FE-FRT: Ferro-Electric Fast Reactive Tuner to combat microphonics in SRF Cavities

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on behalf of

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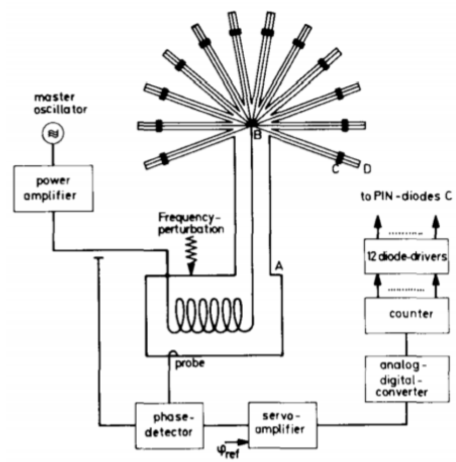
A fast reactive tuner for SRF

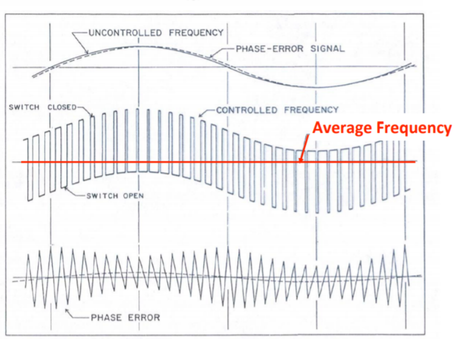
- **Goal: Develop a Fast Reactive Tuner for SRF cavities**
  - Apply advances in ferroelectrics to develop non-mechanical tuner
    - Idea: induce change in tuner permittivity to shift cavity frequency
  - Reduce effects of microphonics on cavity operation
- **Applicability: Low beam-loading SRF machines**
  - Examples: low-beta accelerators or high current ERLs
  - Suppression of micro-phonics, Lorentz & other detuning
- **Expectations with a viable FE-FRT**
  - Continuous tuning range
  - Tuner system out side cryostat and with no moving parts
  - Significant reduction in RF power, with increase in tuning sensitivity
  - Eliminate frequent actuation of mechanical tuners
    - Set and forget" mechanical tuners

Reactive Tuners: not a new idea

Pin Diode Tuners

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

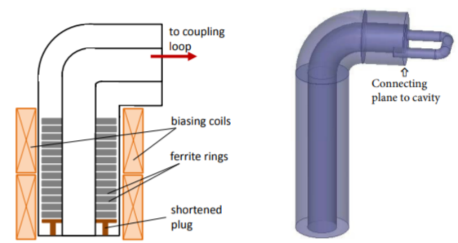




O. Despe, K. Johnson and T.~Khoe, IEEE Trans. Nucl. Sci.,vol. 20 1973.
D. Schulze et al., Proton Linear Accelerator Conf, 1972

Ferrite Tuners

Ferrite stub to moderate reactance
Frequency control by external coil.



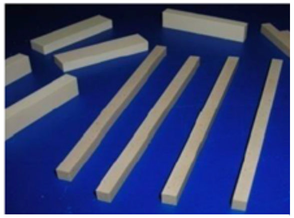
C. Vollinger and F. Caspers, Ferrite-tuner Development for 80 MHz Single-Cell RF-Cavity Using Orthogonally Biased Garnets, IPAC 15.

Why a Ferro-electric Tuner?

- **Pin Diode Tuners**
  - Operating frequency limited by lumped nature of diodes
  - Binary on-off diode switching introduces phase ripple

