

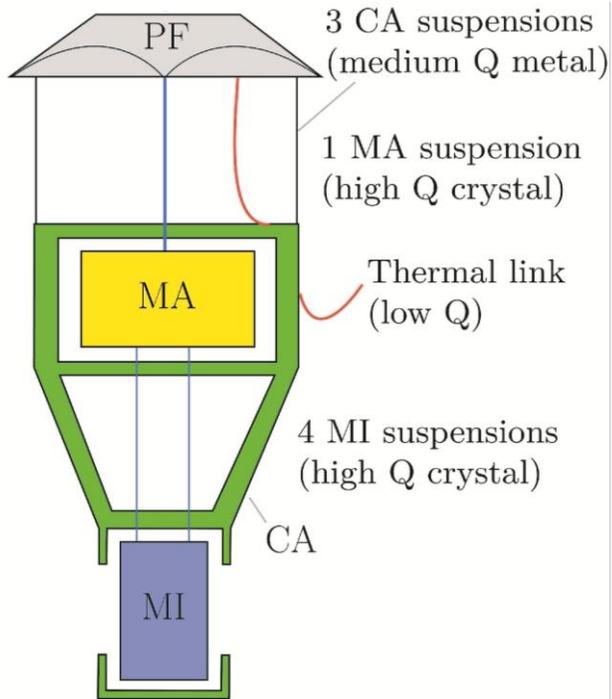
# Experimental investigations of monolithic cryogenic payload suspensions for the Einstein Telescope @ KEK

Xhesika Koroveshi

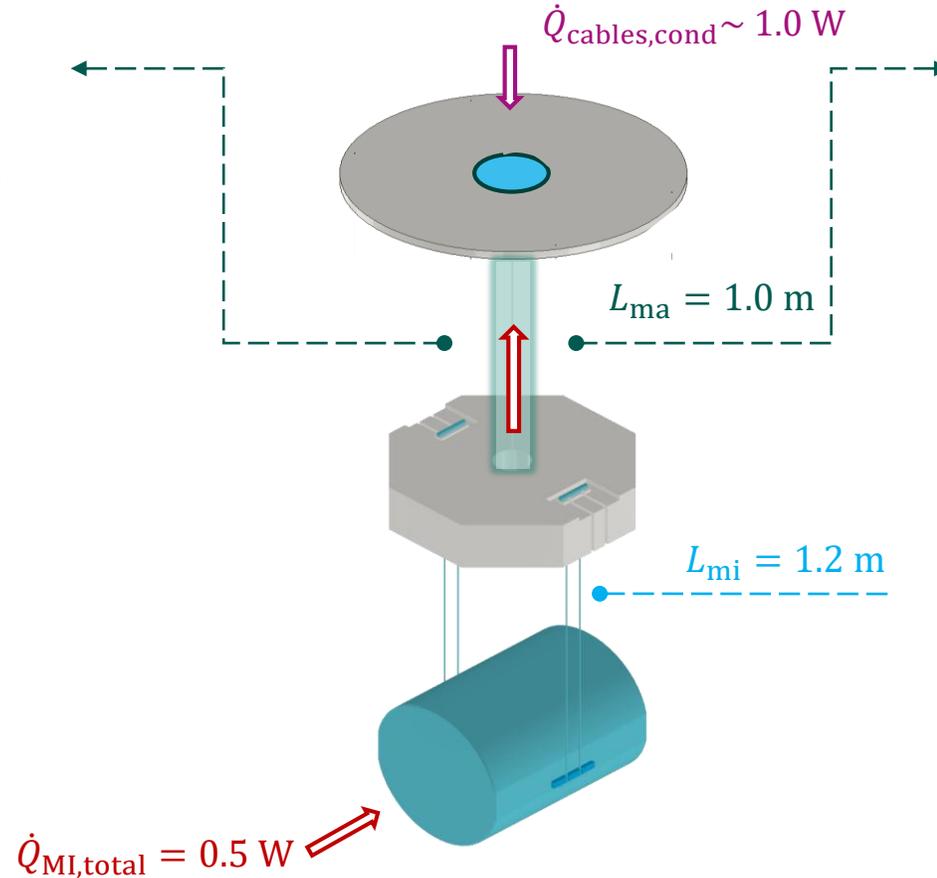


# Einstein Telescope cryogenic payload

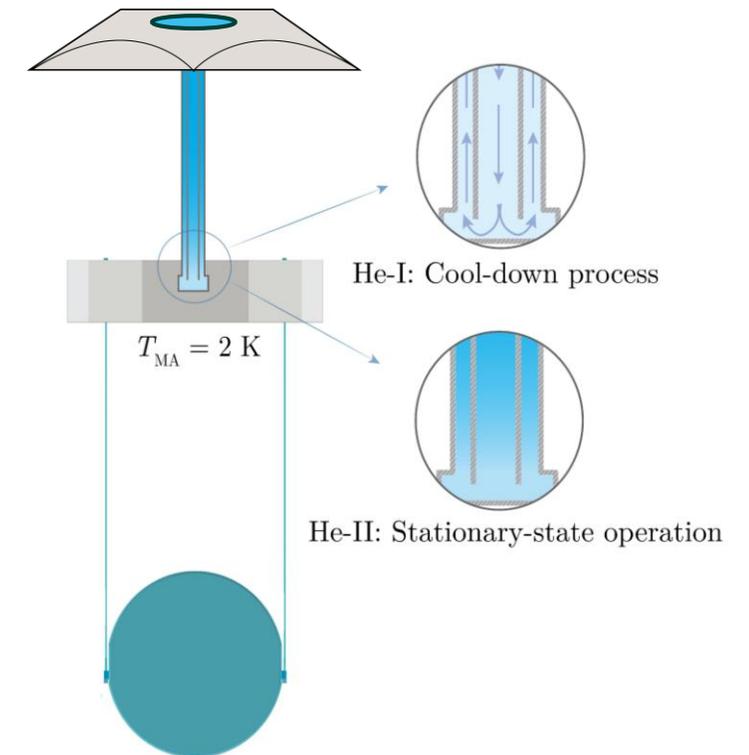
## ■ Monocrystalline suspension



## Two heat extraction concepts



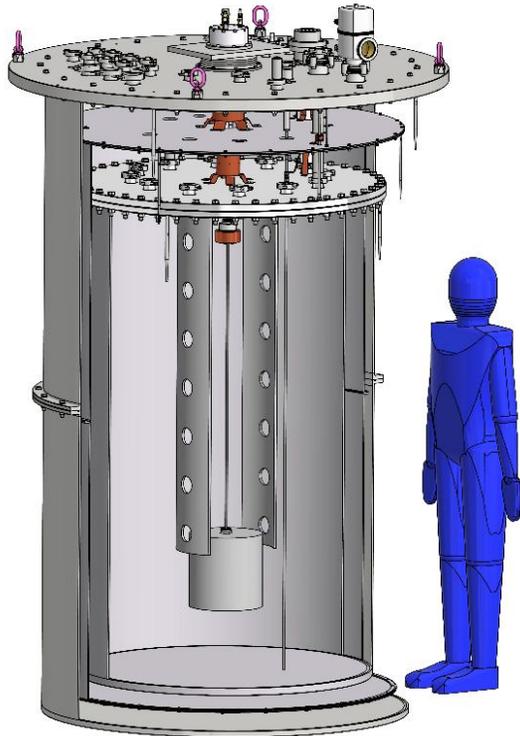
## ■ He-II filled suspension tube



Reference: X. Korovesi et al. (2023), DOI: [10.1103/PhysRevD.108.123009](https://doi.org/10.1103/PhysRevD.108.123009)

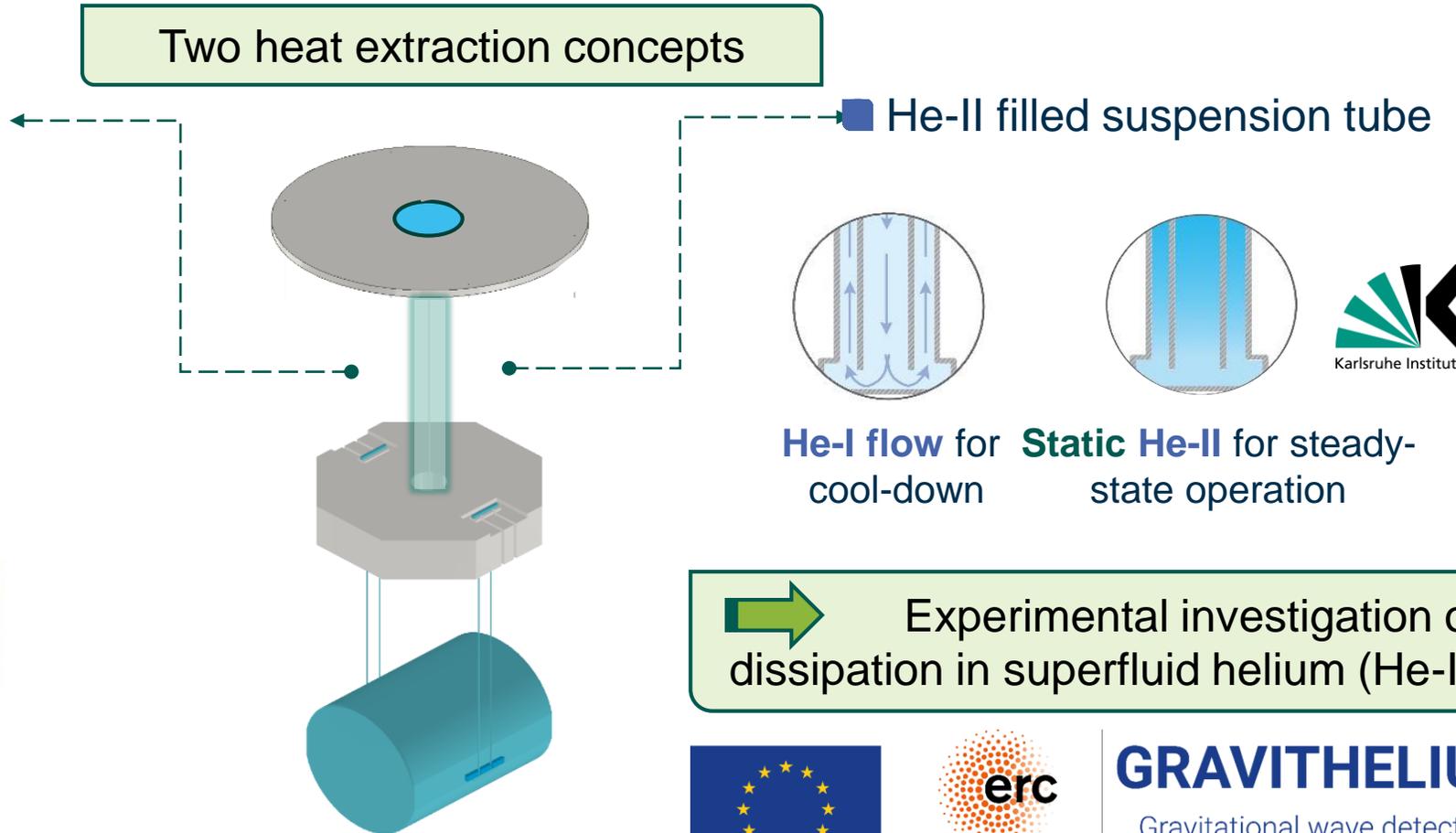
# GRAVITHELIUM: Cryogenic suspensions for ET

