Tunable haloscope at 10 GHz probing up to KSVZ QCD axion models

Giosuè Sardo Infirri
on behalf of the QUAX collaboration

20th PATRAS workshop
La Laguna (Tenerife), 22-26 September 2025

Contact me @ giosue.sardoinfirri@phd.unipd.it

Agenda

1. Overview of the QUAX apparatuses
2. QUAX-LNL haloscope:
   - Dilution refrigerator
   - Low-noise electronics
   - Dielectrically loaded cavity
   - Cavity tuning
3. Improvements on automatic haloscope:
   - Data acquisition
   - Data analysis
4. Recent results
5. Upcoming improvements and research lines @ PD-LNL
6. Conclusions

QUAX-aγ haloscopes

	LNF	PD-LNL
Magnetic Field	9 T	8 T
Target frequency ranges	8 – 9 GHz	9 – 11 GHz
Base temperature	30 mK	100 mK
Cavity mode	TM_{010}	TM_{030}
Unloaded quality factor	~ 50000	~ 75000
Cavity effective volume	0.139 L	0.450 L
Cavity frequency (@ cold)	8.817 GHz	10.212 GHz
Scannable region	289 MHz	90 MHz
Scanned region	6 MHz	38 MHz
Sensitivity	~ 6 $g_{a\gamma\gamma}$	~ 2 $g_{a\gamma\gamma}$
Scan rate @ KSVZ	0.12 MHz/day	1.5 MHz/day

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Laboratori Nazionali di Frascati

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$$\frac{\partial f}{\partial t} \propto f^{-4}$$

$$\frac{\partial f}{\partial t} \propto \frac{{V_{eff}}^2 Q_0 B^4}{{T_{sys}}^2}$$

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Dilution refrigerator

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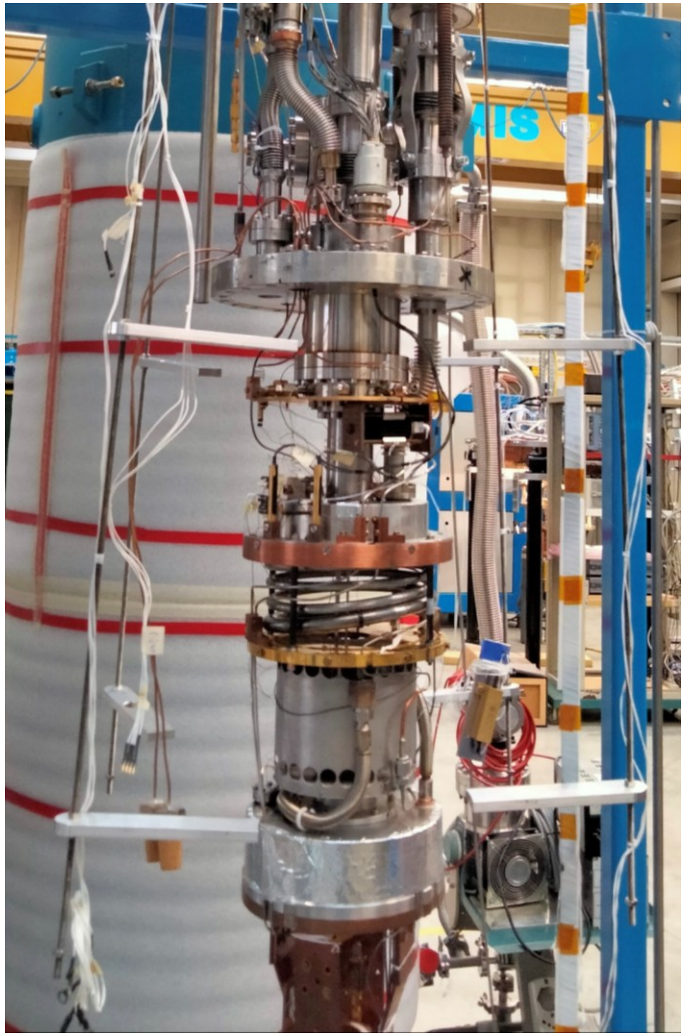

Wet dilution refrigerator:

- 100 mK @ Mixing Chamber (MC)
- Liquid-He to cool the magnets

Dilution refrigerator

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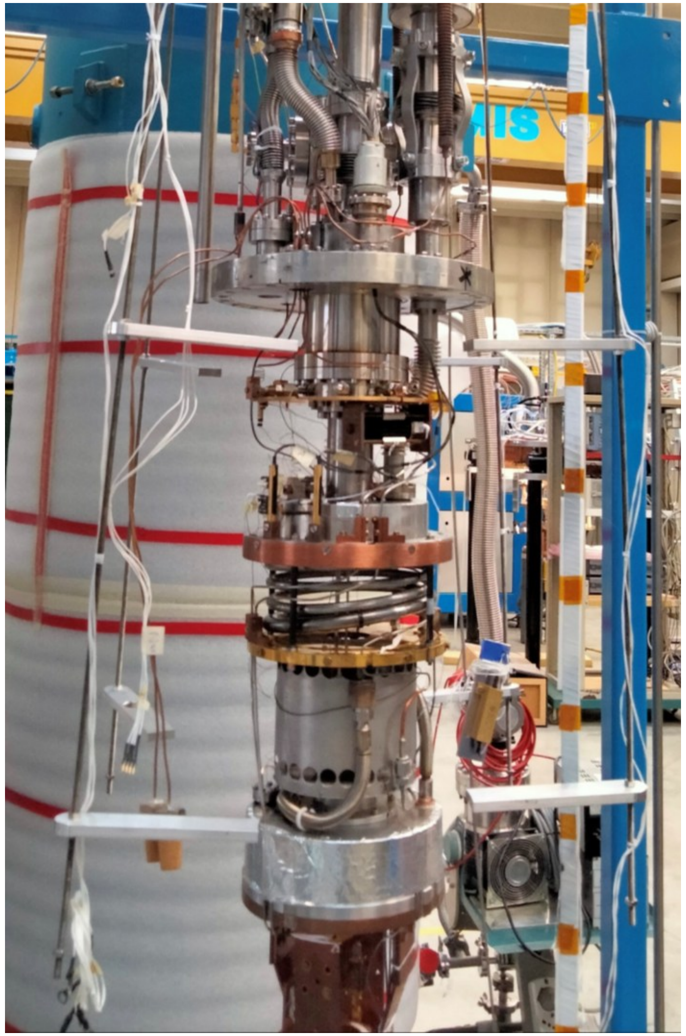

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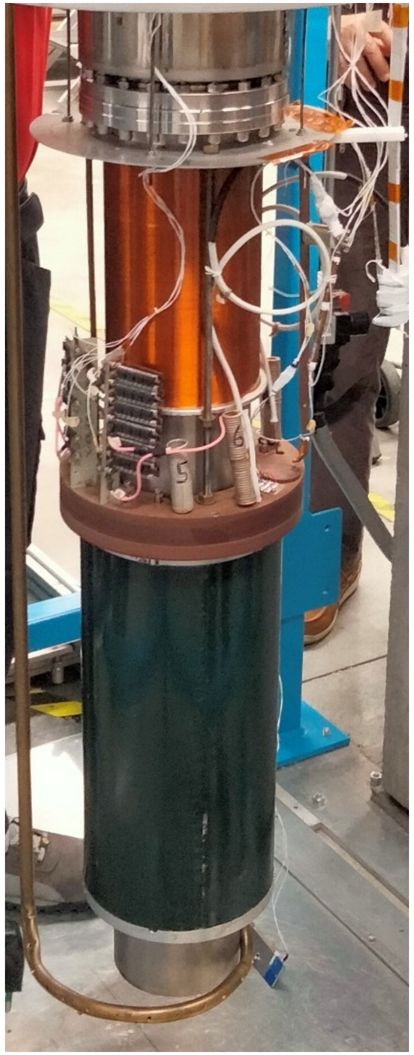
Magnets:

- Working in persisting current mode @ L-He temperature



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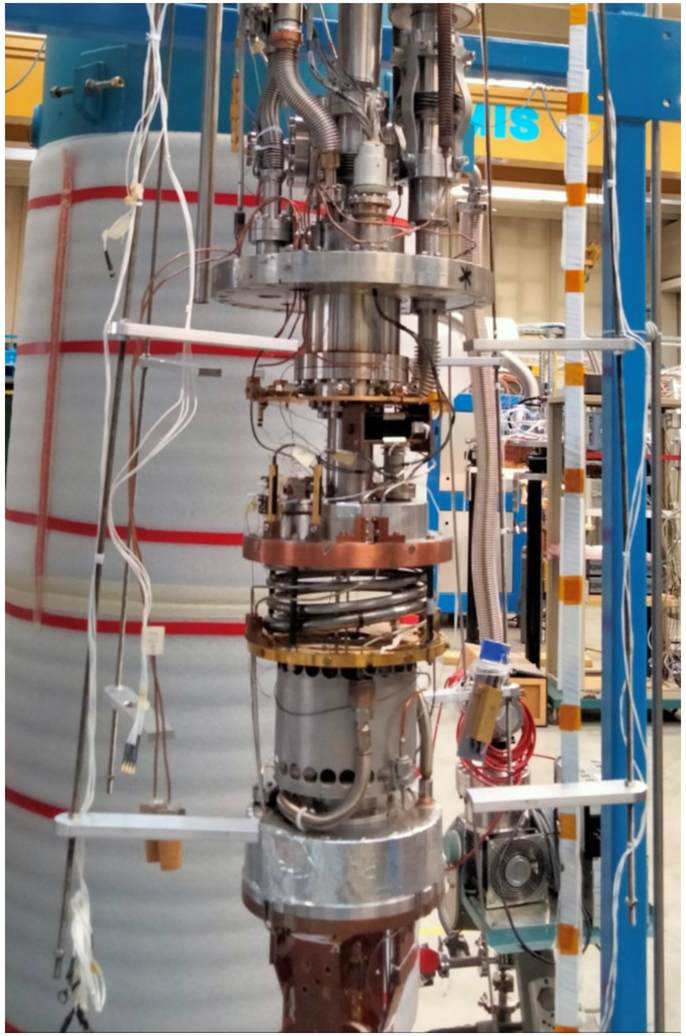

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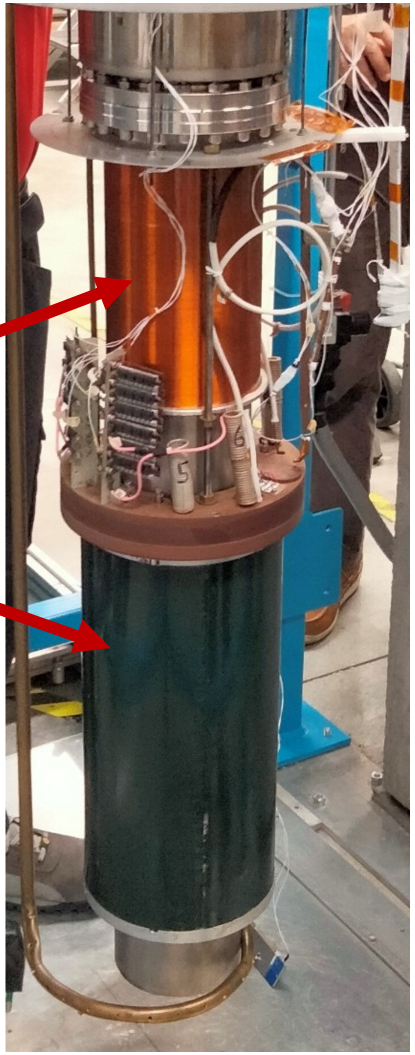

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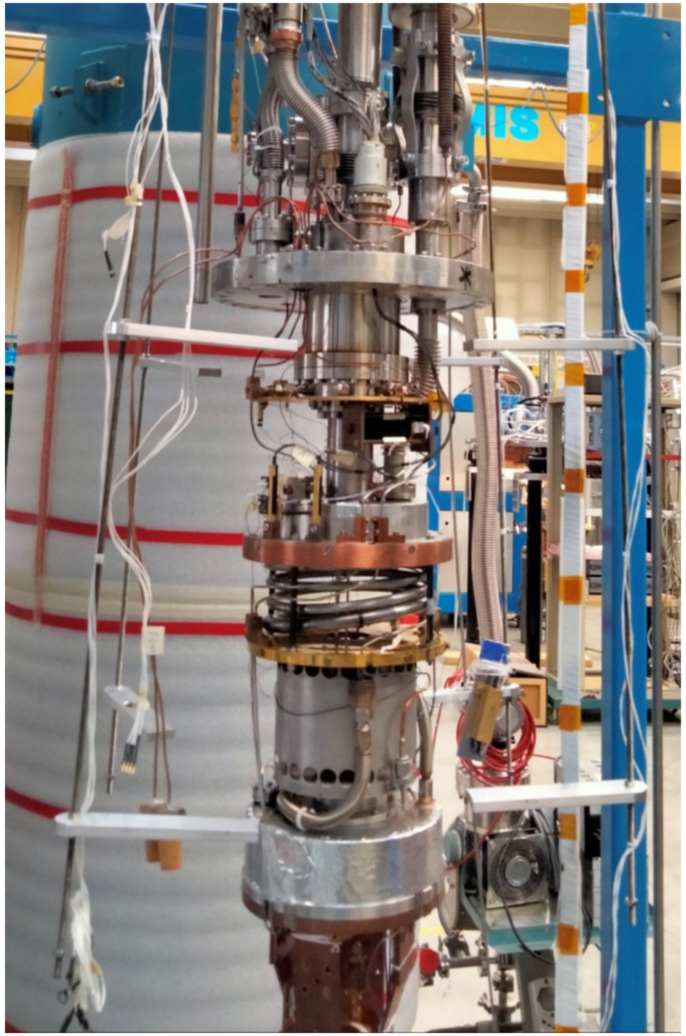

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Magnets:

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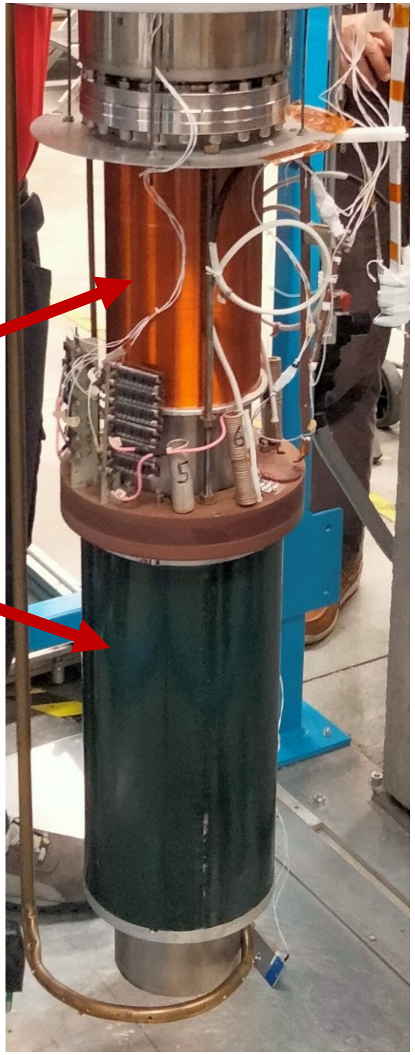
Typical values for acquisition:

- 3500 L-He dewar ~= 20 days run



Low-noise electronics

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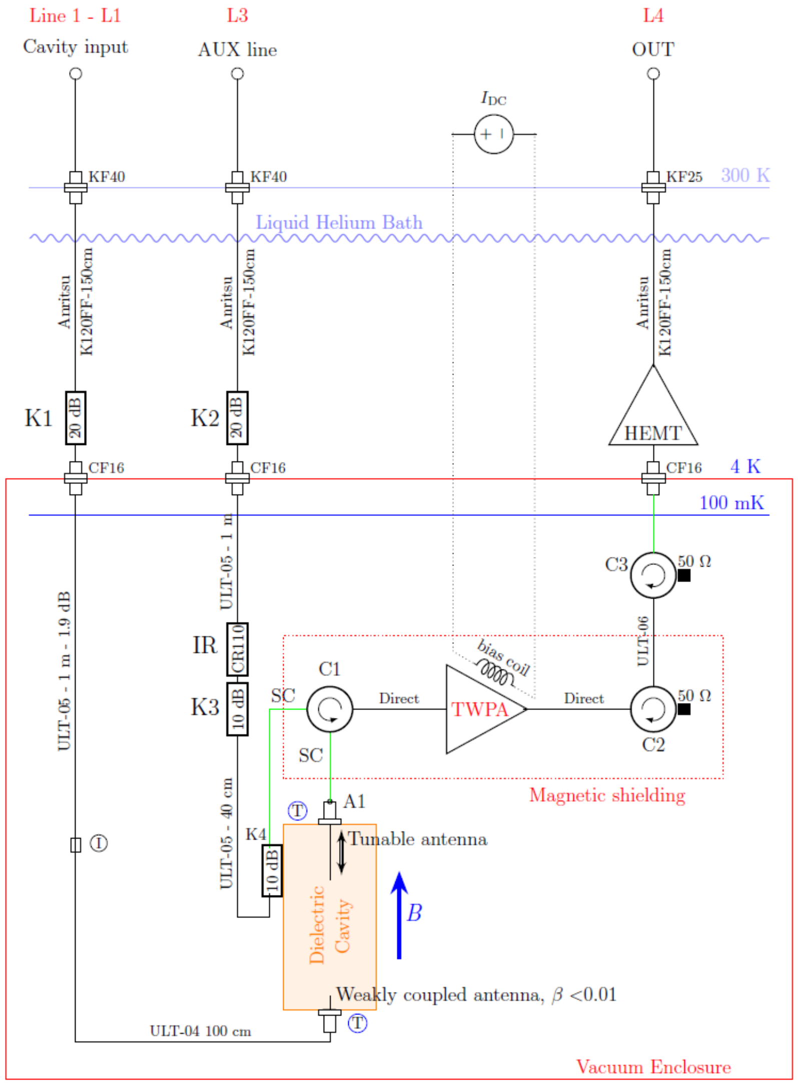

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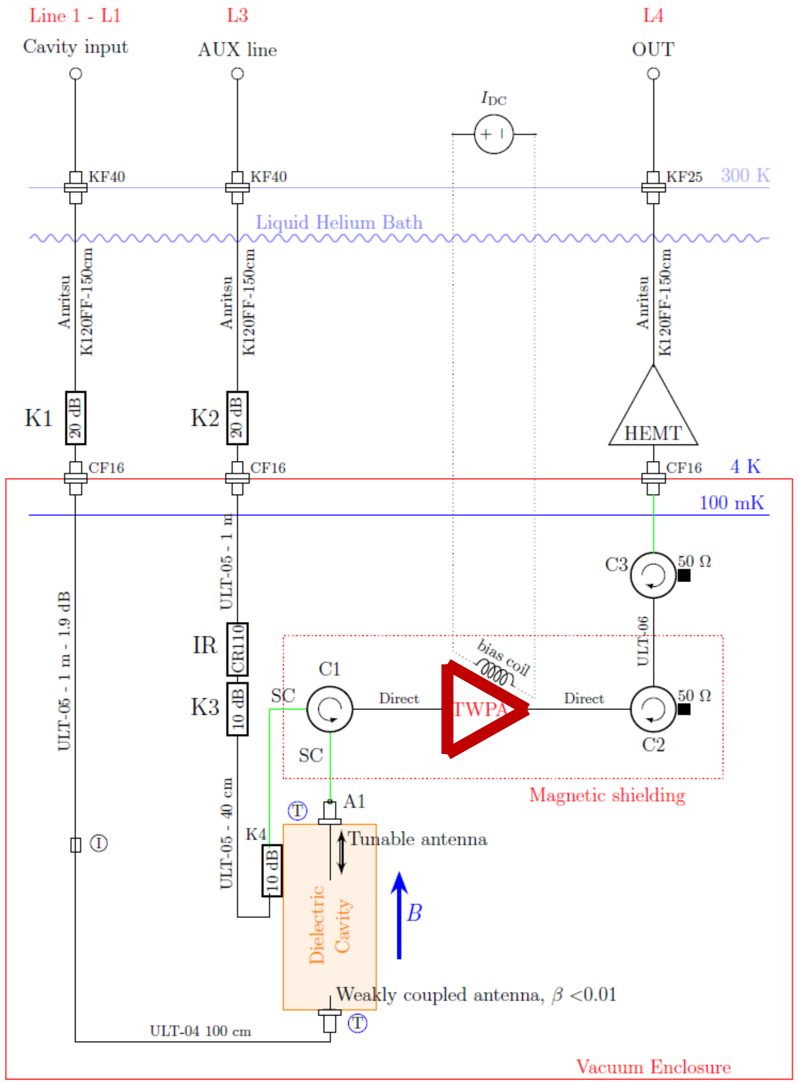
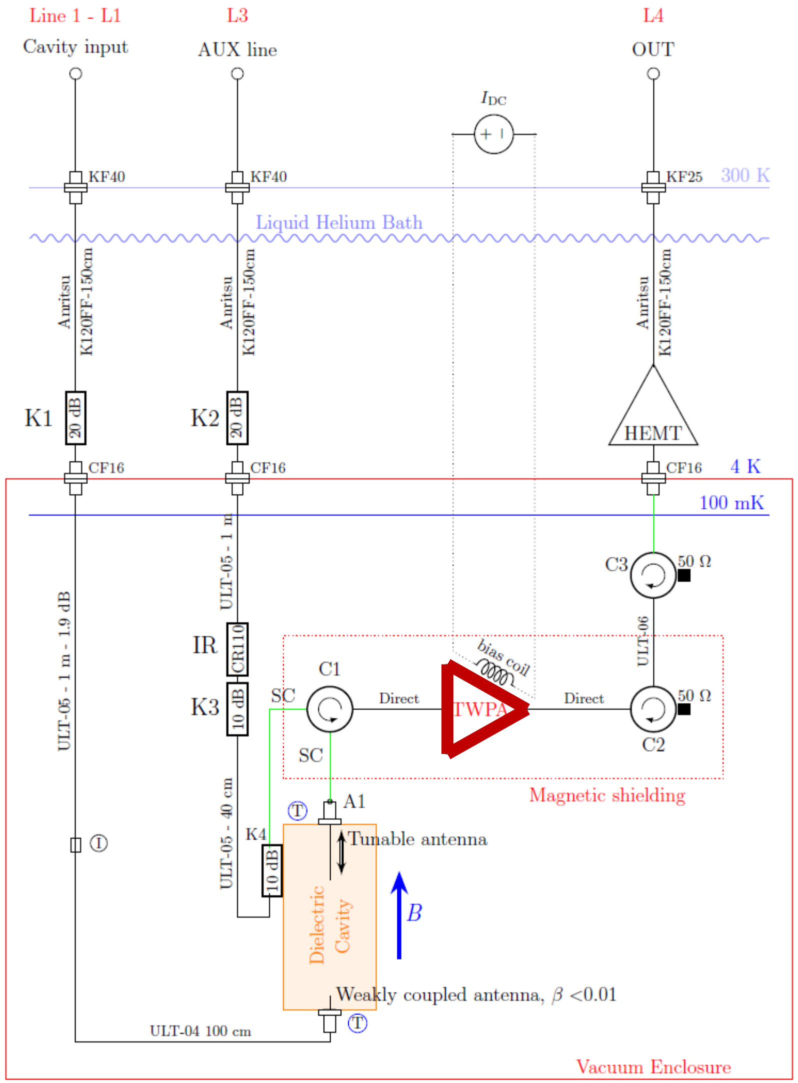
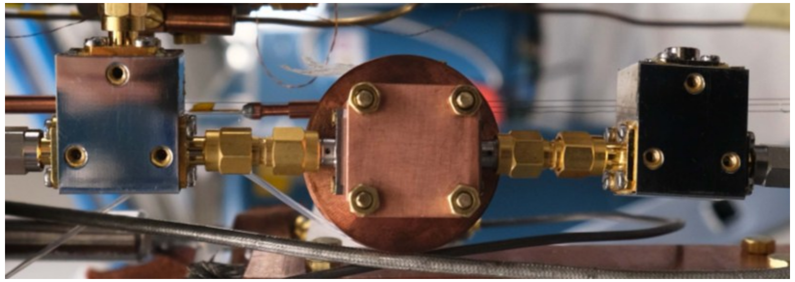


