TUNING OF CLIC ACCELERATING STRUCTURE PROTOTYPES AT CERN

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Abstract

An RF measurement system has been set up at CERN for use in the X-band accelerating structure development program of the CLIC study. Using the system, S-parameters are measured and the field distribution is obtained automatically using a bead-pull technique. The corrections for tuning the structure are calculated from an initial measurement and cell-by-cell tuning is applied to obtain the correct phase advance and minimum reflection at the operation frequency. The detailed tuning procedure is presented and explained along with an example of measurement and tuning of CLIC accelerating structure prototypes.

INTRODUCTION

The X-band accelerating structure R&D program at CERN, as a part of the CLIC-study project, aims at developing structures that run at a gradient of 100MV/m at low breakdown rate (10^{-7}/pulse/m). Many prototype structures are being produced for high-power test. Currently, machining typically reaches a dimension accuracy of several μm. However in a 12GHz, $2\pi/3$ mode traveling-wave structure with group velocity $v_g = 0.01c$, for example, a 1μm error in cell-radius will cause 1MHz frequency shift and $1°$ cell-to-cell phase advance error. Thus, tuning is necessary to have the right phase advance between adjacent cells, and minimize the reflection from the output matching cell, to avoid standing wave in the structure, which will introduce local field enhancement and may limit the overall accelerating gradient.

A method to tune a traveling-wave structure using field distribution obtained by "bead-pull" measurement was presented in [1, 2]. However, these papers did not include the discussion of tuning the matching cells and were not clear about the reflection change during tuning. We re-derive some important quantities and present a complete tuning procedure which has been successfully applied to a prototype structure at CERN.

THE REFLECTION DUE TO DE-TUNING IN TRAVELING-WAVE STRUCTURES

The reflection from the input port that couples to an RF resonant cavity is:

$$\Gamma = \frac{(\beta - 1)(\beta + 1) - Q_0^2(\Delta F)^2}{(\beta + 1)^2 + Q_0^2(\Delta F)^2} - j\frac{2\beta Q_0 \Delta F}{(\beta + 1)^2 + Q_0^2(\Delta F)^2} \quad (1)$$

where Q_0 is the unloaded quality factor of the cavity, $\beta = Q_0/Q_e$ is the coupling factor, Q_e is the external quality factor and

$$\Delta F = \frac{f}{f_0} - \frac{f_0}{f} \approx -2\Delta f_0/f_0, \quad (2)$$

where f is the operating frequency and f_0 is the resonant frequency of the cavity, $\Delta f_0 = f_0 - f$ is the detuning of the cavity[3].

In a traveling-wave structure each cell is coupled to the adjacent cells or to the waveguides if it is an input or output matching cell. Following the power flow, each cell can be considered having an input port and output port. If the power flow P_f to the output port (or the next cell) is treated as intrinsic loss, counted into Q_0, the reflection seen from the input port (or the previous cell) looks exactly the same as equation (1). We define

$$Q_0' = \frac{\omega U}{P_w + P_f} \quad (3)$$

where P_w is the RF power dissipated on the cavity wall. If the group velocity of the structure is given as v_g, the power flow is $P_f = W v_g$, where W is the stored energy per unit length.

$$Q_0' \approx \frac{\omega U}{P_f} = \frac{\omega W D}{W v_g} = \frac{c\varphi}{v_g}, \quad (4)$$

where D is the cell length and φ is the phase advance per cell and $D = \varphi \cdot c/\omega$. It can be seen that the approximation is true since $(c\varphi)/v_g$ is much smaller than Q_0 in most accelerating structures.

In equation (1), the reflection will be zero when the structure is at critical coupling, $\beta = 1$, $Q_e = Q_0$, at resonant frequency. In a traveling wave structure, this condition is also required, especially for the matching cells, where the matching irises must be carefully designed to satisfy $Q_e = Q_0'$. For regular cells, the cell-to-cell coupling with the previous cell and the next cell is approximately the same if the group velocity change is small, making $Q_e \approx Q_0'$. Since $Q_0' \sim 100$, and $\Delta f_0/f_0 \sim 0.001$, we can make a first order approximation that the reflection only gain a imagery part due to a frequency de-tuning:

$$\Gamma \approx -j\frac{2\beta Q_0' \Delta F}{(\beta + 1)^2 + {Q_0'}^2(\Delta F)^2} \approx j\frac{Q_0' \Delta f_0}{f_0}. \quad (5)$$

Q_0' can be calculated using equation (4) in a traveling-wave structure, while is simply the unloaded quality factor, Q_0, in a standing-wave cavity.
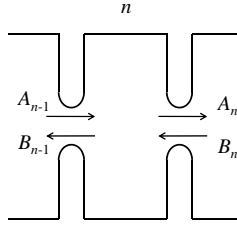
Figure 1: Forward wave (A) and Backward wave (B) through a cell