■ Monocrystalline suspension



Two heat extraction concepts

■ He-II filled suspension tube



➔ Experimental investigation of dissipation in superfluid helium (He-II)



**GRAVITHELIUM**  
Gravitational wave detectors cooled with superfluid helium



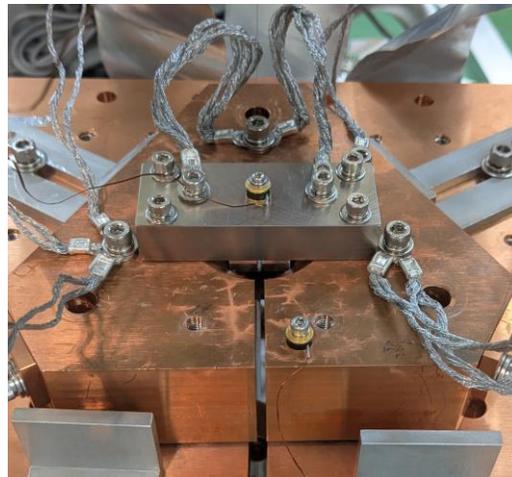
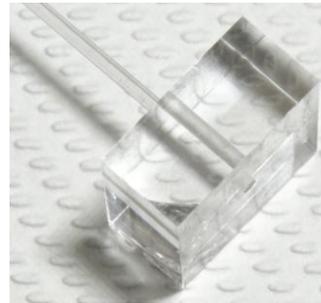
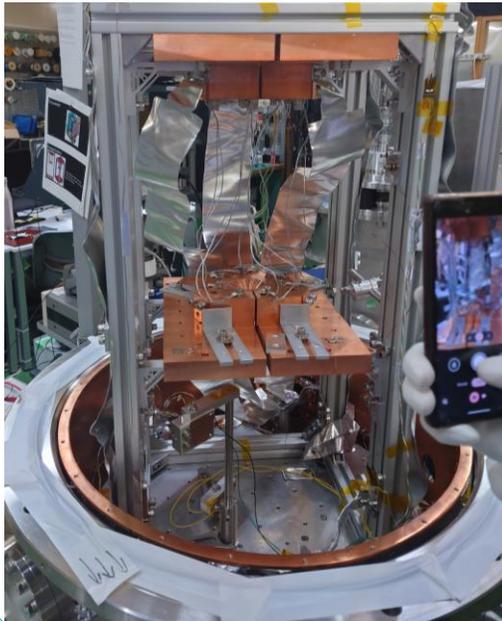
# *Q*-measurement setup @ KEK

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# Research Visit – Objective

## Part I:

Experimental know-how & Sapphire sample  $Q$ -measurements



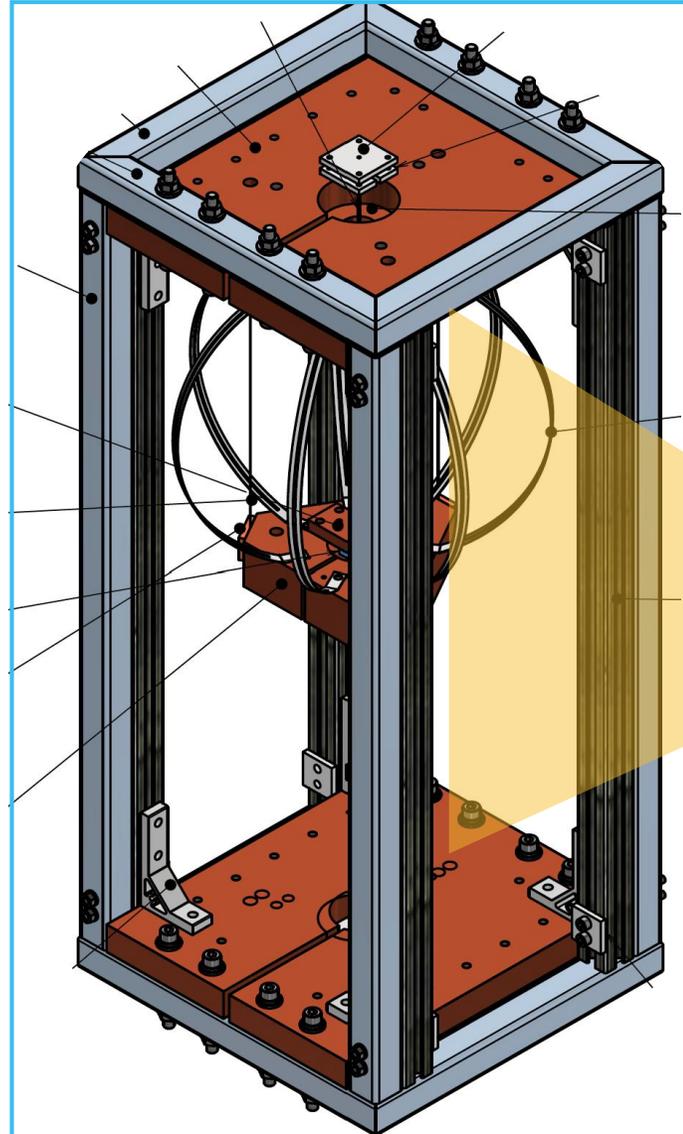
## Part II:

New Clamp Design & Silicon samples  $Q$ -measurements



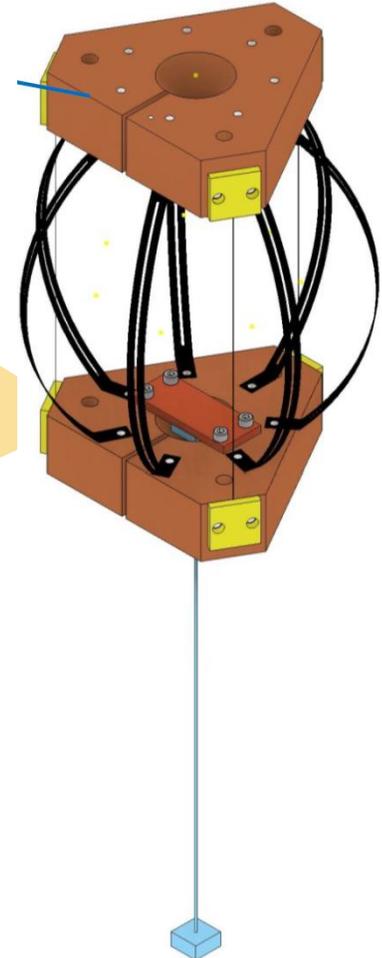
# Q-measurement setup @ KEK-GW: Overview

- Cryostat with thermal shield @ ~100 K
- $p$  down to  $10^{-8}$  ...  $10^{-7}$  mbar
- Cooled via CC PT415 RM
  - Sample @ 14 K
  - No heaters for T-control



3D Drawings: Courtesy of R. Bajpai

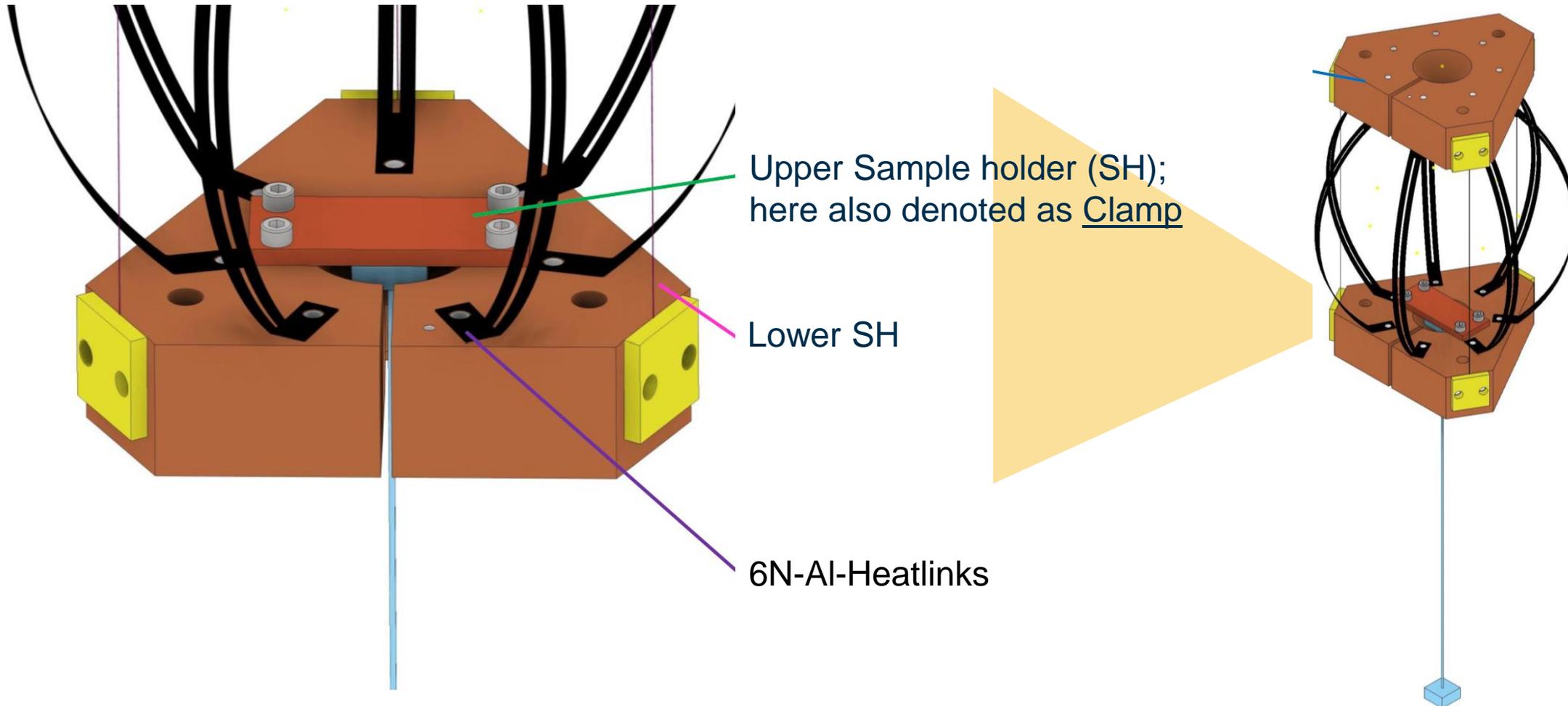
- Sample support system (SSS)



