WAKE-FIELD SUPPRESSION IN THE CLIC MAIN LINAC

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Abstract

The CLIC linear collider aims at accelerating multiple bunches of electrons and positrons and colliding them at a centre of mass energy of 3 TeV. These bunches will be accelerated through X-band linacs, operating at an accelerating frequency of 12 GHz. Each beam readily excites wake-fields within the accelerating cavities of each linac. The transverse components of the wake-fields, if left unchecked, can dilute the beam emittance. The present CLIC design relies on heavy damping of these wake-fields in order to ameliorate the effects of the wake-field on the beam emittance. Here we present initial results on a modified design by detuning the cell frequencies of each structure in order to enhance the overall decay of the wake-field. Interleaving of cell frequencies is explored as a means to improve damping.

INTRODUCTION

The CLIC scheme aims at colliding electrons and positrons at a centre of mass energy of 3 TeV. To achieve this will require 10^5 accelerating structures with an overall collider footprint of 50 km. The design for the main accelerating structures of CLIC has matured to the extent that 12 GHz (i.e. X-band) is now the chosen RF accelerating frequency and 100 MV/m is the associated gradient aimed for in structures consisting of 25 cells. The spacing between neighbouring bunches is 6 RF cycles (~ 0.5 ns) in a train consisting of 312 bunches. These parameters have been chosen on the basis of an optimization procedure in which both the luminosity and RF power have been part of this process [1]. There are variants to this design but the parameters do not vary considerably from this chosen set. A number of accelerating structures have been fabricated and tested with a view to achieving these gradients with minimal breakdown and this is indeed the focus of an ongoing program at CERN [2] in collaboration with KEK and SLAC. However, another issue that has serious consequences on the beam quality is the wake-field excited by the passage of the bunch train of electrons and positrons. The present baseline design for CLIC relies on heavy damping (with Qs as low as 15) in order to suppress these wake-fields. This is based on a quadrant structure [3] damped by cutting slots into the cavity and inserting damping materials into this region.

Here, we consider an alternative design in which the cells are detuned and moderate damping is assumed (Q~1000). It should be emphasized that the present study has not been optimized with respected to the breakdown fields. It consists of a damped and detuned design which obviates the necessity for high damping and as a consequence the damping materials can be located at an extended distance from the beam and accelerating structure. A detuned design which is more strongly coupled to the latest CLIC high gradient test structure designs will be the subject of a future publication.

We focus on the dipole modes as they have the most significant impact on the beam emittance (compared to other multipoles for small offsets). In order to force the wakefield to rapidly decay we chose an erf distribution in the cell parameters and optimized the associated bandwidth and σ to minimizing any strong sensitivity on structure parameters.

The procedure to design wake-field suppression stems from a limited number of fiducial cells and intermediate ones are then obtained from a set of polynomial fits. We investigate 8-fold interleaving of structures. The initial design is based on an uncoupled model in which cell-to-cell coupling is ignored. This is expected to be a good prediction of the wake-field over the first several bunches and the behaviour of the wake-field over the full bunch train is obtained with a two-band circuit model. We note that for the 2π/3 phase advance structures designed, the wake-field associated with the modes of the first dipole band is the dominant component. We complete the analysis by adding a damping Q to the modes in order to prevent recoherence of the modes

UNCOUPLED WAKE-FIELD

The initial design of the structure begins with calculating the synchronous frequencies and kick factors of the fiducial cells. Each of the 25 cells in the structure consists of an elliptical iris of radius a, thickness t and, a gap of radius b. We utilised HFSS version 8.5 [4] to determine the electromagnetic fields within each cell and employed a frequency convergence criterion of 0.005%. We model 7 cells and enforce a polynomial fit such that all other cell parameters are obtained from these fits. The iris radii are tapered with an erf distribution and the accelerating mode frequency is preserved by tuning the b dimension of the cells. In addition, the ellipticity and thickness of the iris are varied to achieve a group velocity of 1.93c % and 1.03c % at either end, with a ratio of average iris radius to wavelength (<a>/λ) of 0.155.

