BEAM CHARACTERISTICS VERSUS CAVITY MODELS IN CLIC

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Abstract

The luminosity requested for linear colliders with center-of-mass energies exceeding 500 GeV, implies a multibunch operation be considered in order to limit the RF power consumption. In the Compact Linear Collider (CLIC), though the repetition rate is high, a train of at least 20 bunches is necessary to obtain the performance needed for the experiments. Since at high RF frequency the wakefields are large, beam break-up is critical and stability simulations have been carried out for different pre-estimated models of detuned and/or damped cavities. The results obtained give indications about the wakefield level that should not be exceeded along the train, to avoid significant emittance growth. They also show the sensitivity to some specific parameters and the dependence on the scaling of focusing with energy. Eventually, they are used as guide lines for accelerating structure development and as a basis for a possible set of CLIC parameters.

1 INTRODUCTION

In CLIC, studies of multibunch beam dynamics were required since the luminosity requested for the physics implies the use of trains of bunches. For such investigations, analytical models were developed and numerical codes written, that simulate the beam behaviour in the presence of both short- and long-range wakefields [1]. The MBTR code [1] allows one to track simultanously an arbitrary number of bunches. using wakefield Green's functions computed either from the frequency modes or the dependence in the time domain. The bunches are subdivided into slices and the wakefield kicks are then calculated for all possible combinations of pairs of slices j and k, with j smaller than k. Two utility programs MBUNCH and MOVIE help for an efficient use of MBTR. MBUNCH deals with editing the input file, handling the emittance graphs and the output files, running the codes and allowing an automatic optimization of some preselected parameters. MOVIE presents animated graphics of the transverse motion of the slices during acceleration. Off-sets of bars represent the displacements of the slices of each bunch and evolve with the distance s down the linac. The motion of any subset of 5 bunches can be observed simultanously on the screen and instabilities brought into evidence. More recently, a representation of the motion in the phase space of the center-of-charge of every slice of charge has been added [2]. The phase-space oscillations of any subset of 5 bunches can be displayed simultanously, informing on the quality of the focusing constraint. In both cases, a single bunch can also be followed on the monitor. Fig. 1 gives such a picture frozen at $s = 265m$ for a bunch controlled by BNS damping (the head being at the origin).

These tools have been used to investigate the long-range field attenuation necessary to damp the beam break-up. Two models issued from recent design studies and field calculations made for CLIC structures have been retained for the simulations reported below. The first one is a damped structure with radial wave-guides in each cell and the second is a damped-detuned structure with staggered tuning of the cells and reduced damping. Calculations were done with these two models and different beam parameters. The charge was either pushed to the single bunch limit or decreased by a factor two, focusing was increased and scaling with energy optimized on the single bunch stability. Bunch-length was reduced with the charge per bunch. Microwave quadrupoles for BNS damping were used in the high-charge case and momentum spread in the other. BNS-damping was adjusted for minimizing the single-bunch emittance in the presence of misalignments of all linac elements and autophasing condition on minimizing the growth due to a betatron oscillation.

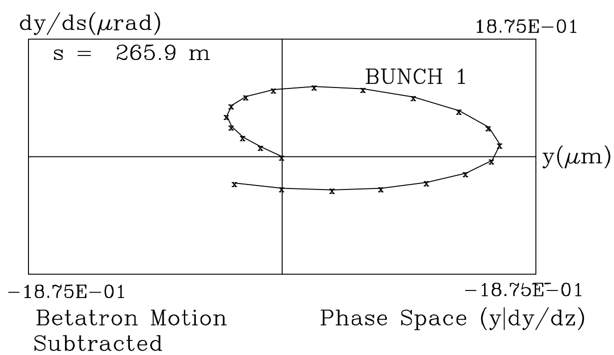

Figure 1: Controled off-sets of bunch 1 in phase space.

