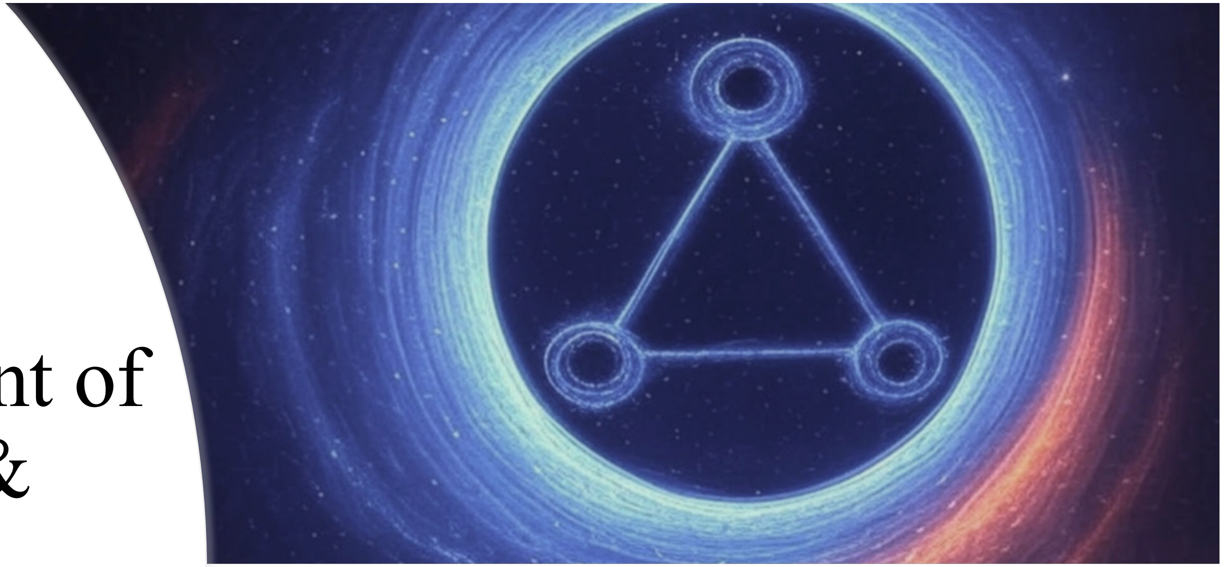
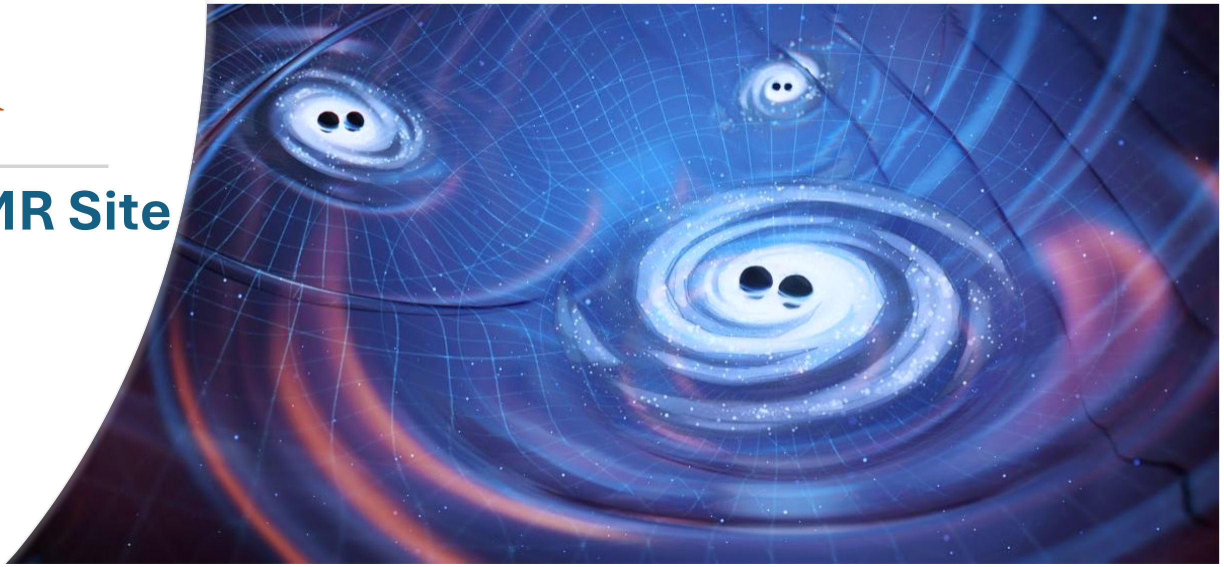
MAD 2025

Precision Measurement of Mechanical Loss & Thermal Noise Characterisation

E-TEST: Einstein Telescope EMR Site





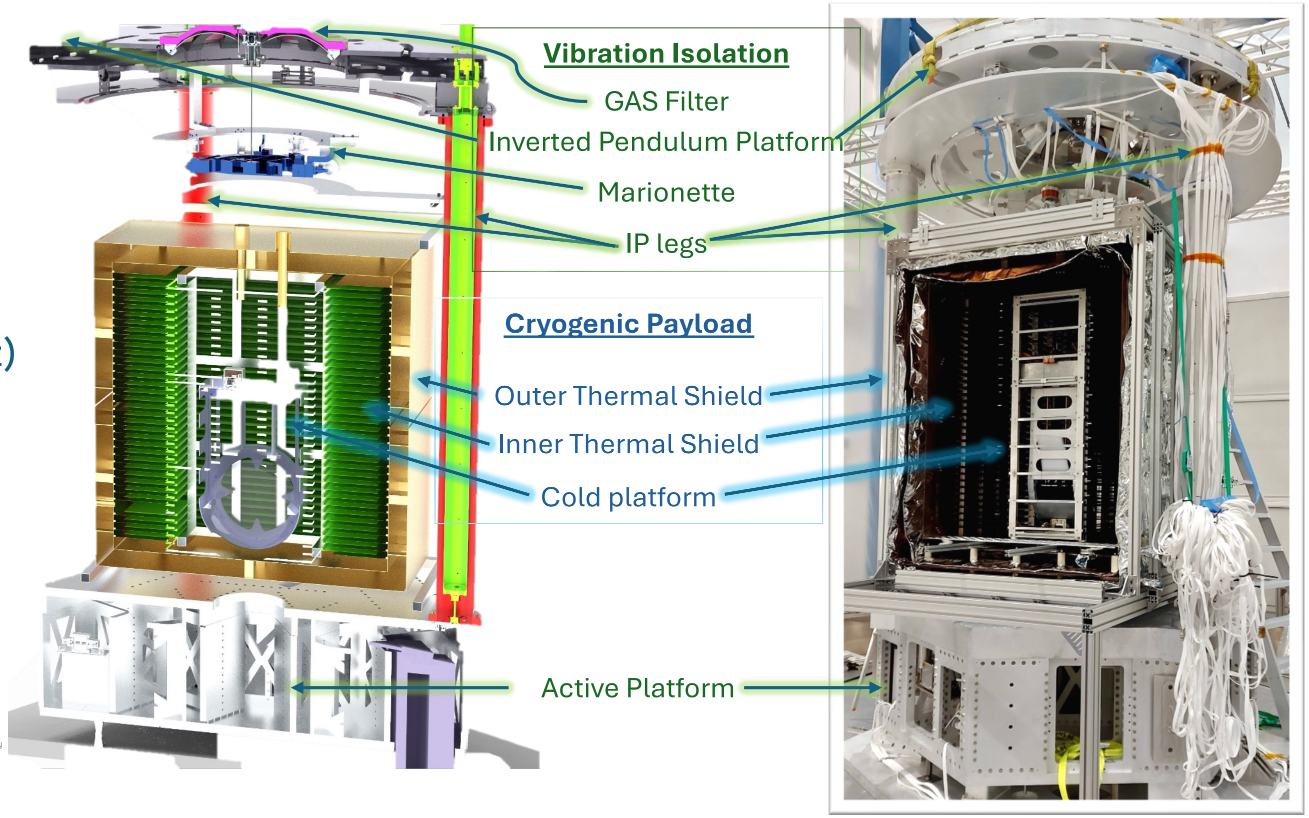
Hemendra Singh
Precision Mechatronics Laboratory - ULiege
https://www.pml.uliege.be

E-TEST Cryogenic Prototype

*From **Concept**, through **Design**, to **Creation!!***

The E-TEST project, supported by Interreg EMR and ET2SME, uses CSL's existing infrastructure to build the facility.

