Fast Reactive Tuner development based at CERN

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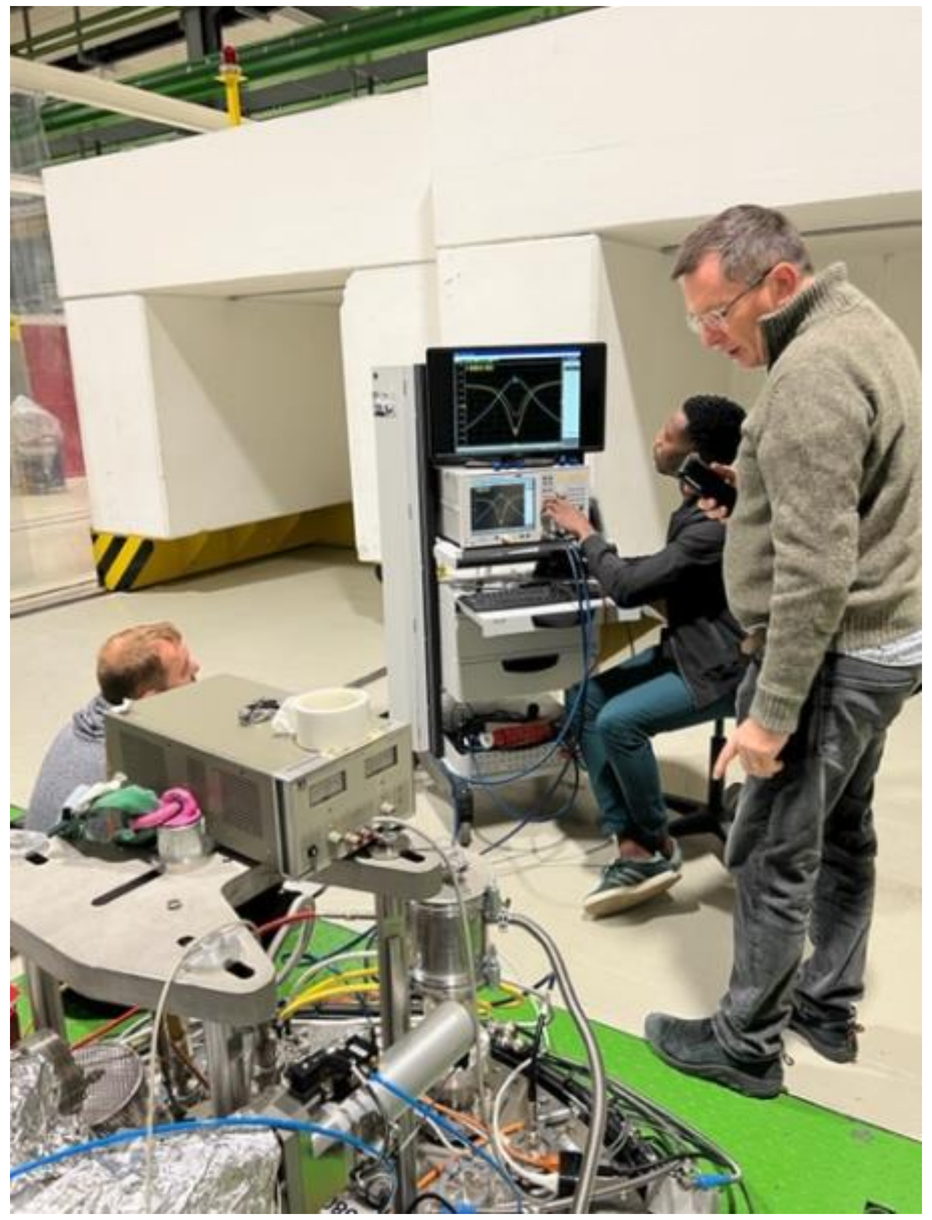
Introduction

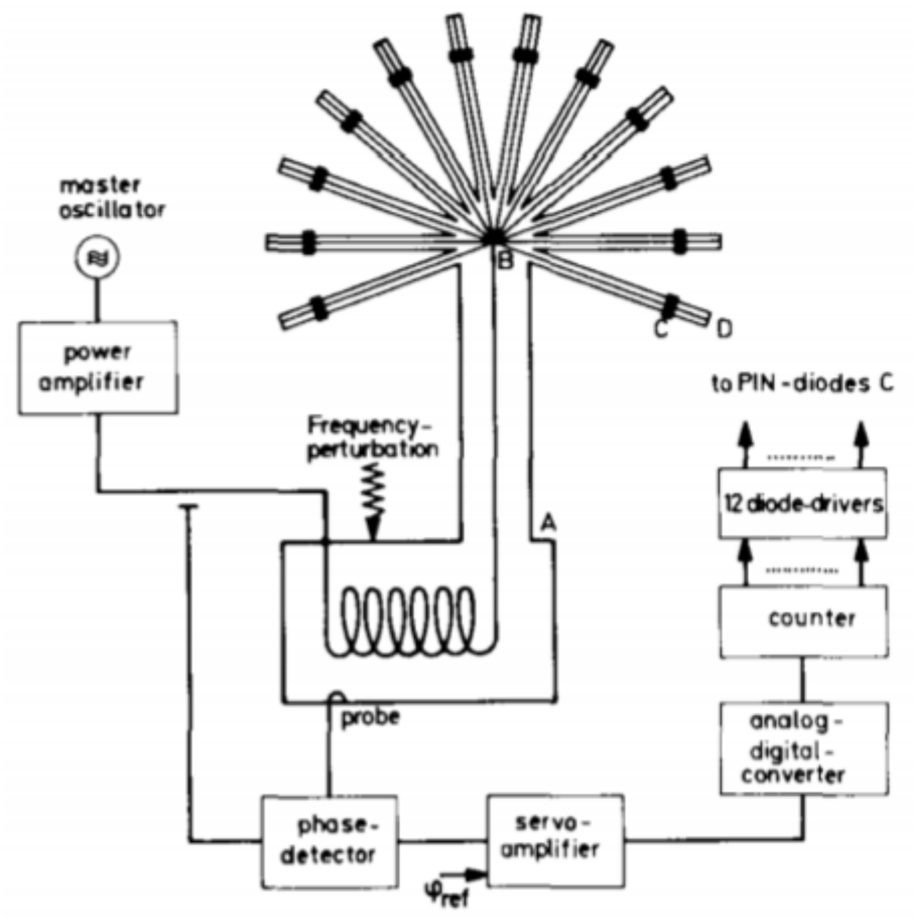
- **This talk is not about the Muon Collider**
  - This talk has been about **fast non-mechanical tuning of RF cavities**
  - Concept is FE-FRT: **Ferroelectric Fast Reactive Tuners**

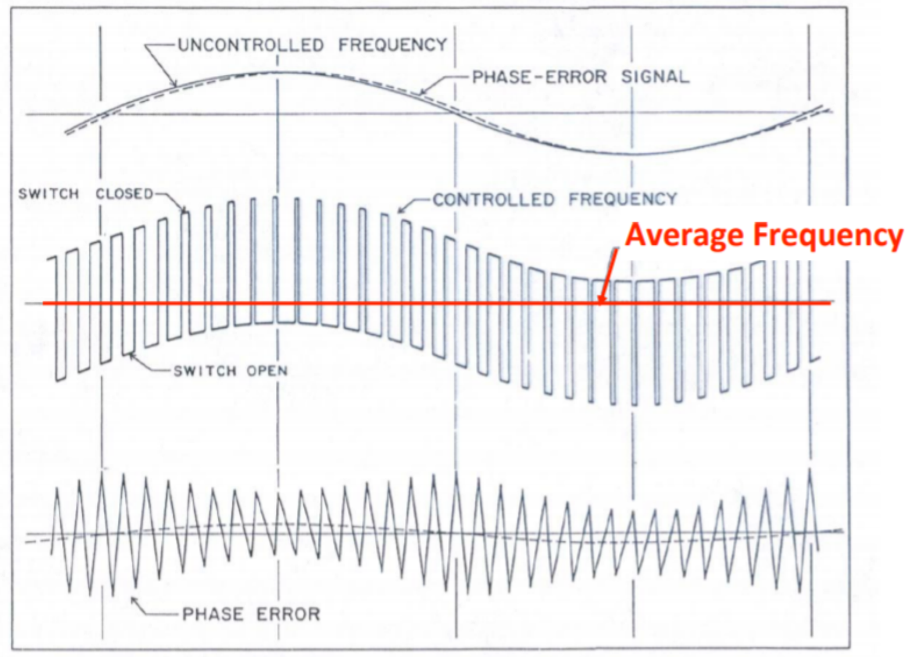
- **This talk is to show an ongoing program based at CERN**
  - Development and application of FE-FRTs
    - Beam Loading compensation, Microphonics Suppression, Power savings
    - Focus: **Transient Detuning Demonstrator for LHC 400 MHz Nb-on-Copper Cavity**



Non-Mechanical Tuners: Not a new idea

- **Non Mechanical Tuners: tuning by reactance**
  - Use terminated transmission line attached to cavity & modify line reactance
  - **Reflected RF couples back to cavity induced phase shift => indues a net frequency shift**

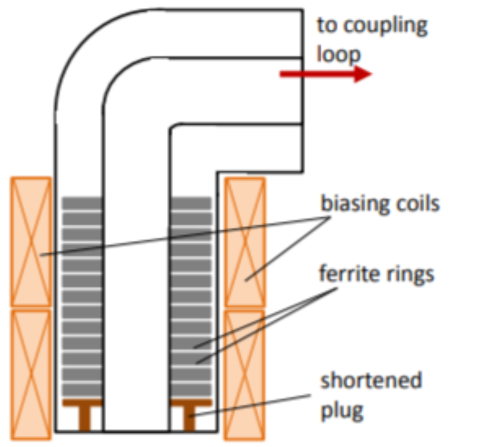


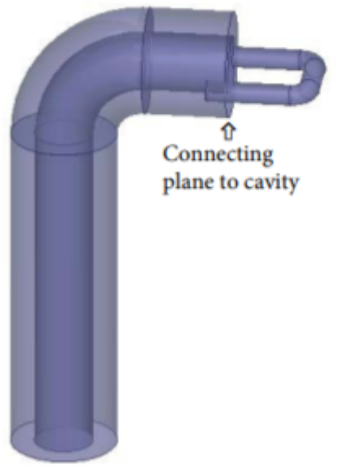


Diode switching alternates sign of reactance.
Frequency control by pulse-width modulation.

Pin Diode Tuners

O. Despe, K. Johnson and T.~Khoe, IEEE Trans. Nucl. Sci.,vol. 20 1973.
D. Schulze et al., Proton Linear Accelerator Conf, 1972





Ferrite stub to moderate reactance
Frequency control by external coil.

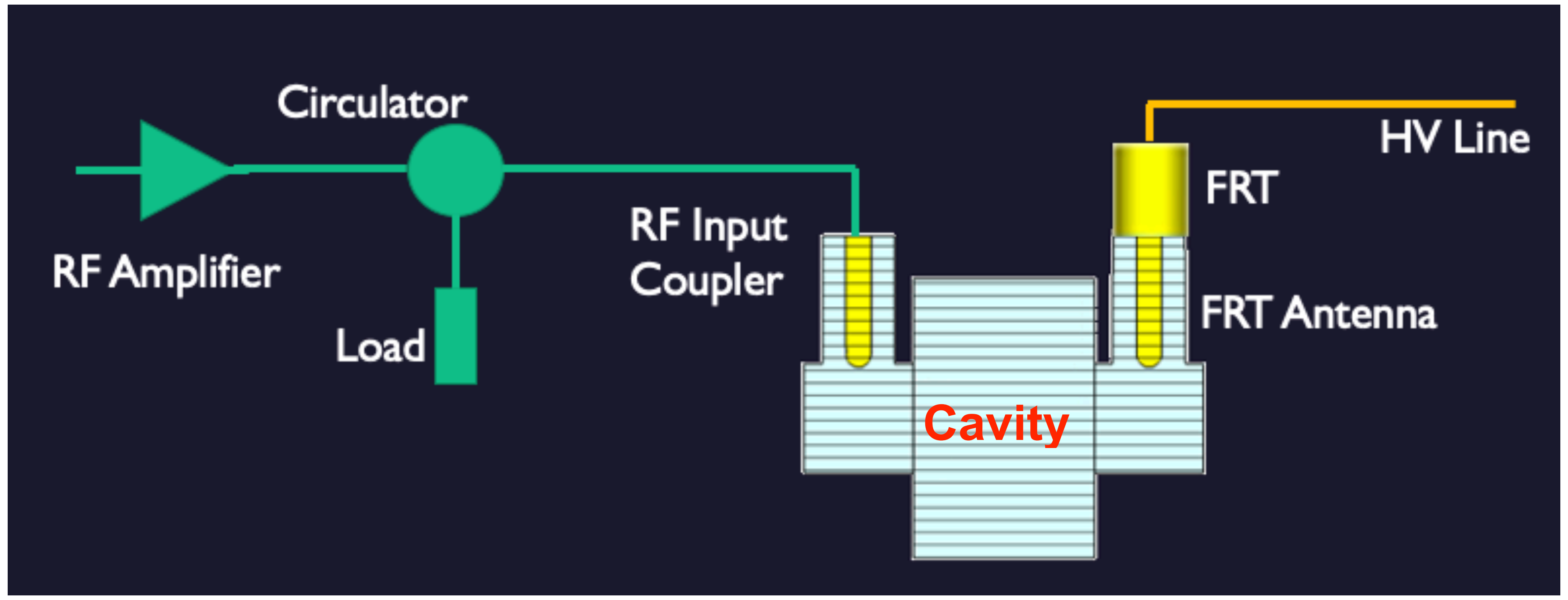
Ferrite Tuners

C. Vollinger and F. Caspers, Ferrite-tuner Development for 80 MHz Single-Cell RF-Cavity Using Orthogonally Biased Garnets, IPAC 15.

Fast Reactive Tuner Concepts

Overview: Fast Reactive Tuner (FRT)

- **FRT is a shorted transmission line attached directly to the cavity**
  - FRT stub contains a dielectric phase shifter element => modifies reactance
  - **Phase shifted RF, when reflected back into the cavity, results in a frequency shift**



- **Ferroelectric FRT: Ferroelectric ceramic is mechanism for fast phase shifts**
  - **Device has a controllable permittivity, based on HV biasing across ceramic**

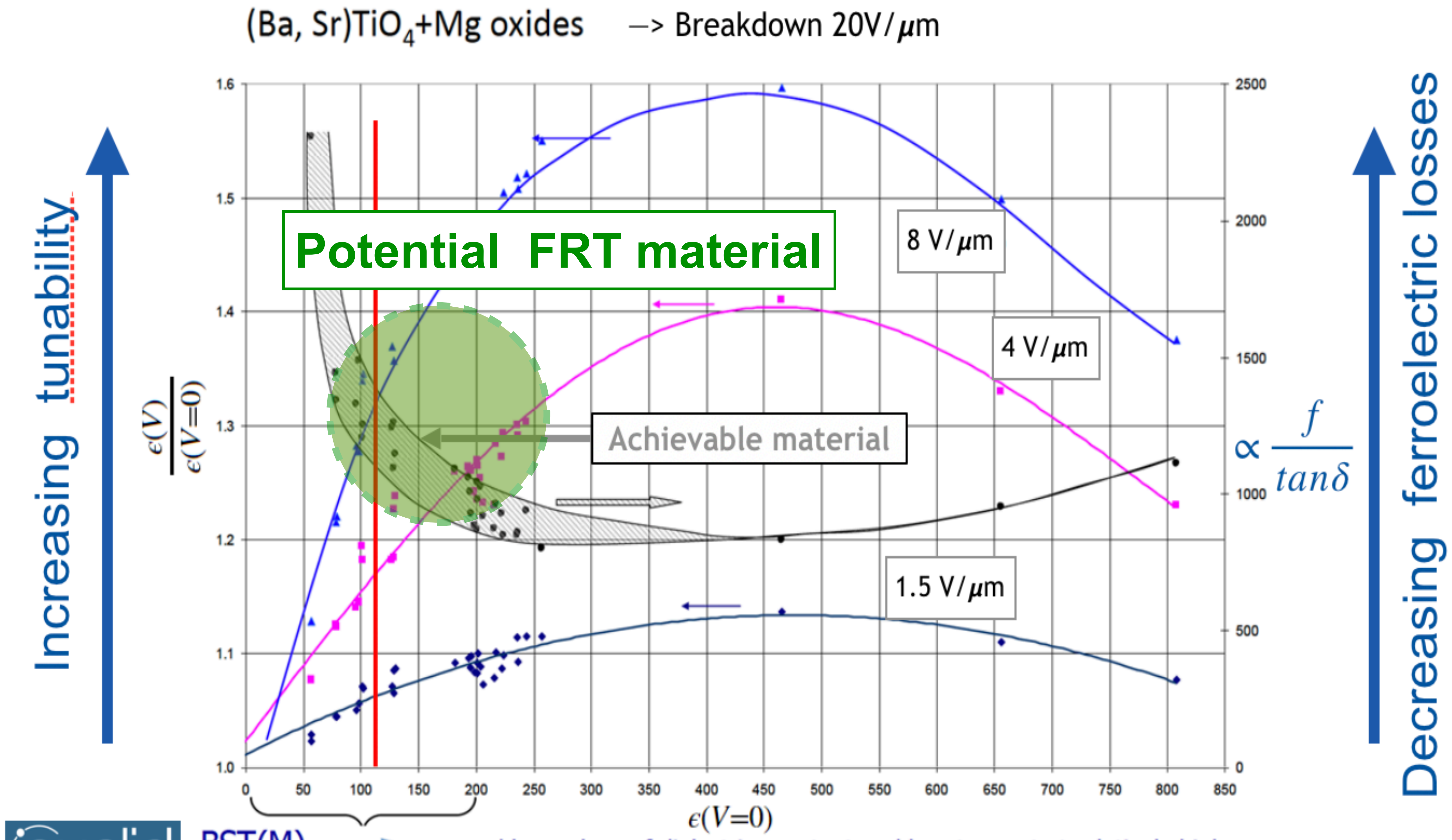
- **Observations**
  - FRT: a 1-port device attached directly to cavities => normally FRTs would require a dedicated cavity port
  - FRT: short transmission line segment => **Can be installed outside cold volume of cryomodule**
  - FRTs do not mechanically deform cavity
  - FRTs are fast by design => Applicable to cavity frequency tuning loops

