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Modeling Large Heterogeneous RF Structures[1]

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Abstract

Large heterogeneous structures are difficult to model on a numerical grid because of the limitations on computing resources, so that alternate approaches such as equivalent circuits and mode-matching have been developed to treat this problem. This paper will describe the three methods and will analyze a structure representative of the SLAC and JLC detuned structures to compare the efficacy of each approach.

1. Introduction

Large heterogeneous structures have been in use for many years in accelerator systems such as the Stanford Linear Collider (SLC) which employs 3-m long 86-cell tapered disk-loaded waveguides (DLWGs) to provide constant acceleration. The SLC experienced beam breakup due to cumulative deflection of the bunch by transverse wakefields in the linac. In the TeV scale linear colliders proposed by SLAC and KEK, wakefield effects will be important since multi-bunch operation (versus single bunch in the SLC) is required to reach desired luminosity. A primary goal of the accelerator structure design has been the suppression of wakefields to preserve the low-emittance of the long bunch trains (90 bunches) during their delivery to the interaction point.

2. Detuned Structure

A promising candidate being considered for SLAC's Next Linear Collider (NLC) [1] and KEK's Japan Linear Collider (JLC) [2] is the detuned structure whereby the cell dimensions are varied by design to detune the most dangerous dipole modes in a Gaussian manner. This detuning decoheres the dipole modes so that the aggregate wakefield is reduced to a safe level (a factor of 100 from peak) over the length of the bunch train. SLAC has fabricated and tested a detuned structure to confirm the wakefield reduction [3]. Meanwhile, considerable effort has been devoted to the analysis of wakefields to assess the effectiveness of this suppression mechanism.

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3. Modeling Approaches

The NLC detuned structure is a 1.8-m 206-cell DLWG while the JLC prefers a 1.3-m 150-cell design, both operating at X-band. Due to the size of the geometry and the small variation in cell to cell dimensions (of the order of 10th's of microns), direct numerical simulation is beyond most computing capabilities, except on multi-processor supercomputers [4]. Alternative approaches such as equivalent circuits and mode-matching have been developed, and calculations based on these methods have been documented in the literature.

This paper discusses three methods for modeling large heterogeneous structures: (1) equivalent circuits with two circuit chains [5], (2) mode-matching with open modes [6], and (3) grid-based simulation using code MAFIA [7]. Due to limited space, the reader is referred to the original work for theoretical details. The emphasis here is to apply these methods to a test structure small enough that's numerically practical, yet has properties representative of the NLC and JLC detuned structures. More importantly this enables for the first time a direct comparison between the three approaches.

The wakefield analysis will assume the structure is closed at both ends since the dipole modes couple weakly to the input/output waveguides. Then one is looking at essentially a large standing-wave cavity in which the eigenmodes in the dipole band of frequencies are of interest. The transverse wakefield is obtained from the eigenmodes by summing their contributions as follows

$$W(s) = 2 \sum_{m=1}^{M} K_m sin(\frac{\omega_m s}{c}) \tag{1}$$

where M is the number of modes, ω_m and K_m are the eigenfrequency and the transverse kick of the mth mode respectively. In all the models described below the cell geometry is taken to be from disk to disk, and cell data such as dispersion curves and mode patterns are obtained with MAFIA.

4. Two-chain Model

A two-chain circuit model comprises two rows of LC circuits with coupling between neighbors as well as cross-couplings between rows. To parametrize each LC circuit, the corresponding cell is considered as part of a periodic chain and one uses selected passband frequencies from the Brilloun diagram to determine the circuit frequency and the coupling coefficient. Accordingly two chains of circuits can be parametrized by considering two passbands.

The motivation for the two-chain model is because the dipole modes consist of a mixture of TE111 and TM110 modes. The two circuit chains incorporate the cell response in the lower and upper dipole passbands, and therefore include both TE and TM components. The two-chain result in the periodic

limit is found to approximate far better the actual dispersion curves than the single-chain case. Once the parameters of the $2\times N$ circuits are determined and the boundary conditions at the two end cells are fixed, the eigenvalue problem is completely specified. One then solves for the eigenfrequencies and computes the transverse kick of each eigenmode from the kick factors of the individual cells by following the results derived in [5].

