The MAGO cavity and prospects for HFGW searches

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Mainz, 8. July 2025

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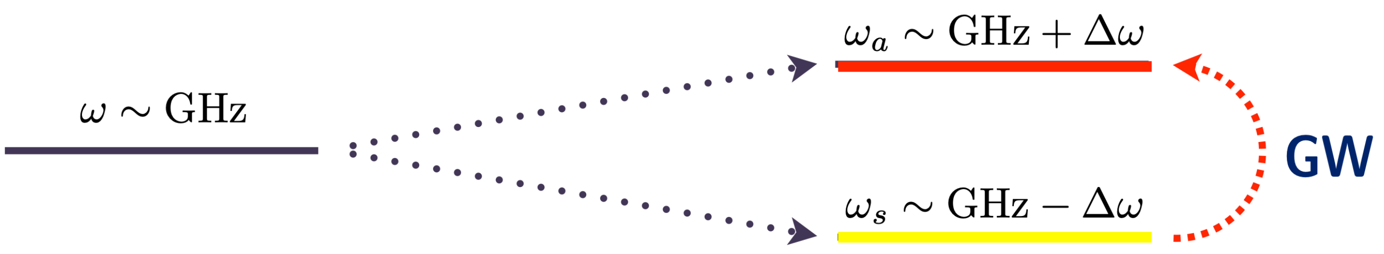
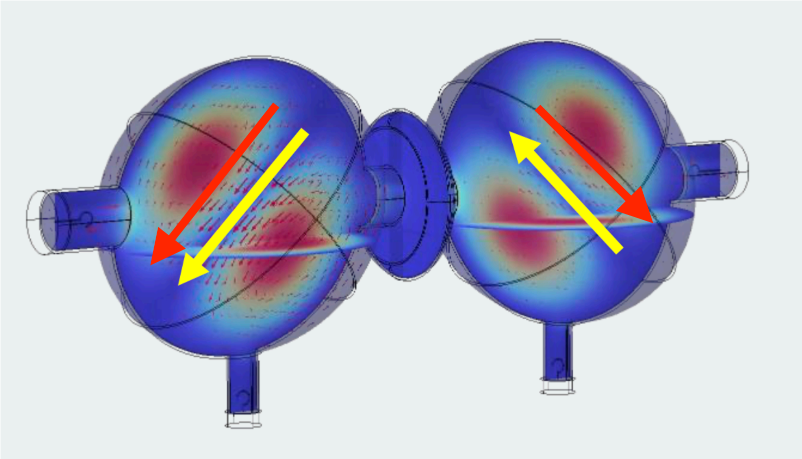
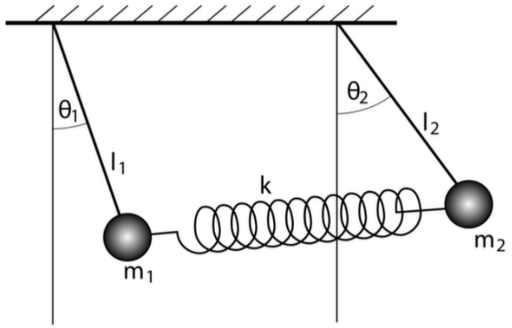
Heterodyne detection

GWs induce energy transfer between two levels of an EM resonator



$$\Delta\omega \sim (a/R)^3 \sim kHz - MHz$$





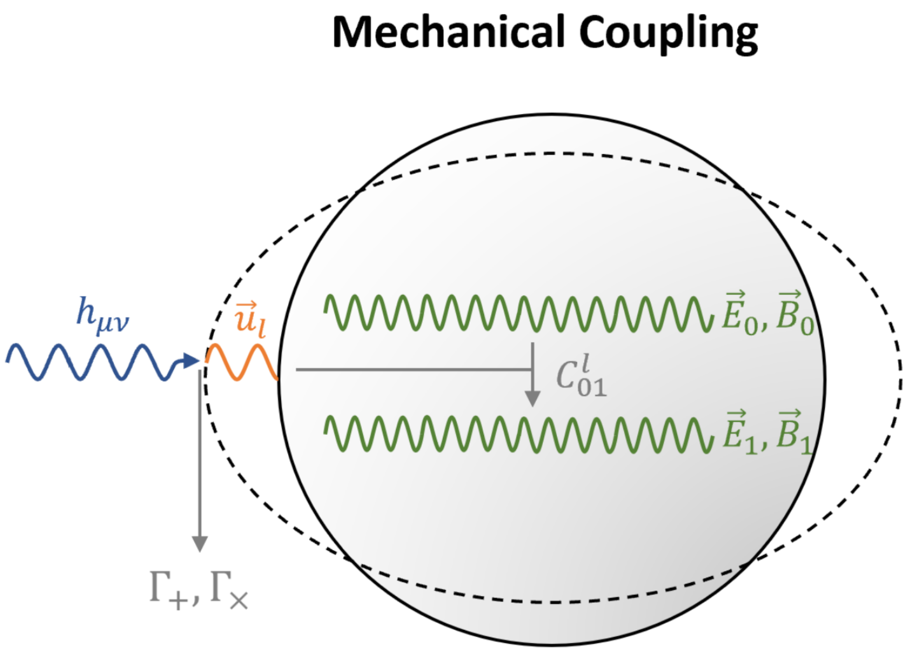
$$\ddot{\theta}_1 = -\frac{g}{l}\theta_1 - \frac{k}{m}(\theta_1 - \theta_2) \quad \text{and} \quad \ddot{\theta}_2 = -\frac{g}{l}\theta_2 + \frac{k}{m}(\theta_1 - \theta_2)$$

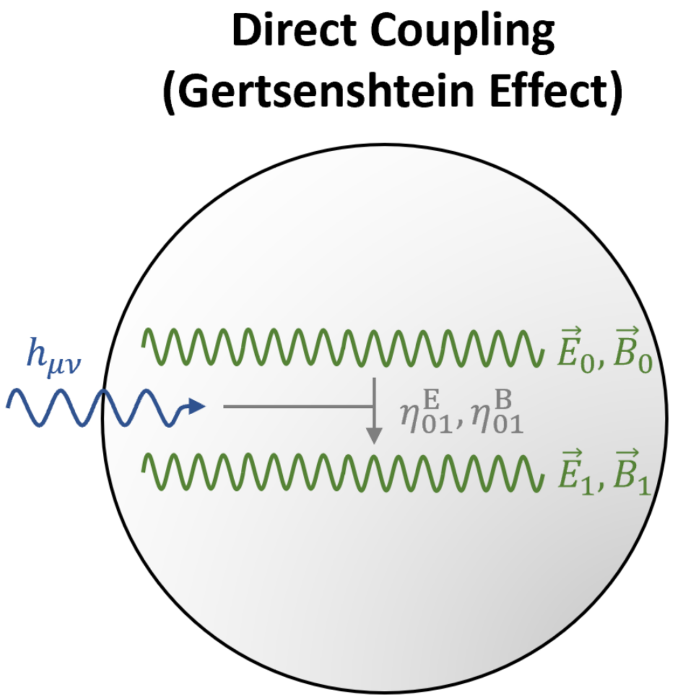
$$\Rightarrow \omega_0 = \sqrt{\frac{g}{l}} \quad \text{and} \quad \omega_\pi = \sqrt{\frac{g}{l} + 2\frac{k}{m}}$$

tunable

Two interaction principles

Mechanical and EM coupling





For frequencies below the GHz range mechanical coupling dominates

The MAGO proposal

… and the PACO cavities

Initial idea from the 70s, which led to the MAGO proposal

JETP LETTERS VOLUME 13, NUMBER 11 5 JUNE 1971

HIGH-FREQUENCY DETECTION OF GRAVITATIONAL WAVES

V. B. Braginskii and M. B. Menskii
Physics Department, Moscow State University
Submitted 18 March 1971
ZhETF Pis. Red. 13, No. 11, 585 - 587 (5 June 1971)

J. Phys. A: Math. Gen., Vol. 11, No. 10, 1978. Printed in Great Britain

On the operation of a tunable electromagnetic detector for gravitational waves

F Pegoraro†, E Picasso‡ and L A Radicati‡§
†Scuola Normale Superiore, Pisa, Italy
‡CERN, Geneva, Switzerland

Received 6 December 1977, in final form 20 April 1978

ELECTROMAGNETIC DETECTOR FOR GRAVITATIONAL WAVES

F. PEGORARO, L.A. RADICATI
Scuola Normale Superiore, Pisa, Italy

and

Ph. BERNARD and E. PICASSO
CERN, Geneva, Switzerland

Received 29 June 1978

MAGO was a proposal for a scaled-up experiment with 500 MHz cavities targeting the kHz GW frequency range (project not funded)

During the R&D activities 3 superconducting cavities were built

1. PACO-3GHz-pillbox

- 2-cell cylindrical pillbox-cavity @ 3GHz as proof-of-principle experiment
- Low Q, test of RF system, excitation of signal mode

The MAGO proposal

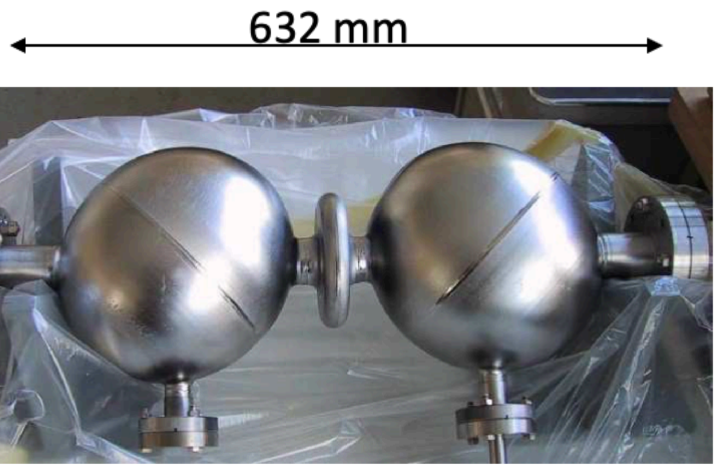
… and the PACO cavities

PACO-2GHz-fixed

- 2-cell cavity with optimised geometry
- Underwent chemistry and cold test to obtain $Q_0(U)$ for TE011

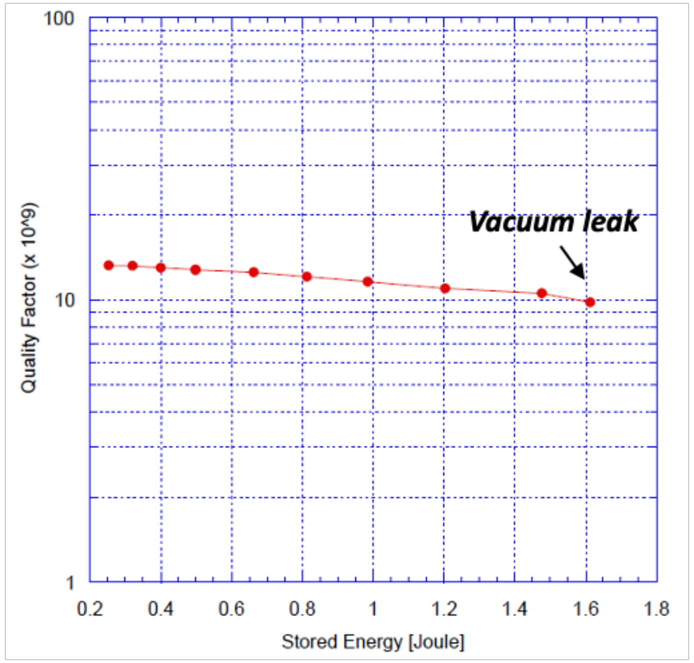
PACO-2GHz-variable

- 2-cell cavity with same geometry but variable coupling
- Never treated nor tested – on shelf for >15y @ INFN Genova



In the following, denoted as “MAGO cavity”

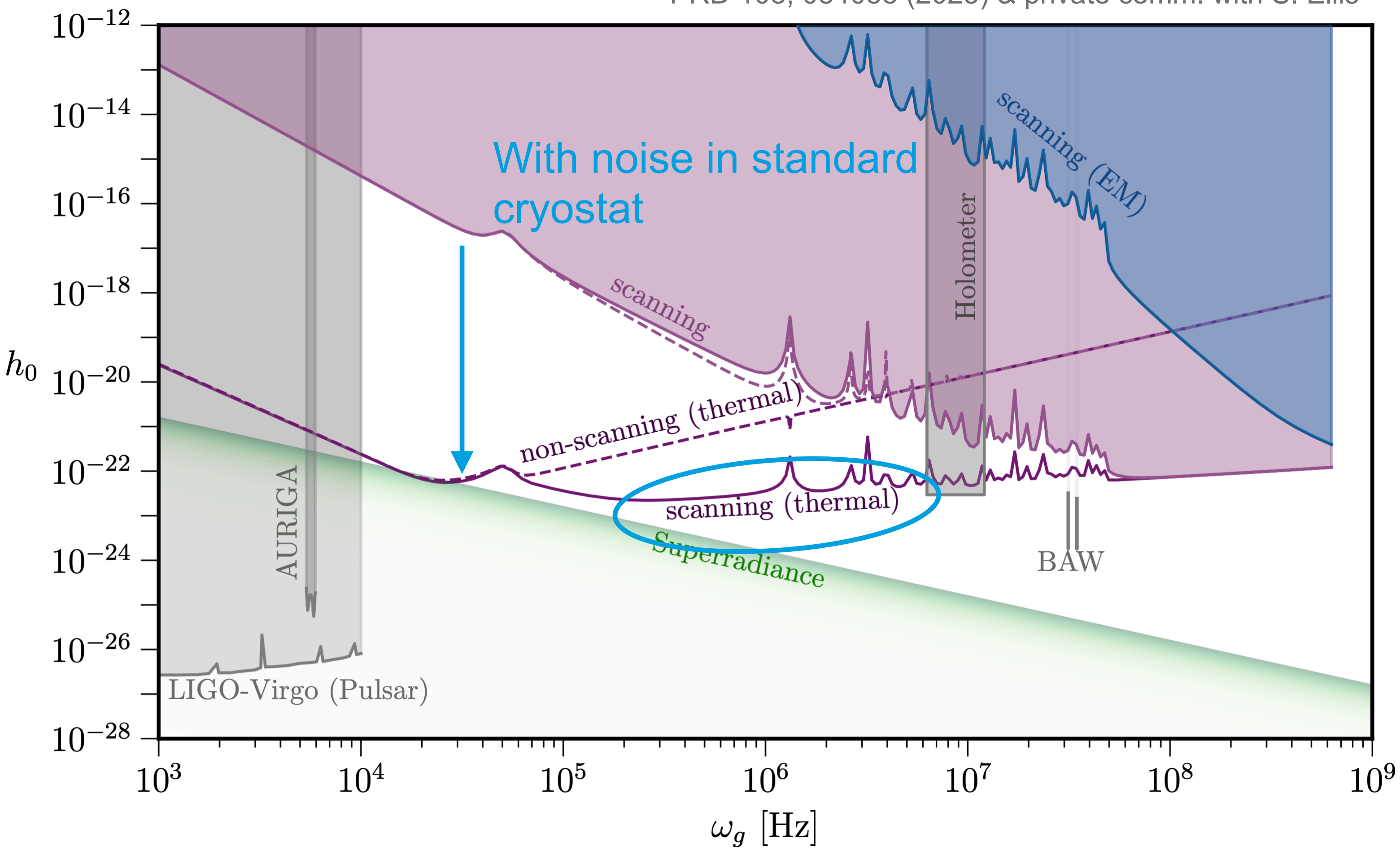
Figure 5. Niobium spherical cavities (fixed coupling).



Promising experimental reach

Unique broadband sensitivity

PRD 108, 084058 (2023) & private comm. with S. Ellis

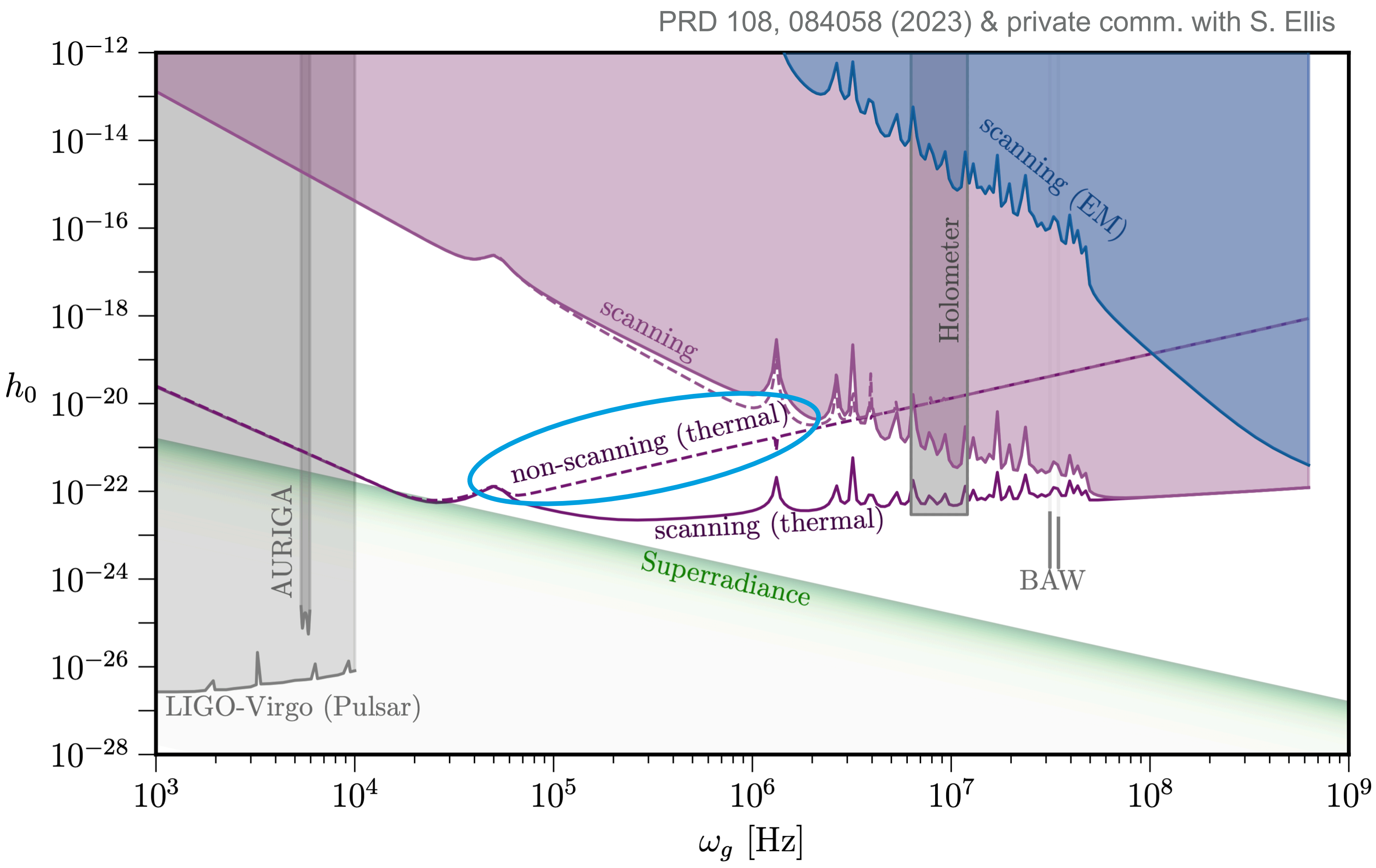


Even with a standard cryostat, novel frequency ranges can be explored, albeit with limited sensitivity

Strongly improve reach by attenuating vibrational noise to its thermal level

Promising experimental reach

Unique broadband sensitivity



Even with a standard cryostat, novel frequency ranges can be explored, albeit with limited sensitivity

Strongly improve reach by attenuating vibrational noise to its thermal level

Unique broadband sensitivity!

