A FerroElectric Fast Reactive Tuner (FE-FRT) for ERLs
Reducing power consumption by microphonics compensation

N. Shipman\textsuperscript{1}, J. Bastard\textsuperscript{1}, M. Coly\textsuperscript{1}, F. Gerigk\textsuperscript{1}, A. Macpherson\textsuperscript{1}, N. Stapley\textsuperscript{1}, I. Ben-Zvi\textsuperscript{2}, C. Jing\textsuperscript{3}, A. Kanareykin\textsuperscript{3}, G. Burt\textsuperscript{4}, A. Castilla\textsuperscript{4}, E. Nenasheva\textsuperscript{6}

\textsuperscript{1}\textit{CERN}, \textsuperscript{2}\textit{Brookhaven National Laboratory}, \textsuperscript{3}\textit{Euclid Techlabs LLC}, \textsuperscript{4}\textit{Lancaster University}, \textsuperscript{6}\textit{Ceramics Ltd.}

Electrons in the LHC, October 2019
How much RF power do we need per cavity in PERLE?

The issue

What can we do?

Reactive Tuners

Ferroelectric Material

Prototype Tuner

Experimental Results

Case Studies

Conclusion

How much power do we "need"?

No beam loading.

\[ P_0 = \frac{V^2}{Q_0} \]

\[ P_0 \approx 44 \text{ W} \]

How much power is budgeted?

\[ P_{avg}^{RF} \approx 23 \text{ kW} \]

\[ P_{peak}^{RF} \approx 45 \text{ kW} \]

Table: PERLE Cavity Parameters

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Why so much power?

- Microphonics!
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- $\approx 99.8\%$ of power is reflected and...
Why so much power?

- Microphonics!
- Detuning $\gg$ natural cavity bandwidth.
- $Q_e \ll Q_0$
- $\approx 99.8\%$ of power is reflected and
- Dissipated in load.

$P_{RF} = \frac{V^2}{4Q\gamma Q_L} \left[ 1 + \left( \frac{2Q_L \Delta \omega_i}{\omega_0} \right)^2 \right]$
What can we do?

- What we already do.
  - Design stiff cavities/cryomodules
  - Reduce noise sources.
  - Use over-coupled power couplers

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- **What we’ve just started doing.**
  - Actively compensate microphonics with fast piezo tuners.²

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- What we already do.
  - Design stiff cavities/cryomodules
  - Reduce noise sources.
  - Use over-coupled power couplers
- What we’ve just started doing.
  - Actively compensate microphonics with fast piezo tuners.²
- What we are proposing.
  - Actively compensate microphonics with FerroElectric Fast Reactive Tuner **FE-FRT**!

How does it work?

\[ \Delta \omega_{12} = -\omega_0 \Delta B'_{t12} \sqrt{L_c/C_c} / 2N^2 \]

\[ \Delta BW_n = \frac{G'_{tn}}{N^2 C_c} \]
Other Reactive Tuners

Pin Diode Tuners


D. Schulze et al., in *Proc. 1972 Proton Linear Accelerator Conference*, Los Alamos, NM, USA, October 1972, G01, pp. 156–162.

Ferrite Tuners

Why use an FE-FRT?

- No moving parts
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- Outside cryomodule
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- Outside cryomodule
- Continuous tuning range
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- So why hasn’t this been done before?

---

Newly Developed Ferroelectric

Suitable material only recently developed.\textsuperscript{4}

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  - BaTiO\(_3\) - SrTiO\(_3\) solid solution (BST)
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- Added linear (non-tunable) Mg-based ceramic component\(^5\)

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  - \(\text{BaTiO}_3 - \text{SrTiO}_3\) solid solution (BST)
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  - Enhanced tunability with low losses

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**Table:** Material Properties at \(\approx 800\) MHz

<table>
<thead>
<tr>
<th>Parameter</th>
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<tbody>
<tr>
<td>Max. (\varepsilon_r)</td>
<td>140</td>
</tr>
<tr>
<td>Min. (\varepsilon_r)</td>
<td>131.6</td>
</tr>
<tr>
<td>(\tan \delta)</td>
<td>(9.1 \times 10^{-4})</td>
</tr>
<tr>
<td>(\Delta \varepsilon_r/\varepsilon)</td>
<td>0.6 kV(^{-1}) cm</td>
</tr>
<tr>
<td>(\tau)</td>
<td>(&lt; 10) ns</td>
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Prototype Tuner, 3D model and transmission line model.
Experimental Setup

FE-FRT mounted on cryostat.

