# Ferro-Electric Fast Reactive Tuners (FRTs)

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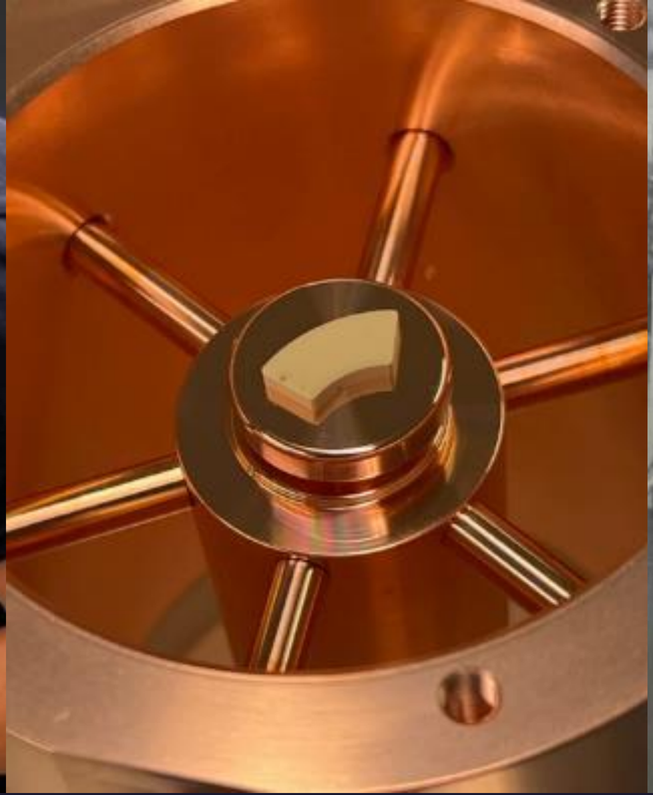
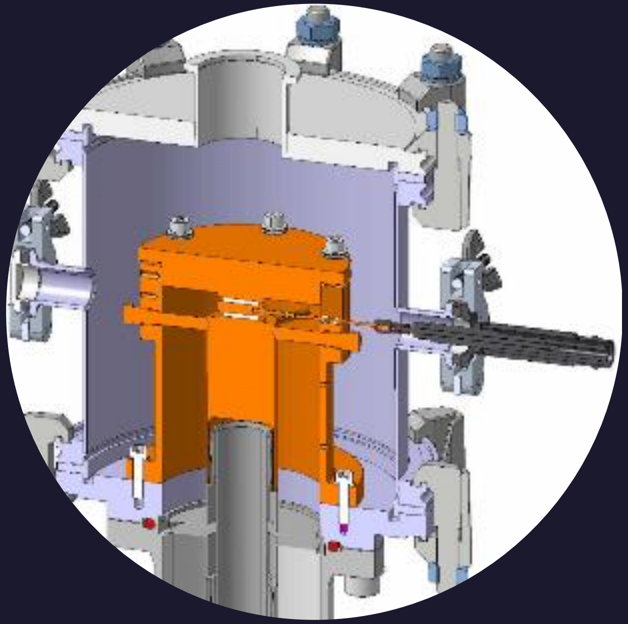


# Introduction

- FRTs are a new type of extremely fast non-mechanical tuner
- Microphonics suppression with a prototype FRT already demonstrated
- CERN is developing and testing improved FRT designs
- Research focus at CERN is now "transient detuning" for HL-LHC
  - Compensation of transient beam loading using an FRT

# Agenda

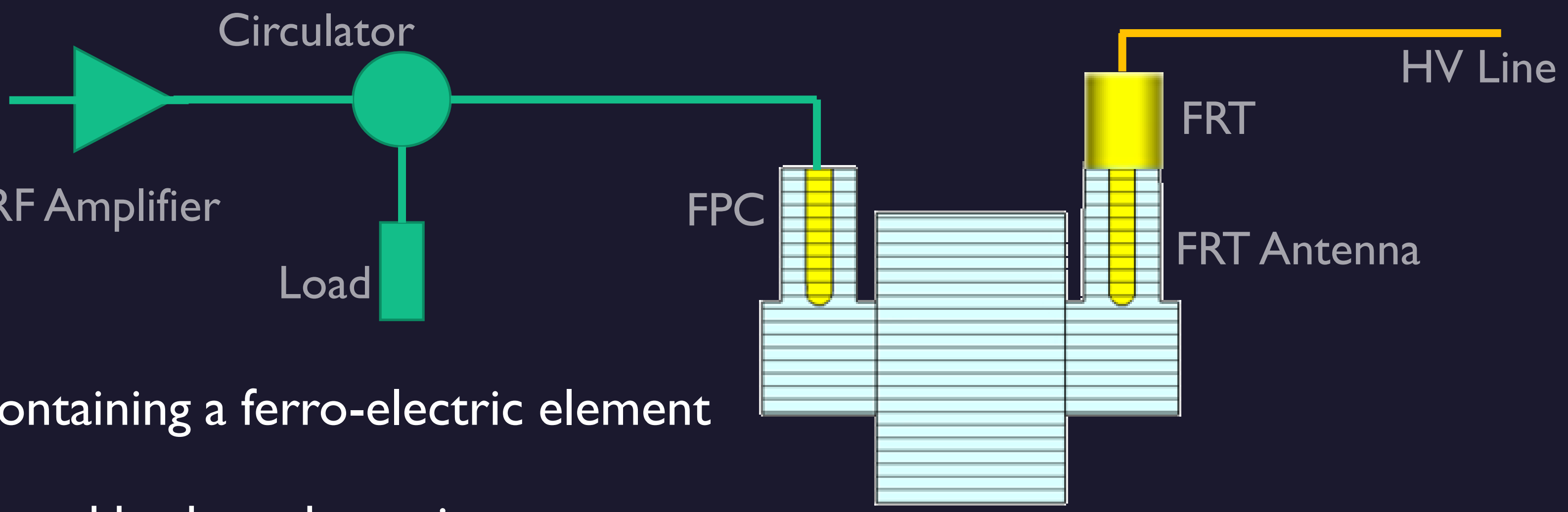
- FRTs
- Microphonics Suppression
- Transient Detuning
- Transient Detuning Project
- Other use cases and projects
- Summary



# FRTs

Introduction to Ferro-Electric Fast Reactive Tuners

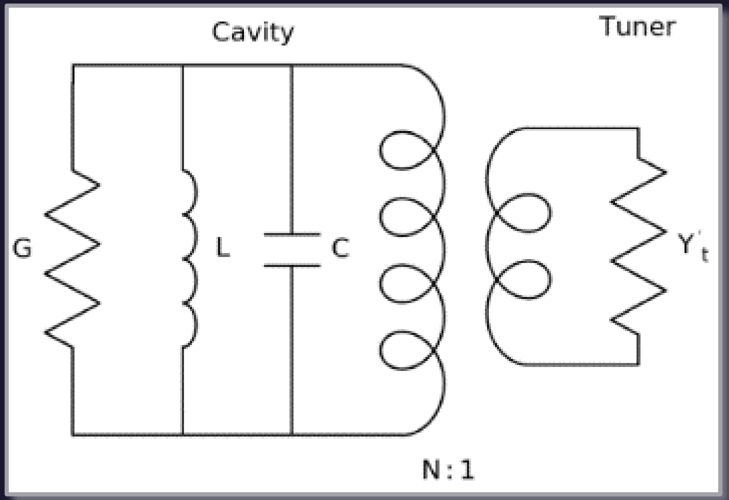
# FRT Concept




- An FRT is a shorted co-axial structure containing a ferro-electric element
- RF power flows into the FRT and is reflected back to the cavity
- Voltage applied to the ferro-electric changes its permittivity
- Permittivity change → Phase change of the reflected power → Cavity frequency change
- Usually, the FRT would require its own port, although other arrangements have been proposed
- Operates outside cryomodule at room temperature
- Tunes cavity without mechanical deformation
- Tuning speed measured at less than 600ns, limited by HV circuit

