Ferro-Electric Fast Reactive Tuners (FRTs)

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Presented at:

PERLE Collaboration Meeting

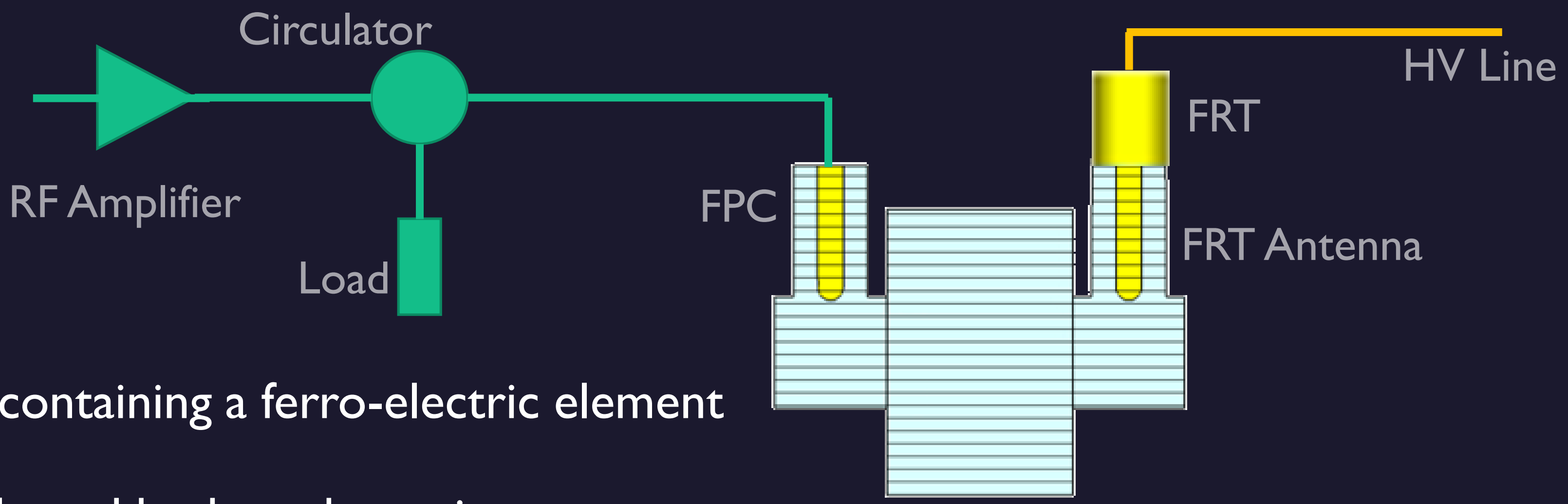
Introduction

- FRTs are a new type of extremely fast non-mechanical tuner
- CERN/Lancaster are 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
- Microphonics suppression with prototype FRT already demonstrated
  - PERLE is an ideal use case!

FRTs

Introduction to Ferro-Electric Fast Reactive Tuners

FRT Concept



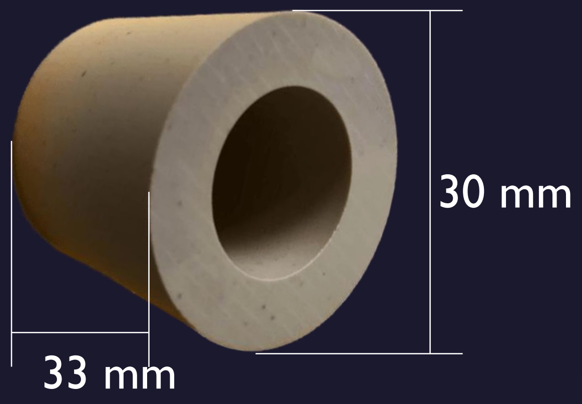
- An FRT is a shorted co-axial structure containing a ferro-electric element
- RF power flows into the FRT and is reflected back to the cavity
- Voltage applied to the ferro-electric changes its permittivity
- Permittivity change → Phase change of the reflected power → Cavity frequency change
- Usually, 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

Figure of Merit and Ferro-Electric (FE) Material

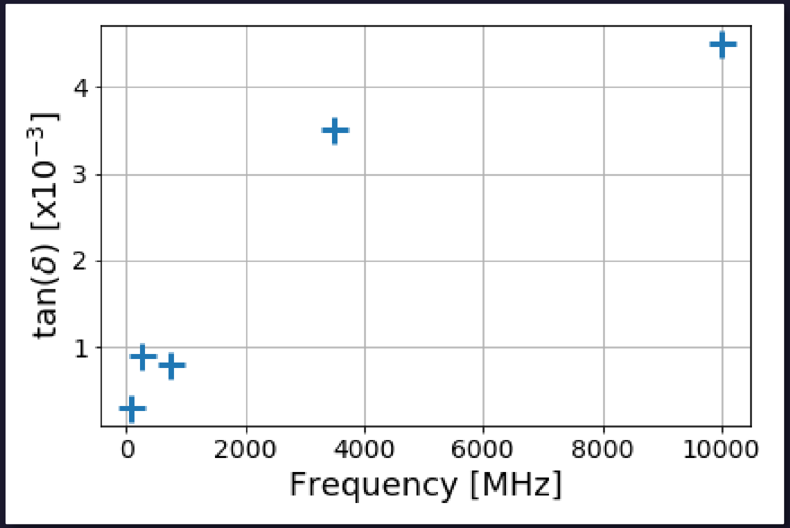
- FoM allows:
  - Comparison of FE-FRT designs
  - Estimation of benefit e.g. power reduction
- FoM is ~tuning range divided by increase in bandwidth
  - $\mathrm{FoM} = \frac{|\Delta\omega_{12}|}{\sqrt{\mathrm{BW}_1\mathrm{BW}_2}}$
  - Subscripts 1 and 2 refer to the two extreme high voltage 'end' states
- Material FoM is FoM of a FE capacitor with only dielectric losses
  - $\mathrm{FoM}_{\mathrm{Mat}} = \frac{\ln\frac{\epsilon_1}{\epsilon_2}}{2\tan\delta}$
  - 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}

