DETAILED DESIGN OF A TWIN-AXIAL TYPE FE-FRT FOR SASE

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Abstract

A Twin-axial type Ferro-Electric Fast Reactive Tuner (FE-FRT) is under development for UK-XFEL, aiming to provide fast and efficient microphonics suppression. The tuner consists of two magnetically coupled cylindrical resonators operating in opposing phases. In a high-frequency FE-FRT, the temperature rise may limit the tuning range. The twin-axial configuration doubles the tuning range for the same temperature rise in the ferroelectric wafers. A key innovation of this work is the use of CST eigenmodes to rapidly optimize the figure of merit (FoM) of the FRT tuner, with some approximations, by sweeping the parameter space, including the FE wafer dimensions and cavity geometry. The thermal analysis has also been performed to assess the temperature rise during operation.

INTRODUCTION

In modern particle accelerators, the frequency tuning system is a cornerstone for the stable operation of Radio Frequency (RF) cavities. It is imperative to tune these cavities to their design resonance and maintain this state amidst operational perturbations. Superconducting Radio Frequency (SRF) cavities, characterized by their extremely high-quality factors and narrow bandwidths, are particularly susceptible to resonance frequency shifts caused by mechanical vibrations, a phenomenon known as microphonics. Consequently, both ”slow” and ”fast” tuners have become indispensable components of SRF systems [1]. Fast Reactive Tuners are proposed as a method of changing the frequency in timescales that are sub microsecond, where an external reactance is coupled in parallel to the cavity reactance. In Ferroelectric-Fast Reactive Tuners (FE-FRT) an external capacitance is varied by applying a voltage across a ferroelectric [2].

The performance of an FE-FRT is primarily governed by its Figure of Merit (FoM) which is the ratio of the change in reactive power to the resistive power dissipated in the device. This paper presents a new FoM fast optimization method by CST eigenmode, and a novel FE-FRT structure specifically optimized for the 1.3 GHz superconducting cavities. We introduce a configuration that integrates an increased number of ferroelectric wafers to simplify the cooling requirements and propose an efficient optimization methodology for the FoM applicable to arbitrary geometries using electromagnetic simulation.

THE NEW TWIN-AXIAL TYPE FE-FRT

An FE-FRT typically is a coaxial resonator with ferroelectric wafers placed in capacitive gaps in series along its length. The more gaps the more efficient the device is but cooling on the central conductors becomes an issue if using two or more wafers. At L-band frequencies, and above, the FE-FRT becomes very compact and access to cool the central conductor becomes a major limitation. With two wafers it may be possible to only cool from the outside and cool the central conductor via conduction through the wafers but the temperature rise could be excessive if the power loss is too high. We propose two use two coaxial resonators in parallel, operating in a dipole mode, to share the heat load across 4 wafers rather than two, which will allow cooling only fom the outside. The new type of Twin-axial FRT structure is shown below in Fig. 1, in this type there are two sub-FRTs coupled together by the magnetic field.

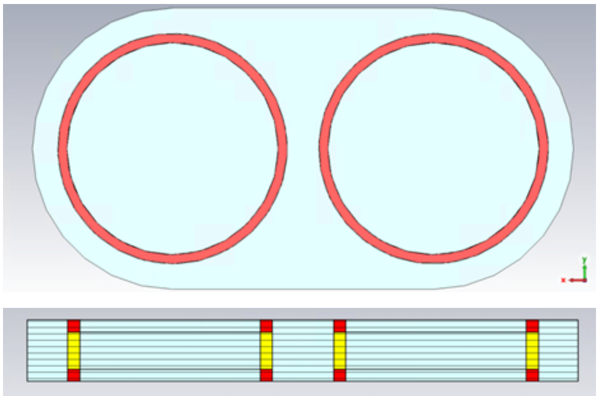

Figure 1: The geometry of the Twin-axial type FE-FRT

SRF Cavities and Microphonics

The energy stored (U_c) in an SRF cavity is a function of its accelerating gradient (E_{acc}) and the R/Q ratio. For a TESLA 9-cell cavity operating at nominal gradients, for example the UK-XFEL is about 19 MV/m, U_c typically reaches approximately 100 J [1].