2 QUADRUPOLE VERSUS DIPOLE MODE OF SINGLE BUNCH MOTION

Single bunch emittance growth is vanishing if all its slices oscillate coherently in a dipole mode. This can approximately be obtained by a proper setting of RF quadrupoles or energy-spread minimizing the effect of the transverse self-wakefields. It seems evident that the long-range transverse effects of a bunch on a second are dominant when the first bunch is submitted to a dipole mode. These effects should indeed be weaker when the first bunch oscillates with the same amplitude but in a higher coherent mode or incoherently. However, the single bunch emittance increases in the latter case. Taking into account the fact that BNS damping is an efficient method to preserve this emittance and that such a method is not practical in multibunch mode [1], it can be a useful strategy to deviate from a coherent dipole mode in the first bunch. This is in fact what is happening in the autophasing case.

In this section, the effect on the second bunch of a first oscillating in a quadrupole mode is investigated analytically. Following Ref.1, the equations of motion for a slice of charge with index n in bunches 1 and 2 are given by

$$y''_{1n} + \mu^2/(4\pi^2) y_{1n} = 0 \quad (1)$$

$$y''_{2n} + \mu^2/(4\pi^2) y_{2n} = \mu^2/(4\pi^2)\beta^{3/2}(\theta) \times \frac{q}{E}\sum_{k=1}^{N} y_{1k}(\theta) W^T(z_n - z_k) \quad (2)$$

where θ and y are the usual Courant and Snyder variables, i.e.

$$\theta = \frac{1}{\mu/(2\pi)}\int_0^s \frac{ds}{\beta(s)} \quad (3)$$

and N is the total number of slices. The function W represents the transverse wake potential of bunch 1 acting on bunch 2 and E and q are the bunch energy and the charge of one slice respectively (a constant charge distribution across the bunch is assumed). While the first equation has a trigonometric solution, the second equation is evidently resonant. Keeping only the secular term we obtain:

$$y_{2n}(\theta) = \frac{q_B \alpha_1}{E\mu/\pi}\sigma_n B_0 \theta \sin \mu/(2\pi)\theta \quad (4)$$

where $q_B = Nq$ is the total charge of the bunches and α_1 represents the strength of the lowest dipole mode of the transverse wakes. The n dependent quantity σ_n is given by

$$\sigma_n = \sum_{k=1}^{N} Y_k \cos\left[\frac{\omega_1}{c}(z_{sep} + (n-k)\Delta z)\right] \quad (5)$$

where Y_k are the initial transverse displacements of the slices in bunch 1 , z_{sep} is the separation between the two bunches, Δz is the length of one slice and ω_1 and c are the circular frequency of the dipole wake and the light velocity respectively. In the case of a coherent dipole oscillation of bunch 1, $Y_k = Const. = Y_0$ where Y_0 represents the oscillation amplitude. In the case of a coherent quadrupole oscillation, the first and the last slices oscillation are of the same amplitude but out of phase by π. This is exactly fulfilled by a distribution of the initial conditions such as:

$$Y_k = Y_0\left[1 - 2\frac{k-1}{N-1}\right]. \quad (6)$$

The relation between the two solutions for bunch 2, valid with the quadrupole mode and the dipole mode respectively, is found to be

$$\rho_n = \frac{y_{2n}^{(Q)}}{y_{2n}^{(D)}} = \frac{\sigma_n^{(Q)}}{\sigma_n^{(D)}} = 1 + \frac{2}{N-1} - \frac{\sum_{k=1}^{N}\frac{2k}{N-1}C_{kn}}{\sum_{k=1}^{N} C_{kn}} \quad (7)$$

with

$$C_{kn} = \cos\left[\frac{\omega_1}{c}\left(z_{sep} + (n-k)\frac{l_b}{N-1}\right)\right] \quad (8)$$

Fig. 2 shows ρ along the second bunch for an increasing number of slices. As can be seen the reduction of the excited amplitudes in bunch 2 when bunch 1 oscillates in a quadrupole mode rather than in a dipole mode is tremendous, namely about 0.4%.