- Isolated at low frequency (0.01-10 Hz)
- Radiative cooling (20 K)
- Large Si mirror (~100 Kg)



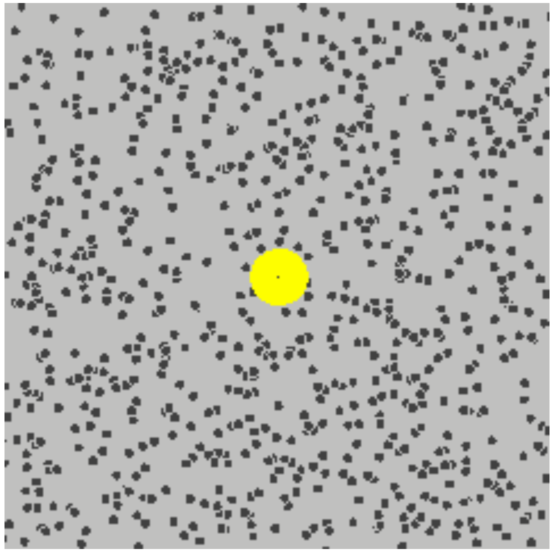
Precision Mechatronics Laboratory | CSL Centre Spatial de Liège | E-TEST Einstein Telescope EMR Site & Technology

Nikhef | UCLouvain | KU Leuven micas | Fraunhofer ILT | KU LEUVEN | RWTH AACHEN UNIVERSITY | Interreg Euregio Meuse-Rhine European Regional Development Fund | European Union

Overview: Thermal Noise

Fluctuation-Dissipation Theorem

Relates noise spectrum + system's linear responses to applied perturbations:



Brownian motion of a particle

Power spectrum of noise

$$x^2(\omega) = \frac{4k_B T k\phi(\omega)}{\omega[(k - m\omega^2)^2 + k^2\phi^2]}$$

- This equation depends on one unknown, ϕ, the loss angle.
- **Quality Factor** = ϕ^{-1} (dimensionless)

- Thermal Noise Reduction:
  1. **Lower Temperature**
  2. **Larger Test Mass**
  3. **Increase Q factor** to shift noise above the signal band
- The **mechanical Q-factor** varies with **Temperature**.
- Some materials show a **peak in Q-factor** at certain low temperatures due to changes in **atomic lattice vibrations**.

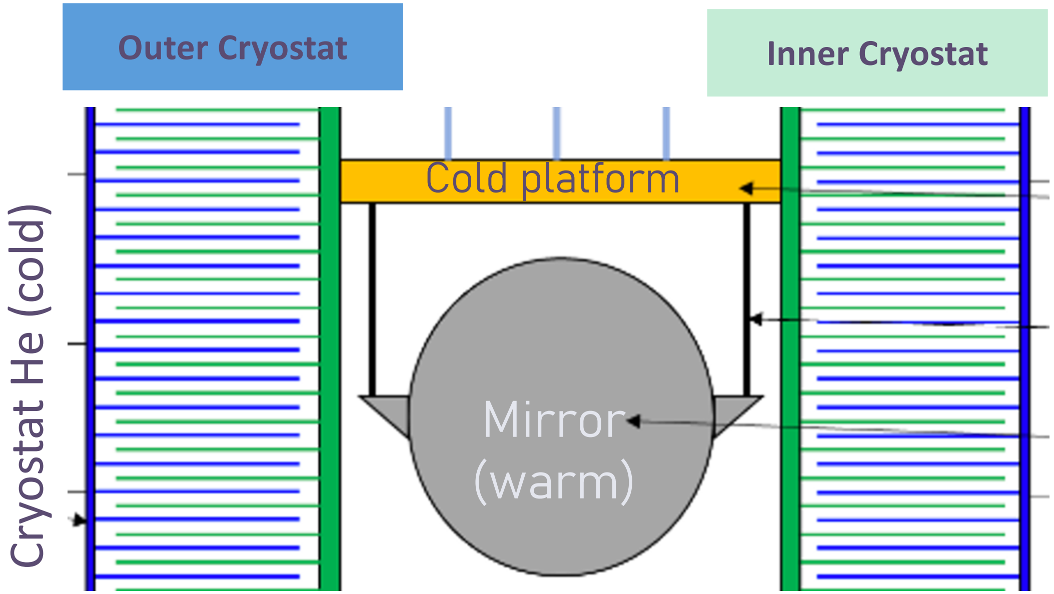
Graphic: Francisco Esquembre, Fu-Kwun and Loo Kang Wee

Ref: Peter Saulson

1. To reach a lower temperature

Radiative Cooling:

- Interlacing fins to increase the radiative heat exchange area (80m² for E-TEST, ~500m² for ET).
- Thermo-mech. topology optimisation of fin geometry with radiation
- Emissivity enhancement at low temperature (coating)



GDTECH engineering · open engineering · CRM GROUP · EHP · UCLouvain · PIX COATING · Mecasoft · CSL CENTRE SPATIAL DE LIÈGE

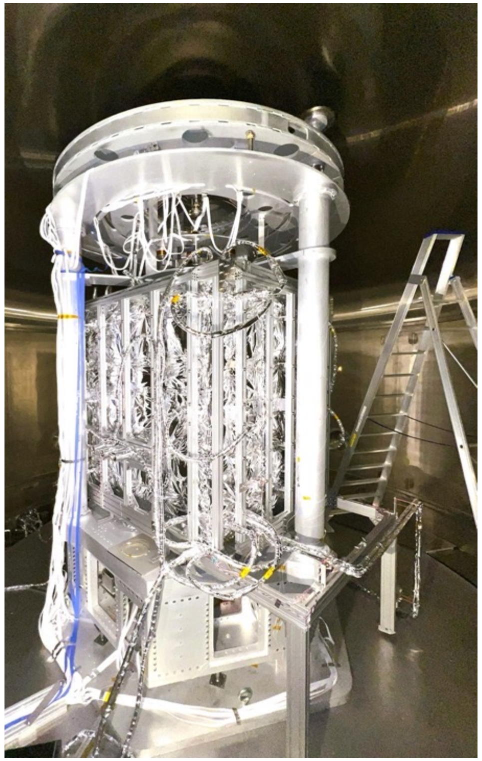
1. To reach a lower temperature

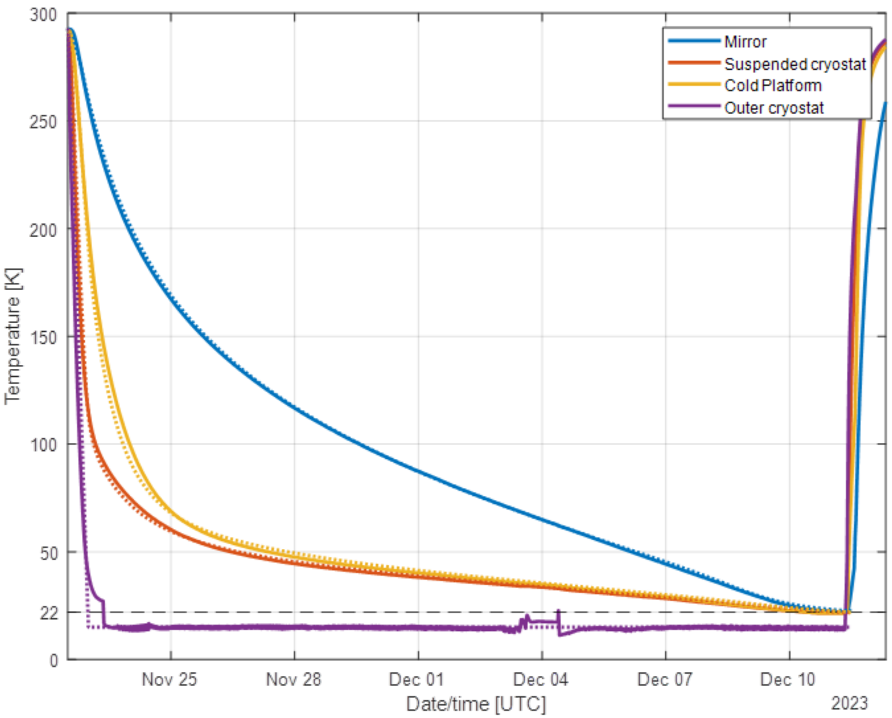
Prototype assembly completed
Nov 2023

First Run (Vacuum)

1st run at CSL 2023
22K achieved in 18days !

