The MAGO cavity and prospects for HFGW searches

Krisztian Peters
CERN, 4. Dec. 2023

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
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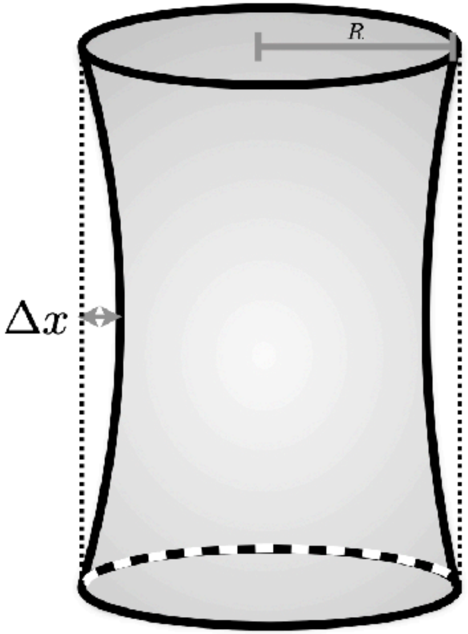
DESY.

GW interaction with SRF cavities

Two detection principles

Mechanical coupling

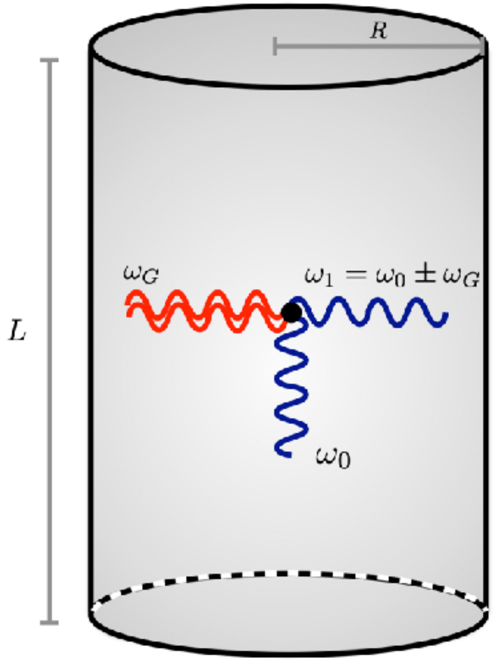
- GWs perturb detector, spreading power in frequency space



Initial focus of our R&D efforts

EM-coupling

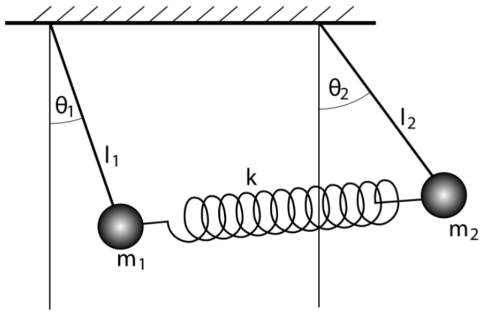
- Graviton - photon mixing (Gertsenshtein effect)
GWs induce in a magnetic field an effective current



Gertsenshtein, M. E. (1962). *Sov Phys JETP, 1962, 14: 84, 85*

Heterodyne detection

GWs induce energy transfer between two levels of an EM resonator



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

tunable

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

Two EM levels achieved by coupling identical cavities

- Each resonant mode of the individual cavities is split in two modes of the coupled resonator with different spacial field distribution (ω_0 and ω_π, symmetric and anti-symmetric modes)

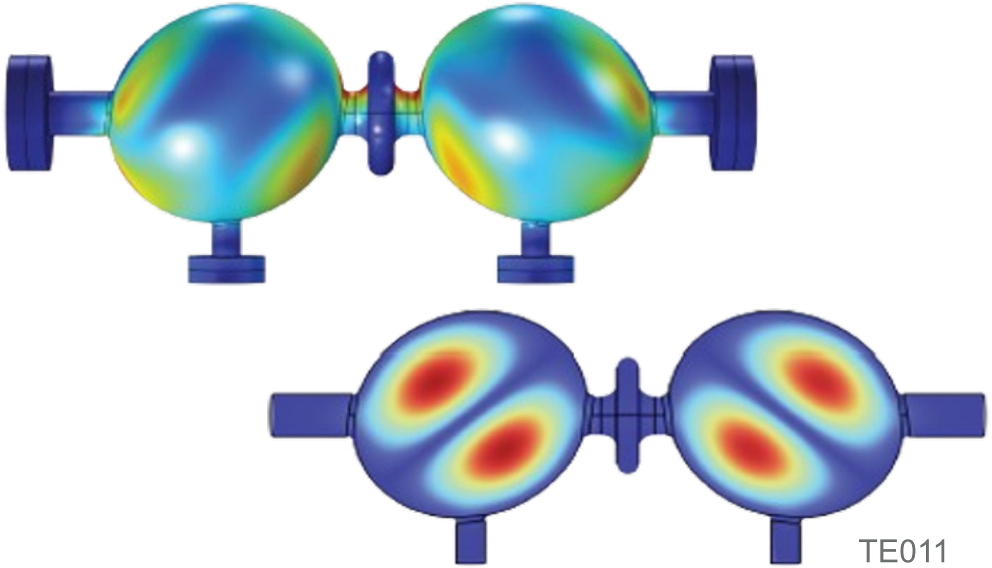
$\Delta\omega = \omega_\pi - \omega_0$ is tunable by "spring constant" k, which is given by the geometry of the tuning cell

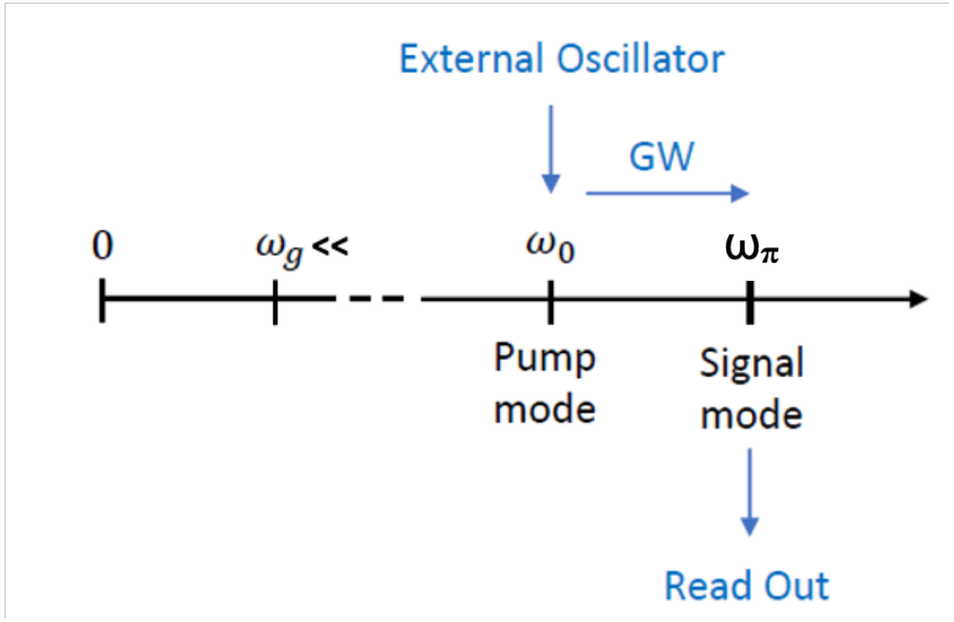
- Original plans for this cavity were to tune the distance between the two cells with piezo elements

Heterodyne detection

Further requirements

Mechanical quadrupole mode





GW couples to modes with quadruple symmetry: mechanical l=2 mode and slightly deformed spheres to induce orthogonal field polarisations such that two EM levels in TE011 mode have l=2 difference

GW with ω_g transfers energy from ω_0 to $\omega_0+\omega_g$. Resonantly enhanced if $\omega_g = \omega_\pi - \omega_0$

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 (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

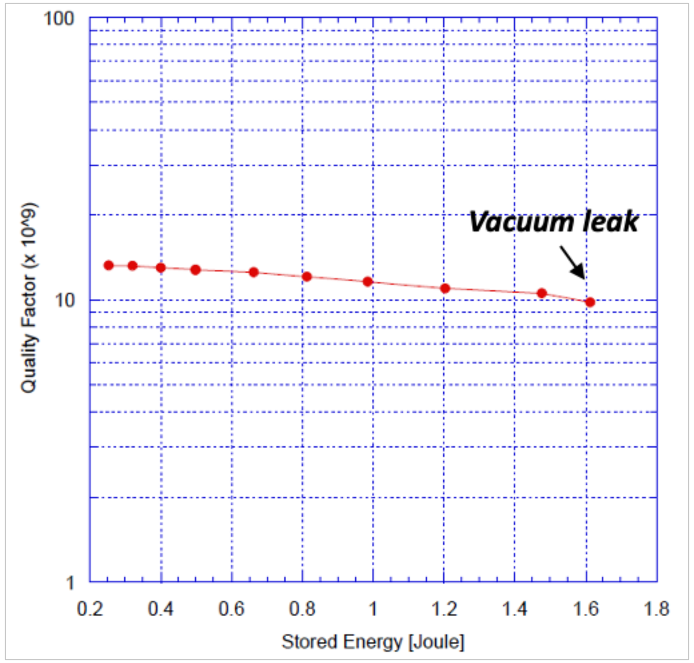
- 2-cell cavity with optimised geometry
- Underwent chemistry and cold test to obtain $Q_0(U)$ for TE011

PACO-2GHz-variable

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

Figure 5. Niobium spherical cavities (fixed coupling).

In the following, denoted as "MAGO cavity"



Continuation of R&D efforts

DESY/UHH - FNAL - INFN collaboration

June 2023

Cavity at DESY

- Mechanical characterisation and RF measurements at room temperature (done)

Today

Cavity at FNAL

- Treatment of cavity, construction of a support structure and RF antennas, first cryogenic characterisation

Mid. 2024

Cavity back at DESY

- Cryogenic test with (initial) LLRF system

End 2024

Cavity back at FNAL

- First GW search in existing cryostats at Fermilab

In parallel, work started on an LLRF system to drive and read-out the cavity

University Genova

Towards GW experiments with SRF cavities

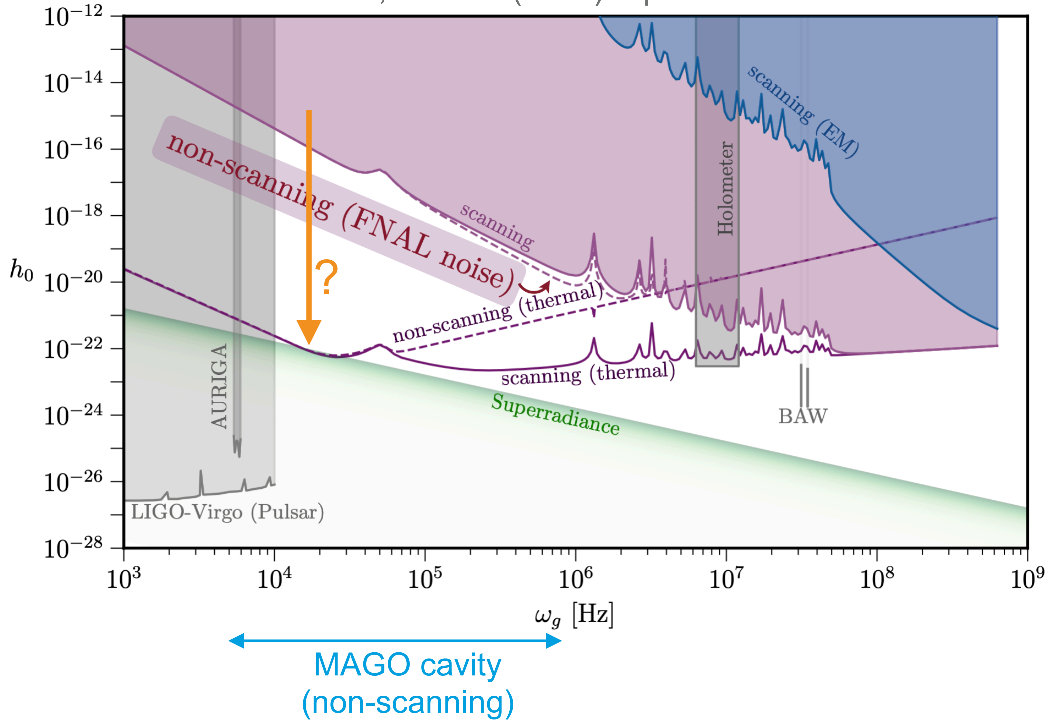
DESY/UHH - FNAL - INFN collaboration

Main pillars (and plans) for a future experiment

- Based on the experience with MAGO, fabricate **new cavities** with optimised geometry
- Design **LLRF system** to drive and read-out the cavity with highest possible sensitivity
- Design a **suspension system** to eliminate mechanical noise (from environment and ground motion)
- Design a **cryostat** with required thermal properties and which minimises acoustic noise in the He bath

Coordinated and **synchronised observatories** at DESY, FNAL and possible other locations for different frequencies

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



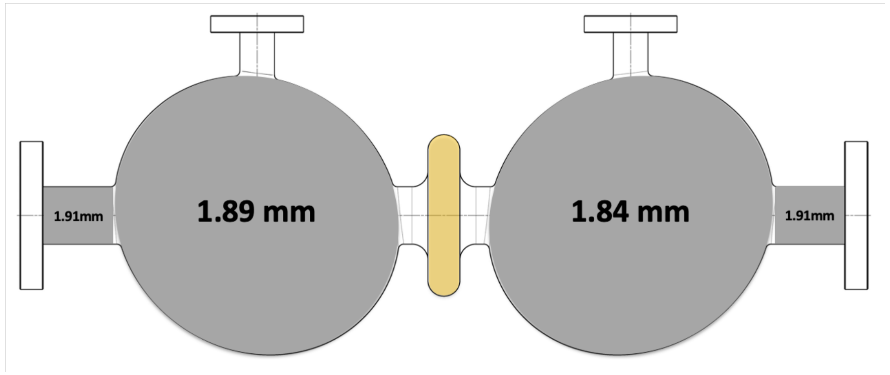
This talk with focus on DESY activities and plans, Bianca's talk with focus on FNAL