R&D efforts with the MAGO cavity

DESY/UHH - FNAL collaboration

Cavity at DESY (2023)

- Mechanical characterisation and RF measurements at room temperature

Cavity at FNAL (2024)

- Treatment of cavity, RF antenna design, cavity tuning and first cryogenic characterisation

Cavity back at DESY (2025)

- Cryogenic tests for LLRF system development

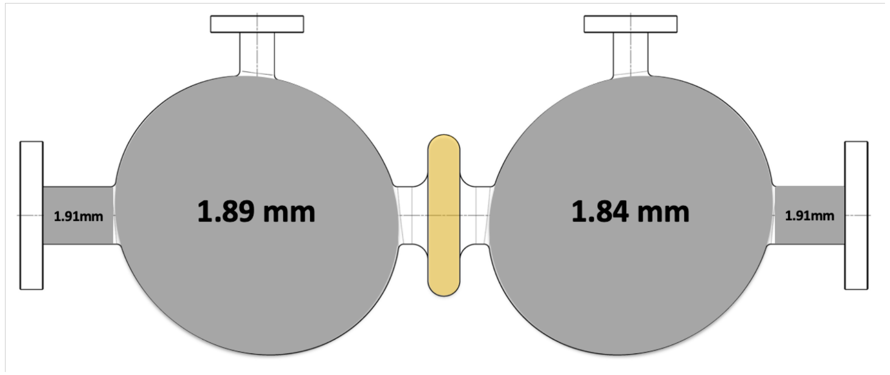
FNAL or DESY tbd. (2026)

- First GW search in existing cryostats

Cavity is out of shape

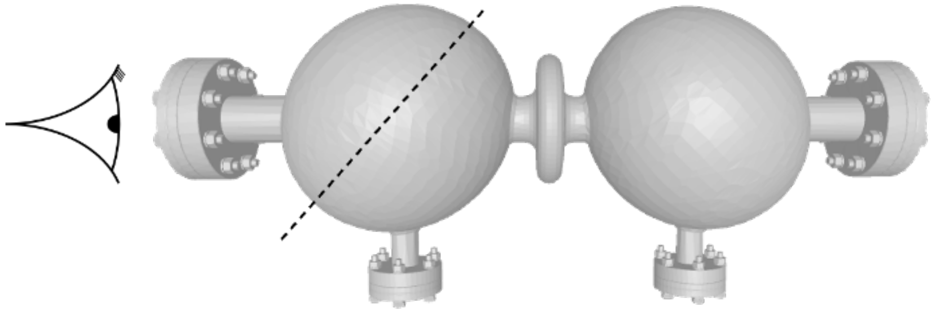
Mechanical survey

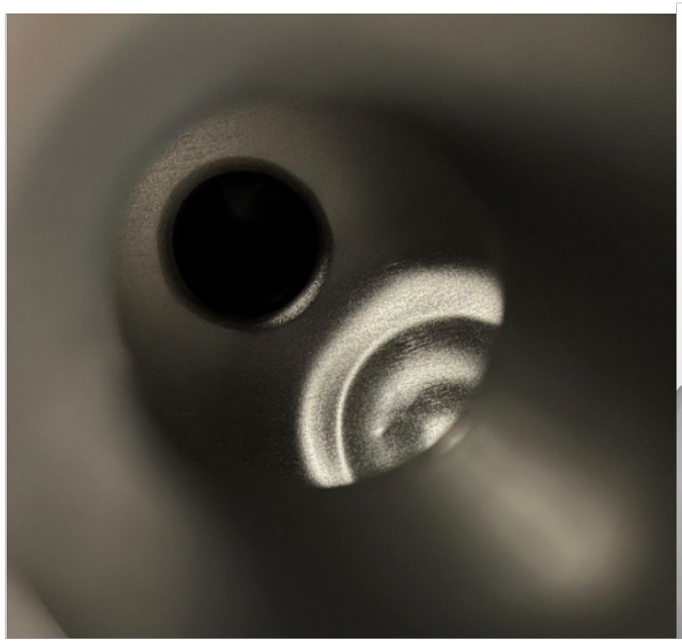
Measurement of the cavity geometry at arrival at DESY with a laser line scan and an ultrasonic wall thickness measurement (expected wall thickness 2mm)

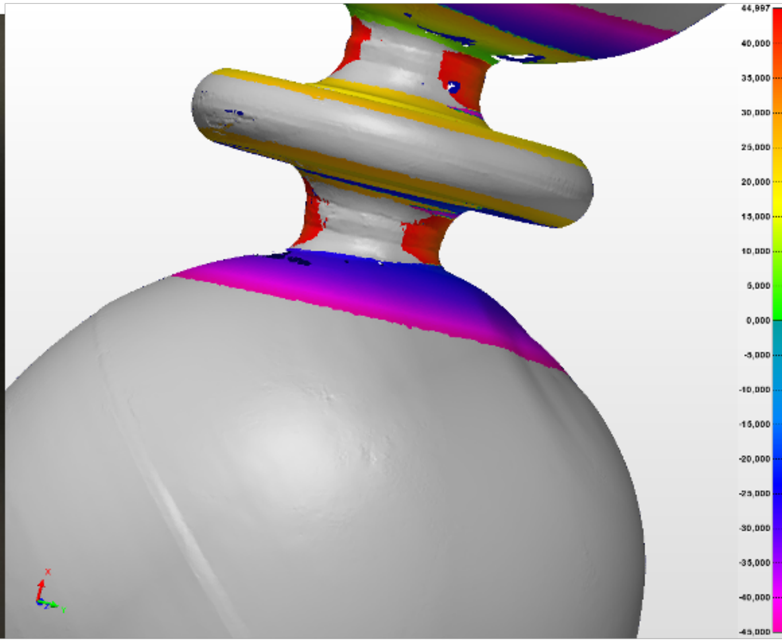


Measured wall thickness
10 points per cell, 4 per tube, average values shown

Donut-shaped dent
around symmetry axis

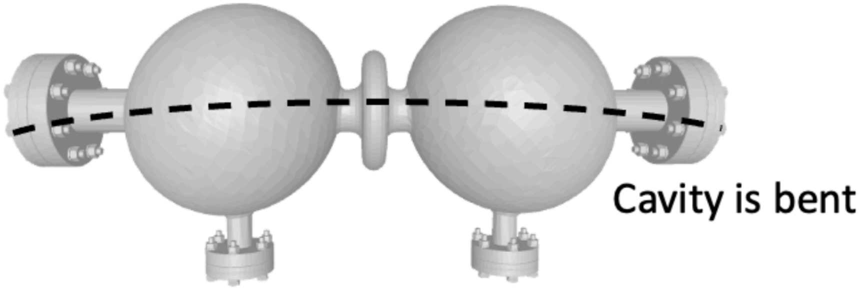


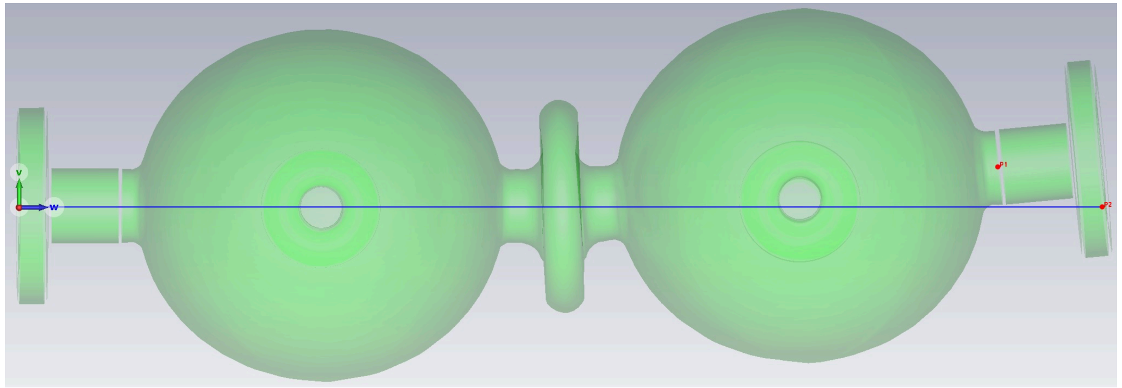


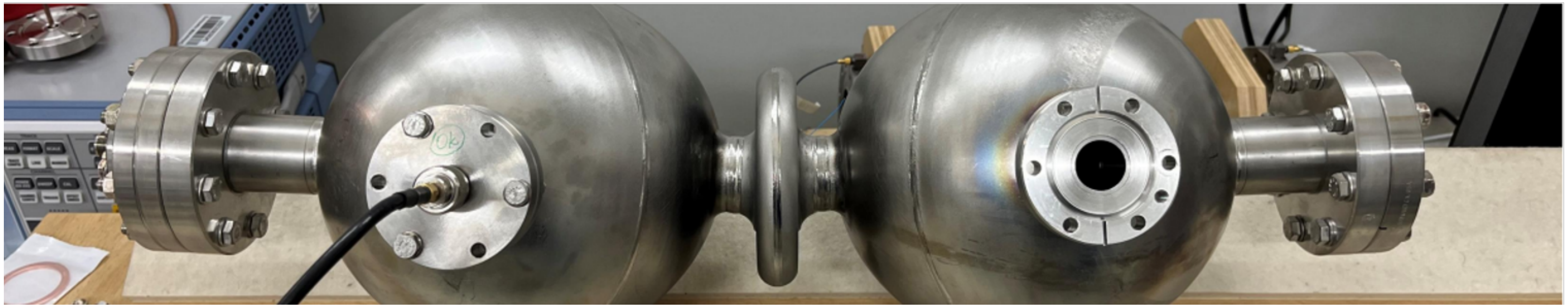


Cavity is out of shape

Mechanical survey



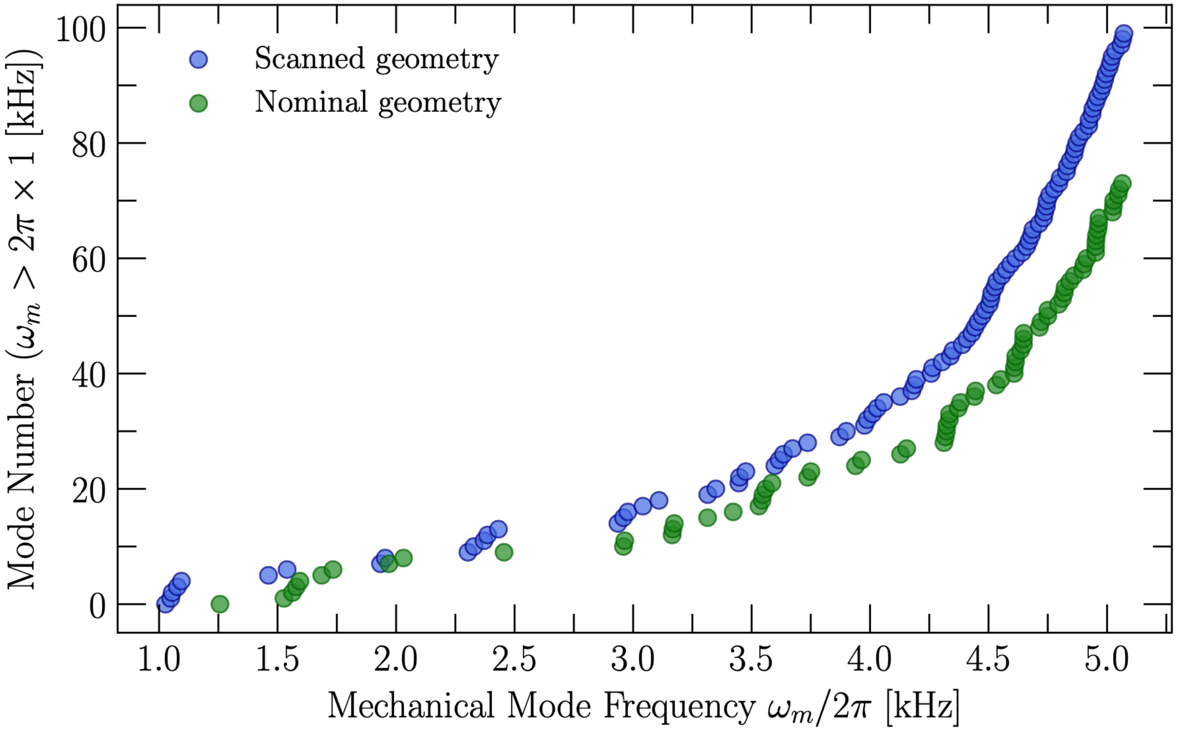


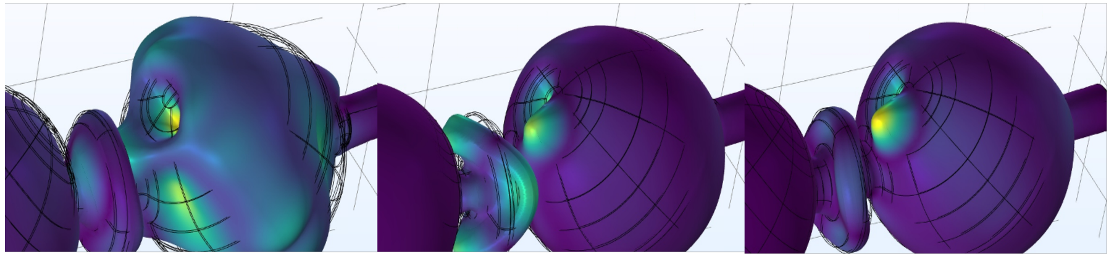


No damage to flanges or sealing surface, cavity leaktight

Mechanical resonances

Many more and densely populated mechanical normal modes with distorted detector





f = 3.90 kHz f = 3.98 kHz f = 3.99 kHz

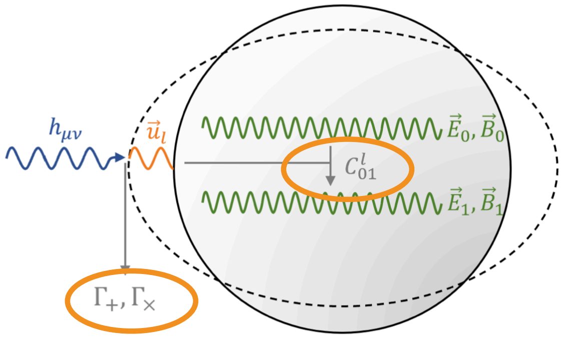
Dent in cell causes oscillation maximum in vibration Eigenmodes

Interpreting mechanical resonance measurements so far difficult, plan to improve with a laser doppler scanning vibrometry

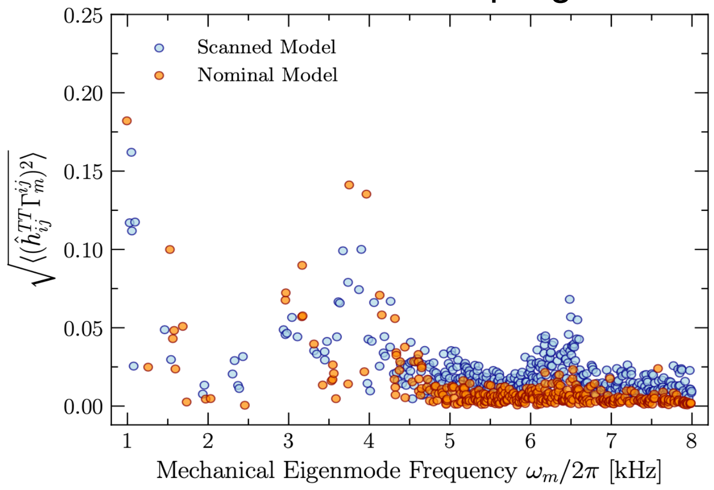
Measure also with piezo excitations in He-II with cavity in frame and attached to insert

Consequences of distorted geometry

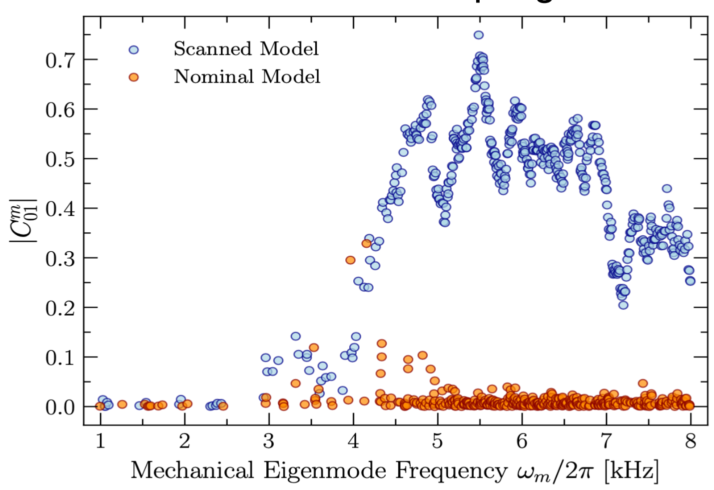
Γ a measure how much quadrupole moment a mechanical mode has



