

A Ferroelectric Fast Reactive Tuner

N. Shipman

Reactive Tuners

Ferroelectri Material

Applications

Prototype Tuner

Experimenta Results

Conclusion

A Ferroelectric Fast Reactive Tuner for Superconducting Cavities

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Paper WETEB7



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New class of tuner.



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New class of tuner.

Fast (really fast).



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Fast (really fast).

No moving parts.



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New class of tuner.

- Fast (really fast).
- No moving parts.
- Low losses.



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- New class of tuner.
- Fast (really fast).
- No moving parts.
- Low losses.
- Outside cryomodule.



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- New class of tuner.
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Eliminate microphonics.



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Reduce power.



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Eliminate microphonics.

- Reduce power.
- ERLs.



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Eliminate microphonics.

- Reduce power.
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- Heavy Ion.



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- Eliminate microphonics.
- Reduce power.
- ERLs.
- Heavy Ion.
- Nb_3Sn/New Materials.



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Thank you for Listening.

Any Questions?

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Other Reactive Tuners

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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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No moving parts

Outside cryostat

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No moving parts

Outside cryostat

Continuous tuning range

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No moving parts

Outside cryostat

Continuous tuning range

■ No need to generate a large magnetic field

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No moving parts

Outside cryostat

Continuous tuning range

No need to generate a large magnetic field
 Intrinsic speed < 10 ns¹

¹S. Kazakov *et al.*,"Fast Ferroelectric L-band Tuner", in *Proceedings of the 12th AAC Workshop*, Lake Geneva, WI, USA, Jul. 2006, AIP Conf.Proc. (877), pp. 331–338.



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No moving parts

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Continuous tuning range

■ No need to generate a large magnetic field

 \blacksquare Intrinsic speed $< 10\,{\rm ns^1}$

Low losses/small increased bandwidth

¹S. Kazakov *et al.*,"Fast Ferroelectric L-band Tuner", in *Proceedings of the 12th AAC Workshop*, Lake Geneva, WI, USA, Jul. 2006, AIP Conf.Proc. (877), pp. 331–338.



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- No moving parts
- Outside cryostat
- Continuous tuning range
- No need to generate a large magnetic field
- \blacksquare Intrinsic speed $< 10\,{\rm ns^1}$
- Low losses/small increased bandwidth
- So why hasn't this been done before?

¹S. Kazakov *et al.*,"Fast Ferroelectric L-band Tuner", in *Proceedings of the 12th AAC Workshop*, Lake Geneva, WI, USA, Jul. 2006, AIP Conf.Proc. (877), pp. 331–338.



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Suitable material only recently developed.²

²E. Nenasheva *et al., Journal of European Ceramic Society*, vol. 30, pp. 395–400, Jan. 2010.

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Suitable material only recently developed.²
 BaTiO₃ - SrTiO₃ solid solution (BST)

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■ Suitable material only recently developed.²

- \blacksquare ${\rm BaTiO_3}$ ${\rm SrTiO_3}$ solid solution (BST)
- Added linear (non-tunable) Mg-based ceramic component³

²E. Nenasheva *et al., Journal of European Ceramic Society*, vol. 30, pp. 395–400, Jan. 2010.

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

Parameter	Value
Max. ϵ_r	140
Min. ϵ_r	131.6
$ an\delta$	$9.1 imes10^{-4}$
$\frac{\Delta \epsilon_r}{F}$	$0.6 \ \mathrm{kV}^{-1} \mathrm{cm}$
τ^{-}	$< 10\mathrm{ns}$

²E. Nenasheva *et al., Journal of European Ceramic Society*, vol. 30, pp. 395–400, Jan. 2010.

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Low beam loading machines





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 Low beam loading machines

ERLs





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ERLs

Heavy Ion Accelerators





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- Low beam loading machines
- ERLs
- Heavy Ion Accelerators
- If repetitive mechanical stresses must be avoided




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

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 Low beam loading machines

- ERLs
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- If repetitive mechanical stresses must be avoided
- Whenever you need really fast tuning

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- Heavy Ion Accelerators
- If repetitive mechanical stresses must be avoided
- Whenever you need really fast tuning
- Where easy maintainability is a key concern





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Table: PERLE SC 5-cell Cavity Parameters Value Parameter $801.58\,\mathrm{MHz}$ ω_0 $2\times 10^{10}\,$ Q_0 R/Q 393 Ω U_c 141 J 10^{7} Q_{FPC} P_{RF} $45 \,\mathrm{kW}$ Max. Δf_{μ} $40\,\mathrm{Hz}$



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$\sigma_{ m Cu}$	$5.96\times 10^{-7}\mathrm{S/m}$



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	Parameter	Value
	ω_0	$801.58\mathrm{MHz}$
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	R/Q	393 Ω
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	Q_{FPC}	10 ⁷
	P_{RF}	$45\mathrm{kW}$
	Max. Δf_{μ}	$40\mathrm{Hz}$

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



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	Parameter	Value	
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	P _{RF} Max. Δf _µ	45 kW 40 Hz	

Monte Carlo method applied to FE-FRT Transmission Line Model for 801.58 MHz.