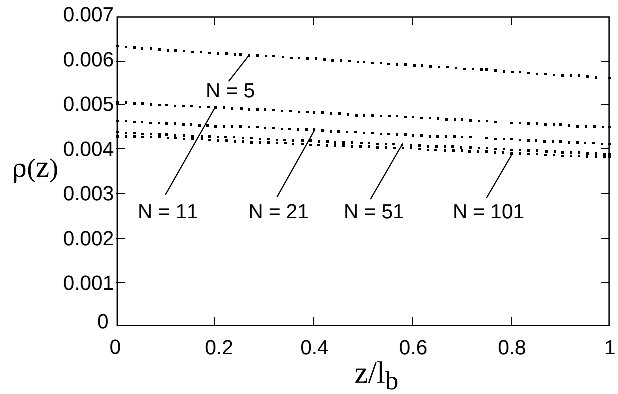

Figure 2: Ratio between oscillation amplitudes caused by a dipole and a quadrupole mode in bunch 1

This result indicates that deviating from a dipole mode in the single bunch should reduce multi-bunch emittance growth along a train of bunches. However, the single bunch emittance will be increased by such a method and one has to find a good balance between these two quantities.

3 WAKEFIELDS FOR DS AND DDS

Studies of accelerating structures for multibunching have been carried out. Three schemes of wakefield reduction have been considered, detuning [3], damping [4] and detuning with additional damping [5]. A detuning scheme does not provide a sufficient level of performance, according to previous simulations [1]. Hereafter are given the simulations required to demonstrate the adequacy of the other two schemes. First, the models of long-range wakefield deduced from the structure studies are briefly described. The short-range wakefields are taken equal to those obtained from the frequency mode analysis of the structure with no field reduction and constant impedance (CIS).

The damped structure (DS) is based on frequency discriminated waveguide damping. Damping waveguides, connected to the outer cavity wall are chosen to have a cut-off frequency above the fundamental but below all higher modes. Time domain MAFIA computations [4] were used to determine the transverse and longitudinal wakefields. A constant impedance structure has been assumed. The initial exponential drop-off of the transverse wakefield is shown on Fig. 3 over a distance of 2m behind bunch 1. The resonance associated with the the cut-off frequency of the waveguide creates a persistent wake at 33 GHz, which becomes dominant beyond this distance and decreases with

$x^{-1.5}$. The numerical model for tracking keeps only this persistent component after 2m, with an amplitude at this point which is equal to the value given by the initial drop-off. For the longitudinal wakefield, all modes beyond the fundamental have been assumed to be reduced by a factor 10, with respect to the modes of CIS.

The damped-detuned structure (DDS) is a detuned accelerating section with low level damping obtained by coupling all cavities to several identical and symmetrically located waveguides (manifolds) which run parallel to the structure and are terminated at each end by matched loads. As for DS, MAFIA computations [5] were performed to determine the wakefields. The roll-off of the transverse wakefields and the effect of damping over a distance of $2m$ behind bunch 1 is also drawn on Fig. 3. In the absence of a dominant persistent wake, the field was calculated over a total distance of 12m (i.e. 40 bunches separated by 30 RF periods). In this design, the attenuation of the longitudinal wakefield was also estimated and the corresponding function of distance included in the tracking. Fig. 3 shows that DDS has been optimized for a bunch separation of 30 RF periods (field reduction of 100 at 0.3m) and the field recoherence in DDS implies higher wakes than in DS after a distance of 1m behind bunch 1.

