The Archimedes Experiment: a way for exploring the Vacuum-Gravity Interaction

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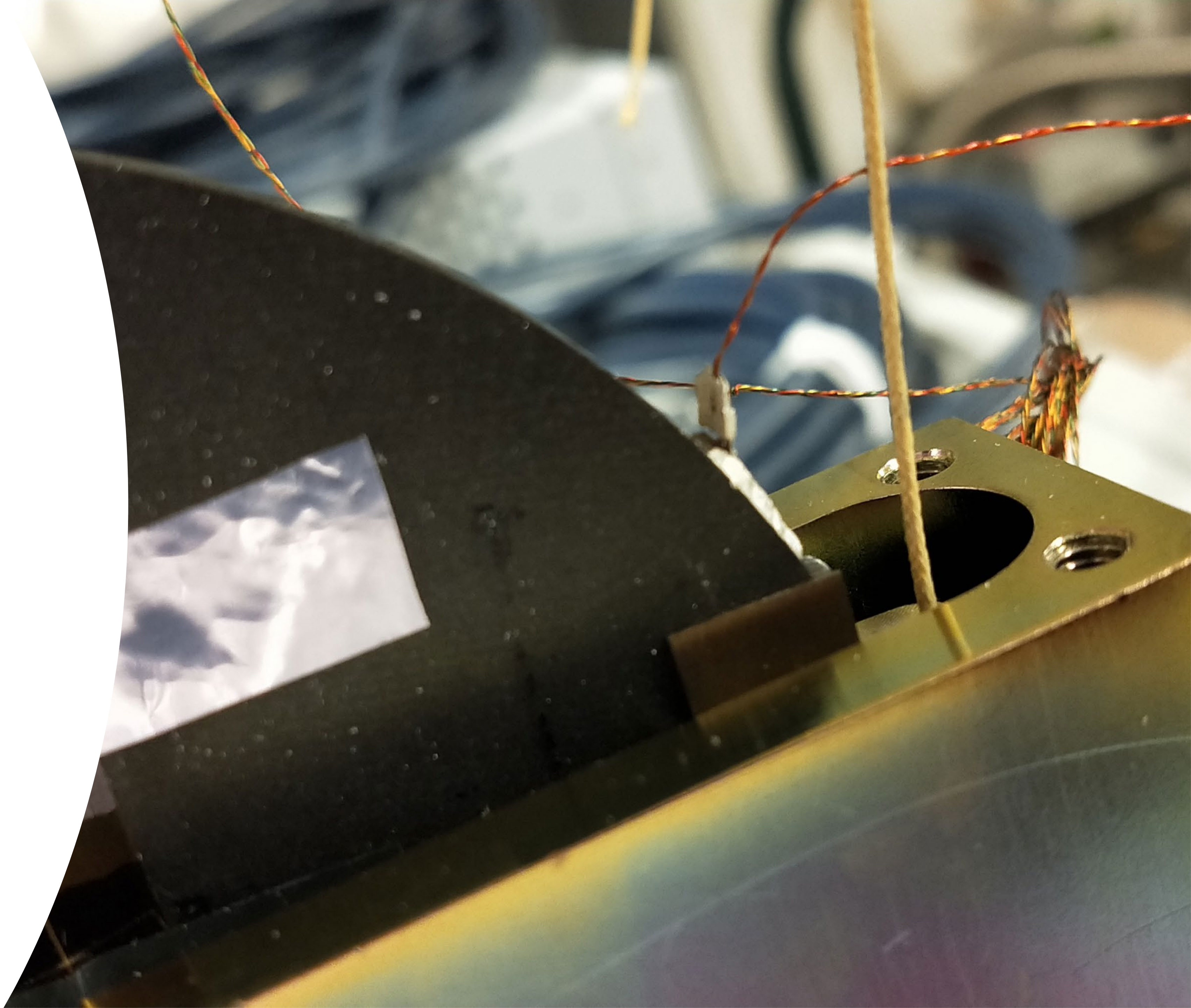
on behalf of the *Archimedes collaboration*

The Low-Energy Frontiers of Particle Physics

10–12 Feb 2025 INFN-LNF Frascati (RM)

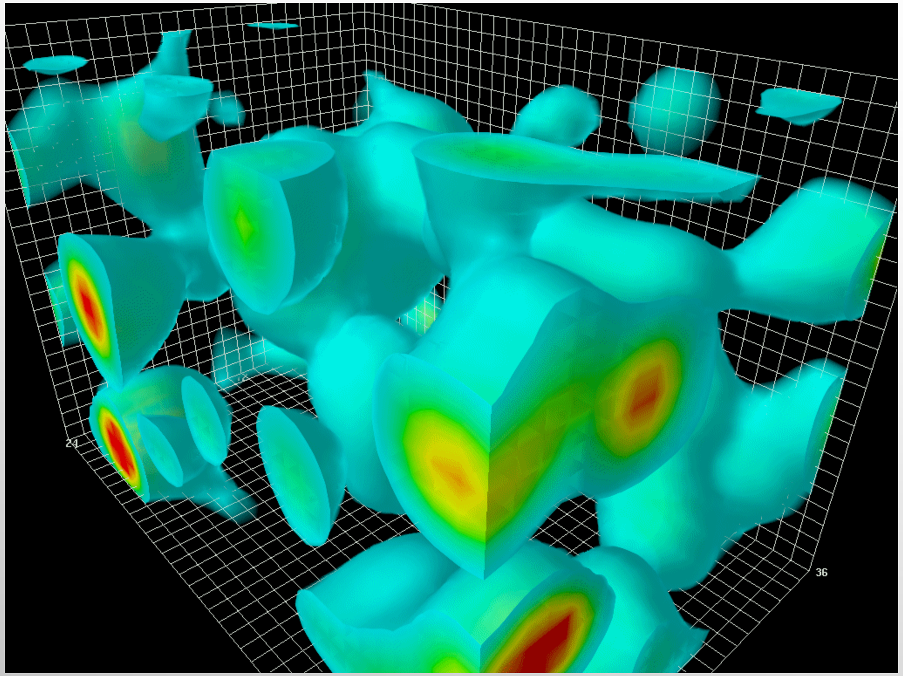


SCIENTIFIC MOTIVATIONS AND GOAL OF THE EXPERIMENT

DOES VACUUM FLUCTUATIONS INTERACT WITH GRAVITY?

DOES THE VACUUM STRESS GRAVITATES?

DOES VACUUM WEIGHS?



The theoretical understanding and experimental evidences are still not completely satisfactory

We can already put interesting upper limit, for instance:

Dark photon (see E. Calloni talk)

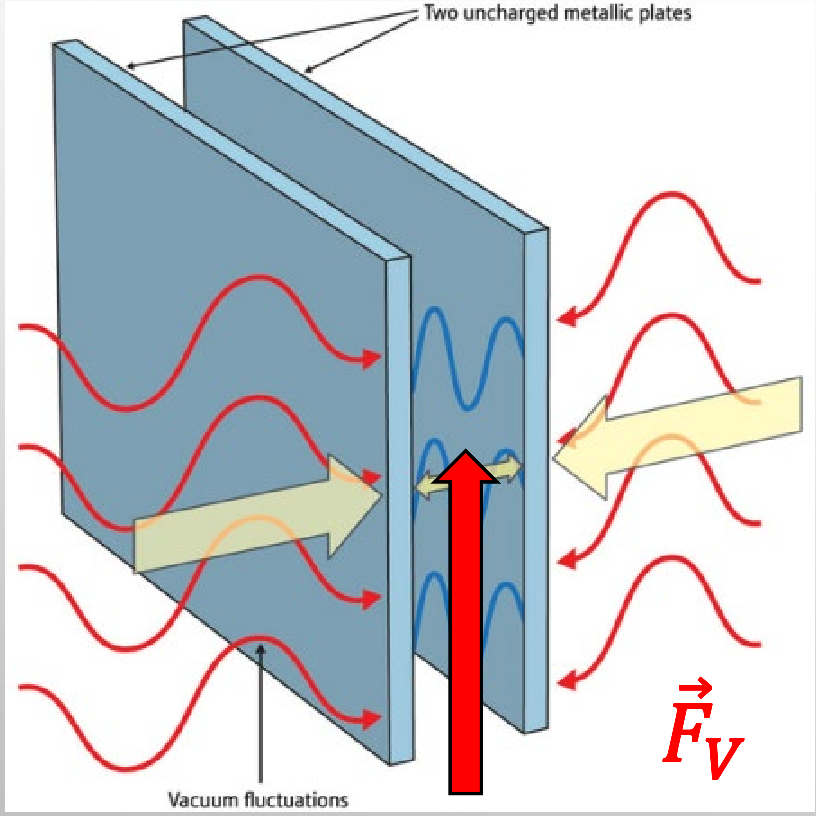
$$\sum \frac{1}{2}\hbar\omega \Rightarrow \infty$$

THE VACUUM WEIGHT

The Casimir effect is one of the macroscopic manifestations of vacuum fluctuations.

If the vacuum «weighs» then there is a force, directed upward, equal to the weight of the modes expelled from the cavity. In analogy with the Archimedes force[*].

Gravitational field $\downarrow \vec{g}$

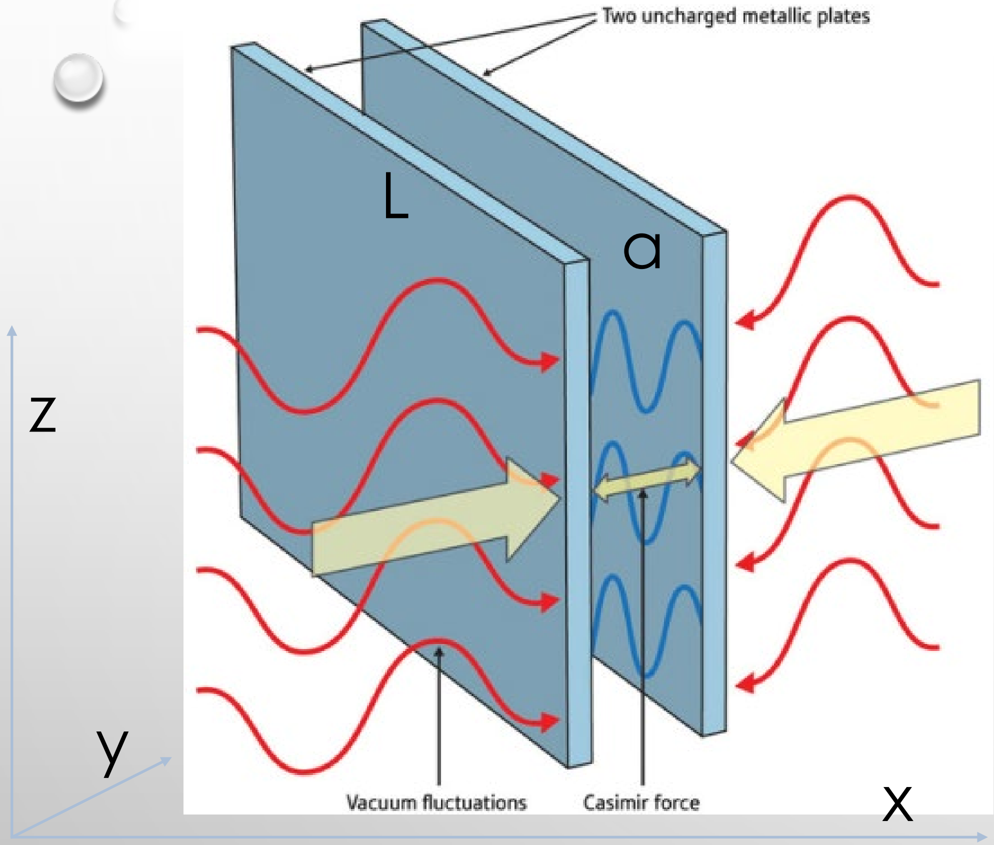


$$\vec{F}_V = -\frac{|E_C|}{c^2}\vec{g}$$

E_C :Casimir Energy

[*] G. Bimonte, E. Calloni, G. Esposito, L. Rosa – Physical Review D 76, 025008 (2007) – DOI: 10.1103/PhysRevD.76.025008

The Casimir effect is derived considering the zero point e.m. energy contained in a casimir cavity, i.e. in the volume defined by two perfectly reflecting parallel plates



If the plates are perfectly reflecting, the modes that can oscillate must have discrete wavenumbers on horizontal axes $k_y = n\pi/a$ while all values are allowed for k_x e k_z

$$E = \sum \frac{1}{2}\hbar\omega$$

$$E(a) = \frac{hcL^2}{2}\sum_{n=-\infty}^{n=\infty}\int\frac{d^2k}{(2\pi)^2}\sqrt{k^2+\left(\frac{n\pi}{a}\right)^2} \longrightarrow \infty$$

The Casimir Energy is the change in energy when the plates are at distance “a” with respect to the plates having a→∞

$$E_C = E(a) - E(\infty)$$

CASIMIR ENERGY $E_C = -\frac{\pi^2 L^2 hc}{720 a^3}$

CASIMIR PRESSURE $P_C = \frac{1}{L^2}\frac{\partial E_C}{\partial a} = -\frac{\pi^2 hc}{240 a^4} = 1.3\,\frac{\mathrm{mN}}{\mathrm{m}^2} @\ a = 1\mu m$

First prediction: Casimir 1948
First measure (force): Sparnay 1956
On parallel conductiong plates (0.5-3um, 15% precision): G. Bressi, G. Carugno, R. Onofrio, G. Ruoso (2002)
Presently tested (force) with an accuracy of 0.5% (Mohideen: 2005)

HOW TO MEASURE THE VACUUM WEIGTH?

