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SIMULATION OF LONG RANGE WAKE FIELD IN A DETUNED STRUCTURE BASED ON EQUIVALENT CIRCUIT MODEL

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Abstract

In the X-band accelerating structure for the Japan Linear Collider(JLC), the effect of the most severe transverse wake field, TM110-like mode, must be damped below 1% at the following bunches compared with that excited by the preceding bunches. A cancellation of the wake field among all of the cells in a structure will reduce the effective wake field felt by the following bunches. This situation can be realized in a so called detuned structure by properly distributing the dipole mode frequencies of all the cells in a structure[1]. To study this kind of damping of the wake field, we applied an equivalent circuit model. Possible detuned structures were found where the excited dipole wake field was damped below 1% at the following bunches. In these structures, the accelerating field along the structure was found to be nearly constant except for input and output region.

Introduction

In order to increase the luminosity of the JLC[2], a multi-bunch operation is adopted with 20 bunches in an RF pulse, each bunch 1.4nsec apart. Severe emittance growth will occur unless proper damping or some cancellation of the wake field excited by the preceding bunches is realized at the following bunches. The former is described in another paper[3] while the latter is the main theme in this paper. A rough criterion for the JLC main linac states that the excited wake field of the TM110-like mode should be cancelled below 1% of the amount initially excited [4].

The excited wake field in a structure was already found to be easily damped well below 1% by distributing the frequency of the mode if we neglect the coupling between cells. In this case, it is easy to estimate time variation of the excited wake field since the wake field can be described simply as the sum of the amplitude of all the independent cells.

On the other hand, the cells in a real structure are coupled with each other. Then, for the evaluation of the wake field in such a system, such a code as TBCI is needed at a glance. However, it is difficult to calculate the wake field by TBCI in such a structure as the detuned structure, since the change of dimension from cell to cell is very small and the exact shape cannot be described by the mesh of the code. Furthermore, the wake field in such a many-cell system cannot be calculated due to the lack of CPU time, since the detuned structure usually consists of more than 100 cells. However, it is not necessary to make the field analysis as TBCI does if the wake field is dominated by a small number of modes[5]. In this case, only the behavior of the modes of interest should be analyzed. Then we can evaluate the wake field using an equivalent circuit model representing the modes in the coupled cells in a structure[6]. The amplitude of the mode was estimated by integrating the differential equations describing the circuit model. In the following sections, the circuit model and its parameters are described. An example of possible detuned structure is also presented.

Equivalent Circuit Model

Since the transverse wake field of the lowest dipole passband is the most serious component of the long-range wake field, we consider only the mode in this paper. In this passband for the disk loaded structure operated at 11.424 GHz in $2\pi/3$ mode with the beam hole radius around 4 to 6 mm, the modes synchronous to the beam is very near to the π mode and the fields of those modes are similar to that of TM110-π mode. Therefore, it is reasonable to assume that the wake field excited in each cell of the structure is proportional to the R/Q value of the TM110-π mode. The R/Q value for each cell is assumed to be constant for easiness, since this approximation does not seriously perturb the damping characteristics of the wake field.

By assuming that the field in each cell is always TM110-like, time variation of the amplitude and phase of each cell in a structure is estimated by a coupled resonator model shown in Fig-1. All parameters, resonant frequency ω_n of the n'th cell and the coupling coefficient κ_n between cell n and n+1, were estimated by using URMEL as described in the next section. Assuming the boundary condition of half end cell, the equivalent circuit can be expressed as Eq.(1). These equations were solved in time domain by Runge-Kutta method with numerical error less then 10^{-6}. The excitation of each cell is assumed to be performed at the time beam passes the center of the cell. The wake field is evaluated by summing the wake fields of all the cells.

$$\begin{aligned} &\frac{d^2I_1}{dt^2} + \frac{\omega_1}{Q}\frac{dI_1}{dt} + \omega_1^2 I_1 + \kappa_1 \frac{d^2I_2}{dt^2} = 0 \\ &\frac{d^2I_n}{dt^2} + \frac{\omega_n}{Q}\frac{dI_n}{dt} + \omega_n^2 I_n + \frac{\kappa_n}{2}\frac{d^2I_{n+1}}{dt^2} + \frac{\kappa_{n-1}}{2}\frac{d^2I_{n-1}}{dt^2} = 0 \qquad (1) \\ &\frac{d^2I_N}{dt^2} + \frac{\omega_N}{Q}\frac{dI_N}{dt} + \omega_N^2 I_N + \kappa_{N-1} \frac{d^2I_{N-1}}{dt^2} = 0 \end{aligned}$$