# Q-measurement setup @ KEK-GW: Overview

3D Drawings: Courtesy of R. Bajpai

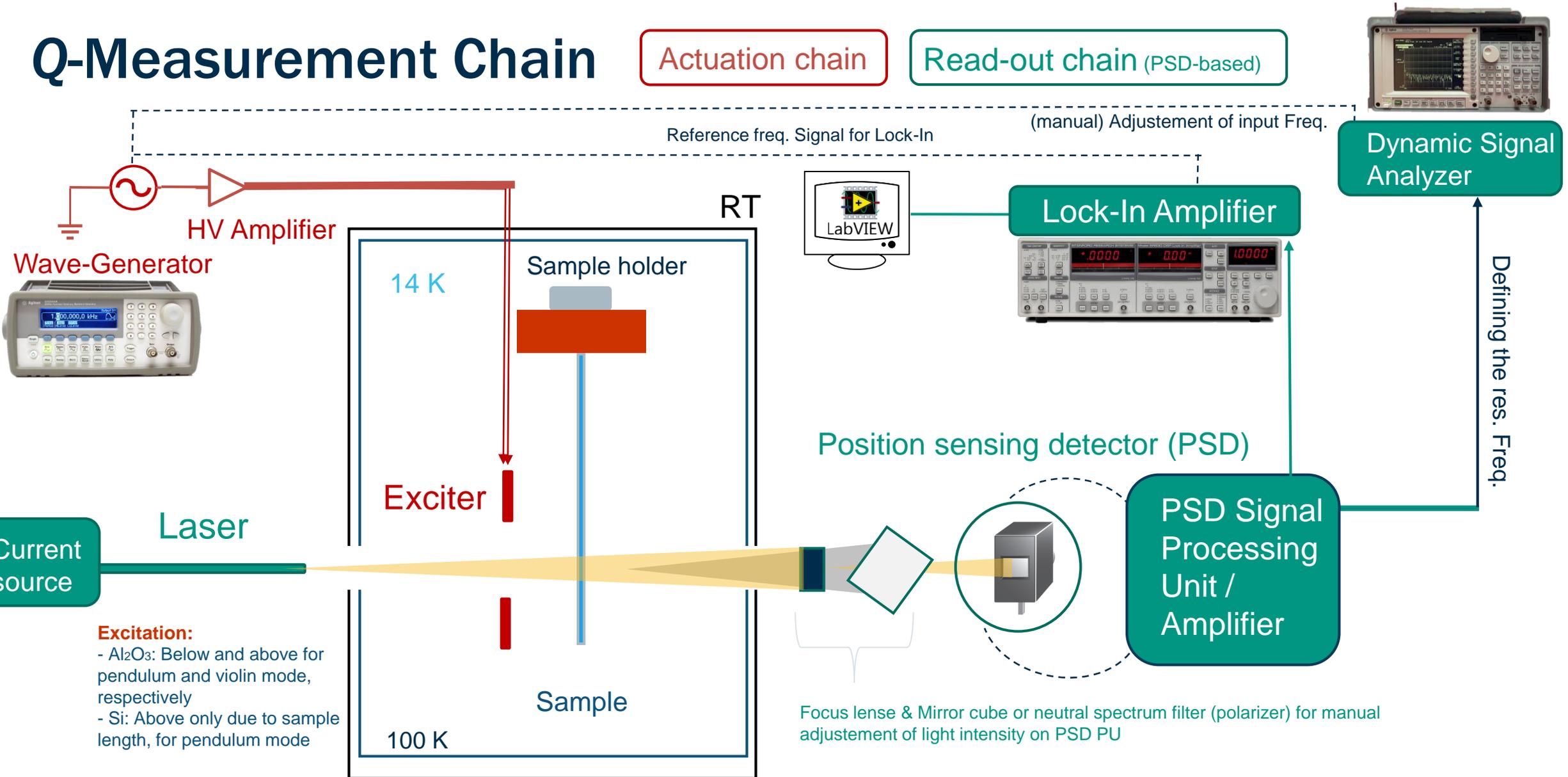
- Sample support system (SSS)



# Q-Measurement Chain

Actuation chain

Read-out chain (PSD-based)



# Part I

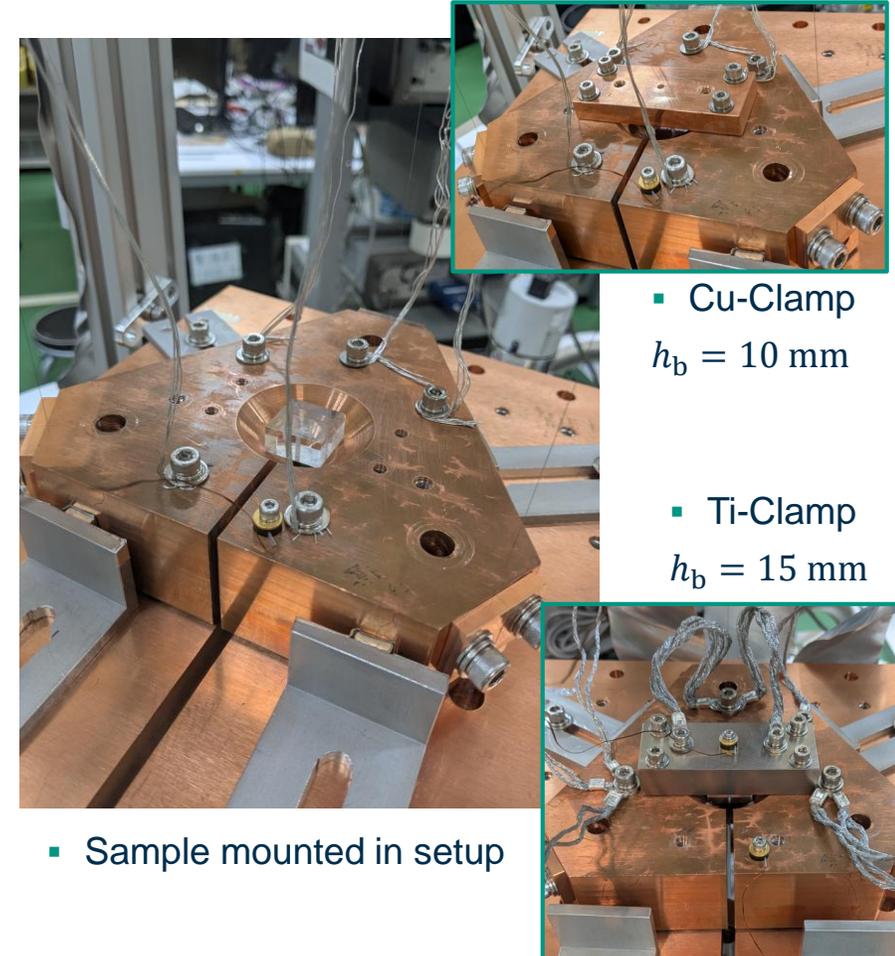
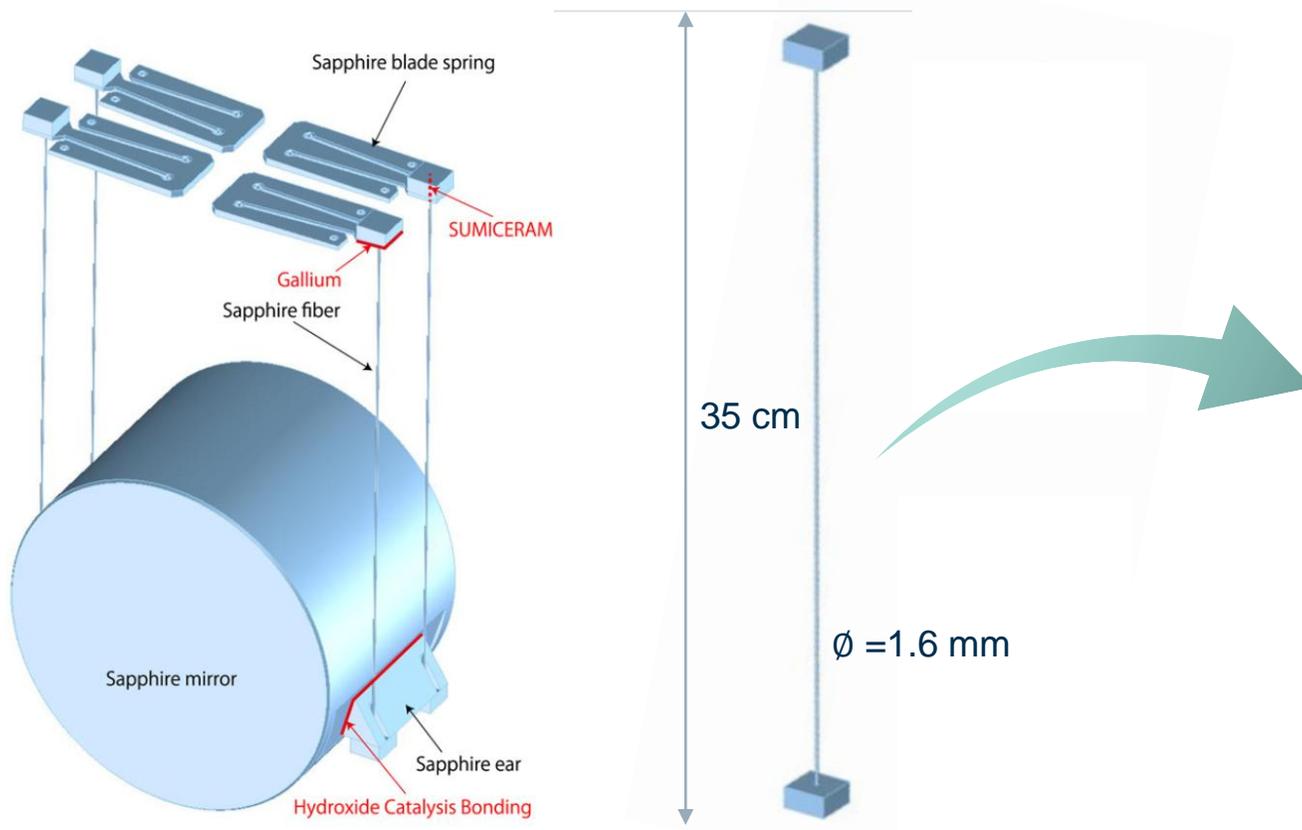
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## Sapphire samples and setup validation