THE TUNING METHOD

In order to use equation (5), one needs to have the reflection of each cell in order to calculate the required tuning and correct it cell-by-cell. This can be obtained if we can calculate forward wave and backward wave along the structure. Reference [1, 2] gives the method to calculate the waves using a linear model. The field of the structure I_n is the superposition of two waves traveling forward A_n (from input to output coupler) and backward B_n (from output to input coupler) in the structure (Fig. 1). So we have

$$A_n = A e^{j(\omega t - n\varphi)}, \quad B_n = B e^{j(\omega t + n\varphi)}, \qquad (6)$$

and

$$I_{n-1} = A_n e^{j\varphi} + B_n e^{-j\varphi}, \quad I_n = A_n + B_n, \quad (7)$$

from which one can derive:

$$A_n = \frac{I_{n-1} + I_n e^{-j\varphi}}{-2j \sin\varphi}, \quad B_n = \frac{I_{n-1} + I_n e^{j\varphi}}{2j \sin\varphi}. \qquad (8)$$

For a nth cell, the reflected wave is the difference between the backward waves seen before and after the cell:

$$\Gamma_{\text{local}} = \frac{B_n - B_{n+1} e^{-j\varphi}}{A_n}, (2 \le n \le N - 1) \qquad (9)$$

However, we still need to derive the expression at the ends of the structure, $n = 1$ or $n = N$. For the output matching cell, there is no reflection from the output waveguides that are connected to matched load, so it is simply

$$\Gamma_{\text{local}}|_N = \frac{B_N}{A_N} \qquad (10)$$

For the input matching cell, we can use $A_1 = A_2 e^{j\varphi}$ as an approximation, while the backward wave corresponds to the measured reflection coefficient (S_{11}) of the structure. However, the phase offset of the input wave-guide must be corrected. The factor to correct the phase offset can be obtained by the bead perturbation of the cell, which always decreases the frequency and the reflection change $\Delta S_{11}^{(1)}$ should have a phase factor of "$-j$" according to equation (5).

$$\Gamma_{\text{local}}|_1 = \frac{\left[-j |\Delta S_{11}^{(1)}| / \Delta S_{11}^{(1)} \right] S_{11} A_1 - B_2 e^{-j\varphi}}{A_1}. \qquad (11)$$

The value of frequency de-tuning of each cell is not sufficient during a actual tuning, since the relationship between the frequency shift and the deformation or the movement of the tuning studs is required. The purpose of tuning is to correct the reflection of each cell by changing the frequency, so we can always monitor the reflection from input coupler, the S_{11}, (or the *global reflection* for convenience), to see how much local reflection is corrected.

The relationship between the global reflection and the local reflection can be derived as follows. There is a wave traveling from the input coupler to the location where the local reflection occurs and then travels backward to the input port, which attenuates due to the power loss on the cavity wall, described as:

$$\frac{dP}{dz} = -\frac{\omega}{Q_0} \frac{1}{v_g} P, \quad P = P_0 \exp\left(-\int \frac{\omega}{Q_0 v_g} dz \right) \quad (12)$$

So we have

$$|\Delta\Gamma_{\text{global}}| = e^{\alpha(n)} |\Delta\Gamma_{\text{local}}(n)| \qquad (13)$$

where

$$\alpha(n) = -\frac{1}{2} \cdot 2 \cdot \int_0^{(n-1)D} \frac{\omega}{Q_0 v_g} dz. \qquad (14)$$

The factor of "1/2" occurs because the wave amplitude is the square root of power, and the "2" is because the wave travels forward and back. Writen in a discrete series ($D = \varphi c/\omega$):

$$\alpha(n) = -\sum_{m=1}^{n-1} \frac{c\varphi}{Q_0(m) v_g(m)}. \qquad (15)$$

In summary, the steps of the tuning procedure are:

- Measure the field distribution using the "bead-pull" method [4].
- Calculate the local reflection of each cell by equation (8), (9), (10) and (11)
- Calculate the global reflection change ($|\Delta\Gamma_{\text{global}}|$ or $|\Delta S_{11}|$) due to local reflection correction using equation (13) and (15)
- Tune cell-by-cell while monitoring $|\Delta S_{11}|$ on the network analyzer to the target calculated in the previous step