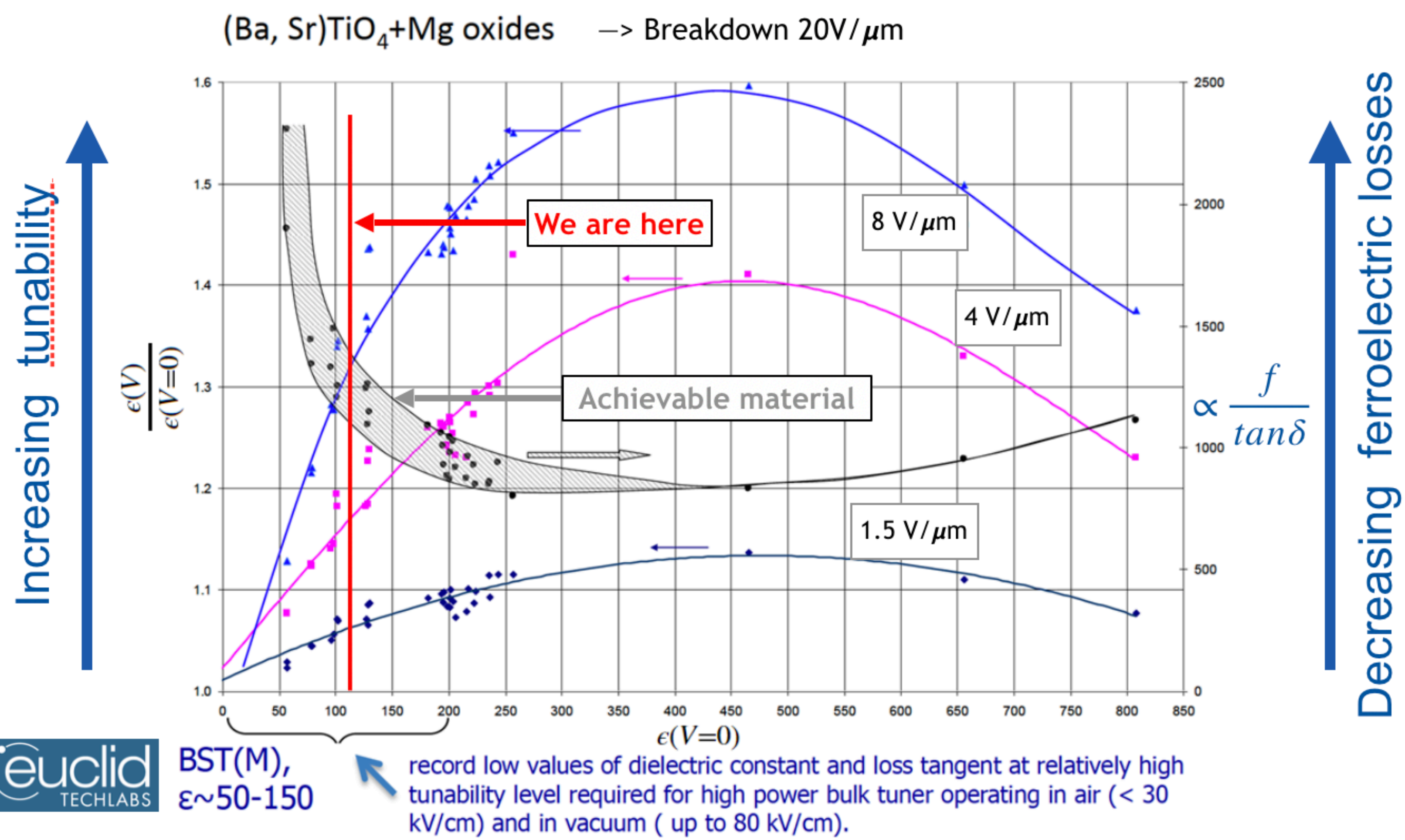
- **Ferrite Tuners**
  - Typically suffer from heavy losses particularly at saturation.
  - Tuning speed limited by coil generating (large) magnetic field

- **Ferro-electric Material**
  - **Advances in ferro-electric ceramics makes this possible**
    - Ceramic: $BaTiO_3$ - $SrTiO_3$ (BST) with Mg-based additives
      - Fast switching and tunability at high biasing voltage field
      - ε_r tunability of 6 − 8% at a 15 kV/cm
      - response times of tau < 10 ns
      - Very low loss tangents: $\tan \delta < 10^{-3}$ in L band
  - **Allows for tuner design such that:**
    - Continuous tuning range.
    - Tuner is outside cryostat and has no moving parts



Ferro-electric material

- **Development of ferro-electric ceramic**
  - Material parameters developed sufficiently to consider application
    - May be further development for mechanical/RF considerations



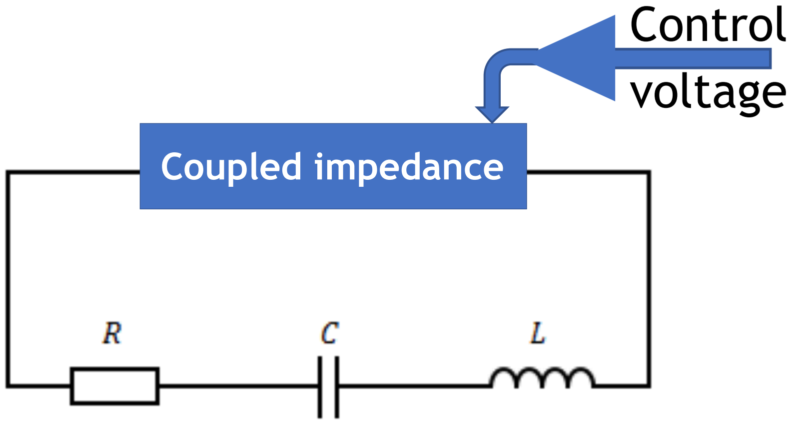
FE-FRT: Overview of how it works

- **Cavity Tuning**
  - Cavity's frequency tuned by a coupled voltage controlled reactance

