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WAKEFIELD SUPPRESSION IN A MANIFOLD DAMPED AND DETUNED STRUCTURE FOR A 380 GEV CLIC STAGED DESIGN

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Abstract

The first stage of the Compact Linear Collider (CLIC) project aims to collide electrons and positrons at a 380 GeV center of mass energy. In the baseline design the main linacs for this staged approach are required to achieve a gradient of 72 MeV/m, with the surface electromagnetic fields (EM) and the transverse long-range wakefields bound by beam dynamics constraints. The baseline design utilizes heavy damping in a traveling wave (TW) structure. Here we report on an alternate design, which adopts moderate damping along with strong detuning of the individual cell frequencies. In the context of this Damped and Detuned Structure (DDS) design, we study Gaussian and hyperbolic secant dipole distributions, together with interleaving of successive structures, to facilitate long-range transverse wakefield suppression. Both analytic and modal summation approaches, in the quasi-coupled approximation, produce consistent results. In the optimisation scheme we opt for a dipole frequency bandwidth of 17.7% (2.92 GHz).

INTRODUCTION

A 380 GeV staged design will provide an opportunity to study Standard Model (SM) Higgs and top quark physics. The first stage in the baseline design will deploy a two-beam acceleration (TBA) scheme, to source the power to the accelerating structures which will provide an accelerating gradient of 72 MV/m at 11.994 GHz and $2\pi/3$ phase advance [1–3]. The gradient is reduced from the 3 TeV design of 100 MV/m, to accommodate an increase in bunch charge from 0.59 nC to 0.83 nC. The electric and magnetic fields on surface are limited to 220 MV/m and 500 kA/m respectively to minimise electromagnetic breakdown. The loss in the average accelerating gradient is partially compensated by increasing the number of accelerating cells per structure from 24 to 33.

In addition to the monopole mode, the dipole modes must be accounted for. These eigenmodes give rise to a transverse momentum kick to the beam. The short-range wakefield is affected by the average iris aperture and the long-range wakefield can be suppressed by damping. As the CLIC design entails 352 bunches spaced from each other by 6 RF cycles (0.5ns) then the long-range wakefield must be suppressed to minimise emittance dilution. For the CLIC project the overall emittance dilution is constrained to no more than 10% [1–4] and this limits the wakefield on the trailing bunches to be no more than 3.7 V/pC/mm/m [1–3, 5, 6]. The baseline design [1, 7] opts for heavy damping (Q∼10) by coupling out the wakefield through slots to attached damping materials.

Here we offer an alternate approach which invokes strong detuning along with moderate damping in a TW structure. The frequencies of the dipole modes are detuned and in addition moderate damping is applied by coupling the field out to four attached manifolds. Simulation of an entire structure is impractical from a design point of view. Thus we investigate and optimize a structure based on a first-order design using a quasi-coupled structure –which serves as a rapid design tool. A more accurate final calculation of the wakefield, based on the spectral function method [8] (verified against numerous experiments on previous designs [5, 8]) will be reported on in a subsequent publication.

The structure is designed by maximizing the accelerating gradient, minimizing the transverse long-range wakefield, whilst constraining the surface EM fields to tolerable values, and this approach is discussed in the next section. This is followed by a section on the details on the minimisation of wakefield, which is effected by detuning the individual cell frequencies. We conclude with some final remarks.

RF STRUCTURE DESIGN

In our TW structure design we focused on a 2D representation of cells (and omit the slots which affect the manifold coupling and break the symmetry). In the optimization scheme we modify the shape of the cell in order to minimize the surface EM fields and at the same time we investigate several dipole distributions. In the design of the dipole distribution we aim at maximizing the bandwidth and at the same time we modify the dipole σ of the distribution in order to place the first trailing bunch on the zero of the transverse wakefield.