Ferroelectric Ceramics at heart of FRT

- **BST(M) Ceramic: BaTiO3 - SrTiO3 (BST) with Mg-based additives**
  - **Relative Permittivity ε_r can be controlled by application of voltage**

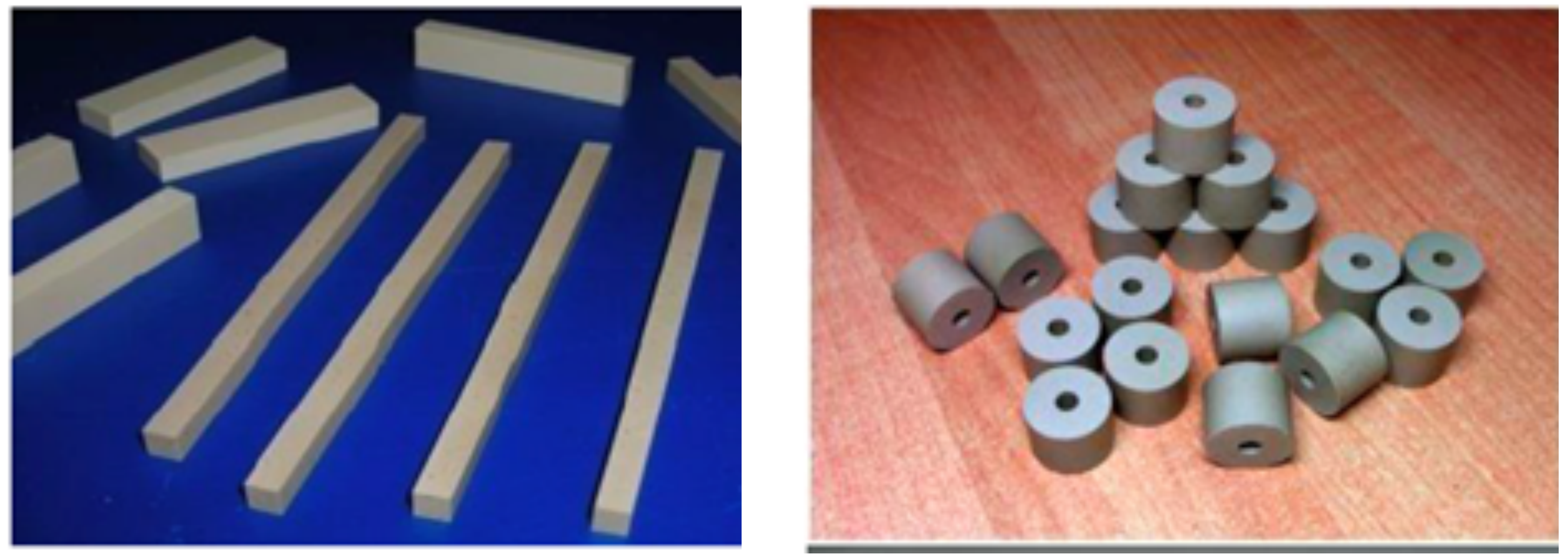
    => Machinable ceramic with very low loss tangent

    => Material response time is very fast (~10 ns) => ideal for fast feedback tuning systems



BST(M), ε~50-150

record low values of dielectric constant and loss tangent at relatively high tunability level required for high power bulk tuner operating in air (< 30 kV/cm) and in vacuum (up to 80 kV/cm).



Parameter	Value
Relative Permittivity	160
Tunability of Permittivity	**1.4**
Breakdown Strength	20 Vμm^{-1}
Thermal Conductivity	7.02 Wm^{-1}K^{-1}
Response time to HV pulse	**10 ns**
Typical loss tangent (tanδ)	**8x 10^{-4} @400 MHz**
Broad low loss tangent range	10 MHz - 10 GHz

FRT: Equivalent Circuit Description

- **Change in frequency between bias states n and m**

$$\Delta\omega_{mn} = \frac{-\omega_0 {}^{R}\!/_{Q} \Delta B'_{tmn}}{2N^2}$$

- **Change in System bandwidth due to FE-FRT in bias state**

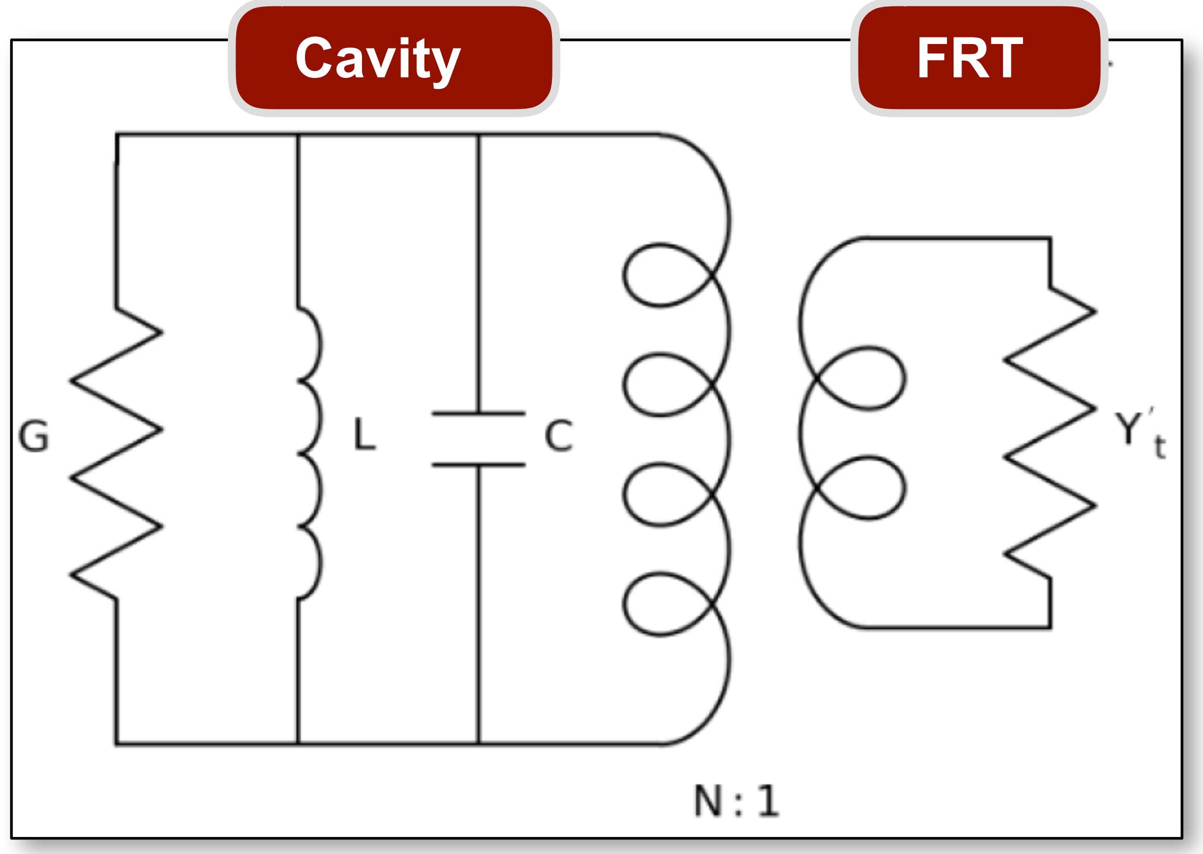
$$\mathrm{BW}_n = \frac{\omega_0 {}^{R}\!/_{Q} G'_{tn}}{N^2}$$

- **Susceptance B$_t$ is our controllable “knob” =>** $Y'_t = G'_t + iB'_t$
  - Change in HV bias of ceramic => change in ε_r = change in B$_t$

- **Figure-of-Merit (FoM) for evaluating a tuner**

$$\boxed{\textbf{FoM} = \frac{\text{Tuning Range}}{\text{Geometric Average of increase in BW}}}$$

  - Large tunability => large $\Delta\varepsilon_r$ => susceptance over sustainable HV range of ceramic
  - Minimal power dissipation => minimise conductance => compact device & low loss ceramic



$$\omega_0 = \frac{1}{\sqrt{LC}} \qquad {}^{R}\!/_{Q} = \sqrt{{}^{L}\!/_{C}} = \frac{V_c^2}{2\omega_0 U_c}$$

Notation	Meaning
G'_t	Conductance of FE-FRT
B'_t	Susceptance of FE-FRT
N	Coupler turn ratio
V_c	Cavity voltage
U_c	Cavity stored energy

FE-FRT: When to use One

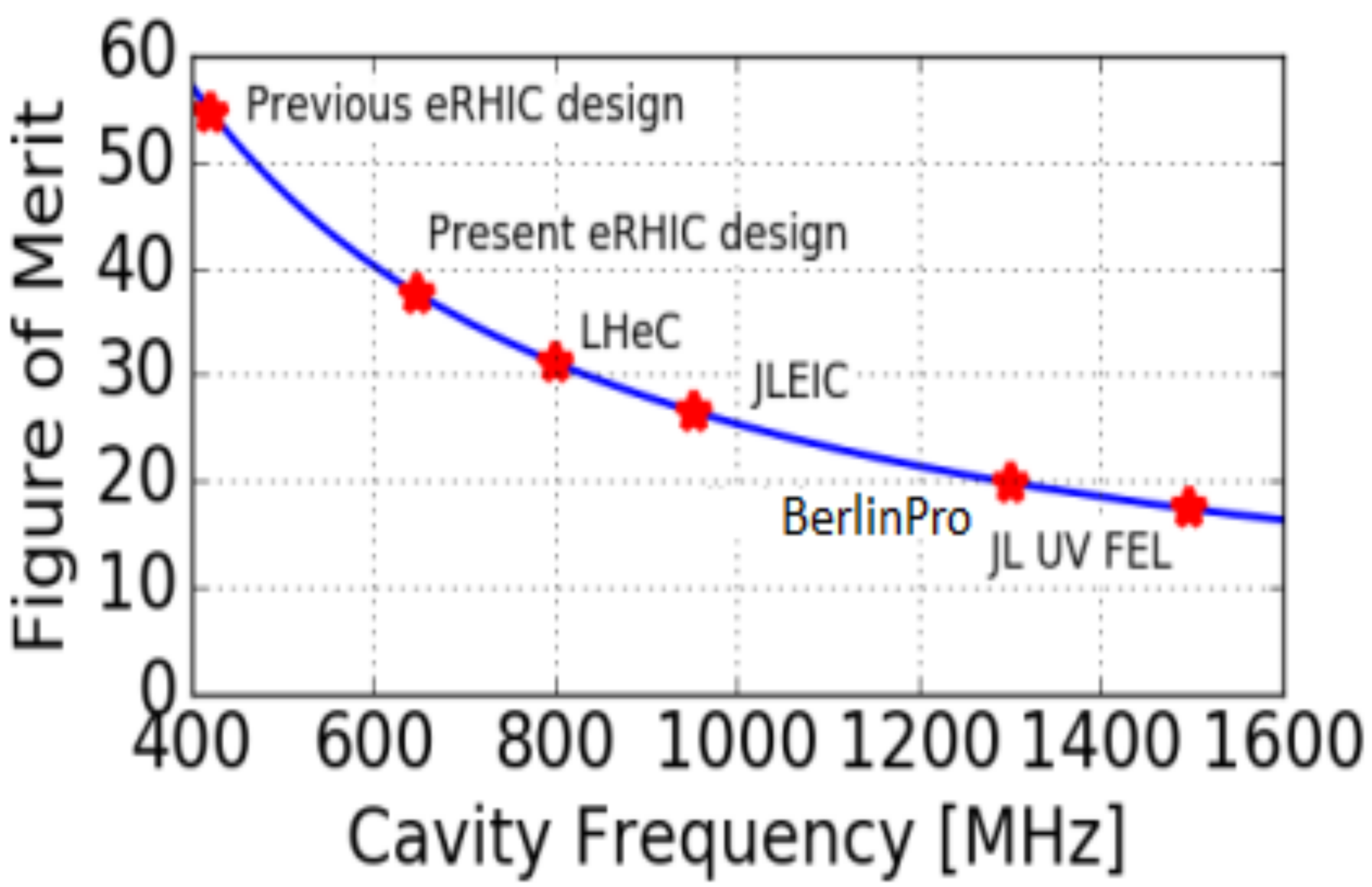
- **Scenarios when an FE-FRT could be applicable:**
  - **Tuning speed is paramount**
  - An extremely stable frequency must be maintained
  - Tuning range is small to moderate
  - Mechanical tuning is not possible/desirable: **potential for tuning of thin film SRF cavities**

- **FE-FRT Tuning range guideline:**

$$\frac{\Delta f}{f_0} \ll \frac{100}{Q_L}$$

Q_L= Loaded Q of cavity

  - Larger proportional tuning ranges easier at lower frequencies
  - FoM: Expect values in the 10 - 100 range



- **When not to use an FE-FRT solution:**
  - **If fast tuning is not required**
  - **If there is no available cavity port**
    - integration with FPC or HoM ports invites complications
  - If a very large tuning range is required

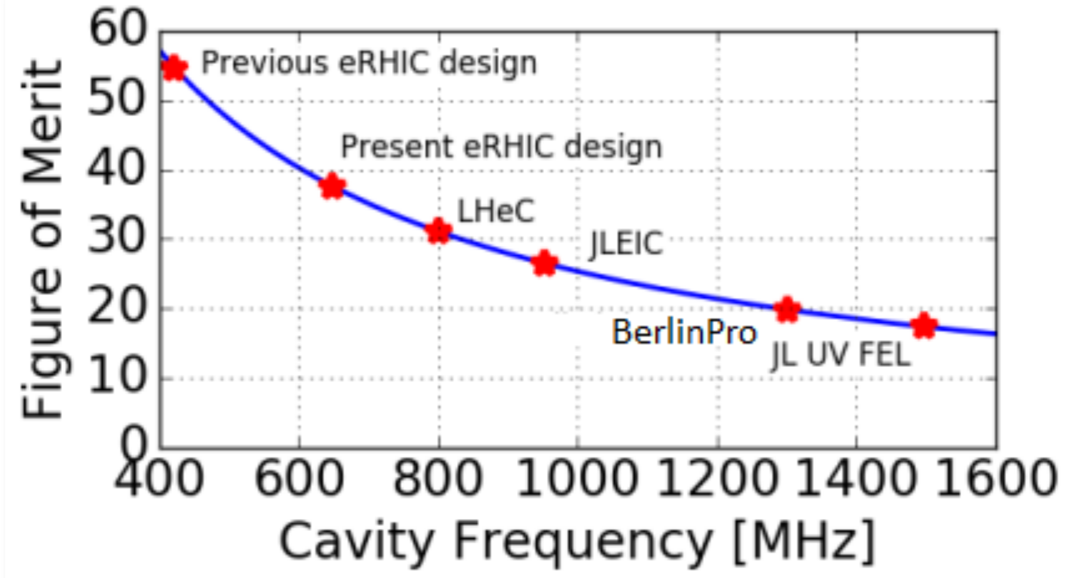
FE-FRT: Tuning use cases

- **Adjustable Tuning**
  - **Frequency correction is variable & continuously updated**
    - uses fast response of FRT to "correct" cavity frequency
  - **Use case: Suppression of microphonics noise spectrum**
    - Cavities not operated in heavily over-coupled state