Microphonics Compensation: Operational experience with TESLA cavities indicates that microphonics-induced detuning typically spans a range of ±30 Hz [3]. To provide a sufficient safety margin, the FE-FRT in this work is designed with a tuning range of ±50 Hz. Reactive Power Requirement:The required reactive RF power (P_{reactive}) is proportional to the stored energy and the detuning bandwidth $\Delta\omega$:

$$P_{\mathrm{reactive}} = \Delta\omega U_c. \tag{1}$$

Given the 100 J stored energy and the ±50 Hz tuning requirement, the FE-FRT must handle a reactive power of approximately 3.14 kVAR.

Equivalent Circuit and Perturbation Theory

The FE-FRT tuning system can be modeled as a coupled system consisting of the main power coupler, the SRF cavity,

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and the tuning cavity. The tuning mechanism is fundamentally described by the Slater perturbation theory regarding material properties [4]:

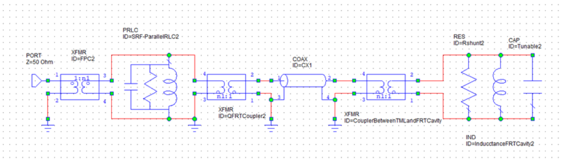

Figure 2: Equivalent Circuit of the superconducting cavity with FE-FRT

Equivalent circuit representation of the FE-FRT system coupled to the SRF cavity. The diagram in Fig. 2 illustrates the interaction between the cavity's stored energy and the reactive load provided by the ferroelectric tuner.

The total frequency deviation of the system is the superposition of the cavity volume deformation (caused by microphonics) and the permittivity shift in the ferroelectric material (triggered by the tuner):

$$\frac{\omega-\omega_0}{\omega_0} \approx \frac{\int_{\Delta V}\left(\mu|H_0|^2-\epsilon|E_0|^2\right)\,dv-\int_{V_{\mathrm{frt}}}\Delta\epsilon|E_0|^2\,dv}{\int_V\left(\epsilon|E_0|^2+\mu|H_0|^2\right)\,dv}. \tag{2}$$

By modulating the bias voltage, the permittivity ϵ of the ferroelectric wafers is adjusted to counteract the detuning caused by ΔV. The tuning efficacy is directly linked to the electric field intensity and energy density within the wafers.

SELF-CONSISTENT THERMAL ANALYSIS

A critical aspect of FE-FRT reliability is the temperature dependence of the material properties. We conducted a self-consistent study that couples the RF power dissipation with the thermal distribution, specifically accounting for the relationship between the ferroelectric loss tangent ($\tan\delta$) and temperature (T), shown in Fig. 3 [5].

$$\Delta T = \frac{gP}{6AKN_w^2} = \frac{g_0 P}{6AKTN_w}, \tag{3}$$

$$P = \frac{\Delta\omega U_c}{\mathrm{FoM}_{FE}}, \tag{4}$$

$$\mathrm{FoM}_{\mathrm{mat}} = \frac{\ln\left(\frac{\epsilon_2}{\epsilon_1}\right)}{2\tan\delta}. \tag{5}$$

Under the nominal operating conditions of 100 J stored energy and a ±50 Hz detuning range, the steady-state temperature rise of a standard FE-FRT when cooling only from the outside remains well within the safe operational limits of the ferroelectric ceramics, but the need to increase the radius and the higher operating temperature reduces the FoM, as seen in Fig. 4. By splitting the tuning load between two symmetric branches, the power density in each unit is halved and hence a smaller radius can be used at a lower temperature, increasing the FoM by around 50 %, as shown in Fig. 5. This design prioritizes single-side avoid the requirement to directly cool the high-voltage (HV) spacers in the restricted 1.3 GHz housing.

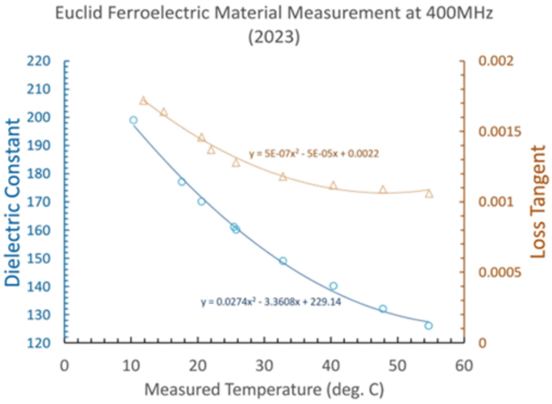

Figure 3: Temperature and loss tangent dielectric constant at 400MHz [5]

The results demonstrate that the Twin-axial Dipole structure, even with simplified single-side cooling, effectively prevents thermal runaway and ensures stable frequency control for the TESLA cavity.