# Equivalent Circuit Theory

- The admittance of the FRT is:
  - $Y_t' = G_t' + iB_t'$
- The change in angular frequency between high voltage states n and m is:
  - $\Delta\omega_{mn} = \frac{-\omega_0 {}^{R}\!/_{Q} \Delta B_{tmn}'}{2N^2}$
- The increase in the system bandwidth due to the FRT in high voltage state n is:
  - $\mathrm{BW}_n = \frac{\omega_0 {}^{R}\!/_{Q} G_{tn}'}{N^2}$
- Here the R-over-Q is defined as:
  - ${}^{R}\!/_{Q} = \sqrt{{}^{L}\!/_{C}}$
- The angular frequency of the cavity without FRT is:
  - $\omega_0 = \frac{1}{\sqrt{LC}}$



*Equivalent circuit of FRT connected to cavity*

| Notation | Meaning |
|---|---|
| $G_t'$ | Conductance of FRT |
| $B_t'$ | Susceptance of FRT |
| $N$ | Coupler turn ratio |
| $V_c$ | Cavity voltage |
| $U_c$ | Cavity stored energy |

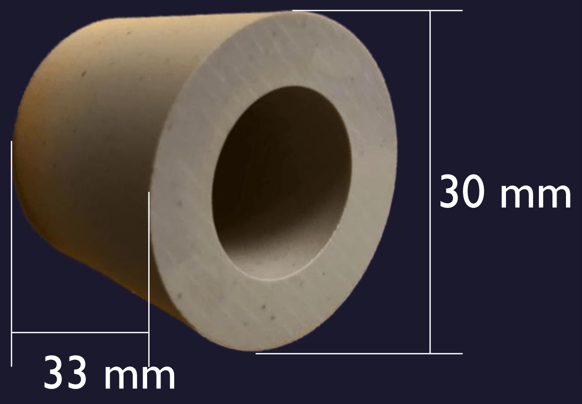
*Symbol definitions*

# Figure of Merit and Ferro-Electric (FE) Material

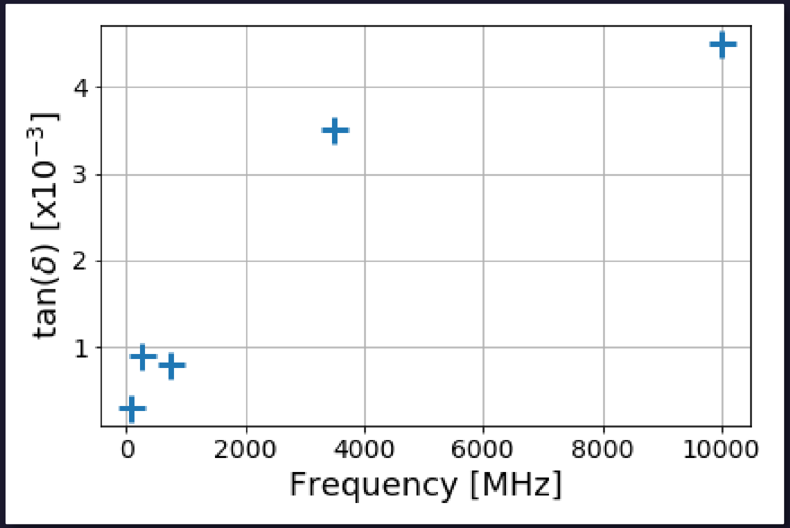
- FoM allows:
  - Comparison of FE-FRT designs
  - Estimation of benefit e.g. power reduction
- FoM is ~tuning range divided by increase in bandwidth
  - $$\text{FoM} = \frac{|\Delta\omega_{12}|}{\sqrt{\text{BW}_1\text{BW}_2}}$$
  - Subscripts 1 and 2 refer to the two extreme high voltage 'end' states
- Material FoM is FoM of a FE capacitor with only dielectric losses
  - $$\text{FoM}_{\text{Mat}} = \frac{\ln\frac{\epsilon_1}{\epsilon_2}}{2\tan\delta}$$
  - Material FoM is a theoretical upper limit of FoM
  - Would allow comparison of different ferro-electric materials
- FE is $BaTiO_3$-$SrTiO_3$ with Mg based additives
  - Loss tangent roughly ~ frequency

| Parameter | Value |
|---|---|
| Relative Permittivity | 160 |
| Tunability | 1.4 |
| Tuning Field | 8 Vμm$^{-1}$ |
| Breakdown Strength | 20 Vμm$^{-1}$ |
| Thermal Conductivity | 7.02 Wm$^{-1}$K$^{-1}$ |

