

WAVEGUIDE STUB TUNER ANALYSIS FOR CEBAF APPLICATION*

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Abstract

Three-stub WR650 waveguide tuners have been used on the CEBAF superconducting cavities for two changes of the external quality factors (Q_{ext}): increasing the Q_{ext} from $3.4\sim 7.6\times 10^6$ to 8×10^6 on 5-cell cavities to reduce klystron power at operating gradients and decreasing the Q_{ext} from $1.7\sim 2.4\times 10^7$ to 8×10^6 on 7-cell cavities to simplify control of Lorenz Force detuning. To understand the reactive tuning effects in the machine operations with beam current and mechanical tuning, a network analysis model was developed. The S parameters of the stub tuner were simulated by MAFIA and measured on the bench. We used this stub tuner model to study tuning range, sensitivity, and frequency pulling, as well as cold waveguide (WG) and window heating problems. Detailed experimental results are compared against this model. Pros and cons of this stub tuner application are summarized.

INTRODUCTION

Most applications of a three-stub tuner modifying a superconducting cavity input coupling are on storage rings, to match RF power to heavy beam loading and off-crest conditions. An early implementation was at DESY [1]. The analysis method used an equivalent circuit including the three-stub tuner. Recently, a similar application has been employed at CESR, Cornell. The analysis method has been improved from lumped elements to a network distributed system [2]. Reactive tuning by H or E stubs and other fast response tuning devices could also compensate Lorenz Force detuning and microphonic problems in the SRF control system [3]. In a WG iris/stub tuning design [4], reactive tuning was dominated by the fixed inductance of an iris. The stubs only change the frequency pulling. So the Q_{ext} can only be increased. Three stubs can act as both frequency tuner and reactive device to increase or decrease the Q_{ext} .

The WR650 waveguide three-stub tuners have been used at JLab on 5-cell (mean value of $Q_{\text{ext}}=5.5\pm 0.8\times 10^6$) cavities to reduce required klystrons' power [5]. They were also installed on the SL21 cryomodule, with new 7-cell cavities and $Q_{\text{ext}}=1.7\sim 2.4\times 10^7$. The heating effect on the SL21's cold WG fundamental power coupler (FPC) and warm ceramic windows have been observed [6] with little understanding. Under existing RF low level control (amplitude modulation) and high level power (5kW klystron) systems, the system Q at 8×10^6 is more tolerable. Then there is motivation to decrease the Q_{ext} to overcome the problem of Lorenz-force bump during cavity gradient ramp-up [7]. Otherwise a manual tuning of up to 3 bandwidths (225Hz) and slow increase of

gradient are necessary. A network model has been developed to analyze stub tuner tuning properties, such as range, sensitivity and reactive heating effect.

NETWORK ANALYSIS MODEL

A two-port microwave network can be described by a 2×2 transmission matrix \mathbf{T} :

$$\begin{pmatrix} a_1 \\ b_1 \end{pmatrix} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} \begin{pmatrix} b_2 \\ a_2 \end{pmatrix} \quad (1)$$

Here a_1 and b_1 are incident and reflected waves (or voltages) on input port 1 respectively. The a_2 and b_2 are for output port 2 and reversed in raw position. So a total \mathbf{T} matrix represents a cascaded wave transmission from three-stub tuner to the Field Probe (FP) of the cavity.

$$\mathbf{T}_{\text{tot}} = \mathbf{T}_{3\text{st}} \bullet \mathbf{T}_{\text{wg}2} \bullet \mathbf{T}_{\text{tp}} \bullet \mathbf{T}_{\text{hb}} \bullet \mathbf{T}_{\text{wg}1} \bullet \mathbf{T}_{\text{FPC}} \bullet \mathbf{T}_{\text{ca}} \bullet \mathbf{T}_{\text{b}} \bullet \mathbf{T}_{\text{FP}} \quad (2)$$