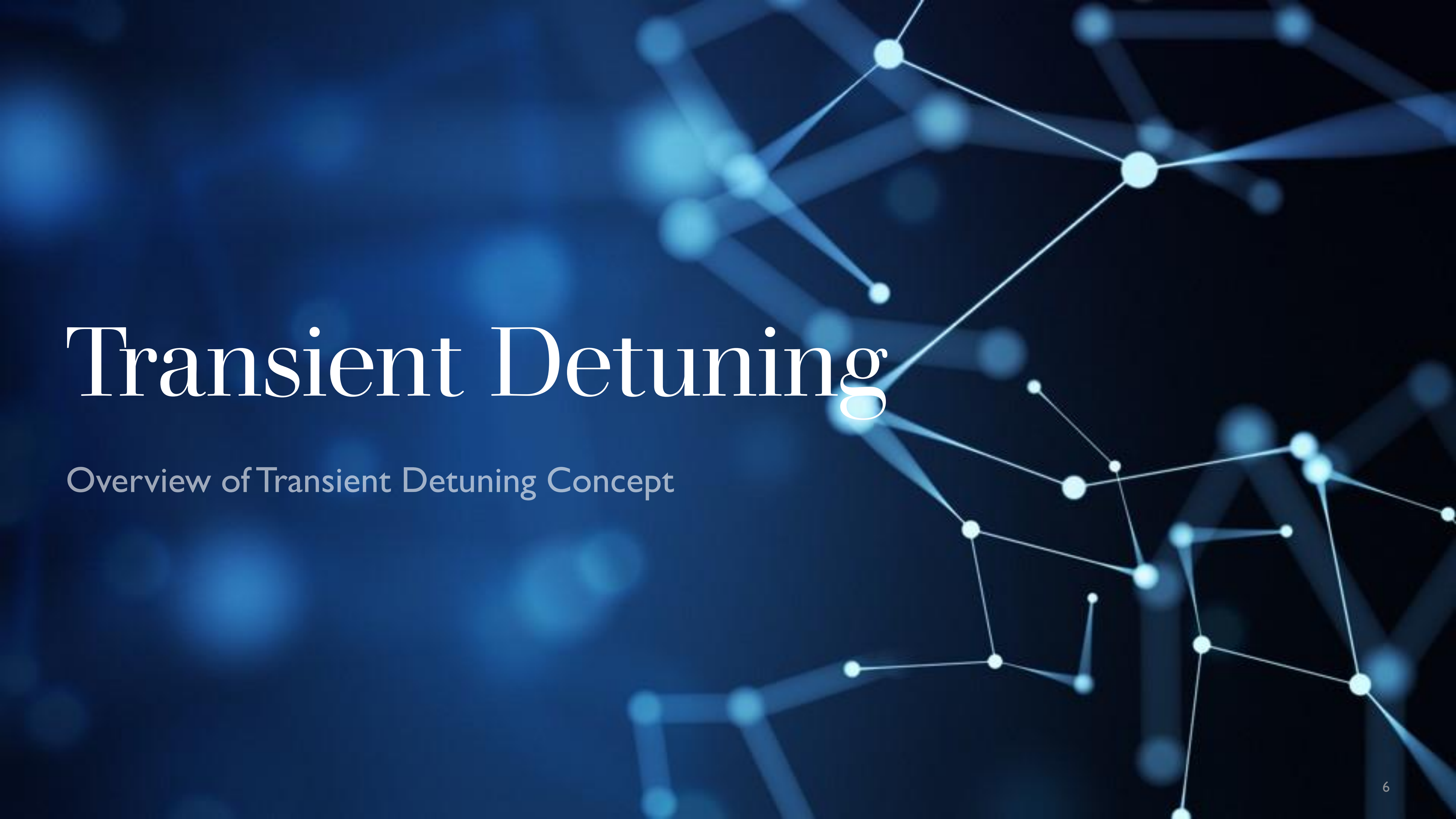
FE material parameters



A BST(M) Ferroelectric Sample



Loss tangent vs RF frequency (Courtesy Euclid TechLabs)



Transient Detuning

Overview of Transient Detuning Concept

Use cases: transient detuning

RF power required for cavity with beam

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

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

Can change
Fixed

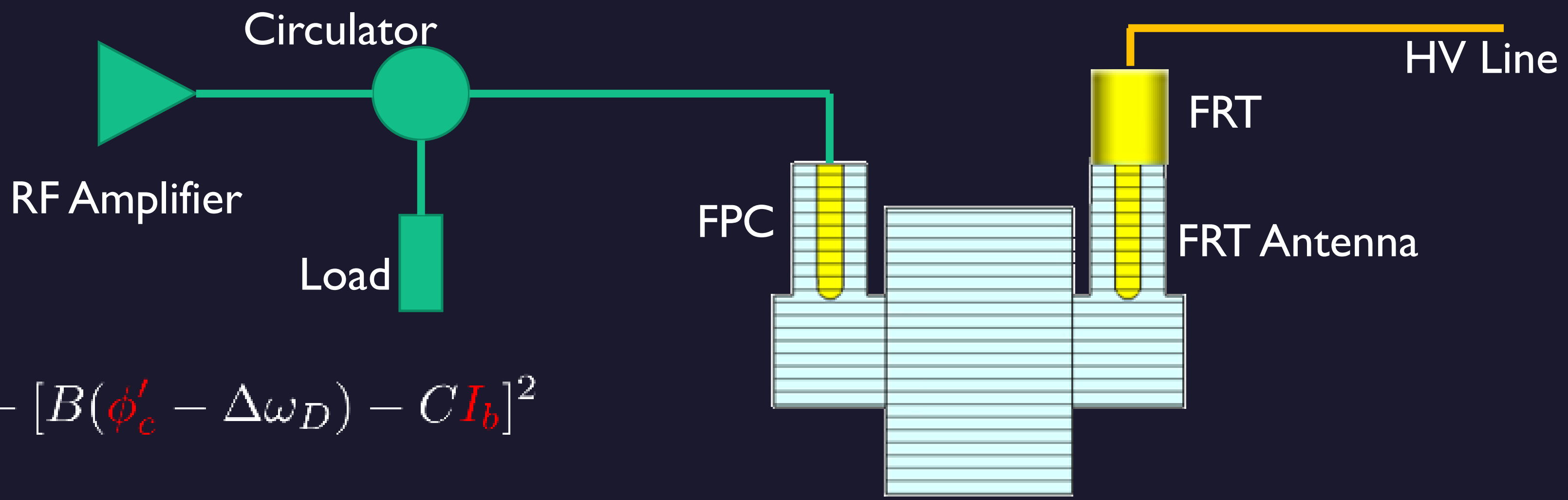
- I_b will change so either:
  - P_{RF} or ϕ_c must change
- Normally, choice between:
  - Increased RF power
  - Cavity phase errors
- Recently we proposed a **new scheme "Transient detuning"**
- Transient detuning uses FE-FRT to change $\Delta\omega_D$
  - Reduced average RF power (by up to FoM/2)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