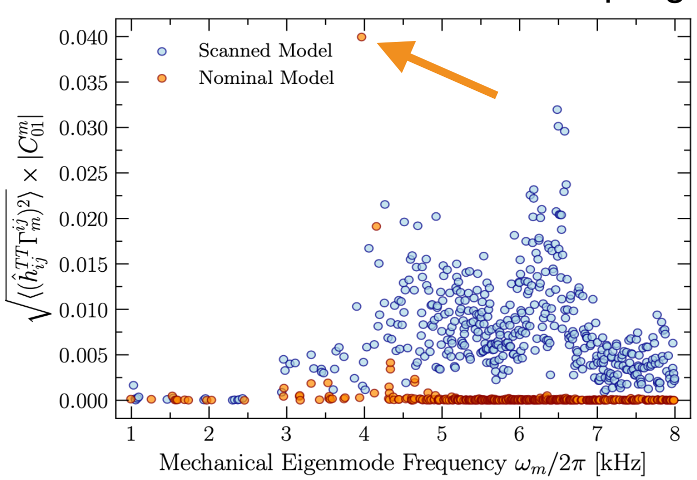
GW-mech coupling



mech-EM coupling



GW-mech * mech-EM coupling



Averaged over direction and polarisation

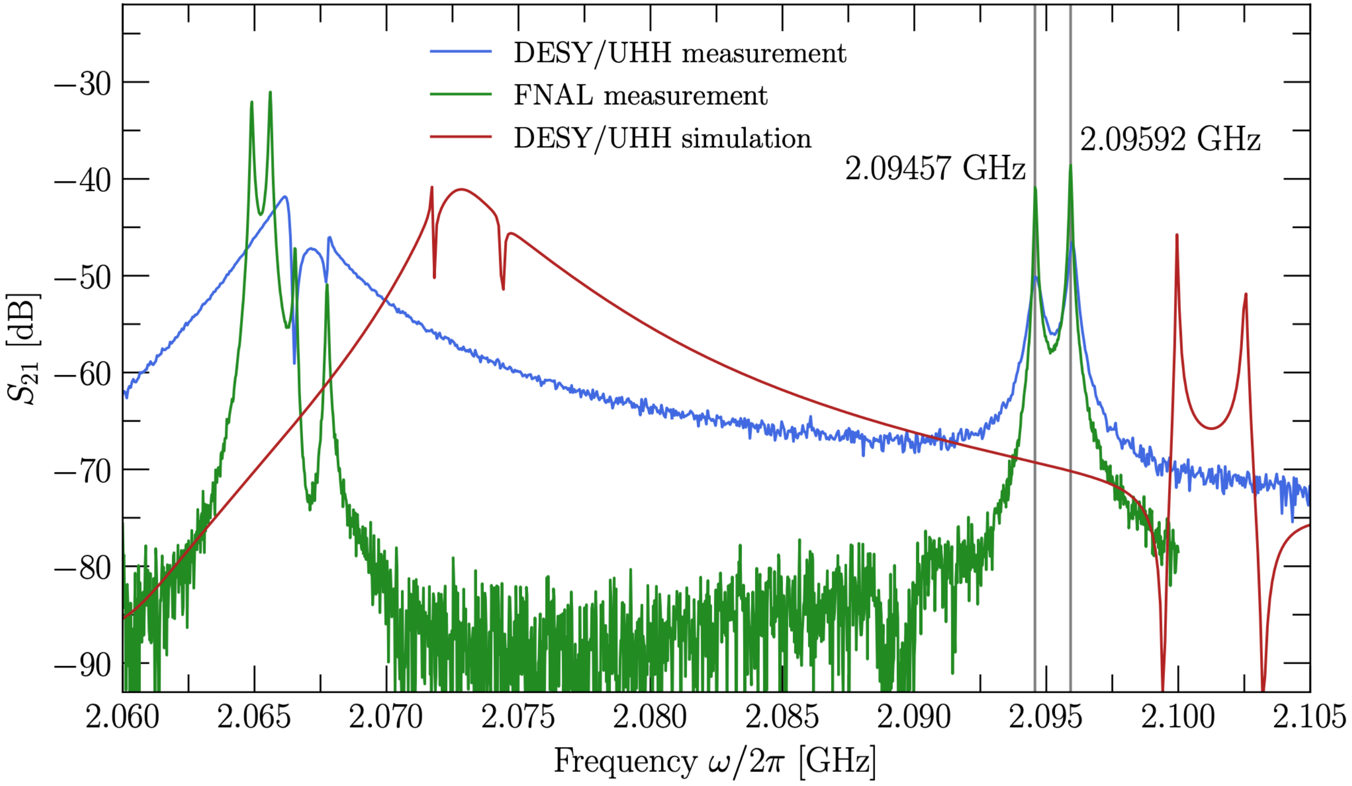
With distorted geometry

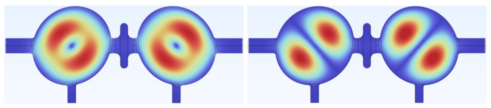
- Several multipoles with quadrupole fractions (otherwise mech-EM coupling zero)
- Suppression of higher modes (which contribute to noise) lost in the distorted detector

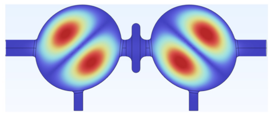
RF measurements worrisome

Not what expected from ideal geometry at room temperature

Transmission spectrum from one cell to the other $\Delta\omega = 1$ MHz







Three TE_{011} pairs of the quasi-degenerate symmetric and anti-symmetric modes visible

Verified with an equivalent circuit simulation: **The eigenfrequencies of the individual cells do not match.** An undesired and unexpected result (remember the coupled pendulum?)

Fisher et al., Class. Quantum Grav. 42 115015 (2025)

Cavity needs mechanical tuning

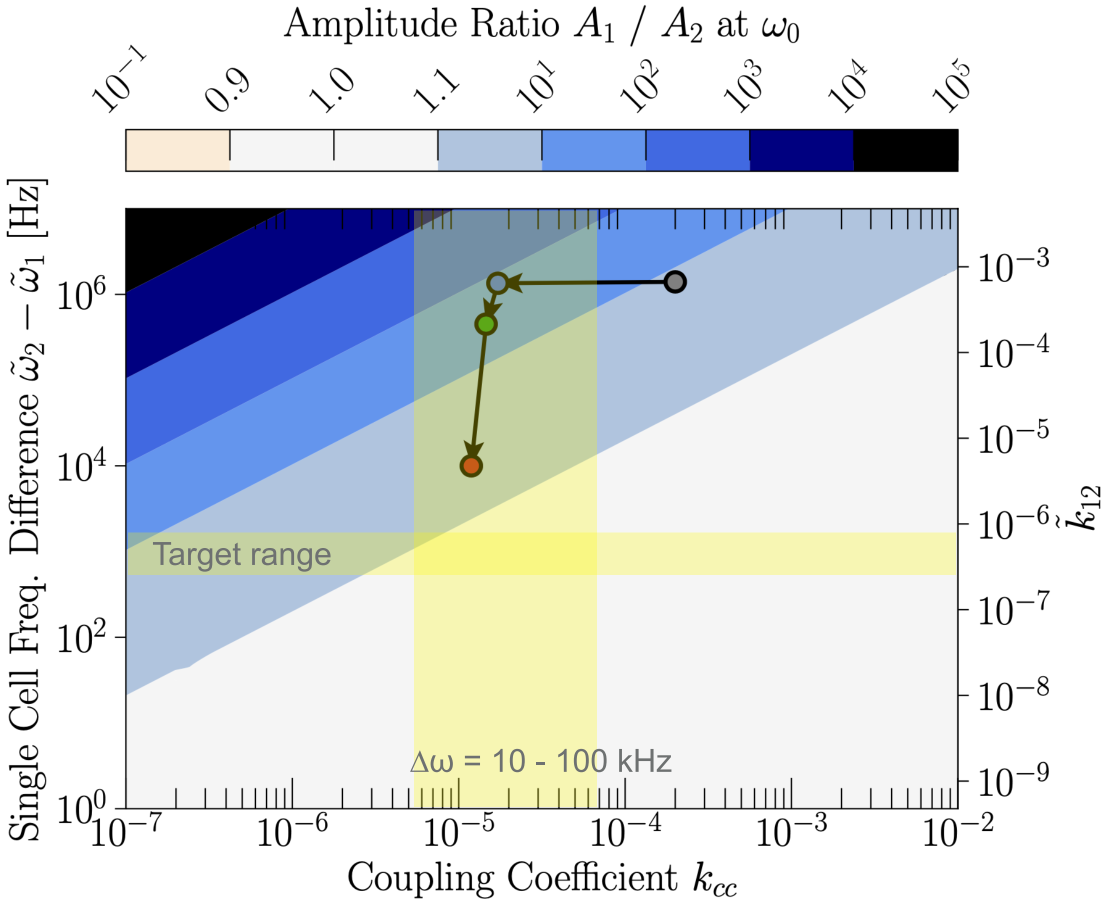
Limit single cell frequency differences

$\Delta\omega = \omega_\pi - \omega_0$ depends on the **tuning cell geometry** (coupling coefficient) and on the **single cell frequency difference**

Single cell frequency differences introduce a **large amplitude difference** between the two cells which limits the sensitivity

Need to tune cavity cells to achieve wanted Δω

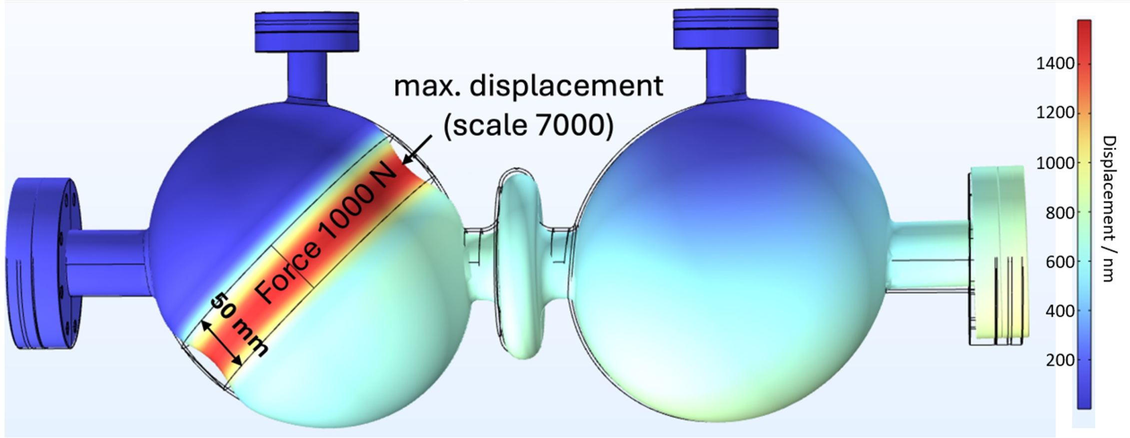
Some degree of tuning is practically unavoidable, even for newly fabricated cavities. (For GHz cells, a relative difference in the radii 0.1 % will already lead to Δω = 1 MHz)

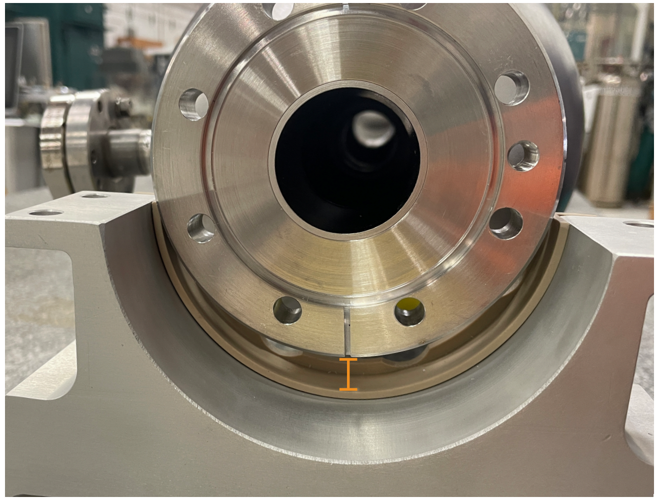


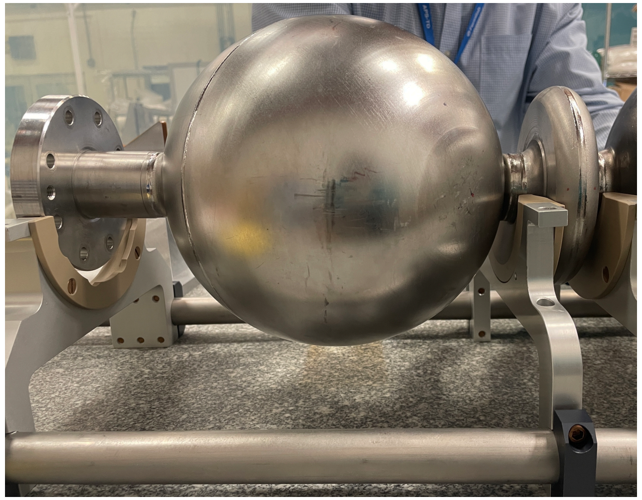
Cavity Inelastic Tuning at Room Temperature

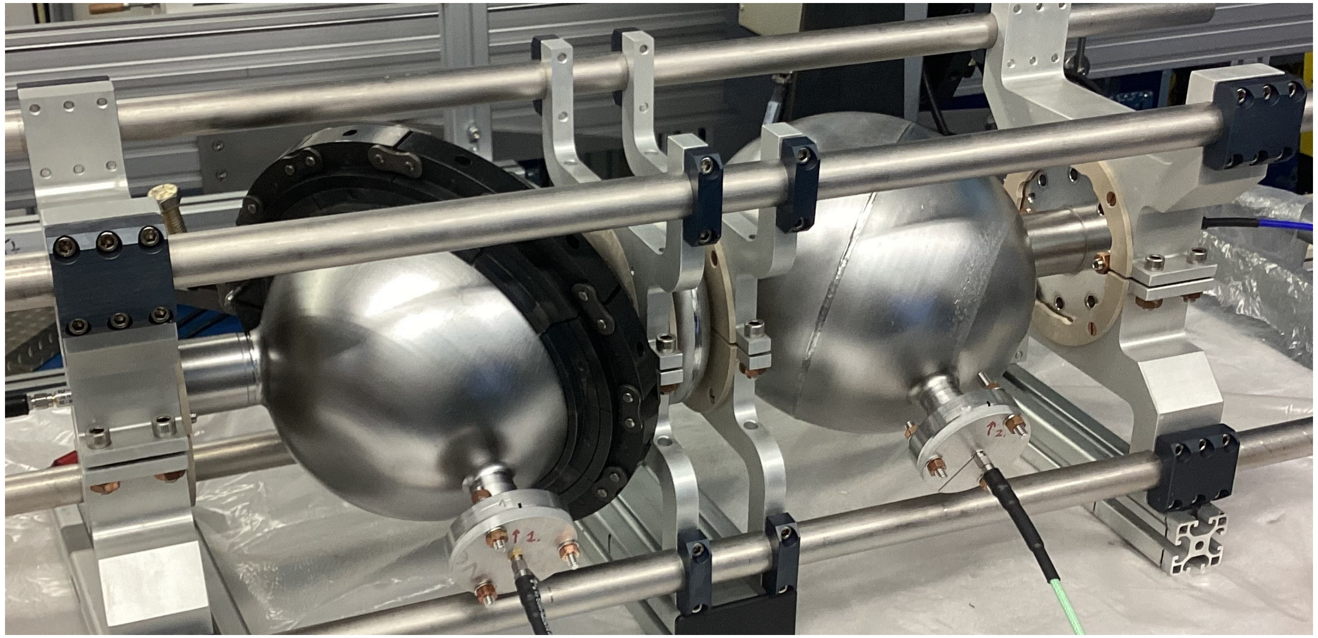
Straightening and Frequency Tuning

- First straighten cavity to eliminate bend and fit in mechanical frame that will be used for all following steps to support and constrain the cavity
- Then install chain tuner and slowly compress lowest frequency cell. Alternate compression and relaxation to assess elastic vs inelastic tuning. Repeat until cells frequency is matched (within limits of RT measurement)