# Sapphire suspension samples

## ➤ KAGRA suspension fiber: EFG-method grown fiber with SUMICERAM-glued nailheads

- Comparison to results of R Bajpai for setup validation
- Effect of clamp material/mass



# Sapphire sample: Experimental campaigns I

**Sapphire:** KAGRA Suspension fiber with nailheads joined by SUMICERAM

## Problems/Solutions:

- Low  $Q$  measured, due to newly installed damping magnet → removed it!
- Slow cooldown ~ 7 d (long heat extraction path)
  - ✓ optimized heat extraction path → direct connection cooling bar and SSS
  - ✓ Installed new, vacuum-annealed Al6N heatlinks
- Cooldown-test to test efficiency of new heat extraction path (with  $T$ -sensor on sample)
  - ✓ Acceleration by ~ 2 d!
- Measurements with Cu-clamp, to validate setup and test various clamping torques (0.4 Nm - 1.0 Nm)
  - cracked the nailhead @ **1.0** Nm → Afterwards **0.6** Nm was used



# Sapphire sample: Experimental campaigns II

- Results – Sapphire campaigns:

- ✓ 1. Setup validation run: with Cu-clamp (0.8 Nm) →  $Q = 2000$  @ 14 K same as RT, whereas @ 150 K,  $Q = 1.5 \cdot 10^4$  → caused by installed damping magnet

- ✓ 2. Setup validation run: with Cu-clamp (~ 200 g, 0.6 Nm) → setup validation

Pendulum mode @ 4.1 Hz:

- $Q = 1.0 - 1.5 \cdot 10^5$  @ 14 K and 1950 - 2000 @ RT

Violin mode @ 83 Hz:

- $Q = 5.9 - 7.8 \cdot 10^4$  @ 14 K

→ consistent with previous measurements of R Bajpai - SUMICERAM losses!

- ✓ 3. Material impact: with Ti-clamp (~ 153 g, 0.6 Nm)

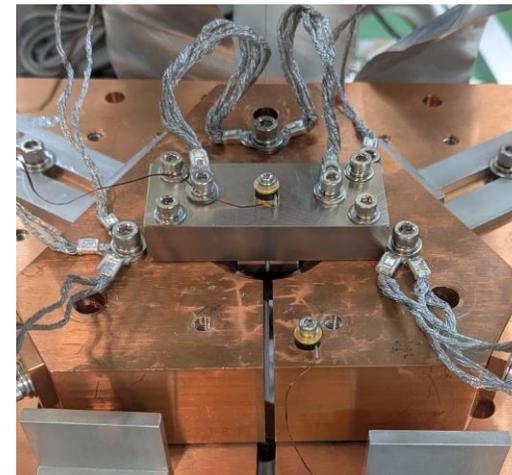
Higher cryogenic  $Q$  highly probable due to Ti-clamp

$$Q = 1820 \text{ @ RT}$$

$$Q = 2.06 - 2.33 \cdot 10^5 \text{ @ 16 K}$$

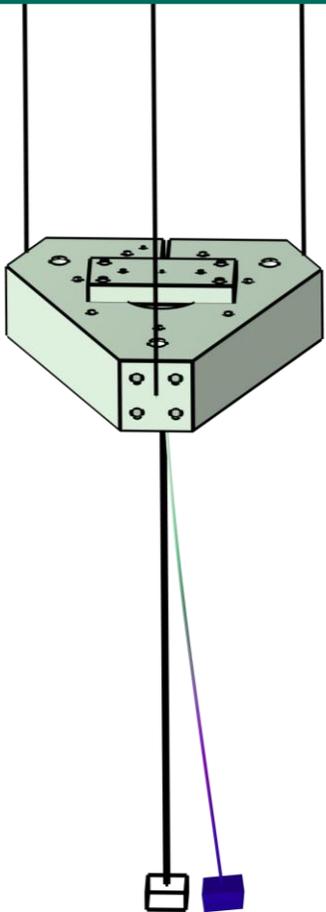
$$Q = 2.0 - 2.5 \cdot 10^5 \text{ @ 13.8 K (pendulum mode } \uparrow)$$

$$Q = 1.8 \cdot 10^5 \text{ @ 13.5 K (violin mode)}$$

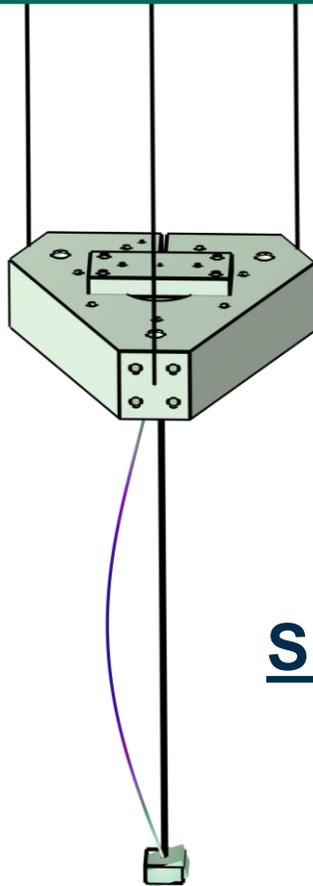


# Modal Analysis of KEK-SSS (Sapphire)

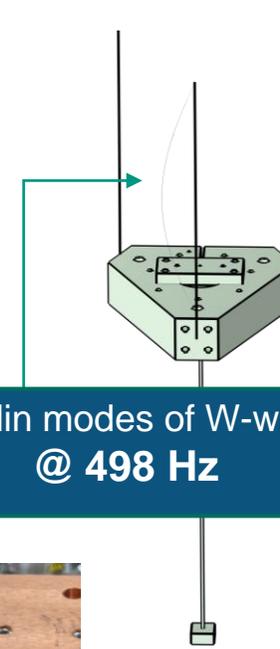
1. Sample mode  
(Pendulum mode) @ 4.5 Hz



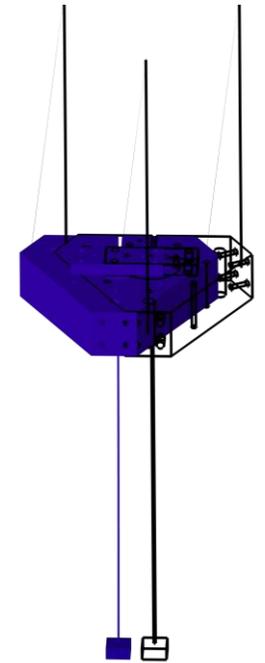
2. Sample mode  
(Violin mode) @ 87 Hz



1. Violin modes of W-wires  
@ 498 Hz



Pendulum mode SSS  
@ 1.045 Hz



## Simulation results:

- ✓ Resonant freq. consistent with measurements (4 - 8%)
  - 4.13 Hz and 83 Hz, respectively