CENTRE SPATIAL DE LIÈGE

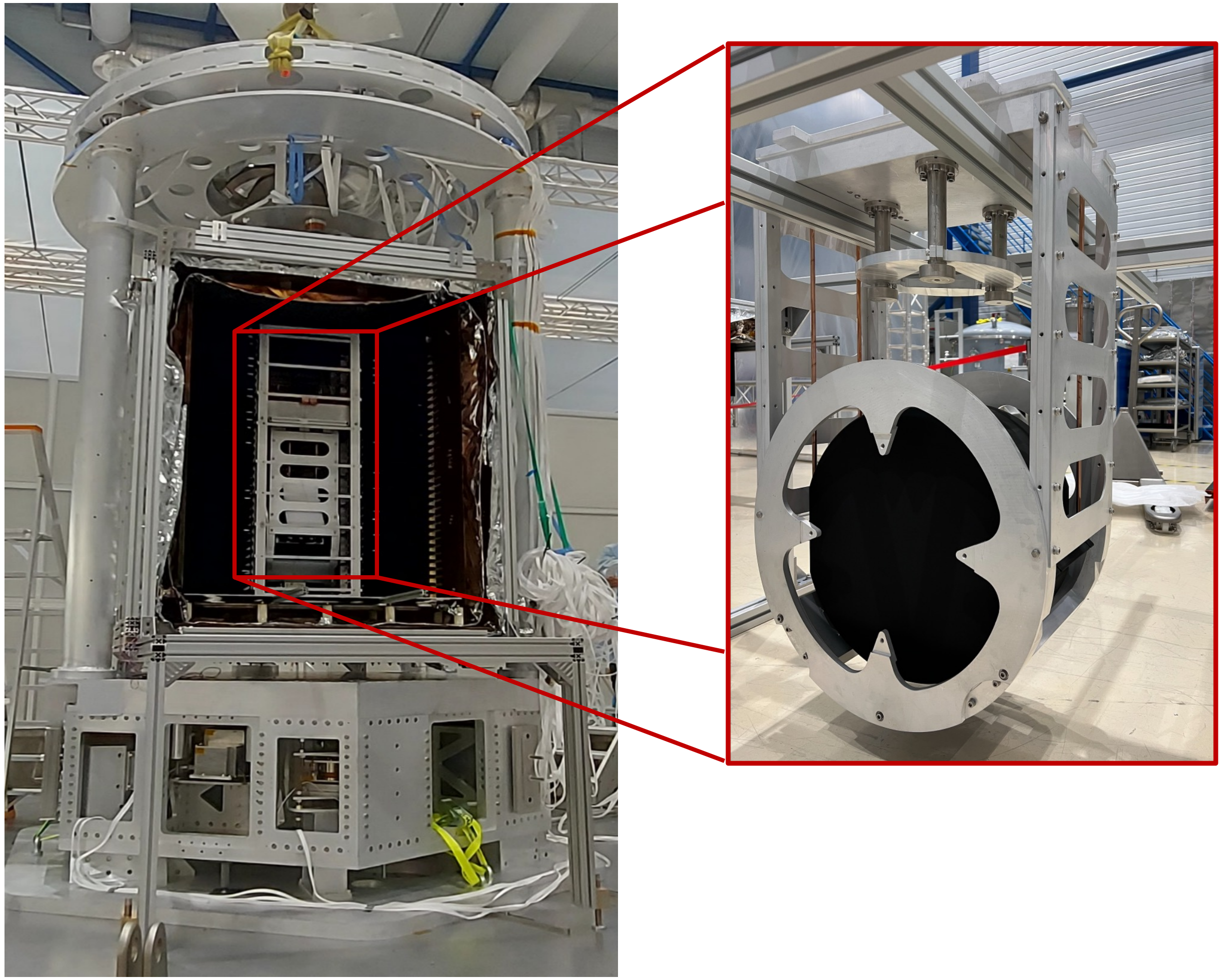




Note: Dummy Test Mass (Aluminium) was used.

Ref: Jacques Lionel et al.

2. TEST MASS (First Run:2023)

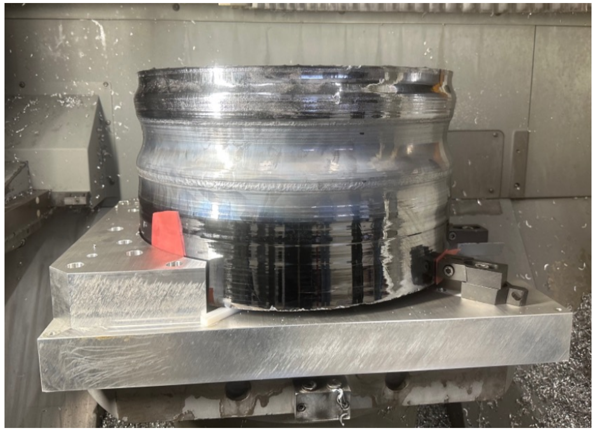


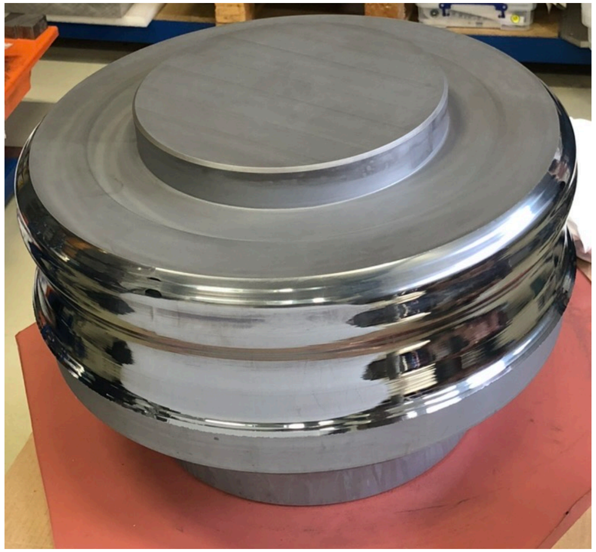
2023: 1st Run: Dummy Test mass

- 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)

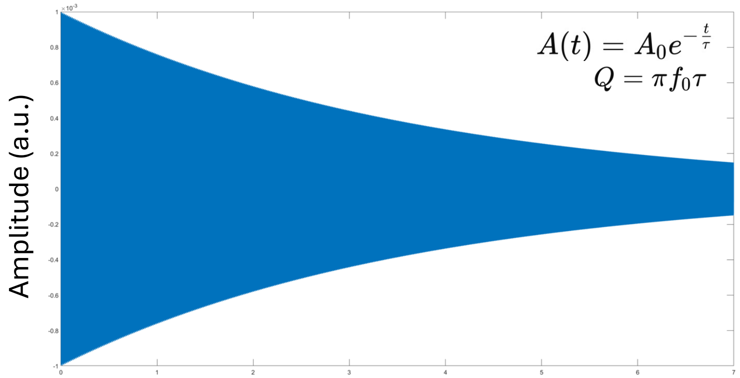
- Diameter: 45 cm
- Thickness ~ 17 cm

MMOS

3. Mechanical Loss Measurement

Traditional Q- Measurement Method

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



E-TEST Decay Period

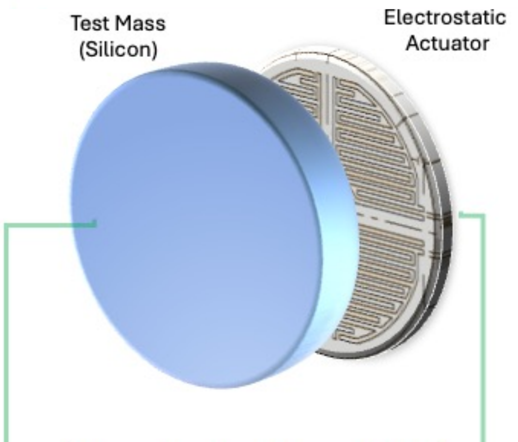
↕

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.



