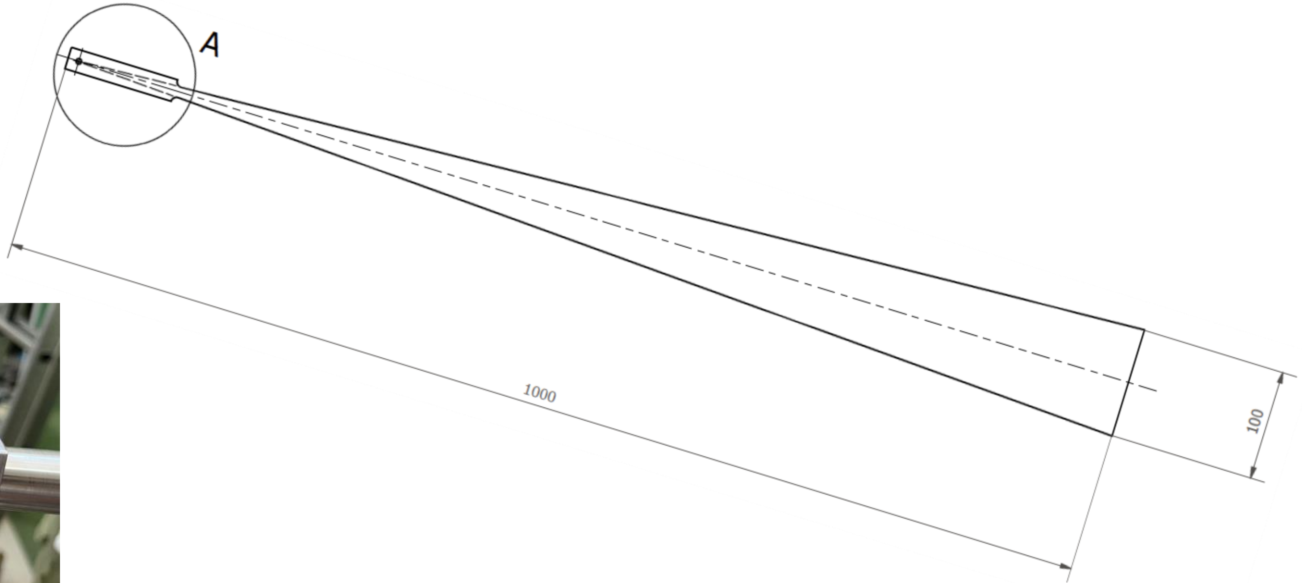
Thus, any noise in the vertical direction has a component that directly affects ET-LF sensitivity



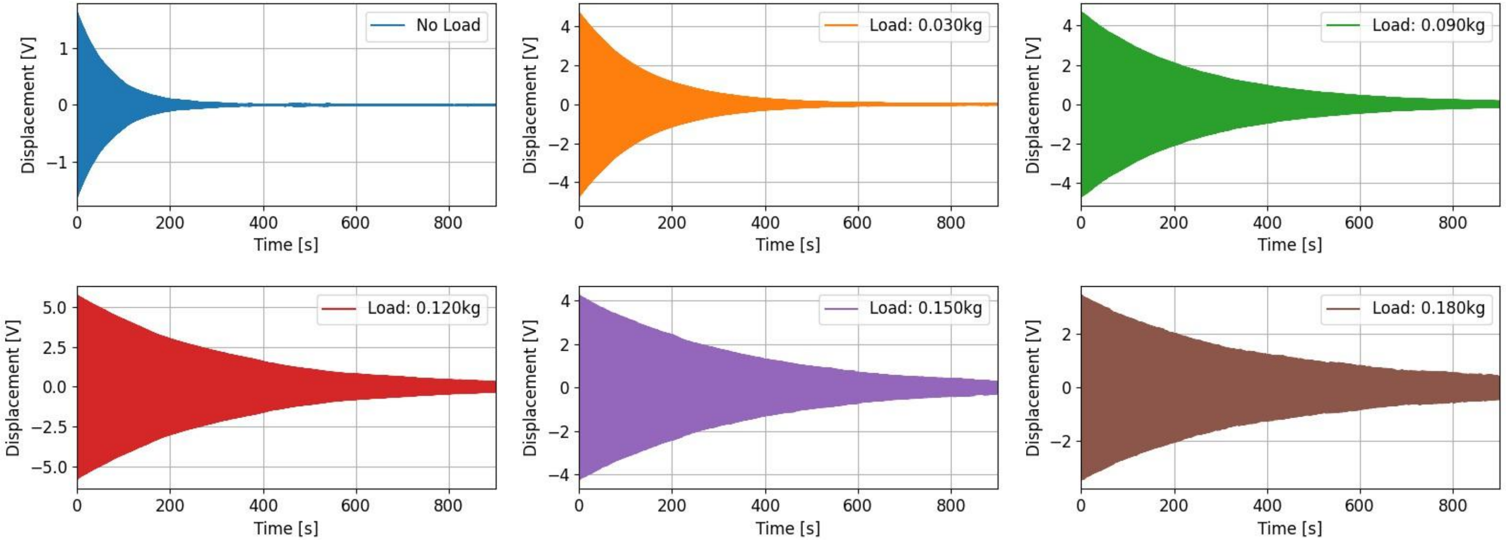
# From Calculations to Laboratory

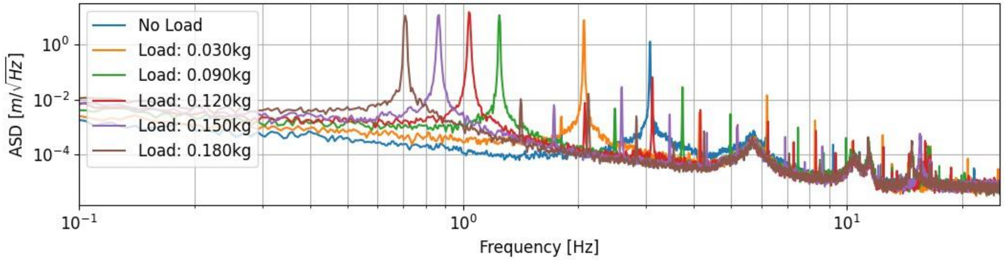
1. Goal: assess if the real contribution to the thermal noise of GAS filters is as expected from calculations
2. Method: measure the quality factor of a maraging steel blade in the frequency region of our interest
3. Experimental Setup: a purpose-built maraging steel blade, at room temperature and in free air, initially standing up therefore under no significant stress





# Oscillation Measurements




## Measurements strategy

- Three different blade lengths: 200mm, 300mm, 400mm
- Fixed the length, different loads are applied on top: from 0g to 180g
- Data taking 15 minutes long to measure at least two lifetimes decay

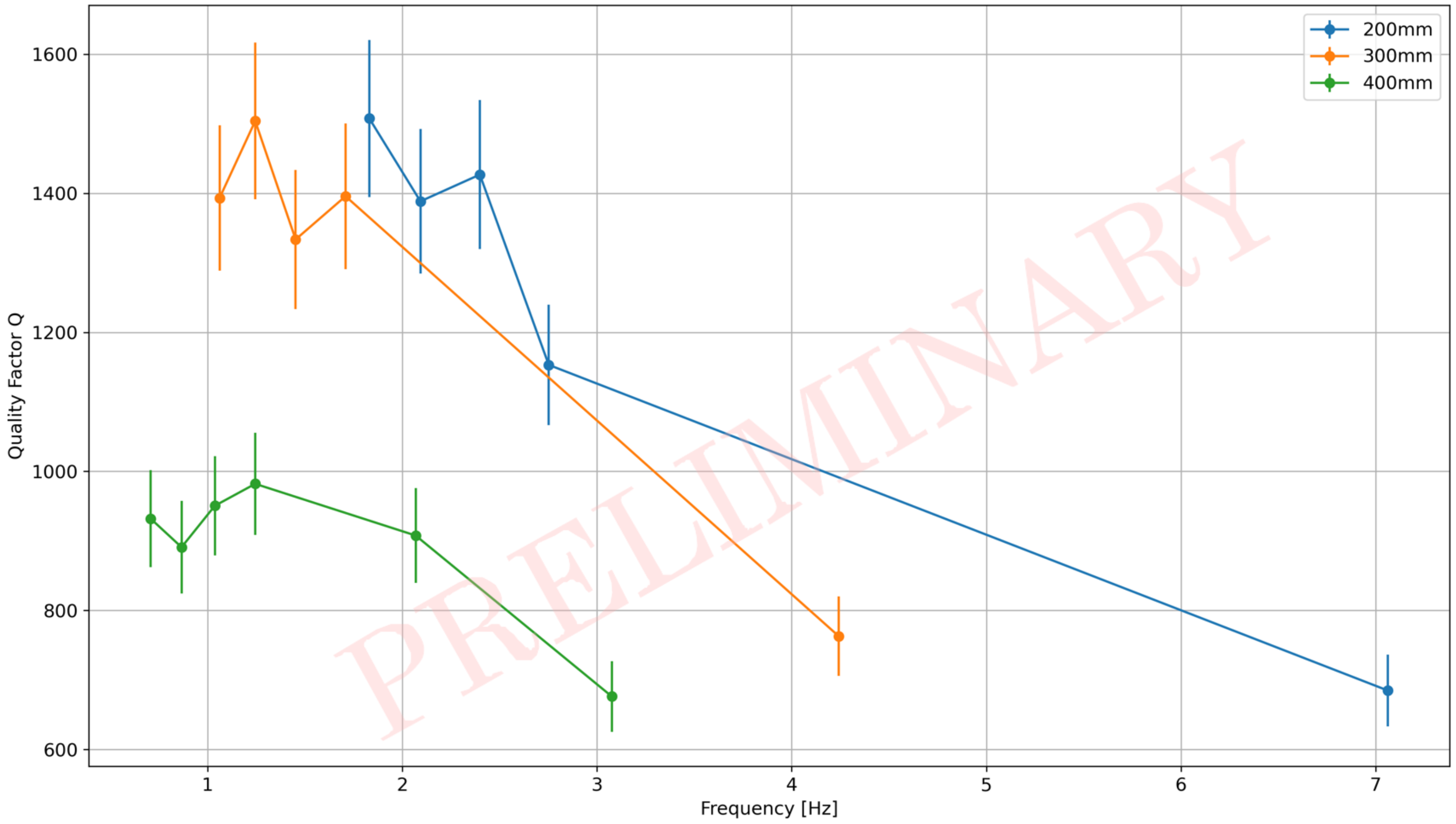
| | Resonant Frequency [Hz] |
|---|---|
| No Load | 3.08 ± 0.10 |
| Load: 0.030kg | 2.07 ± 0.10 |
| Load: 0.090kg | 1.25 ± 0.10 |
| Load: 0.120kg | 1.04 ± 0.10 |
| Load: 0.150kg | 0.87 ± 0.10 |
| Load: 0.180kg | 0.71 ± 0.10 |

From spectrum analysis we get the resonant frequencies $f_0$

# Quality Factor vs Resonant Frequency

Given the resonant frequency $f_0$ and the decay constant $\gamma$, it is possible to calculate the blade quality factor:

$$Q = \pi \frac{f_0}{\gamma}$$




The quality factor as a function of the resonant frequency shows a strange behavior, common to the different blade setups

So far, we can't explain this behaviour

Many possible different causes are being investigated

- Inverted pendulum behaviour may affect $Q$?
- Clamp losses?
- Air friction?