Here $\mathbf{T}_{\text{wg}1}$ and $\mathbf{T}_{\text{wg}2}$ are WR650 WG matrices in two section lengths l_1 and l_2 with attenuation α and propagation β constants for TE01 mode.

$$\mathbf{T}_{\text{wg}} = \begin{pmatrix} e^{(\alpha+j\beta)l} & 0 \\ 0 & e^{(\alpha-j\beta)l} \end{pmatrix} \quad (3)$$

The \mathbf{T}_{FPC} and \mathbf{T}_{FP} are ideal transformer matrices for FPC (subscript 1) and FP (subscript 2), with $n_1 = \sqrt{Q_0 / Q_{\text{1ext}}}$, and $n_2 = \sqrt{Q_0 / Q_{\text{2ext}}}$ respectively:

$$\mathbf{T}_{\text{FPC}} = \begin{pmatrix} 1+n_1^2 & n_1^2-1 \\ 2n_1 & 2n_1 \end{pmatrix} \quad \mathbf{T}_{\text{FP}} = \begin{pmatrix} 1+n_2^2 & 1-n_2^2 \\ 2n_2 & 2n_2 \end{pmatrix} \quad (4)$$

The \mathbf{T}_{ca} and \mathbf{T}_{b} corresponds normalized cavity and beam load shunt susceptances:

$$\mathbf{T}_{\text{ca}} = \begin{pmatrix} 1 + \frac{Y_{\text{ca}}}{2} & Y_{\text{ca}} \\ -\frac{Y_{\text{ca}}}{2} & 1 - \frac{Y_{\text{ca}}}{2} \end{pmatrix} \quad \mathbf{T}_{\text{b}} = \begin{pmatrix} 1 + \frac{Y_{\text{b}}}{2} & Y_{\text{b}} \\ -\frac{Y_{\text{b}}}{2} & 1 - \frac{Y_{\text{b}}}{2} \end{pmatrix} \quad (5)$$

The Y_{ca} is a function of cavity's intrinsic quality factor Q_0 , drive frequency f (1497MHz for CEBAF) and cavity tuned resonance frequency deviation df .

$$Y_{\text{ca}} = 1 + iQ_0 \left(\frac{f+df}{f} - \frac{f}{f+df} \right) \quad (6)$$

The Y_{b} is a function of beam current I_0 , cavity's shunt impedance per unit length $(r/Q)Q_0$, acceleration gradient E_{acc} and the beam current to RF voltage's phase Φ_{b} .

$$Y_{\text{b}} = \frac{I_0(r/Q)Q_0}{E_{\text{acc}}} e^{i\Phi_{\text{b}}} \quad (7)$$

The $\mathbf{T}_{3\text{st}}$ is the transmission matrix for the three-stub tuner. The \mathbf{T}_{tp} , a WG taper, transforms from WR650 to a reduced height WG ($5.292''\times 0.986''$). The \mathbf{T}_{hb} is for a reduced height 90° H-bend. Their transmission matrices can be converted from their S-parameters.

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$$\begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} = \frac{1}{T_{11}} \begin{pmatrix} T_{21} & |T| \\ 1 & -T_{12} \end{pmatrix} \text{ or } \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} = \frac{1}{S_{21}} \begin{pmatrix} 1 & -S_{22} \\ S_{11} & -|S| \end{pmatrix} \quad (8)$$

All S-parameters can be measured on the bench with a network analyzer and TRL calibrations, or calculated by 3D simulations like MAFIA (time domain) and HFSS (frequency domain) at 1.5GHz frequency. The three-stub tuner can be divided into three individual elements. Each element has one stub plus two small sections of WG on each side. The S-parameters of each element can be characterized as a function of each individual stub height. Then three stubs can be combined like cascaded elements. Figures 1 and 2 show a good agreement between measurement and simulations. The polynomial fits can be used in the analysis.

