A FerroElectric Fast Reactive Tuner(FE-FRT) for ERLs

Reducing power consumption by microphonics compensation

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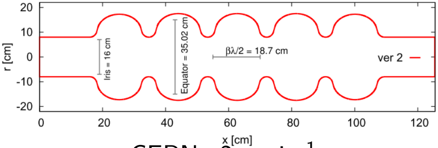
[1]CERN, [2]Brookhaven National Laboratory, [3]Euclid Techlabs LLC, [4]Lancaster University, [6]Ceramics Ltd.

Electrons in the LHC, October 2019

How much RF power do we need per cavity in PERLE?



CERN v2 cavity[1]

Table: PERLE Cavity Parameters

Parameter	**Value**
Q_0	2×10^{10}
R/Q	$393\,\Omega$
V_c	$18.7\,\mathrm{MV}$

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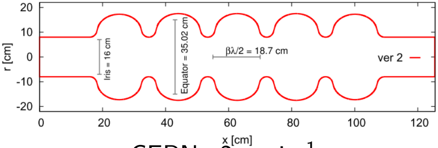

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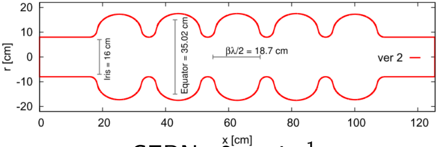

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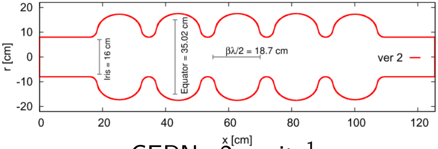

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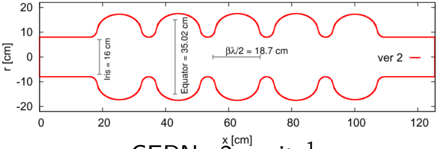

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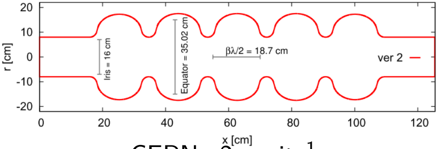

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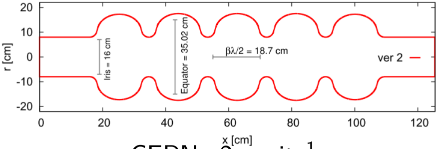

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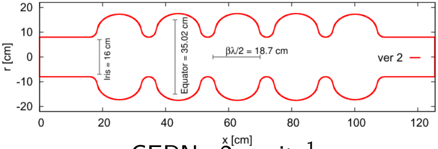

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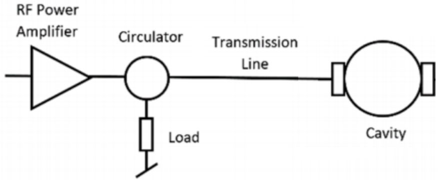

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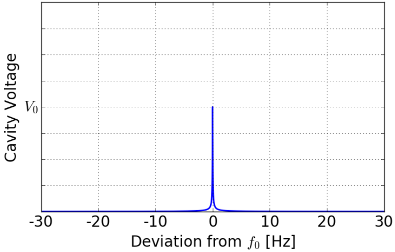

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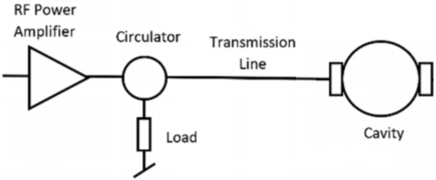

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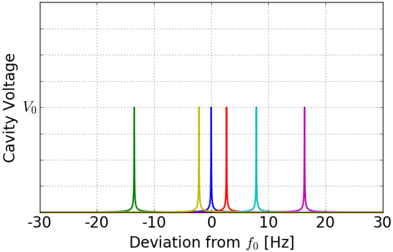

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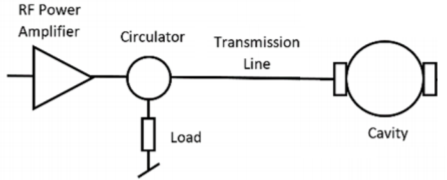

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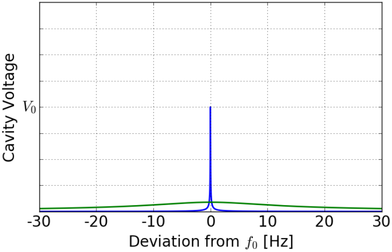

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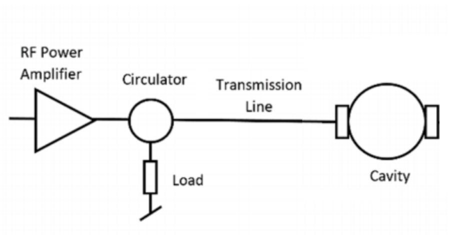