Dispersion engineering Travelling Wave Parametric Amplifier **TWPA:**

Low-noise electronics





Ranadive, A., Esposito, M., Planat, L. *et al.* *Nat Commun* **13**, 1737 (2022)

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- Developed by Nicholas Roch @ Grenoble

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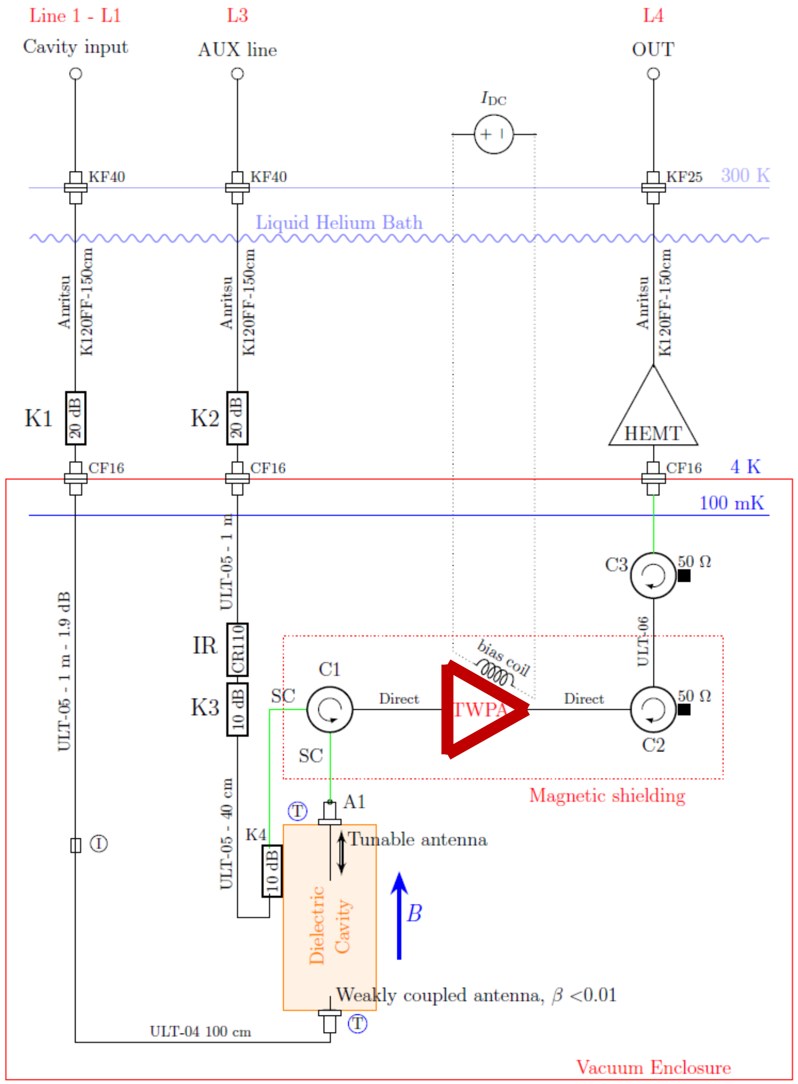

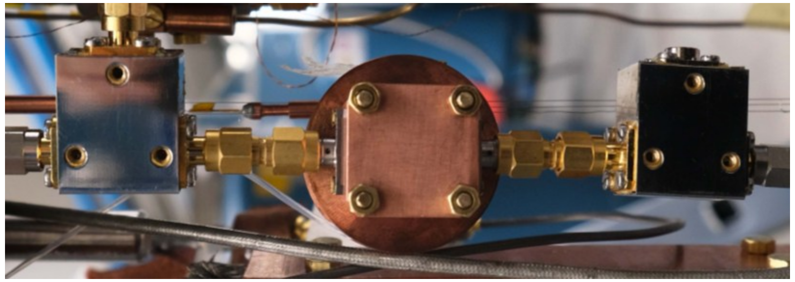

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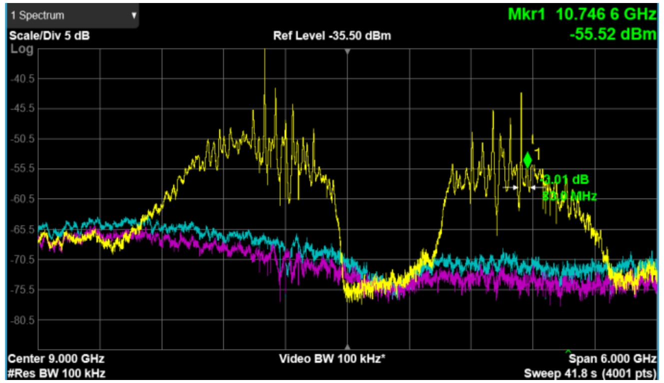
- Wide-band amplification range (6-12 GHz)



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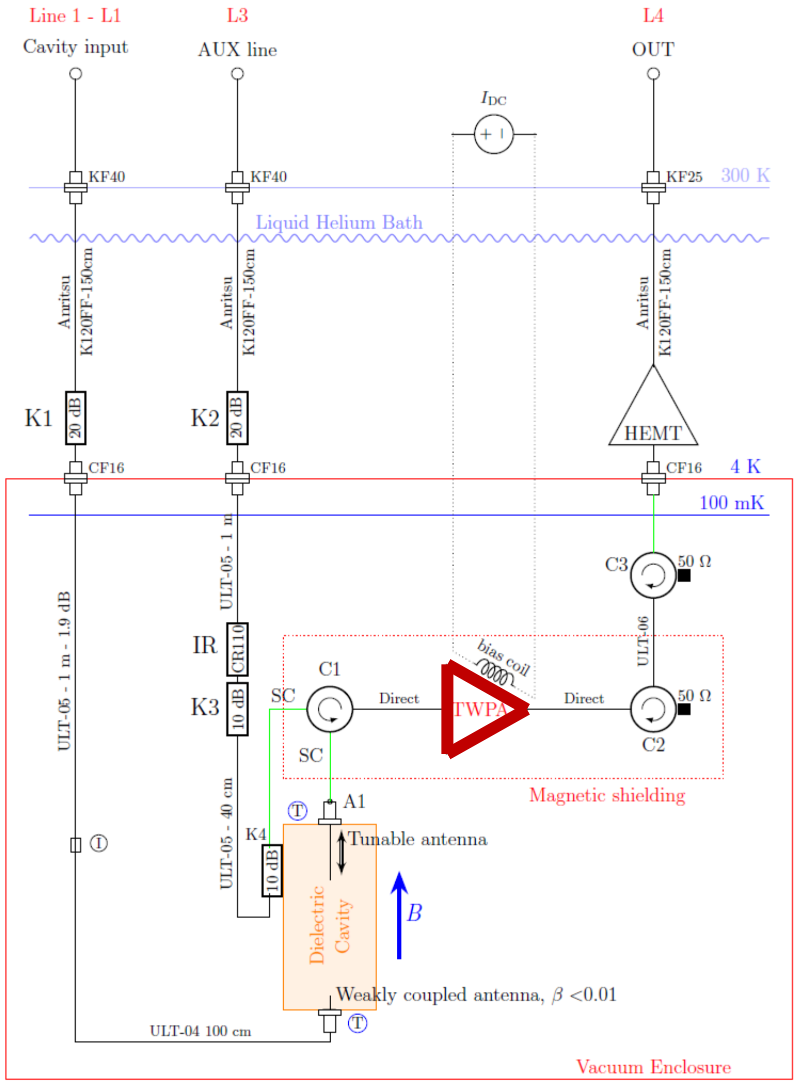

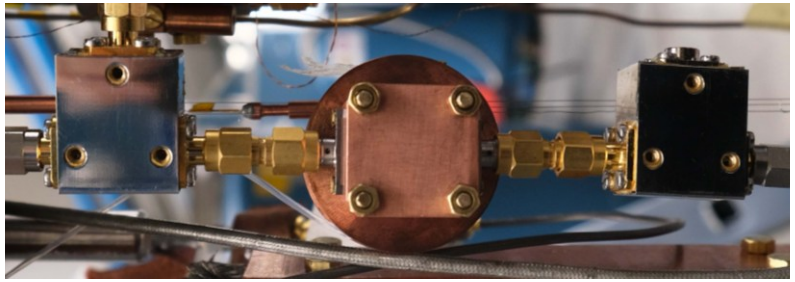

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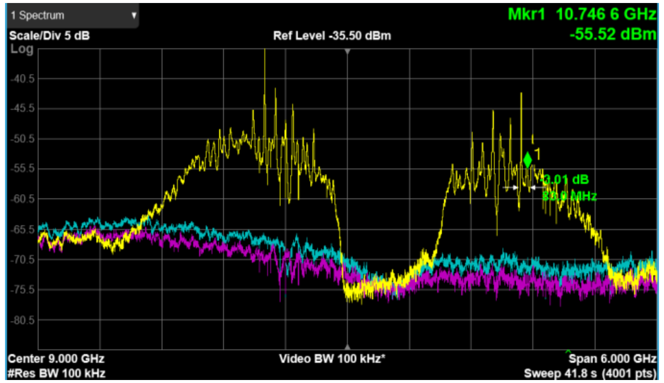
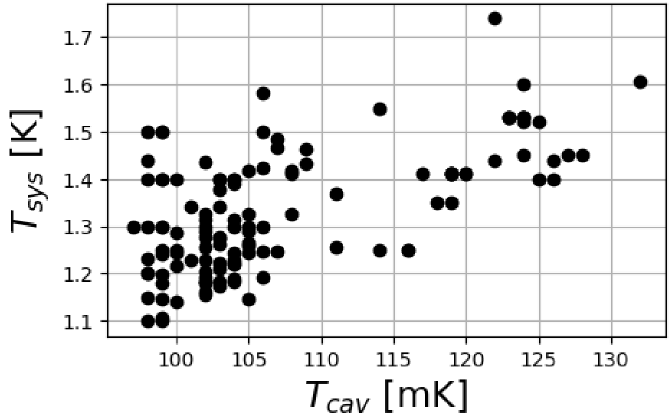


Typical values:

- Working @ 100-110 mK



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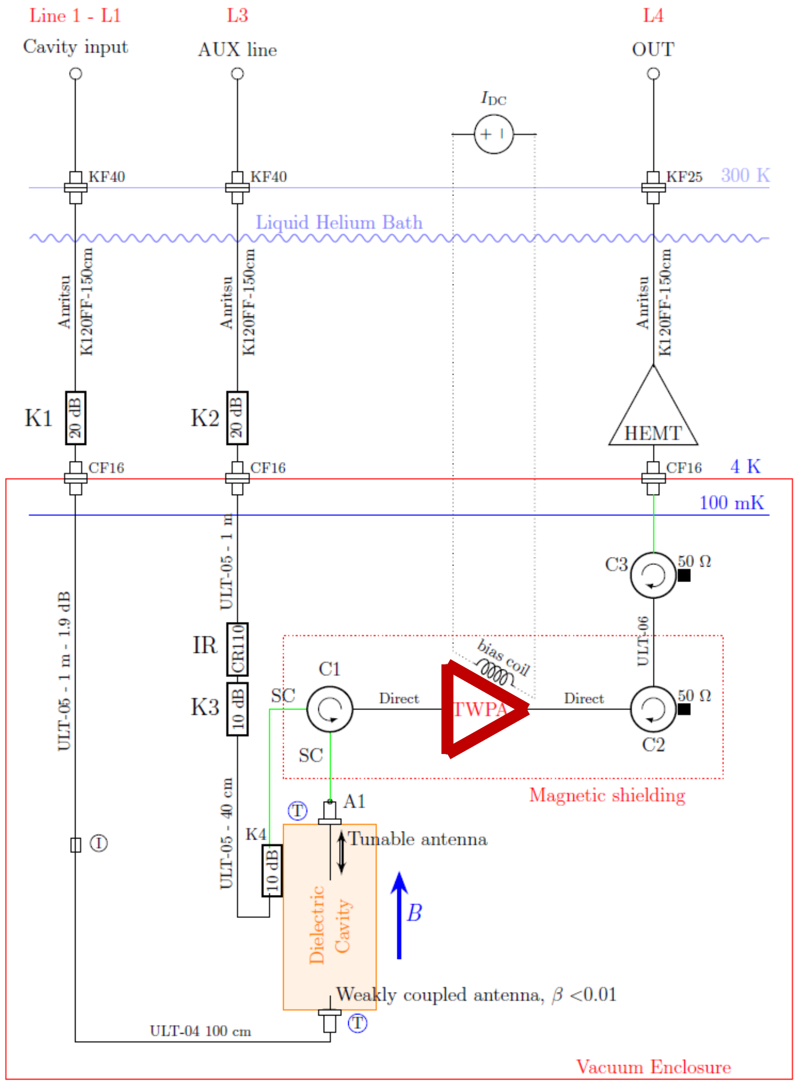

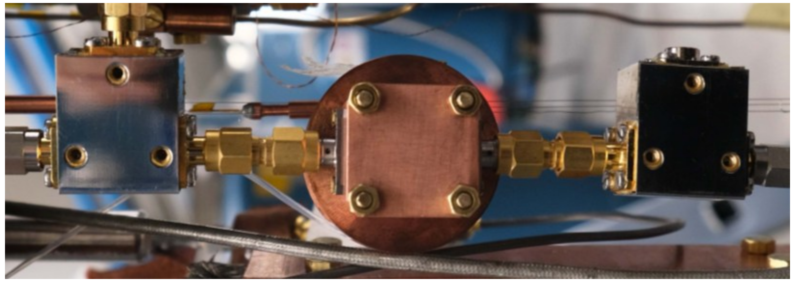

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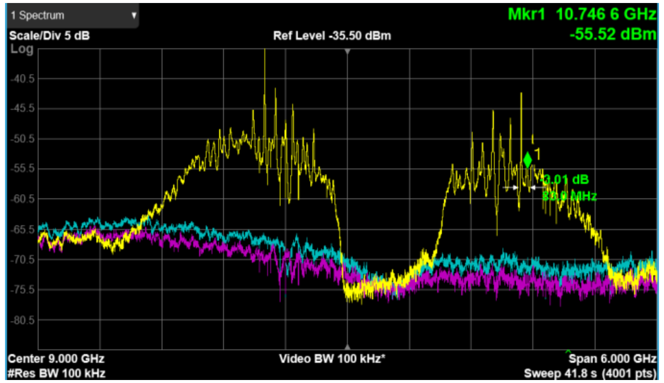
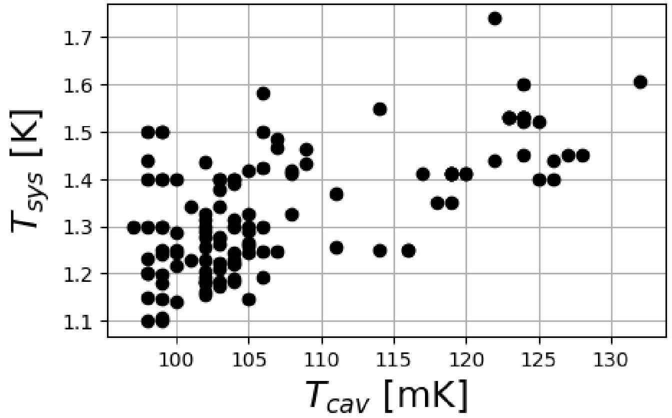
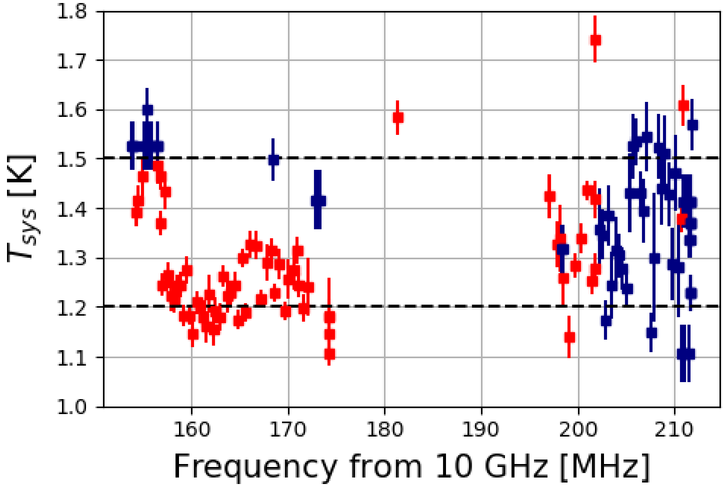


Typical values:

- Working @ 100-110 mK
- Noise temperature T 1.2 -1.5 K (2 SQL @ 10 GHz)





Dielectrically loaded cavity

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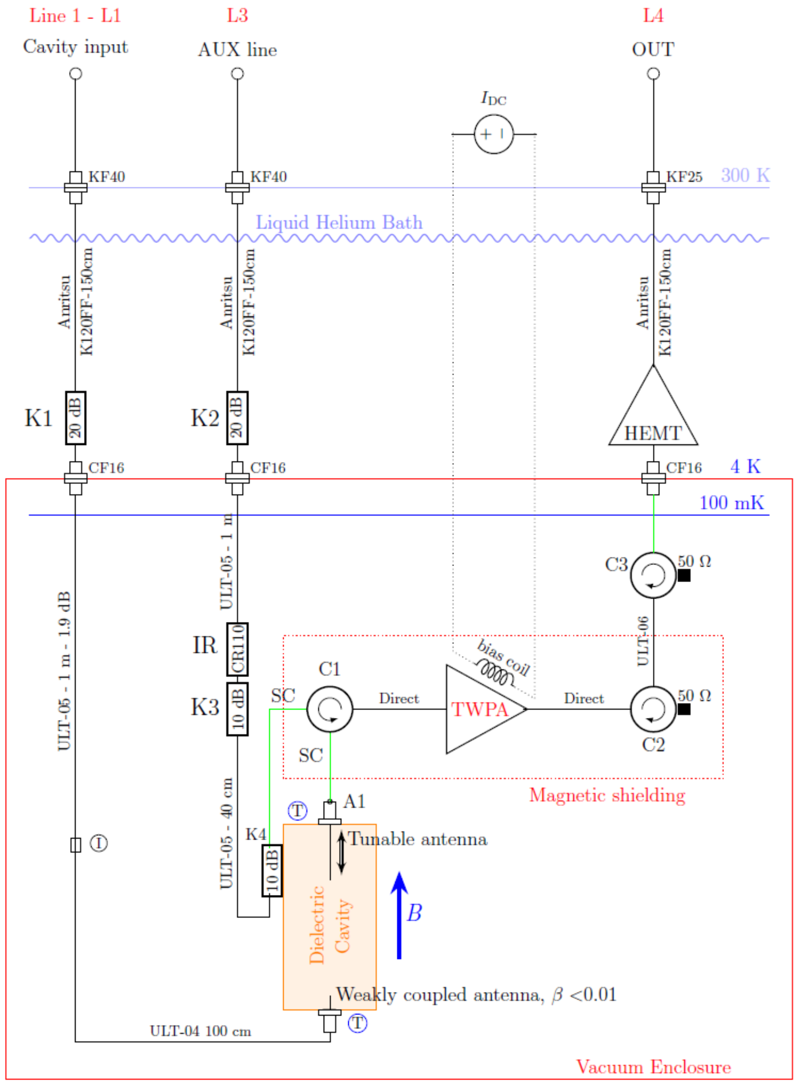

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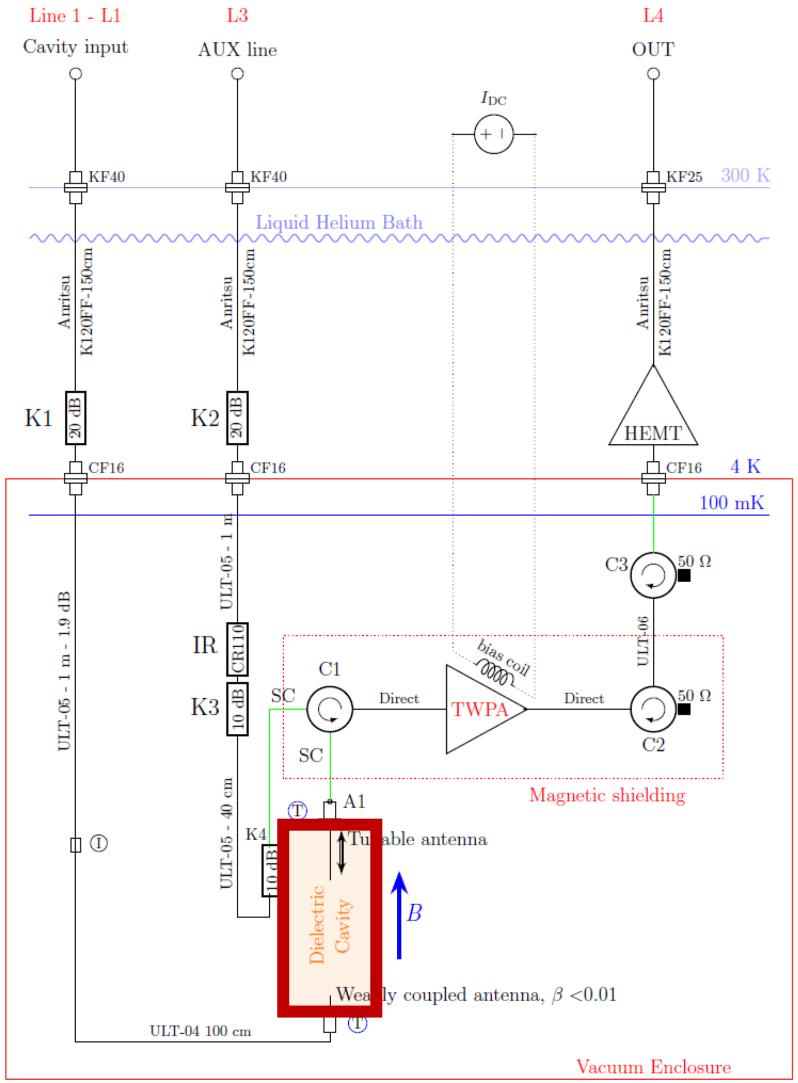