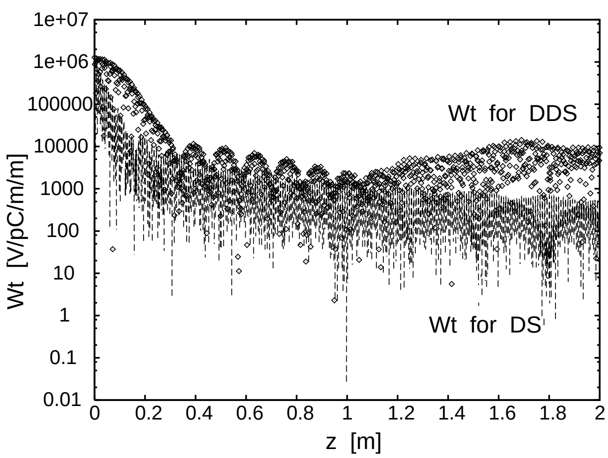

Figure 3: Transverse long-range wakefields.

4 EMITTANCE GROWTH

Tracking simulations were carried out, to compare the merits of the two structures DDS and DS and to check if the wakefield level obtained in these designs at the position of bunch 2 is acceptable for the emittance preservation. Previous calculations [1] indicated that the long-range field should at least be attenuated by a factor 100 at this point, and both designs are achieving this, for a bunch separation of 30 and 15 RF periods with DDS and DS, respectively. Tracking with a small number of bunches confirmed that this requirement is about right. However, for a long train made of 20 bunches or more (beam loading being compensated), it came out that a maintained decay of the long-range field as in DS is a strong advantage in preventing beam break-up by propagation of an instability.

Results depend strongly on the beam parameters and on the assumptions made. It was established that raising the focusing by a factor 2 with respect to the nominal case (1996 parameters) successfully limited the blow-up of the effective emittance. In addition, the emittance growth was found to be sensitive to small variations of the scaling of focusing with energy: the scaling of the quadrupole strength was varied for a given set of misalignments, while the scaling of the cell length was not modified. These two elements were introduced in the simulations. BNS damping was first optimized for single bunch blow-up in the presence of misalignments and off-sets all along the linac (BNS). It was then adjusted either for the blow-up of the whole train or for minimizing the (dipole mode) effect of a betatron oscillation (autophasing). Cases with a charge per bunch of $8 \cdot 10^9$ and a bunch length of $160\mu m$ (1996 parameters) and then $4 \cdot 10^9$ and $60\mu m$, respectively, were computed; the latter aiming at a substantial reduction of the wakes. Results related to 500 GeV linacs (with a gradient of 100 MV/m) are given in Table 1, for the two structures, the two BNS conditions and the two beam characteristics defined above, and different train lengths.

N_e	n_b	DDS (BNS)	DDS (Auto)	DS (BNS)	DS (Auto)
$8 \cdot 10^9$	20	47/24000	216/3742	47/269	216/236
$4 \cdot 10^9$	40	7/1809	30/68	7/15	30/39
$4 \cdot 10^9$	45	26/4580	145/280	26/35	145/170

Table 1. Relative emittance growths (single-/multi-bunch) in % with DDS and DS structures, two BNS conditions and misalignments of $5\mu m$ for the first two cases and of $10\mu m$ for the last.

The conclusion from these results is threefold: a field attenuation by 100 at one bunch separation is required, a further and continuous reduction of the wake behind the exciting bunch is preferable (clear advantage of DS over DDS), and autophasing reduces beam break-up at the expense of the single bunch emittance. The latter is in agreement with the inference of the analysis summarized in Section 2 and results show that the use of DS would allow a compromise between single- and multi-bunch optimization of the emittance preservation.

5 REFERENCES

[1] G.Guignard, J.Hagel, Multibunch Emittance Preservation in CLIC, Proc. 5th EPAC , Sitges, Spain, 1996.

[2] G.Guignard, J.Hagel, Letter to the Editor, ICFA Beam Dynamics Newsletter, No. 13, April 1997.

[3] I. Wilson, W. Wuensch, Multibunch studies for CLIC, CERN-SL/93-20(DI), 1993.

[4] M.Dehler, I.Wilson, W.Wuensch, CLIC Waveguide Damped Accelerating Structure Studies, CERN/PS 96-39 (LP), 1996.

[5] M.Dehler *and 5 co-authors*, Design of a 30 GHz Damped Detuned Accelerating Structure, in this Conference.