*FE material parameters*



*A BST(M) Ferroelectric Sample*



*Loss tangent vs RF frequency (Courtesy Euclid TechLabs)*

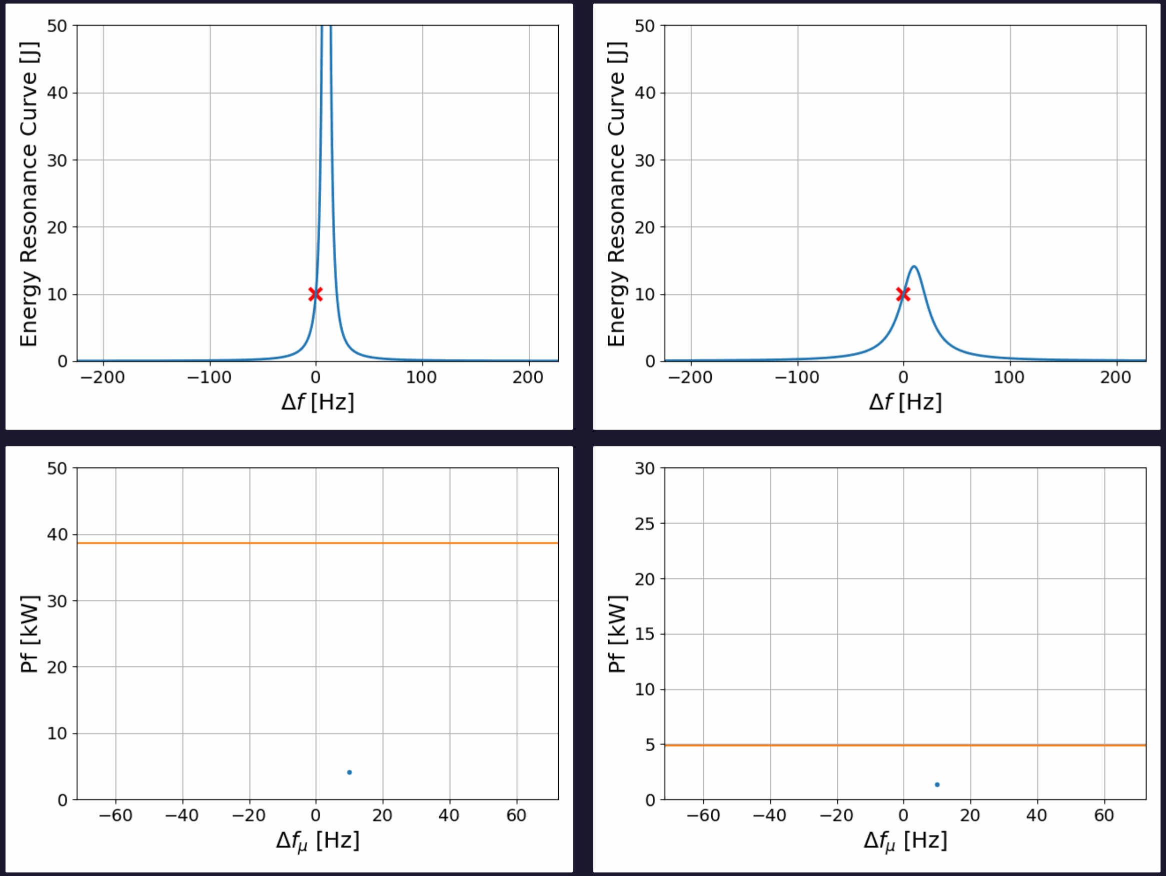
# Microphonics Suppression with FRT

Benefits of suppressing microphonics with an FRT

# Use cases: microphonics suppression

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

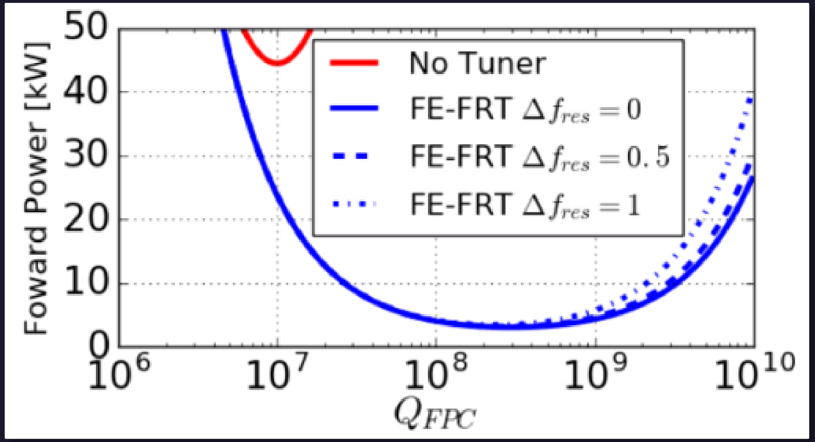
- For low beam loading machines RF power is dominated by microphonics
- The effect of microphonics can be reduced passively or actively
  - Stiffening of cavity
  - Isolation of noise sources
  - Active feedback e.g. piezo tuners
- Residual microphonics require over-coupled FPC
- Typically, RF power required is still many times larger than for critical coupling case



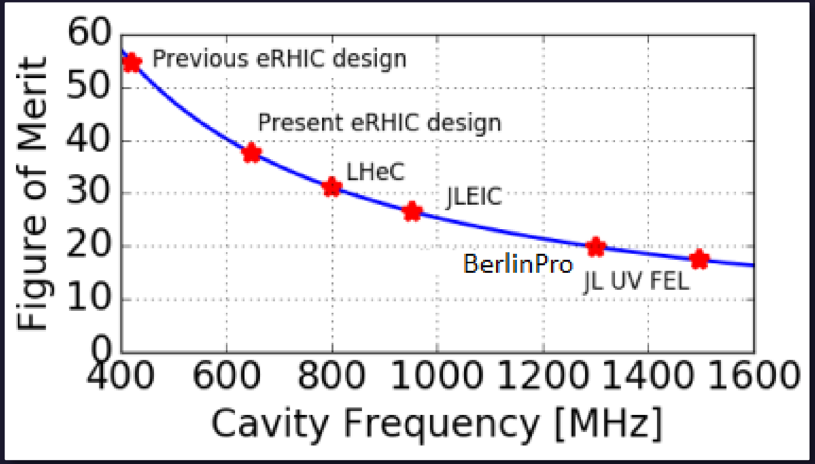

Decreasing $Q_L$

# Use cases: microphonics suppression

- FRTs are an excellent tool for microphonics suppression
  - High Tuning speed
    - ~600ns measured limited by external HV circuit
  - No excitation of mechanical modes
  - Simple transfer function/negligible phase delay at frequencies of interest
- Peak and average RF power reduced by $\frac{\text{FoM}}{2}$ and $\frac{\text{FoM}}{4}$ respectively
  - Increased dielectric and conductor losses at higher RF frequencies reduce effectiveness
- FRTs can be combined with other suppression technologies
  - E.g. piezo tuners
- PERLE power savings:  732 kW
- LHeC power savings:   22 MW!!
  - ~150GWh per year, **~50,000 tons of $C0_2$**



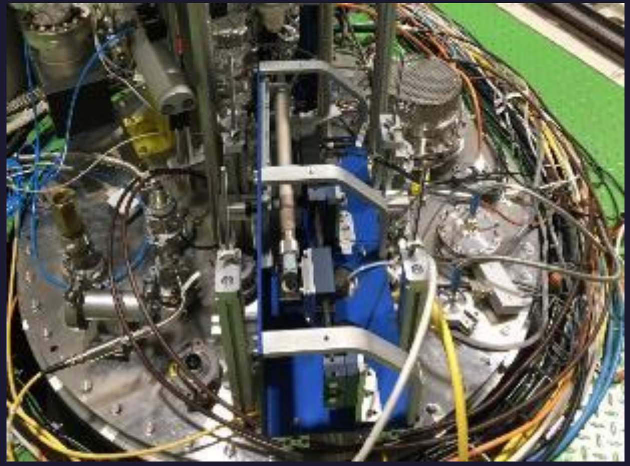

*Case study: RF power for PERLE vs QL with and without FRT*




*Estimated FRT FoM vs RF frequency*

# Microphonics suppression results

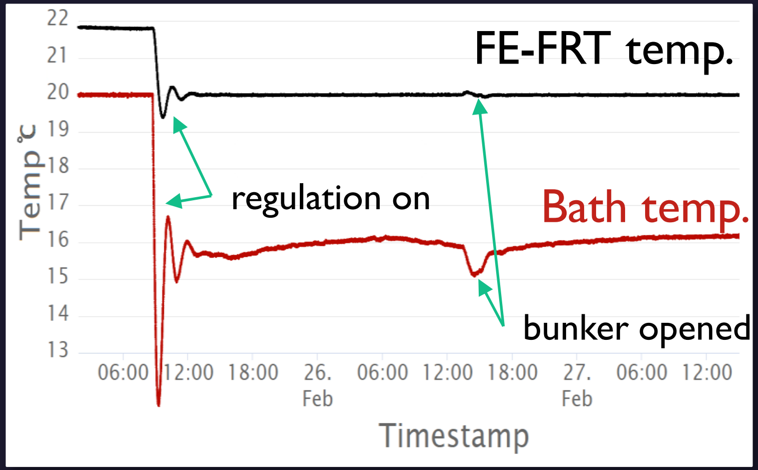
- Lower order Mode of UK4R crab cavity at 374MHz
  - Very stiff → very low levels of microphonics → used vibration generator
- Euclid designed prototype FRT
- No slow tuner → operated in SEL mode
- Chiller, phase shifter, vibration generator
- Deliberately simple purely integral feedback used
  - More performant solutions surely possible



