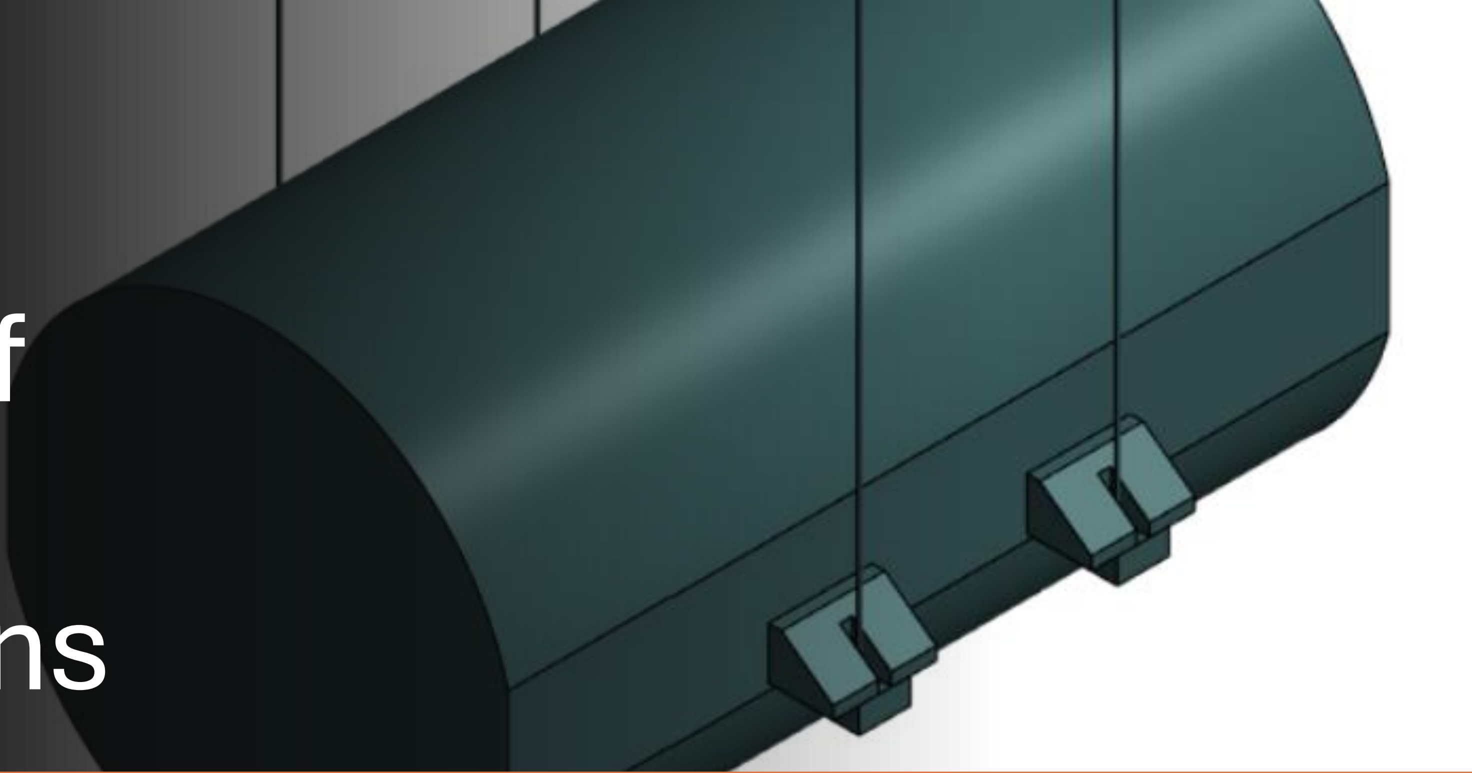
State of the art of crystalline test mass suspensions



Flavio Travasso

University of Camerino / INFN Perugia

on behalf of ET – Test Mass Suspension WP

GRASS – Trento – 02/10/2024

Outline

- Why crystalline TM suspension
- Projects involved in the design and test of TM Suspension
- Production
- Characterization
- Designs summary

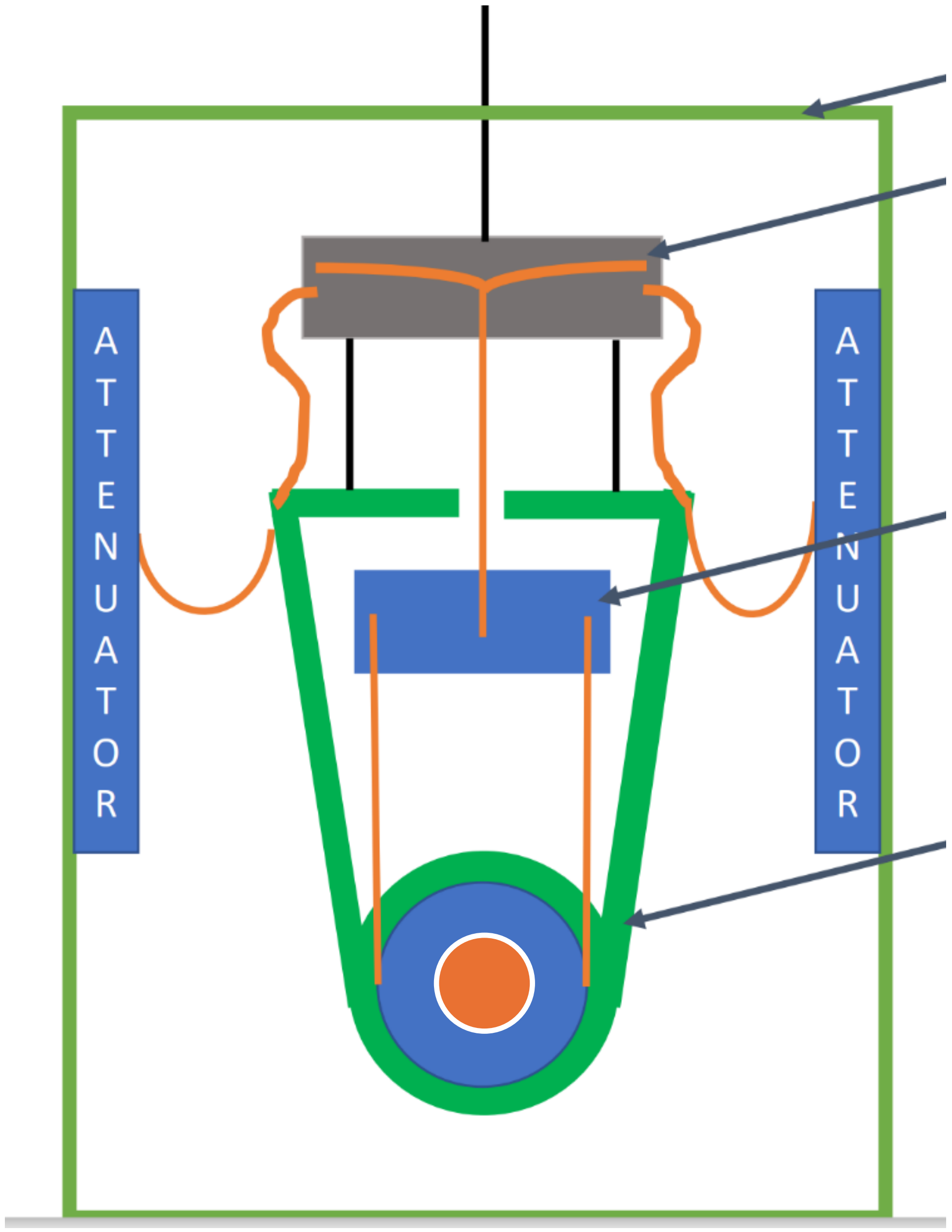
Why crystalline TM suspension

ET will integrate cryogenic technology:

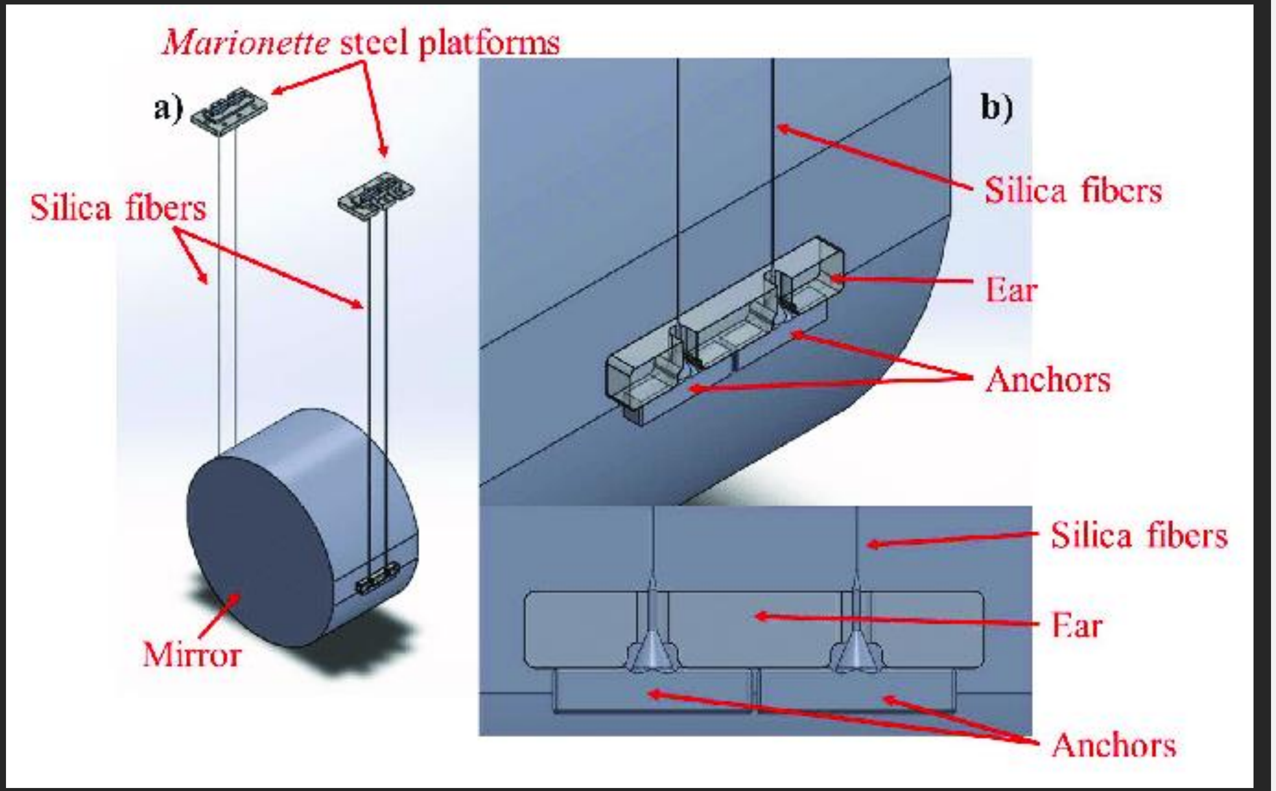
Identify suitable materials for both suspensions and substrates that must have:

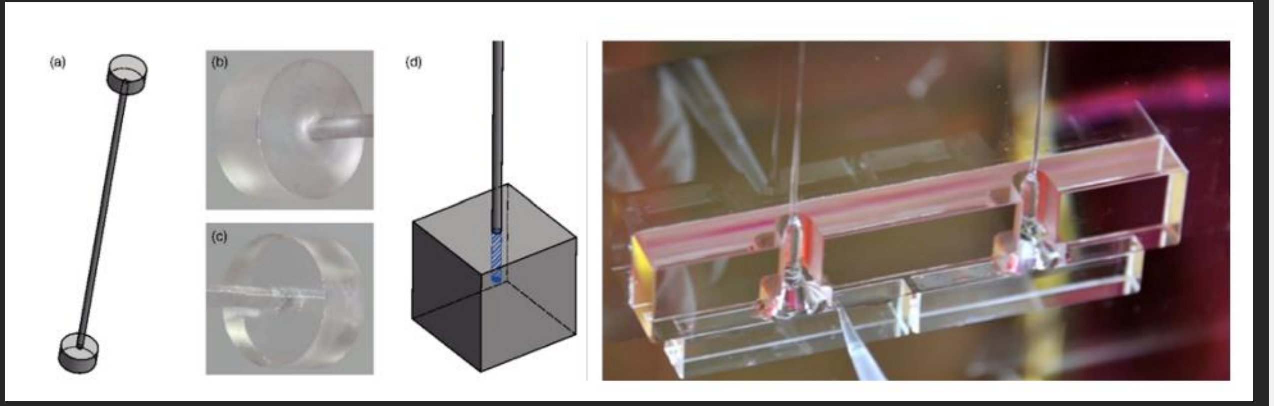
- good thermal conductivity => no fused silica
- low thermal noise => no metals and no fused silica
- high breaking strength => exceptional surface quality

Silicon and sapphire emerged as interesting candidates.

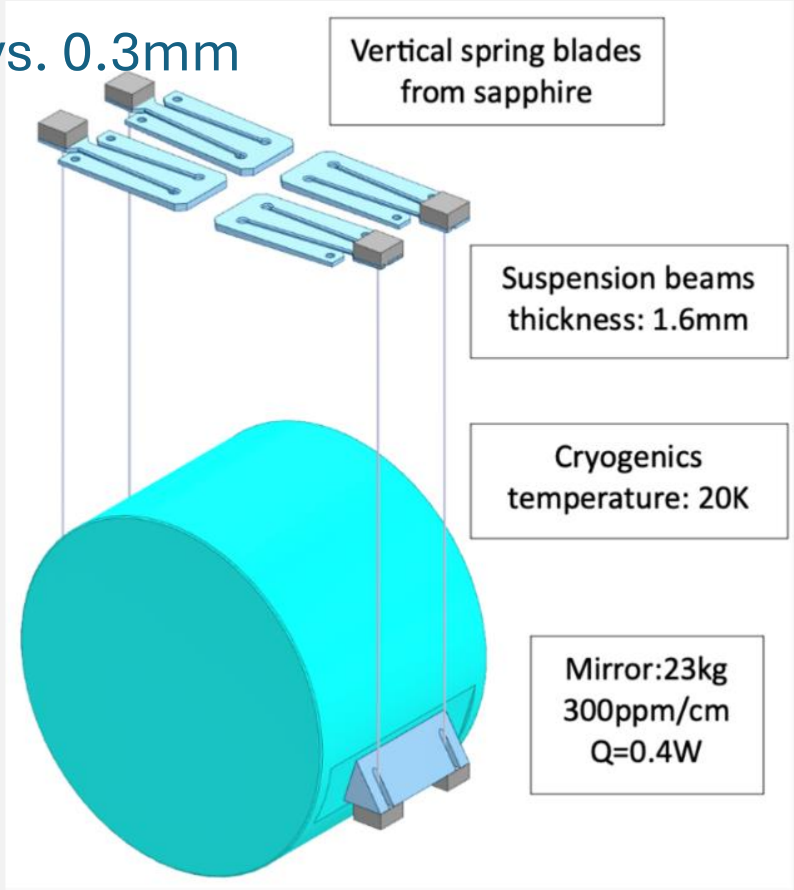


Fused silica vs. crystalline suspension



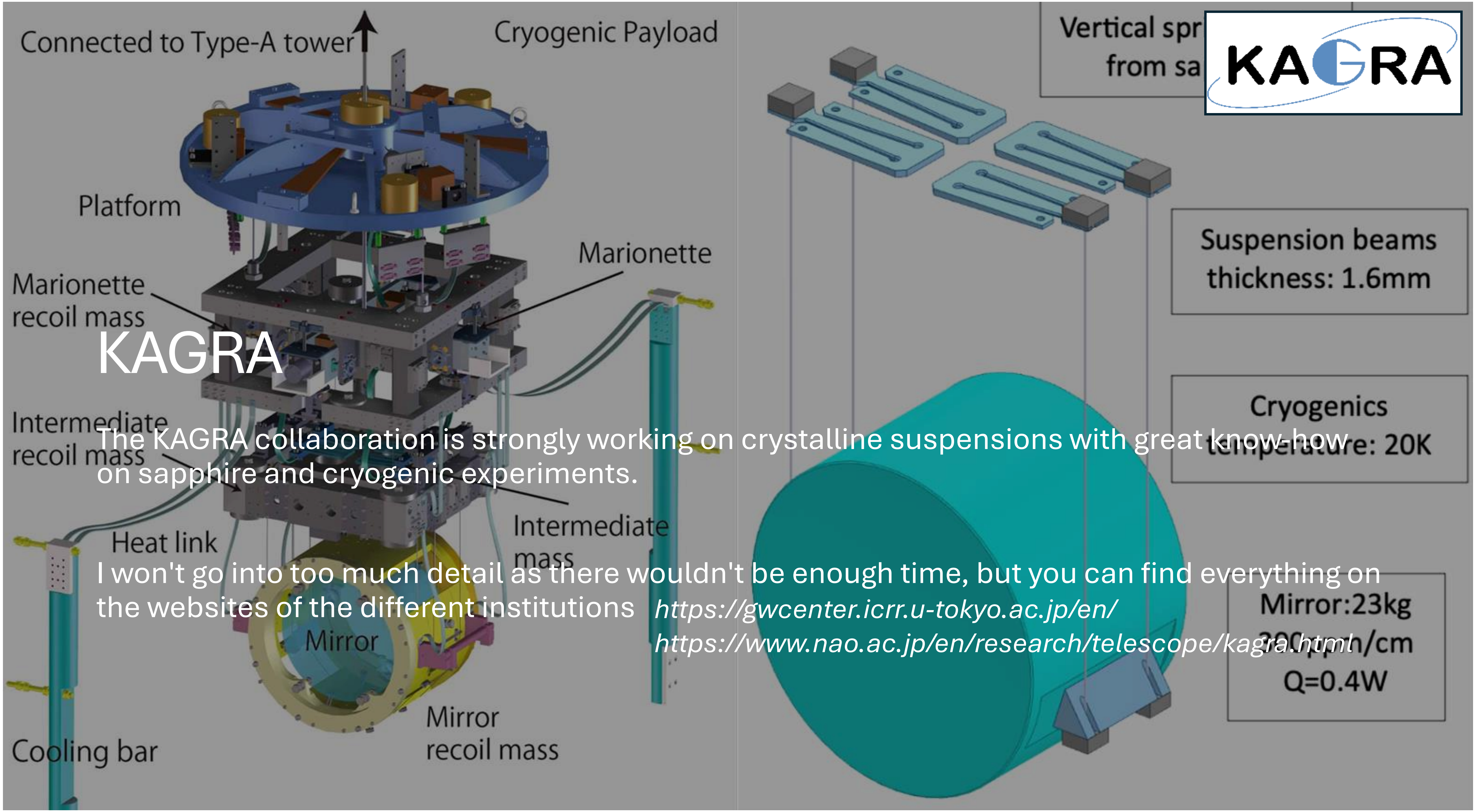


- Melting vs. growing => fiber and heads/anchors
- Elasticity vs. Rigidity => new tools and new procedure to avoid suspension breakage
  - Φ: 0.2mm vs. 3mm
  - Δl: 7.5mm vs. 0.3mm



Projects

KAGRA



KAGRA

The KAGRA collaboration is strongly working on crystalline suspensions with great know-how on sapphire and cryogenic experiments.

I won't go into too much detail as there wouldn't be enough time, but you can find everything on the websites of the different institutions *https://gwcenter.icrr.u-tokyo.ac.jp/en/* *https://www.nao.ac.jp/en/research/telescope/kagra.html*

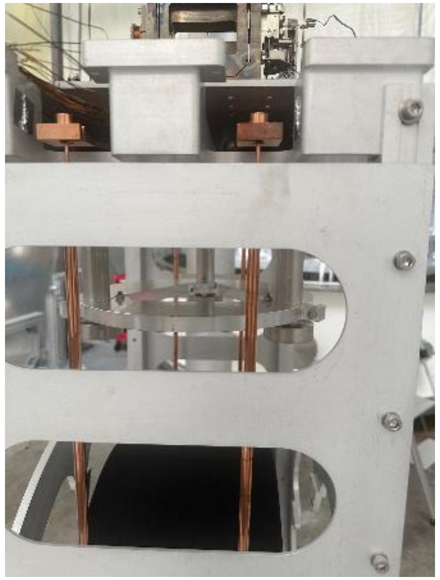
E-TEST

E-TEST in a nutshell

- Large silicon mirror (100 Kg)
- Cryogenic temperature (20 K)
- Radiative cooling
- Low frequency seismic isolation (10 mHz)
- Compact hybrid suspension (4.5 m high)