The MAGO cavity

Cavity is out of shape

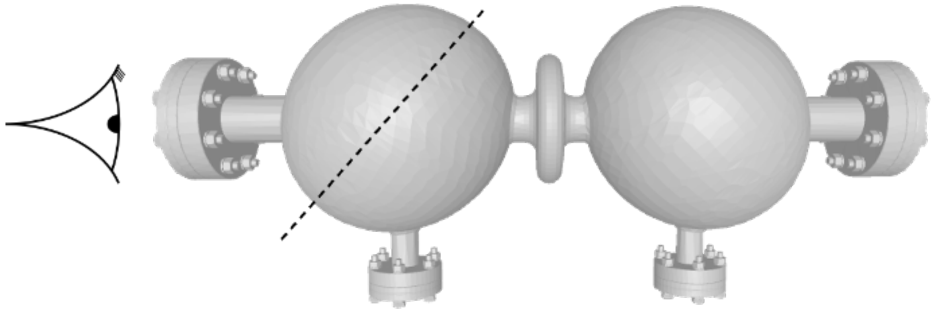
Mechanical survey

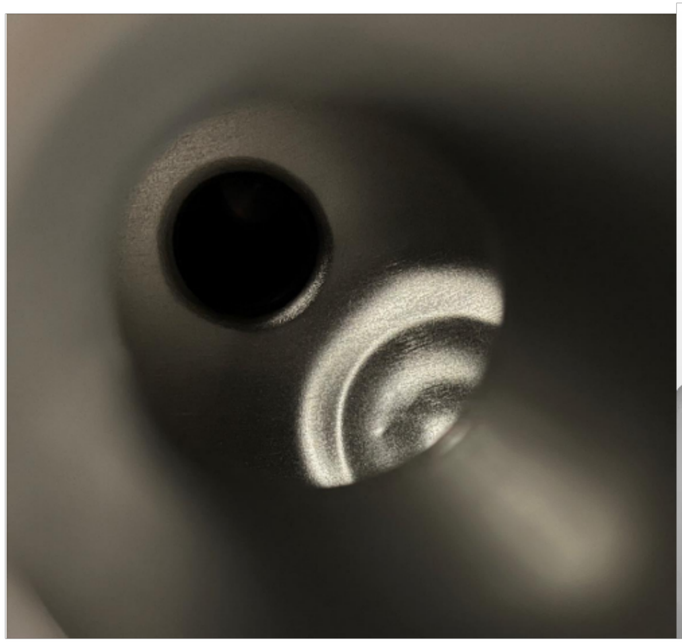
Measurement of the cavity geometry at arrival at DESY with a laser line scan and an ultrasonic wall thickness measurement (expected wall thickness 2mm)

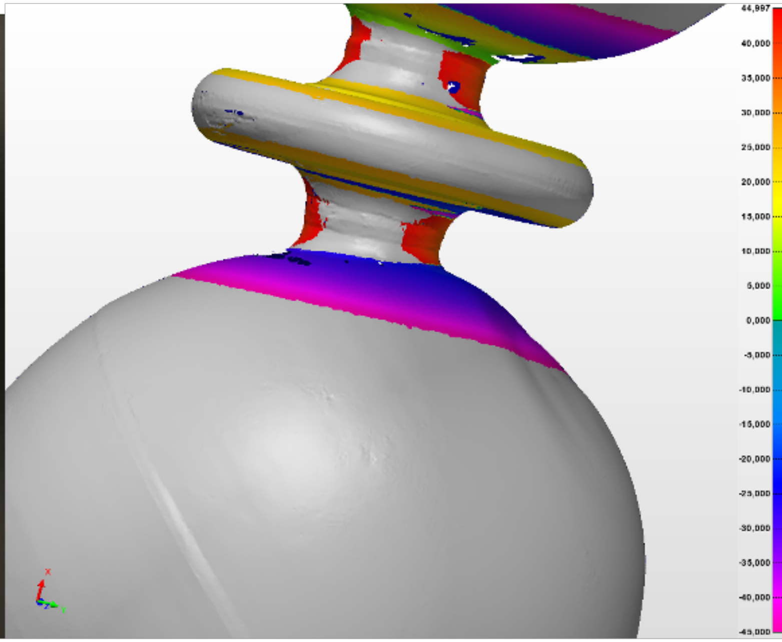


10 points per cell, 4 per tube, average values shown

Donut-shaped dent around symmetry axis

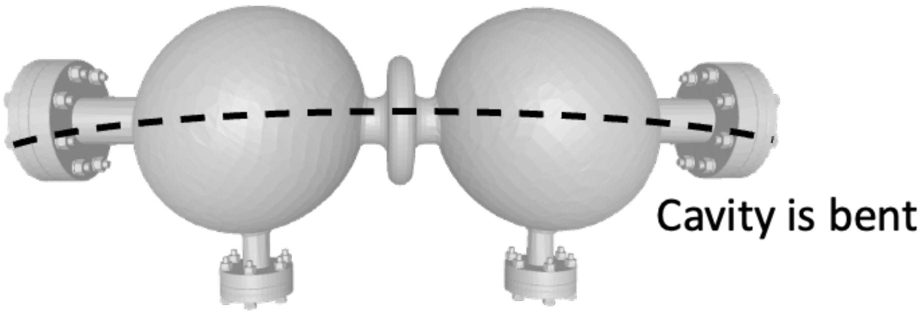




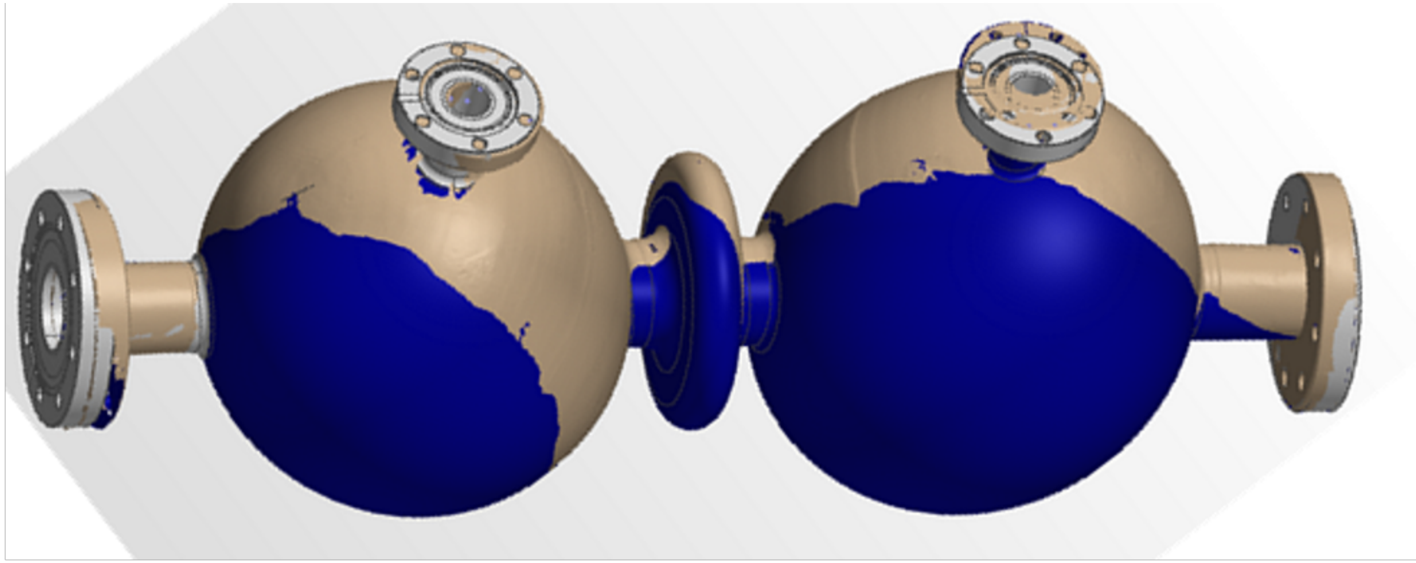


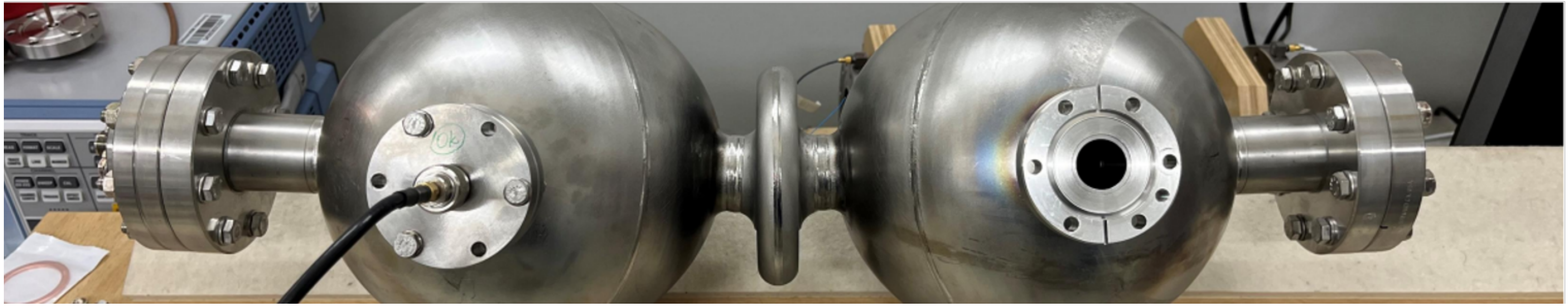
Cavity is out of shape

Mechanical survey



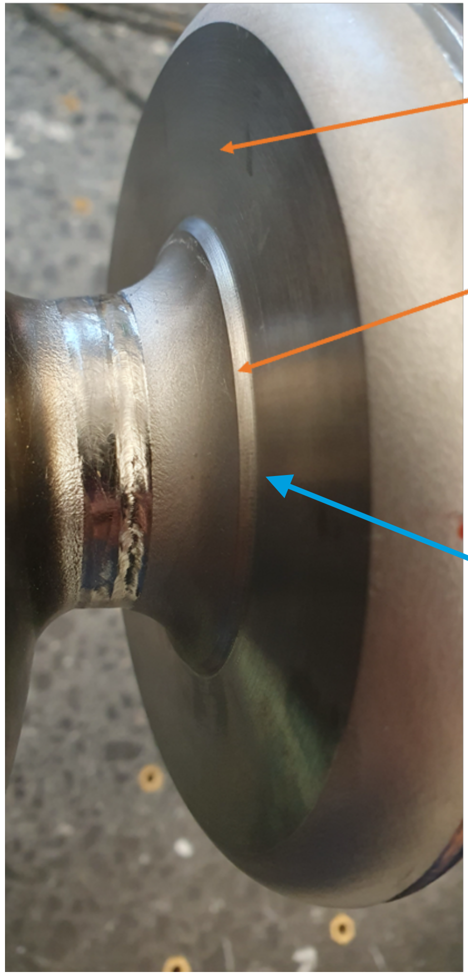
Colour coding shows deviations from technical drawings





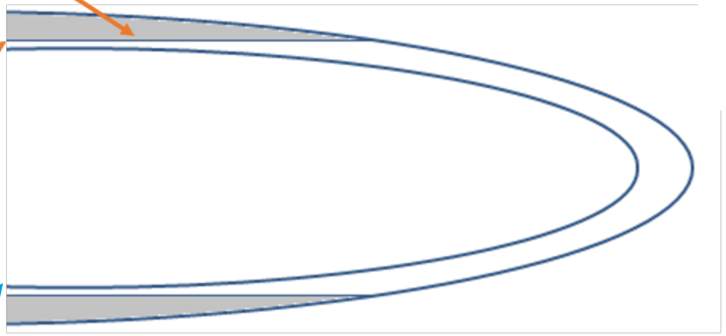
A delicate part of the cavity

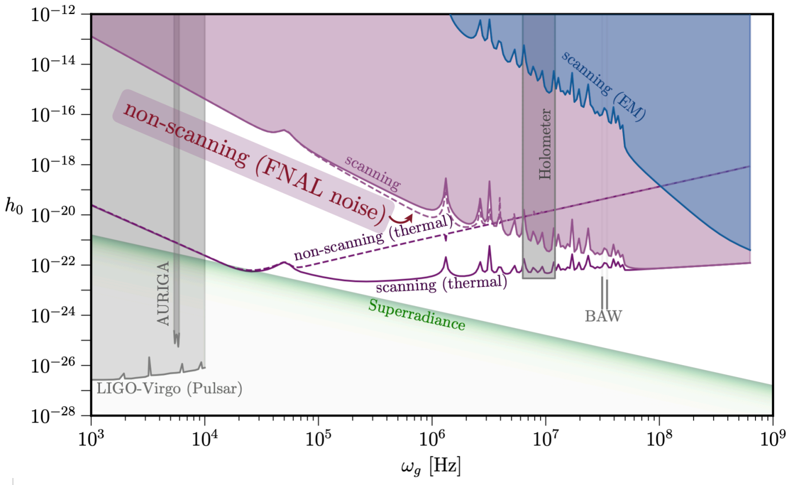
Tuning cell



Turned surface
(both half cells)

Step after turning

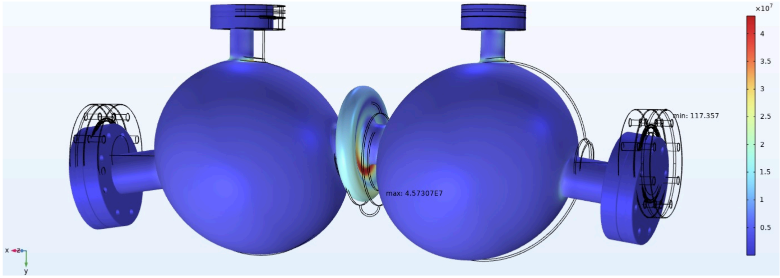




At low r, wall thickness is only (1 ± 0.1) mm!