TUNING OF A CLIC-G PROTOTYPE

The CLIC-G is a 12GHz waveguide-damped structure at 12GHz, operating with a $2\pi/3$ phase advance and with 24 regular cells (TD24) and 2 matching cells[6]. A prototype version of the structure was measured by a 2-port vector network analyzer (VNA). The two VNA ports are connected to the input waveguides ports via coaxial-WR90 adapters, and the output waveguides are connected to matched loads, as shown in Fig. 3. The S-parameters from the network analyzer need to be summed to get the reflection from the input [5]. The "bead-pull" measurement
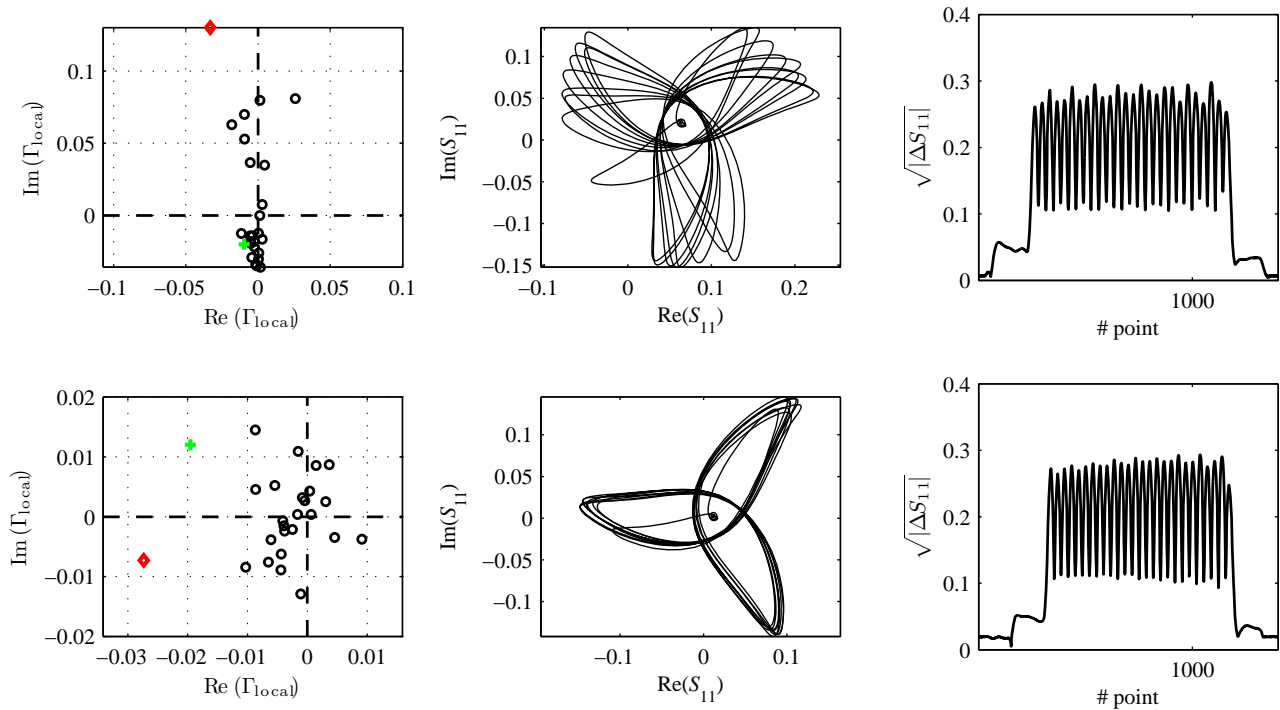
Figure 2: RF measurement results of a CLIC-G (TD24) structure before (TOP) and after (BOTTOM) tuning (left: Calculated local reflection; red-diamond: output cell, green-cross: input cell, black-circles: regular cells; middle: bead-pull results showing the RF phase; right: bead-pull results showing field amplitude)

is done using a motor rolling a thread vertically. Following the steps described in the previous section, we did four iterations to tune the structure. The result is shown in Fig. 2.
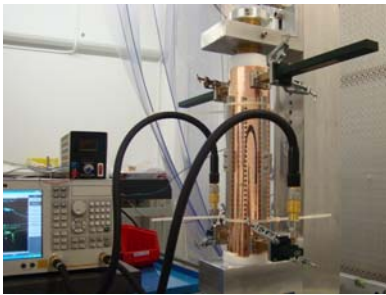

Figure 3: Photo of the structure on bench

Tuning "dimples" are pushed and pulled on cells that have lower frequency and higher frequency, respectively. After tuning, the average phase shift error along the structure is $0.07°$ per cell. The local reflection of the output matching cell had an imaginary part of "$j0.13$", which means about 6MHz frequency error at $v_g = 0.8\%c$. This large reflection yields a standing-wave pattern in the field distribution (Fig. 2 up-right), which is corrected after tuning. However, since tuning only corrects the imaginary part of the reflection, a small residual reflection (real part) from the output matching cell still exists, which is due to the matching iris error.

CONCLUSION

The method of tuning a traveling wave structure is explained and an example of tuning a CLIC-G prototype is presented. From the experience, an error of $0.01(-40\text{dB})$ of local reflection was achieved.

An integrated software with user-friendly interface for doing both "bead-pull" measurement and S_{11} monitoring is being developed to improve the efficiency during production.

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