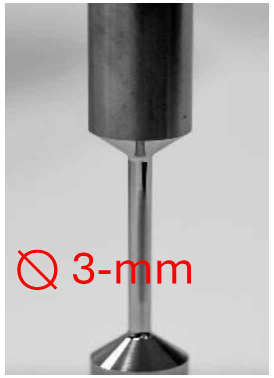
E-TEST

Currently, we use fibers in CuCrZr alloy

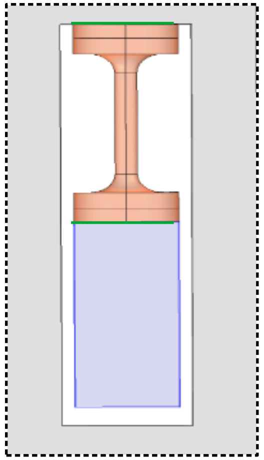


We are investigating

Improving the manufacturing process



Alternative design, based on fibers in compression



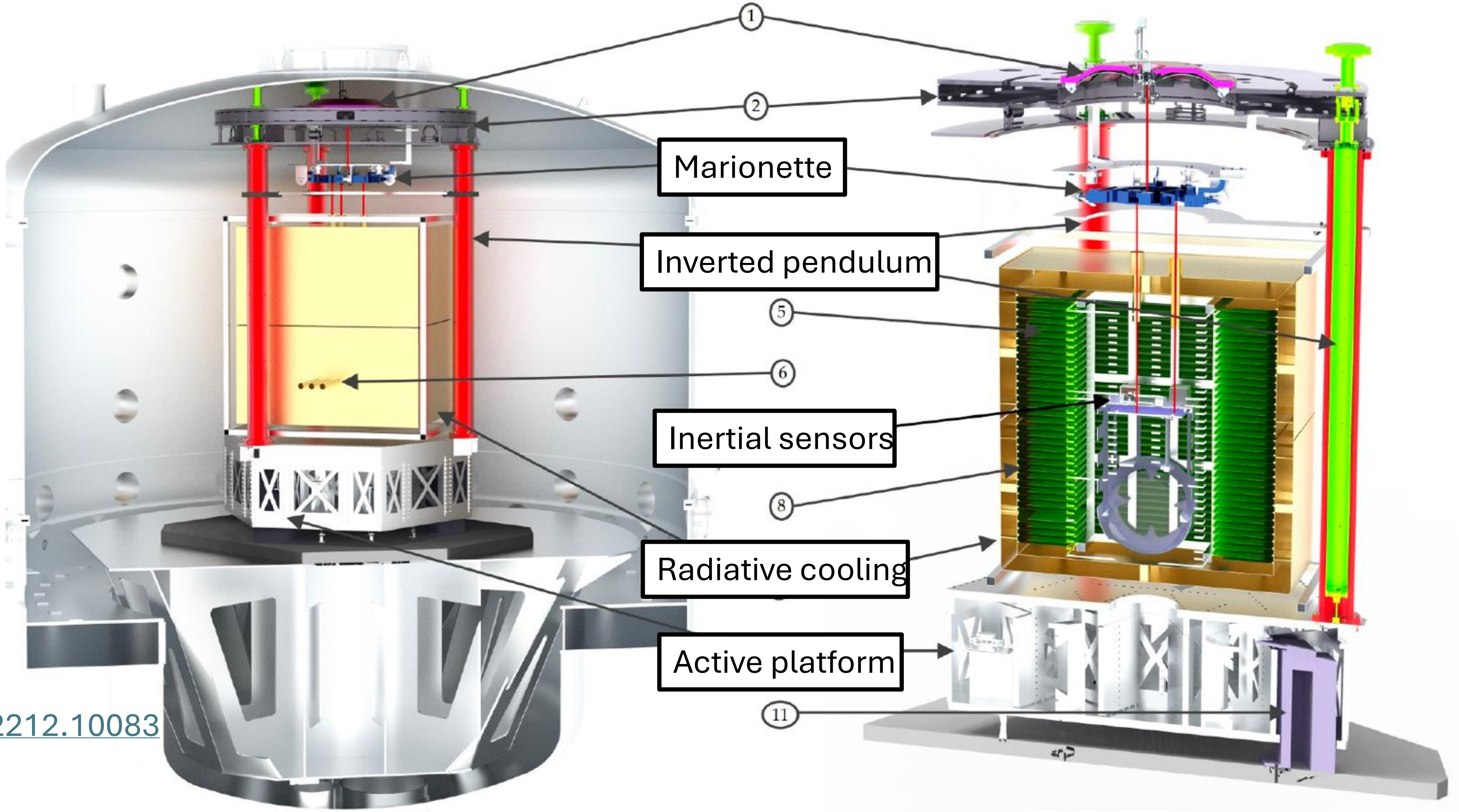
https://arxiv.org/abs/2212.10083

https://www.etest-emr.eu/prototype-2/

Conceptual design

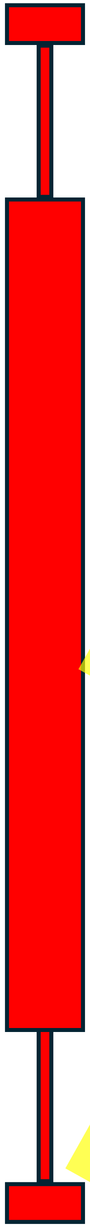
Submitted: 12/2021
Revised: 03/2022

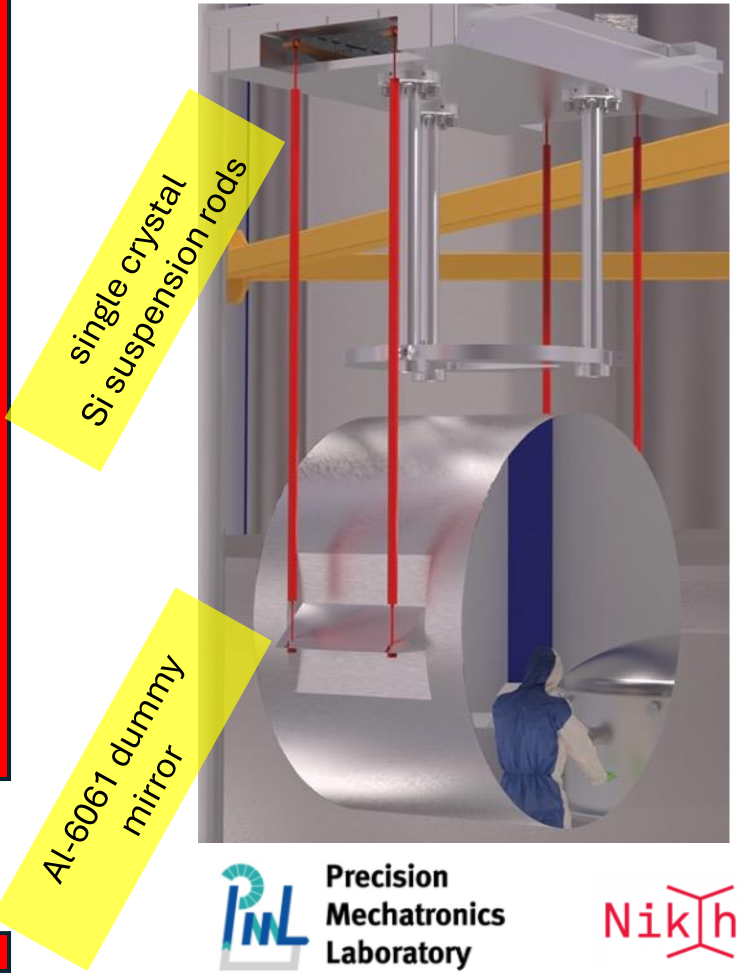
https://arxiv.org/abs/2212.10083

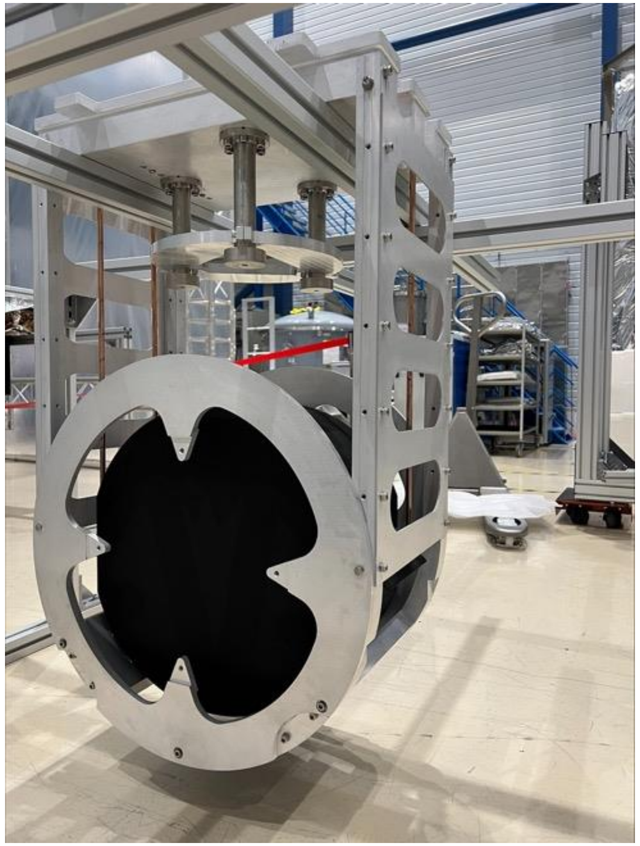


100 kg test mass & suspension

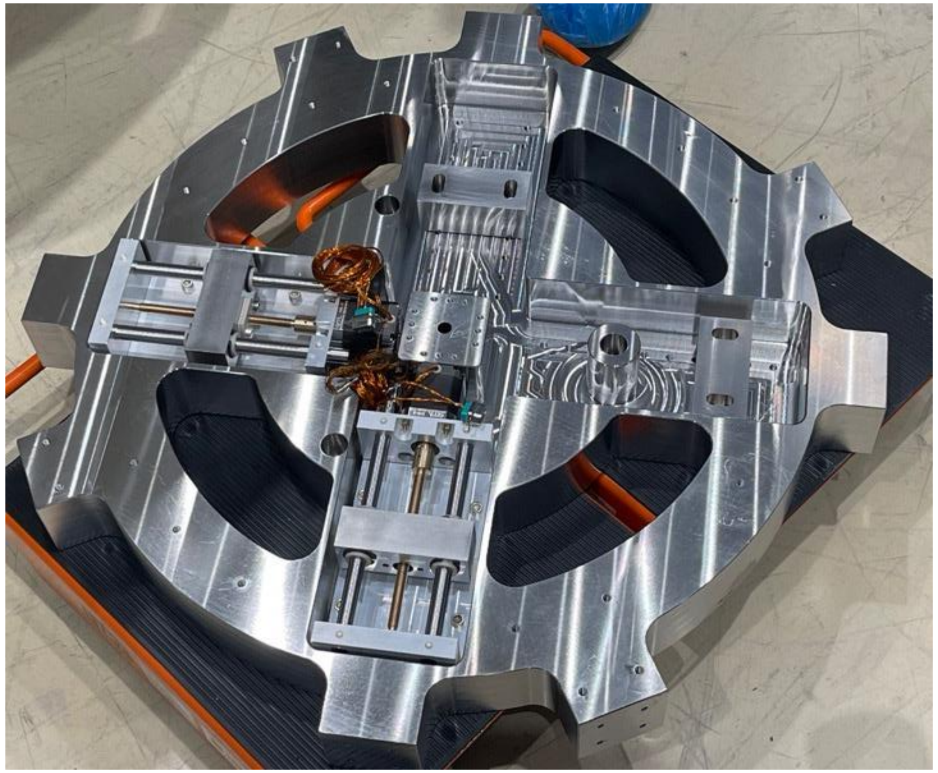
- Crucial technology aspect for ET: no proven solution exists
- Four machined samples delivered
- Silicon mirror ordered (delivery end of 2024)







Marionette



Contact: Alessandro Bertolini (Nikhef)
alberto@nikhef.nl

Precision Mechatronics Laboratory

Nikhef

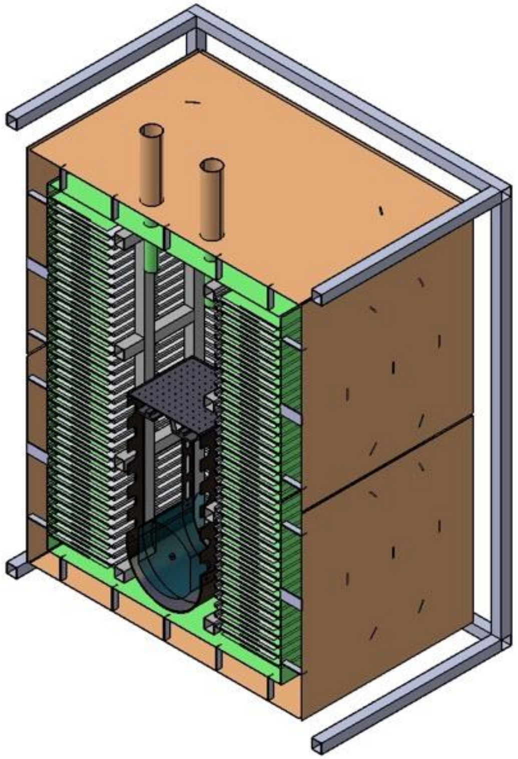
CSL CENTRE SPATIAL DE LIÈGE

UCLouvain

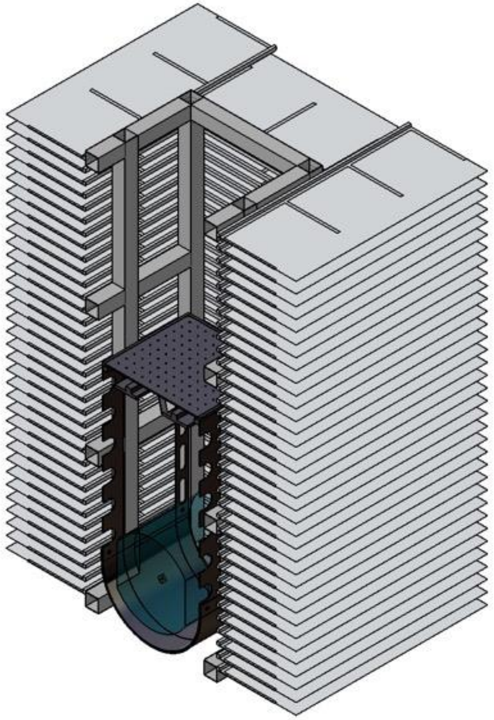
Cryostat development

- ✓ overall dimensions: 1.8 x 1.6 x 2 m^3
- ✓ conventional radiator design with horizontal fins (25K)
- ✓ three 30-mm diameter optical feedthroughs towards the mirror

CENTRE SPATIAL DE LIÈGE



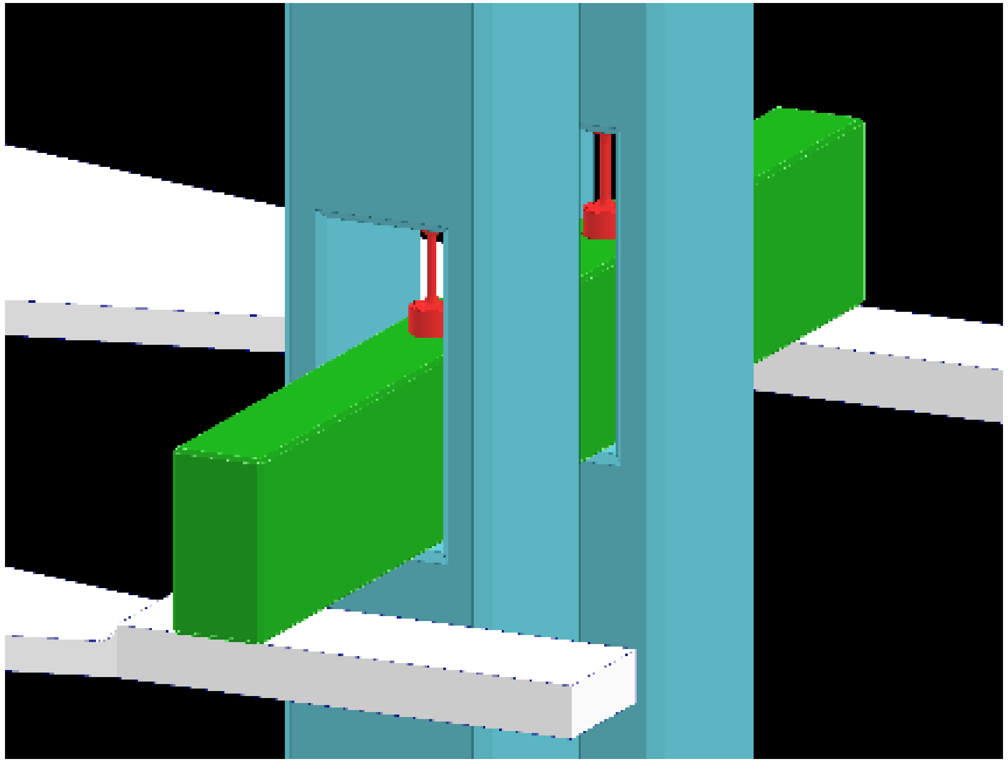
Outer cryostat:
80K LN2 shield (brown)
25K GHe panels (green)



Inner cryostat suspended and conductively linked to the silicon mirror

Contact: Cedric Lenaerts (CSL)
Cedric.Lenaerts@uliege.be

Suspension in compression



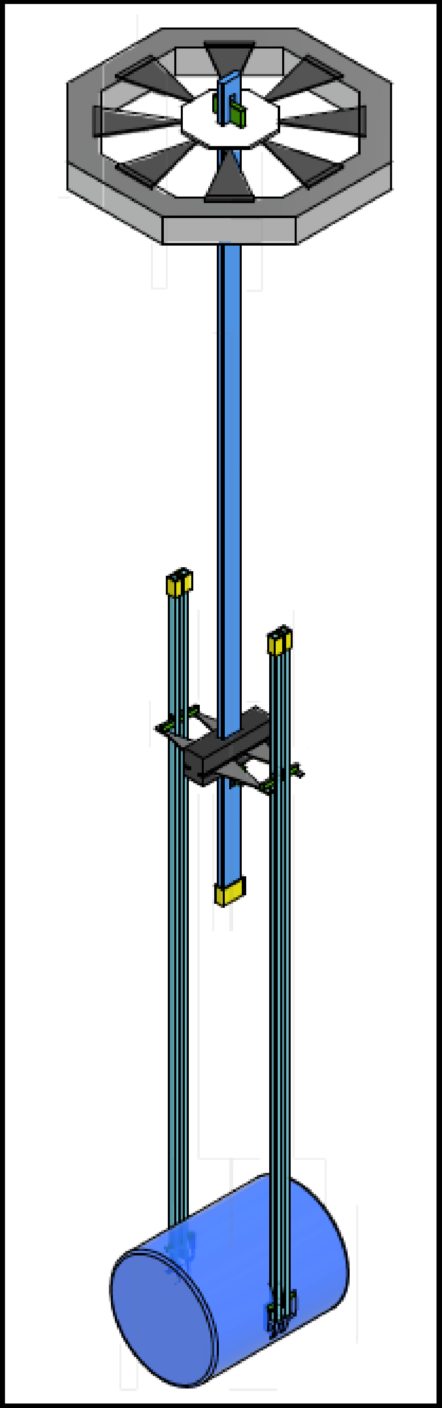
Cryogenic suspension with flexures in compression

Fabián Peña, Nelson Leon, Leonardo González,

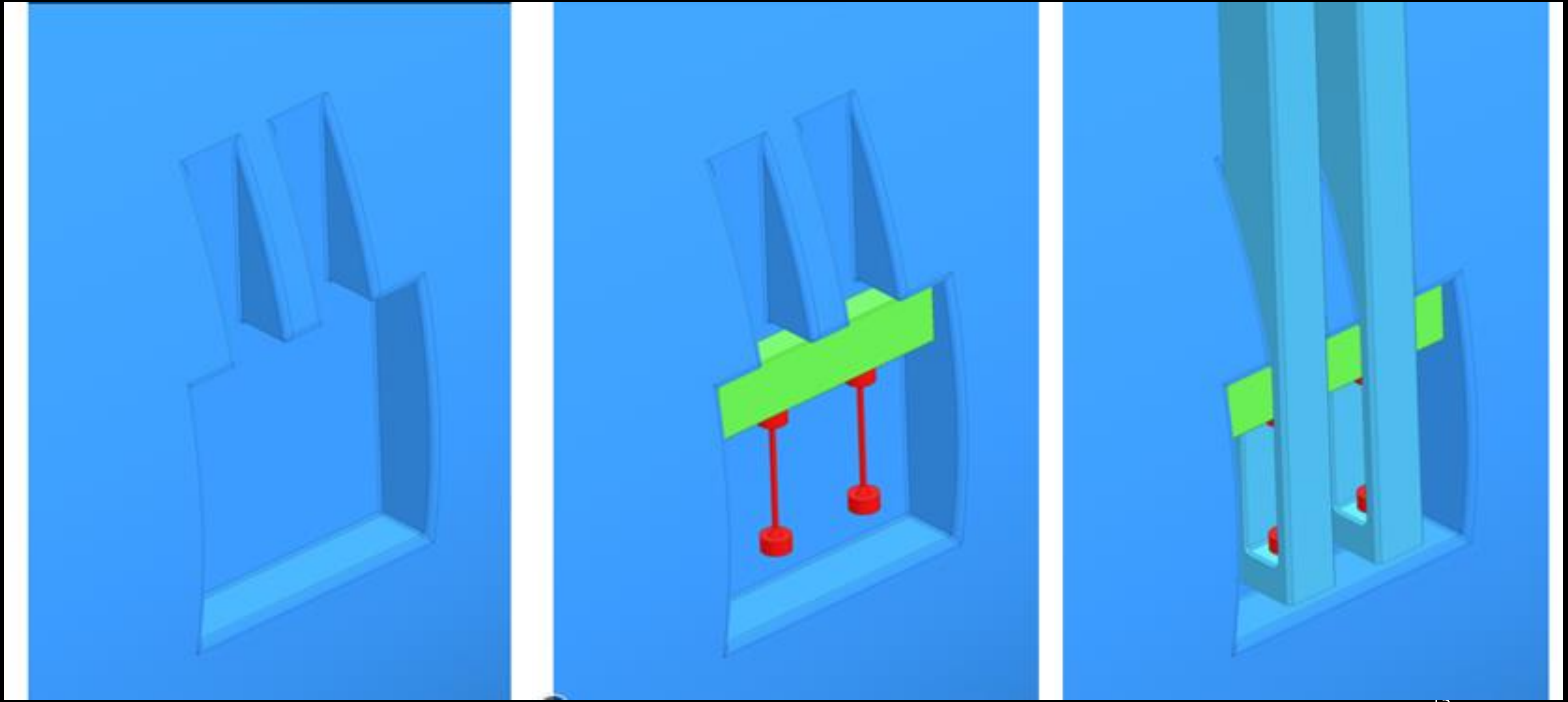
Harry Themann, Riccardo DeSalvo,

University of Guadalajara, California State University,

University of Salerno.



