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Proof-of-principle Experiment of a Ferroelectric Tuner for the 1.3 GHz Cavity

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Abstract

A novel tuner has been developed by the Omega-P company to achieve fast control of the accelerator RF cavity frequency. The tuner is based on the ferroelectric property which has a variable dielectric constant as function of applied voltage. Tests using a Brookhaven National Laboratory (BNL) 1.3 GHz electron gun cavity have been carried out for a proof-of-principle experiment of the ferroelectric tuner. Two different methods were used to determine the frequency change achieved with the ferroelectric tuner (FT). The first method is based on a S11 measurement at the tuner port to find the reactive impedance change when the voltage is applied. The reactive impedance change then is used to estimate the cavity frequency shift. The second method is a direct S21 measurement of the frequency shift in the cavity with the tuner connected. The estimated frequency change from the reactive impedance measurement due to 5 kV is in the range between 3.2 kHz and 14 kHz, while 9 kHz is the result from the direct measurement. The two methods are in reasonable agreement. The detail description of the experiment and the analysis are discussed in the paper.

I. 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. At CERN a fast transmission type phase shifter using specially developed low loss ferrite was built and successfully tested at 352 MHz. The tuning speed of the device is limited by the ability of the tuning magnetic field to penetrate the ferrite region [1]. The tuning speed of a phase-shifter is dramatically increased by using a ferroelectric material instead as suggested by a Russian-Yale collaboration [2, 3]. 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 $\text{BaTiO}_3\text{-SrTiO}_3$ (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.

The Omega-P at Yale group used a bulk BST for an X-band phase shifter at 11.4 GHz [4], and also applied a properly modified BST to the first construction of a 1.3 GHz electrically controlled fast ferroelectric phase shifter suitable for operation with the SC 9-cell ILC cavity [5]. A conceptual design for a ferroelectric phase shifter for the 700 MHz Brookhaven ERL cavity was based on a coaxial line with ring BST rings, having a diameter of 104 mm, a thickness of 2.6 mm, and a length of 20.4 mm, for which the parameters had been carefully studied [6, 7]. However, it emerged that this design has the technical problems of being very complicated to manufacture, because it requires brazing of a large ceramic cylinder to the coaxial walls. A previously suggested coaxial-planar version is simpler to manufacture, but the large volume of ferroelectric ceramic evidently would lead to a high spectral density of parasitic modes that, in turn, leads to electric field enhancement and additional losses in the phase shifter.

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 [8]. The phase shifter is built into a rectangular waveguide by supporting 6 ferroelectric rods, having $\epsilon \approx 500$, into three planar layers of dielectric material with $\epsilon \approx 20$. 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 $50\ \Omega$ connector. In this configuration the phase shifter functions as a voltage-controlled reactance which can be connected by cable to the resonant cavity for the proof-of-principle ferroelectric tuner test presented in this paper. The frequency change of a 1.3 GHz gun cavity produced by an electric field from a 5 kV applied voltage applied across the ferroelectric material has been determined by two methods and is the topic of this paper.

II. THE 1.3 GHz ELECTRON GUN CAVITY

The 1.3 GHz electron gun cavity [9] 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 [10]. The cavity can be represented by an L-C-R resonant circuit with the equivalent parameters given as, $C = 1.048\ \text{pF}$, $L_0 = 14.3\ \text{nH}$, and the $R/Q = 116.8\ \Omega$. From these quantities follows the value for $\omega_0 L = 117\ \Omega$ which is the reference value for the comparison with the measured change of reactance in the FT. Also needed is the shunt impedance R_{SH} of the cavity which requires making a S21 measurement shown symbolically in Fig. 1. The network analyzer provides the loaded quality factor, but assuming weak in and output coupling, the unloaded $Q_0 \approx 8200$ directly leading to $R_{\text{SH}} \approx 9.58 \times 10^5\ \Omega$, or $R_s \approx 1.43 \times 10^{-2}\ \Omega$ for a series equivalent circuit.

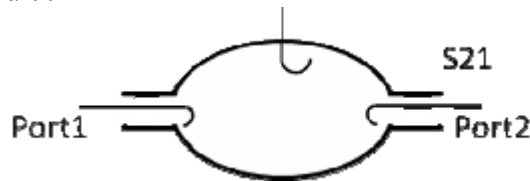


FIGURE 1: Q determination with a S21 measurement

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 a S_{11} measurement of the cavity port. As shown in Fig. 2, the Vector Network Analyzer (VNA) is directly attached to the cavity via the tuner coupling port. At 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

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

with $R_0 = 50 \Omega$ yielding $R_{\text{port}} = 7.6 \Omega$.

