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TOWARDS HIGH POWER TESTS OF AN FE-FRT FOR TRANSIENT DETUNING

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Abstract

The design, fabrication and validation progress towards a ferroelectric fast reactive tuner (FE-FRT) as a demonstrator of a high-power tuner for beam loading compensation at LHC injection settings is presented. Such compensation is referred to as transient detuning compensation and involves discrete frequency switching of an LHC cavity configuration on sub-microsecond time scales. The FE-FRT is operated in a two-state mode with a 7 kV bias applied across a $BaTiO_3/SrTiO_3$-Mg ferroelectric material in the tuner stub to provide the required cavity frequency shift. To achieve this, the device has been designed to operate as a coupled resonant tuner that provides an 8 kHz cavity tuning range. As an FE-FRT design, the tuner must tolerate a reactive power load of +/- 226 kVAR and 3 kW of dissipated power. The key design decisions taken are presented along with the specific optimisation of the tuner in terms of the expected performance. Finally, measurements and first results for the tuner demonstrator validation process are discussed.

INTRODUCTION

The ability to tune an RF cavity's frequency on fast timescales is important for a variety of accelerator applications, including but not limited to: compensation of Lorentz force detuning, transient detuning and microphonics compensation. In recent years the idea of using ferroelectric materials to create fast and high average power tuners has been developed [1, 2], with successful results shown using an FE-FRT prototype to compensate for microphonics [3]. However, despite these results, to date, there has been no experimental validation of an FE-FRT at high reactive power levels (> 10 kW). To address this, this paper details the design and development work leading towards validation of a high power FE-FRT that would be capable of tuning ± 225 kVAR reactive power.

FE MATERIAL

At the heart of all FE-FRT designs is the ferroelectric material used to provide real-time tunability of the device, and the designs considered in this paper utilise a commercially available ferroelectric ceramic, developed by Euclid Techlabs [4, 5]. This material is a $BaTiO_3/SrTiO_3$-Mg ceramic, and as a ferroelectric, it changes its permittivity in response to an externally applied electric biasing field. This material is of particular interest as it exhibits low loss for the range of frequencies of interest as well as having a high permittivity tunability: Some of the key material properties at 400 MHz are given in Table 1.

Table 1: FE Material Properties at 400 MHz

Parameter	Value	Units
ϵ_r at 0 V bias and ≈ 25 °C	160	-
Loss tangent δ	1e-3	-
Tunability at 8V/µm	1.4	-
Thermal conductivity	7.02	$Wm^{-1}K^{-1}$
Breakdown strength	20	V/µm

Like all ferroelectric materials, the material permittivity response changes with temperature, with the highest sensitivity just below the material's Curie temperature. For such BST ceramics this temperature limit is typically above 100°C, implying that FE-FRTs operated at or above ambient temperature. Indeed, the choice of operational temperature can be exploited, as by adjusting the operating point, the permittivity and loss tangent of the material can be shifted in order to provide an optimum operating temperature of the material in terms of required tuning range and RF losses. As an example, the temperature dependence on unbiased ferroelectric material is shown in Fig. 1.

CONCEPT

The FE-FRT presented in this paper was initially designed for a transient detuning use case with the preliminary design reported in Ref. [2]. The tuner is constructed by integrating

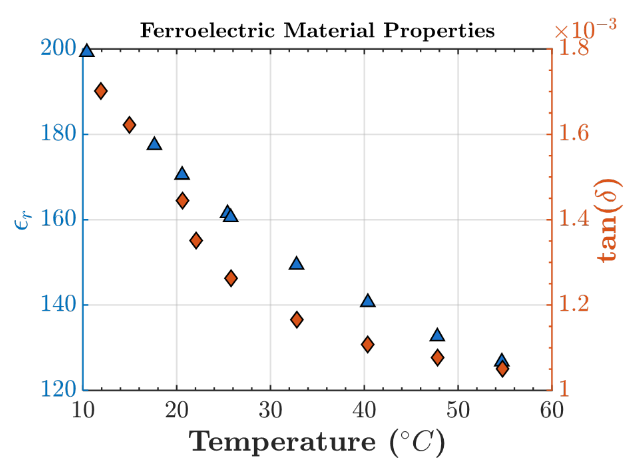

Figure 1: Temperature dependence of Ferroelectric material properties at 400 MHz [6].

