THE NONRESONANT PERTURBATION THEORY BASED FIELD MEASUREMENT AND TUNING OF A LINAC ACCELERATING STRUCTURE *

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Abstract

Assisted by the bead pull technique, nonresonant perturbation theory is applied for measuring and tuning the field of the linac accelerating structure. The method is capable of making non-touching amplitude and phase measurements, real time mismatch feedback and field tuning. Some key considerations of the measurement system and of a C-band traveling-wave structure are discussed, and the bead pull measurement and the tuning of the C-band traveling-wave linac accelerating structure are presented at last.

INTRUDUCTION

The Shanghai soft X-ray Free Electron Laser test facility(SXFEL)is presently being planned and designed at the Shanghai Institute of Applied Physics, CAS [1]. This facility will be located close to the Shanghai Synchrotron Radiation Facility, which is the first 3rd generation light source in mainland China [2]and it requires a compact linac with a high gradient accelerating structure and high beam quality. As a key R&D item, a room temperature C-band (5712 MHz) accelerating structure has been developed [3, 4]. For fabricating the C-band structure with high performance, the bead pull measurement system based on nonresonant perturbation theory has been developed.

There are several methods for RF structure measurement or tuning, such as the resonant perturbation method [5] and the phase shift method, however several limitations appear when they are applied to a traveling-wave accelerating structure. The resonant perturbation method picks up the amplitude of the electromagnetic field, therefore it is limited in the measurement of the standing-wave accelerating structure and the phase shift method only shows the phase information in the RF structure. For the accurate and fast tuning of a traveling-wave linac RF structure, nonresonant perturbation theory is the preferable method, which can measure the electromagnetic field distribution with both amplitude and phase, and this method is capable of making non-touch measurement, which can maintain the clean inner surface of the accelerating structure and reduce its RF breakdown rate. Furthermore, this method is also very effective in performing an accurate and fast real-time tuning of the accelerating structure, which is economical for mass fabrication of accelerating structures.

In this paper we present a cold test application of nonresonant perturbation theory on a linac RF structure [6]. This method based on the bead pull technique can pick up the amplitude and phase distribution of a linac structure, particularly for a traveling-wave structure, and is a preferable and efficient method for accelerating structure cold testing and tuning. In the following we describe firstly the theory of nonresonant perturbation and the tuning procedure and then discuss the key considerations of our measurement system with the bead pull technique. At the end we give several experimental results of our newly developed C-band traveling-wave accelerating structure tuning, which verify the feasibility of this method.

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NONRESONANT PERTURBATION THEORY AND TUNING PRINCIPLE

According to nonresonant perturbation theory, the variation of the reflection coefficient in the input port is measured with and without a perturbation bead, which is placed at different points along a line to pick up the amplitude and phase distribution of the electromagnetic field strength, a schematic drawing is shown in Figure 1. Based on the results and post-processing, RF tuning is processed with accurate and fast real-time feedback.

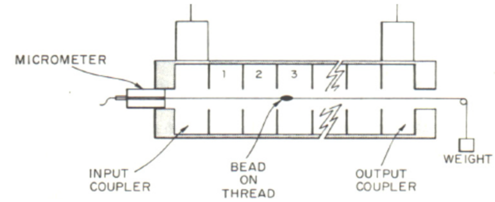

Figure 1: The field measurement based on nonresonant perturbation theory.

Nonresonant Perturbation Theory and Field Measurement

In nonresonant perturbation theory, the desired field strength is calculated as the following [6]:

$$2P_i(\Gamma_p - \Gamma_a) = -j\omega[k_e E_a^2 - k_m H_a^2] \quad (1)$$

For an accelerating structure, the TM mode is used for beam acceleration and the crucial longitudinal electrical field Ez is the unique field component on axis, thus the first equation of equation (1) is used for field measurement, and is renamed as equation(2) with reflected coefficient S11 of the Network Analyzer:

$$\Delta S11 = \Gamma_p - \Gamma_a = S11_P - S11_a = -\frac{j\omega k_e}{P_i} E_a^2 \quad (2)$$

whereS11p and S11a are acquired from the Network Analyzer, respectively corresponding to Γp and Γa in equation (1) above. In equation (2), Ea is complex data, its amplitude is the square root of the amplitude of ΔS11, and its phase is half of the phase ofΔS11. As the

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bead goes through the RF structure, the distribution of Ez on axis can be measured step by step.

