PROOF-OF-PRINCIPLE EXPERIMENT OF A FERROELECTRIC TUNER FOR A 1.3 GHZ CAVITY*

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Abstract

A novel ferroelectric frequency tuner was developed by the Omega-P company and was tested at the Brookhaven National Laboratory on a 1.3 GHz RF cavity at room temperature. The tuner is based on the ferroelectric property of having a permittivity variable with an applied electric field. The achievable frequency tuning range can be estimated from the reactive impedance change due to an applied voltage via a S_{11} measurement at the tuner port. The frequency shift can be measured directly with a S_{21} measurement across the gun cavity with the tuner connected and activated. The frequency change due to an applied 5 kV obtained from the two methods is in reasonable agreement. The reactive impedance measurement yields a value in the range between 3.2 kHz and 14 kHz, while 9 kHz is the result from the direct measurement. The detail description of the experiment and the analysis will be discussed in the paper.

INTRODUCTION

The operation of superconducting (SC) cavities in accelerators is impacted by fast detuning by microphonics and the Lorentz force which if uncontrolled leads to amplitude and phase errors of the accelerating voltage. The conventional mitigating solution is based on a powerful driving amplifier combined with a piezoelectric fast frequency tuner. The piezoelectric tuner acts via the mechanical movement of the cavity wall or a penetrating probe and is located in or close to the cryogenic region with its unavoidable limitations. Not surprisingly, the search for fast tuner operating outside the cavity has been carried out at several laboratories. The ultimate objective is the fast frequency tuning of a superconducting cavity with a tuner at room temperature. The small frequency range required in a SC cavity can be achieved in the room temperature cavity with appropriately changed coupling.

The use of ferroelectric material to achieve fast tuning speeds was suggested by a Russian–Yale collaboration [1] The ferroelectric ceramic has an electric field-dependent dielectric permittivity that can be altered by applying a bias voltage with a very short response time of potentially down to 10 ns. The ferroelectric barium strontium titanate $BaTiO_3$-$SrTiO_3$ (BST) has a relatively low dielectric constant in the range from 300 to 600 and is changed by about 10 to 20 % with an electric field of 20 to 50 kV/cm.

Recently, a new planar geometry for an L-band phase shifter has been developed that has the advantages of the previous designs, but with a smaller volume of ceramics [2]. The phase shifter BST material in the form of two 5×6 mm ceramic "waveguides" is placed between three planar layers of dielectric material with $\varepsilon \approx 20$. The assembly is placed into a rectangular waveguide by 6 supporting ferroelectric rods, having $\varepsilon \approx 500$. For the purpose of the present test, the waveguide was modified into a cavity by placing shorts at either end of the ferroelectric ceramic assembly and providing one 50 Ω connector. In this configuration the phase shifter functions as a voltage-controlled reactance which can be connected by cable to the 1.3 GHz gun cavity for the proof-of principle ferroelectric tuner (FT) test presented in this paper. The frequency change due to ~5 kV voltage applied across the ferroelectric material is the topic of this paper and in more detail of an internal report [3].

THE 1.3 GHZ ELECTRON GUN CAVITY

A change of the cavity frequency imposed by the FT depends on the cavity properties, in particular on the stored energy as given by the L-C-R values in an equivalent circuit and on the coupling strength to an external tuner capacity.

The 1.3 GHz electron gun cavity [4] was built for studies of photo emission in an electron gun and the circuit parameters required for the present study were computed with SUPERFISH and are found in Zhao's report [5]. The cavity can be represented by an L-C-R resonant circuit with the equivalent parameters given as, $C = 1.048$ pF, $L = 14.3$ nH, and the $R/Q = 116.8$ Ω. Also needed is the shunt impedance R_{SH} of the cavity which is obtained from a S_{21} measurement. The network analyzer provides the loaded quality factor, but assuming weak in and output coupling, the unloaded $Q_0 \approx 8200$ which leads directly to $R_{SH} \approx 9.58\times10^5$ Ω. From these quantities follows the value for $\omega_0 L = 117$ Ω which is the reference value for the comparison with the measured change of reactance in the FT.