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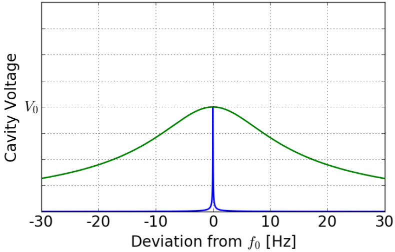

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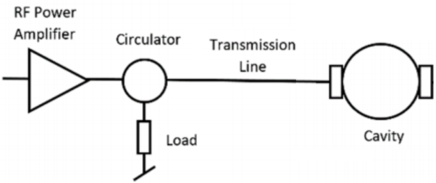

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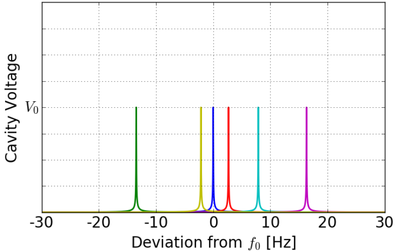

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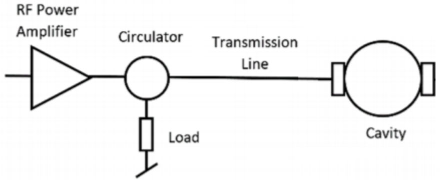

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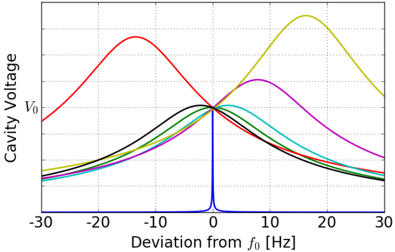

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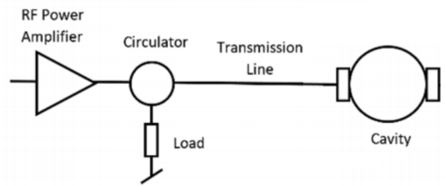

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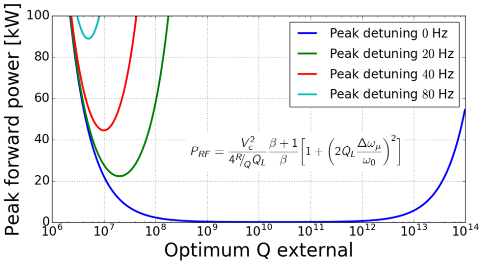

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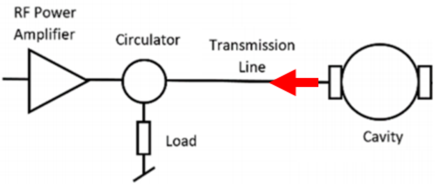

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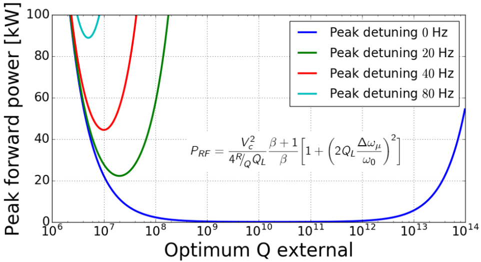

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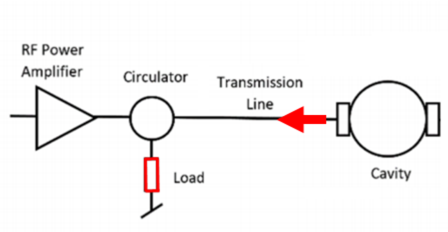

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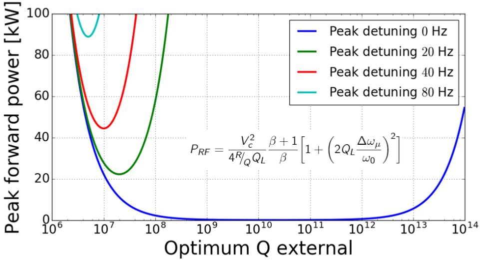
- Dissipated in load.



What can we do?

- What we already do.
  - Design stiff cavities/cryomodules
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- What we are proposing.
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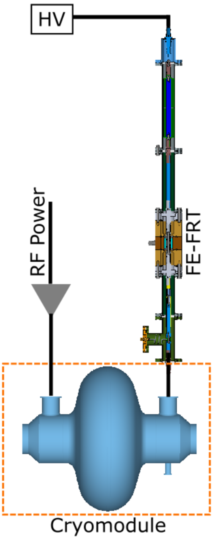
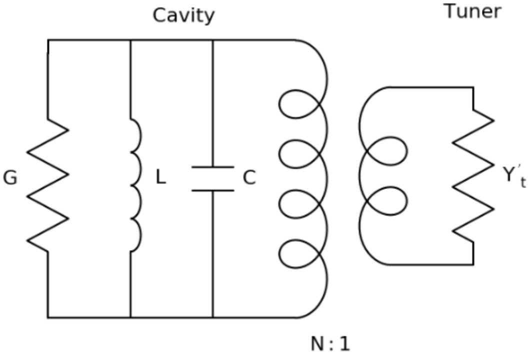
How does it work?