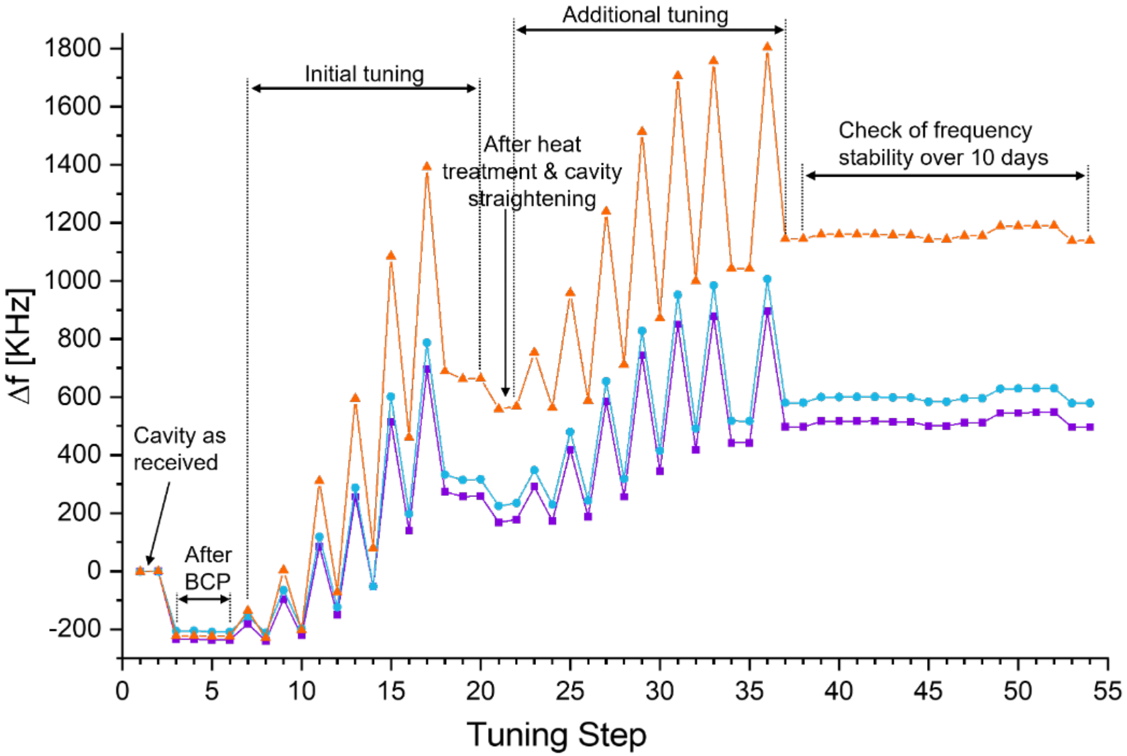




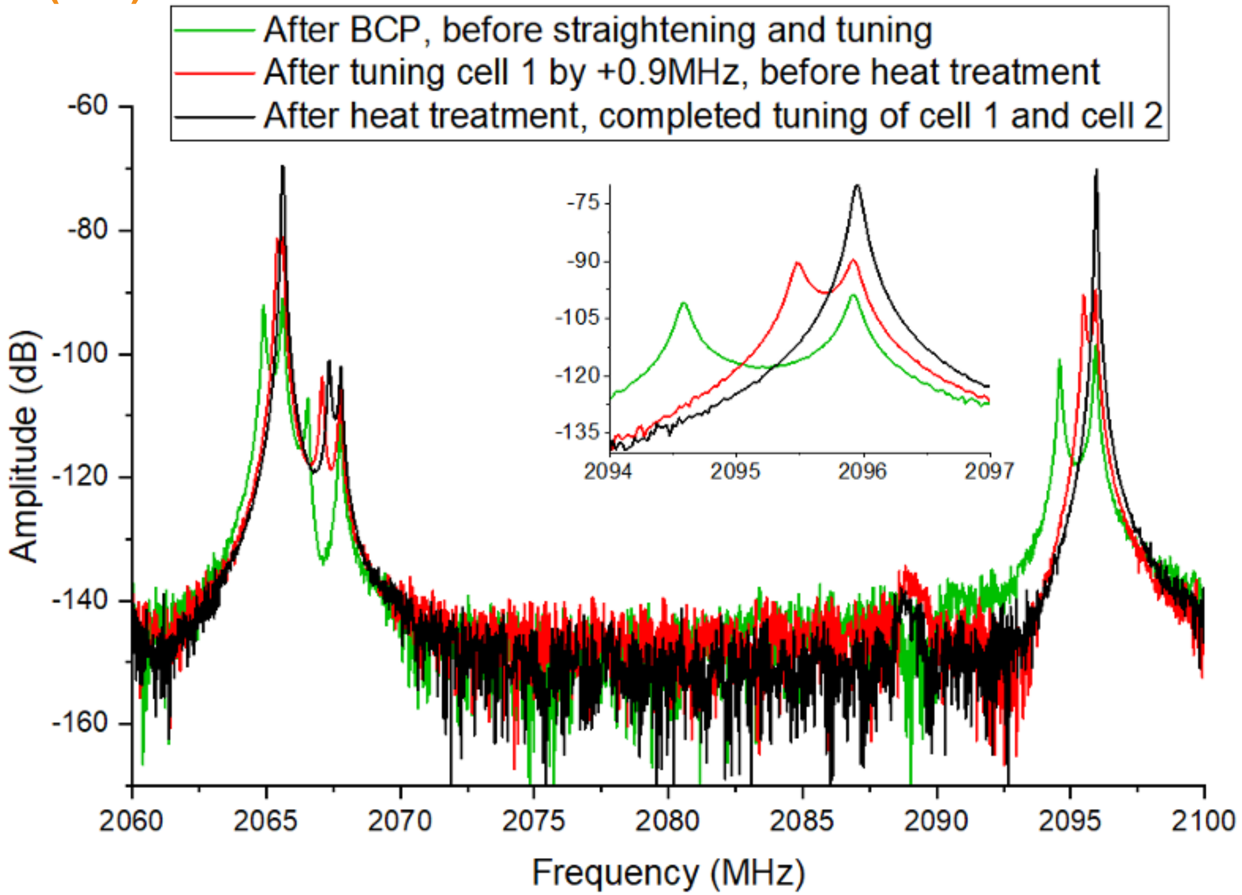


Cavity Frequency History and Final Room Temperature Results

Achieved frequency difference at room temperature ≈ (4-7) kHz

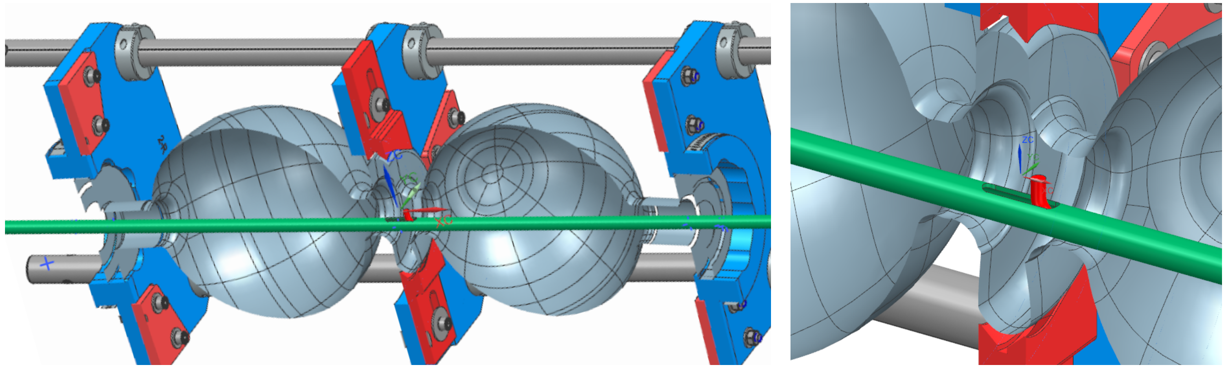


Frequency history of the cavity at room temperature. Tuning pattern of compression and relaxation is clearly visible.

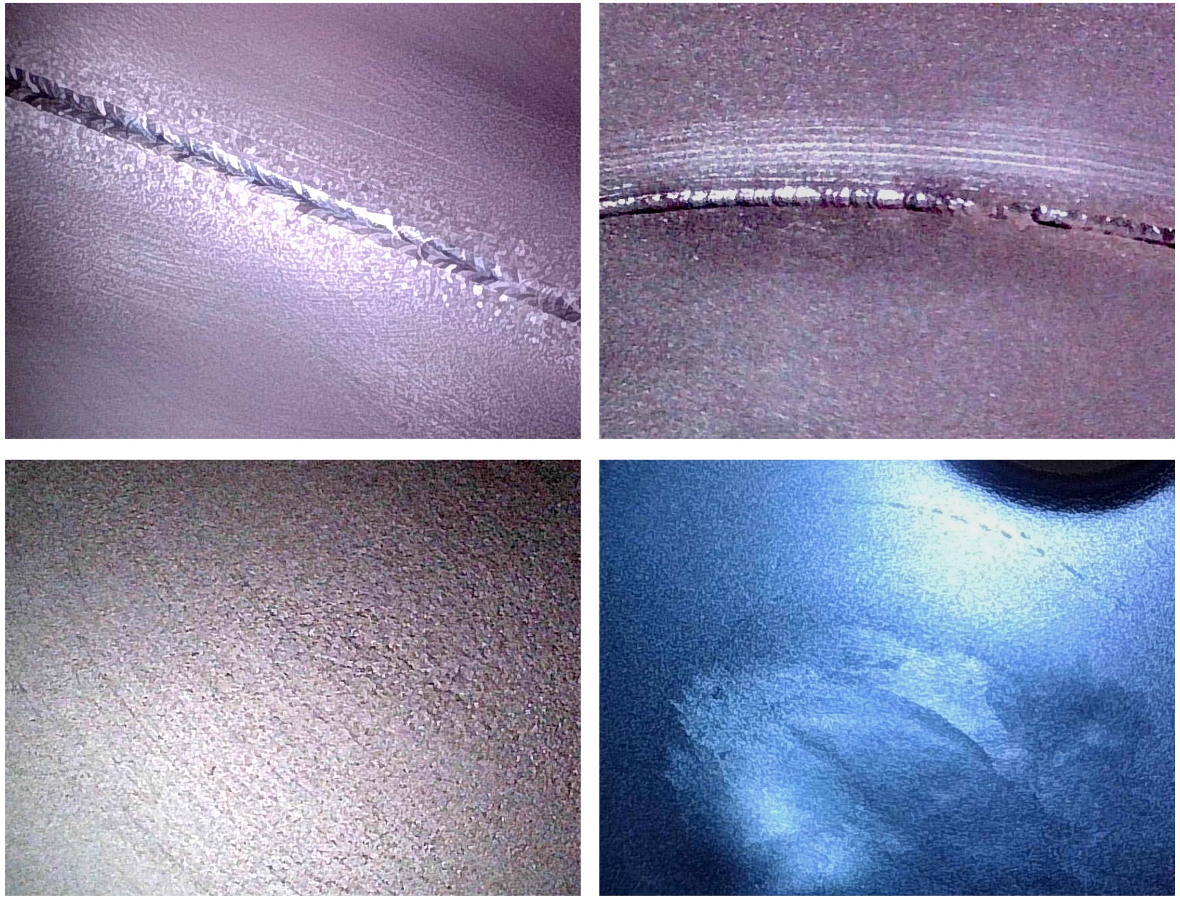


RF spectrum at room temperature at different steps of the cavity frequency history. After tuning the two peaks appear as one due to the broad RT bandwidth.

Cavity Surface Inspection



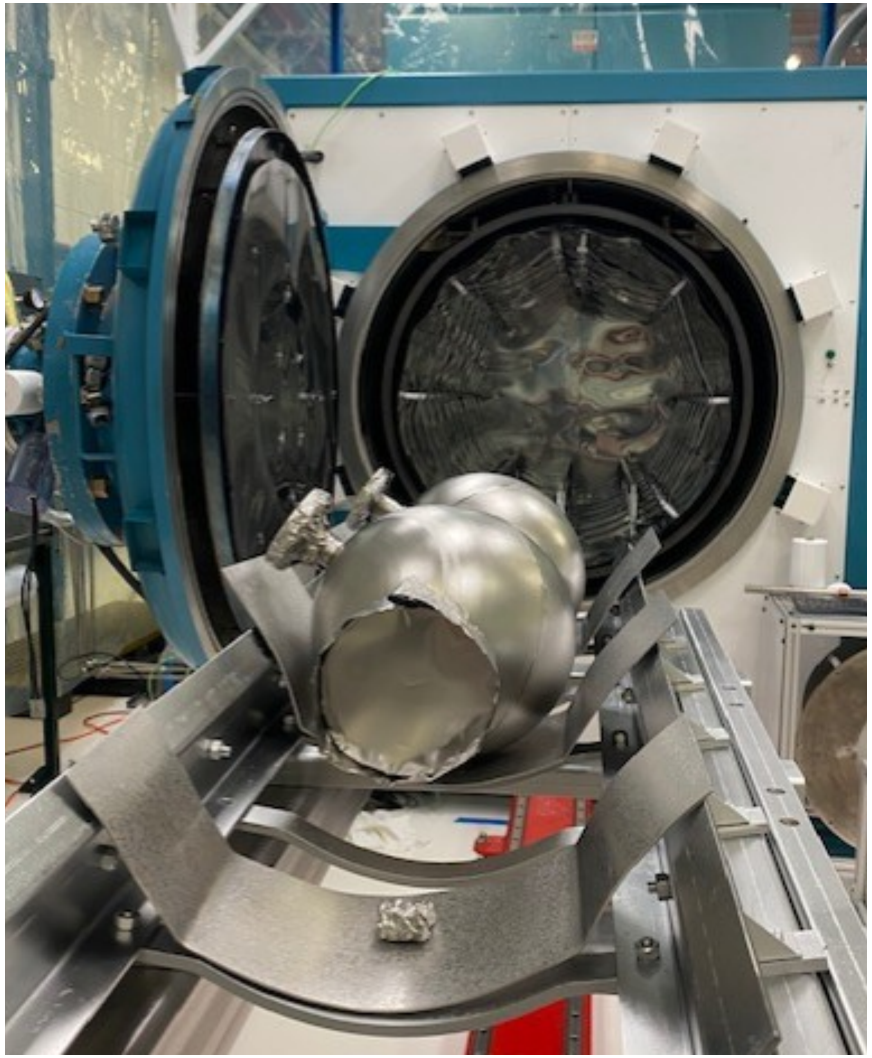
- Typical Optical Inspection tool was not compatible with this cavity
- Used Boroscope supported via rigid wand to photograph inner surface
- Found several imperfections (dents) and remaining traces of fabrication on the surface such as scratches and rolling marks
- Normally fabrication is followed by bulk EP/BCP to remove damaged layer → here probably not conducted yet



Cavity Surface Processing

Surface Removal and Heat Treatment

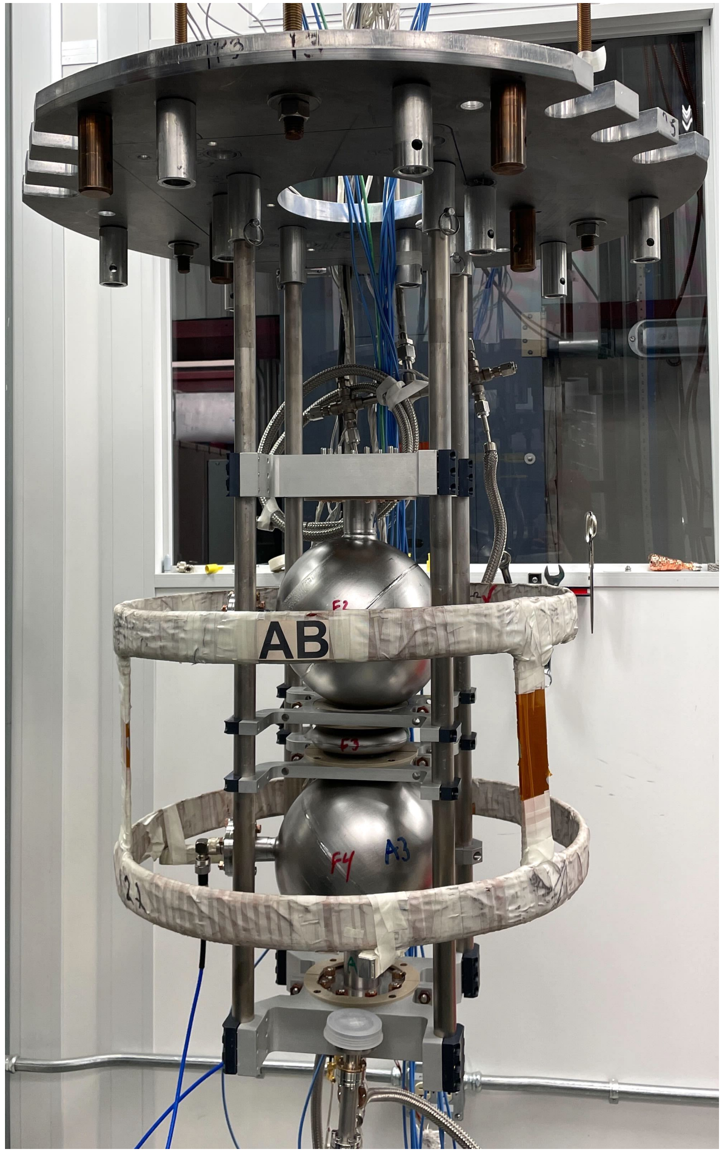
- Conducted only flash BCP (few um) at ANL to avoid further decreasing the thickness of the coupling cell (already <1mm thick!)
- Heat treatment applied to degass (remove hydrogen from the surface) and to relieve internal stresses introduced by the fabrication
- Heat treatment temperature limited to 600C due to stainless steel flanges to prevent contamination of cavity and furnace



First RF Cold Test

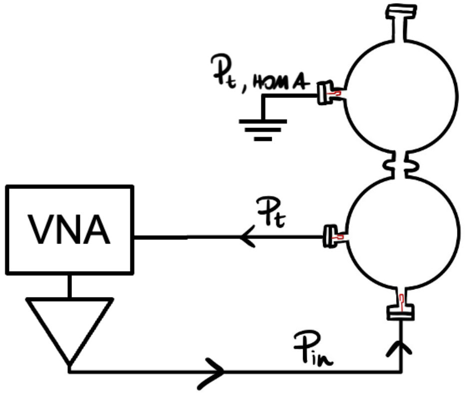
Preparation and plan

- RF setup oriented for cavity characterization, not for search
  - 1 input coupler (critical coupling), 2 pick up antennas (weak coupling)
- Goals:
  - Track frequency behavior during cooldown (thermal and pressure effects)
  - Characterize cavity performance (Q vs U)
  - Measure microphonics in the cryogenic environment

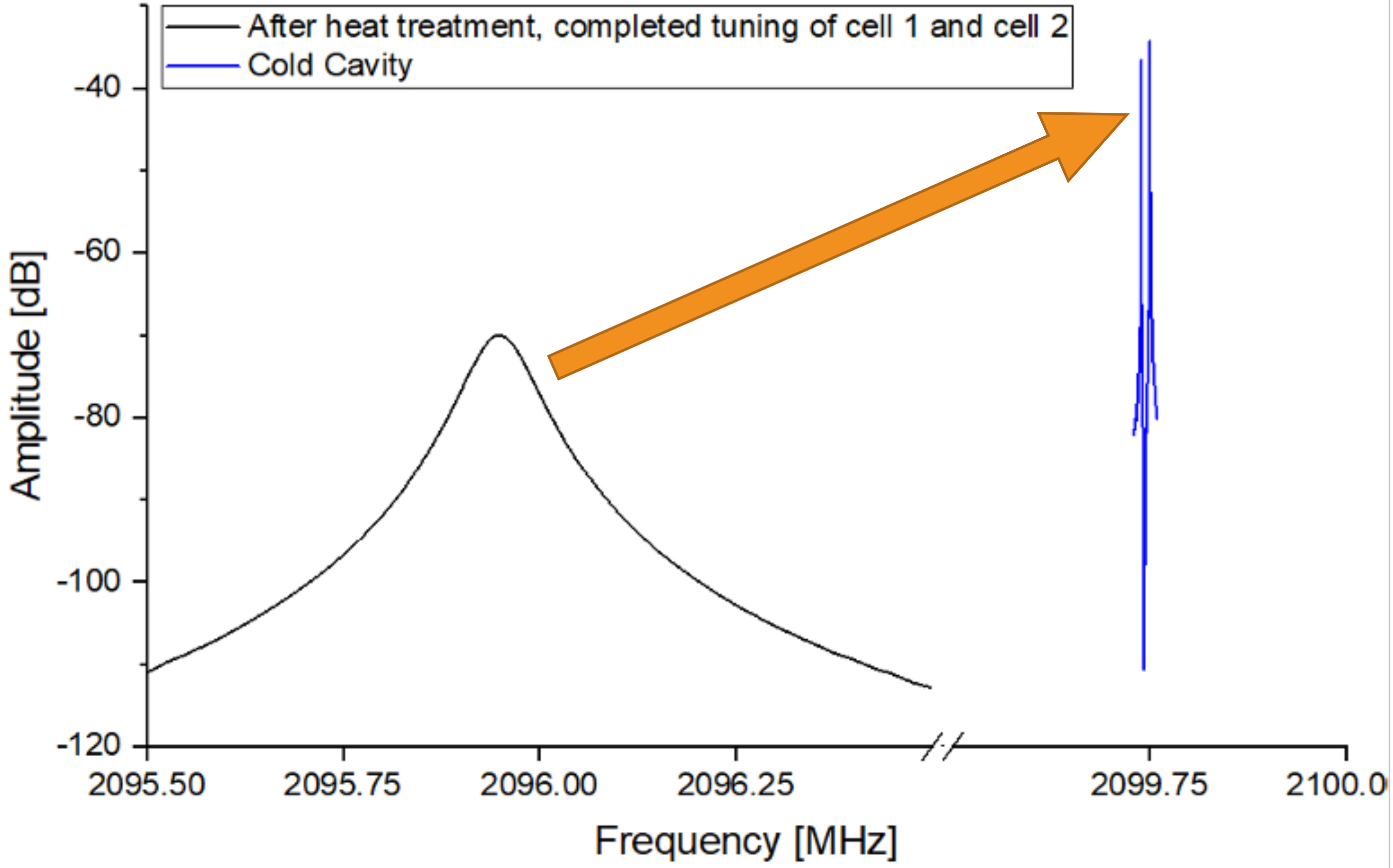


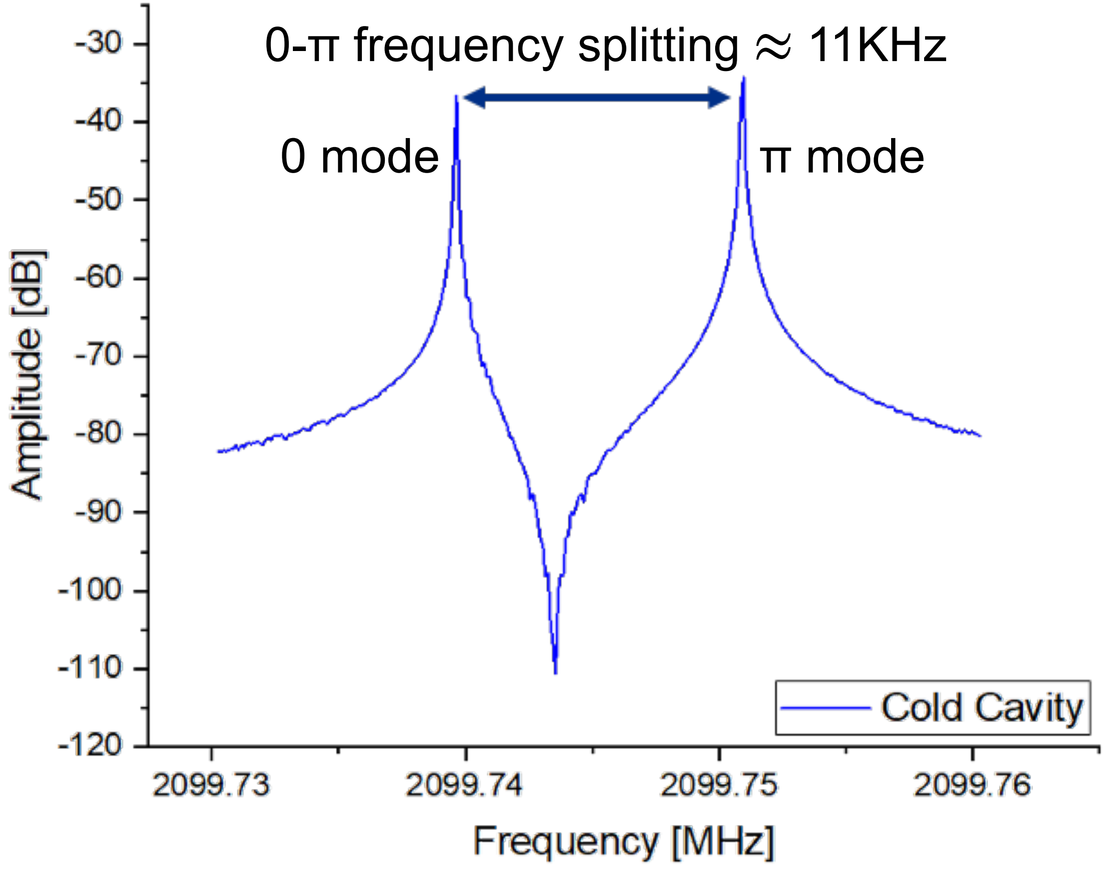
First RF Cold Test

Frequency Behavior



Once the cavity becomes superconducting, we can see the modes' BW decreases and the modes split!

