Towards high power tests of an FE-FRT for transient detuning

Sam Smith

CERN Team:

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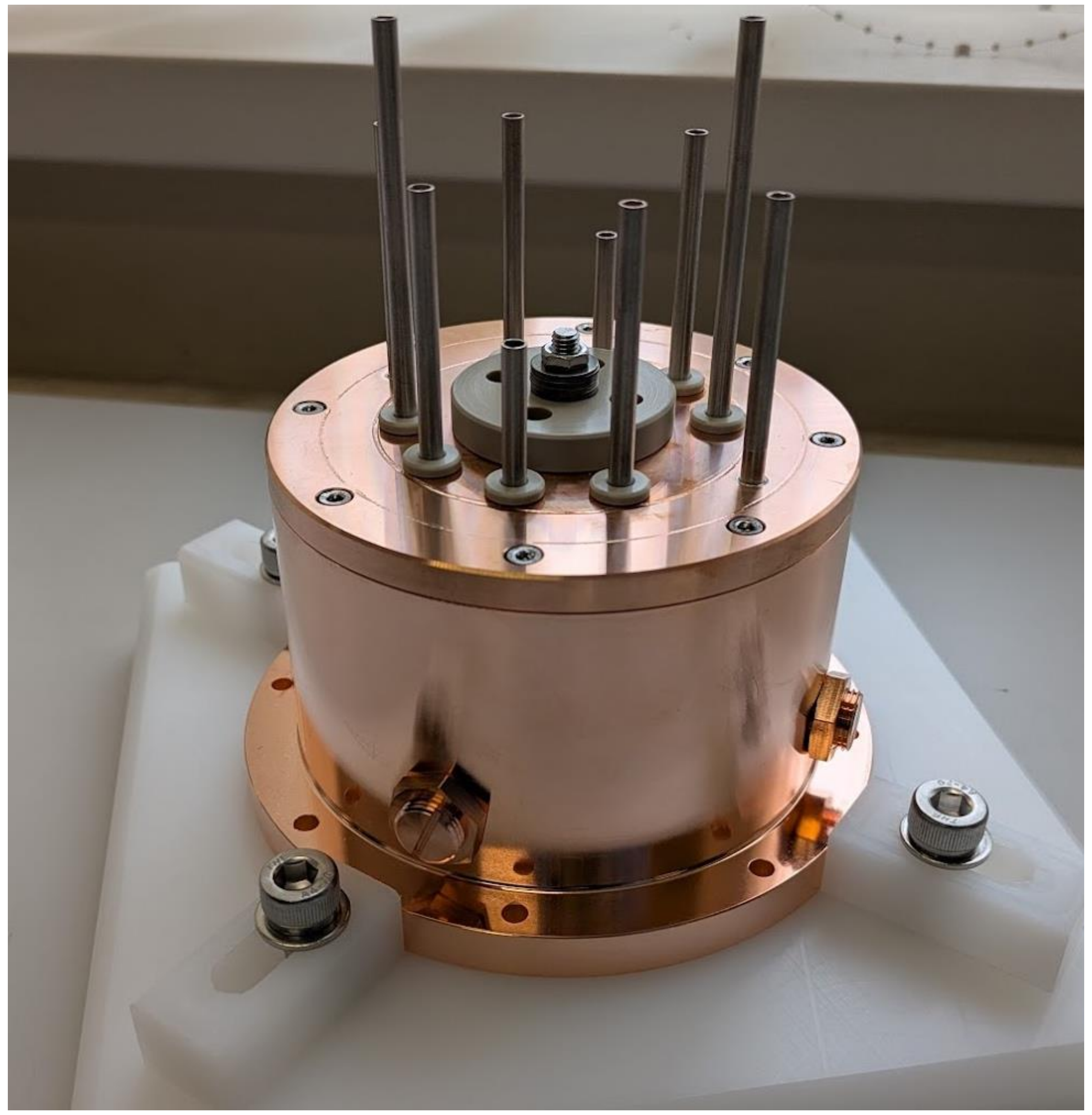

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CERN
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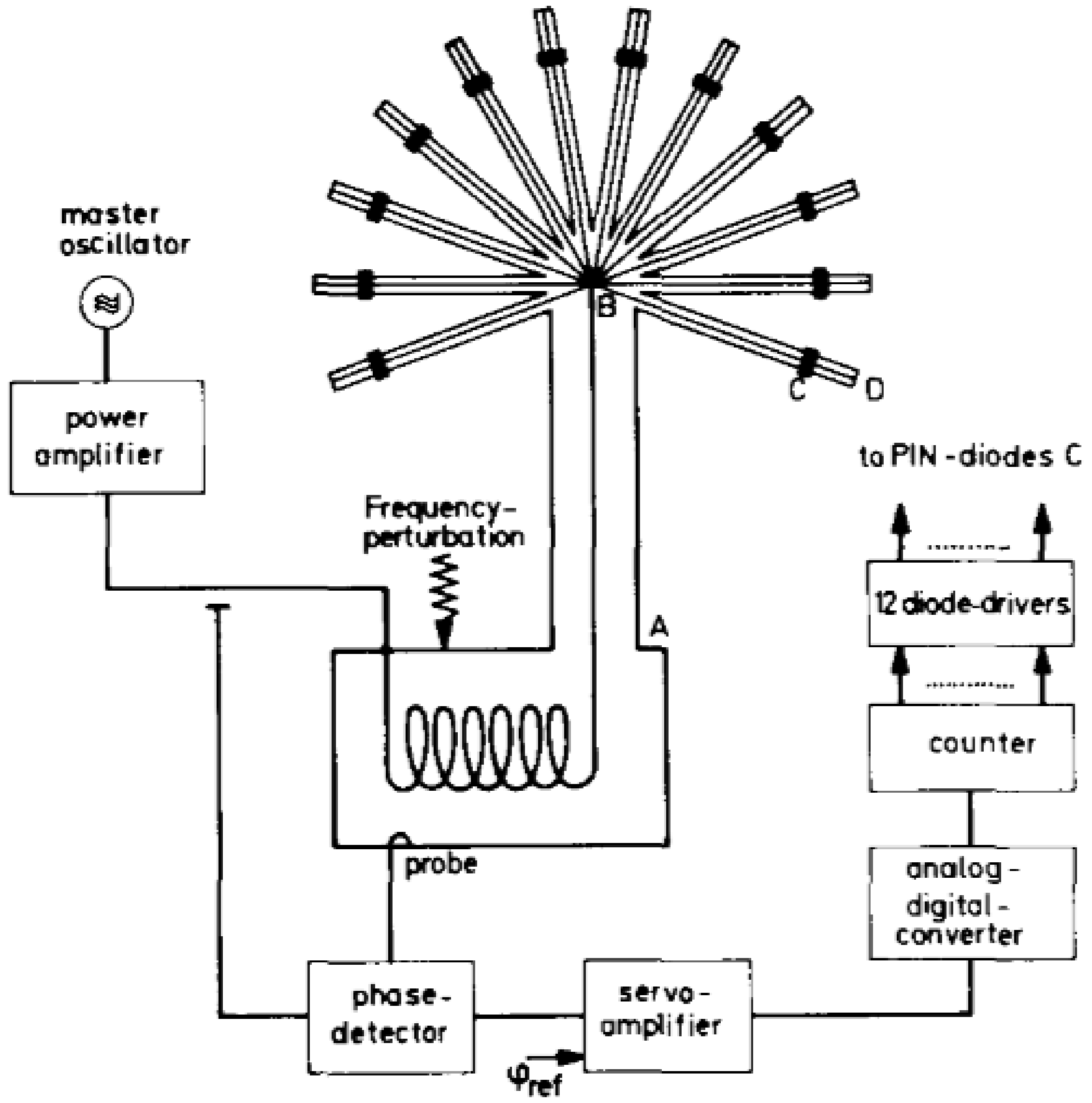
Overview

- Background
  - Types of cavity tuner
  - What is reactive tuning?
  - Ferroelectric materials
  - Operation of FE-FRTs
- Previous FE-FRTs
  - Applications of FE-FRTs
  - Previous results at CERN
- High power FE-FRT design
  - Concept
  - RF Design
  - Mechanical design
- Measurement program
  - Warm measurements
  - Cold tests
  - Lessons learned
- Future of FE-FRTs
- Summary

Background: RF cavity tuners

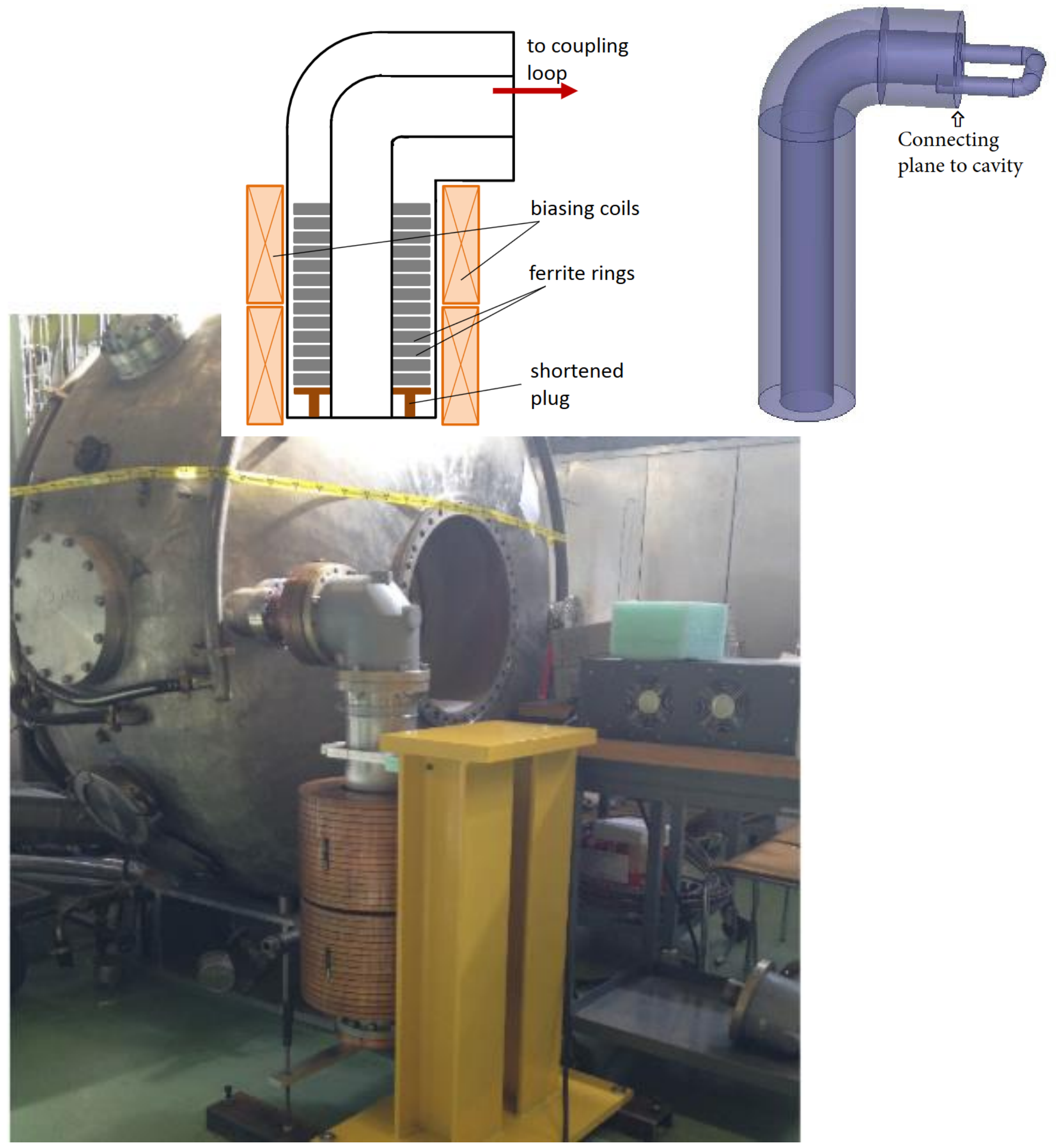
Pin Diodes



Schulze, D., Brandelik, A., Hietschold, R., Hochschild, G., Hornung, A., Spielbock, F., & Szecsi, L. (1972, January). Rf control of superconducting helically loaded cavities. In The 1972 Proton Linear Accelerator Conference, Los Alamos, NM.

- Mature technology
- Moderate powers
- Two state device
- Limited repetition rates

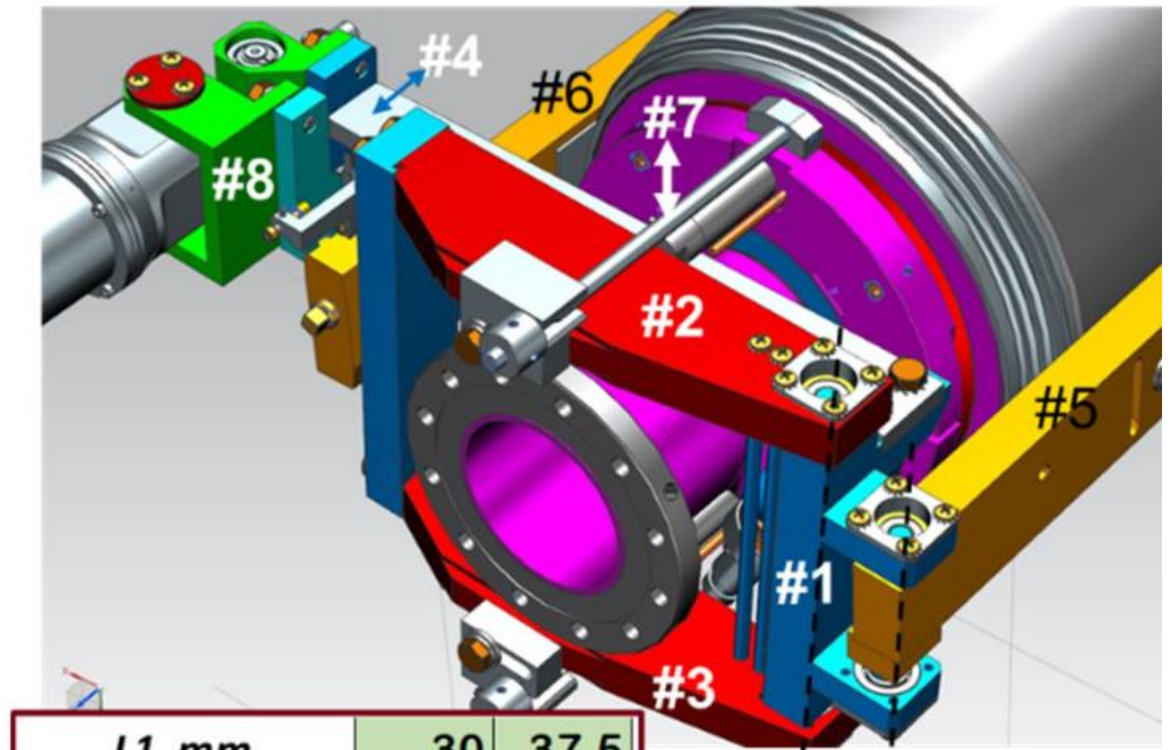
Ferrite tuners



Vollinger, C. and Caspers, F., 2015. Ferrite-tuner Development for 80 MHz Single-Cell RF-Cavity Using Orthogonally Biased Garnets (No. CERN-ACC-2015-227, p. WEPHA023).

- Several in operation
- Limited response times
- Lossy

Mechanical tuners

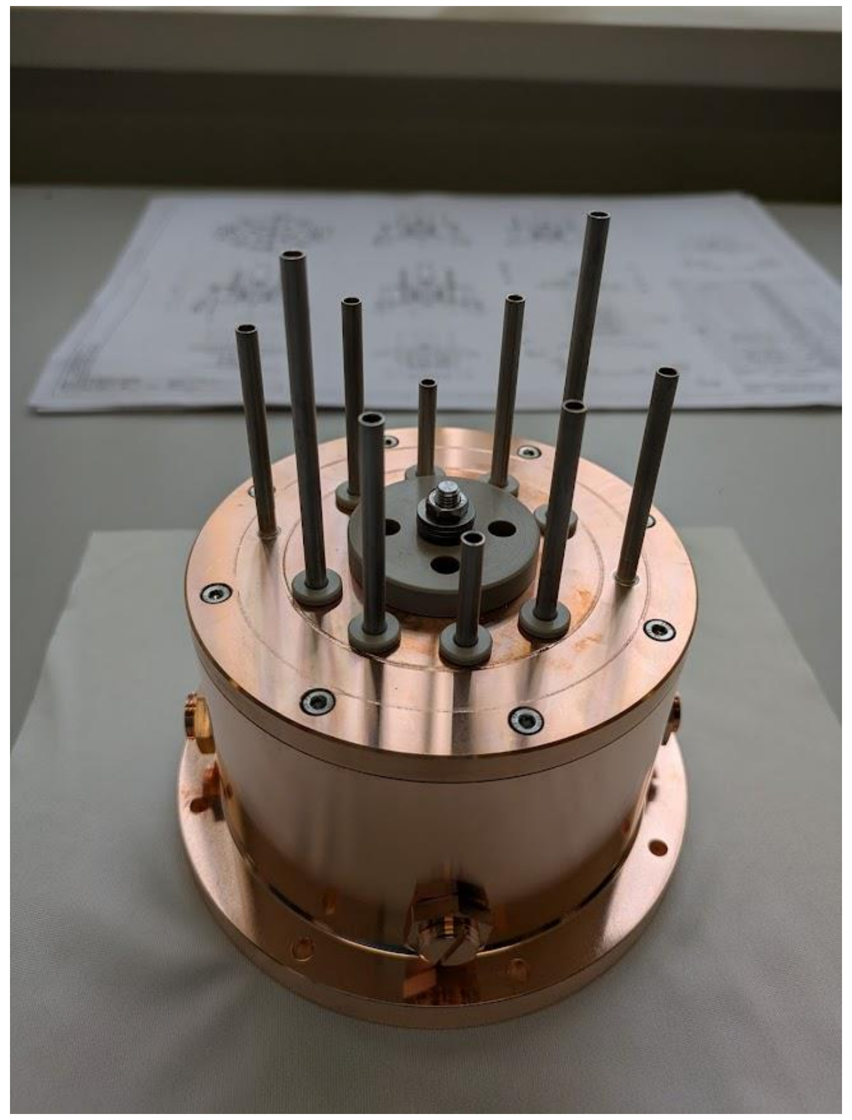


L1, mm	30	37.5
Tuner Ration	20	16
Hz/step	1.4	1.8

Pischalnikov, Yuriy, et al. *Extended range SRF cavity tuner for LCLS II HE Project*. No. FERMILAB-CONF-22-821-AD-TD. Fermi National Accelerator Lab.(FNAL), Batavia, IL (United States), 2022.

