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

A. Macpherson & N. Shipman

on behalf of

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.

Ferrite Tuners

Ferrite stub to moderate reactance. Frequency control by external coil.

D. Schulze et al., Proton Linear Accelerator Conf, 1972
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: BaTiO3 - SrTiO3 (BST) with Mg-based additives
      - Fast switching and tunability at high biasing voltage field
      - $\varepsilon_r$ 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

(Ba, Sr)TiO₄+Mg oxides  $\rightarrow$ Breakdown 20V/μm

- Increasing tunability:
- BST(M), $\varepsilon \approx 50-150$
- We are here
- $8$ V/μm
- Achievable material
- $4$ V/μm
- $1.5$ V/μm
- Decreasing ferroelectric losses

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).
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)

\[ \Delta \omega_{12} = \frac{-\omega_0 \cdot \Delta B \cdot R/Q}{4N^2} \]

• Bandwidth (BW) change wrt no tuner

\[ \Delta BW = \frac{G}{N^2C_c} \]
Evaluating FE-FRT performance

• Define State Ratio:
  • SR is tuning range per change in bandwidth wrt cavity with no FRT
  
  \[ \text{State Ratio} = SR = \frac{\text{Tuning Range}}{\text{Increase in BW}} = \frac{\Delta \omega_{12}}{\Delta BW} = \frac{\Delta B}{2G} \]
  
  • SR dependent on bias voltage applied to the FE-RFT

• Define Figure of Merit:
  
  \[ \text{FoM} = \frac{\text{Tuning Range}}{\sqrt{\text{Geometric Average of increase in BW}}} \]
  
  \[ \text{FoM} = \sqrt{SR_1 \times SR_2} = \sqrt{\frac{(\Delta B_{12})^2}{4G_1 G_2}} = \frac{\Delta \omega_{12}}{\sqrt{\Delta BW_1 \Delta BW_2}} \approx \frac{2 | \sin \frac{\Delta \theta_{12}}{2} |}{\sqrt{(1 - |\Gamma_1|^2)(1 - |\Gamma_2|^2)}} \]
  
  • 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 $\omega$ 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 $\omega_0$, decreased $Q_L$

![Graph showing FoM and state ratio vs. length of transmission line](image)
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

![Diagram of FE-FRT model](image)

### Real Component of Impedance
- Measured
- Transmission Line Model
- CST
- FE/RF short matching section

### Imaginary Component of Impedance
- Measured
- Transmission Line Model
- CST
- FE/RF short matching section
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 $\Delta f$ on SRF cavity from FE-FRT
- Cavity-FRT response much faster than cavity filling time

![Graph showing frequency response from I & Q measurements.](image)
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 $< 50 \mu s$
      • Cavity time constant $\tau = \frac{Q_L}{\omega_0} \approx 46 \text{ ms}$

• Present response time limited by measurement setup
  • $\Rightarrow$ expect cavity response to tuner $<< 50 \mu s$
    • 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 $\Delta f = 80$ Hz (at peak detuning)

<table>
<thead>
<tr>
<th>PERLE 5-cell Cavity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_0$</td>
</tr>
<tr>
<td>$Q_0$</td>
</tr>
<tr>
<td>$R/Q$</td>
</tr>
<tr>
<td>$U_C$</td>
</tr>
<tr>
<td>$Q_{FPC}$</td>
</tr>
<tr>
<td>$P_{RF}$</td>
</tr>
<tr>
<td>Max $\Delta f_\mu$</td>
</tr>
</tbody>
</table>

- FE-FRT Parameters: Material/Mechanical optimisation

Ferro electric parameters

| Max $\varepsilon_r$ | 140 |
| Min $\varepsilon_r$ | 131.6 |
| $\tan \delta$     | $9.1 \times 10^{-4}$ |
| $\Delta \varepsilon_r/E$ | 0.6 cm/kV |
| $\sigma_{Cu}$     | $5.96 \times 10^{-7}$ S/m |
FE-FRT Case study: PERLE

- **FE-FRT configuration:**
  - Input: FoM = 30 and require tuning range of $\Delta f = 80$ Hz

- **Implication:**
  - Operating closer to critical coupling $\Rightarrow$ RF power reduced
    \[
    P_{RF} = \frac{V_c^2}{4R/\sqrt{Q_Q_L}} \frac{\beta + 1}{\beta} \left[ 1 + \left( 2Q_L \frac{\Delta \omega_{\mu}}{\omega_0} \right)^2 \right]
    \]
  - Can achieve $\sim 15$ fold reduction in RF power
    - $\sim 70$ kVar of peak reactive power $\Rightarrow$ Reactive HV $\sim 2.2$ kV

- **PERLE 5-cell Cavity**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>FoM</td>
<td>30</td>
</tr>
<tr>
<td>$\Delta f$</td>
<td>80 Hz</td>
</tr>
<tr>
<td>$Q_{FPC}$</td>
<td>$3 \times 10^8$</td>
</tr>
<tr>
<td>$P_{RF}$</td>
<td>3 kW</td>
</tr>
<tr>
<td>$P_t$</td>
<td>2.4 kW</td>
</tr>
<tr>
<td>Max $\mathcal{P}_t$</td>
<td>71 kVar</td>
</tr>
</tbody>
</table>
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

- State Ratio
- Dissipated Power
- Reactive Power

Parameters:
- $\Delta f_t$
- $\epsilon_r$

Graph shows the relationship between state ratio and power flow parameters.