The wake-field for an N-cell structure is determined from a summation which is a function of dipole kick factors K_i and synchronous frequencies f_i:

$$W_{t1} = \frac{2}{N} \mathrm{Im}\left\{ \sum_{i=1}^{N} K_i \exp\left[i2\pi f_i t \left(1 + \frac{i}{2Q_i} \right) \right] \right\} \qquad (1)$$

where a damping factor Q_i has also been incorporated. Provided the frequencies are sufficiently close, t is not too large, and Q is large, this can be approximated as:

$$W_{t1} \approx \frac{2}{N} \mathrm{Im}\left\{ \int_{-\infty}^{\infty} df\, K \frac{dn}{df} e^{i2\pi ft} \right\} \qquad (2)$$

This makes it clear that the initial decay of the wake-field is obtained by the Fourier transform of Kdn/df, the kick-factor weighted density function. The maximum excursion in the wake-field is given by the envelope function which is obtained by replacing the Im factor in Eqs. (1) and (2) with the absolute value.

We prescribed a Gaussian distribution:

$$K\frac{dn}{df} = N\frac{\bar{K}}{\sqrt{2\pi}\sigma} e^{-\frac{(f-f_c)^2}{2\sigma^2}} \qquad (3)$$

where $\bar{K}$ is the average kick factor and f_c is the centre synchronous frequency. Once the frequencies and kick end points have been specified, those of intermediate cells are obtained from Eq. (3).

Provided the bandwidth is sufficiently large, the effects of truncation can be minimised and the envelope is:

$$W_{t2} = 2\bar{K}\, e^{-2(\pi\sigma t)^2} \qquad (4)$$

However, in practise there will be a truncation in the Gaussian due to the finite bandwidth Δf:

$$W_{t3} = 2\bar{K}\, e^{-2(\pi\sigma t)^2} \left|\chi[t,\Delta f]\right| \qquad (5)$$

$$\text{where } \chi[t,\Delta f] = \frac{\mathrm{Re}\left\{\mathrm{erf}\left[\left(\Delta f - i4\pi\sigma^2 t\right)/\left(2\sqrt{2}\sigma\right)\right]\right\}}{\mathrm{erf}\left[\Delta f/\left(2\sqrt{2}\sigma\right)\right]}.$$

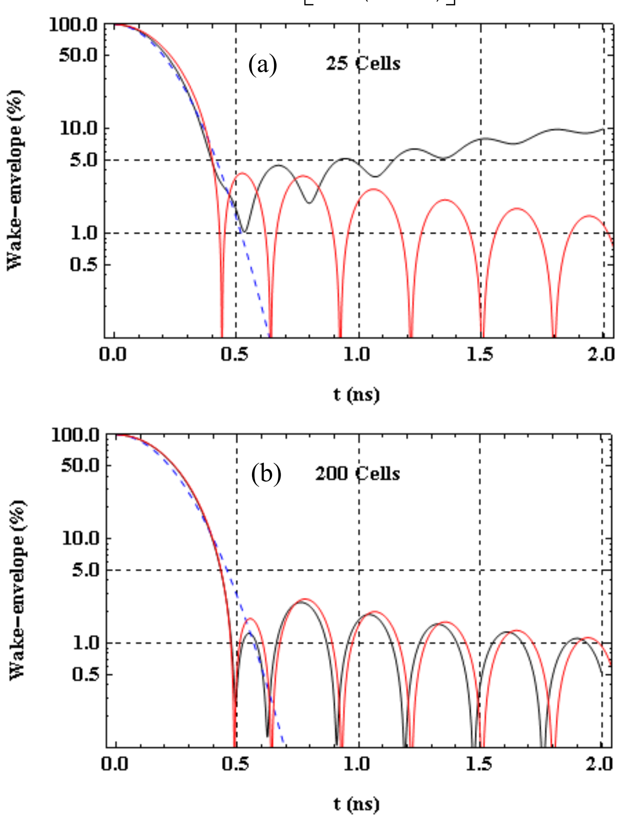

Figure 1 Uncoupled normalised and loss-less wake-field of 25 cell and 200 cell structures. The black, blue-dashed and red curves represent Eqs. 1 (Im replaced with abs), 4 and 5 respectively. The Qs are assumed to be infinite.

