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Development of a nonresonant perturbation technique and its application to multicell traveling-wave deflectors ☆

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ABSTRACT

A tuning method augmented by the bead-pull technique based on nonresonant perturbation field distribution measurements has been widely applied for traveling-wave (TW) accelerating structures. The method is also suitable for deflecting structures, but some key considerations of the field components of the HEM_{11} mode and the selection of bead merit discussion. A "cage"-type perturbing object has been designed, fabricated and applied in nonresonant perturbation measurements. Measurements on an S-band TW deflecting structure are carried out, and the measurement and tuning method will be used on the newly developed X-band deflecting structure at Shanghai Institute of Applied Physics.

1. Introduction

As the R&D towards the x-ray free electron laser user facility in China, an 840-MeV C-band linac based free electron laser test facility (SXFEL) is being developed at the Shanghai Institute of Applied Physics (SINAP), Chinese Academy of Science [1]. The bunch length at the exit of the linac is about 120 μm [2]. For precisely measuring this ultrashort bunch length, deflecting structures have been used recently in the existing facilities [3,4]. To measure the bunch length in the SXFEL facilities, an X-band traveling-wave-(TW-) deflecting structure with a high deflection gradient and high time resolution has been designed and fabricated at SINAP. This deflecting structure, which is approximately 1 m long, operates at 11.424 GHz, in $2\pi/3$ mode, with two symmetric caves for canceling mode degeneracy, as shown in Fig. 1.

As described in Ref [5], nonresonant perturbing methods make the field measurement procedure fast, especially for multicell structures, and applied on x-band accelerating structures [6]. But in fact, there are several differences between deflecting and accelerating structures, deflecting structure operating in the HEM_{11} mode, degenerates into twofold, axis-symmetric structure, which contains a hybrid of the TM_{11} and TE_{11} modes. The field components E_X, E_Y, E_Z, H_X, H_Y, and H_Z all exist in the disk-loaded waveguide [7], and hence the shape, scale, and material of the bead all have a great influence on the measurements. For dipole mode measurement and tuning, there are other methods to realize, and have good performances [8,9]. In this paper, based on the analysis of the field distribution, several experimental schemes have been studied and the best process have been selected. For measuring and tuning a TW-deflecting structure, a bead-pull measurement based on nonresonant perturbation technique has been developed and applied.

2. Nonresonant perturbation theory and electromagnetic field component distribution

According to nonresonant perturbation theory [10], the reflection coefficients are measured at the input port of the structure both in the absence of and the presence of the perturbation object. When the perturbing bead moves through the cavity, the magnitude and phase distribution of the electromagnetic field can be measured, which can, in turn, be applied to obtain the information for tuning the structure after post-processing.

2.1. Nonresonant perturbation theory for the HEM_{11} mode field component

In nonresonant perturbation theory, the reflection coefficient and the field distribution in the structure have the following relationship:

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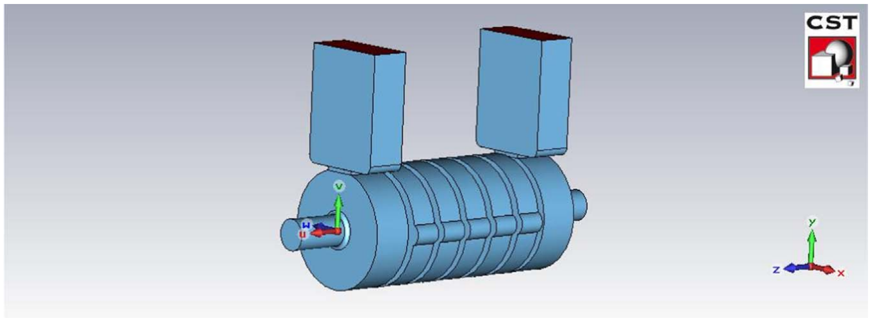

Fig. 1. Schematic of deflecting structure.