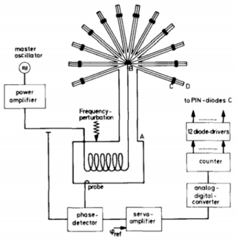


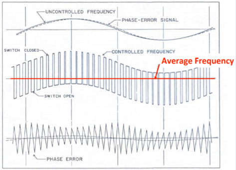
$$\Delta\omega_{12} = \frac{-\omega_0 \Delta B'_{t12} \sqrt{{}^{L_c}\!/_{C_c}}}{2N^2}$$

$$\Delta \mathrm{BW}_n = \frac{G'_{tn}}{N^2 C_c}$$

Other Reactive Tuners

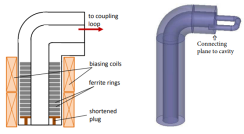
Pin Diode Tuners





O. Despe, K. Johnson and T. Khoe, *IEEE Trans. Nucl. Sci.*, vol. 20 (3), p. 71, Jun. 1973.
D. Schulze *et al.*, in *Proc. 1972 Proton Linear Accelerator Conference*, Los Alamos, NM, USA, October 1972, G01, pp. 156–162.

Ferrite Tuners



C. Vollinger and F. Caspers, "Ferrite-tuner Development for 80 MHz Single-Cell RF-Cavity Using Orthogonally Biased Garnets", in *Proc. IPAC'15*, Richmond, VA, USA, May 2015.

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- So why hasn't this been done before?

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Table: Material Properties at $\approx 800\,\mathrm{MHz}$

Parameter	Value
Max. ϵ_r	140
Min. ϵ_r	131.6
$\tan\delta$	9.1×10^{-4}
$\frac{\Delta\epsilon_r}{E}$	$0.6\ \mathrm{kV^{-1}cm}$
τ	$< 10\,\mathrm{ns}$

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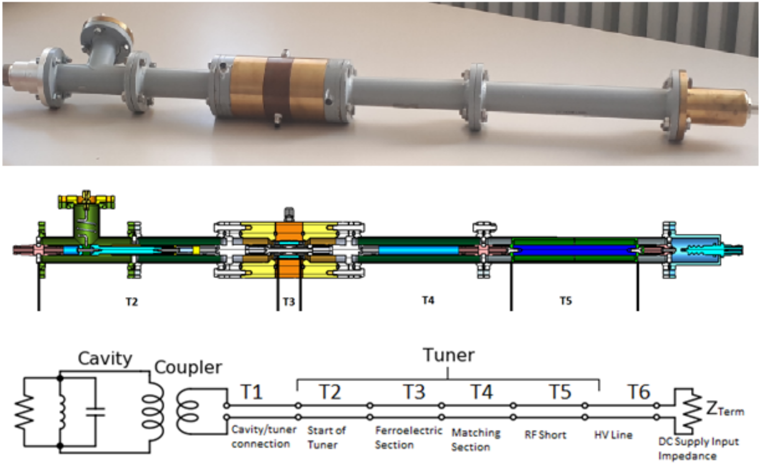
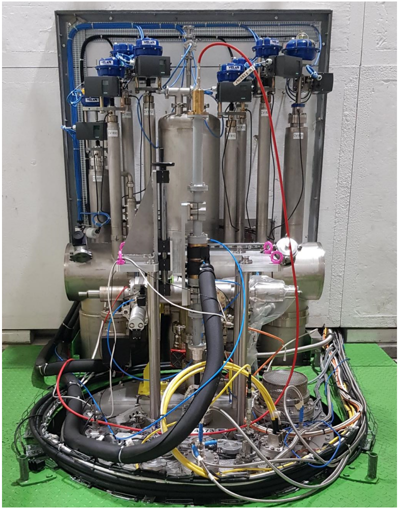
Prototype Tuner



Prototype Tuner, 3D model and transmission line model.

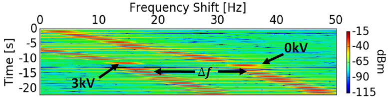
Experimental Setup



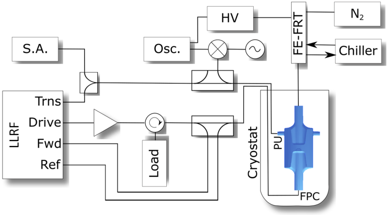
FE-FRT mounted on cryostat.

Cryostat insert.

Demonstration of Frequency Tuning



Signal analyser measurement.



