MULTIBUNCH EMITTANCE PRESERVATION IN CLIC

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Abstract

In high-frequency linacs, where the wakefields are strong, the stability of a train of bunches is critical. The beam break-up due to long-range wakefields induces a decoherence of the bunch oscillations and a consequent blow-up of the effective betatron emittances of the whole train. Since the Compact Linear Collider (CLIC) study now includes several bunches per pulse, it is important to analyse numerically and theoretically this emittance blow-up. Possibilities of controlling the beam break-up without upsetting the single-bunch stability have been considered: first a multi-bunch generalization of the BNS damping principle, secondly an attenuation of the long-range fields, and thirdly an increase of the focusing in order to overconstrain the beam. Simulation codes have been written for both checking the theoretical predictions and investigating the requirements associated with a possible application to the main linac. Animated graphics make it possible to get a didactic display of the multibunch instability.

1 SIMULATION CODES DESCRIPTION

For linear accelerators with many bunches per pulse, it is judicious to study the multibunch stability while including the single-bunch behaviour. Merging both mechanisms is necessary to understand the properties of the whole beam. Therefore in CLIC, the multibunch codes of the MBTRACK series are based on the MTRACK codes [1] written for single-bunch stability studies. The main characteristics of the MTRACK family are therefore recalled hereafter.

1.1 Characteristics of the MTRACK codes

The group of codes of MTRACK type solves the equation of motion of a single bunch travelling through drifts, accelerating cavities, position monitors, magnetic and microwave quadrupoles, in using a matrix formalism with the following points: solution derived in the two transverse directions x and y for both trajectories and emittances; realistic strong focusing of FODO type which can be arbitrarily scaled with the energy, i.e. with the distance along the linac (assuming thin lenses in the simpler version); transverse and longitudinal self (short-range) wakefields either approximated by close formulae (resistive cylindrical pipes in drifts) or obtained from a separate calculation providing a large number of loss factors and frequencies of synchronous modes (accelerating structures); longitudinal motion containing acceleration and beam loading; coupling between the transverse and the longitudinal motions through the energy dependence of the focusing; random transverse misalignments of all the linac components; different kinds of trajectory corrections [2]; and longitudinal division of the bunch in slices, populated according to a Gaussian distribution and having the same initial transverse emittances. The beam is assumed to be fully relativistic so that there is no longitudinal redistribution of the different slices ('frozen' beam).

The specific points of the MTRACK codes are the strong focusing, BNS damping with microwave quadrupoles rather than with energy spread, independent scaling of quadrupole strength and cell length to balance dispersion and wakefield effects [3], the use of Green's functions for the short-range wakefields and the beam model (slices). The effective emittance of the bunch is calculated by projection onto the transverse phase plane of the individual ellipses of each slice which are off-centred by the betatron motion. Main inputs are the beam parameters, the r.m.s. misalignment amplitudes, and the lattice and wakefield data. Main outputs are the trajectory deviations, transverse effective emittances, the characteristics in energy as functions of the position in the linac.

1.2 Characteristics of the MBTR code

The MBTR code allows one to track simultaneously an arbitrary number of bunches, all with identical short-range fields and self-consistent long-range fields. Both are computed within MBTR, using Green's functions and according to the actual positions of the slices. The bunches are subdivided in N slices and separated by a distance z_{sep} (multiple of the RF period). Arrays of wakefield amplitudes are then created for distances z ranging from a minimum equal to the distance Δz between two slices, to a maximum given by the separation of the first slice of the first bunch to the last slice of the last bunch. The dipole kicks are then calculated for all the combinations of pairs of slices j (the exciter) and k (the follower), j smaller than k, the wakefield associated with the distance from j to k being retrieved from the precalculated arrays. Hence, short-range and long-range wakefields are treated similarly, though it is possible to attenuate the long-range contribution in order to simulate damped cavities.

In the group of codes MBTRACK, to which MBTR belongs, single-bunch and multibunch BNS damping can be simulated. Indeed, thin microwave quadrupoles are supposed to be installed next to each magnetic quadrupole of the FODO lattice, with their appropriate amplitudes, frequencies, and phases. MBTR uses a one-to-few (more beam position monitors than quadrupoles) algorithm of trajectory correction. Compared to MTRACK, the MBTR input contains in addition the required multibunch parameters like the long-range field attenuation and the possible BNS damping quadrupole strengths. The output files with trajectories and emittances are duplicated for the last bunch, as well as for an intermediate bunch selected arbitrarily. Besides the individual emittances of each bunch, the code gives the effective emittance of the whole train by including the bunch off-sets relative to the average position of the train.