*Phase shifter on top plate*

*UK4R on insert*

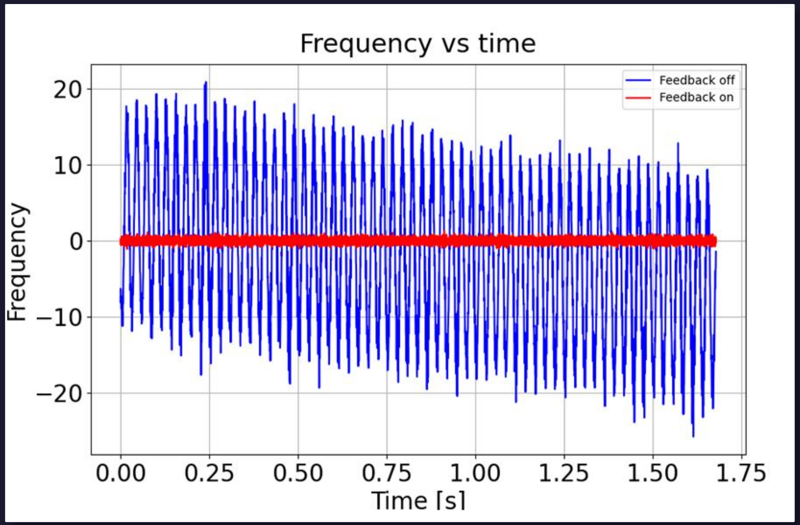
*Euclid FE-FRT prototype*

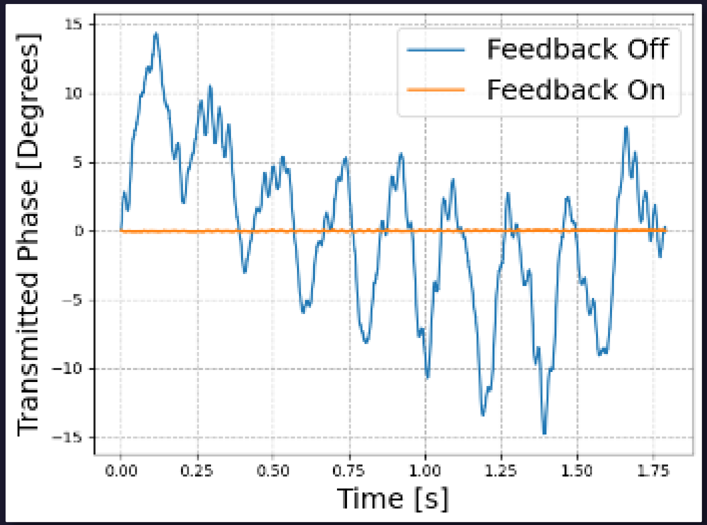


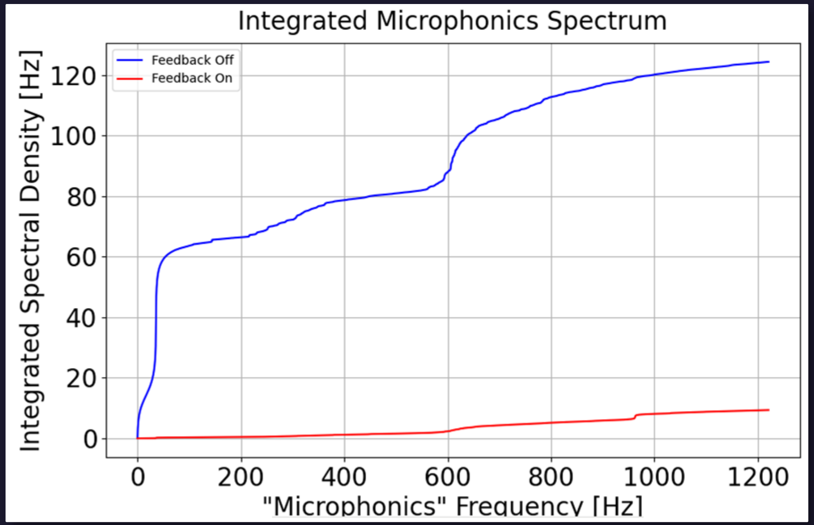

*Temperature regulation with chiller*

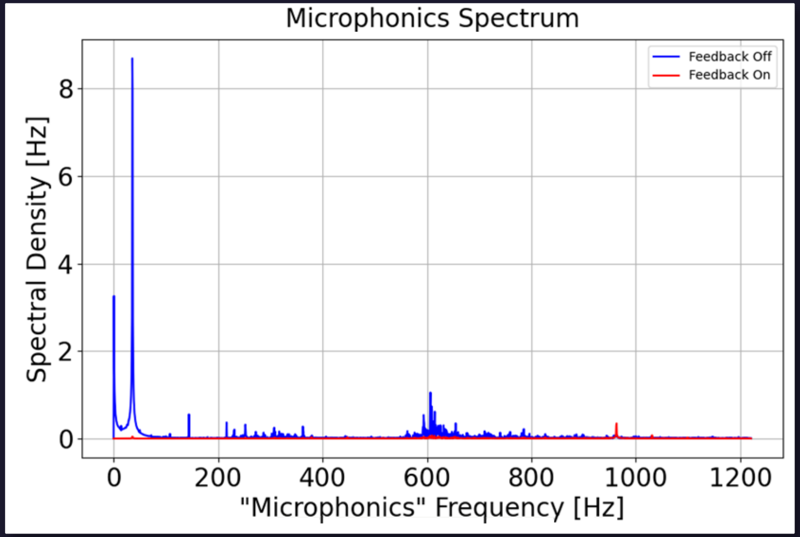

*Vibration generator*

# Microphonics suppression results

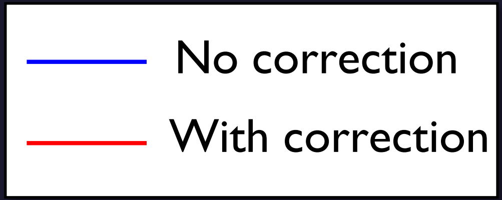



- Test of prototype FRT with UK4R cavity
  - UK4R very stiff, used vibration generator to create microphonics
- Microphonics ~completely eliminated
  - ~20x reduction in integrated microphonics spectrum up to 1kHz
  - Order of magnitude better than other technologies
- Deliberately simple purely integral feedback algorithm



# Transient Detuning

Overview of Transient Detuning Concept

# Use cases: transient detuning

RF power required for cavity with beam

$$P_{RF} = \frac{R/Q\, Q_e}{2}\left(\left[\frac{V_c'}{\omega_0 R/Q} + \frac{V_c}{2 R/Q\, Q_L} - I_b \sin \Delta\phi_{bc}\right]^2 + \left[\frac{V_c}{\omega_0 R/Q}(\phi_c' - \Delta\omega_D) - I_b \cos \Delta\phi_{bc}\right]^2\right)$$

Can change
Fixed

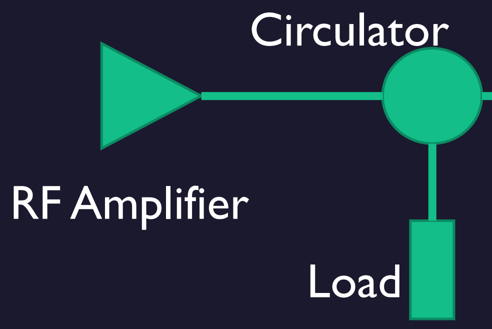
Simplifying assumptions
$\Delta\phi_{bc} = 0$
$V_c' = 0$

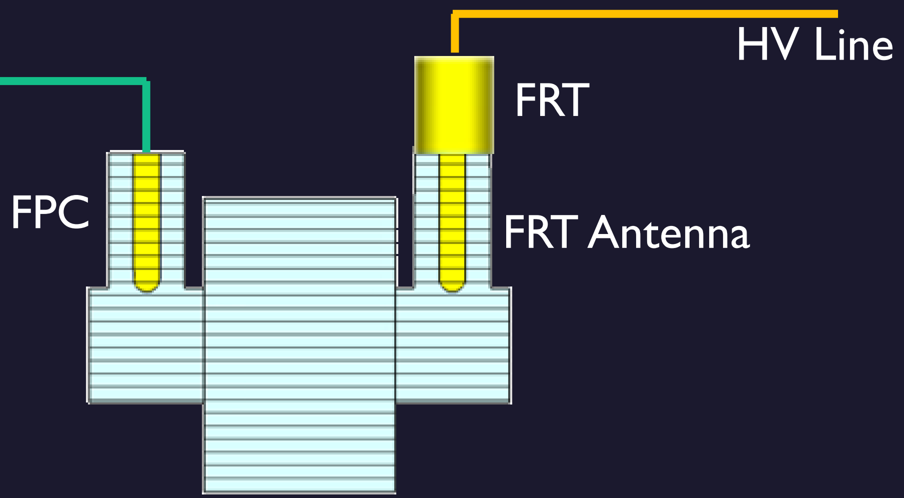
- $I_b$ will change so either:
  - $P_{RF}$ or $\phi_c$ must change
- Normally, choice between:
  - Increased RF power
  - Cavity phase errors
- Recently we proposed a **new scheme "Transient detuning"**
- Transient detuning uses FE-FRT to change $\Delta\omega_D$
  - Reduced average RF power (by up to FoM/2)
  - Increased phase stability
  - Fixed RF bucket position → ideal for injection
- In the future, we hope to apply this to HL-LHC, project underway!