The Poisson Superfish code [6] facilitates rapid computation of the monopole EM fields and a front end to this was written in Python to aid the tuning of each cell. A Superfish model for a typical cell is shown in Fig. 1. To expedite design, only 9 fiducial cells are required to be simulated, as parameters for all 33 cells are interpolated from a mapping function [5]. RF parameters such as quality factor (Q), normalized shunt impedance (R/Q) and maximum normalised surface electric (E^{surf}_{max}/E_{acc}) and magnetic (H^{surf}_{max}/E_{acc}) fields are extracted from the output file, while the group velocity v_g is calculated using dispersion relation obtained from circuit model [9, 10]. The dipole characteristics parameters are simulated using HFSS [11]. To expedite the design optimisation, cell dimensions a and t were scanned to create a 2-D interpolation mesh of RF parameters.

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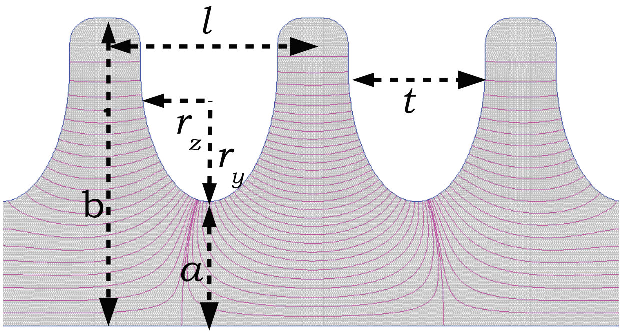

Figure 1: Parameterised cells used in Poisson Superfish simulations.

The cell dimensions for all 33 cells are calculated by interpolating the synchronous frequencies obtained from calculation of the kick factor weighted mode density function (Kdn/df) as is discussed in the next section on wakefield minimisation. The iris radius a and thickness t were varied to follow a prescribed error (erf) function on cell number and this ensures the dipole synchronous frequencies vary with an erf function. The RF parameters corresponding to the dimensions are interpolated from 2-D mesh. RF parameters of the optimised design are simulated explicitly, and were in good agreement with their interpolated values. The cell dimensions and RF parameters of 33 cells for an optimised design are shown in Fig. 2 and 3 respectively. These parameters allow the power and E.M. fields along the structure to be calculated.

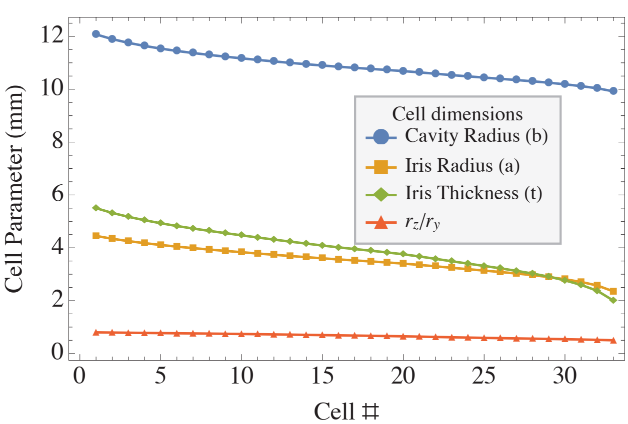

Figure 2: Cell dimension of an optimised 33-cell design.

The power P_n in the n^{th} cell along the structure is calculated according to [9]

$$\frac{dP_n}{dz} = -\frac{\omega_{acc}P_n}{Q_n v_{gn}} - \sqrt{\frac{\omega_{acc}}{v_{gn}}\left(\frac{R'}{Q}\right)_n} I\sqrt{P_n}, \quad (1)$$

where, n denotes the cell number, $\omega_{acc}/2\pi$ is the accelerating frequency, $(R'/Q)_n$ is the n^{th} shunt impedance per unit length divided by the Q and, I is the beam current. The first term represents the power decay due to intrinsic losses, while the second term represents coupling to the beam. The equation is solved in Mathematica [12], by dividing the N-cell structure into equal lengths l. The corresponding accelerating gradient in the n^{th} cell can be calculated as,

$$E_n^2 = \frac{\omega_{acc}P_n\left(\frac{R'}{Q}\right)_n}{v_{gn}}. \quad (2)$$

The input power P_0 is subsequently varied to achieve the required average accelerating gradient. The accelerating gradient and maximum surface fields in each cell are shown in Fig. 4. The required average accelerating gradient of 72 MV/m is achieved with a 64 MW input power. The maximum surface electric and magnetic fields are within the limits of 220 MV/m and 500 kA/m respectively.