Phase Locked Loop (PLL)

Force the system at Resonance

Phase Estimation → **Controller**

Enables in-situ monitoring and automation

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 !!

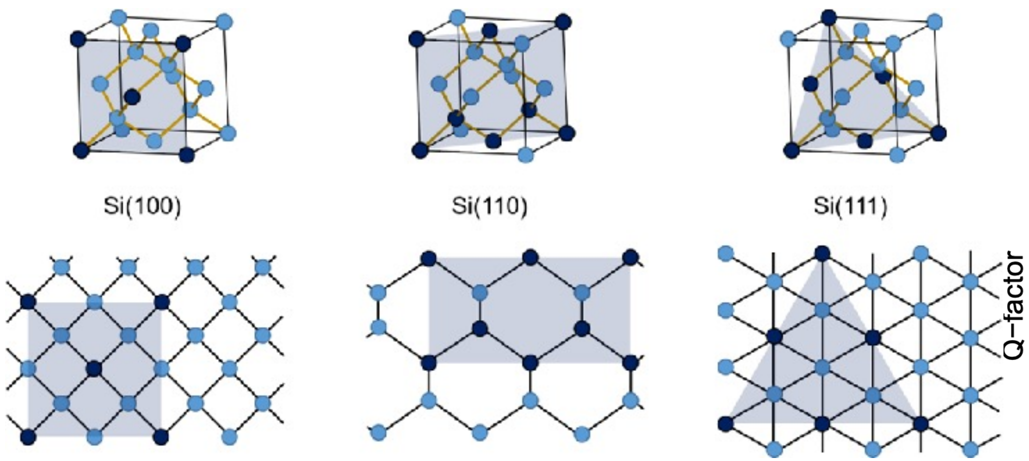
Ref: PLL: Nic Smith et al., ESD: John Miller Thesis, LIGO-T1700446, Challenges : LIGO-T1400226/010

@François Winand
francois.winand@uliege.be

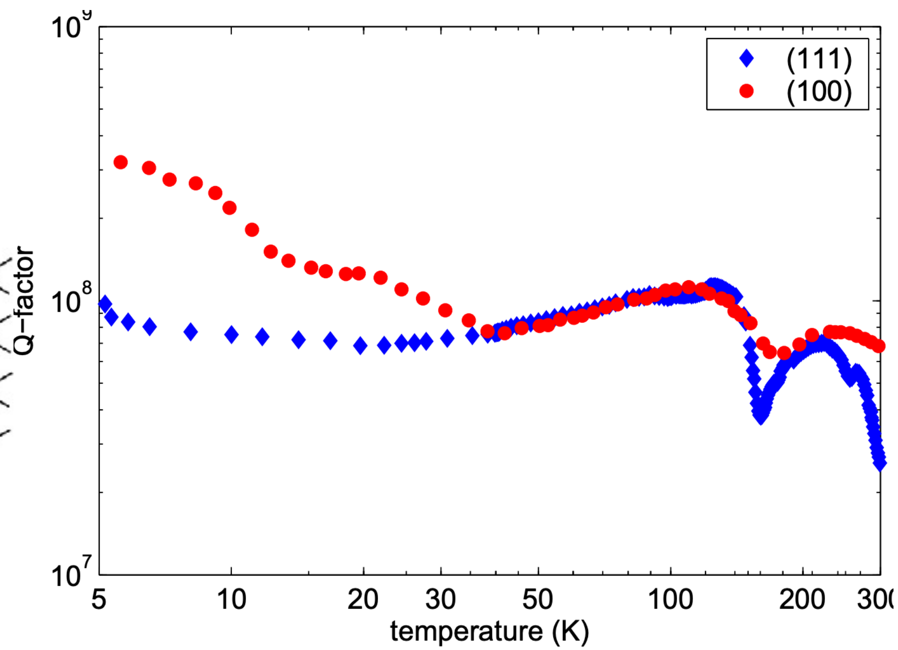
Mechanical Loss Measurement

As Q vs T plot reveals mechanical behaviour of Si Test Mass at **negative CTE (~120K).!!**

- <40 K: Si(100) > Si(111) Q
- Lower phonon scattering
- Reduced dislocation mobility
- Reduced internal friction



Dependency on Crystal orientations



Ref: R Nawrodt et al., A Schroeter et al.

Development of Actuator

Non-contact Method

aLIGO
For 40 kg mass
Max force: 400 μN at 950 V

To achieve the same displacement
For 100 kg Test mass,
1000 μN Force required!!

Explored two candidates
(for E-TEST)

1. **Photon Actuators (P~150kW)**
2. **Electrostatic Actuator (V~ 1kV)**

Resulting Force

$$F_{\mathrm{ESD}} = \alpha(\Delta V)^2,$$

α : ESD actuation coefficient, depends on the separation, material properties, and ESD geometry.

$\alpha = 2.95 \times 10^{-10}\ \mathrm{N/V^2}$

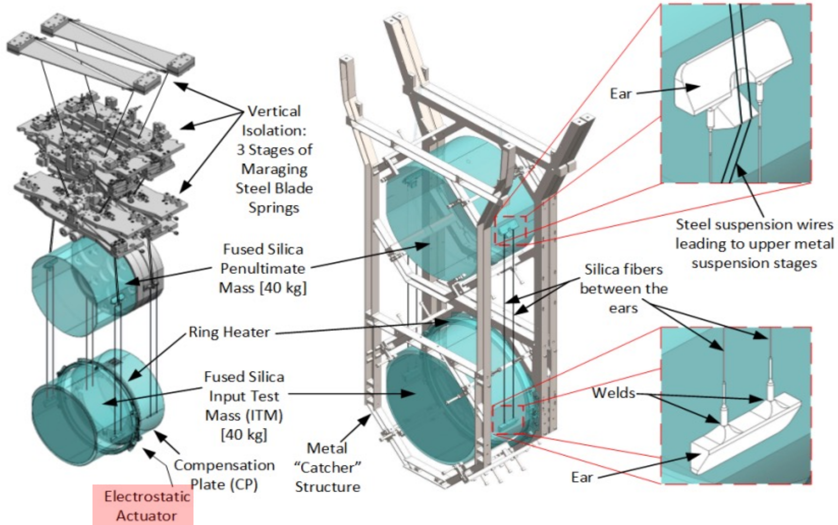
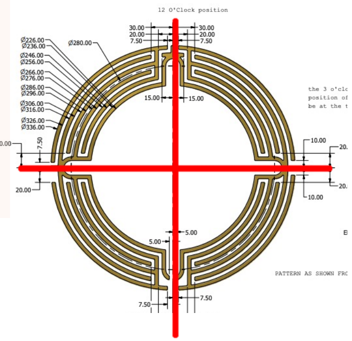
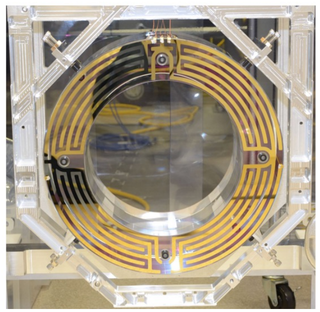


Figure 8 Quadruple pendulum suspension for the Input Test Mass (ITM) optic.