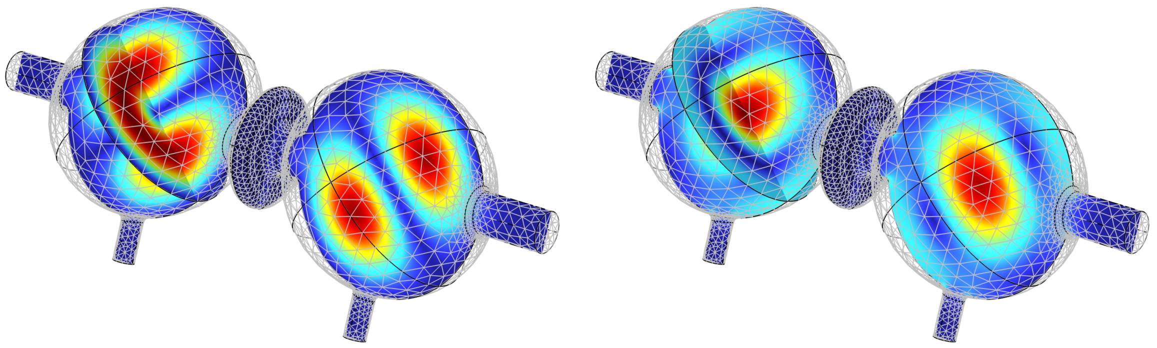


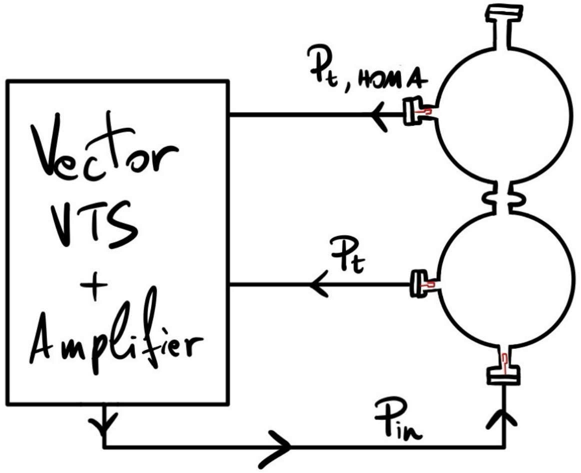


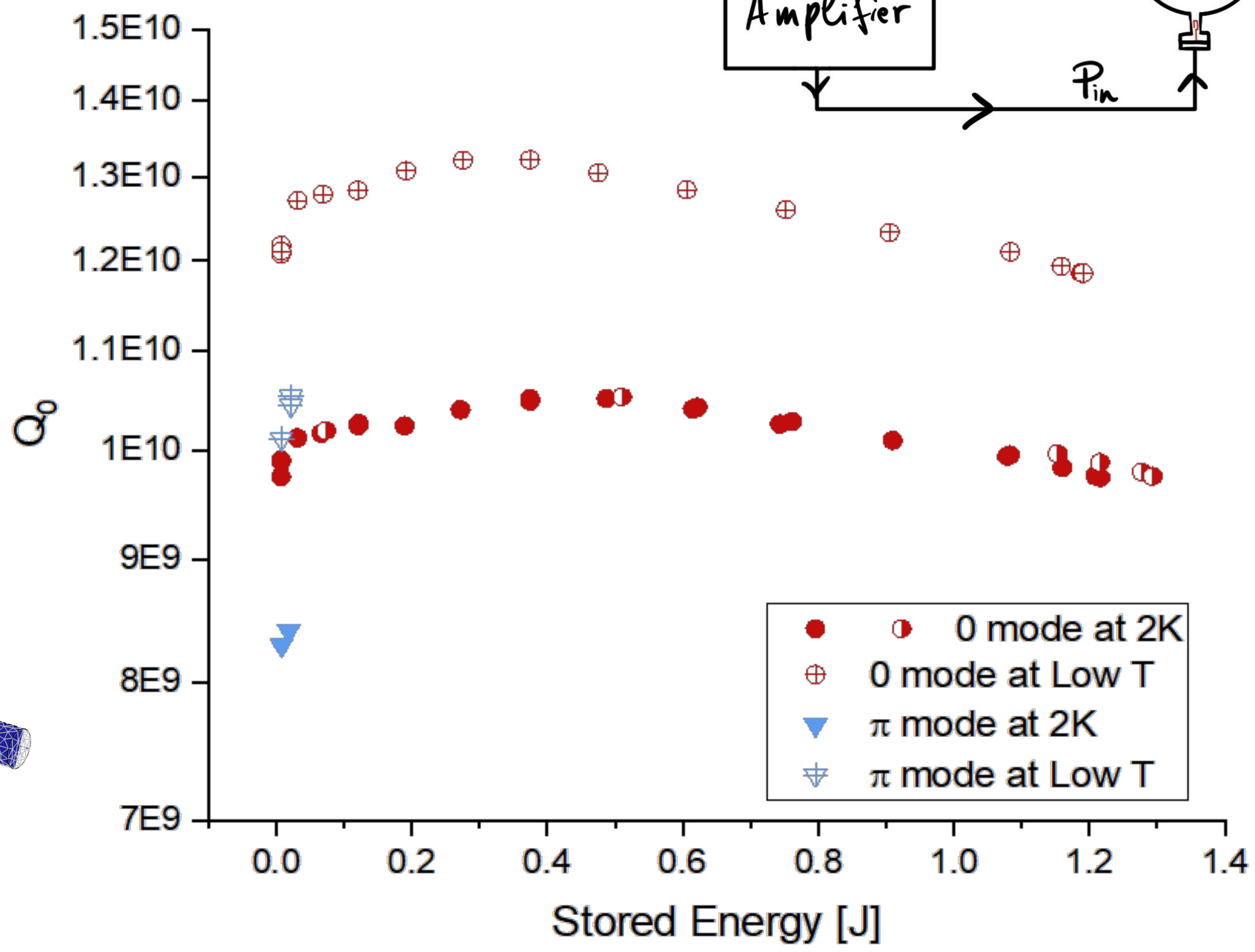
First RF Cold Test

Q vs U Results

- Ultrahigh-Q cavities → ultranarrow bandwidth: need frequency/phase tracking to remain on resonance with cavity (PLL or other methods)
- Despite surface imperfections cavity quality factor $Q_0 \approx 1 \times 10^{10}$ at 2 K (high Geometric Factor $\approx 800\ \Omega$ and low surface fields)
- Cavity quenched at lower U value than hoped → probably due to surface defects?







First RF Cold Test

Q vs U comparison with previous PACO prototype

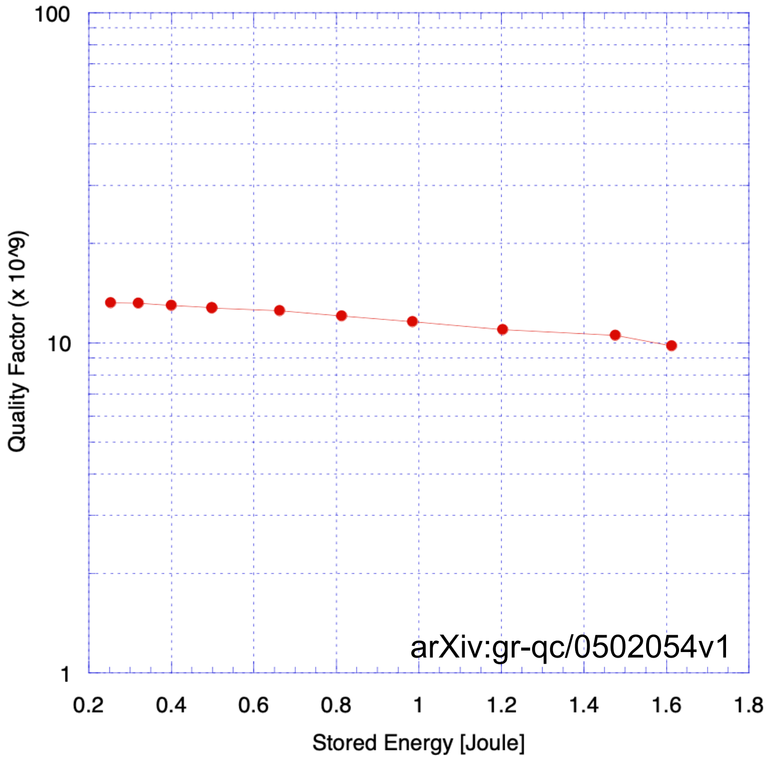
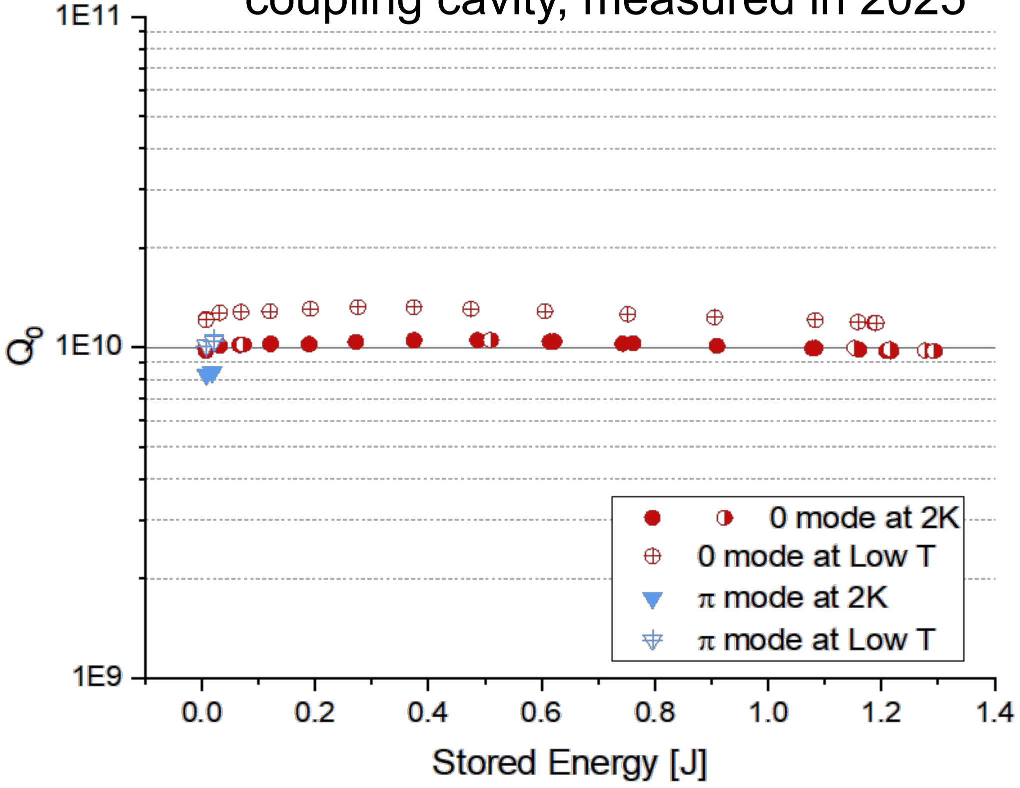
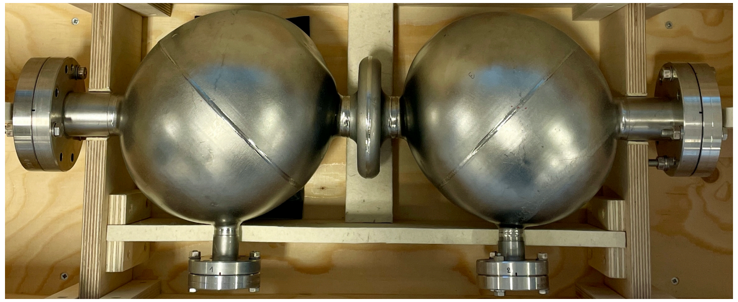


FIG. 11: Quality factor vs. stored energy for the fixed–coupling cavity

Quality factor vs Stored Energy for the variable coupling cavity, measured in 2025

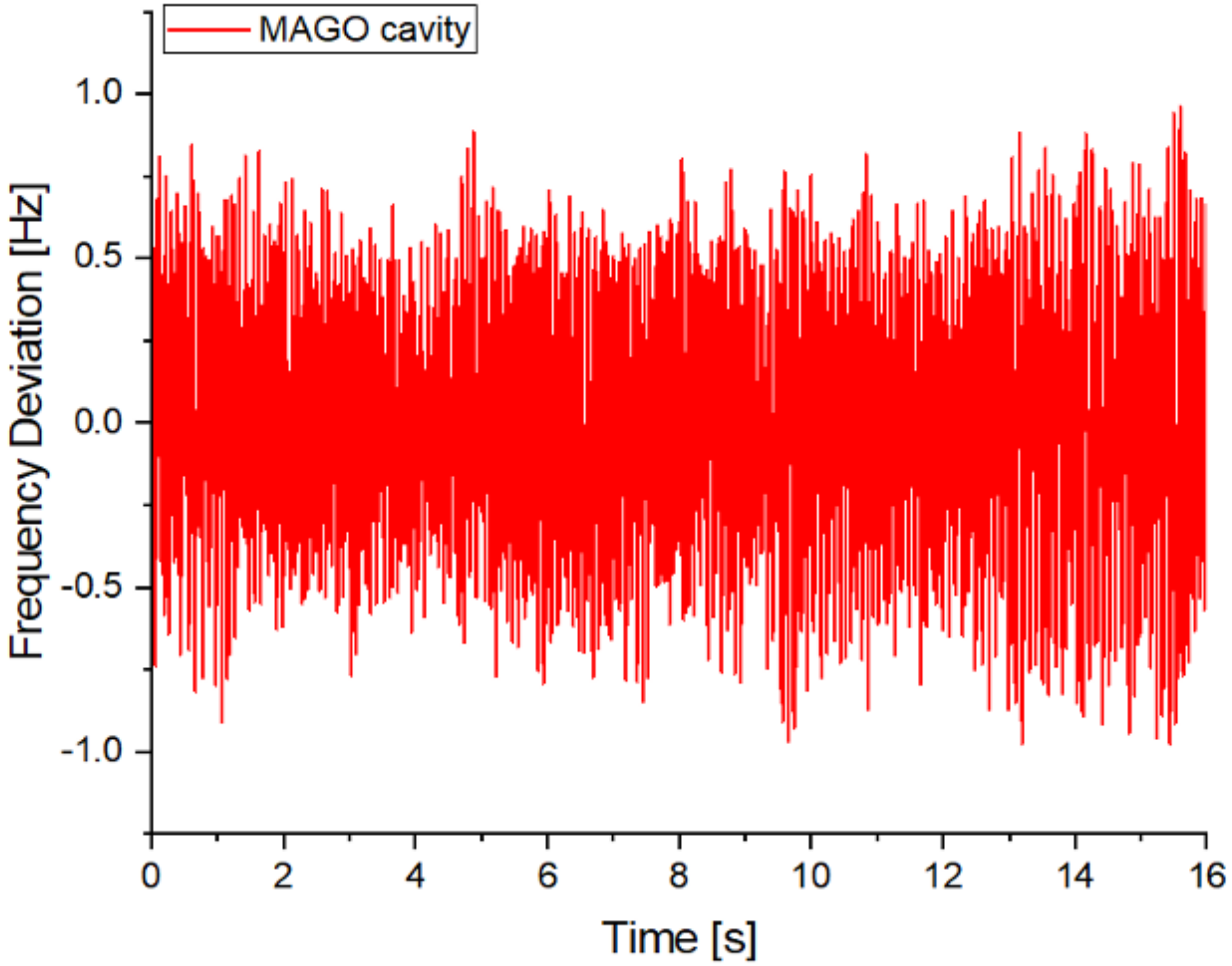




First RF Cold Test

Microphonics

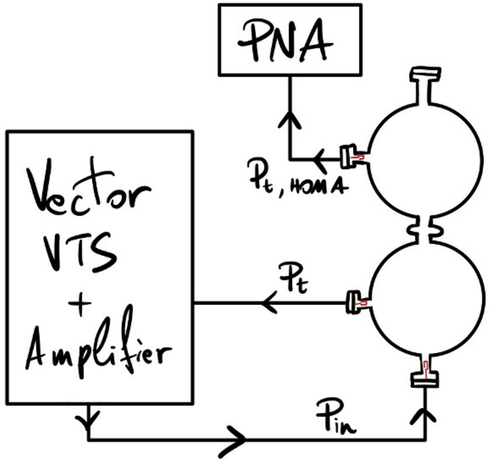
- Cavity is powered and frequency locked
- Here: pump mode is excited to max stored energy below quench value
- We measure frequency vs time signal to evaluate microphonics → frequency fluctuations that can be caused by:
  - External vibrations (ground motions, cryo pumps, etch)
  - Helium pressure fluctuations and dissipation induced perturbations
  - Mechanical resonances