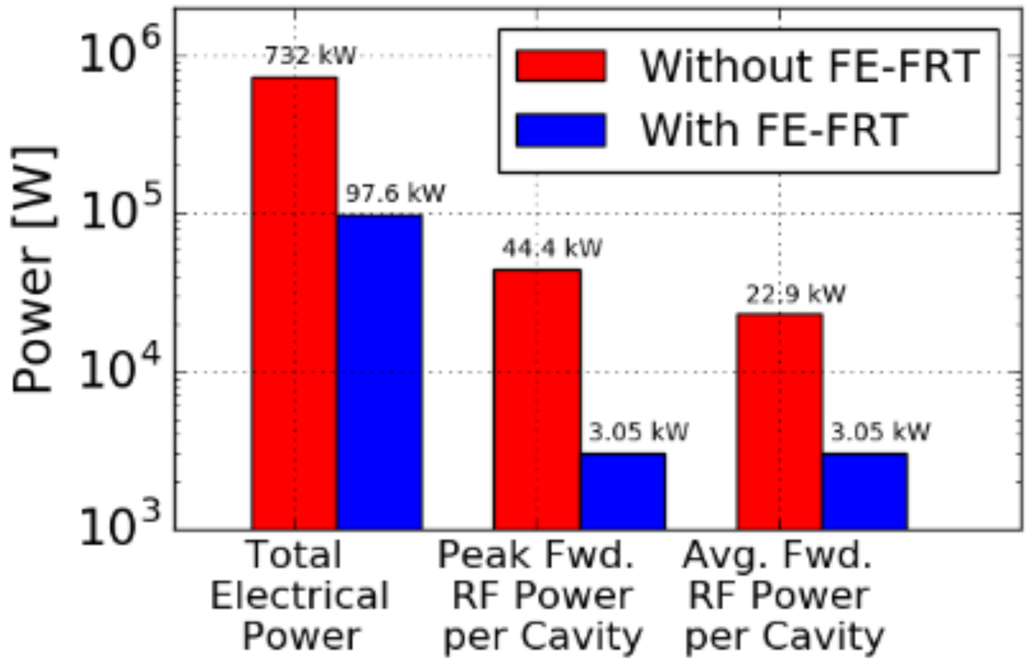
      => Potential for significant operation power savings

      => Potential for improved cavity stability
- **Discrete Tuning**
  - **Switching between well defined cavity frequency states**
    - uses fast response of FRT to switch cavity config
  - **Use case: Compensation of beam loading**
    - Switching cavity config between beam & no beam segments
      - Does so with modifying the RF bucket length

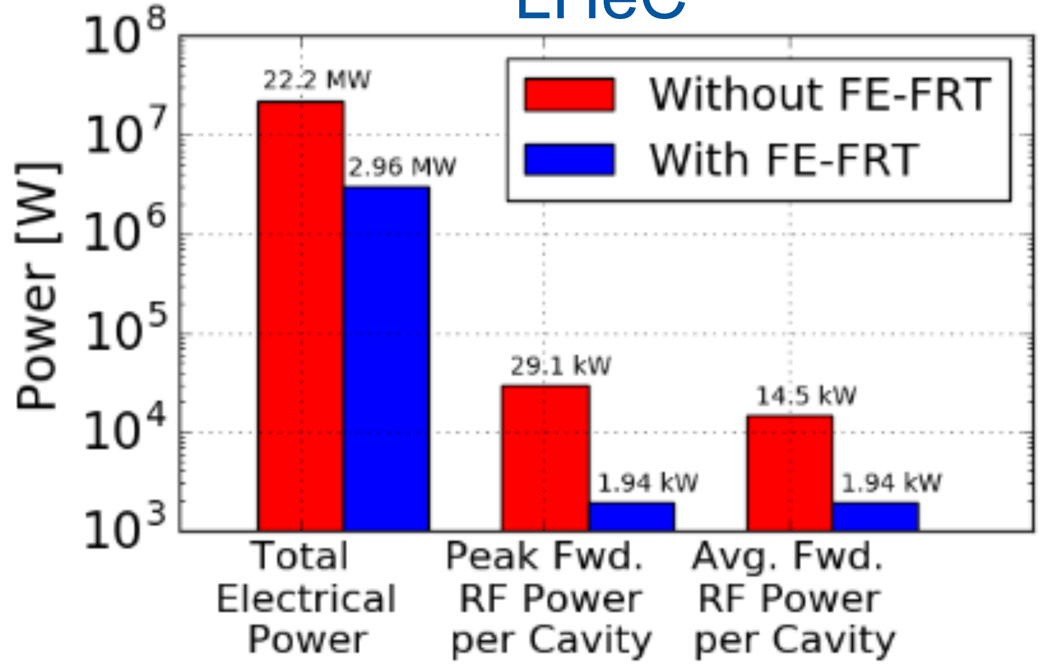
=> Potential for significant operation power savings at injection



PERLE



LHeC



ERL Case study estimates

FE-FRT for Microphonics Suppression

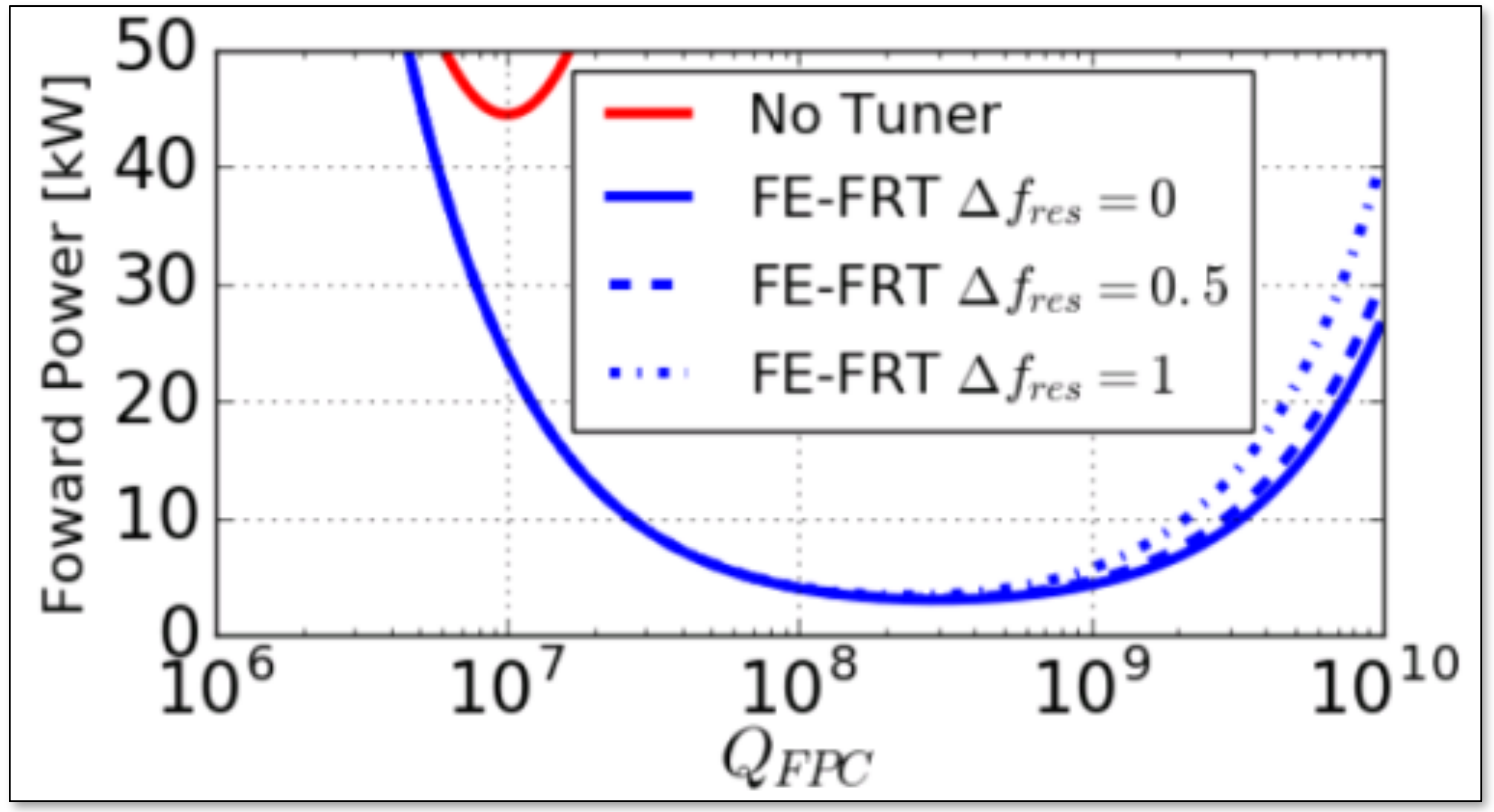
- **Microphonics contribution to required RF power**

$$P_{RF} = \frac{V_c^2}{4\,{}^{R}/_{Q}\,Q_L}\,\frac{\beta+1}{\beta}\left[1+\left(2Q_L\frac{\Delta\omega_\mu}{\omega_0}\right)\right]$$

$\Delta\omega_\mu$ = microphonics frequency source

- **Low beam loading machines: RF power can be dominated by microphonics**
  - Suppression of microphonics can be both passive and/or active
    - Stiffening of cavity & Isolation of noise sources & active feedback systems
  - Residual microphonics requires over-coupled RF power inputs
    - Broadened resonance buffers against perturbations, but at cost of RF power budget

- **Alternative: microphonics suppression by FRTs**
  - High Tuning speed: measured ~600 ns due to external HV
  - **No excitation of mechanical modes**
  - Possibility of significant RF power reduction
    - **Peak power reduced by factor FoM/2**
    - **Average power reduced by factor FoM/4**
  - Can be combined with other suppression technologies



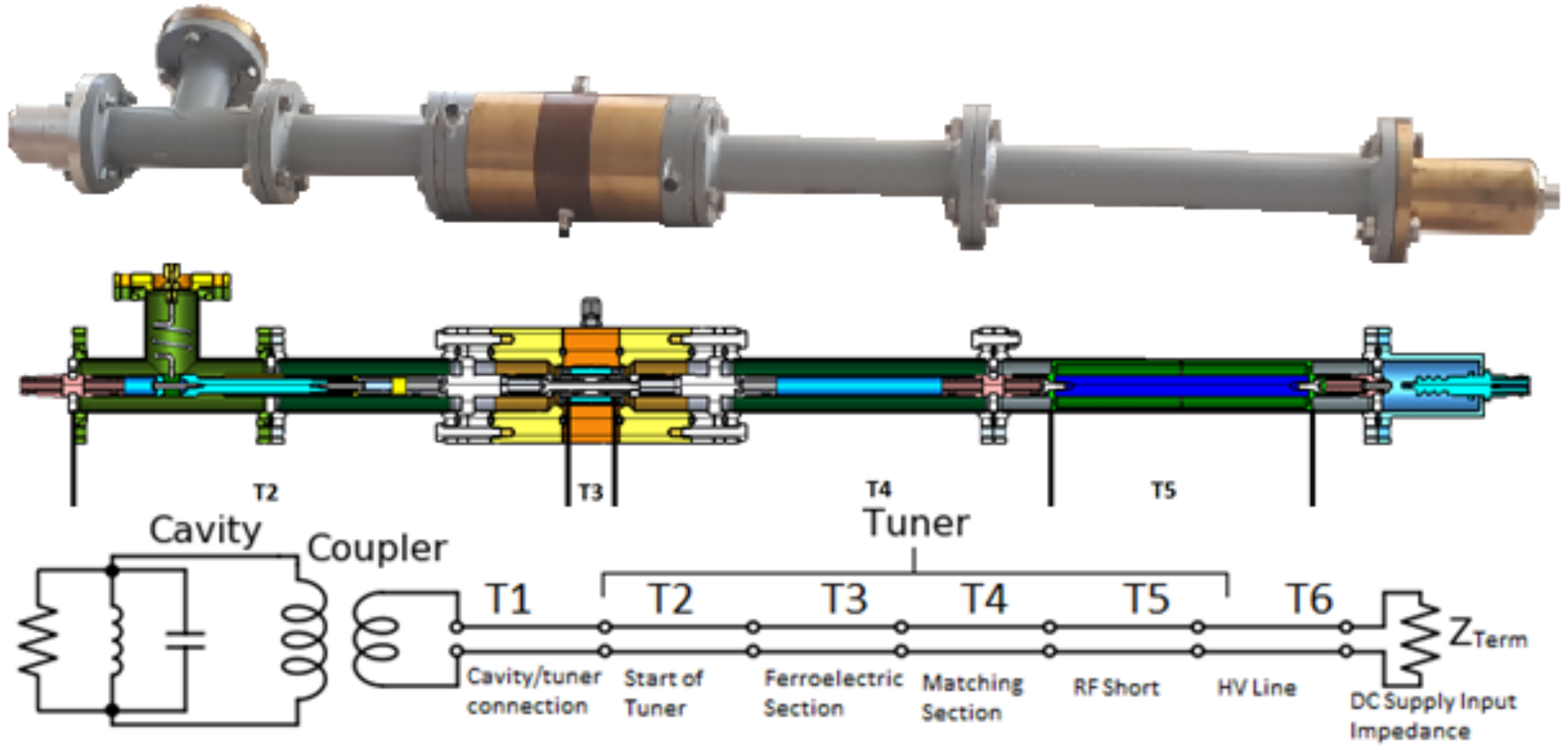
P_{RF} vs. Q_{FPC} for PERLE. Without FE-FRT and with FE-FRT.