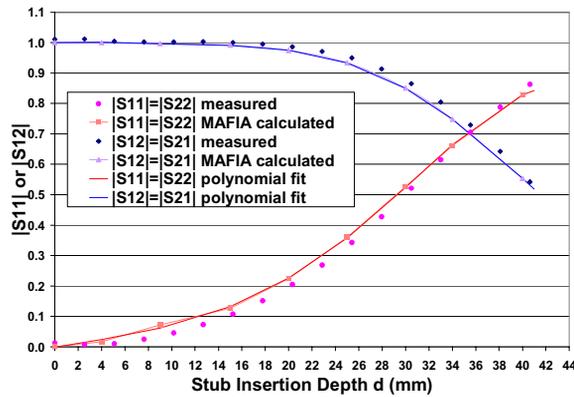


Figure 1: S amplitudes of a single stub inside of a 12" long WR650 WG.

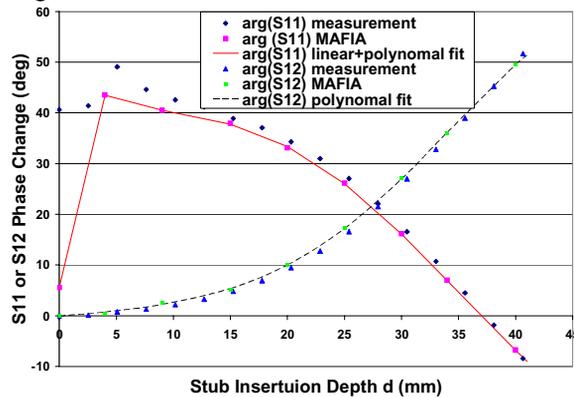


Figure 2: Phase change of S parameters of Figure 1.

After applying all parameters for a 7-cell cavity, without beam current present, we can plot $|S_{21}|$ from Equation 8 for the total transmission from FPC to FP with the variables of d_1 , d_2 , d_3 (three stubs' heights) and df (in Figure 3). The same quantities can be measured in a cold cavity with a network analyzer. The loaded Q of the system has been reduced (can be increased too) by different stub settings. An important observation from this graph is that even with a "flush" stub settings ($d_1=d_2=d_3=0$), there is still about +4Hz frequency pulling (the peak is at $df=4$ Hz) caused by the unmatched WG taper and H-bend. With the third stub in ($d_3=31$ mm), the loaded Q dropped from 2.55×10^7 to 8.03×10^6 , but frequency was pulled by -26Hz. Inserting the second stub ($d_2=18$ mm) can bring the peak back, but the Q drops

further to 6.37×10^6 . This behavior also has been experienced during stub tuning practice.

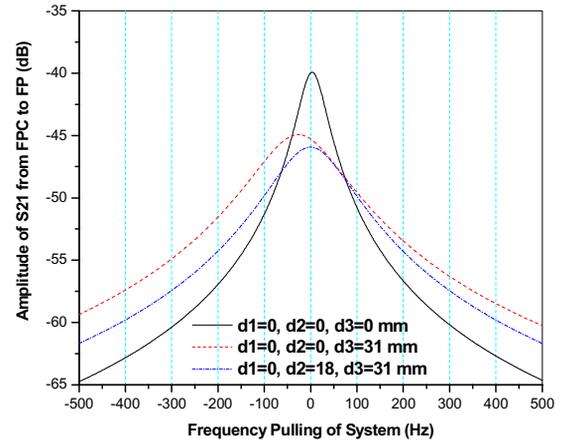


Figure 3: Three stubs with different heights change the superconducting cavity's Q_{ext} , seen by the $|S_{21}|$ peaks from FPC to FP.