Cavity has to be braced and restrained

Perform non-scanning measurement
(~6 kHz tuning range not much gain anyways)



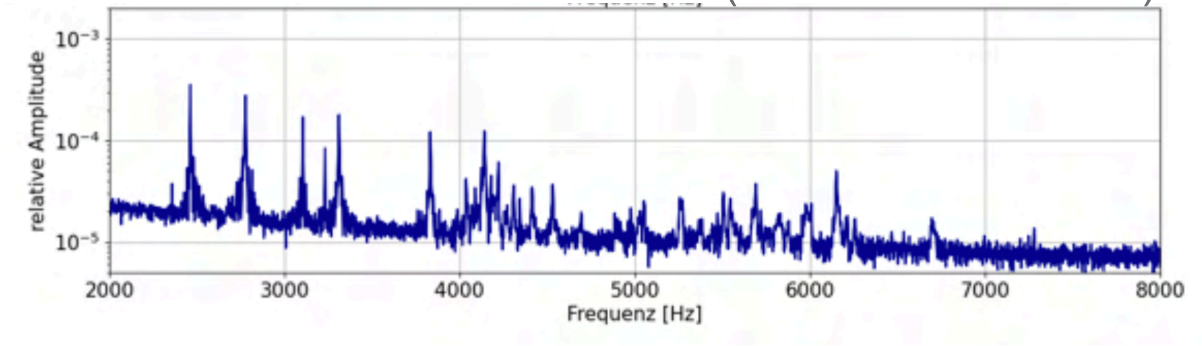
No damage to flanges or sealing surface

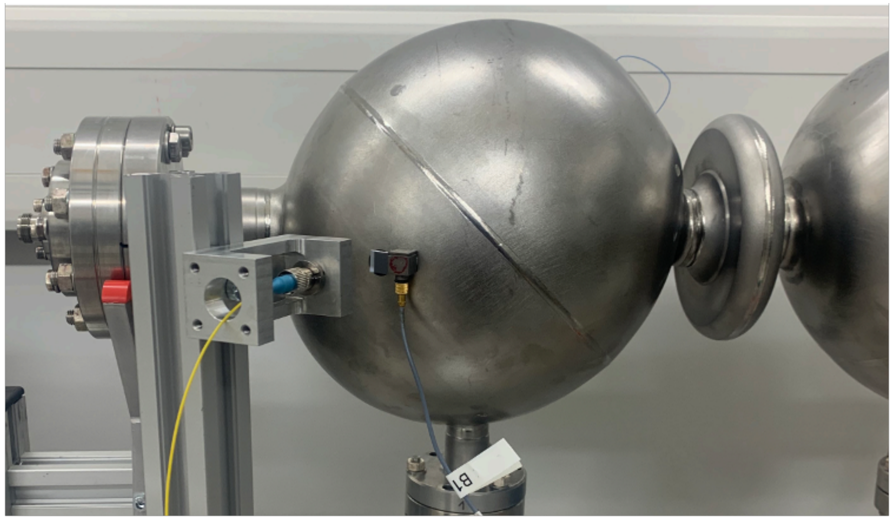
Leaktight at room temperature

Mechanical resonances

Measurement with accelerometers and interferometric sensors

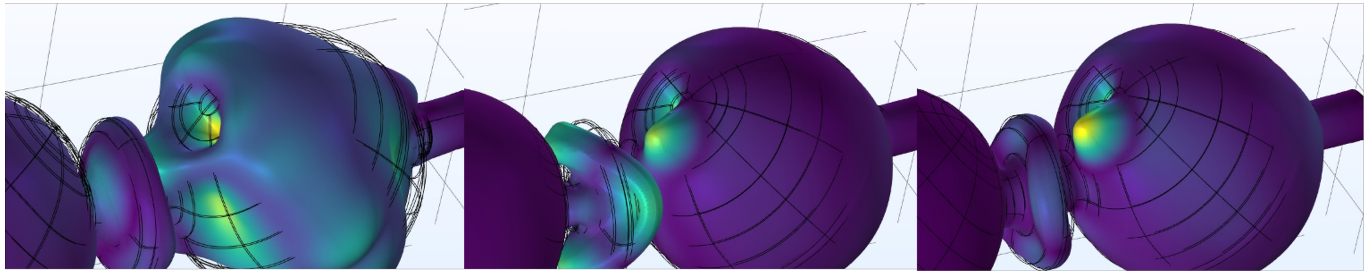
Interferometer measurement (1 out of 6 locations)





Results difficult to interpret, better understanding with simulations

Dent in cell causes oscillation maximum in vibration Eigenmodes

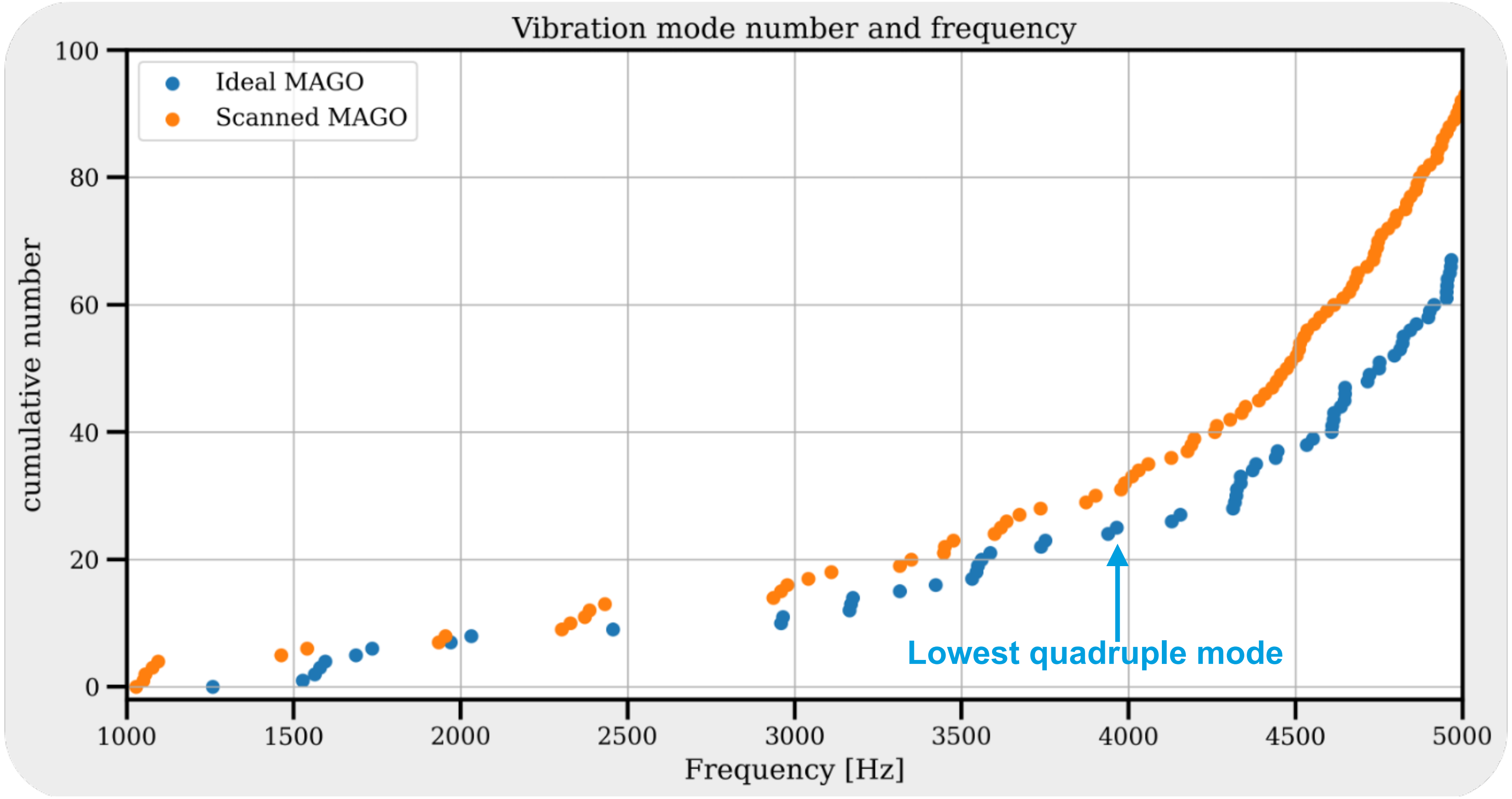


f = 3.90 kHz f = 3.98 kHz f = 3.99 kHz

Mechanical resonances

Many more and densely populated mechanical normal modes with distorted detector

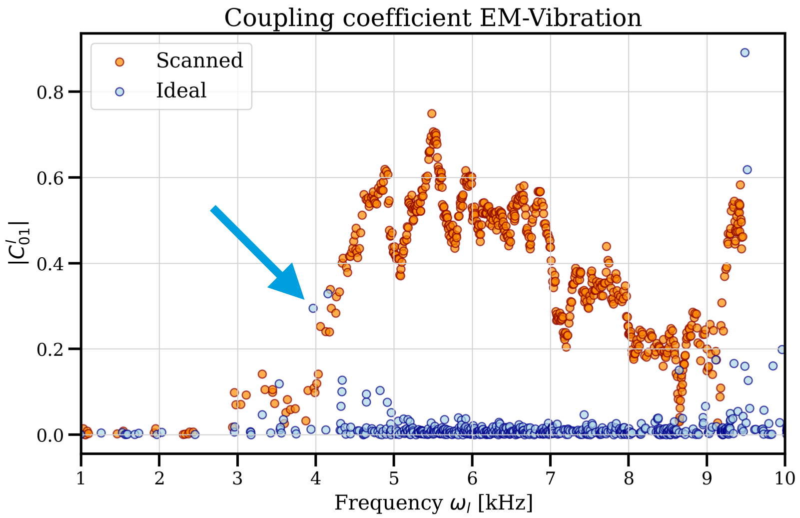
Ideal MAGO = cavity from technical drawings



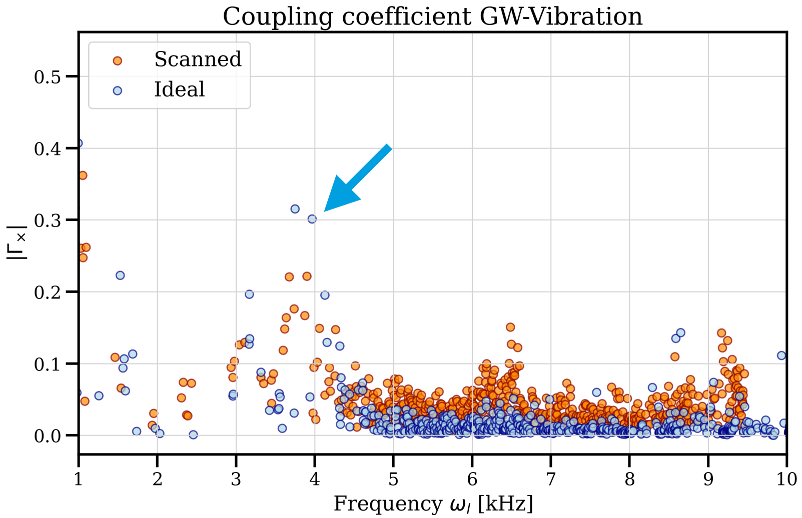
Couplings to mechanical resonances

Simulation with ideal and measured cavity

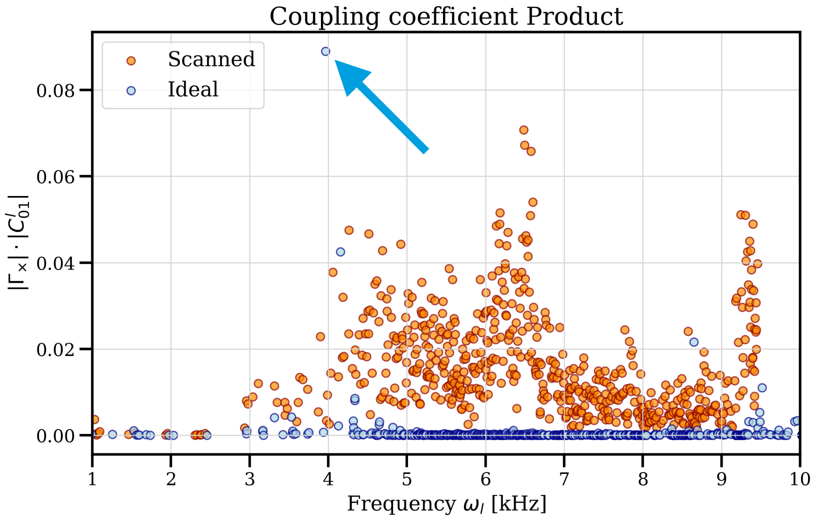
Mech-EM coupling



GW-mech coupling



Product



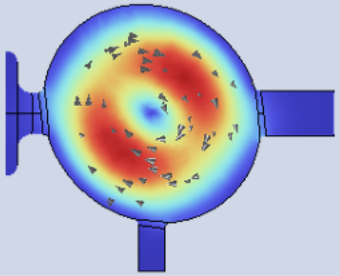
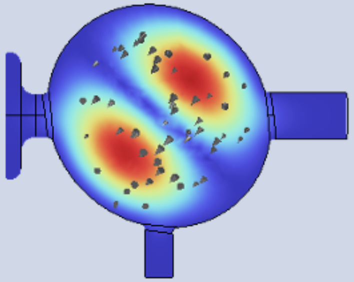
Frequency of mechanical resonances, GW propagating in z-direction to the cavity

With distorted geometry

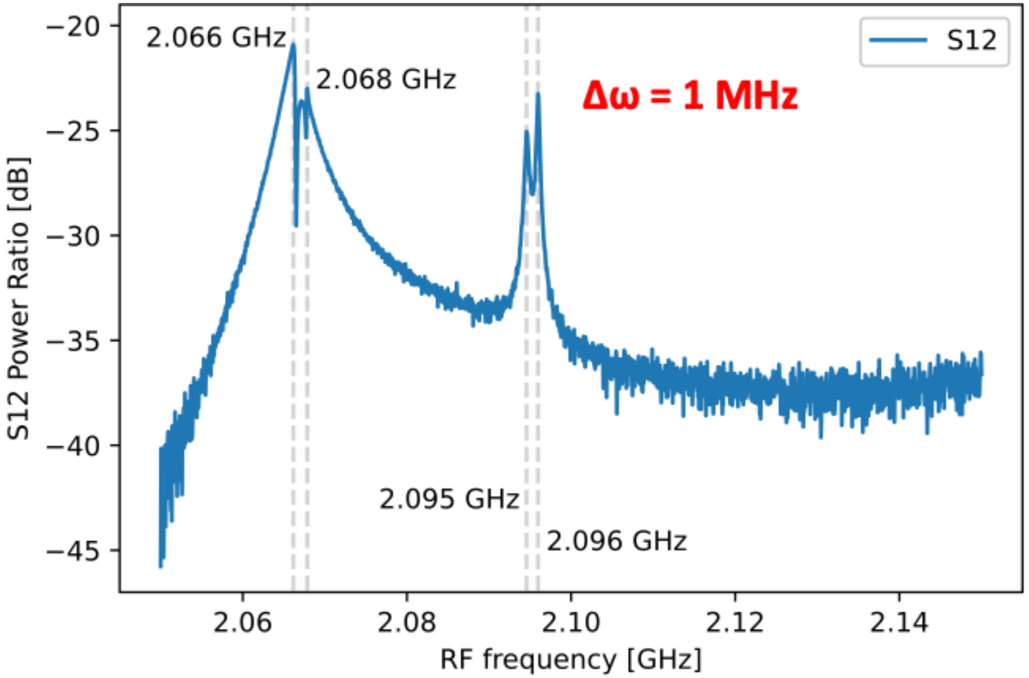
- Several multipoles with quadrupole fractions (otherwise mech-EM coupling zero)
- Not a clear lowest lying dominating quadruple resonance like with a clean (ideal) geometry