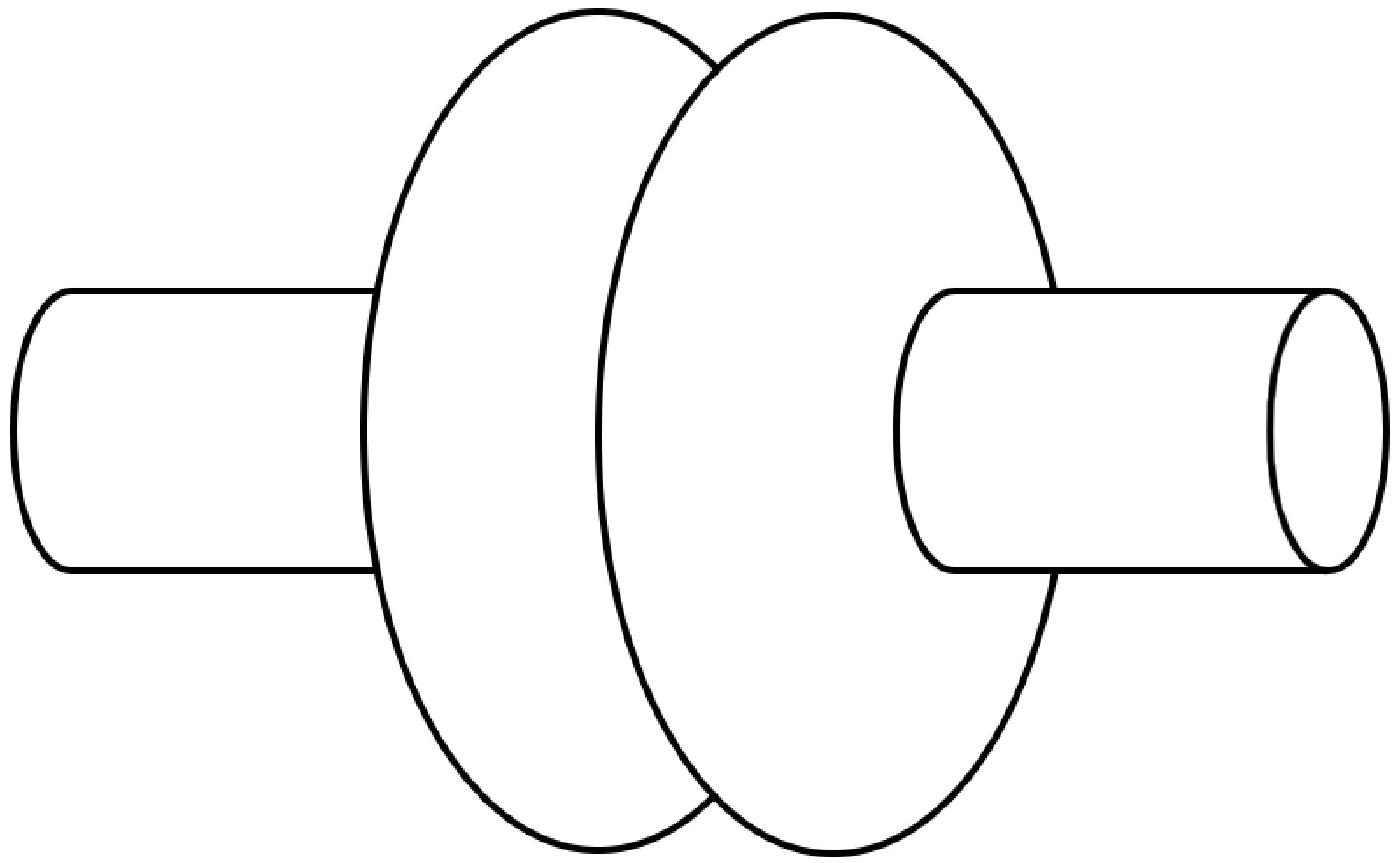
- Large range
- Established technology
- Comparatively slow
- Mechanical issues

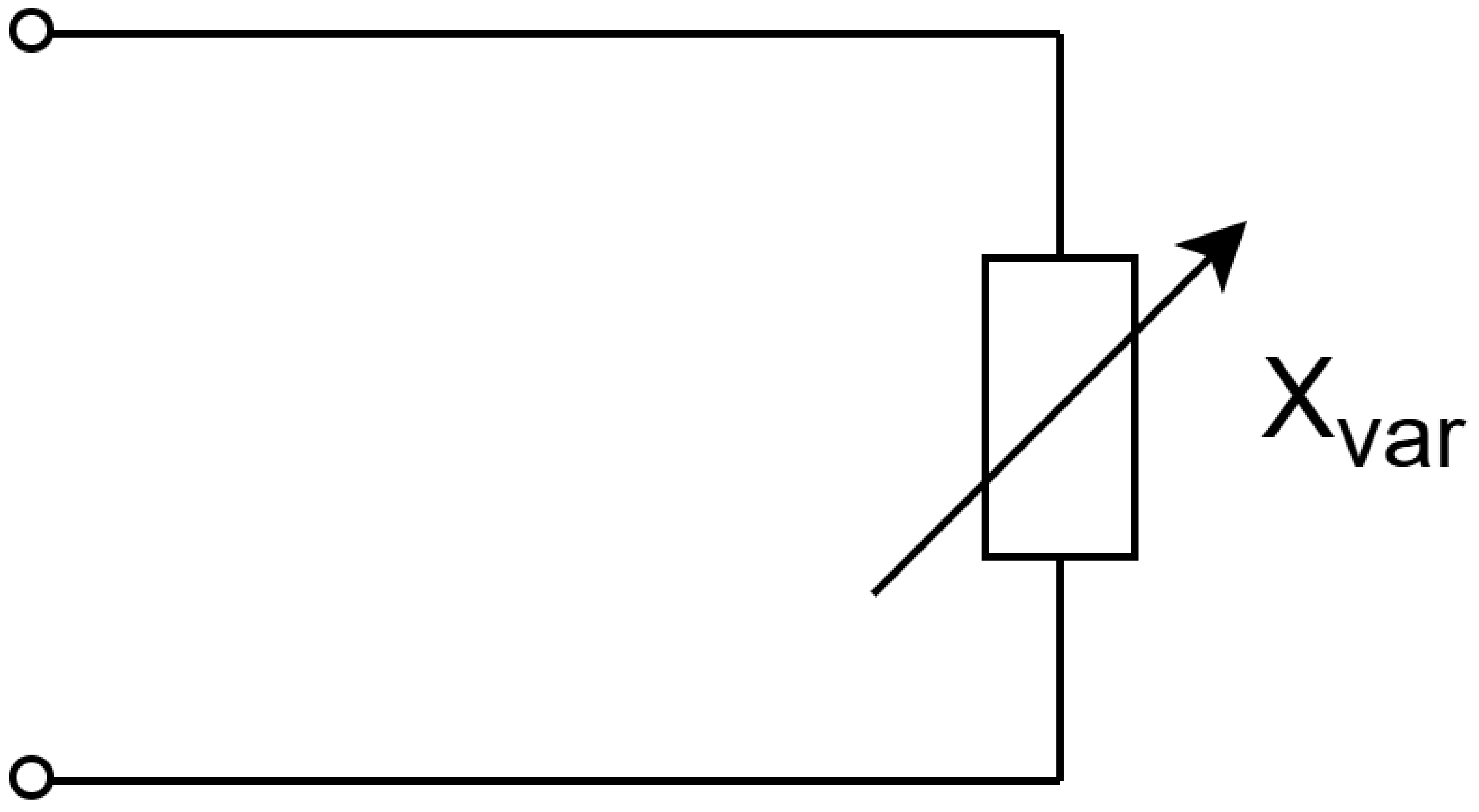
FE-FRTs



- Relatively new
- Extremely fast
- Can also be lossy
- No existing high-power devices

Background: What is reactive tuning?



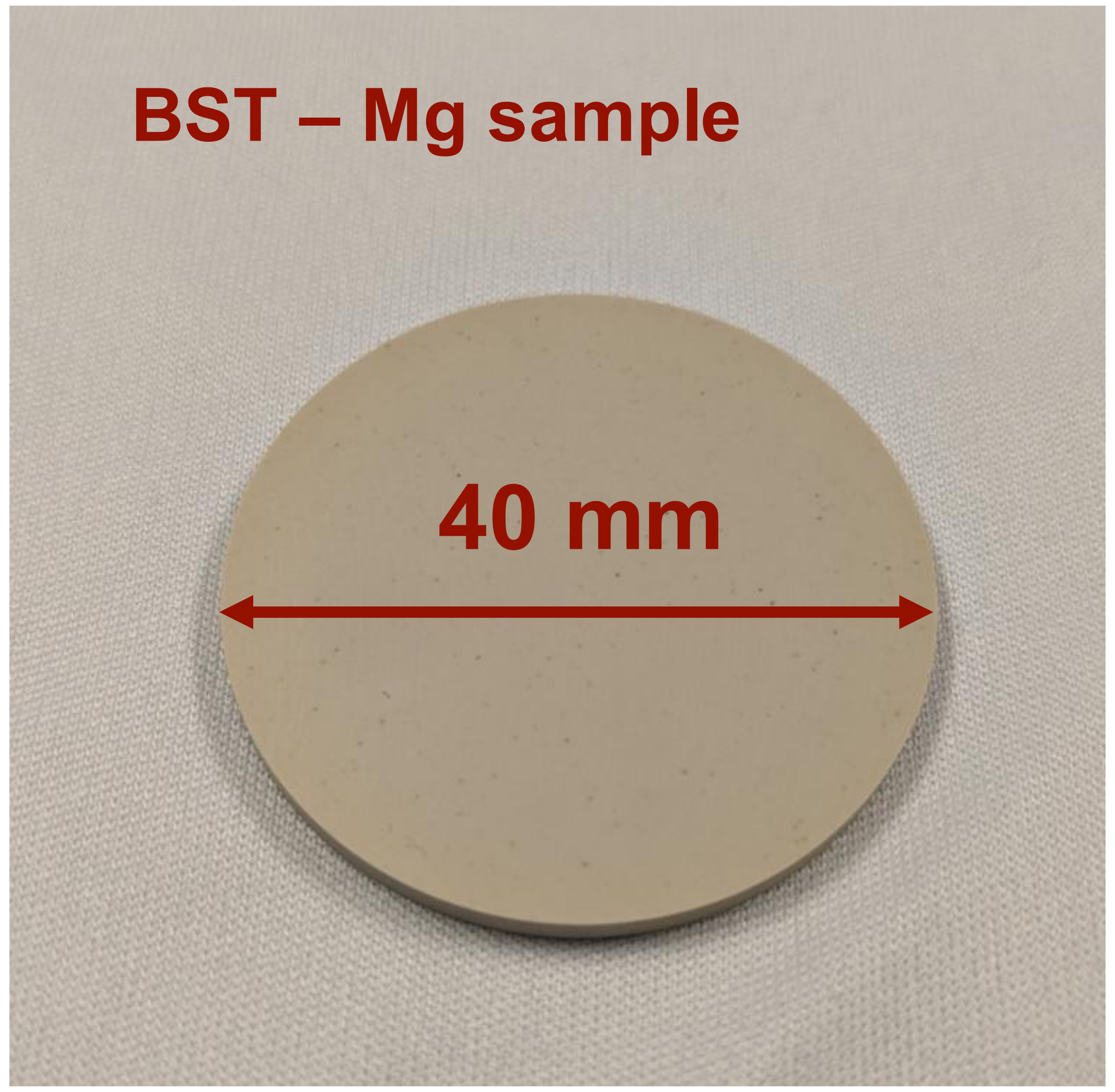


Reactive tuning is the controlled change of a cavity frequency using a coupled tuneable reactance

Background: Ferroelectric material

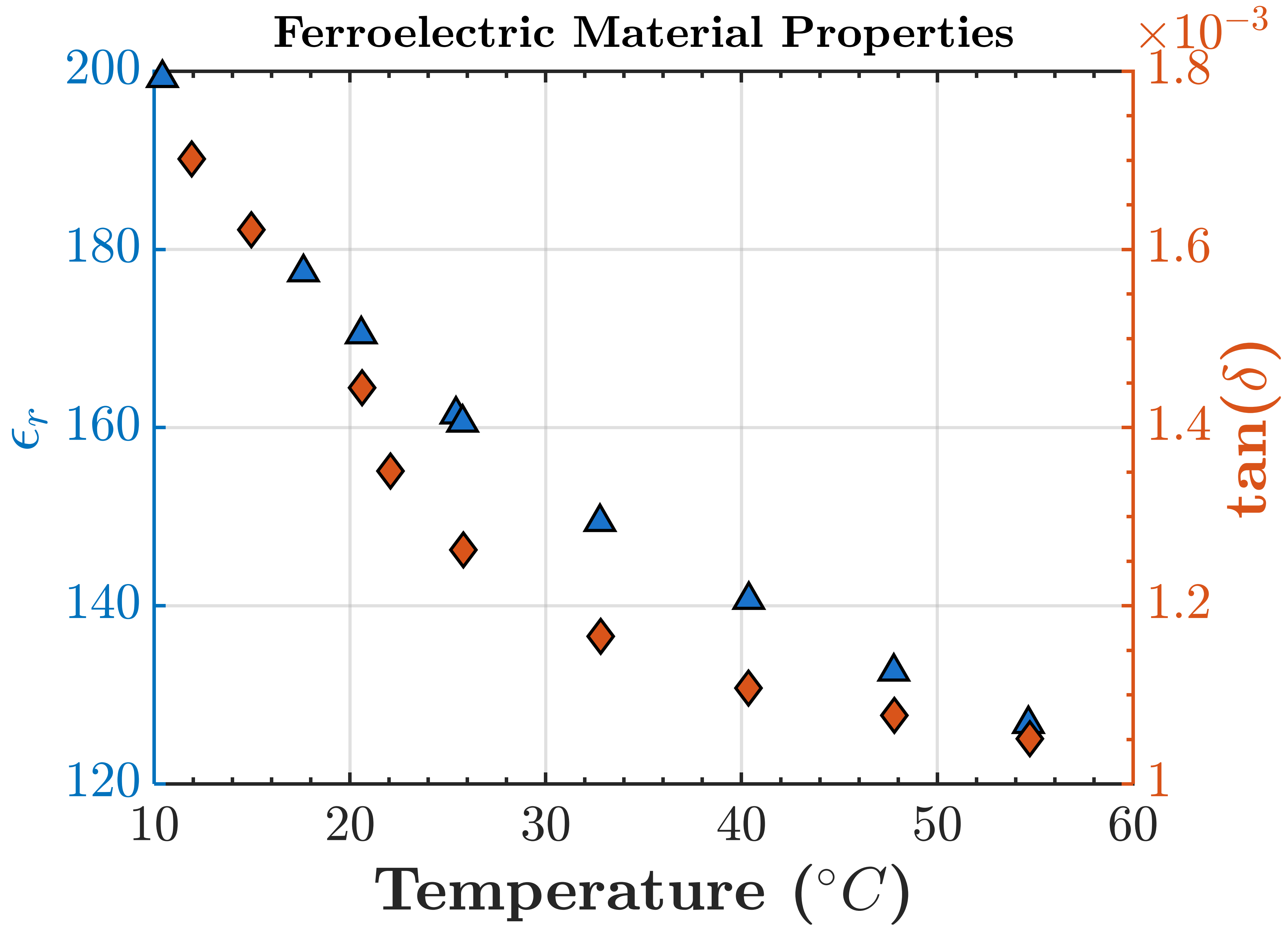
Heart of FE-FRTs:

- $BaTiO_3$-$SrTiO_3$ (BST) with Mg additives developed by Euclid Techlabs



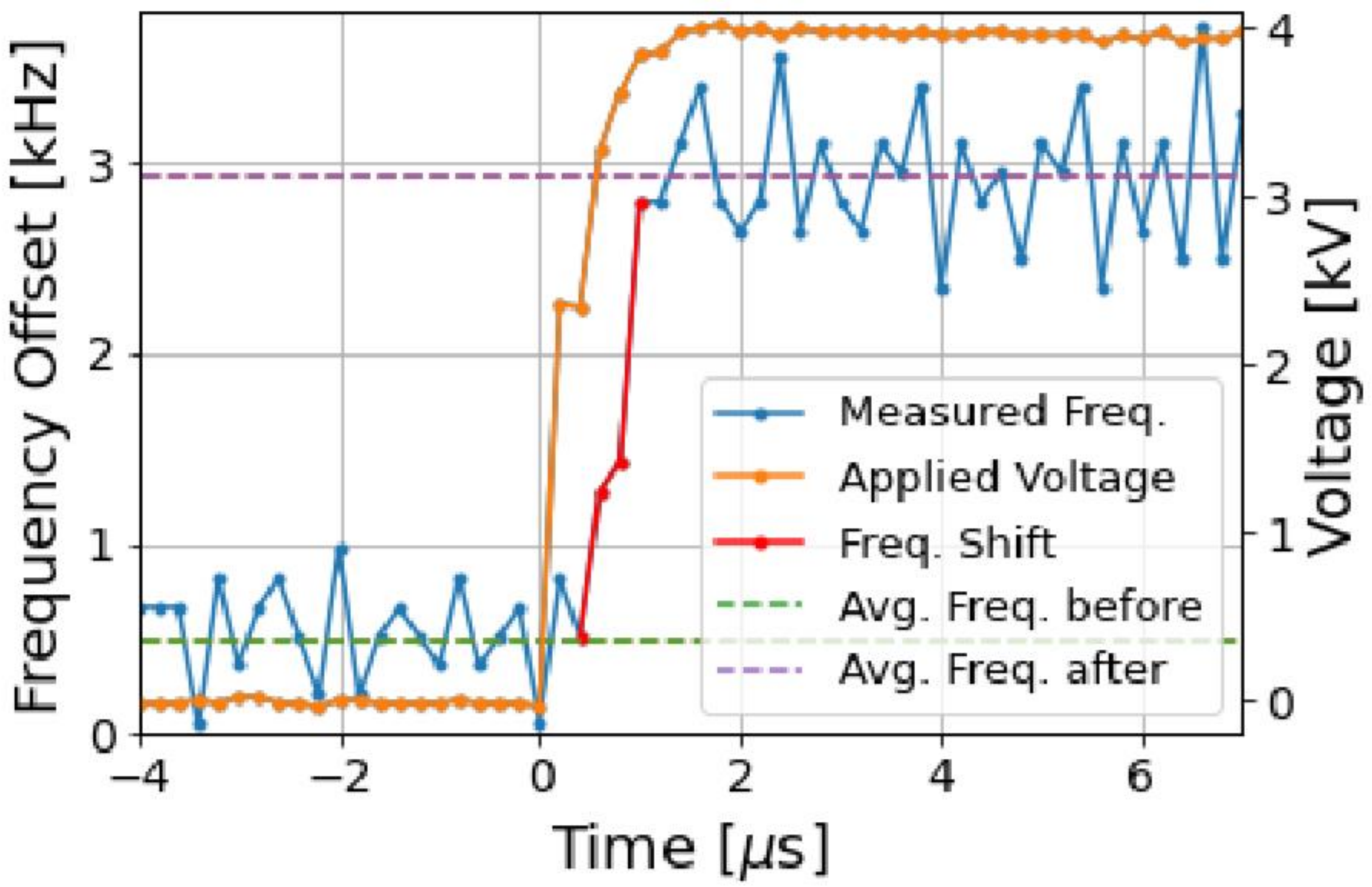
Attractive properties:

- Low loss tangent, ~ 1×10^{-3} at 400 MHz
- Fast response times < 30 ns[1]
- High tunability (35 % for 8 V/µm bias field)
  - High breakdown strength (~ 20 V/µm through the bulk)
- Minimum losses at around 50 °C



*Data measured at 400 MHz by C. Jing

Speed > cavity time constant

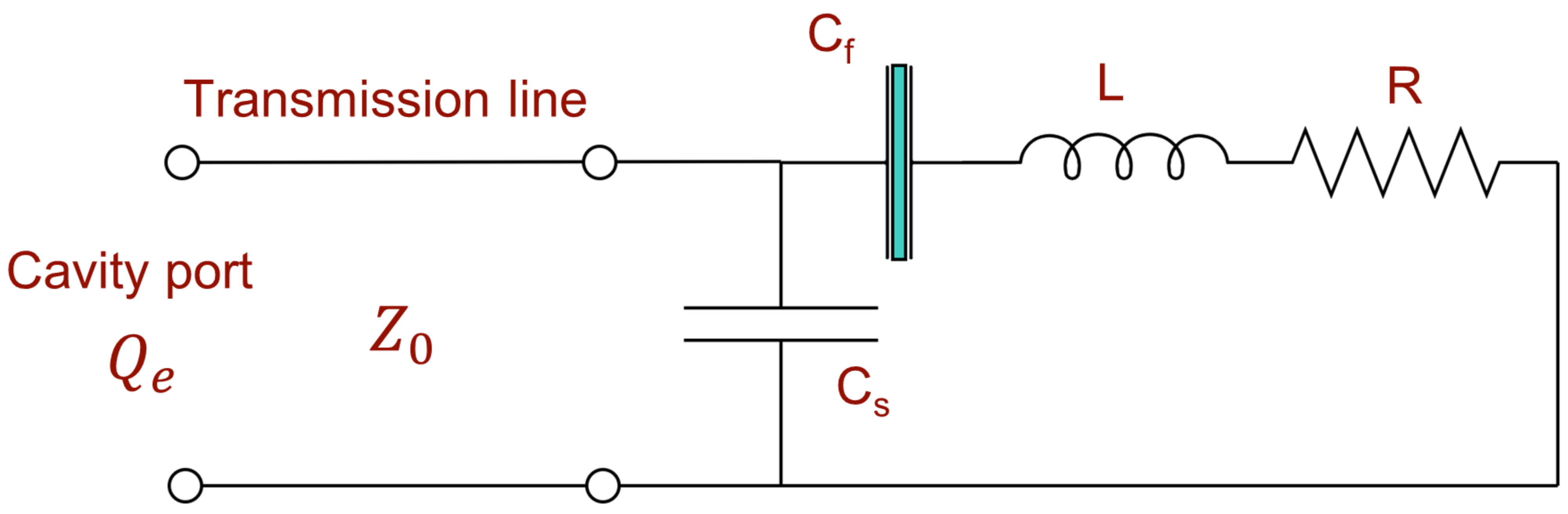


Shipman, Nicholas C., et al. "JACoW: Ferro-Electric Fast Reactive Tuner Applications for SRF Cavities." JACoW IPAC 2021 (2021): 1305-1310.

[1] S. Kazakov et al., "Fast High-Power Microwave Ferroelectric Phase Shifters for Accelerator Application", 2009.