# Part II

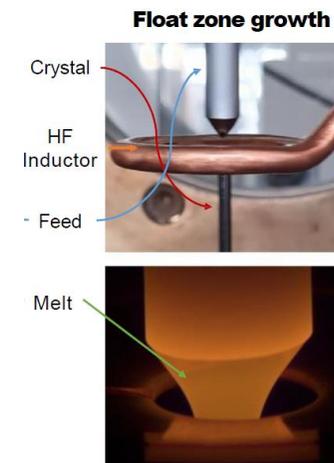
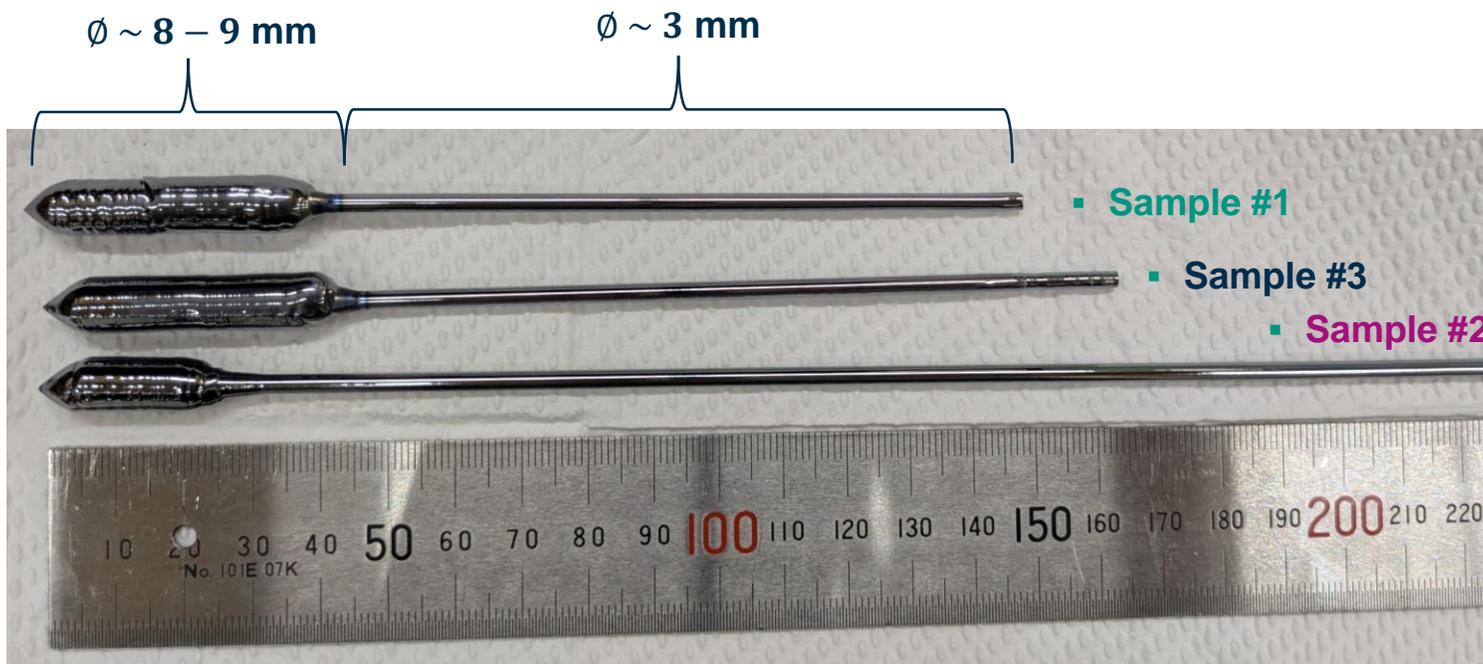
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## IKZ Silicon samples

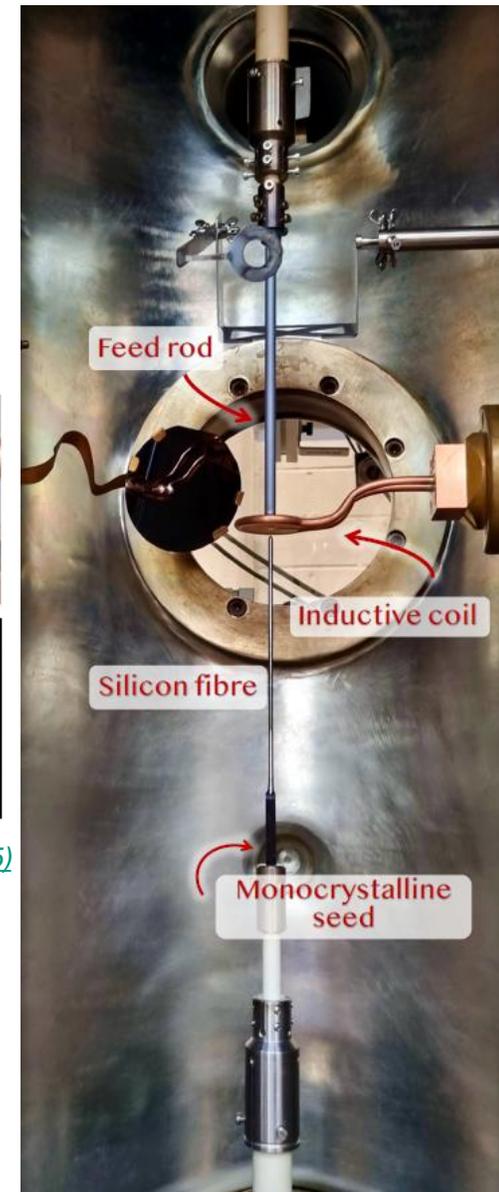
# IKZ Silicon suspension samples

3 FZG-grown Silicon samples from IKZ to be used in  $Q$ -measurement @ KEK:

- ✓ **Sample #1 & #3** (transportation scratches highly probable)
  - thermal & mechanical characterization @ KIT of 2 samples from same charge
- ✓ **Sample #2** – sent from F Travasso with appropriate packaging to avoid surface scratches!



[I. Buchovska et al. \(2025\)](#)



[A. Nela et al \(2025\)](#)

# Silicon samples: Transportation method

- **Sample #1 & Sample #3**

→ Transportation in a normal cushioned box, but not fixed!



- **Sample #2**

Flavio Travasso's idea:

→ Transportation inside Al-rod with wax-glued ends



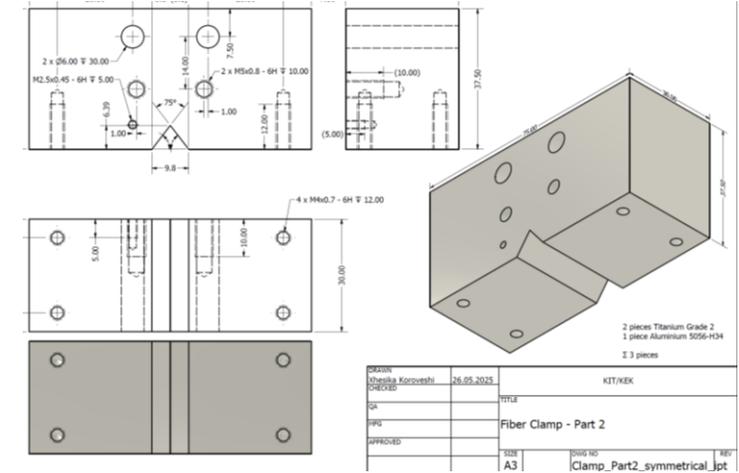
# Clamp adaptation for silicon sample

## Problem for integration in existing KEK SH Design:

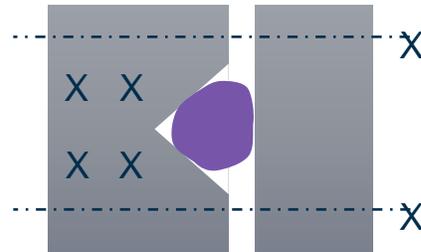
- Silicon sample head inhomogeneous: ~ 4 cm long and with  $\varnothing \sim 8$  mm

→ *Solution: New Clamp design and new materials.*

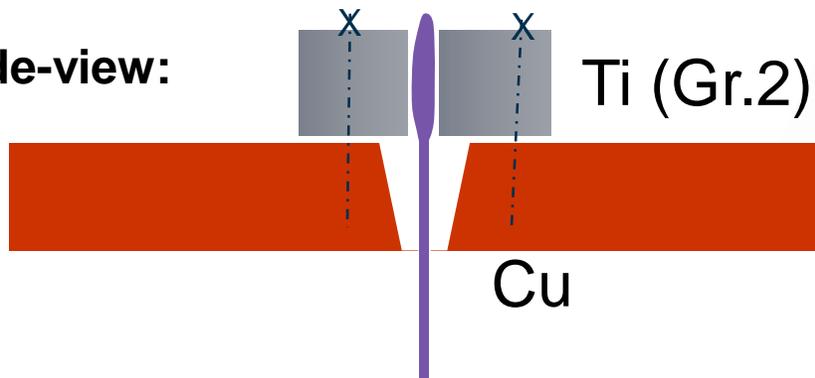
- Titanium Gr. 2 was chosen based on ET-LF Payload/GRAVITHELIUM design, due to  $Q_{\text{bulk}} \sim 10^6$  [1] and high yield strength



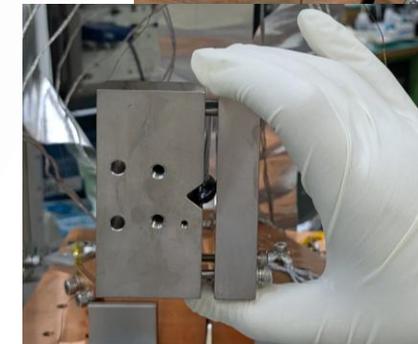
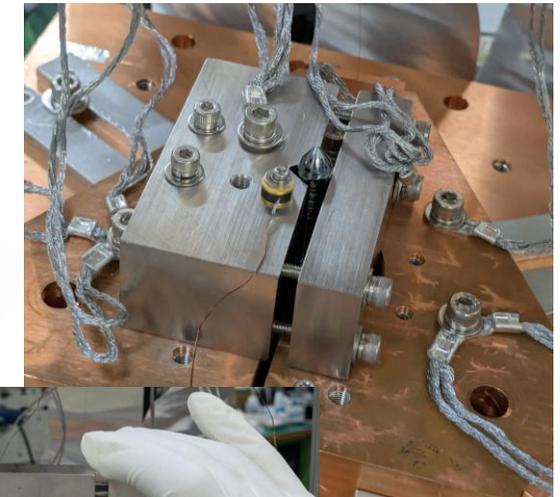
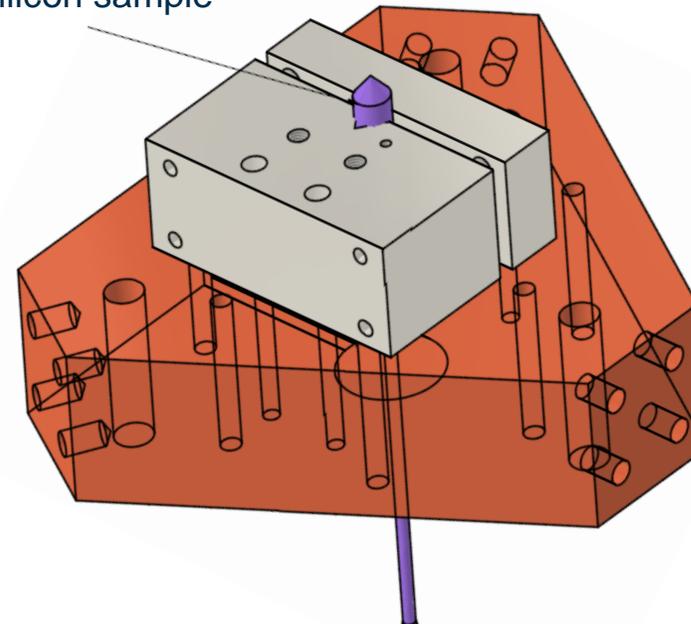
Top-view:



Side-view:



IKZ Silicon sample



[1] Duffy, W. (2000)

# Silicon experimental campaigns I

## Boundary Conditions:

- **New Clamp:** Design for compatibility with existing setup suspension was challenging → Manufacturing time with **new materials Ti** (and Al5056, but limited tests)
  - Cooldown test successful with  $T \sim 14$  K achieved at the sample
  - **Clamping torque sensitivity tests** massive effect – broke silicon seeds to test !
- **Si Fiber:** **Surface quality** of Si sample due to transportation
  - Seeds were cut off with a diamond blade
  - Only Sample #1 and #2 measured, due to limited time and clamp issues with sample #3
- **Setup Adjustment**
  - Shorter sample than setup design → only 1. Sample mode (pendulum mode)
  - Laser realignment needed and new optical polarisation filters
  - Challenging to measure  $Q$  @ intermediate temperatures, due to lack of heaters to control CC → future implementation foreseen
  - Excitation, clamp tightness and DAQ instrument issues + 1 failed cooldown attempt due to CC Compressor overheating problems

# Silicon experimental campaigns II

- **Sample #1 @ ~ 280 Hz ( $L_{\text{fiber}} \sim 110$  mm)**

- Torque on clamp: 1.5 Nm → too much, head broke after demounting
- Higher  $Q$  expected but „worst“ sample wrt. to surface losses used

- **Sample #2 @ ~ 81.5 Hz ( $L_{\text{fiber}} \sim 213$  mm)**

- **Highest measured  $Q$  at KEK-GW Q-setup so far!**

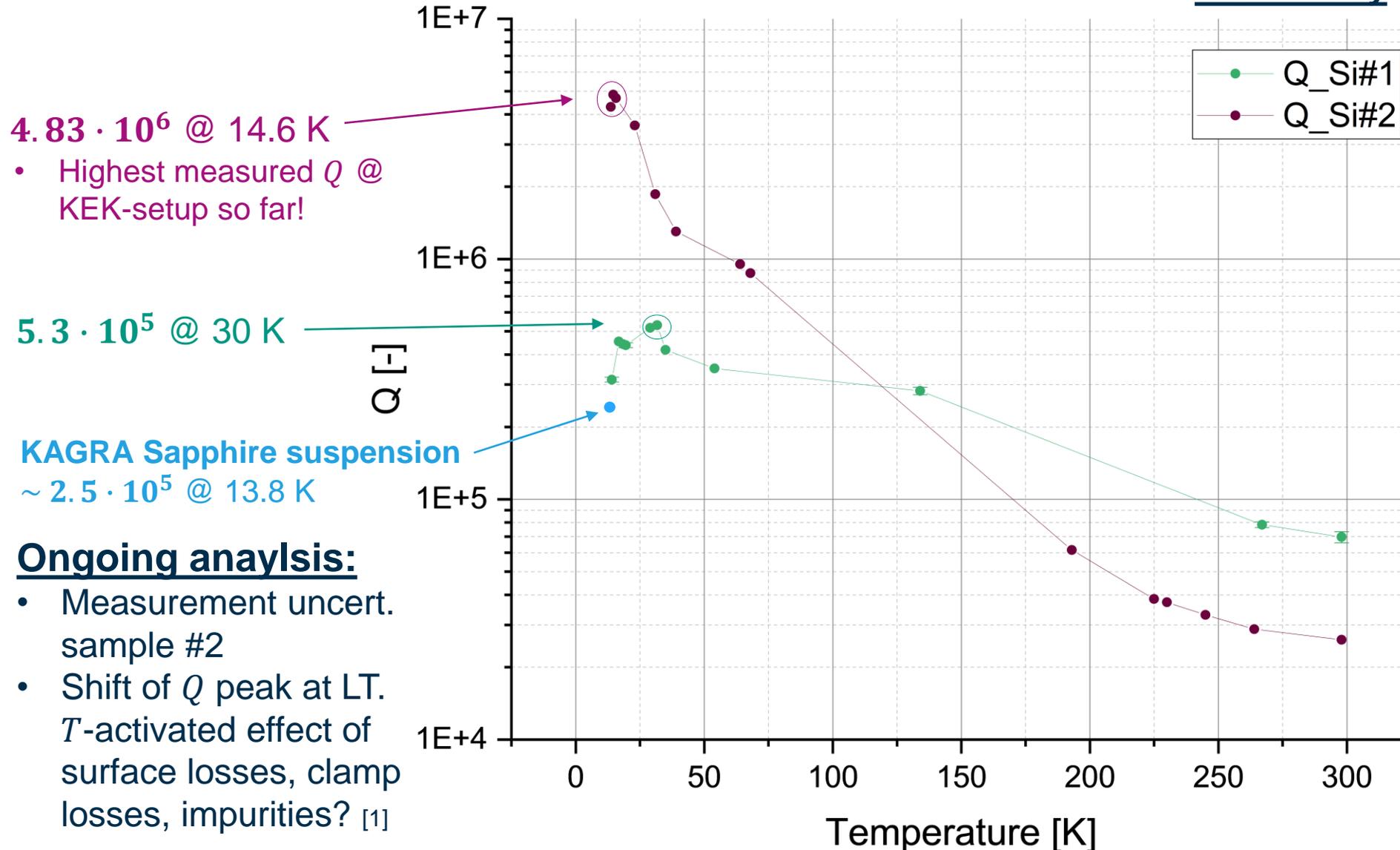
- Torque on clamp 1.0 Nm
- RT- $Q$  was lower than sample #1, but as expected due to thermo-elastic contribution  
→ best sample (good transportation conditions) and highest measured  $Q$  @ 14.5 K

✓ Completed Sample #1 and #2 measurements



# Silicon samples (w. Ti Clamp): $Q$ - factor

Preliminary



Sample #2 Sample #1



# Silicon samples (w. Ti Clamp): Loss angle

Sample #2 Sample #1

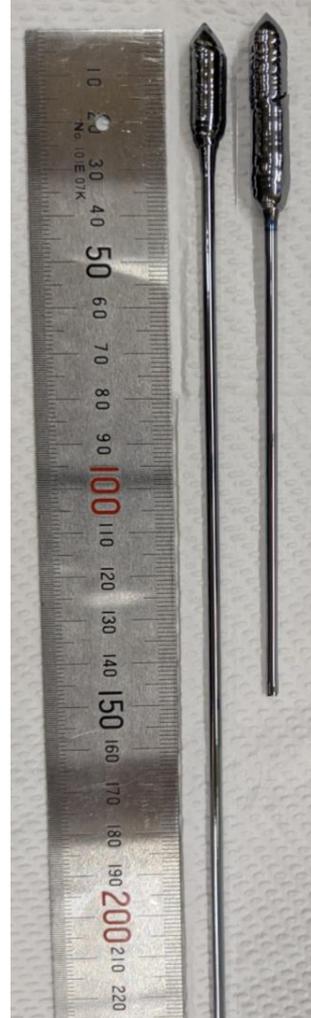
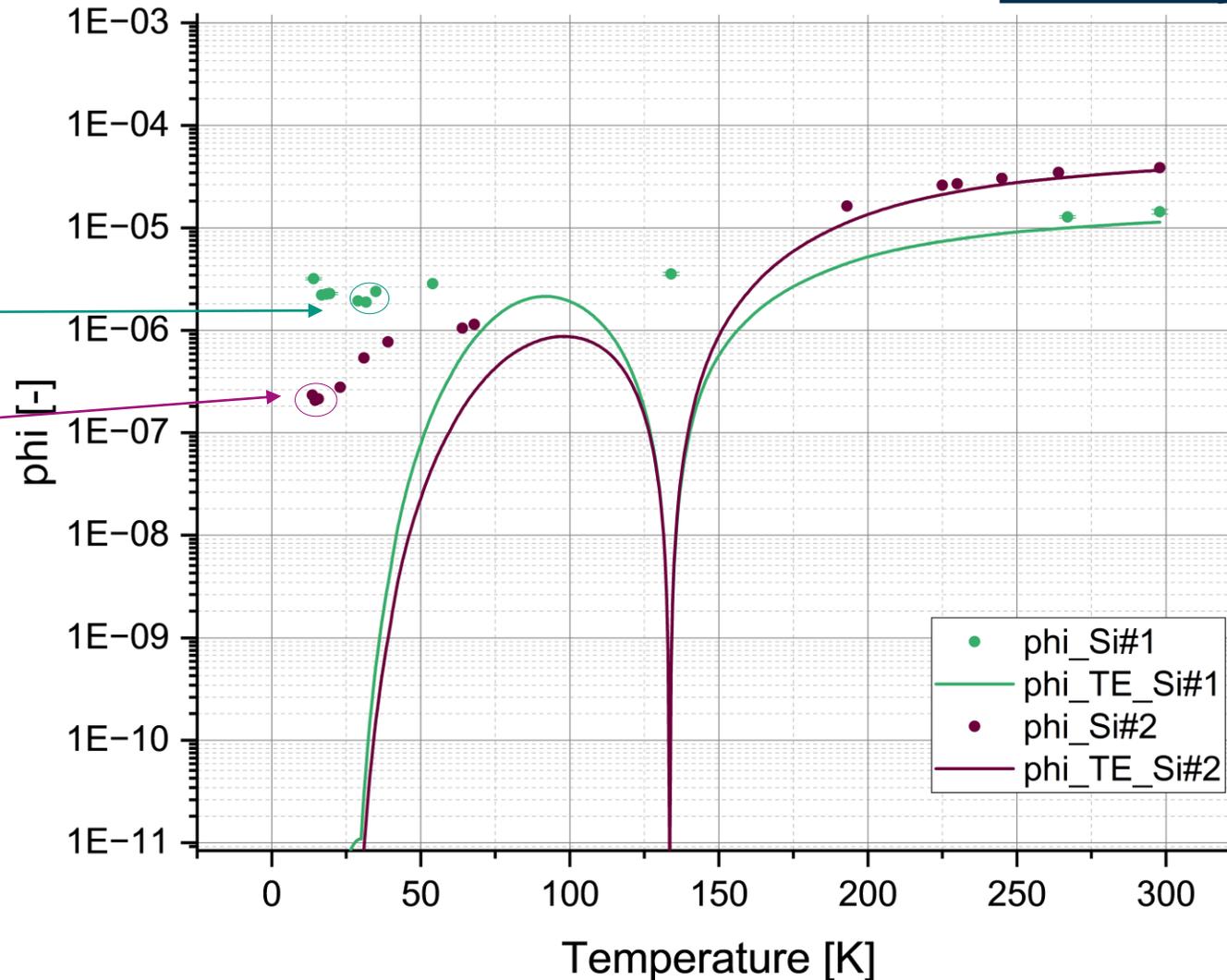
Preliminary