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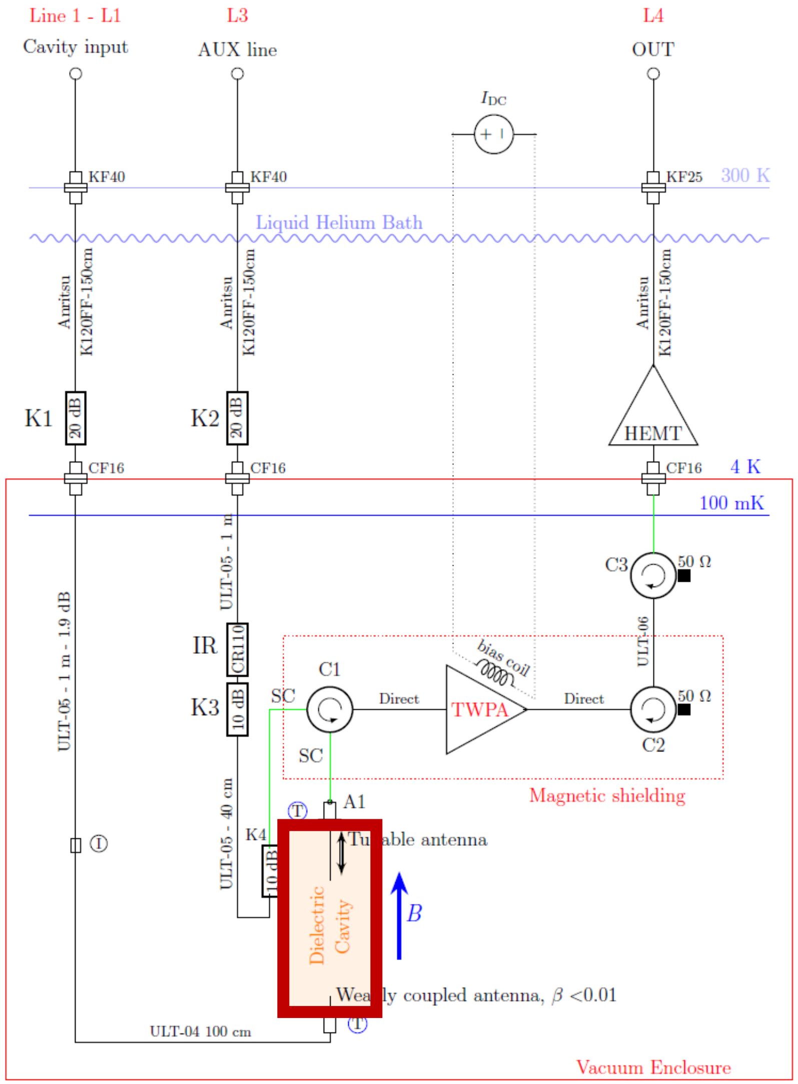

Dielectrically loaded cavity:

- Working frequency $\nu_{030} \sim 10$ GHz

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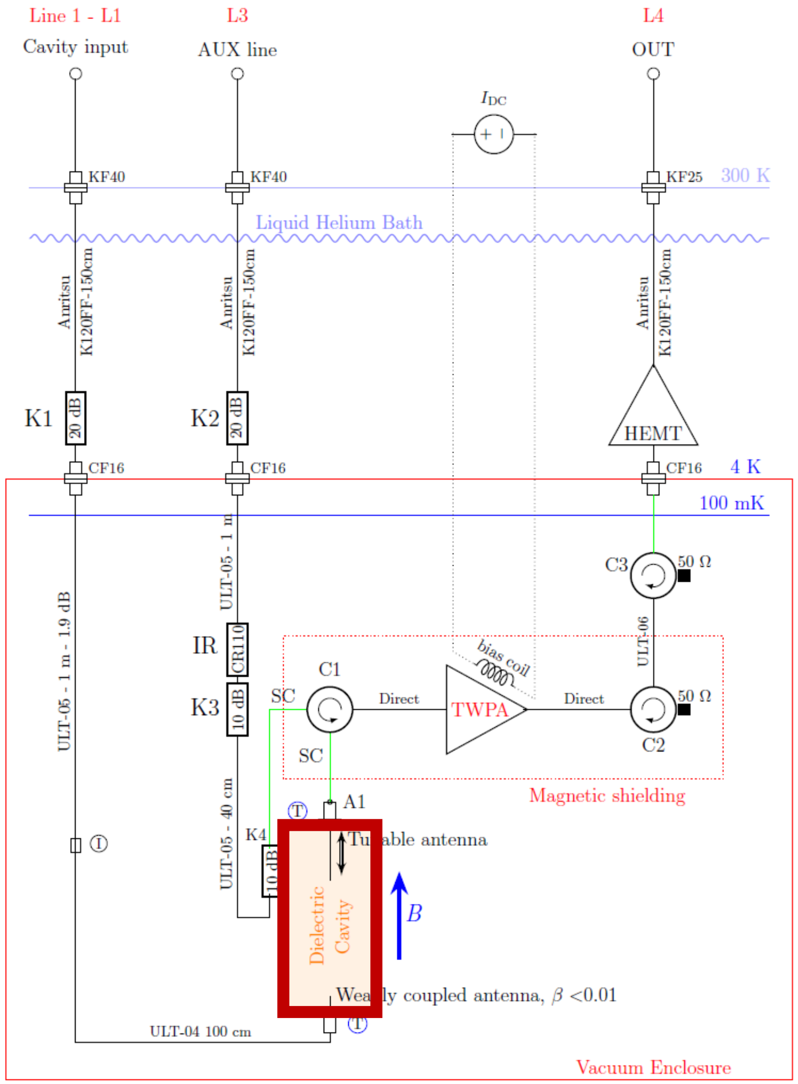

Dielectrically loaded cavity:

- Working frequency $\nu_{030} \sim 10$ GHz
- Use of high-order mode TM_{030}

Dielectrically loaded cavity

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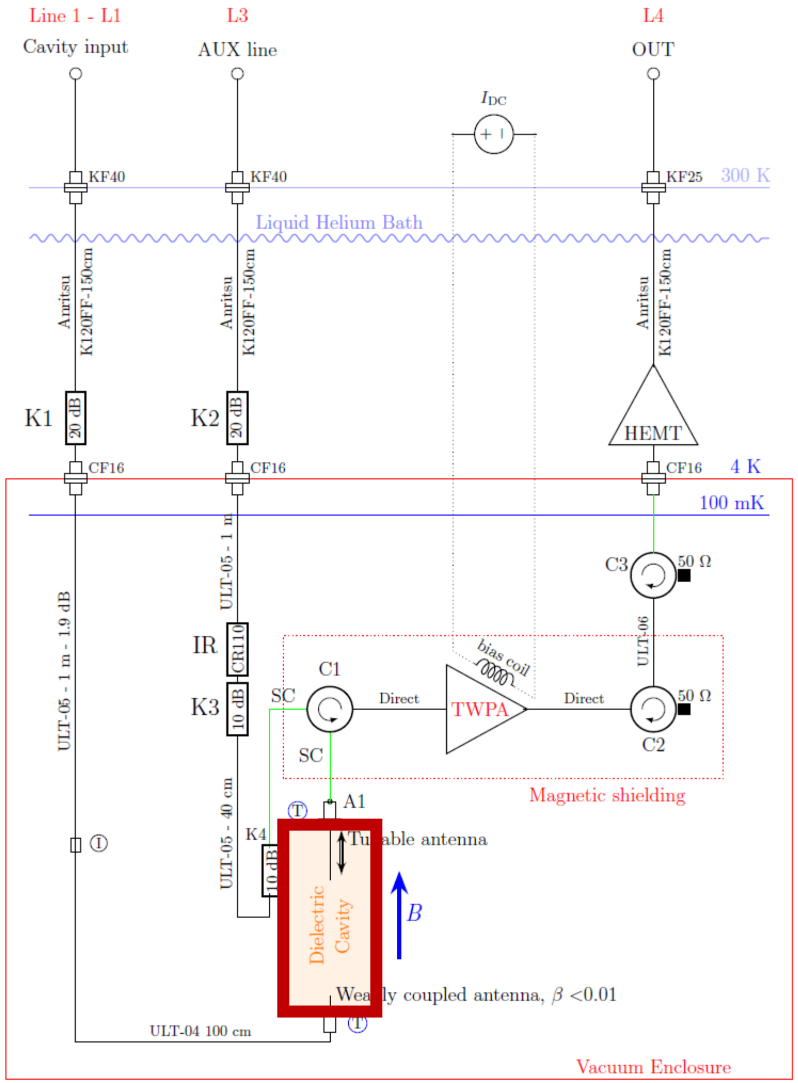

Dielectrically loaded cavity:

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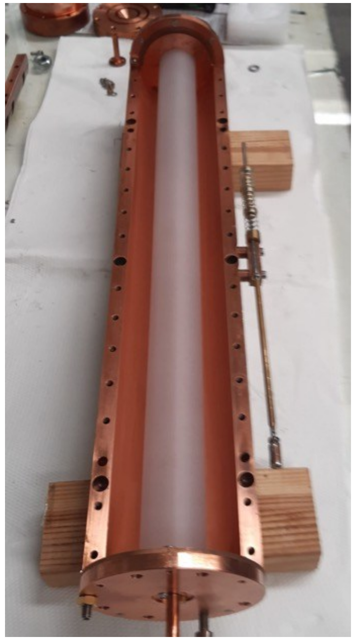
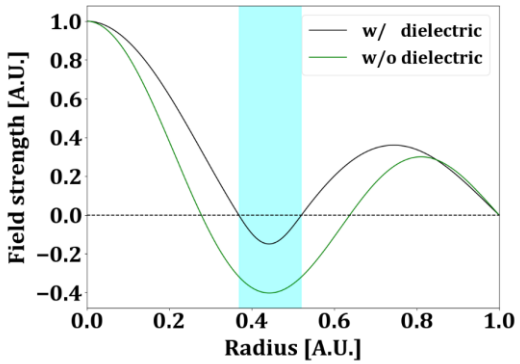
- Use of high-order mode TM_{030}
- Cavity field profile reshaped using sapphire tube





R. Di Vora et al.
Rev. Sci. Instrum. 96, 085204 (2025)

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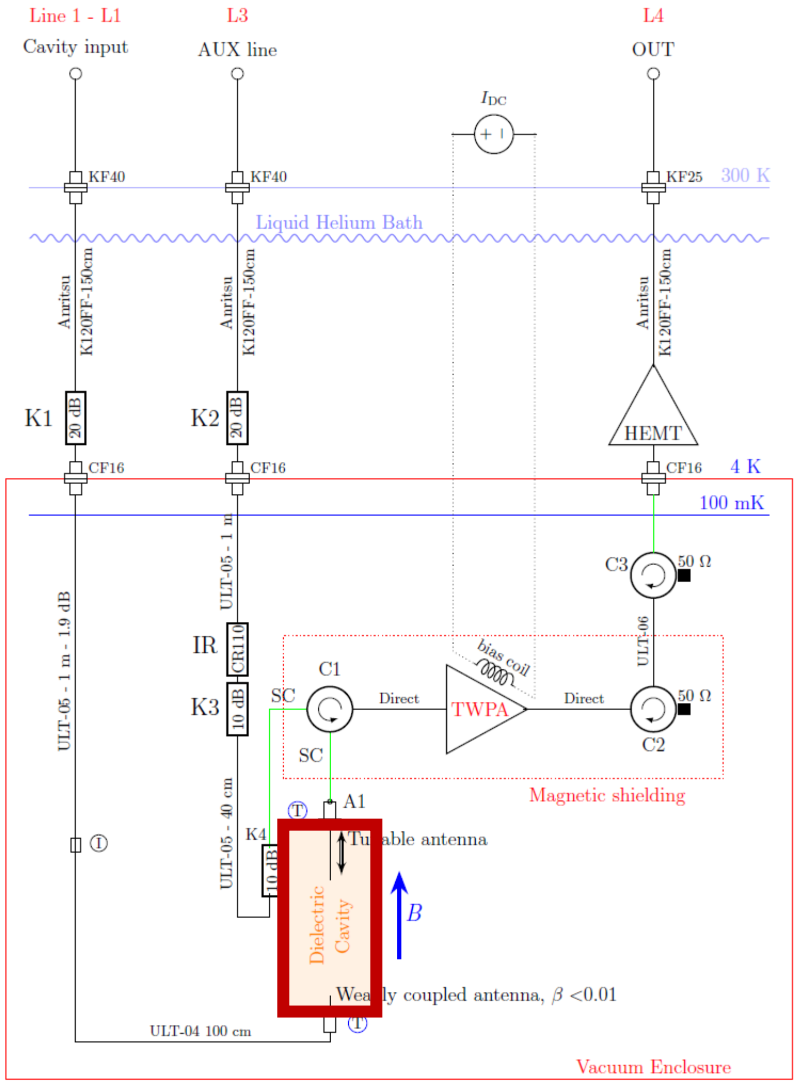

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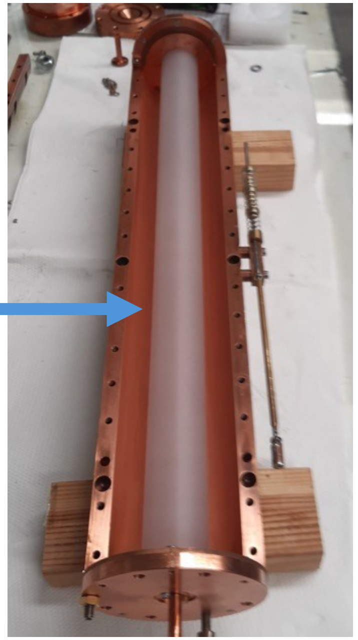

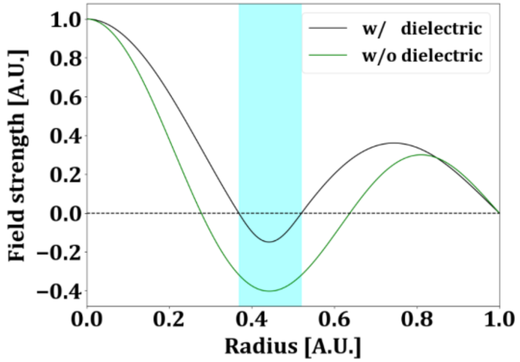

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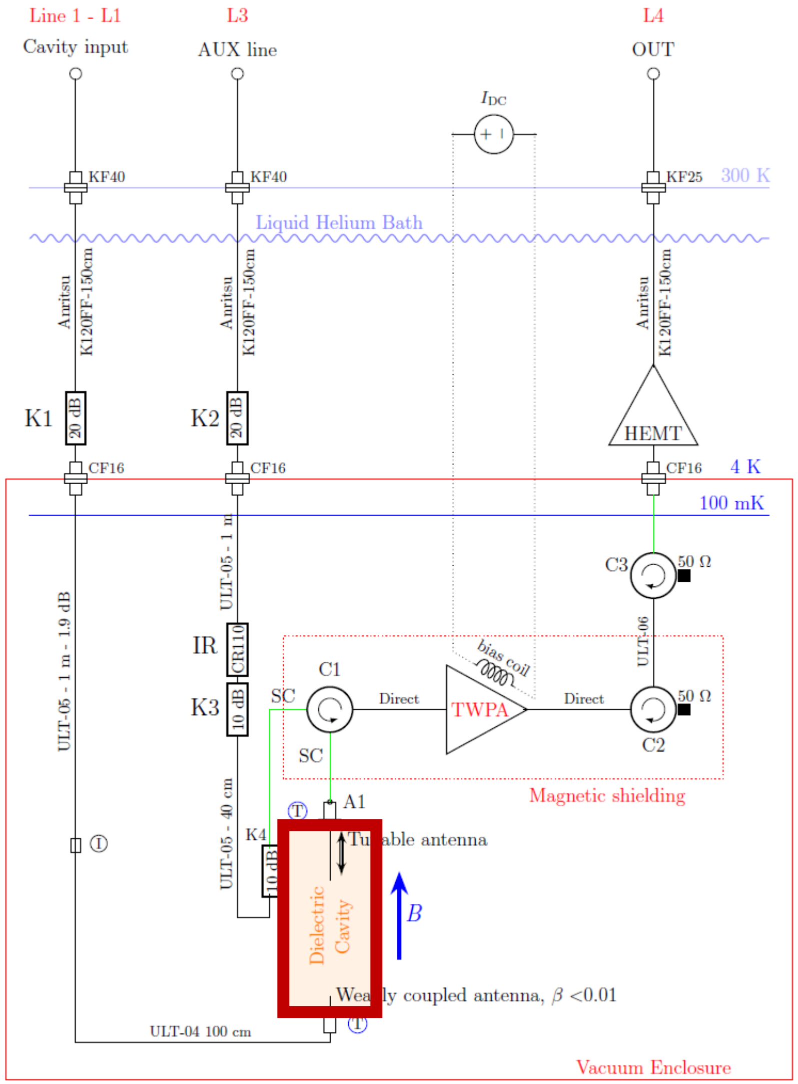

Dielectrically loaded cavity:

- Working frequency ν_{030} ~ 10 GHz
- Use of high-order mode TM_{030}
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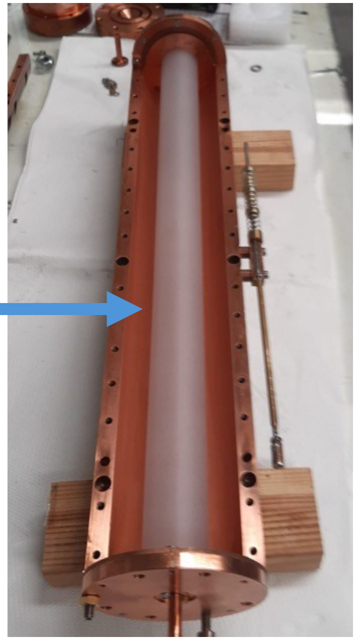
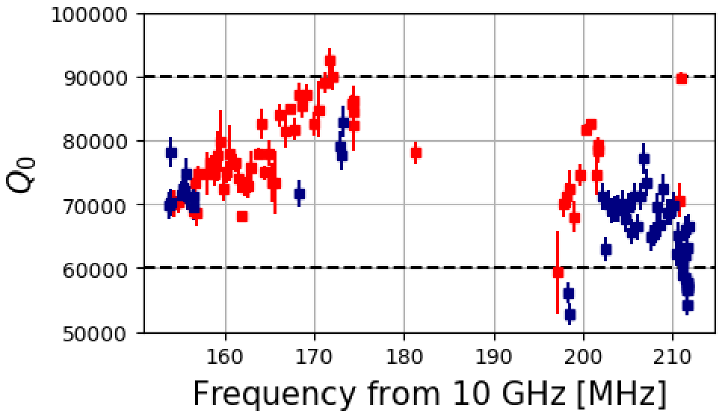
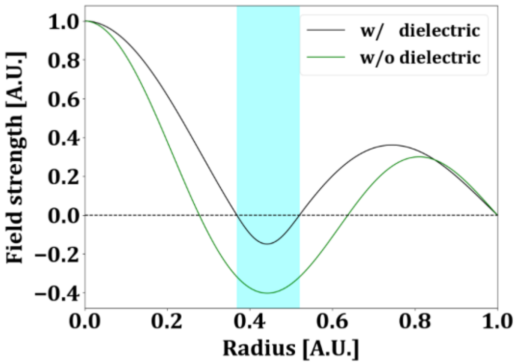


Form factor	C_{030} ~ 0.43
Volume	V ~ 1 L (V_{eff} = V*C_{030})
Quality factor	Q_0 ~ 60000-90000





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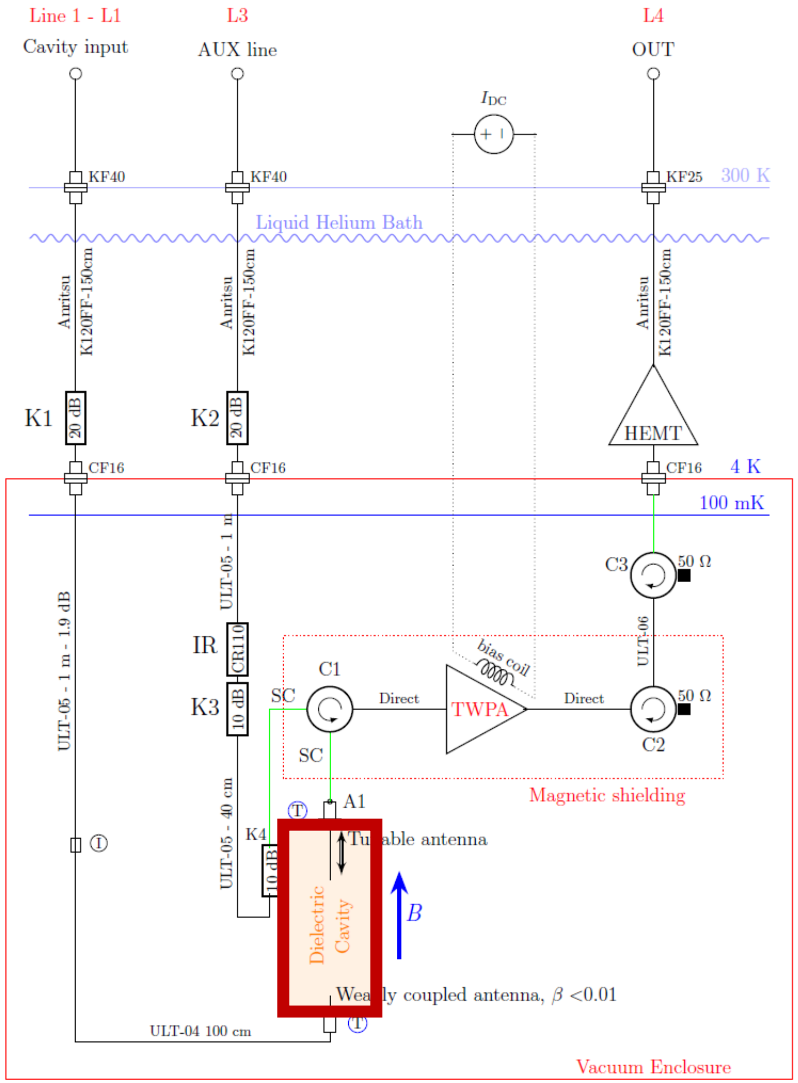

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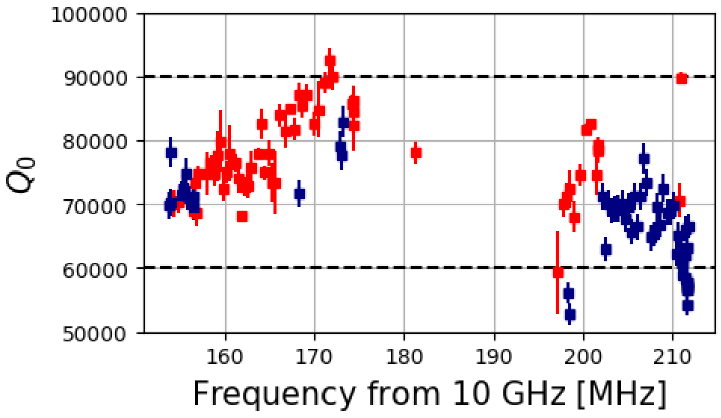
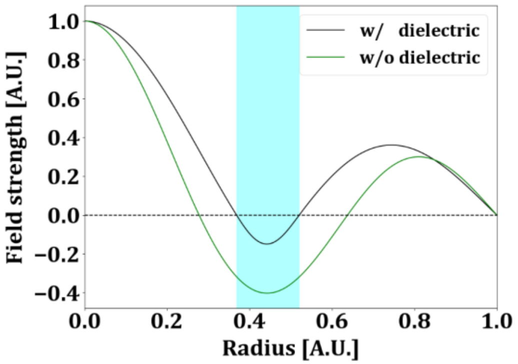


