Ultrafast Ferroelectric Based Tuning for EIC Applications

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Euclid Techlabs, LLC

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Euclid Techlabs LLC

Euclid Techlabs, LLC is a research and development company specializing in linear particle accelerators, ultrafast electron microscopy, and advanced material technologies for energy, defense, and medical applications. The company was formed in 2003. Euclid has developed expertise and products in several innovative technologies: time-resolved ultra-fast electron microscopy; ultra-compact linear accelerators; electron guns with thermionic, field emission or photo-emission cathodes; fast tuners for SRF cavities; advanced dielectric materials; HPHT and CVD diamond growth and applications; thin-film applications in accelerator technologies; and beam physics. Merging these technologies allows Euclid to create cost-effective, compact and reliable solutions, which provide potential access to a wide variety of markets.

- 32 employees, 15 PhD, particle physicists, material scientists, as well as electrical and mechanical engineers
- 2 Lab/offices: Bolingbrook, IL and Washington DC.
- Tight collaborations with National Labs and Institutes: FNAL, ANL, BNL, LBL, SLAC, LANL, Jlab, NIST, NIU, IIT, etc.
Key Euclid Technologies

- Ferroelectric based fast tuner
- Accelerator components (RF windows, couplers…)
- Ultra-compact MeV energy range accelerators
- Electron guns for accelerators: Photo-, thermo-, field emission (FE)- and SRF guns. Photocathodes.
- SRF cavities, conduction cooled cryomodules
- Stroboscopic pulser for Transmission Electron Microscope
- Other high power microwave/RF components and beam physics instrumentation

Fast ferroelectric 400 MHz tuner successfully tested at CERN

L-band RF window for AWA ANL

UFPTM for TEM

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With the talk, we present recent developments on fast active ferroelectric tuner designed based on the recently developed and demonstrated “smart” low loss tunable ceramic materials especially engineered for high power accelerator applications.

The Fast Ferroelectric Tuner with the tuning ceramic element made of the composite low loss ferroelectric, which dielectric constant can be altered with temperature (slow tuning,) and DC voltage (fast tuning). As long as the DC voltage changes the dielectric constant at 10-100 ns time range, it opens possibility for the development of the fastest ever tuning high power components.
A fast controllable phase shifter would allow microphonics compensation for the SRF accelerator (application of transient beamloading detuning is under consideration)

Nonlinear ferroelectric microwave components can control the tuning or the input power coupling for rf cavities. Applying a bias voltage across a nonlinear ferroelectric changes its permittivity. This effect is used to cause a phase change of a propagating rf signal or change the resonant frequency of a cavity. The key was the development of a low loss but still tunable ferroelectric material. The parameters have to be:

- **Dielectric constant** has to be low (~ 100-150)
- **Loss factor** has to be low ~ 10^{-3} at 1 GHz and 3\times10^{-4} at 100 MHz
- **Tuning range** has to be high ~ 6-8% at ~15 kV/cm
- Can be done with (Ba, Sr)TiO_{4}+Mg based oxides

*Ferroelectric tuning for SRF cavity was proposed by I. Ben-Zvi*
Frequency dependence of $\varepsilon$ and $\tan\delta$ for the ferroelectrics with low permittivity at ~GHz range

$Q \times f = \text{FoM, GHz}$

$Q \times f = f (\text{GHz})/\tan\delta$

$Q \times f \sim \text{const. at 50 MHz – 100 GHz}$

BST(M) is microwave ceramic – it means that its permittivity does not depend on frequency.

Same time, loss factor $\tan\delta$ of microwave ceramic linearly increases with frequency.

$\tan\delta = 2.8 \times 10^{-4}$ (80 MHz), $= 4.8 \times 10^{-4}$ (400 MHz),
Ferroelectric ceramic properties, temperature

Curie temperature shift from 250K to 170K with increase of Mg-based oxides in BST-Mg oxide solution.

Dielectric constant of BST based ferroelectrics strongly is dependent on temperature. With the low linear ceramic content in BST, Curie temperature is ~250K shifting to the ~170K range with linear ceramic content increase. For the BST(M) material with its dielectric constant ~150 at room temperature, $\Delta \varepsilon(T)/\varepsilon \sim 1\%/0K$ or $\Delta \varepsilon/T = 1.2/0K$.

Optimal operations for BST (M) has to be in the 10°C-50°C temperature range.

Temperature dependence of the BST(M) material permittivity in the 25C-50C temp. range.
Progress on BST(M) Material Development

(Ba,Sr)TiO₄+Mg oxides in various proportions at room temperature

K_{dc} = \frac{\varepsilon(V=0)}{\varepsilon(V_0)}

tunability

Q\times f = f (GHz)/\tan\delta

Q\times f \sim \text{const. at} 50\text{ MHz} – 100\text{ GHz}

\tan\delta = 4 \times 10^{-4} \text{ at } 400\text{ MHz}

8\% at 15\text{kV/cm}

tan\delta=4\times10^{-4} \text{ at } 400\text{ MHz}

8\% at 15\text{kV/cm}

K_{dc} = \frac{\varepsilon(V=0)}{\varepsilon(V_0)}

tunability

BST(M), \varepsilon\sim 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).
# Ferroelectric ceramic properties