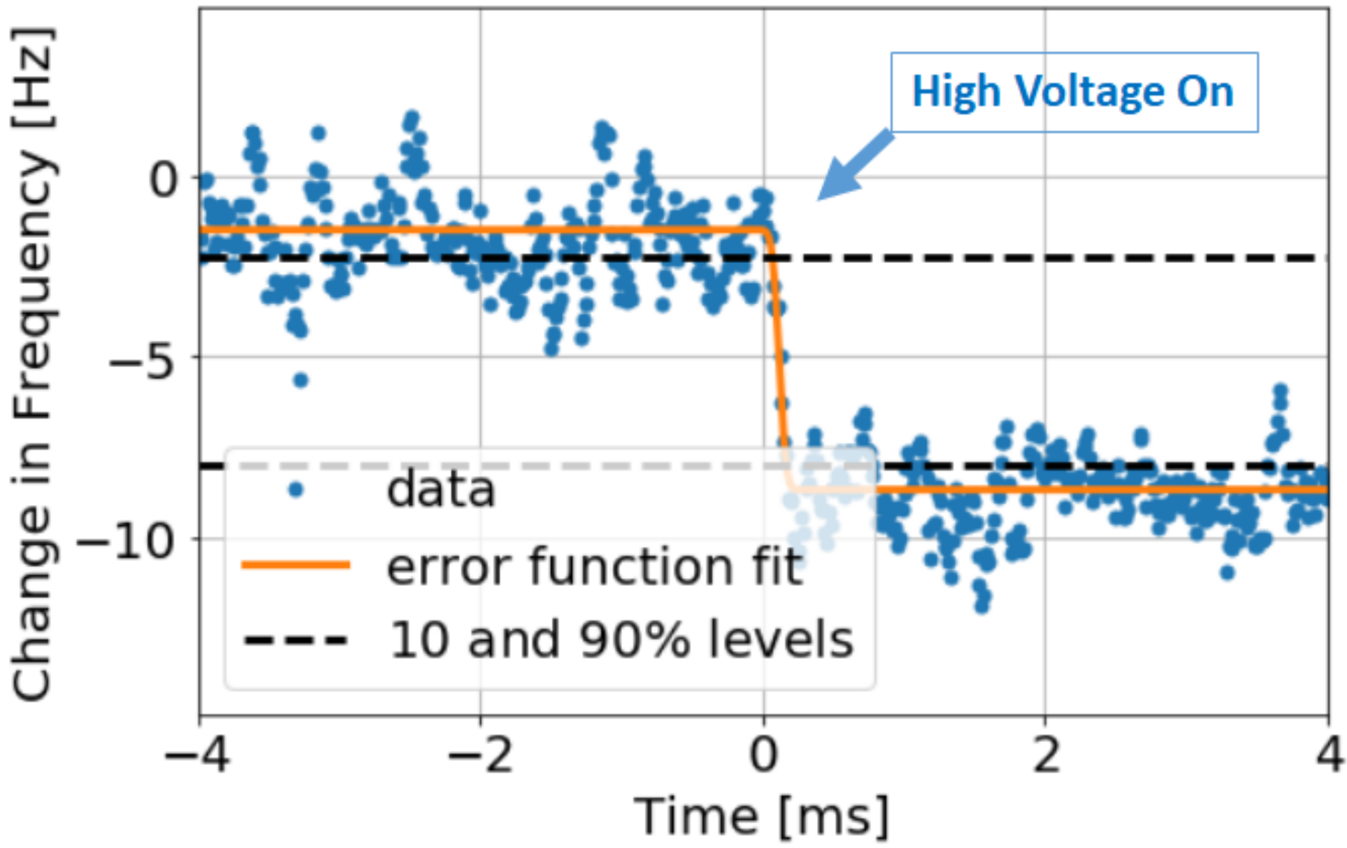
Case study for PERLE: Power reductions

Examples and Prototypes

FE-FRT Prototype - Initial tests on 374 MHz SRF cavity

- **Initial prototype FRT: Based on simple coaxial ceramic section**



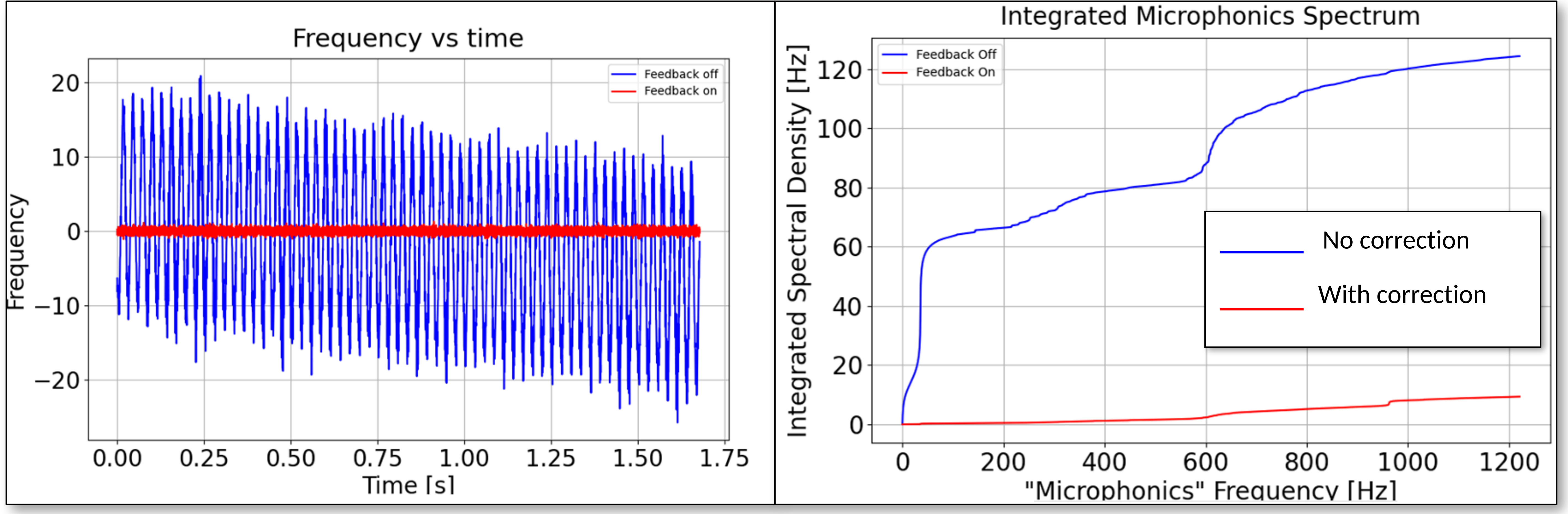


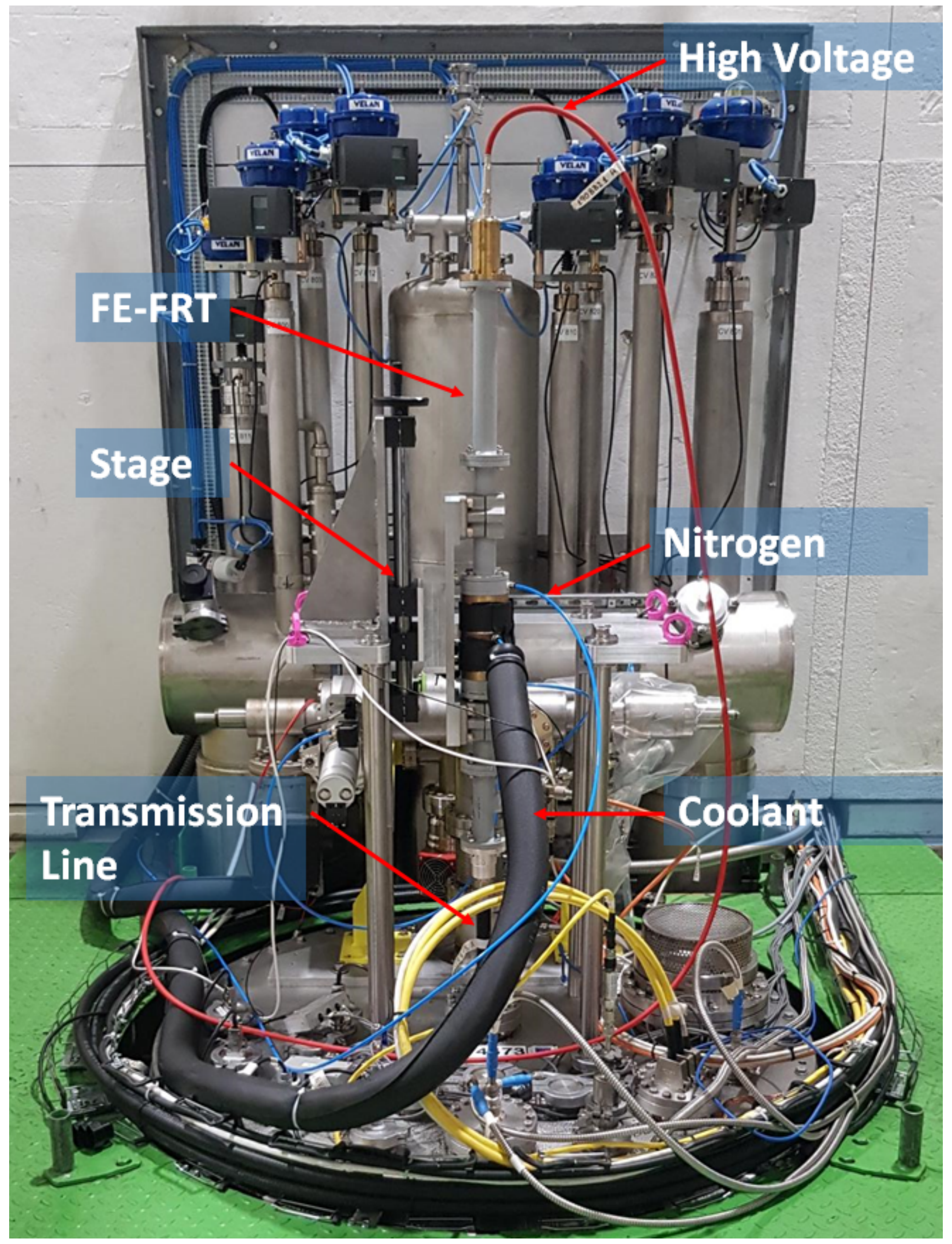
Tuner much faster than cavity

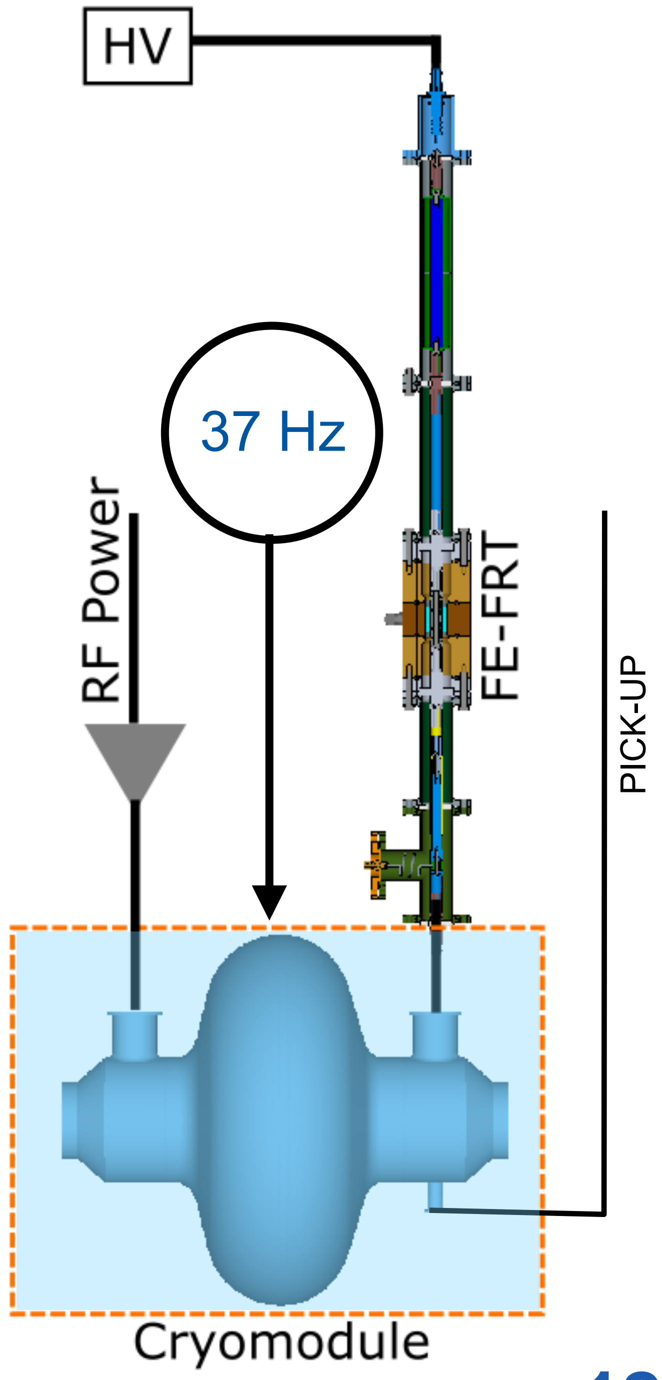
- Cavity response to tuner
  - < 50 μs
- Cavity time constant

$$\tau = \frac{Q_L}{\omega_0} \approx 46\ ms$$

Example: Microphonics suppression - external 37 Hz vibration source





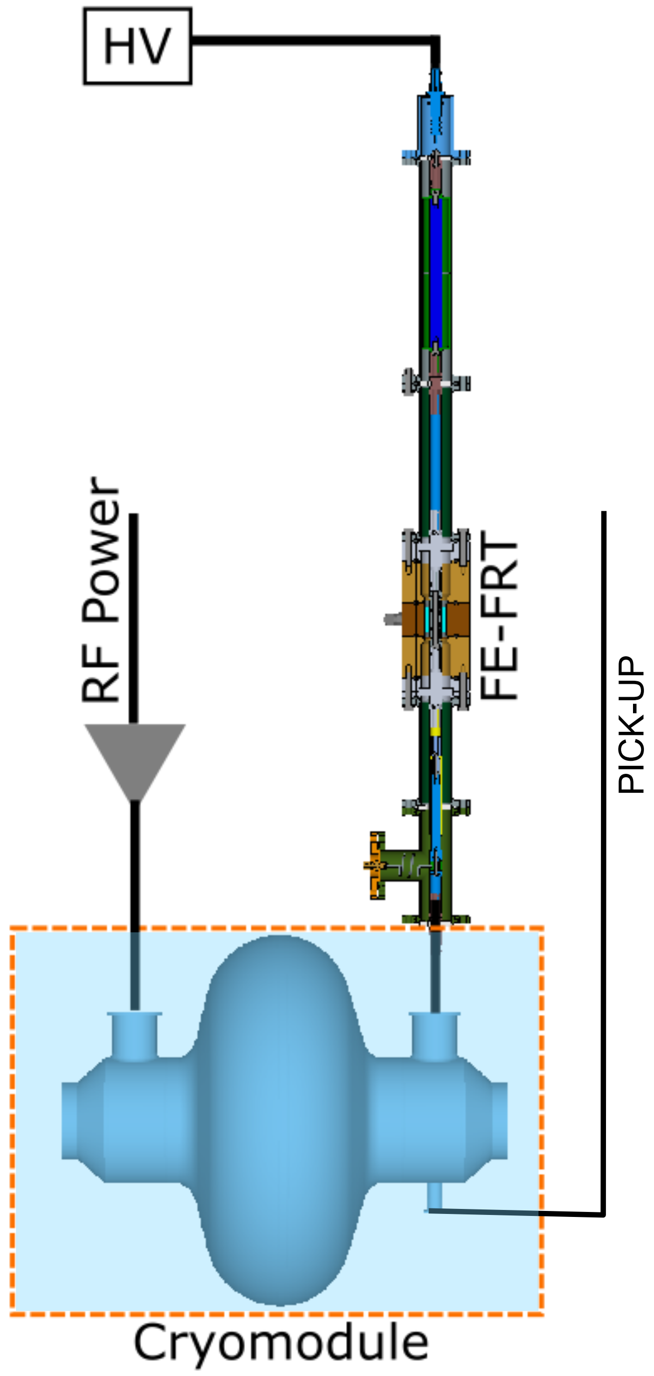


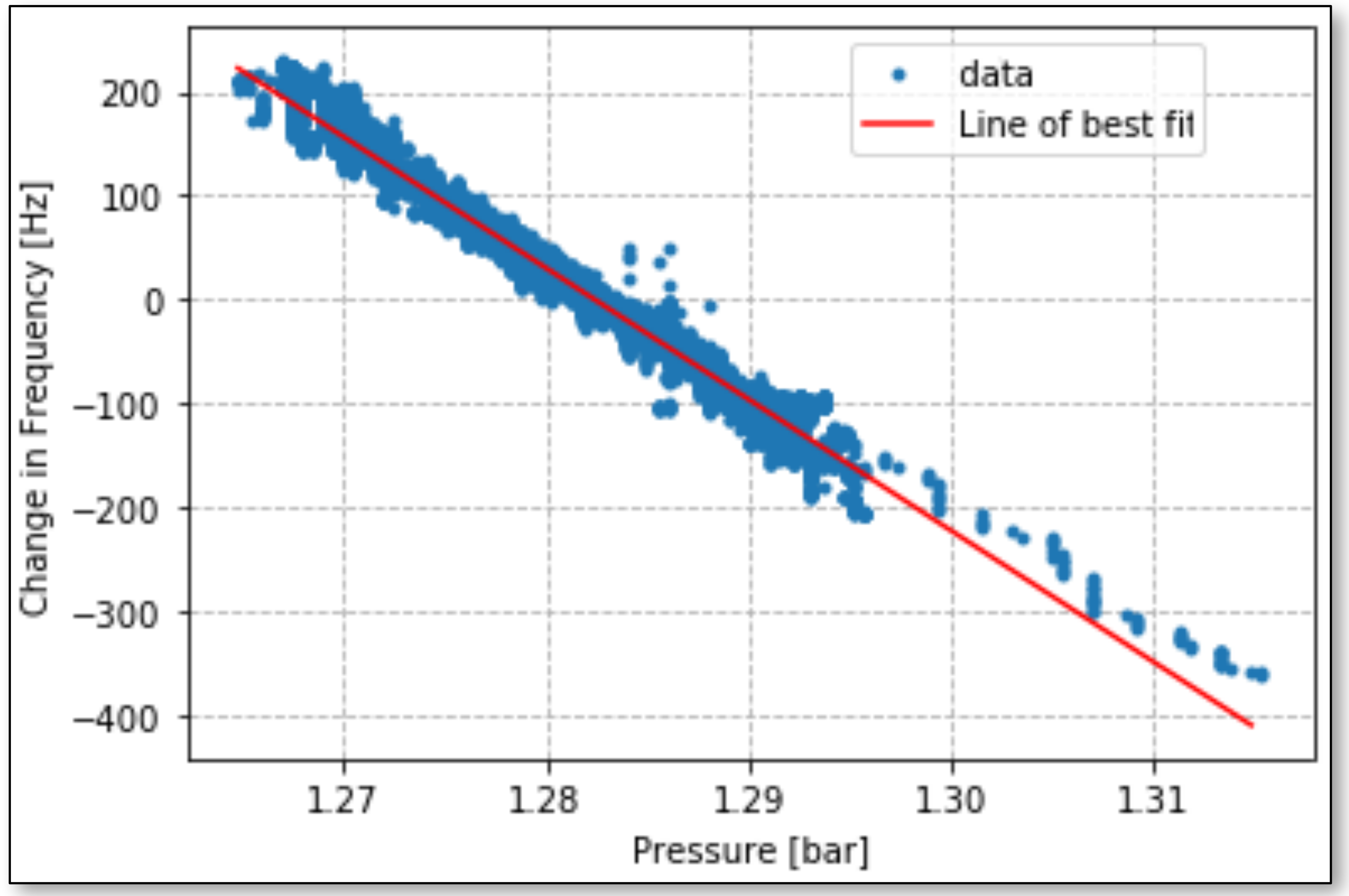
- **Integrated microphonics spectral density up to 1kHz**
- **Microphonics reduced by factor ~14**