- Comprised of two copper halves



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Cavity tuning

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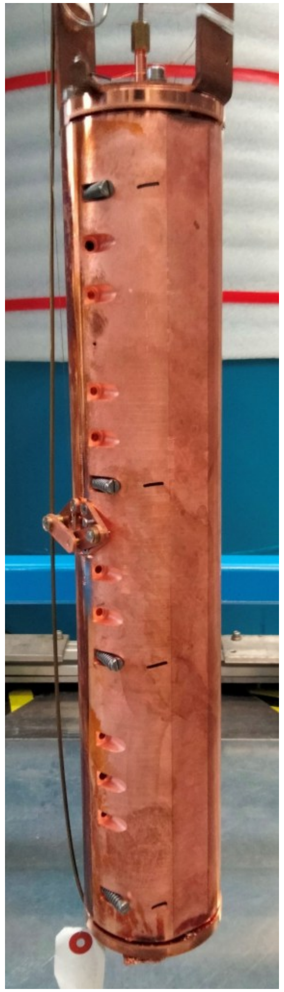
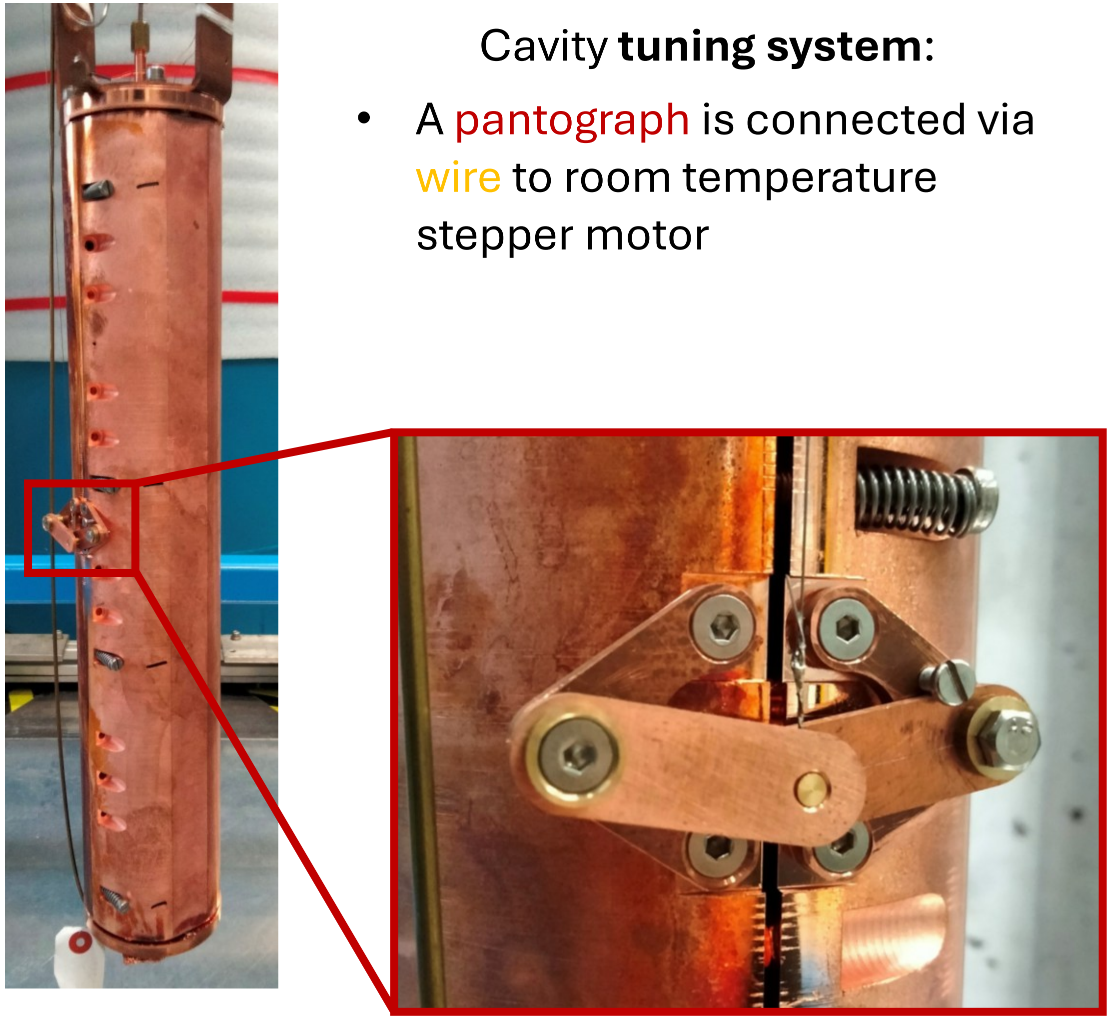


Cavity **tuning system**:

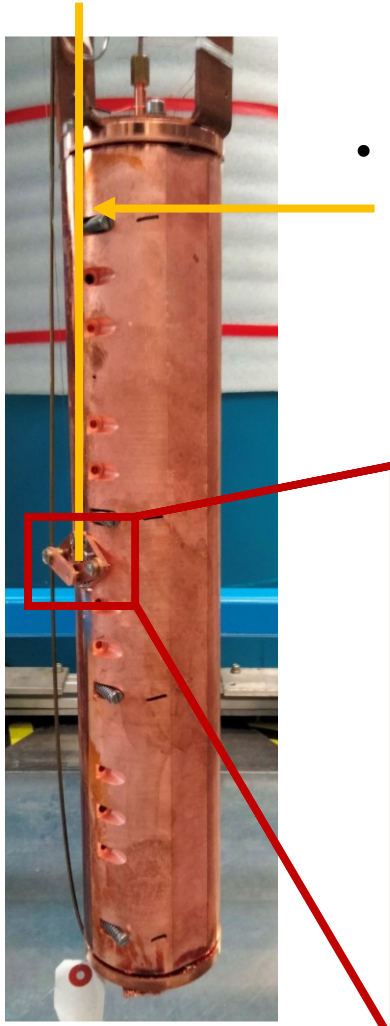
Cavity tuning



Cavity **tuning system**:

- A pantograph is connected via wire to room temperature stepper motor

Cavity tuning



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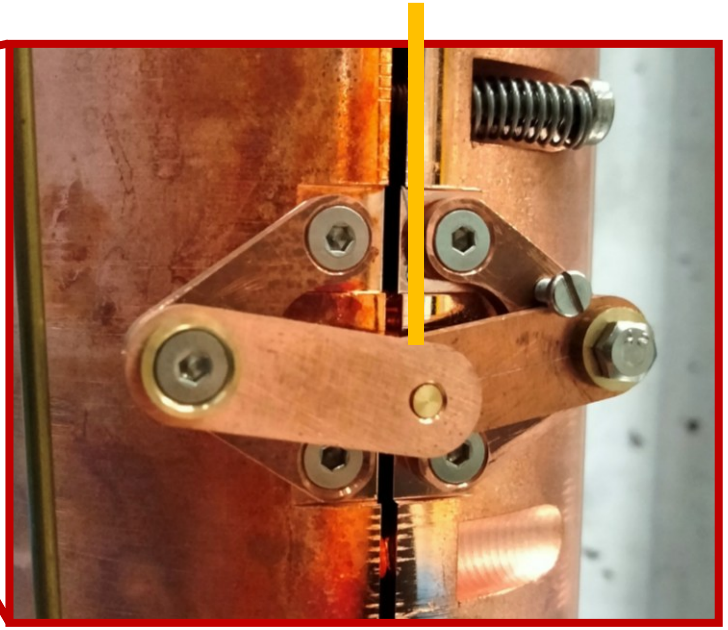

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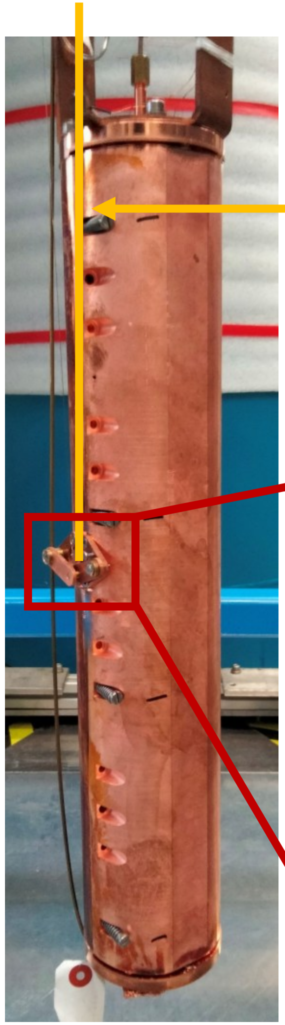
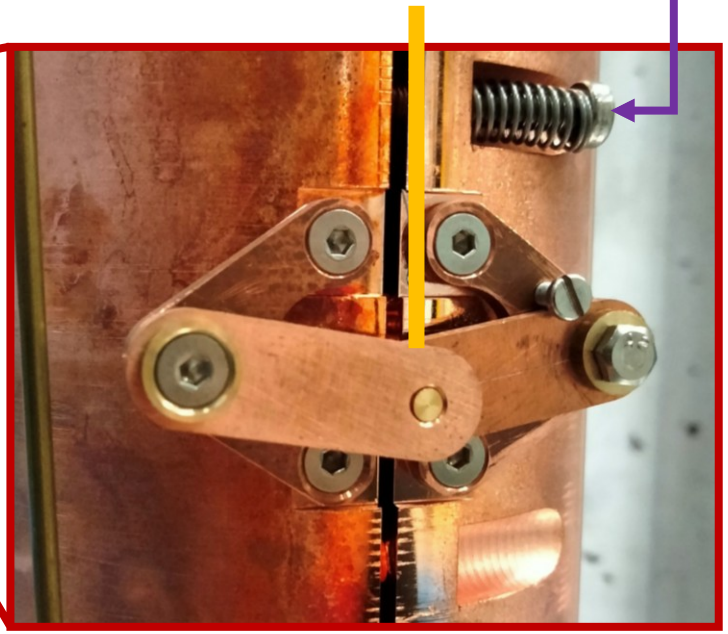


Cavity **tuning system**:

- A pantograph is connected via wire to room temperature stepper motor
- Restoring springs



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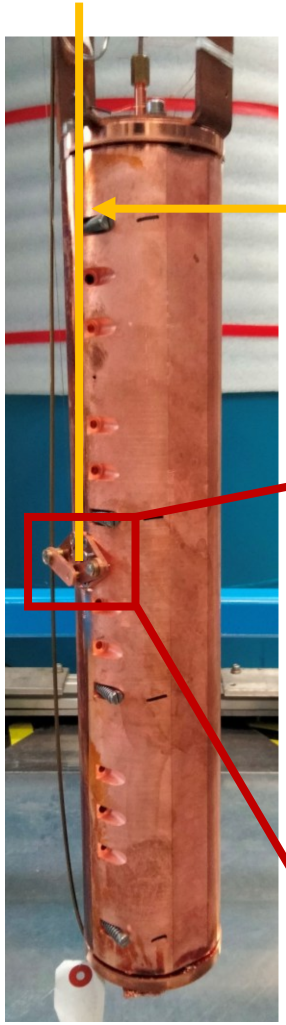

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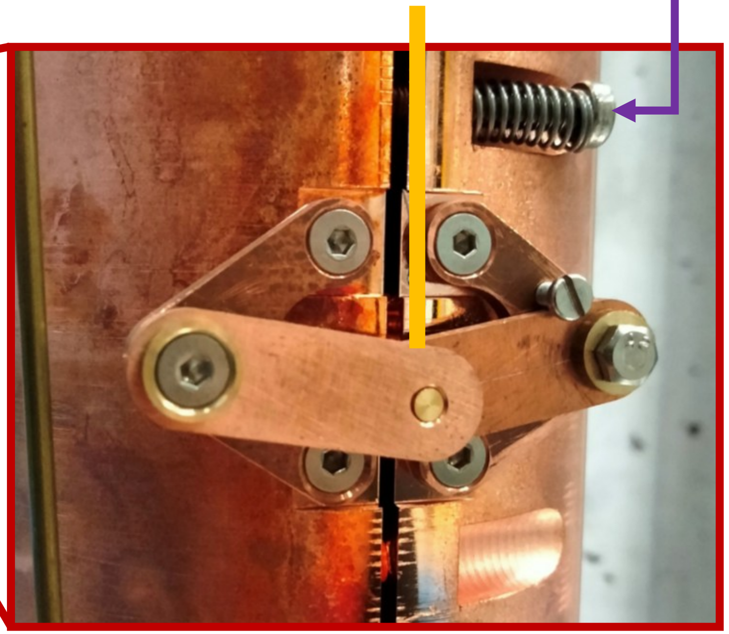
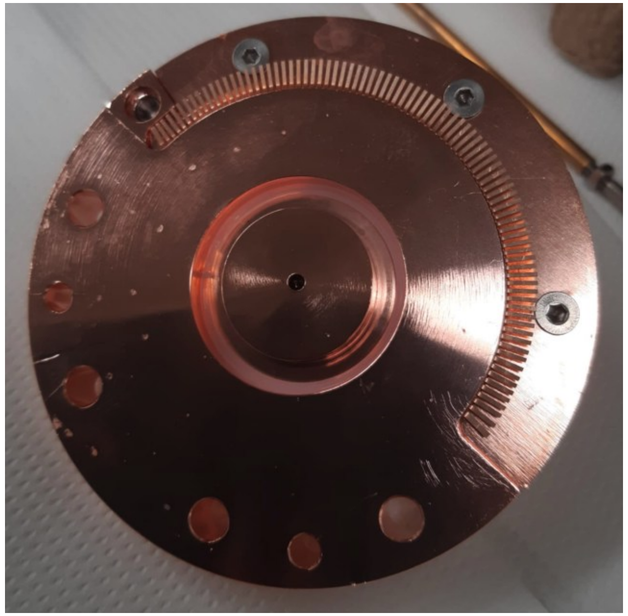
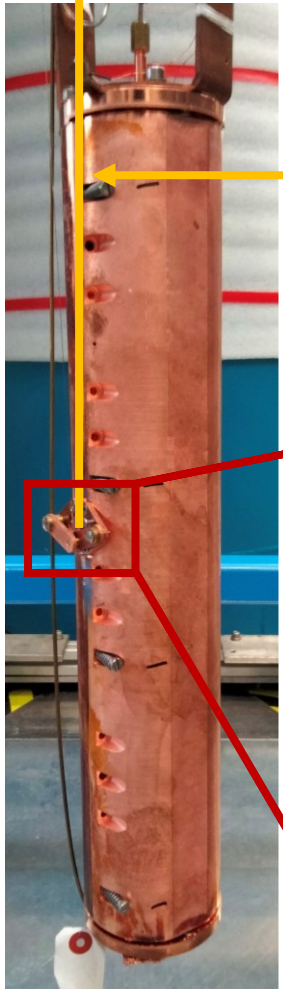
- A pantograph is connected via wire to room temperature stepper motor
- Restoring springs



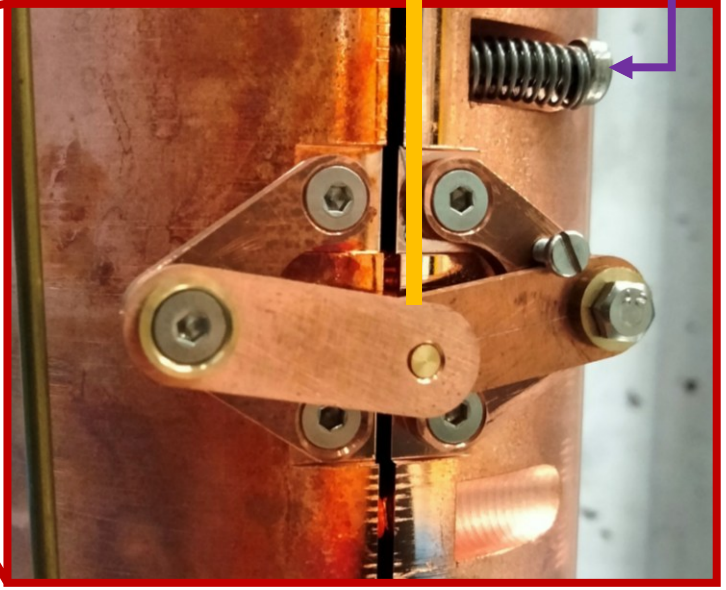


Cavity tuning

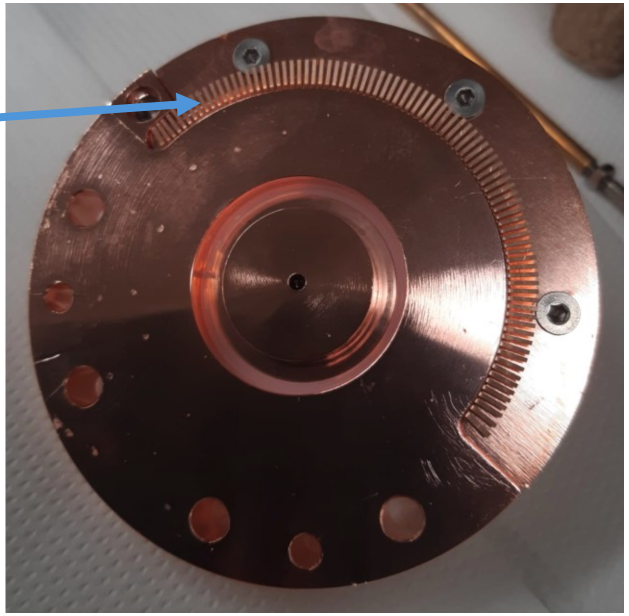


Cavity **tuning system**:

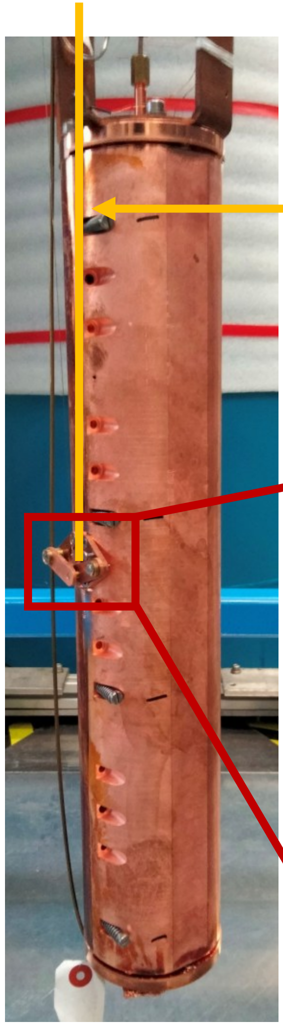
- A pantograph is connected via wire to room temperature stepper motor
- Restoring springs



- Several springs to guarantee rf contact on endcaps

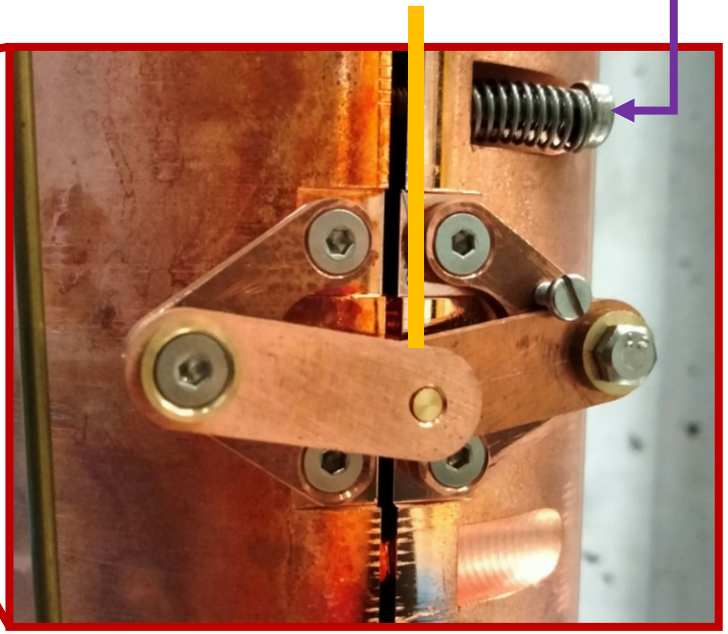


Cavity tuning

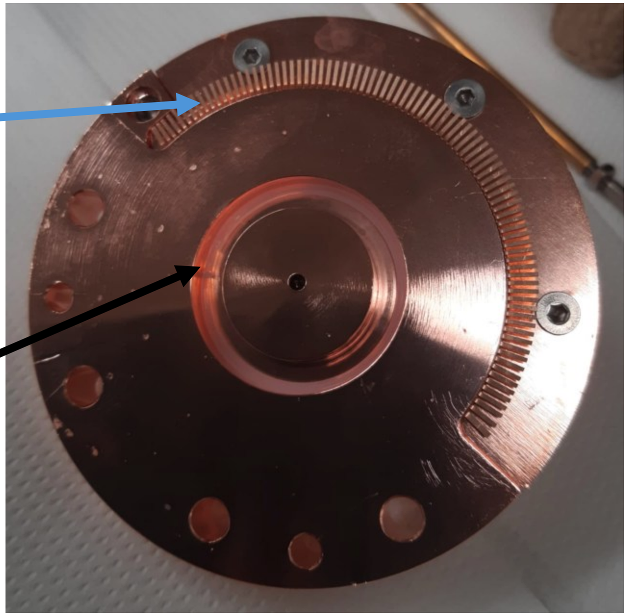


Cavity **tuning system**:

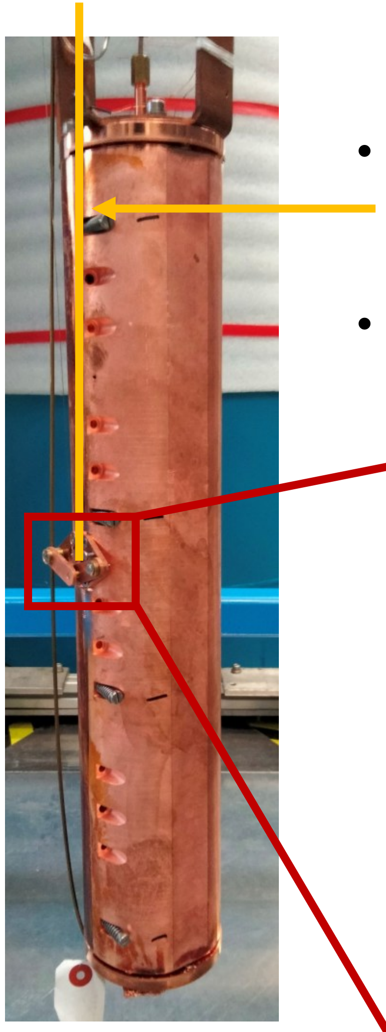
- A pantograph is connected via wire to room temperature stepper motor
- Restoring springs



- Several springs to guarantee rf contact on endcaps
- Annular **grooves** to hold the sapphire on endcaps