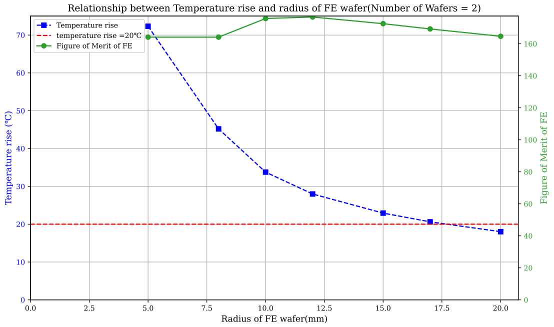

Figure 4: Temperature rise for a single side cooling 2 wafers in a standard FE-FRT

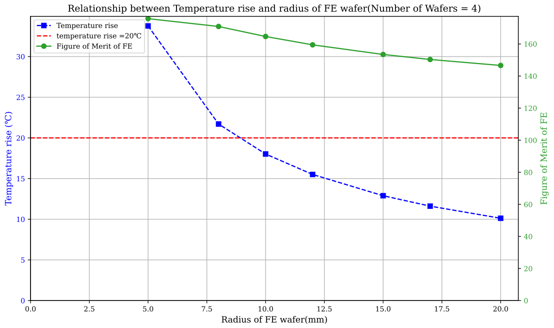

Figure 5: Temperature rise for a single side cooling with 4 wafers in the Twin-axial FE-FRT

OPTIMIZATION STUDY OF FE-FRT FIGURE OF MERIT (FOM)

Identification of the Tuning Eigenmode

When optimising any resonator, the first step is to identify the appropriate working eigenmode. Simulation results from the CST Eigenmode Solver show that for the dipole mode of a twin-axial FRT, the electric field is highly concentrated within the ferroelectric (FE) wafers, which is essential for maximizing the tuning efficiency. Conversely, the magnetic field is primarily distributed between the FE wafers and the outer boundary of the cavity.The two sub-FRT cavities are coupled through the common magnetic field with opposite electric-field directions in the FE wafers. The electromagnetic field patterns are shown in Fig. 6:

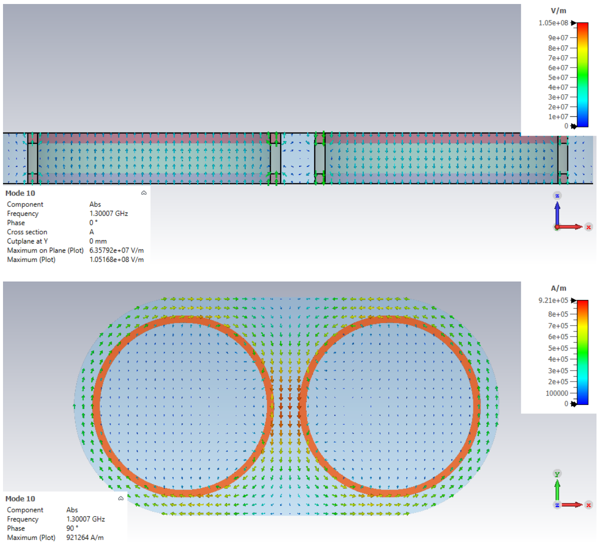

Figure 6: The EM pattern of the twin-axial dipole mode FRT, with electric field on the top and magnetic field on the bottom

Theoretical Approximation

The definition of FoM in terms of energy and admittance is given in [6].