Fast Reactive Tuners: A. Macpherson - Muon Collider Collaboration Meeting 12/10/2022

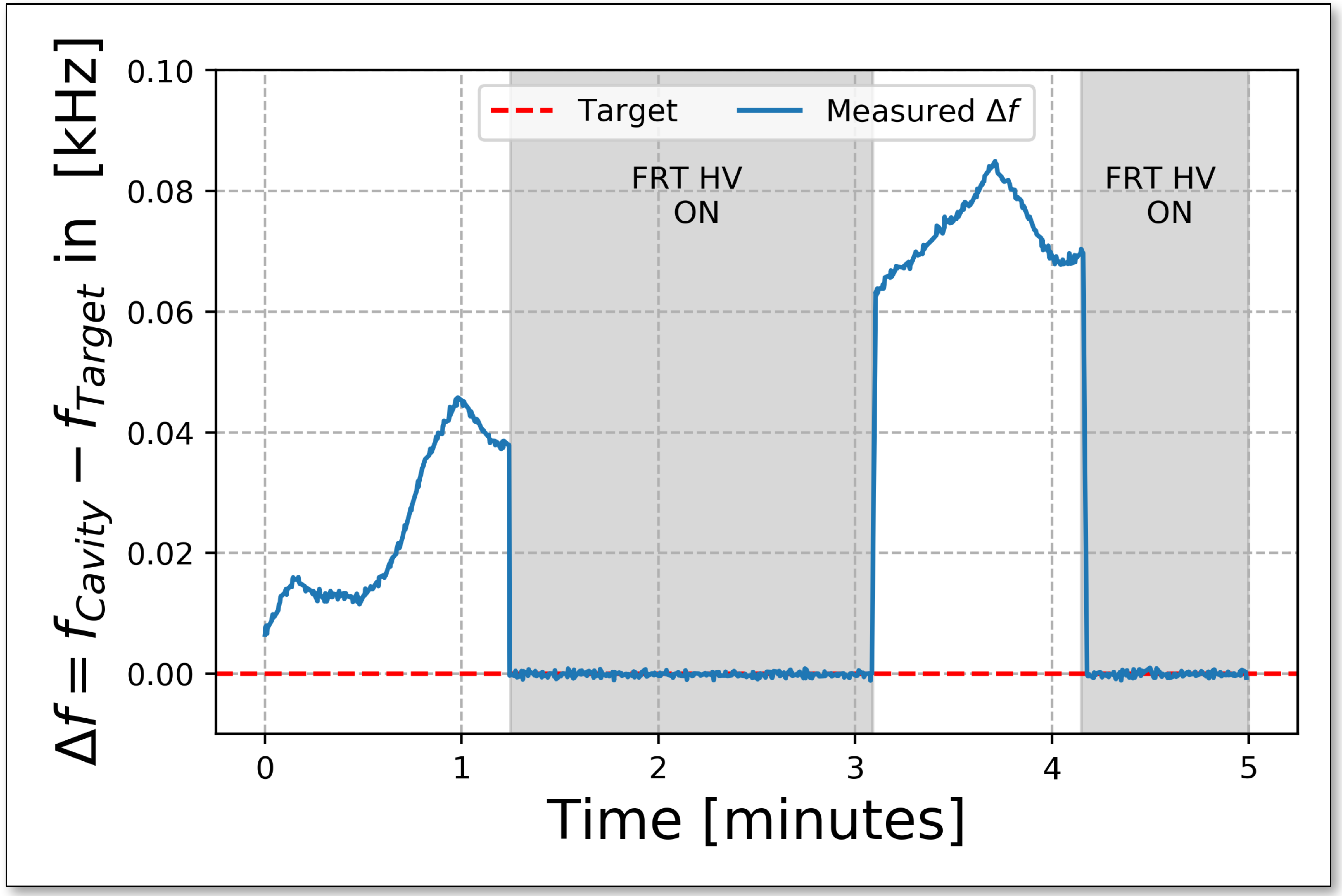
FE-FRT Prototype - also a slow tuner

- **Basic tuning functionality**
  - **Corrected slow frequency variations from helium bath pressure fluctuations**
  - Frequency quickly corrected to target
- **Long term slow tuning**
  - can be written into tuning loop





Helium bath Influence on cavity frequency

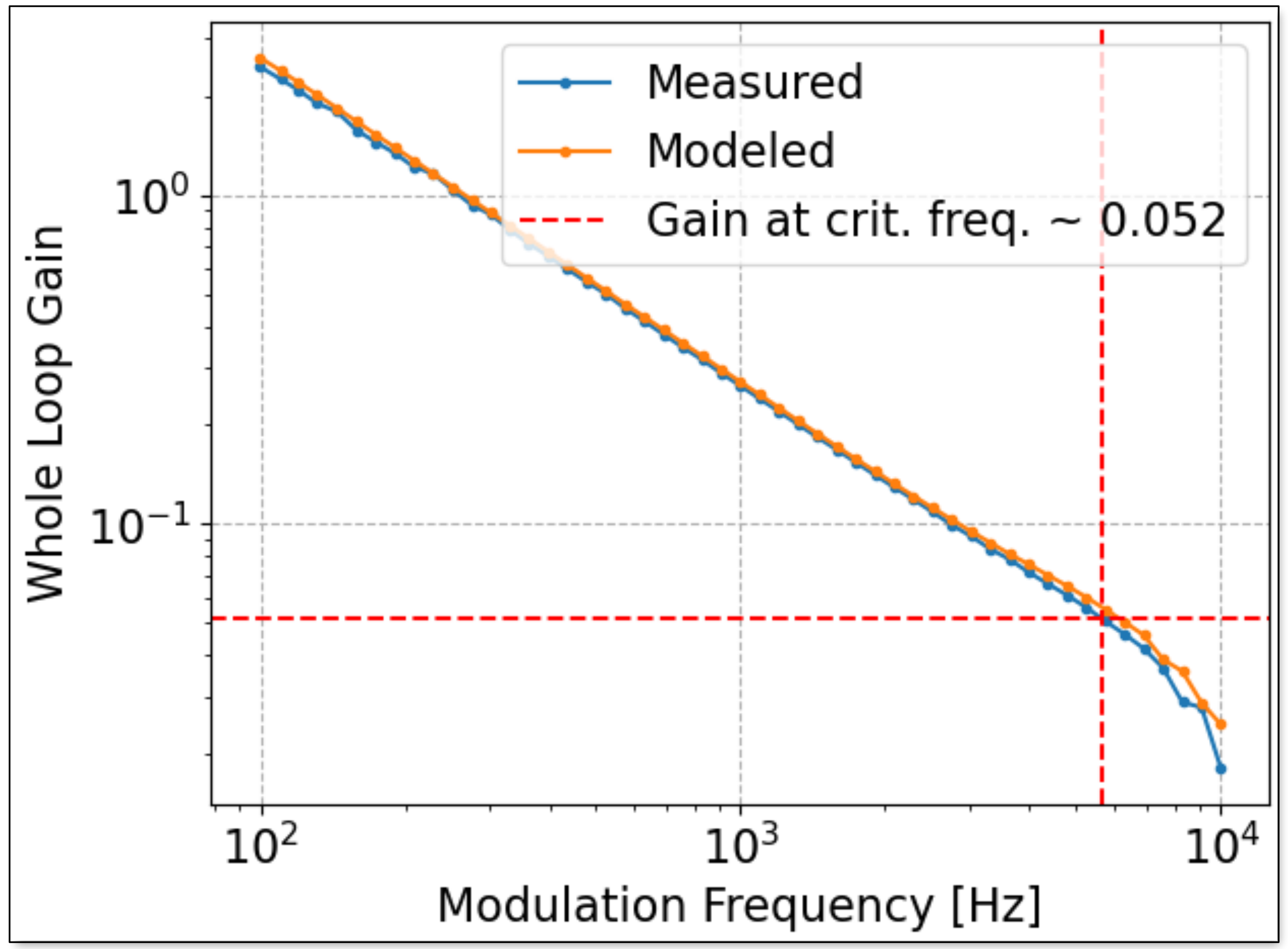


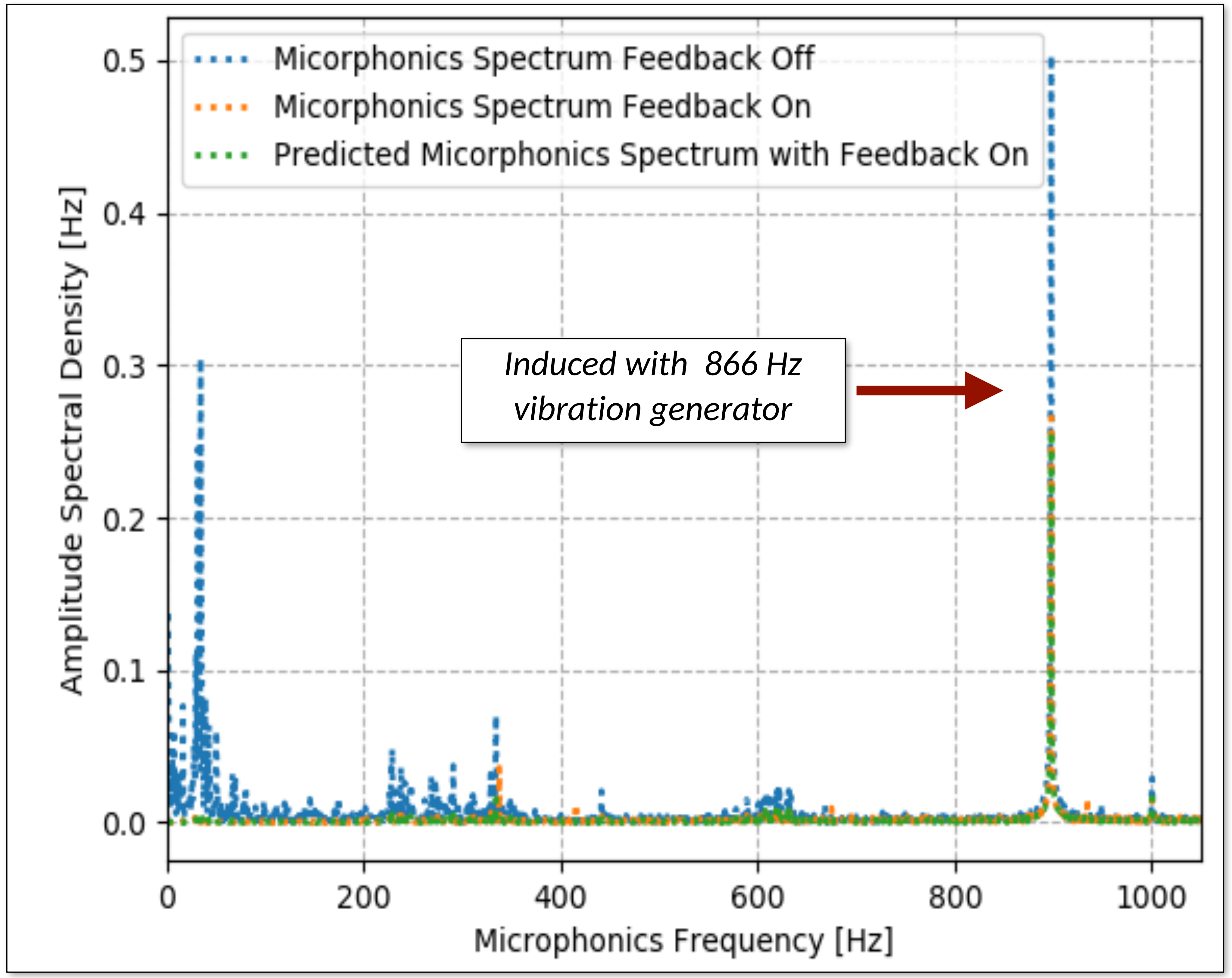
“Slow” tuning loop with FE-FRT prototype

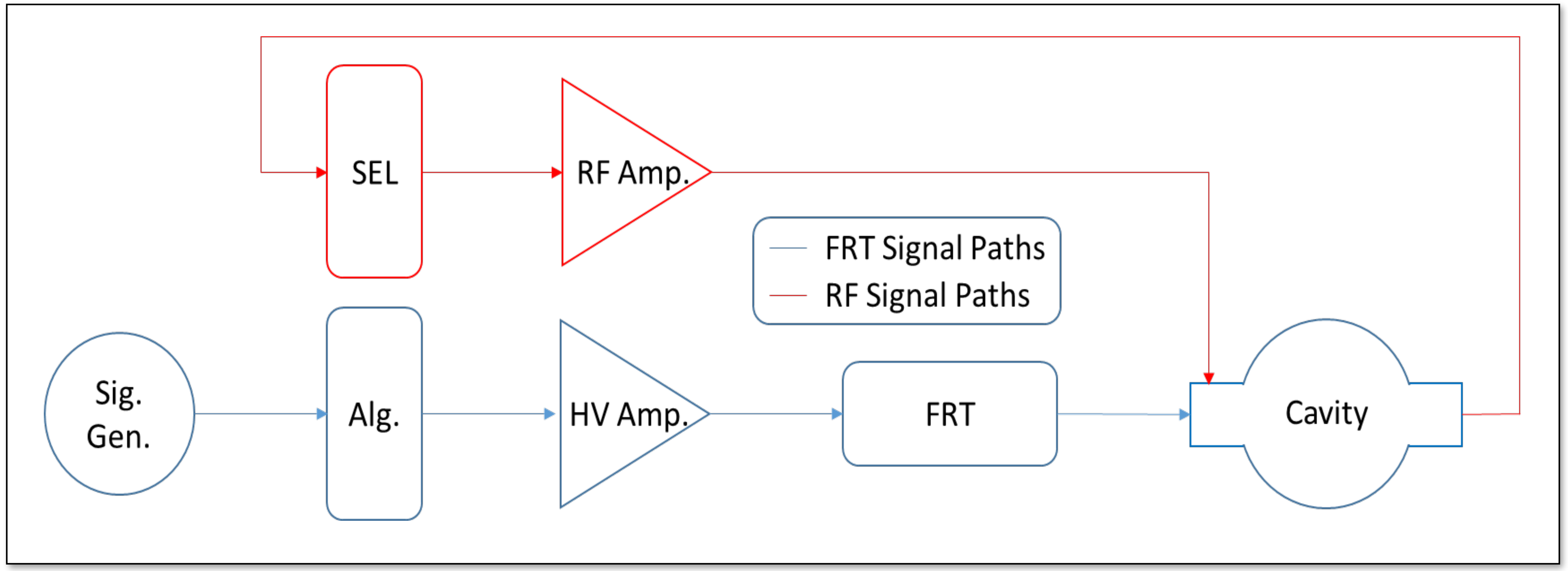
Microphonics Suppression:

- **Simple Integral feedback algorithm**
  - Phase delay is dominated by algorithm and HV amplifier
- **Loop Gain critical frequency ~5.6 kHz**
  - **microphonics suppression feasible in 0 - few kHz range**

Loop Gain vs frequency







Schematic of setup

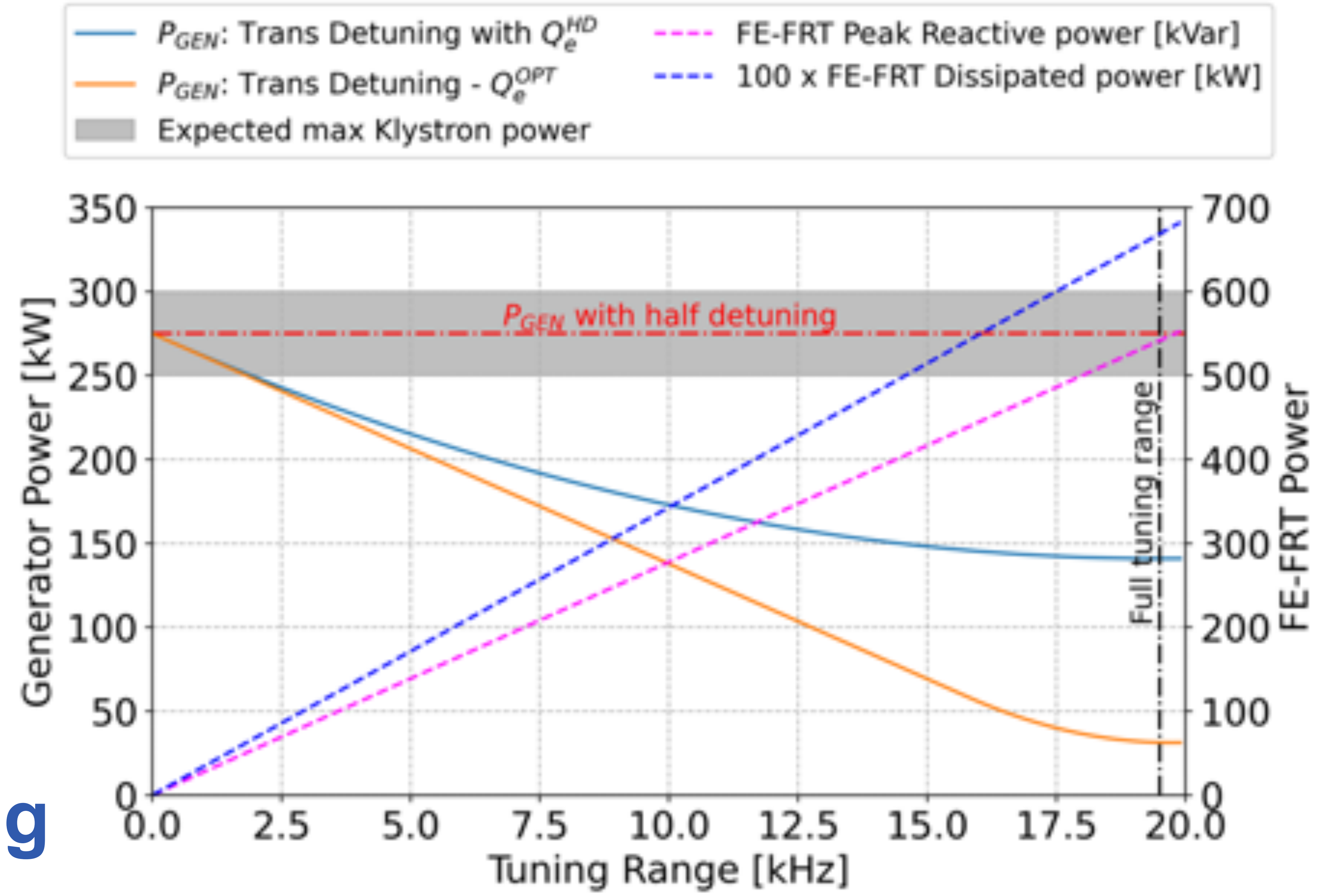
Transient Detuning Project: Overview

- **Concern: HL-LHC may lack RF power to capture full beam current at injection**
  - Options: Install high efficiency Klystrons or Add cryomodules or Transient detuning with FE-FRT