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

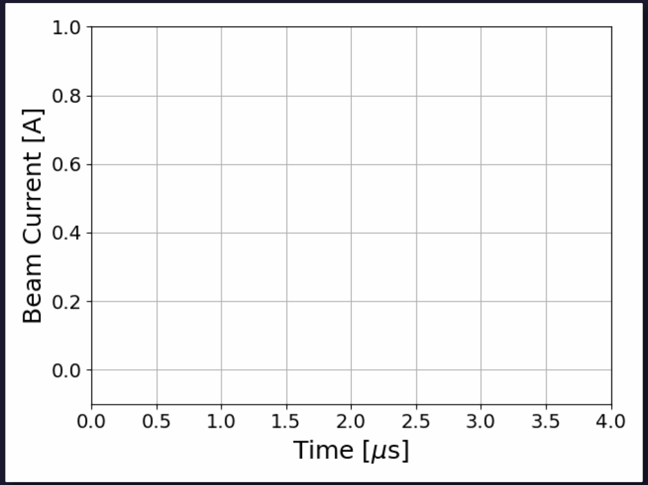
Notation	Meaning
P_{RF}	RF power
ϕ_c'	Cavity phase derivative
$\Delta\omega_D$	Detuning
I_b	Beam Current

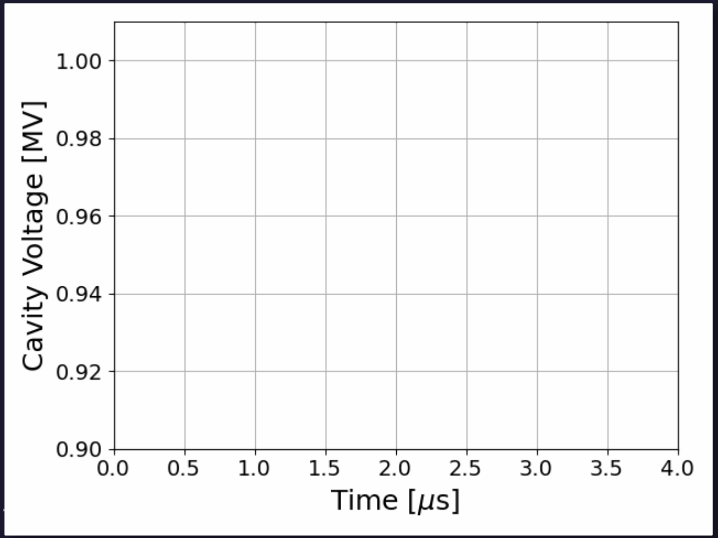
Use cases: transient detuning

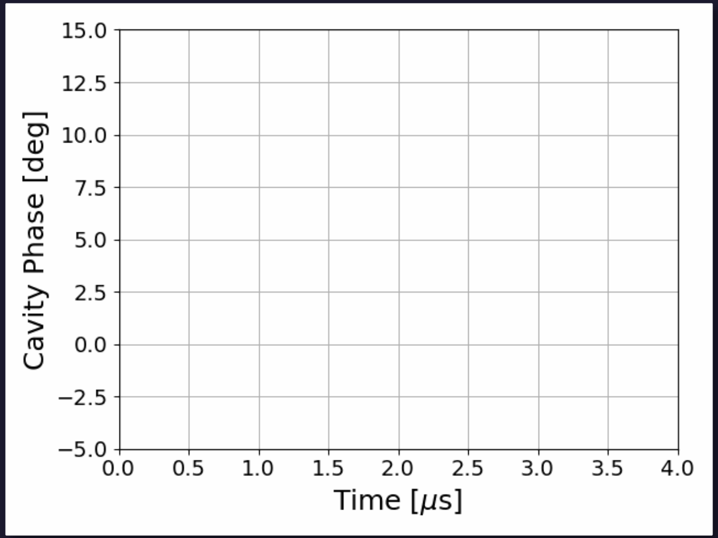
Beam + fixed detuning

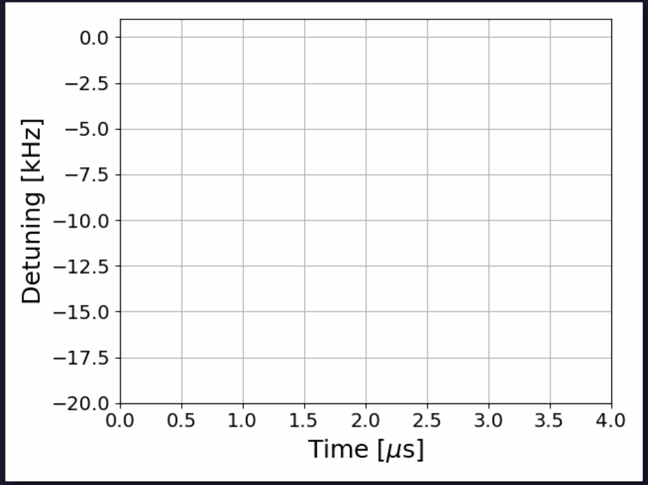


$$P_{RF} = A + [B(\phi_c' - \Delta\omega_D) - C I_b]^2$$



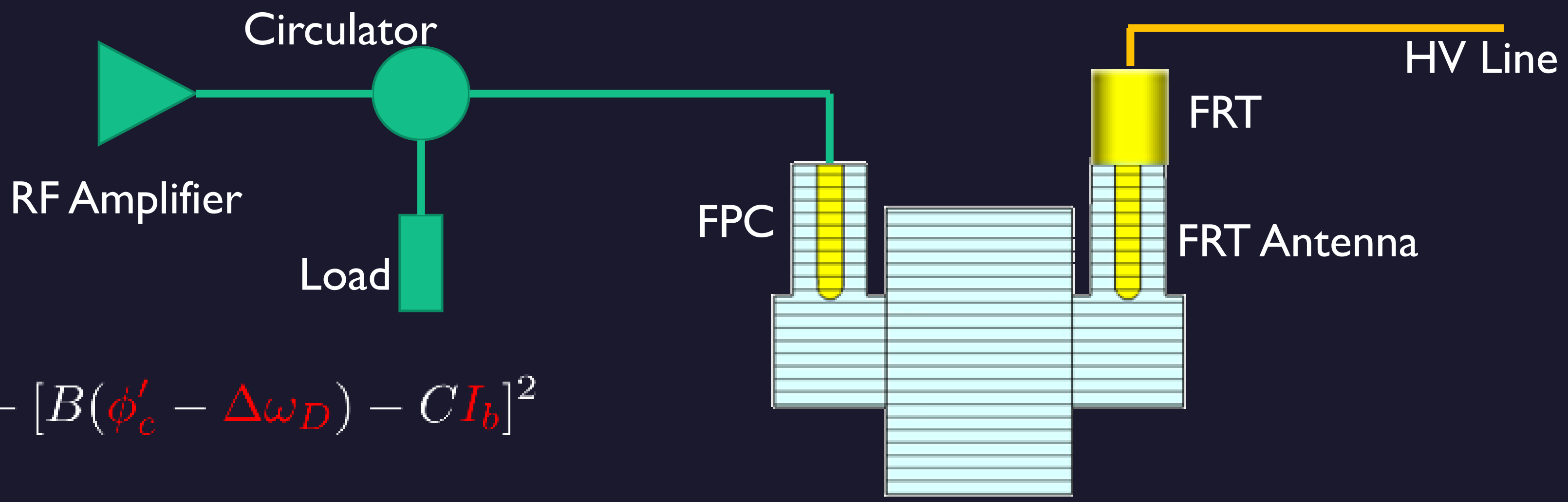




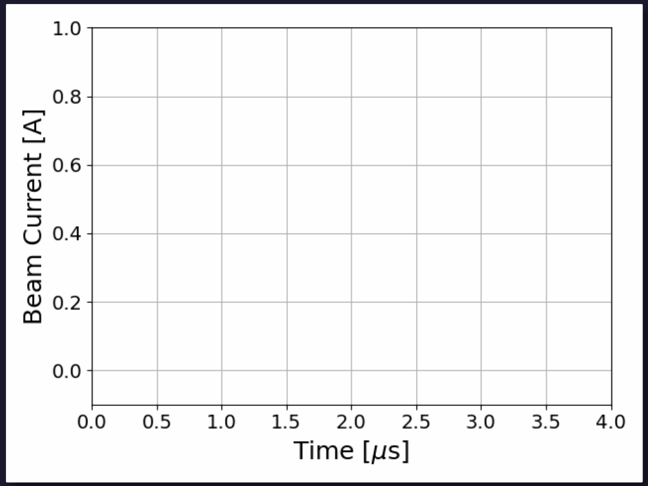


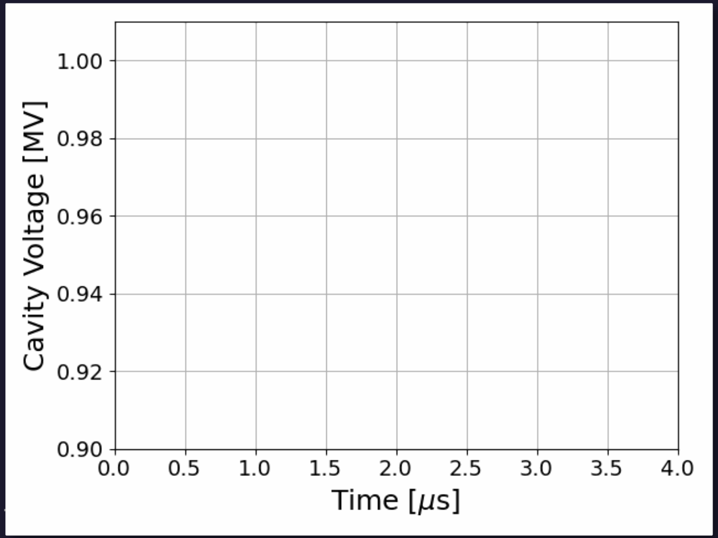