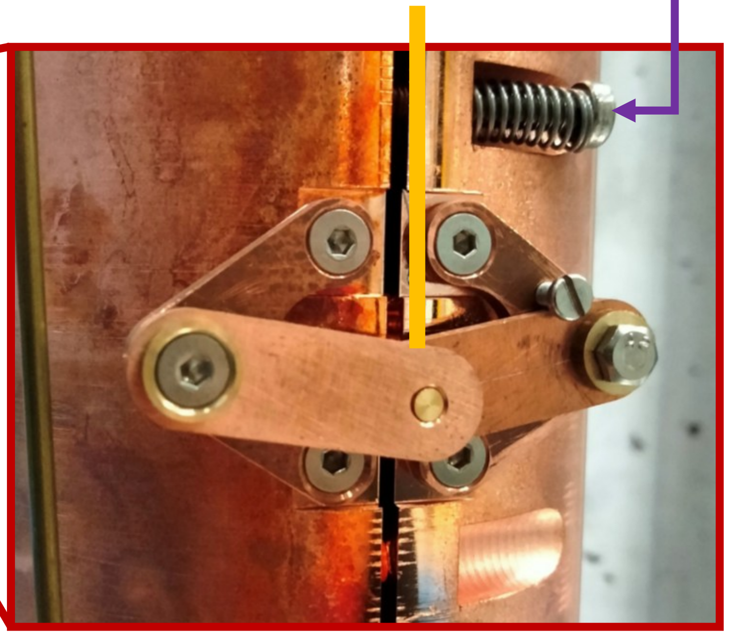


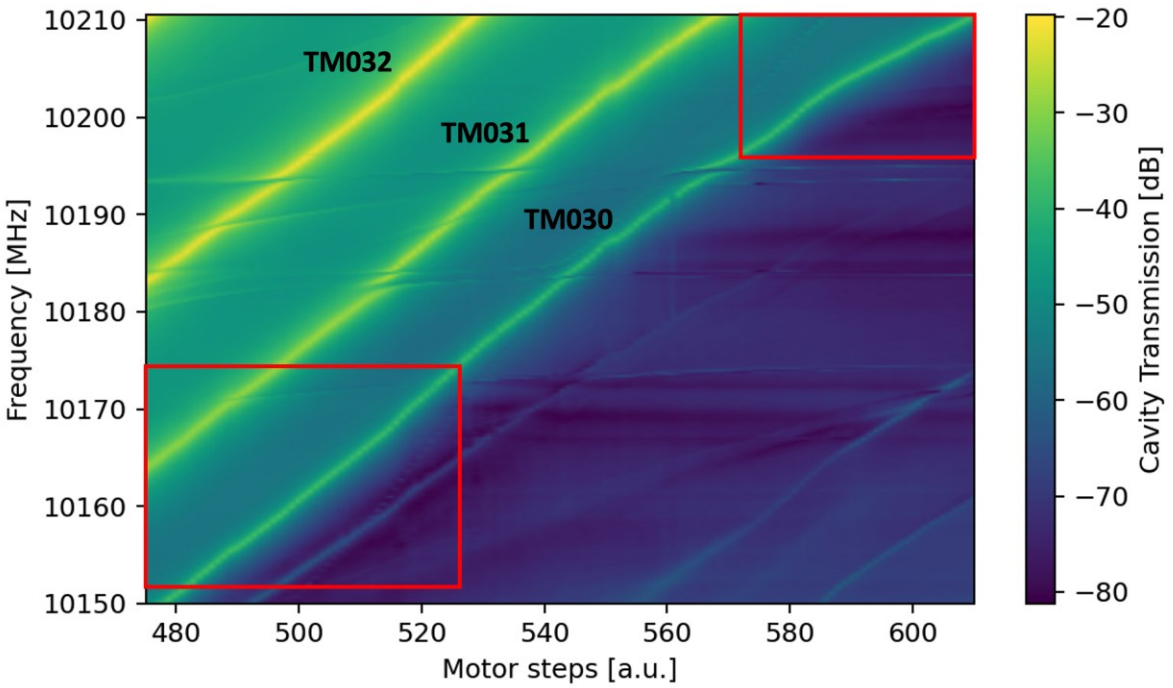
Cavity tuning



Cavity **tuning system**:

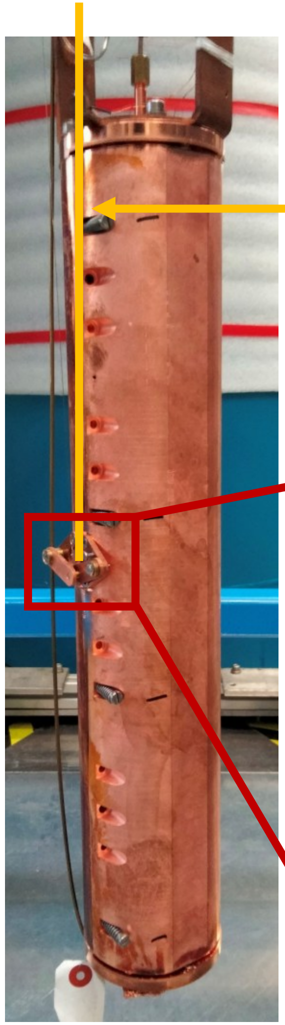
- A pantograph is connected via wire to room temperature stepper motor
- Restoring springs





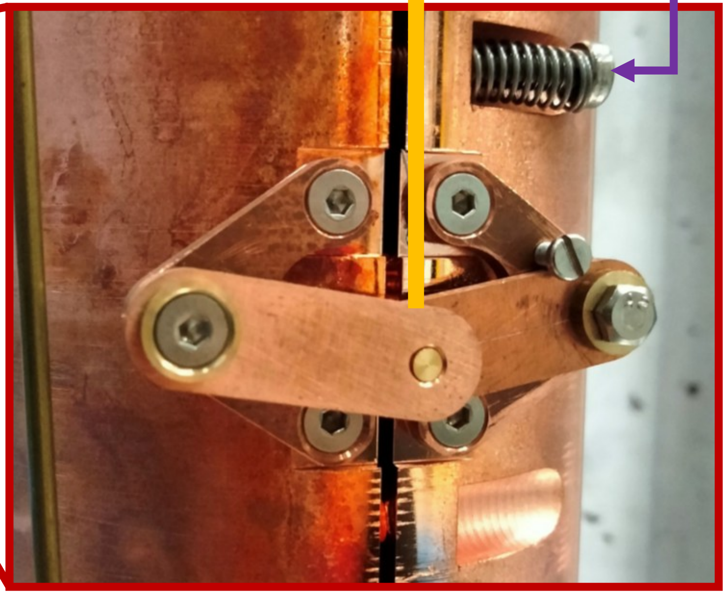
Cavity physical tuning: ~ 200 MHz
Allowed by tuning mechanism: ~ 90 MHz
Without spurious modes: ~ 80 MHz
Probed as of today: ~ 38 MHz (not contiguous)

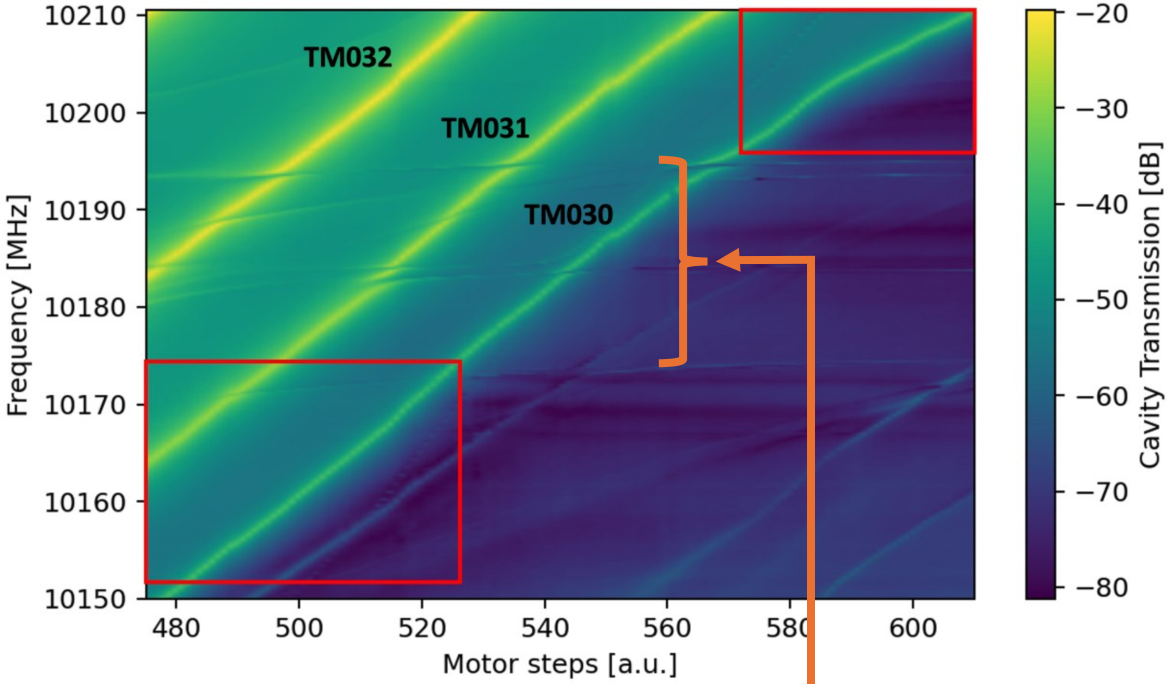
Cavity tuning



Cavity **tuning system**:

- A pantograph is connected via wire to room temperature stepper motor
- Restoring springs





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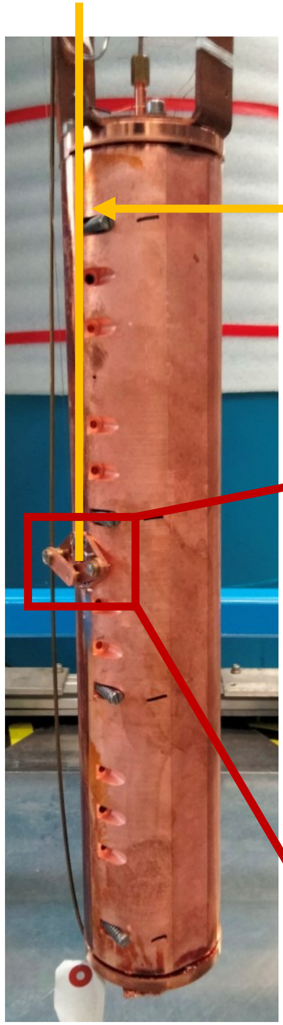
Cavity tuning



Cavity **tuning system**:

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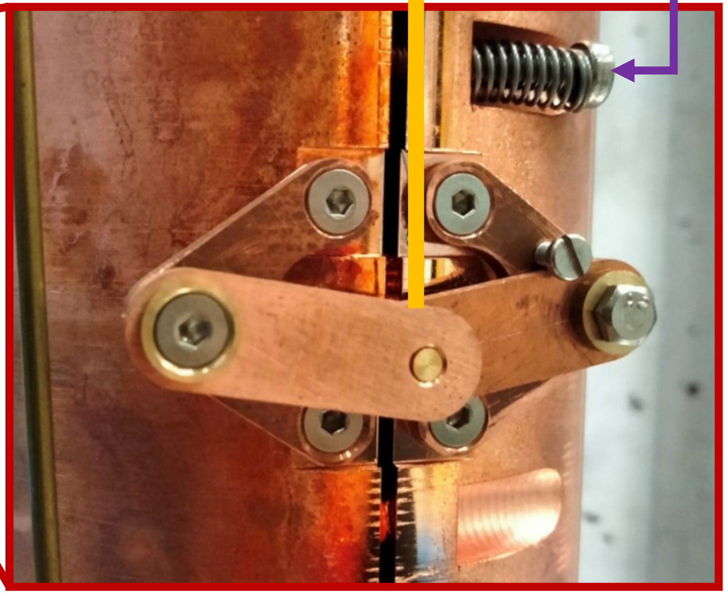

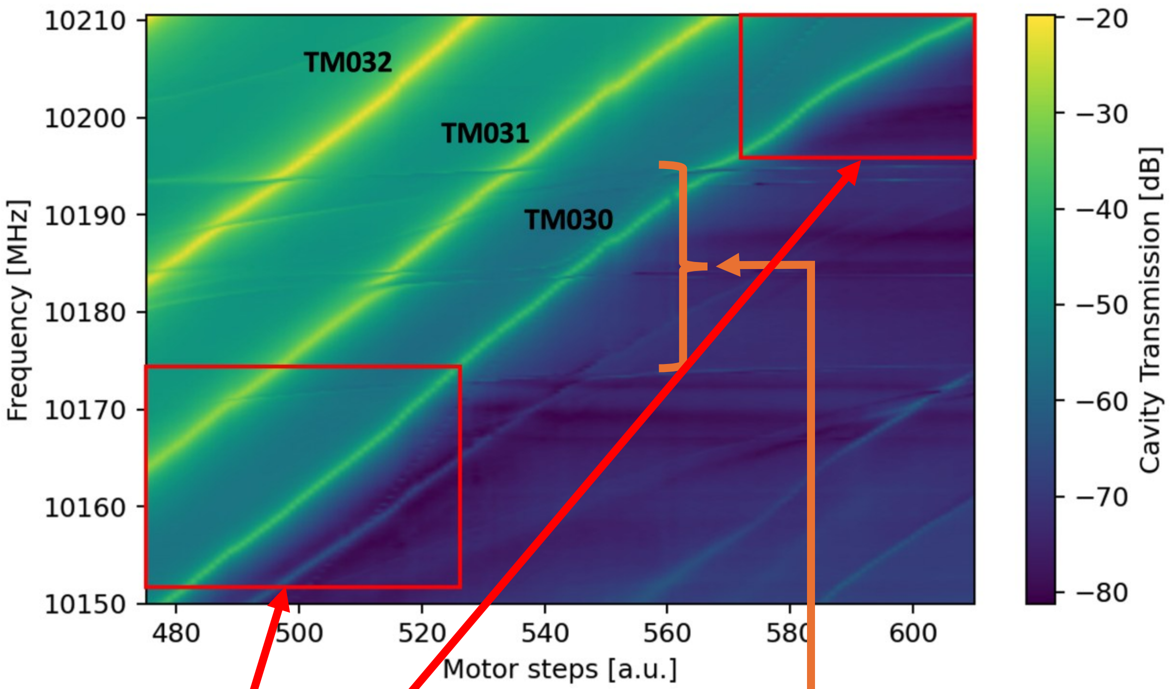

Cavity physical tuning: ~ 200 MHz
Allowed by tuning mechanism: ~ 90 MHz
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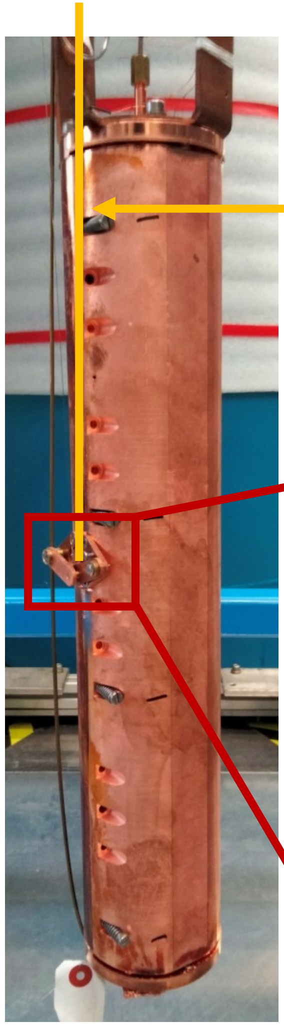
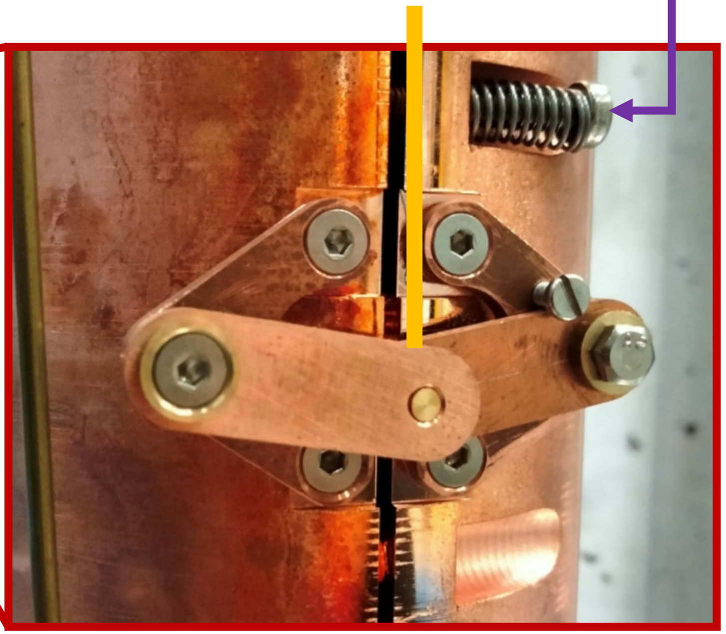
Probed as of today: ~ 38 MHz (not contiguous)

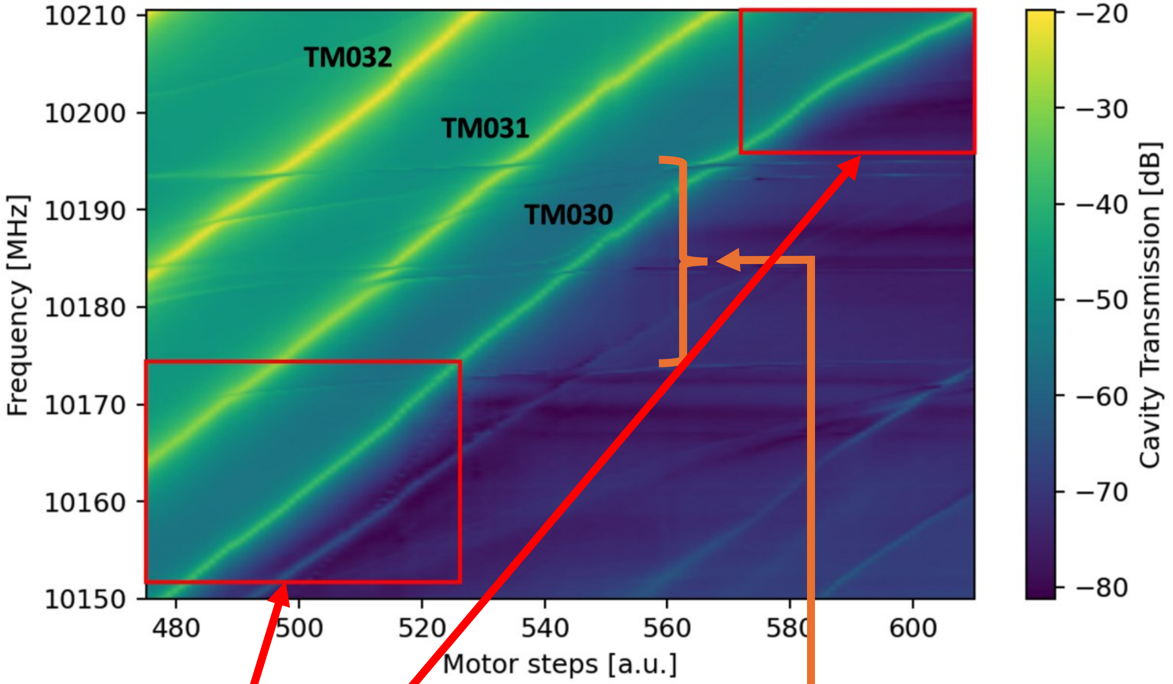
Cavity tuning



Cavity **tuning system**:

- A pantograph is connected via wire to room temperature stepper motor
- Restoring springs

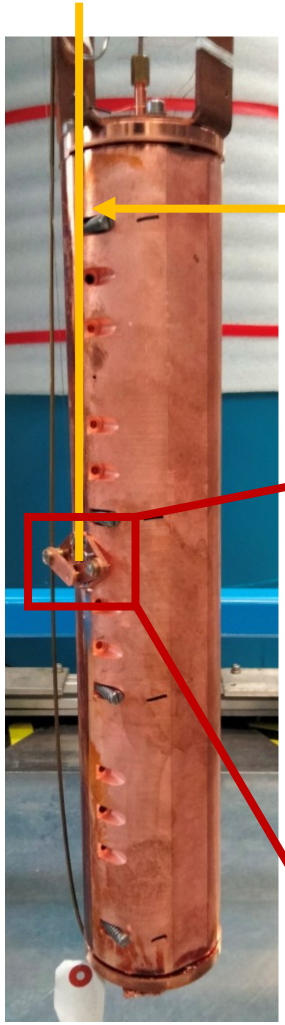




Cavity physical tuning: ~ 200 MHz
Allowed by tuning mechanism: ~ 90 MHz
Without spurious modes: ~ 80 MHz
Probed as of today: ~ 38 MHz (not contiguous)

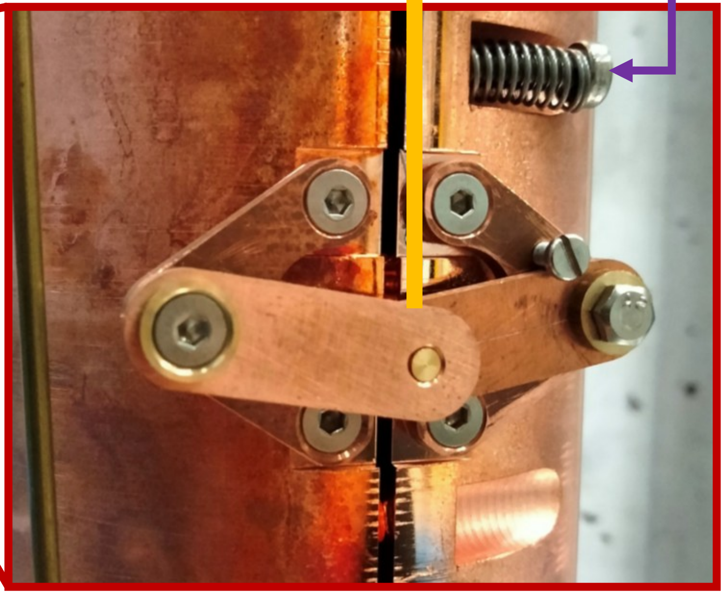
BUT

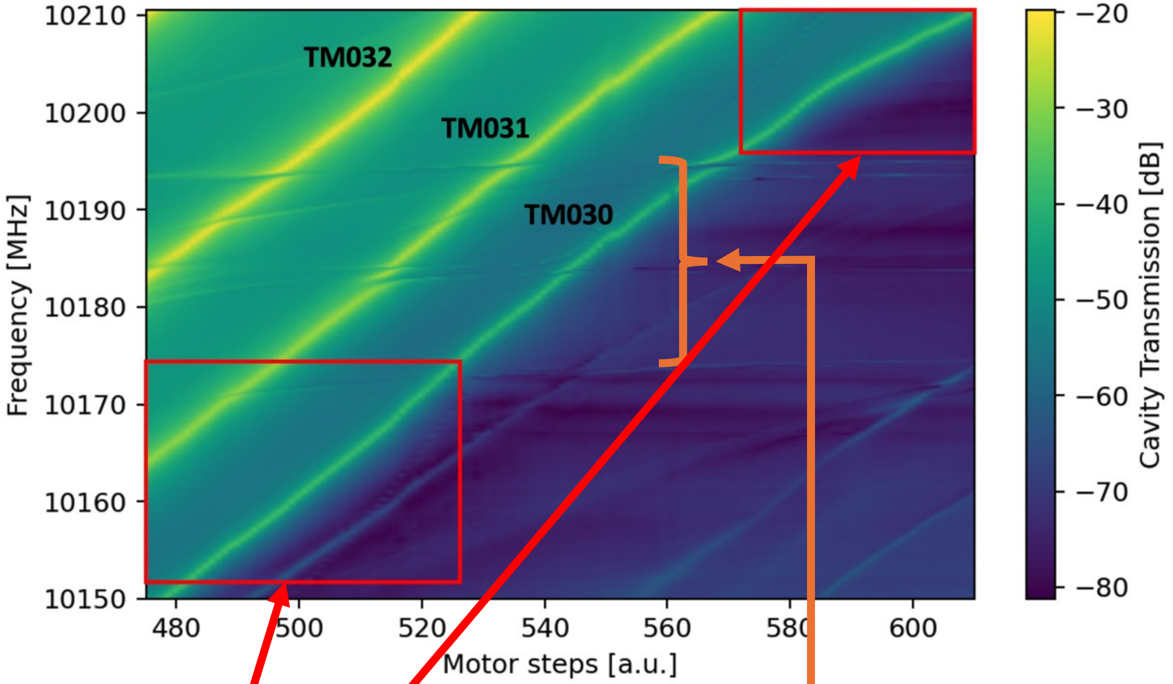
Cavity tuning



Cavity **tuning system**:

- A pantograph is connected via wire to room temperature stepper motor
- Restoring springs



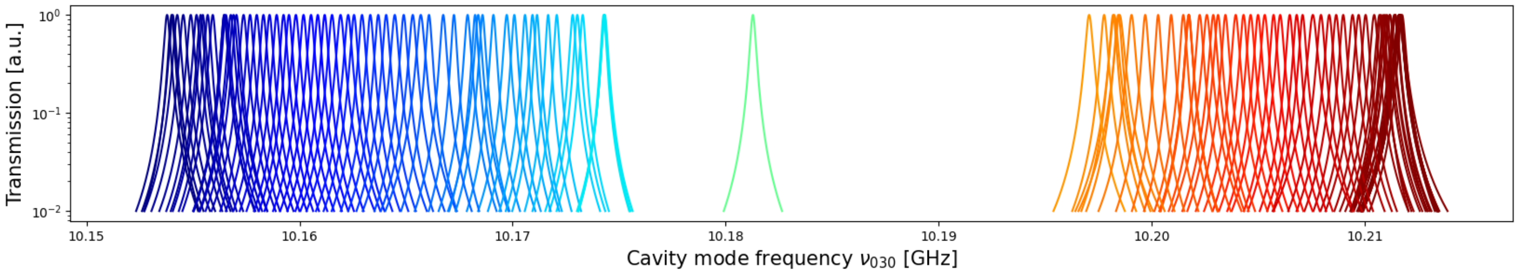


Cavity physical tuning: ~ 200 MHz
Allowed by tuning mechanism: ~ 90 MHz
Without spurious modes: ~ 80 MHz
Probed as of today: ~ 38 MHz (not contiguous)

BUT New cavity tuning range: ~ 400 MHz

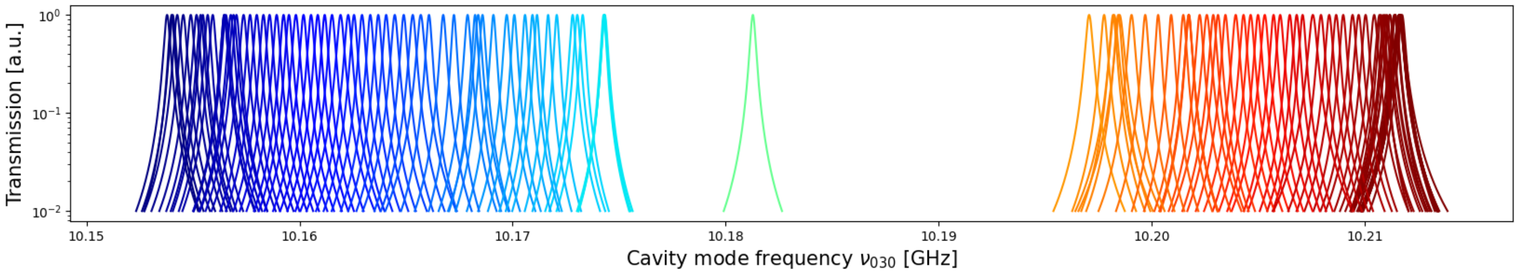
Data acquisition

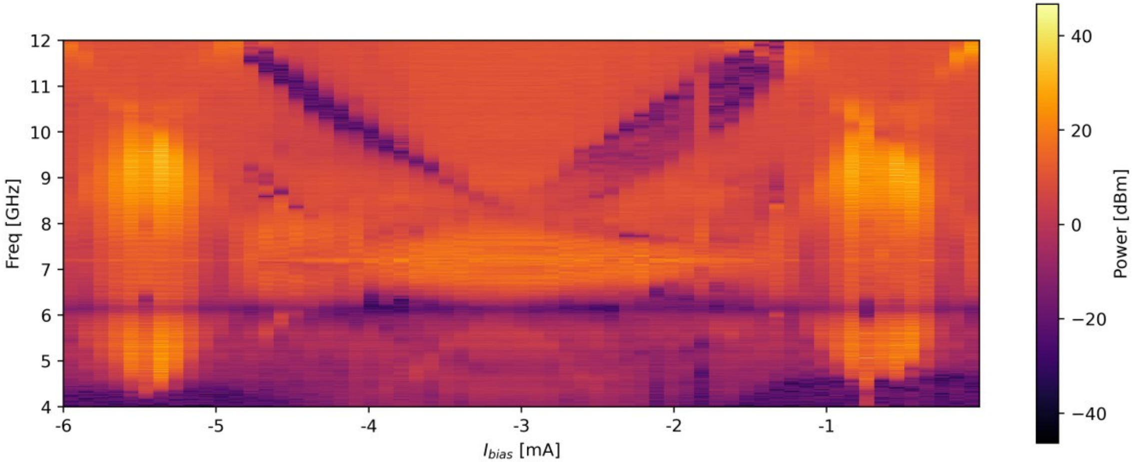
Data acquisition



- Setting cavity frequency

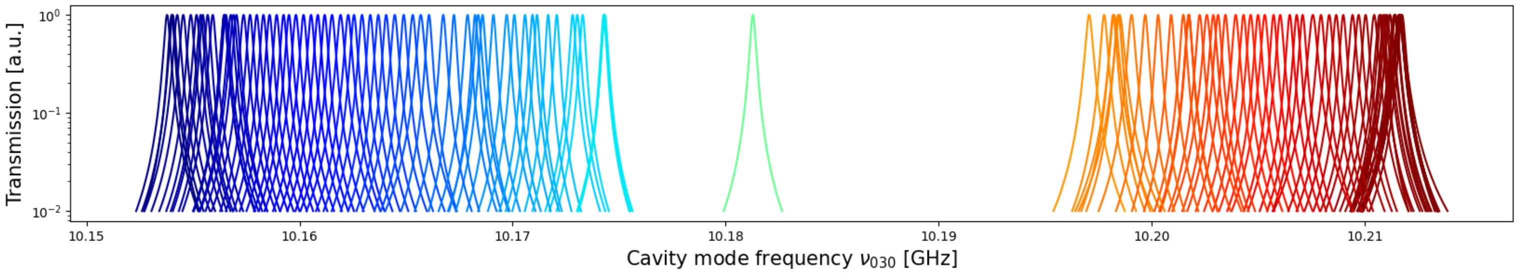
Data acquisition

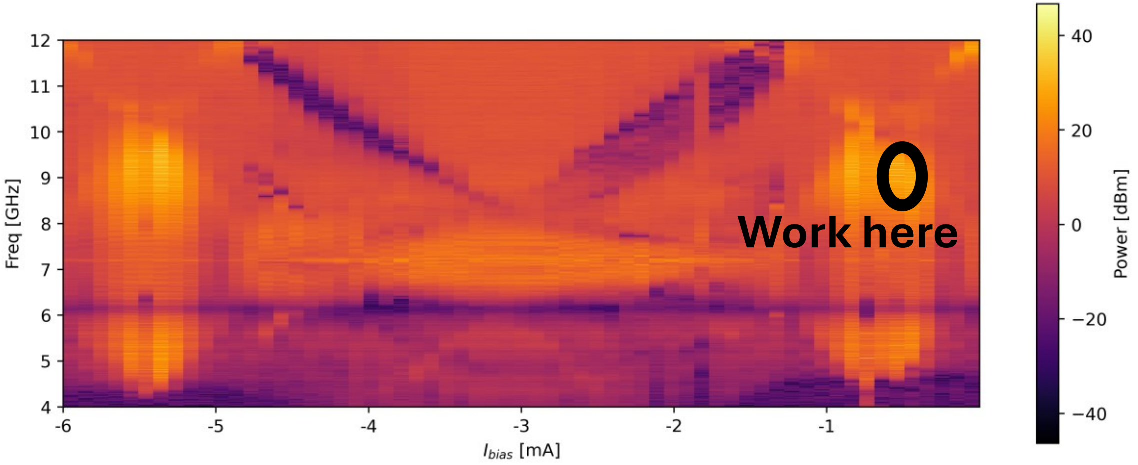




- Setting cavity frequency
- TWPA optimization

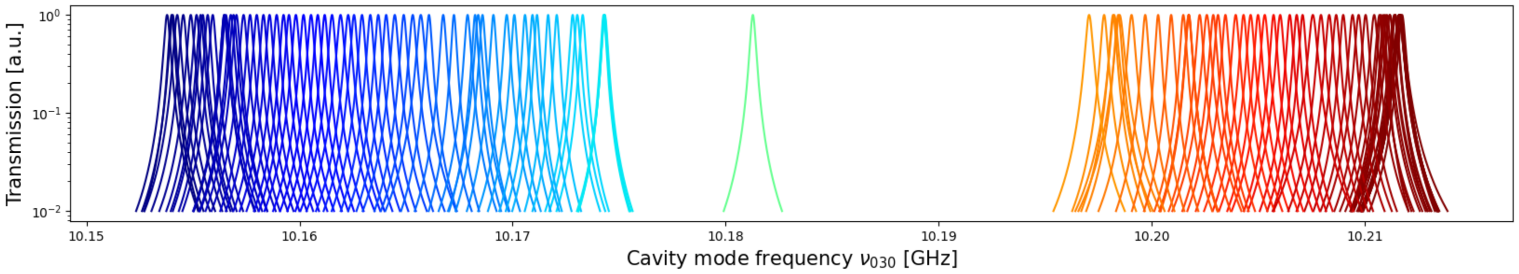
Data acquisition



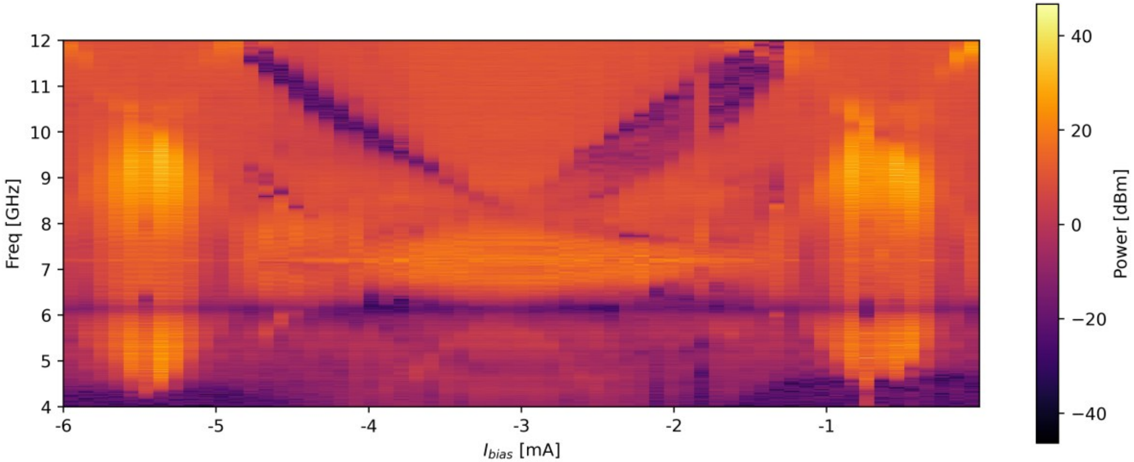


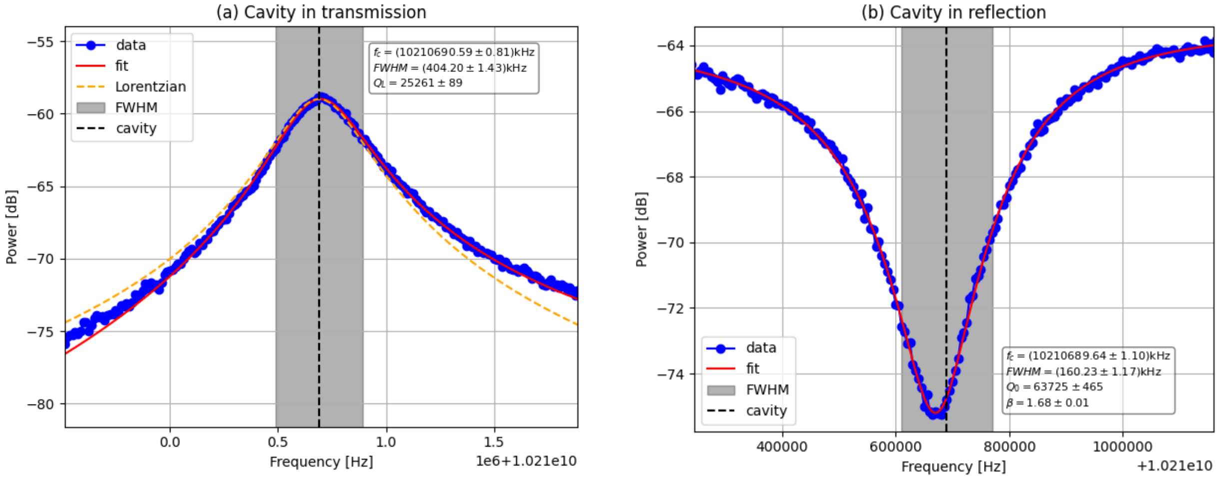
- Setting cavity frequency
- TWPA optimization

Data acquisition



- Setting cavity frequency
- TWPA optimization
- Cavity parameter estimation





Data acquisition

- Setting cavity frequency
- TWPA optimization
- Cavity parameter estimation
- Calibration of the lines and noise temperature estimation

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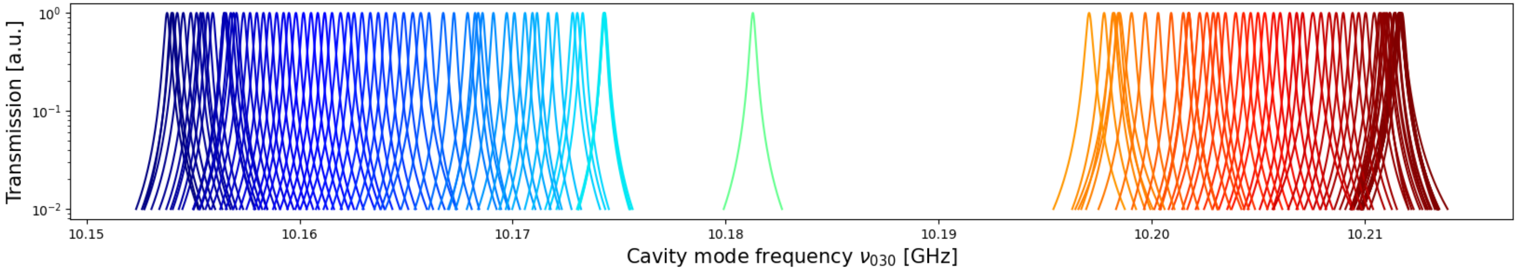
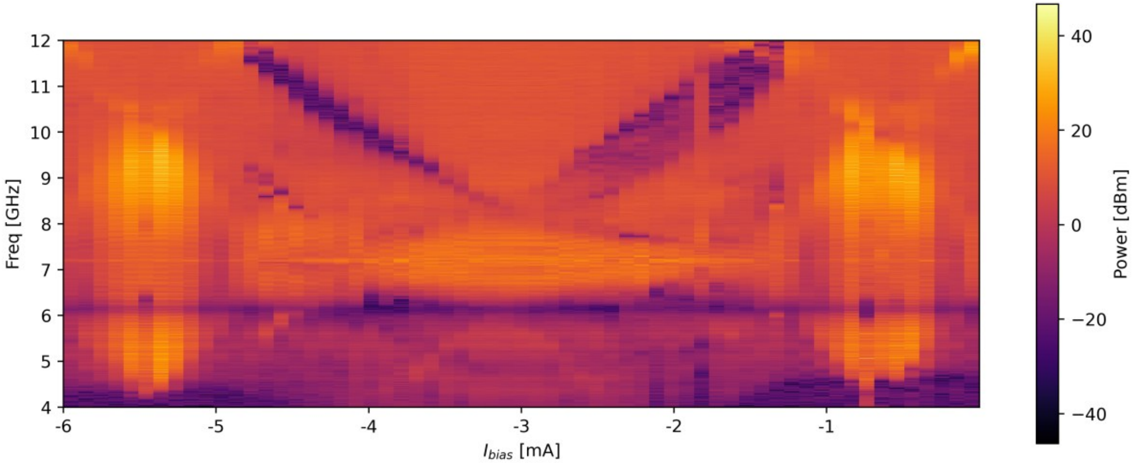
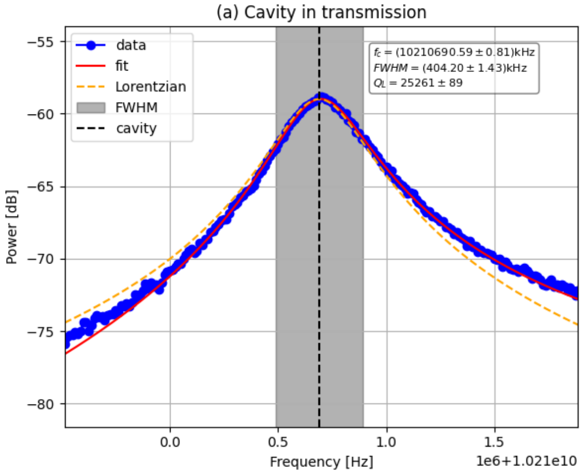
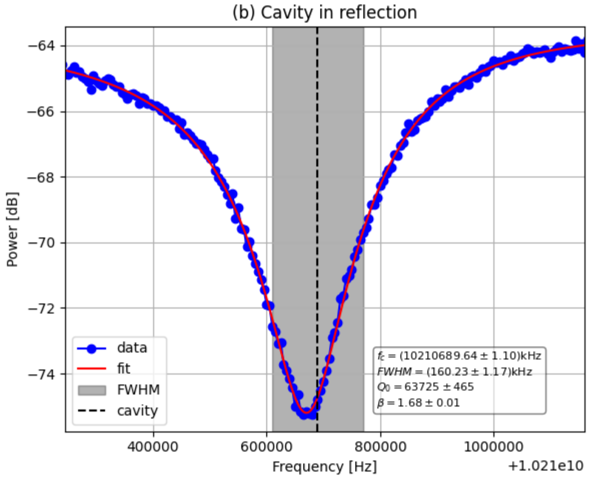
[*Rev. Sci. Instrum.* 93, 094701 (2022)]

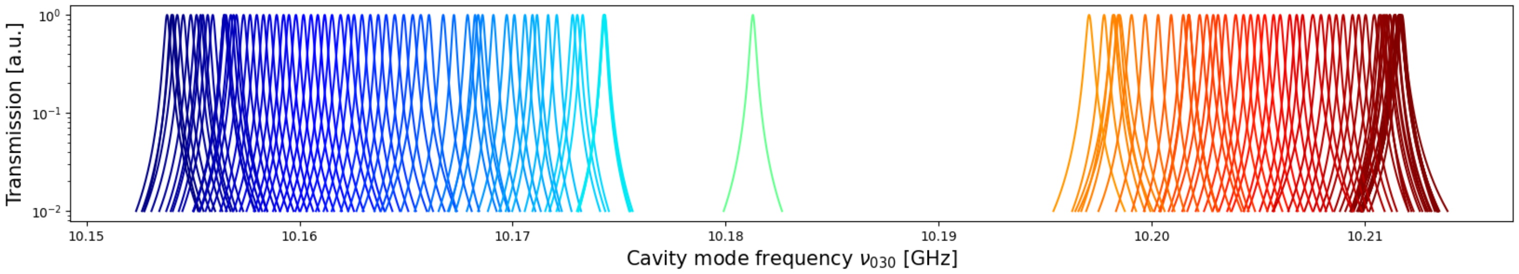


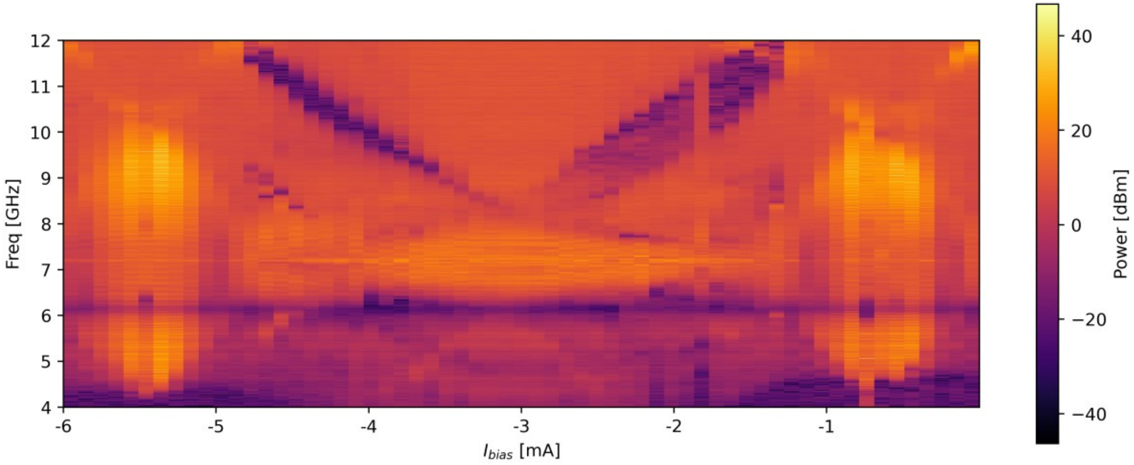




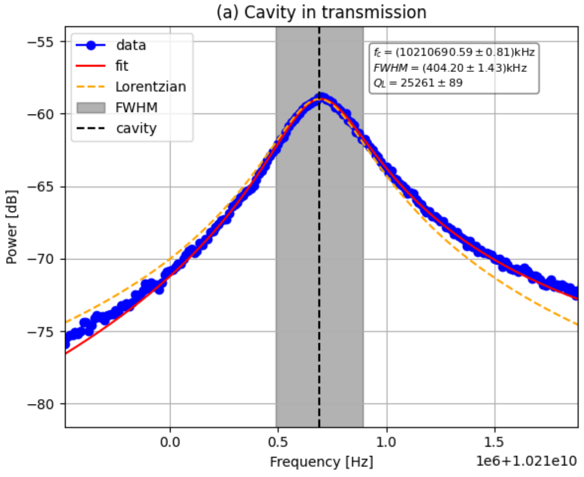


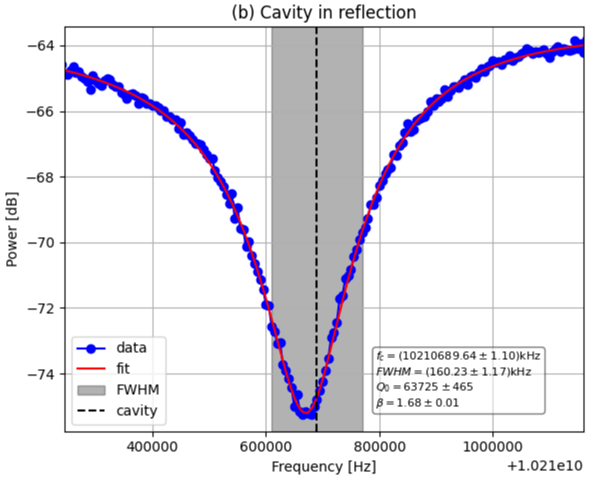
Data acquisition





- Setting cavity frequency
- TWPA optimization
- Cavity parameter estimation
- Calibration of the lines and noise temperature estimation
- Acquisition and saving of both temporal data and 4 ms Fourier Transforms (FT)