$$R = \frac{R_{sh}}{Q_0}$$

$$C = \frac{1}{R_{sh}\omega}$$

$$L = \frac{R_{sh}}{\omega}$$

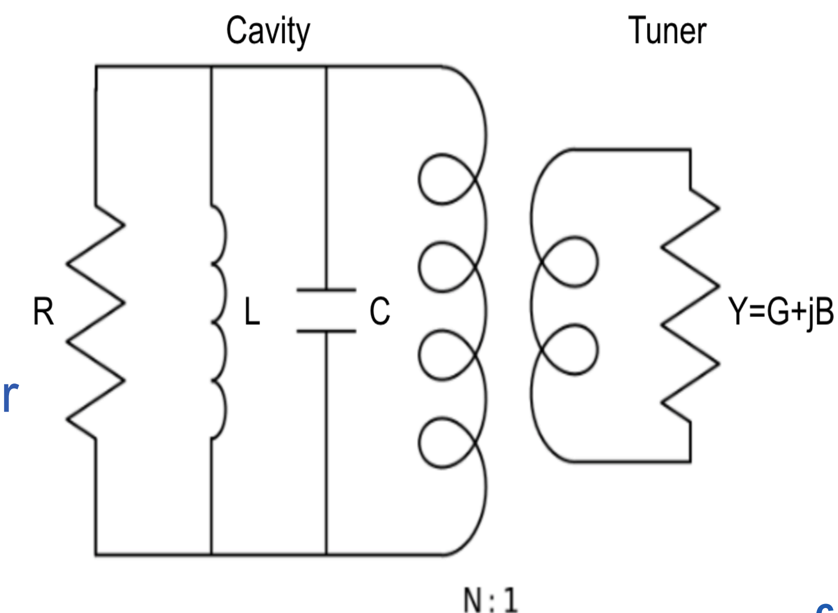


- **Evaluating Tuning response**
  - Frequency shift (tuner HV on/off)

$$\Delta\omega_{12} = \frac{-\omega_0 \, . \, \Delta B \, . \, R/Q}{4N^2}$$

  - Bandwidth (BW) change wrt no tuner

$$\Delta \mathrm{BW} = \frac{G}{N^2 C_c}$$



Evaluating FE-FRT performance

- **Define State Ratio:**
  - SR is tuning range per change in bandwidth wrt cavity with no FRT

$$\text{State Ratio} = SR = \frac{\text{Tuning Range}}{\text{Increase in BW}} = \frac{\Delta\omega_{12}}{\Delta\text{BW}} = \frac{\Delta B}{2G}$$

  - SR dependent on bias voltage applied to the FE-RFT

- **Define Figure of Merit:**

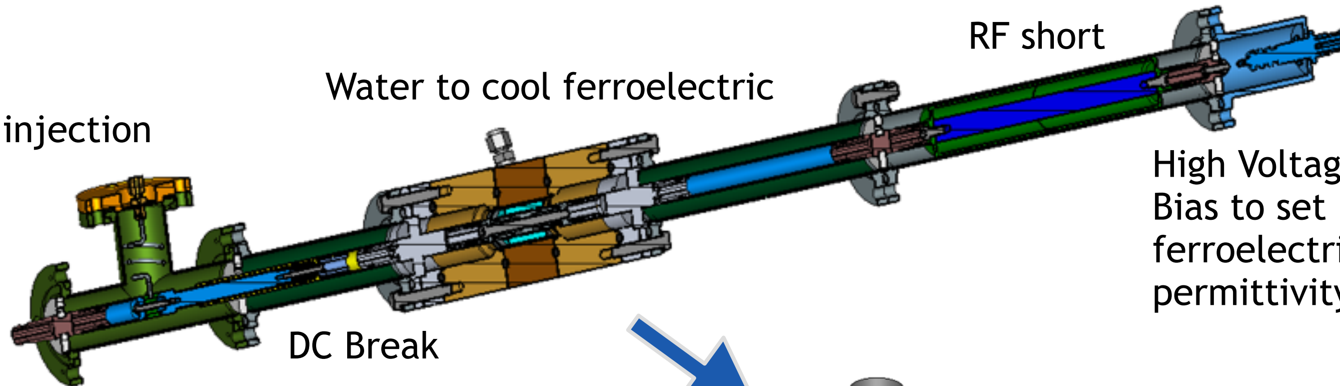
$$\text{FoM} = \frac{\text{Tuning Range}}{\text{Geometric Average of increase in BW}}$$

$$\text{FoM} = \sqrt{\text{SR}_1 \times \text{SR}_2} = \sqrt{\frac{(\Delta B_{12})^2}{4G_1G_2}} = \frac{\Delta\omega_{12}}{\sqrt{\Delta\text{BW}_1\Delta\text{BW}_2}} \approx \frac{2\left|\sin\frac{\Delta\theta_{12}}{2}\right|}{\sqrt{(1-|\Gamma_1|^2)(1-|\Gamma_2|^2)}}$$

  - SR_1 and SR_2 are states corresponding to the full HV range of FRT

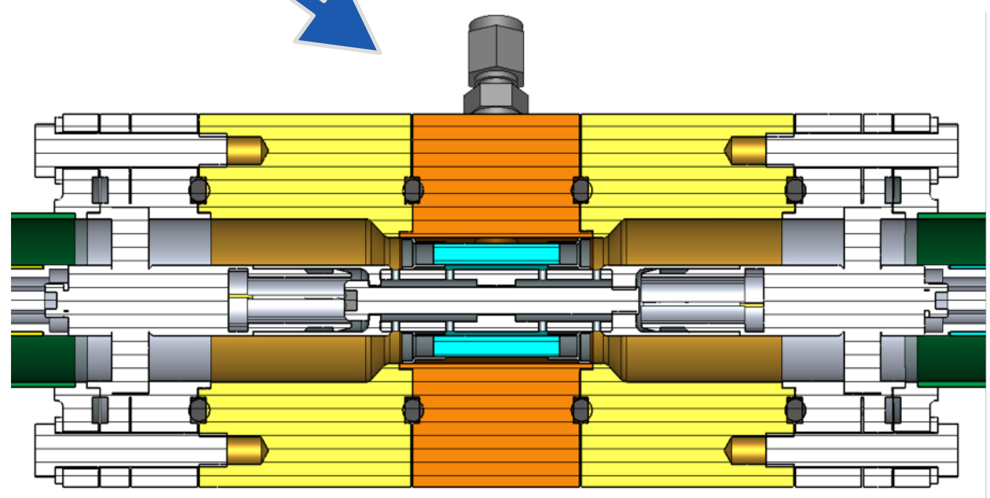
Our Prototype FE-FRT

- **Prototype FE-FRT**
  - RF design: S. Kazakov, FNAL. Fabrication: Euclid Techlabs in USA
  - Testing and development program, now ongoing at CERN