RF measurements worrisome

Not what expected from ideal geometry at room temperature

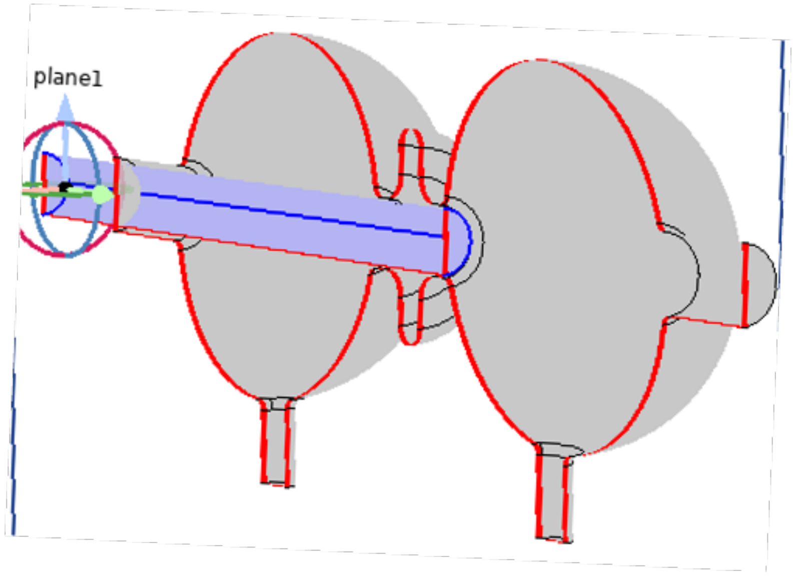
Simulated Eigenfrequency	Electric Field Distributions
2.073 GHz (2 merged peaks)	
TE_{011} **0-mode: 2.10381 GHz** **π-mode: 2.10390 GHz** **Δω ≈ 9 kHz** **→ 2 merged peaks**	

Transmission spectrum from one cell to the other

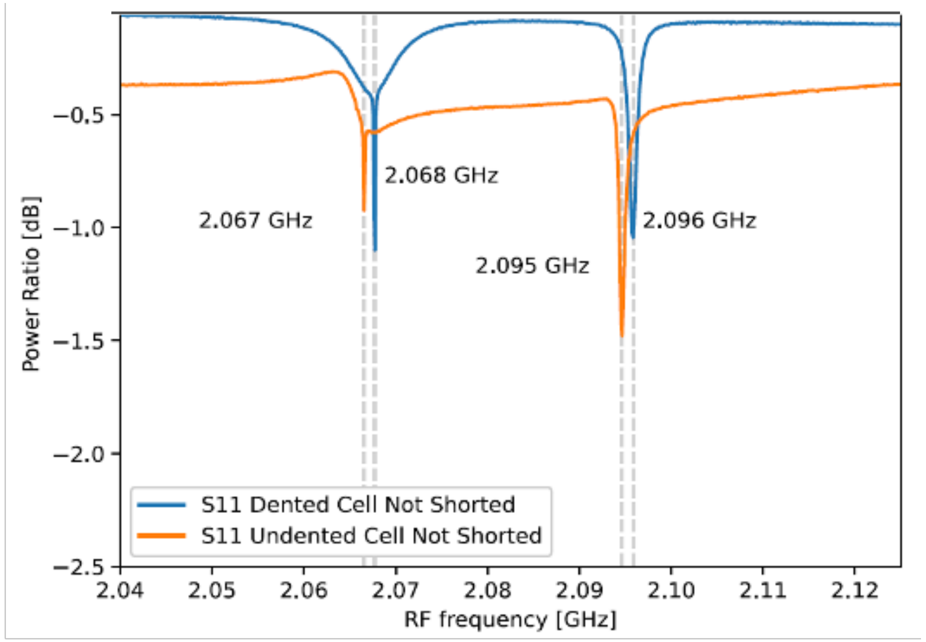


Eigenfrequencies of single-cells do not match

Idea: Short one cell and measure the other



Absorption spectra for both cells



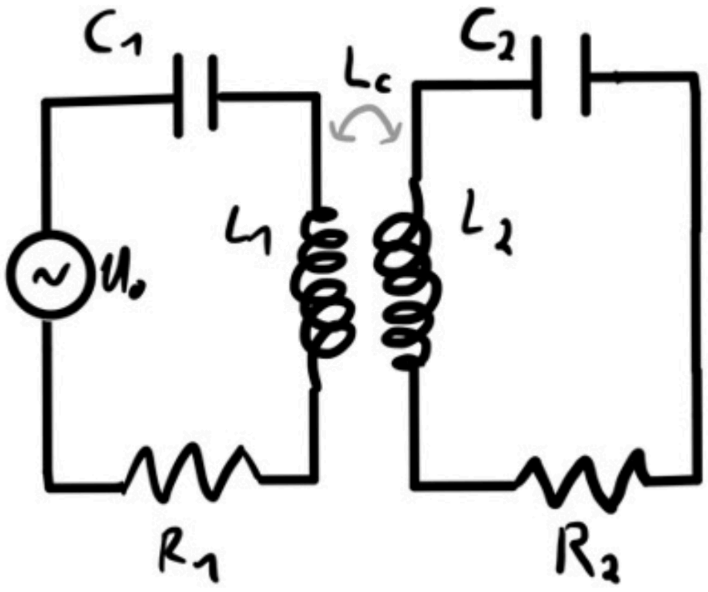
Not wanted nor expected!

Remember the coupled pendulum?

Shed light on RF measurements

Model two MAGO cells as inductively coupled RLC circuits

Driven by an external oscillator U(t) on one side



$$L_1\ddot{I}_1 + R_1\dot{I}_1 + \frac{1}{C_1}I_1 = -L_c\ddot{I}_2 + \dot{U}$$

$$L_2\ddot{I}_2 + R_2\dot{I}_2 + \frac{1}{C_2}I_2 = -L_c\ddot{I}_1$$

Define parameters:

$$k = L_c/\sqrt{L_1 L_2}$$

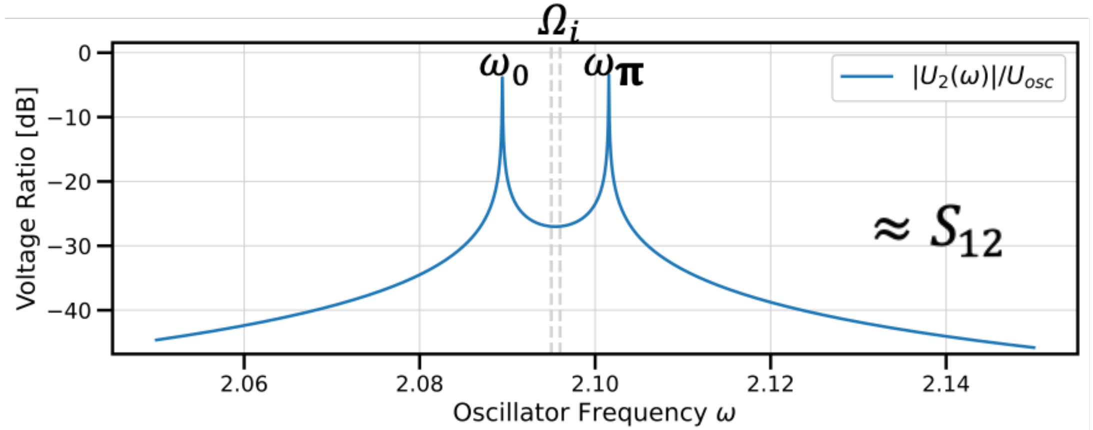
Coupling strength

$$\Delta\Omega = \Omega_2 - \Omega_1, \;\; \Omega_i = \frac{1}{\sqrt{L_i C_i}}$$

Single cell eigenfrequencies

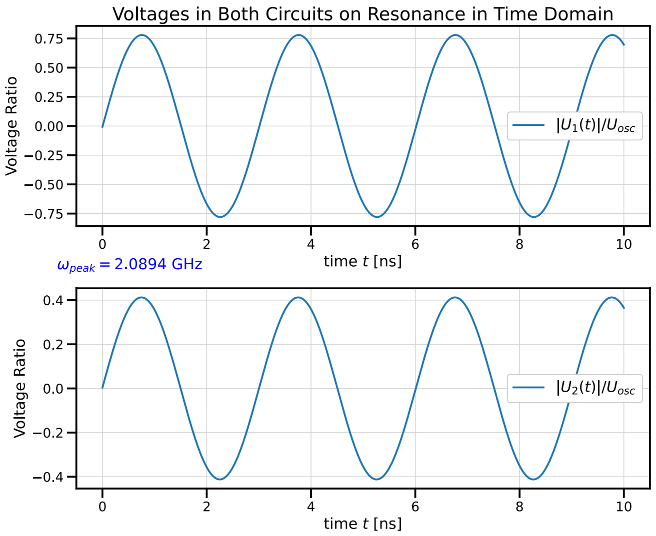
Solution of the coupled e.o.Ms

In frequency and time domain

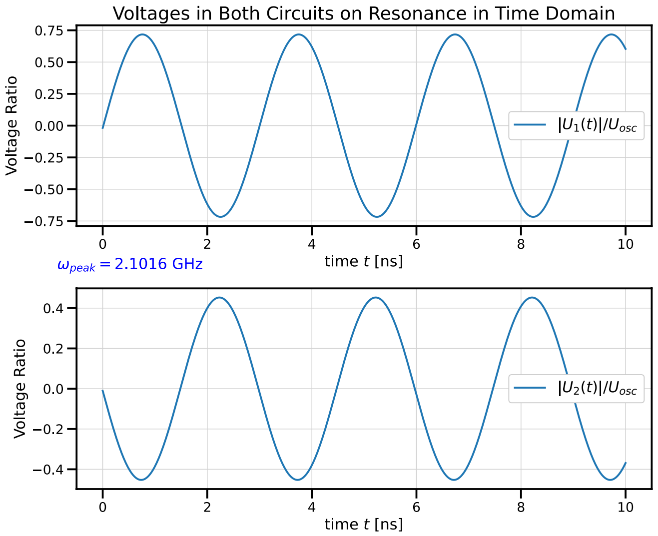


$k_0 = 10^{-2}, \Delta\Omega = 1MHz$

Symmetric mode ω_0



Anti-symmetric mode ω_π



Loaded mode

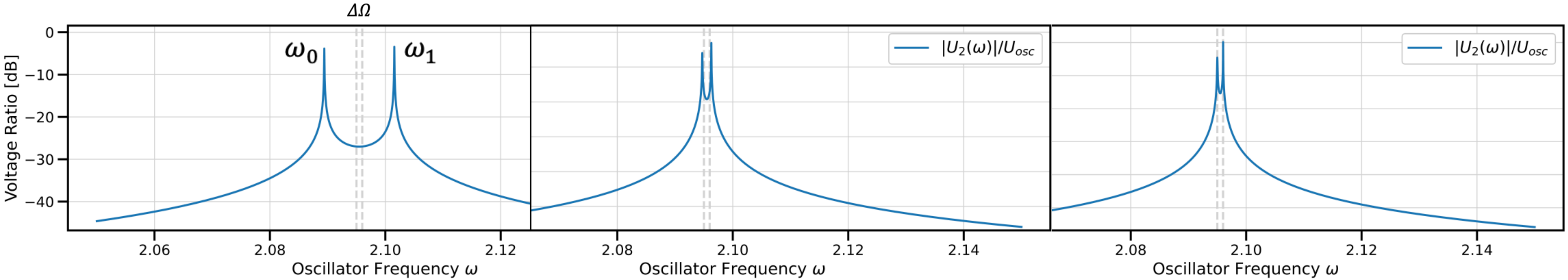
Cell 1

Cell 2

Signal mode

Varying the coupling parameter

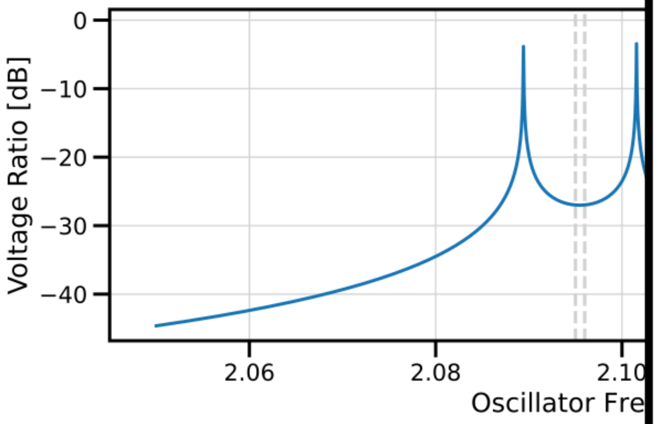
Leads to different peak sizes



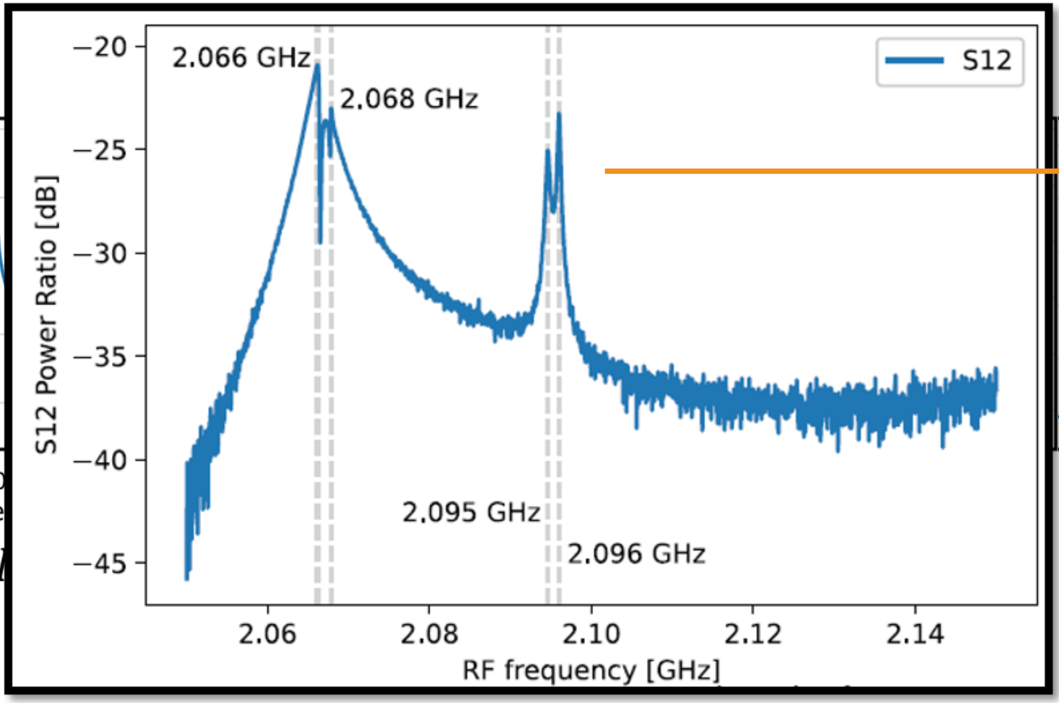
$k_0 = 10^{-2}, \Delta\Omega = 1MHz$ $\quad$ $k_0 = 10^{-3}, \Delta\Omega = 1MHz$ $\quad$ $k_0 = 10^{-4}, \Delta\Omega = 1MHz$

