BEAM DYNAMICS AND WAKEFIELD SUPPRESION IN INTERLEAVED DAMPED AND DETUNED STRUCTURES FOR CLIC*

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Abstract

Acceleration of multiple bunches of charged particles in the main linacs of the Compact Linear Collider (CLIC) with high accelerating fields provides two major challenges: firstly, to ensure the surface electromagnetic fields do not cause electrical breakdown and subsequent surface damage, and secondly, to ensure the beam-excited wakefields are sufficiently suppressed to avoid appreciable emittance dilution. In the baseline design for CLIC, heavy wakefield suppression is used (Q ~ 10) [1] and this ensures the beam quality is well-preserved [2]. Here we discuss an alternative means to suppress the wakefield which relies on strong detuning of the cell dipole frequencies, together with moderate damping, effected by manifolds which are slot-coupled to each accelerating cell. This damped and detuned wakefield suppression scheme is based on the methodology developed for the Japanese Linear Collider/Next Linear Collider (JLC/NLC) [3]. Here we track the multi-bunch beam down the complete collider, under the influence of transverse wakefields and record the final emittance dilution at the end of the linac. We utilize the code PLACET [4] for all tracking simulations and include systematic and random fabrication errors; the latter are particularly beneficial in reducing the impact of the wakefield on the beam quality. Results of some initial alignment studies are also provided.

INTRODUCTION

The CLIC scheme entails two beams, one of which is the high-current drive beam (~ 100 A), and the other is a low-current accelerated beam. The drive beam is decelerated and provides an electromagnetic field which is coupled to the main accelerating linac. These main linacs are required to accelerate electron-positron beams to a final collision centre of mass energy of 3 TeV. Recent studies anticipate a staging to a reduced centre of mass energy of 375 GeV, as a prelude to the full collision energy. Here we focus on the 3 TeV design, which requires more than 71,000 accelerating structures. In this baseline design, each structure accelerates 312 bunches, each of which consists of ~ 4 x10^9 particles per bunch. The corresponding beam current of ~ 1 A removes energy from the accelerating electric field, and loads it down. The beam-loaded accelerating field is designed, on average, to be 100 MV/m. The electric field is a little more than a factor of two larger on the walls and the magnetic field is constrained to provide a pulse temperature rise on the copper walls of no more than 56 K [5]. A relatively compact accelerating structure is obtained by adopting an X-band accelerating frequency of 11.994 GHz. The iris radius of each accelerating cell largely determines the shunt impedance, which ideally should be maximized, but since shrinking it down also enhances the transverse dipole fields, a compromise must be achieved. In our design we focus on an average iris radius to free space wavelength: $\langle a\rangle/\lambda \sim 0.13$. The average iris radius determines the short-range wakefield, or the field experienced along the bunch itself. The transverse wakefield experienced by succeeding bunches in the multi-bunch train is influenced by several factors. In principle it can be suppressed by heavy damping, and this is indeed the method adopted in the baseline design for CLIC in which field is coupled out from each cell and immediately dissipated in attached ceramics. This ensures the wakefield on the first trailing bunch is constrained to less than 6.7 V/pC/mm/mm [5] and all subsequent bunches experience an even lower wakefield. Recent high power tests have indicated this structure is able to sustain the requisite surface electromagnetic fields at the design gradient [6].

However, here we discuss a method which entails changing the dipole frequency of each of the cells within a given structure and hence ensuring the eigenmodes, corresponding to these fields, add up in a deconstructive manner [3]. In our alternative design the iris is tapered down in an erf function manner, and this ensures the wakefield decays with a Gaussian envelope. However, the finite number of cells within each structure corresponds to a sampling of the field. This will ultimately lead to a point at which the eigenmodes add together coherently and hence will force the wakefield to rise above the constrained value. We provide four waveguide-like manifolds, slot-coupled to each cell in the structure, to ensure this recoherence in the wakefield is sufficiently suppressed. We have constrained our design to utilize the same number of cells as the baseline design, namely 24. This short structure is of course insufficient to provide adequate sampling, and hence we interleave the frequencies of several neighbouring structures in order to obtained the requisite wakefield suppression -12 and 16 fold interleaving is focused on in this article (corresponding to an equivalent structure of 288 and 384 cells, respectively).

This paper is organized such that the next section provides a description of the wakefield suppression used, followed by a section entailing tracking the beam throughout the complete linac under the influence of expected fabrication errors, and finally by a penultimate

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section concerned with an initial investigation of the implication of structure misalignment on emittance dilution. A final set of concluding remarks is also given.

