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A REACTIVE FERROELECTRIC TUNER FOR MICROPHONICS COMPENSATION*

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Abstract

Jefferson Lab (JLab) is actively pursuing an extensive research program focused on developing advanced Nb_3Sn superconducting technology for particle acceleration. Due to the brittle nature of Nb_3Sn coatings, a Ferroelectric Tuner (FRT) currently represents the most viable approach for microphonics compensation in these next-generation cavities. We suggest a novel, fast-responding FRT integrated directly into the main coupler, eliminating the need for an additional RF port. Leveraging a unique RF design based on a magic-T configuration, this advanced FRT will enable microphonics compensation in the ±30 Hz range without undesirable changes to the external quality factor.

INTRODUCTION

One of the major challenges faced by the SRF accelerators is microphonics [1-3]. Microphonics refers to frequency detuning of SRF cavities caused by external vibrations. As the cavities detune, additional RF power is required to maintain the desired accelerating gradient. For example, CEBAF cavities are currently unable to utilize the full RF power available from their klystrons [4]. This limitation significantly increases both the capital and operational costs of the accelerator.

An FRT can be considered a fast phase shifter coupled to the SRF cavity, capable of altering the total reactive power delivered from the RF source to the cavity [5-8]. This phase shift results from changes in the dielectric permittivity of an inserted ferroelectric sample. The permittivity can be rapidly adjusted—typically within nanoseconds—by applying a bias voltage. Dielectric permittivity values typically range from 100 to 200 for bias electric fields between 0 and 10 kV/cm, with loss tangents as low as 10^{-3} [9].

Preliminary analysis and experimental results from CERN with an FRT connected to an SRF cavity [6, 7], along with room-temperature tests conducted by Euclid Techlabs [8], indicate that FRTs can support stable operation of SRF cavities such as the 1500 MHz C100 (CEBAF) and novel Nb_3Sn cavities. These studies suggest that up to 50% of the RF power—currently used to counteract detuning—could instead be redirected to beam acceleration.

FRT CONCEPT

Our concept is based on an analytical solution that defines the required amplitude and phase characteristics of the reflected signal from the FRT in order to (1) shift the cavity's resonant frequency appropriately, and (2) maintain a constant external quality factor (Q_{ext}). To explore this, we consider a universal model (Fig. 1) that includes the main coupler and a "black box" representing the tuner used for microphonics compensation. Analyzing this simplified system requires determination: (1) how the phase of the reflection from the black box must be controlled to detune the SRF cavity frequency over the desired range, and (2) how the amplitude of the reflection must be adjusted in conjunction with the phase shift to ensure that the total reflected signal remains constant on amplitude—thus preserving the cavity's external Q-factor.

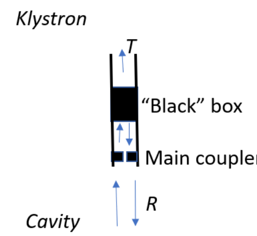

Figure 1: "Black" box FRT model.

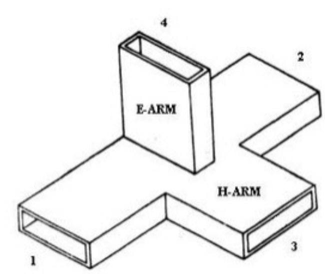

Figure 2: Magic T.

We begin this analysis with the simplest case, assuming negligible losses in the black box. Losses will be included in final simulations to show how good a lossless approach is. Without losses, the complex reflection coefficient of the resonant system (main coupler + black box) is given by the following equation:

$$R = r_0 - \frac{(1-r_0^2)\cdot r\cdot e^{i\varphi}}{1-r_0\cdot r\cdot e^{i\varphi}}. \quad (1)$$

Where r_0 – is amplitude of reflection from the main coupler (it can be considered as the real number), r – is an amplitude of the reflection from the black box (real number), φ - is a phase of black box reflection so that the complex "black" box reflection equals $r\cdot e^{i\varphi}$. The frequency shift due to the black box insertion is naturally proportional to the argument of R. Now we need to require that the amplitude of the reflection R from the equation (1) must be constant and equal to the reflection from the unperturbed SRF cavity for any value of the "black" box phase φ. This

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requirement means that we keep constant the external Q-factor of the SRF cavity, i. e. $|R|=r_0 = const$. The analytical solution with (1) considered is:

$$re^{i\varphi} = \frac{2r_0}{1+r_0^2} cos\,(\varphi) \cdot e^{i\varphi}. \qquad (2)$$

Note that if we consider that $1 - r_0 \ll 1$, then we obtain $r=cos\varphi$. The solution (2) shows how the amplitude of tuner reflection must depend on reflection phase.