We optimised the wakefield by minimising the wake-field at the first few trailing bunches and also by ensuring that the ripples in the wakefield (due to truncation) are kept within tolerable limits. This resulted in the following set of parameters: N = 25 cells, $\Delta f = 3.6\sigma$ (= 3.36 GHz) and $\Delta f/f_c$ = 20%. In this case, the wake-field at the first trailing bunch is 1.64% of the peak value (W_{max} = 110 V/pC/mm/m). The uncoupled wake-field for 25, 100 and 200 cell structures has been investigated. The wake-field of the latter structure is displayed in Fig. 1 (b). In this case the truncated Gaussian wake-field (given by Eq. (5)) is in good agreement with the modal summation and this is a reflection of the improved sampling. We envisage interleaving frequencies of successive structures to obtain these structures. The wake-field at the first trailing bunch for 8-fold interleaving is 0.43 % and the ripples in the wake-field give rise to ~ 2 % of the peak.

After the first few bunches a model which takes into account the cell-cell coupling is required.

COUPLED WAKE-FIELD

The modes in the N-cell cavity will be modified according to the cell-to-cell coupling. A finite element or finite difference simulation of the multi-cell structures will be a time and memory intensive operation. To facilitate rapid redesigns in the structure we employ a coupled circuit model of the 2 dipole modes [5]. We proceed with this analysis taking 7 fiducial cells and in the first instance we take a uniform structure subjected to infinite periodic conditions. We then take the 0 and π modes of the HFSS simulations for this structure and enforce a fit to the circuit model equations. The resulting Brillioun diagram for three representative cells is illustrated in Fig. 2. The agreement of the intermediate points with the circuit model serves as an indicator as to the accuracy of the model. The first dipole band is well represented with the circuit model. The second band is not as accurately predicted. Furthermore, the model for the second band is improved as the iris size is reduced.

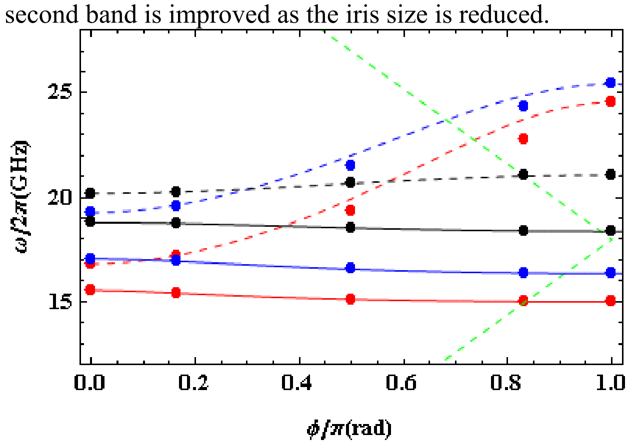

Figure 2: Dispersion curves of three cells. The points represent simulations and curves represent the circuit model. The red, blue and black represent geometries with a(mm) = 4.95, 3.95, and 2.15 respectively. The light line is shown dashed.

From these dispersion curves we are able to obtain all the relevant parameters for the 7 fiducial cells in the circuit model. The parameters for the remaining cells are obtained from polynomial fits to the parameters of the fiducial cells. These parameters are inserted into the eigensystem of the circuit model and this allows the coupled frequencies and kick factors to be determined.

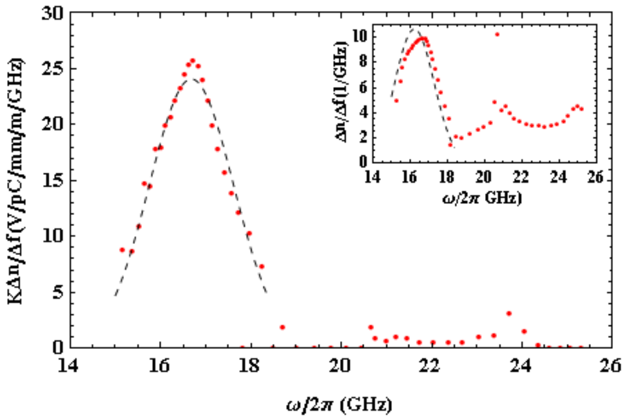

Figure 3: KΔn/Δf of first two dipole bands (Δn/Δf inset) for a 25 cell structure. The dashed curve represents uncoupled and the dots the coupled mode values.

These results are displayed in Fig. 3 together with the uncoupled curves. The coupling makes a small perturbation about the uncoupled for the first band although there are some pronounced differences.