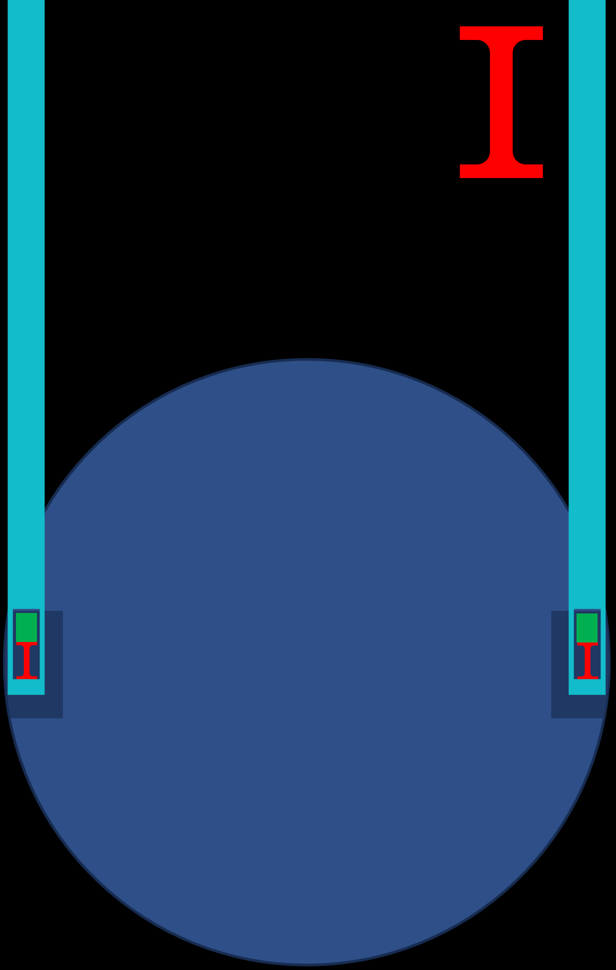
Hardware configuration



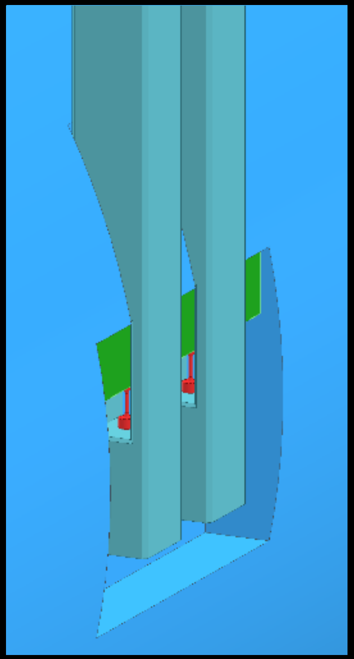
Hardware configuration

- Mirror
- Cross beam
- Side Feature
- Flexures
- Suspension beams

Side view



Front cross section view

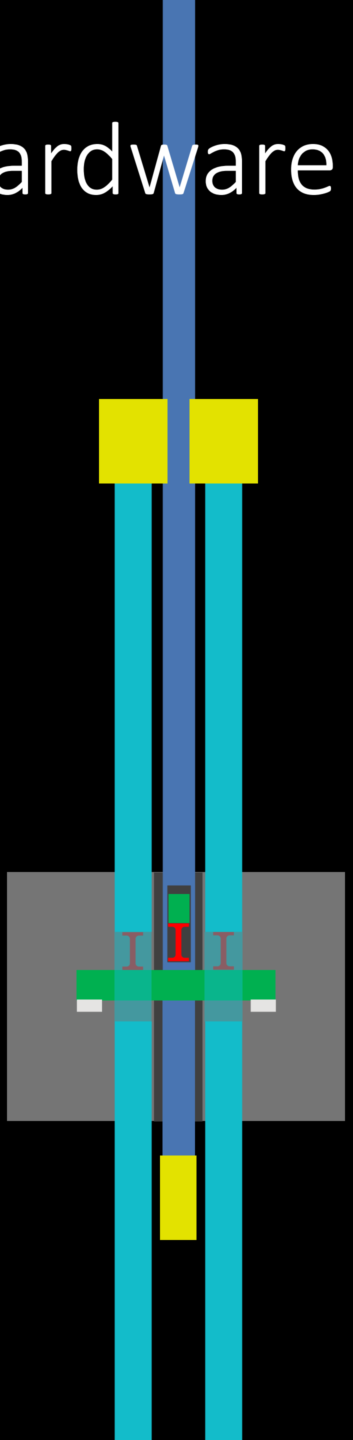


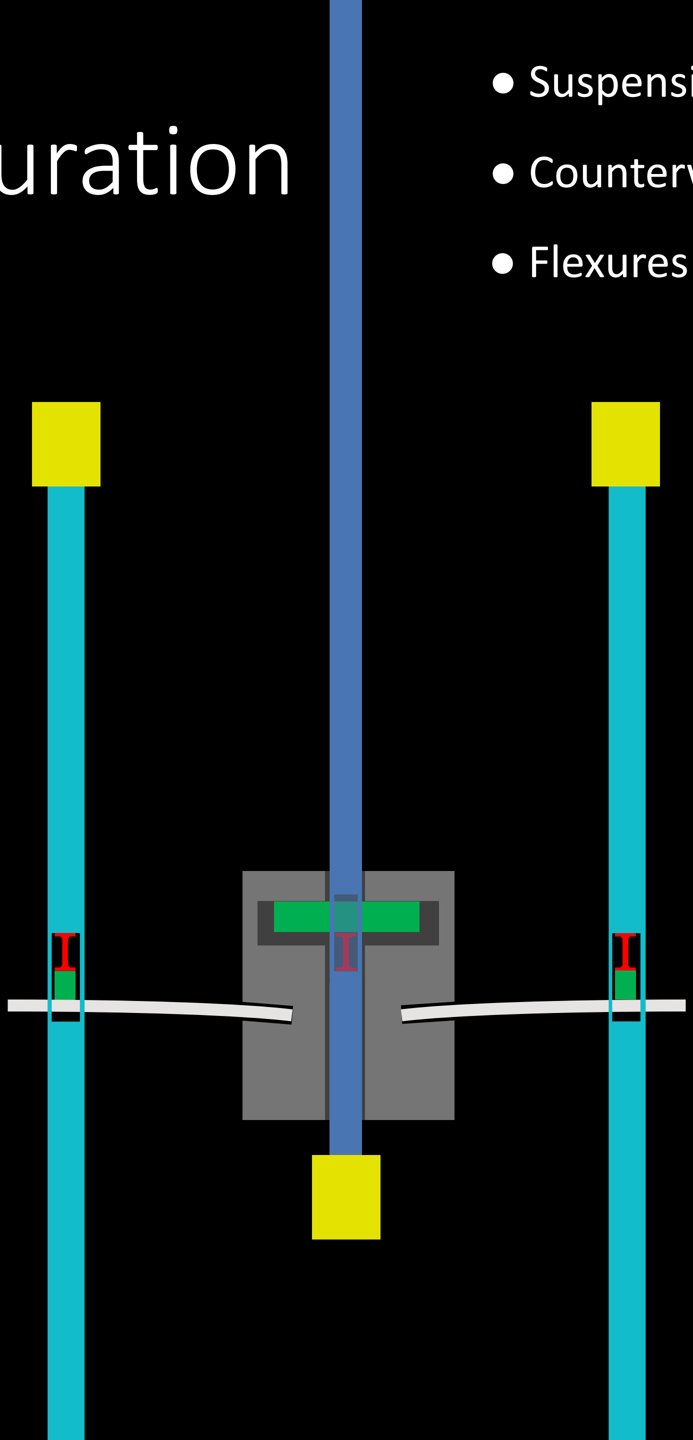
Mirror side 3D-CAD

Hardware configuration

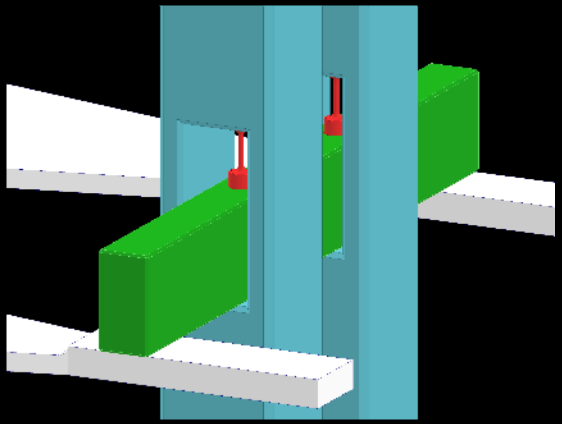
- Suspension beams
- Counterweight
- Flexures

- Cross beam
- Spring blades
- Intermediate body



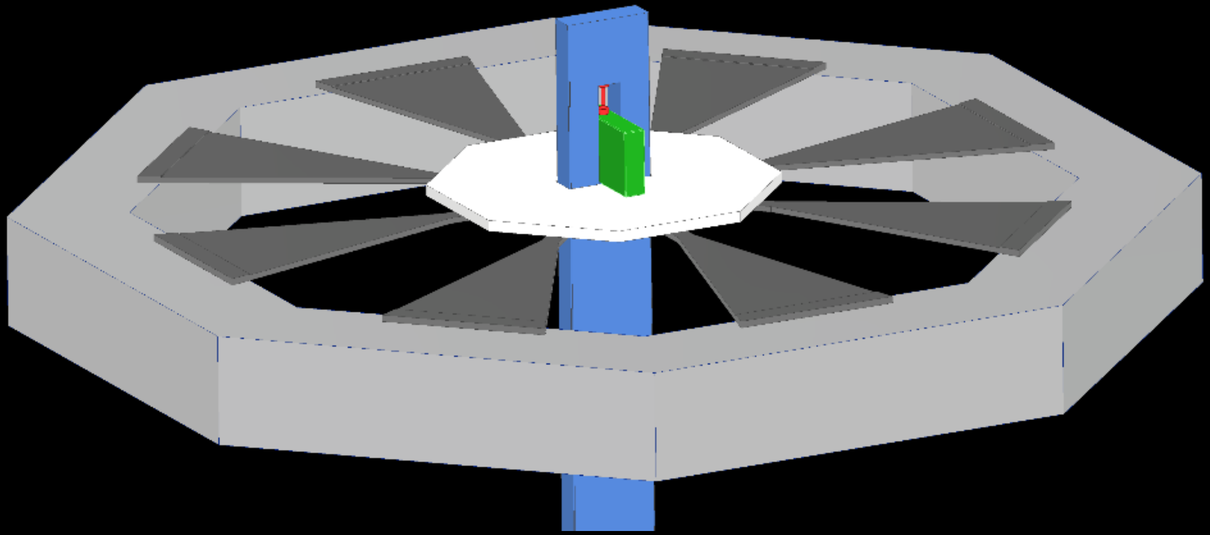


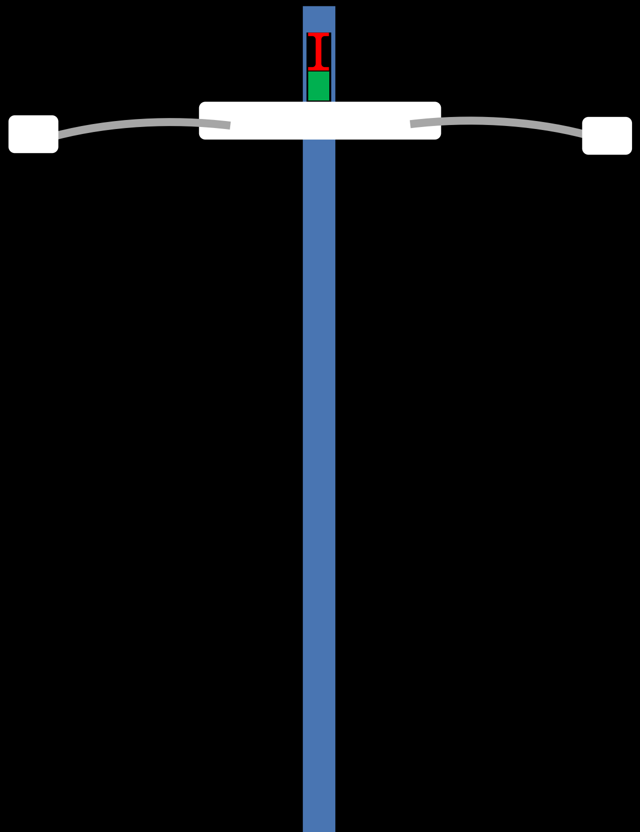
- Cross beam
- Flexure
- Suspension beam
- Counterweight

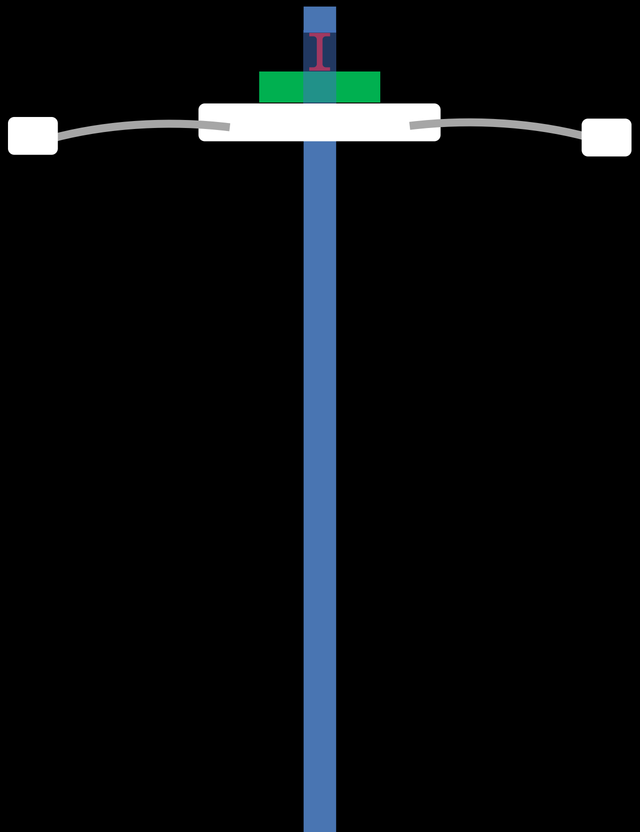


3D-CAD

Hardware configuration



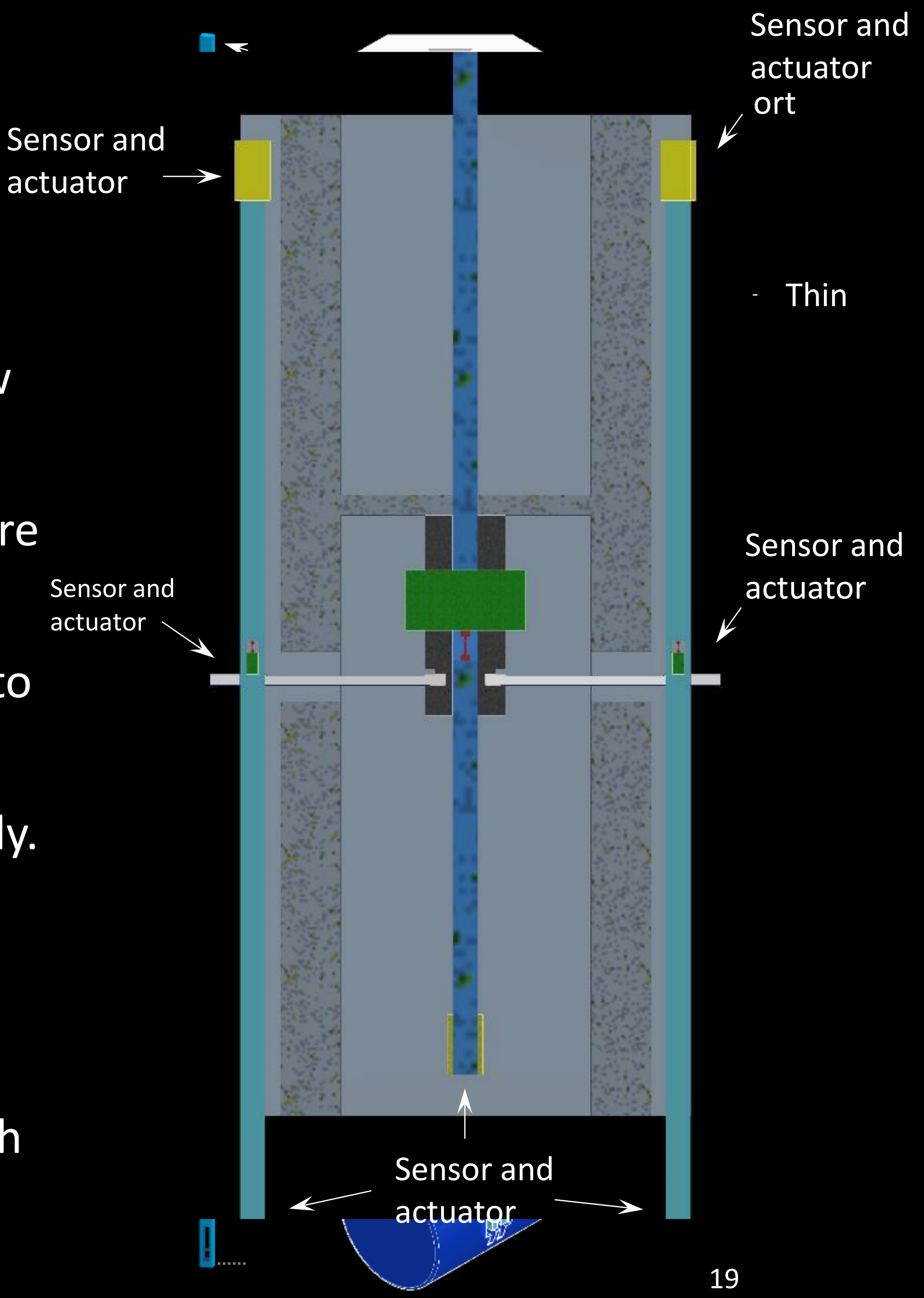




- Suspension beam
- Flexure
- Cross beam
- Vertical filter

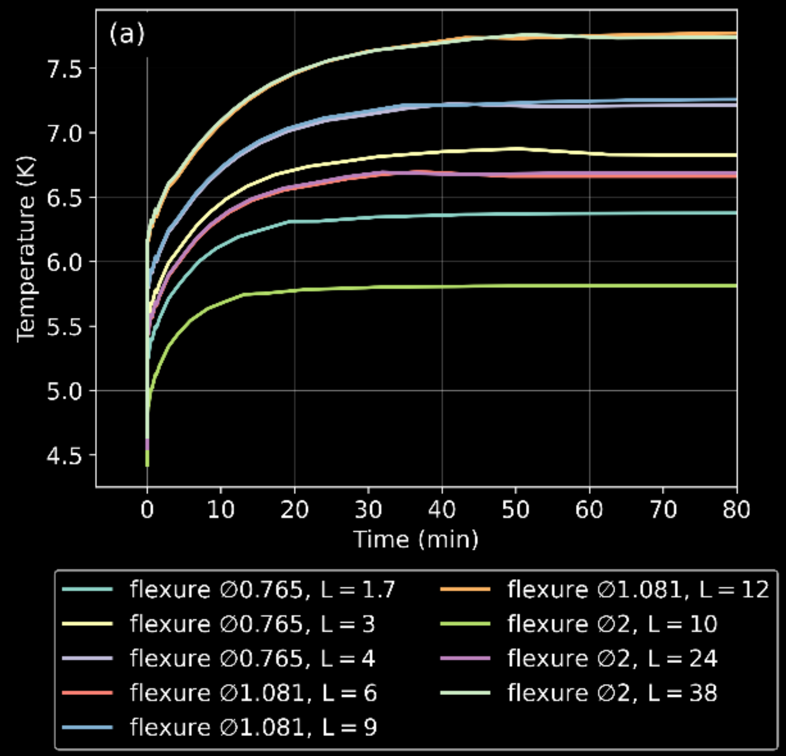
Key element: a short and thin flexure

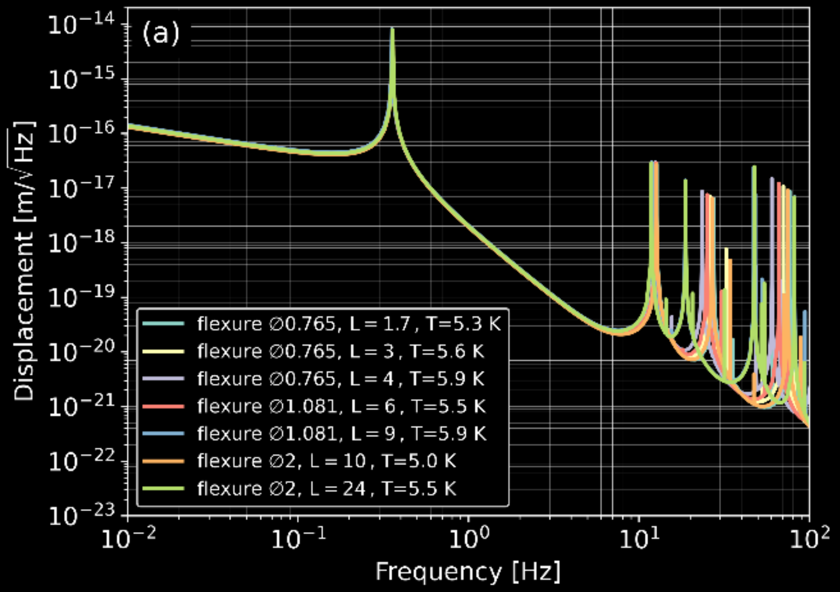
- Suspension is achieved with large cross-section beams:
  - Low tensional stress and low thermal resistance.
  - Hinged with soft thin flexures to produce a pendulum with a low resonant frequency.
  - With counterweights to modify mechanical behaviour (e.g. centre of percussion effect)
- Flexures work in compression to avoid silicon fragility and are short to achieve low thermal resistance.
- Joints in compression with brazing for easy assembly and disassembly.
- Active control systems can be used from an Intermediate Mass:
  - Active damping of resonant modes.
  - Lock acquisition and general control without a recoil mass.
  - Possible dynamic lowering of pendulum resonant frequency with optical springs.



Performance

- Safety factor maintained above 6 everywhere.
- Can use ^{28}Si in flexures (10 × thermal conductivity).
- Expected working temperature around 10K.
- Fast response to beam power change due to active control system.
- Beam resonances can be actively damped down to around local sensor sensitivity.
- Thermal noise may be shifted further below GW detection threshold if optical anti-springs are successful in lowering the pendulum resonant frequency.
- So far, we have only analyzed one suspension pendulum:
    - Load Temperature: 6.6 K.
    - Displacement thermal noise: $1\times10^{-19}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 3 Hz.
    - We'll be doing calculations with the two-level payload soon.



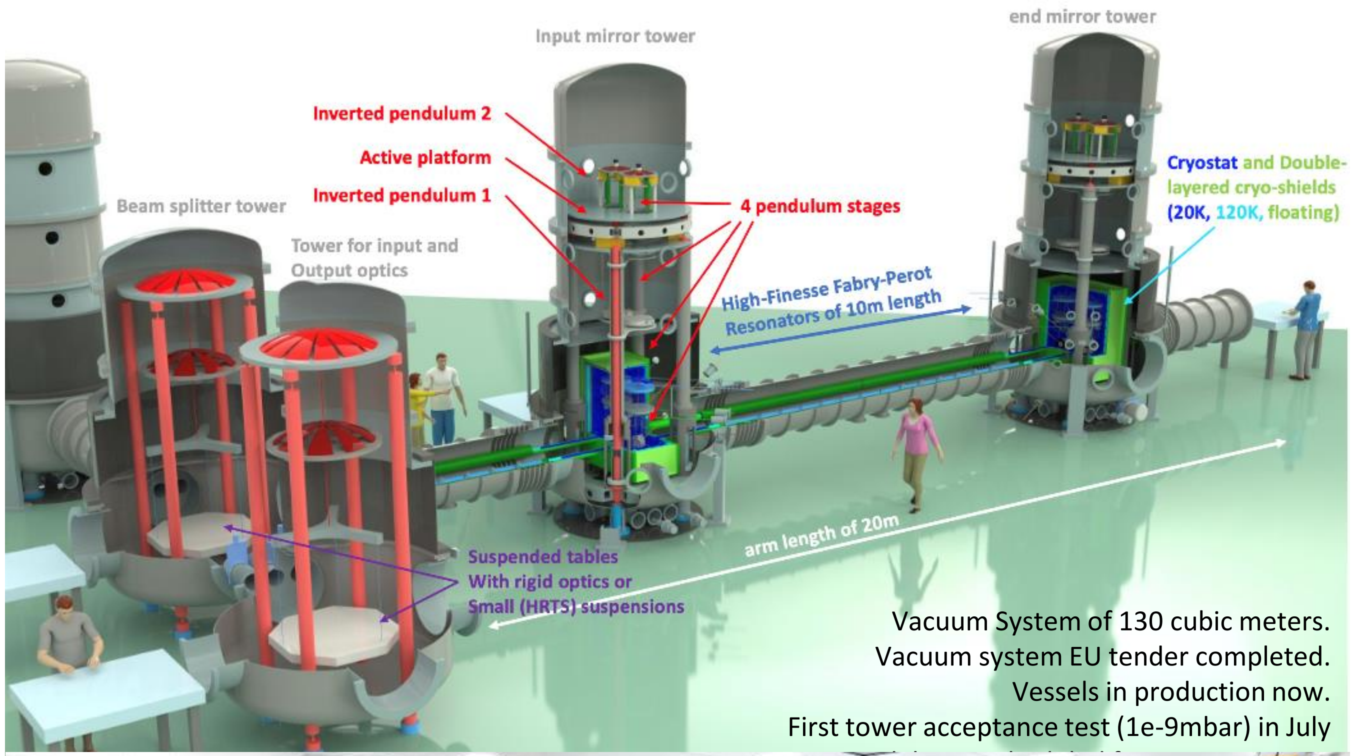


ETPathfinder

ETpathfinder

ETpathfinder Overview

- New facility for testing ET technology in a low-noise, full-interferometer setup.
- Key aspects: Silicon mirrors (3 to 100+kg), cryogenics   cryogenic liquids and sorption coolers, water/ice management), “new” wavelengths (1550 and 2090nm), coatings …
- Start with 2 FPMI, one initially at 120K and one 15K
- 20+ partners from NL/B/G/FR/SP/UK/PL
- Initial capital funding of 14.5 MEuro.
- Detailed Design Report available at apps.et-gw.eu/tds/?content=3&r=17177
- Open for everyone interested to join.
- www.etpathfinder.eu

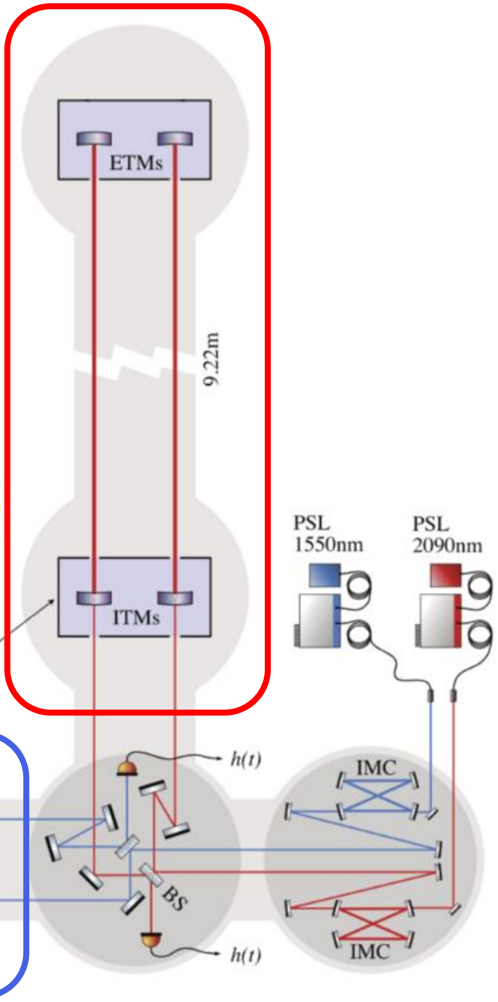


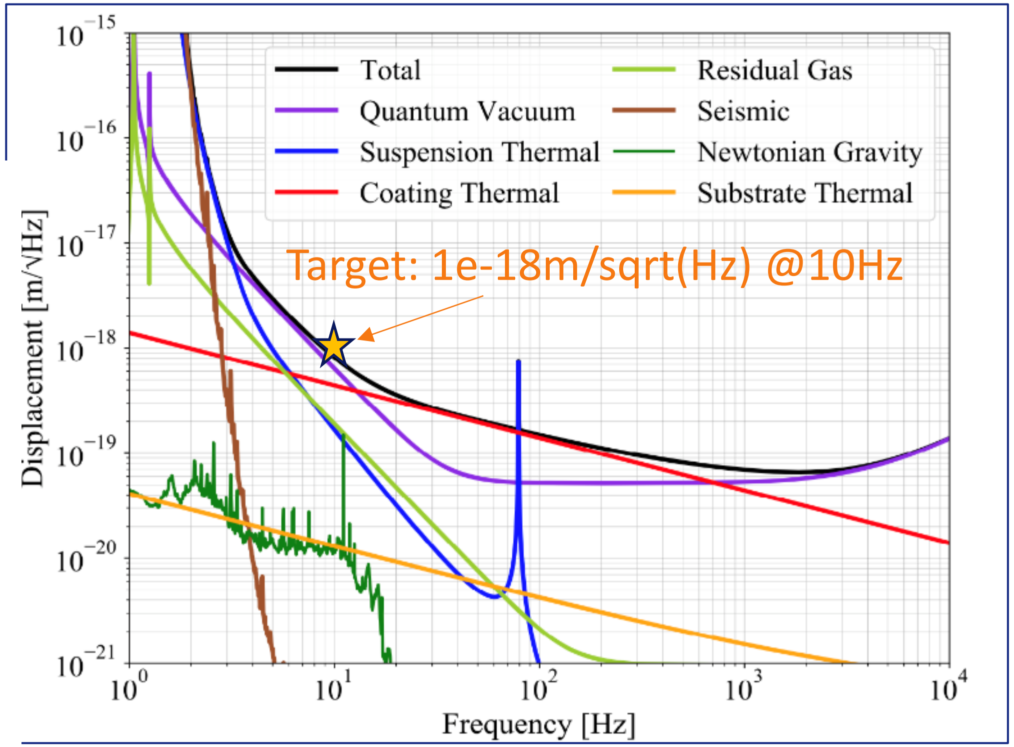
Vacuum System of 130 cubic meters.
Vacuum system EU tender completed.
Vessels in production now.
First tower acceptance test (1e-9mbar) in July

