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STABILIZING CHARACTERISTICS OF POST-COUPLERS

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Abstract: A model of Alvarez linac equipped with post-couplers was constructed. The field distribution and the resonant frequency of the accelerating mode were measured to study its properties against perturbations. The experimental results were compared with an analysis using equivalent circuits. Post-couplers have an effect to distort the field distribution as well as to stabilize it depending upon the length of the posts.

Introduction

At KEK, an extension of the proton linac was planned and a model tank with the post-coupled structure was constructed. As the result of the experiment, we obtained the interesting fact. If the two passbands, which are an accelerating and a post one, get too close together, the field is distorted. When the field is distorted, there is a remarkable change in the accelerating frequency.

In the other stabilized structures than the post-coupled, nothing is known about the distortion. It is clear that information on the distortion is important for understanding the mechanism of the post-coupled structure and also for the other stabilized structures.

Experimental Results

Perturbations

Main parameters of the model tank are shown in Table 1. We introduced static perturbations. We moved both end plates to the same direction by the same amount. Three kinds of perturbations were prepared. The amounts of the movement were,

1-st cell	=	−1 mm ,	3 mm ,	−5 mm ,
15-th cell		1 mm	−3 mm	5 mm

where we take positive value when a cell is lengthened. Corresponding frequency shifts were,

1-st cell	=	−1.5 MHz ,	3.5 MHz ,	−6.0 MHz .
15-th cell		1.0 MHz	−3.0 MHz	4.0 MHz

We will obbreviate these cases as $\Delta 1$ mm, $\Delta 3$ mm and $\Delta 5$ mm respectively.

Field Distribution

We studied the behavior of the field distribution versus the post length inserted into the tank. First, the field without perturbations was measured as shown in Fig. 1(a). Due to the perturbation, the field was deformed (Fig. 1(b)). When the post length was about 12.5 cm, the field was distorted (Fig. 1(c)). After the post passed this point, the field distribution showed an inverse slope as before, and when the post length was about 13.5 cm, the field became flat (Fig. 1(d)). The field was flatter than that without perturbations. When posts were inserted further, the field distribution had a slope again in the same direction as that for without posts.

To represent the slope of the field numerically, we define the distortion parameter as follows [1].

$$D_x = \Sigma_i |F_i - \overline{F}| \quad ,$$

where F_i is the field level of each of the fifteen cells, and $\overline{F}$ is the average of them. Using D_x, the dependence of the field on the post length is shown in Fig. 2. In this figure, D_x of perturbations, $\Delta 1$ mm and $\Delta 3$ mm, and without these perturbations are also represented. In all cases, the field is distorted at about 12.5 cm and stabilized at about 13.5 cm.

Accelerating Frequency

For all perturbations, the dependence of the accelerating frequency on the post length is shown in Fig. 3. When the posts were around 12.5 cm, where the field was distorted, the accelerating frequency went down and then jumped up above the previous value. Then, the accelerating frequency fell down and went up slowly. When the post length was about 13.5 cm, where the field stabilized, no sign denoting the stabilization was observed in the frequency.

Table 1

Main parameters of the model tank

Number of Cells		15
Frequency		401.05 MHz
Tank Length		2.51 m
Inside diameter		0.45 m
Drift-tube	Outer diameter	8.0 cm
	Bore diameter	1.5 cm
Energy		20.60 − 28.78 MeV
Beta		0.2062 − 0.2421

Analysis of Equivalent Circuit

Equivalent Circuit

For the post-coupled structure, an equivalent circuit has been proposed by T. Nishikawa [2] and shown in Fig. 4. The L_0, L_1, and L_2 represent the inductances of a drift-tube, a stem, and a post. The C_0, C_1, and C_2 represent the capacitances between adjacent drift-tubes, a drift-tube and the outer wall, and a post and a drift-tube. The M_0, M_1, and M_2 represent the mutual inductances between one half of a drift-tube and the other, adjacent stems, and adjacent posts.

Suppose that there is the phase shift θ between adjacent stems and adjacent posts. We define k_c as

$$1/k_c = \frac{2L_0}{L_1(1-k_1^2)}\left[\frac{\omega^2}{\omega_1^2}(1-k_1^2) - 1 + k_1\cos\theta\right] + \frac{2L_0}{L_2}\,\frac{\omega_2^2/\omega^2 - 1 + k_2\cos\theta}{(\omega_2^2/\omega^2-1)^2 - k_2^2}, \quad k_1 = M_1/L_1,\ k_2 = M_2/L_2,\ \omega_1 = 1/\sqrt{L_1C_1},\ \omega_2 = 1/\sqrt{L_2C_2}, \tag{1}$$