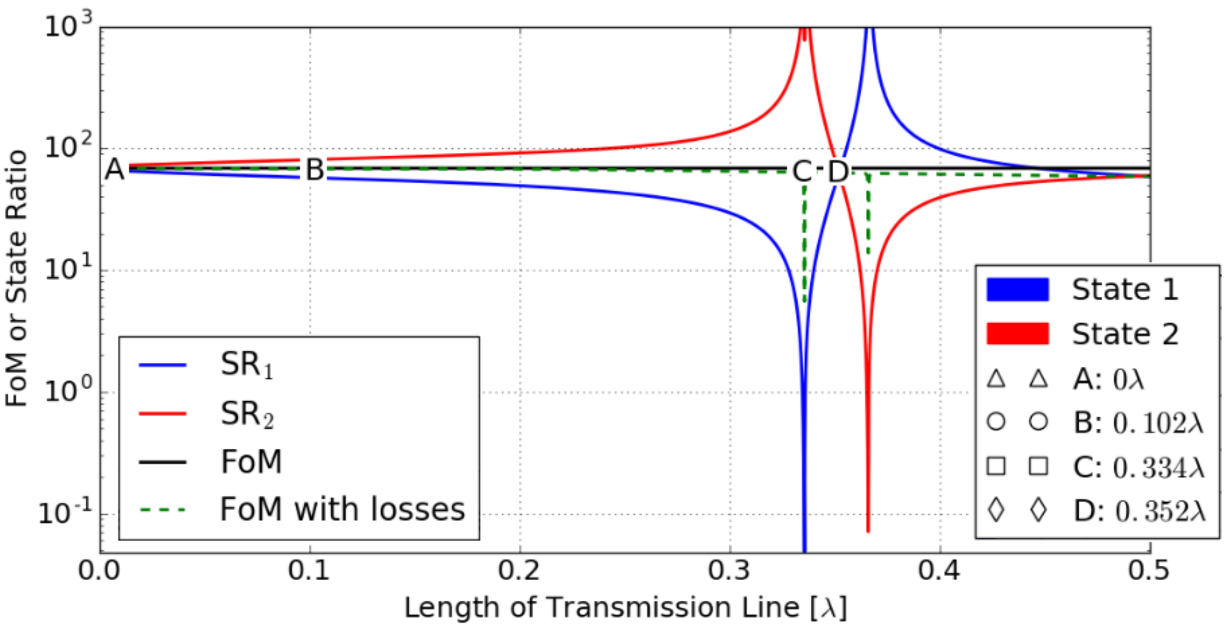
Ferroelectric (light blue)

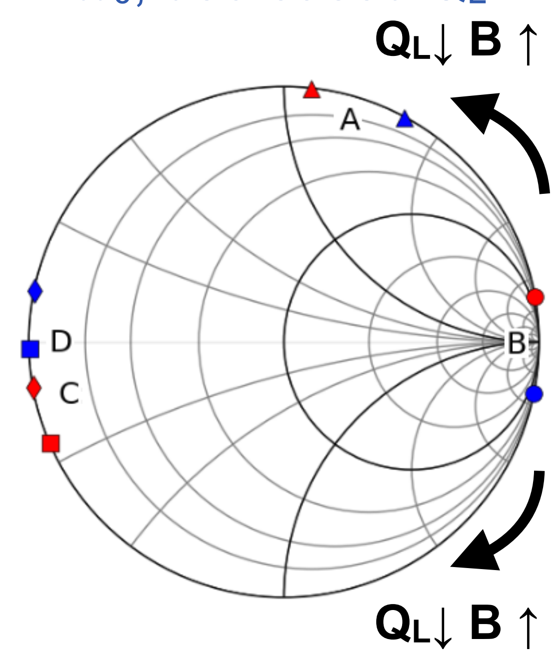
- Brazed to rings
- Active cooling
- Designed for 400 MHz
- Mechanical design limits HV