We rewrite the FoM in the admittance form:

$$\mathrm{FoM} = \frac{\Delta P_{\text{reactive}}}{2\sqrt{P_{1\text{dis}} P_{2\text{dis}}}} = \frac{|B_2 - B_1|}{2\sqrt{G_1 G_2}} = \frac{B_1}{\sqrt{G_1 G_2}}. \tag{6}$$

Assuming that the differences in dissipated power

$$P_{\text{dis}} = \frac{1}{2}|V|^2 G$$

between the two end states and the resonant state have only small variations, namely

$$\Delta G_2 \approx \Delta G_1 \ll G_0,$$

we obtain:

$$\begin{aligned} \sqrt{G_1 G_2} &= \sqrt{(G_0 - \Delta G_1)(G_0 + \Delta G_2)} \\ &= \sqrt{G_0^2 + G_0(\Delta G_2 - \Delta G_1) - \Delta G_2 \Delta G_1} \approx G_0. \end{aligned} \tag{7}$$

In this case,

$$\mathrm{FoM} = \frac{B_1}{\sqrt{G_1 G_2}} \approx \frac{B_1}{G_0}. \tag{8}$$

There are two contributions to the dissipated power P_{dis}: one from the ferroelectric loss tangent represented by G_d, and one from the resistive surface loss of the FRT cavity represented by G_s:

$$P_{\text{dis}} = \frac{1}{2}|V|^2 G_0 = \frac{1}{2}|V|^2 G_d + \frac{1}{2}|V|^2 G_s, \tag{9}$$

$$G_0 = G_d + G_s. \tag{10}$$

Therefore,

$$\mathrm{FoM} \approx \frac{B_1}{G_0} = \frac{B_1}{G_d + G_s}. \tag{11}$$

If we set $G_s = 0$, then

$$\mathrm{FoM} = \mathrm{FoM}_{\text{mat}} = \frac{B_1}{G_d} = \frac{\ln\left(\frac{\epsilon_2}{\epsilon_1}\right)}{2\tan\delta}. \tag{12}$$

Finally, the FoM of the FRT can be written as

$$\mathrm{FoM}_{\text{FRT}} \approx \frac{G_d}{G_d + G_s}\mathrm{FoM}_{\text{mat}} = \frac{P_d}{P_{\text{total}}}\mathrm{FoM}_{\text{mat}}. \tag{13}$$

Influence of Geometric Parameters on FoM

We conducted a systematic study on how the dimensions of the FE wafers, as well as the cavity length, affect the system performance.The properties of the ferroelectric materials are listed in Table 1.

Table 1: Properties of the Ferroelectric Materials

Parameter	**Value**
Relative Permittivity	114–160
Loss Tangent	1–2 × 10^{-3}
Tunability	1.4
Field for Maximum Tuning	8 V µm^{-1}
Breakdown Strength	20 V µm^{-1}
Thermal Conductivity	7.02 W m^{-1}K^{-1}
Estimated Maximum Temperature Rise	50 K

The figure of merit of the materials is defined as [2, 7]:

$$\mathrm{FoM}_{\text{mat}} = \frac{\ln\left(\frac{\epsilon_2}{\epsilon_1}\right)}{2\tan\delta} = 168. \tag{14}$$

From the last theoretical approximation, we can obtain the FoM using eigenmode simulation, by considering the losses on each component and applying the known material FoM formula. The inverse of the total FoM can be decomposed into loss contributions from the material properties, the cavity walls, and the transmission lines (which can be ignored):

$$P_{\text{dissipated}} = P_{\text{disFE}} + P_{\text{disFRT}} + P_{\text{disTL}} \approx P_{\text{disFE}} + P_{\text{disFRT}}. \tag{15}$$

We utilize the CST Eigenmode Solver to directly calculate the RF power dissipation in the ferroelectric wafers and on the cavity surfaces [8]. This approach allows for a streamlined post-processing evaluation of the FoM. Furthermore, it enables the use of built-in optimization algorithms to automatically refine the tuner geometry, maximizing the FoM while maintaining the resonance frequency.The optimization methodology was applied to this twin-structure to maximize the Figure of Merit (FoM).The sensitivity of the FoM to the cavity length and wafer dimensions in the twin-axial structure follows the trends identified in the simplified model, as shown in Figs. 7 and 8:

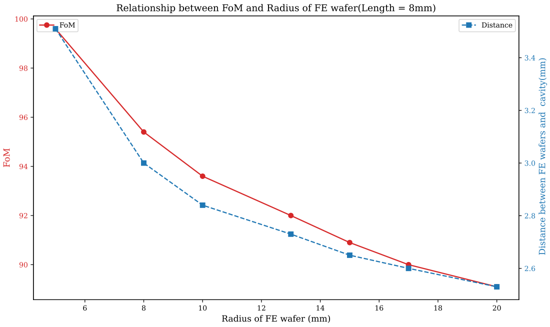

Figure 7: The FoM vs the Radius of FE wafer with 8 mm in length.