By calculating the -3dB bandwidth on each $|S_{21}|$ peak or the absolute value of the peak, we can derive and map out the equivalent external Q of the input coupling as a function of the stub settings. Figure 4 shows an example with the first stub fixed at $d_1=0$, and d_2 and d_3 as variables. Q_{ext} can be tuned from its original value of 2×10^7 down to 1×10^6 or up to 2×10^8 . Tuning sensitivity varies from stub to stub with travel heights. The most sensitive stub in this example is at $d_3=20$ to 30 mm, being 10dB change on the Q_{ext} , or a sensitivity of is up to 10dB/cm. We can also conclude from these calculations that different stub settings can get a same Q_{ext} value but with different frequency pulls. The following analysis shows that the best stub setting is the one with minimum frequency pull from 1497MHz.

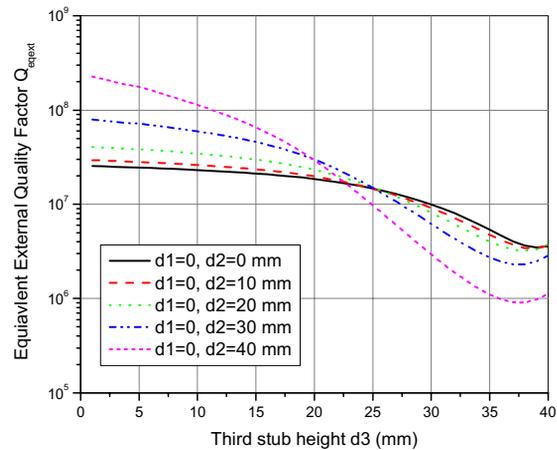


Figure 4: One case of tuning range and sensitivity of external Q with different stub settings.

Using this transmission matrices technique, we can separate the T_{wgl} into two sections in Equation (2). We shall get a WG input voltage for a known cavity voltage (or E_{acc}) first, then use the inverse of transmission matrix on the left side of the separation point in Equation (2).

We can calculate the standing wave voltage (SWV) inside of WG near the FPC as a function of the WG distance. To get an absolute SWV value, one needs to de-normalize the waves (a , b) by the local impedances. Figure 5 shows the result with the stub setting, frequency pull (could be due to others than the stub setting) and beam current as the variables [8].

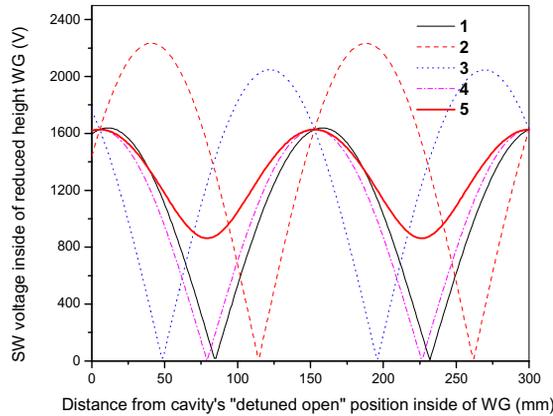


Figure 5: Standing wave voltage patterns at a constant gradient of $E_{acc}=12\text{MV/m}$ inside of FPC's WG (either on short or long wall) with following conditions:

1. $d1=0, d2=0, d3=0$, peak at $df=+4\text{Hz}$, $Q_{ext}=2.55E7$.
2. $d1=0, d2=0, d3=0$, -3dB pt. at $df=+32\text{Hz}$, $Q_{ext}=2.55E7$.
3. $d1=0, d2=0, d3=31\text{mm}$, peak at $df=-26\text{Hz}$, $Q_{ext}=8.03E6$.
4. $d1=0, d2=18, d3=31\text{mm}$, peak at $df=0\text{Hz}$, $Q_{ext}=6.37E6$.
5. Same as curve 4, and beam $I_0=0.3\text{mA}$, $\phi_b=0$ (on-crest).

One important conclusion drawn from this calculation is that when the stub tuner decreases (or increases) the external Q of the system, at a fixed gradient, a setup with a minimum frequency pulling (df) always minimizes the SWV ratio inside of the WG between the stubs and the cavity. So the heating in this section can be reduced.