- **Ideal: Perfect compensation of beam loading by FRT => reduce RF power 10-fold**
  - FE-FRT to handle high reactive power ~500kVar
  - If Qe of FPC is increased by optimal amount
  - **Partial compensation gives significant reductions**

- **If proven feasible …**
  - Transient detuning is elegant solution
  - Electricity saving up to ~ 2GWh per year
    - ~1M€ (estimate from French electricity cost)

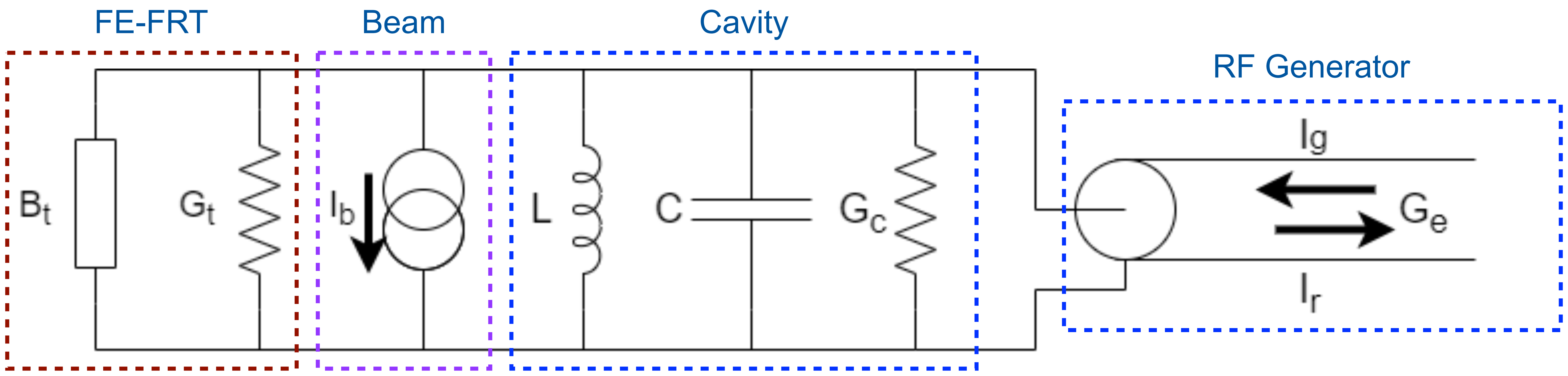
- **Aim: demonstrate FRT based Transient Detuning**
  - Show feasibility for HL-LHC at injection
    - **R&D activity ongoing at CERN**



Estimated power reduction vs achievable tuning range with transient detuning

FE-FRT for Beam Loading Compensation

- **Transient Detuning Concept:**
  - **Fast frequency switching between bunch trains to minimise required RF power (P_{RF})**
    - Potential power savings over present half-detuning scheme used at LHC injection settings



Notation	Meaning
P_{RF}	RF power
ϕ'_c	Cavity phase derivative
$\Delta\omega_D$	Detuning
I_b	Beam current

Assumes $V'_c = 0$ $\Delta\phi_{bc} = 0$

- **Required RF generator Power**

$$P_{RF} = \frac{R/_Q Q_e}{2}\left(\left[\frac{V'_c}{\omega_0 R/_Q} + \frac{V_c}{2 R/_Q Q_L} - I_b \sin\Delta\phi_{bc}\right]^2 + \left[\frac{V_c}{\omega_0 R/_Q}(\phi'_c - \Delta\omega_D) - I_b \cos\Delta\phi_{bc}\right]^2\right) \Rightarrow P_{RF} = A + [B(\phi'_c - \Delta\omega_D) - C I_b]^2$$

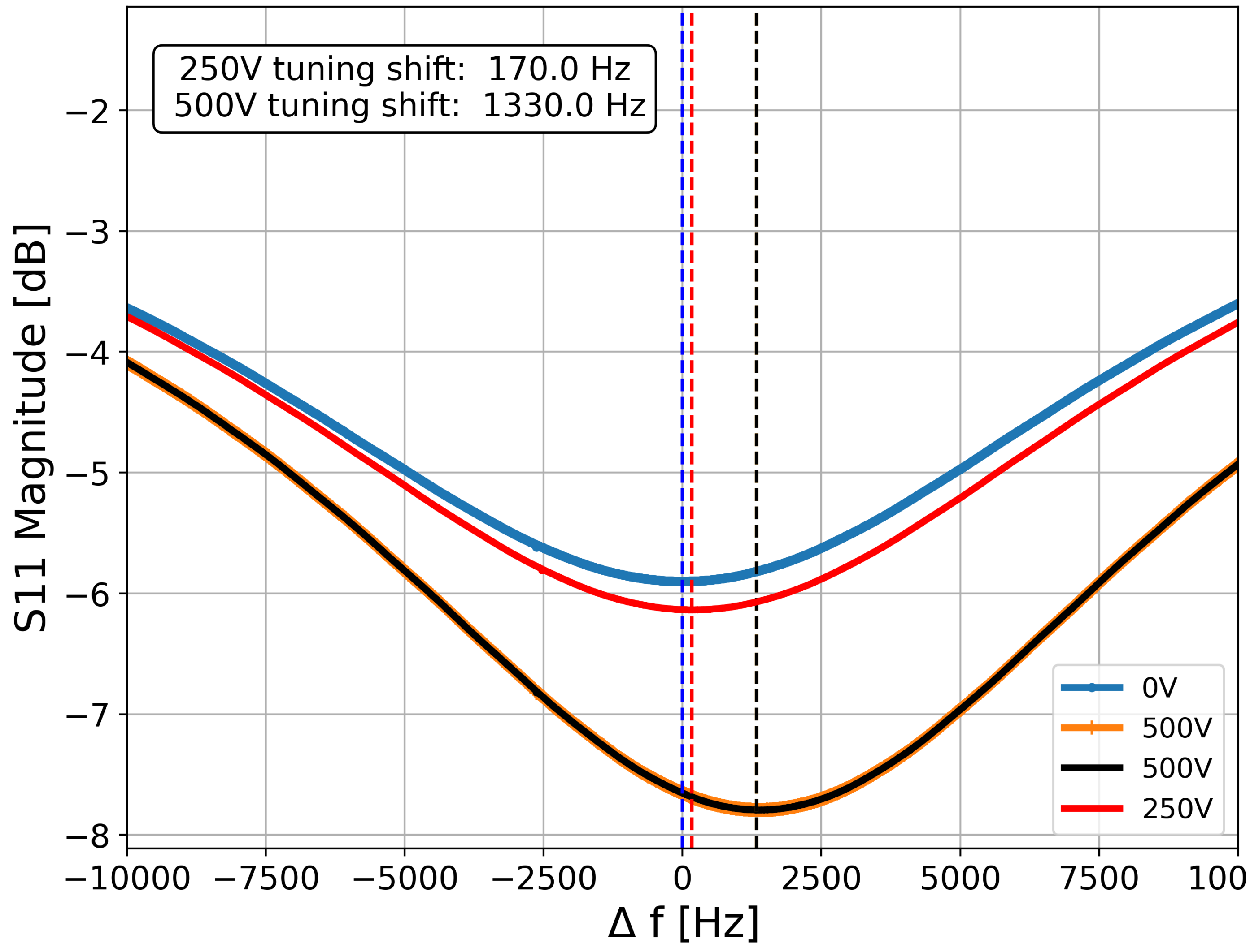
- Beam loading => I_b changes => either increased P_{RF} or cavity phase errors
- Transient detuning: **Use tunable $\Delta\omega_D$ to cancel (Φ'_c - $\Delta\omega_D$)** => frequency switching in no-beam segments
  - For LHC, accessible bunch train gaps are 200 and 800 ns duration
- **Increased phase stability and fixed RF bucket position => ideal for injection schemes**
- Potential to reduced average P_{RF} by up to FoM/2

TDD: First Prototype

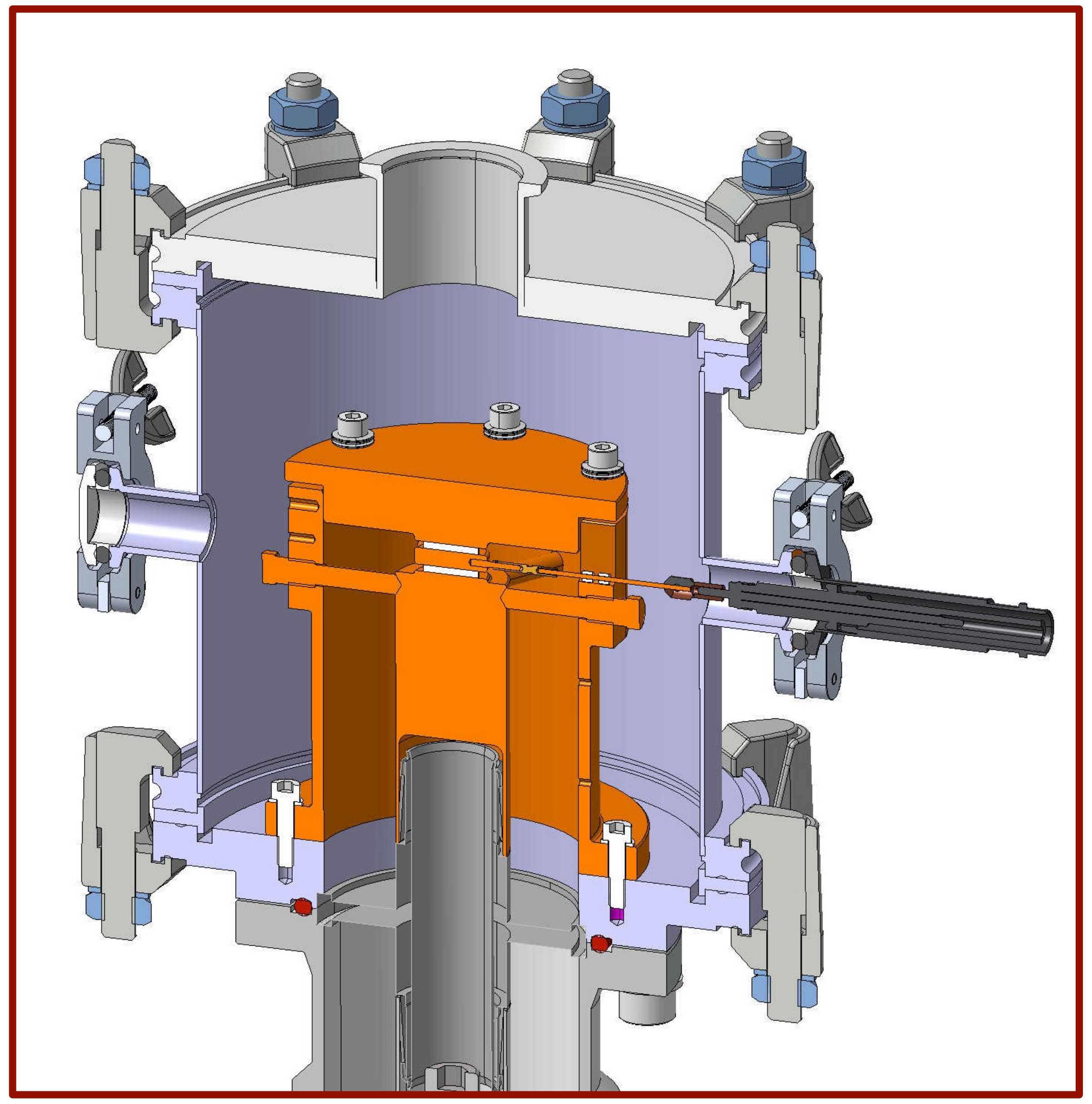
- **TDD: Ongoing R&D**
  - **RF design: Coupled cavity-FRT mode scheme**
    - => Larger tuning range with smaller antenna
  - Discontinuous tuning range
    - FRT resonance jumped across cavity resonance
    - Not for microphonics suppression
  - Coupled Mode Ferroelectric Core:
    - **Based on thin wafers of ferroelectric in vacuum**
      - reduced losses + higher biasing electric fields
    - Compression based assembly to unnecessary losses

Sample Ceramic: Optical polish surface finish surfae area of 75 mm^2 to set capacitance

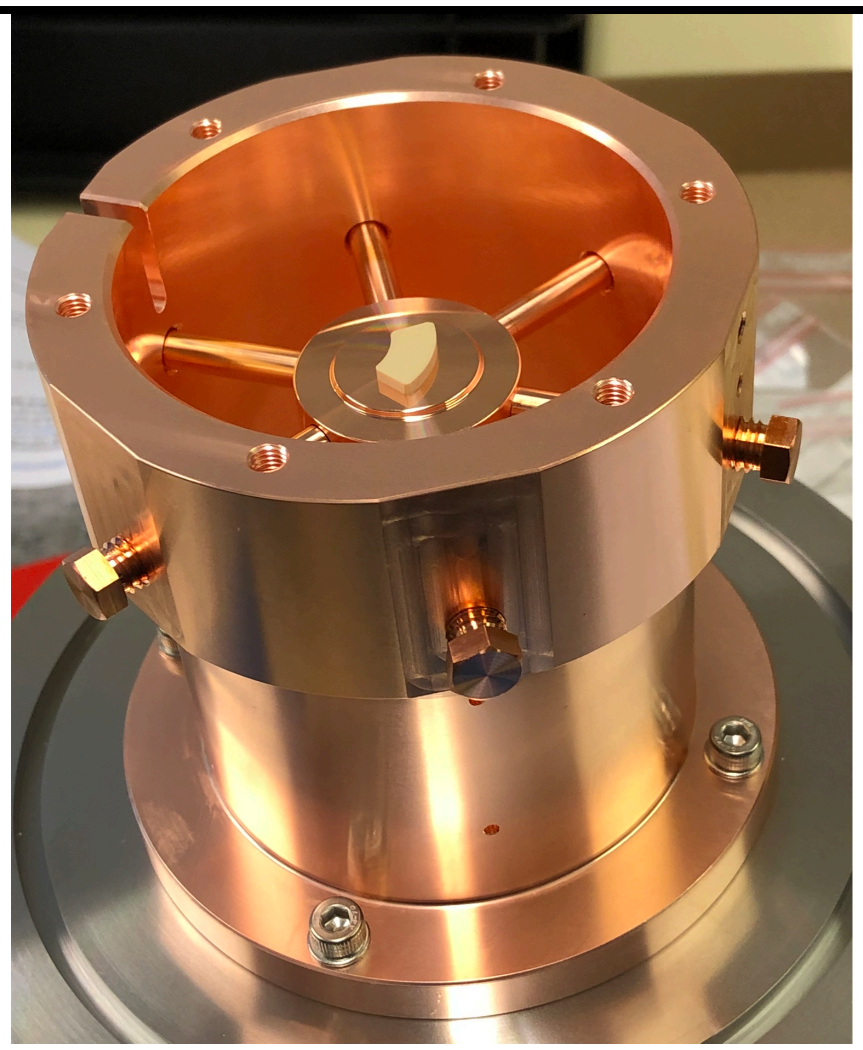
- **Initial prototype: TDD_0**
  - Installed on spare LHC 400 MHz SRF cavity & under test at CERN
    - **Design concept validated**
    - Initial 1.3kHz tuning shift observed with only 500V bias