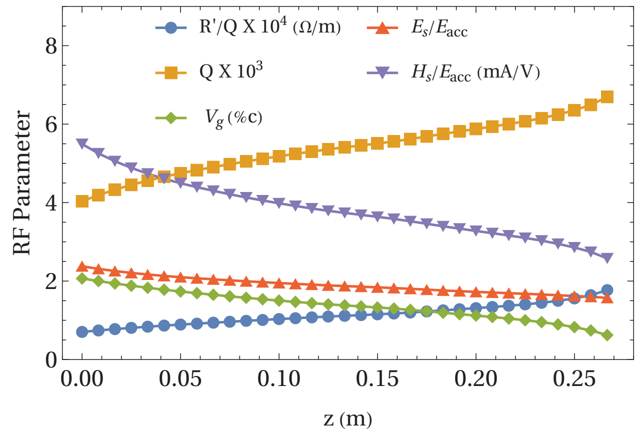

Figure 3: Monopole RF parameters associated with Fig. 2.

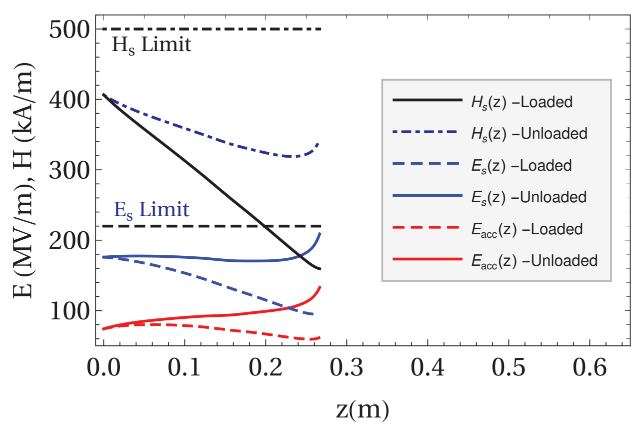

Figure 4: Accelerating gradient and maximum surface electric and magnetic fields along an optimised structure.

MINIMISATION OF TRANSVERSE WAKEFIELD THROUGH DETUNING

For the first few bunches the wakefield can be quite accurately calculated in the time domain from the inverse Fourier transform of the kick factor weighted density function Kdn/df [5, 9, 13] (where K is the transverse kick factor, n is cell number and f is the dipole synchronous frequency).

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Initially for an N-cell structure we prescribed a Gaussian distribution,

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

where, $\overline{\mathrm{K}}$ is an average kick factor for the optimised design, f_c is the center frequency of the distribution and σ is the standard deviation of the Gaussian distribution. We compared Gaussian Kdn/df distributions with fractional powers of a sech (hyperbolic secant) function ($\mathrm{sech}^{1/2}$ and $\mathrm{sech}^{3/2}$) in order to assess the optimal decay in the transverse wakefield, and these are shown in Fig. 5. The envelope of the transverse wakefield can be calculated from the inverse Fourier transform of the $2Kdn/df$ function, which for a truncated Gaussian distribution takes the form of,