EXPERIMENT RESULT

Based on this conclusion, a test plan has been carried out at SL21's #4 cavity with low temperature diodes installed on the cold section of WG. We tuned the stubs from $Q_{ext}=2 \times 10^7$ to 5×10^6 by every means to minimize the frequency pull with $df=-20\text{Hz}$ only. We recorded the klystron forward power, phase angle offset in the auto-track mode of the cavity tuner. Cold WG temperature follows a parabolic shape as the klystron power's fitting shown in Figure 6. Except the drift from a phase transit, no sign of temperature increase in this stub setting. We also found the ceramic window warm temperature has no correlation with this stub setting. The cavity can ramp up to a 10MV/m gradient in 1 second.

CONCLUSION

Based on our model analysis and experimental data, we have concluded that three-stub tuner can modify (increase or decrease) the external coupling Q of a superconducting cavity over a range of 2 orders of

magnitude. Stub position could be sensitive to the Q and phase change. Minimizing the frequency pulling away from the matched system is the key step to properly set up the stubs to avoid extra RF heating on the WG components. The phase drifting problem as the tunnel's temperature variation is related to the reactance change on the WG components. To relief this problem, we recommend installing the stub tuner close to the cavity inside accelerator tunnel with a stepper-motor remote control. We can use this network model study the problem further. This model can be also modified to improve the reactive tuning compensation technique [4] for other applications.

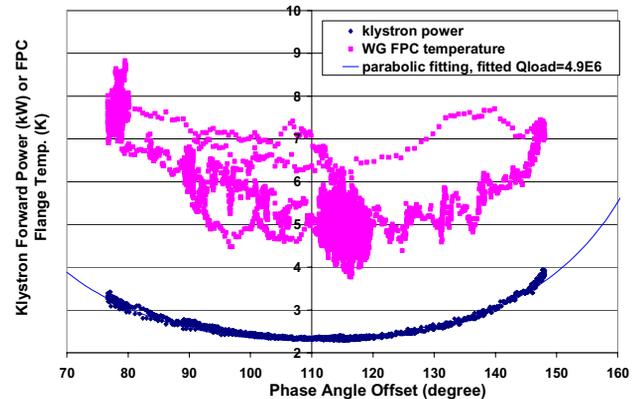


Figure 6: Cold waveguide temperature readout at SL21 cavity #4 with $E_{acc}=7.8\text{MV/m}$, stub tuner set as $Q_{ext}=5 \times 10^6$, $df=-20\text{Hz}$.

REFERENCES

- [1] B. Dwersteg, "SC-Cavity Operation Via WG-Transformer", Proc. Of the 4th SRF Workshop, Aug 14-18, 1989, KEK, Japan, KEK report 89-21, Vol. II, p. 593.
- [2] V. Veshcherevich, S. Belomestnykh, "Correction of the Coupling of CESR RF Cavities to Klystrons Using Three-Post Waveguide Transformers", Cornell LNS Report SRF 020220-02, 2002.
- [3] Y. Kang, M. Tiefenback, "Reactive RF Tuning for Compensation of a Detuned Accelerating Cavity", Proc. of LINAC2002, Gyeongju, Korea, Aug. 19-23, 2002.
- [4] H. Wang, "Analytical Design of a Waveguide Iris/Stub Tuning Coupler to an Overcoupled Superconducting Cavity", Proc. of PAC2003, Portland, OR, USA, May 12-16, 2003, p. 1101.
- [5] C. Reece, "Optimal Loaded-Qs for CEBAF", internal AccSys Notes, Dec. 12, 2000.
- [6] T. Powers, "Waveguide Heating on SL21, Cavity #3", internal report, May, 29, 2003.
- [7] C. Reece, "Lorentz-force Tuning Effects in CEBAF", JLab Technote TN 98-041, Oct. 6, 1998.
- [8] H. Wang, "A MathCAD Program to Calculate the RF Waves Coupled from a WR650 Three-Stub Tuner to a CEBAF Superconducting Cavity", to be published in a JLab Technote, 2004.