RF COUPLER KICKS AND WAKE-FIELDS IN SC ACCELERATING CAVITIES

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Abstract

The main accelerating cavities of the ILC provide acceleration of both positron and electron beams to 250 GeV per beam and 500 GeV per beam in a proposed upgrade. The wake-fields excited by each ultra-relativistic beam in the accelerating cavities can cause appreciable dilution of the beam emittance. Each cavity is supplied with both fundamental and higher order mode couplers. The geometrical configuration of these rf couplers results in an asymmetrical field and this gives rise to both an rf kick being applied to the beam and a transverse wake-field. Detailed electromagnetic (e.m.) fields are simulated in the vicinity of the couplers in order to assess the impact on the beam dynamics for the ALICE/ERLP [1] couplers.

INTRODUCTION

The ILC main linacs consist of approximately 16,000 superconducting rf cavities [2]. These cavities are based on the TESLA 9-cell cavity design. The rf power is fed into a cavity through the fundamental mode power coupler, and the higher order modes (HOM's) are extracted out through the HOM couplers. The inclusion of couplers breaks the symmetry of the cavity and gives rise to e.m. field which provides an rf kick to the beam and also gives rise to a wakefield. In order to mitigate for these kicks the couplers will need to be redesigned. It is anticipated that reorientation of the couplers will minimise the overall kick imparted to the beam.

The Cockcroft Institute at Daresbury laboratory is in the process of commissioning an energy recovery linac, ALICE/ERLP [3] which will be a multi-user accelerator facility which will also serve as an injector to the EMMA [4] accelerator. The couplers on the accelerating cavities of ALICE are similar to those on the main linacs in the ILC. However, the detailed design is different from the ILC is they are based on the Stanford University and BESY laboratory at Rossendorf couplers (hereafter referred to as the Stanford/Rossendorf coupler) [5]. In this paper we report on finite element simulations on the rf fields in the vicinity of these couplers. The resulting rf kick is compared to that present in the TESLA-style couplers [6].

We also analyse the coupled frequencies and modes in the overall 9-cell TESLA-style cavity by applying a two-band circuit model in order conduct a tolerance study on the sensitivity of the mode frequencies and kick factors to errors in the cell parameters. The results obtained to date constitute an initial parameterisation of the cavity.

This paper is arranged such the circuit model is presented in the following section for a TESLA-style cavity. The kick factors are calculated from this model and compared with an HFSS [7] simulation of the 9-cell cavity. The penultimate main section provides a study of the rf kick imparted by the fundamental mode couplers with MWS [8] simulations.

CIRCUIT MODEL OF A TESLA CAVITY

In order to rapidly assess the sensitivity of the cavity eigenmodes to errors in the cell parameters we apply a circuit model. We focus our study on the first two dipole bands of the cavity. To properly model the frequencies of the first dipole band a two band model is required. This is a reflection of the fact that the dipole modes are neither pure TE nor TM modes but are hybrid in character. We apply a two-band circuit model which was previously developed for X-band accelerating structures [9]. The dispersion curves of the middle cell of a TESLA cavity subjected to infinite periodic conditions are displayed in Fig. 1. It is clear that the first two bands are well-represented by this two-band circuit model.

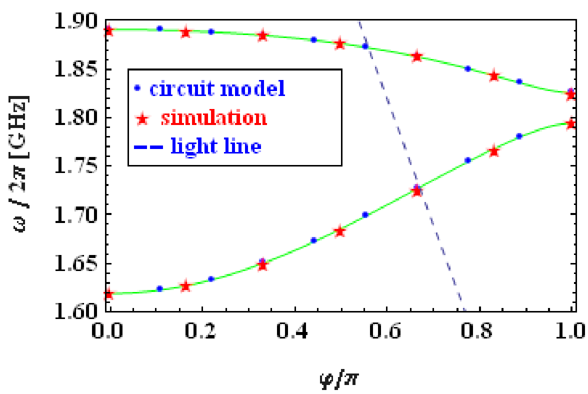

Figure 1: Dispersion curves for the first two dipole bands of a TESLA cavity from a two-band circuit model.