Parameters

Parameters of the equivalent circuit model were estimated from the frequencies of the 0 and π mode in the first dipole mode calculated by URMEL. Actually, coupling coefficient κ and $\pi/2$ mode frequency ω_n in Eq.(1) were estimated by the Eq.(2), where φ is the phase shift per cell. In order to realize a detuned structure in a conventional disk loaded structure with disk thickness of 2mm, the frequency of the TM110 mode is varied by changing the beam hole radius with maintaining the frequency of the accelerating mode.

$$\omega_\varphi = \frac{\omega_{\pi/2}}{\sqrt{1+\kappa\cos(\varphi)}} \qquad (2)$$

Dispersion curves and the characteristics of the field are shown in Fig-2. It is noted that the coupling coefficient κ changes its sign at beam hole radius of about 4.5mm as shown in Fig-3. In the case of beam hole radius $a<4$, field pattern of the lowest dipole passband is like that of the TM110 mode. On the other hand, the mode in the lowest passband with $a>4$ shows the change of field pattern from TE111-like to TM110-like as the phase shift per cell increases from 0 to π. But this mode change within a passband was neglected in the present study, assuming the field remains near π mode within a time scale of interest.

Results and Discussion

In Fig-4, various parameters of a detuned structure with 150 cells are shown. The variation of the beam hole radius is determined to make the frequency distribution gaussian for the first dipole mode synchronous to the beam. This gaussian distribution is set to have the standard deviation of 2.5% of the average frequency and is truncated at the full width of 13%. The wake field of this structure was shown in Fig-5 to be damped well bellow 1%. In this structure, the beam hole radius various from 6.0mm to 3.8mm. Since the slope of short range wake field scales as $a^{-3.5}$, the effective beam hole radius for single bunch wake field ($<a^{-3.5}>^{-1/3.5}$) is 0.18λ and this satisfies the requirement of the JLC. In the case of the input power of 100 MW to this accelerating structure, the accelerating gradient is nearly constant at 50~60 MV/m except input and output coupler cell region as shown in Fig-4.

By increasing the number of cells while maintaining the frequency distribution of the first dipole mode the same as the example stated above, the damping of the wake field after several nano seconds gets better while the first falling pattern till the next bunch changes little. At the same time, total attenuation parameter increases while average accelerating gradient decreases as shown in Fig-6, resulting in the necessity of higher peak power and longer pulse length. The number of cells should be determined by considering these characteristics.

In the following are described the assumptions in the evaluation of the wake field stated above which should be examined and refined as the next step. At first, more realistic R/Q values should be taken. Secondly, the change of mode from TM-like to TE-like in a passband should be included in the modeling using equivalent circuit. This effect may be treated properly by incorporating the coupling (or mixing) between two passbands (TE111 and TM110) as described by R. Miller[7]. Thirdly, the boundary condition in the equivalent circuit model should be treated realistically.

Conclusion

Though there remain in this paper many approximations and assumptions to be checked in the analysis of the wake field, it was found essentially possible to design a detuned structure which meets the requirement on the damping of the wake field in the JLC.

References

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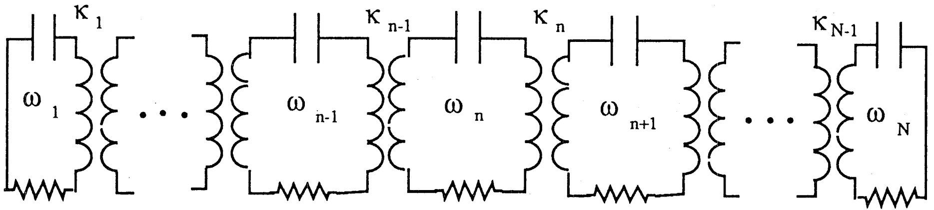

Fig-1 Equivalent circuit model.

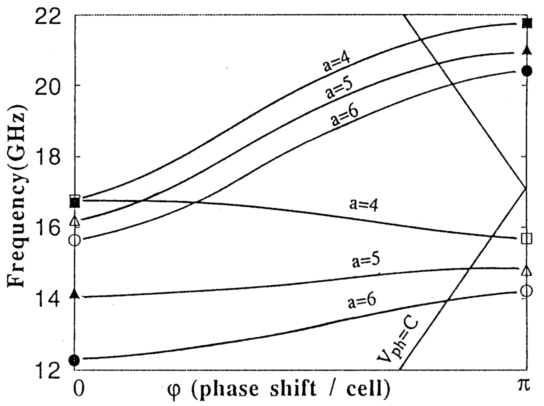

Fig-2 Dispersion curves of lowest two dipole mode passbands. Solid marks show the TE111-like mode, while open marks TM110-like.