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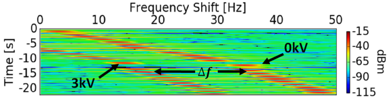

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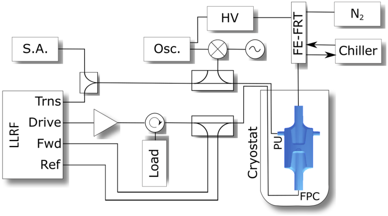

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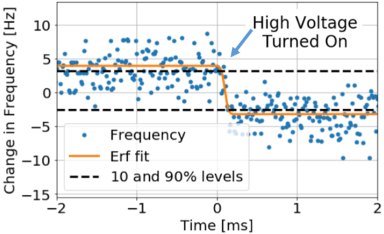
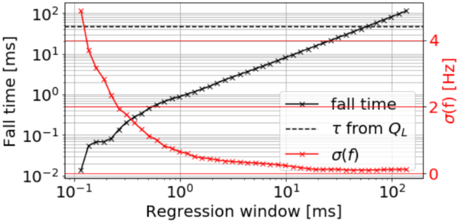


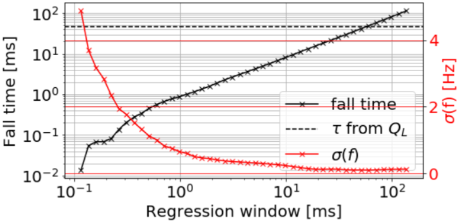
Frequency calculated from I and Q measurements.

Timescale of Frequency Shift



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

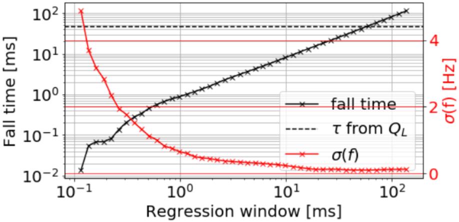
Timescale of Frequency Shift



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

- Cavity response to tuner $< 50\,\mu\mathrm{s}$

Timescale of Frequency Shift



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

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

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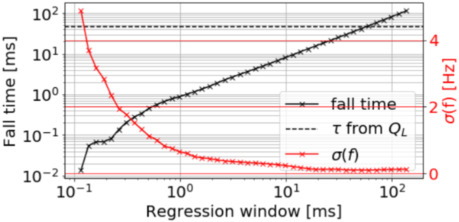

Fall time and $\mathrm{std}(f)$ vs. regression window length.

- Cavity response to tuner $< 50\,\mu\mathrm{s}$
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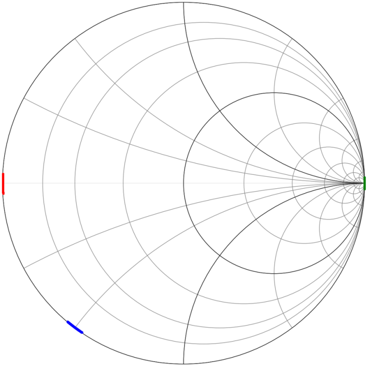
- Cavity responds faster to FE-FRT than τ_L.

FoM and Frequency Dependence

$$\boxed{\mathrm{FoM} \approx \frac{2\left|\sin\frac{\Delta\theta_{12}}{2}\right|}{\sqrt{(1-|\Gamma_1|^2)(1-|\Gamma_2|^2)}}}$$



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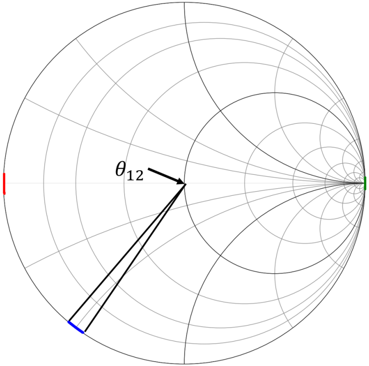

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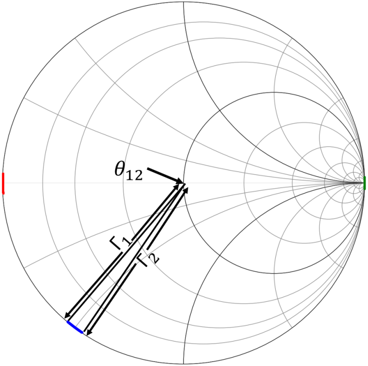

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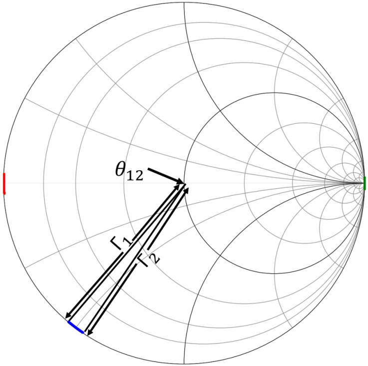