The interaction of the FT with the cavity depends critically on the coupler strength expressed as a coupling parameter β or a transformer ratio, $n:1$ which are found from the S_{11} measurement of the cavity port. At

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resonance, the network analyzer provides the transformed cavity shunt impedance, R_{Port}, directly or in order to correct for cable losses from the S_{11} = 0.7336 as

$$R_{\text{Port}} = R_0 \frac{1 - S_{11}}{1 + S_{11}}, \tag{1}$$

with $R_0 = 50\ \Omega$ yielding $R_{\text{Port}} = 7.6\ \Omega$. The transformer ratio, which is independent of the cavity losses and stays constant at cryogenic temperatures, is also obtained from the port resistance,

$$n = \sqrt{\frac{R_{\text{SH}}}{R_{Port}}} \approx 355 \tag{2}$$

THE FERROELECTRIC TUNER

The relevant electrical properties of the ferroelectric tuner are obtained with a network analyzer from a S_{11} scattering coefficient measurement at the RF port of the tuner. The data is taken in the form $R + jX$, and always for 0 tuner voltage. The reactive component is shown in Fig. 1 as function of frequency.

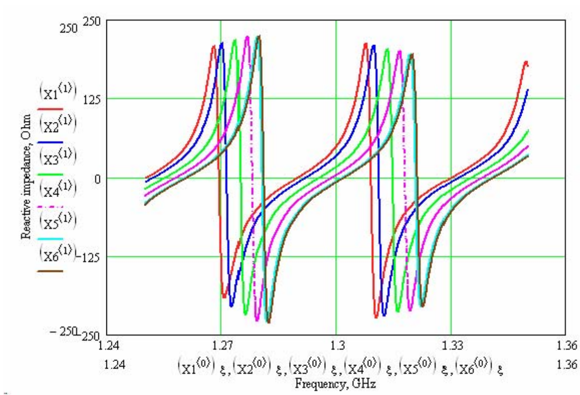

Figure 1: Reactive component of the tuner port impedance versus frequency in GHz. The shown curves are taken spaced in time (hr:min) at zero applied voltage after momentarily applied voltage.
Red 10:14 >3 kV; Blue 10:50 >5 kV; Green 11:39 >1 kV; Magenta 13:41 >6 kV;Cyan 14:26 >4 kV; Brown 14:58 >2 kV

Note that the tuner X-impedance curve moves to the right with time (the total shift in frequency is ~11.5 MHz in 5 hours). It is noted that during that period, the temperature increased by 4 ^{o}C., and the frequency shift is attributed to temperature changes of the ferroelectric.

The resonances within the tuner "cavity" are evident in Fig. 1 and point to a frequency dependence of the reactance available for the gun cavity tuning. The curves are displaced vertically when a bias voltage is applied and it is recommended for best accuracy of the change from the applied voltage to measure S_{11} at a frequency in the middle between the resonances.

Two measurements of the S_{11} change in the tuner induced by a step application of 5.17 kV where performed at the gun frequency of 1.302 GHz. The complex data can be interpreted by the network analyzer either as

- a series impedance, $Z_{FT} = R_Z - j/(\omega C_Z)$, or
- a parallel admittance, $Y_{FT} = G_Y + j\omega C_Y$.

Obviously, a conversion of the impedance into an admittance can easily be done according to

$$Y'_{FT} = G'_Z + j\omega C'_Z = \frac{R_Z(\omega C_Z)^2 + j\omega C_Z}{1 + (\omega C_Z R_Z)^2} \tag{3}$$

and a conversion in inverse direction is found as

$$Z'_{FT} = R'_Y - j/(\omega C'_Y) = \frac{G_Y - j\omega C_Y}{G_y^2 + (\omega C_Y)^2} \tag{4}$$

The two independent measurements were done at different times, the first one was interpreted by the network analyzer as impedance measurement and the other, taken 30 minutes later, as admittance. It was observed that the resonance curve at applied voltage drifted due to temperature changes. Therefore, the reading of S_{11} values at a fixed resonant frequency over a time span may vary, which is attributed to the non-flatness of the impedance curves shown in Fig. 1. The data for the "impedance" measurement plus its converted admittance values are listed in Table I, next to the results for the direct "admittance" measurement. The maximum change in capacitance available to tune the 1.3 GHz cavity is found to be 0.65 pF from the impedance and 0.29 pF from the admittance measurement.

External Q of the Tuner

The estimate of the frequency and *Q*-change in the gun cavity from connecting the tuner depends on the intrinsic gun cavity parameters and also on the coupler strength determined above. Table I shows a tuner resistance of ~15 Ω which transformed into $15/n^2 = 1.2 \times 10^{-4}\ \Omega$ must be compared to $R_S \approx 1.43\times10^{-2}\ \Omega$. The resulting *Q*-external of $Q_X \approx 94{,}400$, is independent of voltage and points to the need of substantial reduction of the tuner losses for use at cryogenic temperatures.