# Sapphire-Based Suspension at ARC-ETCRYO Laboratory
# Ongoing Test Campaigns

Van Long Hoang, Eugenio Benedetti, Emanuele Tofani

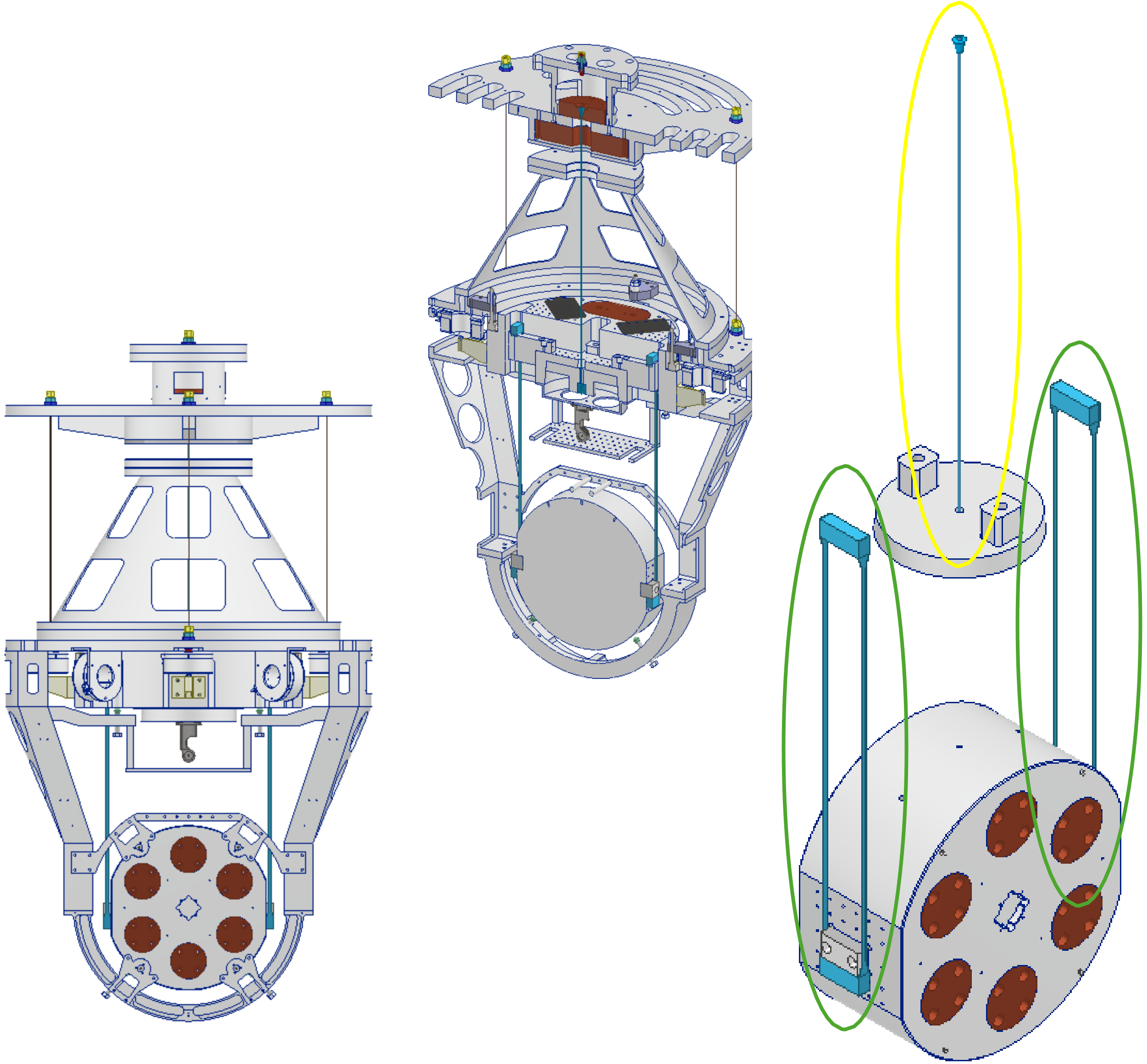
Materials for Advanced Detectors 2025 (MAD25)
Oct. 6-7, 2025
Berlin

EINSTEIN TELESCOPE

SAPIENZA UNIVERSITÀ DI ROMA

INFN Istituto Nazionale di Fisica Nucleare

# Payload in ARC



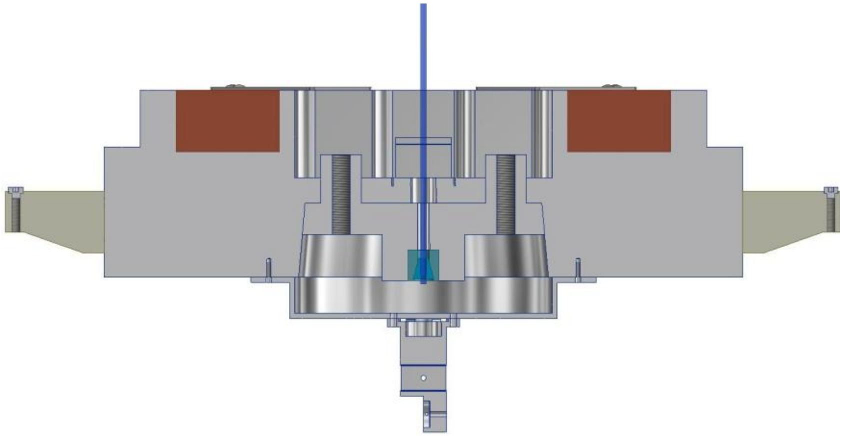
Payload total weight ~ **500 kg**
Marionette weight ~ **125 kg**
Mirror weight ~ **125 kg**

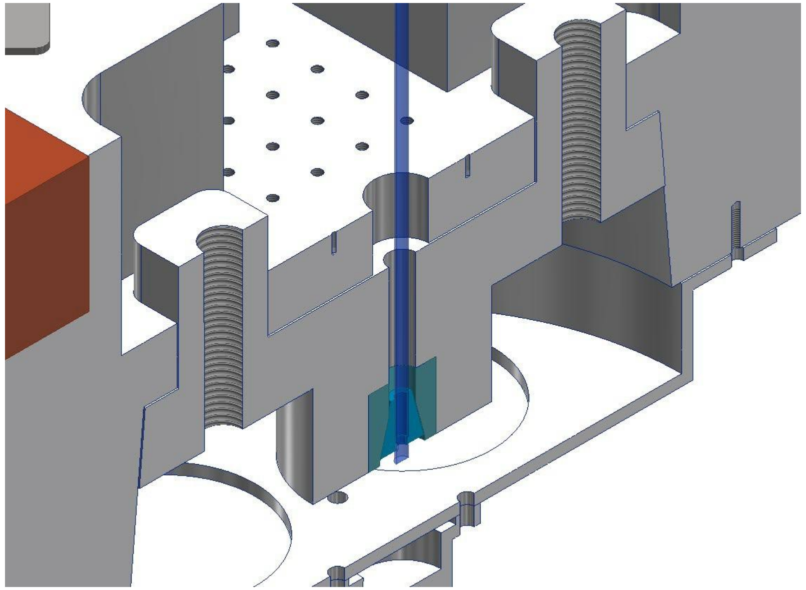
Two main sapphire suspensions:

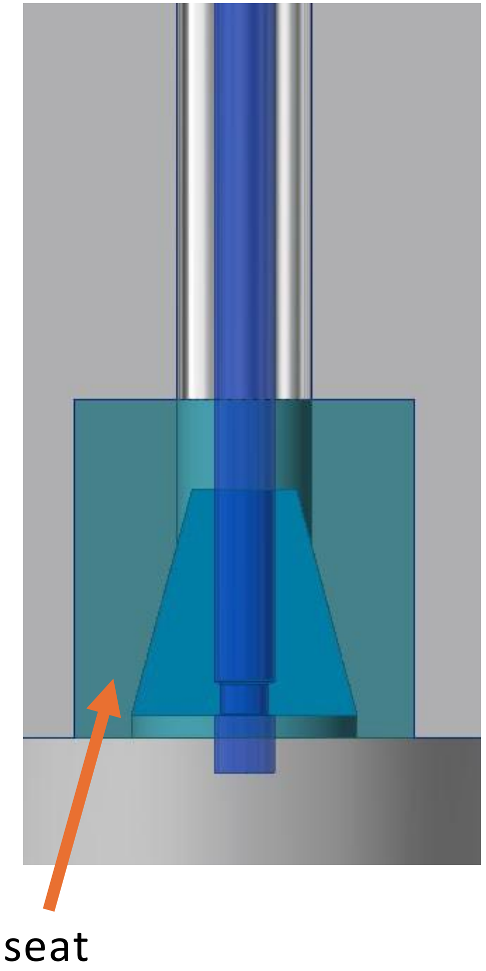
- Marionette suspension
- Mirror Suspension

First dummy test mass in ARC-ETCRYO is made in **aluminum (and copper weights)**
In the future we hope to envisage a sapphire mirror (when technological readiness level is high)

# Marionette Suspension








Two sets of **half sapphire cones** *interlock* a single **sapphire rod**.