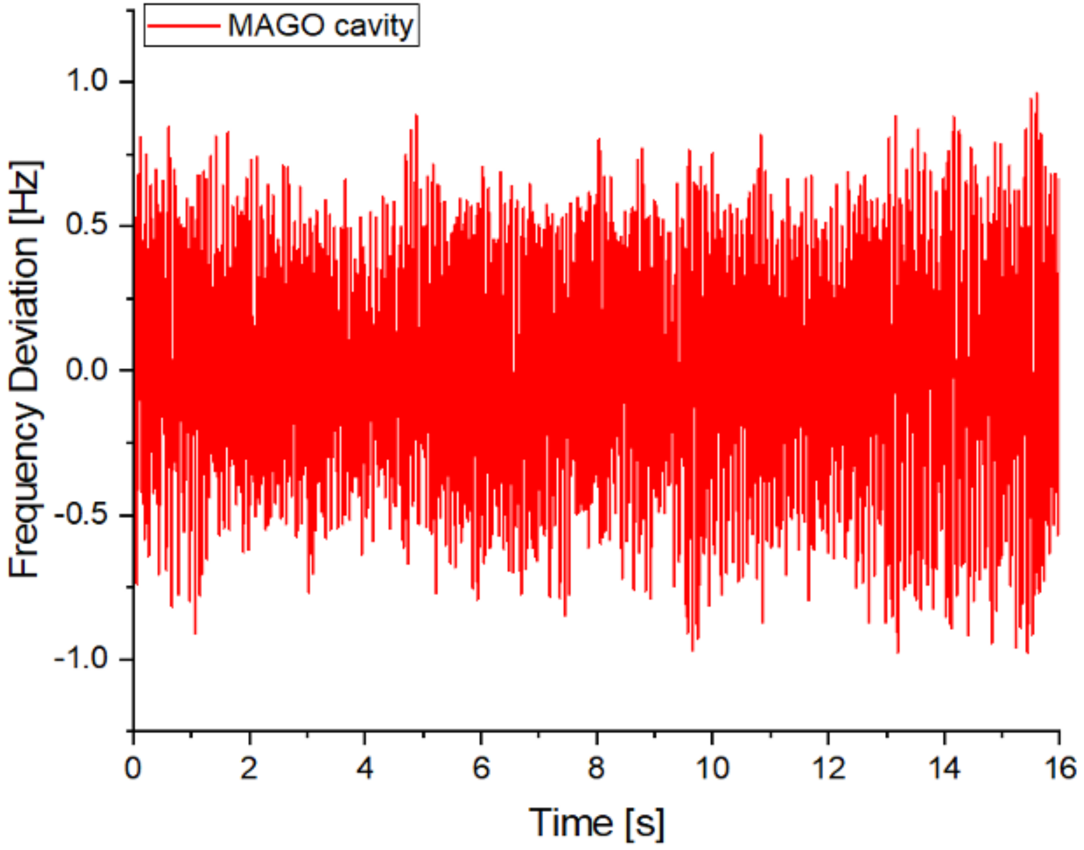


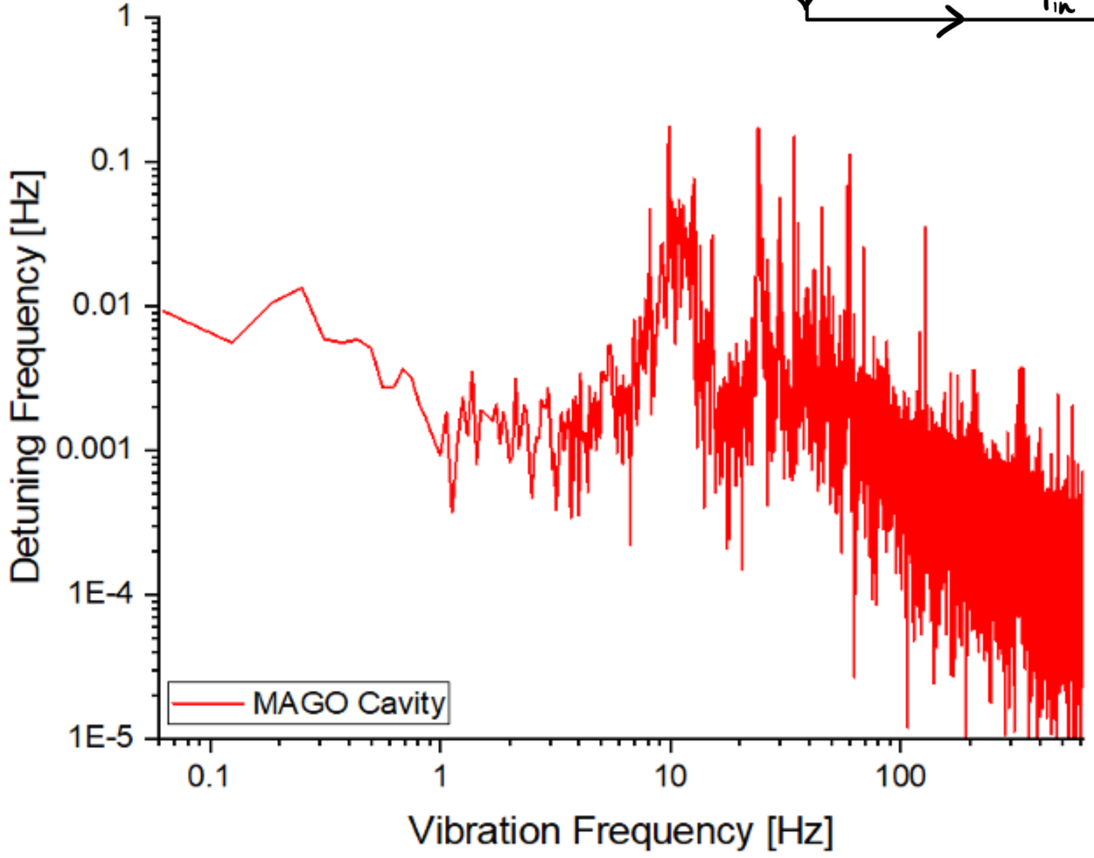
First RF Cold Test

Microphonics (2)

- FFT of the f vs t signal contains info on the frequency of the perturbation and amplitude of the jittering



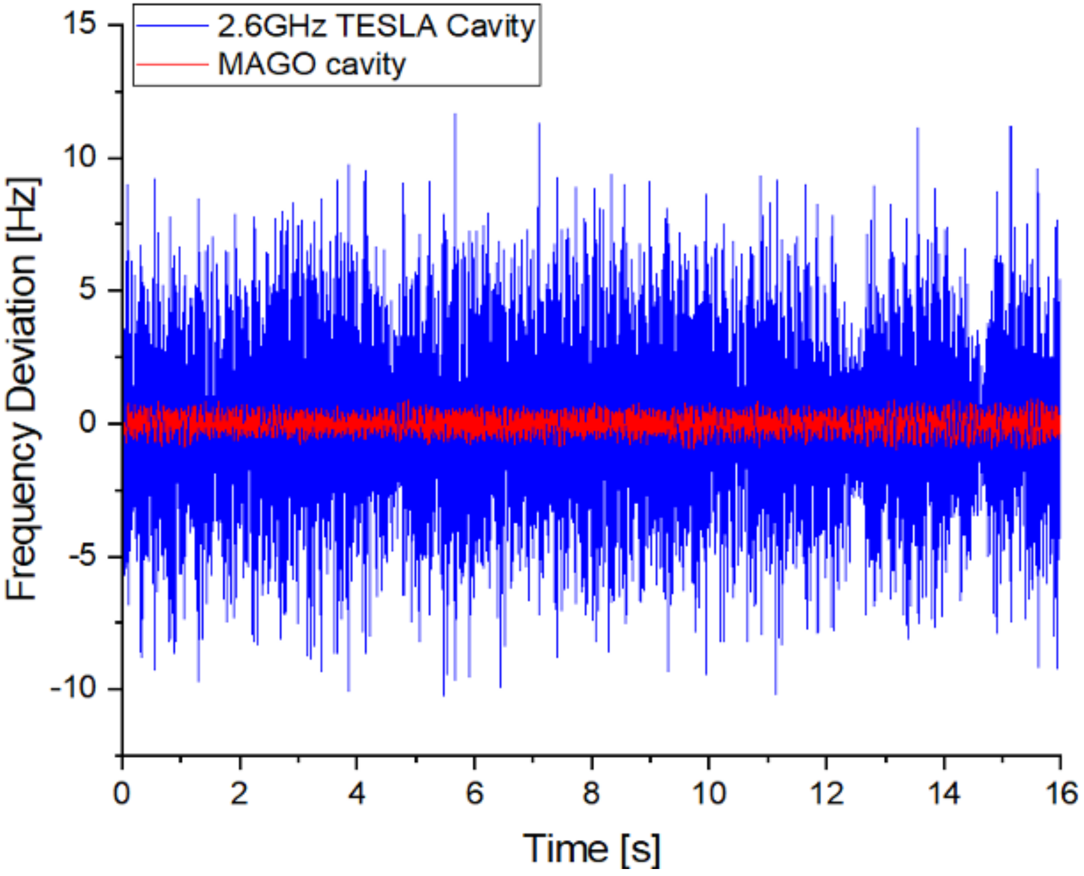




First RF Cold Test

Microphonics (3)

- Microphonics measured on MAGO vs on 2.6GHz TESLA-shaped cavity in same cryogenic environment, at the same temperature, using same instrument (PNA) and measurement parameters
- Cavities were excited using different LLRF system and at different values of stored energy
- 2.6GHz measured RMS (60Hz peak removed): 2.44Hz
- MAGO measured RMS (60Hz peak removed): 0.34Hz
- If DESY test will confirm order of magnitude smaller microphonics compared to TESLA cavity → impact on the expected sensitivity!
  - Berlin et al., Phys. Rev. D 108, 084058 (2023) uses microphonics estimate from Dark SRF 1.3GHz (see Pischalnikov et al., 10.18429/JACoW-SRF2019-TUP085 (2019) and Romanenko et al., Phys. Rev. Lett. 130, 261801 (2023)) with RMS 3.1Hz.



Cryogenic tests for LLRF system development

4k tests at DESY for two weeks

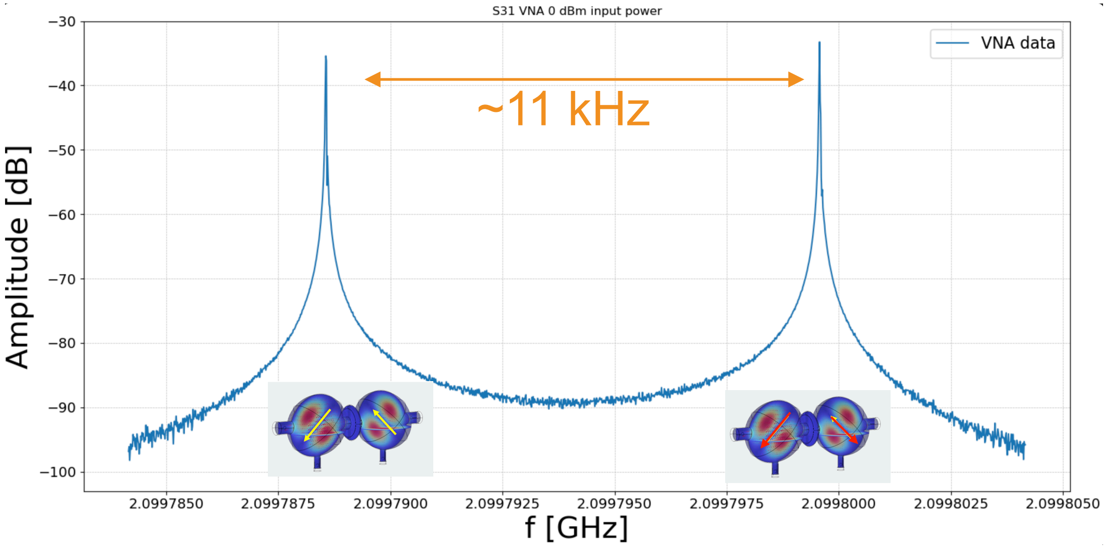
Test stand and power amplifier had to be modified from 1.3 to 2.1 GHz

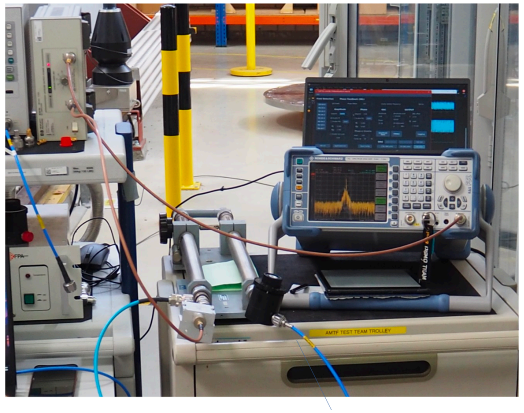
New LOGM (local oscillator generation module) had to be designed for the LLRF system

New firmware and software for the LLRF system to operate and read the signal at 2.1 GHz in closed loop mode

- Achieved frequency tracking
- Next steps include implementing amplitude and phase feedback to further stabilise the system

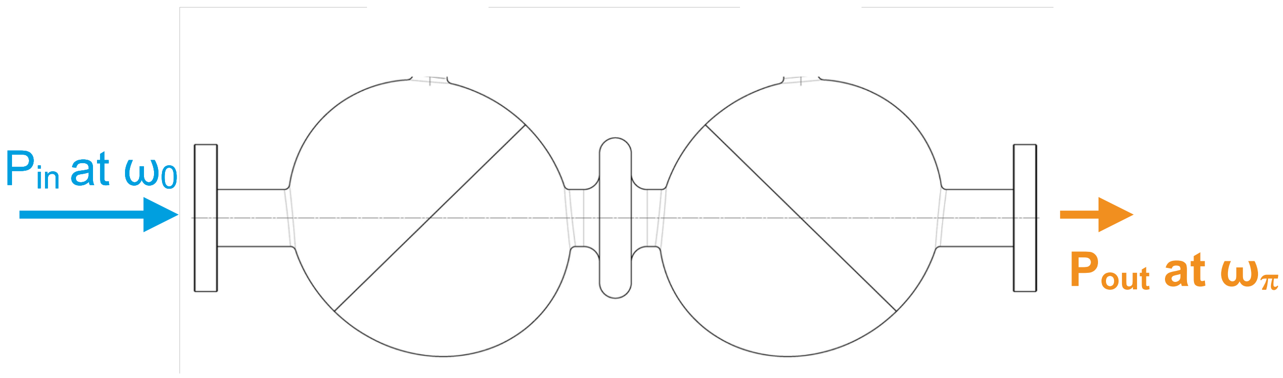
Implement and test first versions of carrier suppression





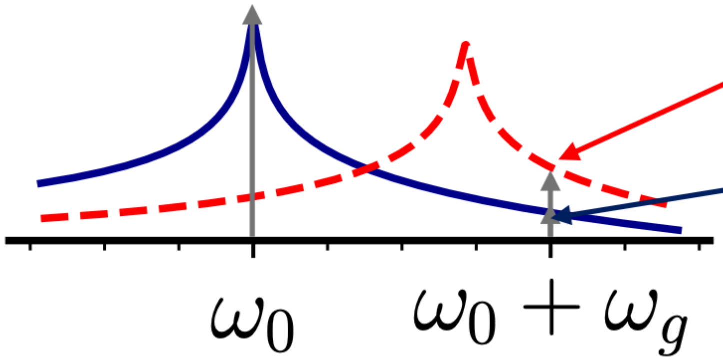
Phase noise from pump mode oscillator

Would be the dominant noise for most parameter space



Pump & Signal mode have same field distributions

⇒ Any antenna couples to both mode the same

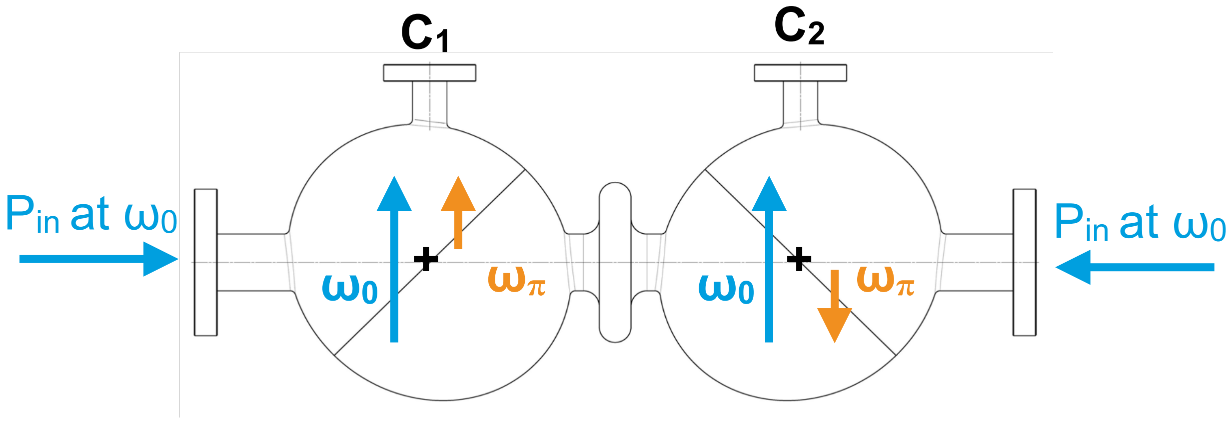


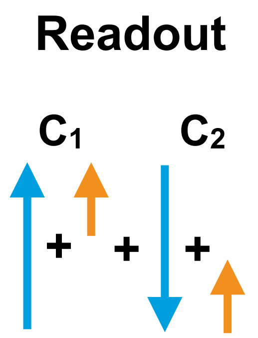
Oscillator accidentally drives signal mode at $\omega_0 + \omega_g$

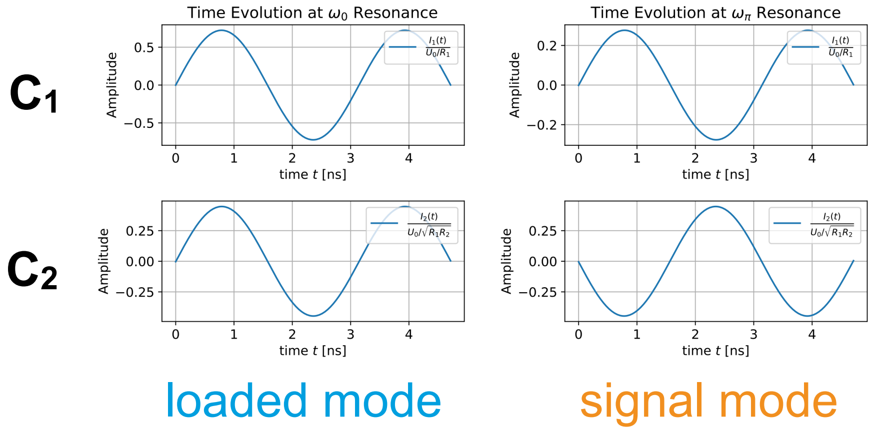
Readout accidentally picks up pump mode at $\omega_0 + \omega_g$