FE-FRT: Realisation as a Device

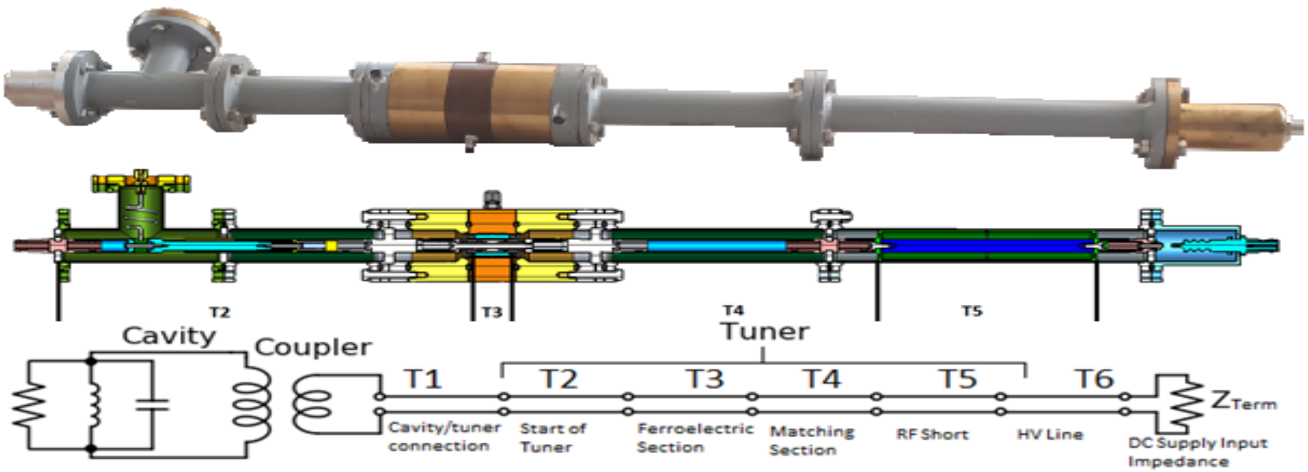
- **FE-FRT: embed ferro-electric in shorted transmission line**
  - FoM is independent of FE-FRT line length
  - Operating ω defined by line length,
    - but $\Delta\omega_{12}$ ($\propto \Delta B$) is set by FE-FRT antenna coupling
  - Line length defines operational configuration an FRT
    - Moving away from open:
      - more reactive power, increased shift from ω_0, decreased Q_L



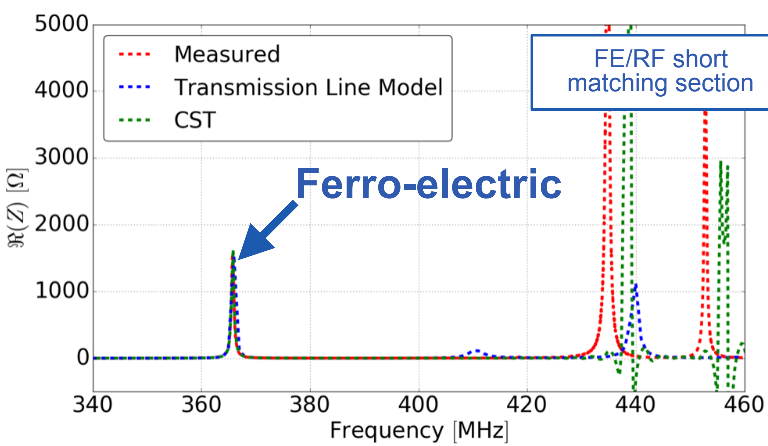


FE-FRT as a transmission line

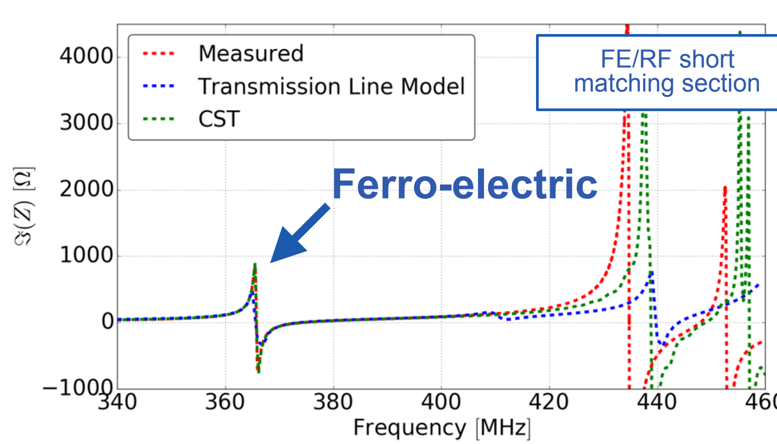
- **Prototype modelled as a composite transmission line**
  - Comparison with warm measurements: good conceptual agreement
  - Only adjustment: braze material resistivity & ferroelectric permittivity