5. Open-mode Model

While conventional mode-matching separates the cell geometry into regions of uniform waveguides, the open-mode model considers the whole cell as one region and expands the electric field in the cell as a superposition of cell modes generated with open (or magnetic) boundary conditions at the disks. In principle, an expansion in closed modes with electrically shorted planes can also be used. The open modes are appropriate here because the dipole mode of interest is synchronous with the beam near π phase which is specified by magnetically shorted planes. The advantage this method has over the usual waveguide mode expansion is superior convergence since only the cell mode close in frequency to the eigenmode of the structure will predominate.

The coupled set of equations relating the mode expansions in one cell to the next have been derived in [6], and each of them has the conservative form which balances the stored energy in the cell against the power flux through the disk openings. It turns out that the closed modes are needed as well (otherwise power flow is zero). The parameters in the coupled system are determined by overlapping volume and surface integrals of the open and closed modes. Setting the boundary conditions at the end cells then completes the eigensystem for the whole structure. There are $j\times N$ eigenvlaues to solve for if the expansion includes j number of modes, and the kickfactors in Eq. (1) can be obtained directly by integrating the fields of the open modes in each cell.

6. Test Structure with Linear Taper

The test structure in this comparison is a linearly tapered DLWG at X-band with flat-ended disks so a structured-grid code like MAFIA can model exactly. Available computing resources limit the length of the structure that can be simulated accurately to around a maximum of forty cells. The taper is chosen to cover a group velocity span v_g/c from 6.46% to 3.91% for the lower dipole mode, which is within the NLC and JLC range. This span of v_g also simplifies the analysis by excluding any overlap with the upper dipole passband. The slope of the taper as measured by $dv_g/dN/c$ with $N = 41$ is close to the average NLC and JLC values of .04% and .05% respectively. A stronger taper is also considered by reducing N to 21 cells. A schematic of the 21-cell linearly tapered DLWG is shown in Fig. 1.

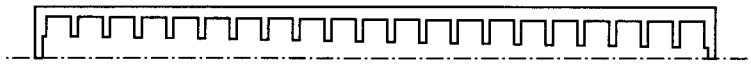

Figure 1: 21-cell linearly tapered structure.

7. Wakefield Results

The 21-cell ($dv_g/dN/c = .12\%$) results from MAFIA and two-chain model on dispersion curves, eigenfrequencies and kickfactors are shown in Fig. 2. Fig. 3 compares the eigenfrequencies and kickfactors from MAFIA and open-mode model. The number of modes included in the open-mode expansion is 8. The wakefields from all three methods are plotted in Fig. 4. Finally the same comparison for a 41-cell structure ($dv_g/dN/c = .061\%$) is shown in Fig. 5.

Taking the MAFIA results close to being exact one can summarize the comparison with the following observations. In the limit of a gradual taper (41 cells), both the two-chain and open-mode model agree well with MAFIA. For a less gradual taper (21 cells), the two-chain model is less accurate than the open-mode model. The difference from MAFIA in the two-chain model can be attributed to how well the dispersion curve and the coupling coefficient are approximated and to terminations at the ends. In the open-mode model the mismatch at the disk openings and the end boundaries are sources of errors.

8. Conclusion

The NLC and JLC detuned structures have tapers more gradual than the test structure, so one can expect less errors from approximations applied at the disk openings. Furthermore, because the modes in these structures extend over many cells, and because those touching the ends contribute less to the wakefields (they are at the tails of the Gaussian distribution), the effects of the end cells are reduced. Therefore both the two-chain and open-mode methods can be considered as viable alternatives to modeling these large heterogeneous structures when numerical simulations become impractical.