THE IDEA IS TO
MODULATE THE VACUUM ENERGY OF A RIGID CASIMIR CAVITY
BY CHANGING THE REFLECTIVITY OF THE PLATES WITH TIME

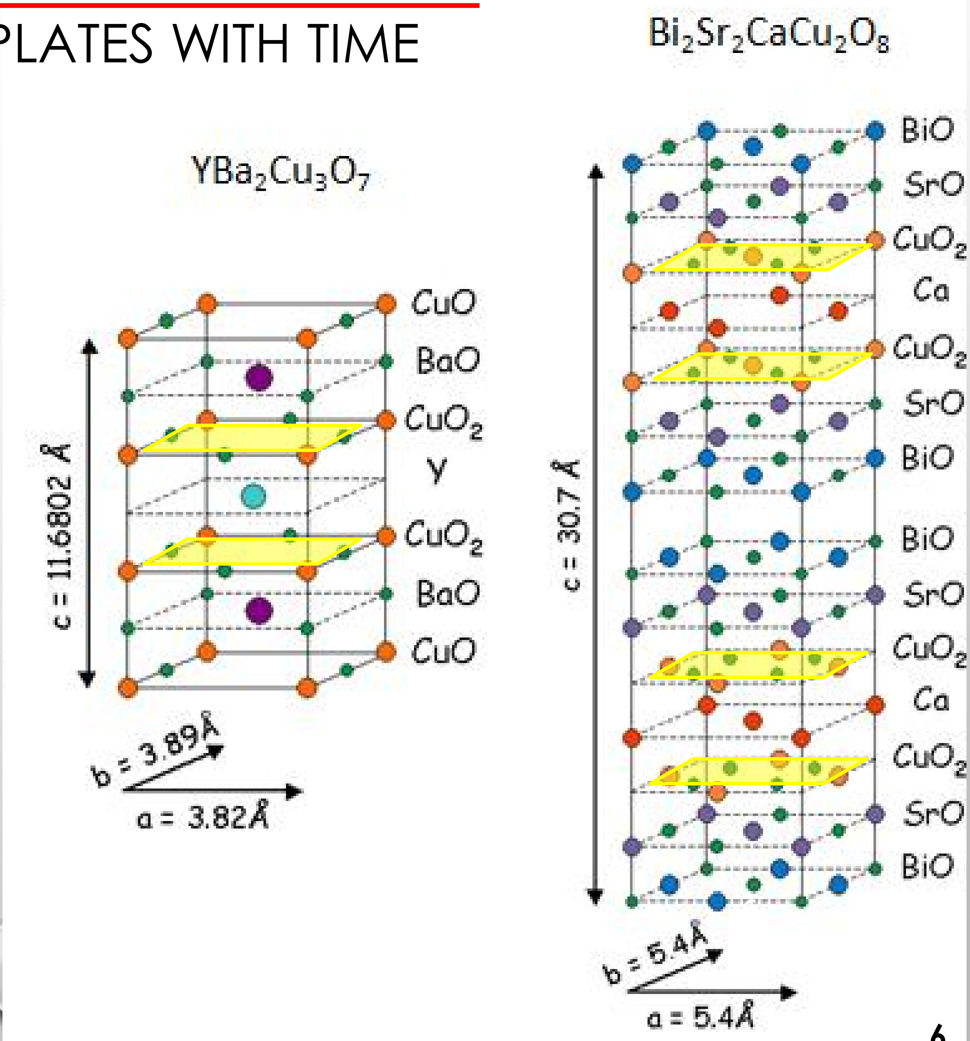
Use **high Tc layered superconductors** as natural multi Casimir-cavities.

- **YBCO, BSCO, GdBCO…** behave as natural **multi-layer Casimir cavities**.
- They containing layered CuO_2 planes in which the superconducting charge carriers are to be localized
- A transition from normal to superconducting state and vice versa can be induced by the **modulation of the temperature** of a superconductor.

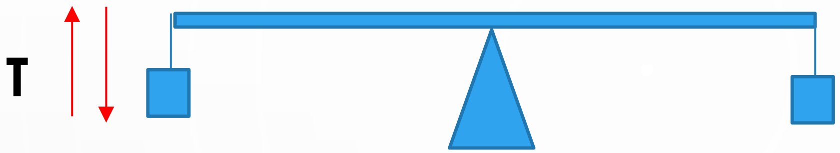
Profit of the fact that in normal state the plane that will become superconducting is a very poor conductor.

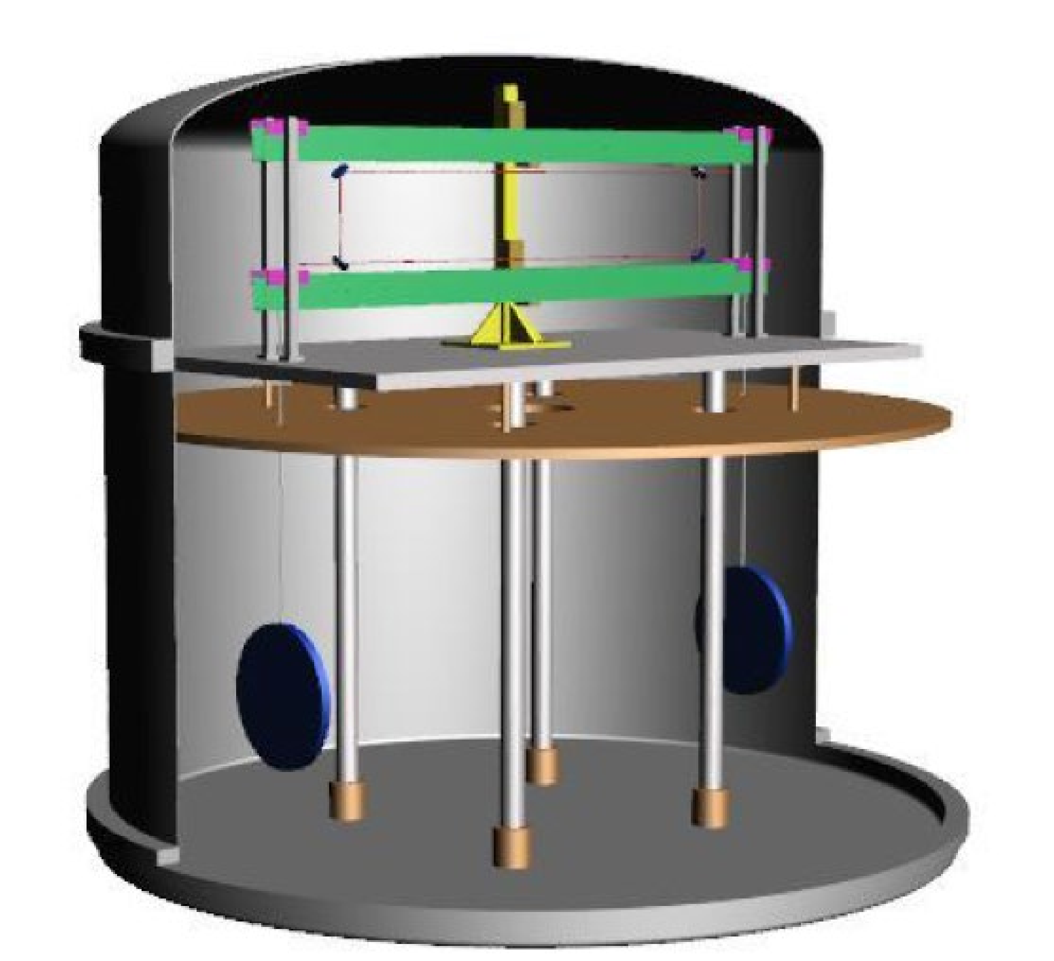
→ high variation of Casimir energy at the transition

Expected upward force 5 10^{-16} N



THE MEASUREMENT STRATEGY





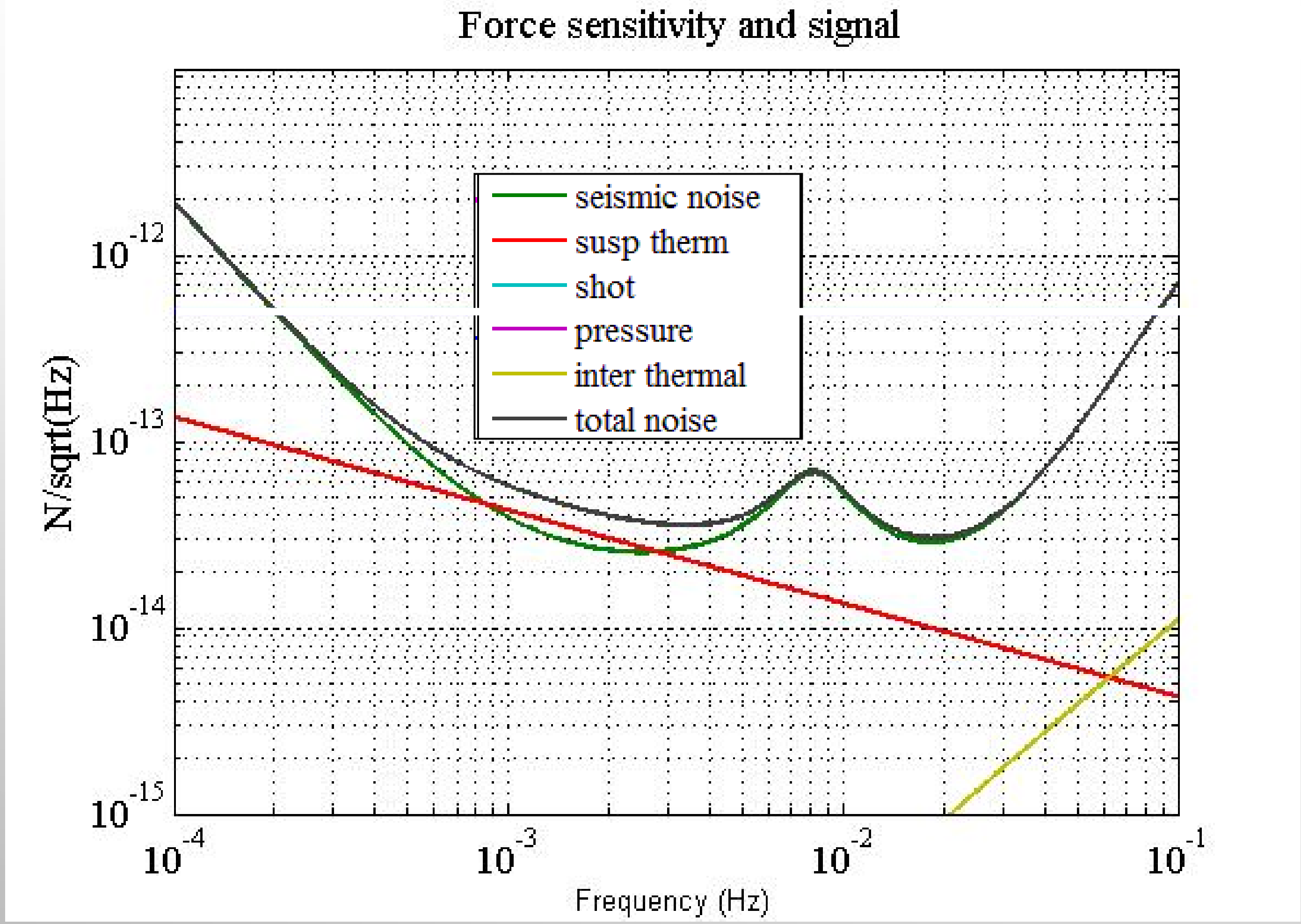
- **High Sensitivity Balance:** arm center of mass and suspension point must be well positioned (within 4μm)

- **Temperature modulation around Tc**

- **Quiet environment:** low human activity(Newtonian noise) and low seismic noise

- **Interferometric Readout**

EXPECTED SIGNAL AND SENSITIVITY



- High Sensitivity Balance
- Temperature modulation around Tc
- Seismically quiet place for the experiment site

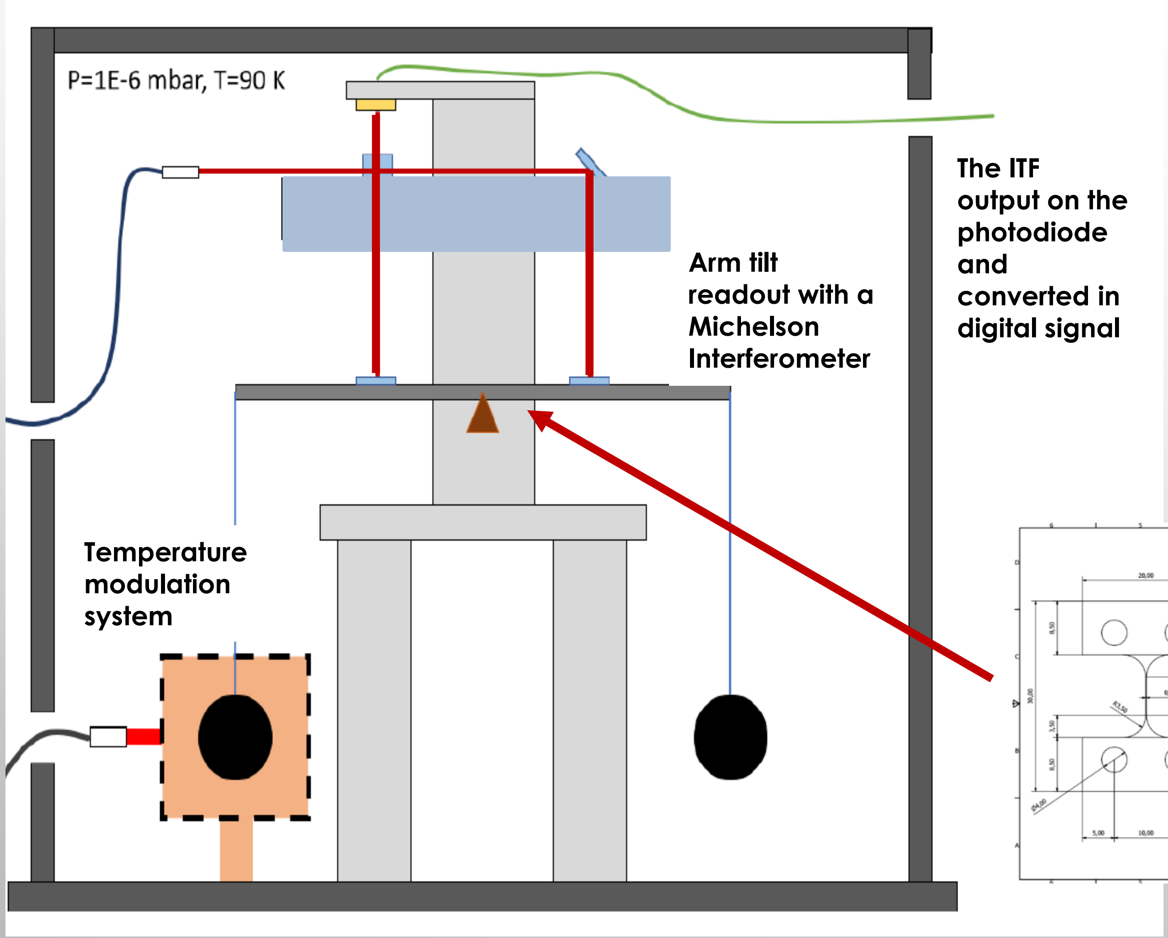
- The modulation frequency value is chosen where the sensitivity is the best.