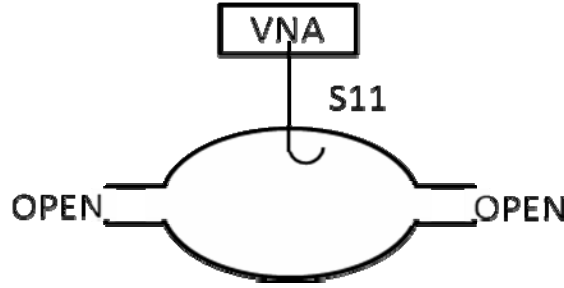


FIGURE 2. S_{11} Measurement at the cavity coupler port

The coupling parameter follows as

$$\beta = \frac{R_{\text{port}}}{R_{\text{SH}}} \approx 8 \times 10^{-6}$$

and the transformer ratio, which is independent of the cavity losses and stays constant at cryogenic temperatures, is also obtained from

$$n = \sqrt{\frac{R_{\text{SH}}}{R_{\text{port}}}} \approx 355$$

The external quality factor of a 50Ω resistor at the port is now found to be

$$Q_x = n^2 \frac{R_s}{R_0} Q_0 \approx 295,000.$$

III. THE FERROELECTRIC TUNER

The relevant electrical properties of the ferroelectric tuner are obtained with a network analyzer from a scattering coefficient measurement at the RF connector of the tuner as seen in Fig. 3. The measured amplitude of S_{11} is shown in Fig. 4 as function of frequency. It is noted that the curves change as function of time, within a few minutes when the voltage is applied, and is believed to be caused by temperature changes of the ferroelectric. The resonances within the tuner “cavity” are evident 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 in S_{21} to measure at a frequency in the middle between the resonances.

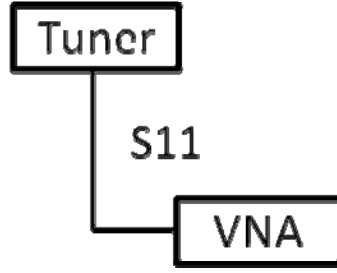


FIGURE 3: The ferroelectric tuner is connected to the Network Analyzer; Resistance and reactance is measured as a function of applied voltages.

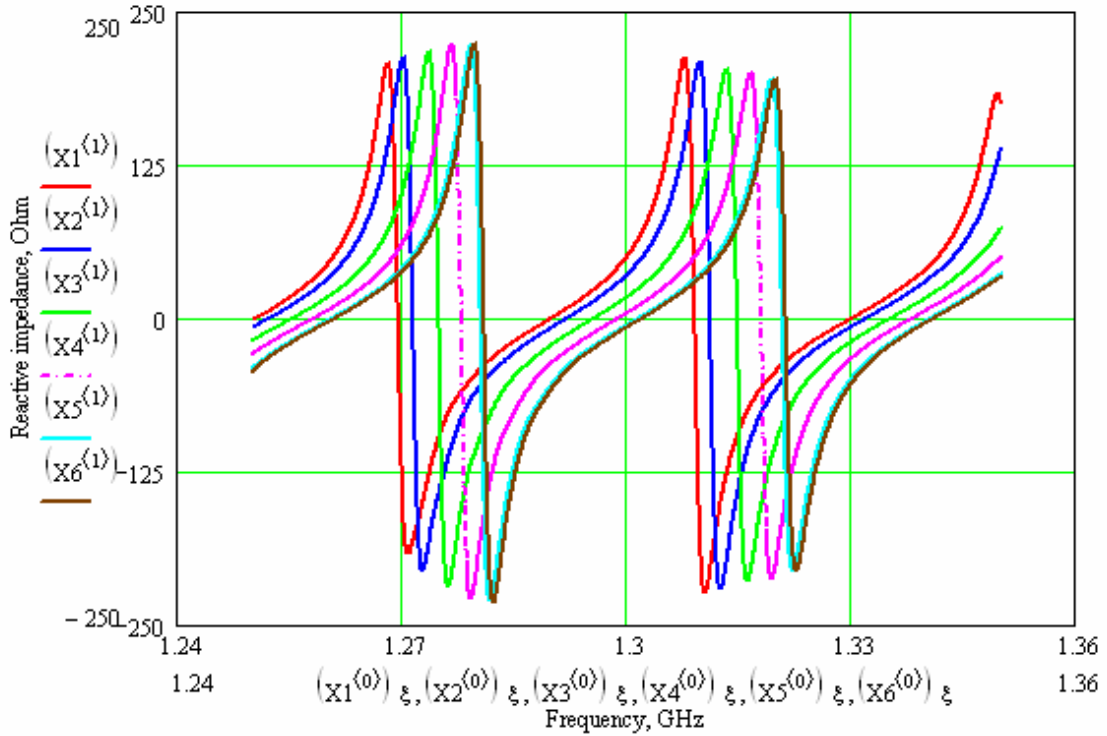


FIGURE 4: Amplitude of S11 Scattering coefficient at the tuner (with cable used) as function of frequency in GHz. The shown curves are taken spaced in time (hr:min) at zero applied voltage after momentarily applied voltage.