then

$$\begin{aligned} V_n &= -\left(1 - \frac{\omega_0^2}{\omega^2} - k_0\right)A_n - (k_0 + k_c)A_{n+1}, \\ V_{n+1} &= (k_0 + k_c)A_n + \left(1 - \frac{\omega_0^2}{\omega^2} - k_0\right)A_{n+1}, \end{aligned} \tag{2}$$

$$k_0 = M_0/L_0,\quad \omega_0 = 1/\sqrt{L_0C_0},\quad A_n = j\omega L_0 I_n .$$

We join N cells and define the boundary condition as $V_1 = V_N = 0$. These equations lead to

$$\begin{aligned} &\frac{k_0+k_c}{2}A_{n-1} + (1-k_0)A_n + \frac{k_0+k_c}{2}A_{n+1} = \frac{\omega_0^2}{\omega^2}A_n, \quad (2<n<N-1) \\ &(1-k_0)A_1 + (k_0+k_c)A_2 = \frac{\omega_0^2}{\omega^2}A_1, \\ &(k_0+k_c)A_{N-1} + (1-k_0)A_N = \frac{\omega_0^2}{\omega^2}A_N . \end{aligned} \tag{3}$$

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This relation suggests the expression in the matrix form

$$\begin{pmatrix} 1-k_c & k_c+k_0 & \\ (k_c+k_0)/2 & 1-k_c & (k_c+k_0)/2 \\ & & — \end{pmatrix} A = \frac{\omega_0^2}{\omega^2} A . \qquad (4)$$

The n-th element of a eigen-vector gives the amplitude of the n-th cell.

Properties of k_c

The k_c+k_0 means the impedance between the drift-tube and the outer wall. Without perturbations the voltage v_c between the drift-tube and the outer wall is zero. When perturbations are introduced into n-th cell and the voltage v_c is produced, the shunt current i_c between them flows as $i_c = v_c/(k_c+k_0)$. If k_c+k_0 is infinite, i_c always becomes zero and the current at n-th cell is not changed by perturbation. If k_c+k_0 is zero, very low voltage makes much shunt current flow and the current to the next cell vanishes at n-th cell.

The denominator of Eq. (1) is separated into two terms, a term of stems and that of posts.

$$(1/k_c)_{stem} = \frac{2L_c}{L_1(1-k_1^2)}\left[\frac{\omega^2}{\omega_1^2}(1-k_1^2) - 1 + k_1\right] , \qquad (5)$$

$$(1/k_c)_{post} = \frac{2L_c}{L_2}\,\frac{1}{\omega_2^2/\omega^2 - 1 - k_2} . \qquad (6)$$

Here, we assumed that the phase shifts between adjacent stems and between adjacent posts are zero.

If the lengths of posts are changed, the value of ω_2 and so the denominator of Eq. (6) changes. When $\omega_2 = \omega\sqrt{1+k_2}$, Eq. (6) becomes infinite, thus k_c approaches to zero. Because the absolute value of k_0 must be smaller than unity, k_c+k_0 gets near zero necessarily.

In an Alvarez structure, ω_1 is located below a half of the accelerating frequency ω. Thus Eq. (5) becomes positive, if k_1 is positive. As a result of combination with two terms, when ω_2 becomes below ω and these terms cancel each other on condition that k_2 is negative, the absolute value of k_c becomes infinite.

Three-Cell Tank Model

We will examine the relation between the value of k_c and the field distribution using three-cell tank model. First of all, we will introduce perturbations into the equivalent circuits. The accelerating frequency ω_0 of n-th cell is rewritten to ω_0' and Eq. (3) becomes

$$\frac{k_c+k_0}{2}A_{n-1} + (1-k_c)A_n + \frac{k_c+k_0}{2}A_{n+1} = \frac{\omega_0'^2}{\omega^2}A_n . \qquad (7)$$

To make eigen-value problem as Eq. (4), we move the perturbed term to the left side. Let $\omega_0' = \omega_0/\sqrt{1+\delta}$, then

$$(1+\delta)\left[\frac{k_c+k_0}{2}A_{n-1} + (1-k_c)A_n + \frac{k_c+k_0}{2}A_{n+1}\right] = \frac{\omega_0^2}{\omega^2}A_n . \qquad (8)$$

Now, we investigate the behavior of the field distribution and the accelerating frequency against perturbations. Suppose that the frequencies of both cell become

$$\omega_0'(1\text{-st}) = \omega_0/\sqrt{1+\delta} , \quad \omega_0'(3\text{-rd}) = \omega_0/\sqrt{1-\delta} . \qquad (9)$$

The eigen-value problem representing this tank becomes

$$\begin{pmatrix} (1+\delta)(1-k_c) & (1+\delta)(k_c+k_0) & \\ (k_c+k_0)/2 & 1-k_c & (k_c+k_0)/2 \\ & (1-\delta)(k_c+k_0) & (1-\delta)(1-k_c) \end{pmatrix} A = \frac{\omega_0^2}{\omega^2} A . \qquad (10)$$