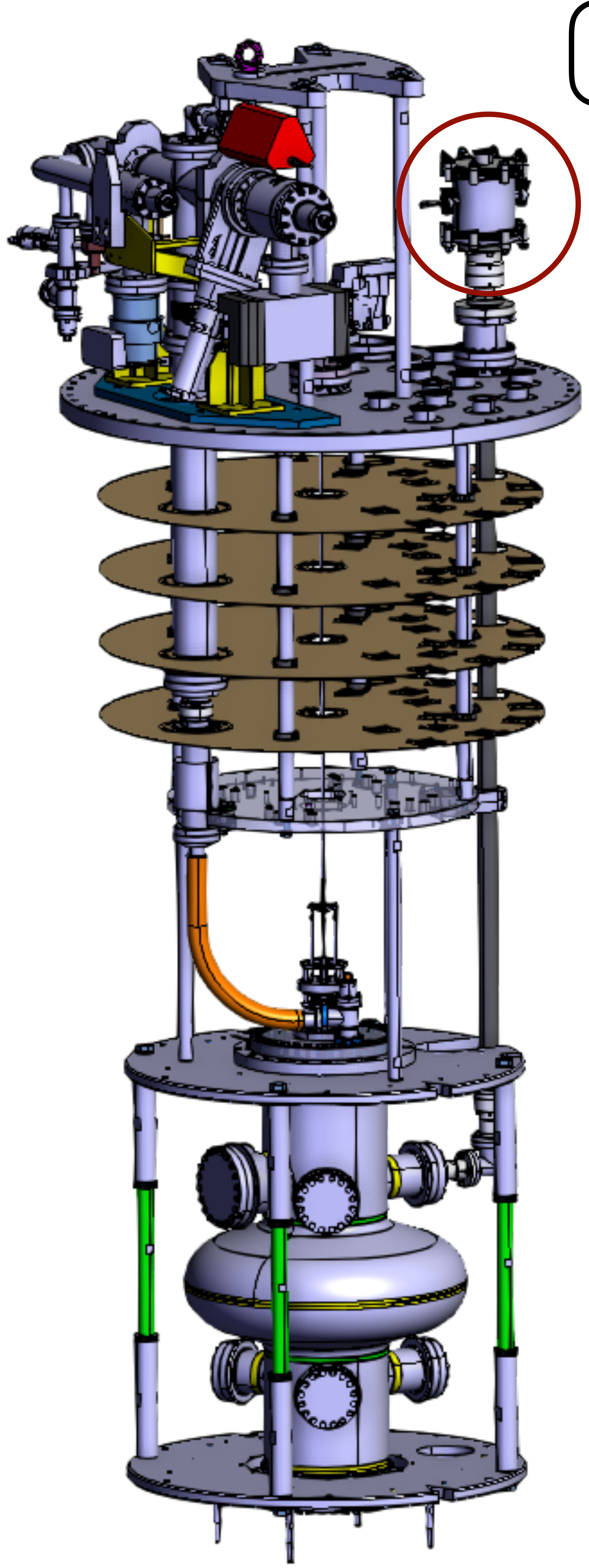


TDD_0: Concept design validation of TDD

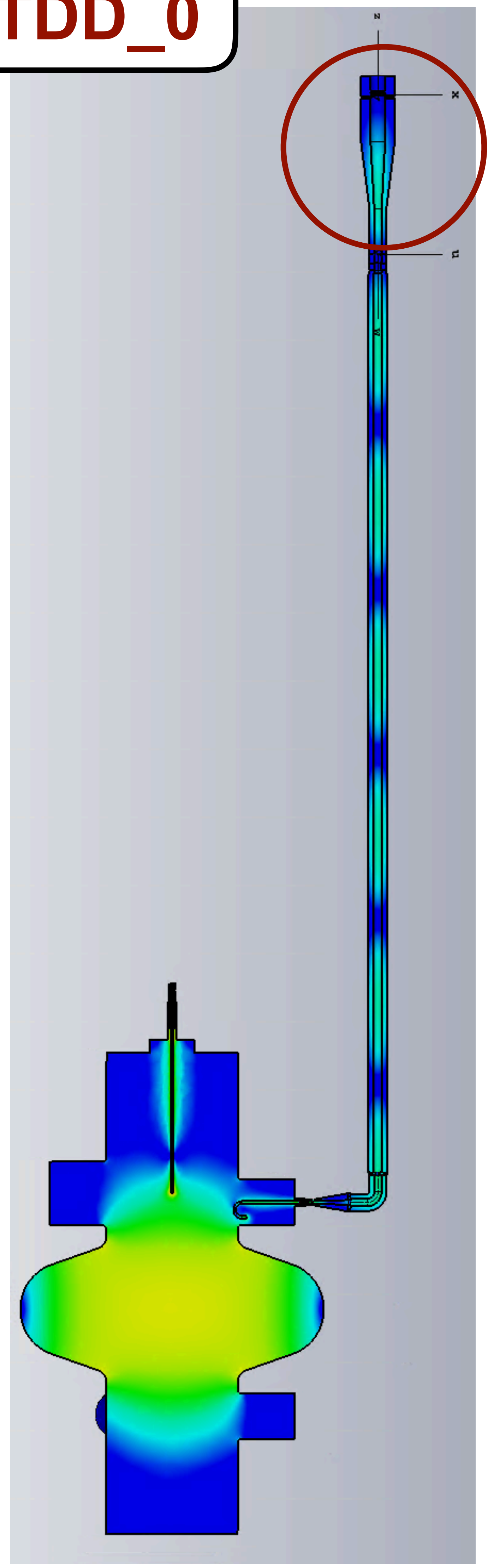


TDD_0: Design vs Reality





TDD_0



E-field (dB scale)

Preparation of RF Test - Oct 2022

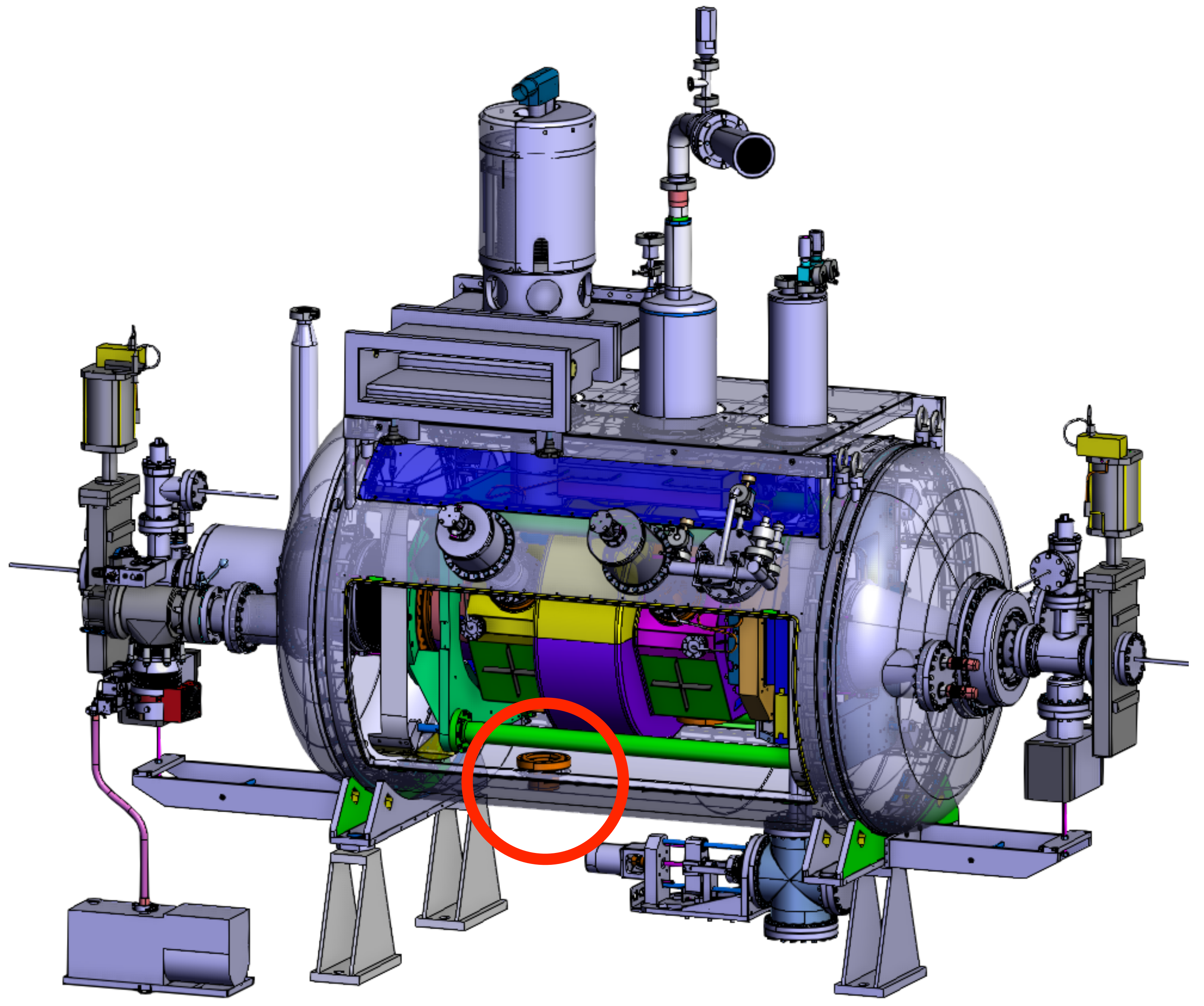
Transient Detuning Demonstrator (TDD)

- **Full Prototype: TDD_1**
  - RF and mechanical design ongoing
    - **Designed for 1-16kV operation, target tuning range of 18 kHz**
  - Focus on compression fit assembly of ceramics
  - Management of power dissipation & cooling circuits
  - **Including integration considerations => must be compact!**
    - We have to reverse engineer device into a LHC cryomodule

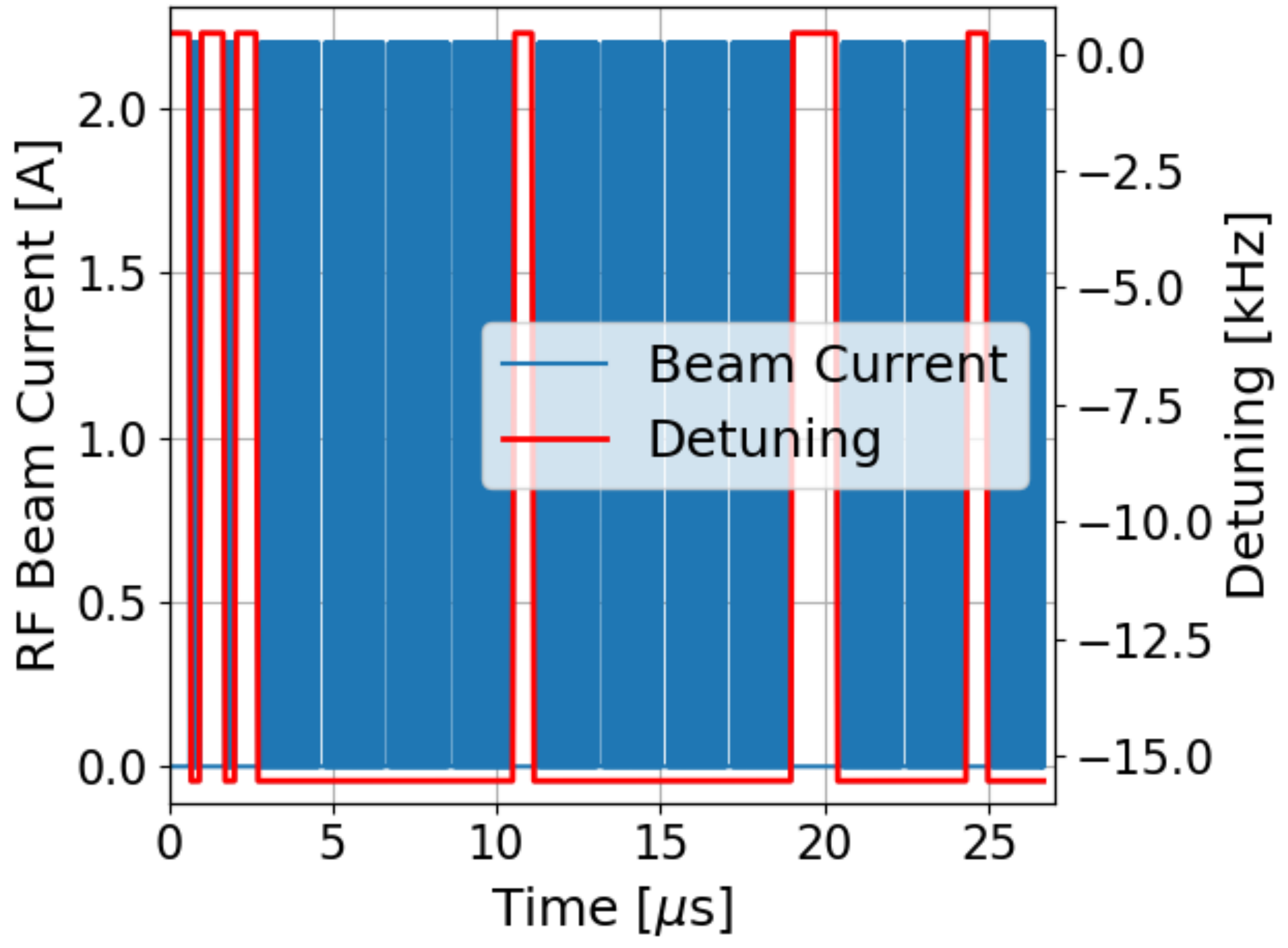
- **Developed on the way …**
  - Copy of LHC-LLRF system in stand-alone mode
  - **BLEEP (Beam Loading Electronic Emulation Project)**
    - BLEEP already tested on SRF cavity
    - Emulates beam by injecting additional power into cavity
  - HV pulser: Off-the-shelf product
    - **10 kV with 160 kHz rep rate for 10ms burst into 2nF load**

      => correlates to > 100 LHC beam revolutions

- **TDD_1 validation at CERN expected mid 2023**



1/4 CM - LHC cavity



Transient Detuning: RF switching in bunch train gaps

Summary

- **This talk is not about the Muon Colliders**
  - This talk has been about fast non-mecanhical tuning of RF cavities
  - Based on reactive tuning using dielectric stub attached to a cavity
  - Concept is FE-FRT: Ferroelectric Fast reactive Tuners

- **An active FE-FRT development program is ongoing at CERN**
  - Multiple applications and uses cases of FE-FRTs are possible
    - Beam Loading compensation, Microphonics Suppression, Power savings, Slow Tuning

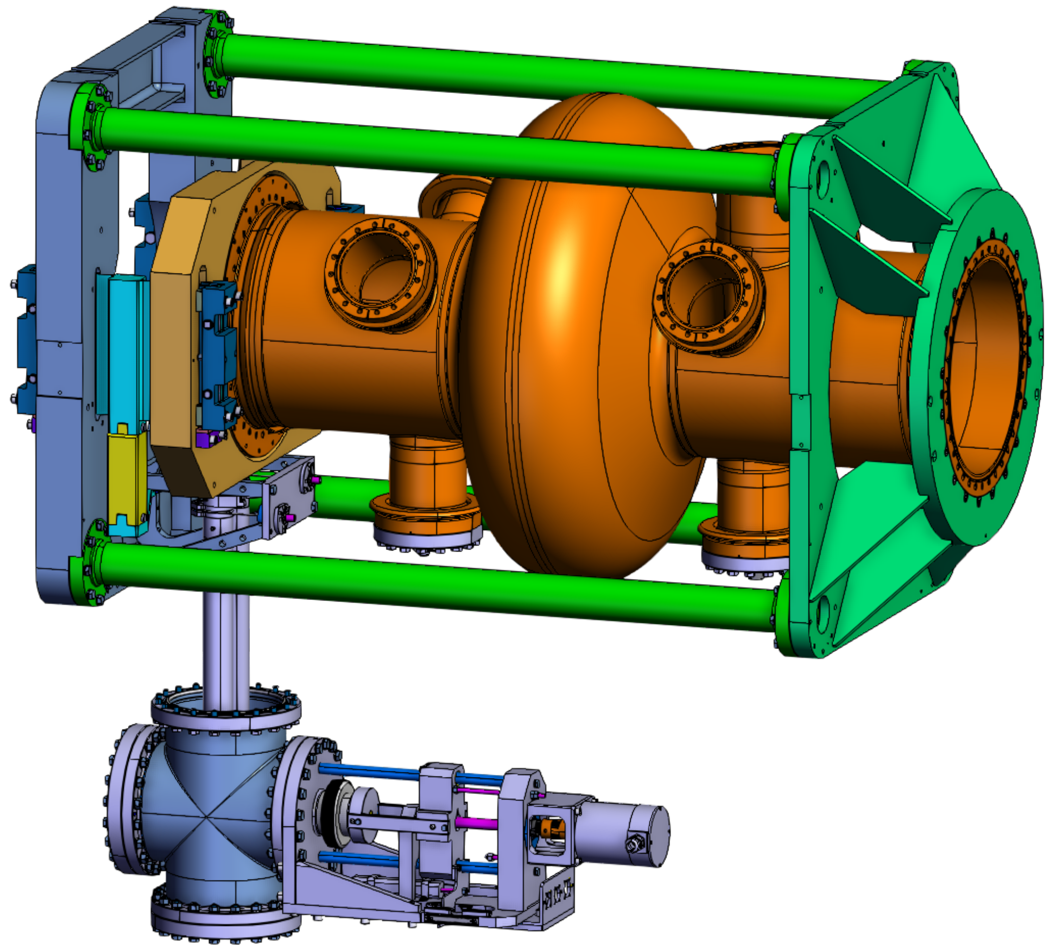
- **CERN’s Primary Use case is Transient Detuning**
  - Transient Detuning Demonstrator on spare LHC SRF cavity:
    - R&D is ongoing and validation expected mid 2023

- **Question: Are FE-FRTs applicable to the Muon Collider?**
  - Expect the answer to be yes, but would welcome opportunity to see your cavity tuning needs
    - Hope this has given you a taste for FE-FRTs.