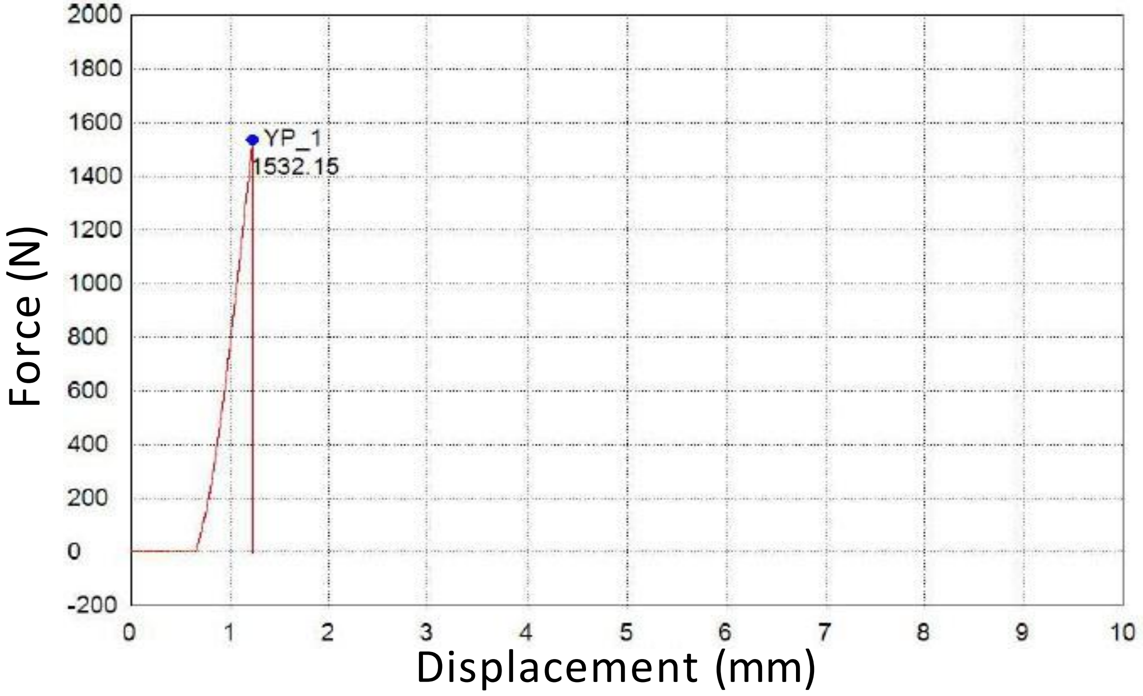
This system *locks* in place the marionette with respect to the platform, **supporting 250 kg** (marionette + mirror)

At the marionette level, the lateral surfaces of the cones impinge on a sapphire «seat», so that heat exchange is maximized

Length: 870mm
Outer diameter: 5.4 mm

# Pull test results

Kyocera Sample result



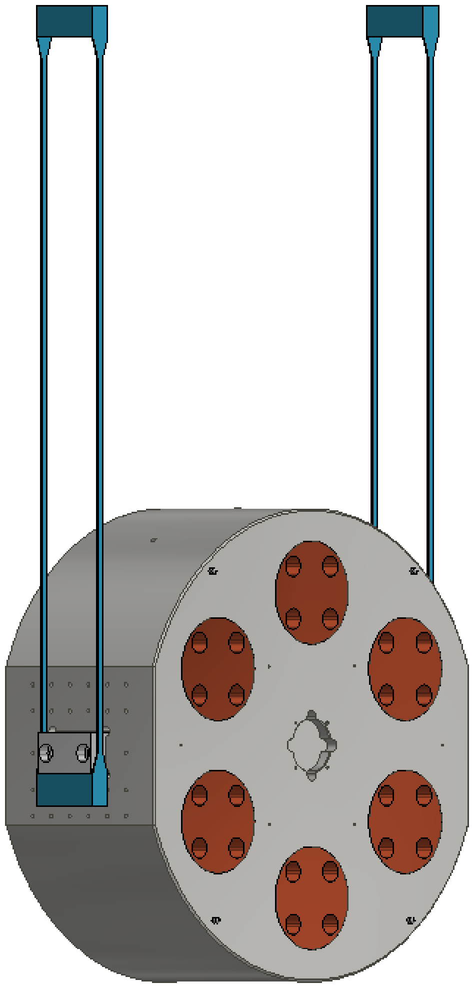

Failure surfaces of the sapphire sample by kyocera

This particular fracture geometry inspired us for further crystal analysis

Second generation cone/rod system (toothed) gave better results, but not good yet.

- **Higher number of samples are needed** → statistical distribution of the results
- Need **to improve design of the system** with production engineers to decrease stress intensification

# Mirror Suspension



Two **ribbon-like suspensions**
*Length*: 760 mm
*Thickness*: 1 mm

Manufacturing limit for this shape and length

We are studying two different approaches:

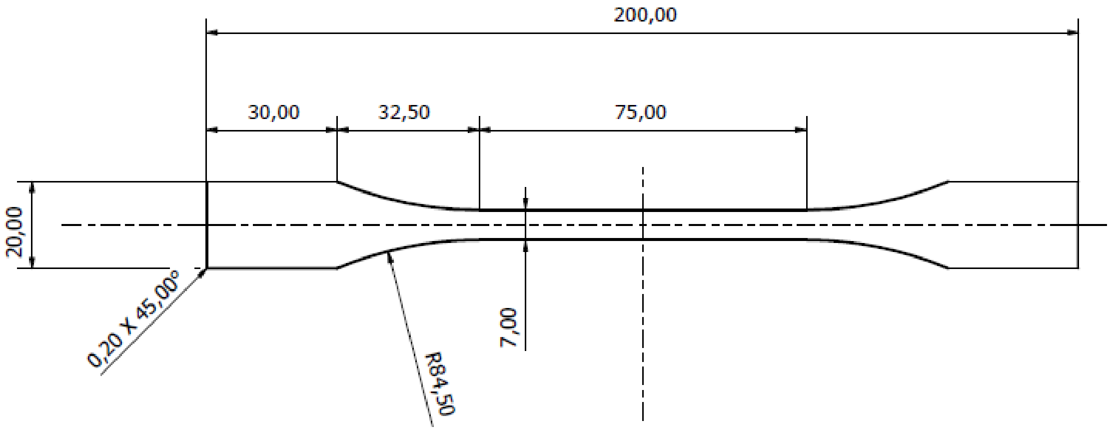
- **HCB bonding** (sodium silicate)
- **Monolithic**

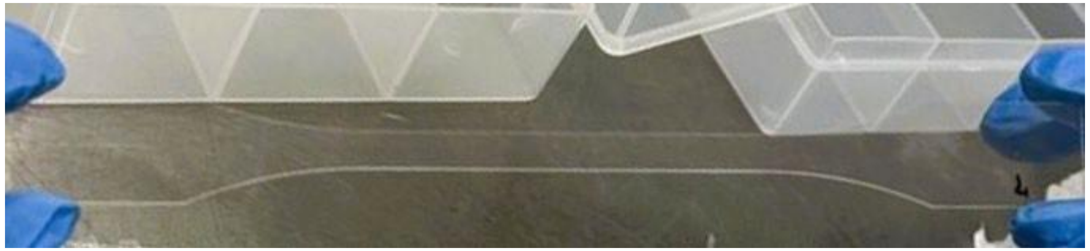
Test to be performed:

- Q test → **Mechanical quality factor**
- Pull test → **Strength**

**Why Ribbon shaped?**
Low thermal noise purposes

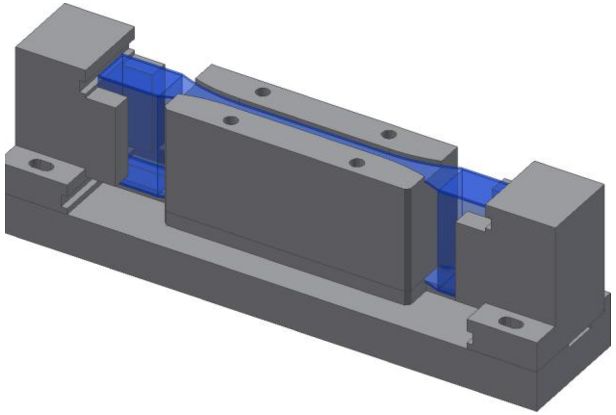
Cumming et al. Silicon mirror suspensions for gravitational wave detectors. Classical and Quantum Gravity. 31. 5017-. 10.1088/0264-9381/31/2/025017.

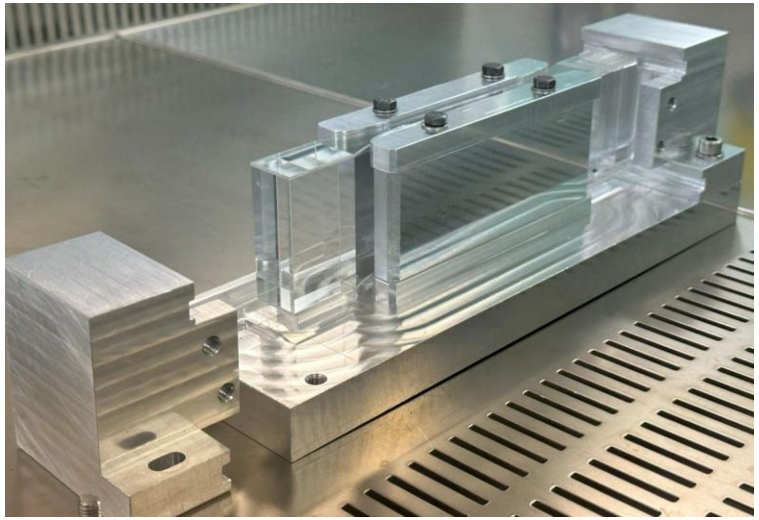


# HCB for ribbon sample

## First Generation Jig for Ribbon Bonding

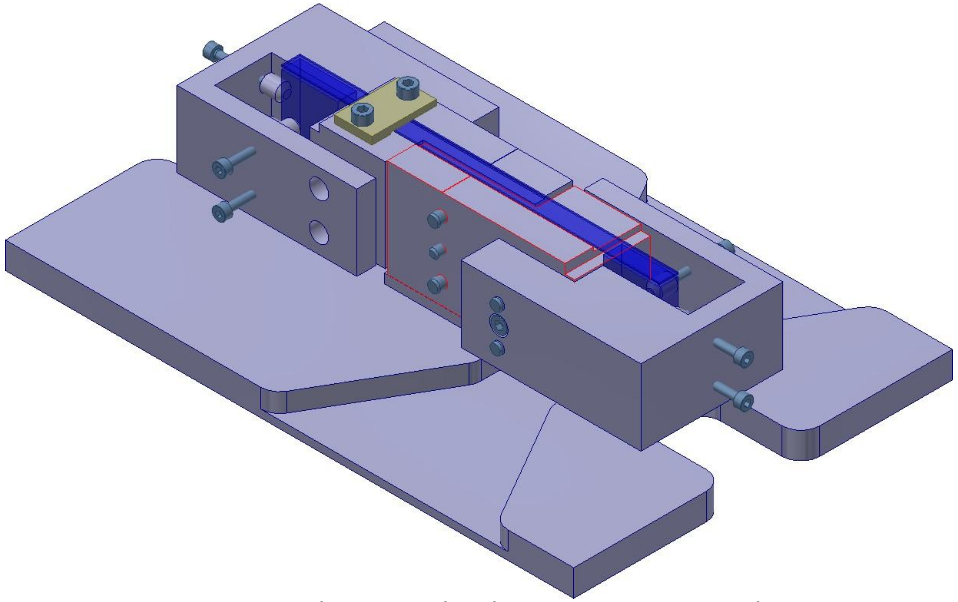




## Jig design driving parameters

- Sliding components
- Parallel faces to ensure low disalignment
- Removable components to ensure extraction
- Peek tips to ensure positioning