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the ferroelectric material into a resonant circuit, with the ceramic acting as a variable capacitor (C_f) as shown in Fig. 2. This circuit is then capacitively coupled to a transmission line connected to the tuner cavity port. As part of the deliberate design, a capacitive window represented by C_w that is introduced, so to separate the cavity and tuner vacuum volumes. Whilst not strictly necessary, this capacitive window, serves as a well defined interface during the assembly process, allowing for the ultra-clean RF surface of the cavity to be maintained.

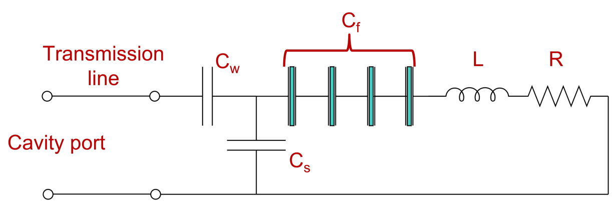

Figure 2: Equivalent circuit for the high power FE-FRT design, showing four wafers making up C_f.

In order to characterise the FE-FRT design, the several key formulas are to be taken into consideration. The first is the reactive power flow from the cavity to the tuner:

$$\Im(P_2) - \Im(P_1) = 2U\Delta\omega_{12}. \quad (1)$$

In this equation:

- $\Delta\omega_{12}$ is change in angular frequency between the states of 0 bias and full bias.
- U is the stored energy in the cavity.
- $\Im(P_2) - \Im(P_1)$ the imaginary part of the power emitted by the cavity at the two states.

Second,the tuner Figure of Merit (FoM), which represents the maximum change in reactance between zero and full bias voltage divided by the total loss in the tuner at these states, it is defined by:

$$FoM \equiv \frac{\Im(P_2) - \Im(P_1)}{2\sqrt{\Re(P_1)\Re(P_2)}} = \frac{X_2 - X_1}{2\sqrt{R_1 R_2}}. \quad (2)$$

Third, when the tuner is coupled to a cavity through a transmission line, the change in frequency of the cavity due to the change in reactance is given by:

$$\Delta\omega_{12} = 2\pi\Delta f_{12} = \frac{\omega_0}{2Q_e}\frac{X_2 - X_1}{Z_0}, \quad (3)$$

where Z_0 is the characteristic impedance of the transmission line and Q_e is the external Q factor of the port that the tuner is attached to.

Finally, a value for Q_{FRT} for each state, which is the Q that is presented to the cavity by the tuner can be found from:

$$Q_{FRT_n} = FoM_{sn}\frac{\omega_0}{\Delta\omega_n}, \quad (4)$$

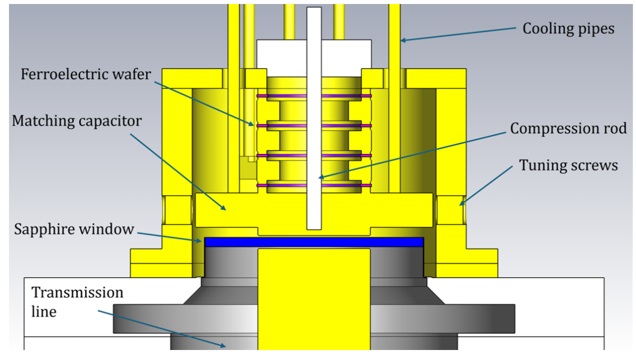

Figure 3: Physical realisation of the circuit shown in Fig. 2.

where FoM$_s$, is the state figure of merit for a given state s, and is defined by:

$$FoM_{sn} = \frac{X_n}{R_n} \quad (5)$$

and in Eq. (4), $\Delta\omega_n$ is the total tuning range.

The physical realisation of this equivalent circuit description is shown in Fig. 3 where the FE wafers make up C_f, the matching capacitor acts as C_s and the sapphire window represents by C_w.