Spare Slides

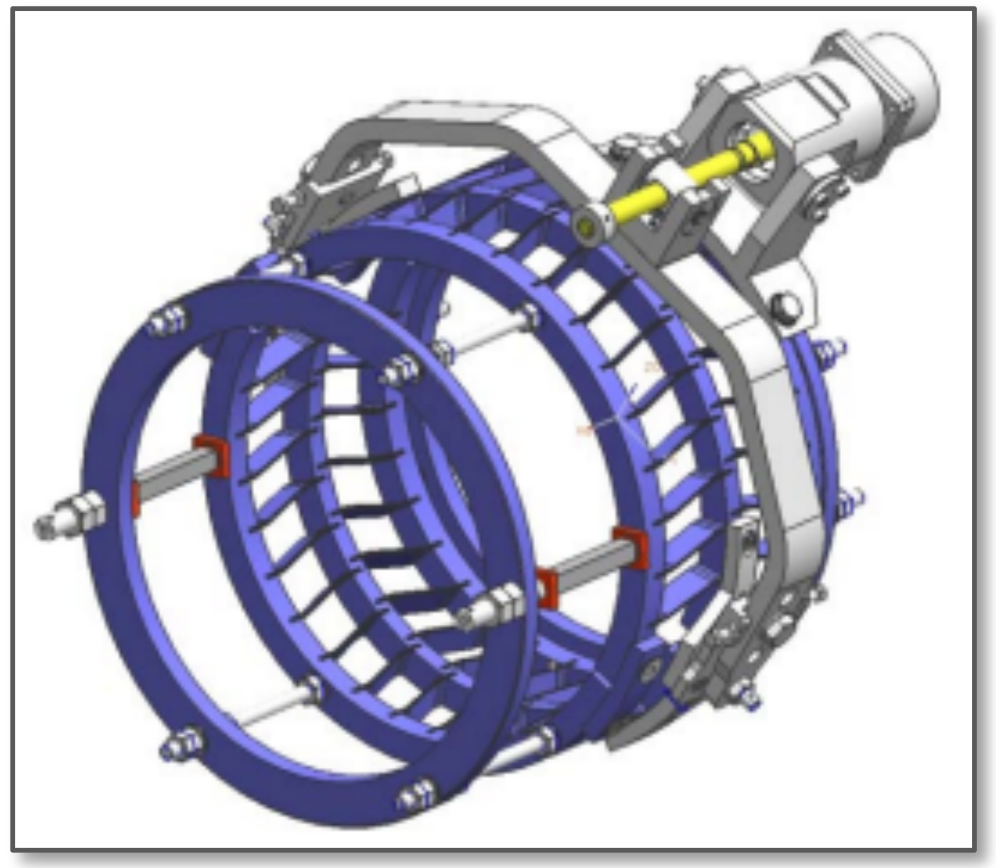
Mechanical Tuning of RF cavities

- **Mechanical Tuning**
  - Controllable mechanical tuning by purely mechanical structures
    - **Large tuning range but tuning is slow**
  - Good for correcting large static or slowly varying frequency deviations
    - From manufacturing errors
    - Cryomodule pressure variations



LHC Compression Tuner

- **Hybrid tuning: Piezo Tuners**
  - Controllable mechanical tuning by piezo ceramics: tuning controlled by applied voltages
    - Mature Technology with faster response times
    - Smaller max. load and smaller max. tuning range
  - Often combined with mechanical tuners
  - Can partially mitigate microphonics and Lorentz Force Detuning
    - Limited system tuning speed
    - Complicated Transfer Functions with excitation of mechanical modes



Piezo equipped INFN blade tuner.
"ILC COAXIAL BLADE TUNER" C. Pagini et al.

FoM: Assessing Performance

- **FoM: Quantifiable quantity for comparison of FE-FRT designs**
  - Standard Material definition converted to system (Cavity + tuner) definition
  - System FoM independent of cavity, coupler turn ratio, transformation by lossless Transmission line etc

Material definiton

$$\mathrm{FoM}_{\mathrm{Mat}} = \frac{\ln {}^{\epsilon_1}\!/_{\epsilon_2}}{2\tan\delta}$$

- Material FoM
  - Independent of capacitor geometry
  - always larger than System FoM

System definiton

$$\textbf{FoM} = \frac{\text{Tuning Range}}{\text{Geometric Average of increase in BW}}$$

$$\mathrm{FoM} = \frac{|\Delta\omega_{12}|}{\sqrt{\mathrm{BW}_1\mathrm{BW}_2}}$$

BW_n = increase of bandwidth due to FRT in state n

$$\mathrm{FoM} = \frac{|\Delta B'_{t12}|}{2\sqrt{G'_{t1}G'_{t2}}}$$

FoM in terms of equivalent circuit parameters

$$\mathrm{FoM} = \frac{|\Delta\omega_{12}|U_c}{\sqrt{P^{FRT}_{diss1}P^{FRT}_{diss2}}}$$

FoM in terms of cavity stored energy & power dissipated in FRT

$$\mathrm{FoM} = \frac{|\Delta\omega_{12}|}{\omega_0}\sqrt{Q_1^{FRT}Q_2^{FRT}}$$

Q_n^{FRT} is contribution of FE-FRT to system Q_L in state n

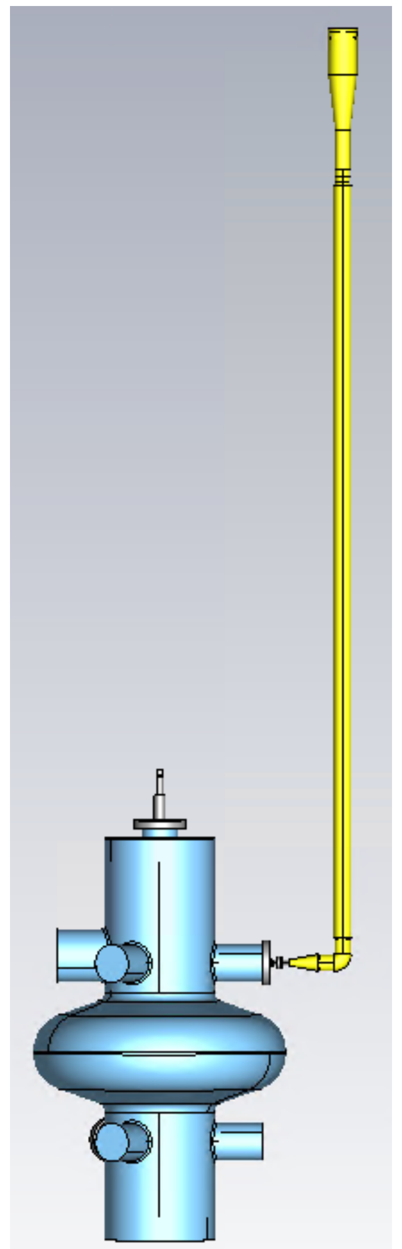
$$\mathrm{FoM} = \frac{2|\sin\frac{\Delta\theta_{12}}{2}|}{\sqrt{(1-|\Gamma_1|^2)(1-|\Gamma_2|^2)}}$$

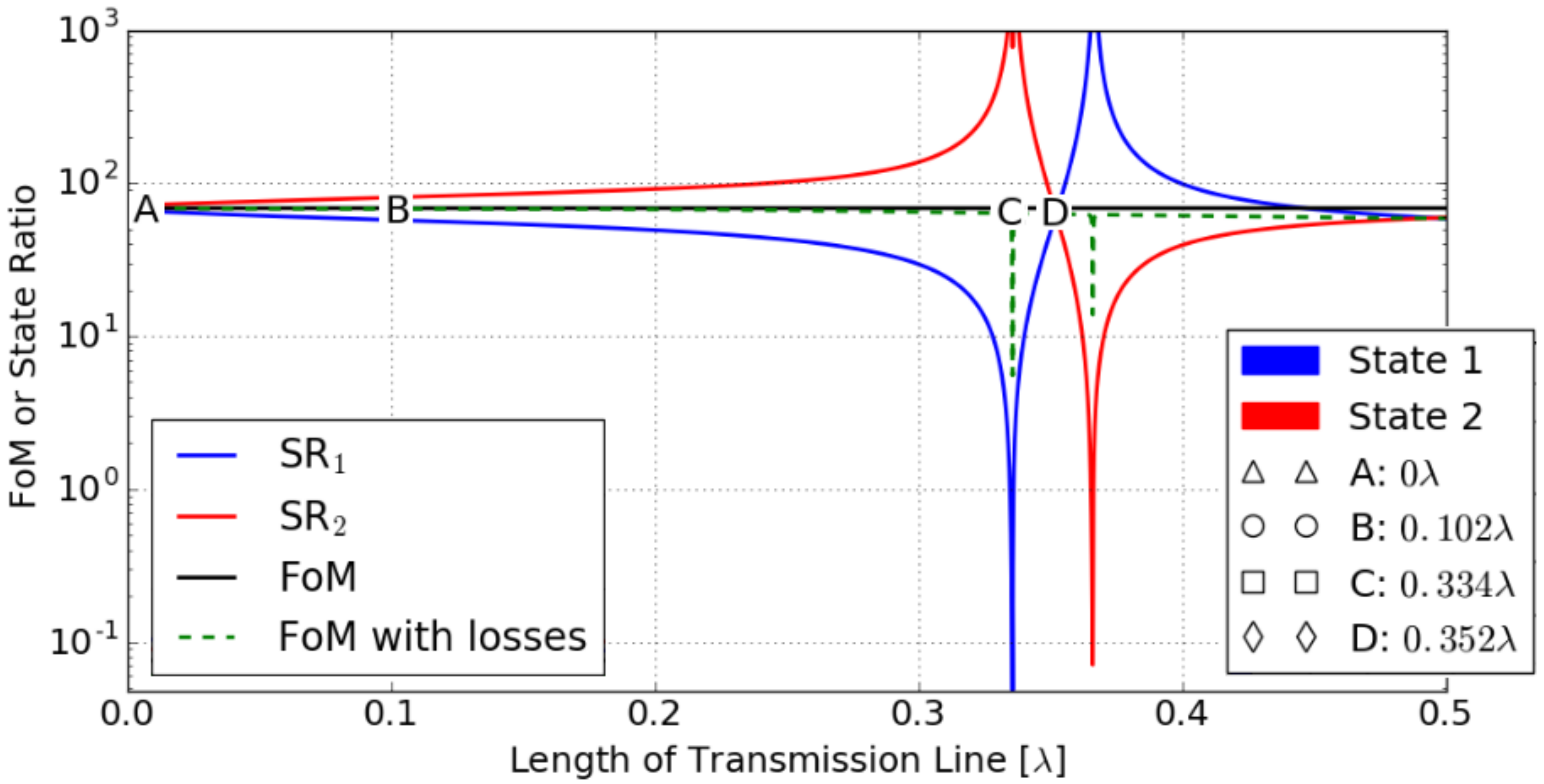
FoM in terms of S_{11} phase and amplitude of FE-FRT

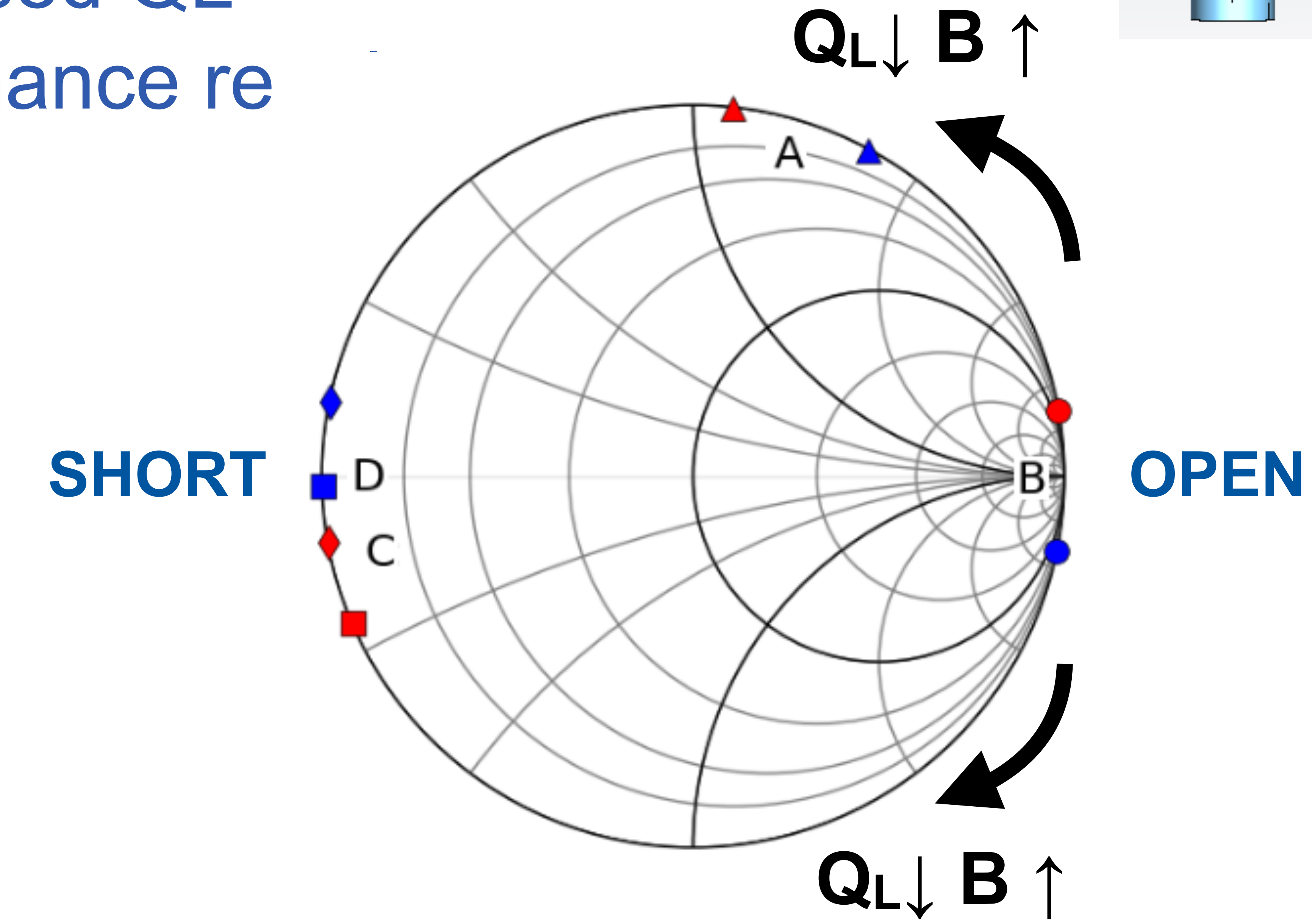
FE-FRT Concept

- **FE-FRT: embed ferro-electric in shorted transmission line**
  - FoM is independent of FE-FRT line length
  - Operating ω defined by line length,
    - but $\Delta\omega_{12}$ (~ ΔB) is set by FE-FRT antenna coupling
  - Line length defines operational configuration an FRT
    - Rotates impedance around the Smith Chart

- **Moving away from OPEN:**
  - more reactive power, increased shift from ω0, decreased QL
    - => Optimisation of line length matched to performance re







Setup of Microphonics test cryostat & hardware