## Second Generation Jig



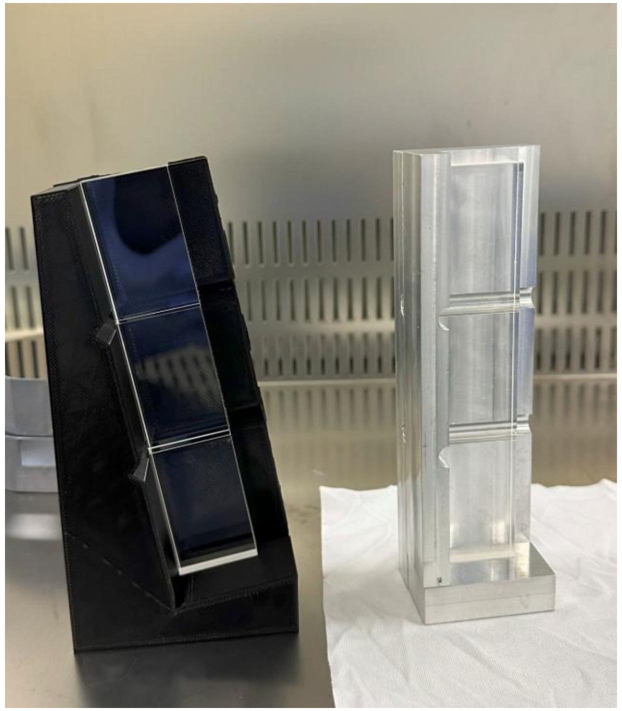
Design by G.Galimberti @INFN Cagliari

This new design (still under construction) ensures:

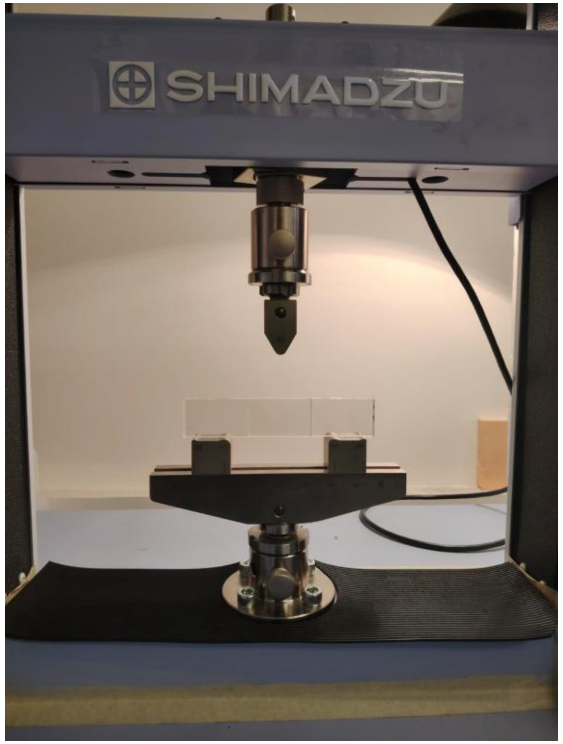
- Better cleanliness
- Better ribbon positioning
- Safer and more fluid extraction

# Preliminary shear tests

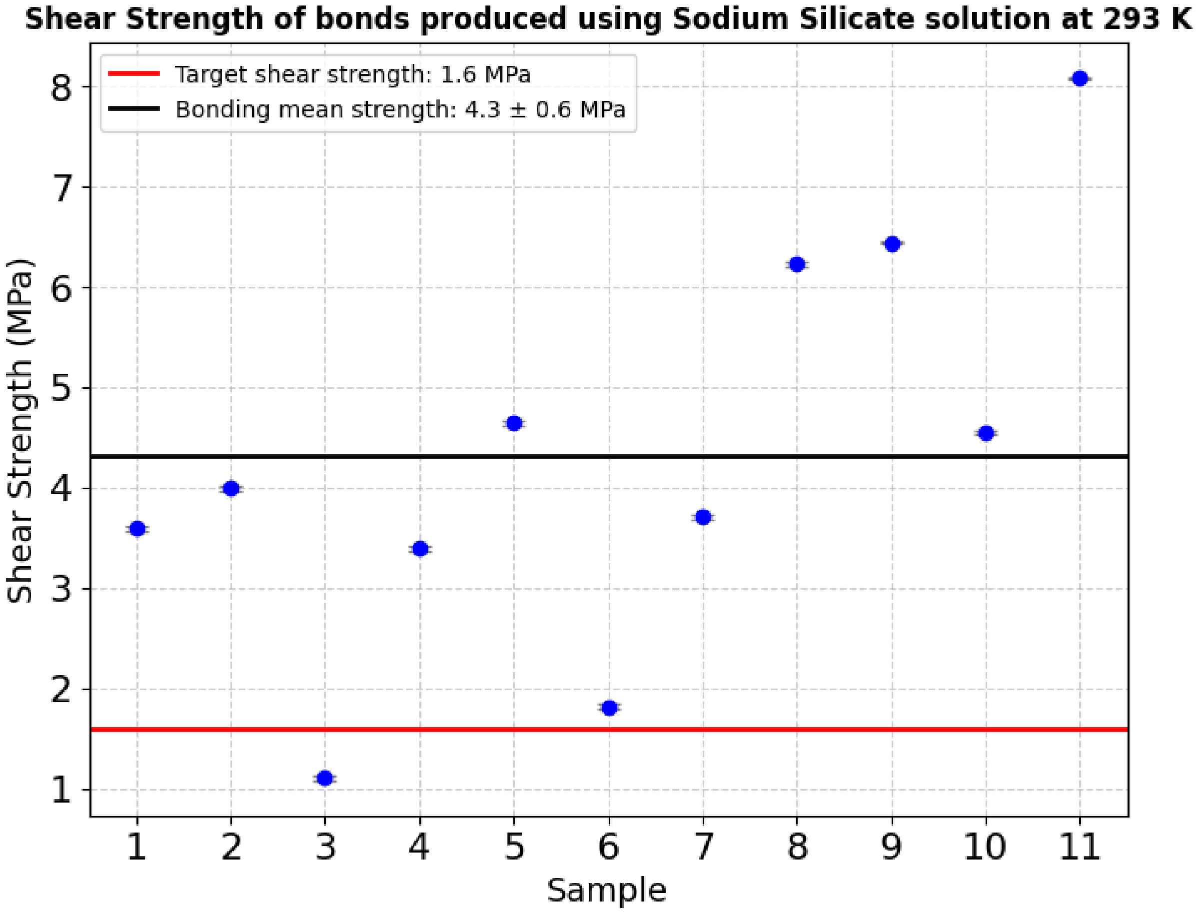
To study how our HCB would perform in our facility, we first decided to bond 3 sapphire blocks (equal to the size of the block sustaining the ear of the mirror).



2 different jis were used
(3D printed & aluminum)

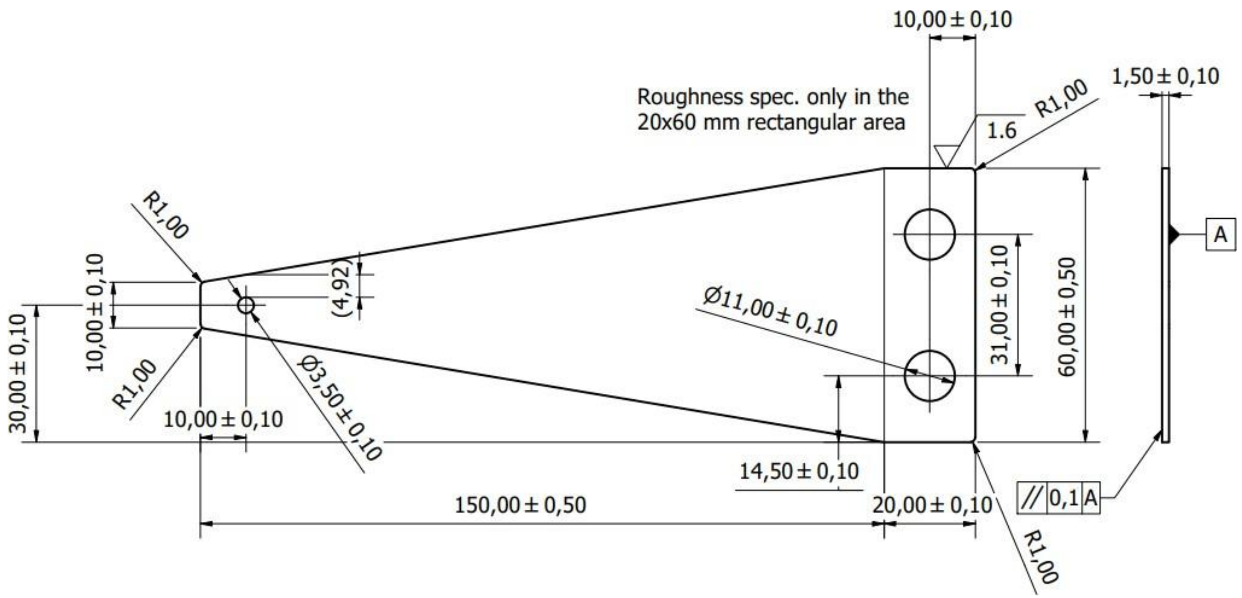


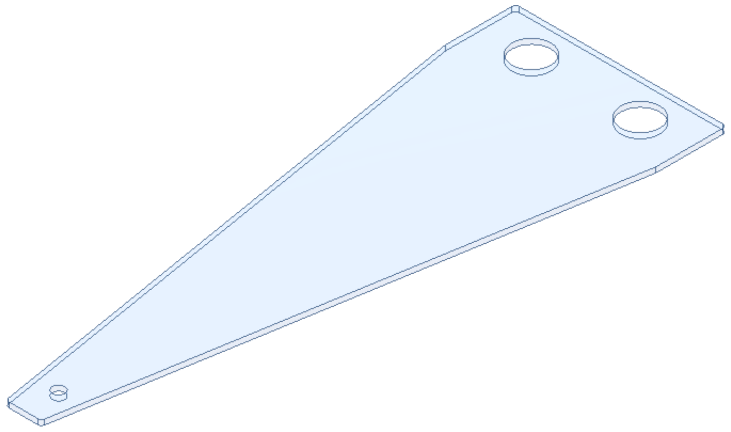

3 point bending setup




Thanks to Benedetta Kalemi for this measurements

# Sapphire Blade



We are also investigating the manufacturing of Sapphire Blades

To be implemented in a vertical vibration isolation system

Bending stress on such a geometry and material will surely end up destructively, so test setup must be well designed

# Conclusions

At Rome, in ETCRYO Lab we are working on sapphire systems for the ET-LF cryogenic payload.

