

TUNING OF AN S-BAND 10 MeV TRAVELING-WAVE ACCELERATING STRUCTURE WITH A NON-UNIFORM SECTION

J. Shao*, C. Gong, S. Zheng, H. Chen, J. Shi, and X. Wu, Tsinghua University, Beijing, China

Abstract

A tuning method of non-uniform traveling-wave accelerating structures has been developed based on the non-resonant perturbation at Tsinghua University. The electric field distribution along the structure is normalized by the shunt impedance, attenuation, and portion of the 0th space harmonic of each cell. The internal reflection can be then calculated and corrected by cell deforming. This method has been successfully applied to an S-band 10 MeV traveling-wave accelerating structure with both non-uniform and uniform sections. In this paper, details of the method and tuning results are presented.

INTRODUCTION

Normal conducting traveling-wave structures have found board applications in low/middle energy medical and industrial accelerators, as well as large scale machines such as colliders and free electron lasers. The structures are narrow-band microwave components and usually have a quality factor of 10^4 . Because of the tolerance and deformation during fabrication, the frequency and the phase advance of each cell may be shifted away from the design values [1]. To minimize the reflection and maximize the acceleration efficiency, the structure has to be tuned cell-by-cell.

A tuning method based on the non-resonant perturbation has been developed during the last decades and applied to various structures consisting of normal cells with identical length and identical or gradually tapered iris [1–6]. For low/middle energy accelerators where the initial kinetic energy of electrons is low, non-uniform section consisting of cells shorter than the normal cell is necessary to bunch the beam before the uniform section. The lengths of the bunching cells vary with the beam energy and the irises are usually heavily tapered, leading to inaccuracy when directly apply the mature tuning method onto uniform structures.

A complicated solution with a coupled cavity model has been reported recently [7]. In our approach, we have modified the mature method by replacing the electric field by the normalized voltage according to the transmission line theory [8]. The new and simple method is suitable for both non-uniform and uniform traveling-wave structures. It has been demonstrated on an S-band 10 MeV traveling-wave accelerating structure.

THE S-BAND ACCELERATING STRUCTURE

The S-band traveling-wave accelerating structure has been developed by the accelerator laboratory at Tsinghua

University for electron irradiation [9]. It operates at S-band 2856 MHz with $2/3\pi$ mode. With 4.5 MW input power, the maximum energy gain is 10 MeV and the average beam power is 20 kW. The lengths and irises of the bunching cells have been optimized to achieve a capture ratio above 70 % and a energy spread less than 5 %. Details of the non-uniform and the uniform sections are listed in Table 1.

Table 1: Parameters of the Non-uniform and the Uniform Sections

	Non-uniform	Uniform
Total length (cm)	~ 30	~ 160
Number of cells	12	44
Length of cell (mm)	15-35	35
Iris radius (mm)	9.9-13.4	9.9
Shunt impedance ($M\Omega /m$)	7-56	57
Attenuation (m^{-1})	0.1-0.37	0.25

After machining and brazing, the typical frequency shift of the cells is ~ 2 MHz and the voltage standing wave ratio (VSWR) of the whole structure is ~ 1.5 . Thus, tuning by the four tuners on each cell is required to minimize the reflection and to obtain the designed field distribution for better performance.

THE TUNING METHOD

Currently, cell tuning to minimize the internal reflection has become a standard procedure for various traveling-wave accelerating structures with normal cells. In this method, the field distribution is measured by moving a bead along the structure while monitoring the global reflection (a.k.a. the bead-pull method). The structure can be viewed as a transmission line where the field is the superposition of the forward and the reflected waves. The internal reflection of each cell can be then calculated with certain assumptions or approximations. Its imaginary part is determined by the frequency detune and can be corrected by cavity deforming [1].

Because of the small variation of the shunt impedance between cells, a uniform structure can be treated as a uniform transmission line where the electric field can be directly used to calculate the internal reflection. However, for a non-uniform structure in which the shunt impedance varies significantly, it's natural to use the normalized voltage instead of the electric field for higher accuracy.

In transmission line theory, the normalized voltage u is defined as

$$u = a + b = \frac{V_f}{Z_c} + \frac{V_r}{Z_c} \quad (1)$$

* jshao@anl.gov

where V_f and V_r denote the forward and the reflected voltage, respectively. a and b are the forward and the reflected wave normalized by the characteristic impedance Z_c . When $|a| \gg |b|$, the forward power P_f can be approximated as

$$P_f = \frac{1}{2}aa^* \approx \frac{1}{2}uu^* \quad (2)$$

In accelerator physics, the power loss on wall per unit length is

$$P_{loss} = 2\alpha P_f = \frac{|E_0|^2}{Z_{eff}} \quad (3)$$

where α is the attenuation factor, E_0 is the electric field of the 0th space harmonic synchronized with the beam, and Z_{eff} is the effective shunt impedance per unit length.