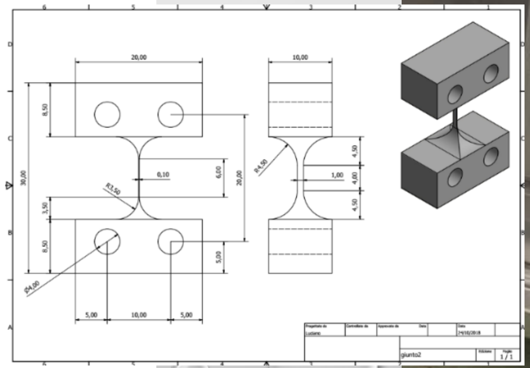
Limited by : thermal noise and seismic noise

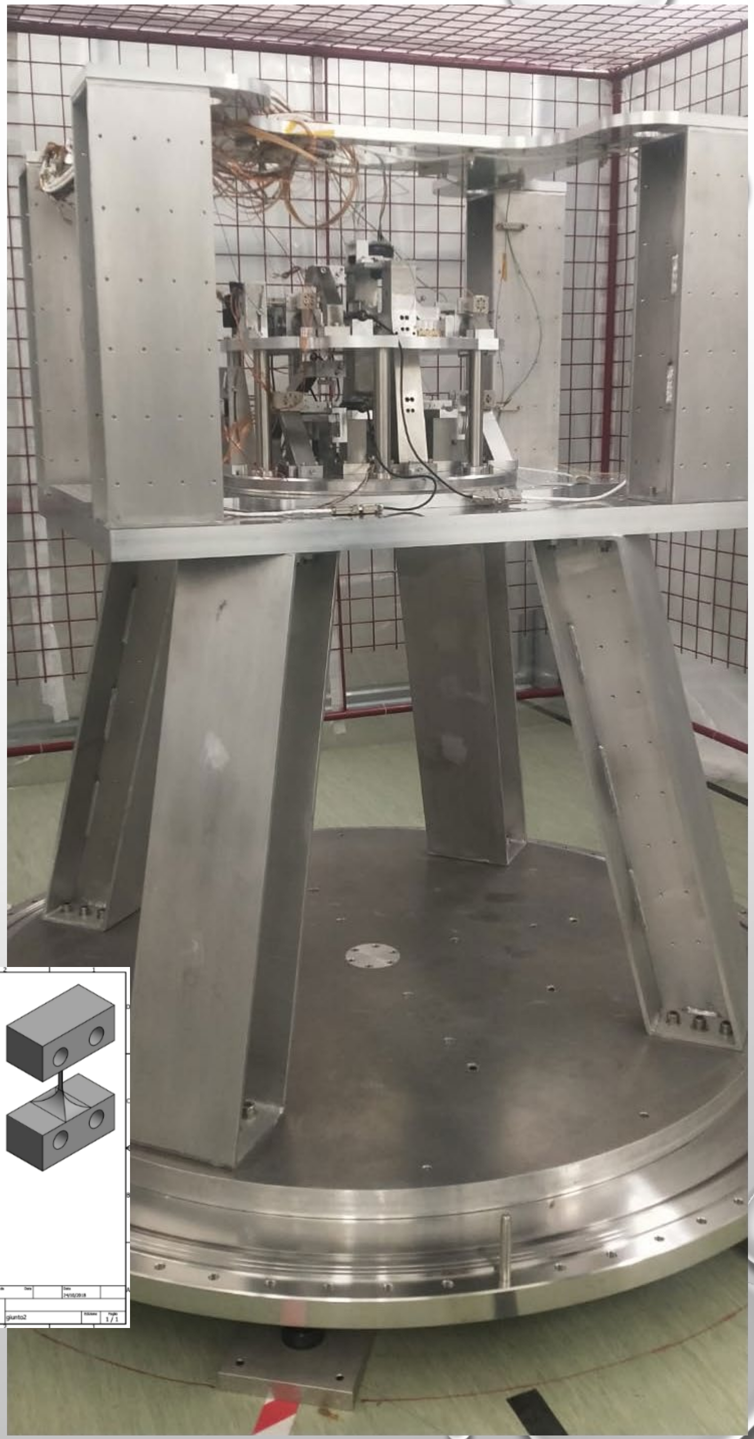
THE BALANCE

THE BALANCE IS SUSPENDED WITH VERY SOFT FLEXURAL JOINTS

→ HIGH FREQUENCY NOISE LOWERED AND HENCE LOCKING ON THE INTERFEROMETER IS POSSIBLE

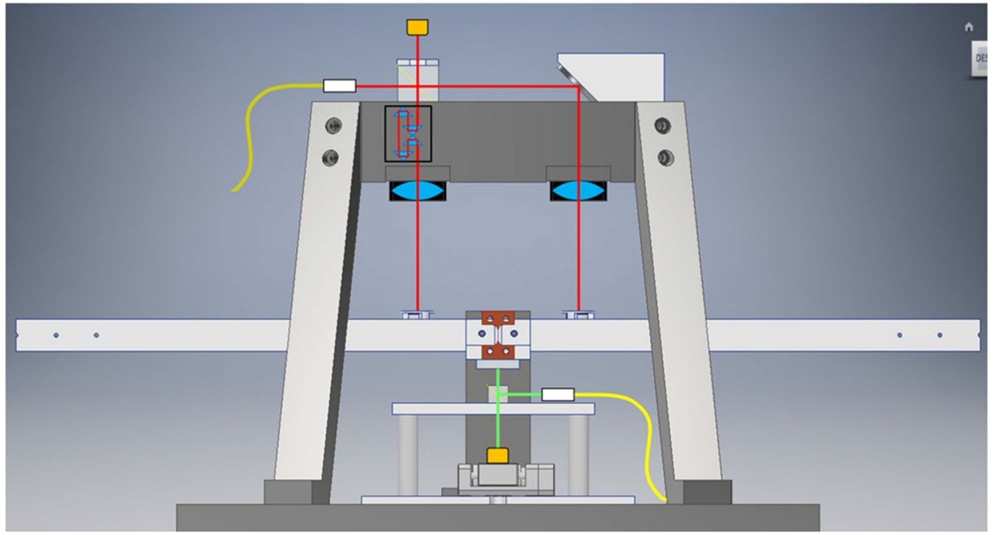


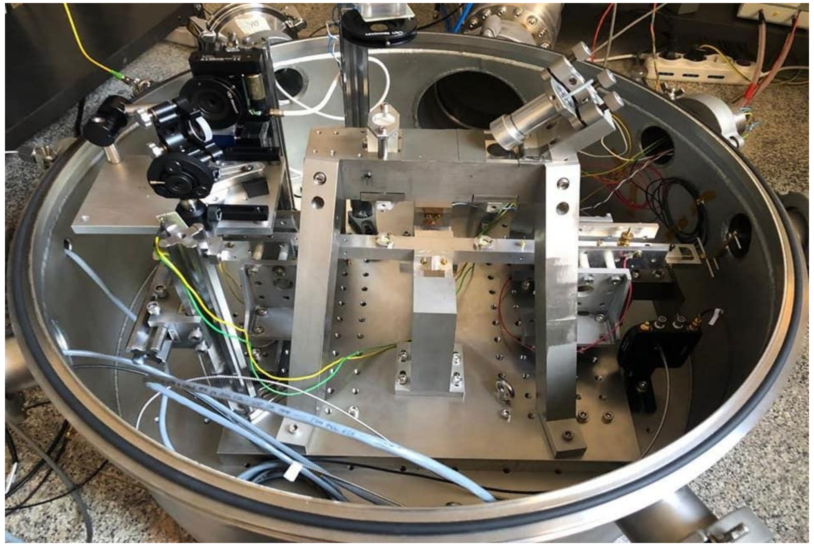




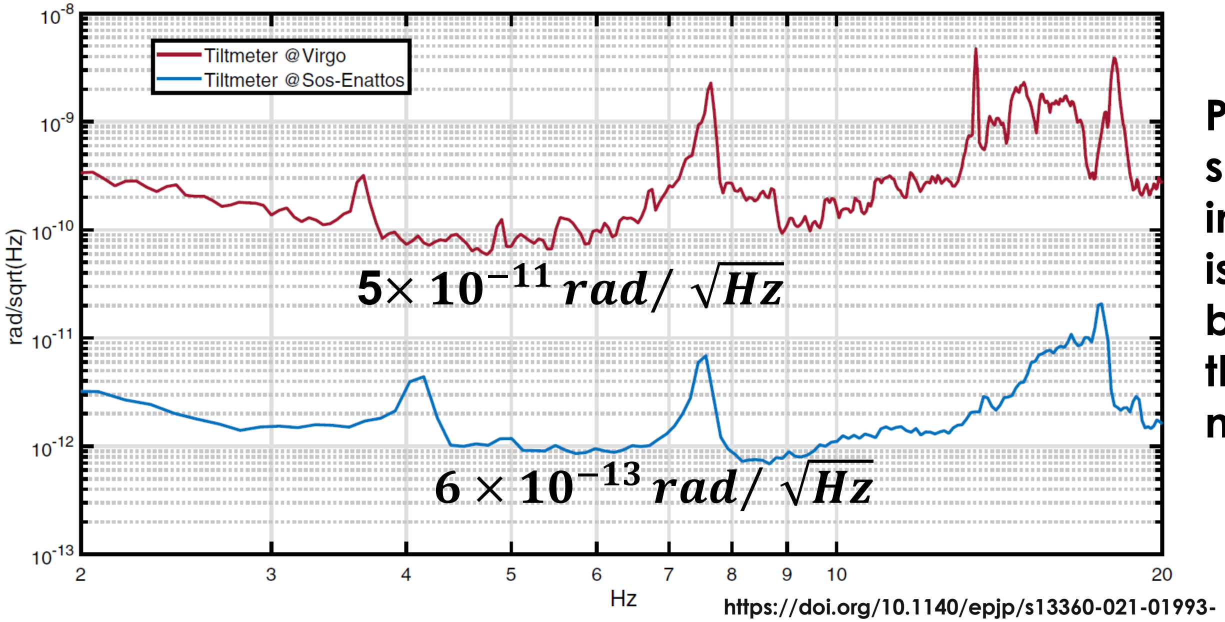
A **prototype of balance** was built to test every component and find the best optic-mechanical configuration for the final balance.

See E. Calloni presentation for details





Tilt measurement comparison between Virgo gravitational wave interferometer (Cascina, Pisa) and Sos Enattos (Sardinia) sites.
Most sensitive tiltmeter in the world in the frequency band from
20 Hz.



https://doi.org/10.1140/epjp/s13360-021-01993-
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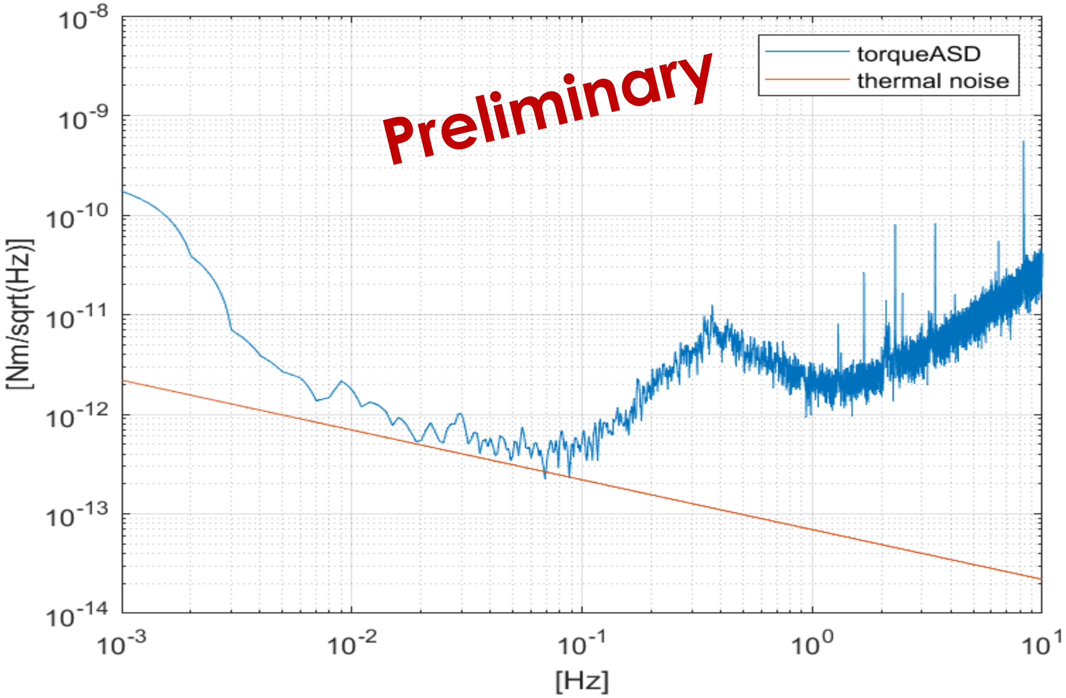
Prototype sensitivity in torque is limited by thermal noise.



The data acquisition system and storage

- Sampling at 25 kHz;

ITF Control loop with a feedback bandwidth of 200mHz performed with a system hardware of National Instruments;

- Data storage in definition;