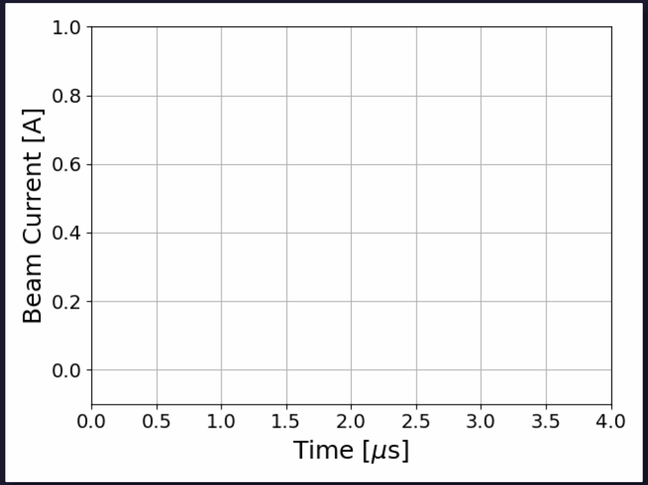
| Notation | Meaning |
|---|---|
| $P_{RF}$ | RF power |
| $\phi_c'$ | Cavity phase derivative |
| $\Delta\omega_D$ | Detuning |
| $I_b$ | Beam Current |