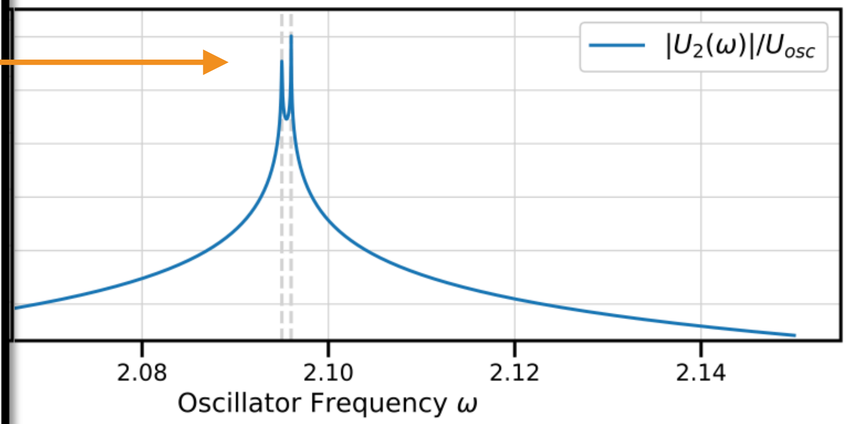
Varying the coupling parameter

Leads to different peak sizes



$k_0 = 10^{-2}, \Delta\Omega = 1$

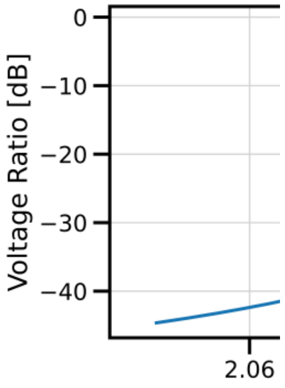




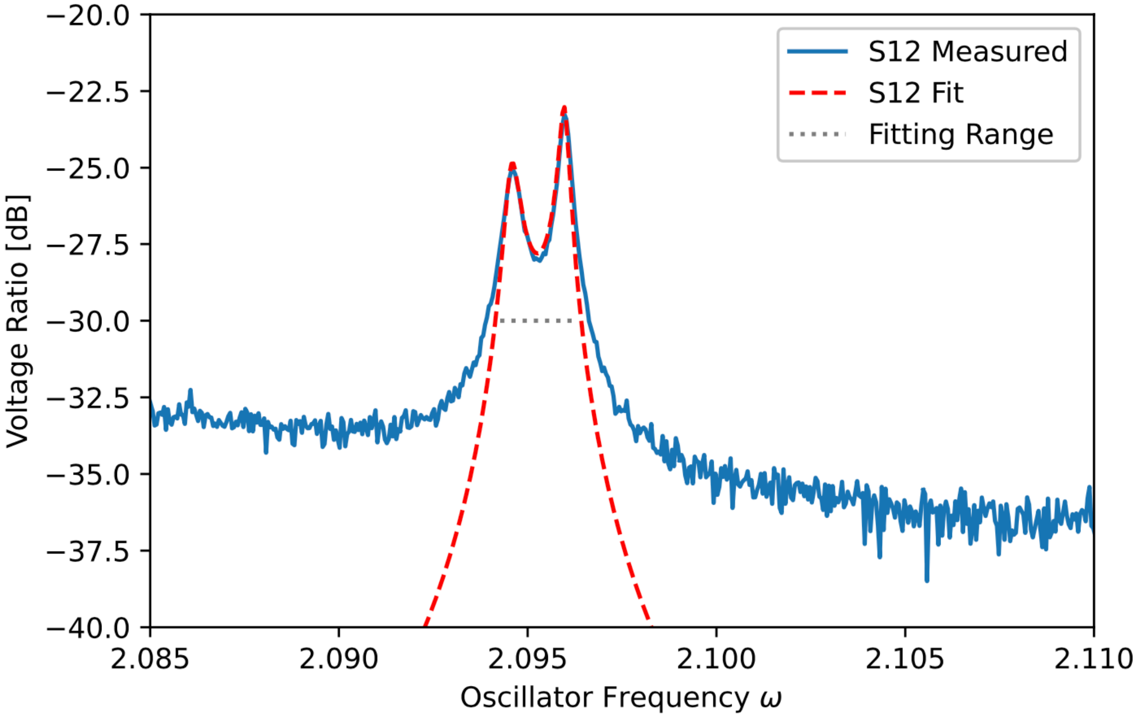
$k_0 = 10^{-4}, \Delta\Omega = 1 MHz$

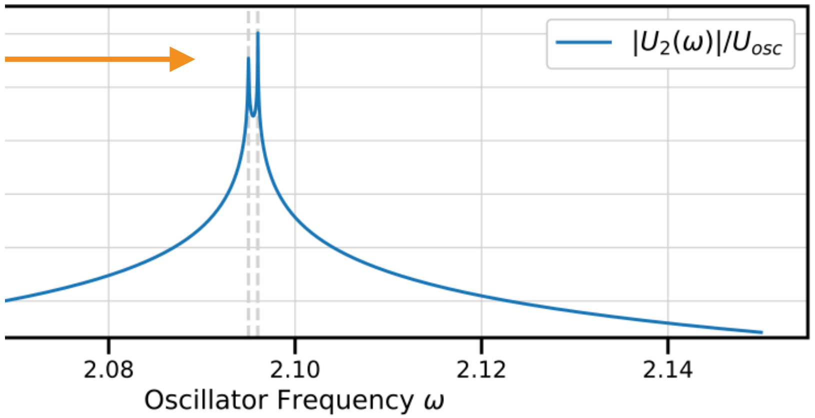
Varying the coupling parameter

Leads to different peak sizes



k





$k_0 = 10^{-4}, \Delta\Omega = 1MHz$

tentative results: (S12 and $|U_2/U_0|$ are not exactly the same)

$k = 0.5 \cdot 10^{-5}, \;\; \Delta\Omega = 1.4 \text{ MHz}, \;\; Q_1 = 0.5 \cdot 10^4, Q_2 = 0.8 \cdot 10^4$

Weak coupling is inherent

Recover by bringing ΔΩ closer together

$$k = 2\frac{\omega_{\pi} - \omega_0}{\omega_{\pi} + \omega_0} \approx 2\frac{1MHz}{4GHz} = 5\times10^{-4}$$

Phase shift which vanishes for high Q!

- $Q_{1,2} \gg 10^9$ to avoid arbitrary phase shifts

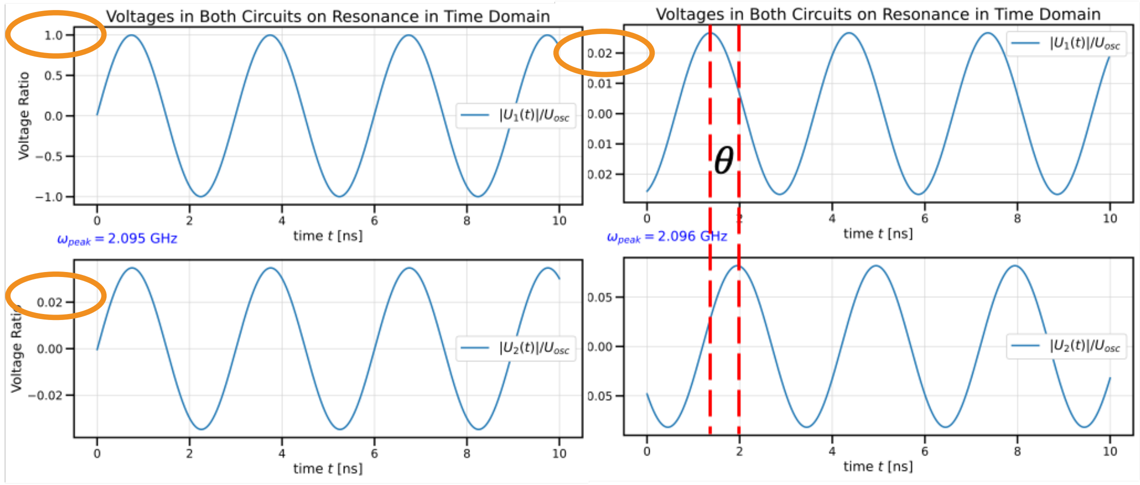
Low amplitude ratio limits sensitivity

- Mech-EM coupling $\propto E_0 * E_\pi$
- Largest amplitude limits operation power

$\Delta\Omega$=1MHz; $k_0=10^{-4}$

Cell 1

Cell 2



Symmetric mode ω_0 Anti-symmetric mode ω_π

Weak coupling is inherent

Recover by bringing ΔΩ closer together

$$k = 2\frac{\omega_{\pi} - \omega_0}{\omega_{\pi} + \omega_0} \approx 2\frac{1MHz}{4GHz} = 5\times10^{-4}$$

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Low amplitude ratio limits sensitivity

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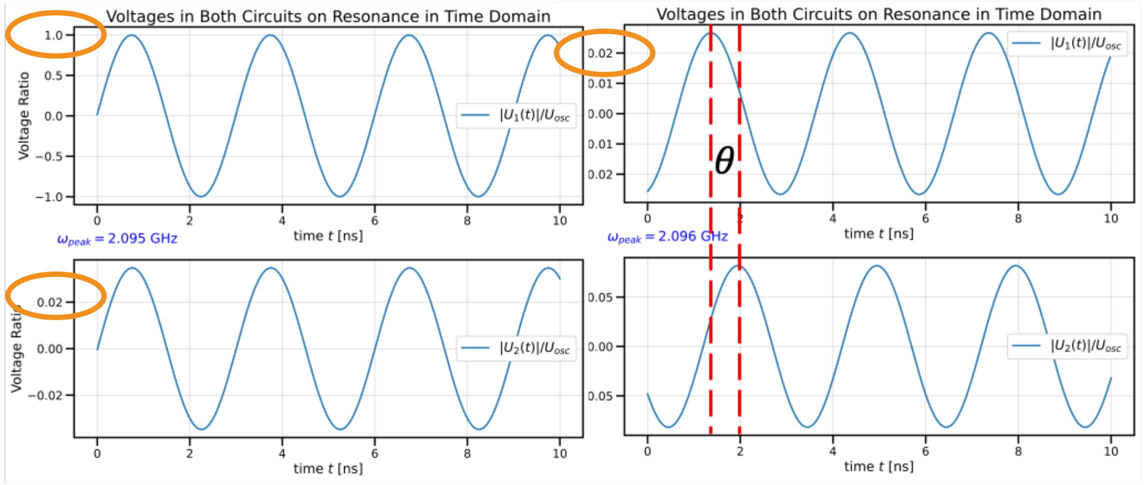
Need to tune cavity/cells to achieve wanted ΔΩ

- Working on simulations to identify origin and possible "turning knobs"
- Mechanical or dielectric tuning?