The measured electric field E_z by bead-pull is composed of longitudinal space harmonics as

$$E_z(z) = \sum_k |E_k(z)| e^{-j\beta_k z} \quad (4)$$

where $|E_k(z)|$ and $\beta_k = 2\pi/3D + 2\pi k/D$ denote the amplitude and wave number of the k th space harmonic mode, respectively. D_k is the length of the cell.

The maximum of $|E_z(z)|$ is usually located at the cell center where we define r as the portion of the 0th harmonic

$$r(z) \equiv \frac{|E_0(z)|}{|E_z(z)|} \Big|_{z=cellcenter} \quad (5)$$

Thus, the normalized voltage at the center of the n th cell can be expressed as

$$u_n = \frac{r_n E_z(z)|_{z=cellcenter}}{\sqrt{\alpha_n Z_{eff,n}}} \quad (6)$$

where r_n , α_n , and $Z_{eff,n}$ can be determined by EM simulation software such as Superfish and CST. The amplitude of the 0th space harmonic and the normalized voltage along the S-band 10 MeV traveling-wave accelerating structure are shown in Fig. 1.

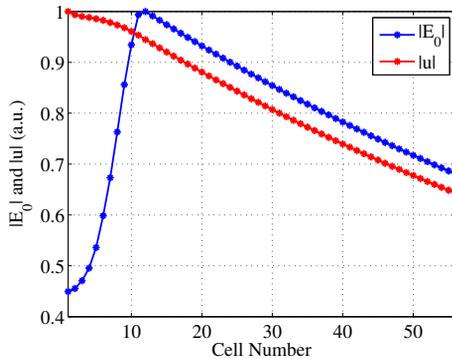


Figure 1: The amplitude of the 0th harmonic (blue) and the normalized voltage (red) along the structure.

Based on the transmission line theory, each cell and its adjacent one can be viewed as a two-port network, as illustrated in Fig. 2. The normalized voltage, the forward and

the reflected waves defined at the center of the cell follow

$$u_n = a_n + b_n \quad (7)$$

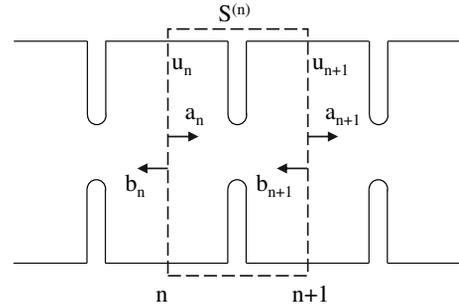


Figure 2: Two-port network model of the cells.

Besides, the forward and the reflected waves also follow

$$\begin{bmatrix} b_n \\ a_{n+1} \end{bmatrix} = \begin{bmatrix} s_{11}^{(n)} & s_{12}^{(n)} \\ s_{21}^{(n)} & s_{22}^{(n)} \end{bmatrix} \begin{bmatrix} a_n \\ b_{n+1} \end{bmatrix} \quad (8)$$

where $s_{11}^{(n)}$, $s_{12}^{(n)}$, $s_{21}^{(n)}$, $s_{22}^{(n)}$ are the scattering parameters of the network $S^{(n)}$. Particularly, $s_{11}^{(n)}$ is the internal reflection of the n th cell (denotes as $\Gamma_{local}^{(n)}$).

In Equ. 7 and 8, only u_n is known from the bead-pull measurement and the number of the unknown variables is more than that of the equations. Thus, the equations can not be solved in a closed form. Here we apply the same iteration method as mentioned in Ref. [5], regardless of the difference in the matrix definition. The required assumptions by the iteration, $s_{11}^{(n)} = s_{22}^{(n)}$ and $s_{12}^{(n)} = s_{21}^{(n)}$, are still valid in our method when the detuning is small ($\Delta f_0/f_0 \sim 0.001$). For the local reflection of the first and the last cell, we have used the same method as introduced in Ref. [1].