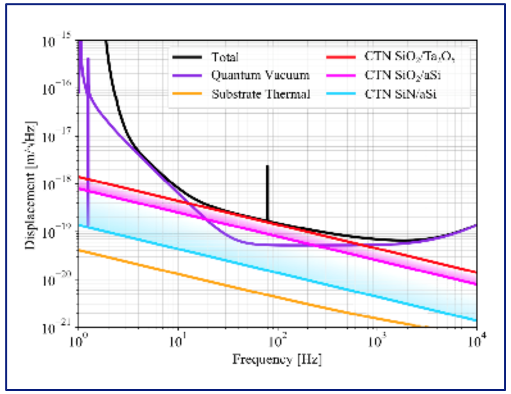
Building 2 FPMI interferometers

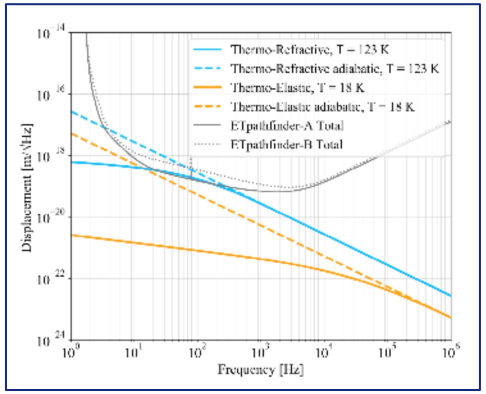
2 FPMI interferometers:

1) **123K --- cooled radiatively, metal wire suspension, targeted 2025**
2) **15K --- cooled via conduction, silicon suspension needed 2026**



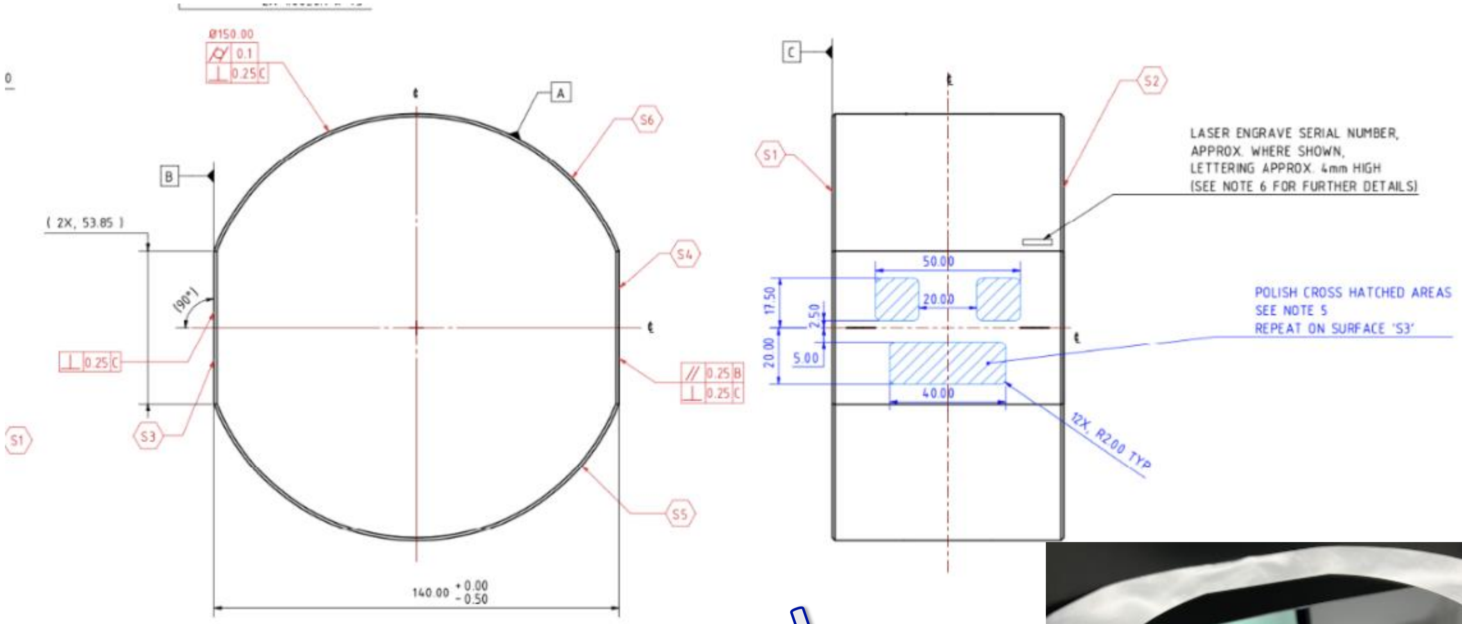




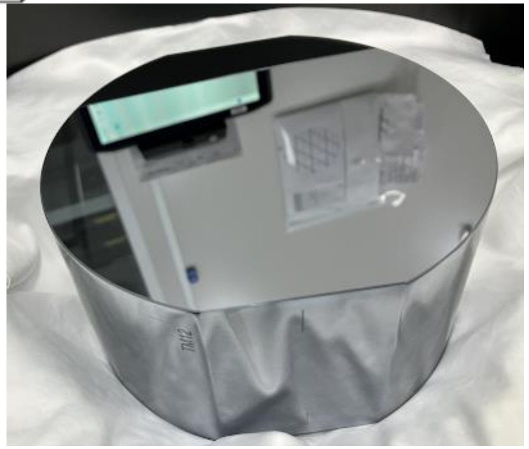


Need: Silicon suspension for 3kg mirrors

- **Looking for a collaboration to develop slicon suspension for our pristine 3kg mirrors.**
- Nikhef and UM are already overloaded with other aspects of Etpathfinder (and Virgo, ET…), so we will not be able to have a large team to take the lead here.
- Can contribute 1 postdoc or phd-student (TBD) and 250k for materials.
- Mirrors (produced by Zeiss) come with polished flats offering different configurations (see blue shaded area).



Anyone interested to help?



CAOS

What can be tested/developed?

1. Crystalline suspension phase I: aluminum substrate with crystalline inserts and fibers

- to test the suspension assembly procedure and define the necessary tools
- to test the payload joining procedure to the SA
- to define the controls and safety structures/tools

2. Crystalline suspension phase II: complete crystalline suspension???

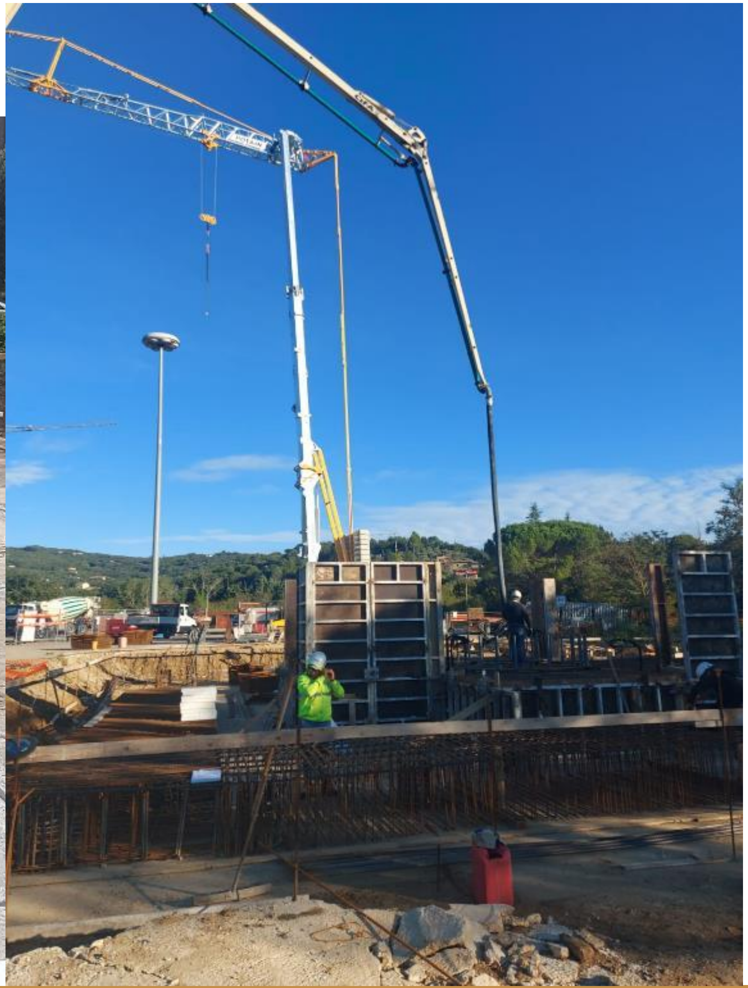
- Specifications and needs to be defined

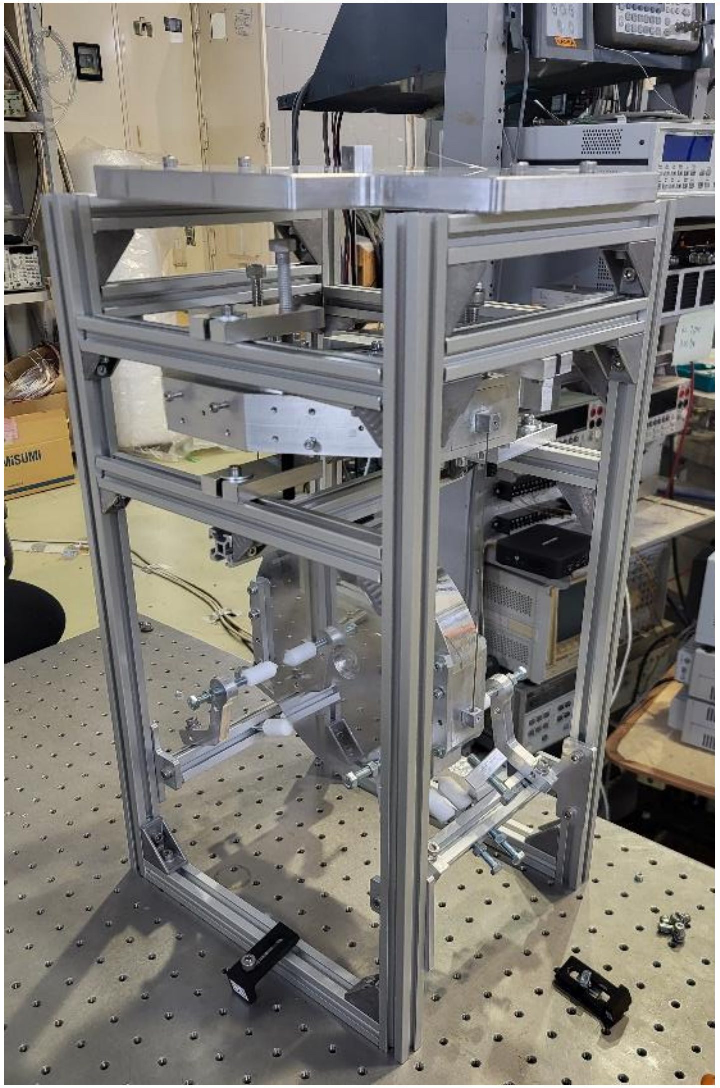
3. Any other idea

- CAOS can really be a test place for any new idea and a training point for students and young researchers

https://web.infn.it/einsteintelescope/index.php/it/home-it-it/infrastrutture-e-labs/caos

Construction statuts





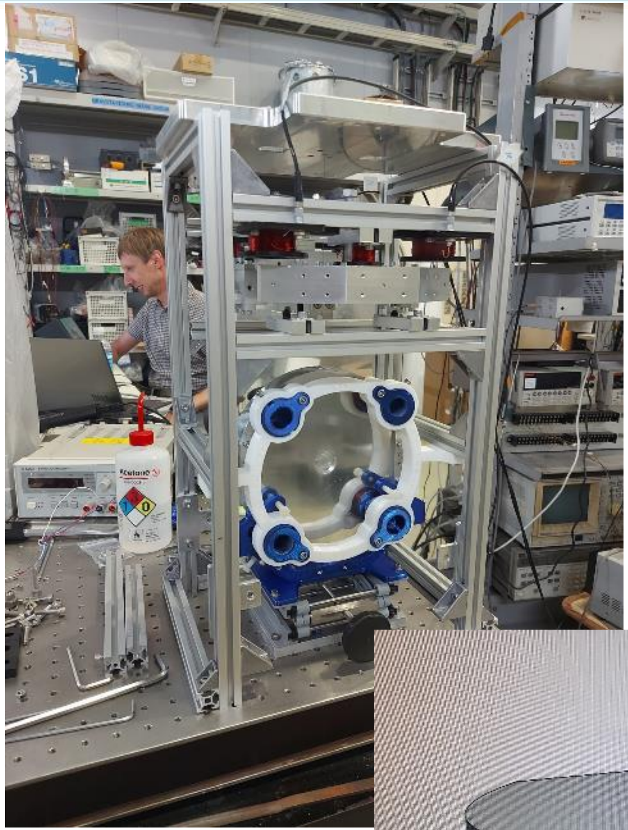
Work at ICRR

1. Crystalline suspension phase I: aluminum substrate and marionetta with aluminum wires

- to test the suspension assembly procedure and define the necessary tools
- to test the controls at room temperature and at cryogenic temperature

2. Crystalline suspension phase II: aluminum substrate and marionette with silicon inserts and silicon fibers

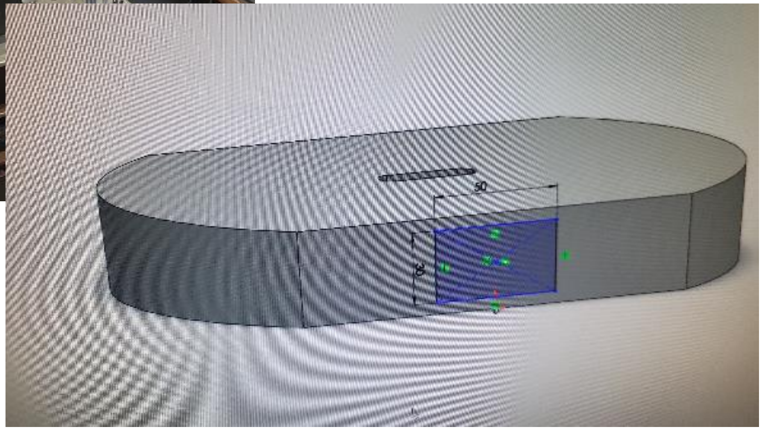
- Specifications and needs to be defined

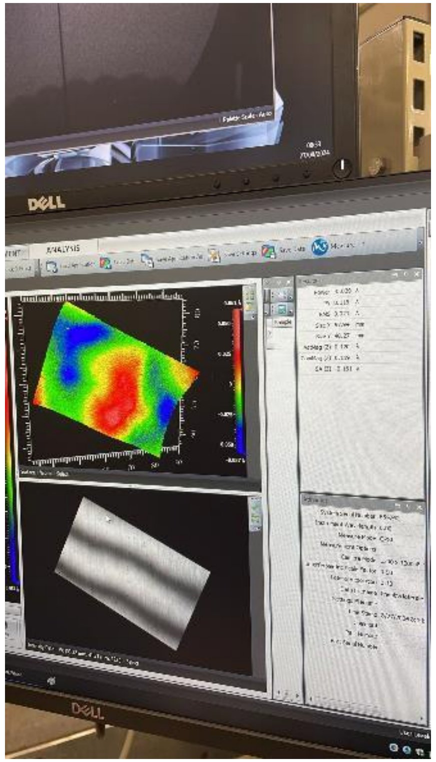


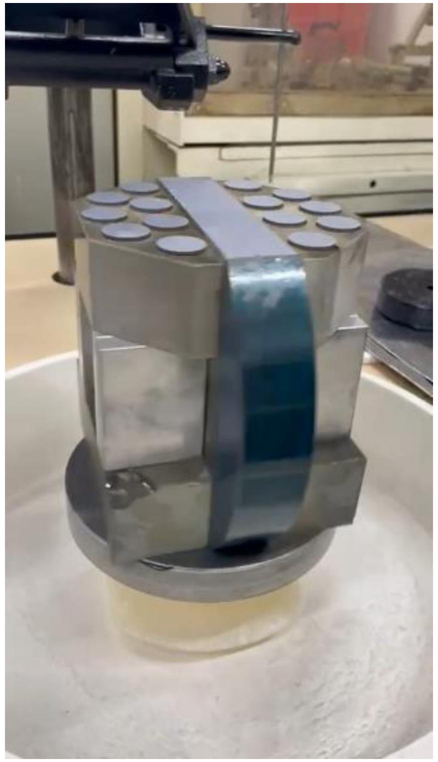
Work at ICRR

3. Crystalline suspension phase III: everything in silicon

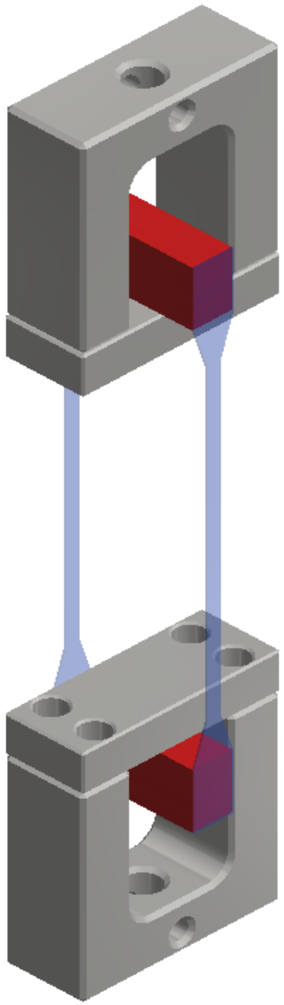
- Specifications and needs to be defined





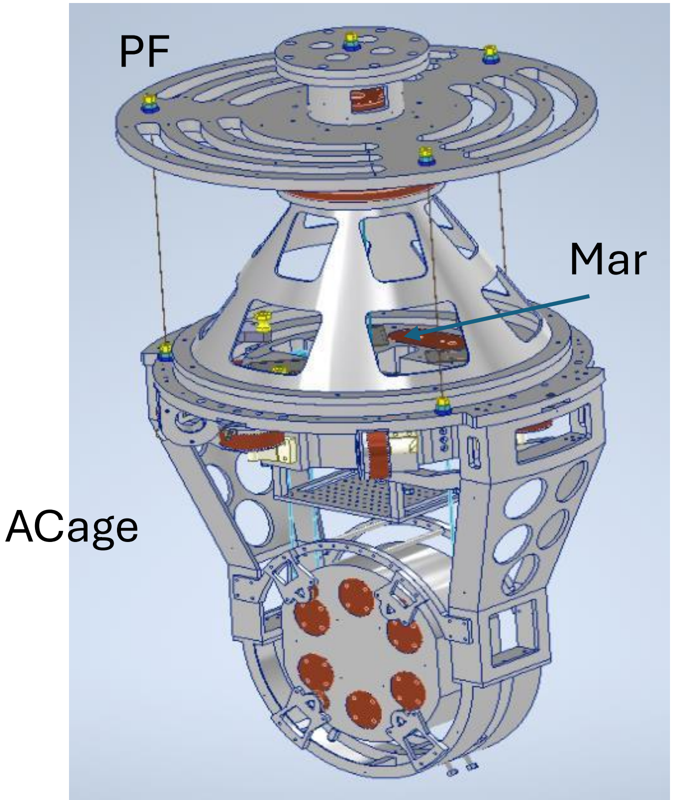


Amaldi Research Center (ARC)



ARC

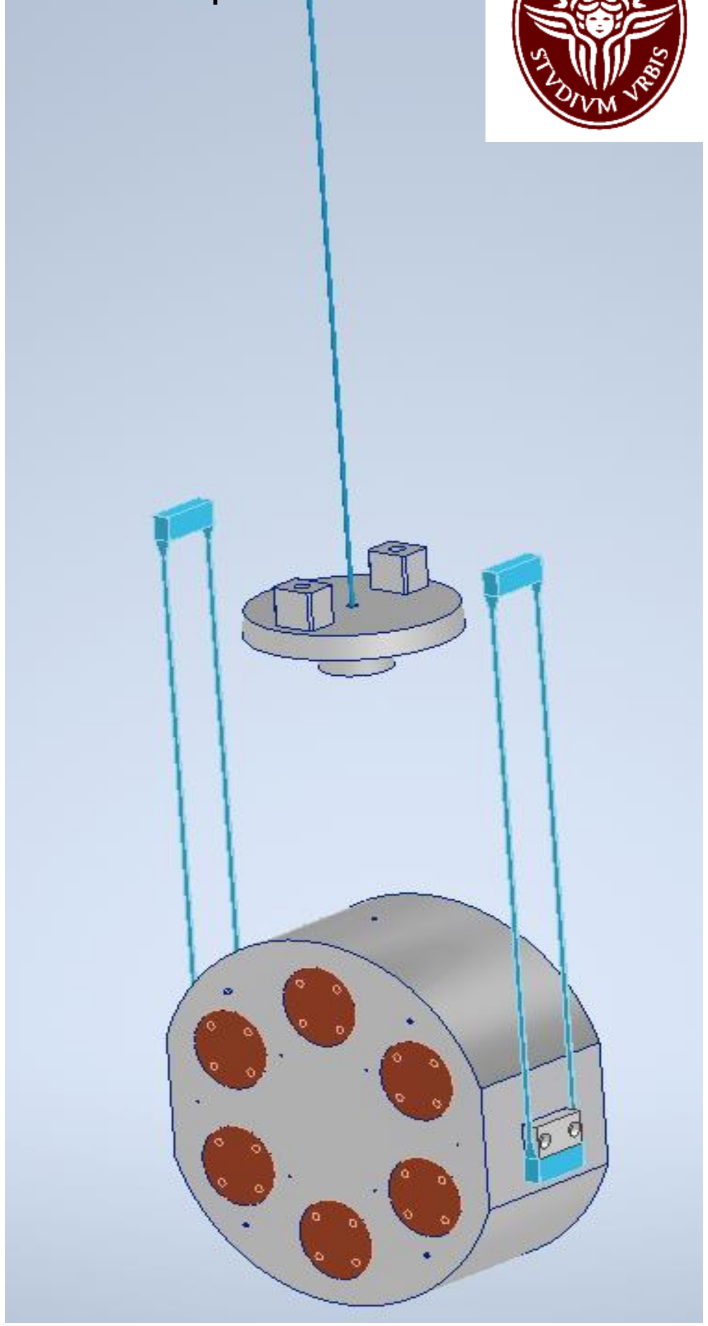
In ARC lab in Rome «La Sapienza”
- ~1:1 payload prototype designed and currently under construction
- Uses solid conduction and soft heat links.
- No seismic isolation system, hosted in a 3m dia cryostat.
- The main focus is on sapphire, due to its favourable mechanical properties, but also Si suspensions can be adopted.