Real Component of Impedance

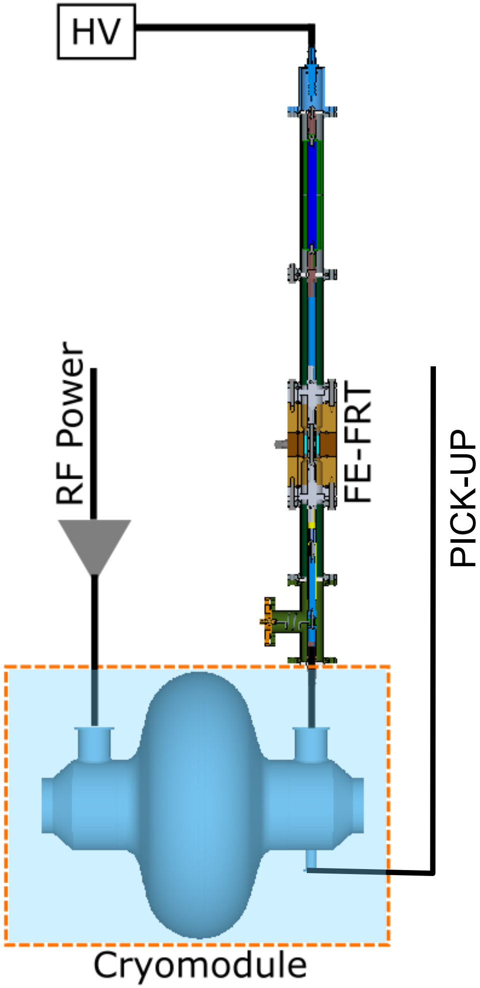


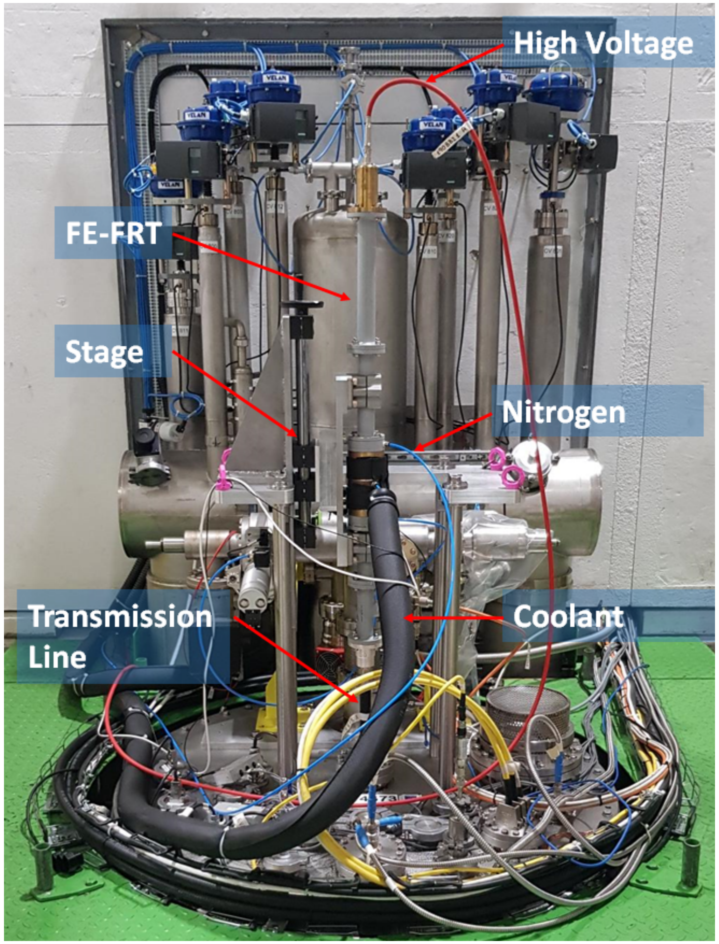
Imaginary Component of Impedance



FE-FRT Test Setup

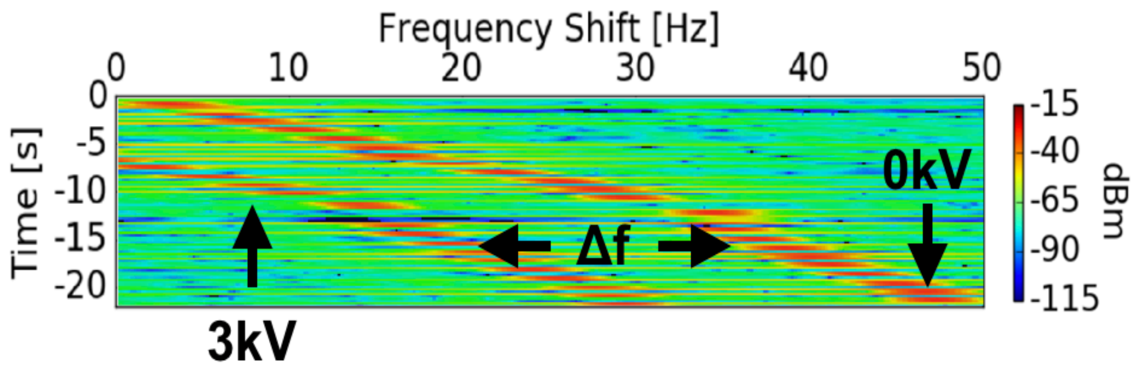
- **FE-FRT test with 400MHz HL-LHC prototype crab cavity**
  - Cavity operated at both 4.5 & 2 K. Fixed antennas