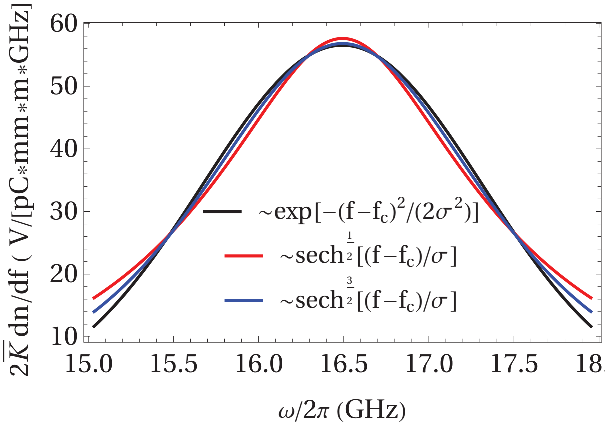

Figure 5: Gaussian and sech dipole frequency distributions.

$$W_\perp(t) = 2\overline{K}\frac{e^{-2(\pi\sigma t)^2\left[\mathrm{erf}\left(\frac{\Delta f-4i\pi t\sigma^2}{2\sqrt{2}\sigma}\right)+\mathrm{erf}\left(\frac{\Delta f+4i\pi t\sigma^2}{2\sqrt{2}\sigma}\right)\right]}}{\mathrm{erf}\left(\frac{\Delta f}{2\sqrt{2}\sigma}\right)}, \qquad (4)$$

where, t is time behind the driving bunch. The wakefields corresponding to our three optimized distributions are shown in Fig. 6 for a 17.7% bandwidth ($\Delta f = 2.198$ GHz).

This analytical method of course allows a rapid approximation of the wakefield, but it is based on smoothly truncated Gaussian which tacilty assumes an infinite number of cells. A finite number of cells can be approximated by a modal summation model [9, 14]. The transverse wakefield for the 33-cell structure re-coheres at approximately 3.5 ns (corresponding to the location of the 7th bunch), and increases above the beam dynamics limit, and in this case detuning alone is not sufficient and manifold loading is needed. This implies a loaded quality factor (Q_l) of 170. The recoherence of the wakefield can be extended further out along the bunch train by increasing the number of cells or by interleaving [5] the cells from successive structures. If we retain the 33-cell baseline design and interleave the dipole frequencies of 8 successive structures then a damping Q of no more than 3500 is required. The corresponding wakefield is illustrated in Fig. 7.

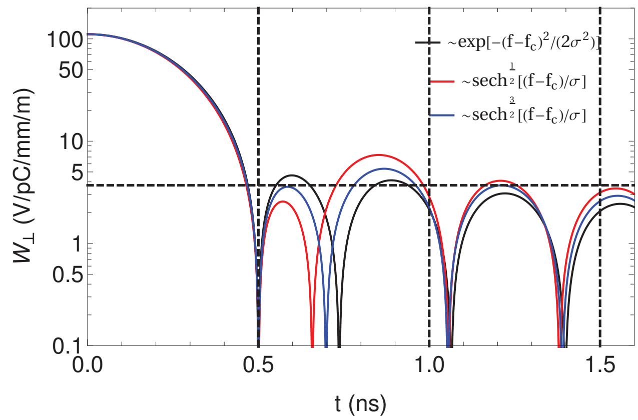

Figure 6: Transverse wakefield for Gaussian and sech frequency distributions. Horizontal and vertical lines mark wakefield limit and bunch arrival time respectively.

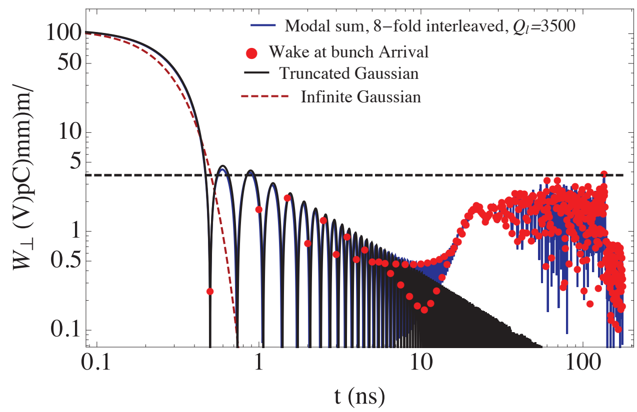

Figure 7: Envelope of the long-range transverse wakefield evaluated for a Gaussian distribution using Eq. (4) and with the modal summation method [5, 9, 14, 15] for an 8-fold interleaving of the dipole frequencies of successive structures.