$1.89 \cdot 10^{-6}$  @ 30 K

$2.07 \cdot 10^{-7}$  @ 14.6 K

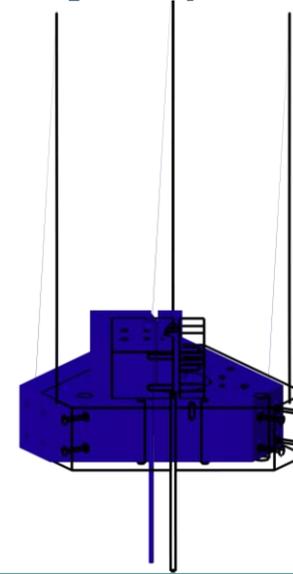
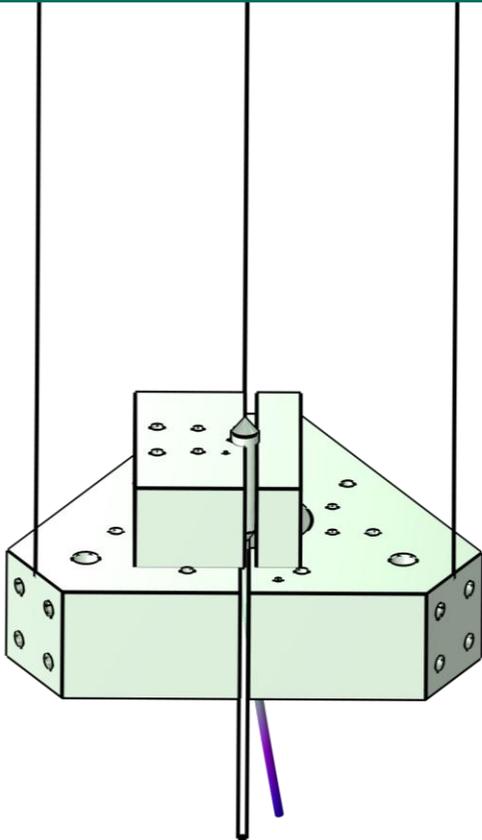
## First remarks:

- TE-losses dominate @ RT and give the trend
- Surface losses major reason in difference between sample #1 & #2
- Clamping losses also impacting (1.5 Nm vs. 1.0 Nm)

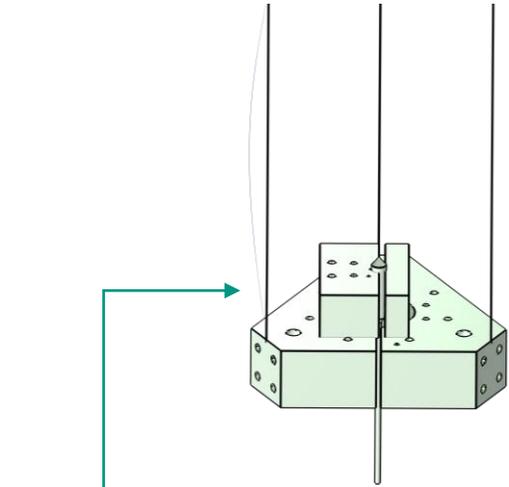


# Modal Analysis of KEK-SSS (Silicon sample)

1. Sample mode (Pendulum mode)  
@ 239.5 Hz (#1)  
@ 69.6 Hz (#2)



Pendulum mode SSS  
@ 1.005 Hz



1. Violin modes of W-wires  
@ 470 Hz

## Simulation results:

- ✓ Consistent with measurements (16% -18%)
  - 278.65 Hz and 81.25 Hz
  - Variation probably due to applied physical properties based on crystal-orientation

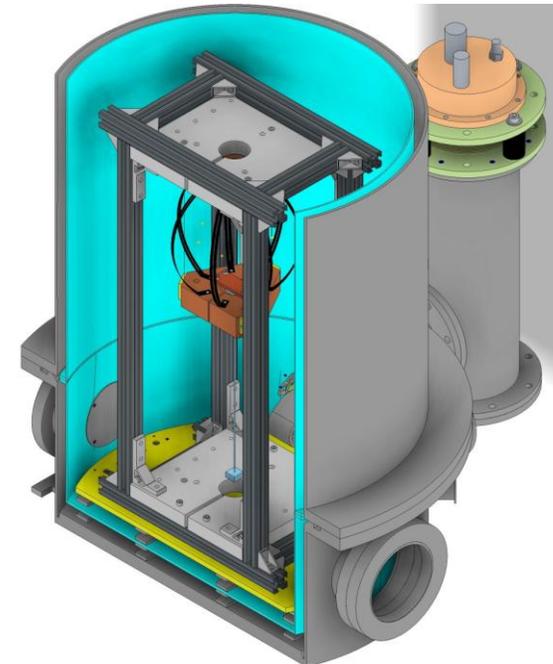
# Conclusions & Outlook I

## Research visit @ KEK: $Q$ -measurements results

- Setup validation by reproduction of previous KAGRA suspension  $Q$ -measurements
- First cryogenic  $Q$ -measurements of IKZ Si samples for ET-LF with  $Q$ s as high as  $4.83 \cdot 10^6$ 
  - Surface losses and clamp losses dominant effect!
  - Low temperature trend of the 2 samples under analysis
- Impact of clamp material was proven, but further tests needed.
  - Sapphire sample measurements (Cu vs. Ti upper sample holder)
- Know-how for  $Q$ -measurements with various samples
  - → Input for GRAVITHELIUM @ KIT (clamp, read-out method)

## Next possible steps @ KEK-setup for further experimental investigations

- Installation of heaters for  $T$ -control in intermediate  $Q$ -measurements
- Further Si-measurements → understand high  $Q$ -peak @ 30 K vs 14 K
- Experiments with clamp variation:
  - Silicon (Ti vs. Al5056) → material impact on cryogenic  $Q$
  - Repeated measurements with varying torque on clamp (upper sample holder)

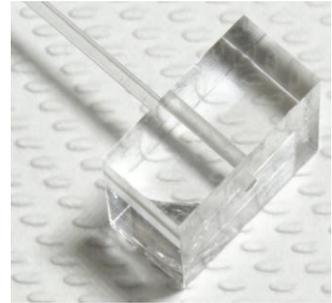


Courtesy of  
R. Bajpai

# Conclusions & Outlook II

## Samples improvement and consideration of jointing methods

- **Sapphire:** KAGRA-suspensions measurements limited by SUMICERAN bonding of nailheads.  $Q \sim 2.5 \cdot 10^5 @ 13.8 \text{ K}$ 
  - Low loss jointing alternatives such as welding seem promising for ET-LF and are being pursued in KAGRA also [1].
- **Silicon:** Only impact of surface quality (impurities, too)? →  $Q \sim 4.83 \cdot 10^6 @ 14.6 \text{ K}$  and  $5.3 \cdot 10^5 @ 30 \text{ K}$ 
  - More homogenous heads? IKZ: technically not feasible! Furnace coil optimized for 3 mm fiber, so in monolithic samples it is a question of trade-off, either homogenous heads or fibers.
  - First welding efforts for silicon have also started.
- **Welding silicon & sapphire samples:** ongoing thermal, mechanical and dissipative characterization with promising first results



IKZ Silicon weld: A Nela (IGR),  
F Travasso (Camerino) et al.

Sapphire weld:  
[1] [J. Docherty et al. \(2026\)](#), (IGR)

# Conclusions & Outlook II

## Considerations for future $Q$ -measurements towards ET-LF payload

**Design of an adequate Sample Support System (SSS) is the first step!**

- SSS @ KEK adequate for measurements between 4 Hz – 280 Hz (within scope of this work)

**Probable loss sources:**

- **Surface losses extremely crucial:** Careful transportation and manufacturing methods for ET-LF suspensions are essential!
- **Clamping losses:** related to used torque & material choice:
  - Ti Gr. 2 chosen due to low bulk losses and high yield strength
  - Clamp losses at cryogenics: Low dissipative materials and trade-off strength/softness for clamp choice needs to be further investigated, since measurements at RT can often be dominated from the sample's TE-losses.
- **Jointing losses:**
  - Integration of fibers into the payload design
  - Ongoing R&D of welded and HCB-bonded silicon & sapphire samples

# Cryogenic payload suspensions: Towards a feasible design

- **Mechanical, thermal and dissipative** characterization
- Integration into the cryogenic payload design

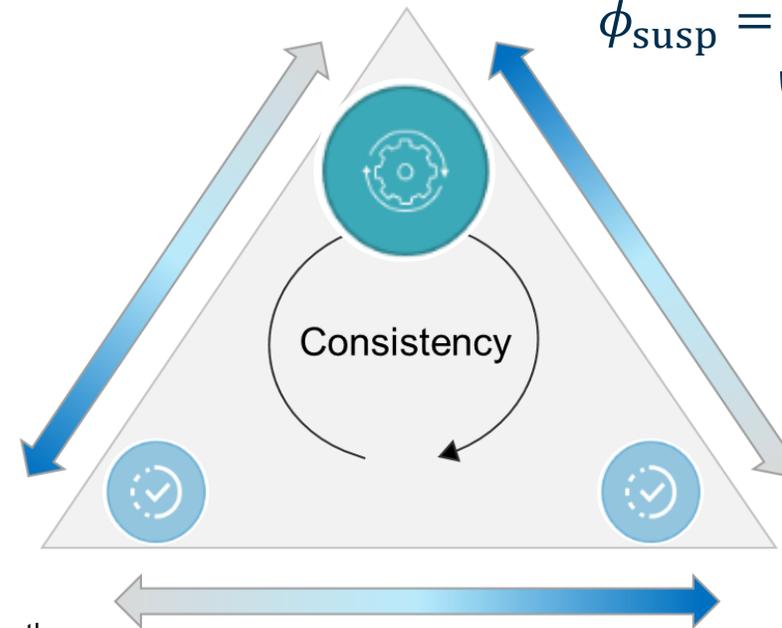
- R&D for welded, HCB-bonded samples ...
- Extrinsic losses
    - Clamping losses
    - Jointing losses
- Interfaces in payload crucial: **joining losses** in suspensions!