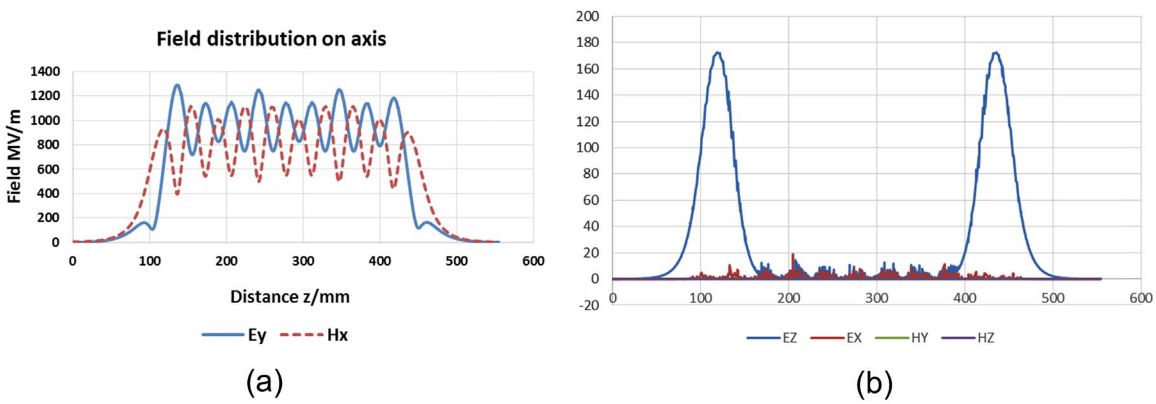

Fig. 2. Deflection field components (a) E_Y and H_X on-axis and (b) other field components.

$$2P_i(\Gamma_p - \Gamma_a) = -j\omega\left[k_e\overrightarrow{E_a}^2 - k_m\overrightarrow{H_a}^2\right] \tag{1}$$

where Γ_p and Γ_a are the reflection coefficients in the input port in the presence and the absence of the perturbing object, respectively. Ea and Ha are the complex vectors of the electric and magnetic field at the position of the bead in the structure, respectively. k_e and k_m are the polarized tensors and they are characteristic factors of perturbation bead for Ea and Ha respectively. For the tuning of structures, it is sufficient to measure and evaluate only one of the six field components: Ez is typically chosen for accelerating structures. Hence Eq. (1) becomes a scalar equation follows:

$$\Delta S_{11} = \Gamma_p - \Gamma_a = S_{11p} - S_{11a} = \frac{-j\omega k_e}{P_i}{E_z}^2 \tag{2}$$

where S_{11p} and S_{11a} are reflection coefficients in the presence and the absence of the perturbing object, respectively, acquired from the Network Analyzer. E_Z is the electric field on the z axis, as the perturbing object goes through the structure along z, it is obvious that the amplitude of E_Z is proportional to the square root of the amplitude of $\Delta S_{11}(z)$, and the phase of E_Z is the half of the phase of $\Delta S_{11}(z)$. Thus the information required for tuning measurements is collected.

For a deflecting structure, the operating mode is HEM_{11}, which is a hybrid of the TE_{11} and TM_{11} modes [11]; the field components have been calculated in [12]. Then Eq. (1) becomes a complicated equation as follows:

$$\Delta S_{11}(z) = \sum_i\left(K_{ei}E_i^2 - K_{mi}H_i^2\right)$$
$$K_{ei} = \frac{-j\omega k_e}{P_i},\ K_{mi} = \frac{-j\omega k_m}{P_i}$$
$$i = x, y, z \tag{3}$$

where E_i and H_i are the electric and magnetic field in different directions, respectively, K_{ei} and K_{mi} are defined as the form factor of the perturbing object for E_a and H_a. Upon further consideration, Eq. (3) can be expressed as

$$\Delta S_{11}(z) = \sum\Big[\left(K_{ei}|E_i|^2\cos 2\varphi_i + jK_{ei}|E_i|^2\sin 2\varphi_i\right) - \left(K_{mi}|H_i|^2 cos2\psi_i + jK_{mi}|H_i|^2\sin 2\psi_i\right)\Big]$$
$$i = x, y, z \tag{4}$$

where φ_i and ψ_i are the phases of the electric and magnetic field, respectively. Eq. (4) is a multielement complex equation, which becomes difficult and complicated for measuring and guiding the tuning of a multicell deflecting structure. It is more difficult, however, to separate out only the desired components in the case of the deflecting structure. A faster and more reliable method of measurement is desperately needed.

2.2. Simulation of HEM11 mode field component

In order to find a reliable method, the electromagnetic fields in a deflecting structure were studied. Taking an S-band deflecting structure as an example, working at 2856 MHz in $2\pi/3$ mode, simulation results are derived from the matched structure that contains eight regular cells and two identical couplers.

In Fig. 2 the field components E_Y and H_X are compared in the