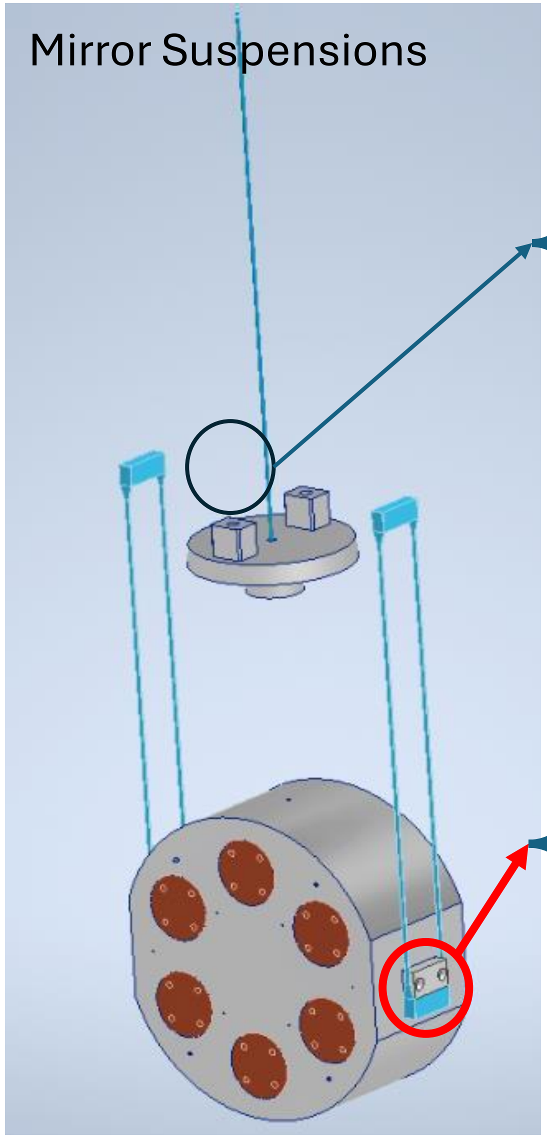
-Mir ~125kg (0.45m dia)
-Mar ~125kg

-Mar-PF CoM2CoM ~0,8m
-Mar-Mir CoM2CoM ~0,7m
-initially, no blades
(we have just the central part, to be tested)

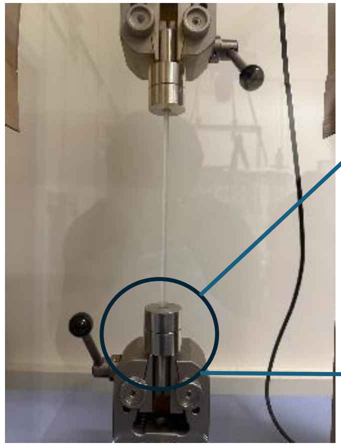
Mirror Suspensions

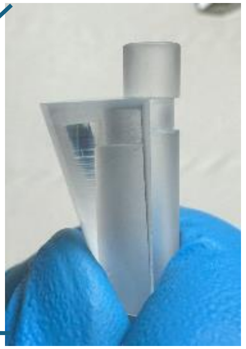


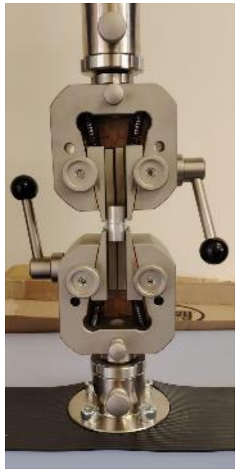
ARC



Testing new mechanical lock for the marionette

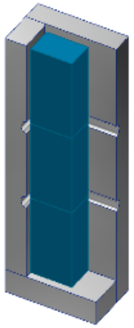




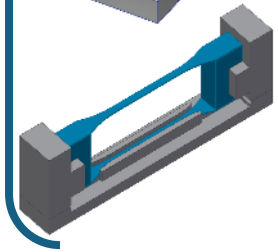


We are also considering the use of glues such as Sumiceram or Stycast.

1. Bonding Phase (HCB)

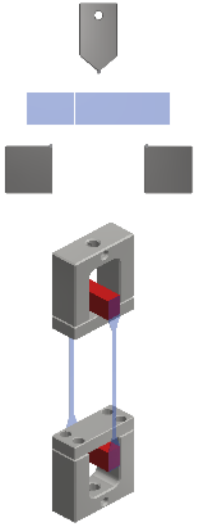


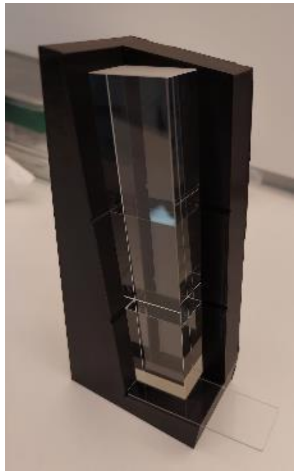
3 Blocks



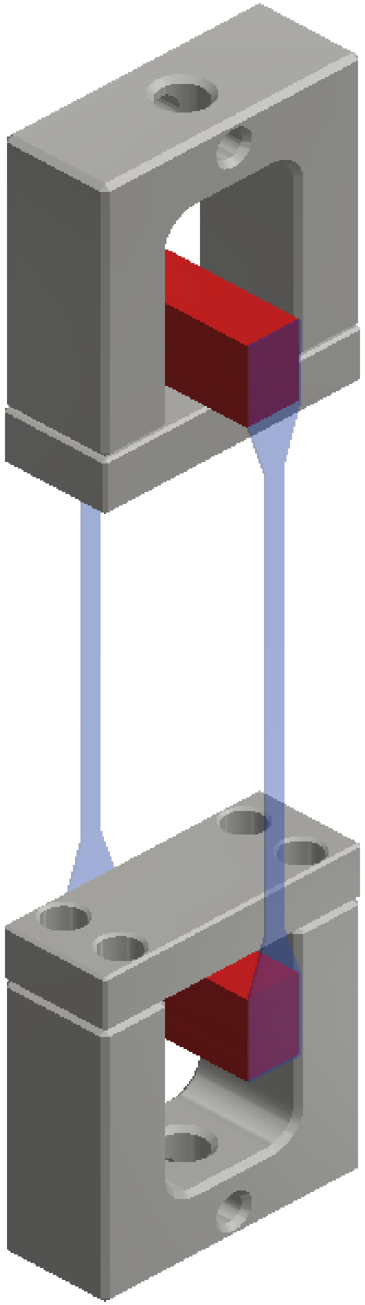
Ribbons + blocks

2. Testing Phase





Bonding phase ongoing (Glasgow collab)



https://web.infn.it/einsteintelescope/index.php/it/home-it-it/infrastrutture-e-labs/arc-etcryo

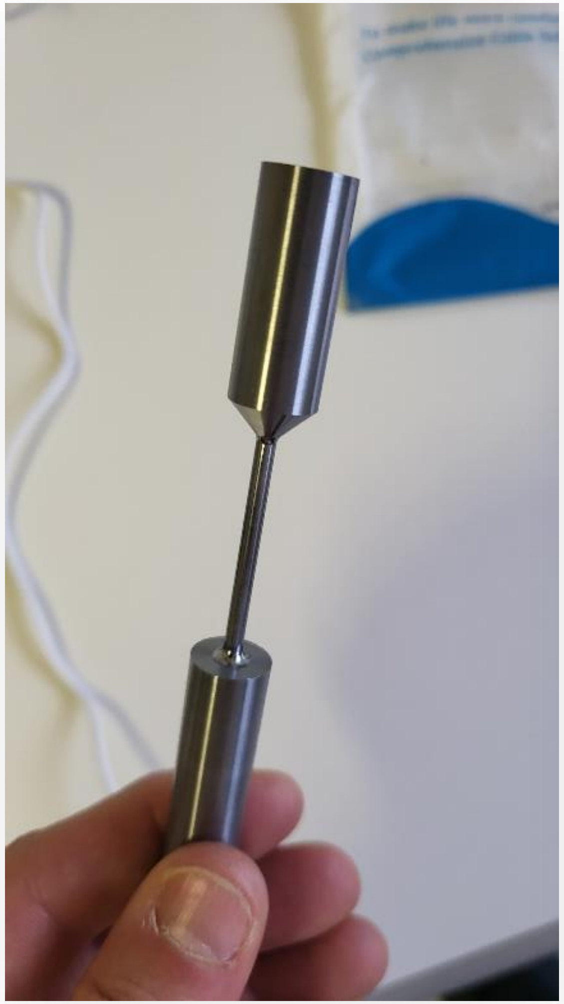
Production

Wielands UPMT

SILICON JOINTS

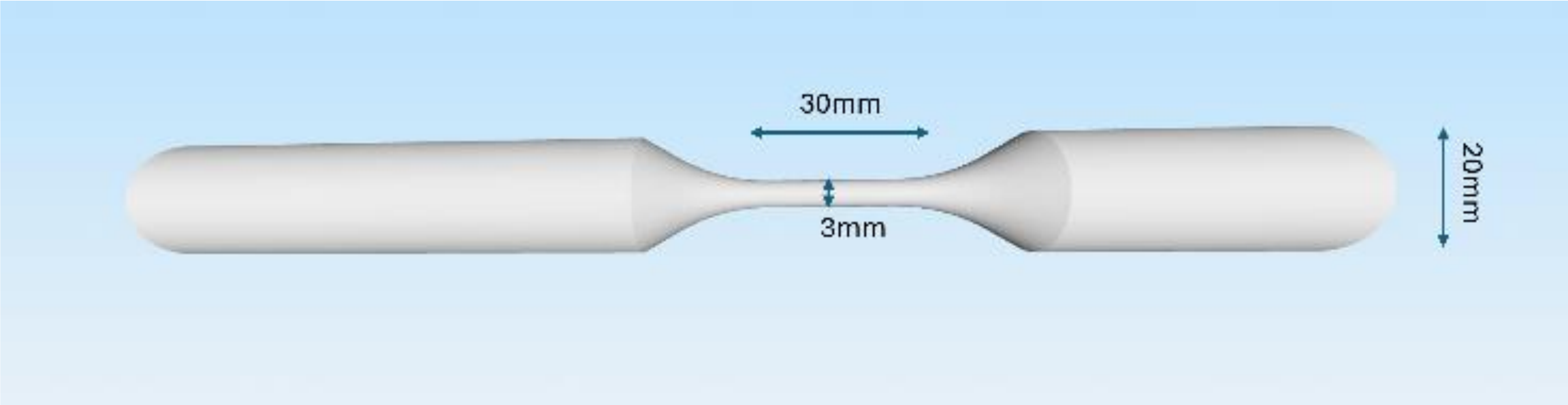
Nikhef

Wielandts upmt

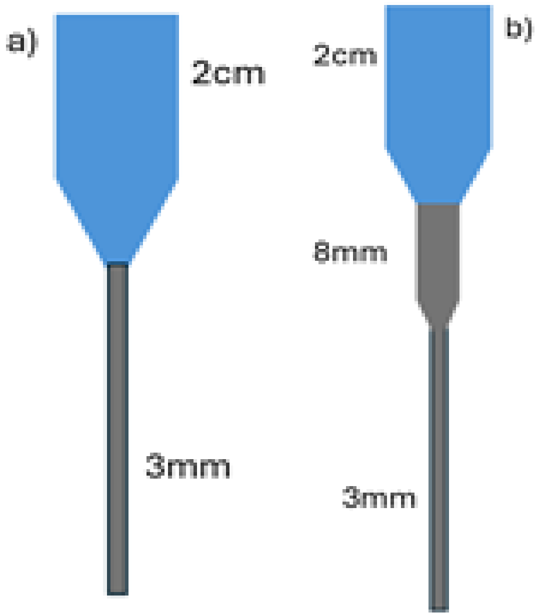


EFIBER project

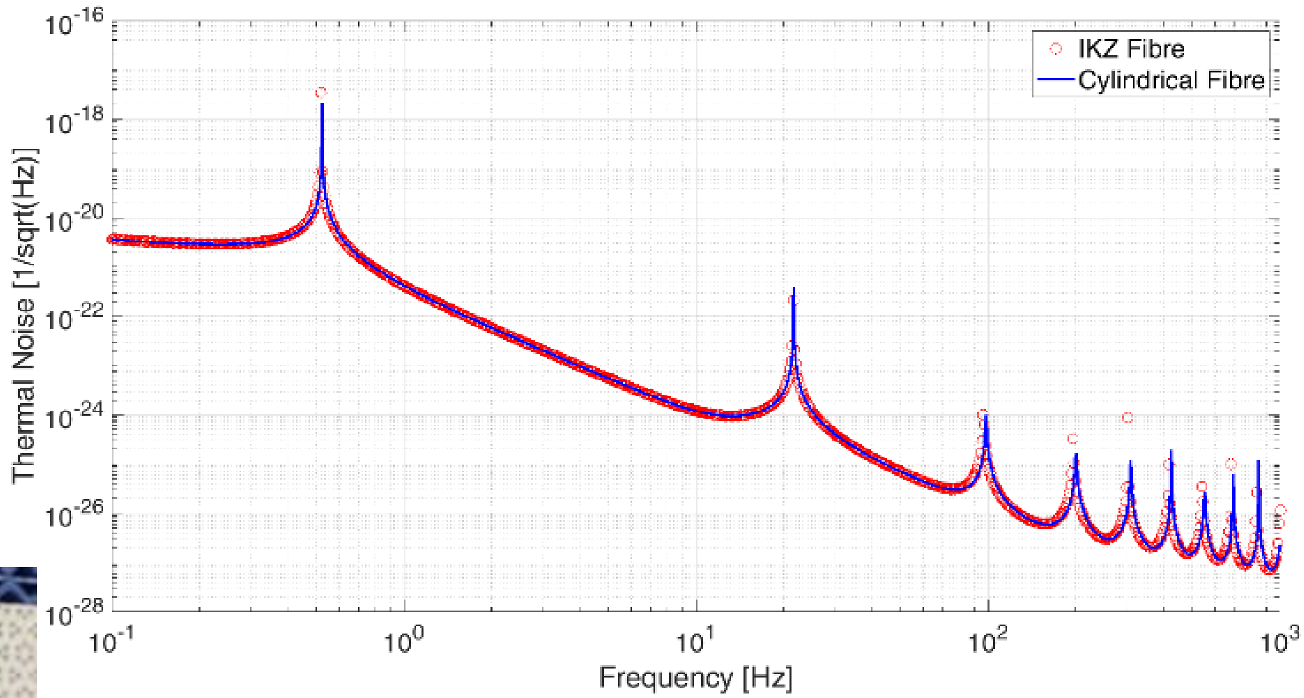
The project, aimed to produced optimized joints, has been just submitted.

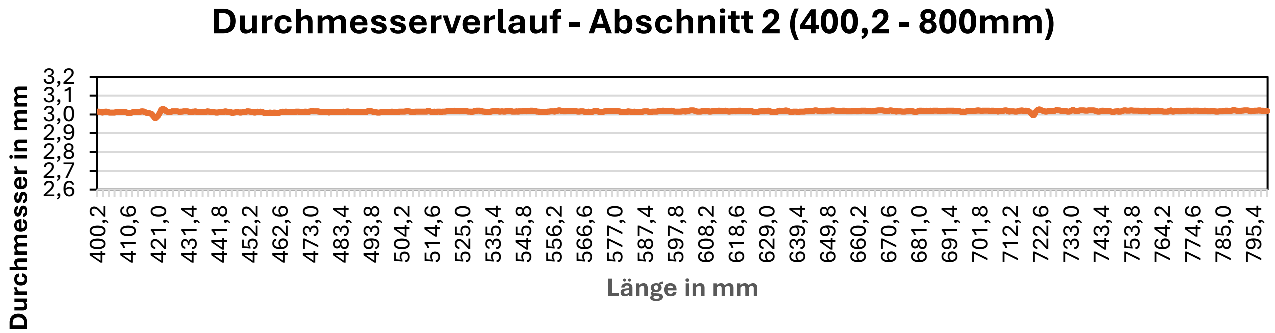


IKZ



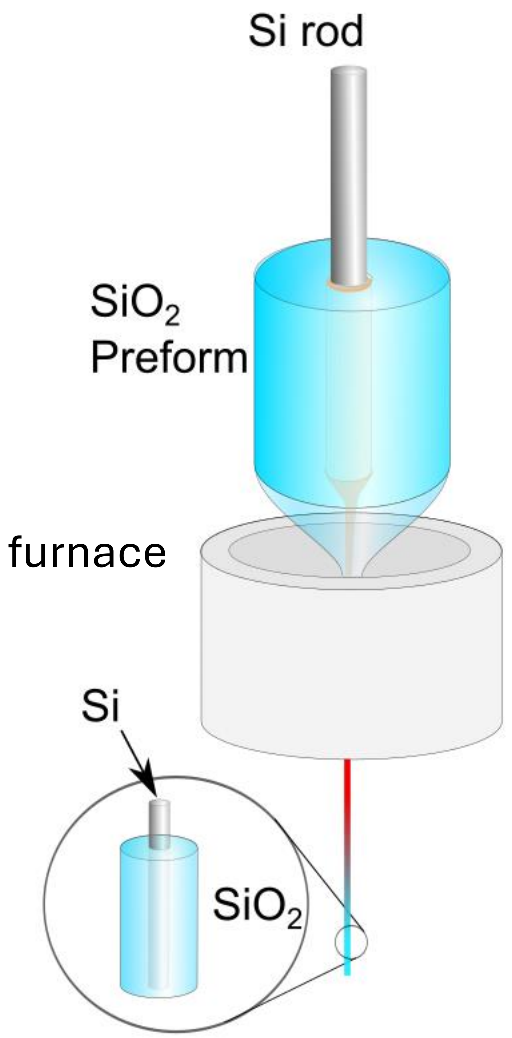
See the nice talk of Iryna Buchovska





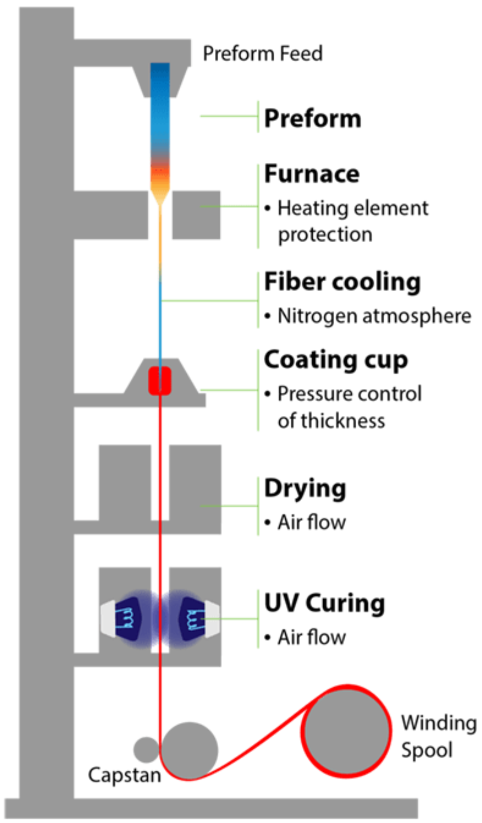
Clemson University

Dartmouth College



Large core Si/SiO_2 fiber draws

Ursula Gibson, Dartmouth College and Clemson University
Wade Hawkins and John Ballato, Clemson University

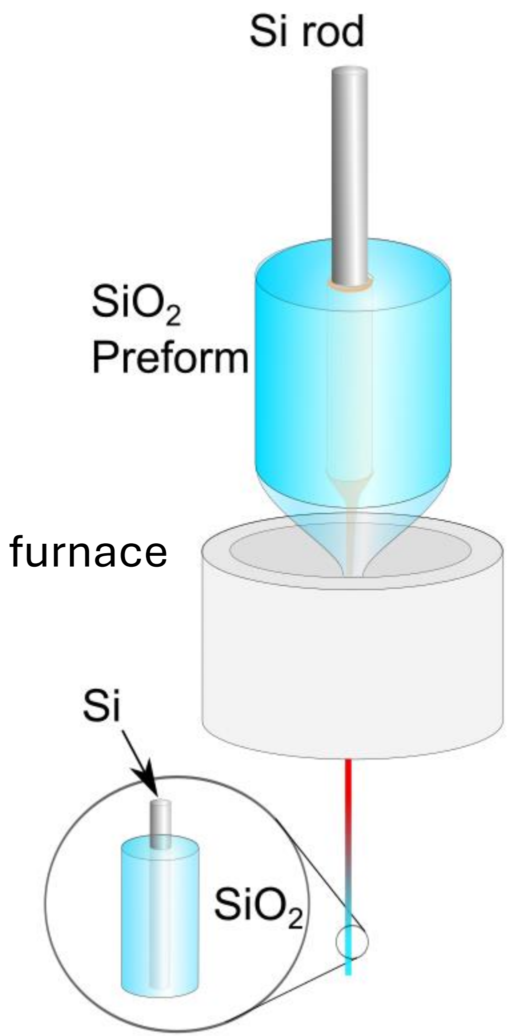


Silica molds silicon, gives smooth surface
prior work on smaller diameters:
CO_2 laser annealing recrystallizes Si

Two draws

1) 30mm OD silica with 8 mm ID
6 mm silicon rod
> **1 mm core** after draw

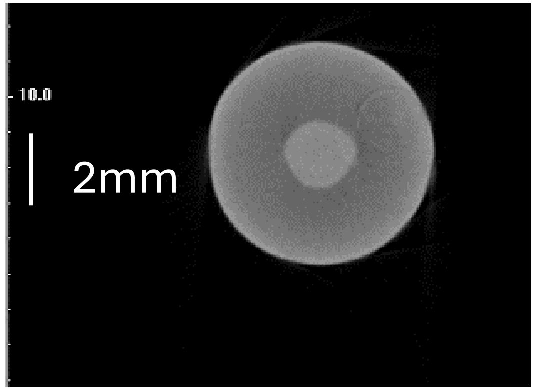
2) 30 mm OD silica with 12 mm ID
6mm silicon pieces
>> **core size > 2 mm**



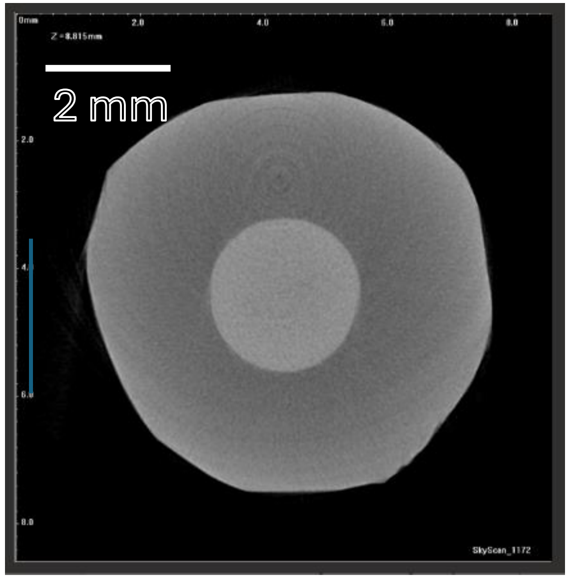
Preliminary analysis

Xray computed tomography

First draw

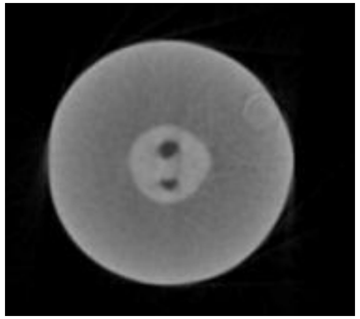


Second draw
 (some glass removed to improve image contrast)