Tuning Principle

With the bead pull measurement, the amplitudes and phases of the field can be measured, and after post-processing the local reflected coefficient can be calculated for the later tuning procedure. For the accelerating structure, the field of the center of the ith cell can be expressed by $E_i e^{j\varphi_i}$, which is the superposition of forward and backward waves $a_n e^{j(-2\pi/3(i-n)+\psi_n)}$ and $b_n e^{j(2\pi/3(i-n)+\phi_n)}$, where the center cell is the nth cell of the three cells in Figure 2.

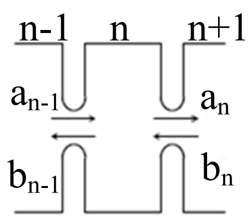

Figure 2: Forward and backward wave of nth cell.

It is supposed that the amplitudes in three adjacent cells are the same, according to [7],

$$a_n e^{j\psi_n} = E_{n-1}e^{j(\varphi_{n-1}-\pi/2)} + E_n e^{j(\varphi_{n-1}-\pi/6)}/\sqrt{3}$$
$$b_n e^{j\phi_n} = E_{n-1}e^{j(\varphi_{n-1}+\pi/2)} + E_n e^{j(\varphi_{n-1}+\pi/6)}/\sqrt{3} \quad (3)$$
$$b_{n+1}e^{j\phi_{n+1}} = E_n e^{j(\varphi_n+\pi/2)} + E_{n+1}e^{j(\varphi_{n+1}+\pi/6)}/\sqrt{3}$$

Based on equations (3), the local reflected coefficient of the nth cell is derived as equation (4)

$$\Gamma_{local,n} = \frac{b_n e^{j\phi_n} - b_{n+1}e^{j(\phi_{n+1}-2\pi/3)}}{a_n e^{j\psi_n}} = A + jB \quad (4)$$

where A and B represent the real and imaginary parts of the reflection respectively.

According to the conclusion in [8], the real part of the reflection coefficient in equation (4) is small and neglected relative to the imaginary part. The left imaginary part is dominated by the frequency detuning of each cell, which is shown in Equation (5).

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

where f_0 is the eigenfrequency, $\Delta f_0 = f_0 - f$, and $Q_0' = c\varphi/vg$ is the eigen-parameter of each cell. In Equation (5), it is easy to find that the reflection coefficient Γ_{local} is more or less than zero respectively when f_0 is detuned above or below the operating frequency f. Based on this principle, every cell can be tuned independently according to the sign of Γ_{local}.

According to equation (5), in equation (4) A is neglected and B presents the frequency detuning. If B is more than zero, the frequency is more than the design value, and to the contrary, frequency is a little less. This is the rule for the automatic tuning process, and the process is not stopped until B reaches zero.

In equation (4), the left side represents the local reflection $\Gamma_{local,n}$ of the nth cell, however in the automatic tuning process, only reflection coefficient Γ_{port} of the input port can be measured, which is the sum of the local reflection coefficients of all cells including coupling cells and periodic cells. Because of the attenuation and reflection of each cell, these reflections are added with different weight, and this is expressed as equation (6),

$$\Gamma_{port} = \sum_1^n C_n \Gamma_{local,n} \quad (6)$$

For a traveling-wave accelerating structure, the attenuated power for the nth cell is [9]

$$\left(\frac{dP}{dl}\right)_n = -2\alpha_n P \quad (7)$$

where α_n is the attenuation factor of the nth cell and P is the power flow of the nth cell, and equation (7) can be solved as

$$P_n = P_0 e^{-2\sum_1^n \alpha_n} = P_0 e^{-2\tau_n} \quad (8)$$

so that the weight from attenuation can be expressed as

$$\Gamma_{port} = \sum_1^n e^{-2\tau_n}\Gamma_{local,n} \quad (9)$$

In equation (9), the global attenuation for all cells from the input waveguide should be added, and equation (9) is revised as

$$\Delta\Gamma_{port} = |S11|e^{-2\tau_n}\Delta\Gamma_{local,n} \quad (10)$$

where $|S11|$ is the global attenuation factor from the input waveguide, which is equal to the reflection coefficient of the input port when detuning the input coupling cell.

Besides the effect of attenuation, the reflection of each cell also occupies some part of the weight C_n in equation (6), however the reflection of each cell is random. So the reflection of each cell cannot be derived analytically, however it can be calculated by the post-processing of the forward and backward waves in equation (3).

For a constant impedance traveling-wave accelerating structure, equation (10) is modified as

$$\Delta\Gamma_{port} = |S11|\left(\frac{a_n}{a_1}\right)^2 \Delta\Gamma_{local,n} \quad (11)$$

where a_n is the same as that in equation (3), and $\left(\frac{a_n}{a_1}\right)^2$ includes both the attenuation factor in equation (10) and the reflection from each cell. The square represents the integrated effect of both forward and backward waves.