Four Quadrants
(DC + AC)

DC bias: creating a static charge environment
AC modulation: oscillating the force

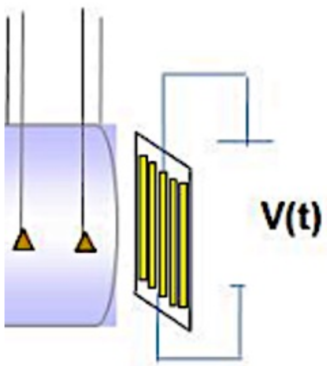




Ref:LIGO-P1400177-v6

Electrostatic Actuator

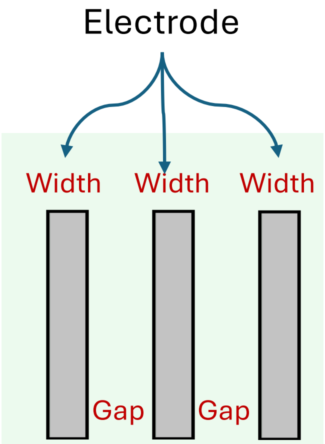
Preliminary Findings



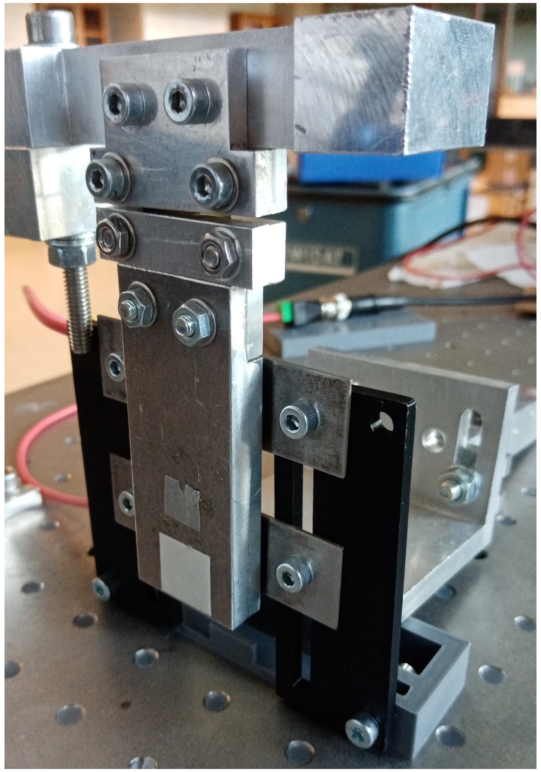
Force depends on:

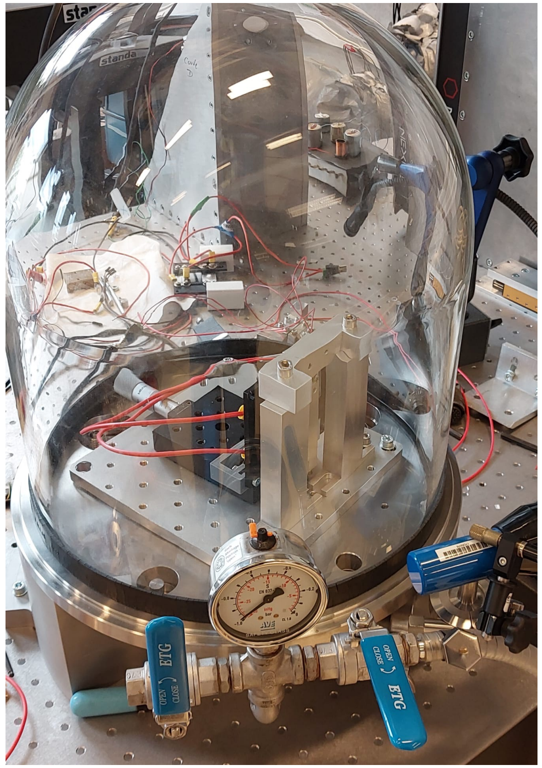
- Voltage (V)
- Gap distances
- Area of interaction (Fringes)

F= $\frac{1}{2}\epsilon A E^2$, and **E=** $\frac{V}{d}$



$$\text{Duty Cycle} = \frac{W}{W+G}$$



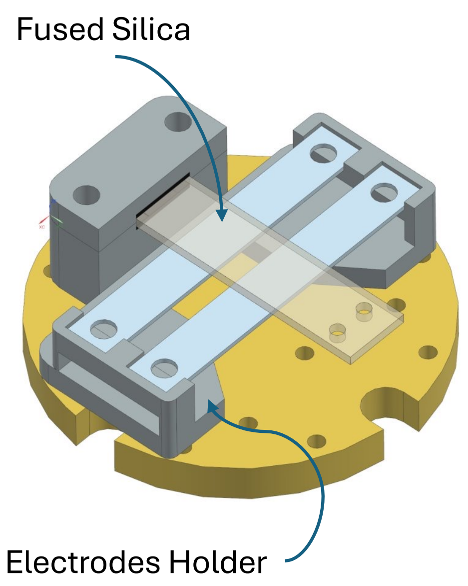


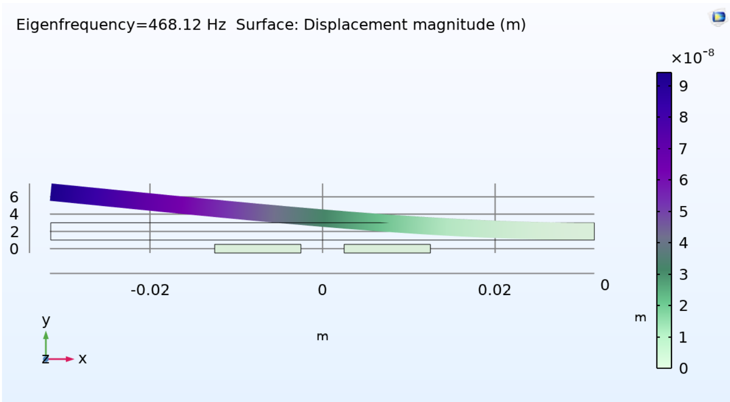
Observations so far:

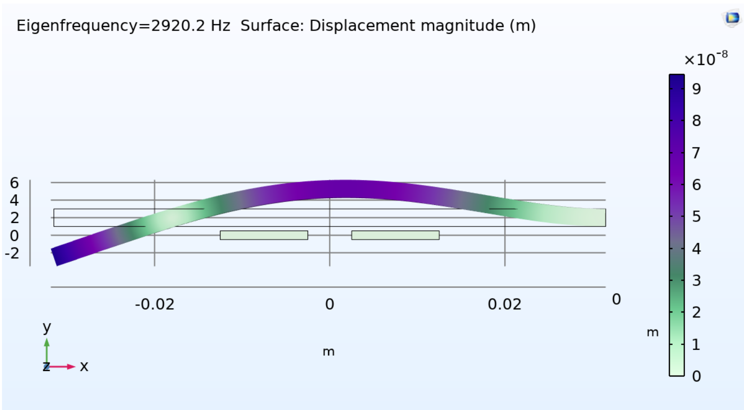
- DC bias with AC bias produces better results.
- Duty Cyle ~ 50% works better etc.