We use this parameterisation of the middle cells in a calculation of the eigenmodes of the cavity. However, the end cells of the cavity are connected to beam pipe tubes which perturb their characteristic mode frequencies. This makes it unclear as to what should be assigned to the frequency and coupling factors to the adjacent cells. In order to parameterise the end cells we calculate the kick factors and coupled frequencies of the system as a function of four end-cell parameters: the TE and TM cell frequencies and the corresponding TE and TM coupling factors. The results of this calculation are compared to an HFSS simulation of the 9-cells with attached beam tubes and the four parameters are varied in order to minimise the sum of the squares of their differences. The results of this calculation for the mode frequencies and kick factors are displayed in Fig. 2 and Fig. 3 respectively. The optimized double chain circuit model has an average mode frequency difference of 1.65 and 1.95 MHz and an average kick factor difference of 0.57 and 0.35 V/pC/m/m for the first and the second dipole pass band, respectively.

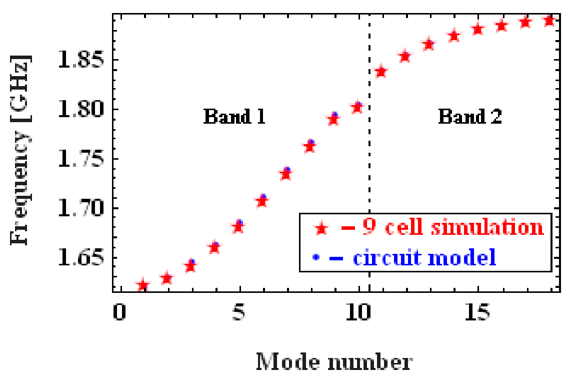

Figure 2: Frequency versus mode number for an optimized circuit model compared to HFSS simulation of a TESLA cavity for the first two dipole pass bands.

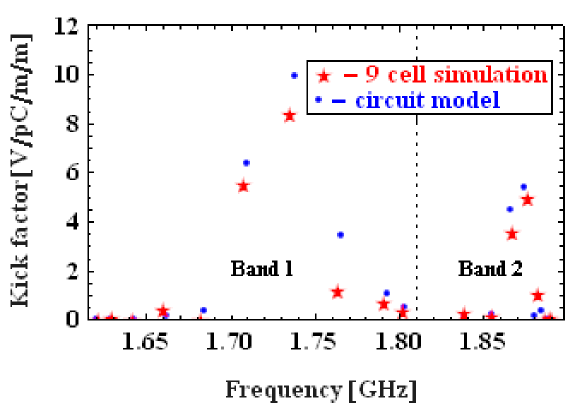

Figure 3: Kick factor comparison between an optimized circuit model and a full structure HFSS simulation of a TESLA 9-cell structure for the first two dipole pass bands.

The kicks factors, displayed in Fig. 3, show a larger discrepancy between that predicted by the model and that obtained from HFSS simulations. Including the coupling to higher bands may improve this model but this remains a subject for future study.

RF COUPLER KICKS

At Daresbury laboratory we are in the process of commissioning an energy recovery linac ALICE/ERLP [3]. A major part of this accelerator consists of TESLA-style cavities which are provided with a set of couplers designed by Stanford/Rossendorf. In order to assess the transverse kick imparted to the beam by these couplers we perform simulations on the last cell. The particular cavity under consideration is illustrated in Fig. 4.

As the bandwidth of the coupler cell is relatively small it is more convenient to perform eigenmode simulations

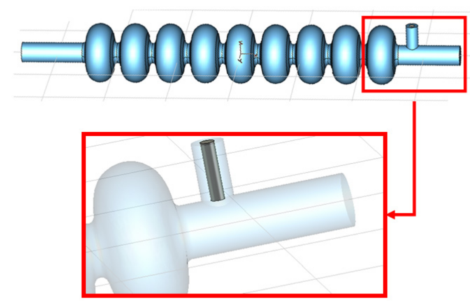

Figure 4:The TESLA cavity with the Stanford/Rossendorf coupler shown lowermost.

on this system. A travelling wave in the coupler waveguide is simulated by performing two independent simulations with shorted and open circuited boundary conditions on the couplers waveguide. These boundary conditions constitute perfect electric (PE) and perfect magnetic (PM) terminations respectively. Provided the coupler has a low external quality factor, it is possible to combine the results of two simulations in order to obtain the fields of a travelling wave in the coupler. For a PE boundary with a short is placed at z=0 the transverse electric field inside the coupler is given by