- **Sapphire suspension for the marionette**
  - Pull test on the locking system
    - Design improvement on crucial parameters
- **Sapphire suspension for the mirror**
  - Two different approaches: HCB and monolithic
    - Design improvement on the bonding jig
  - Q test for mechanical quality factor
    - Investigating main problem on the setup and resonance frequency
  - Pull test
- **Mechanical test machine**
  - Design improvement on test jigs to avoid misalignment on the samples
- **Sapphire blades**
  - Ongoing design
- **Crystal studies on broken samples**
- *Purchase campaign ongoing*
  - Statistical measurements
  - According to FEM analysis and first test results, following design improvements

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# Sapphire suspensions for KAGRA and ET with low loss jointing techniques

MAD Workshop Berlin 2025

Jennifer Docherty*, Jack Callaghan, Sarah Dugmore, Giles Hammond, Karen Haughian, James Hough, Russell Jones, Gregoire Lacaille, Iain Martin, Mariela Masso Reid, Peter Murray, Munetake Otsuka, Sheila Rowan, Andrew Spencer, Claire Wilson, Alan Cumming

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Institute for Gravitational Research
University of Glasgow

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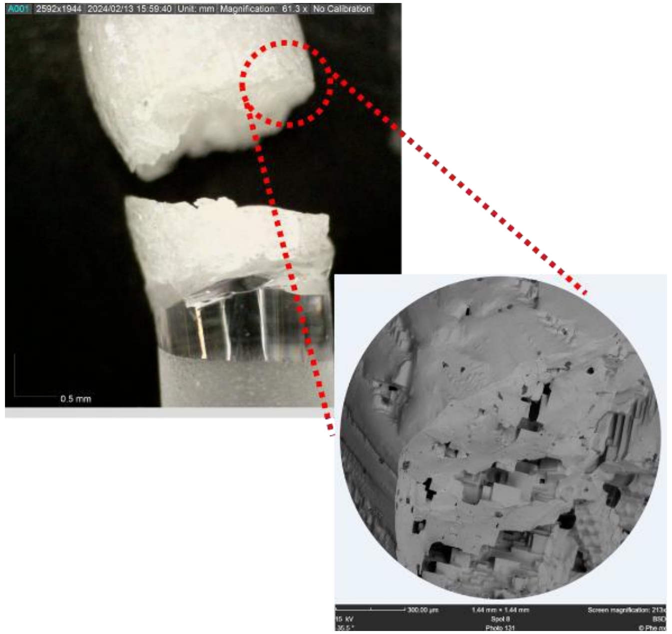
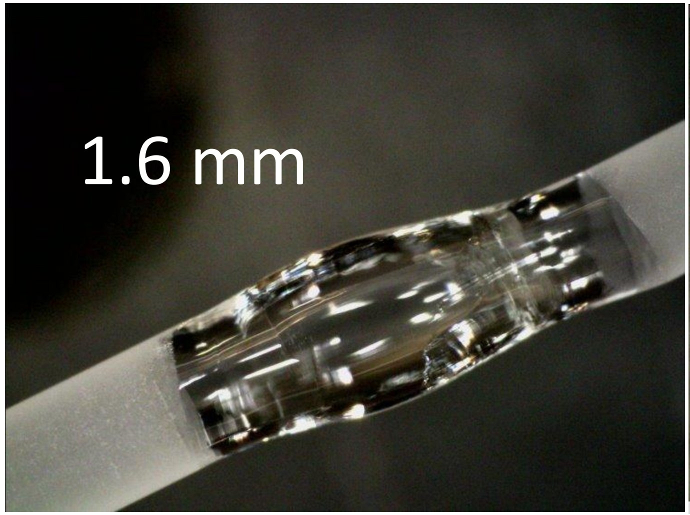
# Sapphire welds

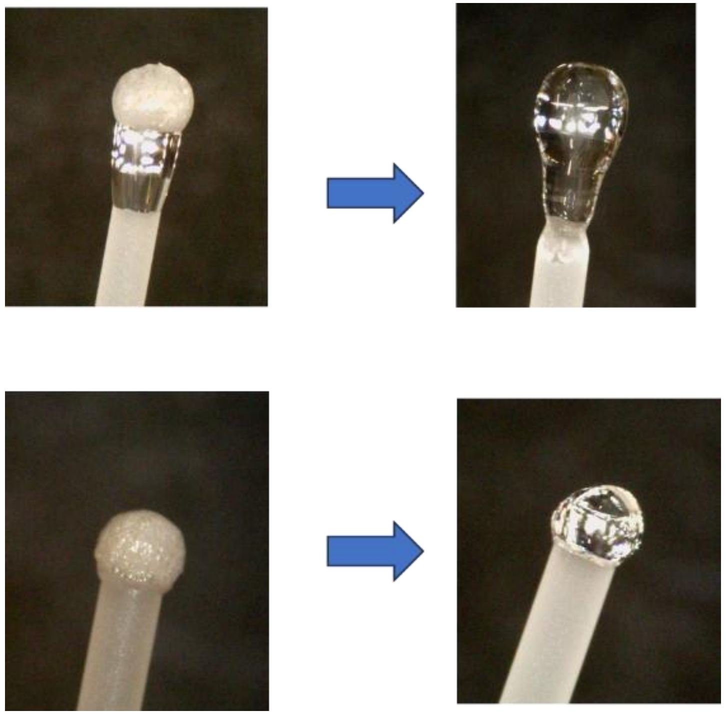
- 100+ welds in total completed
- Smallest diameter: 425 µm
- Largest diameter: 1.6 mm
- Investigated surface quality
- Ability to repair/reweld repeatedly