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140

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

Value

Parameter

Max. ϵ_r

Length of Ferro-Electric [mm]



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 $P_{RF} = rac{V_c^2}{4^R/_{o}Q_L}rac{eta+1}{eta} \left[1 + \left(2Q_Lrac{\Delta\omega_\mu}{\omega_0}
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Foward Power [kW] No Tuner 40 FE-FRT $\Delta f_{res} = 0$ 30 FE-FRT $\Delta f_{res} = 0.5$ FE-FRT $\Delta f_{res} = 1$ 20 10 0∟ 10⁶

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 Q_{FPC} P_f vs Q_{FPC} for PERLE. Without

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tuner and with tuner.



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50 Foward Power [kW] No Tuner 40 FE-FRT $\Delta f_{res} = 0$ 30 FE-FRT $\Delta f_{res} = 0.5$ FE-FRT $\Delta f_{res} = 1$ 20 10 0∟ 10⁶ 1010 107 10⁸ 10⁹ Q_{FPC}

 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}	$3 imes 10^8$
P _{RF}	$3\mathrm{kW}$
P_t	$2.4\mathrm{kW}$
Max. \mathcal{P}_t	$71\mathrm{kVar}$

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 P_f vs Q_{FPC} for PERLE. Without

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tuner and with tuner.

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 $\blacksquare~\approx$ 15 fold reduction in RF power

No Tuner

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 Q_{FPC}

FE-FRT $\Delta f_{res} = 0$

FE-FRT $\Delta f_{res} = 0.5$ FE-FRT $\Delta f_{res} = 1$

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tuner and with tuner.

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We can do even better at lower frequencies!

10⁹



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 P_f vs Q_{FPC} for PERLE. Without

FE-FRT $\Delta f_{res} = 0$

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We can do even better at lower frequencies!

10⁹

• $\alpha_d = 9.11 \times 10^{-8} f \sqrt{\epsilon_r} \tan \delta$



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 $\blacksquare~\approx$ 15 fold reduction in RF power

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 Q_{FPC}

 P_f vs Q_{FPC} for PERLE. Without

FE-FRT $\Delta f_{res} = 0$

FE-FRT $\Delta f_{res} = 0.5$ FE-FRT $\Delta f_{res} = 1$

We can do even better at lower frequencies!

10⁹

- $\alpha_d = 9.11 \times 10^{-8} f \sqrt{\epsilon_r} \tan \delta$
- $\ \ \, {\rm tan}\,\delta\propto f$

tuner and with tuner.

 10^{7}



A Ferroelectric Fast Reactive Tuner

N. Shipman

50

40

30

20 10

> 0^{\lfloor} 10⁶

Foward Power [kW]

Reactive Tuners

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Prototyp Tuner

Experimental Results

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Table: FE-FRT properties for PERLE

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

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 $\blacksquare~\approx$ 15 fold reduction in RF power

No Tuner

 10^{8}

 Q_{FPC}

 P_f vs Q_{FPC} for PERLE. Without

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 10^{7}

Dielectric losses $\propto f^2$



Prototype Tuner

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Prototype Tuner, 3D model and transmission line model.

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A Ferroelectric

Results

Experimental Setup





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FE-FRT mounted on cryostat.





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FE-FRT mounted on cryostat.





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FE-FRT mounted on cryostat.





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FE-FRT mounted on cryostat.





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FE-FRT mounted on cryostat.





Demonstration of Frequency Tuning

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Signal analyser measurement.



Experimental Setup.

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Demonstration of Frequency Tuning



Experimental Setup.



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Fall time and std(f) vs. regression window length.



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■ Cavity response to tuner < 50 µs

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

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Fall time and std(f) vs. regression window length.



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Fall time and std(f) vs. regression window length.

- Cavity response to tuner < 50 µs
- Cavity time constant $\tau_L = \frac{Q_L}{\omega_0} \approx 46 \,\mathrm{ms}$
- Cavity responds faster to FE-FRT than τ_L.



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• Tested an FE-FRT with SC RF Cavity: World First!



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- Tested an FE-FRT with SC RF Cavity: World First!
- Ferroelectric parameters are excellent, no further material development needed.



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• Extremely fast $< 50 \, \mu s$



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- Extremely fast << 50 μs
 - Not limited by cavity time constant.



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- \blacksquare Outside cryomodule, no moving parts \rightarrow easy maintenance and high reliability

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• Ease design and reduce cost of:



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- Ease design and reduce cost of:
 - Power Couplers



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- Ease design and reduce cost of:
 - Power Couplers
 - Cryomodules



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- Ease design and reduce cost of:
 - Power Couplers
 - Cryomodules
 - Cavities



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- Ease design and reduce cost of:
 - Power Couplers
 - Cryomodules
 - Cavities
 - RF power sources



Thank You

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Thank you for listening.

Any Questions?

Paper WETEB7

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