$$E_1 = A\sin(kz)e^{i\omega t} \tag{1}$$

Whereas, for a PM boundary and for a short placed at z=0 the field is given by

$$E_2 = B\cos(kz)e^{i\omega t} \tag{2}$$

Superimposing the two solutions gives an outgoing wave

$$E_{out} = E_1 + i(\frac{A}{B})E_2 = iAe^{i(\omega t - kz)} \tag{3}$$

A travelling wave solution is obtained provided the resonant frequencies of the two simulations are not significantly different. Applying this superposition to all the fields in the cavity enables the fields of the travelling wave solution to be obtained. The incoming waves are obtained by subtracting the two solutions:

$$E_{in} = E_1 - i(\frac{A}{B})E_2 = -iAe^{i(\omega t + kz)} \tag{4}$$

This will give a different coupler kick factor for incoming waves. In an actual cavity there are both incoming and outgoing components. To obtain the overall coupler kick the two components must be superimposed [10], [11]. In this paper we will only concern ourselves with perfectly matched input couplers such that the field is purely incoming.

The resulting coupler kick factor k, is the ratio of the transverse voltage in the cavity to the longitudinal voltage:

$$k = \int (\vec{E} + \vec{v} \times \vec{B})_t \, dz / V_z \qquad (5)$$

Both the transverse voltage and the longitudinal voltage vary sinusoidally, and each has a different phase. The coupler kick has both real and imaginary components. The real component of the kick corresponds to a momentum imparted to the overall bunch (and indeed to each bunch in the train). The corresponding imaginary component imparts a kick to the head of the bunch and this drives an oscillation in the tail of the bunch.

The results of simulations performed with MWS [8] are illustrated in Fig. 5 and Fig. 6. The coupler is a standard coaxial coupler with an outer conductor diameter of 40 mm, and inner conductor diameter of 17.4 mm and the coupler is positioned 45 mm from the end cell. The penetration was simulated at a depth of 5 mm.

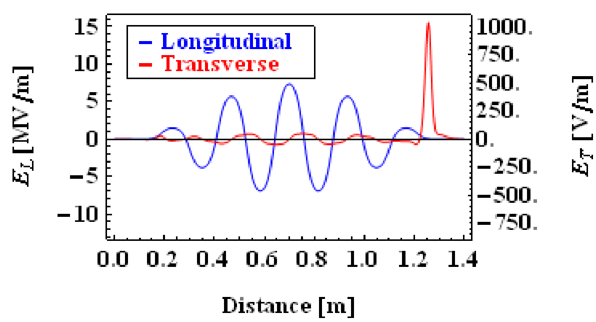

Figure 5: Longitudinal and transverse electric fields on axis with a PE boundary short at the end of the coupler.

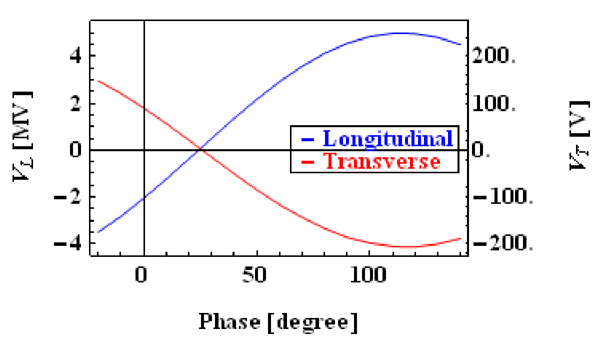

Figure 6: Longitudinal and transverse voltage as a function of phase for a 5mm penetration depth.

In all simulations there were 40 mesh lines per wavelength. This mesh was found to provide sufficient convergence by performing repeated simulations with increasing mesh density. A sufficiently large mesh density is required to resolve the small perturbations to the fields near the coupler. For a 5 mm penetration the transverse and longitudinal voltage is close to π radians out of phase. The coupler kick factor is k ~ (-41.2+i1.4) x 10^{-6} and this compares well to the real part of the TESLA-style coupler (here k ~ (35.6+i76.5) x 10^{-6} [12]). Varying the position of the coupler will modify the phase and hence change the coupler kick.

DISCUSSION

The double chain circuit model provides an accurate calculation of the frequencies of a 9-cell TESLA cavity once the end cells have been parameterized with a suitable optimization scheme. The kick factors show discrepancies between the model and full HFSS simulations. Additional study on higher bands is required in order to assess their influence on these kick factors.

The inclusion of the fundamental mode power coupler breaks the symmetry of a cavity. The resulting rf kick has been calculated for the Stanford/Rossendorf coupler and has been found to be similar to those imparted to the TESLA style couplers.

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