Background: FE-FRT operation

- If tuner is a resonant circuit ➡ amplification of tuning range by a factor of ~ Q_{res}
- FoM – Figure of Merit ➡ quantifies performance



Total Figure of Merit

$$\mathrm{FoM} = \frac{\Im(P_2) - \Im(P_1)}{2\sqrt{\Re(P_1)\Re(P_2)}} = \frac{X_2 - X_1}{2\sqrt{R_1 R_2}}$$

Raw material performance

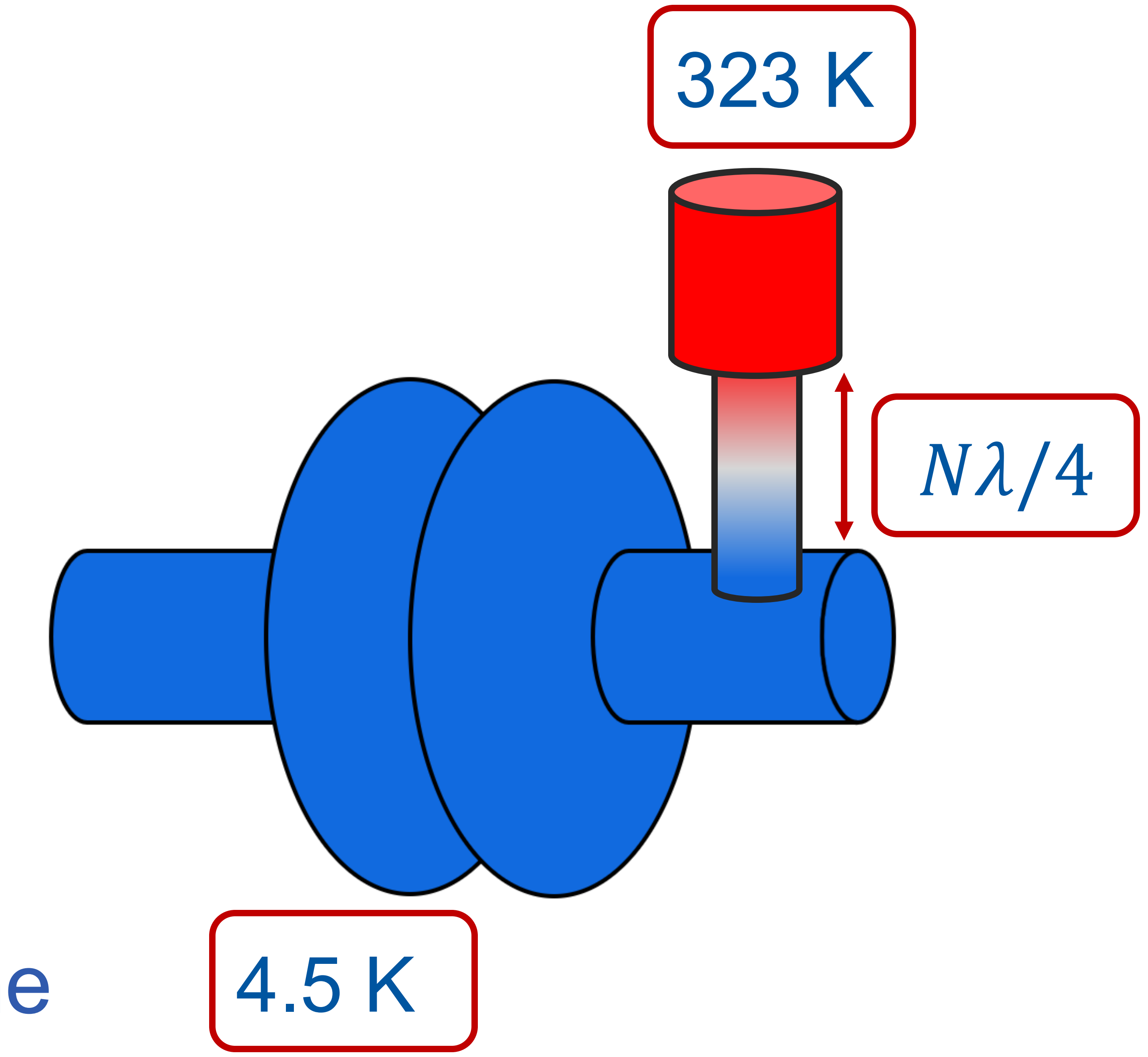
$$FoM_{material} \approx \frac{\Delta\varepsilon}{2\delta\varepsilon_c} \approx 150$$

Tuning range

$$\Delta\omega_{12} = \frac{\omega_0}{2Q_e}\frac{X_2 - X_1}{Z_0}$$

Reactive power

$$\Im(\Delta P_{12}) = 2U\Delta\omega_{12}$$



- Quarter wave transmission line to separate tuner from cavity
  - Needed for SRF cavities to avoid excessive heat load
- Coupling capacitor C_s for impedance matching to the transmission line
- Operation across short > continuous tuning range

Applications of FE-FRTs

- FE-FRT can be operated in various ways depending on the application
- Best suited for applications requiring fast tuning speeds and moderate tuning ranges

Transient detuning:

- Compensate fast reactive beam loading changes
- No other tuners can do this due to the speed required
- Power saving factor of 2 to 10

Typical FoM values for 100 kVAR

Frequency (MHz)	Typical FoM
400	110
800	60
1300	50

*Typical values based on coaxial reflection type tuner design and current best material measurements

Potential other applications:

- Tuning stiff/delicate cavities (e.g Nb_3Sn coated cavities)
- LFD compensation
- Jumping over harmful resonances
- Phase shifting and frequency conversion[1]

Microphonics suppression:

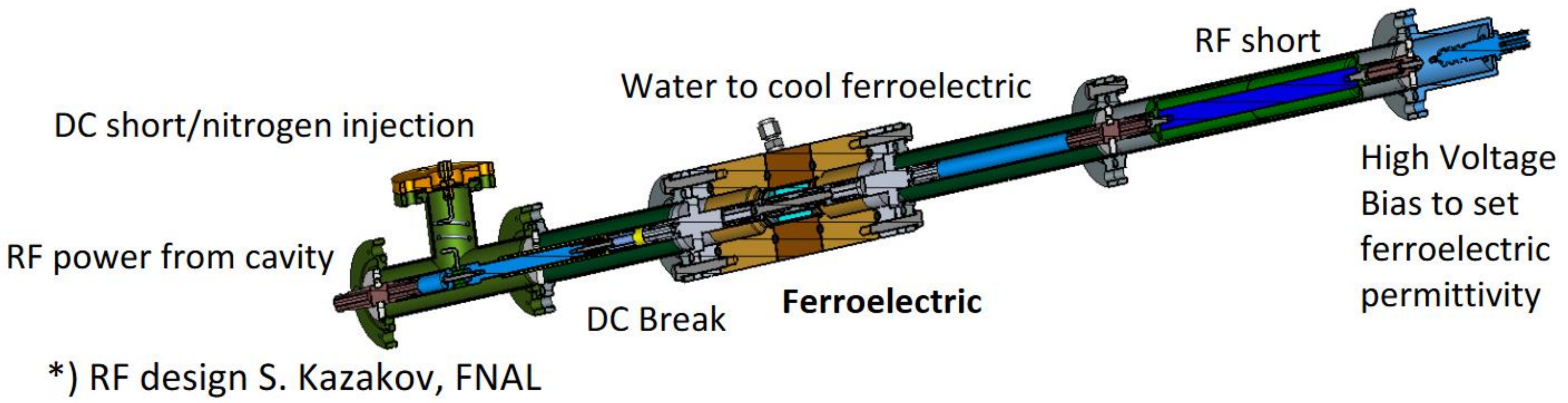
- Low beam loading machines
- Average power reduction ~ FoM/4

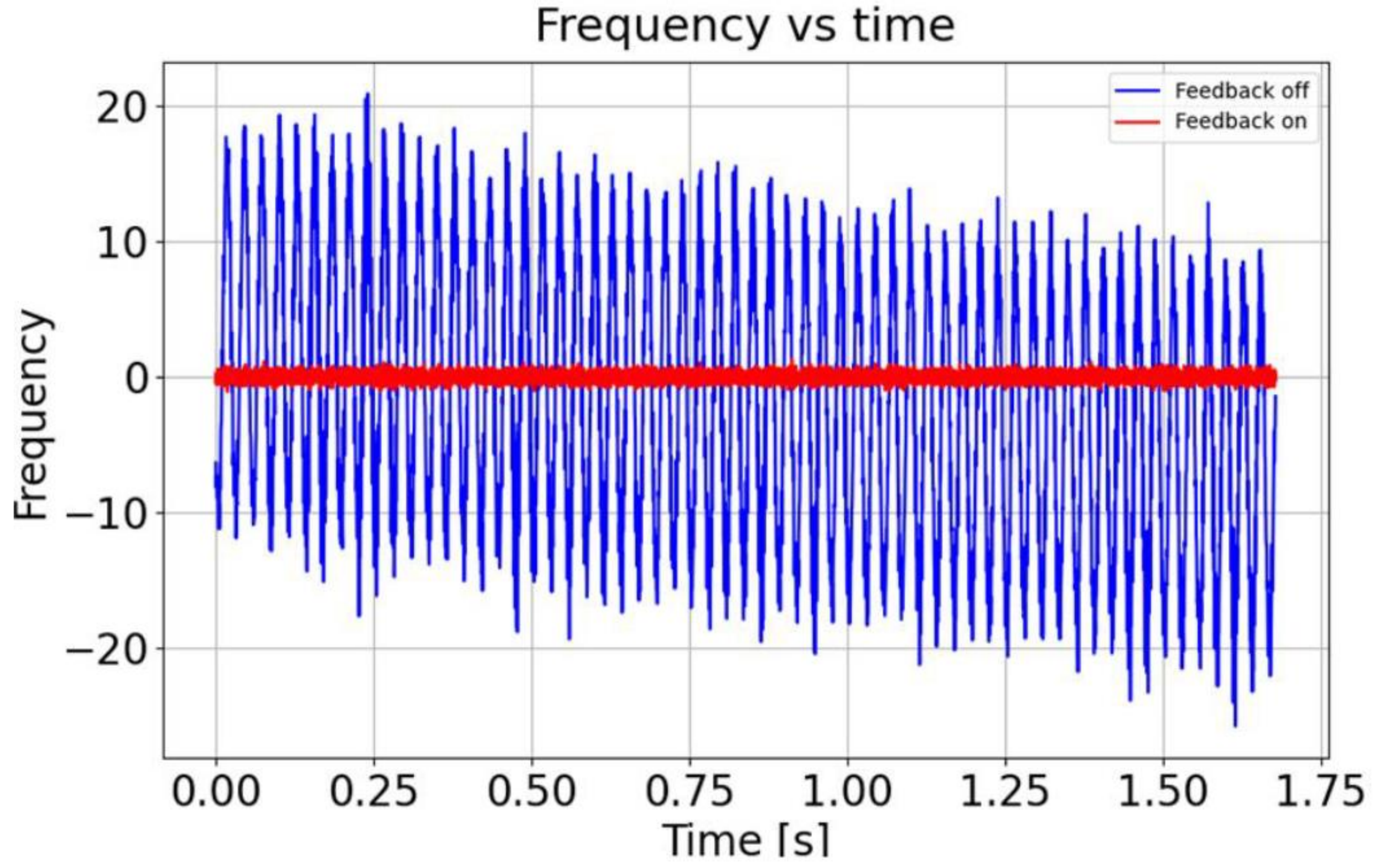
[1] Ben-Zvi, Ilan, Alick Macpherson, and Samuel Smith. "Design of a High-Average-Power Ferroelectric Phase Shifter." *arXiv preprint arXiv:2509.05228* (2025).

Previous results at CERN

Proof of principle test

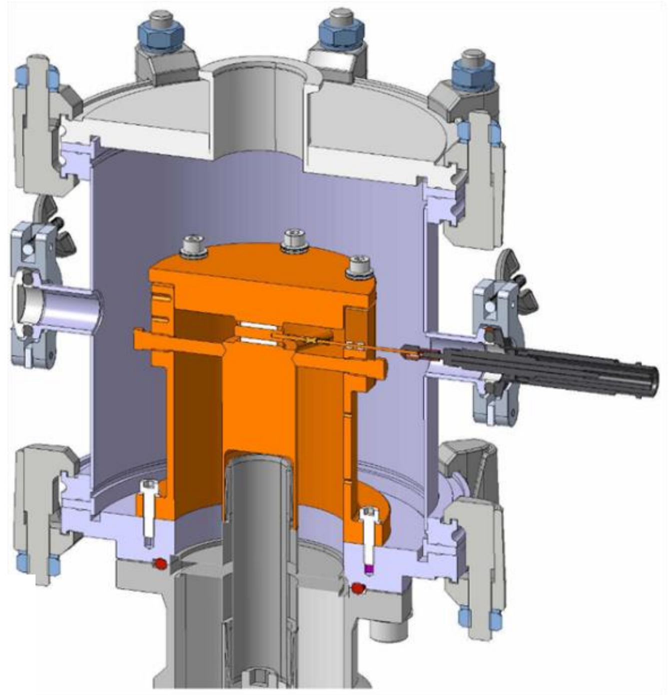
- Transmission type tuner
  - Device developed by Euclid techlabs
  - Tested at CERN in 2019 with 374 MHz SRF cavity
- Microphonics suppression proven
- Low FoM due to brazing issues

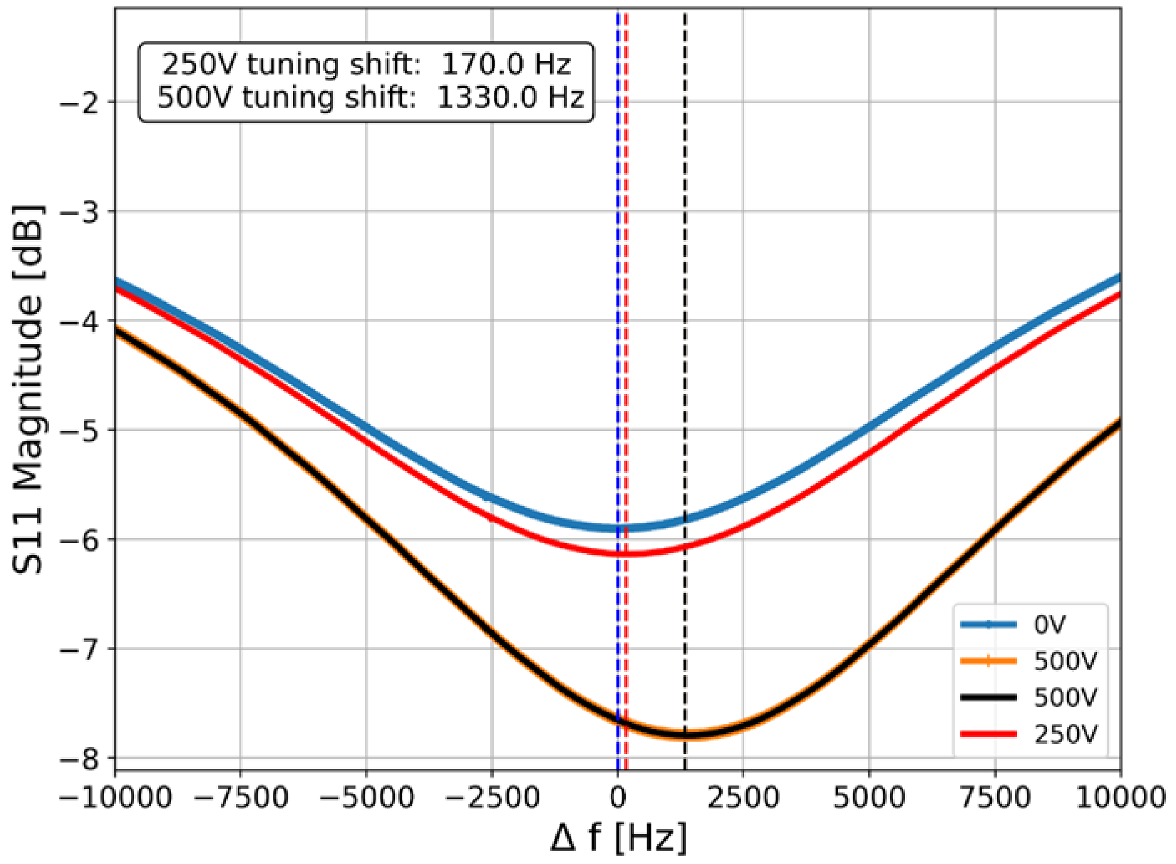




TDD0

- First transient detuning demonstrator (TDD0)
- Resonant reflection tuner, inductive coupling
- Tested on LHC 400 MHz cavity
- Showed 1.3 kHz shift for 500 V
- Issues with ceramic breakdown