2 MULTIBUNCH TRACKING UTILITIES

Although the FORTRAN code MBTR for multibunch tracking was originally designed for the CERN mainframe computer, it was transferred to an IBM-compatible PC. All non-standard FORTRAN library routines were replaced by independent ones [4]. It was then possible to compile and link the tracking program on a PC using any recent compiler and to produce an executable file. On a Pentium computer, the time required for running a typical case is about the same as the average turnround time on the mainframe.

Using the graphics capabilities of a PC, two utility programs MBUNCH and MOVIE that interactively run the tracking code and provide graphical results were written in Microsoft Quickbasic [5], necessary for a fast animation. While MBUNCH deals with editing the input files, running the code itself and handling the output files, the MOVIE code presents animated graphics of the motion of the bunches along the linac. Horizontal bars are used to represent the centre of charge of the slices in every bunch, and their off-set is proportional to their vertical displacement. Different colouring of the slices indicates a variable charge density (Gaussian) in the bunch. The effect of moving bunches is produced by creating 10–20 screens per second where two subsequent screens correspond to the bunch positions at two successive quadrupoles. Input data for the MOVIE program come from the simulation code in a file that contains the vertical positions of all slices at every quadrupole. This utility proved to be very useful for obtaining insight into the physics.

3 ANALYTICAL TWO-BUNCH MODEL

With two bunches coupled by long-range transverse wakefields, the following bunch experiences, besides its own betatron oscillations, an amplitude and emittance blow-up due to the driving force of the transverse wakefields. Since the long-range effects are proportional to the betatron amplitude of the driving bunch and since the eigenfrequency of the follower is just equal to the betatron frequency, the betatron amplitude of the follower bunch behaves in a resonant (secular) way, i.e. increasing linearly with time. For a system of a given number of pointlike bunches this property has been derived in Ref. [6].

We extended the computation to the more realistic case of a system of two bunches of finite length being subdivided into N slices of charge. In Courant and Snyder variables $y(\theta)$ the equations of motion for the slice number n of each bunch are:

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

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

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

where W^{T} is the transverse wakefield computed for the distance between slice k in the first bunch and slice n in the second one, while μ is the phase advance per focusing cell (FODO). The q and E are the charge of one slice (we use a uniform charge distribution along the bunches) and the energy, respectively. Assuming the first bunch has a coherent betatron oscillation with a normalized amplitude Y_0 (Courant and Snyder variable) given by $y_{1n} = Y_0 \cos\mu/(2\pi)\theta$, the second equation can be solved by using a Green's function technique. Keeping only the secular contributions and the first Fourier component of the β function, the result becomes [7]

$$y_{2n}(\theta) = \frac{q_{\mathrm{B}}\alpha_1}{E\mu/\pi}\sigma_n B_0 \theta \sin\mu/(2\pi)\theta \tag{4}$$

$$\sigma_n = Y_0 \cos\left[\frac{\omega_1 N\Delta z}{2c} - \frac{\omega_1}{c}(z_{\mathrm{sep}} + n\Delta z)\right] \times \times \sin\left[(N+1)\frac{\omega_1 \Delta z}{2c}\right]/\sin\left(\frac{\omega_1\Delta z}{2c}\right). \tag{5}$$

Here q_{B} and Δz are the charge of the entire bunch and the length of one slice of charge. α_1 stands for the strength of the lowest dipole mode of the transverse wakefield (the only mode considered). The quantity B_0 represents the average value of the function $\beta^{3/2}$ along the linac. Finally ω_1 is the (circular) frequency of the lowest dipole mode, c the velocity of light and z_{sep} the distance between the two bunches.

Since all computations have been done in Courant and Snyder variables the change of emittance of the second bunch consisting of N slices of same charge q_{B}/N is

$$\Delta\epsilon_N = \frac{1}{N}\sum_{n=1}^{N}[(4\pi^2)/\mu^2 {y'_{2n}}^2 + y_{2n}^2] \tag{6}$$

where the summation extends over all the N slices. However, in reality the bunches are continuous, meaning that the correct emittance is obtained through a process of passing to the limit of an infinite N, $\Delta\epsilon = \lim_{N\to\infty}\Delta\epsilon_N$. The actual computation leads to

$$\Delta\epsilon = 2\pi^2\frac{q_{\mathrm{B}}^2\alpha_1^2 B_0^2 c^2 Y_0^2 s^2}{E^2\omega_1^2 l_{\mathrm{B}}^2 L^2}\sin^2\left(\frac{\omega_1 l_{\mathrm{B}}}{c}\right)\times \times\left[1 + \frac{c}{\omega_1 l_{\mathrm{B}}}\sin\left(\frac{\omega_1 l_{\mathrm{B}}}{c}\right)\cos\left(\frac{2z_{\mathrm{sep}}\omega_1}{c}\right)\right] \tag{7}$$

Here s is the longitudinal distance (m) along the linac, L is the length of one focusing period of the lattice and $l_{\mathbf{B}}$ the length of each bunch (m). Note that up to this level no scaling of the energy and betatron tunes are included. However, if E is replaced by the injection energy for the CLIC main linac this formula should describe the emittance growth due to long-range transverse wakefields along the first part of the linac, in the absence of any damping.