Use cases: transient detuning

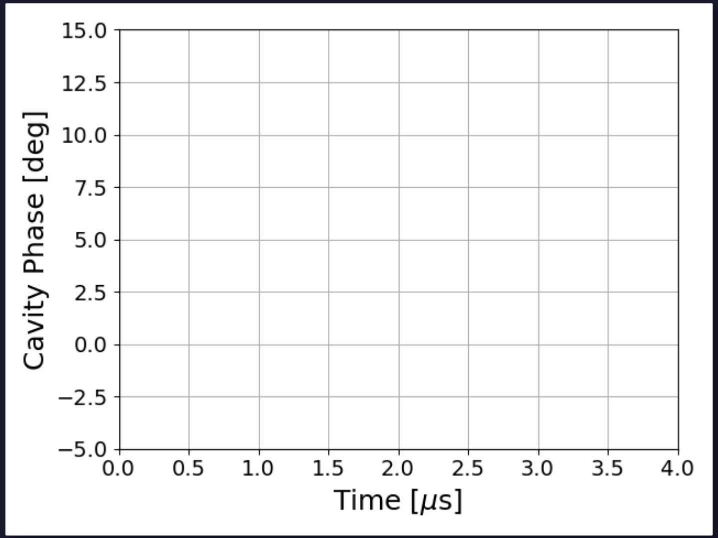
Beam + transient detuning

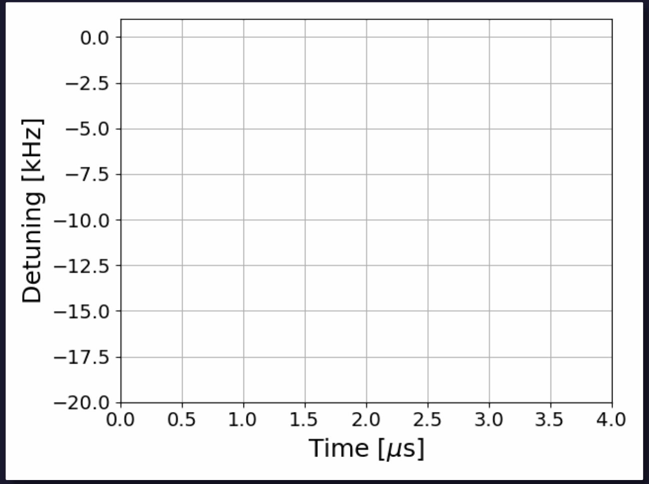


$$P_{RF} = A + [B(\phi_c' - \Delta\omega_D) - C I_b]^2$$







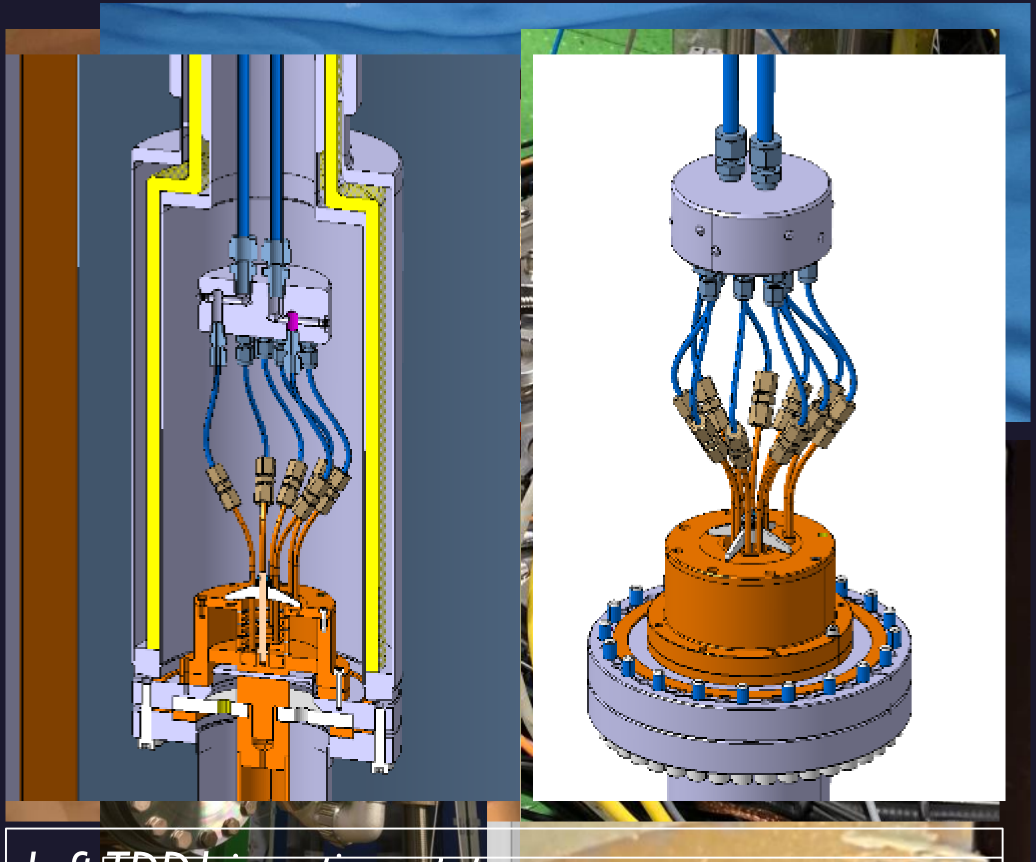


Transient Detuning Project

Overview of transient detuning research at CERN

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



Left: TDD1 in anticryostat.
Right: TDD1 with cooling lines.

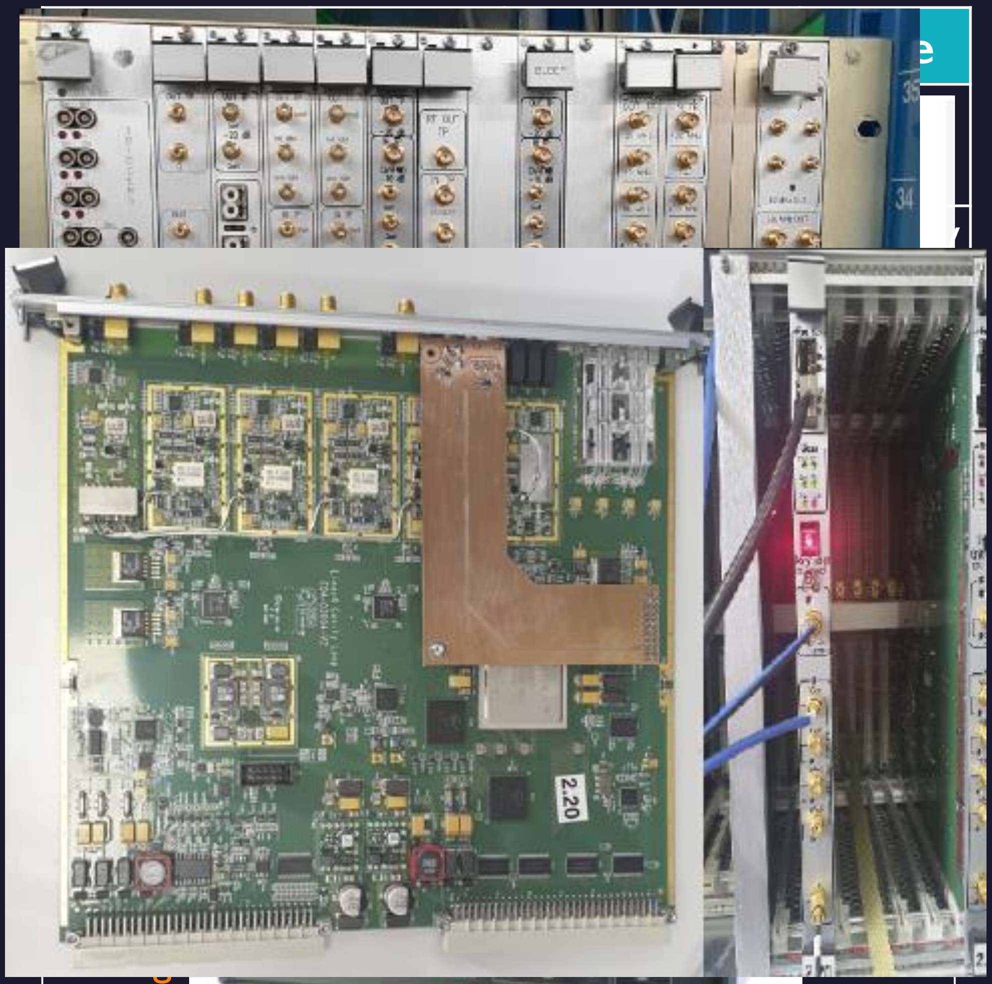
TDD0 produced reproducible **1.3kHz frequency shift on cold LHC cavity** with 500V applied across FerroElectric.

Left: TDD0 during assembly, shape of ferro-electric dictat[illegible] ceramic.
Right: [illegible] vacuum leak.

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
  - **B**eam **L**oading **E**lectronic **E**mulation **P**roject
  - 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 and sent back for diagnosis and repair
  - 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 new "Universal Cavity Controller"



Blue: C
Green:
ut OTEB

UCC
ghter
board and optical output.