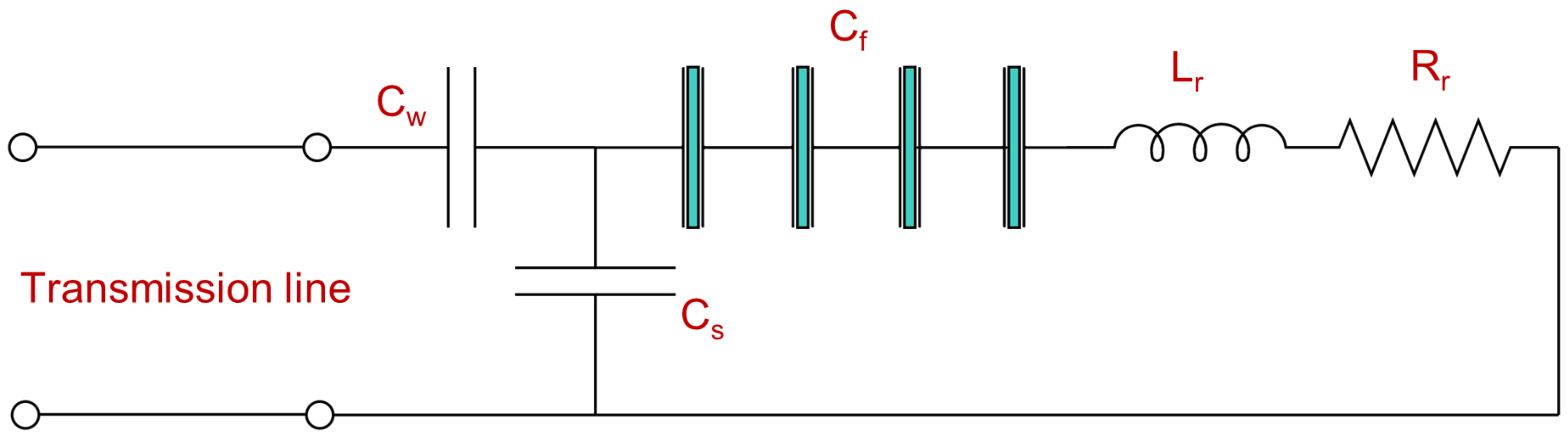


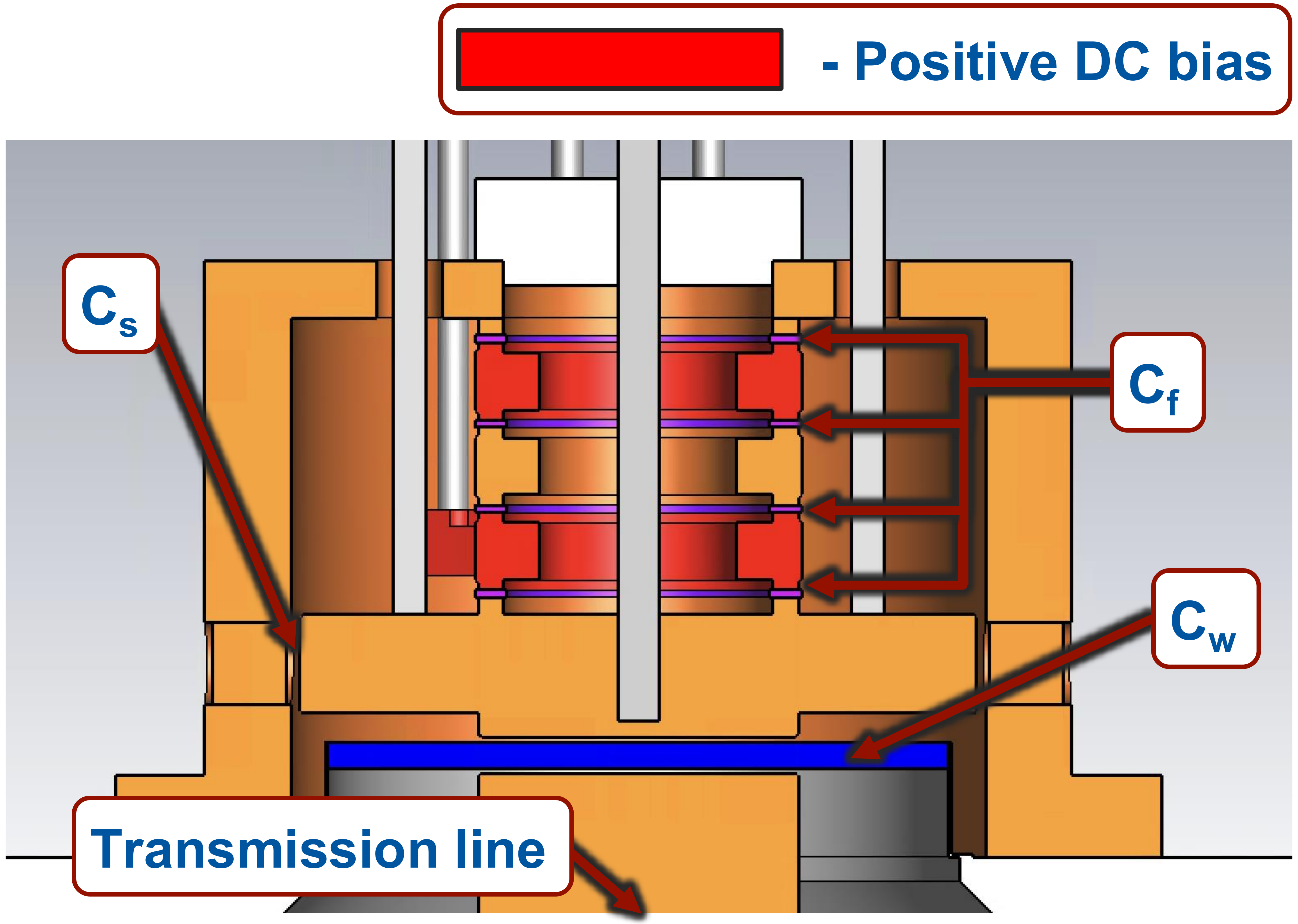


To date, there has been no high-power experimental validation of an FE-FRT

High power FE-FRT concept

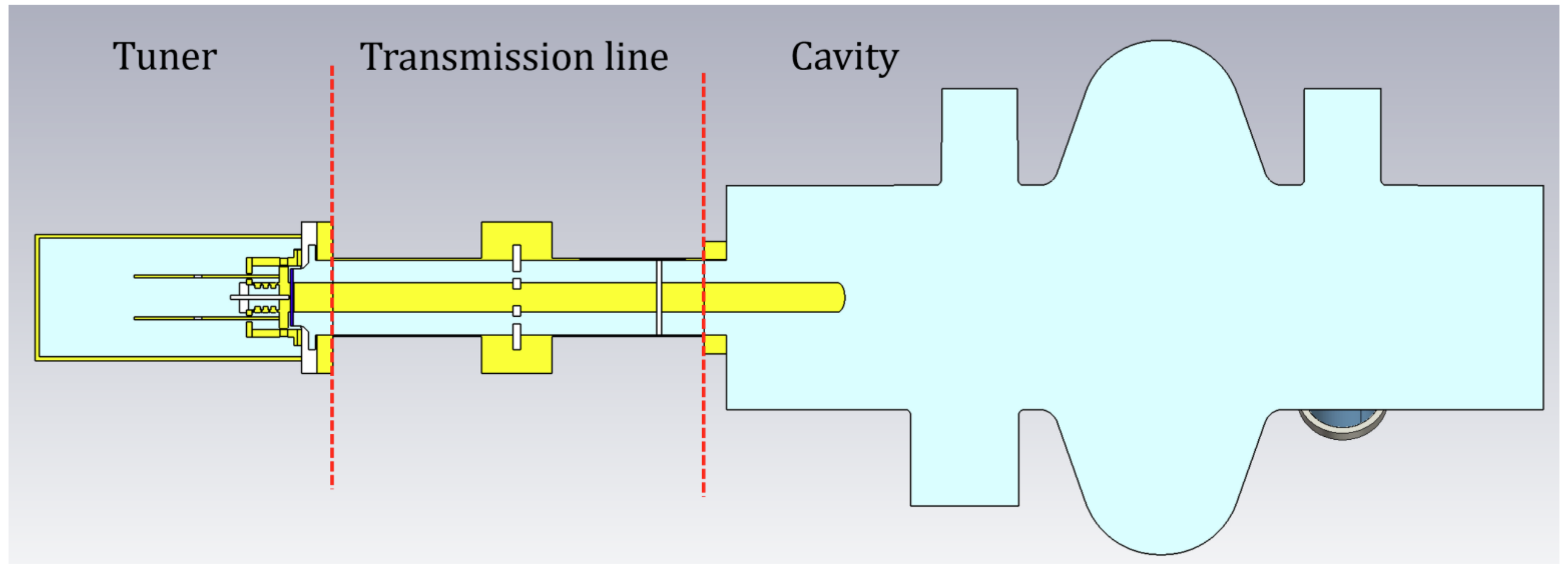
- Use a 400 MHz LHC cavity to test a high reactive power tuner
- Design: coaxial resonant reflection type tuner, capacitive coupling
  - 8 kHz tuning range based on 0 – 7.2 kV ferroelectric bias voltage
  - Designed for large reactive powers ~ +/- 225 kVAR
- Realisation:
  - 4 annular wafer design ➡ minimised inductance
  - Integrated cooling, pipes used for biasing
  - DC bias applied using cooling lines
- Objective: demonstrate high average power tuning

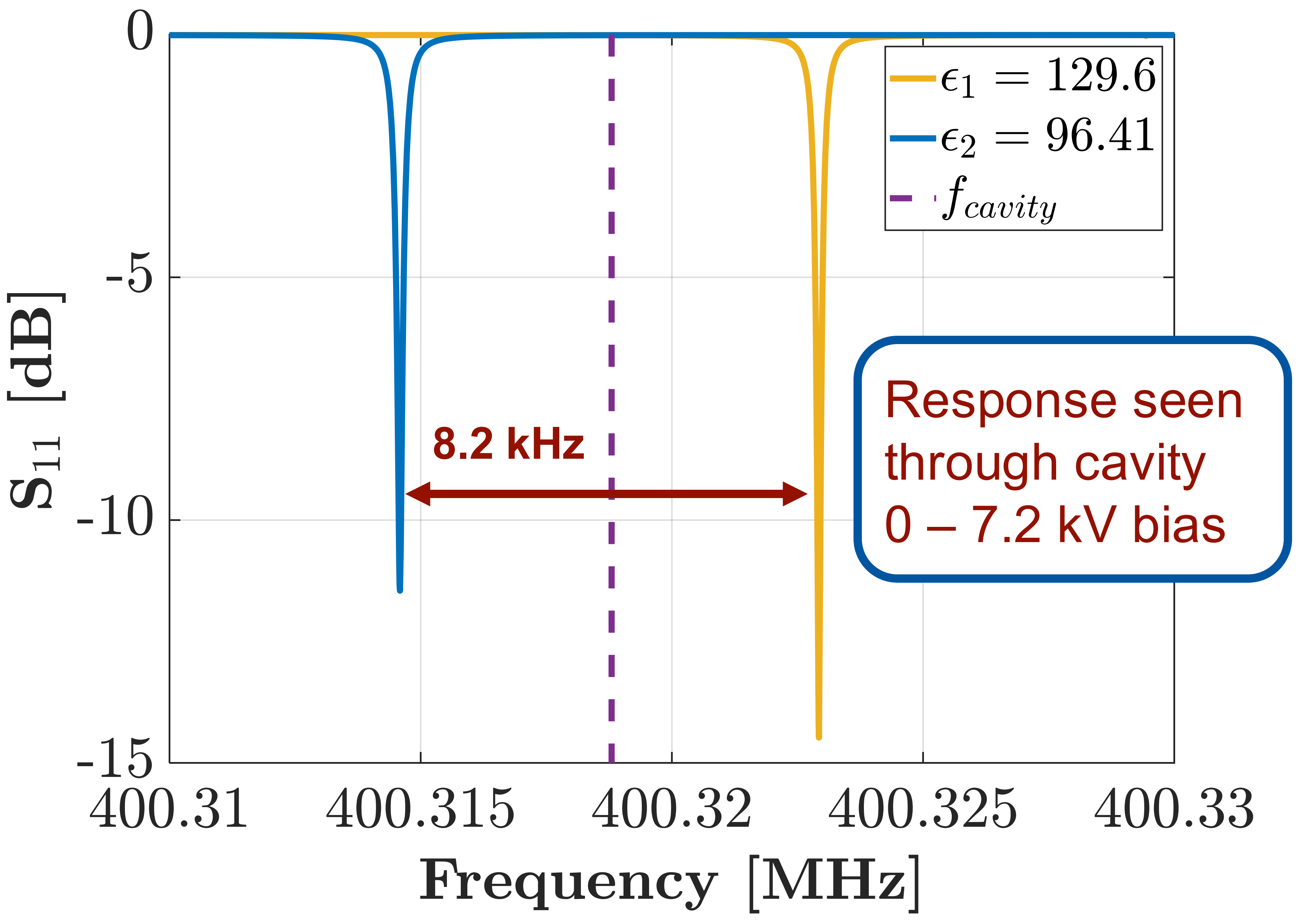




RF design: Expected performance

- Analytical estimates used to guide design
  - Good agreement between analytical model and simulation
- Tuner design optimised using system modelling approach
  - Sub-component optimisation via S-parameter concatenation
- C_s , C_w , and transmission line length > optimisation inputs
  - Constraint: 8 kHz tuning range and centred over cavity frequency
- Tuner infrastructure integral to setting RF design
  - Cooling lines, HV biasing, antenna supports





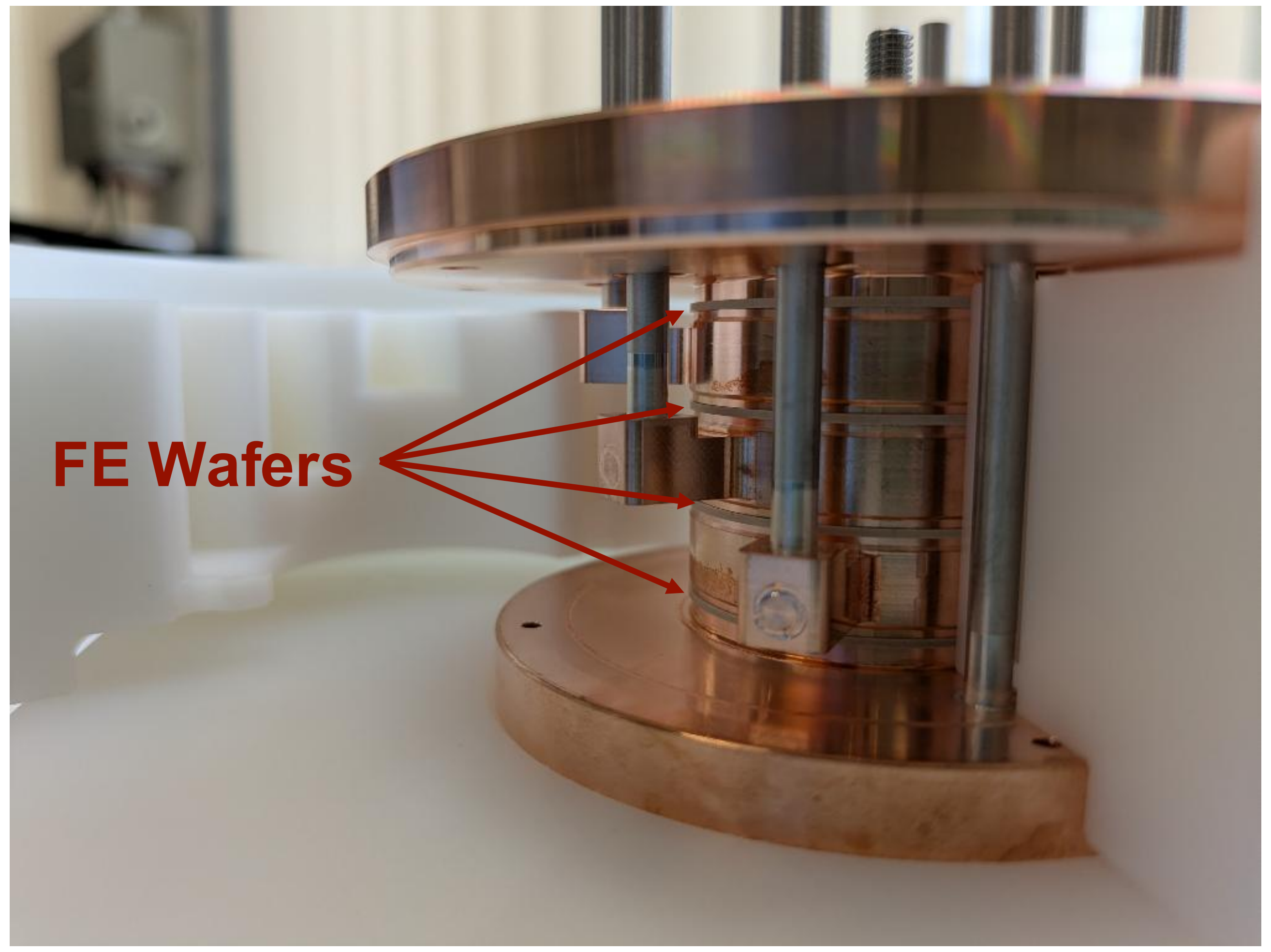
Parameter	Analytical	CST	Units
Tuning range	8	8.2	kHz
$\Delta P_{reactive}$	452	-	kVAR
C_w	4.85	7.3	pF
C_s	35.3	32.8	pF
Z_0	56.18	56.18	Ω
$Q_{FRT,1}$	4.09e6	3.46e6	-
$Q_{FRT,2}$	3.66e6	2.49e6	-
$Q_{e_{FRTport}}$	50000	50000	-
FOM	77.4	61	-

Final tuner FoM: 61

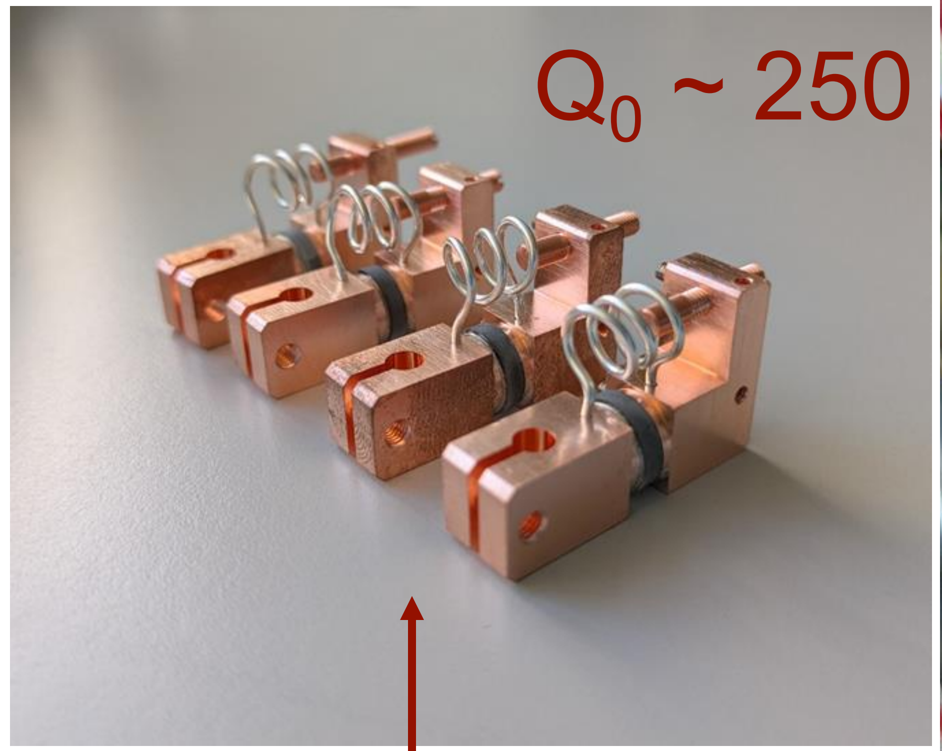
Power dissipation:
- **Total: 3.8 kW**
- **1.5 kW in FE material**
- **2.3 kW in rest of tuner**

From RF to Mechanical: Design features

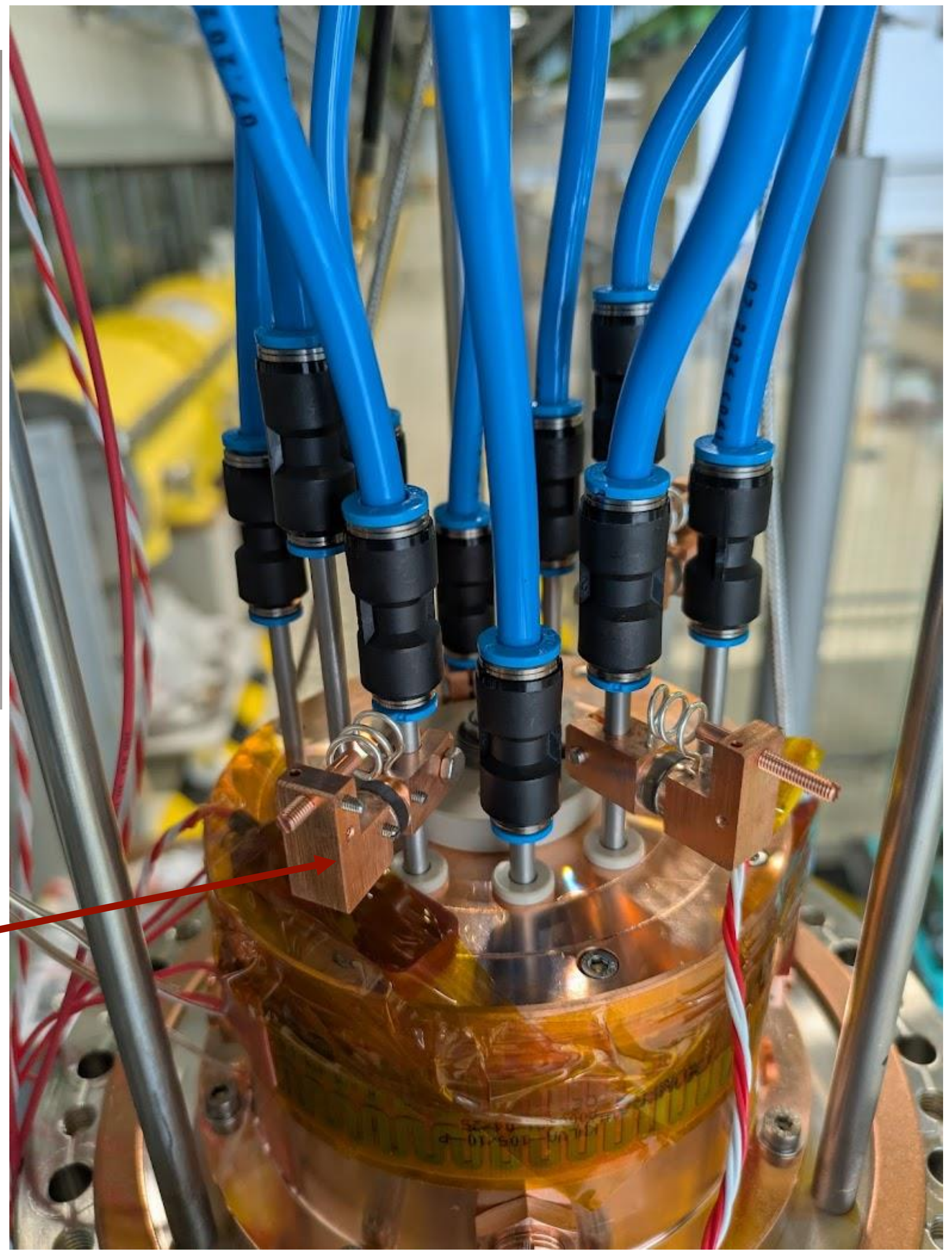
FE wafer overhang to reduce likelihood of breakdown