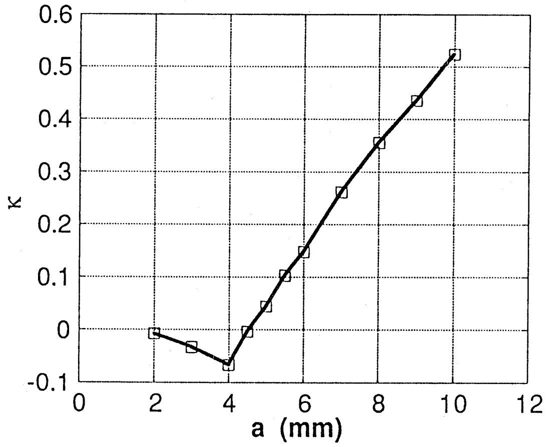

Fig-3 Coupling coefficient κ versus beam hole radius a.

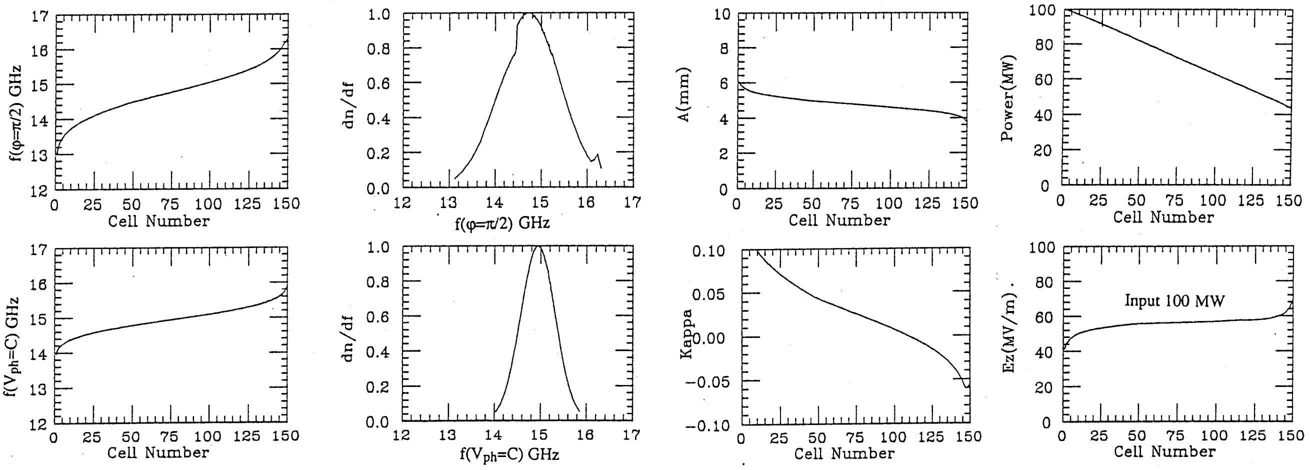

Fig-4 Parameters of a detuned structure with 150 cells.

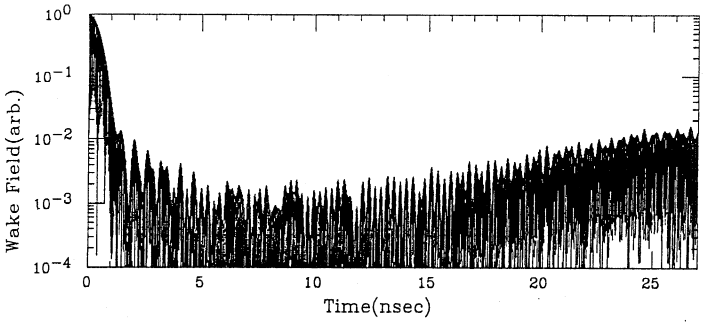

Fig-5 Wake field in a detuned structure with 150 cells.

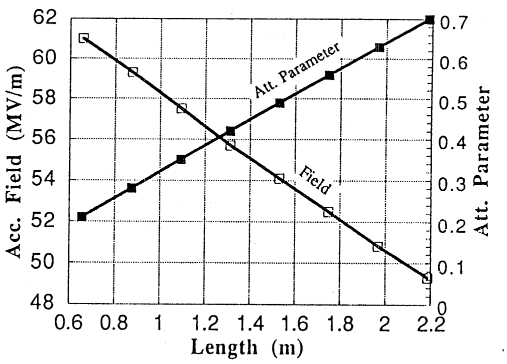

Fig-6 Accelerating field and attenuation parameter versus structure length.