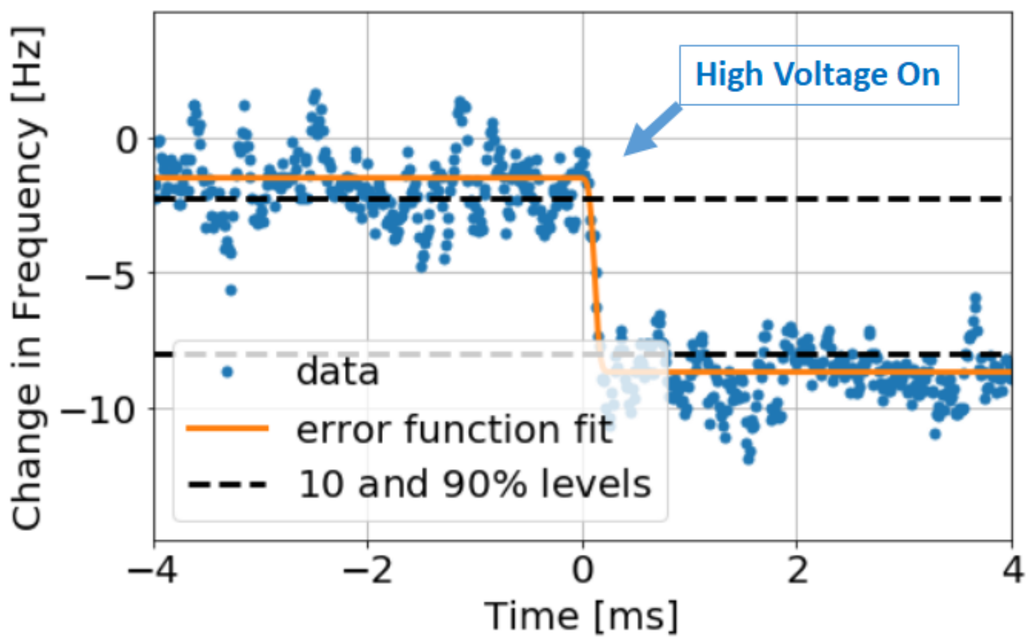


Demonstration of Frequency Tuning

- First measurement of Δf on SRF cavity from FE-FRT



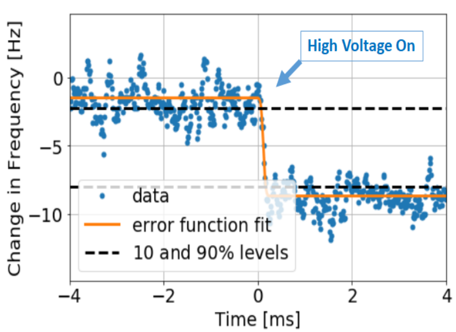
- Cavity-FRT response much faster than cavity filling time

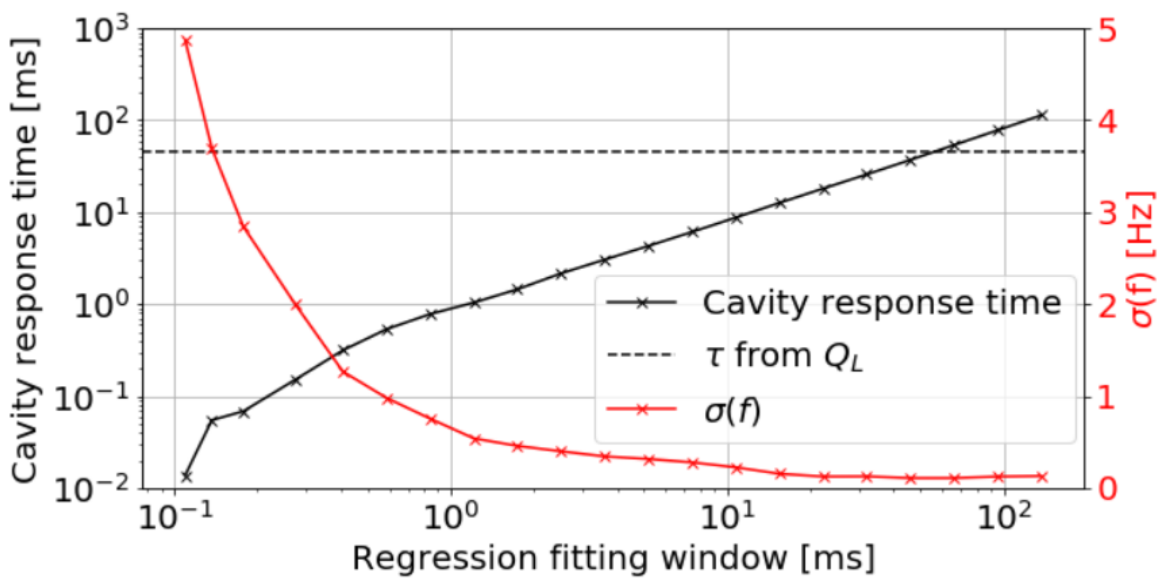


Frequency response from I & Q measurements.

FE-FRT Prototype: Cavity Response

- **Cavity-FRT response is significantly faster than cavity**
  - reaffirms that FE-FRT can be used to correct cavity microphonics
    - **Cavity response to tuner < 50 µs**
    - **Cavity time constant** $\tau = \frac{Q_L}{\omega_0} \approx 46\, ms$
- **Present response time limited by measurement setup**
  - => expect cavity response to tuner << 50 µs
    - LLRF Frequency measurement requires some signal processing
  - Refined measurement and full tuning loop now being implemented





Application of FE-FRT

- **FE-FRT Performance:**
  - **FoM is crucial: FoM ~30 @ 800MHz. Realistic for existing material**
    - defined by quality of ferroelectric & mechanical/RF design
  - Primary function of FRT defined by beam loading scenario

- **FE-FRT Application Scenarios**
  - **High beam loading:** FE-FRT designed to suppress microphonics
    - Target full microphonics spectrum
  - **Low beam loading (eg ERL):** FE-FRT design to reduce RF power
    - (Cavity+Tuner) critical coupled & microphonics suppressed
  - **Mixed Scenario:** FE-FRT in conjunction with Mechanical tuners
    - Different possibilities can be considered
      - eg frequency stabilisation with different beam species
      - Line length defines frequency offset due to tuner