DDS INTERLEAVED DESIGN

The accelerating structures investigated here are based on those optimised in [7], and a single one of these structures is referred to as CLIC_DDS_A. This optimisation was focussed on adhering to the semi-empirical design constraints specified for CLIC –and entails, *inter alia*, ensuring the surface electromagnetic fields are within given bounds [5], and the overall efficiency of the collider is maximised. The inter-bunch spacing was changed from the baseline value of 6 rf cycles to 8, in order to relax the required suppression on the first trailing bunch –which is governed by the frequency spread of the dipole modes. This allowed a bandwidth of 11.8 % (~ 2 GHz) with a span of 3.48σ to be assigned to the first dipole band. Higher order bands provide appreciably smaller transverse momentum kicks [8] to the beam and hence we focus on the first dipole band in this work.

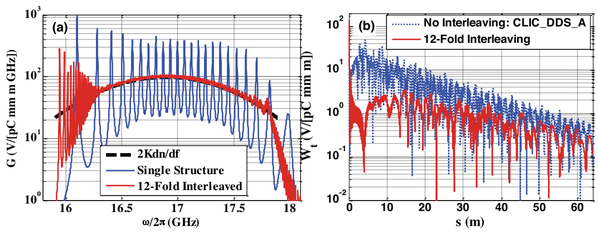

Figure 1: Spectral function (a) for a single structure (in blue) and a 12-fold interleaved series (in red), together with the Fourier transforms thereof, the corresponding wakefunctions W_t (b). Also shown is twice the kick factor weighted frequency density distribution (2Kdn/df).

Before discussing the wakefields, and beam dynamics of the multi-structure configurations relevant to CLIC, we note that a single structure, CLIC_DDS_A, has been fabricated and is being scheduled to be high power tested at CERN. All cells of this 24-cell structure have been precisely made by milling with a carbide tool on the outer area of each cell, followed by diamond-point turning in the beam-hole area and finally, chemically rinsed and diffusion bonded together. It remains to complete the process by attaching couplers and tuning stubs.

The transverse, long-range wakefield in these multi-cell structures is assessed using a spectral function method [9,10]. This method was developed to take into account the strong coupling of modes. The Fourier transform of the spectral function provides the wakefield experienced by the beam. A single structure consists of no more than 24 cells and hence will be woefully inadequate in suppressing the wakefield. However, provided the dipole modes are interleaved between successive structures, the wakefield will be well-suppressed. We have found 12-fold interleaving of modes to be sufficient (equivalent to a single structure consisting of 288 cells). The spectral function, and corresponding wakefunction, for a single structure and a 12-fold interleaved series of structures is shown in Fig 1. Also indicated is 2Kdn/df, the original uncoupled design. The short-range wakefield (the first 2 m or so), corresponding to the Fourier transform of the uncoupled design and coupled spectral functions, should be virtually identical and we have verified this during our calculations. It is interesting to note that the minimum spacing and indeed maximum spacing of the modes (corresponding to the spacing in the peaks in Fig. 1 (a) for example) provides an indication as to where the modes will recohere. The minimum and maximum separation of peaks in Fig. 1 (a) for a single structure is 61 MHz and 342 MHz, and for 12-fold interleaving of structure frequencies it is 5 MHz and 19 MHz. These separations correspond to recoherance positions of 5 m and 1 m for a single structure, and 60 m and 16 m for the interleaved structures. Inspection of the wakefields in Fig. 1 (b) confirms this behaviour. Clearly the interleaving enhances the overall sampling, and hence provides a better representation of the Gaussian distribution, and also pushes the recoherence position further down the bunch train.

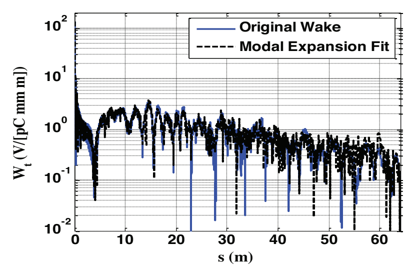

Figure 2: Envelope of fitted transverse wakefunction of (dashed and in black) together with that of the Fourier transform of the spectral function (solid blue) for a 12-fold interleaved structure.

The wakefield presented in Fig. 1 (b) is not that experienced by the beam, as the envelope, or worst case wakefield is illustrated. The tracking code we utilise, PLACET, requires the mode frequencies, Q's, and corresponding kick factors [4,11] as input parameters to assess the impact of these wakefields. We utilize the peaks in the spectral function and assign these to the modal frequencies, the remaining parameters are obtained by taking the usual modal expansion [12] and performing a non-linear least-square error fit. To provide some confidence in the fitting method, we compare the original Fourier transform of the spectral function to the fitted modal sum, and this is displayed in Fig. 2. We analyse the impact of these transverse long-range wakefields on the beam dynamics in the next section

BEAM DYNAMICS STUDIES

Here we assess the implications of these wakefields for two particular situations. In case I we investigate a 12-fold interleaved version of the original design, in which

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bunches were spaced from their neighbours by 8 rf cycles. In case II, we maintain the original distribution, but modify the bunch spacing to 6 rf cycles, and in this case we discover further interleaving, to the extent of 16-fold, is needed to contain the emittance dilution to acceptable limits. This of course has implications on the fabrication tolerances, as the minimum frequency spacing for the latter structure is 3.4 MHz. However, these tolerances are still compatible with those assigned to the accelerating mode –which is < 1 MHz. We performed beam tracking simulations down the complete linac, for a bunch train initially offset by σ_y (0.5 μm), and observed an emittance dilution in case I and II to be 4.4 % and 3.6 %, respectively.