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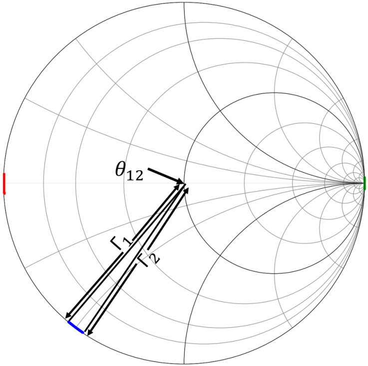

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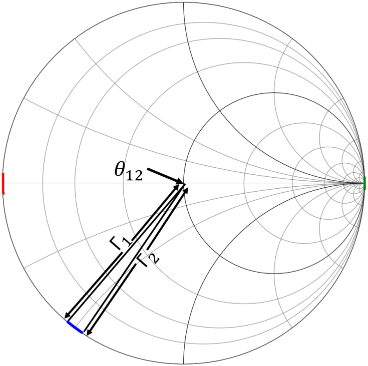

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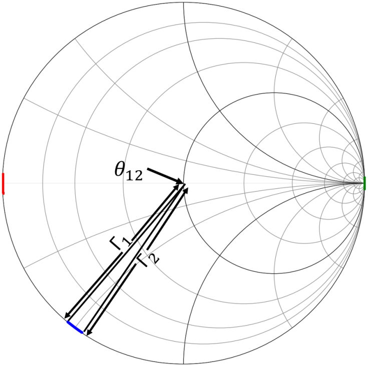

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- Larger FoM gives:
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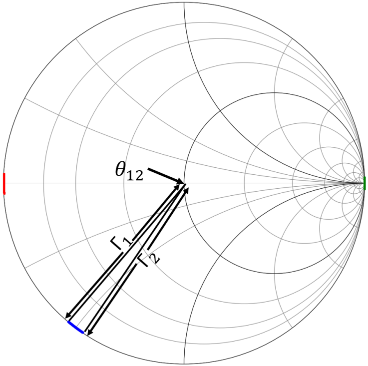
  - Decreased bandwidth



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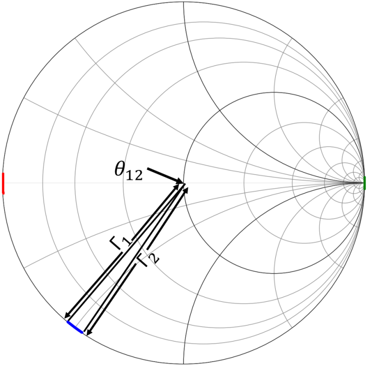

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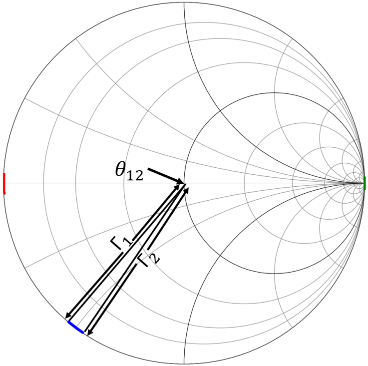

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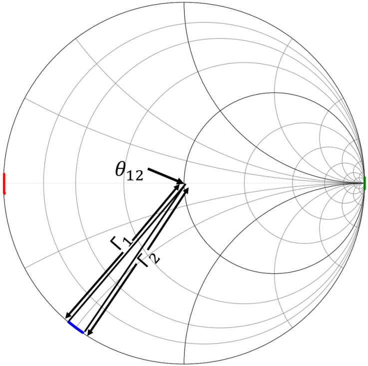

Figure of Merit (FoM) and Frequency Dependence

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

- $\alpha_c = 2.98\ 10^{-7}\sqrt{f}\,\frac{1}{b}(1+\frac{b}{a})\frac{\epsilon}{\ln\frac{b}{a}}\ \mathrm{dB/m}$

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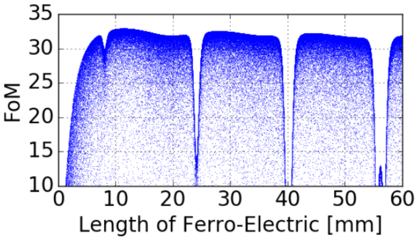

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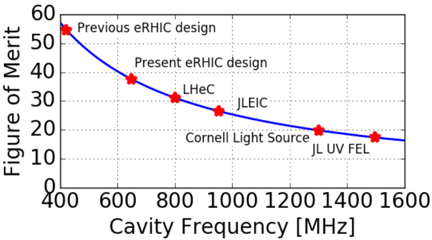

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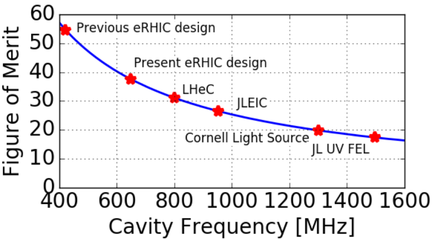