Electrostatic Actuator

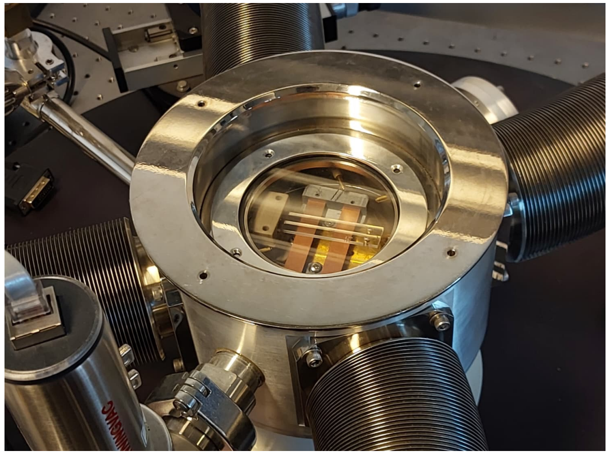
In Progress

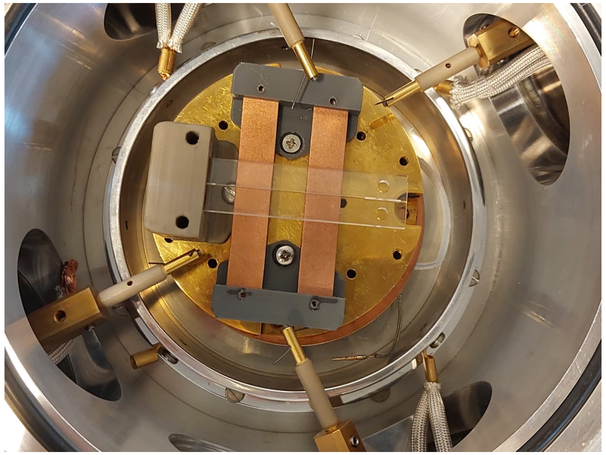






Multiphysics Simulation (COMSOL)





Experiment

Temperature Measurement (Non- contact Method)

ΔT → **Thermo-optic Coefficient**

Thermo-Elastic **α (dL/dT)** ← Thermo-optic Coefficient → Thermo-Refractive **β (dn/dT)**

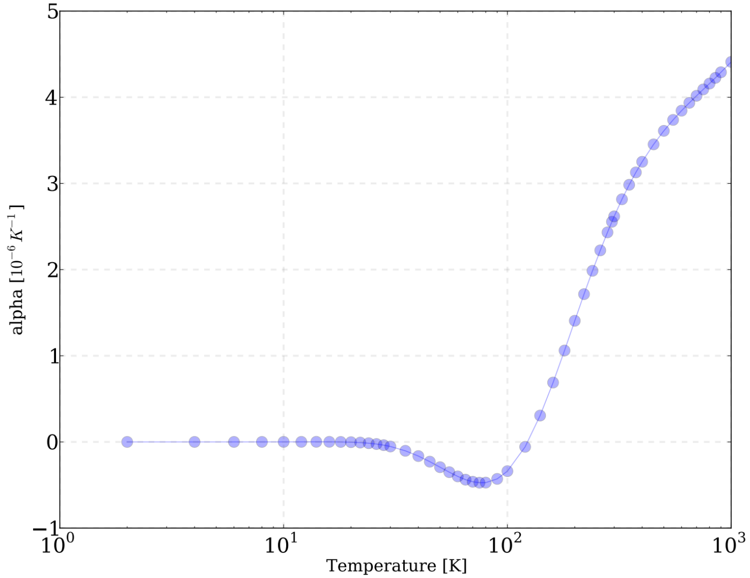


Fig: CTE of Si as function of T

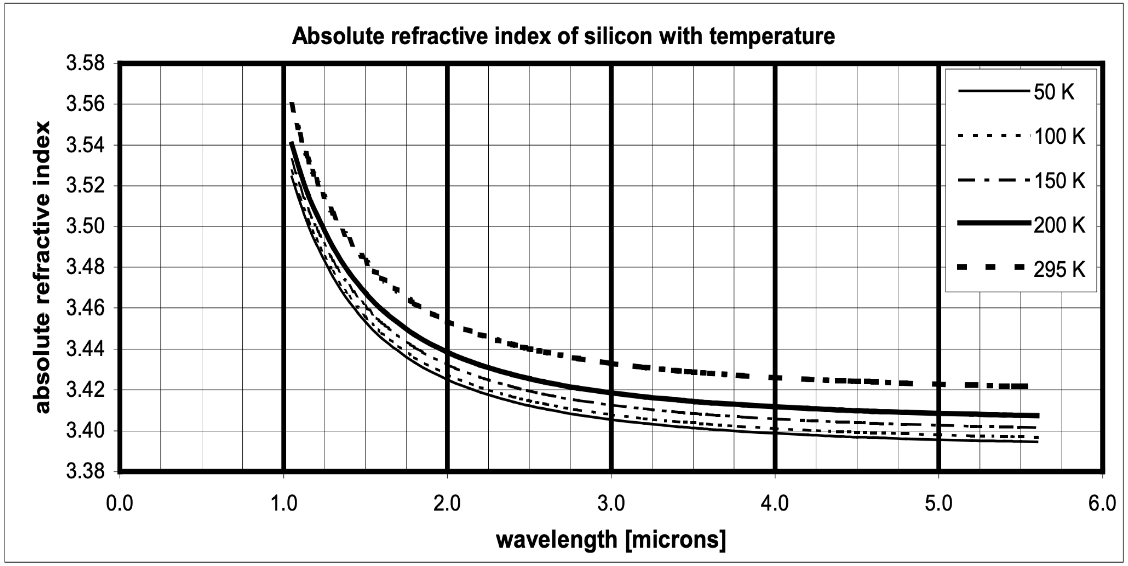


Fig: Measured absolute refractive Index of Silicon
as a function of wavelength for selected Temperature

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

Temperature Measurement (Non- contact Method)

Thermo-refractive Coefficient (β)

i. Silicon (monocrystalline Structure, Semiconductor)

Refractive Index → Electronic structure and polarizability.

High (n) in IR

ii. *Heat Generation*

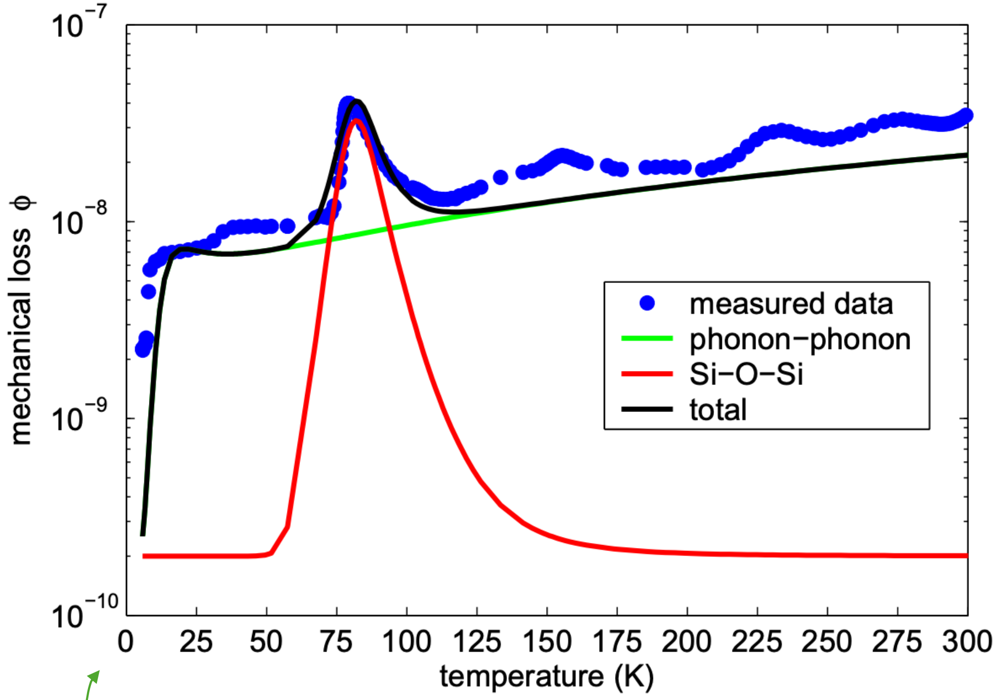
Scattering due to Free carriers (unbound electrons and holes) **+ Laser light Absorption**