$\Delta\Omega$=1MHz; $k_0=10^{-4}$

Cell 1

Cell 2

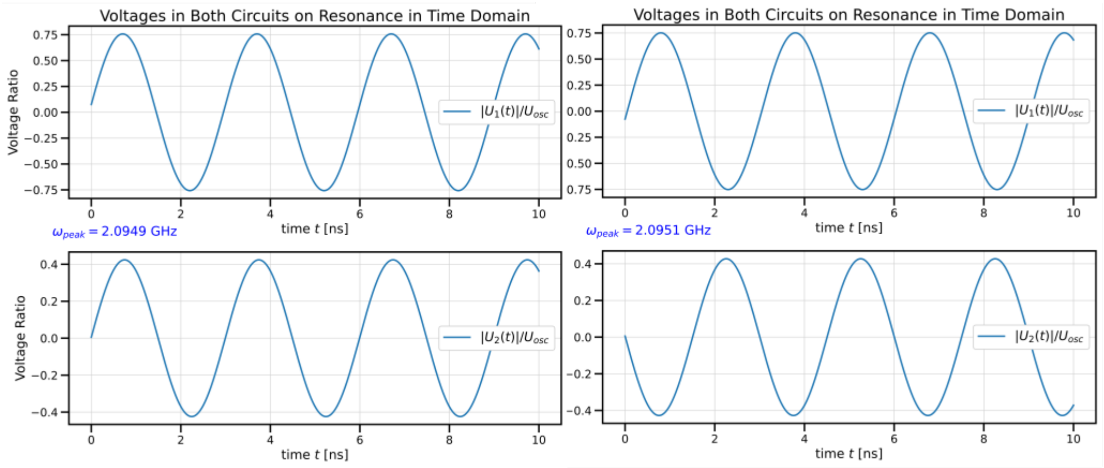


Symmetric mode ω_0 Anti-symmetric mode ω_π

$\Delta\Omega$=1kHz; $k_0=10^{-4}$

Cell 1

Cell 2

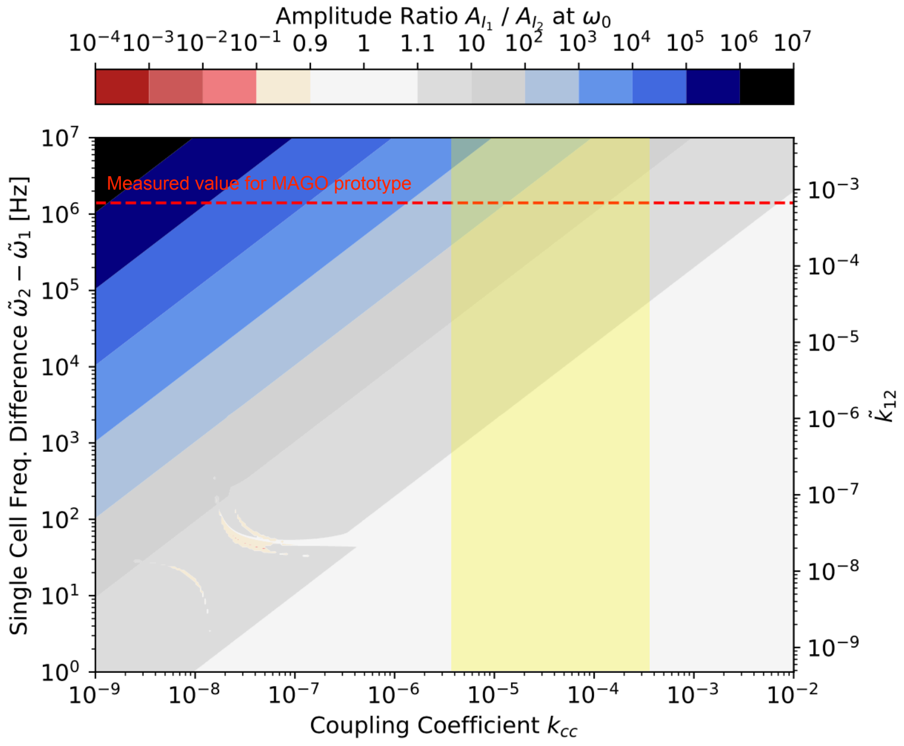


Some tuning practically unavoidable

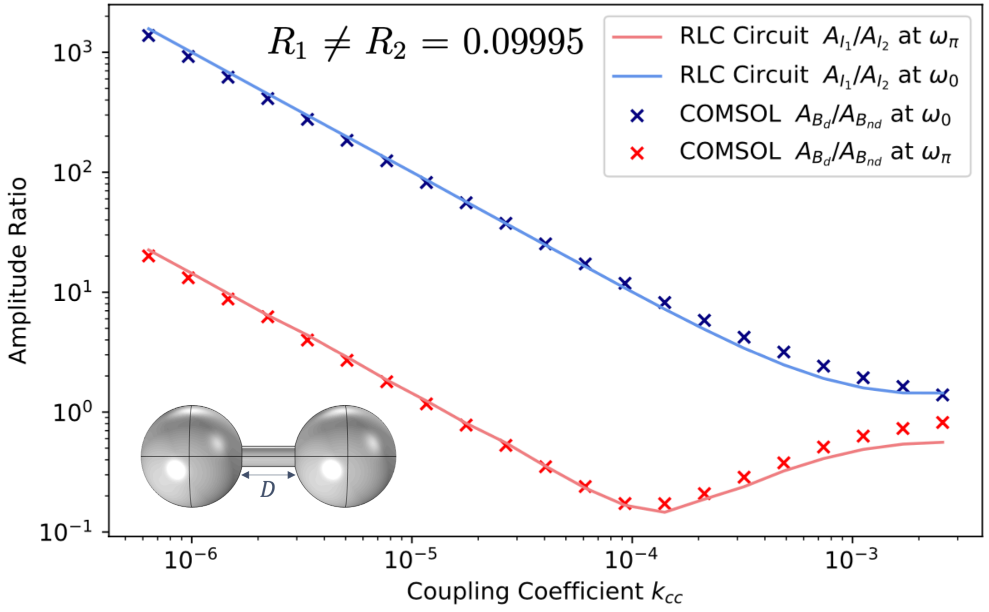
Single cell eigenfrequency differences also expected for close to ideal geometries

For GHz cells, a relative difference in the radii 0.1 % will already lead to Δω = 1 MHz
(This is also what we roughly get from current wall thickness measurement)

$$R_1,\ R_2 = R_1 + \Delta R,$$
$$\frac{\Delta\tilde{\omega}}{\tilde{\omega}_1} = \frac{\Delta R}{R_1}$$



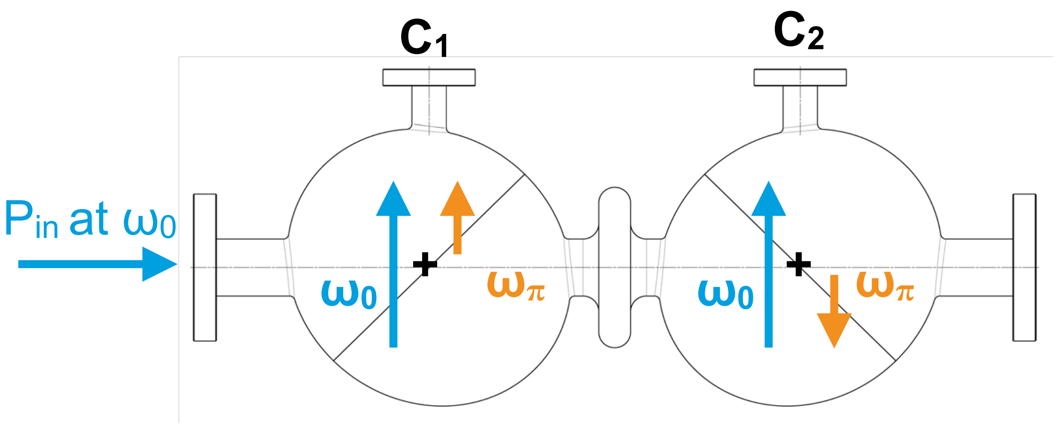
Compare to a simplified MAGO geometry
Good description by RLC circuit



How can we control the cavity and detect the signal?

MAGO's readout

Two similar concepts

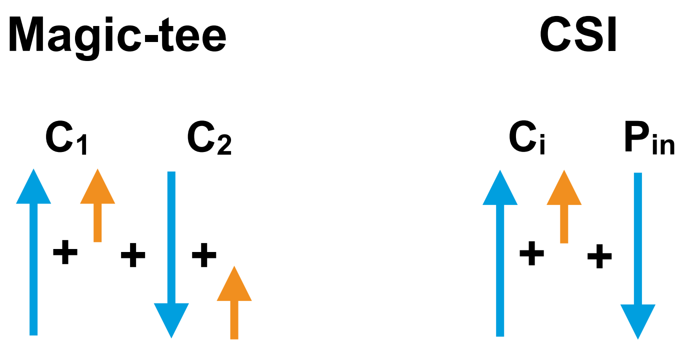


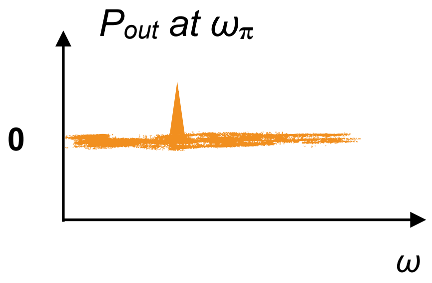
Readout with magic-tee

- Shift signal phase of one cell (with magic-tee) by π
- Loaded mode cancels, signal mode amplified, works well with similar amplitudes

Carrier suppression interferometer (CSI)

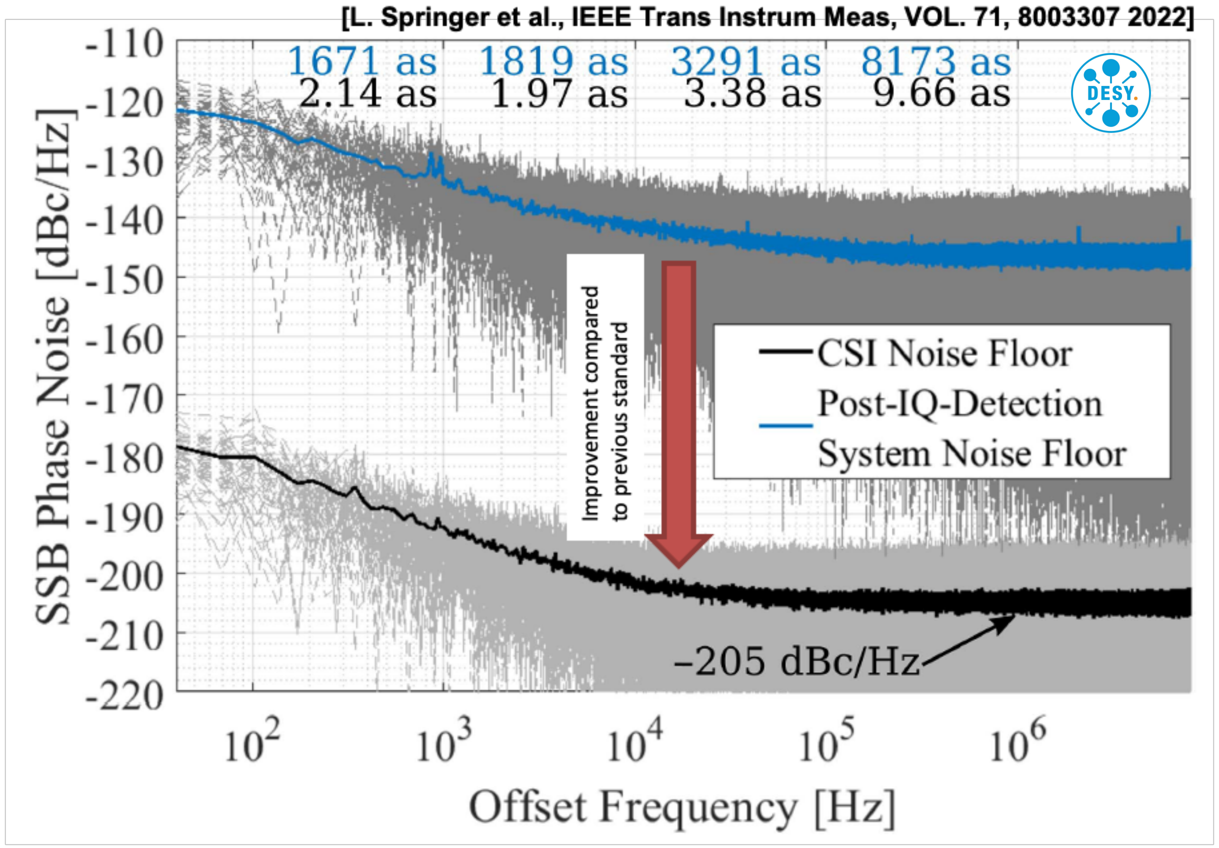
- Shift driving signal phase by π
- Loaded mode cancels with driving signal, less sensitive to amplitude differences





Detecting signals with unprecedented sensitivity

Carrier suppression interferometer



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)

Matches MAGO requirements and conditions

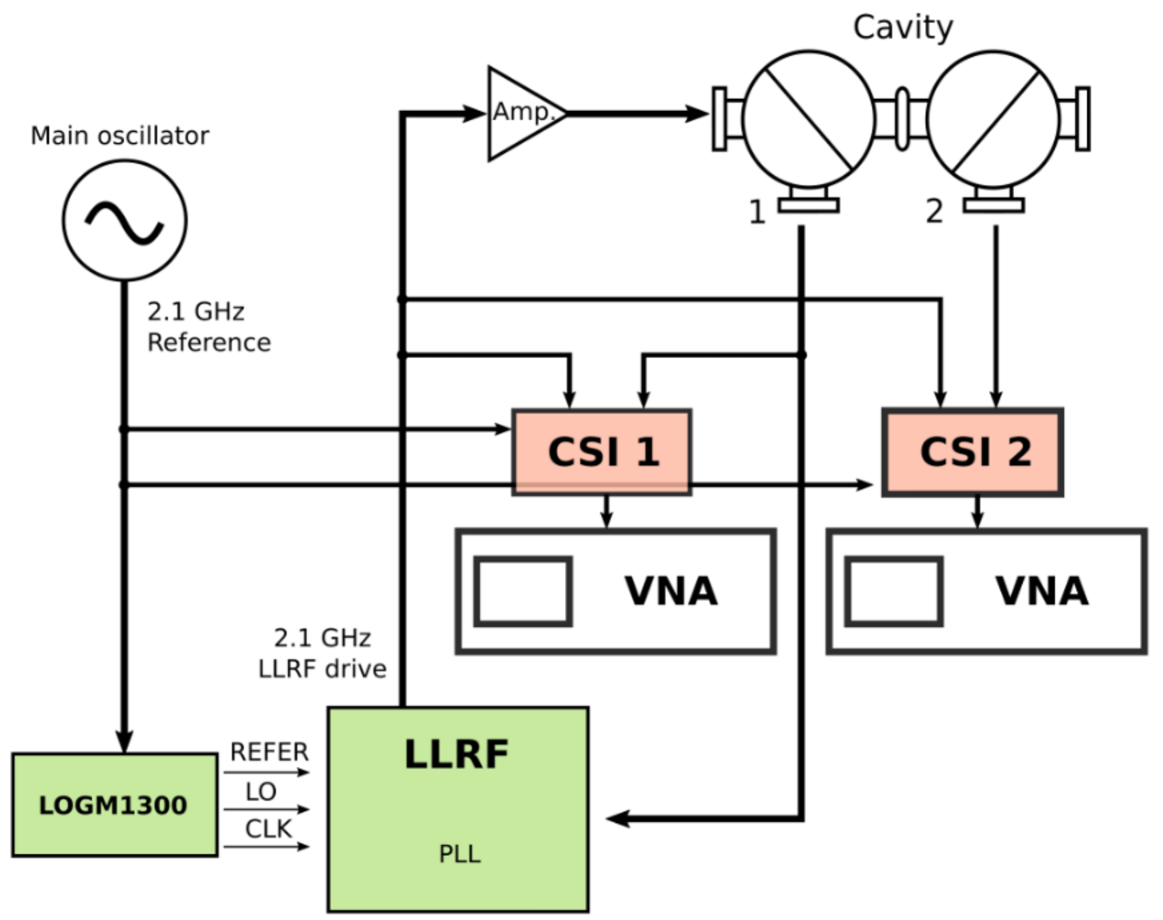
- High RF field amplitude for better sensitivity to GW
- Excited signal by GW is mixed to driving signal, with Δω in the 10-100 kHz range

Preliminary design of our LLRF architecture

Current R&D

- Use FPGA based cavity simulator to develop LLRF/CSI system
- Set up CSI at 2.1 GHz (operational frequency of MAGO)
- Integrate CSI with µTCA LLRF system

Test design with 1 CSI at cold RF test in 2024



How could a future experiment look like?