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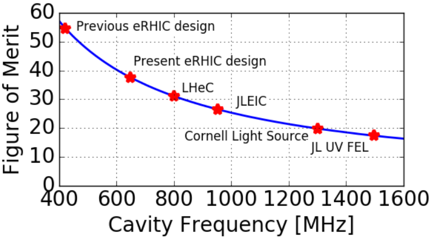

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- FoM frequency dependence
- Cross-checked with CST simulations
- Better for lower frequencies

Case Studies

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

- Black: From a reference
- Orange: Calculated form a referenced value
- Red: Estimated

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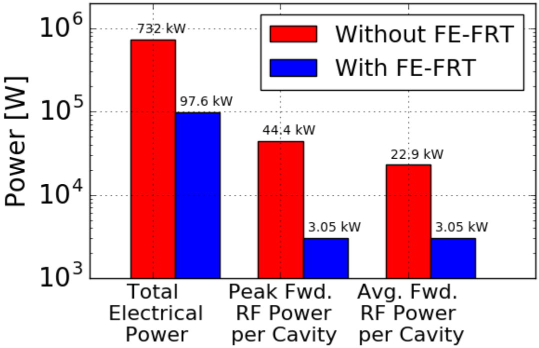
- Every effort was made to ensure consistency.
- No guarantee that these are the latest accepted values.

Case Studies - PERLE

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



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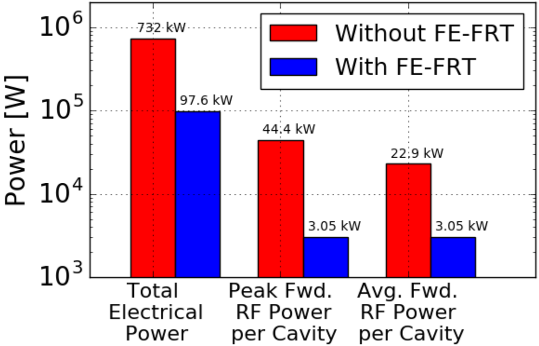

- Peak power per cavity $44.4\,\mathrm{kW} \rightarrow 3.05\,\mathrm{kW}$

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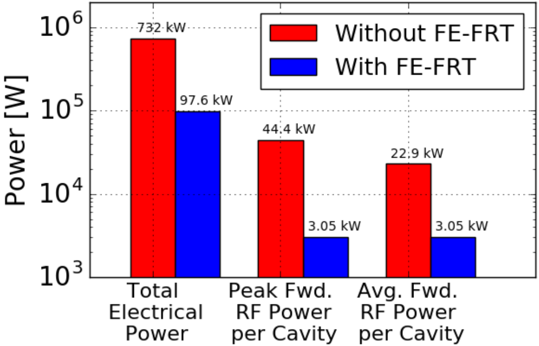

- Peak power per cavity 44.4 kW → 3.05 kW
- Total Electrical Power 732 kW → 97.6 kW

Case Studies - LHeC

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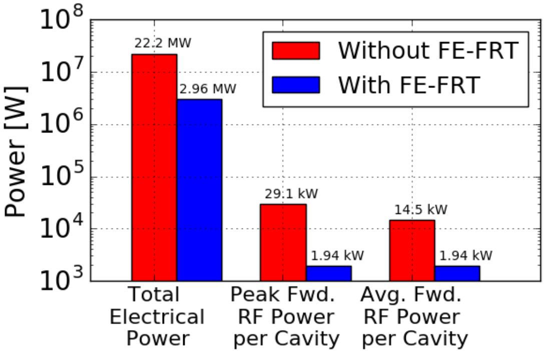

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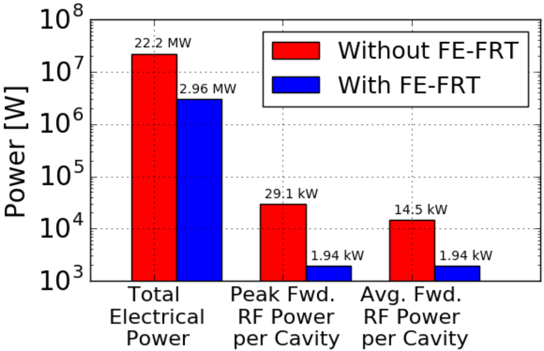

- Peak power per cavity 29.1 kW → 1.94 kW

Case Studies - LHeC

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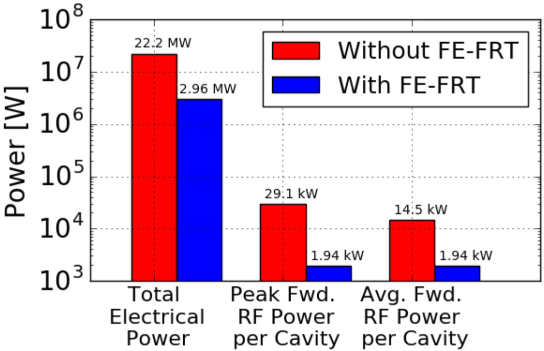

- Peak power per cavity 29.1 kW → 1.94 kW
- Total Electrical Power **22.2 MW → 2.96 MW**

Conclusion

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- Microphonics compensation must be experimentally demonstrated.
- Brazing losses must be addressed.
- Could reduce power requirements by an order of magnitude or more.