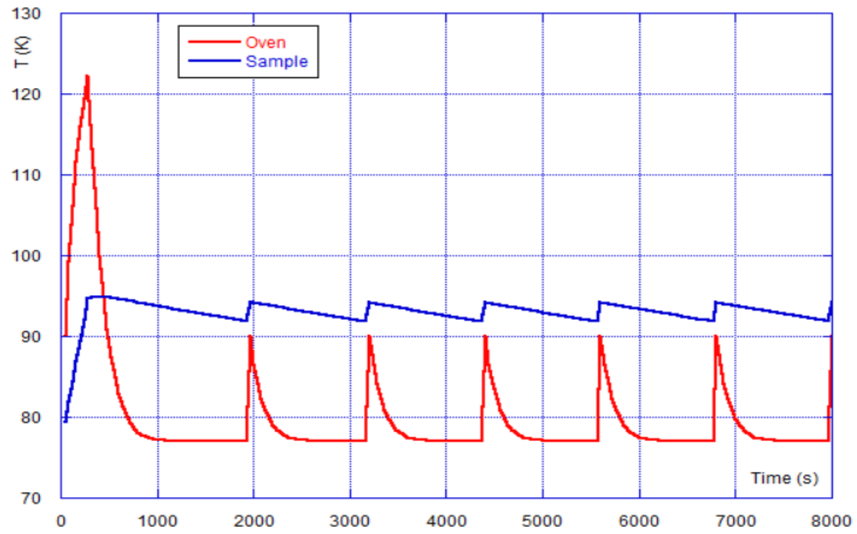
THERMAL MODULATION

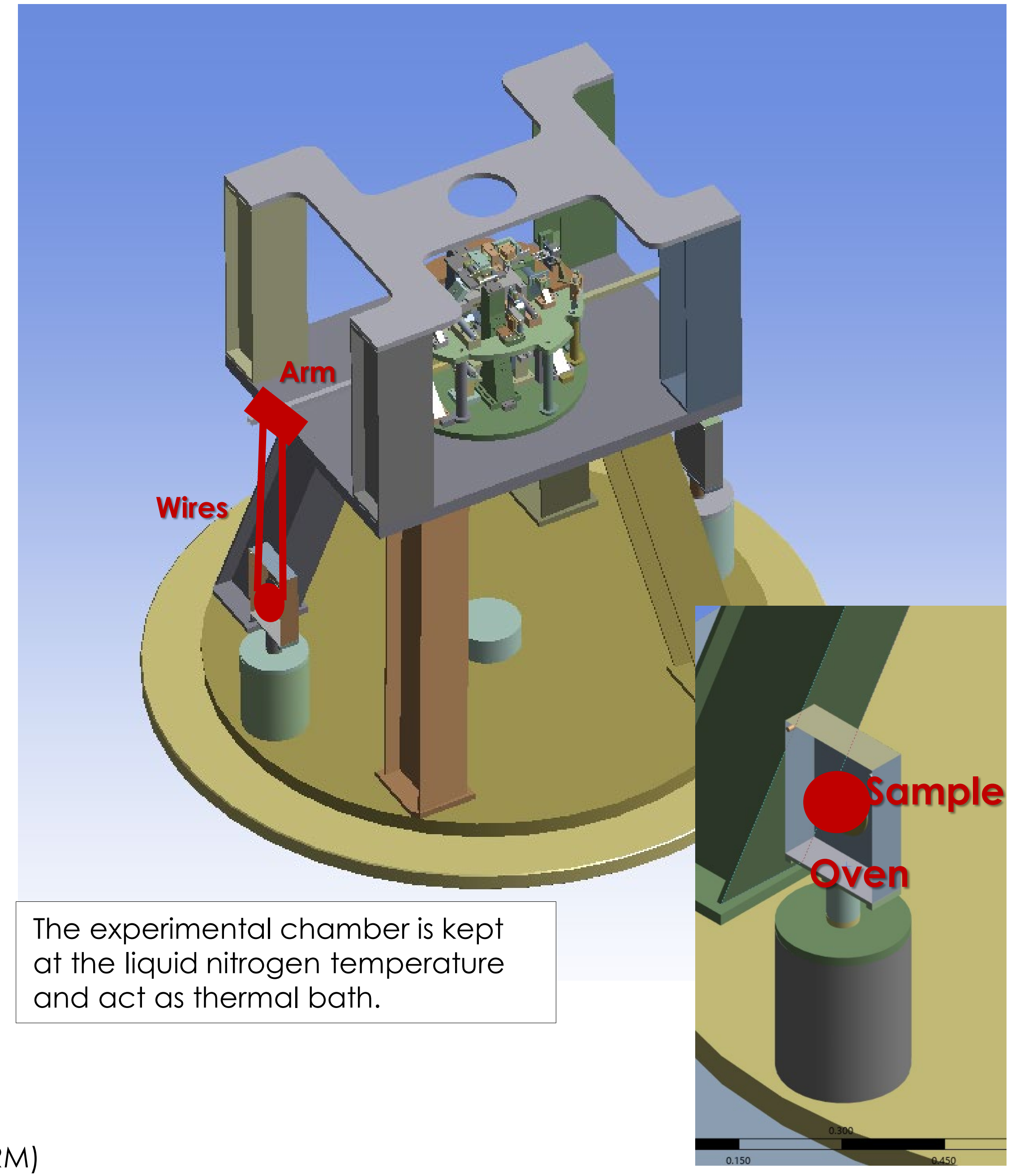
The thermal modulation must be performed by radiative exchange between sample and an oven which surrounds it.

Requirements: **Frequency modulation 10mHz**
Temperature modulation 2K
YBCo, GdBCO, BSCO sample 20cm diam
Tc (90K-100K)

- Modulation frequency and its amplitude around T_c depend on the thermal properties of the materials.
- A finite element study is important for the geometry definition and the material choice.

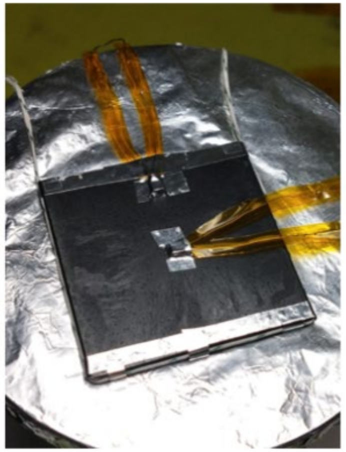
Example of FEM result

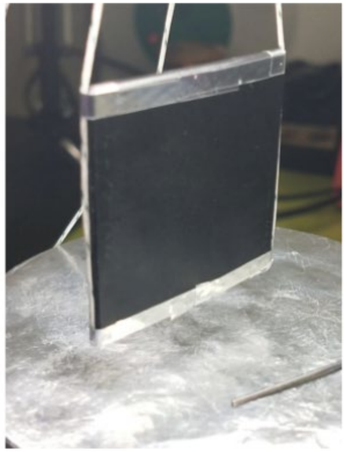




The experimental chamber is kept at the liquid nitrogen temperature and act as thermal bath.