# Use cases: transient detuning

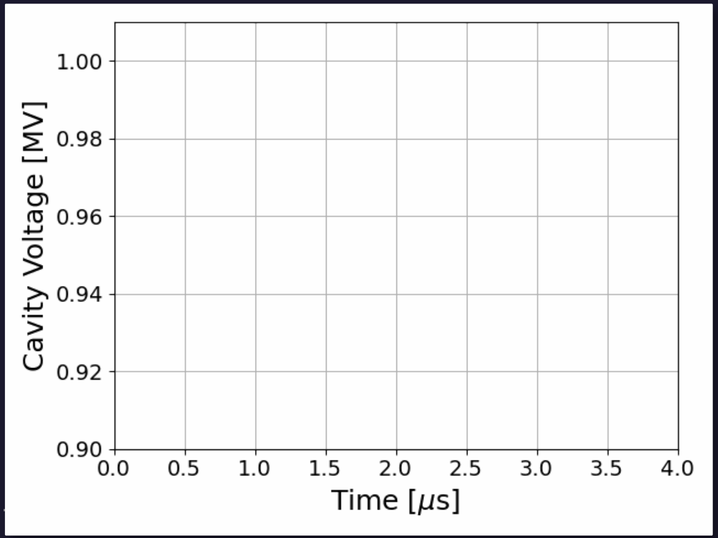
Beam + fixed detuning

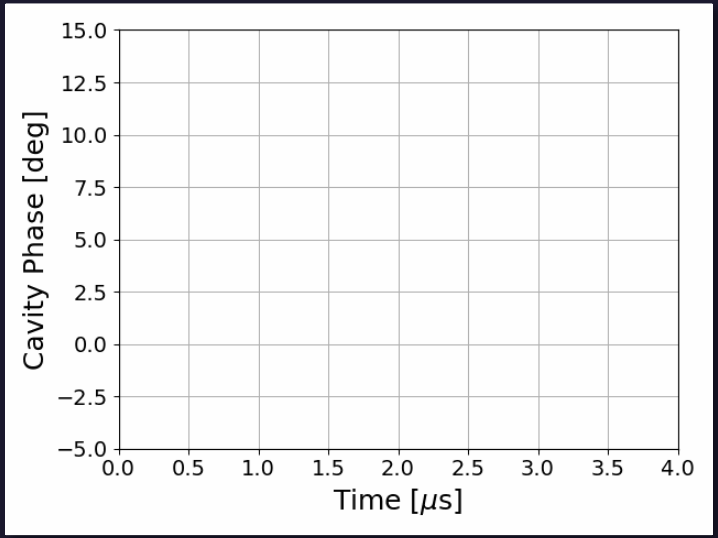


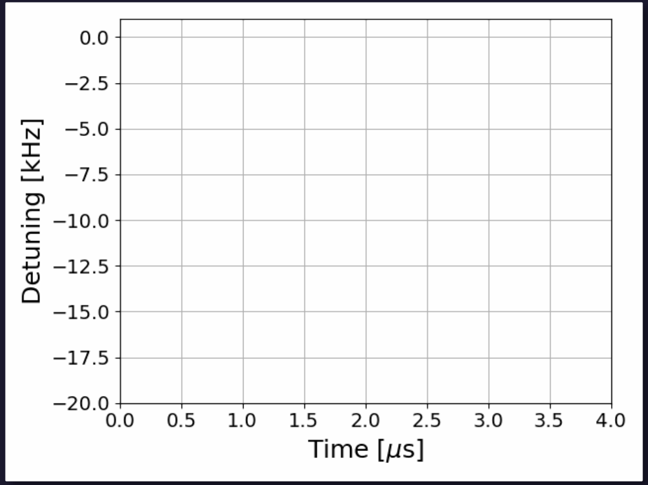




$$P_{RF} = A + [B(\phi_c' - \Delta\omega_D) - CI_b]^2$$

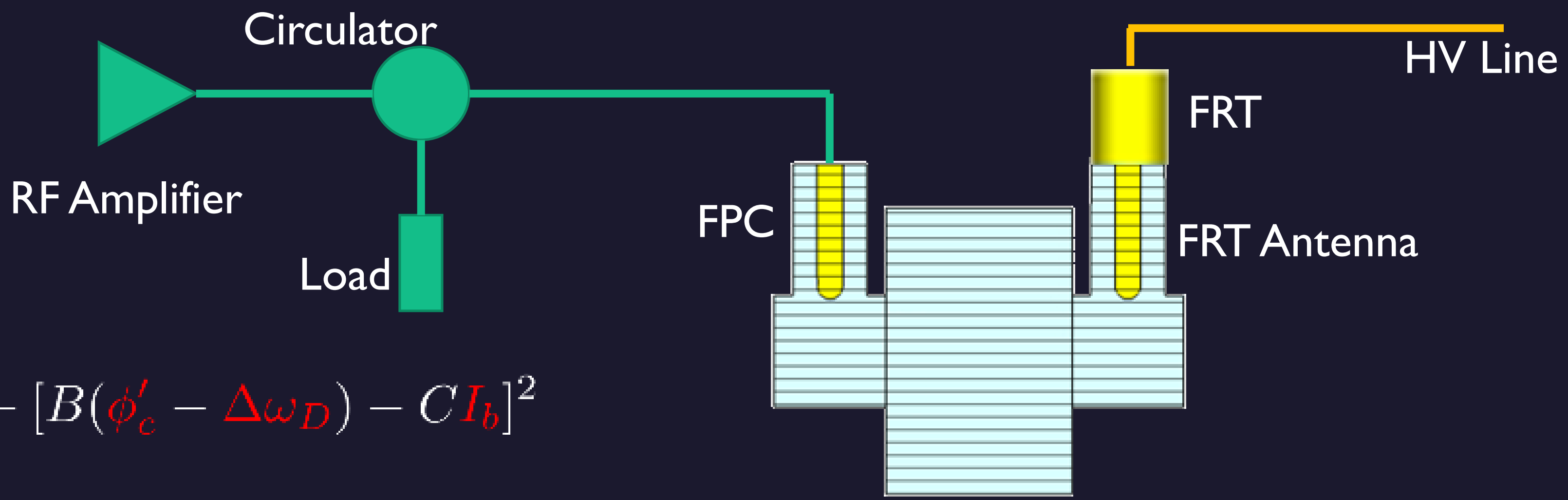


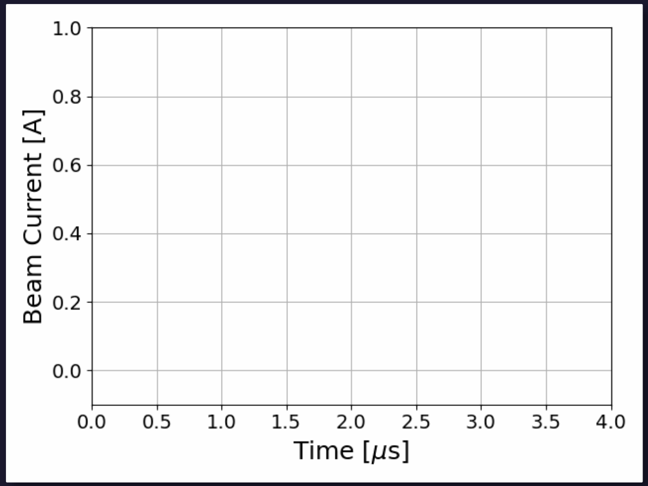



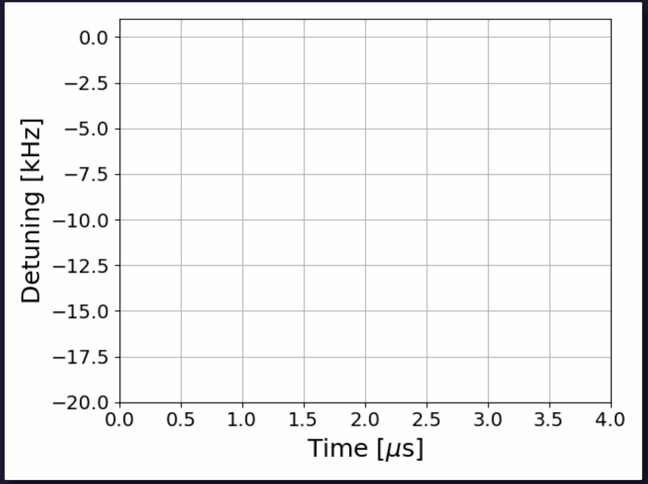
# Use cases: transient detuning

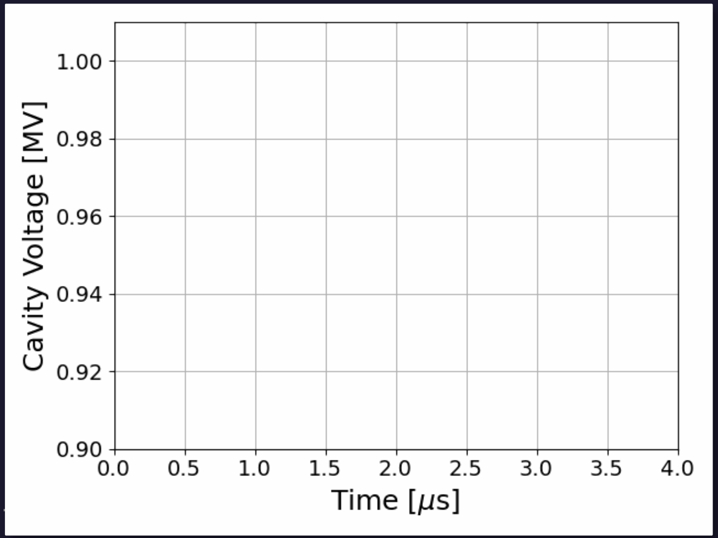
Beam + transient detuning

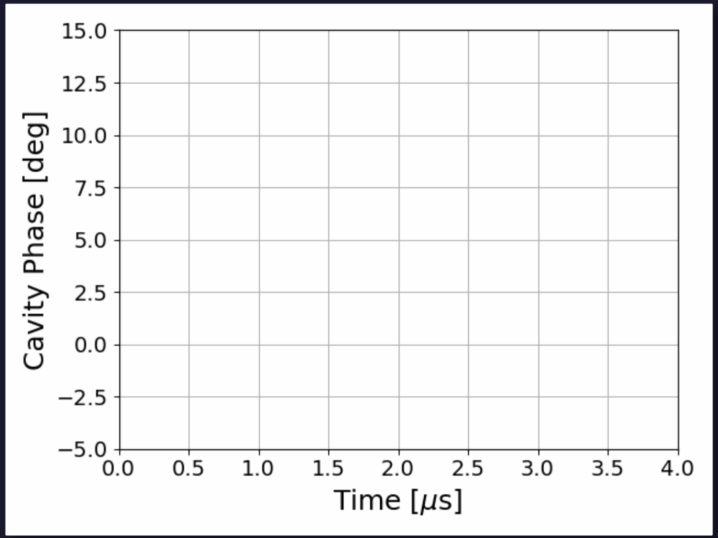



$$P_{RF} = A + [B(\phi_c' - \Delta\omega_D) - CI_b]^2$$



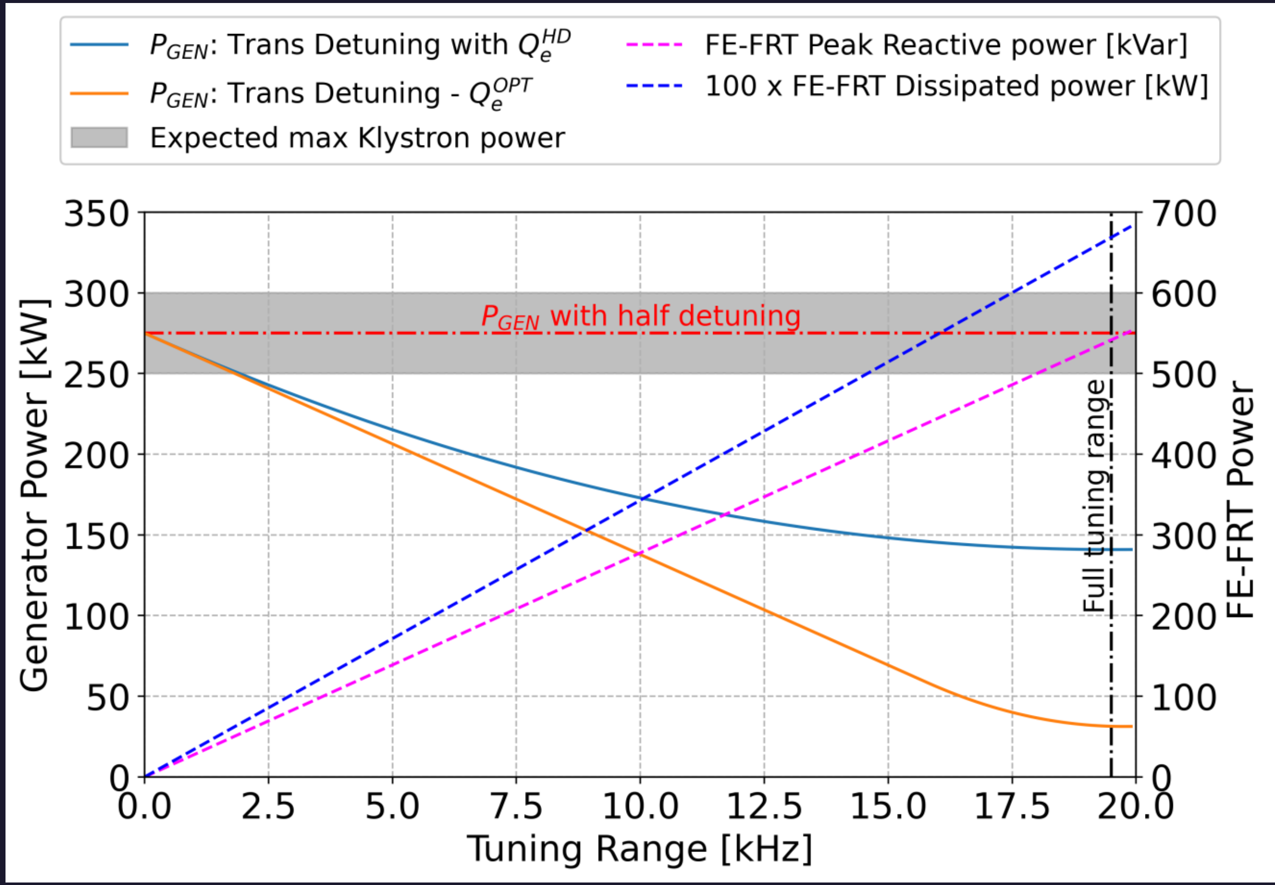



# Transient Detuning Project

Overview of transient detuning research at CERN

# Transient Detuning Project: Overview

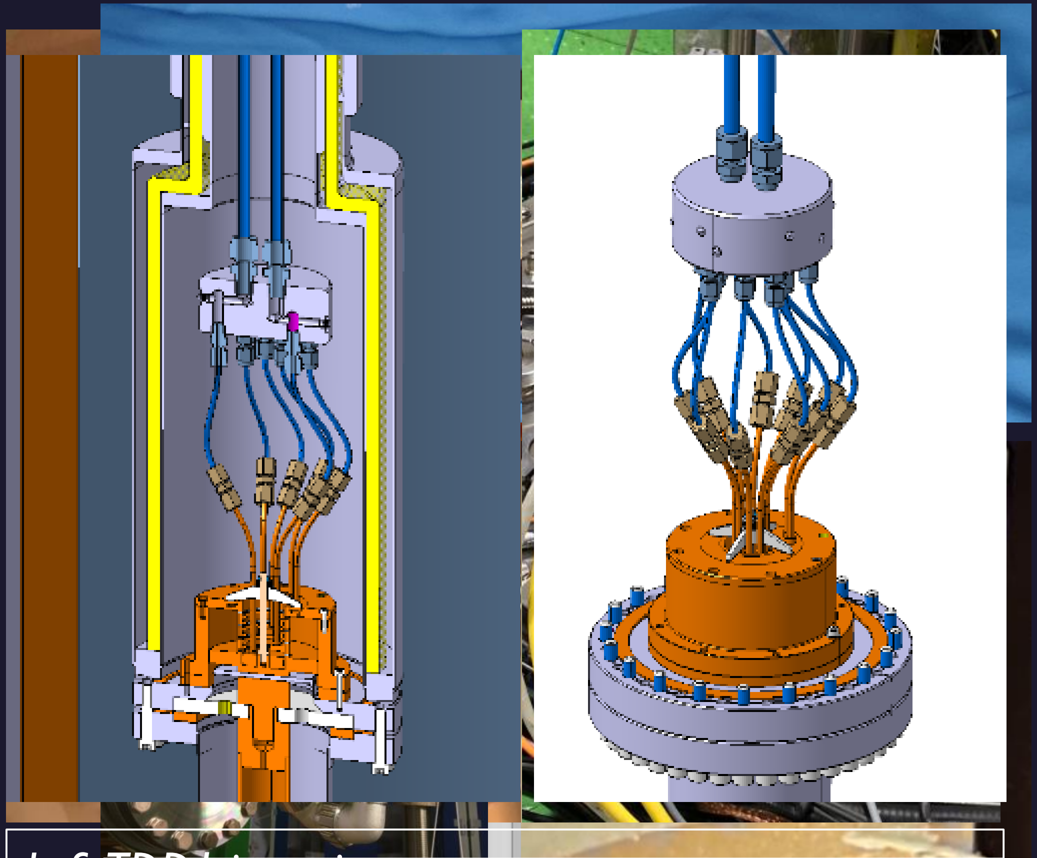
- Likely HL-LHC will not have sufficient RF power to capture full beam current at injection
  - Install high efficiency Klystrons
  - Add new cryomodule
  - Transient detuning with FE-FRT
- Perfect compensation of beam loading with FRT would reduce RF power requirements 10-fold
  - If Qe of FPC is increased by optimal amount
  - Would require FE-FRT to handle high reactive power ~500kVar
  - Partial compensation can also give significant reductions
- If proven feasible transient detuning is elegant and cost-effective solution