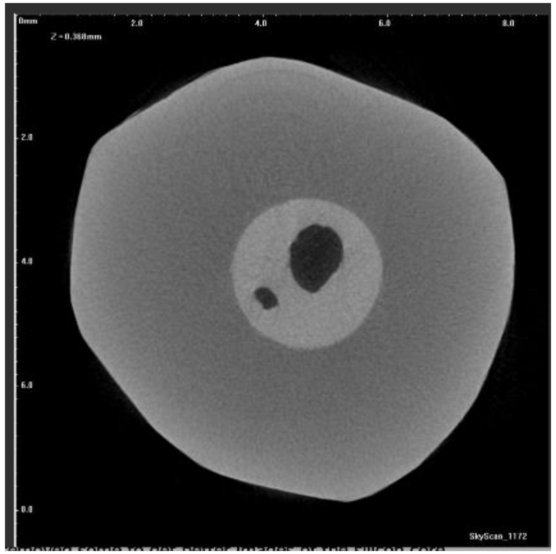


Some regions have voids –
further study needed

First draw

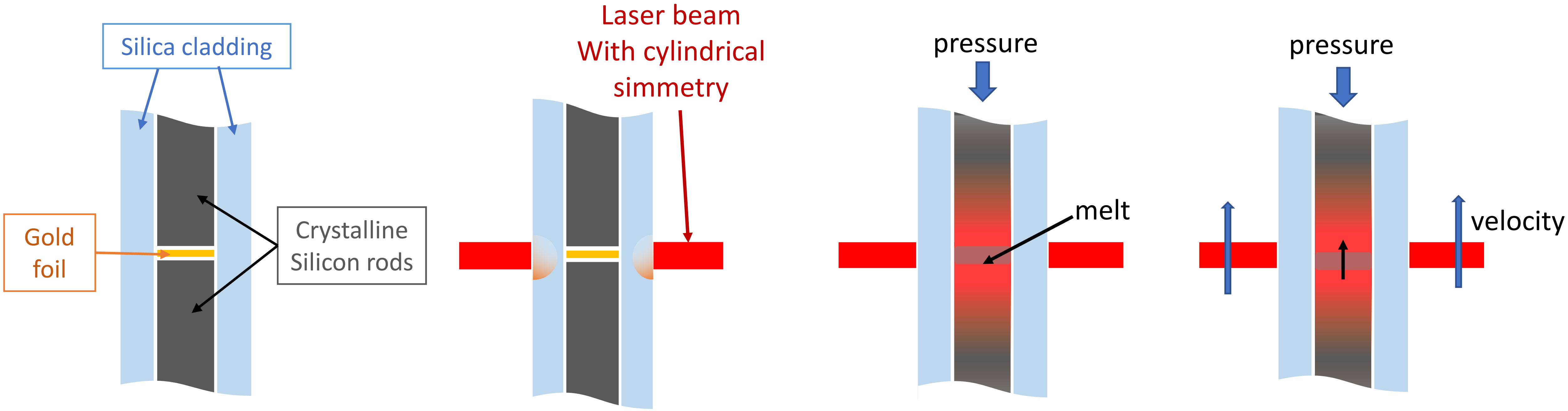


Second draw



University of Urbino

A laser based method to weld silicon using a metal-semiconductor alloy



Sample preparation

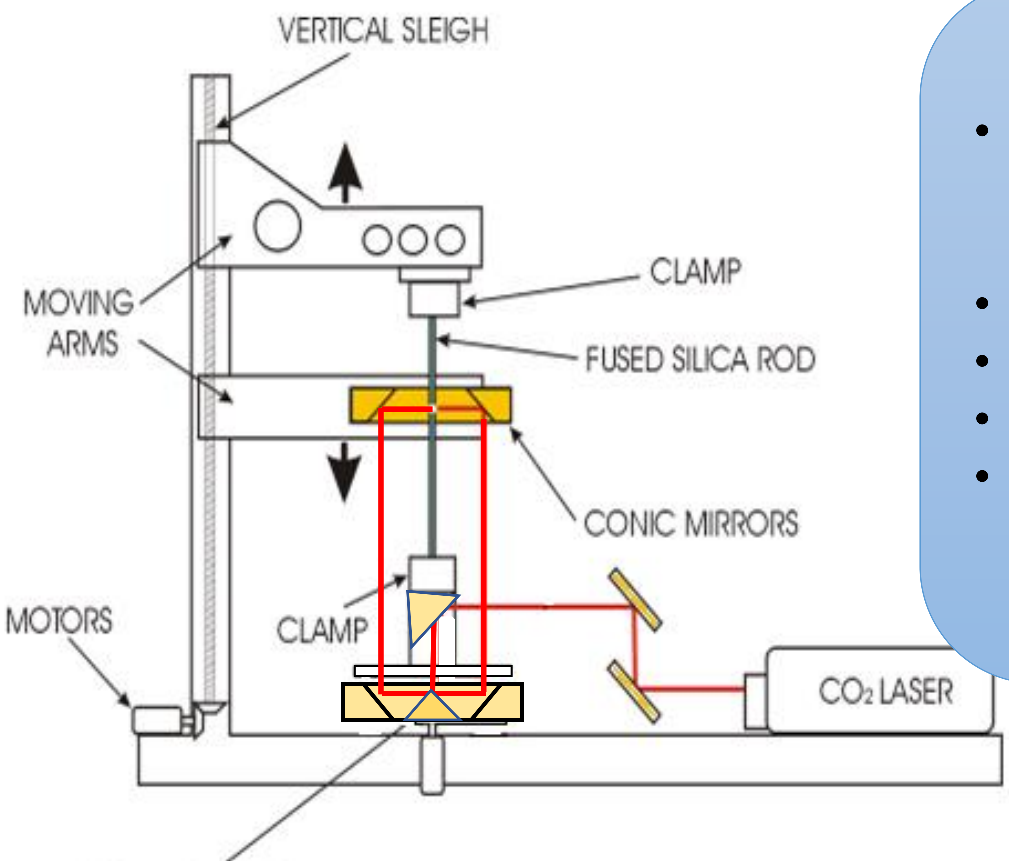
The laser beam starts to heat the silica without reaching its melting point

The silicon and the gold are heated and they form a eutheptic alloy that melt under 1000 °C [1]

The beam position is moved up to melt silicon;
The gold thermo-migrates, following the beam position

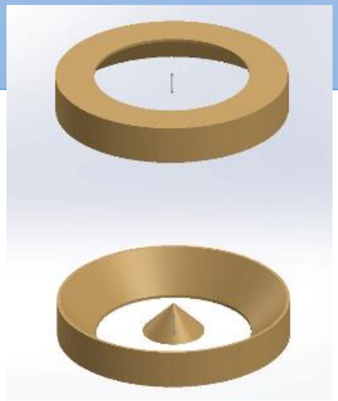
[1] Song et Al. *Nat Commun* **13**, 2680 (2022)

Experimental set up



Axicon and conic mirror

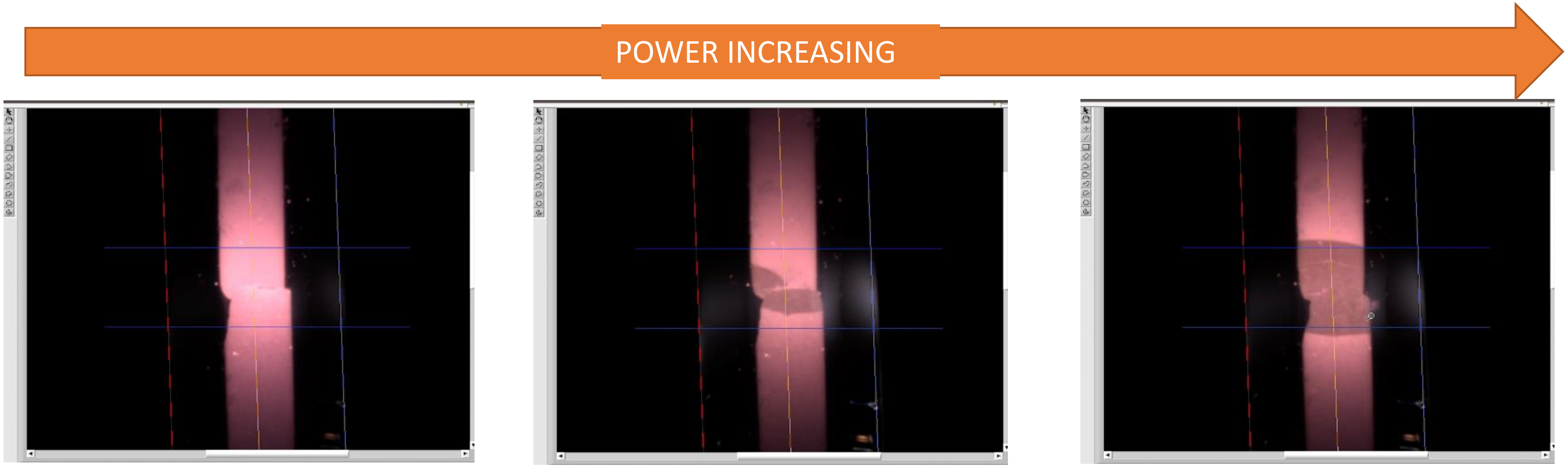
- The machine used is the Fiber pulling machine, developed @Urbino Lab for Virgo silica fibers R&D
- 200 W, CO_2 Laser
- Cylindrical heating system.
- Clamps for rods
- Motors to move the heating point with a low speed of 10^{-5} m/s



Samples

- Ursula Gibson provided us with some ready samples to test the system:
  - some silicon rod tests that had received heat treatment at the contact point (useful for setting up the system)
  - 2 samples ready to be soldered (1 used).
- Crystalline Silicon rod diameter: 1 mm
- Silica Cladding diameter: 2.23 mm or 3,00 mm
- contact pressure of the 2 rods is realized with a weight made by a silica rod 3 mm thick and ~10 mm long.

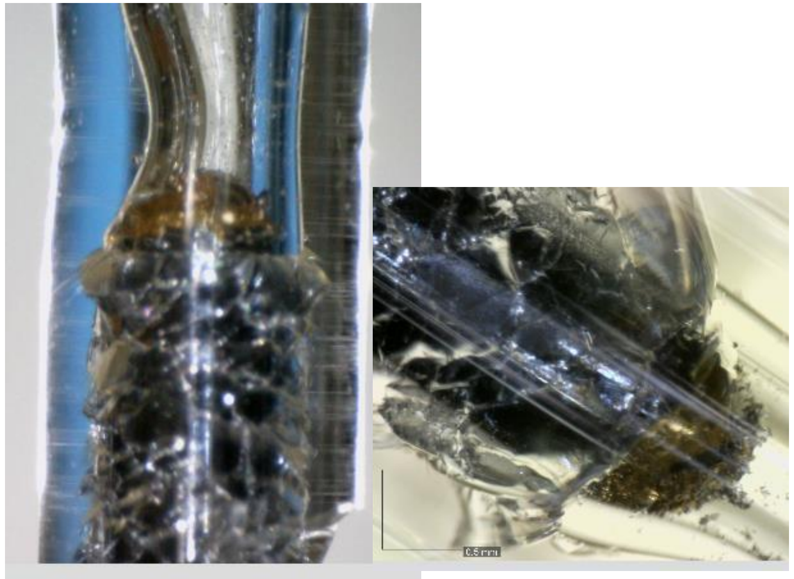
Gold-silicon alloy melting point



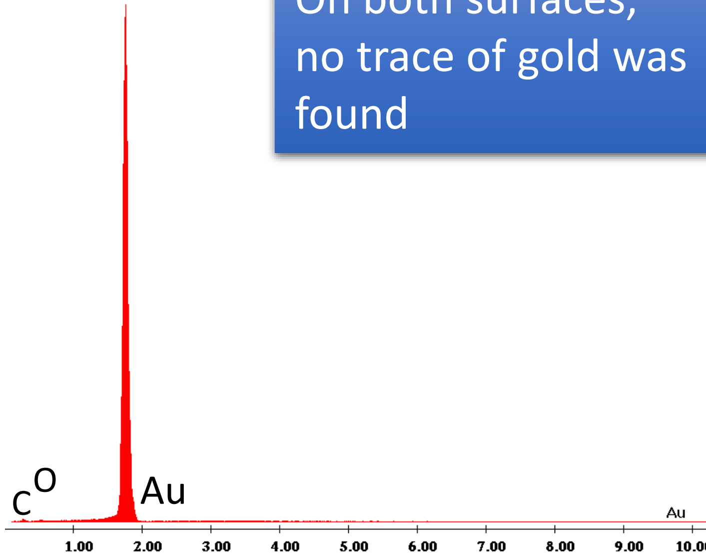
Starting the heating process the silicon starts to emit.
Increasing the power, a darker region is visible (state transition). The dimension of this area is related to the laser power.
Laser Power: 24W; Silica cladding diameter: 3mm; silicon diameter: 1mm

Results

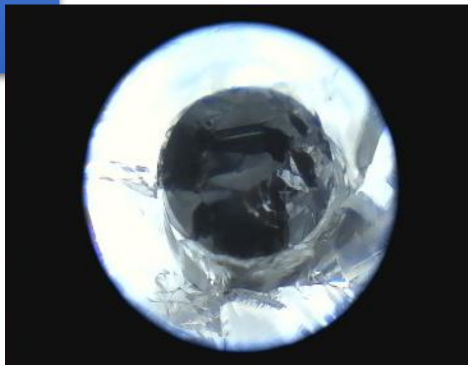
- Qualitatively, it is possible to observe the migration of gold at the end of the silicon rod



- a SEM+ESD analysis was performed on one sample to see the elements present on 2 surfaces:
  - the first close to the starting point of the weld,
  - the second a few millimeters above



On both surfaces, no trace of gold was found



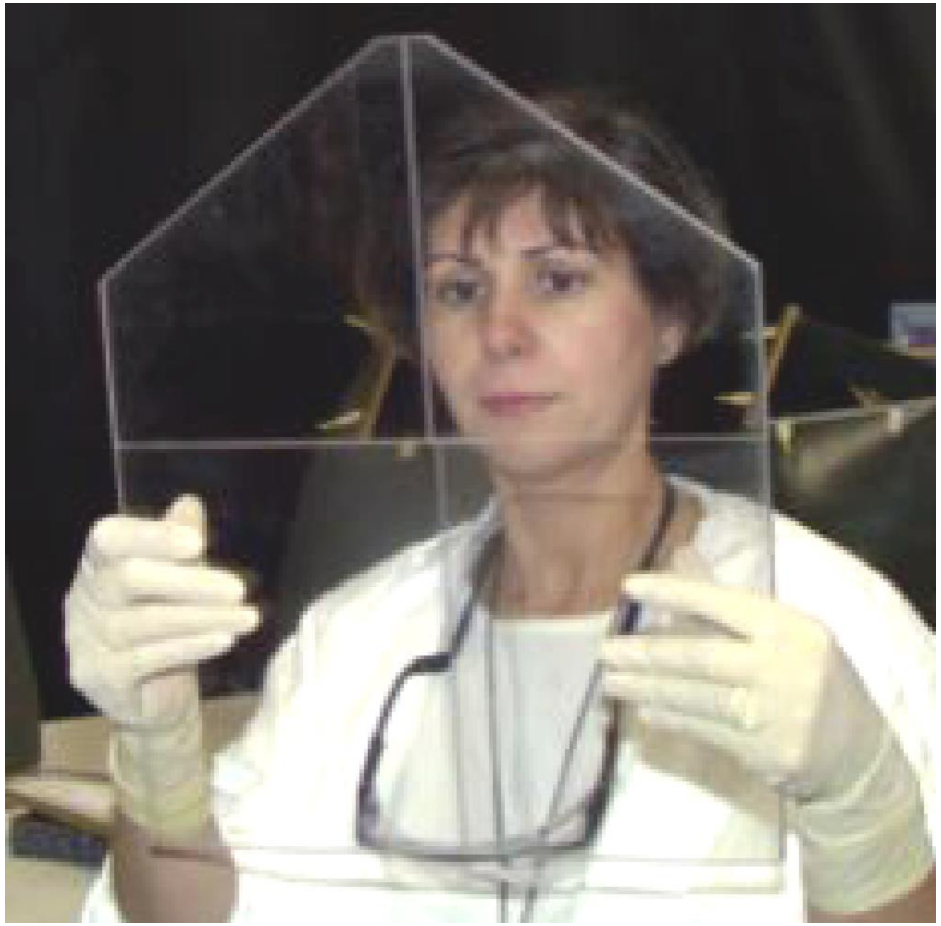
IMPEX HIGH-TECH GMBH (German)

Institute for Single Crystals, (Ukraine)

Sapphire connection methods

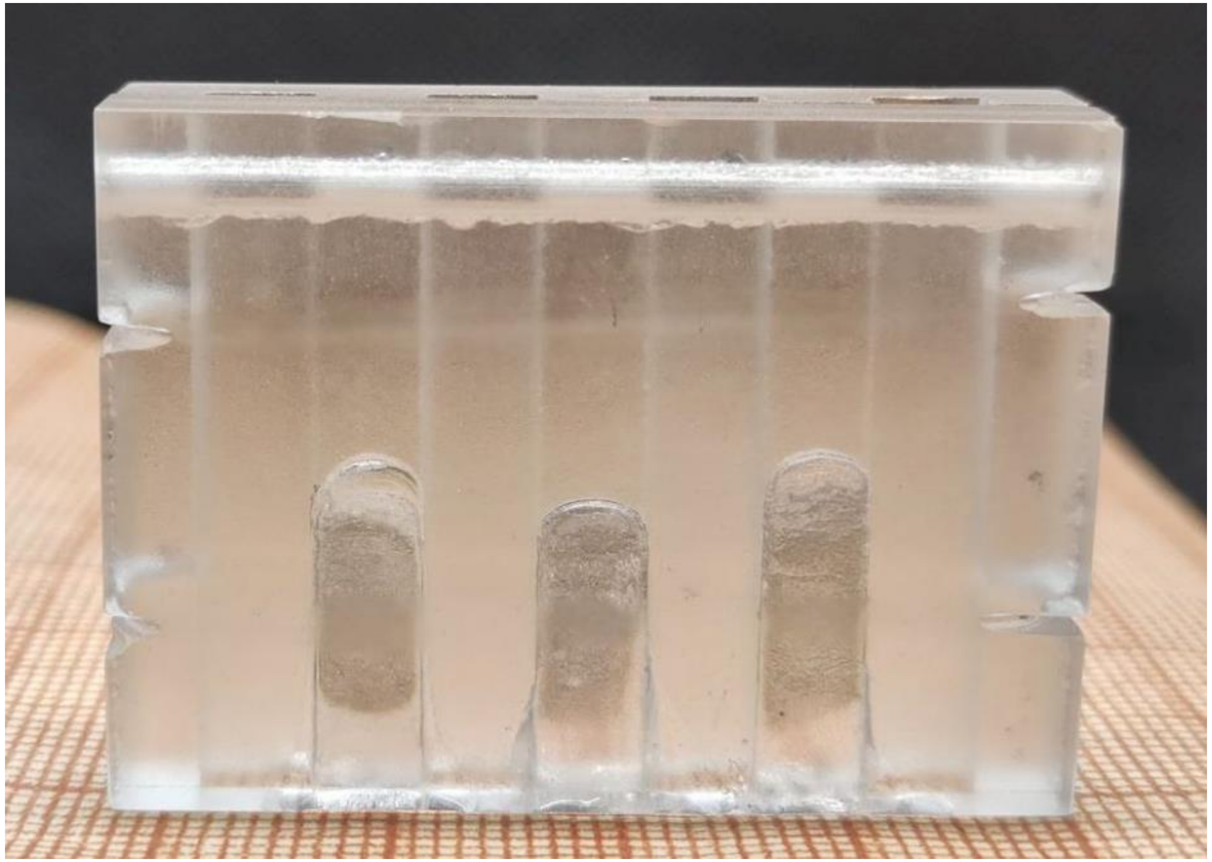
Institute for Single Crystals

- Methods of connection sapphire components and their features
- Testing capillary effect for sapphire melt in sapphire crystal in different configuration and size of channel
- Theoretical Model of Joining Sapphire Blanks by Melt
- Process of Melt Rising in a Capillary Channel
- Defects in the Melted Part of the Crystal
- Joining Sapphire Crystals with Different Vertical Gradients



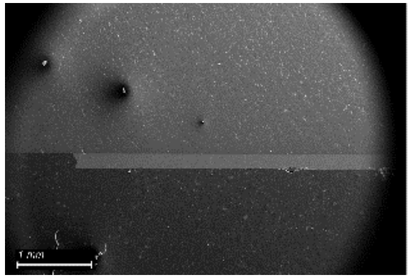
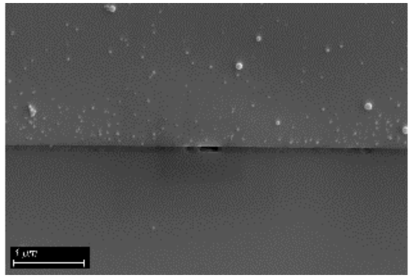
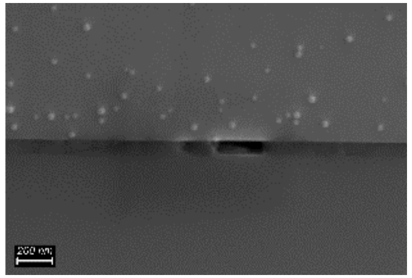
https://www.impex-hightech.de/
https://www.isc.kh.ua
https://scinn-eng.org.ua/ojs/index.php/ni/index

German project with funding code EP201456

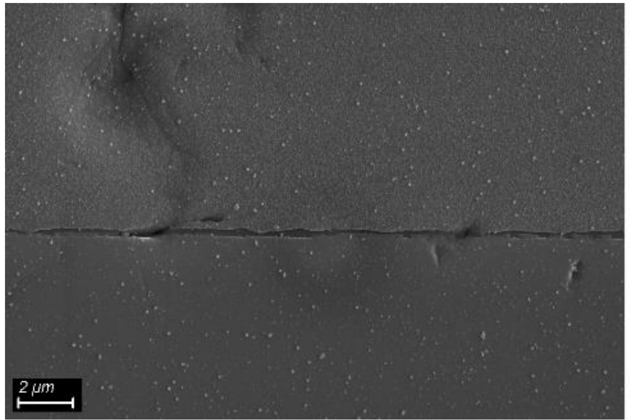


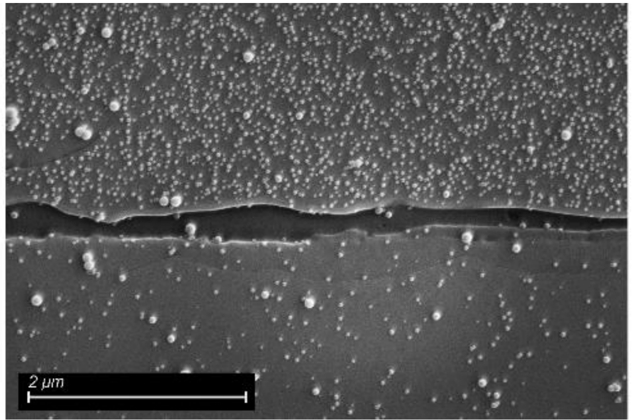
Testing capillary effect for sapphire melt in sapphire crystal in different configuration and size of channel

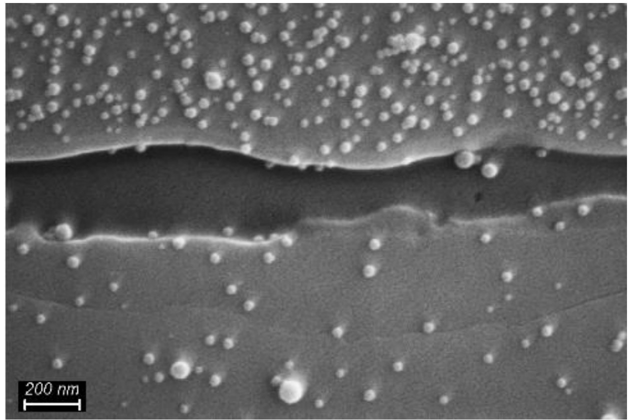
The simultaneous presence of the same substance in both solid and liquid states in the system can last for a relatively short time until equilibrium is reached.