High Voltage Pulser for transient detuning tests.

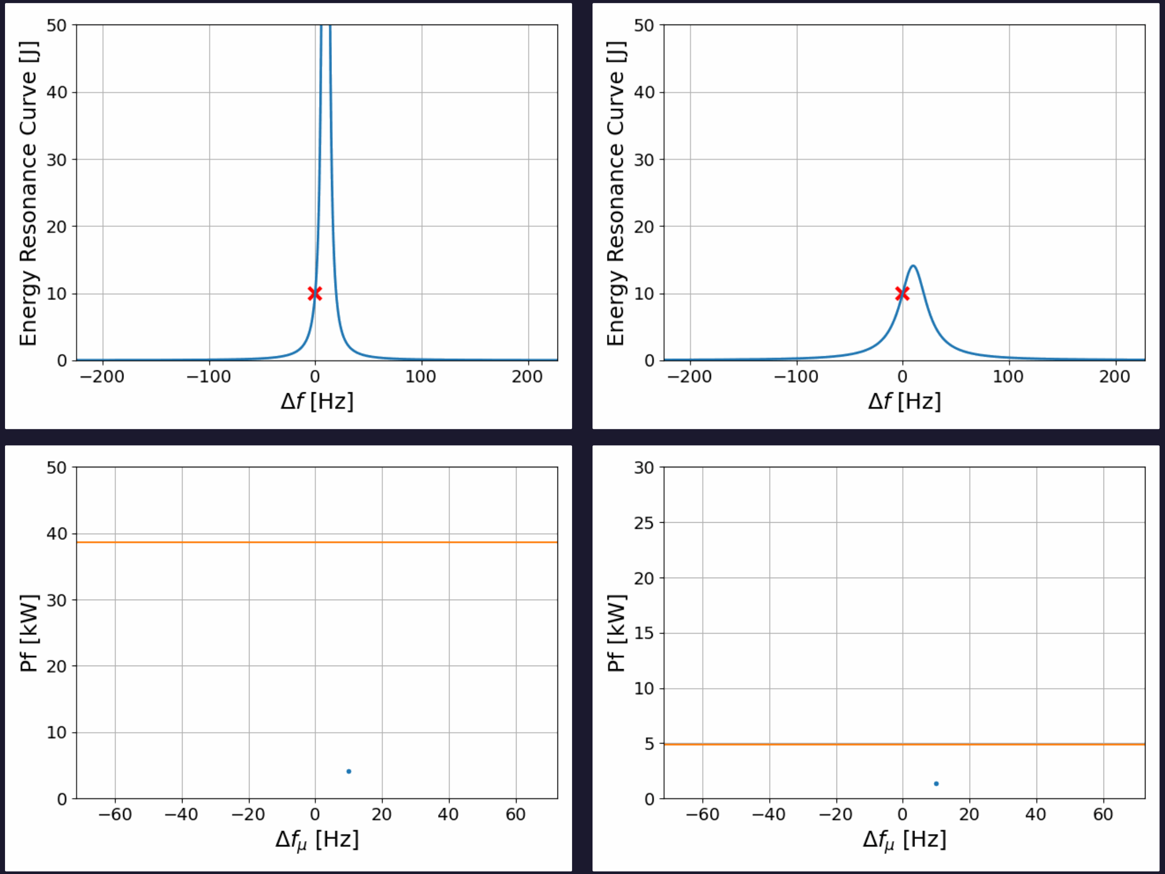
Microphonics Suppression with FRT

Benefits of suppressing microphonics with an FRT

Use cases: microphonics suppression

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

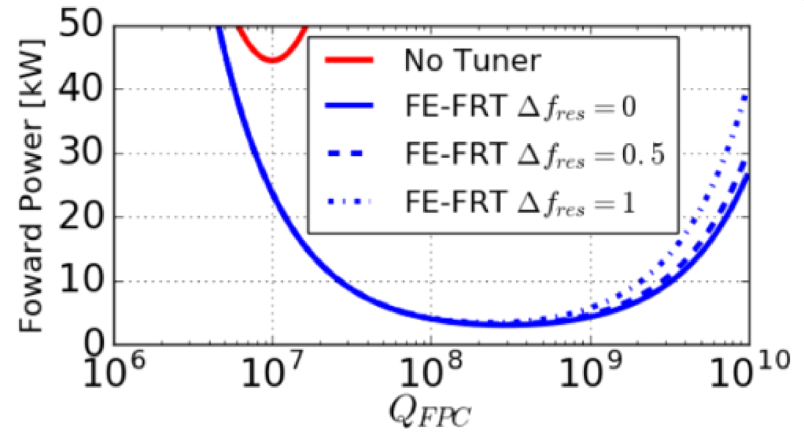
- For low beam loading machines RF power is dominated by microphonics
- The effect of microphonics can be reduced passively or actively
  - Stiffening of cavity
  - Isolation of noise sources
  - Active feedback e.g. piezo tuners
- Residual microphonics require over-coupled FPC
- Typically, RF power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



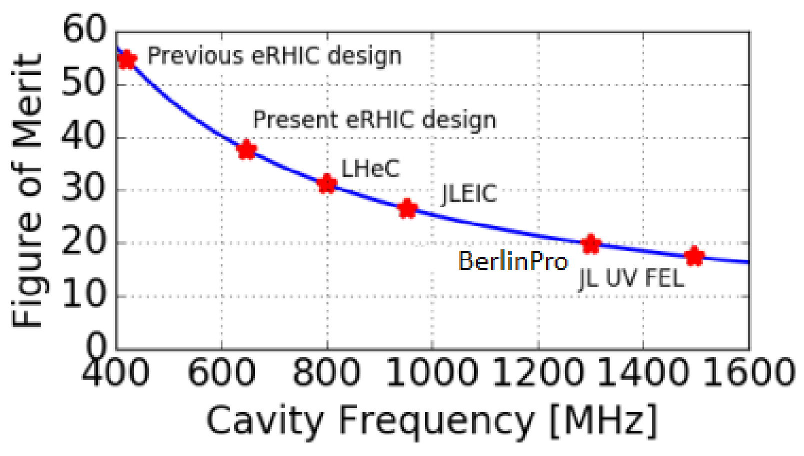
Decreasing Q_L

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 $C0_2$**



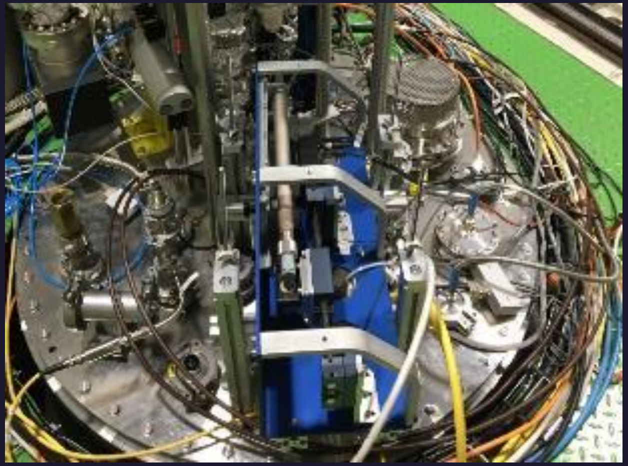
Case study: RF power for PERLE vs QL with and without FRT