For a constant gradient traveling-wave accelerating structure, equation (10) is modified as

$$\Delta\Gamma_{port} = |S11|\left(\frac{a_n}{a_1}\right)^2 e^{-2\tau_n}\Delta\Gamma_{local,n} \quad (12)$$

where $\left(\frac{a_n}{a_1}\right)^2$ only represents the reflection factor, and $e^{-2\tau_n}$ is the attenuated factor, which can be calculated from design parameters.

TUNING EXPERIMENTS

Based on the design in [3], the 1.1m C-band traveling accelerating structure has successfully accomplished cold RF testing and tuning, which is shown in Figure 3. It is necessary to point out that a constant impedance structure is adopted for the 1.1m C-band structure at last, which is different from the preliminary one, for simplifying the fabrication process. The 1.1m C-band structure is tested vertically so that the pull-bead can be placed into the structure easily without touching the inner surface of the structure.

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Figure 3: Vertical cold RF test for the 1.1m C-band traveling accelerating structure.

Before any tuning, the field distribution on axis is measured, which is shown in Figure 4 left. In Figure 4 left, the field distribution including amplitude and phase is very confused, and it predicts that there are complicated standing waves on axis in the accelerating structure. After the analysis by LABVIEW code in Figure4 right, apparently there are three peaks around the 15th, 22th and 50th cells and it is detuned severely. Similarly, the phase advance per cell has large fluctuation, which is expected to be about 120 degrees. Based on this severe detuning of the C-band accelerating structure, several tuning iterations are proceeded necessarily.

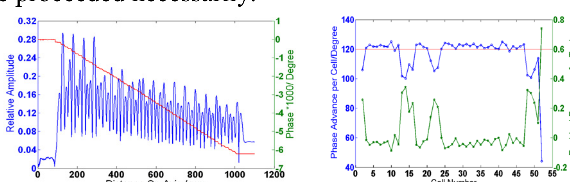

Figure 4: The field distribution and analysis before tuning

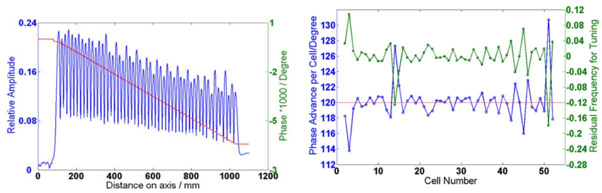

Figure: 5 The field distribution after 1st tuning.

After the first tuning phase, the field distribution and post-processing analysis are shown in Figure 5. In Figure 5 left the amplitude and phase on axis are distributed more smoothly with respect to that before tuning. In Figure 5 right, the phase advance mainly fluctuates between 118 and 122 degrees, and the amplitude of the residual frequency tuning per cell is mainly less than 0.05, which is within the permitted tolerance. However there is some slight detuning among cells, and after four water tubes are brazed, the last tuning phase eliminates the residual detuning finally.

After the final whole-structure tuning, the accelerating structure is almost matched, and the results are shown in Figure 6. According to the design target, the standing-wave ratio on axis is below 1.1 and the amplitude of phase advance fluctuation per cell is 2 degrees, corresponding to the baseline of 120 degrees per cell. In Figure 6 left, the field amplitudes in the center of cells are attenuated exponentially and the standing-wave ratio (SWR) on axis of the accelerating structure is below 1.1.In Figure 6 right, the phase advance per cell fluctuates between 118 and 122 degrees, and correspondingly the residual frequency detuning of all cells is from -0.04 to 0.04, which stays in the range of tolerance from -0.05 to 0.05. However on the both ends of accelerating structure in Figure 6 right, three cells on the each end are detuned out of the range above, which is used for the tuning of couplers.

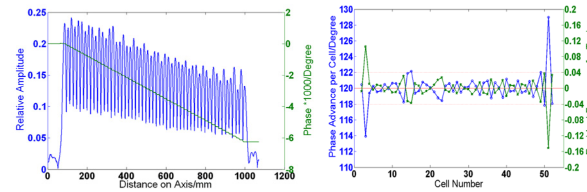

Figure 6: The field distribution after final tuning phase.

CONCLUSION

The nonresonant perturbation theory based on the bead pull measurement technique is an effective means for measuring and tuning a high gradient accelerating structure. The measurement system has been setup and successfully used in the R&D of a 1m long C-band traveling-wave accelerating structure for SXFEL. Now this prototype structure is ready for a high power RF test and since a 1.8 m long C-band constant gradient structure is under development, this measurement system becomes an indispensable tool in the accelerating structure developments.

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