However, these simulations neglected anticipated sources of experimental errors. To provide a more realistic assessment of the beam dynamics we conducted further simulations for both cases, in which systematic and random frequency errors were included. These beam dynamics simulations are time consuming, and in order to provide a rapid initial assessment of the effect of the wakefields on the beam dynamics, we also calculate S_{RMS} (the RMS of the sum wakefield [13]).

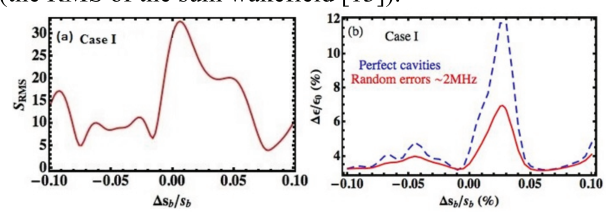

Figure 3: S_{RMS} (a) together with the vertical emittance dilution at the exit to the linac (b), as function of the fractional deviation in the bunch spacing from the nominal case for case I. A linac fabricated with no random errors, is simulated (shown dashed in blue), together with a linac incorporating random errors (the solid red curve).

The results of these beam dynamics simulations, alongside S_{RMS}, for both cases, are displayed in Figs 3 and 4. We note that the random errors adding in both cases had a Gaussian distribution and were restricted to 2 MHz RMS spread. Inspection of Fig. 3 reveals the maximum emittance dilution is 12 % for case I with no random errors. This is reduced to 7 % once random errors are added. Similarly, for case II, random errors bring the maximum emittance dilution down from 9 % to 6 %. We also note that S_{RMS} provides a qualitative guide as to the expected worst-case region for emittance dilution.

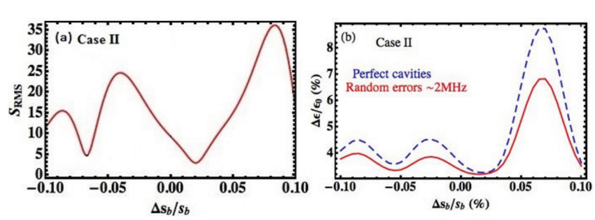

Figure 4: S_{RMS} (a) together with the vertical emittance dilution at the exit to the linac (b) for similar parameters as in Fig. 3, but for case II.

MISALIGNMENT STUDIES

The pre-alignment tolerance on the transverse positions of the components (accelerator structures, BPM, girders) of the CLIC linacs is 10 μm rms over distances of 200 m [14]. Beam-based alignment and emittance tuning bumps [15] are used to ensure the emittance dilution associated with this alignment is kept to acceptable limits.

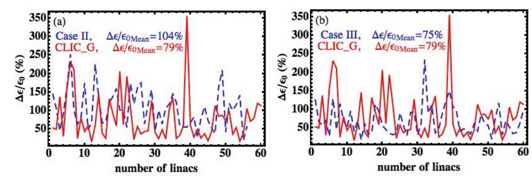

Figure 5: Emittance dilution for misaligned structures for CLIC_G (shown in red), together with case II (a) and III (b) -both shown dashed and in blue.

We investigated a case of which consisted of perfect linacs in which we added vertical random offsets of 10 μm rms to all the structures and this is compared to the baseline design, CLIC_G. We performed simulations for case II (Fig. 5 (a)), and also for case III (Fig. 5 (b)) which consists of 16-fold interleaving of mode frequencies and bunches spaced 8 rf cycles from their neighbours. However, the implications of not being able to accommodate 16 structures on a girder are not taken into account, as it is a considerable task to redesign the associated beam optics, and hence it remains a subject for a future publication.

FINAL REMARKS

A damped and detuned structure, with appropriately interleaved dipole mode frequencies, has been shown to be suitable for the CLIC main linacs. Two cases have been investigated, based on a bunch spacing of 6 and 8 rf cycles. The S_{RMS} parameter provides a qualitative indication as to the location of the worst-case emittance dilution. Preliminary studies on the dilution due to structure misalignments, based on case II and III indicate similar values to the baseline design.

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