1. Inter-band absorption
2. Two-photon absorption
3. **Free carrier absorption**
   (@NIR/IR wavelength)

$$\alpha_{FC} = \frac{e^2 \lambda^2}{4\pi \epsilon_0 n c^3} \frac{n_c}{m_*^2 \mu}$$

α_{FC}: Free carrier absorption coefficient
e: Elementary charge
λ: Wavelength of Light
ϵ_0: Vacuum permittivity
n: Refractive index
c: Speed of light in vacuum
n_c: Free carrier concentration
m_*: Effective mass of the carrier
μ: Carrier mobility

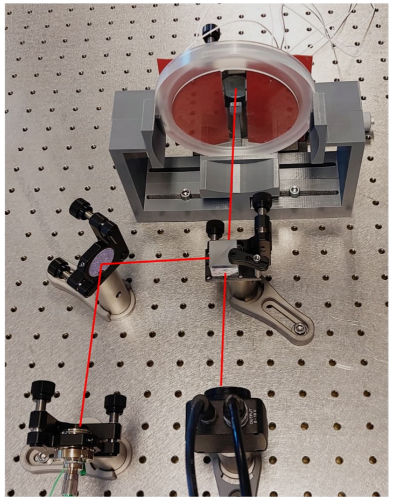
Increases the phonon interactions (local heating)

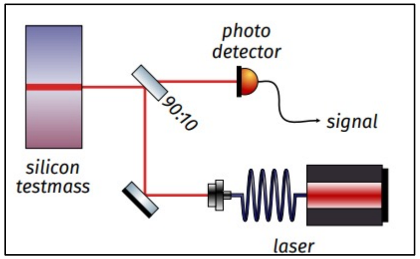


Ref: LIGO-T1400226/010, R Nawrodt et al., A Schroeter et al.

Experimental Framework: Temperature Measurement

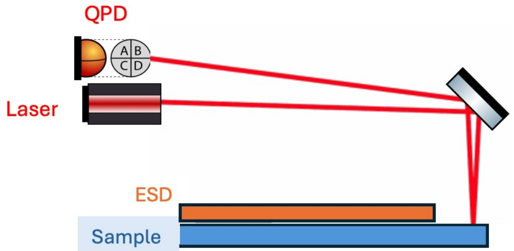
Step 01





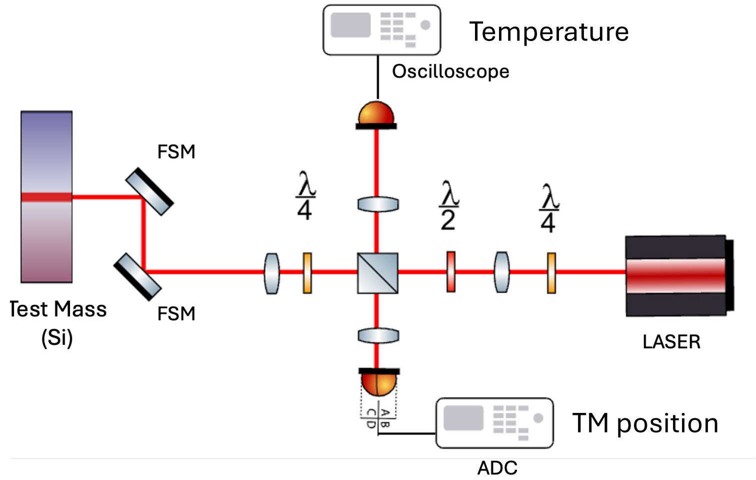
OPL → ΔT → ΔL & Δn → Fringe shift

Step 02



Step 03

@Janis Wöhler

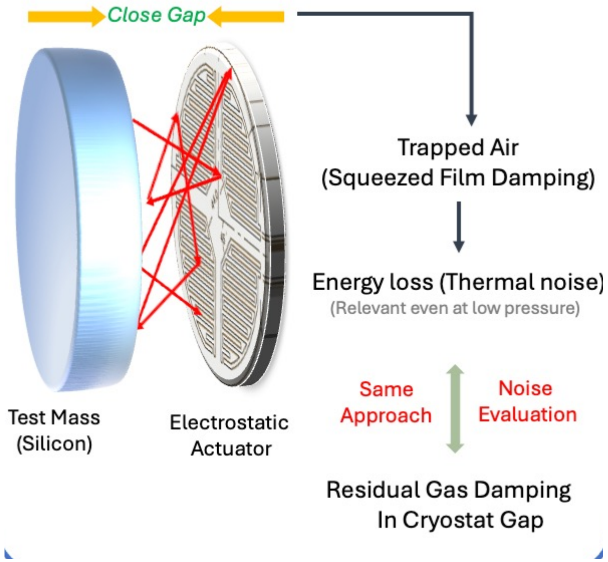


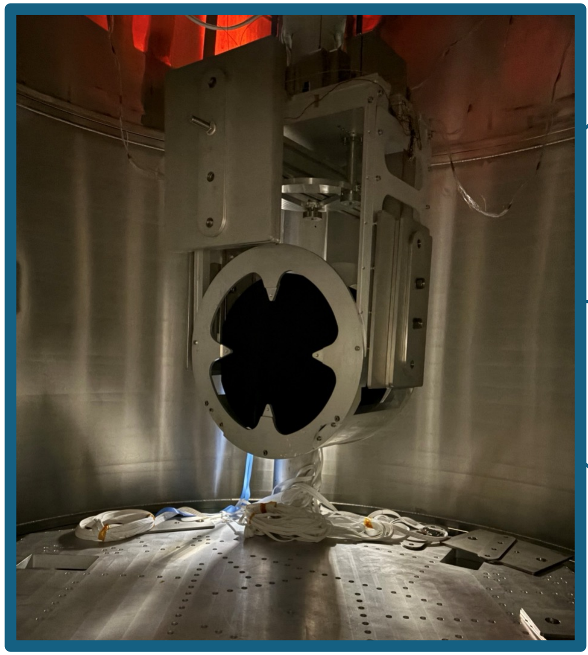
Considerations:

- 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)**

Supplementary Studies





Optical Effect

- Laser Absorption Spectra
- Free Carrier Absorption
- Birefringence in Test Mass
- Parametric Instabilities

Charge & Material Interaction

- Charge Induction and Interaction on surfaces
- Reliability of ESD
- Thermal Gradients in the Material
- Effects of Impurities & Orientation on internal Friction

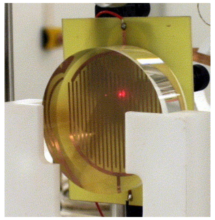
Cryogenic Consideration

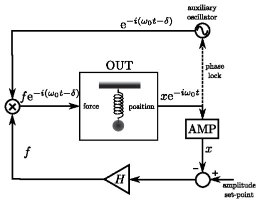
- Ice formation during cooldown
- Impact on optical and mechanical performance
- Residual air squeezed damping

Ref.:LIGO-T0900509-v1, T0900582

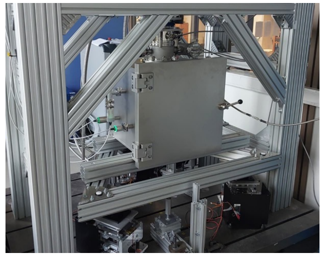
Summary

Quality Factor (Q) Measurement

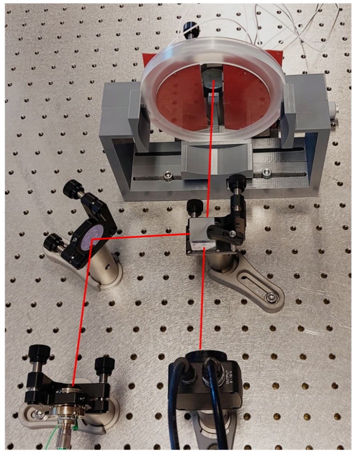




- ☑ Study AC, DC, and AC+DC Current effects
- Ongoing ❑ ESD designs: Duty Cycle impact on Fringe Generation
- Ongoing ❑ Fused silica & Silicon samples
- ❑ Apply Phase-Locked Loop
- ❑ Cryogenic testing