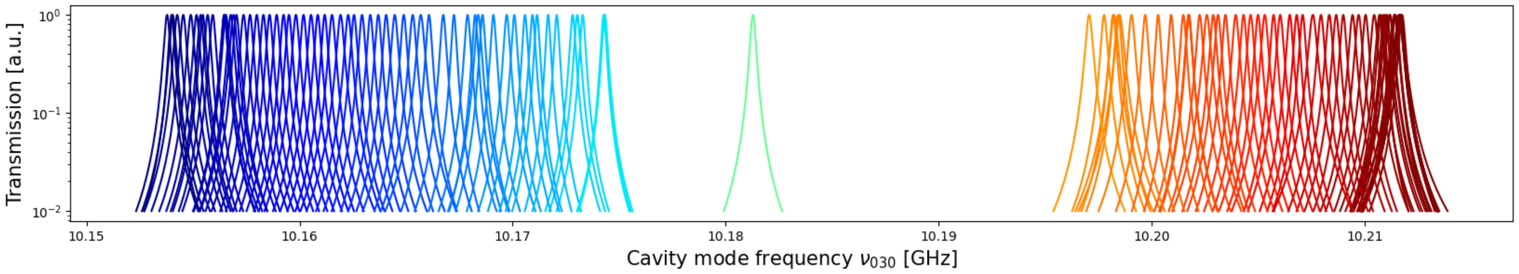




C. Braggio et al.
Rev. Sci. Instrum. 93, 094701 (2022)

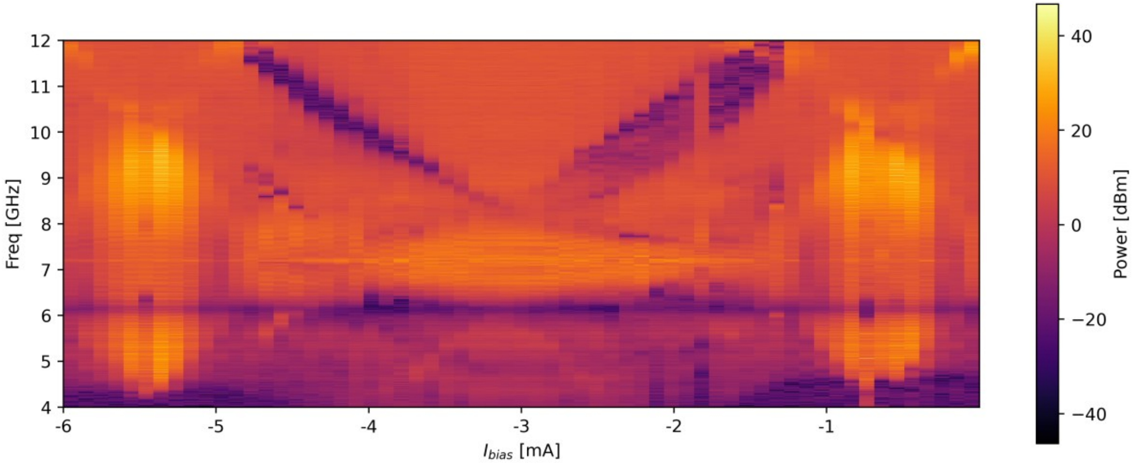
All data (temporal and FT) are saved on Cloud (~ 60 GB/hour) for further analysis

Data acquisition



Automation:

- ✗ Setting cavity frequency
- ✗ TWPA optimization
- ✓ Cavity parameter estimation
- ✓ Calibration of the lines and noise temperature estimation
- ✓ Acquisition and saving of both temporal data and 4 ms Fourier Transforms (FT)



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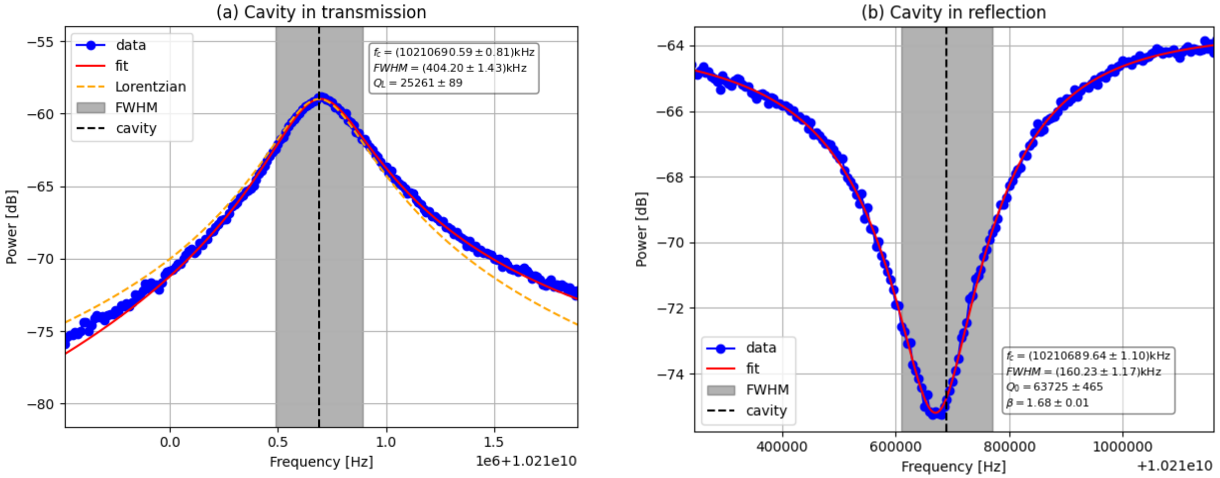
[*Rev. Sci. Instrum.* 93, 094701 (2022)]



All data (temporal and FT) are saved on Cloud (~ 60 GB/hour) for further analysis

Data analysis

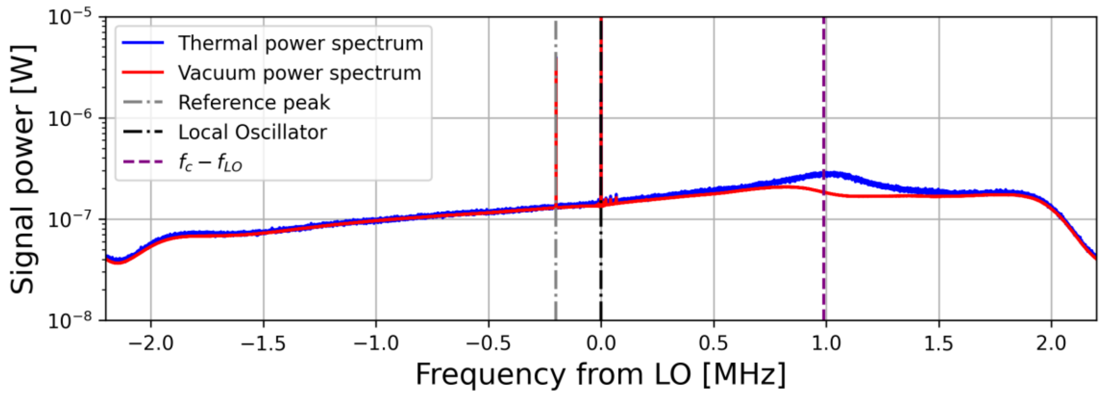
Data analysis

Broad frequency region **analysis**:

Data analysis

Broad frequency region **analysis**:

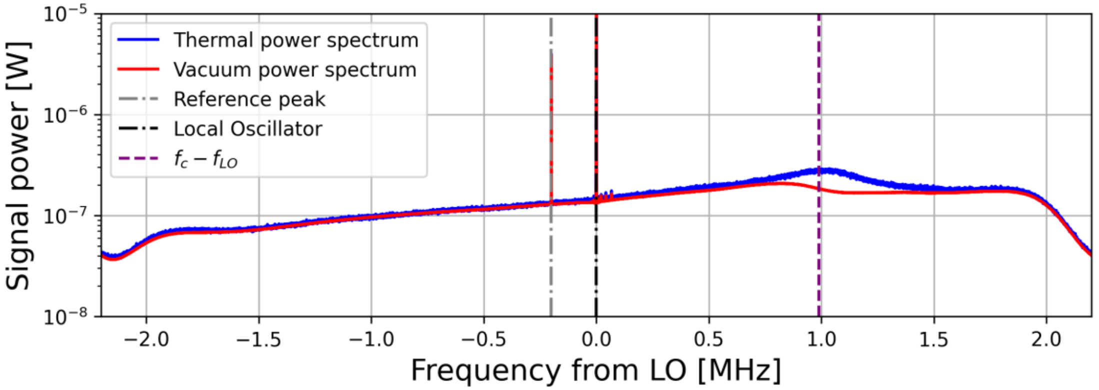
- Evaluate spectrum for each cavity aperture

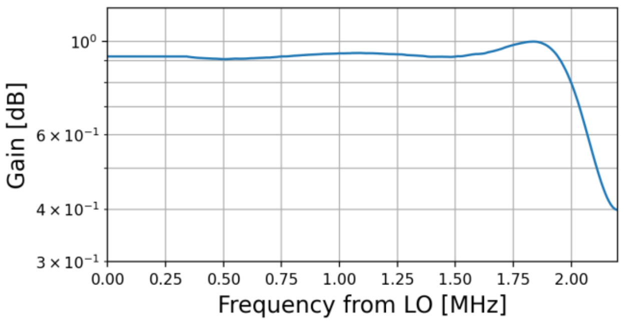


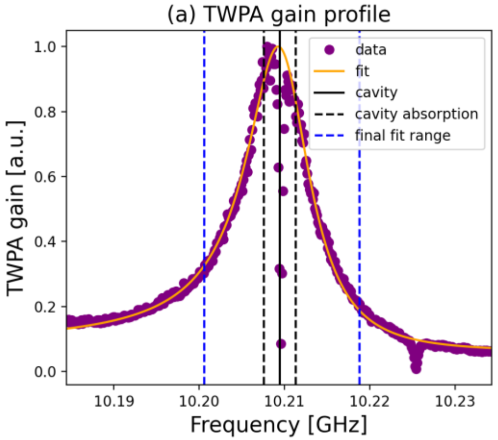
Data analysis

Broad frequency region **analysis**:

- Evaluate spectrum for each cavity aperture
- Removing frequency dependent gains of the lines



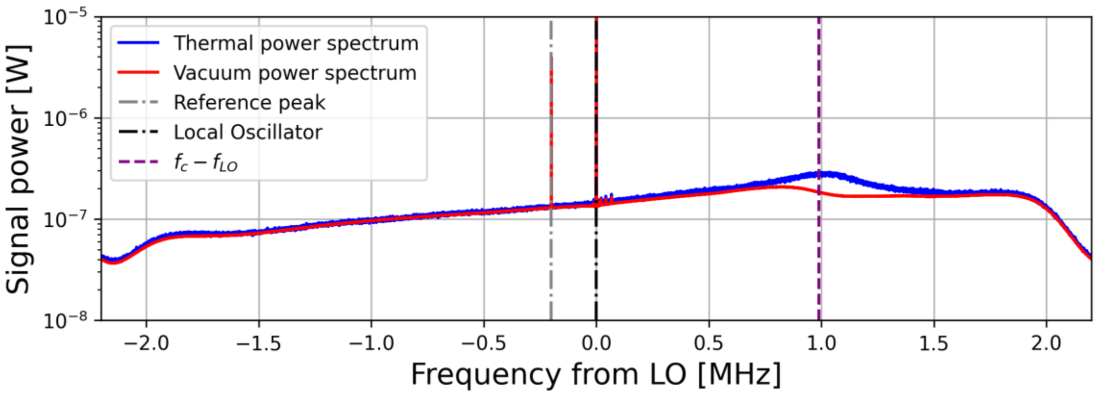


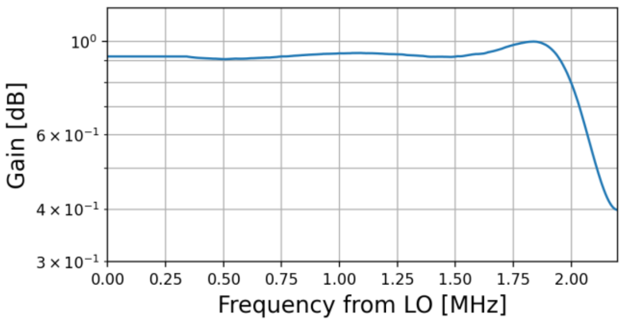


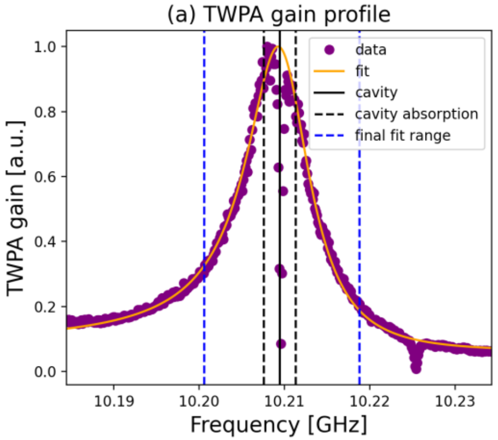
Data analysis

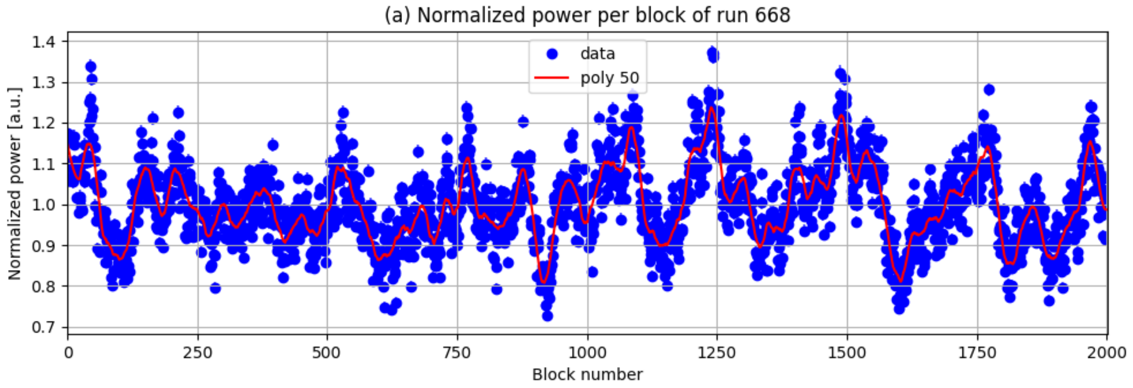
Broad frequency region **analysis**:

- Evaluate spectrum for each cavity aperture
- Removing frequency dependent gains of the lines
- Correct with time-dependent TWPA gain fluctuations





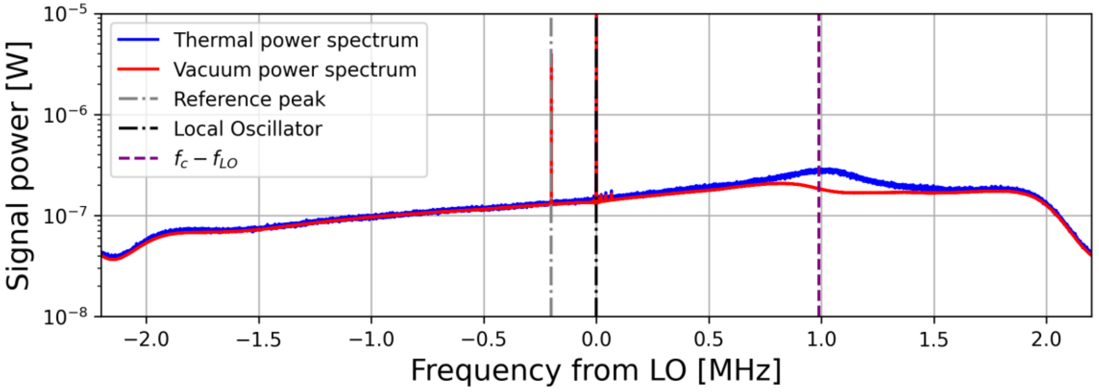


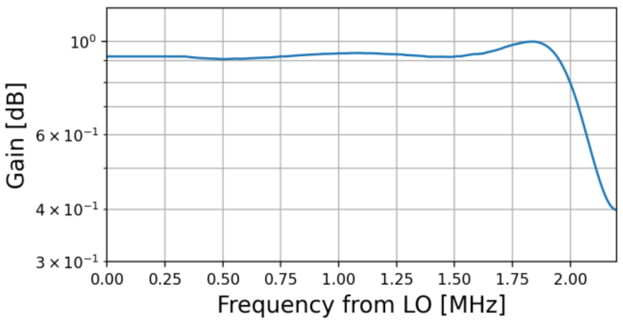


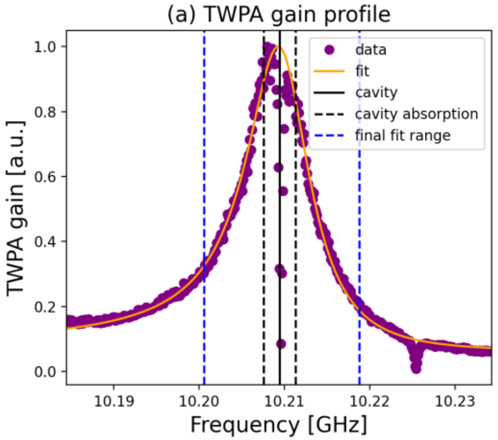
Data analysis

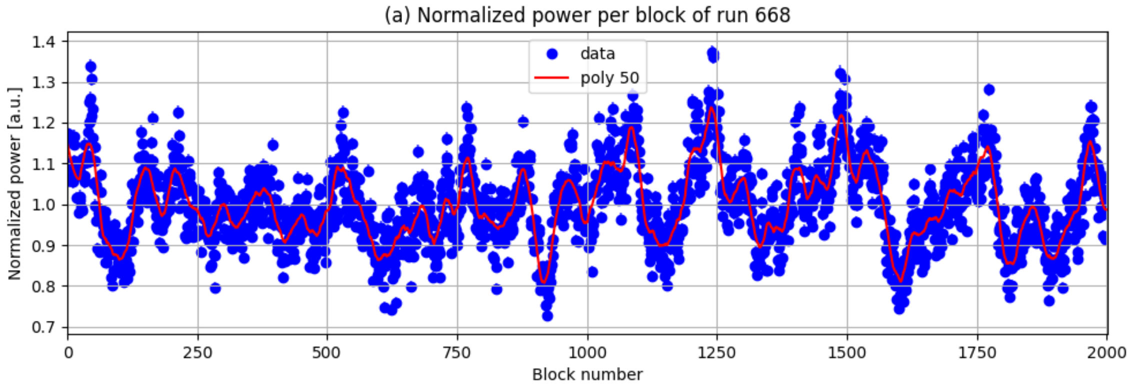
Broad frequency region **analysis**:

- Evaluate spectrum for each cavity aperture
- Removing frequency dependent gains of the lines
- Correct with time-dependent TWPA gain fluctuations
- Remove Lorentzian cavity line shape





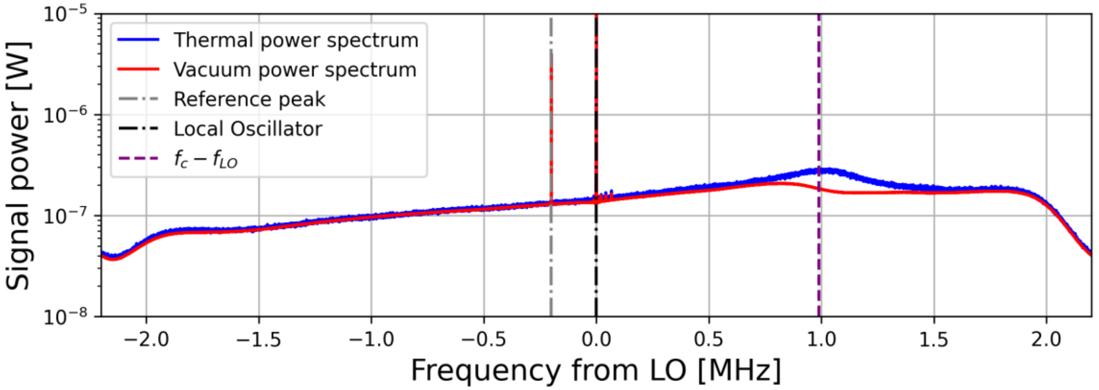


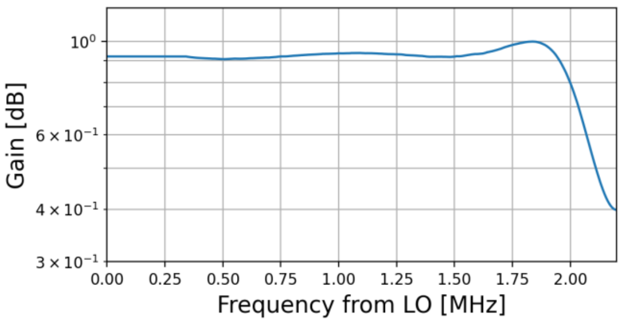


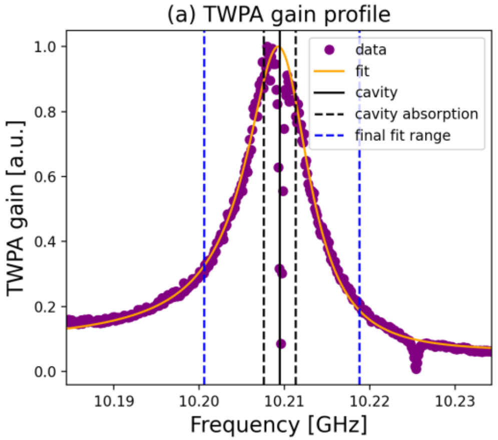
Data analysis

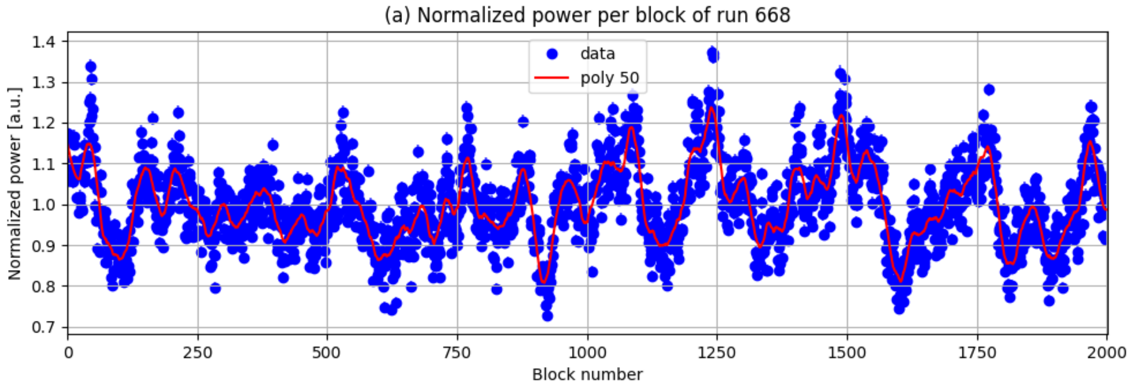
Broad frequency region **analysis**:

- Evaluate spectrum for each cavity aperture
- Removing frequency dependent gains of the lines
- Correct with time-dependent TWPA gain fluctuations
- Remove Lorentzian cavity line shape
- Monte Carlo simulations to determine threshold (ROC) for axion sensitivity (Confidence Belt)





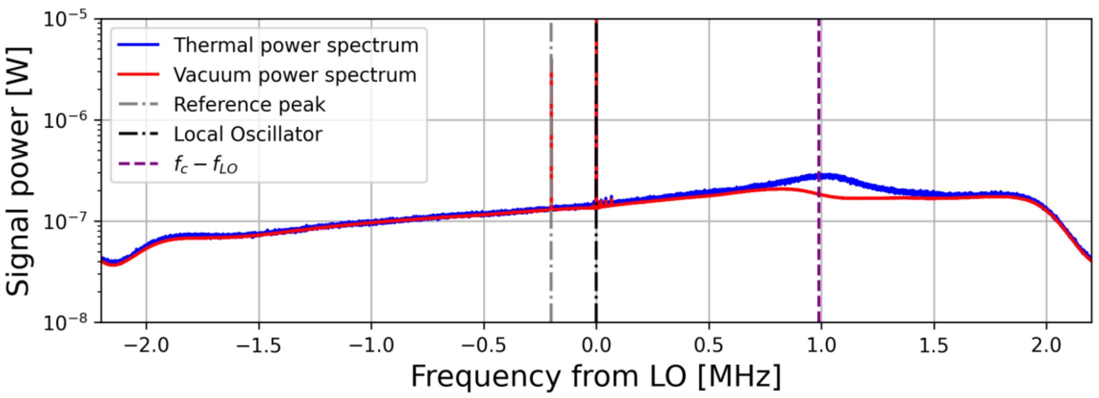


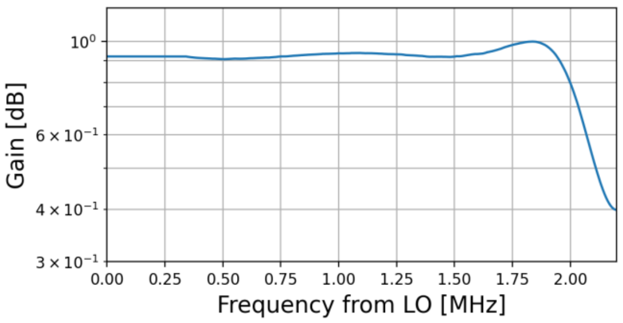


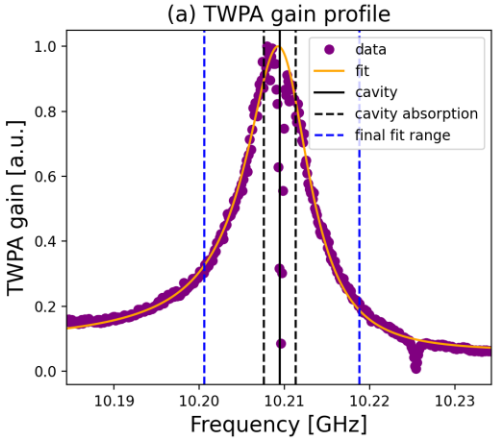
Data analysis

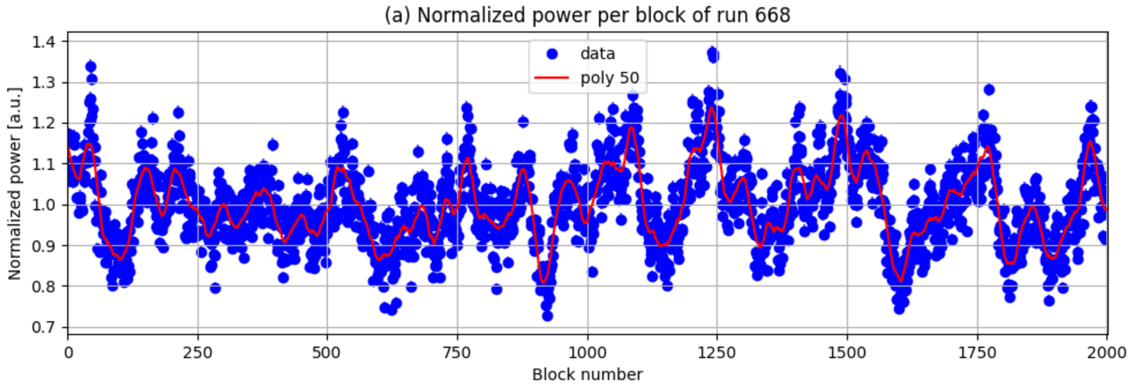
Broad frequency region **analysis**:

- Evaluate spectrum for each cavity aperture
- Removing frequency dependent gains of the lines
- Correct with time-dependent TWPA gain fluctuations
- Remove Lorentzian cavity line shape
- Monte Carlo simulations to determine threshold (ROC) for axion sensitivity (Confidence Belt)
- Combine results on single spectra to look for candidates









Data analysis

Broad frequency region **analysis**:

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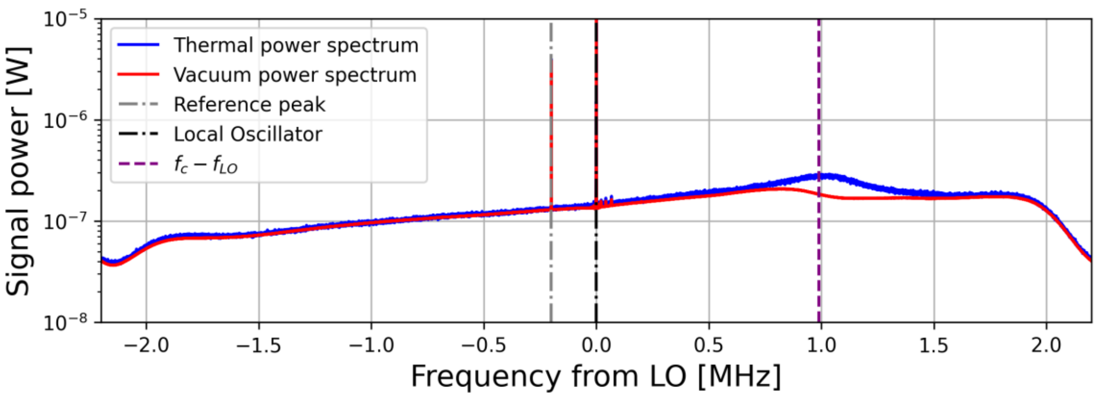
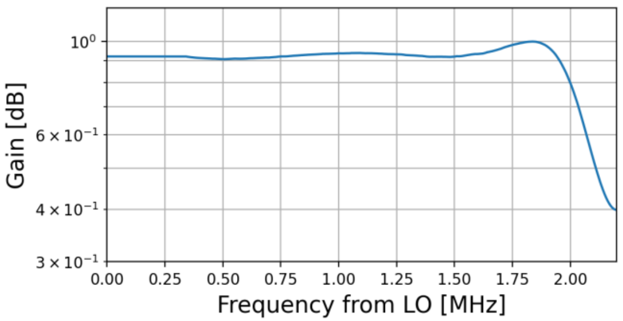
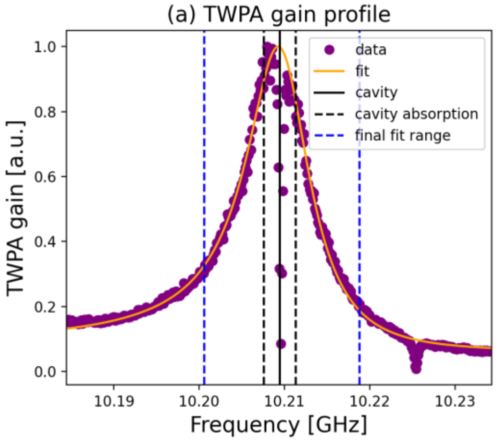
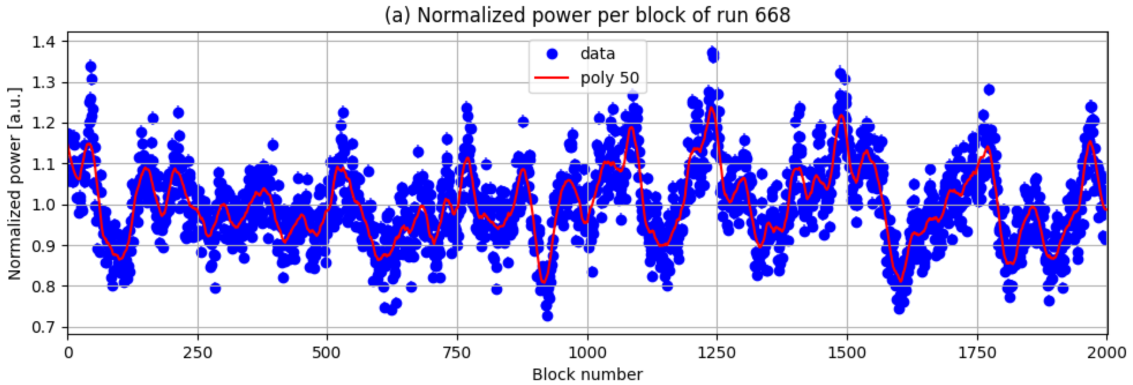








Expectation with threshold set to 4.5 σ:

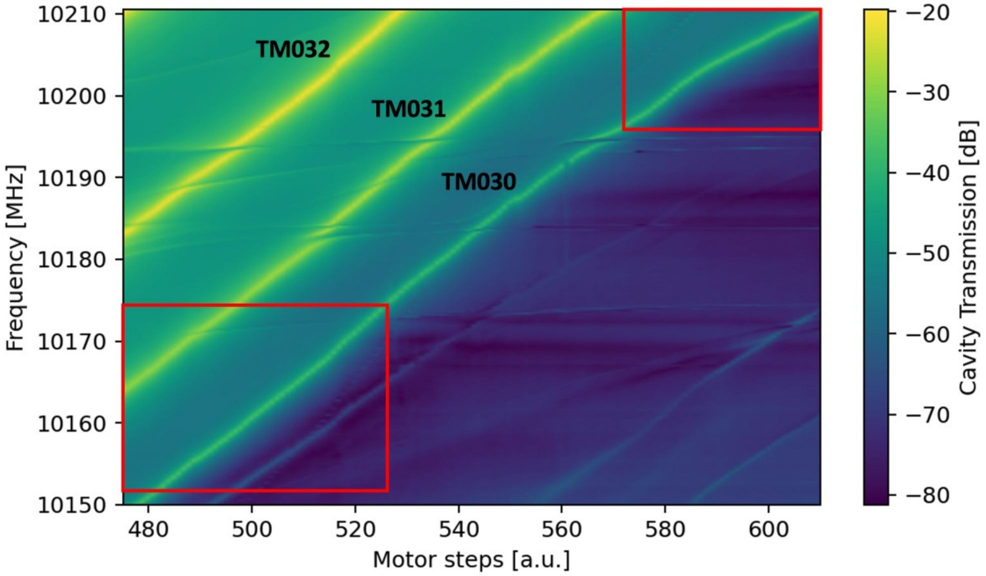
- **One** axion candidate **per month**
- **No found axion candidate** in the 225 hours long acquisition

Recent results

Recent results

Cavity tuning:

- Scanned ~ 38 MHz
- ~ 40 MHz in upcoming run



Recent results

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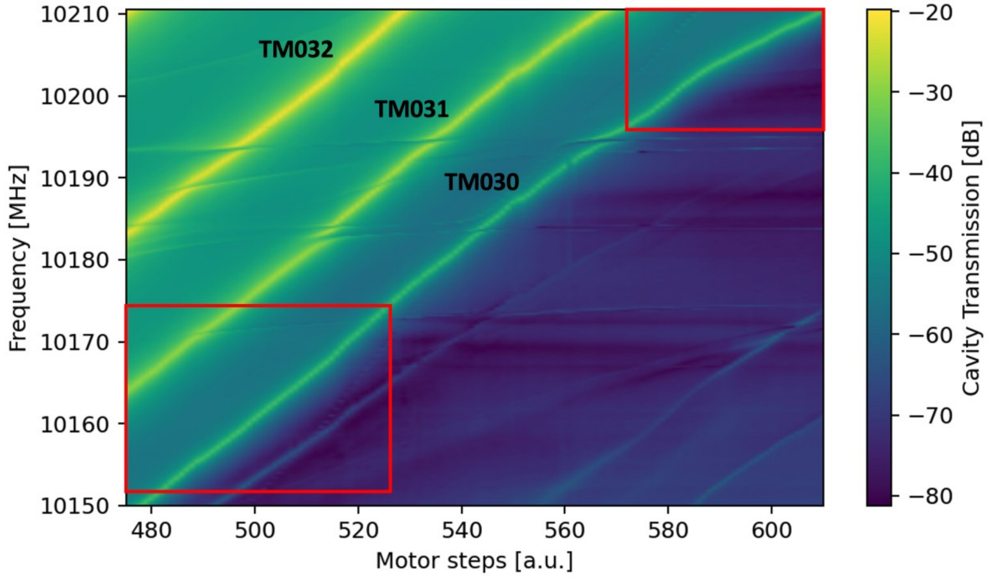
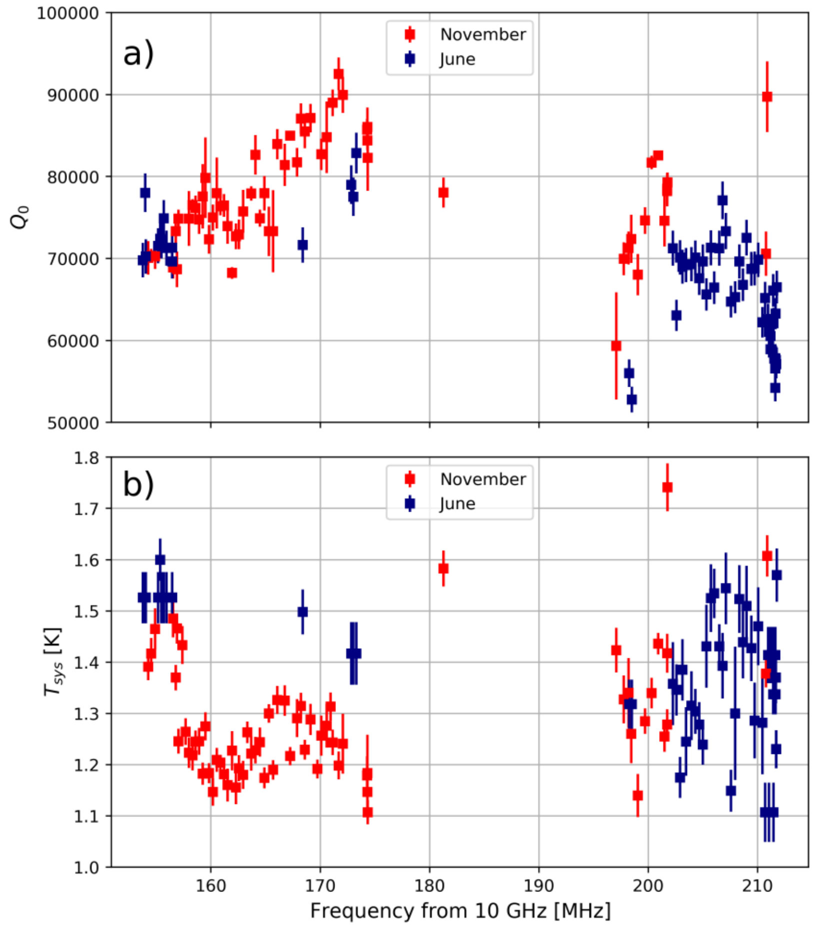


Stability:

- Cavity quality factor not significantly impacted by tuning
- Noise temperature slightly above 2 SQL

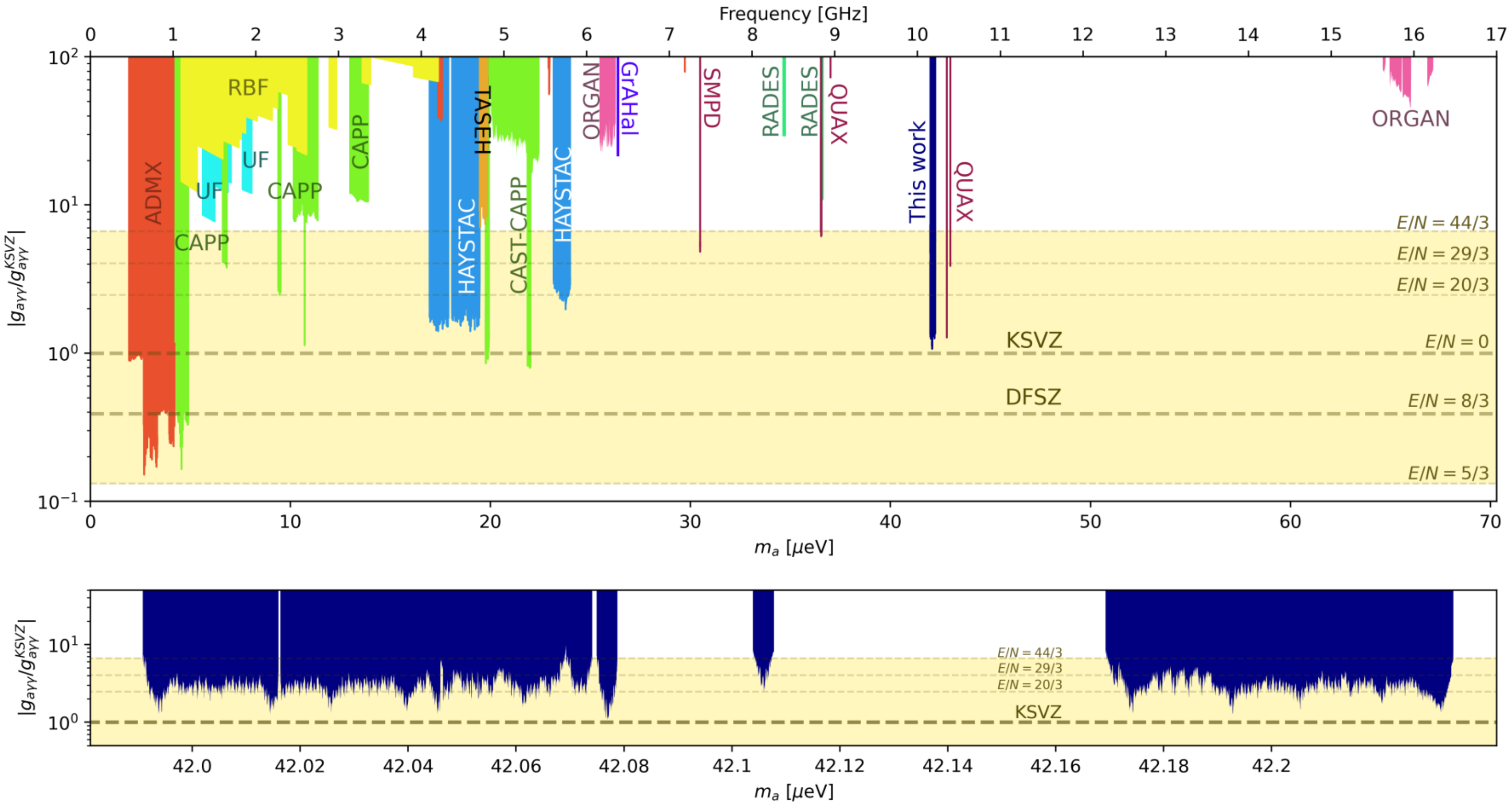


Recent results

Exclusion limits:

- No rescan candidate => All data used for exclusion plot
- Largest frequency interval ever probed @ QUAX-LNL: **we are ready to become an observatory!**

G. Sardo Infirri, G.Ruoso et al.
arXiv:2506.11589



Upcoming improvements and other research lines @ QUAX-LNL

On **main project**:

- 14 T magnet installed in dry refrigerator (in an external re-liquefier system)
- New dielectrically loaded cavity with 400 MHz tuning
- Autopilot for TWPA optimization and cavity tuning
- Hardware axion signal injection

Other ongoing **QUAX projects**:

- Single Microwave Photon Detector (SMPD) @ ~7.4 GHz
- Use of SMPD in a-e and a-γ coupling based haloscopes

C. Braggio et al.
Phys. Rev. X ***15****, 021031*

Conclusions

1. Overview of the QUAX apparatuses
2. Improvements in PD-LNL QUAX haloscope:
   - Dilution refrigerator stability
   - Low-noise electronics stable at ~ 2 SQL noise temperature
   - Dielectrically loaded cavity with V ~ 1L and Q_0 ~ 75000
   - Cavity tuning reliable in an 80 MHz region (soon expanded to 200 MHz)
3. Data acquisition and analysis:
   - Quasi-automated procedure
   - Simulations to set threshold
4. Results:
   - No rescan candidate
   - Exclusion plot in 38 MHz non-contiguous region with ~ 2 $g_{a\gamma\gamma}$ sensitivity
5. Future improvements also concerning SMPD

This is QUAX!

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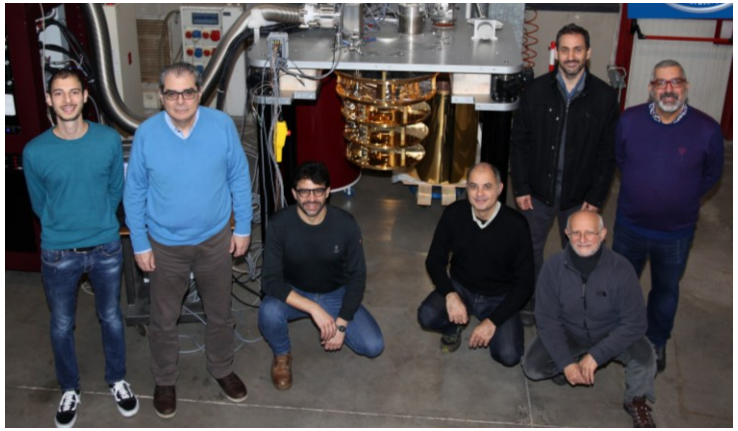

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Thank You!

Giosuè Sardo Infirri
on behalf of the QUAX collaboration

20th PATRAS workshop
La Laguna (Tenerife), 22-26 September 2025

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