4 RESULTS AND CONCLUSION

The principles of a multibunch BNS damping have been investigated. The theory has been extended to the case of a train of bunches equidistant in time and of a strong-focusing FODO lattice [8]. It allows one to predict the correction to apply, in using a small number of families of microwave quadrupoles running at different frequencies. The simulations confirm the theoretical results and the bunch train can be stabilized, but the practical application of this method remains problematic. The strongest limitations for multibunch BNS damping are the following: (a) without some attenuation of the long-range wakefield, the amplitude of the focusing modulation with RF quadrupoles is at times exceedingly large; (b) the required power per microwave quadrupole (around 11 GHz) looks prohibitive (peak power of 6 MW in a fill-time of 25 ns).

The most important outcome expected from the multibunch simulations concerns the long-range field attenuation necessary to damp the beam break-up and the number of dipole modes that have to be attenuated. The results obtained so far with the MBTRACK codes indicate that it is necessary to attenuate a large number of transverse modes (20 or more, favouring damped rather than staggered-tuned structures) and that the attenuation factor should range between 50 and 100.

Simulations with MBTR corroborate the two-bunch model analysis of the emittance growth. Indeed, in a two-bunch case with no BNS damping and no long-range field attenuation, the expected quadratic dependence of $\Delta\epsilon$ with the distance s (Eq. 7) is verified (Fig. 1) (blow-up of bunch 1 is negligible, by comparison). Another outcome from Eq. (7) is that a decrease of β increases the beam stability. This was also observed by raising the focusing; a lattice with two times more quadrupoles than in the nominal case successfully overconstrains the beam and limits the blow-up of the effective emittance. Practical consequences remain to be analysed in detail. Finally, a simplified attenuation model was used: all the computed deflecting modes (218) were assumed to be reduced by the same factor 100, with no additional roll-off with s, while the longitudinal modes were kept unchanged except for the first that was cancelled to simulate beam loading compensation. With this model (short-range fields included), enhanced focusing and a bunch separation of 30 RF-periods, MBTR tracking shows that 10 bunches could be accelerated in the CLIC linac with tolerable blow-up as shown in Fig. 2 (bunch 1 emittance reaches 2×10^{-7} radm). The limitation in this case comes not so much from the transverse fields as from the longitudinal one that induces too high an energy variation from bunch to bunch (outside FF acceptance). A more elaborate model based on wakefield calculation for the CLIC damped cavities will be used next in the simulations.

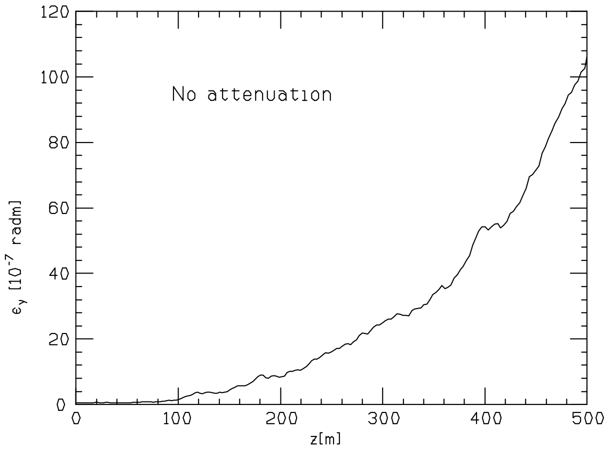

Figure 1: 2nd bunch emittance-growth without RFQs.

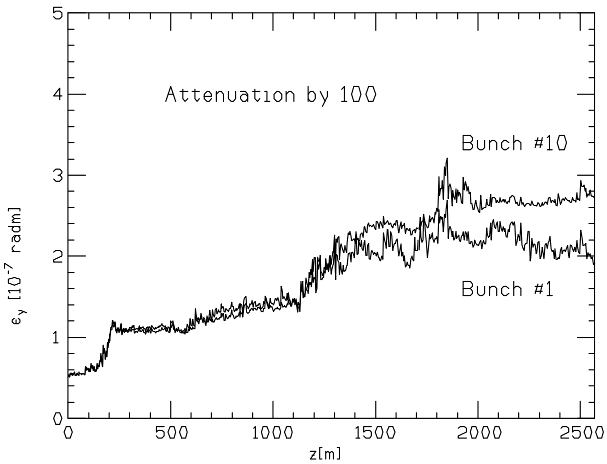

Figure 2: 10th bunch emittance growth with RFQs (1st bunch growth as reference).

5 REFERENCES

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