We neglect δ^2, then

$$\frac{\omega_0^2}{\omega^2} = 1+k_0 , \quad 1-k_c , \quad 1-k_0-2k_c . \qquad (11)$$

For the 0-mode, the eigen-vector becomes

$$A = \begin{pmatrix} (1+\delta)(k_c+k_0)/[(1+\delta)k_c+k_0-\delta] \\ 1 \\ (1-\delta)(k_c+k_0)/[(1-\delta)k_c+k_0+\delta] \end{pmatrix} A_2 . \qquad (12)$$

Here, we define the tilt parameter T as

$$\begin{aligned} T &= (A_3/A_2 - A_1/A_2)/2 \\ &= \frac{-\delta(k_c+k_0)(k_c+1)}{[(1+\delta)k_c+k_0-\delta][(1-\delta)k_c+k_0+\delta]} \\ &\simeq -\delta(k_c+1)/(k_c+k_0) . \end{aligned} \qquad (13)$$

The T has two variables, δ and k_c. When δ increases, T becomes large in the negative direction in proportion to δ. When the absolute value of k_c increases, the denominator of T becomes large. The field becomes flat and that is the stabilization. On the contrary, when k_c+k_0 gets near zero, the denominator of T becomes small and the field slopes steeply. The field is distorted.

These consideration proves whether the field is distorted or stabilized depends upon the value of k_c, and that the distortion occurs peculiarly when there are errors of the frequency in some cells.

Comparison with Experiment

Field Distribution

Using the representation with the equivalent circuits, we will compare the result of the analysis with those of the experiment.

The 1-st and 15-th cells are perturbed in the experiment, three kinds of δ are taken,

$$\delta = 0.005, \quad 0.015, \quad 0.025,$$

these δ correspond to the frequency shift of Δ1 mm, Δ3 mm and Δ5 mm respectively.

We decrease ω_2 by the insertion of posts. Put $\delta = 0.025$. As ω_2 decreases, k_c decreases slowly and the field distribution is little affected (Fig. 6(a)). When ω_2 gets near $\omega\sqrt{1+k_2}$, k_c becomes $-k_0$ and the field is distorted. The distribution completely changes around this frequency (Fig. 6(b) (c)). As ω_2 decreases furthermore, the field recovers from the distortion and has an inverse tilt (Fig. 6(d)). Then k_c becomes infinite in the negative direction and next in the positive one. The field becomes completely flat (Fig. 6(e)). After the stabilization point, k_c changes slowly with the decrease of ω_2 and the slope of the field is produced again in the same direction as before (Fig. 6(f)). The corresponding data of the experiment are shown in Fig. 5.

The distortion parameter calculated from the equivalent circuit is shown in Fig. 7. The field distribution obtained by equivalent circuits agrees fairly with the experimental one.

Accelerating Frequency

For each δ, the dependence of ω on ω_2 is shown in Fig, 8. At around ω_2 = 355 MHz ($k_c \cong -k_0$), the frequency transition occurs proportionally to the amount of δ.

Conclusions

The stabilization by post-couplers was confirmed. However, in some cases, it was shown also that post-couplers have a harmful effect on the field. To understand the mechanism of post-couplers, we analyzed equivalent circuits. In this analysis, the parameter k_c was defined, which corresponds to an element of the impedance between a drift-tube and the outer wall. It was shown that the field is stabilized when k_c+k_0 becomes infinite and the field is distorted when k_c+k_0 is zero.

References

[1] J. Ungrin, S.O. Schriber and R.A. Vokes, "Post-Coupler and Stem Current Measurements for High Current CW Drift-Tube Linacs", IEEE Trans. Nucl. Sci. NS-30, No.4, 3013, 1983.

[2] T. Nishikawa, unpublished communication, 1967.

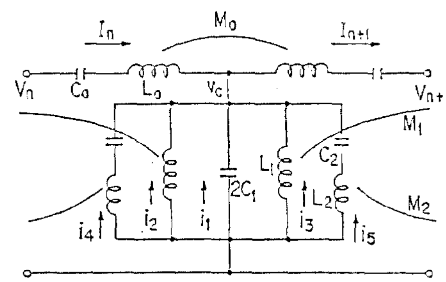

Fig. 4 Equivalent circuit for an Alvarez structure with stems and posts.