Cryoplatform at HERA North hall

Possible realisation of dedicated HFGW experiments

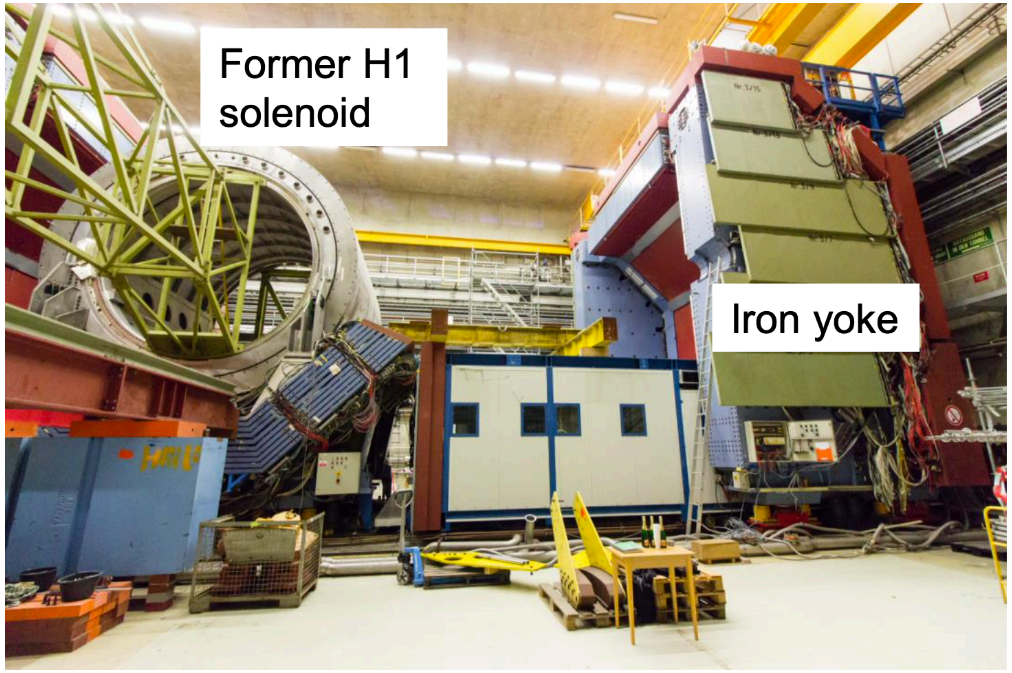
Distribution system of liquid helium (at ~ 4.5 K)

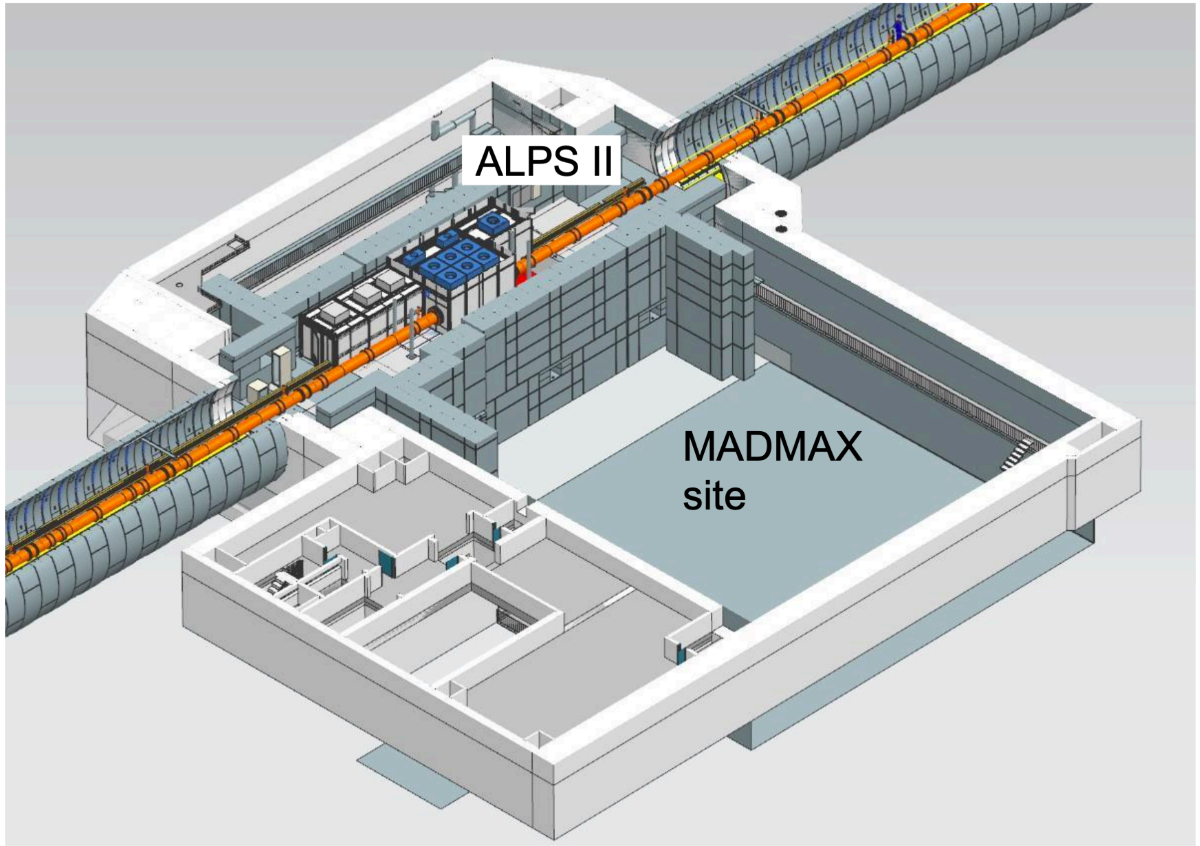
Supply for up to three experiment

In construction, operation from 2026

Located 30 m underground

Dimensions: height = 16 m, area = 1222 m^2





A dedicated cryostat

Main requirements

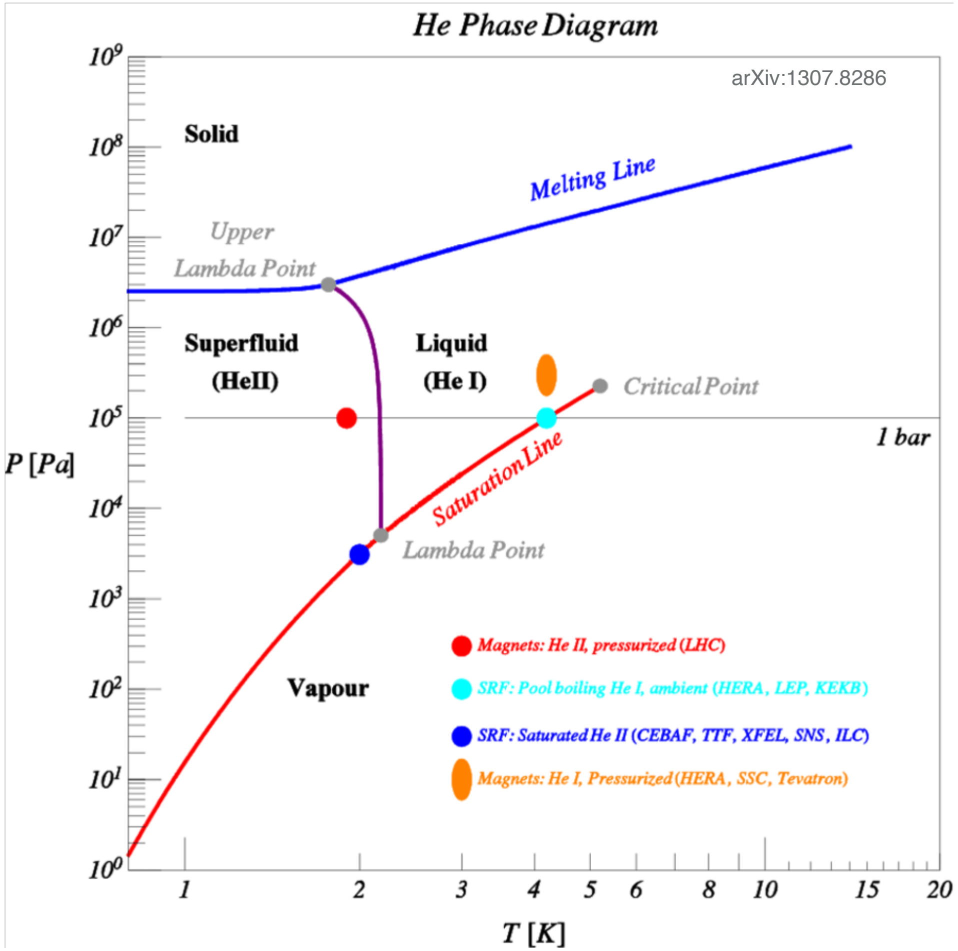
Exploit advantages of RF superconductivity

Avoid acoustic noise in the helium bath

- From thermal dissipation
- Pressure fluctuations
- Seismic and environmental noise coupled to the liquid

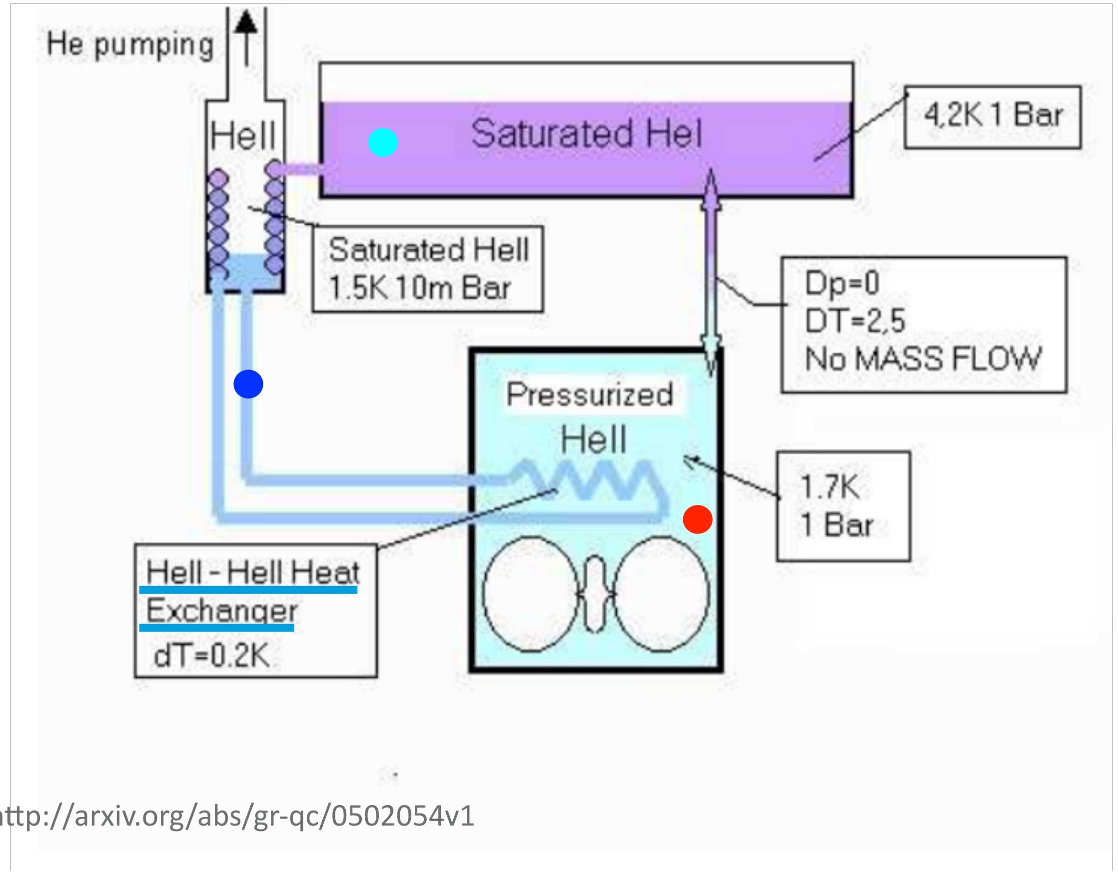
Pressurised superfluid Helium (1 bar, 1.8K) gives best thermal properties and minimised noise from He bath