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>dielectric constant, $\varepsilon$</td>
<td>$\sim 150$</td>
</tr>
<tr>
<td>tunability, $\Delta \varepsilon / \varepsilon$</td>
<td>$\sim 10%$ at $15 \text{kV/cm}$ of the bias field</td>
</tr>
<tr>
<td>response time</td>
<td>$10 - 100 \text{ ns}$</td>
</tr>
<tr>
<td>tan(\delta) at $1 \text{ GHz}$ and $400 \text{ MHz}$</td>
<td>$\sim 1 \times 10^{-3}$ and $\sim 4 \times 10^{-4}$ correspondingly</td>
</tr>
<tr>
<td>breakdown limit</td>
<td>$200 \text{ kV/cm}$</td>
</tr>
<tr>
<td>thermal conductivity, $K$</td>
<td>$7.02 \text{ W/m-K}$</td>
</tr>
<tr>
<td>specific heat, $C$</td>
<td>$0.605 \text{ kJ/kg-K}$</td>
</tr>
<tr>
<td>density, $\rho$</td>
<td>$4.86 \text{ g/cm}^3$</td>
</tr>
<tr>
<td>coefficient of thermal expansion</td>
<td>$10.1 \times 10^{-6} \text{ K}^{-1}$</td>
</tr>
<tr>
<td>temperature tolerance, $\partial \varepsilon / \partial T$</td>
<td>$(1-2) \text{ K}^{-1}$</td>
</tr>
</tbody>
</table>
BST Based Tuner Design (assembly)

design of S. Kazakov and V. Yakovlev
Ferroelectric Based High Power Tuner for SRF Cavities

- Ferroelectric Fast Reactive Tuner (FE-FRT) for SRF accelerator operations
  - Ultrafast tuner: 100 ns range
- In collaboration with CERN
  - Case study: LHeC application
- Offers potential for significant reduction in RF power consumption

N. Shipman, et al., ERL’19, TUOZBS02
Preliminary Test Results, CERN, 2020

• First ever Ferroelectric Fast Reactive Tuner (FE-FRT) test with a superconducting cavity

Courtesy of A.Macpherson and N.Shipman, CERN

Snapshot of preliminary FE-FRT tuning loop results

FE-FRT:
• A non-mechanical tuner for RF cavities
• Validated tuning loop
• Microphonics suppression
• Wide operational parameter space
  • Achievable $\Delta f > 50$ kHz (depends on $Q_L$)
  • Configurable tuning ranges from Hz to kHz
  • Configuration depends on FRT application

“Slow” Tuning”

Microphonics Suppression
Euclid Techlabs is developing the first fast ferroelectric tuner for a SRF accelerator that is currently in operation – CEBAF at JLAB. In comparison with our first tuner prototype, it requires a new configuration, with a single RF power port for both the klystron and the tuner. This is the only option for the current C100 cryomodules at CEBAF, and many other projects.
Euclid has carried out thermal and RF measurements of improved ferroelectric ceramic, completed the tuner RF and thermomechanical design, and is currently finishing the mechanical engineering design for fabrication. HOM analysis is complete too.
Simulink modeling of the FRT microphonics compensation via the single FPC

- Although it is non-ideal to use FRT through FPC, it is possible to maintain $Q_{ext}$ and compensate the microphonics simultaneously.
- Simulink modeling shows the klystron power demanding can be reduced by ~25% in the case of Jlab C100 cavities.
New Research Directions

Transient Detuning using a Ferro-Electric Fast Reactive Tuner

N. Shipman, I. Ben-Zvi, A. Castilla, A. Macpherson, H. Timko


SYMT 8th July 2021

TABLE III. List of parameters for the PS cavity ferroelectric tuner.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of wafers</td>
<td>8</td>
<td>–</td>
</tr>
<tr>
<td>Wafer diameter $d$</td>
<td>48</td>
<td>mm</td>
</tr>
<tr>
<td>Wafer thickness</td>
<td>2</td>
<td>mm</td>
</tr>
<tr>
<td>Coax outer conductor radius $b$</td>
<td>73.18</td>
<td>mm</td>
</tr>
<tr>
<td>Coax inner conductor radius $a$</td>
<td>26.9</td>
<td>mm</td>
</tr>
<tr>
<td>Stub length $L$</td>
<td>105</td>
<td>mm</td>
</tr>
<tr>
<td>Transmission line length $l$</td>
<td>60</td>
<td>mm</td>
</tr>
<tr>
<td>Ferroelectric absorbed power limit</td>
<td>10.1</td>
<td>kJ</td>
</tr>
<tr>
<td>Capacitor’s FoM $C$</td>
<td>497</td>
<td>–</td>
</tr>
<tr>
<td>System FoM</td>
<td>282</td>
<td>–</td>
</tr>
<tr>
<td>Change in reactive power</td>
<td>10</td>
<td>MVAR</td>
</tr>
<tr>
<td>Frequency tuning</td>
<td>230</td>
<td>kHz</td>
</tr>
</tbody>
</table>
Summary

- BST (M) ceramic was developed with dielectric constant ~150, loss factor ~ $5 \times 10^{-4}$ at 400 MHz and tunable ~ 8% at 15 kV/cm at 10-100 ns pulse range.
- The fast 400 MHz BST(M) ferroelectric tuner was designed, fabricated and cold tested at Euclid. Validation test at CERN of the 400 MHz tuner with SRF cavity demonstrated successful microphonics compensation at up to 1 kHz frequency range.
- 1.5 GHz MT single port tuner configuration is currently under development for the Jlab’s C100 cavity for CEBAF.
- New FRT applications are on the horizon.
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  – Fermilab: V. Yakovlev, S. Kazakov,
  – Ceramic Ltd: E. Nenasheva