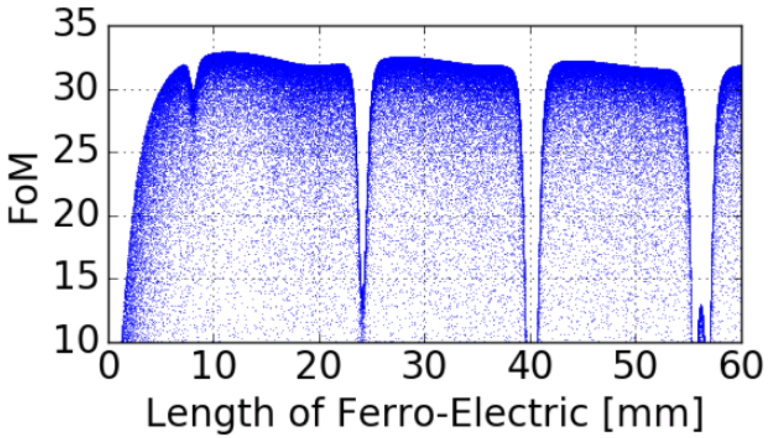
FE-FRT Case study: PERLE

- **PERLE ERL: 5-cell Nb cavity at 802MHz**
  - No significant beam loading and Δf = 80 Hz (at peak detuning)

PERLE 5-cell Cavity	
ω_0	801.58 MHz
Q_0	2 x10^{10}
R/Q	392 Ω
U_C	141 J
Q_{FPC}	10^7
P_{RF}	45 kW
Max Δf_μ	40 Hz

- **FE-FRT Parameters: Material/Mechanical optimisation**

Monte Carlo of ferro electric section



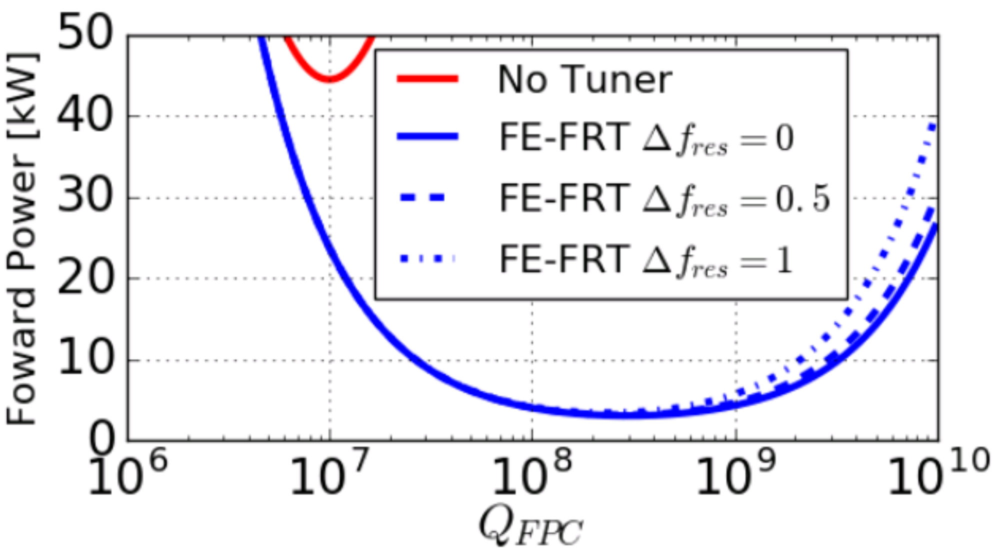
Ferro electric parameters	
Max ε_r	140
Min ε_r	131.6
tan δ	9.1 x 10^{-4}
$\Delta\varepsilon_r/E$	0.6 cm/kV
σ_{Cu}	5.96 x 10^{-7} S/m

FE-FRT Case study: PERLE

- **FE-FRT configuration:**
  - **Input: FoM = 30 and require tuning range of Δf =80 Hz**
- **Implication:**
  - Operating closer to critical coupling => RF power reduced

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

- **Can achieve ~ 15 fold reduction in RF power**
  - ~ 70 kVar of peak reactive power => Reactive HV ~2.2 kV



PERLE 5-cell Cavity	
FoM	30
Δf	80 Hz
Q_{FPC}	3 x 10^8
P_{RF}	3 kW
P_t	2.4 kW
Max $\mathscr{P}_t$	71 kVar

Summary

- **Concept:**
  - Advances in ferroelectric ceramics open possibility of reactive tuner
    - Ceramics are extremely fast: response times < 10 ns
      - **For SRF cavities material sufficiently development for now.**
- **FE-FRT Prototype results:**
  - **SRF cavity response to FRT: extremely fast << 50 µs**
      - Not limited by cavity time constant.
      - Mechanical & RF design crucial to FRT performance
- **FE-FRT Benefits**
  - FE-FRT ideal for low beam loading Machine
      - Eliminate microphonics => drastically reducing RF power
  - Tuning with tuner external to cryomodule
- **FE-FRT prototype with tuning loop under test at CERN**
  - Exploring a number of potential use cases
  - FE-FRT not to be seen as just corrective add on
    - Potential for real benefits if included at cavity/module design stage

FE-FRT: Power Flow - PERLE