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

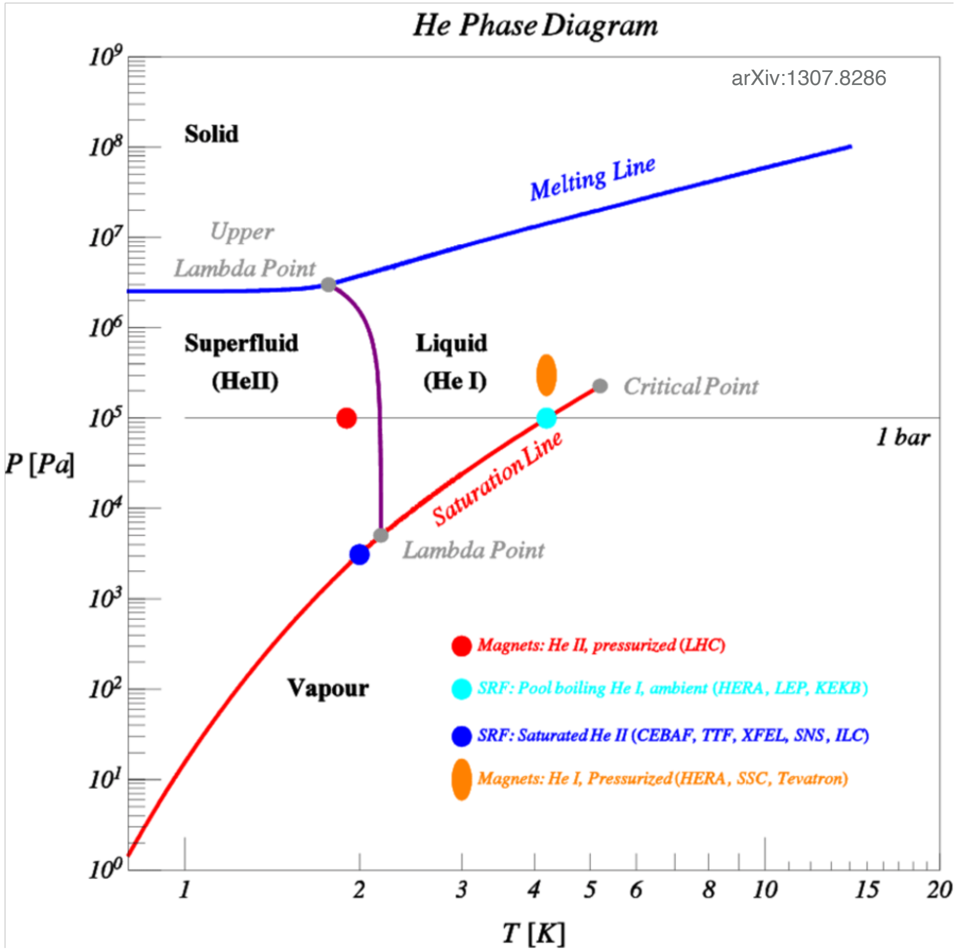


Concept from original MAGO proposal

Use superfluid helium with a heat exchanger

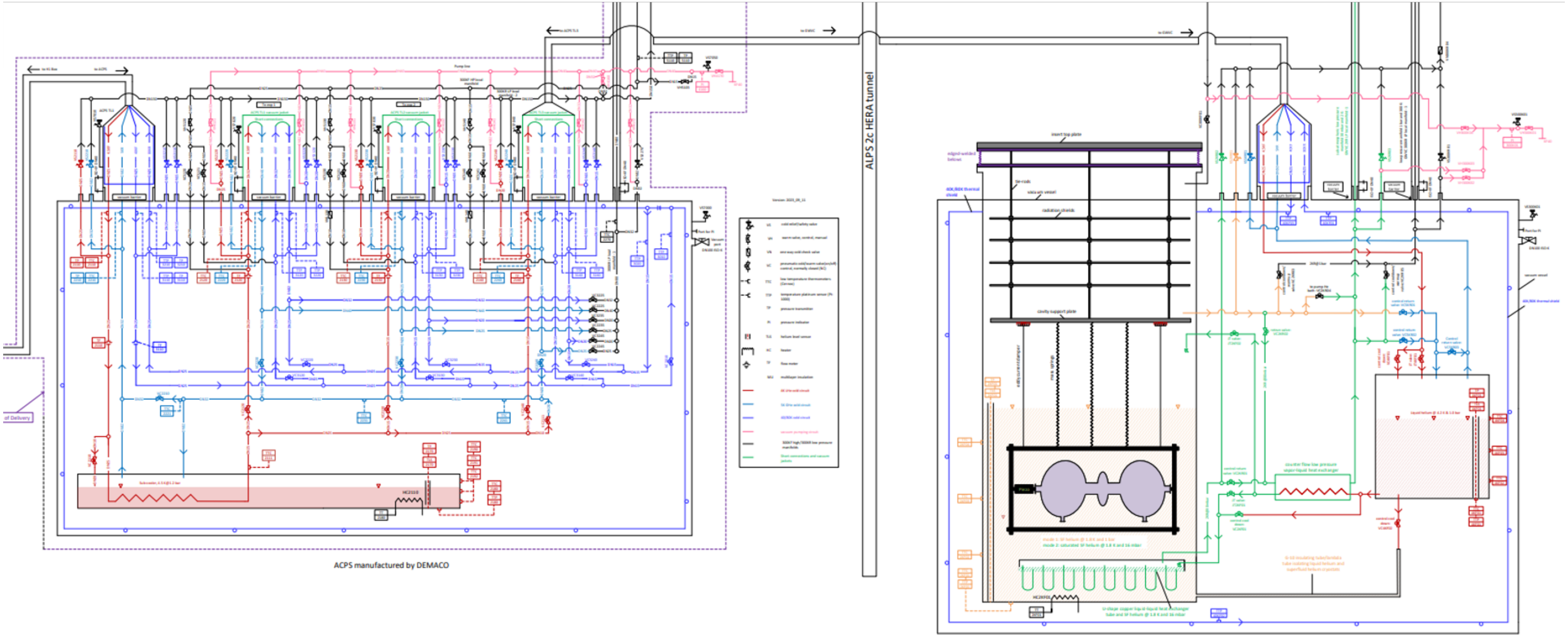


http://arxiv.org/abs/gr-qc/0502054v1



Design of cryostat started

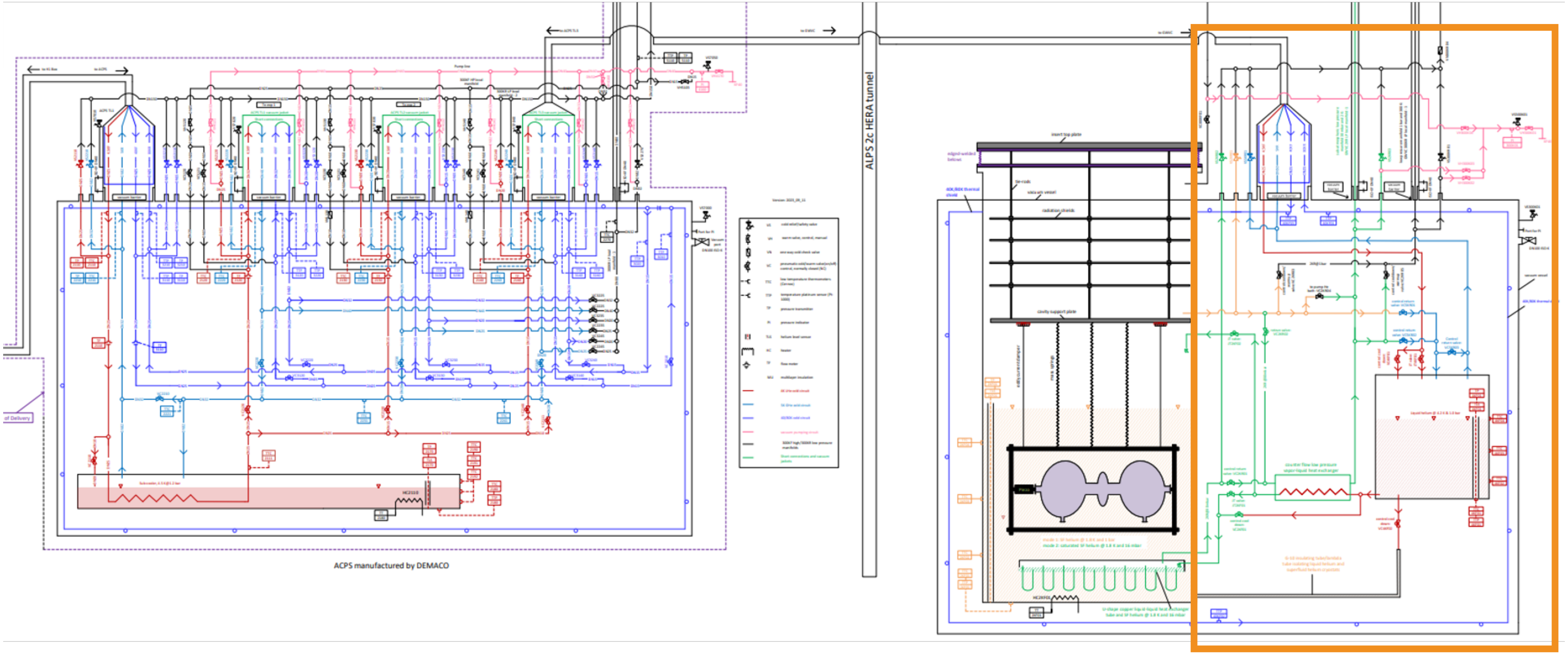
A possible flow scheme to host in DESY cryoplatform



Design of cryostat started

A possible flow scheme to host in DESY cryoplatform

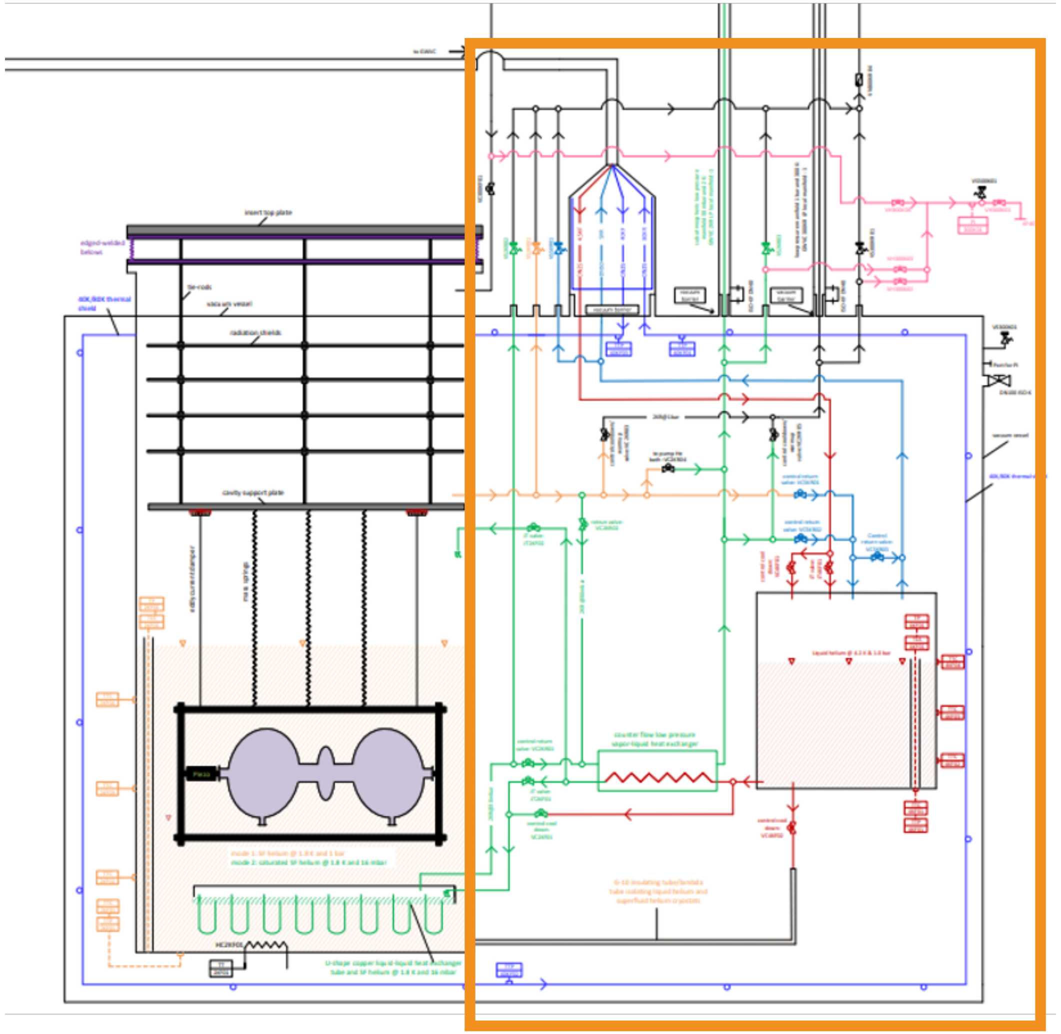
Elevate and outsource this part to maintain pressure and minimise noise



Gersemi vertical cryostat at FREIA Laboratory

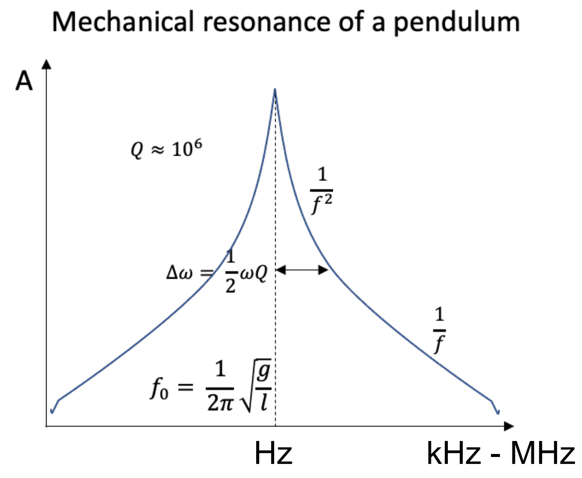
Similar design concepts

arXiv:2103.05265v1



Suspension system

Inspired from Ligo/Virgo concepts



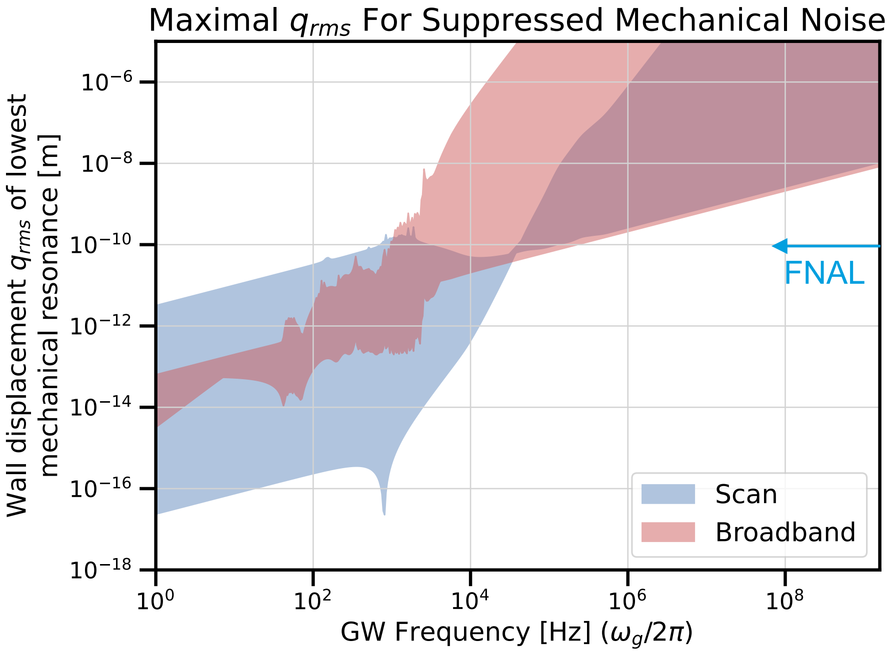
Requirements not as strict as for interferometers
Pendulum resonance ~Hz, measurement in kHz - MHz range
(strong natural damping and high Q factor of superfluid helium)

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

Minimise mechanical shortcut of connections (Vacuum, RF)

Measure ground motion in cryoplatform and **vibration** at cavity insert (accelerometer op. 77 K) to estimate required damping

In general: working on a more realistic 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

With the discovery of GWs, renewed interest in the heterodyne detection method with SRF cavities

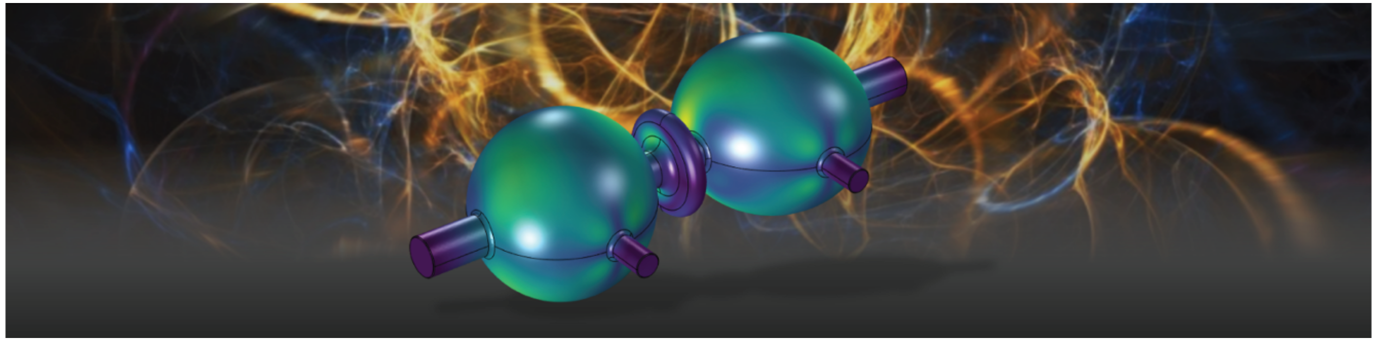
Especially the broad band sensitivity is tantalising

Use the existing MAGO prototype cavity to gain experience and design further optimised cavities

LLRF system development on the way, cryostat and suspension design addressed next

Still a long way ahead to reach projected sensitivities, but could aim for a CDR in 2-3 years for a future experiment

Moderate size of the experiment very attractive, allows also for several synchronised observatories



Thank you

Thanks to

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