Thank You

Thank you for listening.

Any Questions?

- N. Shipman *et al.*,"A Ferroelectric Fast Reactive Tuner for Superconduting Cavities", in *SRF 2019*, Dresden, Germany, Jul. 2019.
- N. Shipman *et al.*,"A FerroElectric Fast Reactive Tuner (FE-FRT) to Combat Microphonics", in *ERL 2019*, Berlin, Germany, Sep. 2019.

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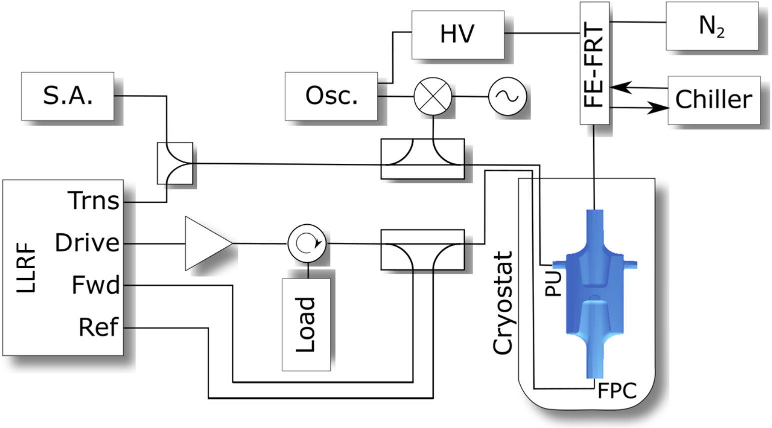
Back Up Slides

Case Study references

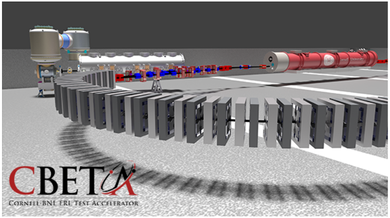
- E. G. H. Hoffstaetteret *et al.*, "Cornell Energy Recovery Linac Science Case and Project Definition Design Report",*Cornell Tech. Rep.*, 2013, p. 518.
- E. C. Aschenauer *et al.*, "eRHIC Design Study: An Electron Ion Collider at BNL", *Tech. Rep.*, Sep. 2014.
- W. Xu *et al.*, "RF and Mechanical Design of 647 MHz 5-CELL BNL4 Cavity for eRHIC ERL", in *Proceedings of IPAC2016*, Busan, 2014.
- 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.
- D. Angal-Kalinin *et al.*, "PERLE. Powerful energy recovery linac for experiments. Conceptual design report", *Journal of Physics G: Nuclear and Particle Physics*, vol. 45, no. 6, pp. 065 003, Jun. 2018.
- J. L. Abelleira Fernandez *et al.*, "A Large Hadron Electron Collider at CERN Report on the Physics and Design Concepts for Machine and Detector", *Journal of Physics G: Nuclear and Particle Physics*, vol. 39, no. 7, pp. 075 001, Jul. 2012.
- R. Calaga, "A design for an 802 MHz ERL Cavity," *CERN-ACC-NOTE-2015-0015*, 2015. .

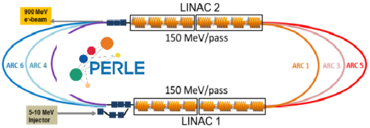
Experimental Setup

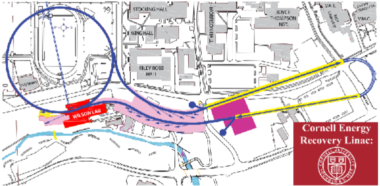


Where is an FE-FRT likely to be most useful?