## Suspension Thermal Noise (STN)

■ ET Sensitivity curve

$$\phi_{\text{susp}} = \underbrace{\phi_{\text{bulk}} + \phi_{\text{thermoelastic}} + \phi_{\text{surface}}}_{\text{Intrinsic losses}} + \phi_{\text{extrinsic}}$$

- Intrinsic losses
  - Surface losses

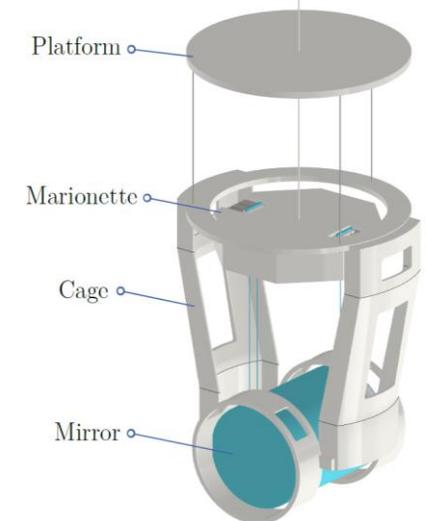


### Thermal Design

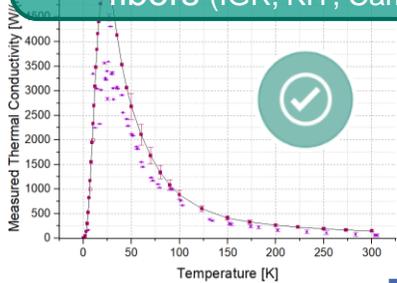
- Heat extraction path
- Interfaces & Temperatures

### Mechanical Design

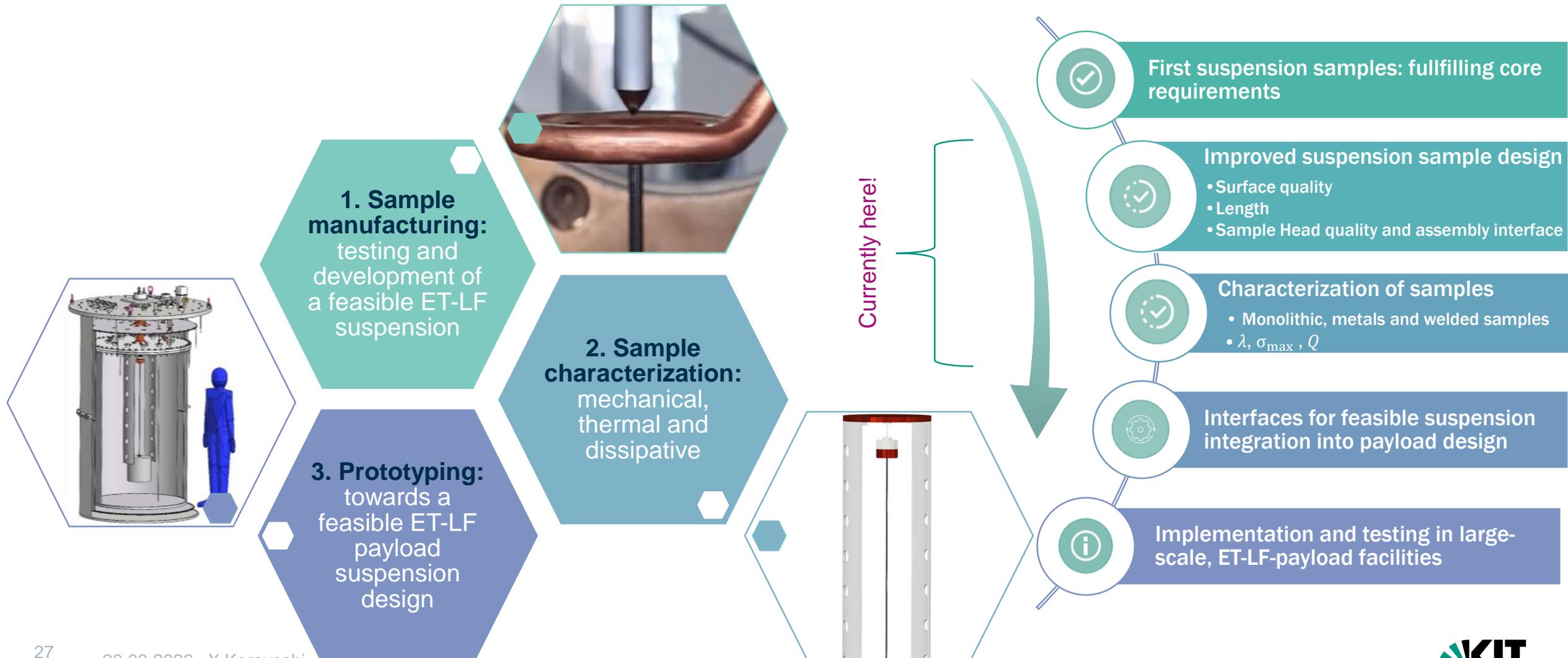
- Materials
- Dimensions



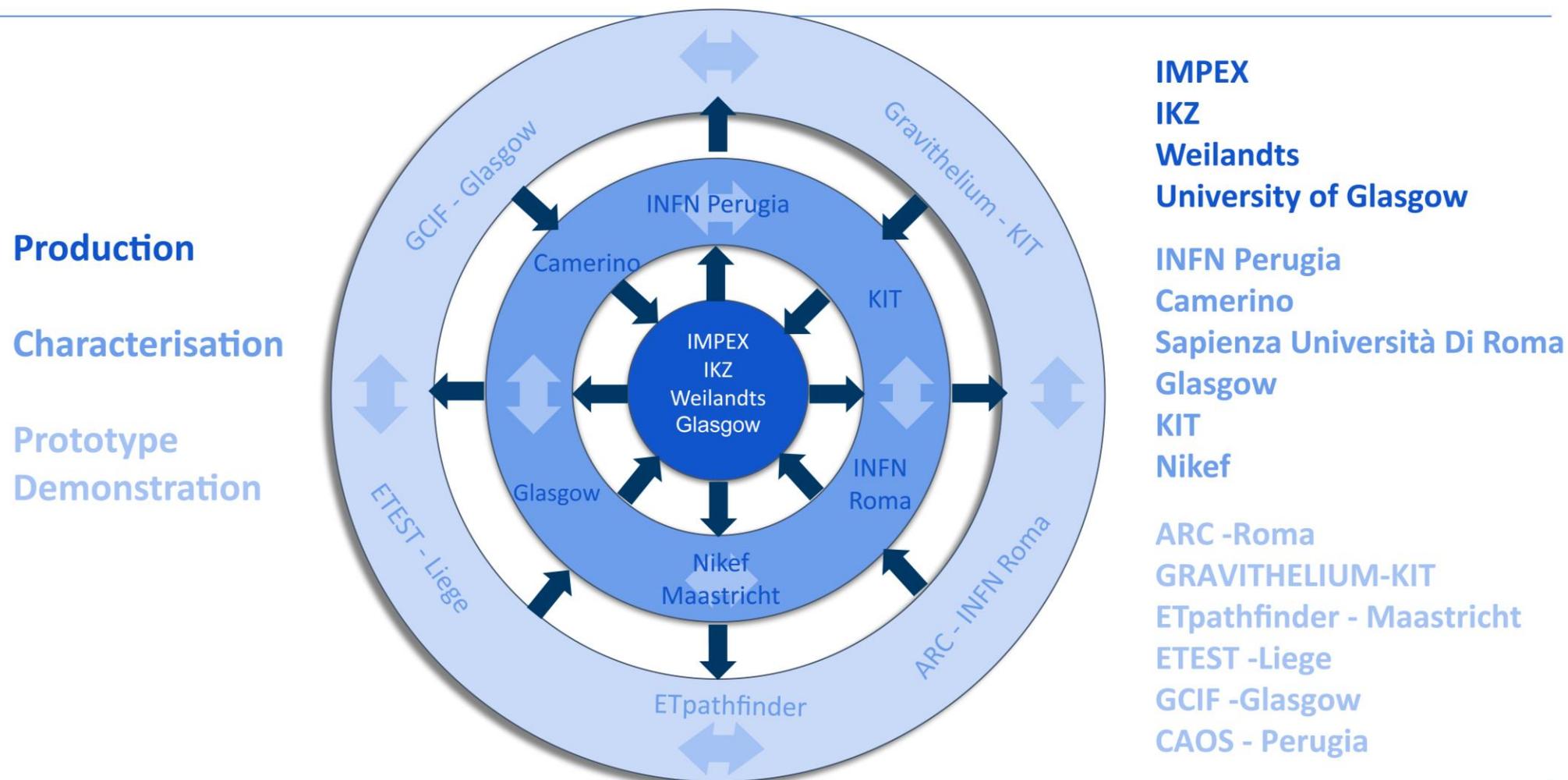
Cryogenic thermal conductivity and strength tests: Si & Al<sub>2</sub>O<sub>3</sub> fibers (IGR, KIT, Camerino ...)



# Cryogenic payload suspensions: Towards a feasible design



# Cryogenic payload suspensions: Collaborative effort



Credit: [Andrew Spencer - MAD Workshop 2025](#)

**Thank you for your attention!**

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