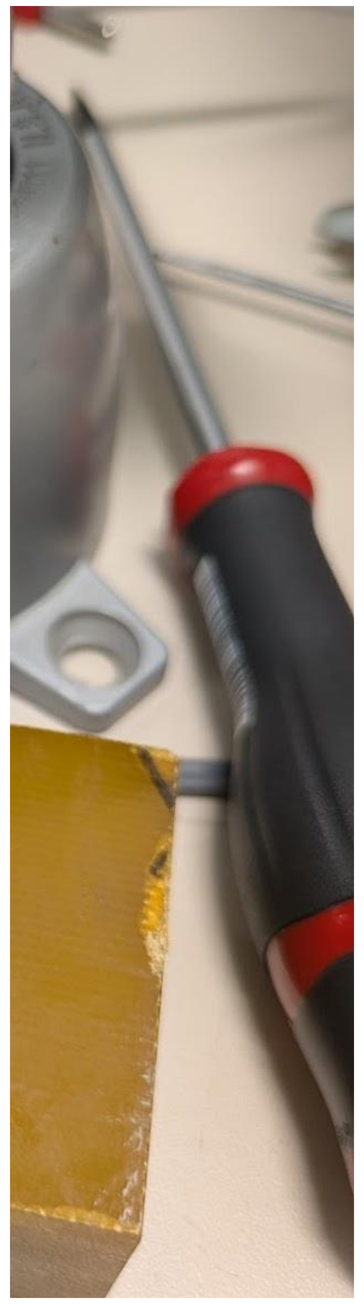


Optically polished ceramic



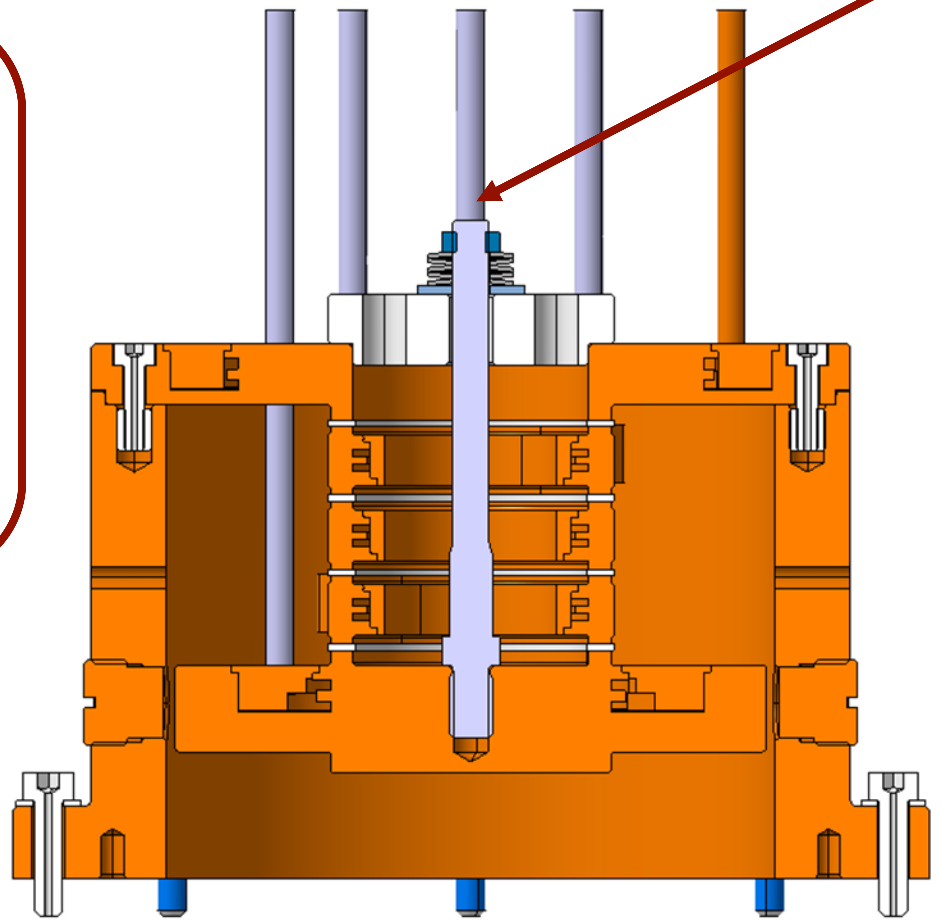
LC filters for HV isolation

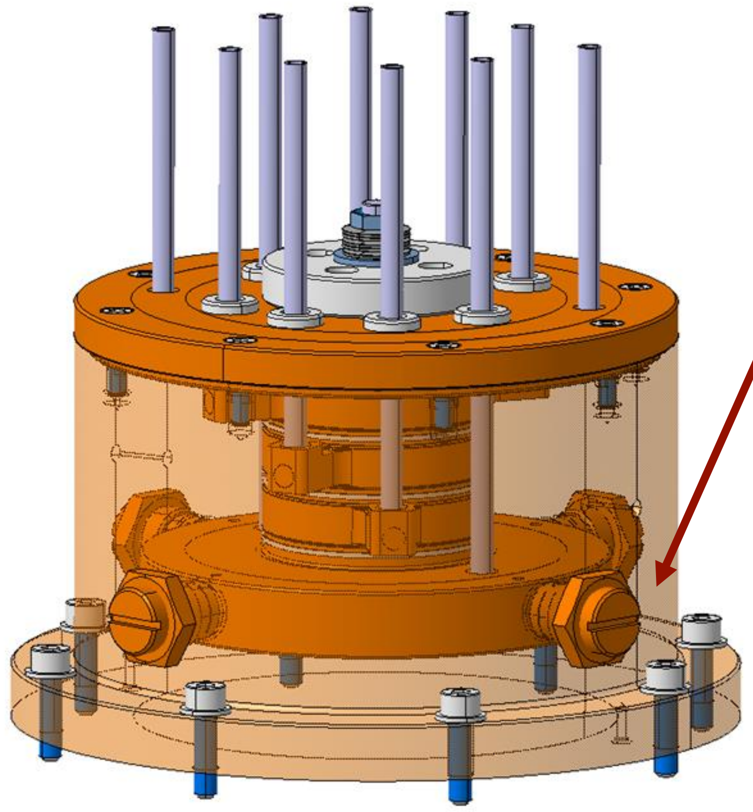




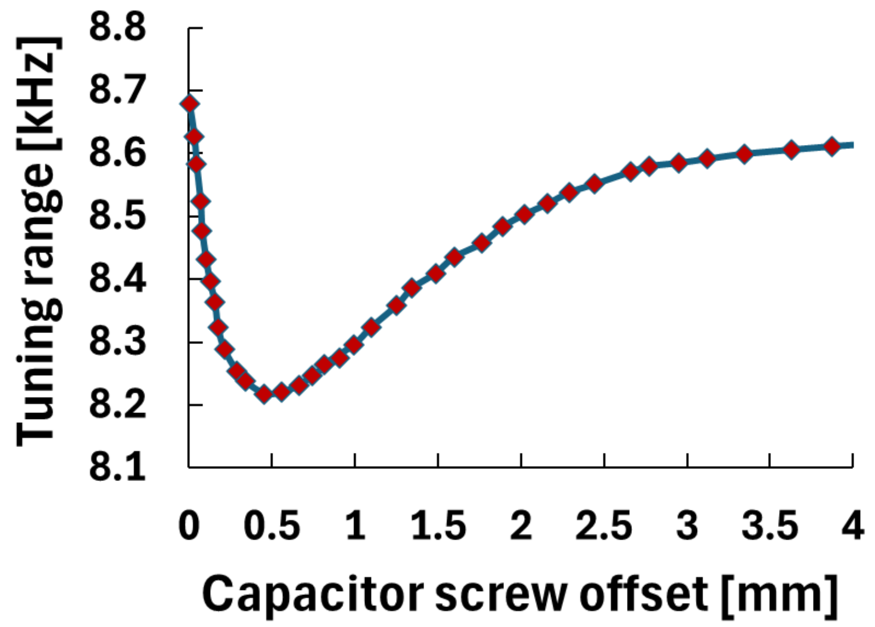
Compression system providing 5 MPa

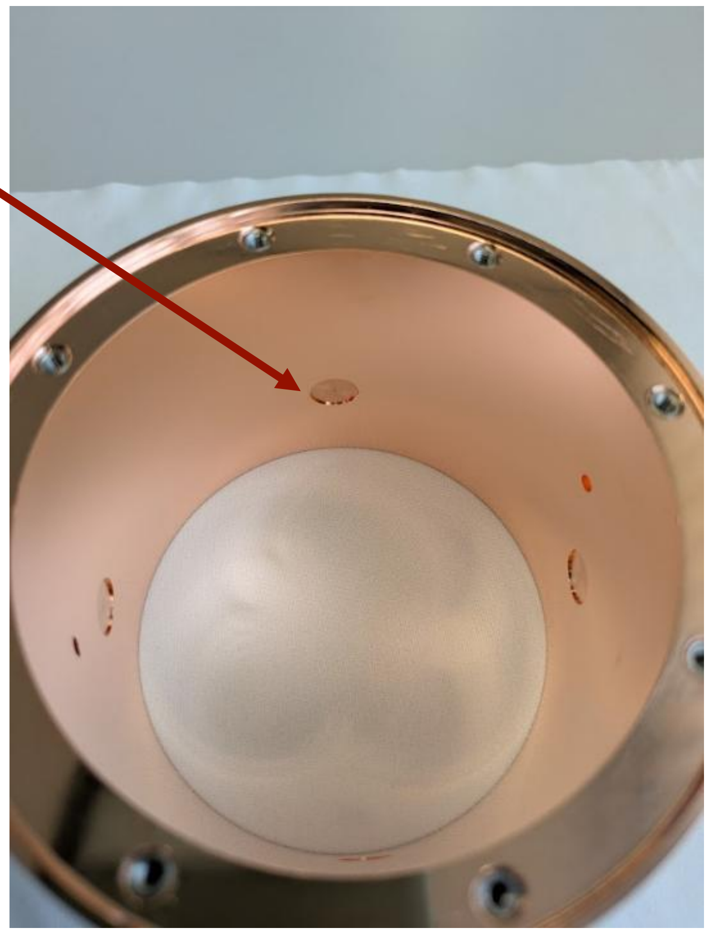
Integrated electrode cooling for removing dissipated power





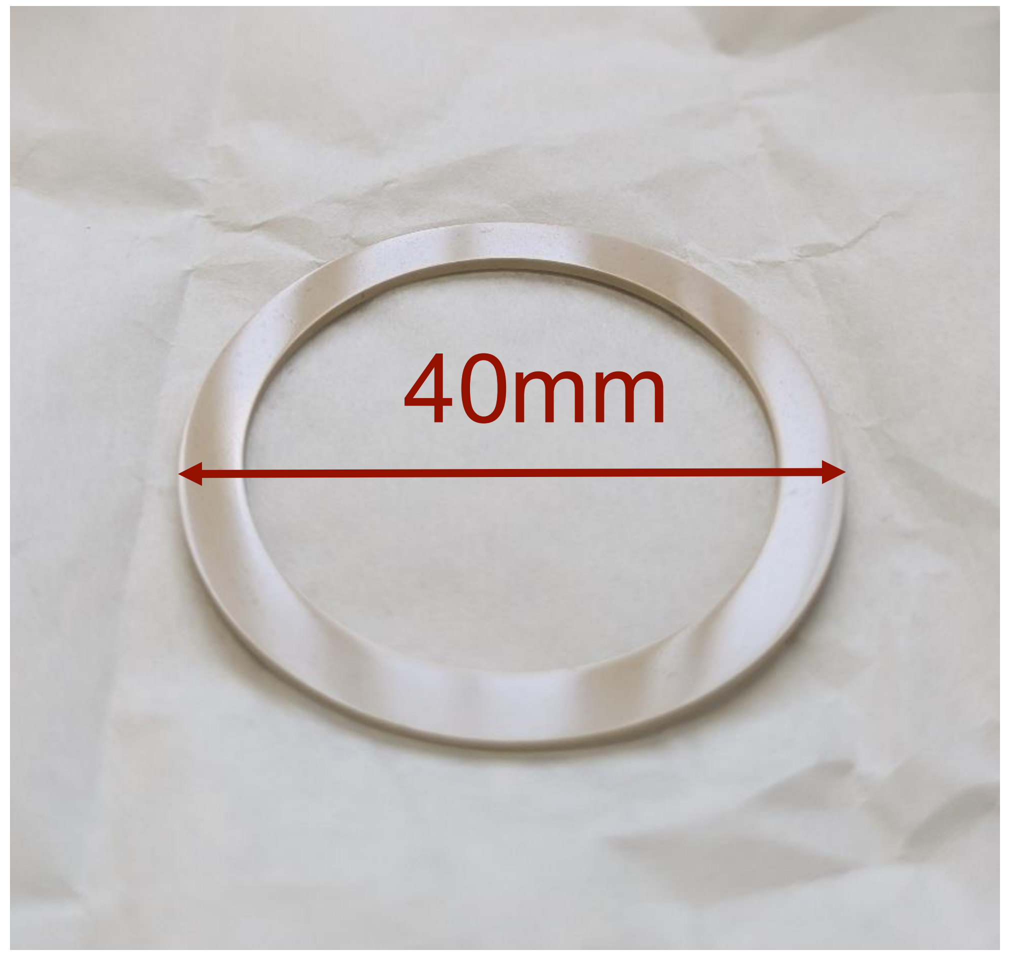
Tuning screws for adjusting coupling capacitance





Ferroelectric sample preparation

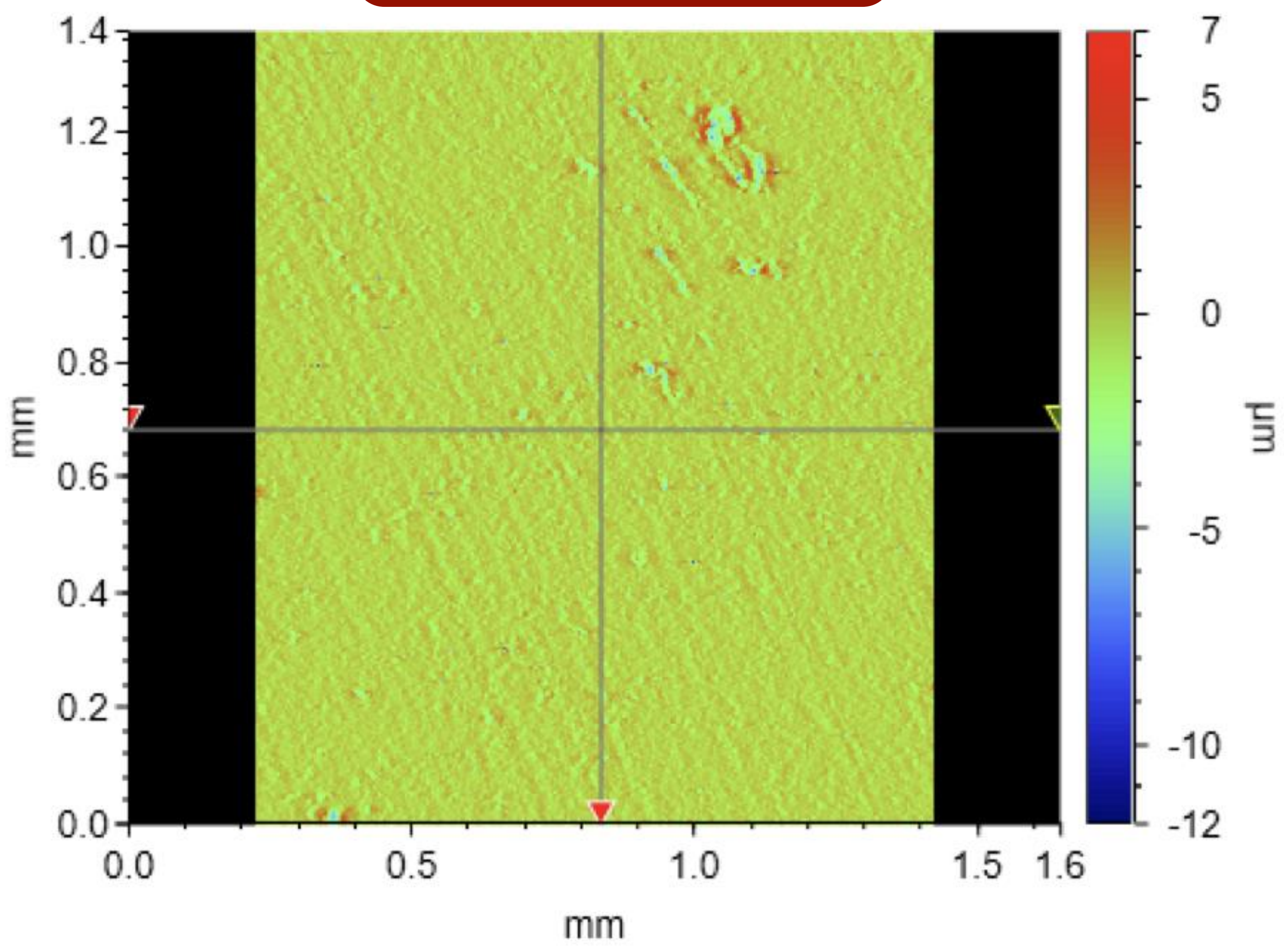
- Established process
  - Diamond saw cutting of wafer slices
  - Machining with diamond tooling also possible
- Grinding/polishing procedure for achieving an optical finish on the ceramics
- Cleaning procedure also developed
  - Ultrasonic bath in water, alcohol wipe then low temperature (120 °C) bake



Supplied by Euclid TechLabs ➔ water jet cutting (±20 µm) ➔ surface polish & vacuum bake

Surface finish: For braze-less compression assembly with diamond machined copper

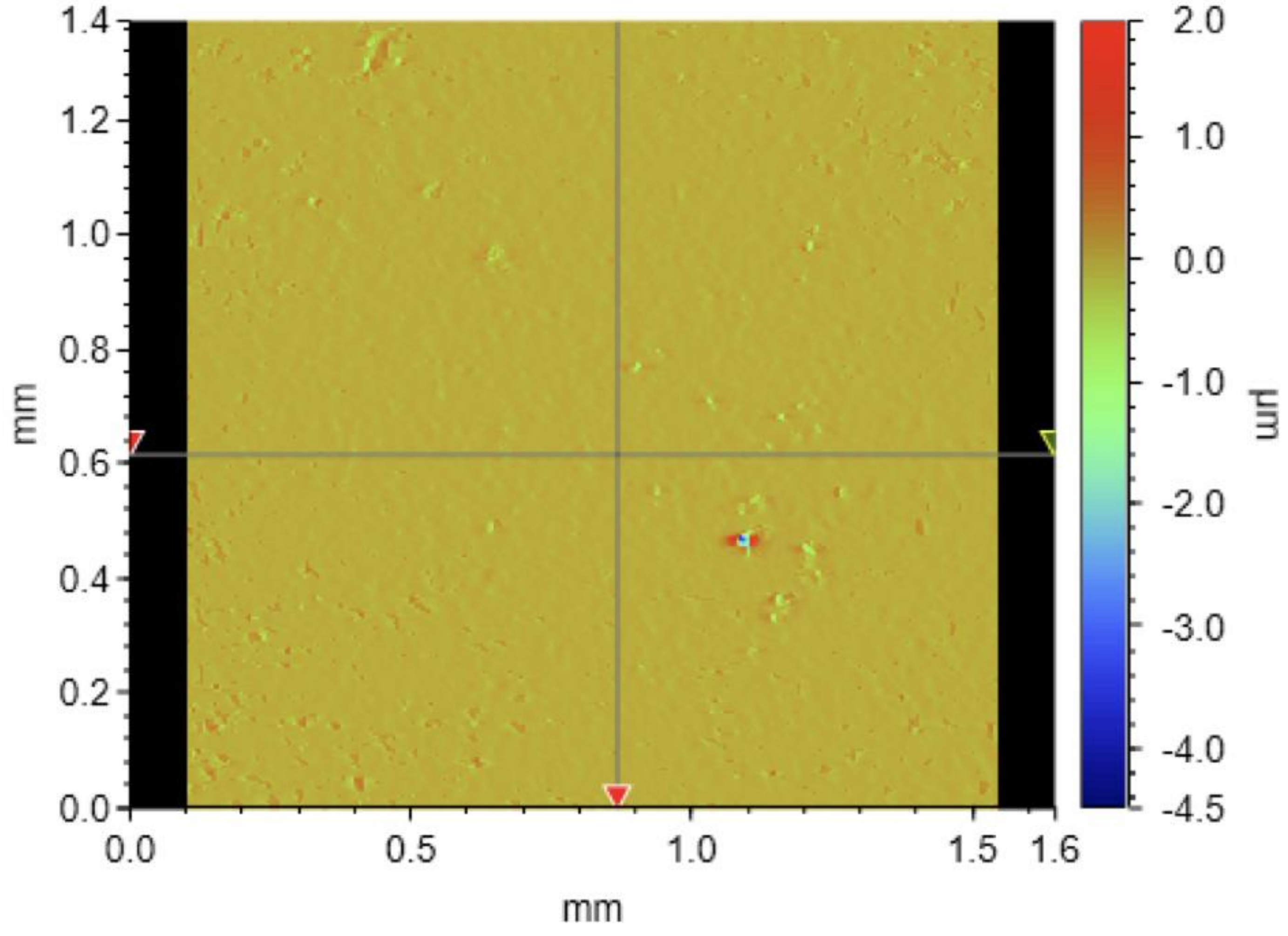
As supplied



Surface Roughness Measurements		
Material	Rt [nm]	Ra [nm]
FE (as supplied)	5600 ± 2180	382 ± 65
FE (polished)	**711 ± 95**	**40 ±9.4**
Copper (diamond machined)	172 ± 29	33 ±1.3
Stainless steel surface	427 ± 248	13 ± 2.2