Additional degree of discrimination

Phase difference in signal







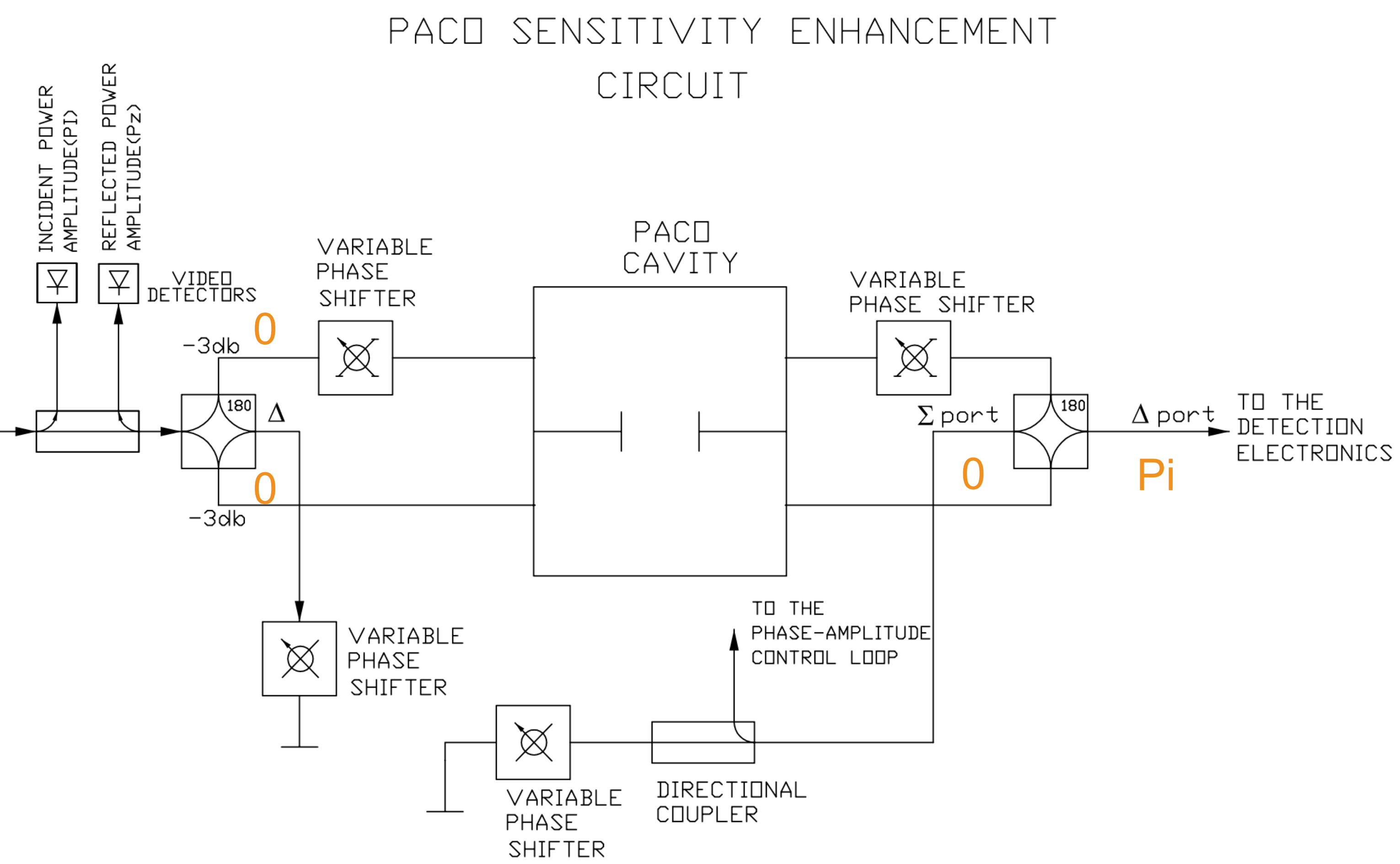
Symmetric loading to suppress signal mode

Shift phase of one cell by π in readout

Loaded mode cancels, signal mode amplified

RF control and detection system for PACO

Pillbox cavity from MAGO collaboration



Two cells loaded in phase to suppress signal mode drive

Readout from two cells with 180 degree phase shift to cancel pump mode

Pump mode from the readout reflected back to cavity (but adds noise?)

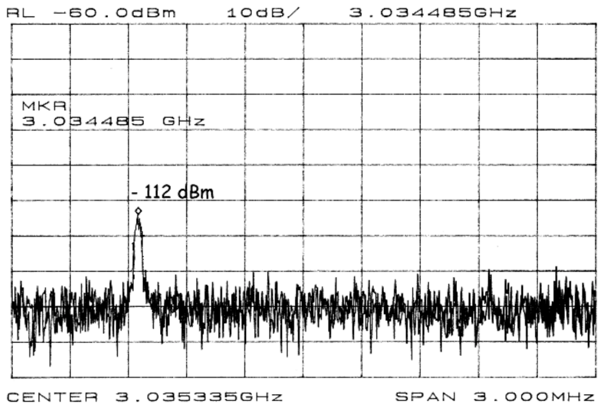
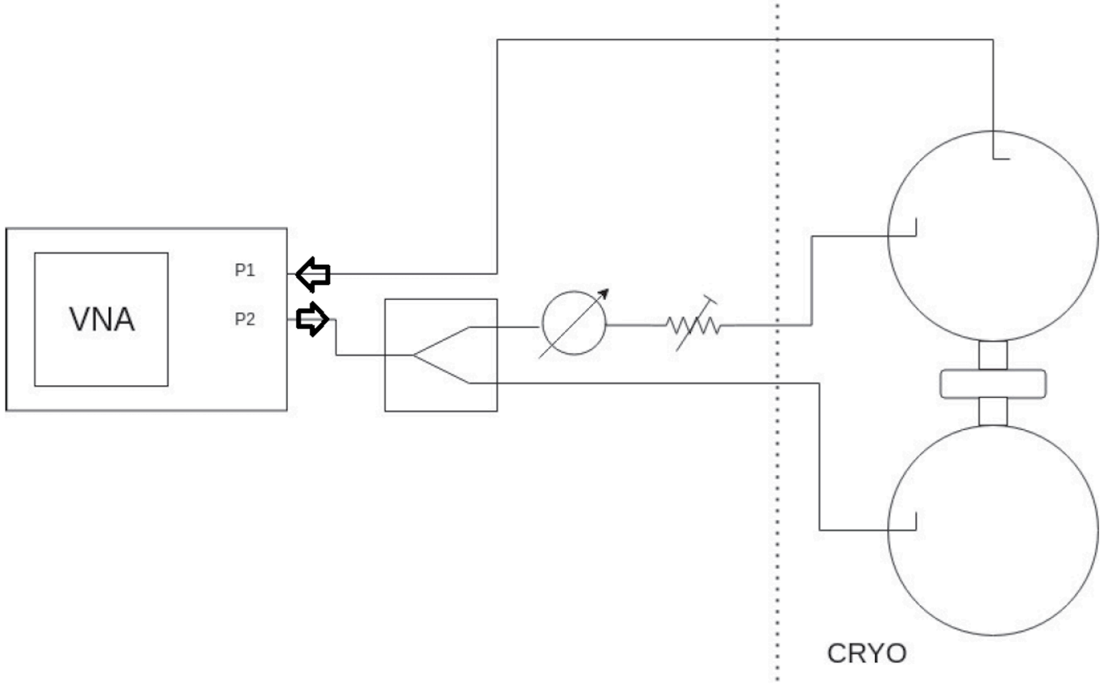
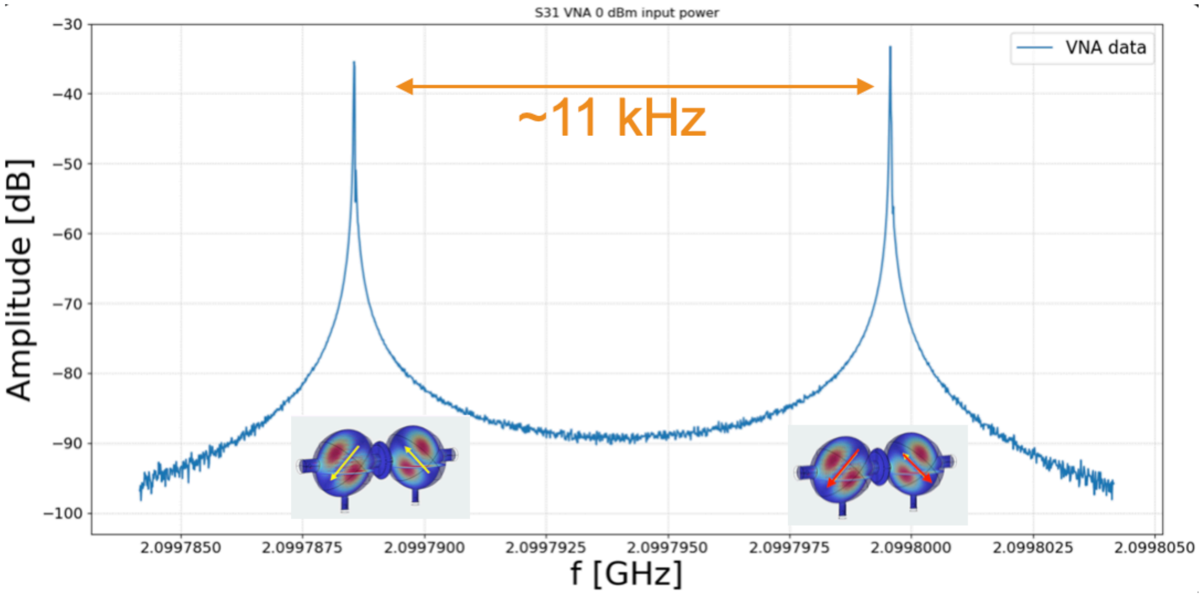


Figure 4. Transmission of the symmetric mode in the optimised system (1 kHz resolution bandwidth; piezo off).

VNA tests

PACO detection scheme (separately for drive and readout)

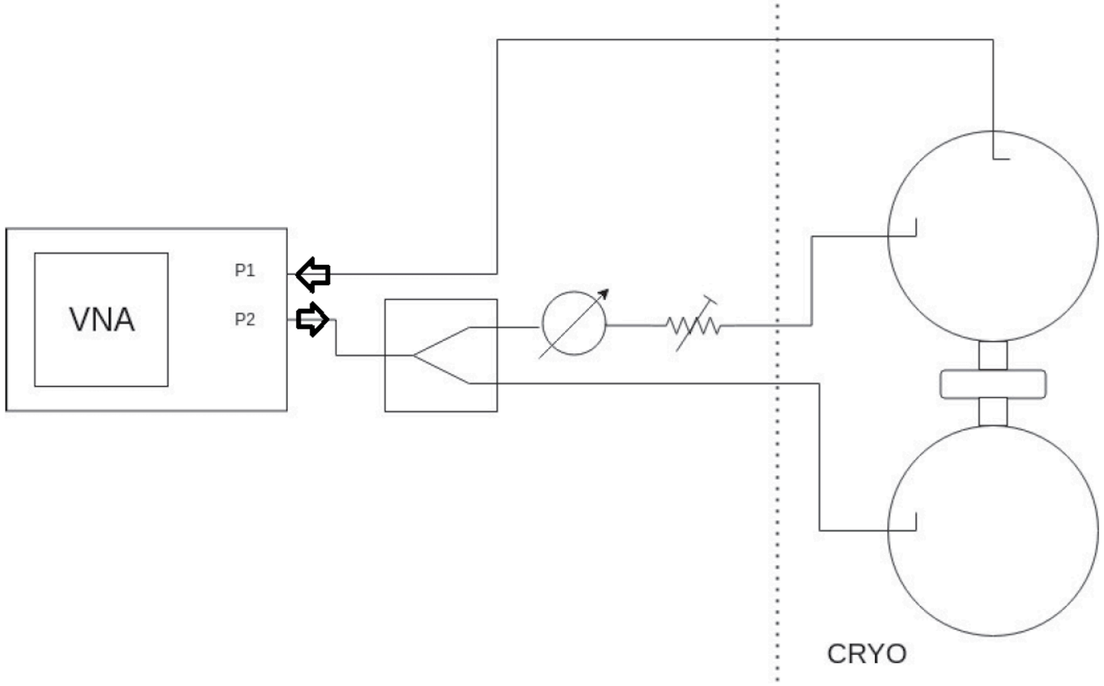


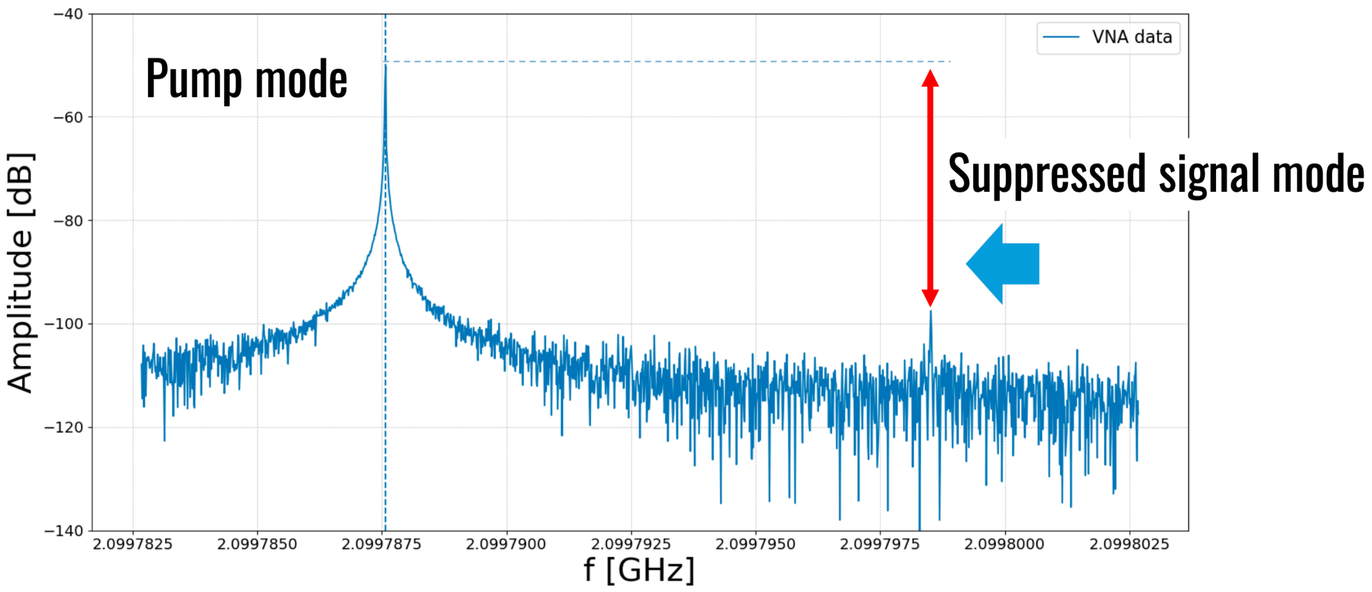


Mode rejection scheme for the input signal with a non optimized setup lead a 50 dB suppression of the signal mode using a VNA

VNA tests

PACO detection scheme (separately for drive and readout)





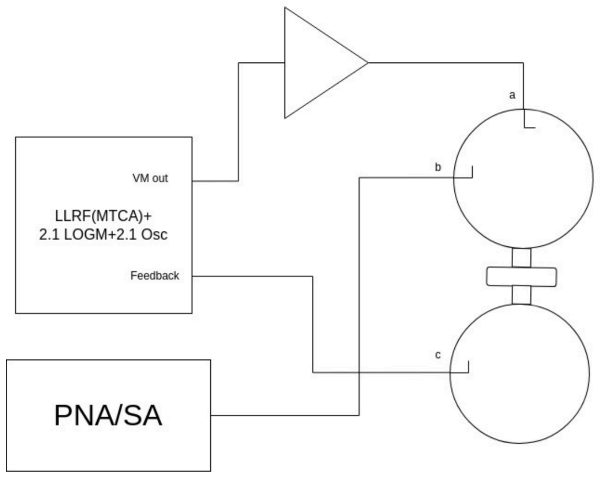
Mode rejection scheme for the input signal with a non optimized setup lead a 50 dB suppression of the signal mode using a VNA

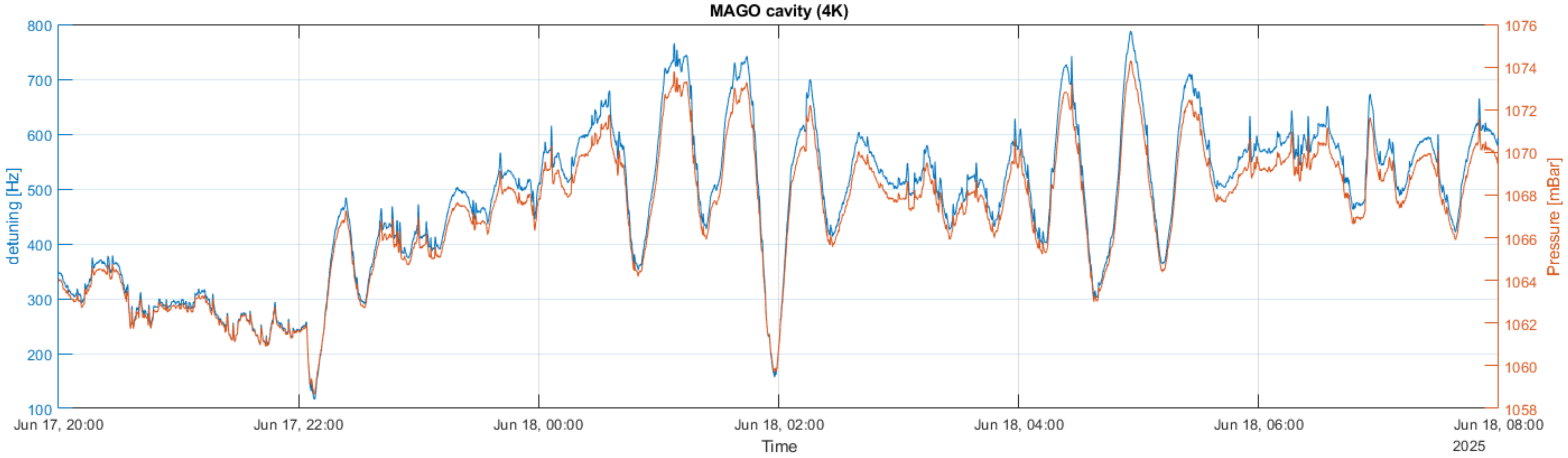
Frequency tracking configuration

Big step towards a functioning LLRF system

Large pressure variations in the cryostat lead to significant frequency change of the pump mode

Tracking the cavity for 13 hours. Frequency tracking works well!