The experiment was conducted in a thermal zone at a temperature below the melting point, where superheated melt was introduced to contact the crystalline blanks





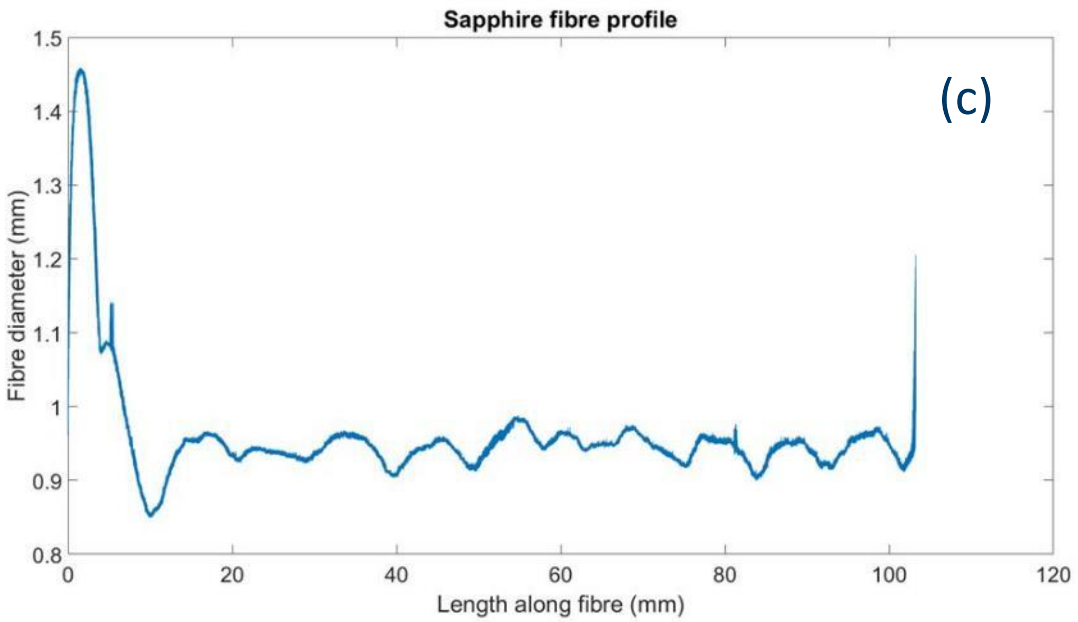


UNIVERSITY OF GLASGOW

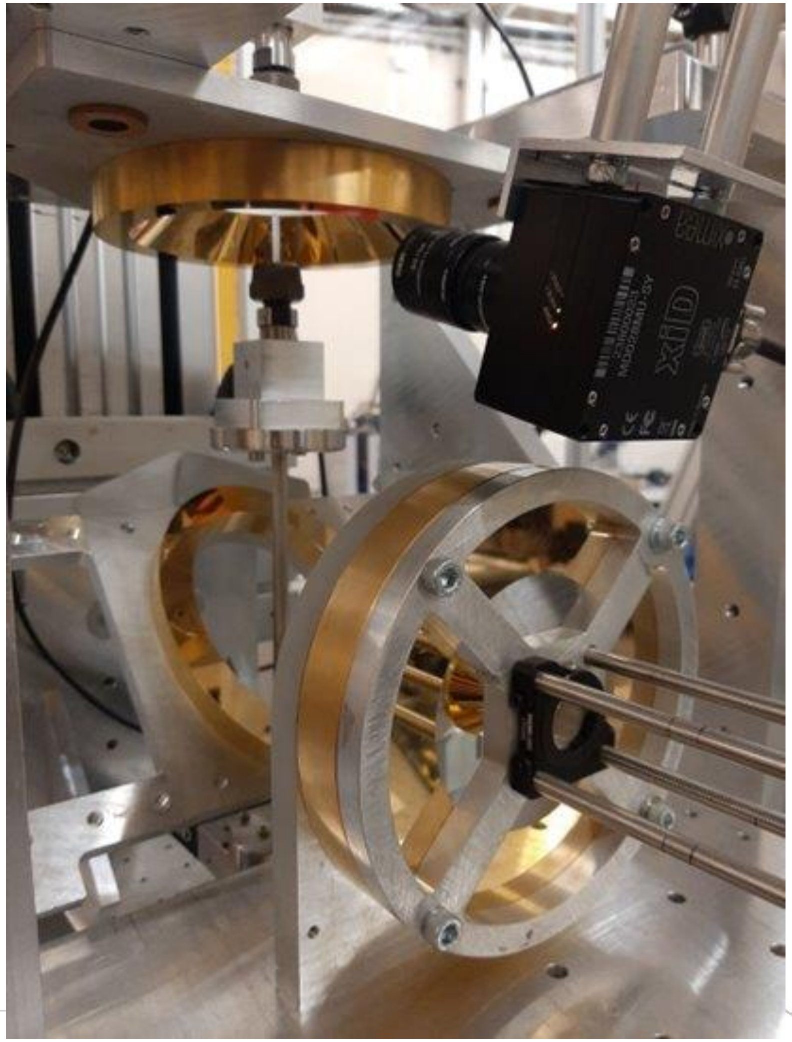
Sapphire Fibres

Sapphire fibres produced (a) by laser heated pedestal growth method (b). Capability to produce:

- 1mm diameter, low diameter variation (c),
- up to 350mm long,
- peak stress of 792MPa almost double typical quoted value of 440MPa,
- Indicates good surface quality.



(a)



(b)

Research conducted *by Dr. Jack Callaghan*

Work on Sapphire

Sapphire Laser Welding

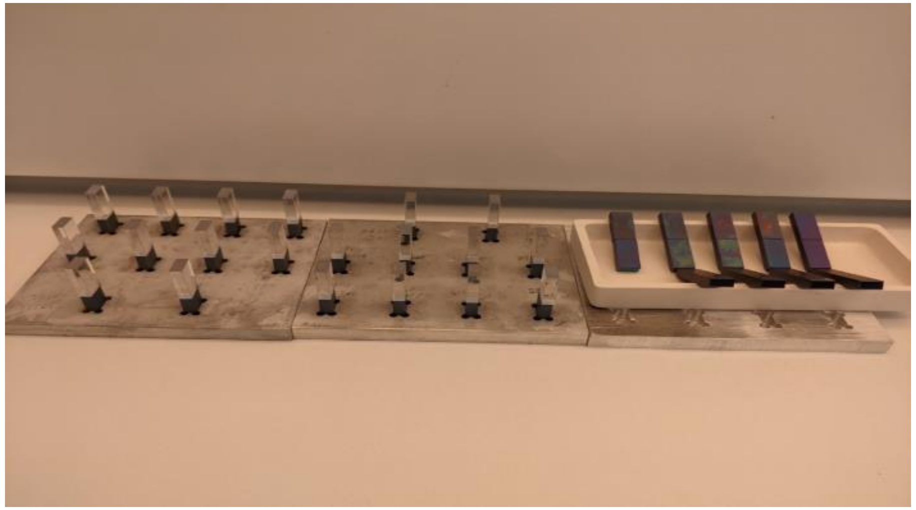
- Successfully welded sapphire to sapphire fibres of varying millimetre diameters
- Characterisation work ongoing:
  - Mechanical loss
  - Thermal conductivity
  - Tensile strength
  - Crystallography

Contacts:

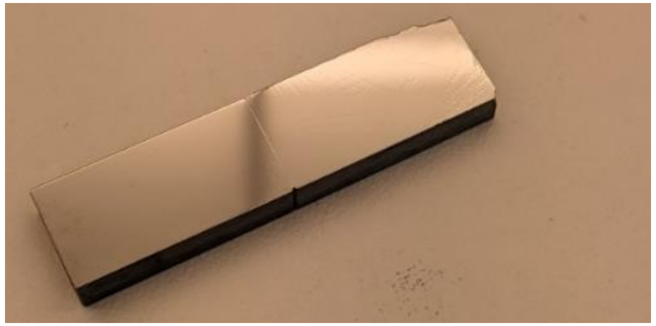
- Jennifer Docherty
- Alan Cumming

Work on bonding

- Direct bonding (DB) and Hydroxide catalysis bonding (HCB) of sapphire-silicon and silicon-silicon
- Cutting and polishing of bonded samples
- Thermal treatment (annealing and/or cryogenic)
- Strength testing
- Mechanical loss of bonds

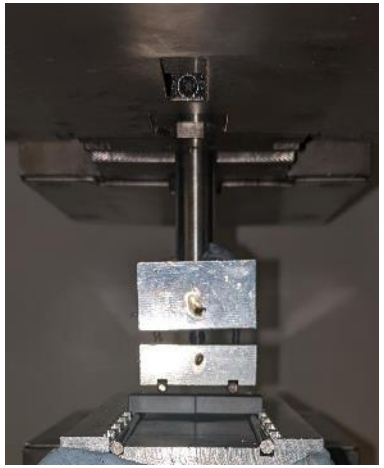


Sets of Sa-Si and Si-Si bonds for 4-point bending



Direct bonded Si-Si sample after polishing

Samples cycled in liquid nitrogen



4 point bending of bonded sample

Contact: Karen Haughian and Gregoire Lacaille

Characterization

UNIVERSITY OF GLASGOW

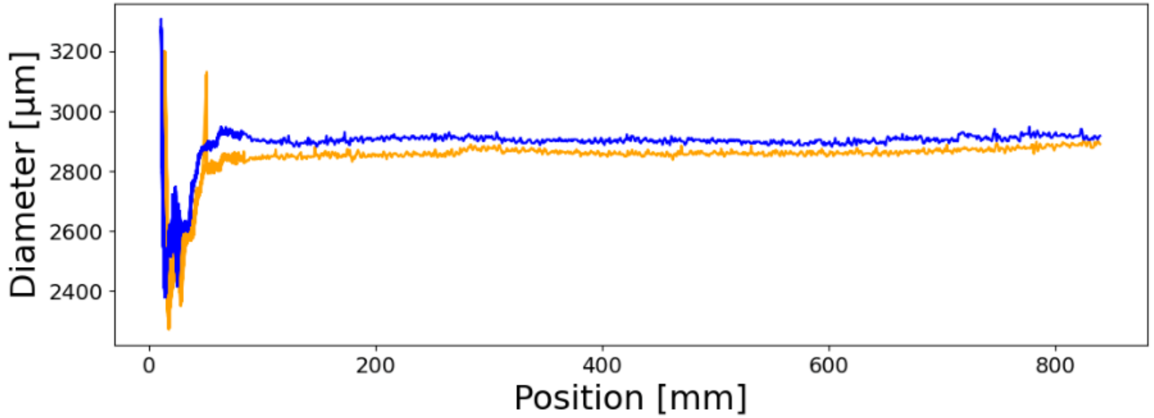
University of Glasgow

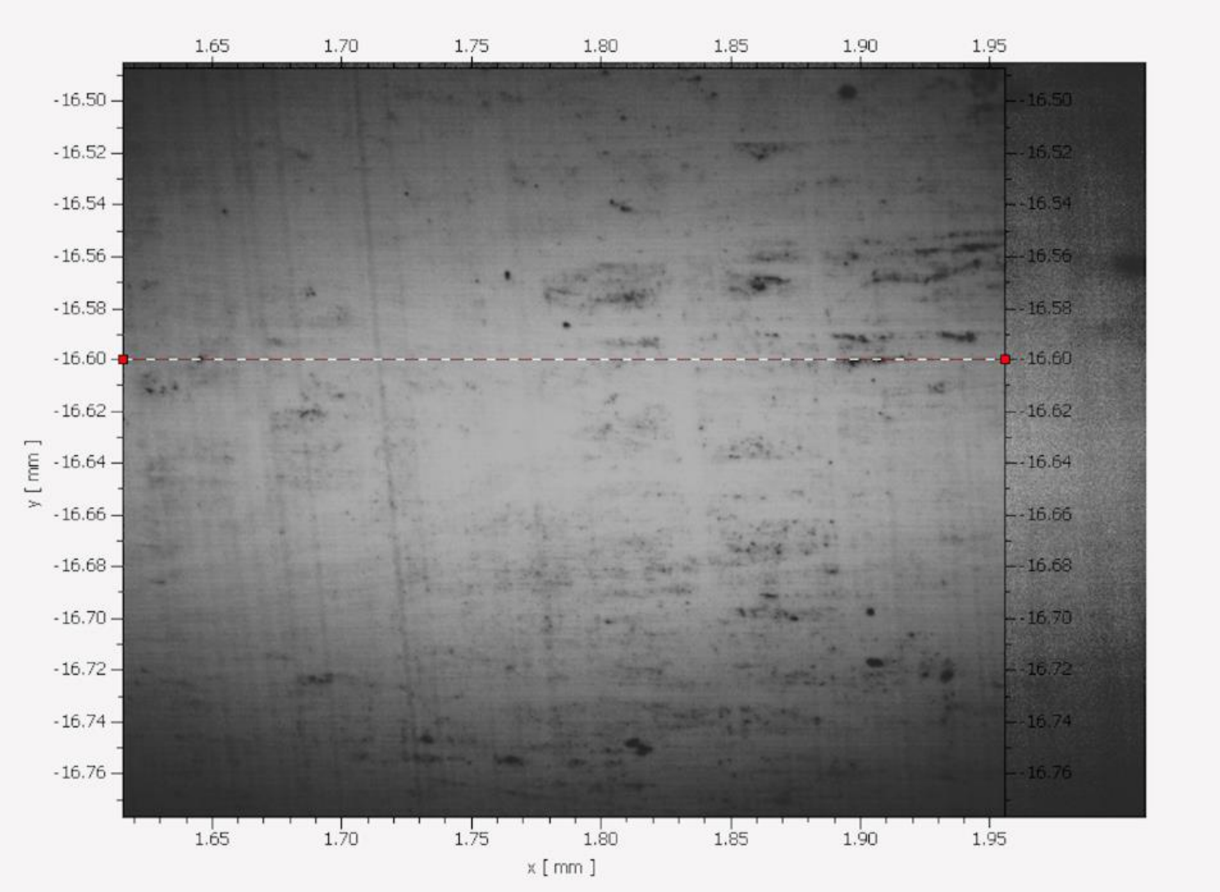
VIA VERITAS VITA

Silicon fibres

- 11 fibres of length from 64cm to 116cm are currently being characterized at Glasgow
- Lowest diameter variation: 4.1%
- Surface quality overall good, with minor chips and indentations

Profile of the fibre

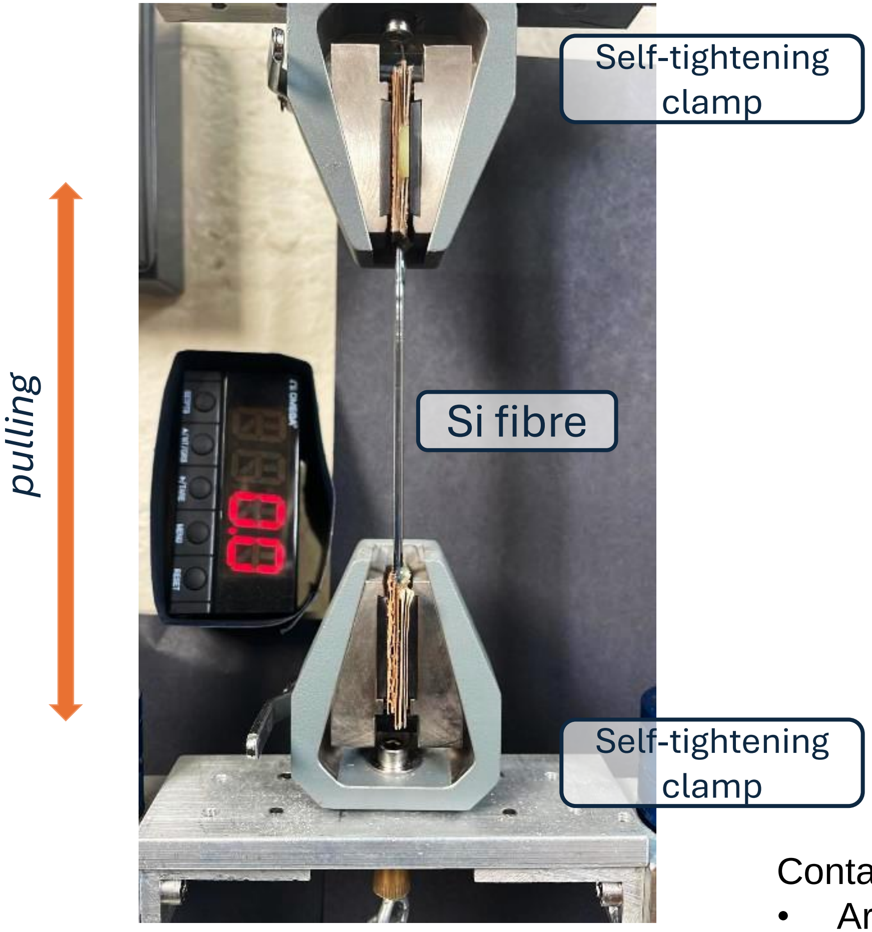




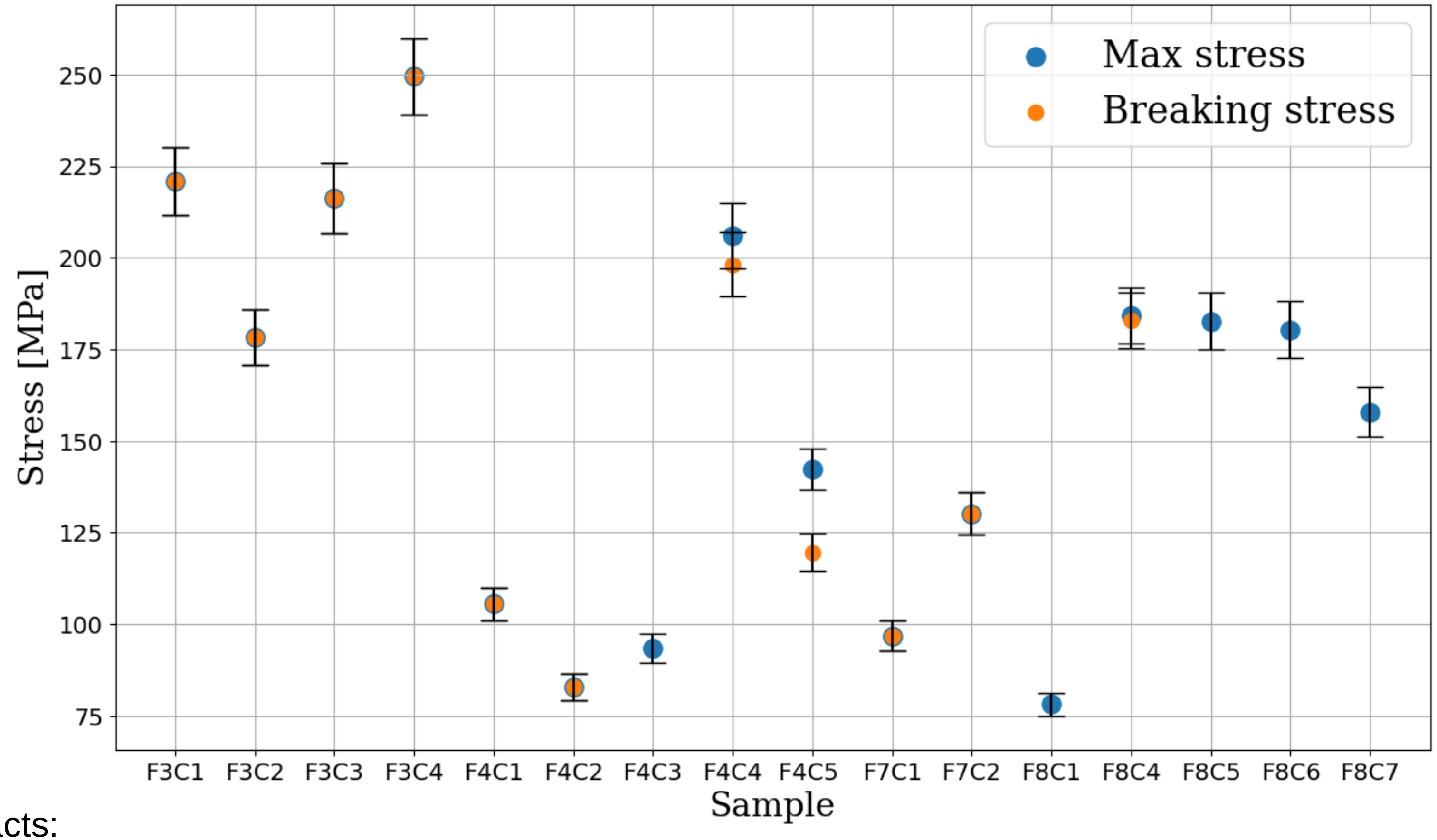
Close-up images taken on a Polytec microscope

Breaking strength tests of fibres

Setup



Tensile stress results

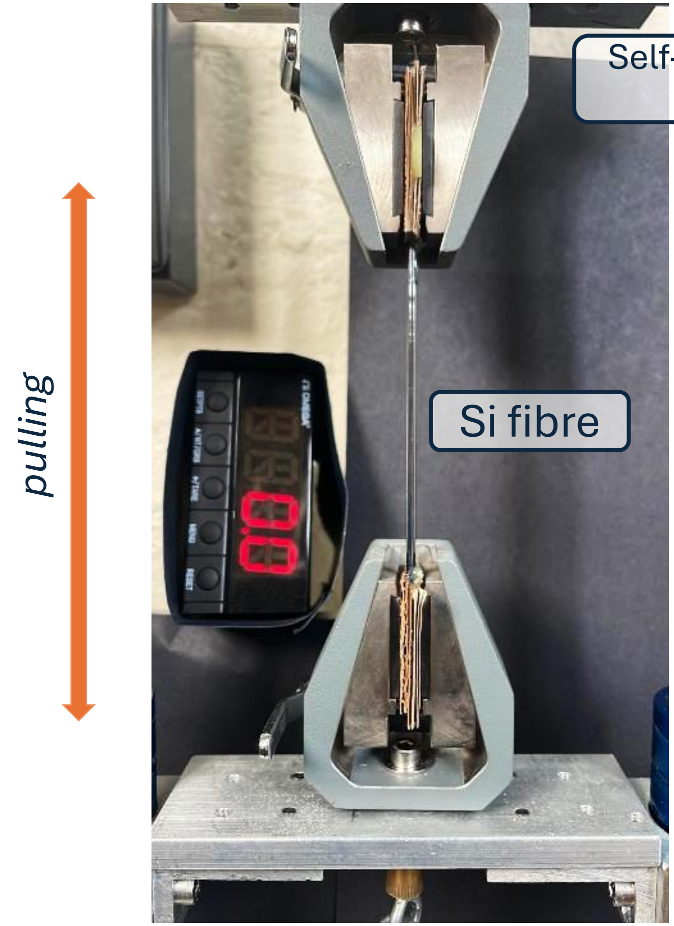


Contacts:

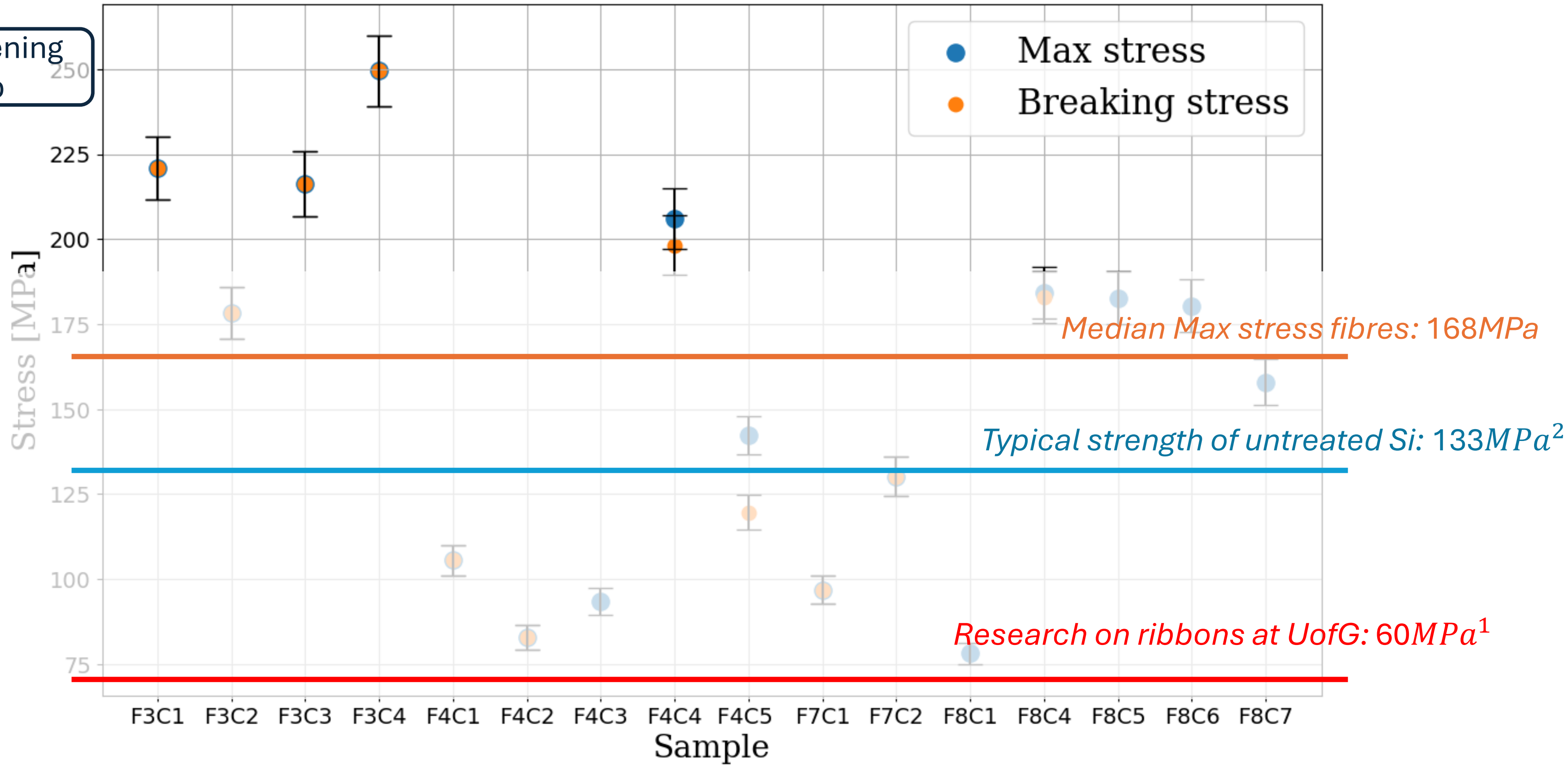
- Ardiana Nela
- Karl Tholand

Breaking strength tests of fibres

Setup



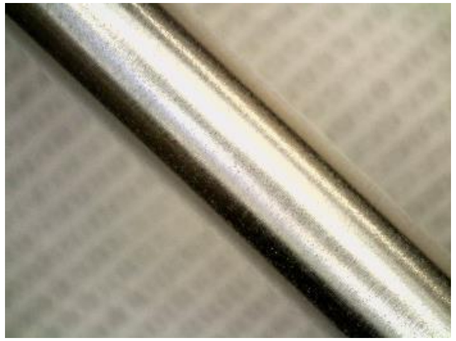
Tensile stress results

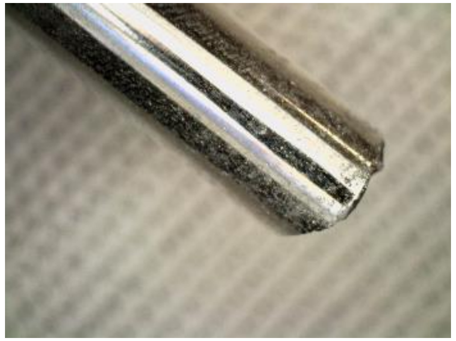


Measured breaking stress is a lower limit due to alignment challenges

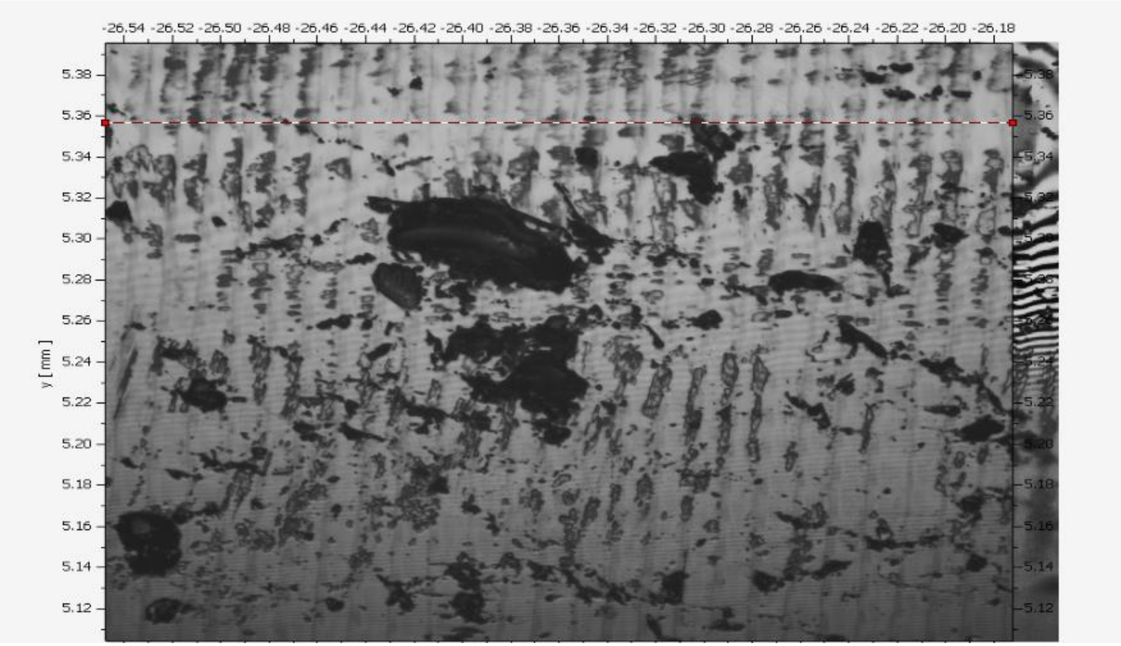
1. Graeme Eddols: LIGO-G2101011-v1
2. 2. A V Cumming et al 2014 Class. Quantum Grav. 31 025017

Ground Si fibre





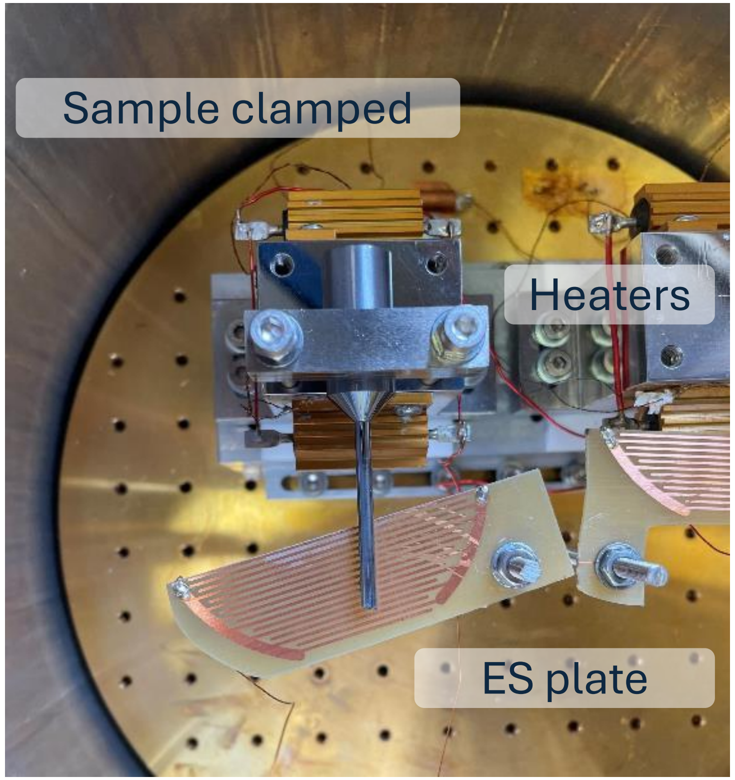
- 3mm diameter, monocrystalline, ground fibre cut out of a 13.7mm diameter stock
- Surface quality: Multiple indentations, chips
- Visible defects on the surface from the grinding process: lines every 0.01mm, 0.08mm wide indentations



Sample manufactured by *Wielandts UPMT*: https://www.upmt.be/en/produits-services/spdt-services/25

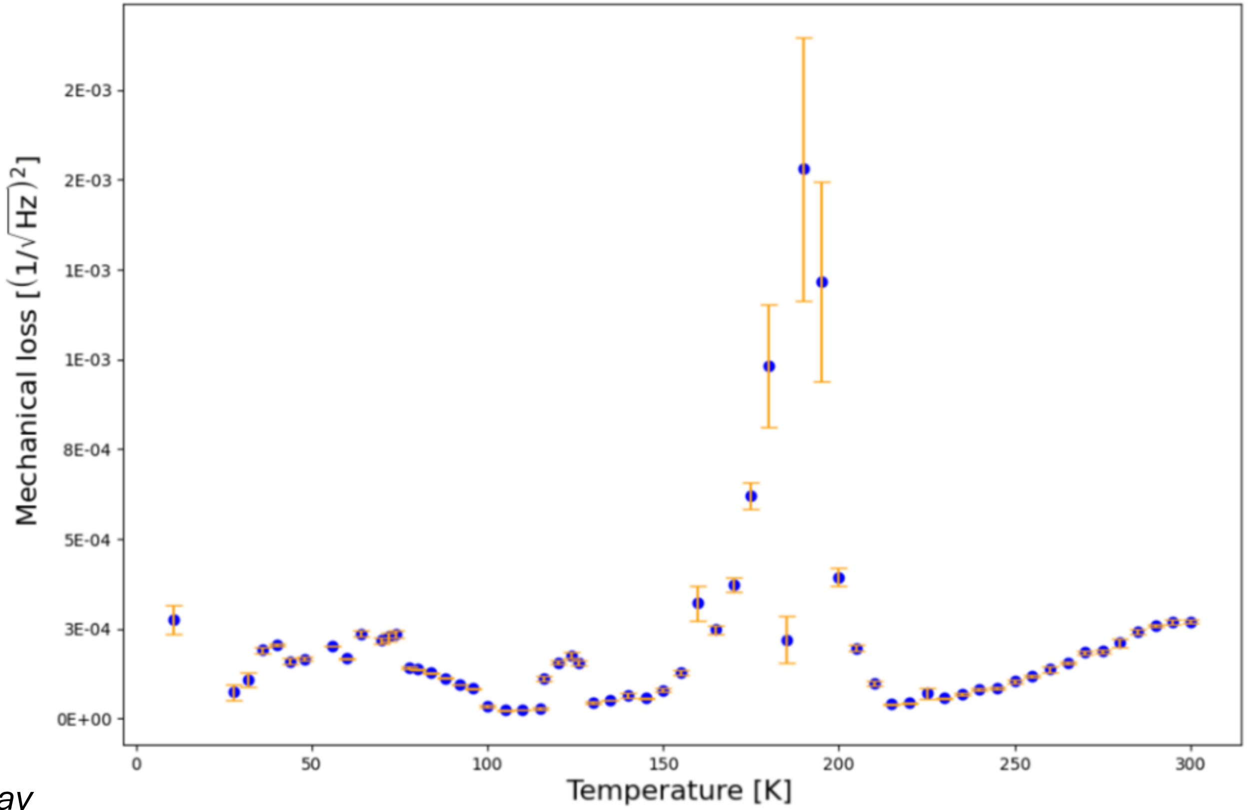
Mechanical loss measurements of ground fibre

Setup



Research conducted by *Ardiana Nela* and *Dr. Peter Murray*

Mechanical loss results on first mode at 2.45kHz



Min loss: 2.3x10^-5 at 105K

KARLSRUHER INSTITUT FUR TECHNOLOGY

Karlsruher Institut für Technologie

Karlsruhe Institute of Technology

GRAVITHELIUM

Test facility for payload suspension studies

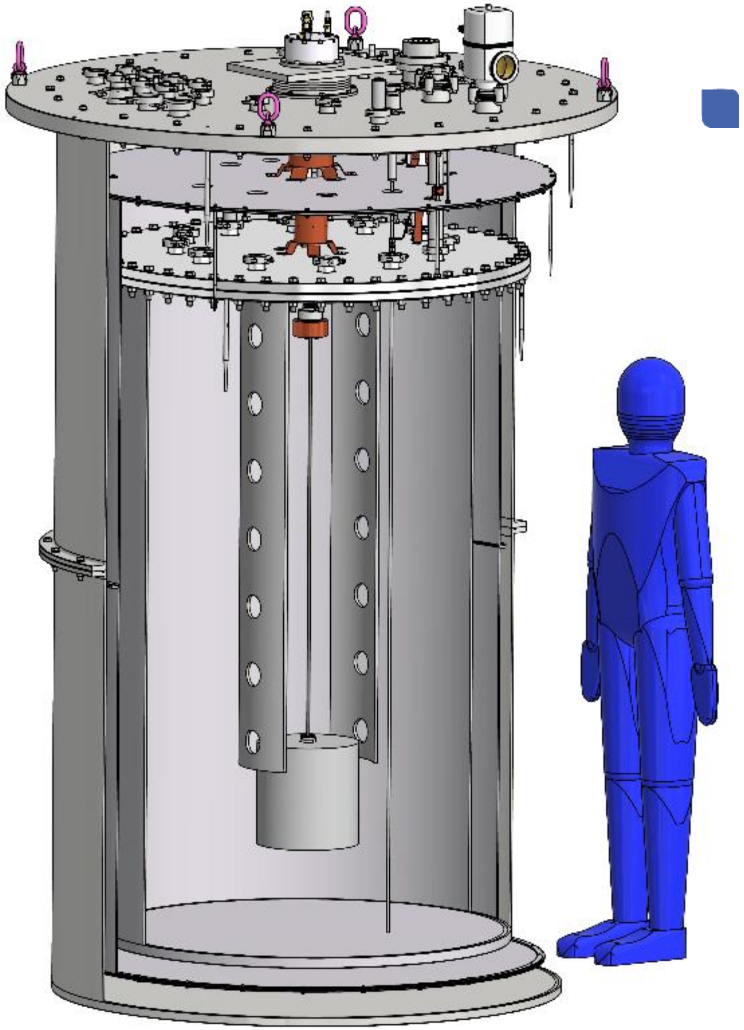
European Research Council
Established by the European Commission

GRAVITHELIUM
Gravitational wave detectors cooled with superfluid helium

S Grohmann et al.

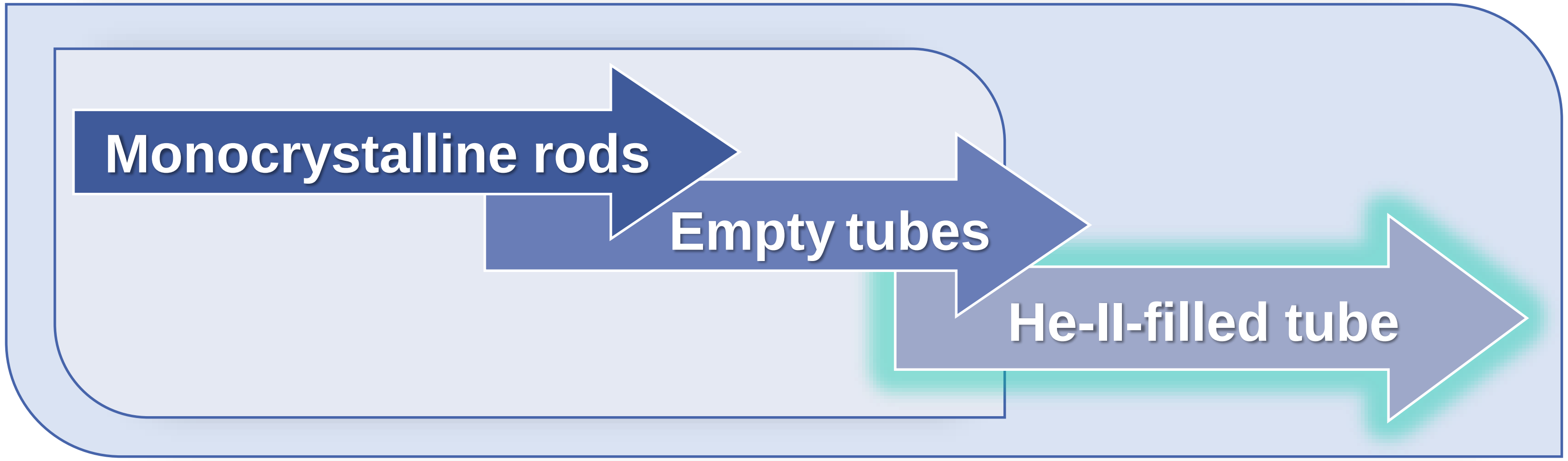
GRAVITHELIUM

Karlsruhe Institute of Technology

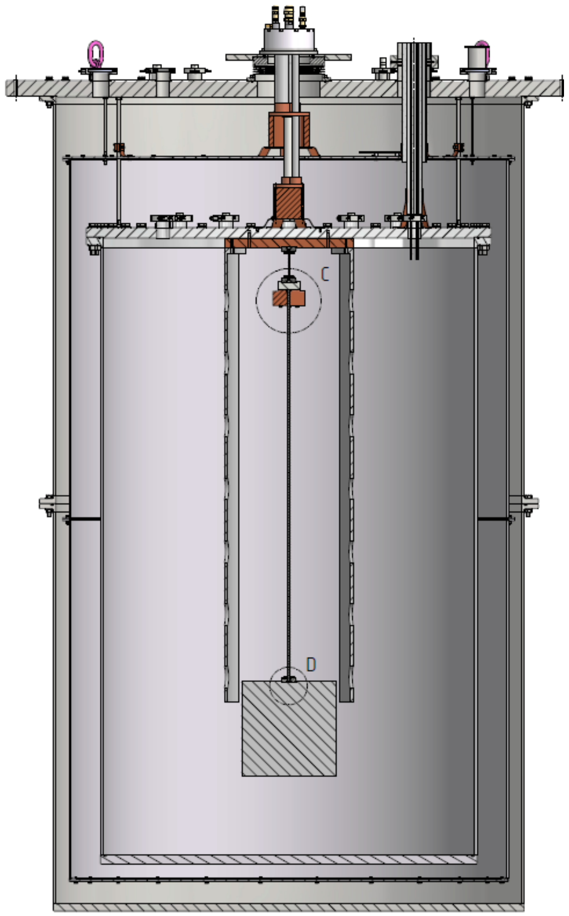


Publication Publication

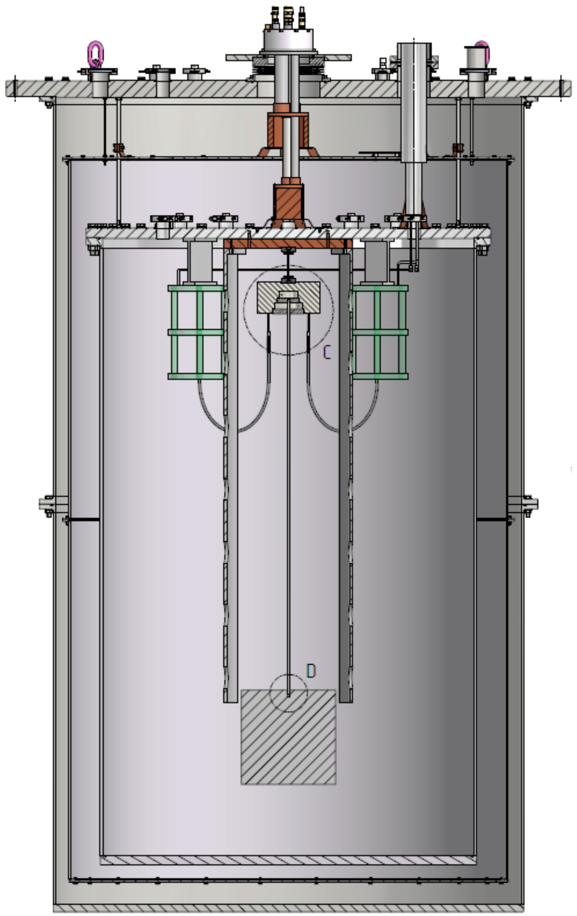
- <u>Q measurement test facility:</u>
  - Full-size monolithic suspension fibers/rods and titanium tubes
  - Investigtaion of loss contributions in suspensions
  - He-II integration in Q measurements
  - Proof of concept for He-II based payload cooling for ET-LF



Design status of the GRAVITHELIUM cryostat



Phase 1:
He-II free campaigns



Phase 2:
He-II filled tube campaigns

- Facility conceptual design
- Facility engineering design
  - Cryostat mechanical design
  - Components
- Experimental procedure
  - Instrumentation
- Sample support system (Phase I + II)
- Vibration attenuation system (Phase II)

Cryogenic Material Tests Karlsruhe (CryoMaK)

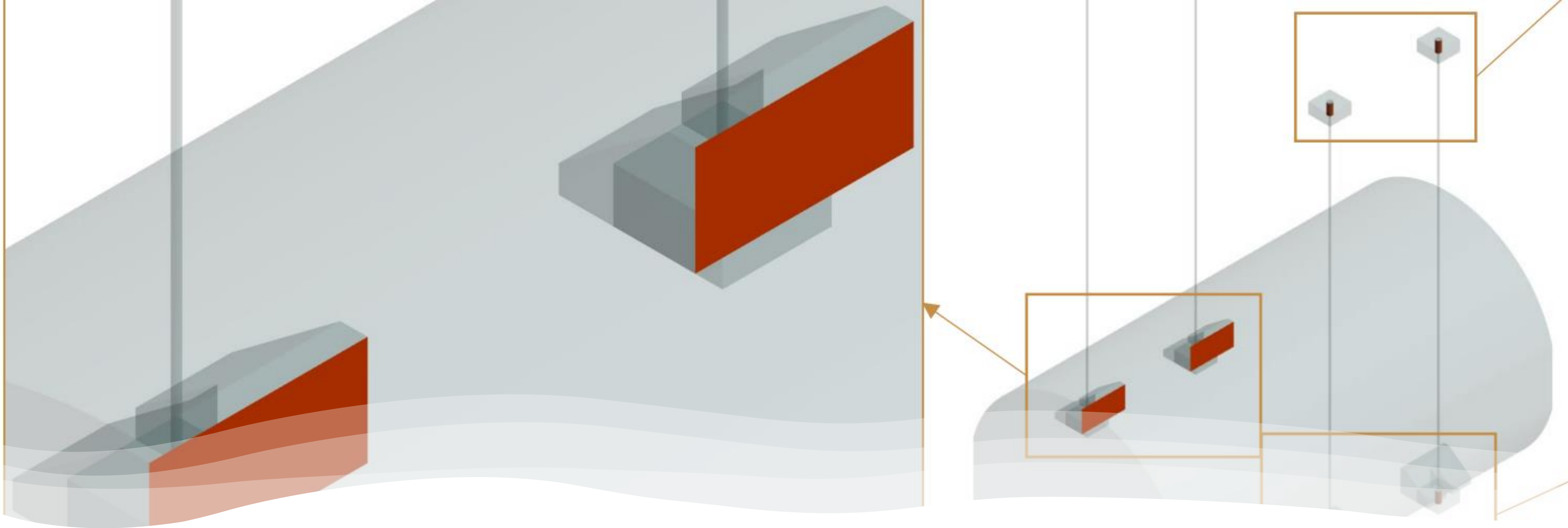
- Comprehensive Si/Sapphire suspensions testing possibilities, including
  - Mechanical properties (4.2 K to 300 K)
    - tensile,
    - fracture,
    - fatigue,
    - …
  - Physical properties (2 K to 400 K)
    - thermal expansion,
    - heat capacity,
    - thermal conductivity,
    - …

→ We would be looking forward to analyse suspension samples - contact us!

Exemplary publication
DOI: 10.12776/ams.v21i4.650

Image: https://www.itep.kit.edu/english/CryoMaK.php

PERUGIA/CAMERINO



Perugia/Camerino labs

- Involved in the design of the samples (IKZ, UMPT, Impex, ...)
- Mechanical test and structural analysis of crystalline samples
- HCB bonding
- Mechanical simulation
- ....

The End

That's all folks!!