The next step is to introduce a system with necessary parameters that would be a substitution for the "black box". Let us show that the Magic T (Fig. 2) that has the short at one port (#1) and has the fully reflective phase shifter at the other port (#2) possesses the necessary properties. Assuming that the first port has a perfect short with reflection phase φ_1=0 and the port#2 also has 100% reflection but with the reflection phase φ_2, one can write the complex reflection coefficient S_{33}, $r{\times}e^{i\varphi}$, from the port#3:

$$re^{i\varphi} = \frac{1}{2}e^{i\varphi_1} + \frac{1}{2}e^{i\varphi_2} = e^{i\varphi_2/2}\cos(\varphi_2/2). \qquad (3)$$

Note that the obtained dependence of the reflection amplitude in this equation (3) on phase is remarkably like the one given by equation (2) (the amplitude depends on cosine of the phase). To conclude, one must consider that $r_0 \approx 1$ in (2) and to consider the equation (3) relative to the variable $\varphi_2/2$. Therefore, the system in Fig. 3 consisting of the Magic T, the short, and the fully reflective phase shifter (FE reflector) can be used as the tuner that does not alter the SRF cavity coupling. If microphonics at a given time do not perturb the cavity, all RF power goes in this cavity. If microphonics shift the frequency, the tuner automatically changes the phase of the reflection and the amplitude of the reflection as well to keep constant eigen frequency and Q external.

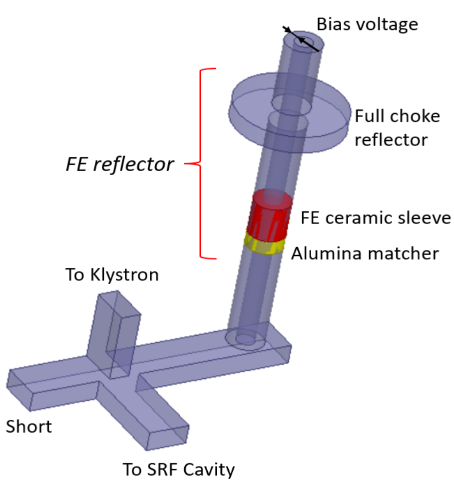

Figure 3: Proposed single port FRT.

PARAMETER STUDY

The proposed FRT was simulated with CST code (Fig. 4). The ferroelectric sleeve had size: OD-28 mm, ID-18 mm, length 40 mm. Fig. 5 presents the results of S-parameter simulations for this phase shifter, designed for the Nb_3Sn cavities currently under test at JLab (f = 1500 MHz, r/Q = 1288 Ω/m, $Q_0 = 3 \times 10^9$, and $Q_{ext} = 3.2 \times 10^7$). The reflection amplitude, S_{11}, remains near –0.25 dB across the full range of ferroelectric dielectric constants from 130 to 150. However, the phase of the reflection is strongly dependent on the dielectric constant—an essential condition for frequency control (Fig. 6). This frequency control capability is illustrated in Fig. 7. Key FRT parameters, inserted amplitude and phase are plotted vs bias voltage amplitude in Fig. 8. Note that applying a bias voltage of 8 kV enables tuning of the ferroelectric permittivity in the assumed range of 130 to 150 in order to to provide microphonics compensation in the range ±30 Hz. The loss tangent as high as $1{\times}10^{-3}$ was used for simulations. The external quality factor shows a slight dependence on the applied bias voltage (Fig. 9). This is because we took into account losses in the FRT itself. Nevertheless, the external *Q* remains close to its value in the case without the FRT.

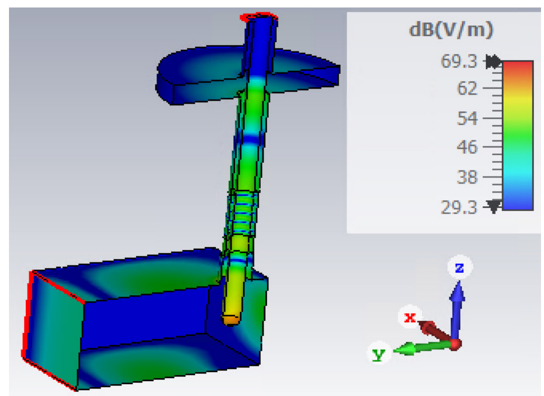

Figure 4: E-field in FRT.

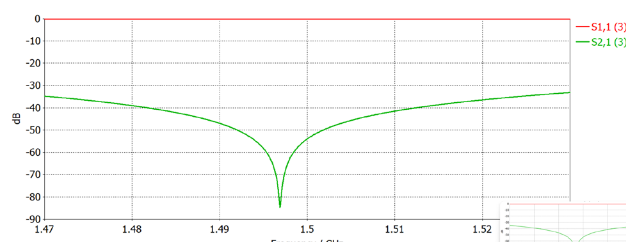

Figure 5: S-parameters amplitude.