RF DESIGN

The electromagnetic design procedure was guided by an analytical model described in Ref. [2], which provided analytical estimates for the capacitances, resonator length, and electrode spacer lengths between the FE wafers, with the design in accordance to the equivalent circuit of Figure 2. Assuming a use-case based on the 400 MHz cavities of the LHC operating at injection settings, a prototype tuner design with 8 kHz tuning range is considered, implying a tuner that must tolerate a reactive power load of +/- 226 kW and 3 kW of dissipated power. This permits the establishment of an analytic model with a design parameter set as given in Table 2.

Table 2: Parameters from the Analytical Model Compared with Simulation Results

Parameter	Analytical	CST	Units
f_{cavity}	400.3188	400.3188	MHz
Tuning range	8	8.2	kHz
$\Delta P_{reactive}$	452	-	kVAR
C_w	4.85	7.3	pF
C_s	35.3	32.8	pF
Z_0	56.18	56.18	Ω
ϵ_{r_1}	96.5	96.5	-
ϵ_{r_2}	129.5	129.5	-
Q_{FRT_1}	4.09e6	3.46e6	-
Q_{FRT_2}	3.66e6	2.49e6	-
$Q_{e_{FRT}}$	50000	50000	-
FOM	77.4	61	-

The electromagnetic CST studio suite [7] model of the tuner, transmission line and cavity is shown in Fig. 4, and was

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simulated using a modular approach in the frequency domain with concatenated S-parameters at each sub-component interface. This gave both clarity and flexibility such that tuner parameters could be changed without re-simulating the entire system. This significantly reduced the frequency domain optimisation both of the stand alone tuner and more importantly, the full cavity-tuner RF system. By careful choice of the parameter optimization set, once geometric parameters such as the resonator length and conductor radii were set, the inputs to the final optimisation were limited to the values of C_s, C_w and the length of the transmission line, and the quantifiable outputs were the tuning range (TR) and the centring of the tuning range around the cavity frequency. For the resultant tuning range TR:

$$TR = |f_1 - f_2|, \quad (6)$$

where f_1 and f_2 are the frequencies of the two end states, while the difference between the central frequency of the two states and the cavity frequency, is given by:

$$\Delta_f = f_{cavity} - (f_1 + f_2)/2. \quad (7)$$

For the use-case design outlined in Table 2, the optimisation targets were simply:

$$7.8 \text{ kHz} < TR < 9 \text{ kHz} \quad (8)$$

and

$$\Delta_f < 0.02 \text{ kHz}. \quad (9)$$

To evaluate the RF performance of this optimization, the S-parameter S_{11} was measured through a probe coupler on the cavity, and for each parameter combination both states were solved ($\epsilon_r = 96.5$ $\epsilon_r = 129.5$). The final optimised results are shown in Fig. 5 with a comparison with the analytical results in Table 2. It is noted that in order to properly account for fringe field effects in the 3D rendering of the capacitances, the CST geometry parameters were first set by determination of expected capacitance values using an electrostatic solver. Whilst agreement between analytic and CST optimisations is generally very reasonable, the noted difference in the FoM between the two is attributed to the extra loss mechanisms included in the model such as the cooling pipes and antenna holders.

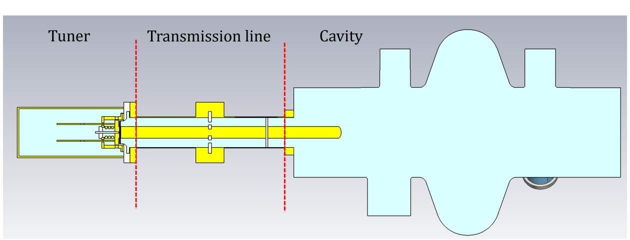

Figure 4: CST model showing separated components.

MECHANICAL DESIGN

Transitioning from the RF model to the mechanical design required the consideration of a number of features, and the most critical are discussed here.