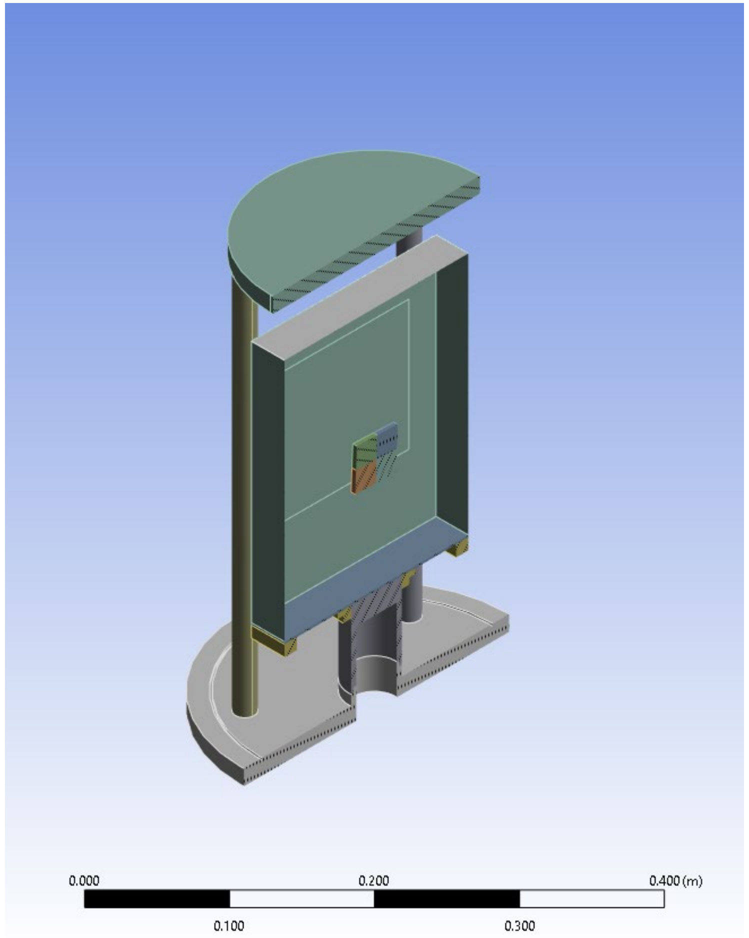
Small scale test



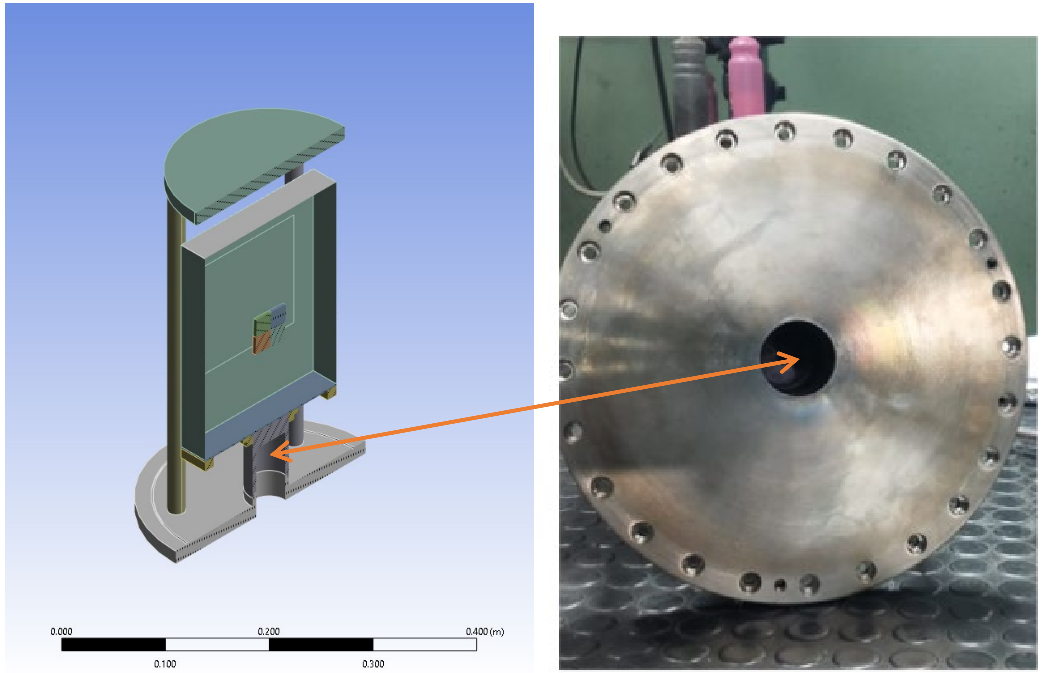


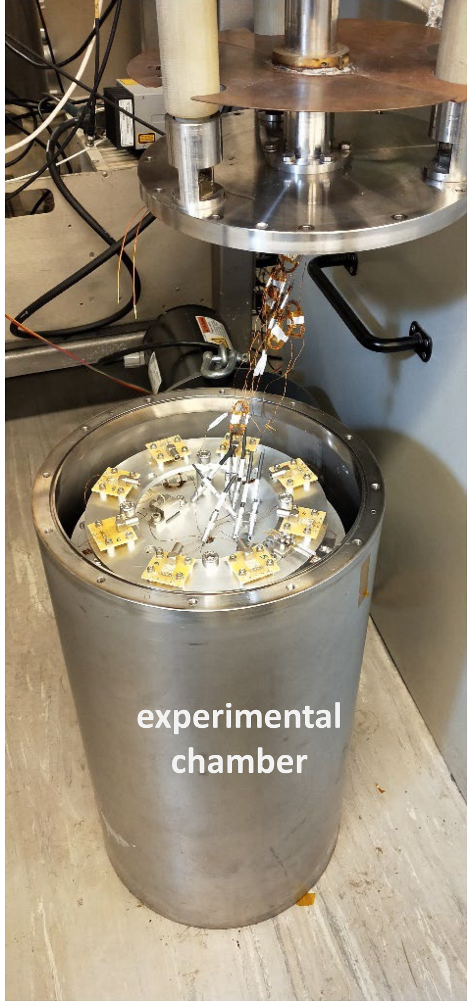
YBCo sample (4cmX4cmX2mm), 40g

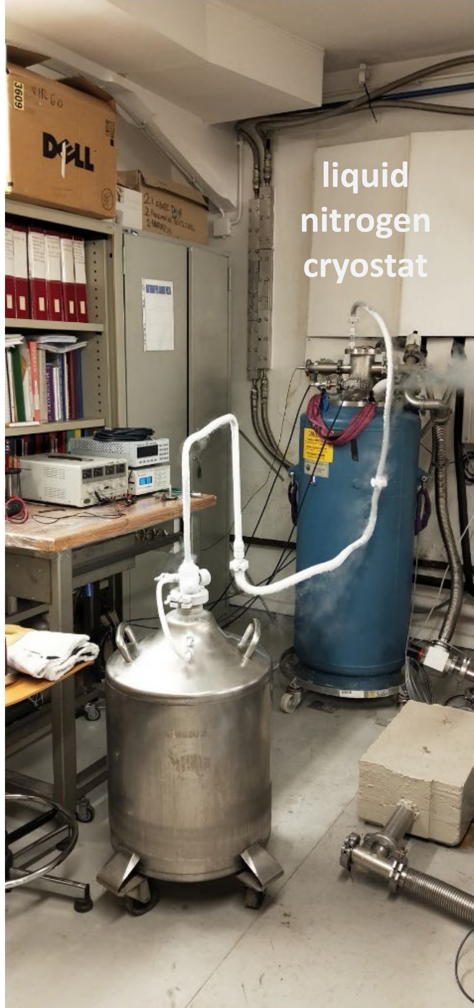
Oven: OFHC copper – thin walls



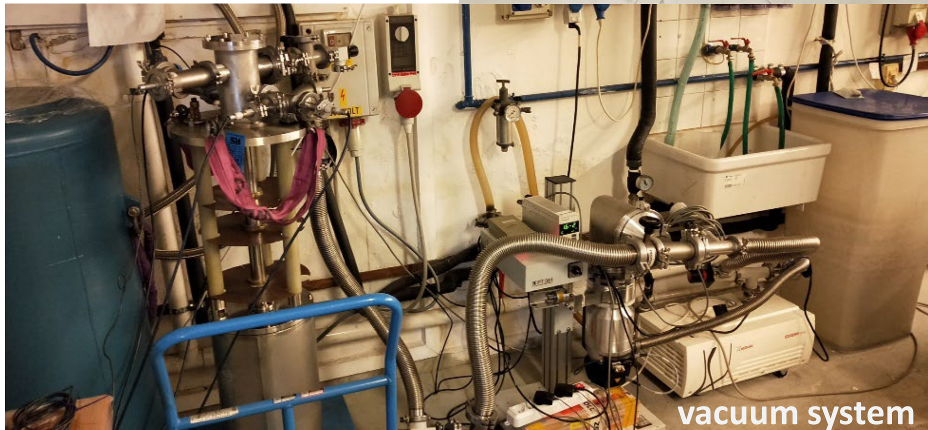
Cooling Setup



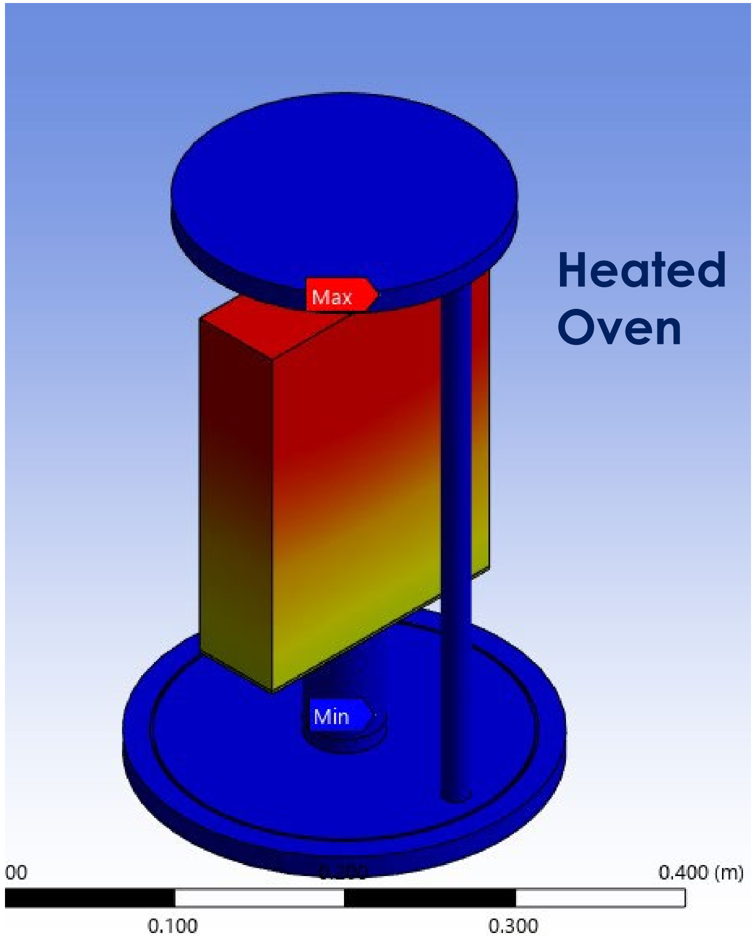




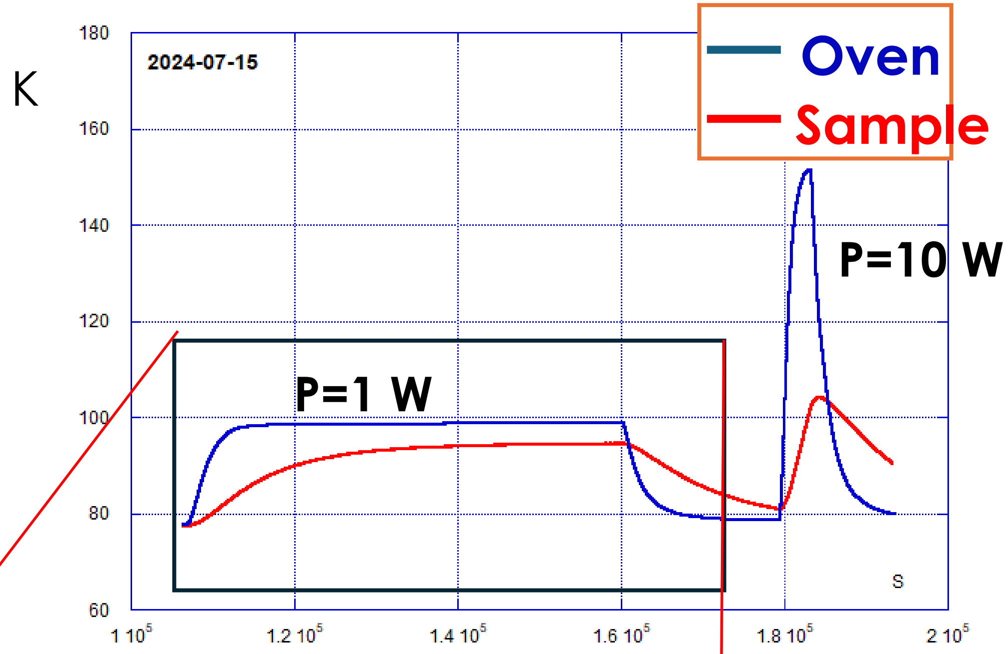
In the oven support there is the liquid nitrogen→ direct contact with thermal bath

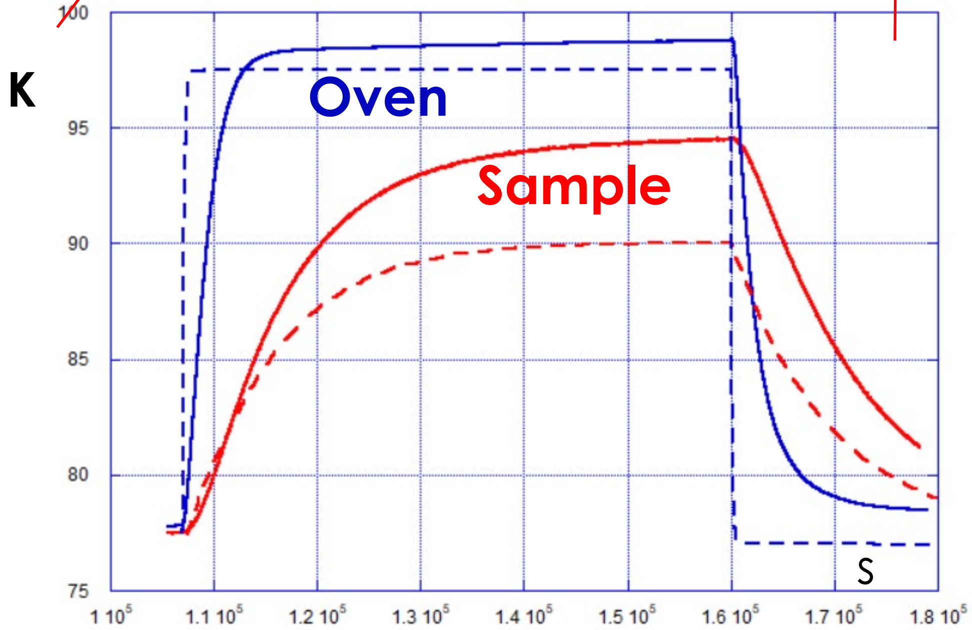


Cooling Tests Example



Heated Oven



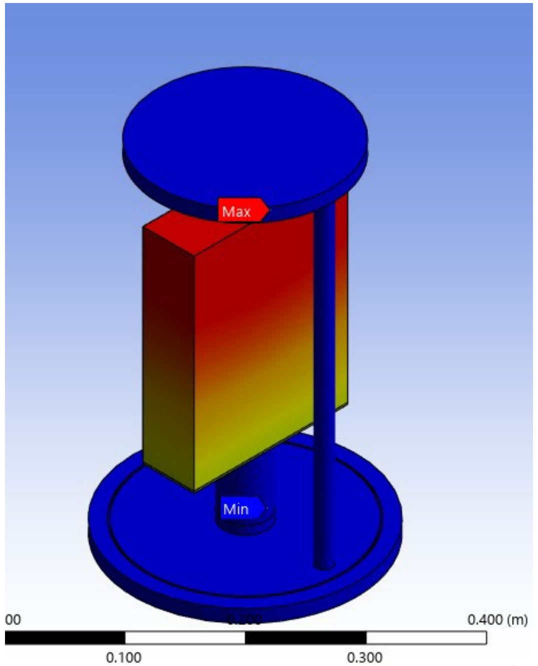


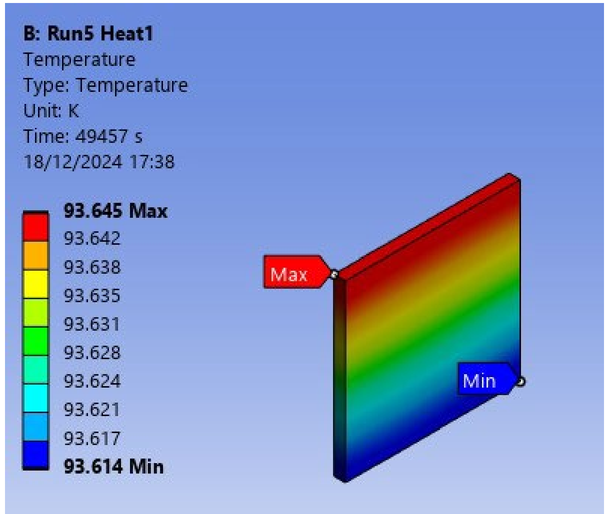
Comparison with FEM (--) without optimization

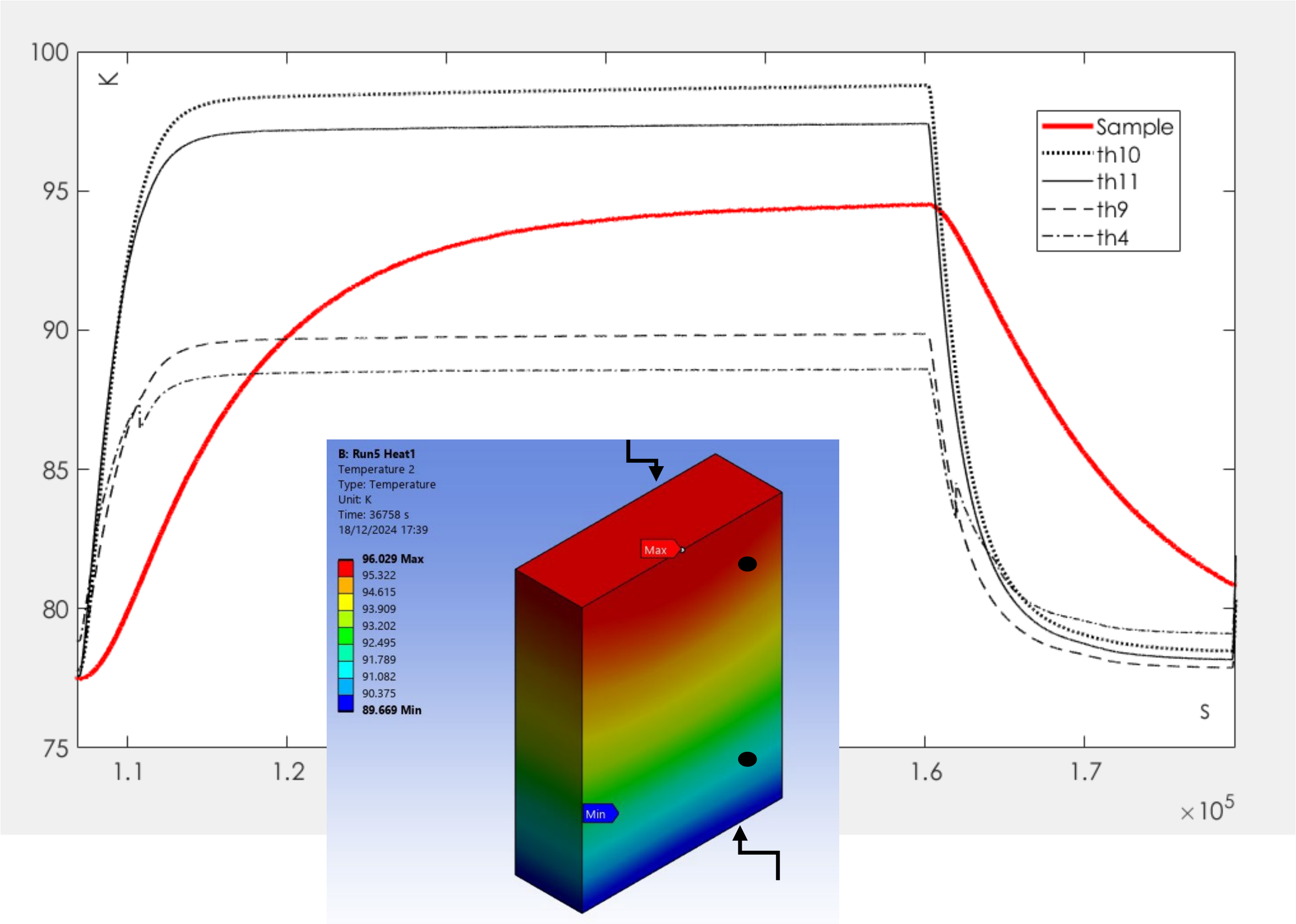
Cooling cycles with different heating powers on the Oven.
Example with 1W heating power performed on middle 2024

Data analysis

- Two Temp sensors on the Sample (negligible gradient) - Red
- Four Temp sensors on the Oven (Black curves – see the gradient)







Residual Thermal Resistance

- Heating Tau_{Oven}=2201 s (heating and cooling phases)

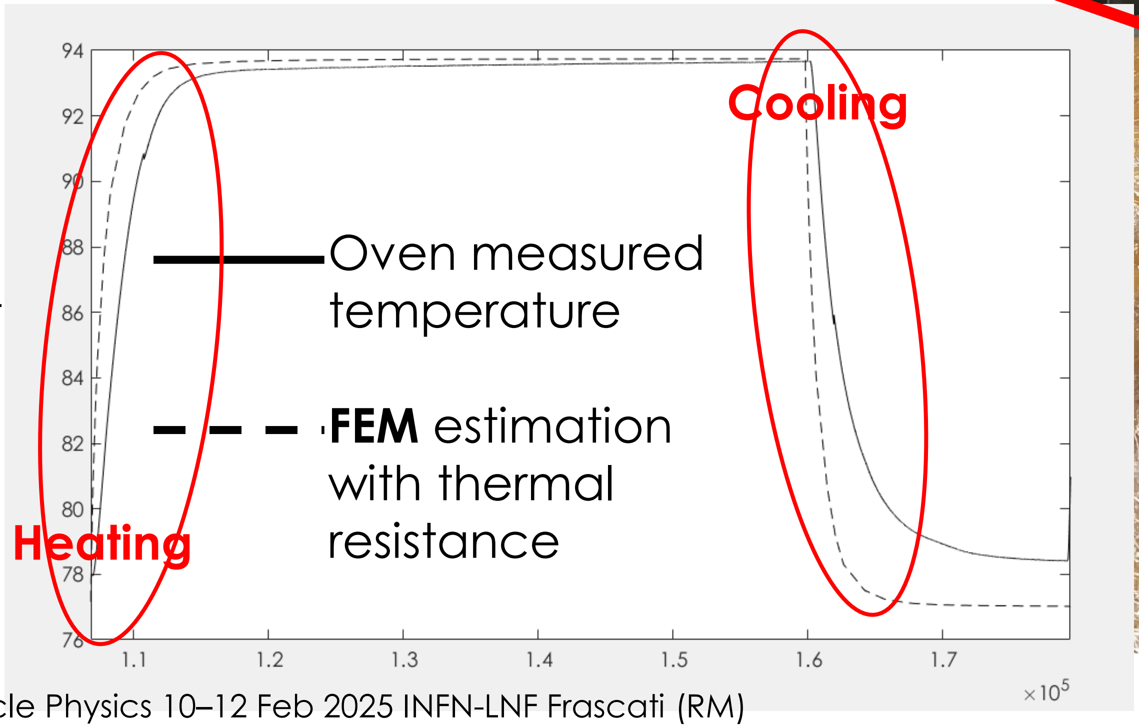
$$\tau = \frac{M_{oven} C_{copper}}{k_c} = Tau_{Oven}$$ Conduction

→ Residual Thermal Resistance (k_C)