The estimate of the *Q*-change in the gun cavity due to connecting the tuner is based on a series equivalent circuit representation. Table I shows that applying the 5 kV to the tuner increases the series damping resistor by $2.2 \pm 0.3\ \Omega$ which must be compared to the transformed cavity resistance of $n^2 R_S = 1800$ resulting in a negligible decrease of the Q-value.

TUNER-INDUCED FREQUENCY CHANGE

The primary goal of the measurements for this paper was proofing that the ferroelectric tuner can in principle serve to control the frequency of a high-Q superconducting cavity. The tests were performed on the normal conducting gun cavity but extrapolation to high-Q

Table 1: Measurement of impedance and admittance of the ferroelectric tuner versus applied voltage.

	Z_{FT} [Ω] (Data and converted from Y_{FT})				Y_{FT} [S] (Data and converted from Z_{FT})			
V (kV)	$\mathrm{Re}\,Z_{FT}$	$\mathrm{Re}\,Z'_{FT}$	$\mathrm{Im}\,Z_{FT}$	$\mathrm{Im}\,Z'_{FT}$	$\mathrm{Re}\,Y_{FT}$	$\mathrm{Re}\,Y'_{FT}$	$\mathrm{Im}\,Y_{FT}$	$\mathrm{Im}\,Y'_{FT}$
0	14.93	15.0	-1.74	-5.90	57.7E-3	65.9E-3	22.7E-3	7.6E-3
5.17	16.83	17.5	-15.75	-21.25	23.1E-3	31.7E-3	28.0E-3	29.6E-3
Δ =	1.9	2.5	-14.01	-15.35	34.6E-3	34.6E-3	5.3E-3	21.9E-3

could be done by changing the "β" of the cavity coupler. Finding the range of the achievable frequency change was done with two methods, the first relies on a numerical application of the measured tuner data, presented above, and the second method involved the direct frequency measurement of the cavity frequency with the tuner connected.

Numerical Estimate of Frequency Changes

The FT connected with the cavity can be represented by an equivalent circuit in which the tuner capacity is in parallel with the cavity capacity transformed by n^2. The frequency change in the FT capacitive impedance, $\Delta\,\mathrm{Im}\,Y_{FT}$, due to the applied 5.17 kV is found in Table I to be 5.3×10^{-3} Ω from the admittance and 21.9×10^{-3} Ω from the impedance measurement. With the cavity capacitive admittance given by $Y_C = 1/\omega_0 L$, the expected frequency change in the cavity is found to be

$$\Delta f \approx \frac{\Delta C}{2n^2 C} f_0 = \frac{\Delta Y_{FT}}{2n^2 Y_C} f_0 \qquad (5)$$

and for the present example of the gun cavity about 3.2 kHz and 13.3 MHz from the respective admission measurement. The expression is written with the transformer ratio instead of the familiar β to emphasize that the frequency change would remain constant when the cavity goes superconducting. As discussed earlier, the difference is attributed to the uncertainty in the measurement due to the non-flatness of the S_{11} curve as function of frequency and temperature drifts.

Direct Measurement of the Frequency Change

A second method involves a direct measurement of the cavity frequency shift as the voltage is applied to the tuner. The configuration of the tuner with cavity for a S21 measurement is shown in Fig. 2. The frequency increase due to a voltage changed from 0 kV to 5.17 kV, taken at the time close to the above admittance measurement, is found to be ~9 kHz (1.302035 GHz vs. 1.302044 GHz, respectively). The frequency change due to the ferroelectric tuner measured by this direct method, is in reasonable agreement with numerical estimates found above.

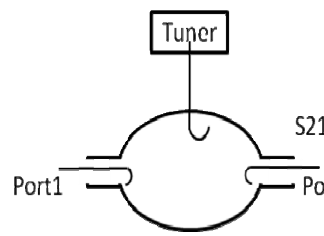

Figure 2: Direct measurement of the change in frequency of the gun cavity with the ferroelectric tuner connected.

CONCLUSION

As a proof-of-principle experiment, the frequency change due to the ferroelectric tuner has been measured in a warm 1.3 GHz cavity. Two different methods were used for the measurement; the indirect frequency change estimate based on the measured capacitance change as the tuner voltage is applied, and the direct frequency change measurement from S21. The two methods are in good agreement., with the results being 3.2 kHz to 14 kHz versus 9 kHz, respectively. With an applied voltage of ~ 5 kV, the ferroelectric tuner is capable of a frequency change by about 10 kHz in the 1.3 GHz gun cavity.

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