Courtesy Mickael Crouvizier (CERN)

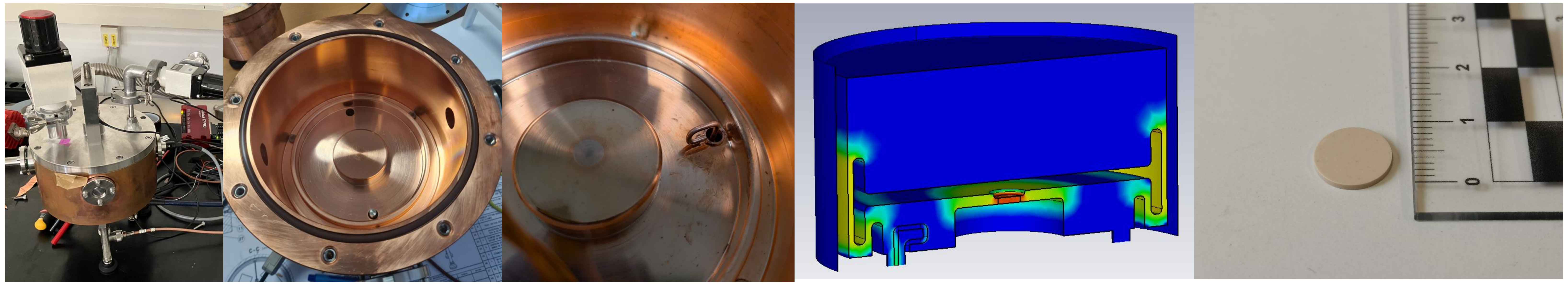
Polished – optical finish

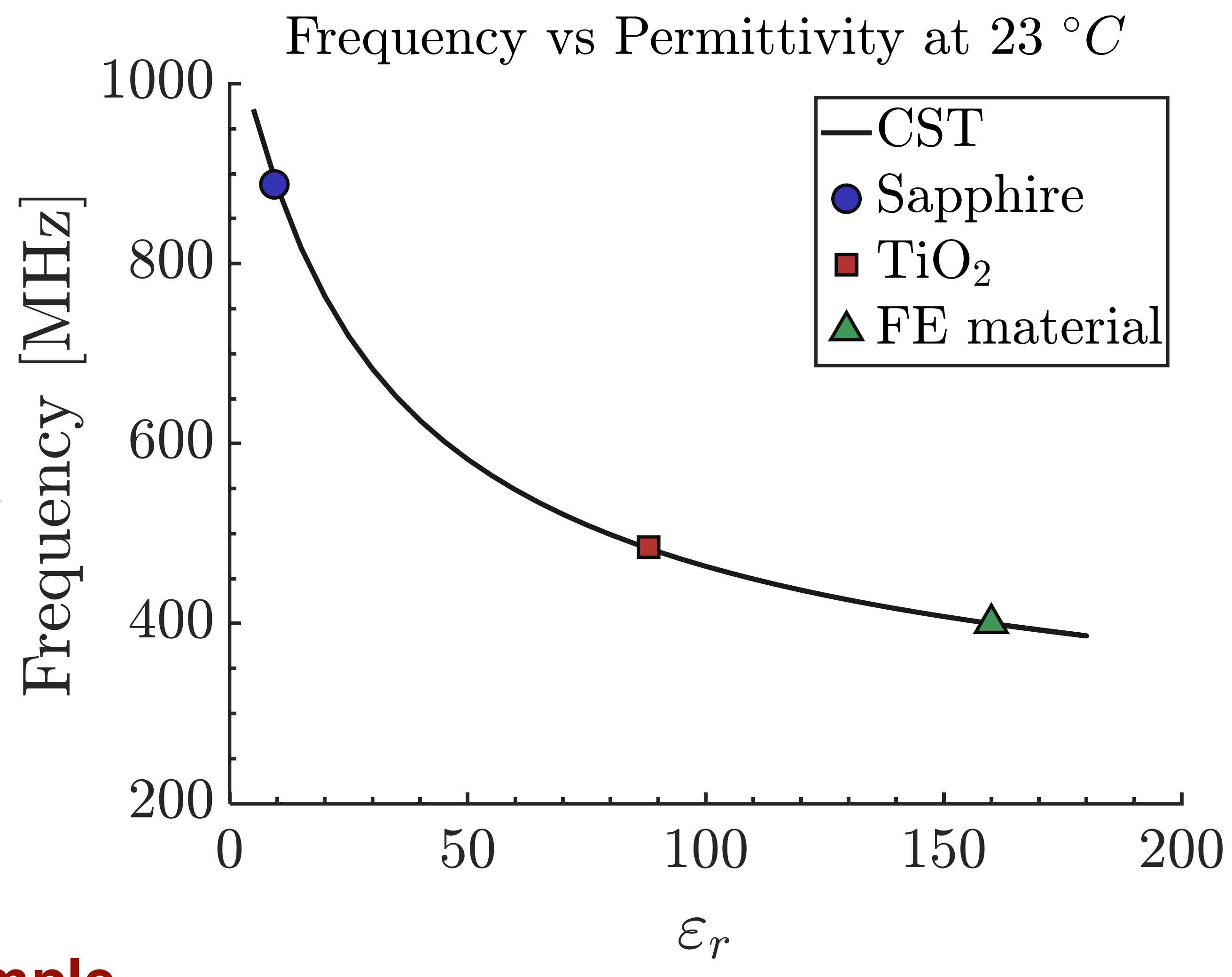


Ferroelectric material characterisation

Material Characterisation – Ferroelectric test stand

- Dedicated quasi-quarter wave test stand for sample testing
- Measurement of $\varepsilon = \varepsilon' - j\varepsilon''$ as a function of DC bias, temperature, and RF power
- Evaluating material performance with RF; frequency range 400-800 MHz

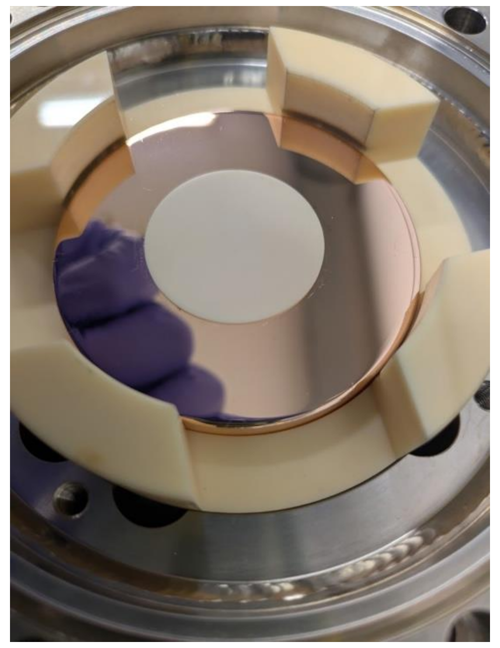


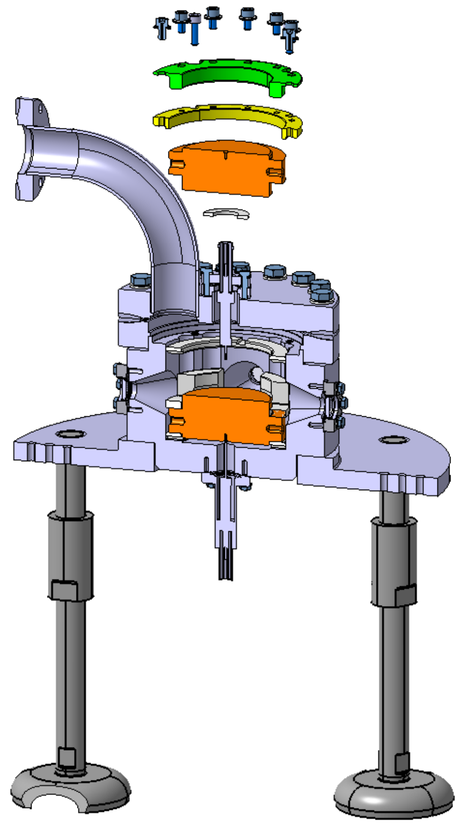


High Voltage breakdown tests

- System modified for FE samples
  - Compression system for un-metalised ceramics
  - DC or pulsed breakdown thresholds
  - Validation of FE machining and cleaning procedure
  - **Reached 7.2 V/µm with moderate polishing finish**

Edge breakdown in FE sample





Courtesy of Walter Wuensch and Victoria Bjelland (CERN)

Tuner Assembly

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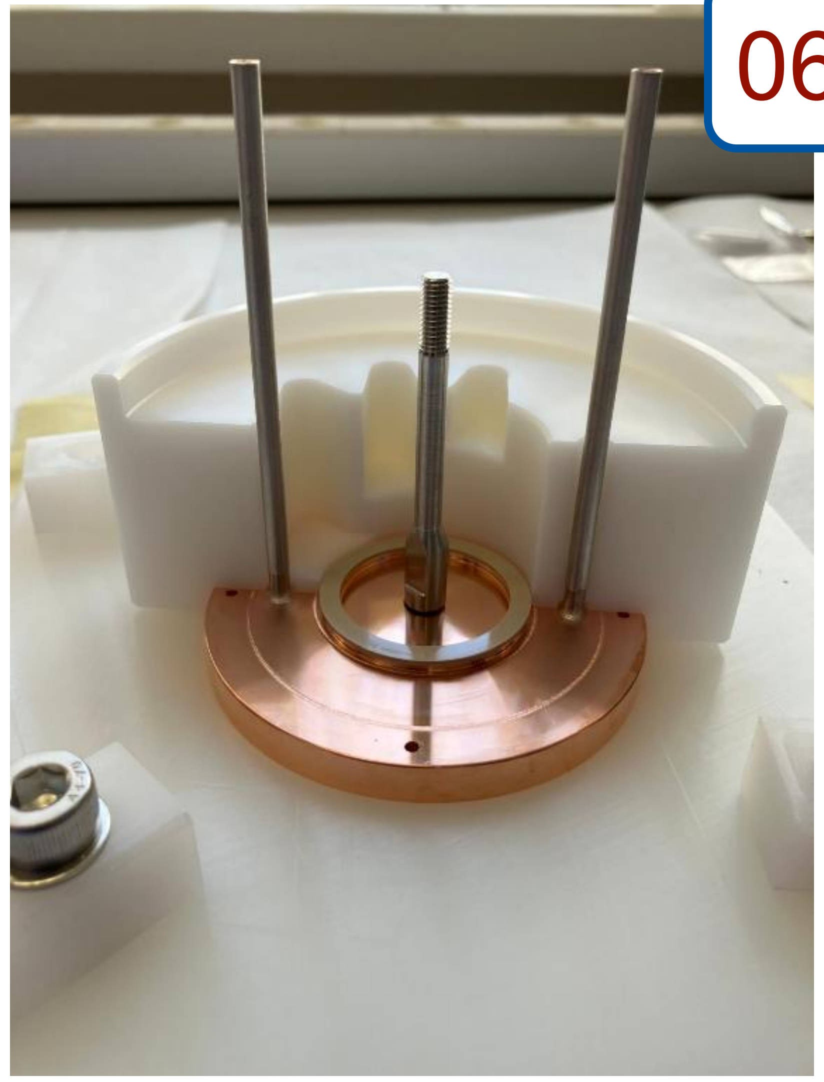