Cryostat insert.
Demonstration of Frequency Tuning

Signal analyser measurement.

Experimental Setup.
Demonstration of Frequency Tuning

Signal analyser measurement.

Experimental Setup.

Frequency calculated from I and Q measurements.
Timescale of Frequency Shift

Fall time and $\text{std}(f)$ vs. regression window length.
Timescale of Frequency Shift

Cavity response to tuner < 50 µs

Fall time and $\text{std}(f)$ vs. regression window length.
Timescale of Frequency Shift

- Cavity response to tuner $< 50 \mu s$
- Cavity time constant $\tau_L = \frac{Q_L}{\omega_0} \approx 46 \text{ ms}$

Fall time and $\text{std}(f)$ vs. regression window length.
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Fall time and $\text{std}(f)$ vs. regression window length.

- Cavity response to tuner $< 50 \mu s$
- Cavity time constant $\tau_L = \frac{Q_L}{\omega_0} \approx 46 \text{ ms}$
- Cavity responds faster to FE-FRT than $\tau_L$. 
FoM and Frequency Dependence

\[
\text{FoM} \approx \frac{2|\sin \frac{\Delta \theta_{12}}{2}|}{\sqrt{(1 - |\Gamma_1|^2)(1 - |\Gamma_2|^2)}}
\]

FoM larger for:
- lower losses
- greater phase change

Larger FoM gives:
- Increased tuning range
- Decreased bandwidth
- Decreased forward power

\[
P_{\text{avg}} \text{RF reduced by } \text{FoM}^4
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P_{\text{peak}} \text{RF reduced by } \text{FoM}^2
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FoM larger for lower losses.

Increased tuning range, decreased bandwidth, decreased forward power due to larger FoM.

P_{\text{avg}} \text{RF} \text{reduced by FoM}_4

P_{\text{peak}} \text{RF} \text{reduced by FoM}_2
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  - Decreased forward power \( P_{\text{avg RF}} \) reduced by \( \text{FoM}^4 \)
  - Decreased peak power \( P_{\text{peak RF}} \) reduced by \( \text{FoM}^2 \)
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- $P_{RF}^{avg}$ reduced by $\frac{\text{FoM}}{4}$
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Figure of Merit (FoM) and Frequency Dependence

- $P_{RF}^{\text{avg}}$ reduced by $\frac{\text{FoM}}{4}$
- $P_{RF}^{\text{peak}}$ reduced by $\frac{\text{FoM}}{2}$

- $\alpha_c = 2.98 \times 10^{-7} \sqrt{f} \frac{1}{b} (1 + \frac{b}{a}) \frac{\epsilon}{\ln \frac{b}{a}} \text{dB/m}$
## Figure of Merit (FoM) and Frequency Dependence

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<td>$\alpha_d$</td>
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- Monte Carlo, transmission line model
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- FoM frequency dependence
- Cross-checked with CST simulations

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- Monte Carlo, transmission line model
- FoM frequency dependence
- Cross-checked with CST simulations
- Better for lower frequencies
### Case Studies