References

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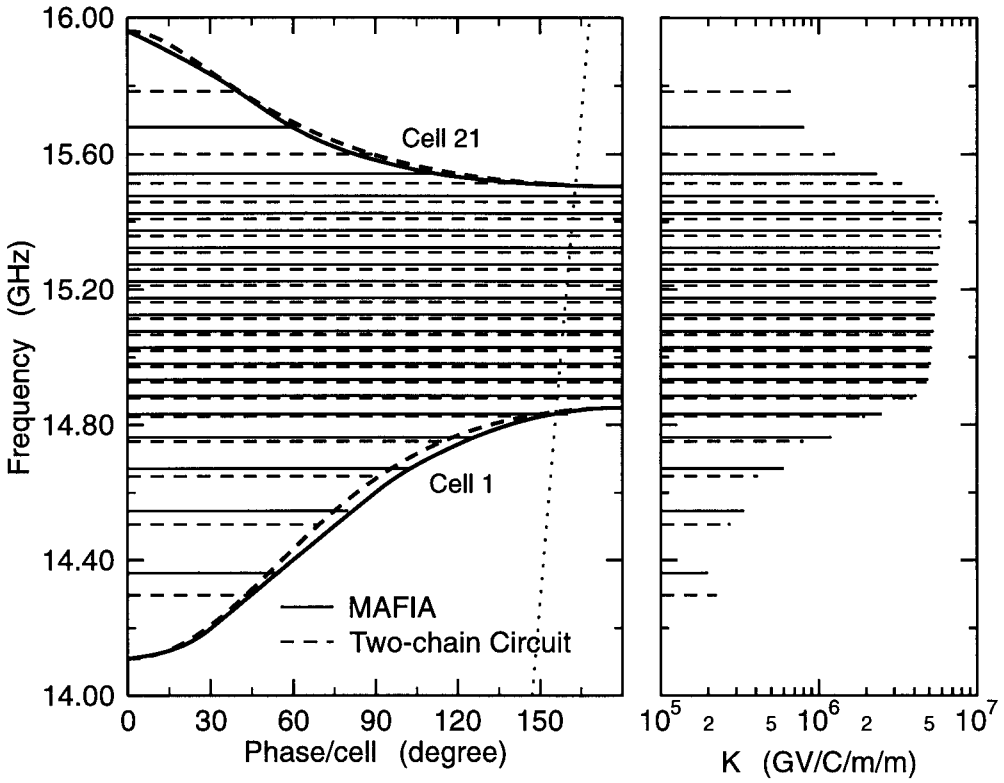

Figure 2: Coupled frequencies and kick factors of a 21-cell structure, MAFIA and two-chain circuit results.

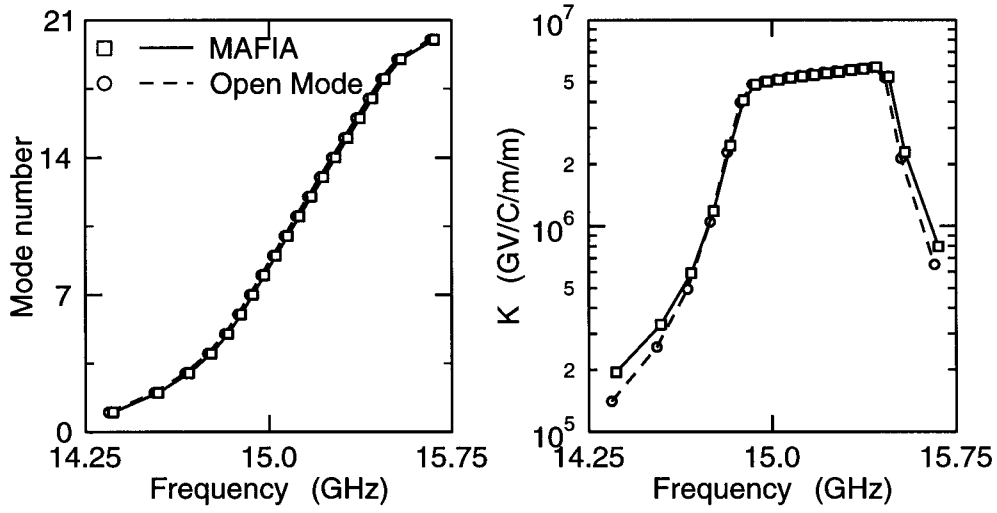

Figure 3: Coupled frequencies and kick factors of a 21-cell structure, MAFIA and open-mode results.