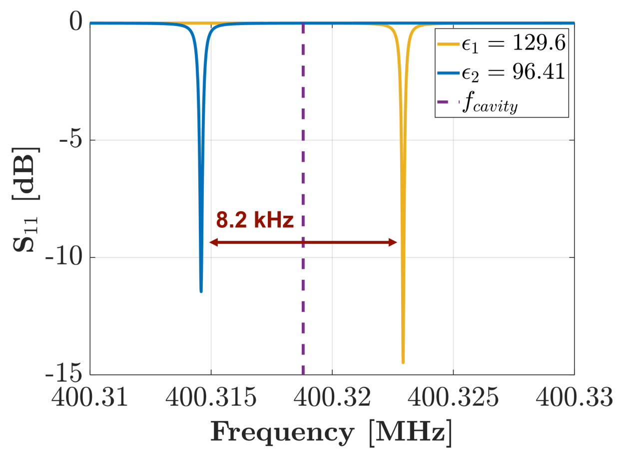

Figure 5: Final tuned S_{11} seen through a probe on the cavity, showing a 8.2 kHz tuning range and the states centred around f_{cavity}.

HV Isolation

The HV biasing to the electrodes that sandwich the ferroelectric wafers is provided through the cooling channels into the resonator body. These lines must be able to pass the DC voltage while blocking the RF. To accomplish this, simple robust LC notch filters were designed and fabricated, as shown in Fig. 6. They are constructed by brazing a 10 mm sapphire disc between two electrodes with a simple inductive coil in parallel, and an adjustable central pin on the coil axis that functions as a fine adjust for the notch filter. The quality factor of these filters is around 250 at 400 MHz.

FE Material Preparation

In order to reduce the likelihood of RF breakdown a grinding and polishing procedure has been developed at CERN in order to achieve a smooth a surface as possible. This is needed as the ceramic as delivered, is not intrinsically smooth, leading to micro-gaps that could initiate localise discharge. To address this, ferroelectric wafers were polished to the level of an optical finish with strict constraints on surface flatness, and then assembled in a compression fit with similarly prepared copper electrodes. As an example,

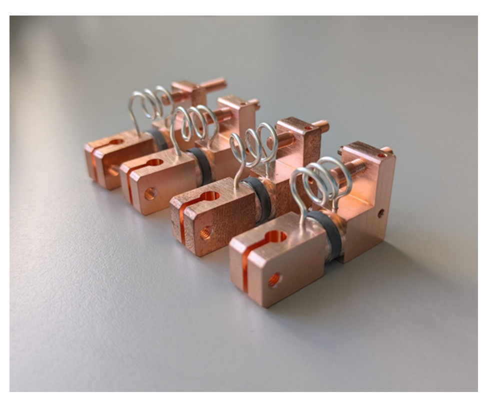

Figure 6: 400 MHz notch filters for HV isolation.

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typical values of R_t and R_a of the bulk material as received from the supplier are compared with the polished material and other engineering materials used in the design in Table 3, and Fig. 7 shows one such polished ferroelectric wafer used in the designed tuner.

Table 3: Surface Finish Measurements

Material	R_t (nm)	R_a (nm)
FE (as supplied)	5600 ± 2180	382 ± 65
FE (after polishing)	711 ± 95	40 ± 10
Stainless steel	427 ± 248	13 ± 2.2
Diamond machined copper	172 ± 29	33 ± 1.3

PRELIMINARY TESTING

Manufacture and preparation of tuner body and electrode components were completed at CERN in June 2025, while in parallel, the ferroelectric wafers were water-jet cut and polished. This permitted the first assembly of a 4-wafer ferroelectric stack, with the wafers held under under compression with a 1.5 KN compression force. The wafer stack can be seen clearly in Fig. 8, showing the cooling lines integrated into the electrodes that provide both both heat absorption from the tuner RF and also the DC biasing across the ferroelectric wafers.

Once the ferroelectric stack is mounted in its outer casing to for the tuner resonator, it is then mounted on the sapphire window and the transmission line sub assembly, which in turn is coupled via a cavity port to the 400 MHz LHC cavity. In this instance, due to vertical test cryostat limitations, the tuner assembly was installed on a cavity beam port (as shown in Fig. 10), rather than a more standard coupling port. Such a configuration is needed for RF tests at cryogenic temperatures, as in this orientation, the tuner can be mounted inside the test cryostat but remain out of the cryogenic fluid, thereby simplifying the stabilization of the ferroelectric wafers at 300 K.

Figure 7: FE wafer with optical finish.