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<thead>
<tr>
<th>Parameter</th>
<th>eRHIC</th>
<th>PERLE</th>
<th>LHeC</th>
<th>Cornell</th>
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<tbody>
<tr>
<td>Frequency</td>
<td>647.4 MHz</td>
<td>801.58 MHz</td>
<td>801.58 MHz</td>
<td>1.3 GHz</td>
</tr>
<tr>
<td>Cavity Voltage $V_c$</td>
<td>26.88 MV</td>
<td>18.7 MV</td>
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<td>13.1 MV</td>
</tr>
<tr>
<td>External Q-Factor of FPC $Q_e$</td>
<td>$1.60 \times 10^7$</td>
<td>$1.00 \times 10^7$</td>
<td>$1.56 \times 10^7$</td>
<td>$6.5 \times 10^7$</td>
</tr>
<tr>
<td>Intrinsic Q-Factor $Q_0$</td>
<td>$2.00 \times 10^{10}$</td>
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</tr>
<tr>
<td>$R/Q$</td>
<td>502 Ω</td>
<td>393 Ω</td>
<td>393 Ω</td>
<td>387 Ω</td>
</tr>
<tr>
<td>Peak Detuning $\Delta \omega_{\mu peak}$</td>
<td>20.0 Hz</td>
<td>40.0 Hz</td>
<td>26.2 Hz</td>
<td>20.0 Hz</td>
</tr>
<tr>
<td>RMS Detuning $\sigma(\Delta \omega_{\mu})$</td>
<td>3.33 Hz</td>
<td>6.67 Hz</td>
<td>4.36 Hz</td>
<td>3.33 Hz</td>
</tr>
<tr>
<td>Accelerating Gradient $E_{acc}$</td>
<td>16 MV/m</td>
<td>20 MV/m</td>
<td>20 MV/m</td>
<td>16.2 MV/m</td>
</tr>
<tr>
<td>Cavity Length</td>
<td>1.68 m</td>
<td>0.935 m</td>
<td>0.935 m</td>
<td>0.81 m</td>
</tr>
<tr>
<td>Final Beam Energy</td>
<td>20 GeV</td>
<td>0.9 GeV</td>
<td>60 GeV</td>
<td>5 GeV</td>
</tr>
<tr>
<td>ERL Passes</td>
<td>12</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Number of Cavities</td>
<td>62</td>
<td>16</td>
<td>1069</td>
<td>384</td>
</tr>
<tr>
<td>Grid to RF conversion efficiency</td>
<td>$\approx 70%$</td>
<td>$\approx 50%$</td>
<td>$\approx 70%$</td>
<td>$\approx 50%$</td>
</tr>
<tr>
<td>Total Electrical Power for microphonics control</td>
<td>1.37 MW</td>
<td>732 kW</td>
<td>22.2 MW</td>
<td>734 kW</td>
</tr>
</tbody>
</table>

- **Black**: From a reference
- **Orange**: Calculated from a referenced value
- **Red**: Estimated
Case Studies

<table>
<thead>
<tr>
<th>Parameter</th>
<th>eRHIC</th>
<th>PERLE</th>
<th>LHeC</th>
<th>Cornell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>647.4 MHz</td>
<td>801.58 MHz</td>
<td>801.58 MHz</td>
<td>1.3 GHz</td>
</tr>
<tr>
<td>Cavity Voltage – $V_c$</td>
<td>26.88 MV</td>
<td>18.7 MV</td>
<td>18.7 MV</td>
<td>13.1 MV</td>
</tr>
<tr>
<td>External Q-Factor of FPC – $Q_e$</td>
<td>$1.60 \times 10^7$</td>
<td>$1.00 \times 10^7$</td>
<td>$1.56 \times 10^7$</td>
<td>$6.5 \times 10^7$</td>
</tr>
<tr>
<td>Intrinsic Q-Factor – $Q_0$</td>
<td>$2.00 \times 10^{10}$</td>
<td>$2.00 \times 10^{10}$</td>
<td>$2.00 \times 10^{10}$</td>
<td>$2.00 \times 10^{10}$</td>
</tr>
<tr>
<td>$R/Q$</td>
<td>502 Ω</td>
<td>393 Ω</td>
<td>393 Ω</td>
<td>387 Ω</td>
</tr>
<tr>
<td>Peak Detuning – $\Delta \omega_{\mu peak}$</td>
<td>20.0 Hz</td>
<td>40.0 Hz</td>
<td>26.2 Hz</td>
<td>20.0 Hz</td>
</tr>
<tr>
<td>RMS Detuning – $\sigma(\Delta \omega_{\mu})$</td>
<td>3.33 Hz</td>
<td>6.67 Hz</td>
<td>4.36 Hz</td>
<td>3.33 Hz</td>
</tr>
<tr>
<td>Accelerating Gradient – $E_{acc}$</td>
<td>16 MV/m</td>
<td>20 MV/m</td>
<td>20 MV/m</td>
<td>16.2 MV/m</td>
</tr>
<tr>
<td>Cavity Length</td>
<td>1.68 m</td>
<td>0.935 m</td>
<td>0.935 m</td>
<td>0.81 m</td>
</tr>
<tr>
<td>Final Beam Energy</td>
<td>20 GeV</td>
<td>0.9 GeV</td>
<td>60 GeV</td>
<td>5 GeV</td>
</tr>
<tr>
<td>ERL Passes</td>
<td>12</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Number of Cavities</td>
<td>62</td>
<td>16</td>
<td>1069</td>
<td>384</td>
</tr>
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</tbody>
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- **Black**: From a reference
- **Orange**: Calculated form a referenced value
- **Red**: Estimated
- **Every effort was made to ensure consistency.**
- **No guarantee that these are the latest accepted values.**
Case Studies - PERLE