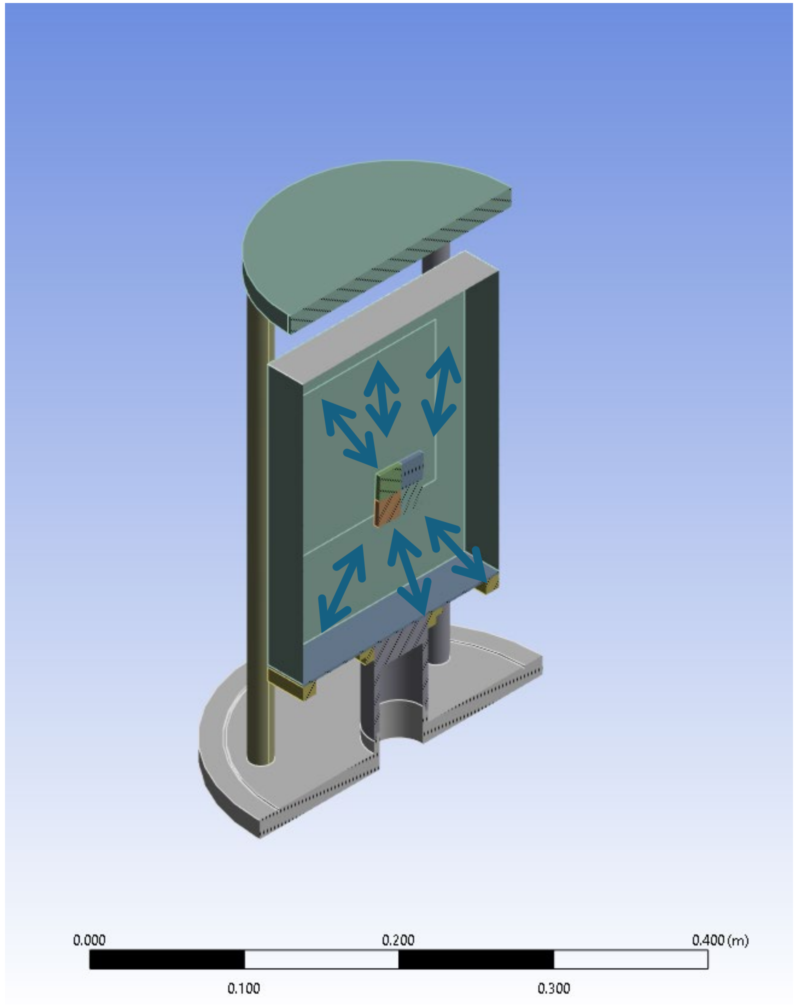
23 W\m²\K

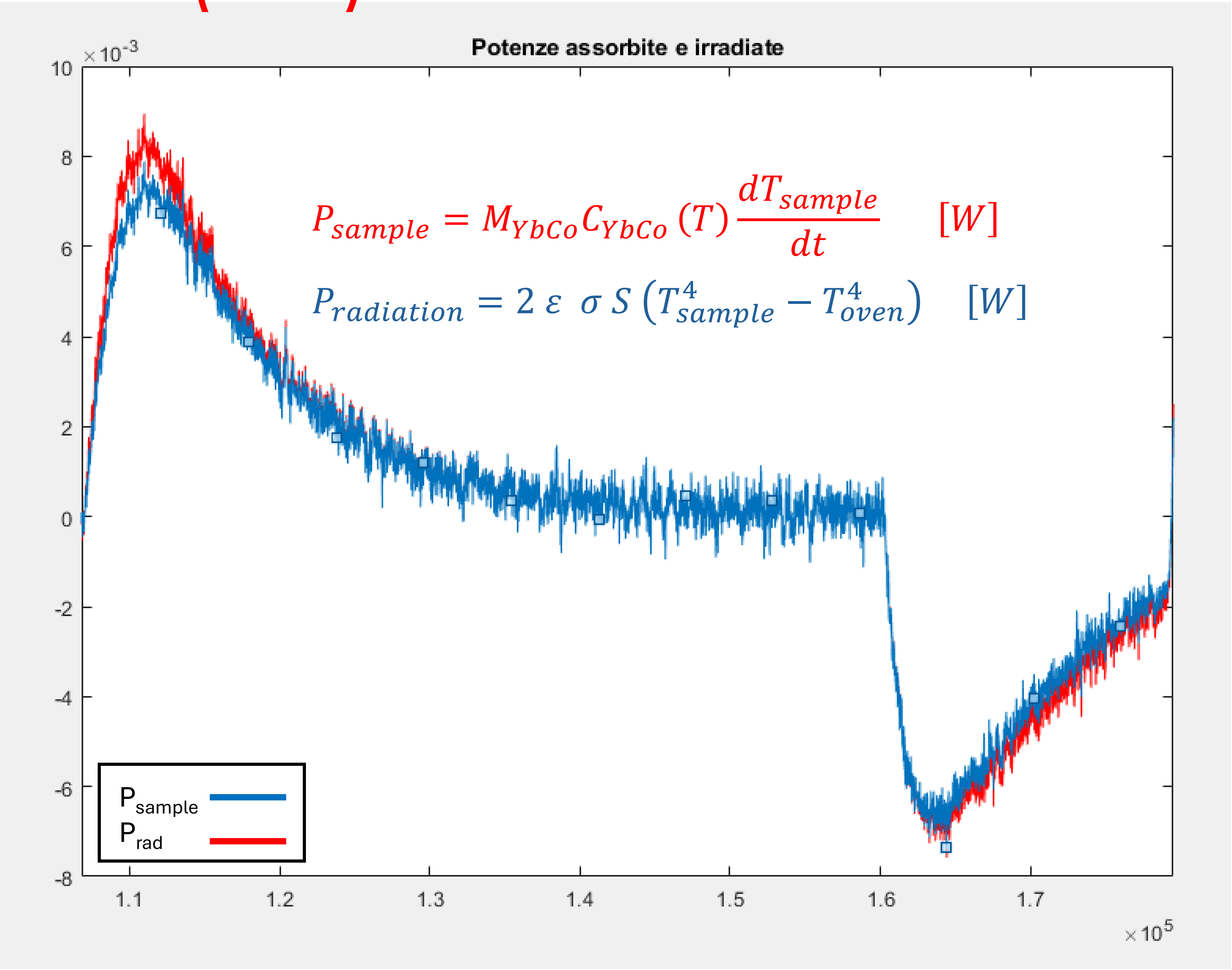
<u>Kc included in the FEM</u>

<u>Good agreement obtained</u>



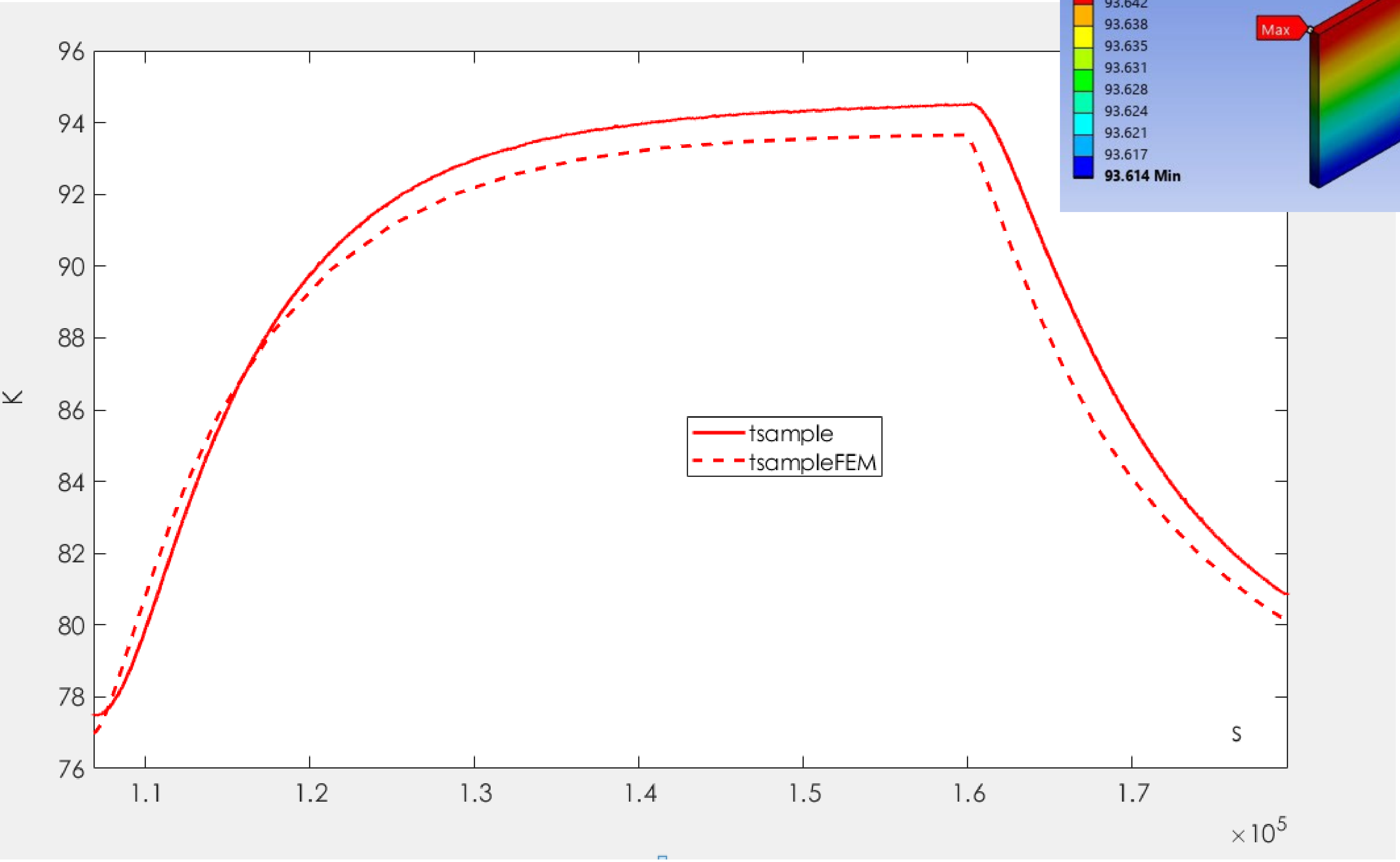
Emissivity estimation (ε=1)

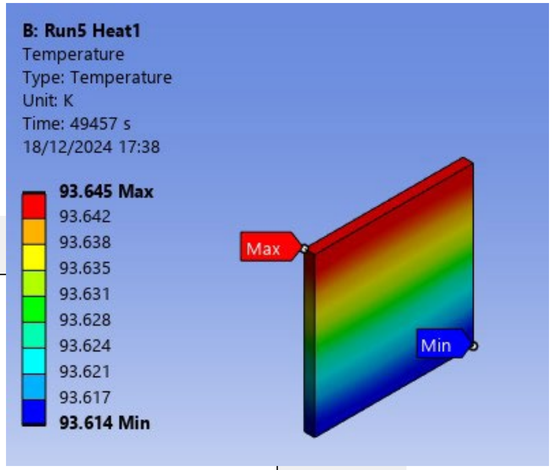




The agreement between P_{sample} and P_{rad} indicates that the data interpretation is correct

Sample





Sample thermal properties and radiative exchange in agreement with the simulation

Comments

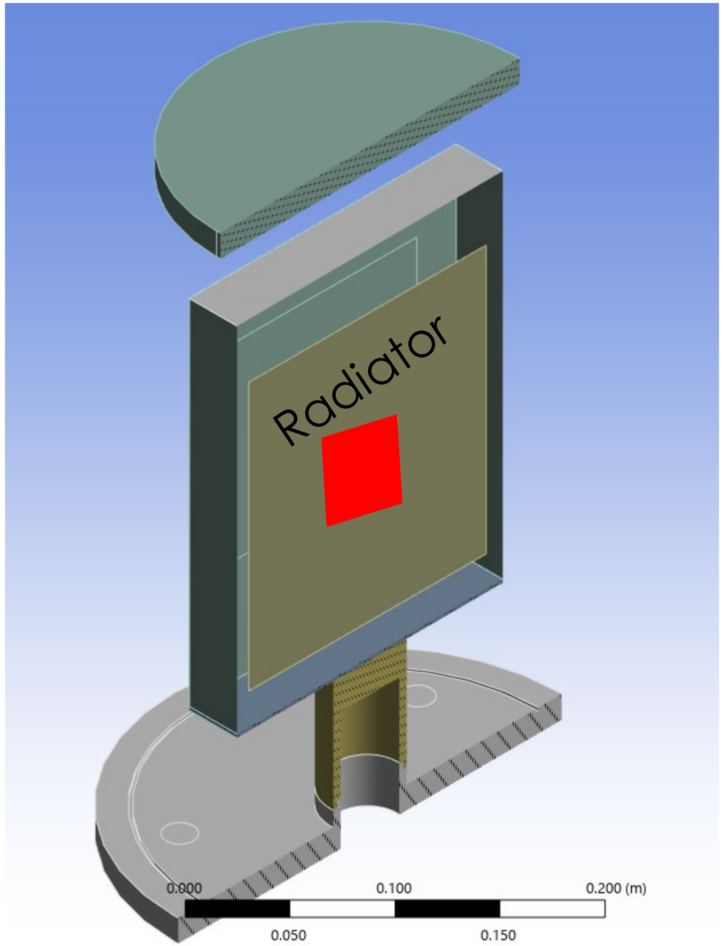
Agreement between data and FEM simulation (model validation)

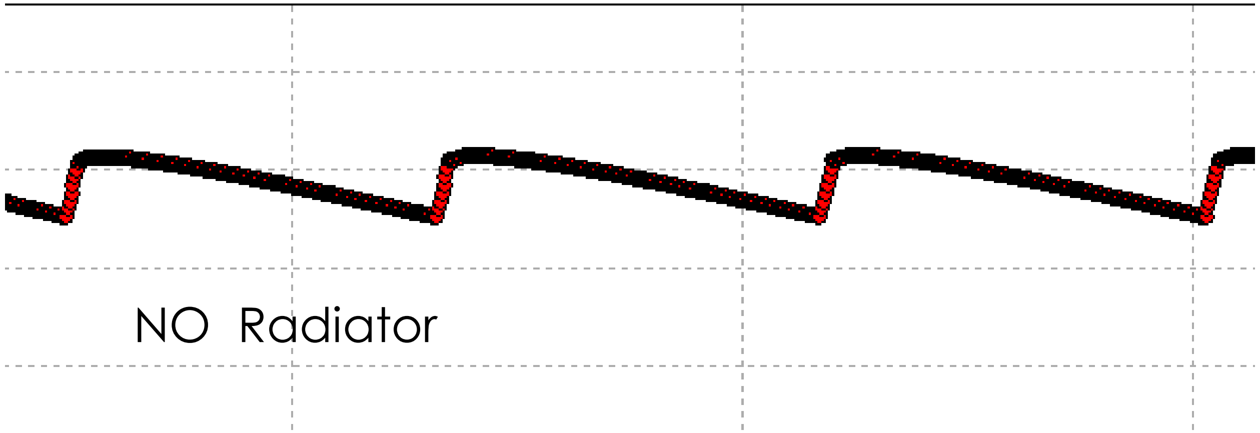
The modulation frequency is <10 mHz, so some improvements are