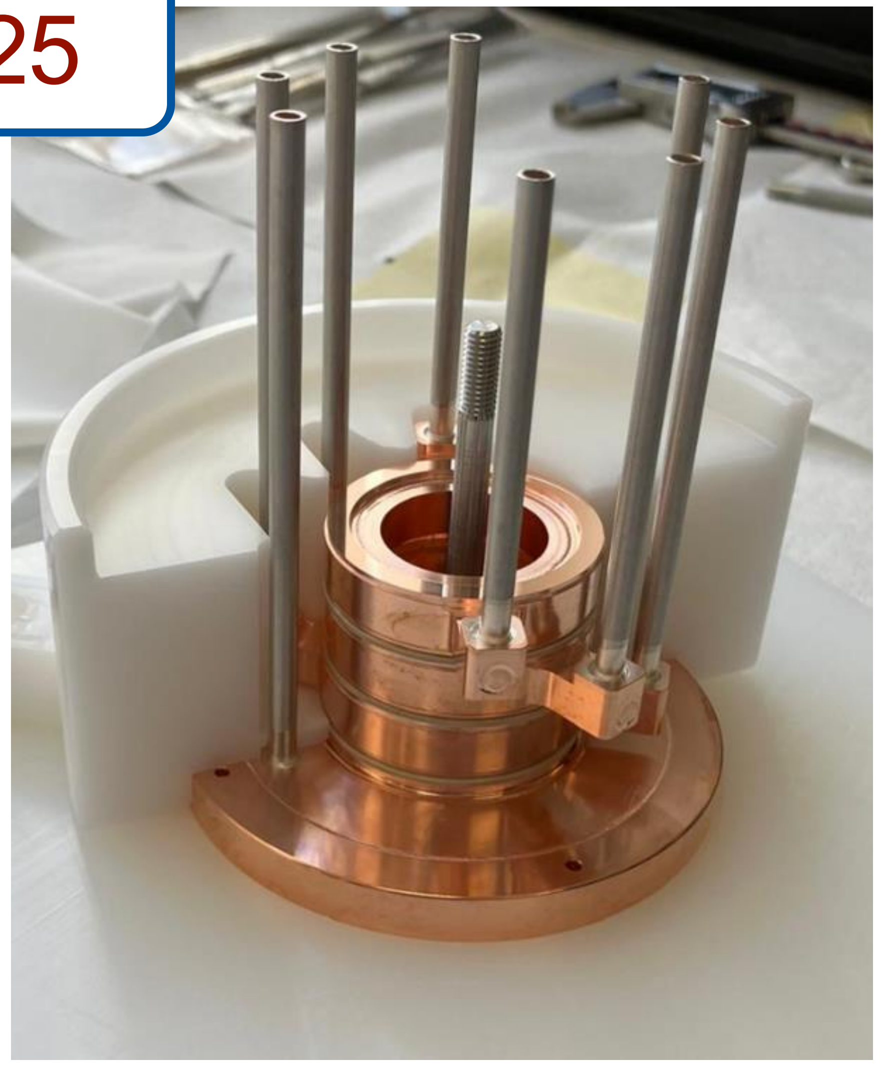

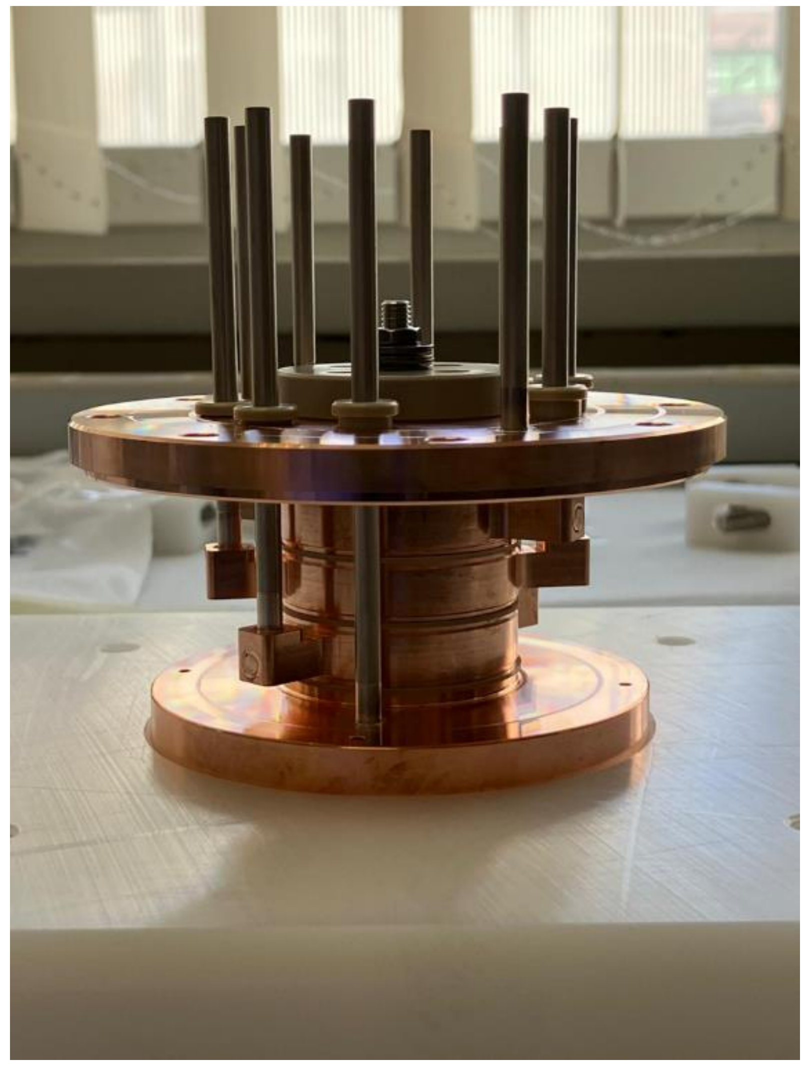

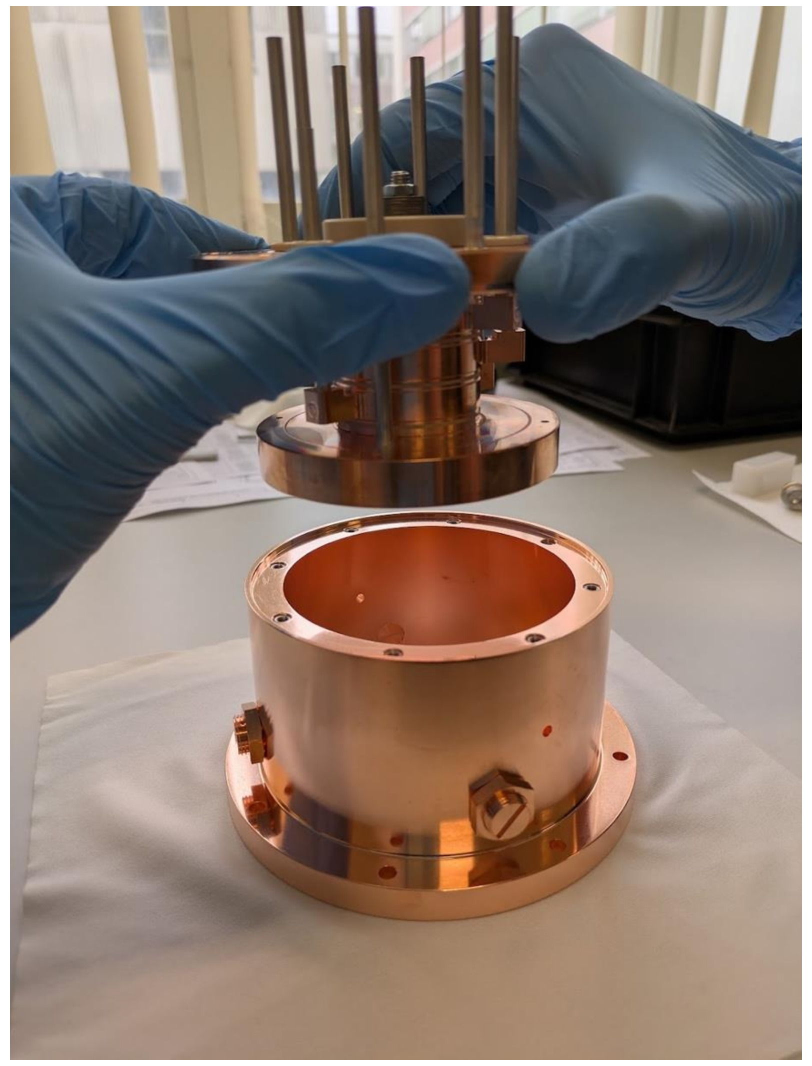

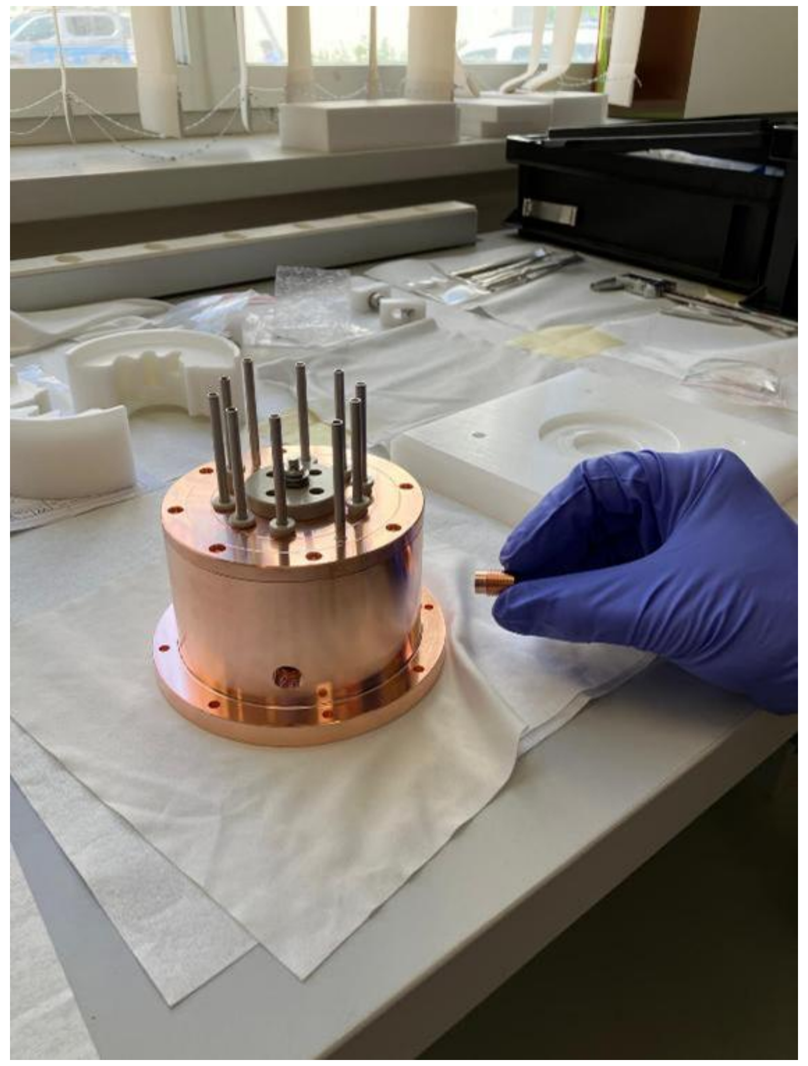

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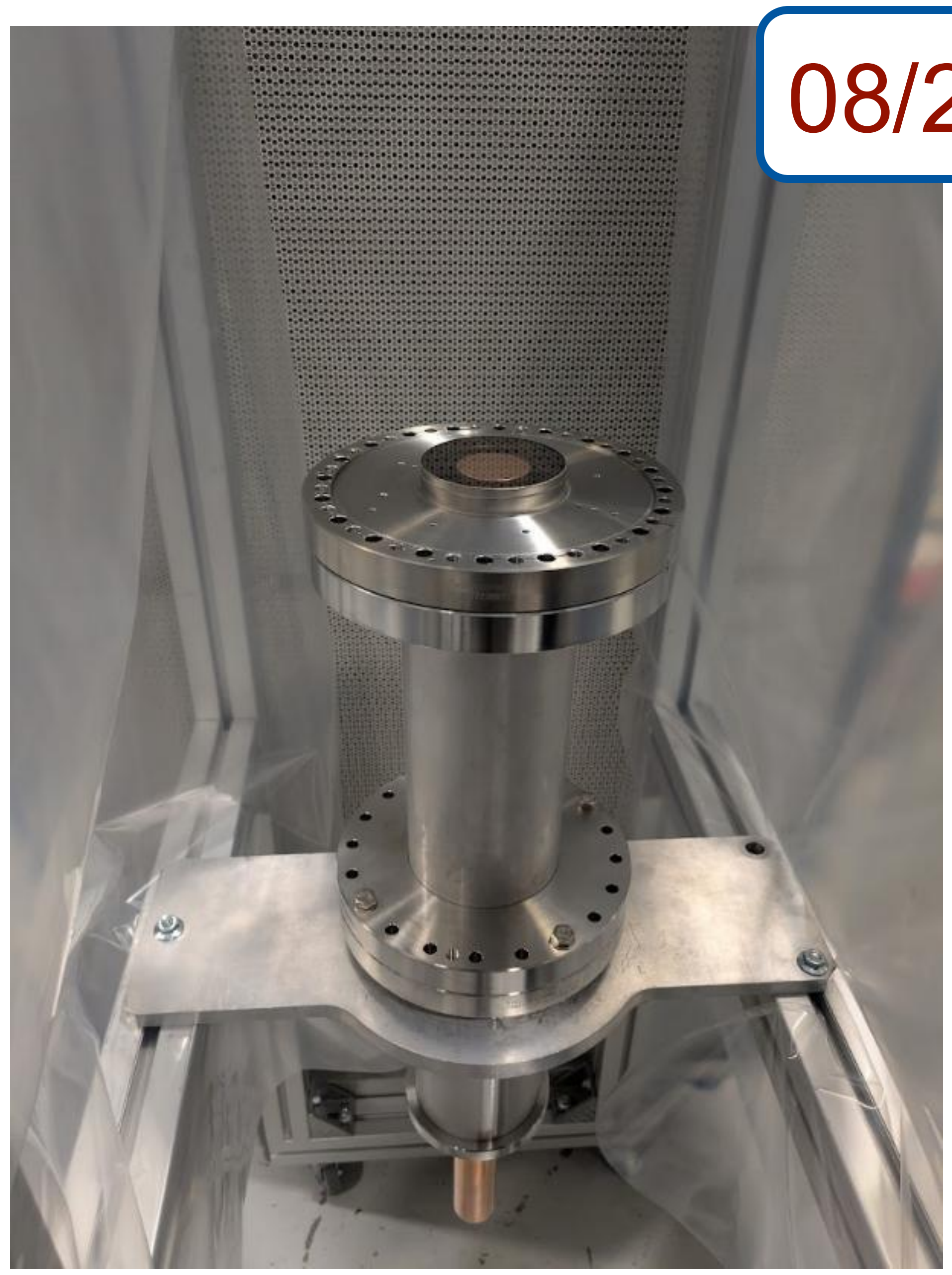

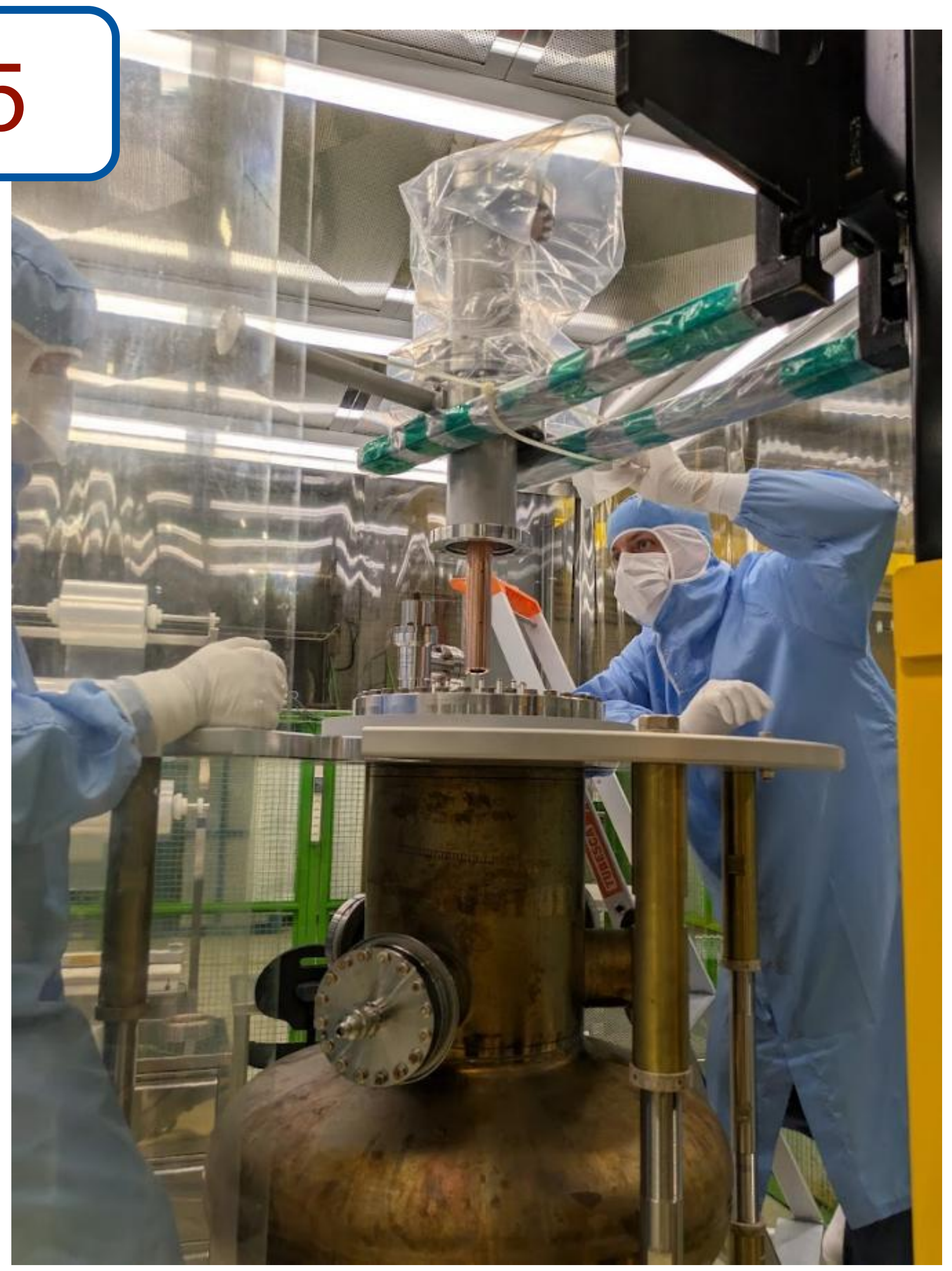

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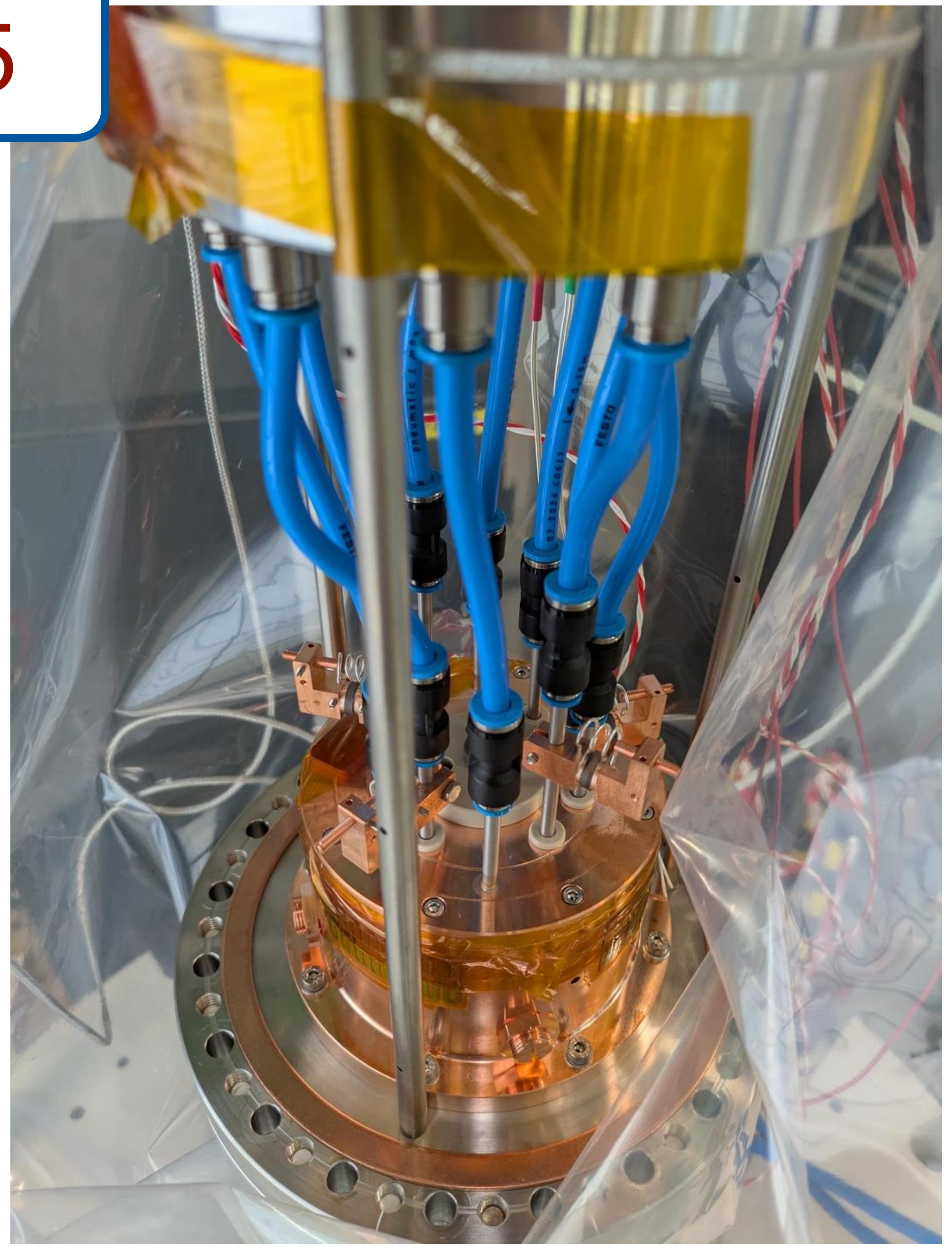
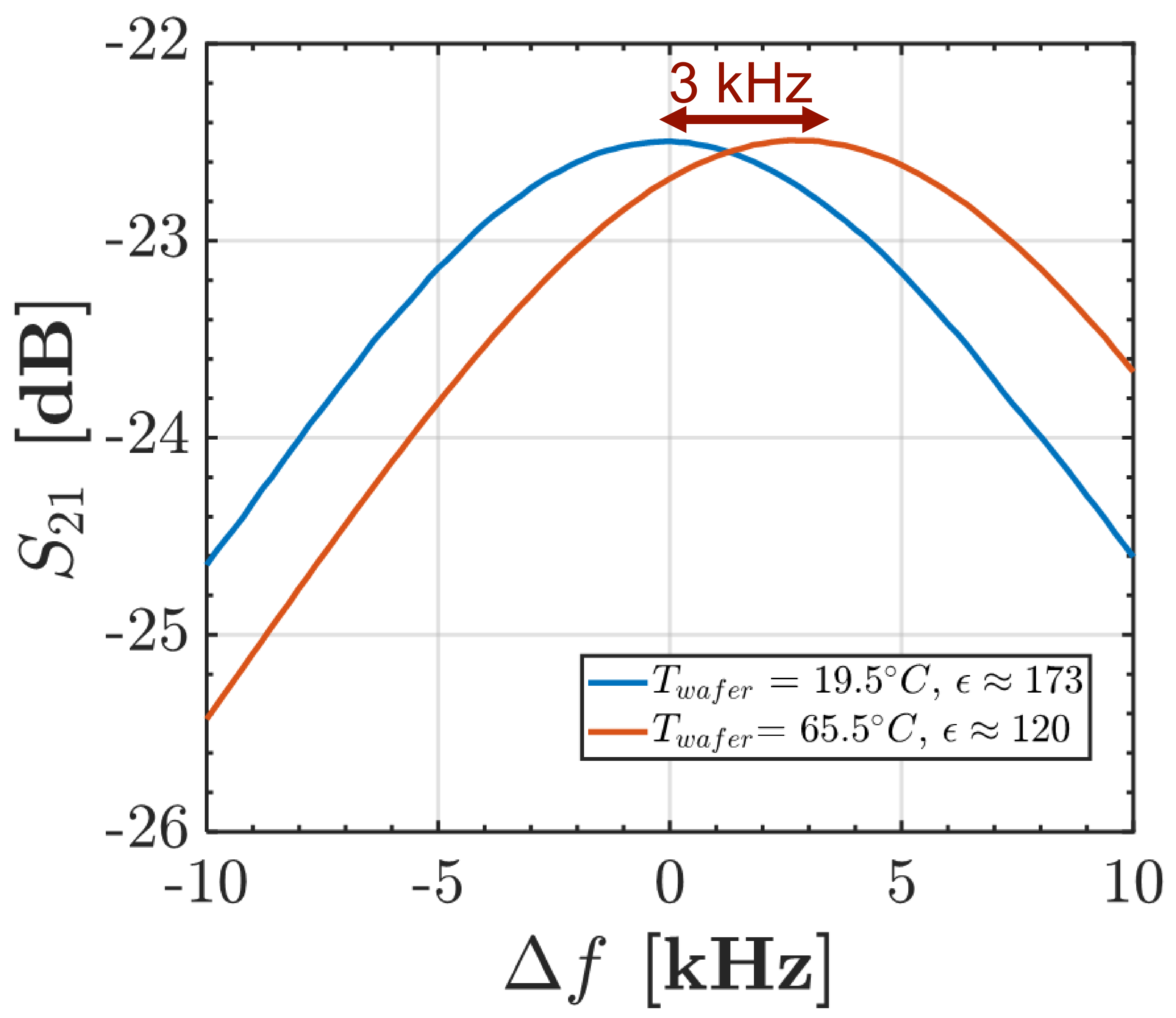


Warm test validation

- Dry run test at warm of tuner attached to cavity
  - Validation of instrumentation/high voltage/cooling network
- Initial measurement:
  - ε_r dependence on temperature exploited
  - Used cooling lines to adjust temperature of FE wafers from 20°C - 65°C
  - Cavity frequency monitored
- Outcome:
  - **Tuner coupled to cavity as expected**
  - Measured tuning shift matches CST estimate
    - 30 % tuning range with temperature scan
- Next steps:
  - Apply high voltage to electrodes

Expected frequency shift from ε_r = 120 to 173 = 3.3 kHz

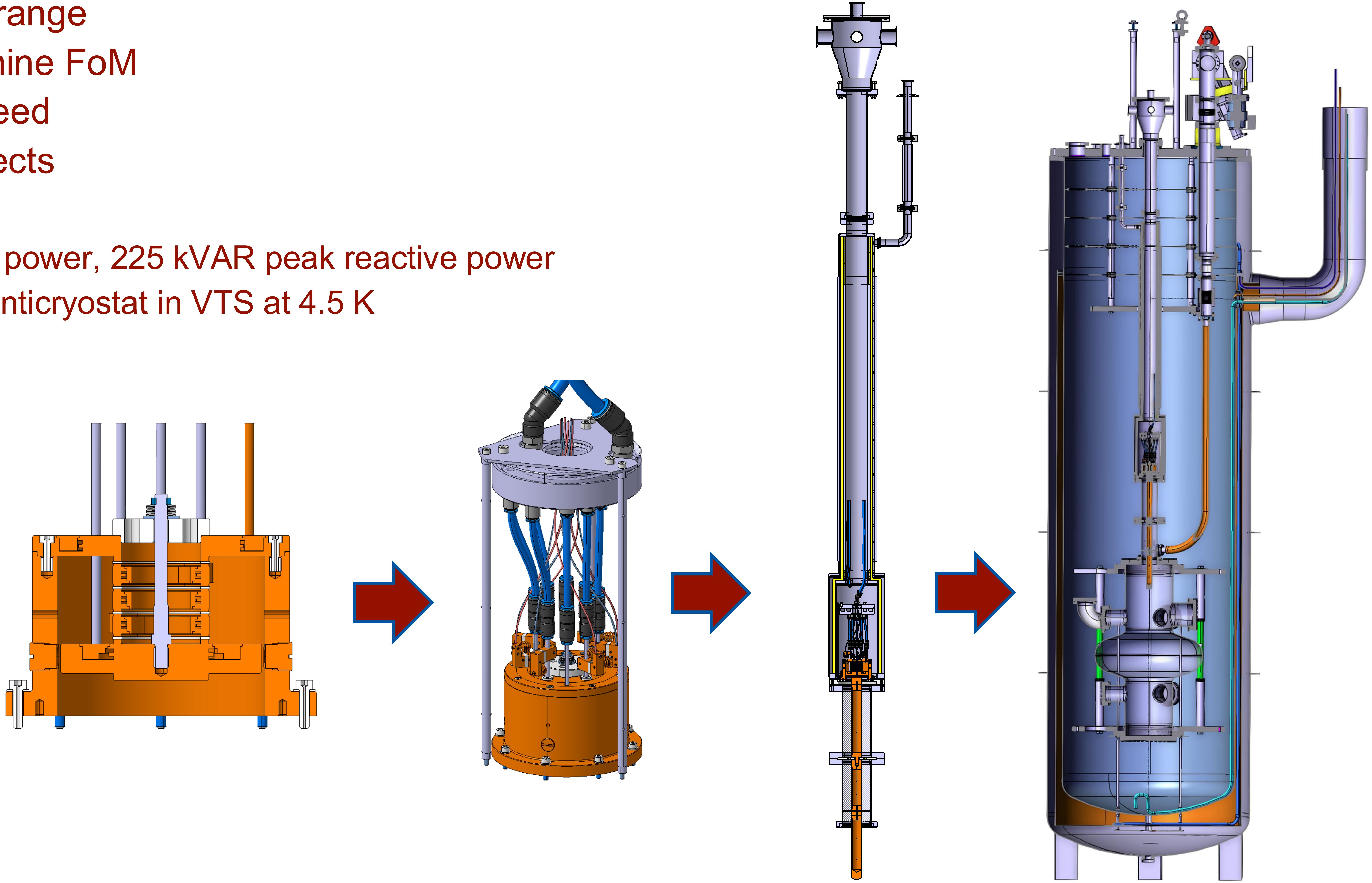


Warm setup

Cold tests

- **Next steps: Q4 2025 cold test in vertical cryostat**
  - Validate 8 kHz tuning range
  - Measure Q_{frt} to determine FoM
  - Measure switching speed
  - Explore hysteresis effects
  - Push to high power
    - Target: 3 kW input power, 225 kVAR peak reactive power
    - Cavity + Tuner + Anticryostat in VTS at 4.5 K