- 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

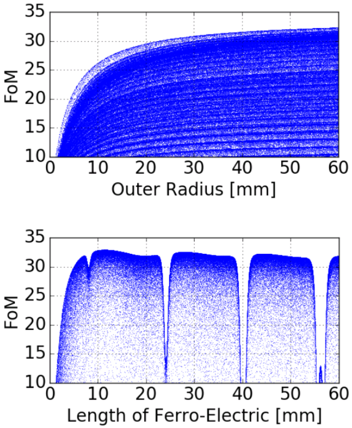
Table: PERLE SC 5-cell Cavity Parameters

Parameter	**Value**
ω_0	$801.58\,\mathrm{MHz}$
Q_0	2×10^{10}
$^{R}/_{Q}$	$393\,\Omega$
Q_{FPC}	10^7
P_{RF}	$45\,\mathrm{kW}$
Max. Δf_μ	$40\,\mathrm{Hz}$

Table: Material Properties at $\approx 800\,\mathrm{MHz}$

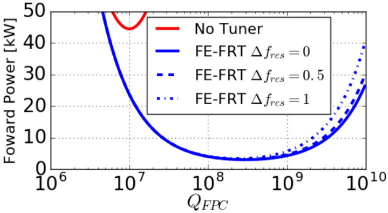
Parameter	**Value**
Max. ϵ_r	140
Min. ϵ_r	131.6
$\tan\delta$	9.1×10^{-4}
$\frac{\Delta\epsilon_r}{E}$	$0.6\ \mathrm{kV}^{-1}\mathrm{cm}$
σ_{Cu}	$5.96 \times 10^{-7}\,\mathrm{S/m}$

Monte Carlo method applied to FE-FRT Transmission Line Model for $801.58\,\mathrm{MHz}$.



PERLE Case Study

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



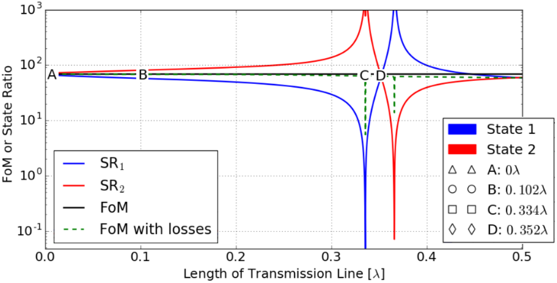
P_f vs Q_{FPC} for PERLE. Without tuner and with tuner.

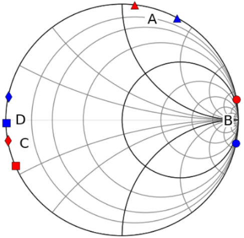
Table: FE-FRT properties for PERLE

Parameter	**Value**
FoM	30
Δf_t	80
Q_{FPC}	3×10^8
P_{RF}	$3\,\mathrm{kW}$
P_t	$2.4\,\mathrm{kW}$
Max. $\mathcal{P}_t$	$71\,\mathrm{kVar}$

- $\approx$ 15 fold reduction in RF power
- We can do even better at lower frequencies!
- $\alpha_d = 9.11 \times 10^{-8} f \sqrt{\epsilon_r} \tan\delta$
- $\tan\delta \propto f$
- Dielectric losses $\propto f^2$

How does it work?





$$\text{State Ratio}_n = \frac{\Delta\omega_{12}}{\Delta \mathrm{BW}_n}$$

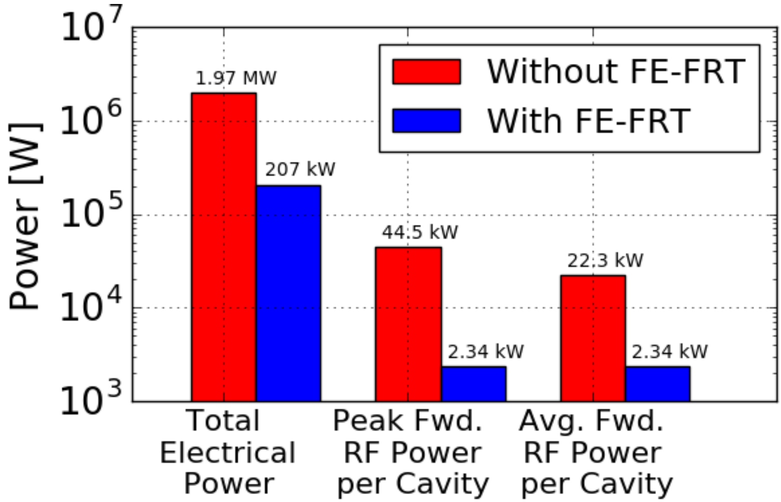
$$\text{FoM} = \sqrt{\mathrm{SR}_1 \times \mathrm{SR}_2}$$

$$\text{State Ratio}_n = \frac{\Delta B_t}{2G_{tn}}$$

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

$$\boxed{\mathbf{FoM} = \frac{\boldsymbol{\Delta\omega_{12}}}{\sqrt{\boldsymbol{\Delta}\mathrm{BW}_1\boldsymbol{\Delta}\mathrm{BW}_2}} \approx \frac{2|\sin\frac{\Delta\theta_{12}}{2}|}{\sqrt{(1-|\Gamma_1|^2)(1-|\Gamma_2|^2)}}}$$

Case Studies - eRHIC



Case Studies - Cornell Light Source ERL