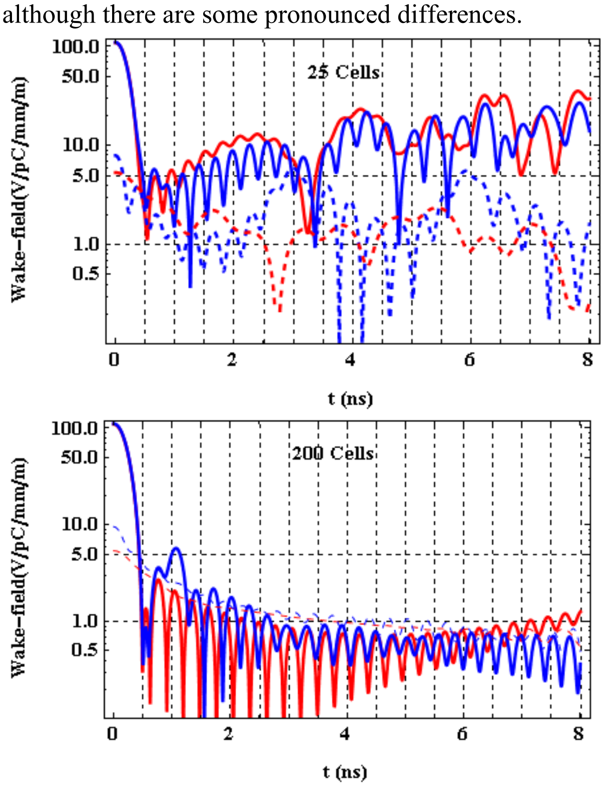

Figure 4: Wake-fields of 25, and 200 cell structures. The red and the blue curves represent the uncoupled and the coupled wake-fields respectively. The solid curves represent the wake-field of the first dipole band and dashed curves that of the second dipole band.

We now study the envelope of the coupled wake-field using Eq. (1) with coupled values and with Im replaced by absolute. The resulting envelope of the wake-field is compared to that of the uncoupled value for both the first and second dipole band in Fig. 4. We observe that for the first 12 (~ 6 ns) or more bunches the uncoupled model is in reasonable agreement with the coupled value and it is in effect an envelope of the envelope wake-field itself. Thus, in designing the detuning the wake-field resulting from the Fourier transform of a truncated Gaussian provides a design tool to ascertain the wake of the initial bunches. We also note that the second dipole band, although small, is not insignificant as it has a maximum amplitude of ~ 5 % of the peak wake-field. The discrepancy between coupled and uncoupled wake-fields is due to the nature of the shape of the second dipole passband as the detuning progresses down the structure.

Finally, we study the longer term behaviour of the wake-field up to the end of the bunch train for an 8-fold interleaved structure. The wake-field in this case recoheres at ~ 85 ns, and this corresponds to the minimum separation of the modes. Increasing the number of cells will of course push this recoherence position further away from its present position. In order to mitigate for this resurgence of the wake-field we provide the modes with a damping Q. In practise a Q of ~1000 is adequate to force the wake-field to be below 1 % of the peak value.

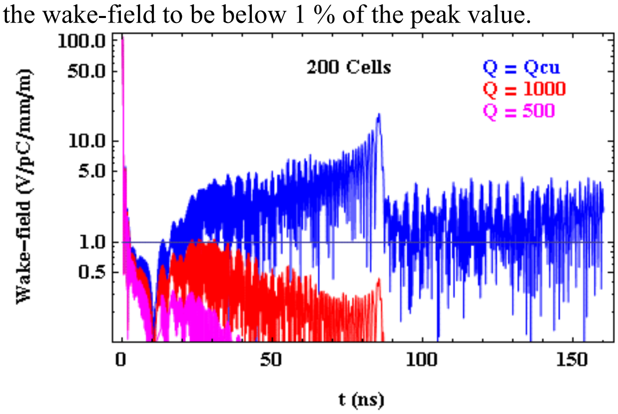

Figure 5: Wake-field of 200 cell structure with finite Qs.

DISCUSSION

The present detuning and moderate damping is sufficient to suppress the long-range wake-field to contain the emittance dilution. Future studies will be focussed on developing similar detuning schemes for the current CLIC structure design in which geometrical parameters are more closely tied to electrical breakdown issues.

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