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

- Total Electrical Power: 732 kW → 97.6 kW
- Peak RF Power per Cavity: 44.4 kW → 3.05 kW
- Avg. Fwd. RF Power per Cavity: 22.9 kW → 3.05 kW
Case Studies - PERLE

A Ferroelectric Fast Reactive Tuner
N. Shipman

The issue
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Reactive Tuners
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Prototype Tuner
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\[ P_{RF} = \frac{V_c^2}{4\frac{R}{Q}QL} \frac{\beta + 1}{\beta} \left[ 1 + \left( 2QL \frac{\Delta \omega_{\mu}}{\omega_0} \right)^2 \right] \]

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- Avg. Fwd. RF Power per Cavity 22.9 kW → 3.05 kW

Peak power per cavity 44.4 kW → 3.05 kW
Case Studies - PERLE

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Case Studies - LHeC

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

Peak power per cavity 29 kW → 1.94 kW

Total Electrical Power 22.2 MW → 2.96 MW

Without FE-FRT

With FE-FRT
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\[ P_{RF} = \frac{V_c^2}{4R/Q Q_L} \frac{\beta + 1}{\beta} \left[ 1 + \left( 2Q_L \frac{\Delta \omega}{\omega_0} \right)^2 \right] \]

![Graph showing peak power per cavity reduction from 29.1 kW to 1.94 kW with and without FE-FRT](image)

- Peak power per cavity: 29.1 kW → 1.94 kW

- Total Electrical Power: 22.2 MW → 2.96 MW
- Peak RF Power per Cavity: 29.1 kW
- Avg. RF Power per Cavity: 14.5 kW

Without FE-FRT
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$$P_{RF} = \frac{V_c^2}{4R/Q Q_L} \frac{\beta + 1}{\beta} \left[ 1 + \left( \frac{2QL}{\omega_0} \Delta \omega \mu \right)^2 \right]$$

- Peak power per cavity $29.1 \text{ kW} \rightarrow 1.94 \text{ kW}$
- Total Electrical Power $22.2 \text{ MW} \rightarrow 2.96 \text{ MW}$

Peak power per cavity $29.1 \text{ kW} \rightarrow 1.94 \text{ kW}$

Total Electrical Power $22.2 \text{ MW} \rightarrow 2.96 \text{ MW}$
Tested an FE-FRT with SC RF Cavity: World First!
Tested an FE-FRT with SC RF Cavity: World First!

Ferroelectric parameters are excellent.
Conclusion

- Tested an FE-FRT with SC RF Cavity: World First!
- Ferroelectric parameters are excellent.
- Extremely fast $< 50 \mu s$
Tested an FE-FRT with SC RF Cavity: World First!

- Ferroelectric parameters are excellent.
- Extremely fast $< 50 \mu s$
  - Not limited by cavity time constant.
- Outside cryomodule, no moving parts $\rightarrow$ easy maintenance and high reliability.
Conclusion

- Tested an FE-FRT with SC RF Cavity: World First!
- Ferroelectric parameters are excellent.
- Extremely fast $< 50 \mu s$
  - Not limited by cavity time constant.
- Outside cryomodule, no moving parts $\rightarrow$ easy maintenance and high reliability.
- Microphonics compensation must be experimentally demonstrated.
Conclusion

- Tested an FE-FRT with SC RF Cavity: World First!
- Ferroelectric parameters are excellent.
- Extremely fast < 50 µs
  - Not limited by cavity time constant.
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- Brazing losses must be addressed.
Conclusion

- Tested an FE-FRT with SC RF Cavity: World First!
- Ferroelectric parameters are excellent.
- Extremely fast < 50 $\mu$s
  - Not limited by cavity time constant.
- Outside cryomodule, no moving parts $\rightarrow$ easy maintenance and high reliability.
- Microphonics compensation must be experimentally demonstrated.
- Brazing losses must be addressed.
- Could reduce power requirements by an order of magnitude or more.
Thank you for listening.