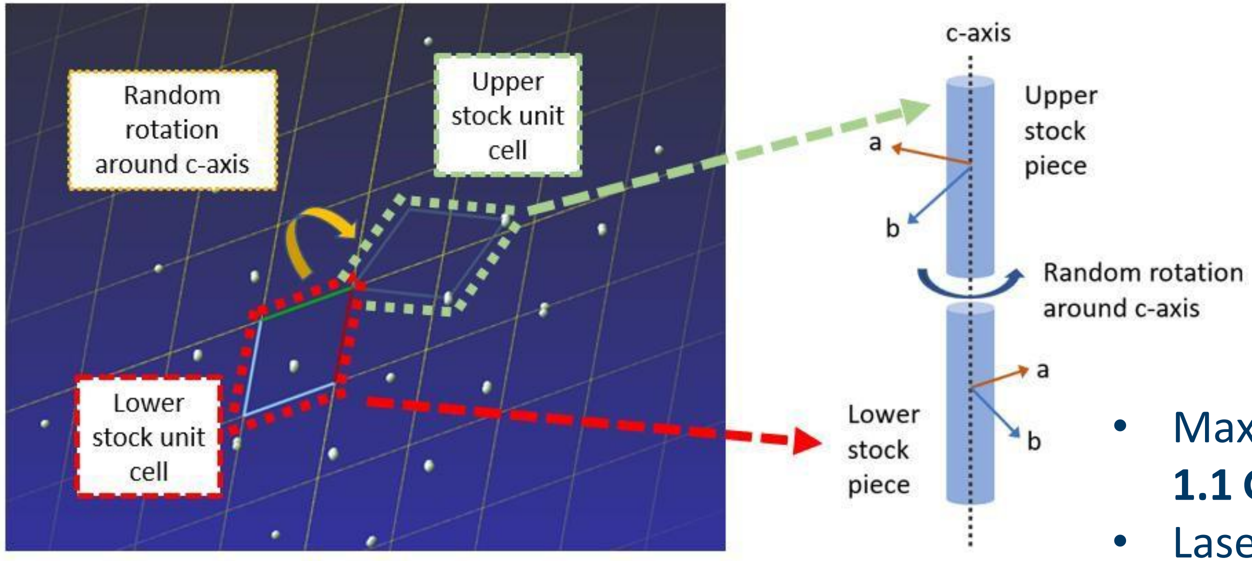


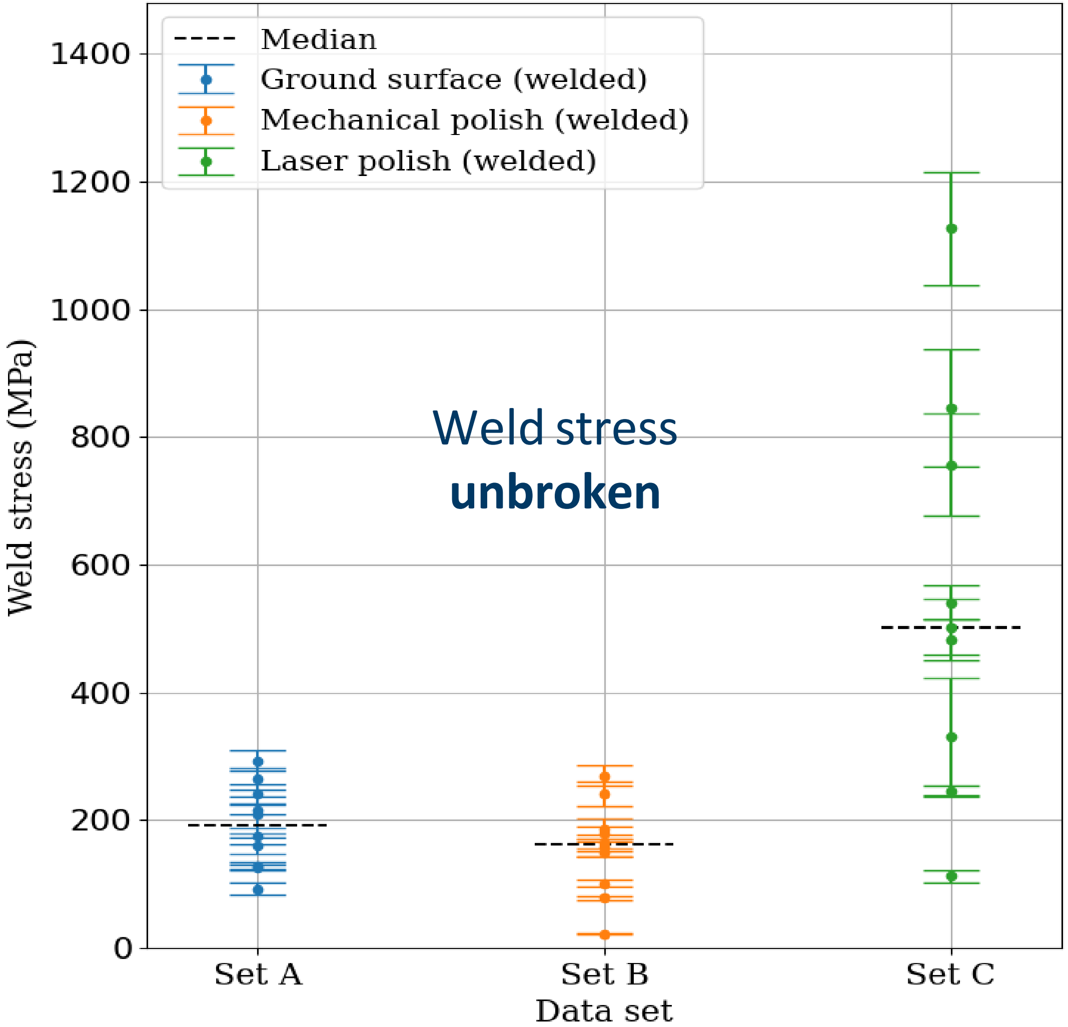
Managing cool down rate is essential



# 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**

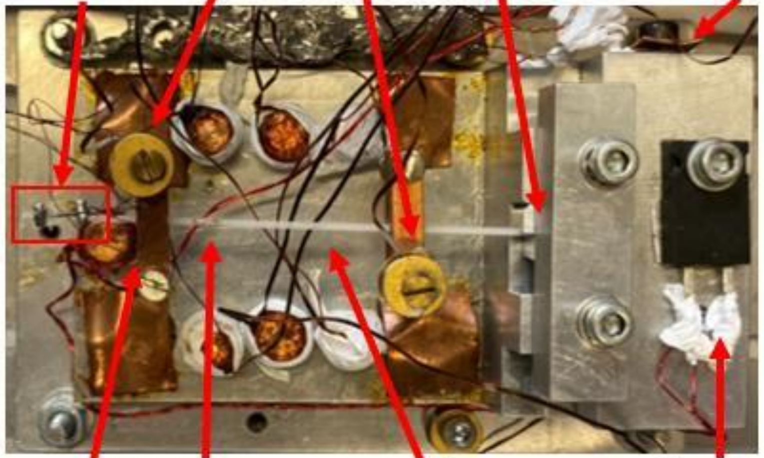


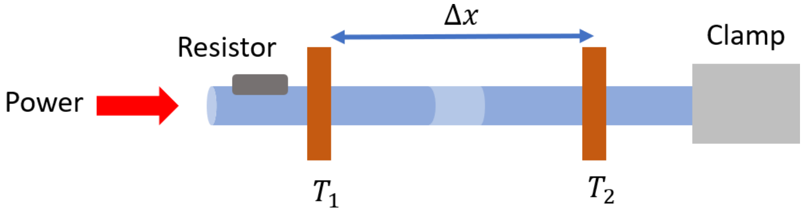



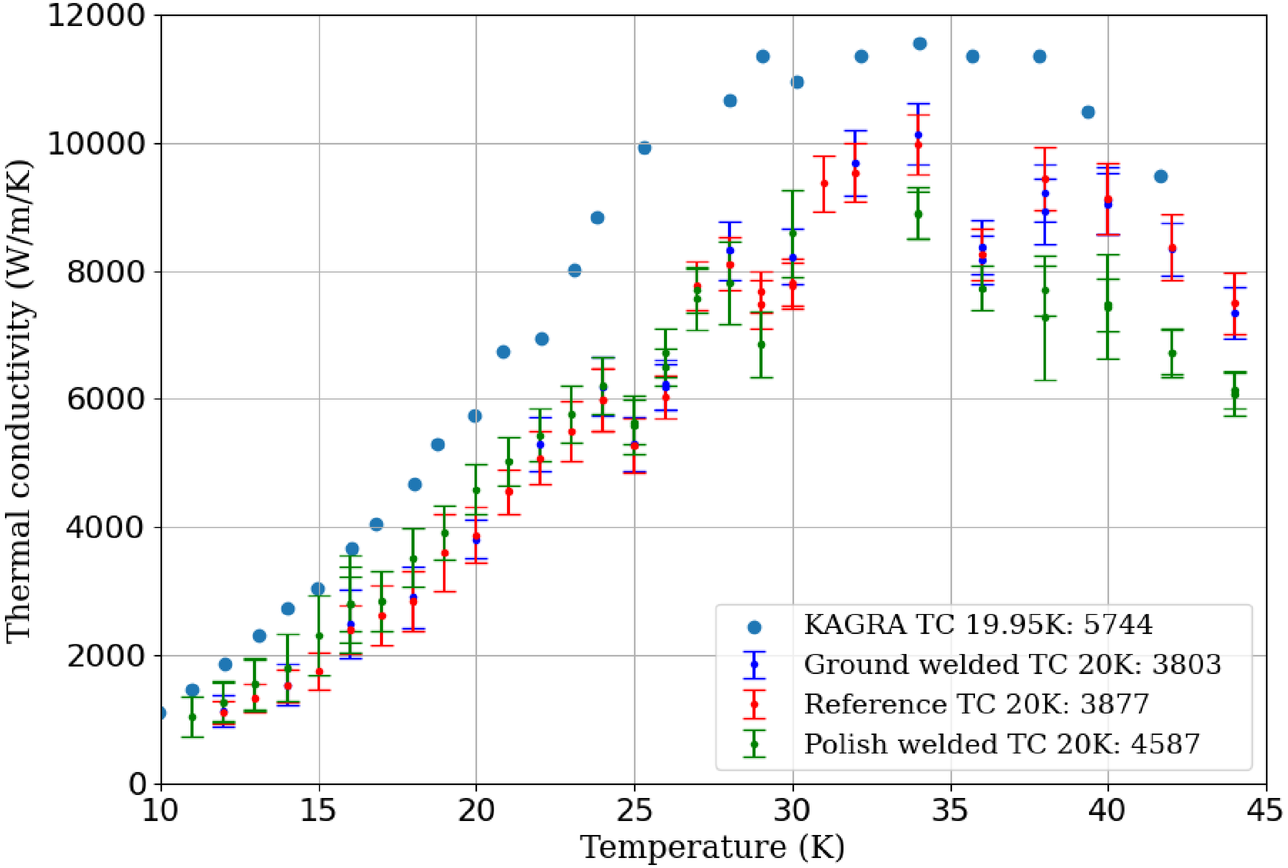

- Maximum stress observed in a laser polished and welded sample: **1.1 GPa, unbroken**
- Laser polishing shown to increase tensile strength up to three times when compared to ground and mechanically polished samples

# Thermal conductivity

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



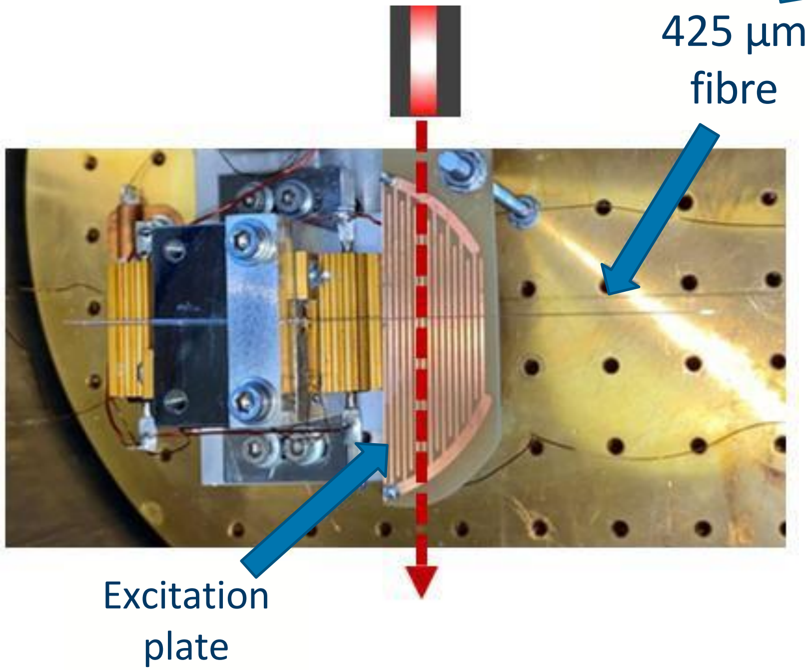

- Measurements of three samples down to 13 K using steady state method
- No appreciable difference between welded and unwelded sample
- Difference to KAGRA curve thought to be due to purity levels in base sapphire