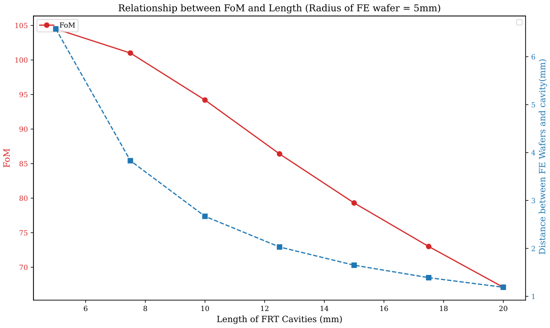

Figure 8: The FoM vs the length of the FE-FRT cavity with radius = 5 mm.

The FoM also decreases with increasing FRT cavity length, but it is more sensitive to the cavity length than to the radius of the FE wafers. Therefore, the FRT cavity should be kept as short as possible. However, some additional space is required for cooling the bias high-voltage spacers if double-sided cooling of the FE wafers is implemented.

SUMMARY AND CONCLUSION

In conclusion, this paper provides a comprehensive and detailed methodology for the design and optimization of ferroelectric fast reactive tuners (FE-FRT) aimed at microphonics suppression in superconducting cavities. While FE-FRTs designed for lower operating frequencies benefit from larger physical dimensions, which allow relatively straightforward integration of water-cooling systems and high-voltage (HV) infrastructures, higher frequencies such as 1.3 GHz present significant engineering challenges, at 1.3 GHz, the compact tuner housing imposes severe spatial constraints that often make traditional double-sided cooling of HV spacers mechanically impractical. To address these challenges, we have developed a novel twin-axial dipole FE-FRT structure. The key innovation of this design lies in its ability to operate effectively using uncooled high-voltage spacers, achieved by strategically increasing the number of ferroelectric wafers to distribute the power load. This approach significantly simplifies the internal mechanical architecture of the tuner and eliminates the need for complex cooling channels within the HV sections.

REFERENCES

[1] B. Aune *et al.*, “Superconducting TESLA cavities”, *Phys. Rev. Spec. Top. Accel. Beams*, vol. 3, no. 9, p. 092001, 2000. `doi:10.1103/PhysRevSTAB.3.092001`

[2] I. Ben-Zvi, G. Burt, A. Castilla, A. Macpherson, and N. Shipman, “Conceptual design of a high reactive-power ferroelectric fast reactive tuner”, *Phys. Rev. Accel. Beams*, vol. 27, no. 5, p. 052001, 2024. `doi:10.1103/PhysRevAccelBeams.27.052001`

[3] S. Posen and M. Liepe, “Measurement of the mechanical properties of superconducting cavities during operation”, in *Proc. IPAC’12*, New Orleans, LA, USA, May 2012, paper WEPPC081, pp. 2399–2401.

[4] D. M. Pozar, *Microwave Engineering*. Hoboken, NJ, USA: John Wiley & Sons, 2011. `doi:10.1201/b16689`

[5] I. Ben-Zvi, A. Macpherson, and S. Smith, “Detailed design and optimization of ferroelectric tuners”, *Phys. Rev. Accel. Beams*, vol. 28, no. 9, p. 093502, 2025. `doi:10.1103/9sf7-wwyb`

[6] N. C. Shipman *et al.*, “Ferro-electric fast reactive tuner applications for SRF cavities”, *JACoW IPAC*, vol. 2021, pp. 1305–1310, Sep. 2021. `doi:10.18429/JACoW-IPAC2021-TUXC03`

[7] N. Shipman *et al.*, “A ferroelectric fast reactive tuner for superconducting cavities”, FNAL, Batavia, IL, USA, Rep. FERMILAB-CONF-19-773-SQMS, 2019.

[8] *CST Studio Suite*, Dassault Systèmes Simulia, Darmstadt, Germany, 2025.