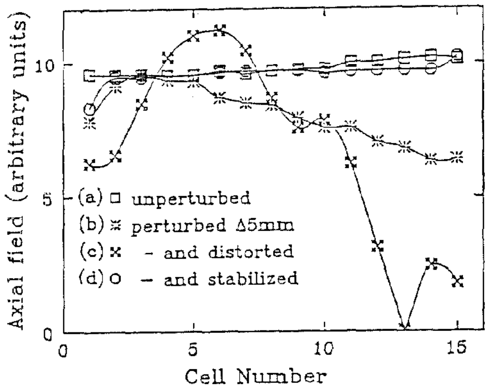

Fig. 1 Electric field on axis of the model tank, before and after stabilization and distortion by posts.

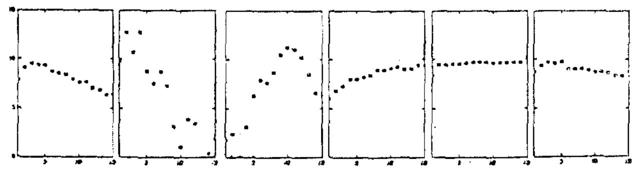

Fig. 5 Electric field dependence on the post frequency ω_2 in the experiment.

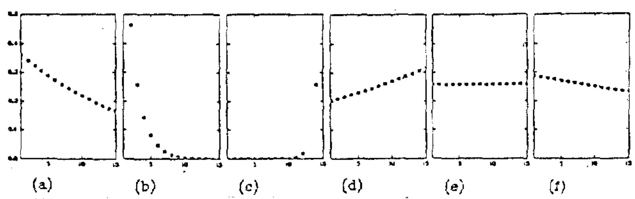

Fig. 6 Electric field dependence on the post frequency ω_2 in analysis of equivalent circuit.

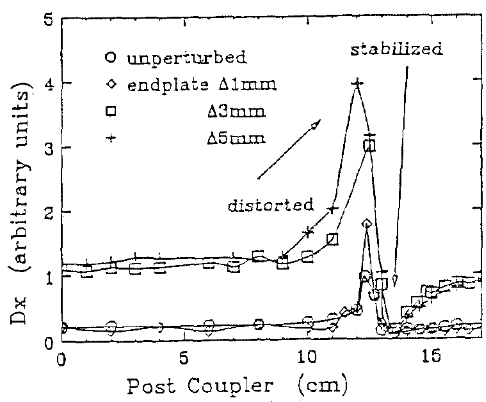

Fig. 2 Distortion parameter vs. the length of posts inserted into the model tank, taking endplates perturbation for parameter.

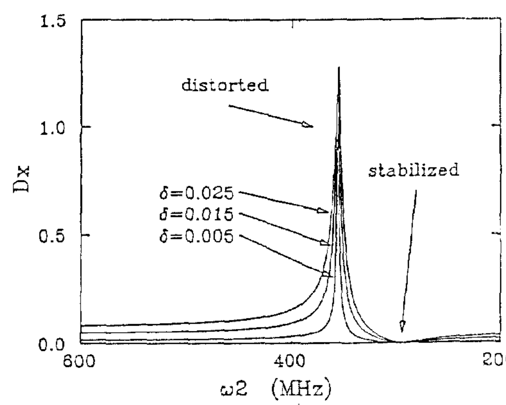

Fig. 7 Distortion parameter Dx vs. the post frequency ω_2, taking endplates perturbation for parameter.

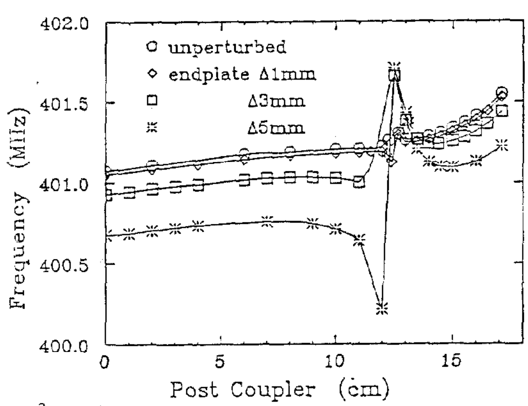

Fig. 3 Resonant frequency shift by insertion of posts, taking endplates perturbation for parameter.

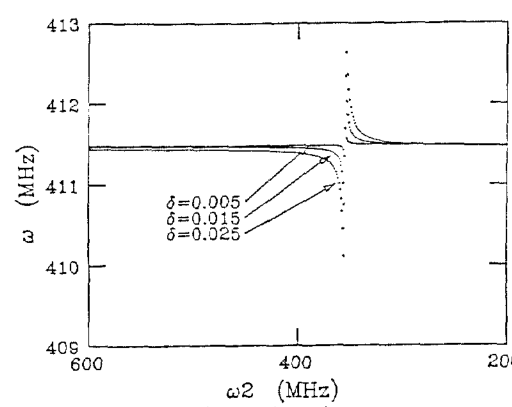

Fig. 8 Resonant frequency shift vs. the post frequency ω_2, taking endplates perturbation for parameter.