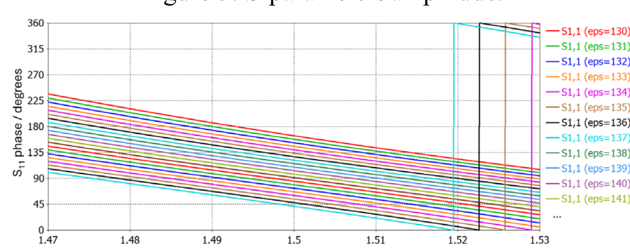

Figure 6: S_{11} phase for several dielectric constants.

One significant objective of the design study is to evaluate how well the field flatness of an SRF cavity can be preserved when implementing an FRT for frequency control. This objective is critical to validating the overall FRT concept. While microphonics induce frequency shifts in a specific manner, an FRT can compensate for these shifts by applying controlled frequency deformation of its own. Preliminary simulations were carried out for a proposed 590

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MHz 5-cell EIC cavity currently in the design phase (Fig. 10). This cavity has a quality factor of $Q_0 = 10^{10}$, R/Q = 599.9 Ω, and 1% coupling between cells.

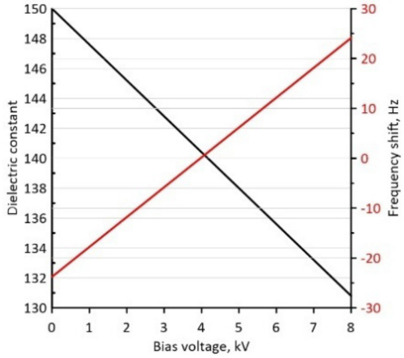

Figure 7: Dielectric constant and frequency tunability.

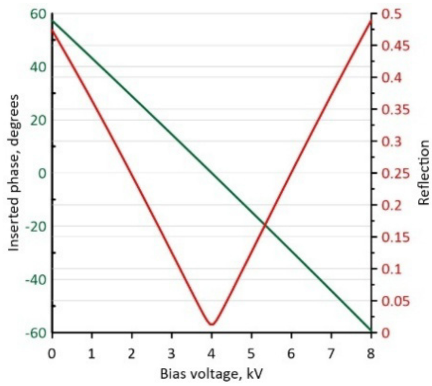

Figure 8: Inserted reflection phase and amplitude.

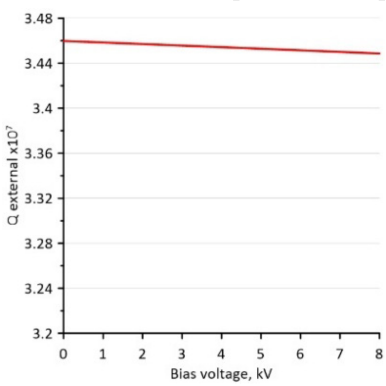

Figure 9: External Q vs bias voltage.

To investigate potential field flatness degradation, we analyzed a worst-case scenario in which the FRT is modelled as a standalone device connected directly to the first cell. By varying only the parameters of the first cell, Fig. 11 was generated, which illustrates how the normalized field difference between the first and fifth cells depends on deviations of the cavity's eigenmode frequency. The results show that field flatness degrades significantly if the eigenmode frequency deviates by several kilohertz from its nominal value. However, in the case of microphonics, the eigenmode frequency typically fluctuates by only a few tens of hertz. Therefore, this preliminary analysis indicates that field flatness will not be a limiting factor for FRT operation aimed at compensating microphonics.

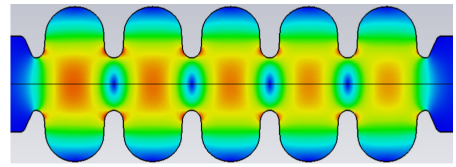

Figure 10: Tilted field distribution in EIC cavity under squeezed first cell.

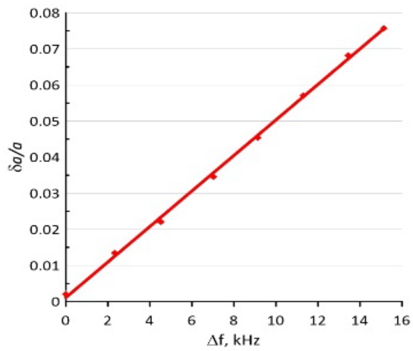

Figure 11: Normalized difference of fields in 1st and 5th cells vs deviation of frequency for the operating eigenmode.

CONCLUSION

We propose a fast-response ferroelectric tuner integrated directly into the main coupler, eliminating the need for an additional RF port. Building on this foundation, we propose a cost-effective, next-generation FRT device. Using a an RF architecture based on a Magic-T configuration, this advanced FRT will enable microphonics compensation in the ±30 Hz range for Nb_3Sn cavities, with minor degrading the external quality factor.

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