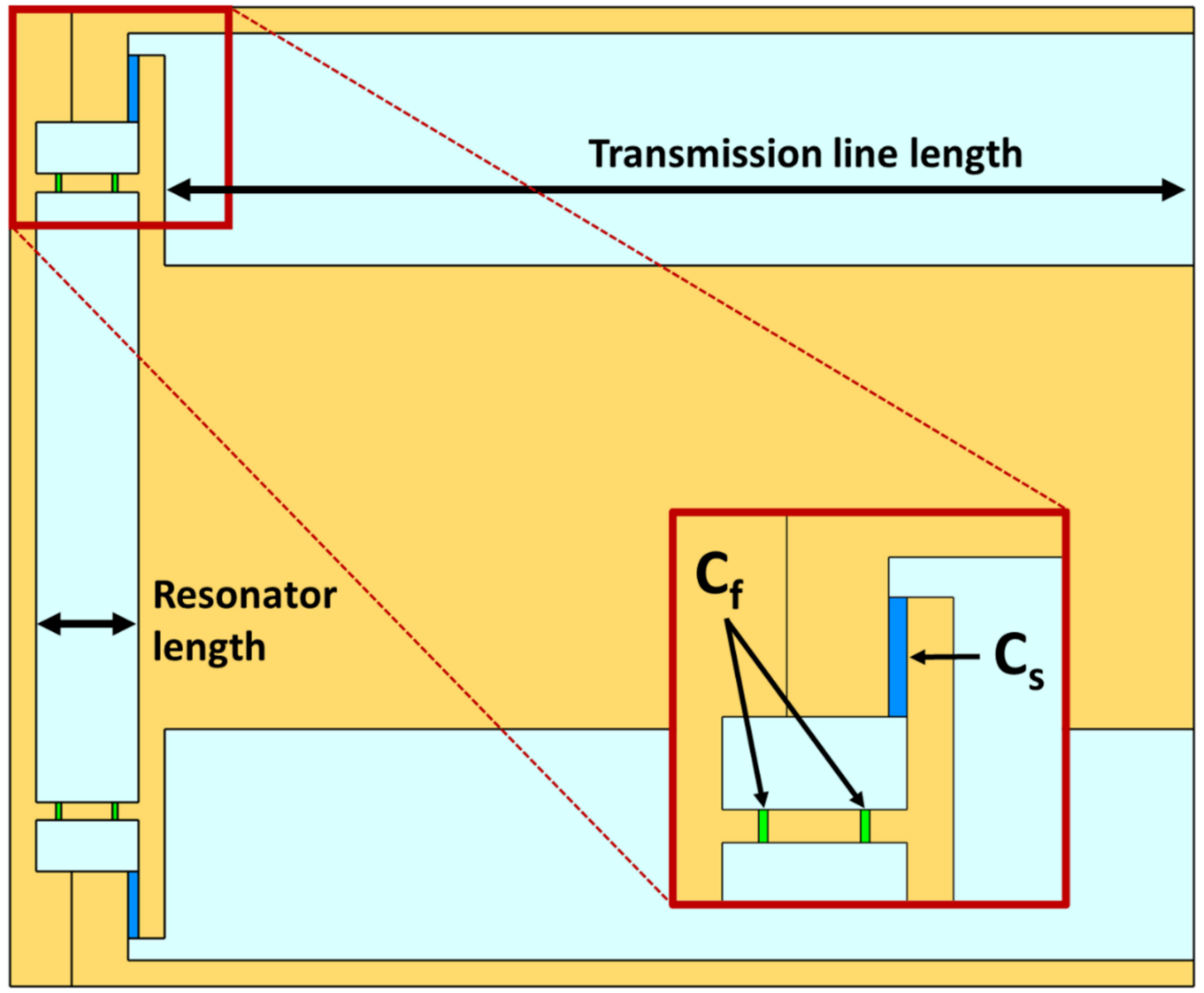
Cold test in vertical cryostat



Lessons learned along the way

If we were to redesign the tuner now:

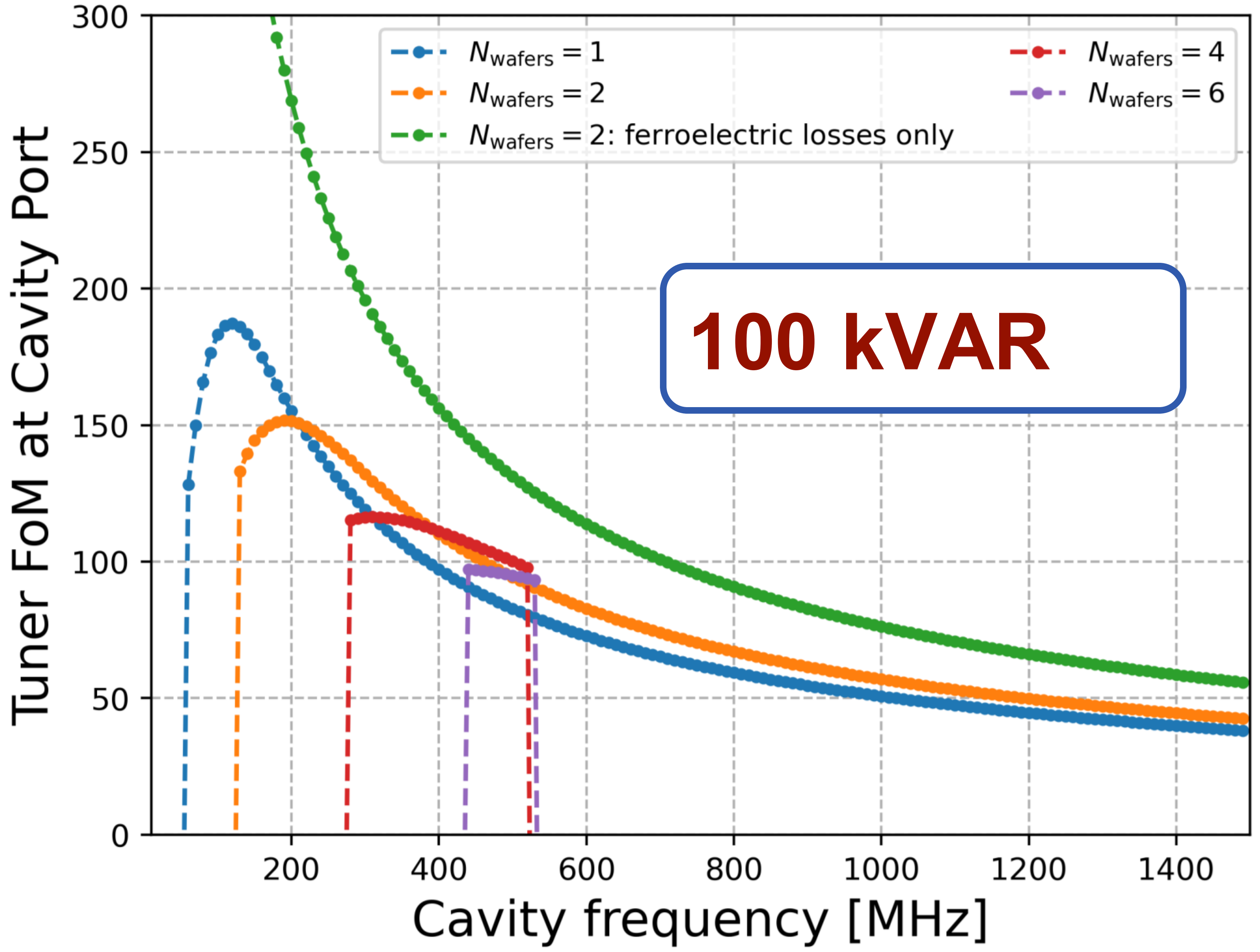
- Integrated window placement
  - Coupling capacitor would act as cavity-tuner vacuum break
- Optimise FoM using coupling between tuner and TL
  - Larger reactance seen at cavity, larger C_s -> improves FoM
  - Increased Q_e of tuner
- Only 2 wafers – simplifies cooling and biasing design



Outcomes from design process:

- Parameter space optimisation of FE geometry
  - Large thin FE wafers and optimised coaxial geometry
  - Optimised ratio of inner/outer resonator conductors

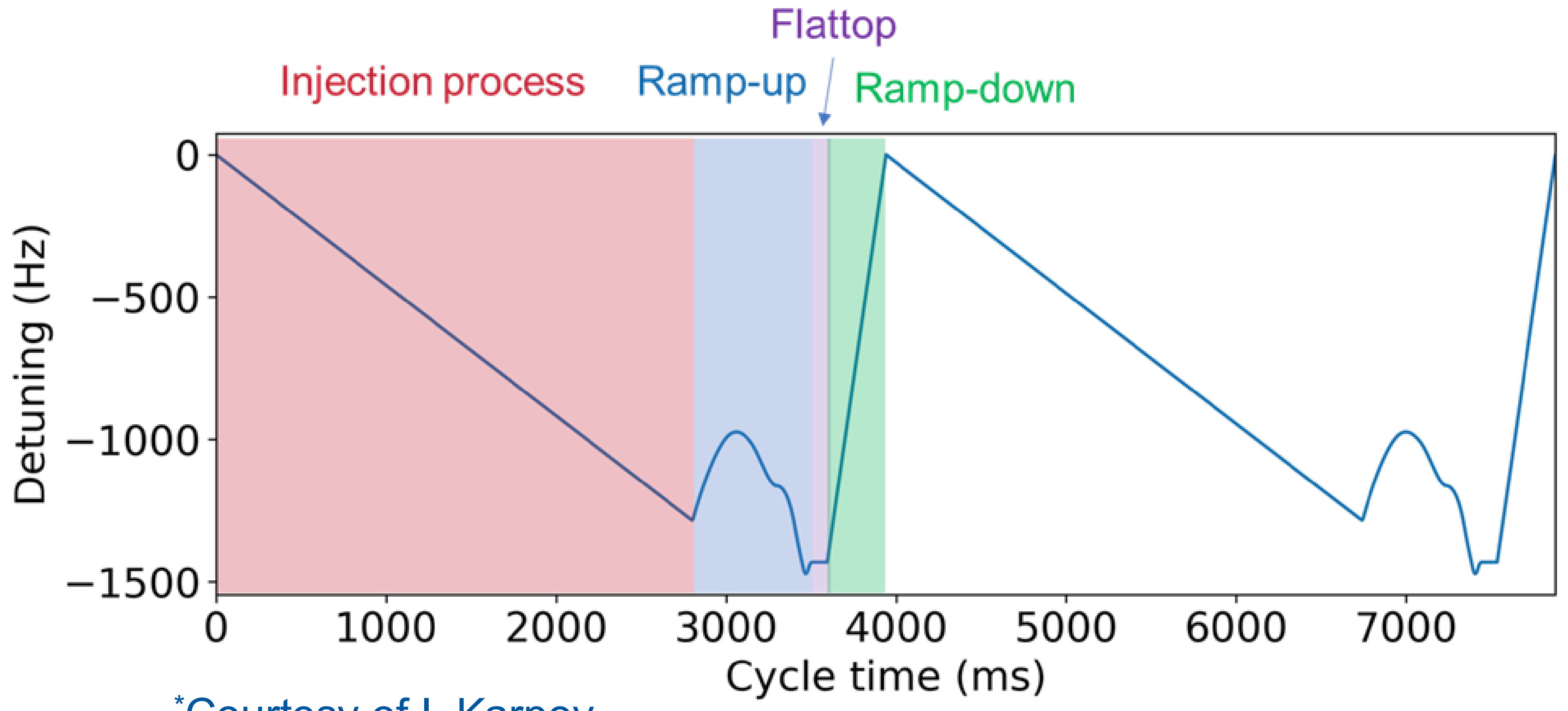
Result: Expected ~ 40% improvement in FoM + simpler design



Ben-Zvi, Ilan, Alick Macpherson, and Samuel Smith. "Detailed design and optimization of ferroelectric tuners." *Physical Review Accelerators and Beams* 28.9 (2025): 093502.

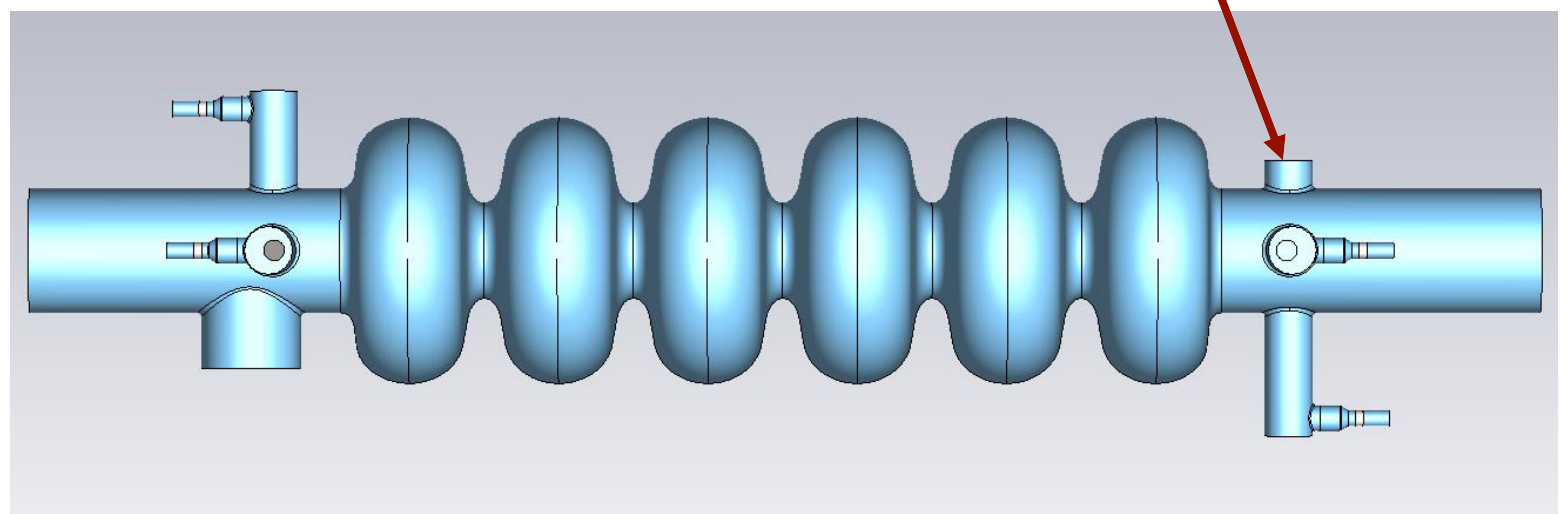
Looking forward…

- Demonstrate high power tuning of 400 MHz LHC cavity
- FE-FRT added to FCC ee Z-mode booster baseline design
  - Applicable to 800MHz 6-cell bulk Nb cavities
  - Request: Controlled detuning during injection cycle
    - Continuous detuning over 3s filling time & during ramps
  - **Status**: Ongoing - Conceptual 2-wafer design
    - Analytical design completed
- Other use cases under consideration–
  - Frequency conversion[1] ,
  - Microphonics compensation[2],
  - Phase shifting/amplitude modulation[3]

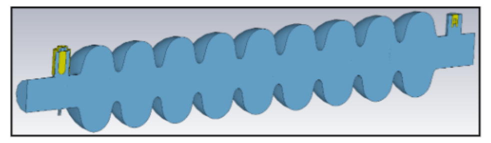
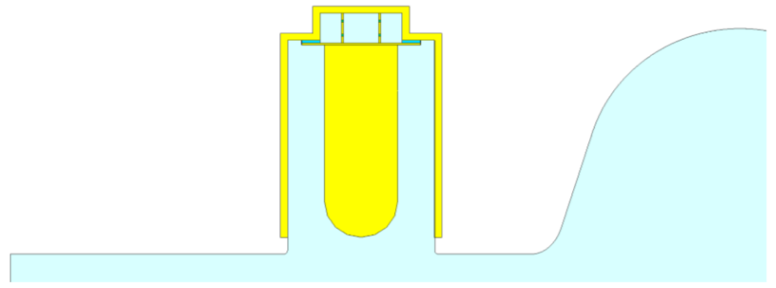


*Courtesy of I. Karpov

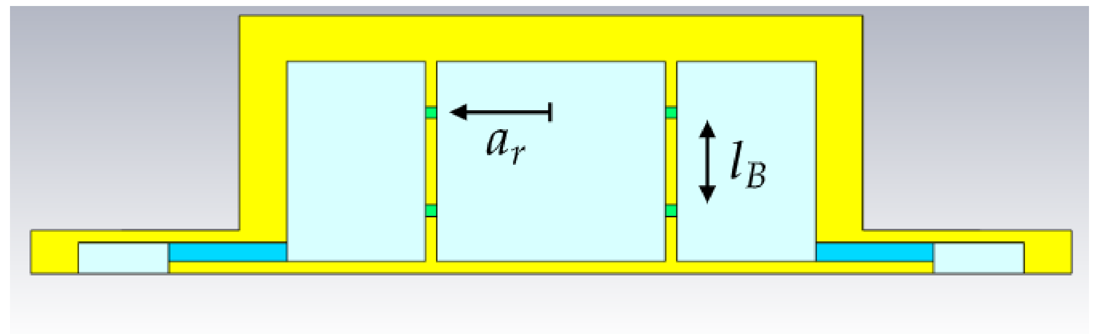
Spare port for FE-FRT



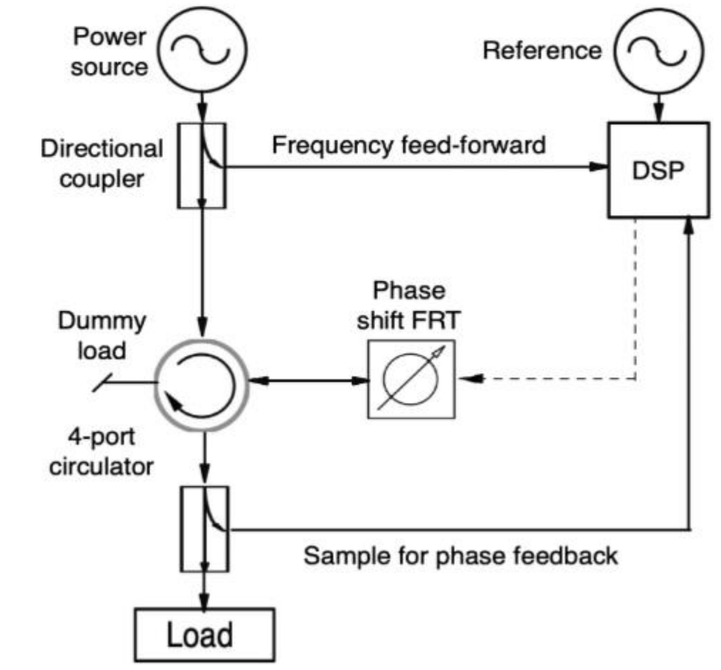
*Courtesy of S. Gorgi Zadeh

See THP81



[2] Monroy-Villa, Ricardo, et al. "Design of a Fast Reactive Tuner for 1.3 GHz TESLA cavities at MESA." *arXiv preprint arXiv:2506.20840* (2025).



[1] Ben-Zvi, Ilan, and Nicholas Shipman. "High Power Fast Frequency Modulation." *arXiv preprint arXiv:2502.13312* (2025).

Ben-Zvi, Ilan, Alick Macpherson, and Samuel Smith. "Design of a High-Average-Power Ferroelectric Phase Shifter." *arXiv preprint arXiv:2509.05228* (2025).

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