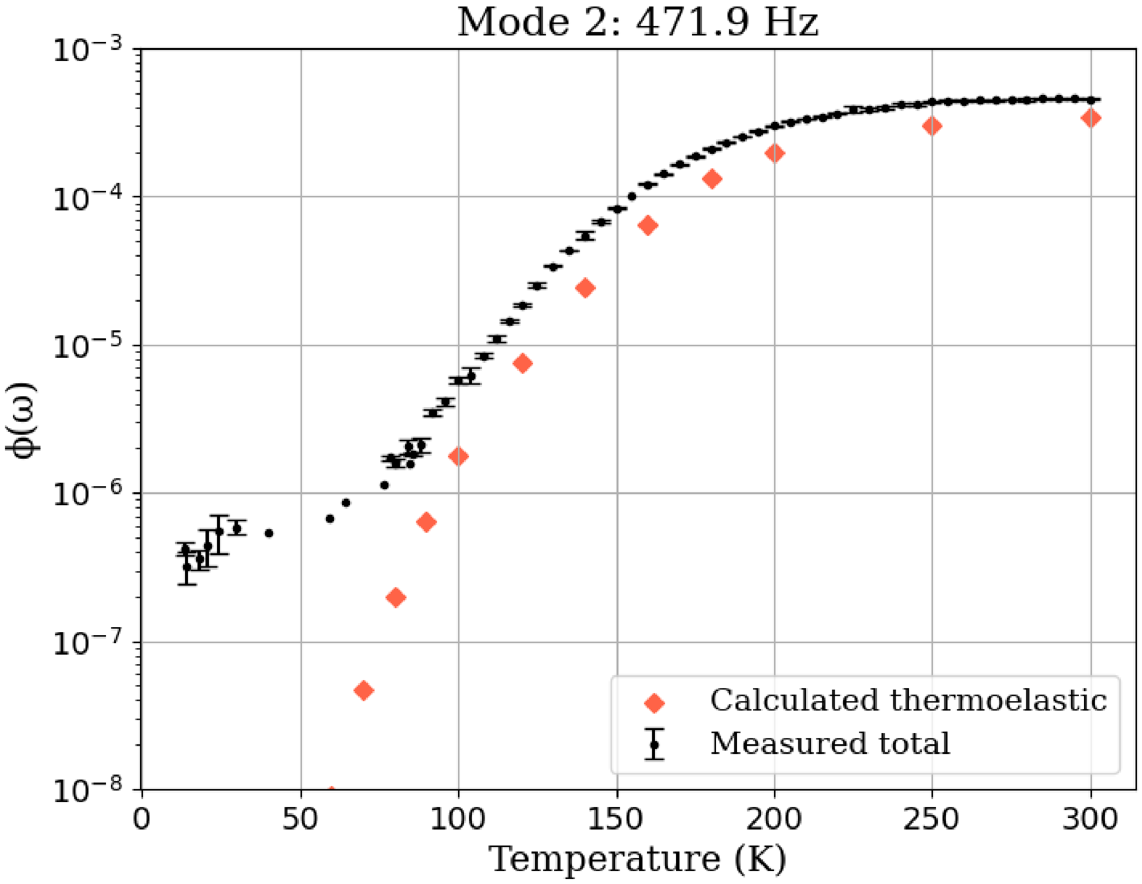
# Mechanical loss

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

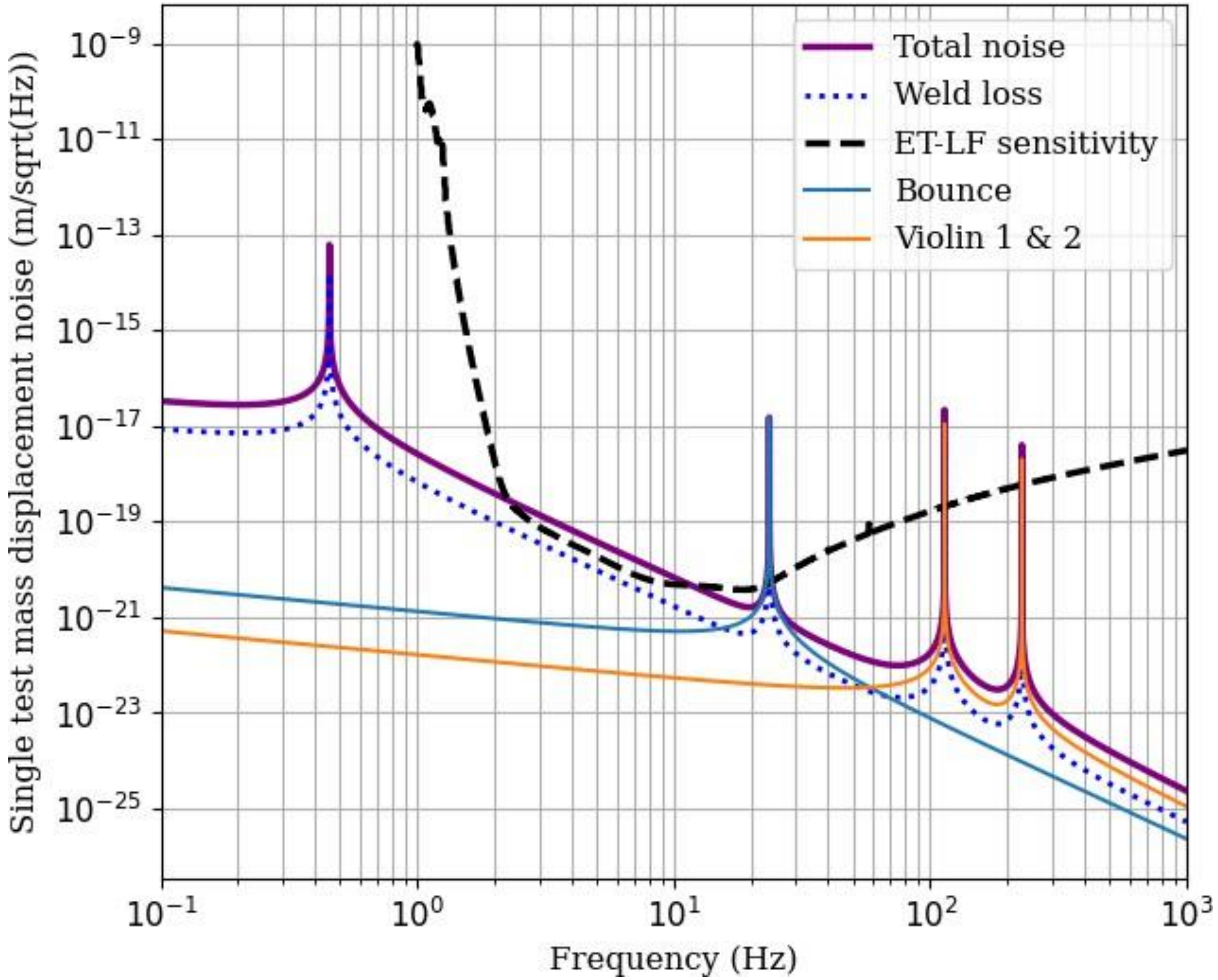
- Measured down to 13 K for six resonant modes
- Using welded 425 µm fibre to 1 mm rod


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



# Suspension thermal noise modelling in ET



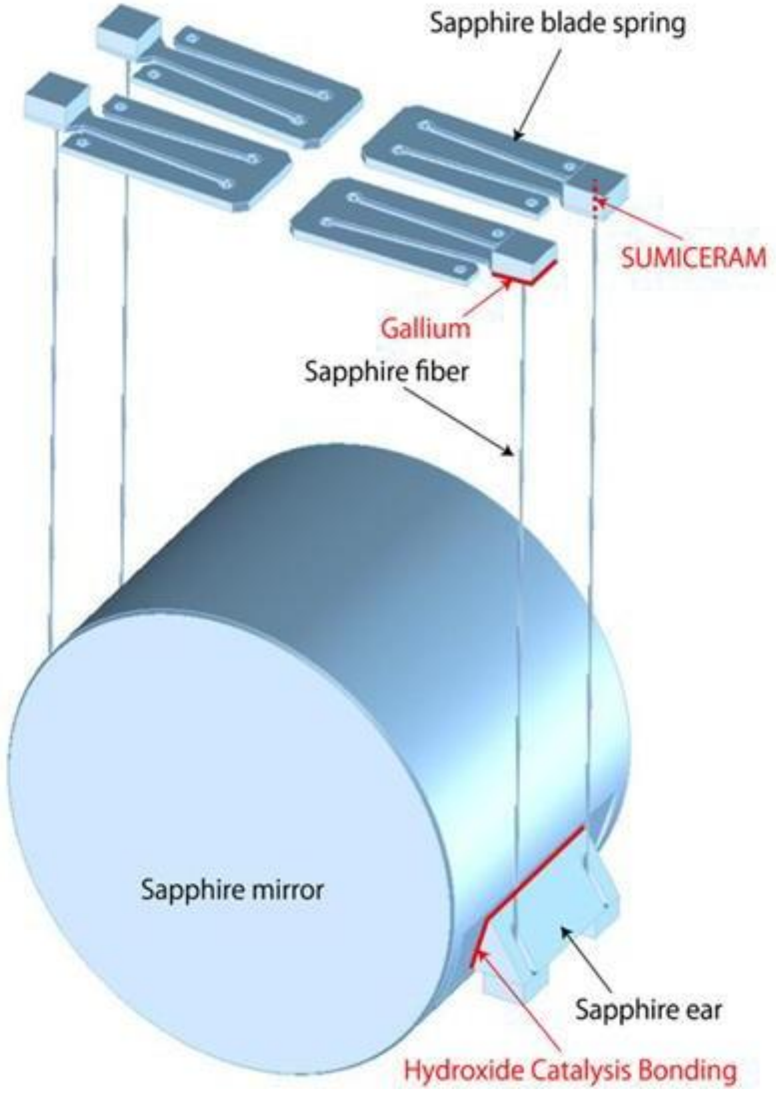

- Includes measured loss, with estimated decoupling
- Model of 1.52 mm diameter fibres with 5 mm stock ends compared to current ET-LF design curve [4]
- Total noise is already approaching design curve without fully optimising weld loss



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

# 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.

# Development of a Silicon Suspension System for the ETpathfinder

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[2]Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands

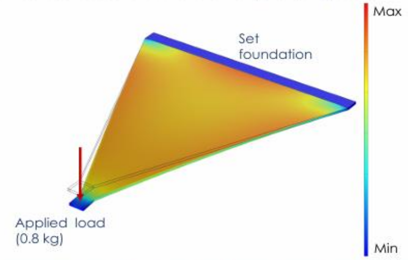
## Motivation: silicon in ETpathfinder

The **ETpathfinder** (ETPF) is a cryogenic test facility in Maastricht, aimed at developing core technologies for the Einstein Telescope, a future third-generation gravitational wave observatory. The facility utilizes a high-sensitivity ($< 1 \times 10^{-18}\ m/\sqrt{Hz}$ at $10\ Hz$), 10-meter interferometer prototype to evaluate crucial subsystems, focusing on the performance of **crystalline silicon test masses** and their suspensions under extreme cryogenic operating conditions, specifically aiming for temperatures around 18 K and 123 K [1].
One key component under investigation is a **low-noise suspension system** designed for cryogenic operation. Due to its low mechanical quality factor and low thermal conductivity at cryogenic temperatures, the so far used material, silica, is not suitable to reach the aimed sensitivity goals [1]. Silicon, therefore, is a strong candidate for use in suspension elements due to its favourable properties at low temperatures, including a high mechanical quality factor, excellent thermal conductivity, and a low thermal expansion coefficient. These characteristics are critical for **thermal noise reduction** and system stability under cryogenic conditions [2]. To address potential variations in the geometry of silicon suspension wires and further minimise thermal noise, the implementation of **silicon blade springs** is being explored. We currently use finite element simulations to study different blade designs with a focus on stress distribution, deformation, and eigenfrequencies. Breaking strength measurements for prototypes of silicon springblades are currently planned. Additionally, we present prototypes of silicon–silicon connections.

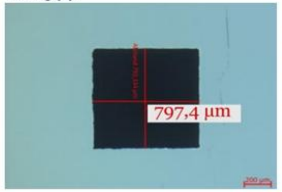
## Springblades

A triangular blade design with 1 mm thickness is currently considered for the first springblade design. Different width and length variations were analyzed using FEA, and the final geometry will be selected based on breaking strength. The target is a first eigenfrequency below 10 Hz.