Temperature Measurement



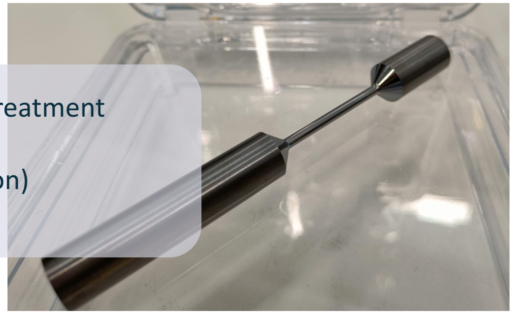
- Ongoing ❑ Fringes → α & β (predict thermo-optic coefficients due to ΔOPL)
- ❑ Laser stabilization, Wavelength absorption & Thermal Gradient (1550 nm vs 2000 nm)
- ❑ Final Optical Setup

Integration

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

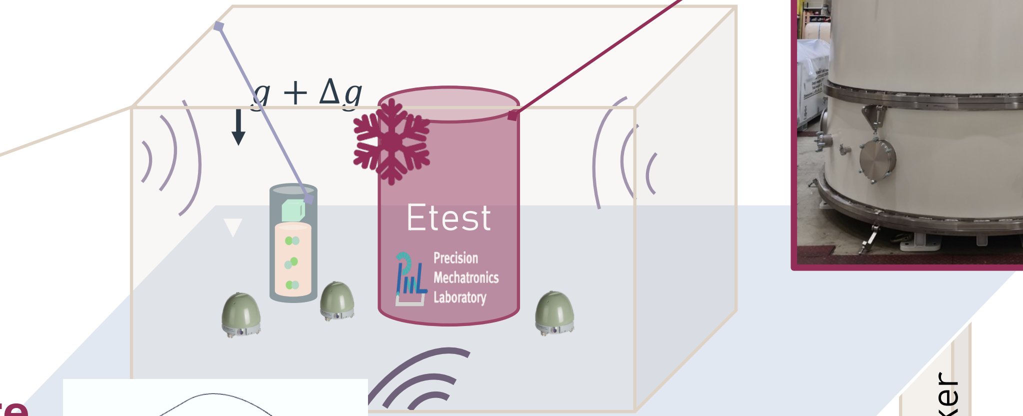
E-Test: Experimental facility RoadMap

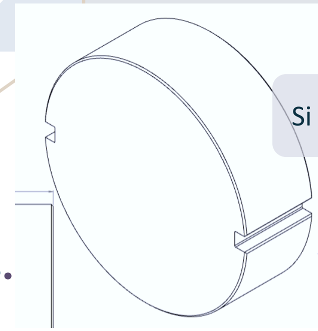
- ☑ 2023, prototype assembled and tested:
  - Suspension for 100 kg
  - Instrumentation developed
  - Radiative cooling validated



Si suspension + surface treatment
Characterisation
(traction tests + inspection)
ET Fiber project

- ☐ 2025: installation at CSL

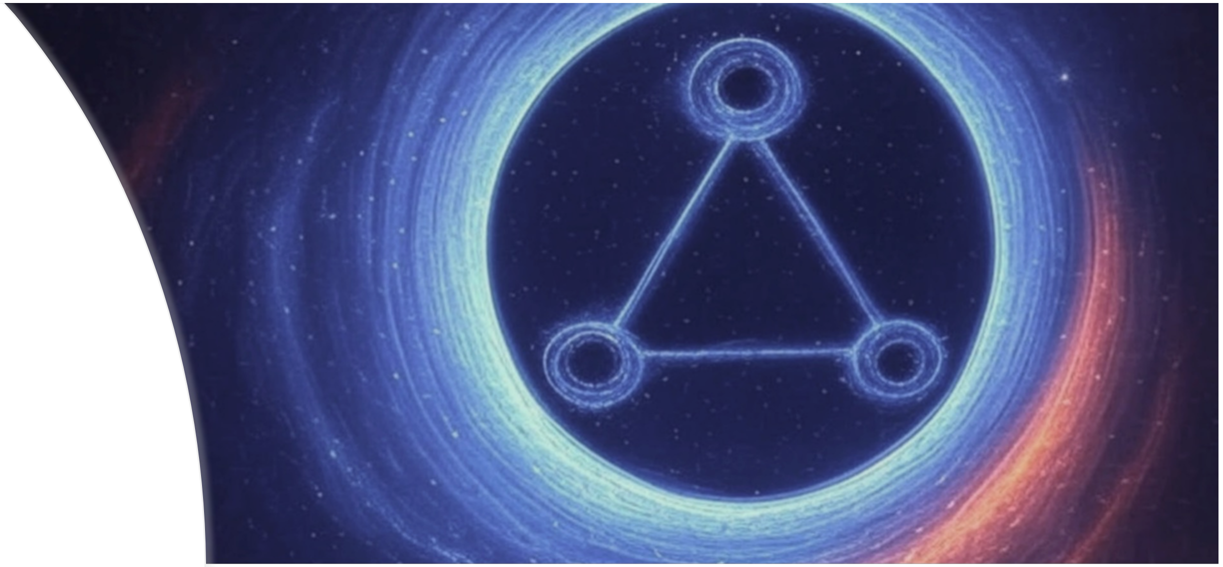


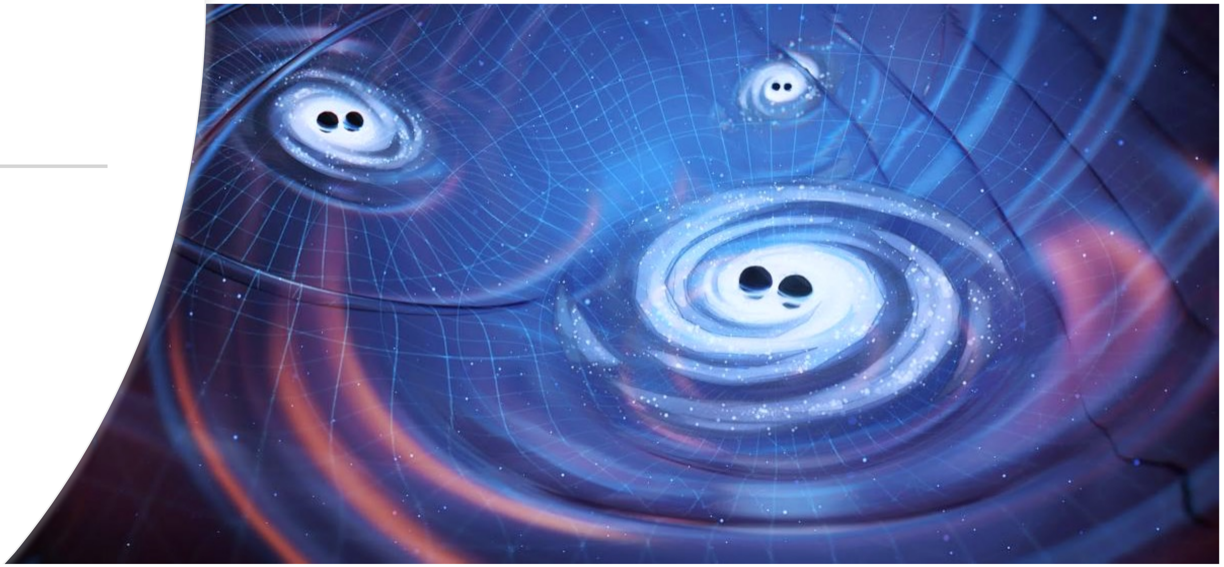


Si Test Mass

- ☐ 2026: R&D @ **Cryogenic Temperature**
  - **Active Isolation & control development**
  - **Silicon Test Mass Installation & ETFIBER**
  - **Inertial sensors development**
  - **Newtonian Noise subtraction techniques.**

Thank you!!





Additional

Silicon Mechanical Loss Map