  - Electricity saving up to ~ 2GWh per year ~1M€ (very rough estimate from French electricity cost on 28.09.22)
- Aim: demonstrate an FE-FRT could compensate transient beam loading for HL-LHC at injection




*Estimated power reduction vs achievable tuning range with transient detuning*

# Transient Detuning Demonstrators

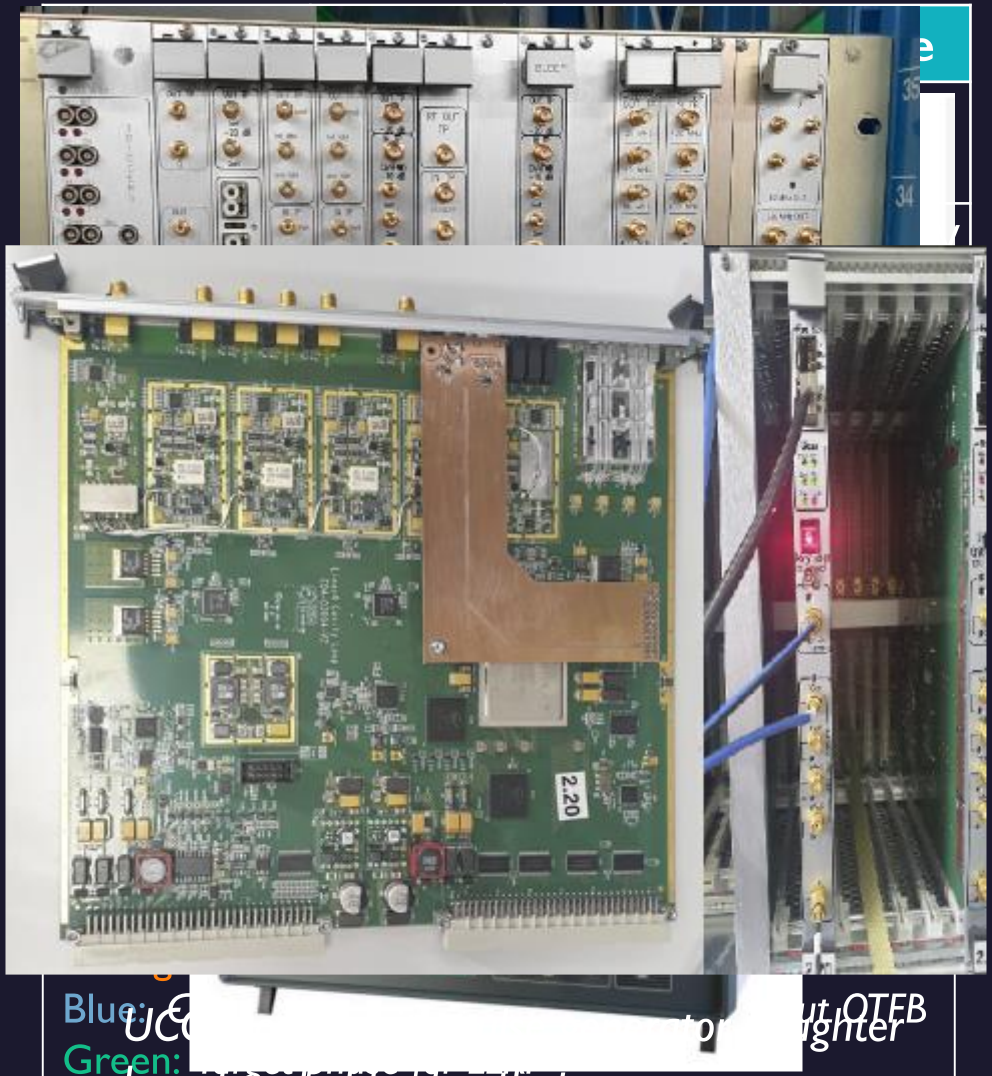
- Brazeless (compression fit) thin wafers of ferro-electric in vacuum
  - Aim: reduced losses + higher biasing electric fields
  - + greater change in permittivity at reduced voltage
- First prototype TDD0 (Transient Detuning Demonstrator) built and tested on cold LHC cavity
  - Test cut short due to cavity vacuum leak
- 1.3kHz tuning shift observed with 500V
  - TDD0 designed for 10-16kV, voltage limited due to vacuum leak on TDD0
- Lessons learned:
  - Very sensitive to air gap/compression force in FerroElectrtic stack
  - Care must be taken to apply compression evenly
  - Rigid line from top plate causes to much mechanical stress on vacuum feedthroughs
    - Move FRT inside cryostat for next test → anti-cryostat
- Parts of TDD1 already in workshop
  - Mechanical design ~1 week away from being finished
  - High performance, high power (100s kW) design
  - 4 doughnut shaped wafers with cooling lines, FoM ~70-80