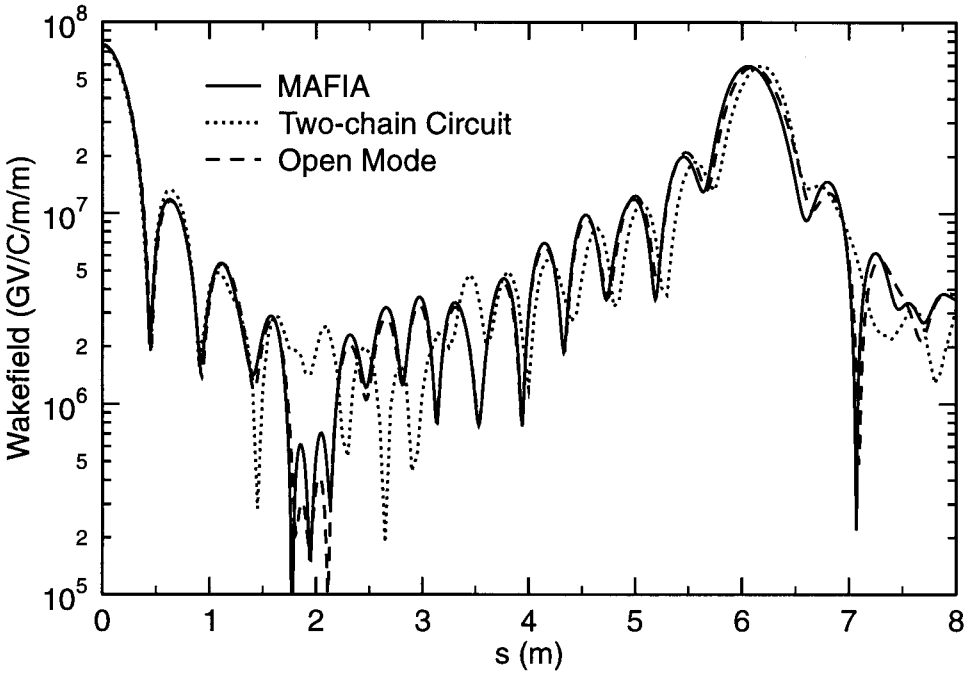

Figure 4: Wakefield envelopes for a 21-cell structure.

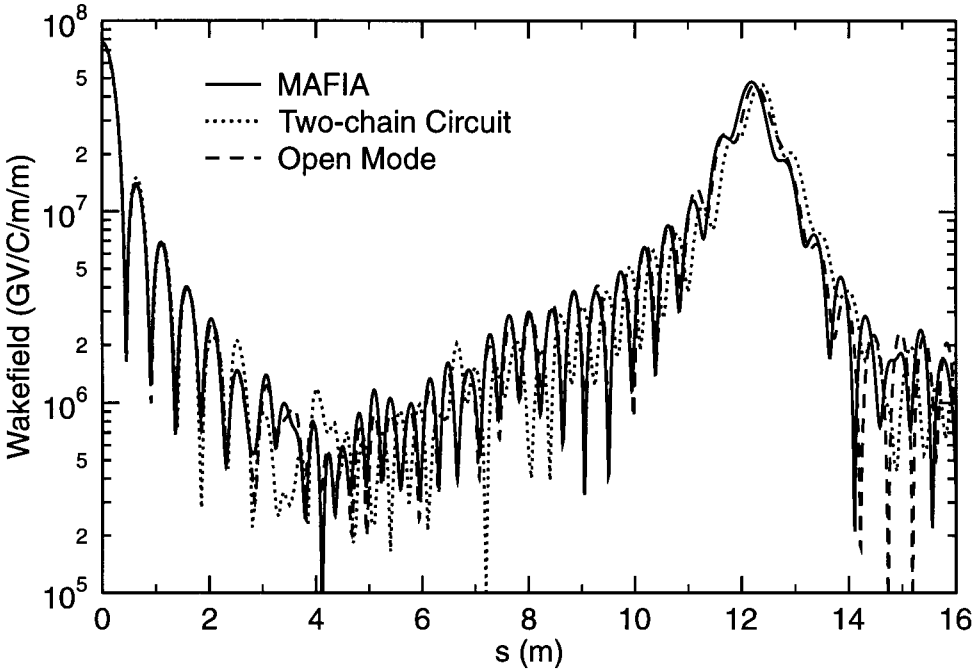

Figure 5: Wakefield envelopes for a 41-cell structure.