FINAL REMARKS

A normal conducting damped and detuned high gradient structure for the CLIC 380 GeV staged design has been discussed. This is based on the baseline 33-cell constant gradient TW structure which has been optimised to provide the required accelerating gradient of 72 MV/m. It requires an input power of 64 MW. We adhere to the surface EM field and beam dynamics constraints on emittance. In addition to a Gaussian dipole distribution we also explored sech distributions. In order to properly damp the wakefield 8-fold interleaving of structures is required together with a moderate damping Q of 3500.

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REFERENCES

[1] CLIC collaboration, “Updated baseline for a staged Compact Linear Collider”, P. N. Burrows, P. Lebrun, and *et al.*, Geneva, 2016.

[2] H. Schmickler, presentation, February 2017, "CLIC", (CAS) Basics of Accelerator Science and Technology at CERN. `https://indico.cern.ch/event/575505/`

[3] A. Aksoy, D. Schulte, and O. Yavas, "Beam dynamics simulation for the Compact Linear Collider drive-beam accelerator", *PRST-AB*, vol. 14, p. 084402, 2011. `doi:10.1103/PhysRevSTAB.14.084402`

[4] D. Schulte, “Multi-Bunch Calculations in the CLIC Main Linac”, in *Proc. PAC’09*, Vancouver, Canada, May 2009, paper FR5RFP055, pp. 4664–4666.

[5] R. M. Jones, "Wakefield suppression in high gradient linacs for lepton linear colliders", *PRST-AB*, vol. 12, p. 104801, 2009. `doi:10.1103/PhysRevSTAB.12.104801`

[6] K. Halbach, R. F. Holsinger, W. E. Jule, and D. A. Swenson, “Properties of the Cylindrical RF Cavity Evaluation Code SUPERFISH”, in *Proc. LINAC’76*, Chalk River, Canada, Sep. 1976, paper C03, pp. 122–128.

[7] H. Zha and A. Grudiev, “Design of the Compact Linear Collider main linac accelerating structure made from two halves”, *PRAB*, vol. 20, p. 042001, 2017. `doi:10.1103/PhysRevAccelBeams.20.042001`

[8] R. M. Jones *et al.*, “Wakefield damping in a pair of X-band accelerators for linear colliders”*PRST-AB*, vol. 9, p. 102001, 2006. `doi:10.1103/PhysRevSTAB.9.102001`

[9] V. Khan, PhD thesis, “A damped and detuned accelerating structure for the main linacs of the compact linear collider.”, University of Manchester, *EuCARD-BOO-2011-001*, 2011.

[10] R. M. Jones, V. A. Dolgashev, and J. W. Wang, “Dispersion and energy compensation in high-gradient linacs for lepton colliders”*PRST-AB*, vol. 12, p. 051001, 2009. `doi:10.1103/PhysRevSTAB.12.051001`

[11] Ansys HFSS, `http://www.ansoft.com`

[12] Wolfram Mathematica, `https://www.wolfram.com/mathematica/`

[13] P. B. Wilson, “Introduction to wake fields and wake potentials”, *SLAC-PUB-4547*, SLAC, 1987.

[14] V. F. Khan and R. M. Jones, “Wake-field Suppression in the CLIC Main Linac”, in *Proc. EPAC’08*, Genoa, Italy, Jun. 2008, paper WEPP089, pp. 2725–2727.

[15] R. M. Jones, “A study of higher-band dipole wakefields in X-band accelerating structures for the G/NLC”, *SLAC-PUB-10682*, SLAC, 2004.