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

Two measurements of the S11 change in the tuner induced by a step application of 5.17 kV were performed at the gun frequency of 1.302 GHz. The complex S21 value 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

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

and a conversion in inverse direction is found as

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

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 S11 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. 4. 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.

Table I: Measurements of impedance and admittance of the ferroelectric tuner versus applied voltage

	Data Z_{FT}		Data Y_{FT}	
V (kV)	Re Z_{FT} (Ω)	Im Z_{FT} (Ω)	Re Y_{FT} (Ω^{-1})	Im Y_{FT} (Ω^{-1})
0	14.928	-1.7349	57.72E-3	22.72E-3
5.17	16.83	-15.75	23.10E-3	28.00E-3
$\Delta =$	1.9	-14.02	34.6E-3	5.28E-3
	Z'_{FT} (Converted Y_{FT})		Y'_{FT} (Converted Z_{FT})	
	Re Z'_{FT} (Ω)	Im Z'_{FT} (Ω)	Re Y'_{FT} (Ω^{-1})	Im Y'_{FT} (Ω^{-1})
0	15.0	-5.90	65.9E-3	7.6E-3
5.17	17.5	-21.25	31.7E-3	29.6E-3
$\Delta =$	2.5	-15.35	34.6E-3	21.9E-3

The estimate of the frequency and Q-change in the gun cavity from connecting the tuner depends on the intrinsic gun cavity parameters and then also the coupler strength determined above. Table I shows a tuner resistance of $\sim 15 \Omega$ which transformed into $15/n^2 = 1.2 \times 10^{-4} \Omega$ must be compared to $R_s \approx 1.43 \times 10^{-2} \Omega$. The resulting Q-external of $Q_x \approx 94,400$, points to the need of substantial reduction of the tuner losses for use at cryogenic temperatures. Comparing the change in the Q-determining series resistance shows a $\sim 30\%$ agreement based on the 1.9 Ω and 2.5 Ω difference in the two measurements. The estimate of the Q-change due to connecting the tuner to the gun cavity 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.

IV. CAVITY FREQUENCY CHANGE by TUNER

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 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.

First method: 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, $\Delta \text{Im} Y_{FT}$, due to the applied 5.17 kV is found in Table I for the two measurements to be $5.28 \times 10^{-3} \Omega$ from the admittance and $21.9 \times 10^{-3} \Omega$ 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

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

and for the present example of the gun cavity about 3.2 kHz and 13.3 MHz from the admittance and impedance measurement respectively. The expression is written with the transformer ration 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 impedance / admittance measurement due to the non-flatness of the S11 curve as function of frequency.

Second Method: 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. 5. 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).

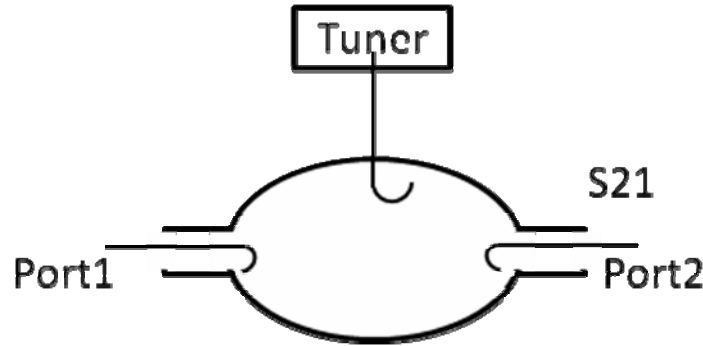


FIGURE 5: Direct measurement of the change in frequency and Q factor of the gun cavity with the ferroelectric tuner connected.

The frequency change due to the ferroelectric tuner measured by this direct method, is in the range of the estimates from the impedance & admittance measurements. It is noted that a reasonable agreement of the frequency change due to the applied ferroelectric tuner voltage is seen between the two different methods: for the impedance method (Method 1, which is a S11 method), one has 3.2 kHz ~ 14 kHz, and for the direct frequency measurement (Method 2, which is a S21 method), 9 kHz.

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. The two different methods were used for the measurement; the indirect frequency change measurement from the direct capacitance change as the tuner voltage is applied, and the direct frequency change measurement from S21, and the results are 3.2 kHz ~ 14 kHz vs. 9 kHz, respectively. The two methods are in good agreement. The ferroelectric tuner is capable of frequency change of the 1.3 GHz cavity around 10 kHz as the voltage of 5 kV is applied.

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