Estimated FRT FoM vs RF frequency

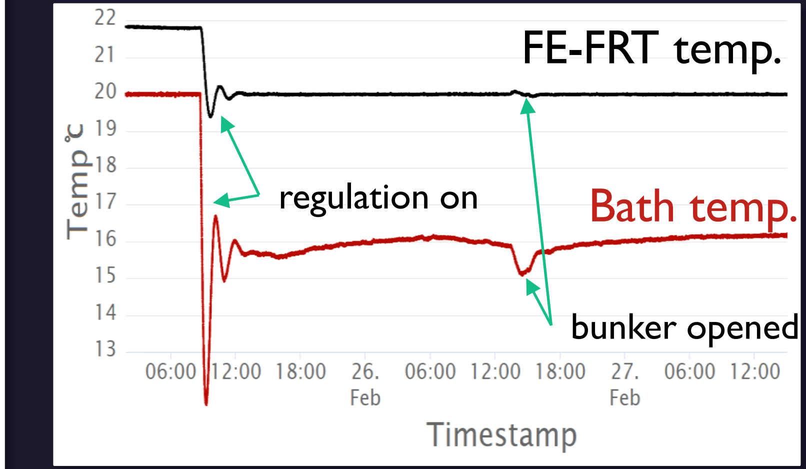
Microphonics suppression results

- 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

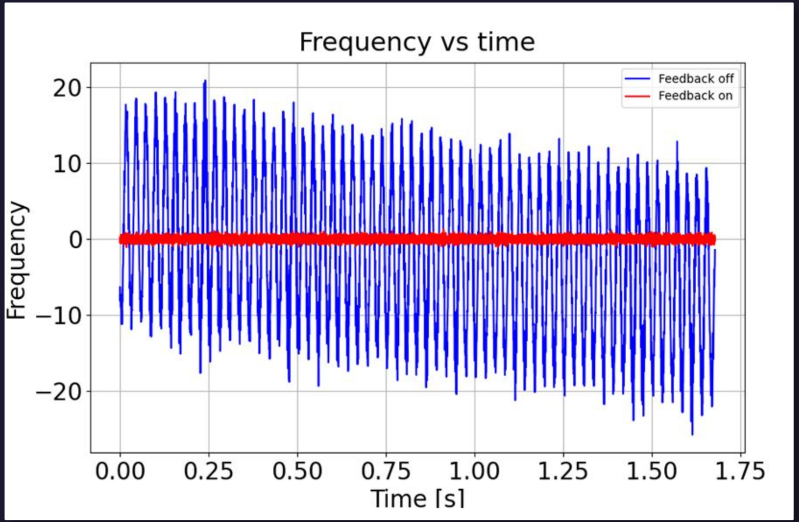

Euclid FE-FRT prototype

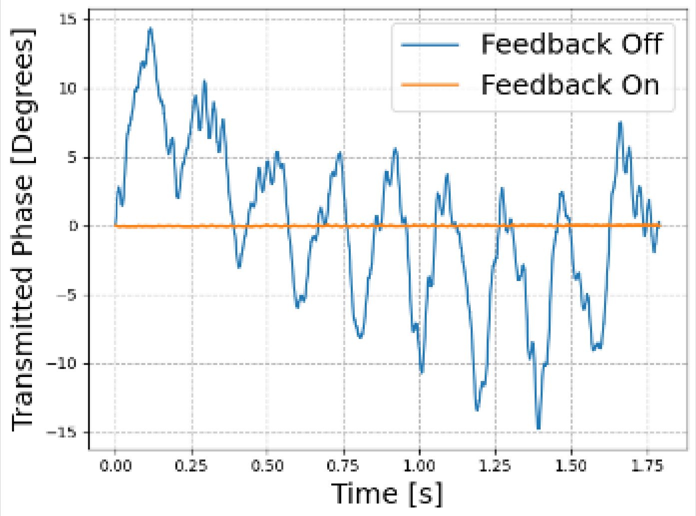


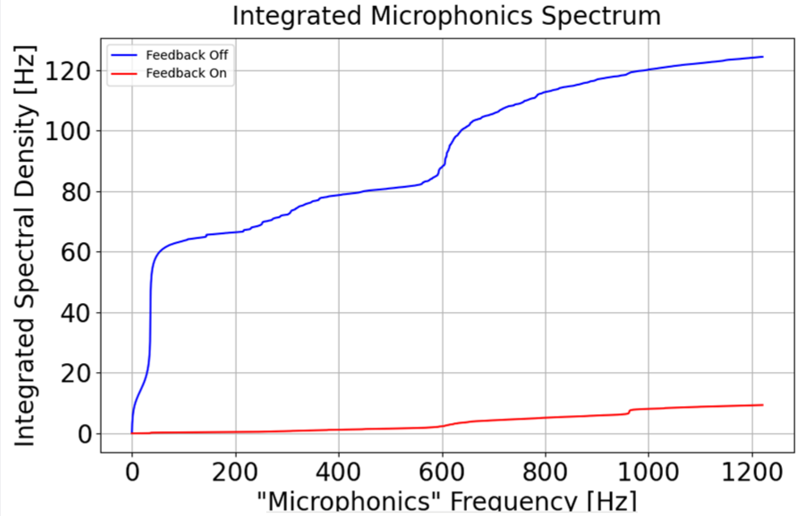
Temperature regulation with chiller

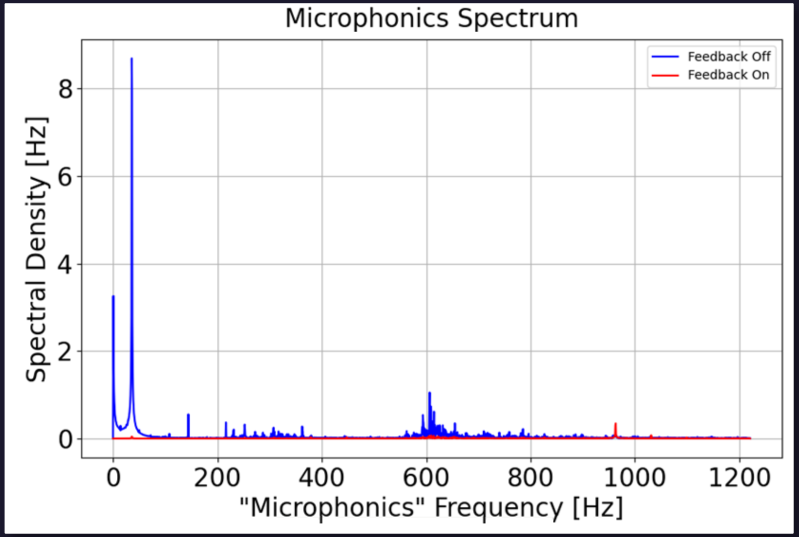
Vibration generator

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

No correction

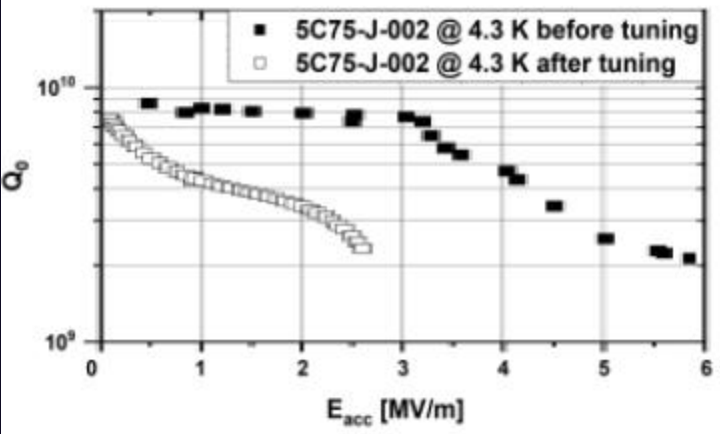
With correction

Other Use Cases and FRT Projects

Overview of current FRT Landscape

Other Use Cases

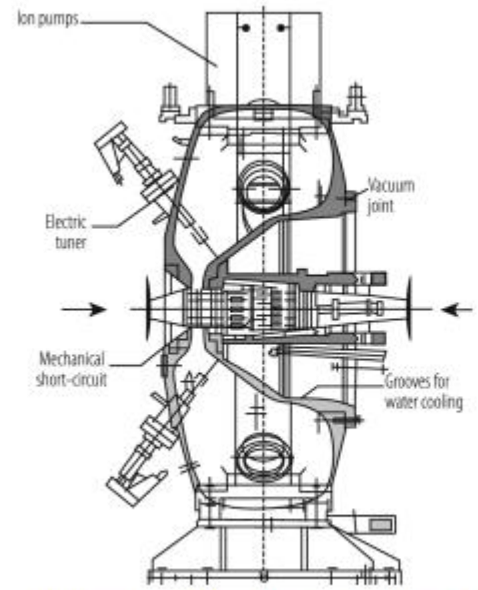
Nb_3Sn Cavities



G. Eremeev et al., "RF Performance Sensitivity to Tuning of Nb_3Sn Coated CEBAF Cavities," in SRF2019, Dresden,2019.

- Nb_3Sn could double or quadruple carnot efficiency
  - Would reduce required cooling power by factor 2-4
- Nb_3Sn 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

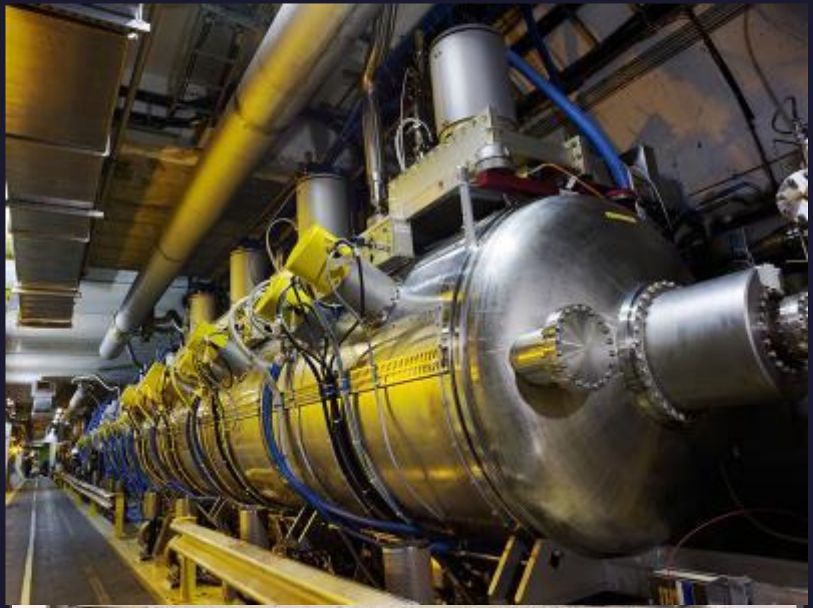
EIC 197 MHz hadron crab cavities

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 23
- 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

FRTs for PERLE

- PERLE is an excellent use case for an FRT
  - Small Tuning Range
  - Relatively low power handling requirements
  - RF frequency is not too high → high FoM
- FRTs need their own port
  - FRTs could potentially have impact on HoMs and coupler kick
  - End group should be designed to accommodate an FRT
- Cryomodule design/adaptation needs to be considered
  - If FRT is inside cryomodule volume need: space, "anti-cryostat", HV feedthrough
  - If FRT outside cryomodule → space for transmission line, RF feedthrough
- Some mechanical, thermal and RF design consideration can take place without finalized FRT design

Parameter	Value
Tuning Range	~80 Hz
Peak Reactive Power	~14 kVar
Dissipated Power	<240 W
FoM (estimated)	>30

Estimated parameters of a PERLE FRT

Summary

Summary

- CERN research currently focused on transient detuning for HL-LHC
- FRTs are perfect for Microphonics suppression for low beam loading machines
- PERLE is an excellent use case for FRTs
- FRTs need there own port
- Preliminary mechanical, integration, thermal, RF work could start without final FRT design
    - Additional cost would be small and could pay off later!

Thank you for your attention

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