Any Questions?

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Case Study references


- W. Xu et al., “Progress of 650 MHz SRF cavity for eRHIC SRF linac”, in *18th International Conference on RF Superconductivity*, Lanzhou, 2017, pp. 64–66.


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Experimental Setup
Where is an FE-FRT likely to be most useful?

- Low beam loading machines
- ERLs
- Heavy Ion Accelerators
- If repetitive mechanical stresses must be avoided
- Whenever you need really fast tuning
- Where easy maintainability is a key concern
PERLE Case Study

Table: PERLE SC 5-cell Cavity Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_0$</td>
<td>801.58 MHz</td>
</tr>
<tr>
<td>$Q_0$</td>
<td>$2 \times 10^{10}$</td>
</tr>
<tr>
<td>$R/Q$</td>
<td>393 Ω</td>
</tr>
<tr>
<td>$Q_{FPC}$</td>
<td>$10^7$</td>
</tr>
<tr>
<td>$P_{RF}$</td>
<td>45 kW</td>
</tr>
<tr>
<td>Max. $\Delta f_\mu$</td>
<td>40 Hz</td>
</tr>
</tbody>
</table>

Table: Material Properties at $\approx 800$ MHz

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. $\epsilon_r$</td>
<td>140</td>
</tr>
<tr>
<td>Min. $\epsilon_r$</td>
<td>131.6</td>
</tr>
<tr>
<td>$\tan \delta$</td>
<td>$9.1 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\Delta \epsilon_r/E$</td>
<td>0.6 kV$^{-1}$cm</td>
</tr>
<tr>
<td>$\sigma_{Cu}$</td>
<td>$5.96 \times 10^{-7}$ S/m</td>
</tr>
</tbody>
</table>
PERLE Case Study

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

Table: FE-FRT properties for PERLE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>FoM</td>
<td>30</td>
</tr>
<tr>
<td>( \Delta f_t )</td>
<td>80</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. ( P_t )</td>
<td>71 kVar</td>
</tr>
</tbody>
</table>

\( P_f \) vs \( Q_{FPC} \) for PERLE. **Without tuner and with tuner.**

- \( 15 \) fold reduction in RF power
- We can do even better at lower frequencies!
- \( \alpha_d = 9.11 \times 10^{-8} f \sqrt{\varepsilon_r} \tan \delta \)
- \( \tan \delta \propto f \)
- Dielectric losses \( \propto f^2 \)
How does it work?

State Ratio \(_n = \frac{\Delta \omega_{12}}{\Delta BW_n}\)

State Ratio \(_n = \frac{\Delta B_t}{2G_{tn}}\)

FoM = \(\sqrt{SR_1 \times SR_2}\)

FoM = \(\sqrt{\frac{(\Delta B_t)^2}{4G_1G_2}}\)

\[\text{FoM} = \frac{\Delta \omega_{12}}{\sqrt{\Delta BW_1 \Delta BW_2}} \approx \frac{2|\sin \frac{\Delta \theta_{12}}{2}|}{\sqrt{(1 - |\Gamma_1|^2)(1 - |\Gamma_2|^2)}}\]
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### Experimental Results

**Without FE-FRT**
- Total Electrical Power: 1.97 MW
- Peak RF Power per Cavity: 44.5 kW
- Avg. RF Power per Cavity: 22.3 kW
- Power: 207 kW

**With FE-FRT**
- Total Electrical Power: 1.97 MW
- Peak RF Power per Cavity: 2.34 kW
- Avg. RF Power per Cavity: 2.34 kW

---

**Legend:**
- Red: Without FE-FRT
- Blue: With FE-FRT
Case Studies - Cornell Light Source ERL

![Graph showing power comparison]

- Total Electrical Power: Without FE-FRT 734 kW, With FE-FRT 271 kW
- Peak Fwd. RF Power per Cavity: Without FE-FRT 4.28 kW, With FE-FRT 353 W