During the tuning process, the global reflection is monitored to determine whether the cell has been well tuned or not. The relationship between the variation of the global reflection and the internal one of the n th cell is

$$|\Delta \Gamma_{global}| = e^{C_n} |\Delta \Gamma_{local}^n| \quad (9)$$

where C_n is two times the total attenuation from the input port to the n th cell

$$C_n = 2 \sum_{k=1}^{n-1} \alpha(k)D(k) + \alpha(n)D(n) \quad (10)$$

TUNING OF THE S-BAND ACCELERATING STRUCTURE

The S-band 10 MeV traveling-wave accelerating structure has been tuned with this new method and the results are shown in Fig 3. After tuning, the imaginary part of the local reflection has been reduced as expected, leading to a better agreement between the measurement field distribution and the designed one as well as a more uniform phase distribution. The global reflection is reduced to 1.1 from 1.5, as illustrated in Fig. 4. The bandwidth where $VSWR < 1.2$ has also been improved to ~ 4.7 MHz.

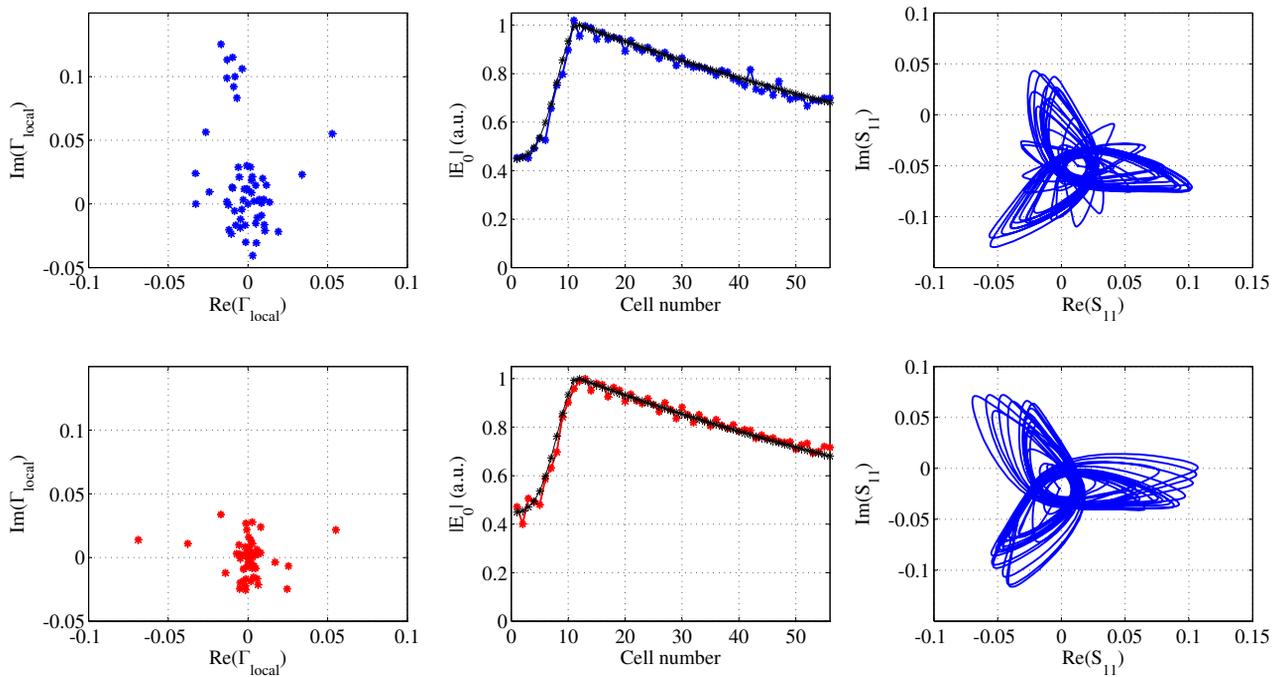


Figure 3: rf measurement results before (top) and after (bottom) the tuning. Left: Internal reflection of each cell. Middle: The amplitude of the 0th harmonic. The black line shows the design values for reference. Right: Measured phase of the electric field along the structure.

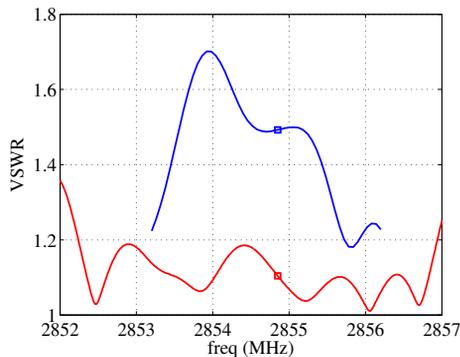


Figure 4: The global reflection before (blue) and after (red) the tuning. The squares present the tuning frequency in air.

CONCLUSION

The mature tuning method for uniform traveling-wave accelerating structures has been adapted for non-uniform ones by replacing the electric field with the normalized voltage when calculating the internal reflection. The method has been demonstrated on an S-band 10 MeV traveling-wave structure with a non-uniform section. So far, more than ten structures have been successfully tuned by this new method.

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