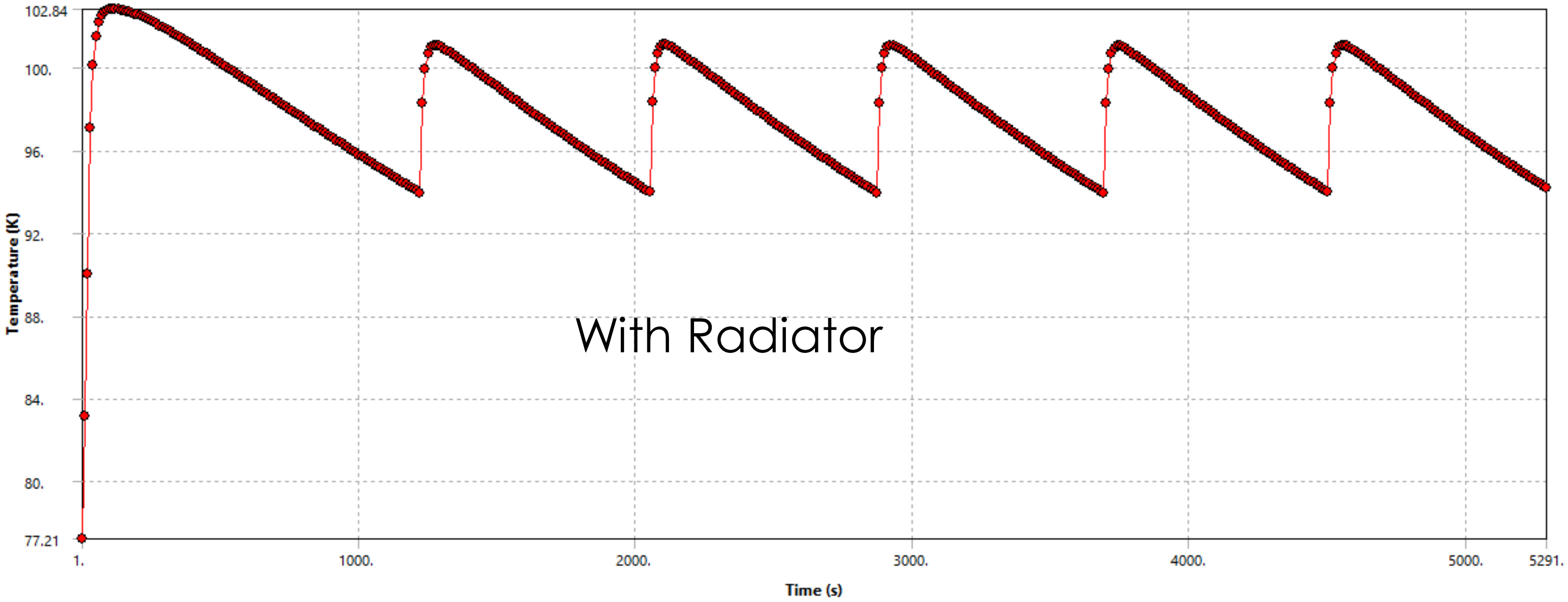
implemented:

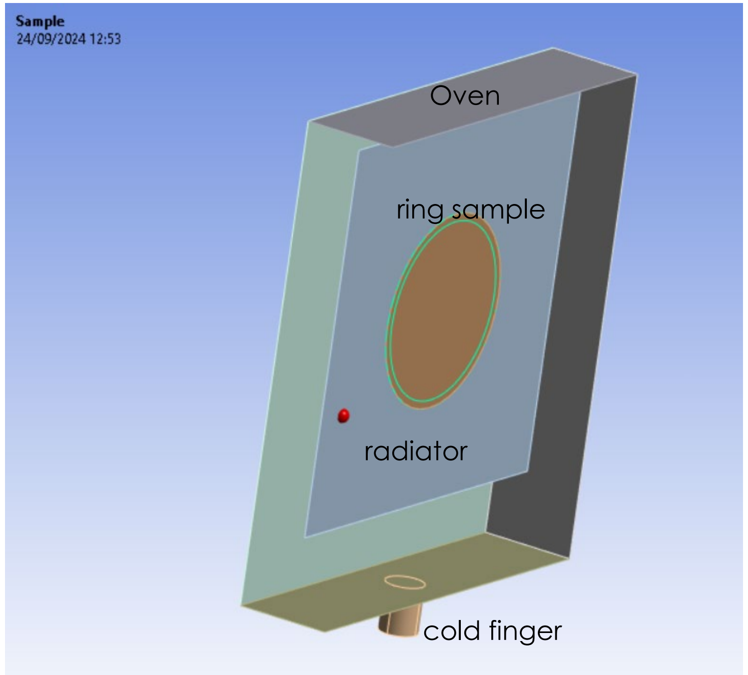
- Use of a radiator
- Change of sample geometry

With a radiator (thin OFHC foil) from 0.5 to 1.5 mHz



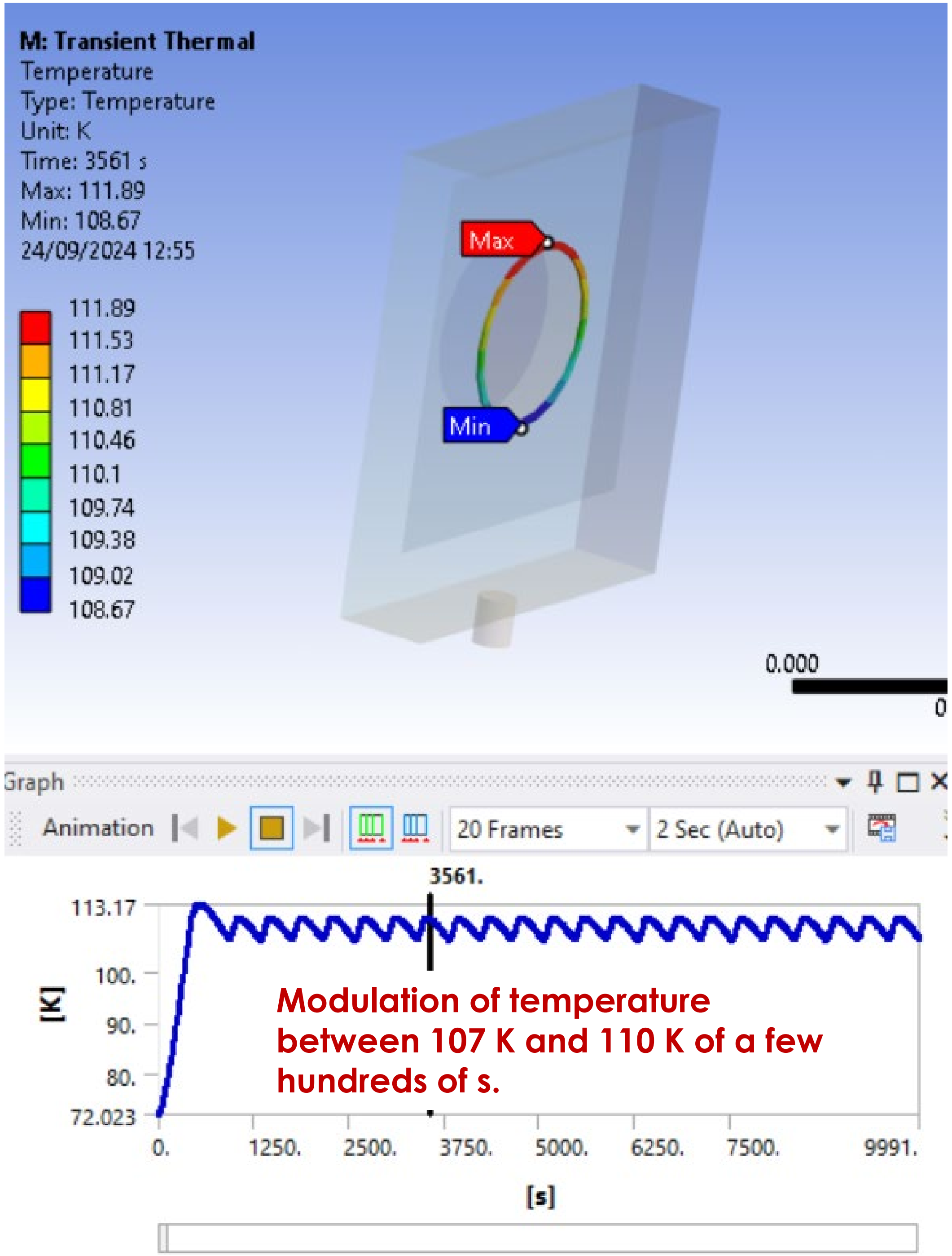






BSCCO ring sample Graphite radiator

R_{in} = 92 mm
400x400 mm
500x100 mm
P = 10 W
R_{out} = 100 mm
thickness = 0.1 mm thickness = 0.1 mm
V = $20 \cdot 10^3$ mm^3



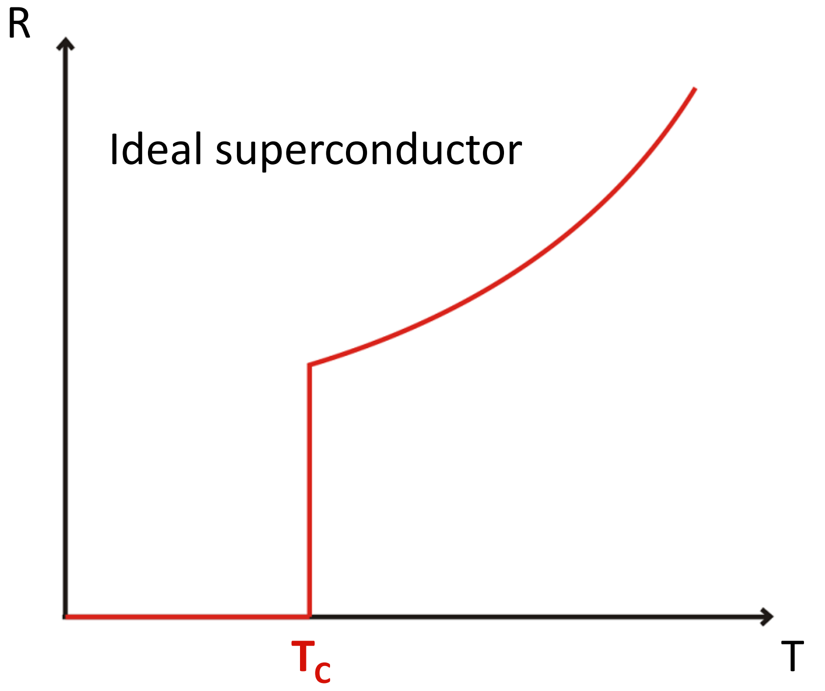
SAMPLES

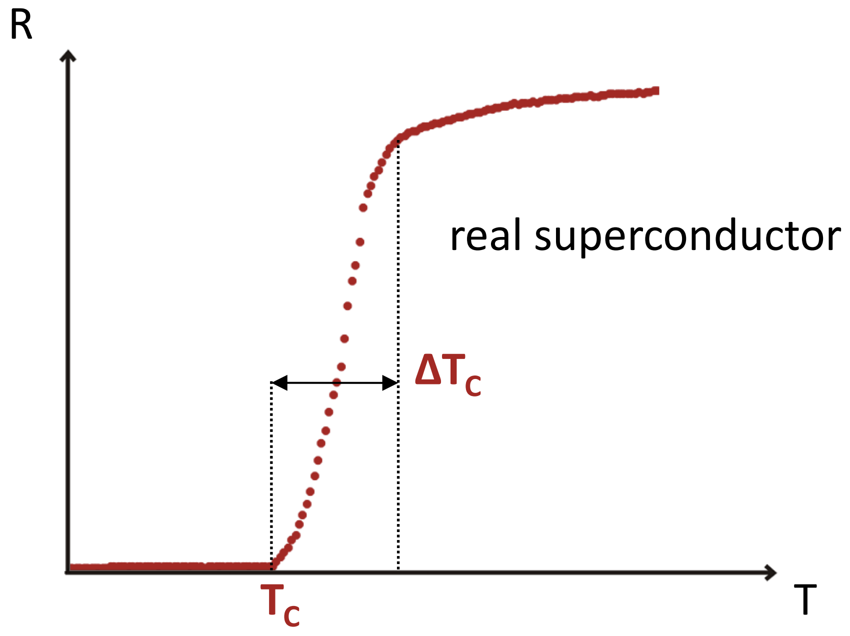
Requirements:

- **T_C > 80 K and ΔT_C 2 K**
- **Large mass > 200 g → samples with a 10 cm diameter**

From the **electrical resistance as a function of temperature plot** it is possible to obtain information on the first requirement.

Also, these plots will let us understand the quality of a sample and if a certain degree of dis-uniformity exits in it.



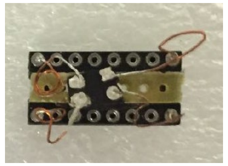


FRAGMENTS OF A DISC | ENTIRE DISC

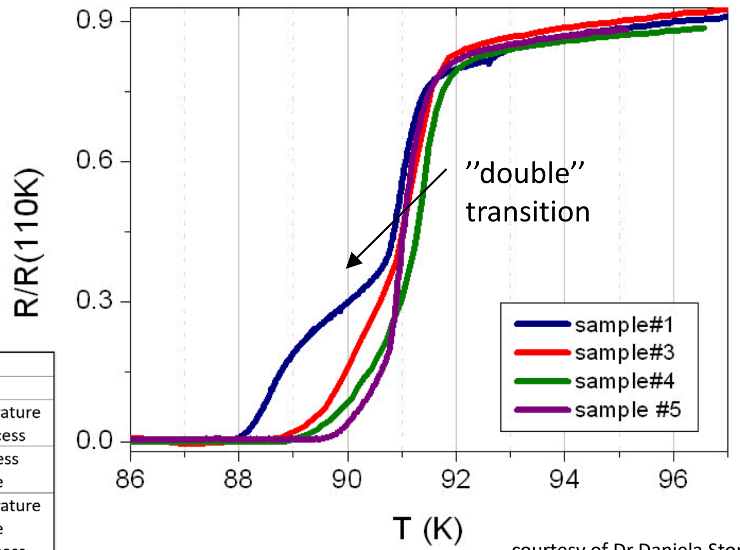
Sintered YBCO

Sintered YBCO discs were prepared in different sintering conditions (temperature, oxidation) in order to maximise T_C and reduce ΔT_C (CAN Superconductors).

Fragments of a disc

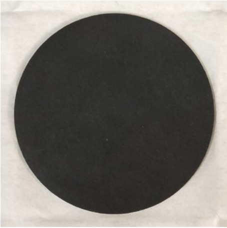


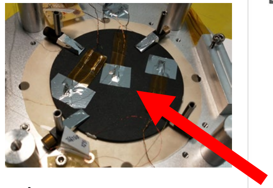
	T_c (K)	ΔT_c (K)	notes
sample#1	88.0	3.5	
sample#3	88.5	3.0	higher sintering temperature + extra oxidation process
sample#4	89.0	2.5	extra oxidation process + isostatic pressure
sample#5	89.5	2.0	higher sintering temperature + isostatic pressure + extra oxidation process



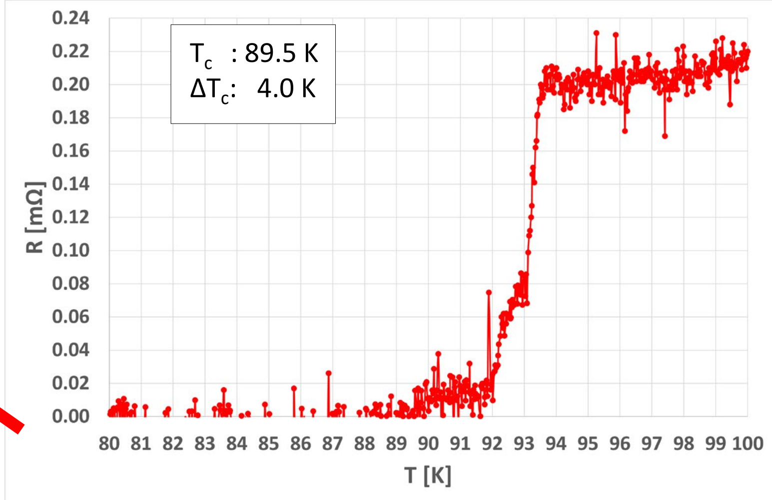
courtesy of Dr Daniela Stornaiuolo

Entire disc





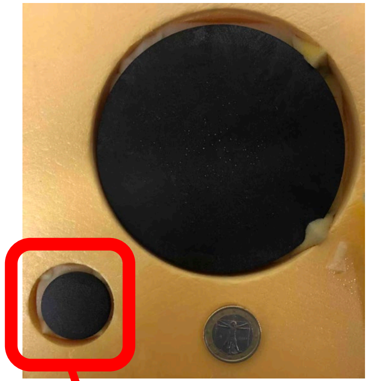
diameter: 100mm
thickness: 3 mm
mass: ~ 124 g
(like sample#3)

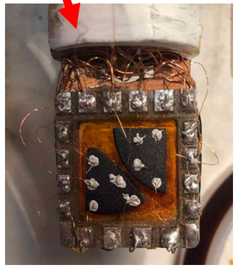


crystalline GdBCO/Ag

Single-domain melt-textured bulk pieces (CAN Superconductors).