*Right: Breakdown through ceramic near cracks?*

# Transient Detuning Project: Peripherals 1

- LHC LLRF System
  - LHC LLRF system is complex and will not be redesigned for HL-LHC
  - Transient detuning must work with existing LLRF system
  - LHC LLRF system replicated in cavity cold testing area
  - No One Turn Feedback Module in last test now installed, waiting to be tested
- BLEEP
  - Beam Loading Electronic Emulation Project
  - Testing with cryomodule with real beam not feasible in initial project timescale
  - BLEEP adds correct RF power and phase to input coupler to replicate beam pattern
- High Voltage Pulser for biasing FE ceramic
  - Prototype HVP capable of running ~10ms:
    - Procured, received, tested, broken, sent back, repaired, re-received
  - Final HVP design more challenging as would need to run continuously
- Pulse generator
  - Programmable pulsed optical output to drive high voltage pulser
  - Triggered with same signal as BLEEP
  - Implemented as daughter board of existing LLRF system "UCC"



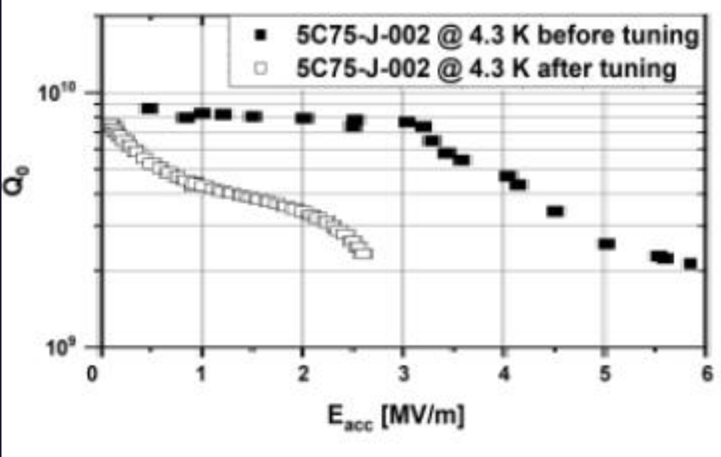
High Voltage Pulser for transient detuning tests.

# Other Use Cases and FRT Projects

Overview of current FRT Landscape

# Other Use Cases

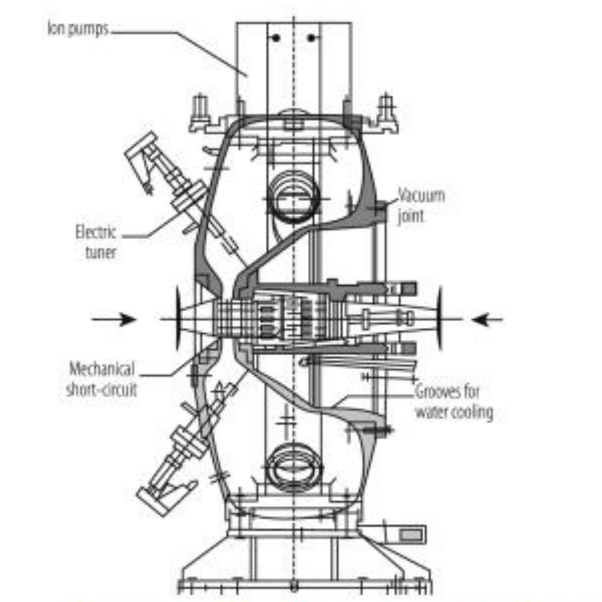
## Nb$_3$Sn Cavities




G. Eremeev et al., "RF Performance Sensitivity to Tuning of Nb$_3$Sn Coated CEBAF Cavities," in SRF2019, Dresden,2019.

- Nb$_3$Sn could double or quadruple carnot efficiency
  - Would reduce required cooling power by factor 2-4
- Nb$_3$Sn performance degraded with mechanical tuning
- There may be a material science solution
- FE-FRTs can provide an alternate solution

## CERN PS 80MHz cavities




E. Jensen "RF cavities" in "Accelerator Engineering and Technology: Accelerator Technology"

- FE-FRTs could provide fast 230kHz frequency switching
- This would allow parallel operation with both protons and ions

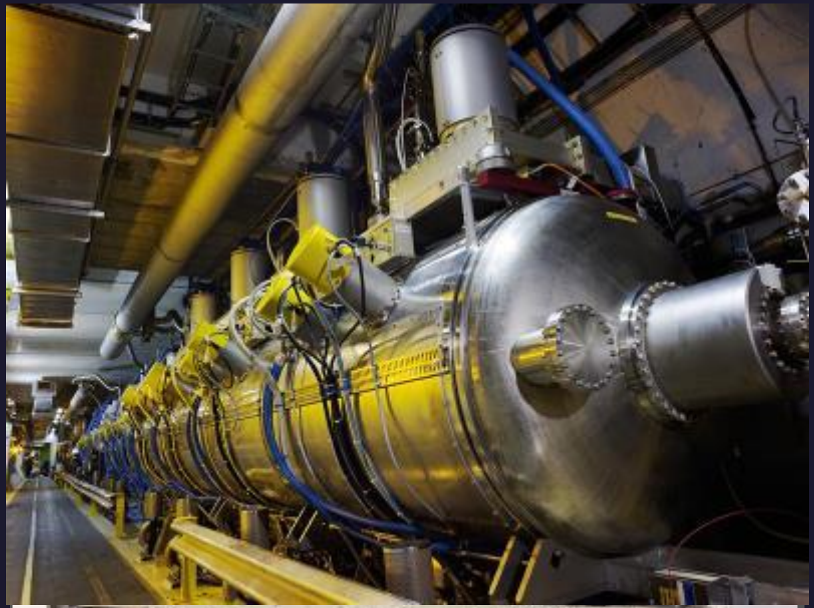
## EIC 197 MHz hadron crab cavities

Bob Rimmer *"SRF Challenges and R&D for the EIC"*

- Cavity should be off during ramp
- Large frequency sweep ~930kHz must not excite resonances.
- Elegant idea:
  - Use FE-FRT to jump cavity resonance over revolution lines during abort gaps.
  - Only 10-100 Hz Tuning required

# FRT projects

- HL-LHC
  - FRTs being seriously studied to reduce power at injection
- CEBAF
  - Aiming to reduce power due to microphonics with combined FRT/FPC port
  - Exciting but challenging
- bERLinPro
  - Plan to start dedicated R&D from Jan 24
- PERLE
  - Plan to integrate FRT in 2nd cryomodule to be installed in beam ~2030
- HIE-ISOLDE
  - Investigating FRTs for microphonics compensation
  - Ideal test case: low frequency, low beam loading, low power
  - Could be first FRT in working machine



LHC Cryomodule

HIE-ISOLDE Cavities

# Summary

# Summary

- FRTs are an exciting and rapidly growing field of research
- FRTs are perfect for Microphonics suppression for low beam loading machines
- FRTs can also solve transient detuning issues in high beam loading machines
- CERN research currently focused on transient detuning for HL-LHC
  - First full low power demonstration Q4 23
  - High power testing Q1/Q2 24
  - If successful next step → Install in cryomodule and test with beam in SPS
- Several other FRT projects are underway or starting around the world
- Aim to have an FRT in working accelerator in the near future

# Thank you for your attention

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