*Simulated stress distribution over a triangular springblade:*

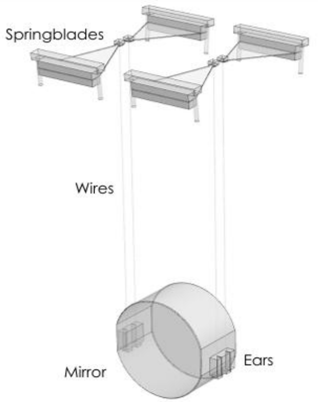



*Quadrature cut in a 1 mm thick silicon wafer using ultrashort-pulse laser cutting [3]:*




The first prototypes will be fabricated from undoped silicon wafers with [100] crystal orientation using an ultrashort-pulse laser cutting process. The wafers have a thickness of 1 mm and are cut into rectangular geometries. The image on the right illustrates a quadrature cut produced in a 1 mm thick wafer with this laser process.

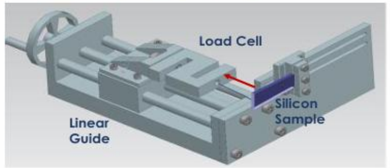
## Schematic view of silicon suspension system



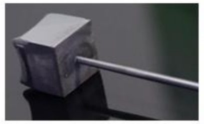

## Test setup for springblades

Breaking strength will be tested with the setup shown below. The aim is to reach a high strength and to demonstrate reproducibility between samples.

*Test setup for breaking strength tests [5]:*




## Silicon-silicon connections



A cylindrical hole was machined into a silicon block to insert a 1 mm silicon wire, after which the assembly was baked in a nitrogen-rich atmosphere. Future tests will evaluate heat conductance, strength, and mechanical loss. The samples are manufactured by *Impex High TechGmbH*.

## References

[1] ETpathfinder: a cryogenic testbed for interferometric gravitational-wave detectors, A. Utina et al., 2022
[2] Design and development of a prototype single crystalline silicon cryogenic suspension for 3rd generation gravitational wave detectors, K. Toland et al., 2025
[3] Fraunhofer Institute for Laser Technology ILT
[4] Courtesy of Rogier Elsinga, r.elsinga@nikhef.nl
[5] Courtesy of Mathijs Baars, m.baars@nikhef.nl

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# Towards Reliable Bonding of Sapphire and Silicon II

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## Bonding of a sapphire fiber by Melting in a Furnace / USP Laser Welding +Tensile Strength Tests on Sapphire Fibers

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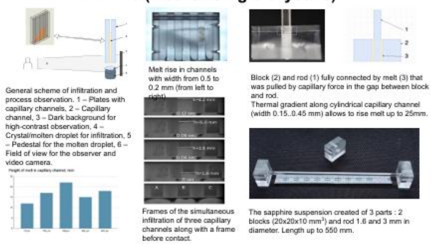
Prof. Dr.-Ing. habil. Andreas Ostendorf

### Bonding of a sapphire fiber by melting in a furnace (Inst. Of Single Crystals)



General scheme of infiltration and process observation. 1 – Plates with capillary channels, 2 – Capillary channel, 3 – Dark background for high-contrast observation, 4 – Crystal/molten droplet for infiltration, 5 – Pedestal for the molten droplet, 6 – Field of view for the observer and video camera.

Melt rise in channels with width from 0.5 to 0.2 mm (from left to right)

Frames of the simultaneous infiltration of three capillary channels along with a frame before contact.

Block (2) and rod (1) fully connected by melt (3) that was pulled by capillary force in the gap between block and rod.
Thermal gradient along cylindrical capillary channel (width 0.15..0.45 mm) allows to rise melt up to 25mm.

The sapphire suspension created of 3 parts : 2 blocks (20x20x10 mm³) and rod 1.6 and 3 mm in diameter. Length up to 550 mm.

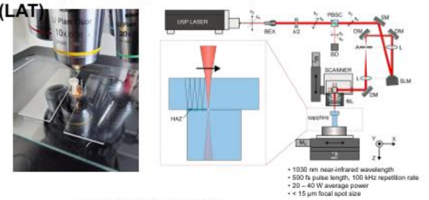
Tension stress testing for sapphire fibers

Machine for testing of tension stress INSTRON-5581, load up to 100 kN. Metal holder for cubic ends was produced. Cuprum layers were used to uniform load to the cubic surface. The cuprum parts in the metal holder for cubic ends were added to solve some misalignment between rod's axis and cubic's axis. The cuprum parts were softened by heat treatment before tests.

The cracks appeared at the same angle 43° +/-5° to axis to the rod. It was found by X-Ray diffraction method that mirror-like elements of surface on the crack's was R-plane

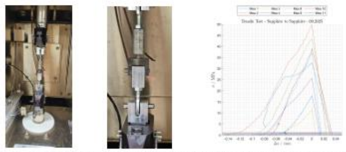
The load of failure for the samples are up to 260 MPa that shows the potential of high strength for assembled sapphire holder using sapphire melt.

### Bonding of a sapphire fiber by Ultrafast Laser Welding (LAT)




- 1030 nm near-infrared wavelength
- 500 fs pulse length, 100 kHz repetition rate
- 20 – 40 W average power
- < 15 µm focal spot size

Tension stress testing for sapphire fibers (LAT)

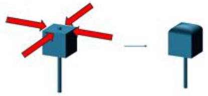


Tensile testing machine: MTS 858 Mini Bionix II , load up to 2.5 kN, Crossbar speed: 0.5 mm/min. Procedure:
- Glue the sapphire cylinder into the corresponding holder. ( 2-component adhesive UHU Plus Endfest)
- Curing for 24 hours
- Screw in the holder with the glued rod
- Move the crossbar and secure both holders with a dowel pin
- Start tensile test

## Silicon Welding Updates:

Dr. Celia Millon,
Dr. Michael Müller

### Bonding of a Silicon Fiber by Float Zone (FZ) method

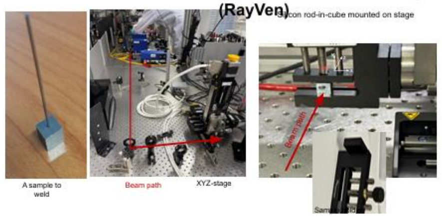


- Matching crystallographic orientations cube/rod
- Argon atmosphere
- Narrow heating zone (4 halogen lamps )
- Heat to just above the melting point (1414 °C).

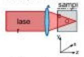
**Outlook:**
- Capillary Gap optimization
- Thermal/Mechanical tests

Bonded half dumbbells (head ~ 9 x 9 x 8 mm, fiber: Ø 1.2 mm, length 60 – 80 mm)

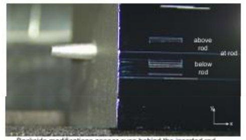
### Trials to Si-Si Welding by Ultrafast Laser 2.1µm (RayVen)




- Laser
  100 kHz, 3.5 W, 35 uJ, 1.5 ps
- Focusing with aspherical lens
  f = 10 mm, $w_0$ = 2.5 mm (radius)
- Scanning
  - Linear scans in x,y
  - Manual setting of z position
  - Velocity 2-20 mm/s



Side view



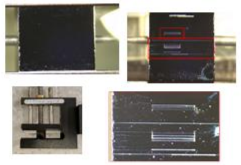

Backside modifications appear even behind the inserted rod.

Focus on the back

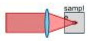
Plasma on backside

Undamaged frontside

Modified backside



Focus on the cube/rod interface



Investigation of the rod after processing

No modifications observed

Conclusion:
Ultrafast Laser technology is not directly transferable to silicon.
Modifications required.

Outlook:
- Systematic scanning of parameters to determine the welding process.
- Increasing energy absorption by gold layers?

The above results were achieved with the support of Central Innovation Program for small and medium-sized enterprises **Funding Nr. EP201456**
and Dutch National Institute for Subatomic Physics (Nikhef)

# Advancing electrochemical micromachining technology for new and difficult-to-cut materials

6 Oct 2025, 14:05
10m
Leibniz-Insitut für Kristallzüchtung (IKZ)

Poster | Poster Session

## Speaker

Dr Muhammad Hazak Arshad (KU Leuven)

## Description

Electrochemical micromachining (ECM) is a non-contact and athermal process that can machine electrically conductive materials through anodic dissolution in the presence of an electrolyte and applied voltage governed by Faraday's law of electrolysis. The absence of mechanical forces and thermal damage make ECM especially suitable for machining advanced materials, regardless of hardness, while preserving surface and subsurface material properties. This is critical for ensuring functional performance in high-tech sectors such as aerospace, biomedical, MEMS and precision tooling.

At the Micro- & Precision Engineering Group (MPE) at KU Leuven, the research is focused on advancing both tool-based and jet-based ECM process configurations using custom-built and commercial setups for shaping and surface structuring applications. One of the key research tracks is to develop strategies for machining advanced materials with high precision and surface integrity. The team has also developed in-house a novel hybrid laser-electrochemical machining (LECM) technology to deliver coaxial microsecond pulsed-electrochemical and nanosecond pulsed-laser process energies simultaneously to the machining zone, to enhance reaction kinetics, material removal rates, precision and surface quality.

These processes have shown promising results on a range of material classes, including superalloys, cermets/carbides and tool steels. These capabilities make ECM an interesting technology to explore further for machining monocrystalline silicon to support the machining/finishing of the suspension system of the Einstein Telescope.

## Author

Dr Muhammad Hazak Arshad (KU Leuven)

## Co-authors

Prof. Krishna Kumar Saxena (KU Leuven)
Prof. Dominiek Reynaerts (KU Leuven)

# Cooling away the absorption - Silicon mirror development for future gravitational wave detectors

6 Oct 2025, 13:45
10m
Leibniz-Insitut für Kristallzüchtung (IKZ)

Poster | Poster Session

## Speaker

Janis Woehler

## Description

Silicon is the substrate material chosen for future gravitational wave detectors such as ET mainly because of the low optical absorption together with a high mechanical quality factor. To optimize the coatings deposited on these silicon substrates, they have to be annealed to temperatures above 600◦C. At temperatures between 450◦C and 600◦C thermal donors start to form, increasing the optical absorption. A careful procedure consisting of heating and cooling has to be found to minimize the impact of these effects. Furthermore, characterizing and understanding the effect of annealing and rapid cooling on internal stress and related birefringence, as well as resulting wavefront distortions and their effect on the laser beam is essential to
understand and minimize the effect on the detector performance.

## Author

Janis Woehler