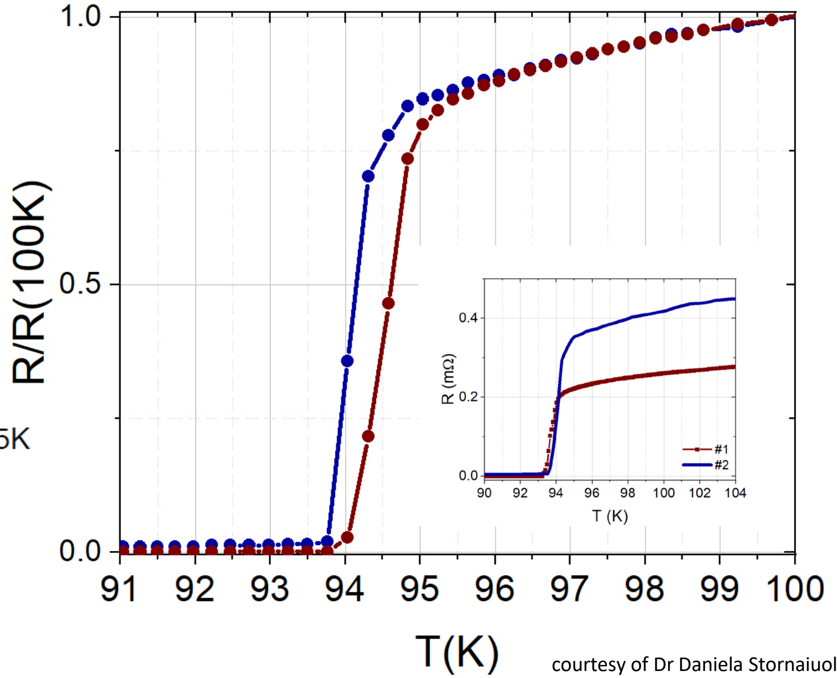
Fragments of a disc





Tc=93.5K

ΔT=1K



courtesy of Dr Daniela Stornaiuolo

Entire disc

diameter: 100mm
thickness: 4 mm
mass: ~ 213 g

work in progress

CRYOSTAT

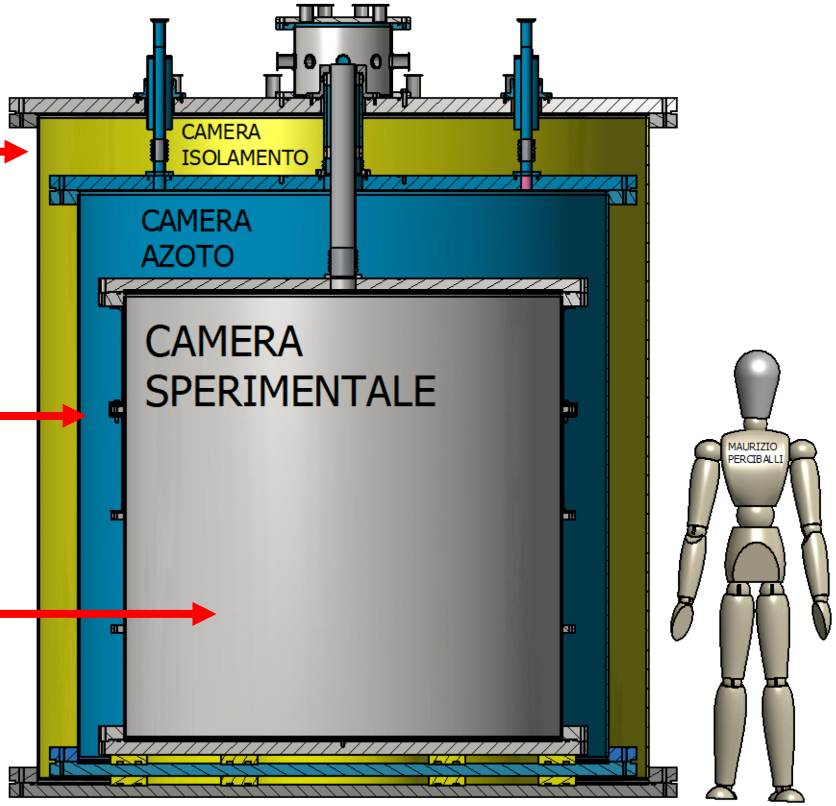
The cryostat consists of three chambers.

The **Experimental Chamber**, that will hosts the balance, will be completely submerged in liquid Nitrogen inside the **Nitrogen Chamber**. The volume of liquid Nitrogen in the tank is approximately 4000 l.

Vacuum/Insulation Chamber
company: Fantini Sud S.p.A. (Italy)
material: steel
height , diameter: 3240 mm , 2730 mm
mass: 8100 kg

Nitrogen Chamber
company: Fantini Sud S.p.A. (Italy)
material: steel
height , diameter: 2003 mm , 2400 mm
mass: 6100 kg

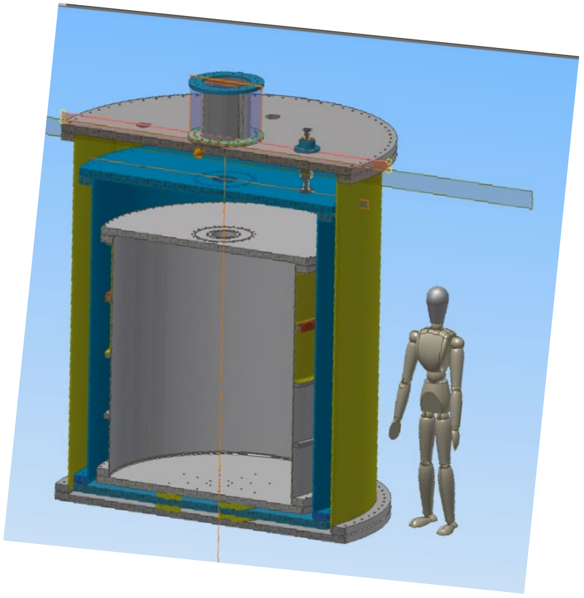
Experimental Chamber
company: L.M.P. Amicuzi (Italy)
material: steel
height , diameter: 1780 mm , 2000 mm
mass: 3500 kg



An Aluminium screen around the Experimental Chamber ensures good thermal uniformity even with low liquid Nitrogen level.

Given a thermal input of about $2 W/m^2$, the evaporation time of liquid Nitrogen is estimated to be about 5 months.

In the **Insulation Chamber** a vacuum ($\sim 10^{-6}$ mbar) will be created to isolate the system from the outside.



Superinsulation system of the Second Chamber

Cryotest of the first and second chamber

Third and second chamber

ARCHIMEDES

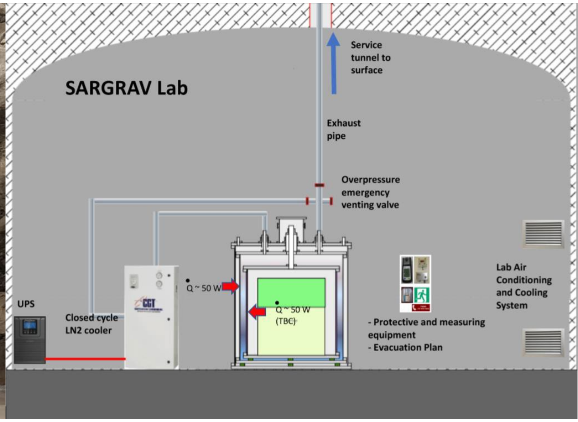
Archimedes is an INFN-funded fundamental physics experiment that searches for small weight variations induced by quantum vacuum fluctuations.

It is the first experiment to be installed in the **Sar-Grav laboratory**, in the area of the disused Sos Enattos mine near Lula (Nu, **Sardinia**). The SarGrav laboratory has both surface and underground facility, and is **dedicated to the research on gravitational waves, gravitational physics and geophysics**.

Archimedes will work in the frequency range from 5 mHz to 10 mHz and the signal will be limited by seismic and thermal noise.

Thanks to the unique geological properties of Sardinia and the low population density, **Sos Enattos area** is an excellent site to host experiments that require **very low seismic noise levels**. Working at **cryogenic temperatures** (cryostat) reduces the **thermal noise**.



CONCLUSIONS

- ✓ **Archimedes** is an experiment conceived to shed light on the discussed **interaction between the gravitational field and the vacuum fluctuations**.
- ✓ The **measurement** must be performed **using an extremely sensitive balance** and **modulating the temperature of superconductors at very low frequencies (about tens of mHz) and with amplitude of a few K**.

  The experiment will work at **cryogenic temperature** and in a **seismically quiet site**
- ✓ An **upgraded thermal modulation system have been set up and first promising results were obtained**
- ✓ The results of the simulations support the **mechanically isolated system, composed of a ring sample (GdBCO or BSCCO) in thermal contact with a radiator, that exchanges heat only with its thermal bath whose temperature is modulated by the screen that surrounded this system**.

SOME REFERENCES

Eur. Phys. J. Plus (2022) 137:826
https://doi.org/10.1140/epjp/s13360-022-03025-7
THE EUROPEAN PHYSICAL JOURNAL PLUS

Regular Article

Check for updates

Casimir energy for N superconducting cavities: a model for the YBCO (GdBCO) sample to be used in the Archimedes experiment

PHYSICAL REVIEW B **106**, 134502 (2022)
doi: 10.1103/PhysRevB.106.134502

Quantum zero point electromagnetic energy difference between the superconducting and the normal phase in a high-T_c superconducting metal bulk sample

PHYSICAL REVIEW D **90**, 022002 (2014) doi: 10.1103/PhysRevD.90.022002

Towards weighing the condensation energy to ascertain the Archimedes force of vacuum

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PARTICLE PHYSICS

How Much Does 'Nothing' Weigh?

The Archimedes experiment will weigh the void of empty space to help solve a big cosmic puzzle

By Manon Bischoff on May 1, 2023

Eur. Phys. J. Plus (2021) 136:511
https://doi.org/10.1140/epjp/s13360-021-01450-8
THE EUROPEAN PHYSICAL JOURNAL PLUS

Regular Article

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Seismic glitchness at Sos Enattos site: impact on intermediate black hole binaries detection efficiency

ARCHIMEDES

The Archimedes Experiment

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https://www.facebook.com/archimedes.experiment/

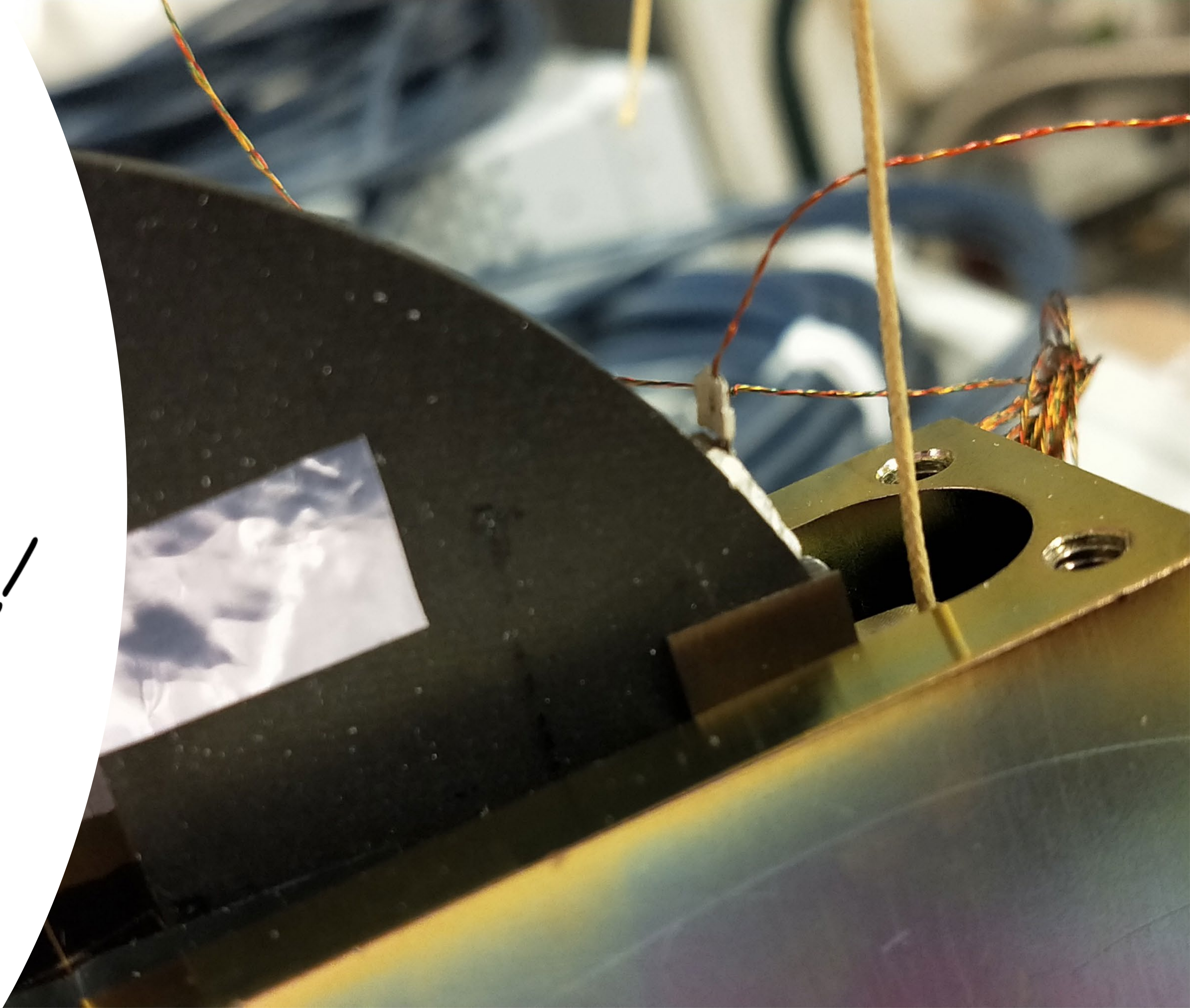
physics MDPI

Physics 2020, 2, 1–13; doi:10.3390/physics2010001

Article

Progress in a Vacuum Weight Search Experiment

Thank you for your attention!



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