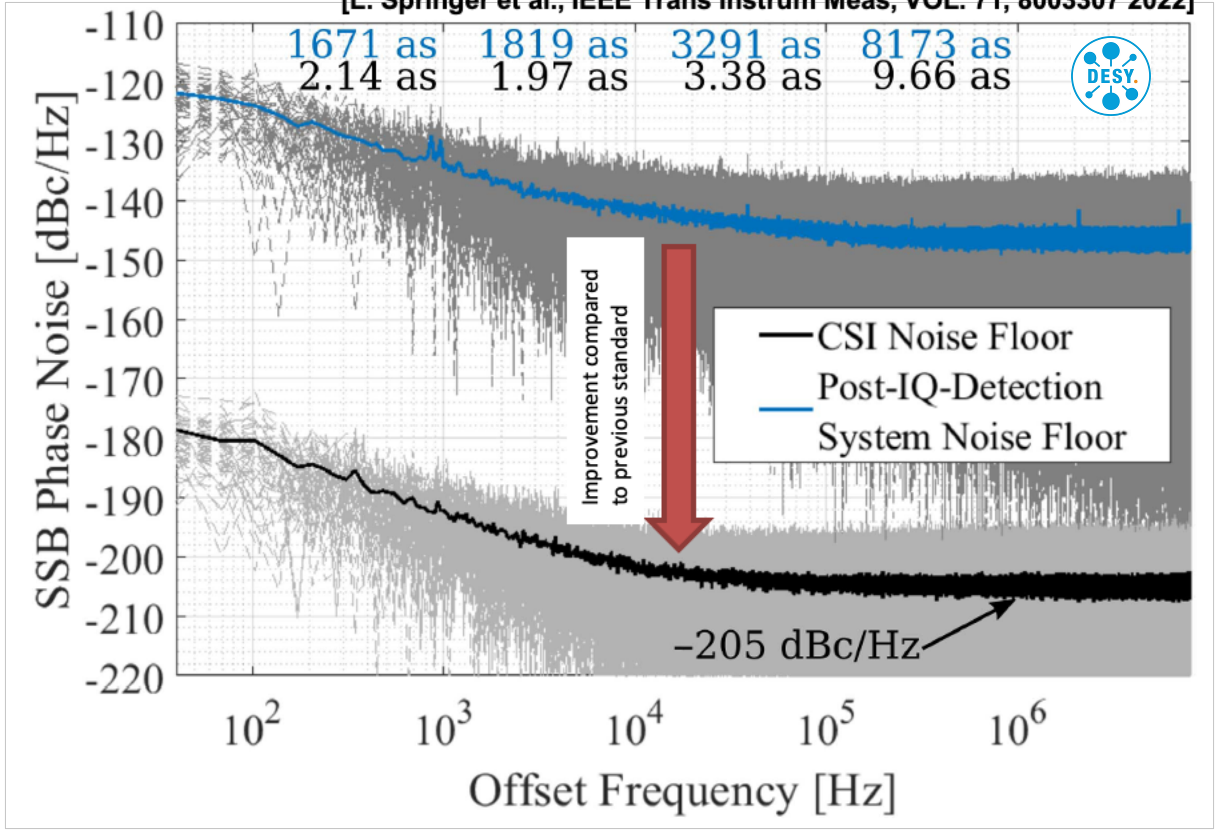




Detecting signals with unprecedented sensitivity

Carrier suppression interferometer

[L. Springer et al., IEEE Trans Instrum Meas, VOL. 71, 8003307 2022]



Established a 60 dB improvement of the detection noise floor at 1.3 GHz in a laboratory-controlled environment

- -205 dBc/Hz (Δω=1 MHz), -180 dBc/Hz (Δω=100 Hz)

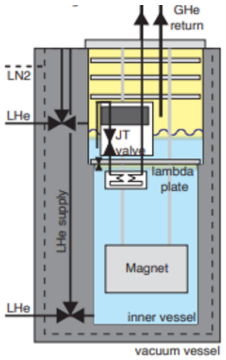
Received funding from Helmholtz to build CSI based read-out system for MAGO

This work is ongoing, with initial tests conducted during the DESY 4K measurement campaign

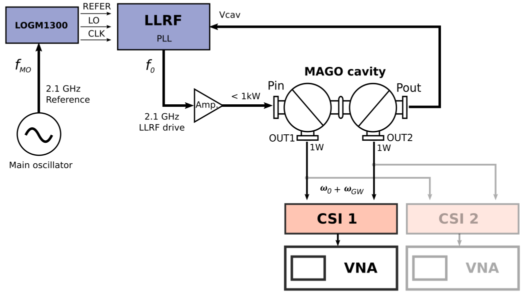
How to realise a dedicated experiment

Four key challenges

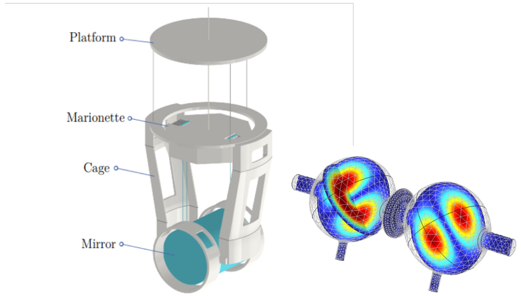
Based on the experience with MAGO, develop and fabricate **new cavities** with optimised geometry



Design a **cryostat** with required thermal properties and which minimises acoustic noise in the He bath



LLRF system to drive and read-out the cavity with highest possible sensitivity



Suspension system to eliminate mechanical noise (from environment and ground motion)

Important cryogenic considerations

Main requirements

Cavity with a high power load to be cooled

Avoid acoustic noise in the helium bath

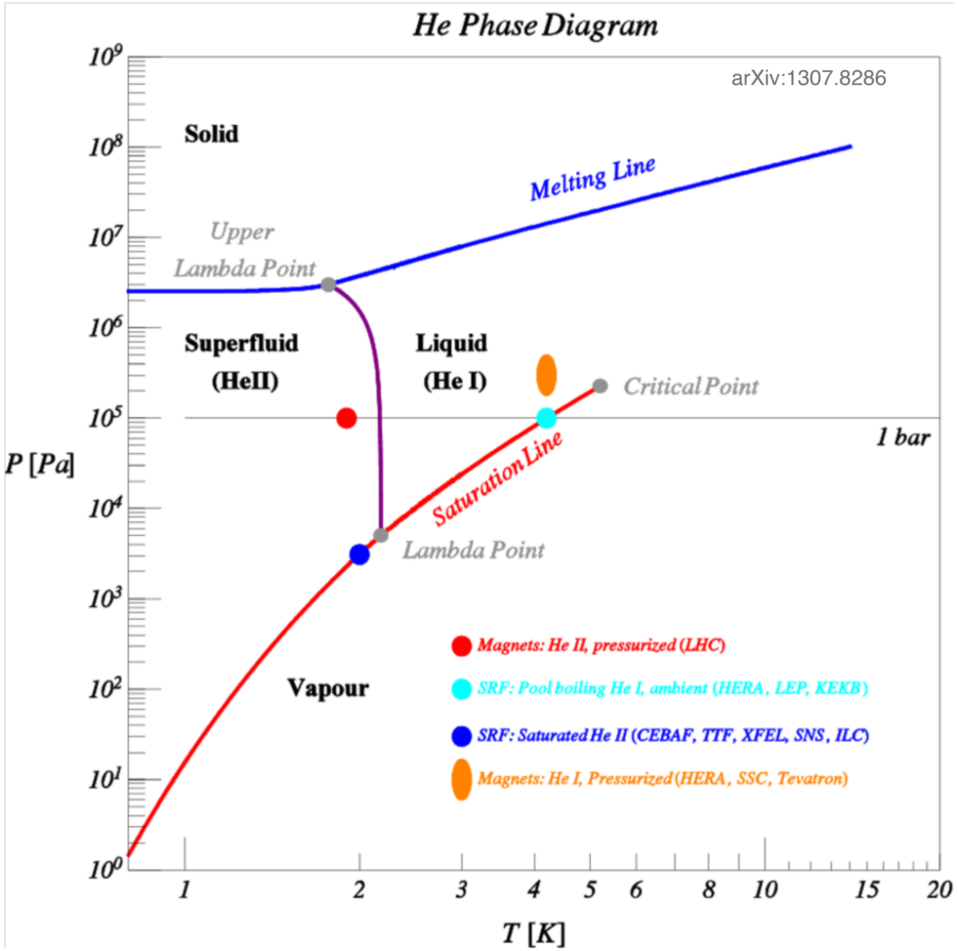
- Seismic and environmental noise coupled to the liquid

Understand noise from thermal dissipation

Minimise the damping of cavity vibrations to preserve mechanical quality factors

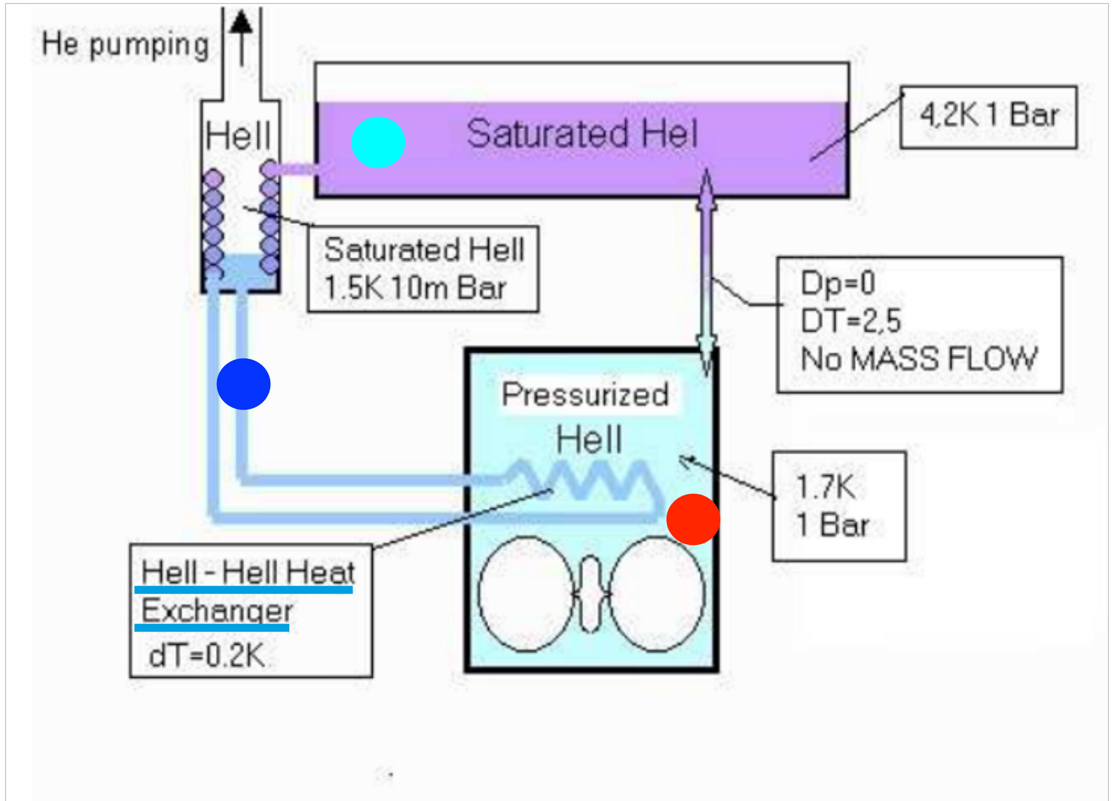
→ Pressurised superfluid Helium (1 bar, 1.8K) gives best thermal properties and minimised noise from He bath ●

- High specific heat and thermal conductivity
- Low sound wave speed
- High mechanical quality factor
- At 1 bar avoids bubble creation

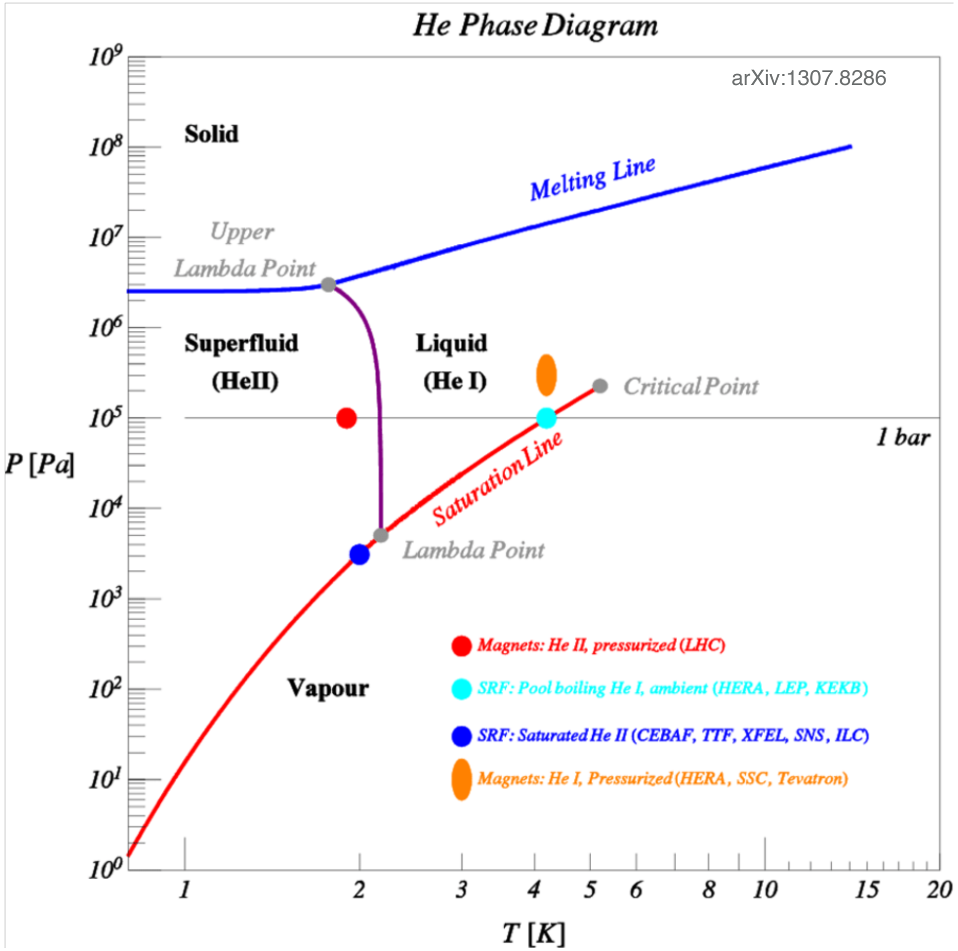


Possible cryostat concept

Use superfluid helium with a heat exchanger



http://arxiv.org/abs/gr-qc/0502054v1



Suspension system

Inspired from Ligo/Virgo concepts

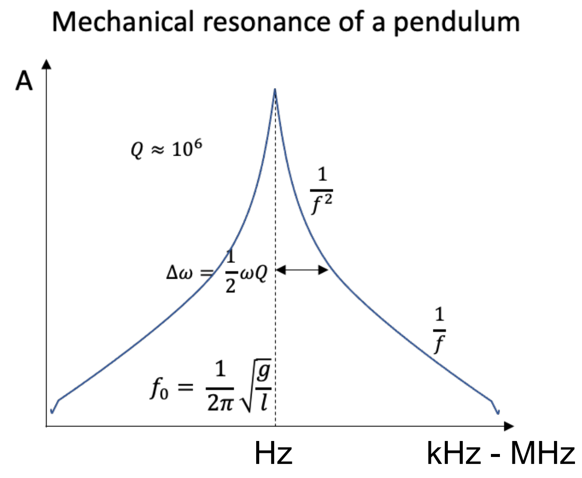
Requirements not as strict as for interferometers
Pendulum resonance ~Hz, measurement in kHz - MHz range
(strong natural damping and high Q factor of superfluid helium)

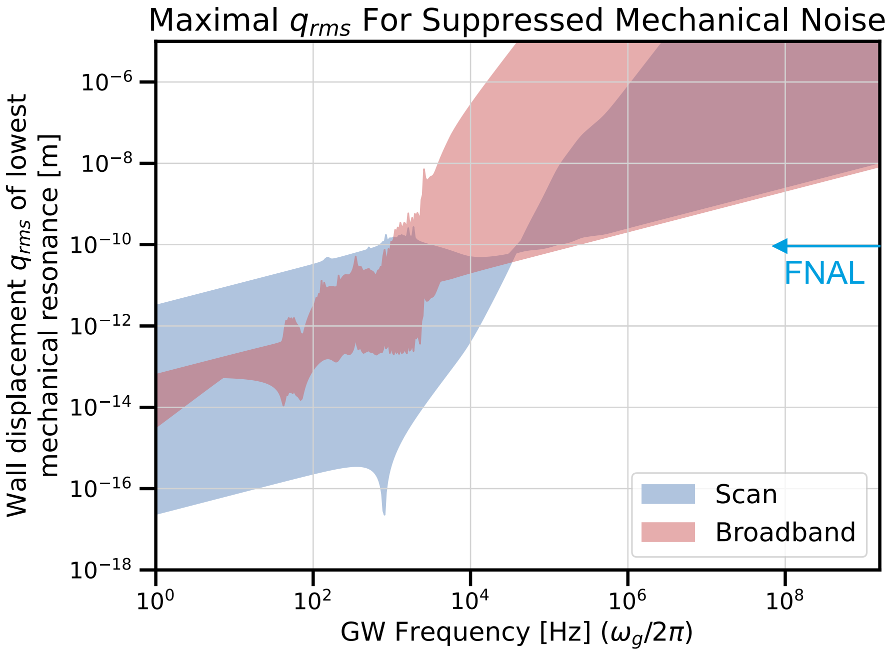
1 or 2 levels of **pendulum** with **leaf springs** for vertical damping

Minimise mechanical shortcut of connections (Vacuum, RF)

Measure vibration at cavity insert to estimate required damping

In general: working on a more refined estimate of all the different noise sources to gauge noise suppression requirements





Upper limit: wall displacement rms such that mech. noise < thermal noise or amp noise

Conclusions and next steps

Successful cryogenic tests at Fermilab and DESY, the cavity can be used for a first physics run!

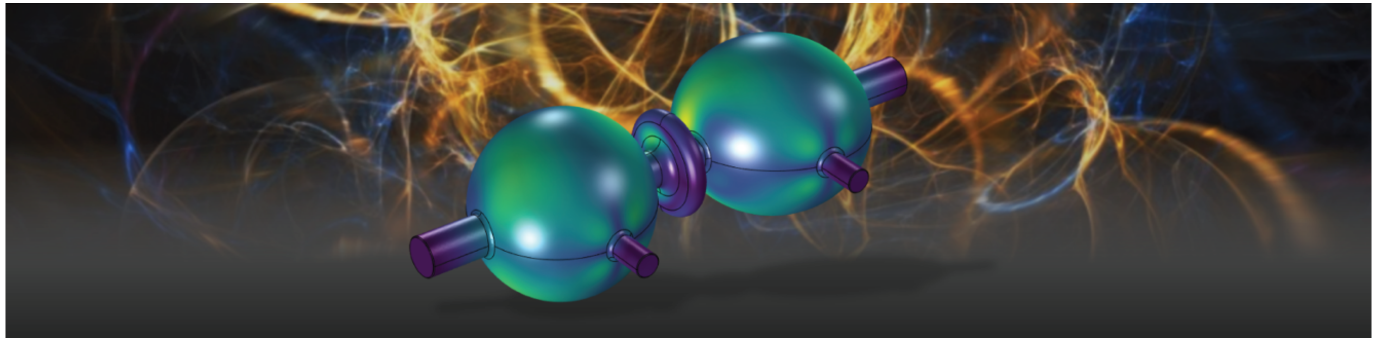
Future plans:

0. Finalize initial LLRF system development. Measure **mechanical deformation of cavity** applied with piezos and **mechanical Q** factor at 2K in He-II

1. Proof-of-principle measurement: HFGW search with MAGO cavity

2. Demonstrator experiment: improve reach with **new cavities** and construction of **suspension system**, but measure in existing cryostat

3. If successful, repeat with **scaled up cavities** and **dedicated cryostat**, explore **beyond SQL readout**



Thank you