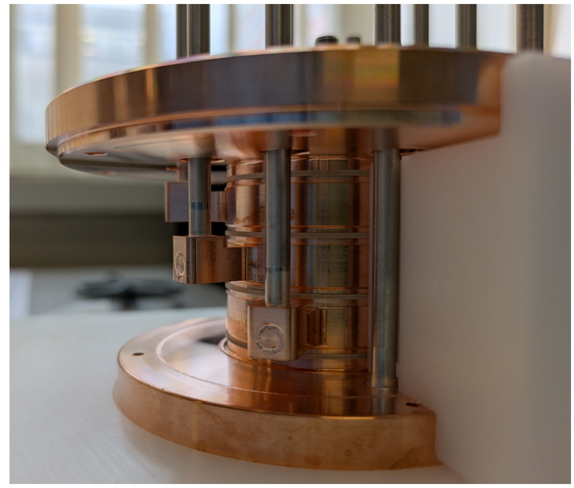

Figure 8: Inner geometry of manufactured tuner showing FE wafers, electrodes and cooling pipes.

Prior to embarking on a full RF cold test of the cavity and tuner system, a first testing has been performed on the tuner to confirm functionality. For this test, as shown in Fig. 1, the cavity was not installed in the cryostat, and so operated as a normal conducting cavity, while the tuner was left open to atmosphere. While lack of a tuner vacuum prevented DC biasing of the ferroelectric, the permittivity tunability was assessed by exploiting the permittivities sensitivity to temperature. For this configuration, dedicated couplers were installed, compatible with a cavity Q_0 43000 so that a direct S_{21} measurement could be performed while adjusting the temperature of the ferroelectric wafers using the cooling network.

This allowed a change in permittivity from ϵ_r = 120 to ϵ_r = 173, which from simulation equates to an expected frequency shift of 3.3 kHz. For comparison, a 3 kHz frequency shift was measured as shown in Fig. 9, indicating

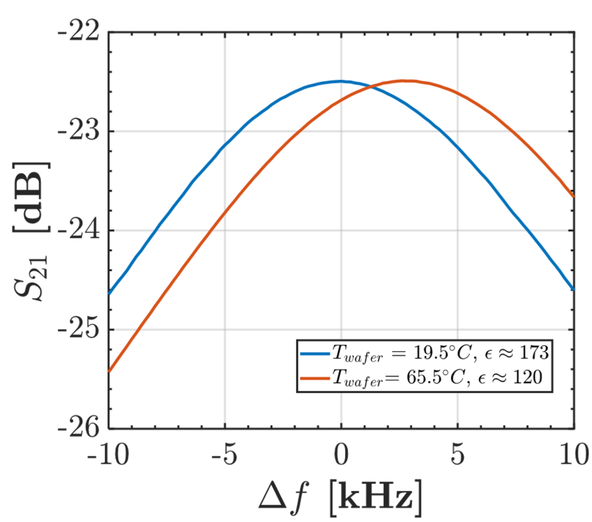

Figure 9: Frequency shift vs S_{21} for two FE wafer temperatures.

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Figure 10: Tuner and transmission line connected to warm 400 MHz LHC cavity.

that the tuner is correctly coupling to the cavity and that the cavity frequency tuning is responding as expected. With this confirmed, the cavity and tuner system are now being reconfigured for RF cavity operation at 4.5 K at CERN's SRF cavity testing facility.

CONCLUSIONS

A ferroelectric tuner has been designed, manufactured and gone through preliminary tests, with these tests showing the expected tuning functionality.

In terms of RF design, the electrical structure of the tuner is a parallel resonant circuit phase shifter coupled to a cavity port through a $\lambda/4$ transmission line, and the tuner is connected to a 400 MHz superconducting cavity. Care has be taken to ensure integrated cooling such that the ferroelectric material can maintain a stable operational temperature under the required use case of a reactive power load of +/- 226 kVAR and 3 kW of dissipated. The tuner system is now moving to a program of cold tests, where the achievable tunability and power handling capabilities will be mapped out.

Finally, it is noted that as a result of the lessons learned from this work, a refined and improved tuner design methodology has be developed [8], applicable to a wide range of SRF cavity scenarios.

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