THE DRIVE BEAM ACCELERATOR OF CLIC

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Abstract

The drive beam of the Compact Linear Collider (CLIC) requires a current of several amperes. The time structure of this beam is discussed. First simulation results on longitudinal single bunch effects are presented and achievable bunch lengths and sensitivity to jitter of the gradient, initial energy and charge are analysed. The transverse stability of the beam is discussed based on the present structure model. Requirements on the damping and detuning of the cavities are given in detail. A beam-based alignment technique is presented and the stability with respect to jitter and ground motion is investigated.

1 INTRODUCTION

CLIC [1] is based on a two-beam scheme. The RF power used to accelerate the main beam (at $30\,\mathrm{GHz}$) is produced by a second beam (the drive beam) running parallel to the main one [2] through so-called "power extraction structures". This beam has a high current but low energy and is decelerated thus producing the RF power.

The drive beam is accelerated to a final energy of $1.2\,\mathrm{GeV}$ in a fully-loaded low-frequency linac ($937\,\mathrm{MHz}$), consisting of 99 $3.1\,\mathrm{m}$ long structures with a loaded gradient of $3.8\,\mathrm{MV/m}$. The beam is then separated into trains of bunches. In so-called "combiner rings", 16 of these trains are merged to form a single one. The length of the final train is the same as that of one of the inital ones, but the distance between bunches is reduced by a factor 16. These short pulses are then sent to the decelerator sectors.

The total length of the charge pulse to be accelerated is equal to twice the main linac length. Assuming a fill factor of $80\,\%$, the main linac will be $13.75\,\mathrm{km}$ long, and the pulse length will therefore be $92\,\mu\mathrm{s}$.

2 TIME STRUCTURE

At the combiner rings, the beam must consist of short trains of bunches, separated by gaps that are larger than the rise time of a kicker. In the drive beam accelerator these gaps would however lead to a significant variation in multi-bunch beam-loading, so it would be difficult to keep the bunch-to-bunch energy variation small, see Fig. 1a. On the other hand, the tolerance on the final energy is tight.

A solution to this problem is not to fill every bucket, but instead only every second one, increasing the train length by a factor of two. Each train is split into two half-trains,

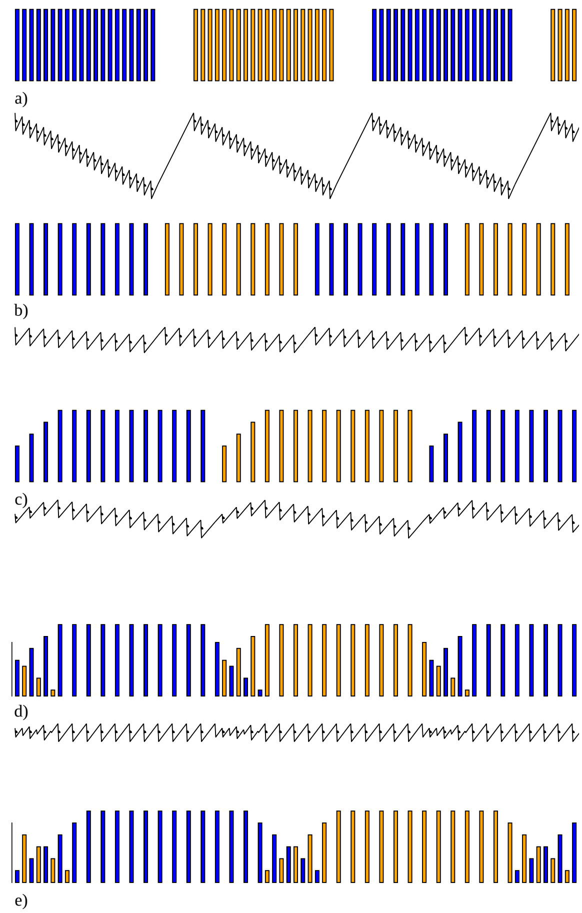

Figure 1: The charge distribution along the pulse—in case a) different trains are shown in different tones, in the other cases different half-trains are shown different tones. The number of bunches on the flat top is constant but different from the real value. The curves indicate the variation of the energy gain. Depending on the injector, a distribution in the range of d) to e) will be chosen.

the bunches of the first half are put into even buckets, and the bunches of the second half into odd ones, see Fig. 1b. In this case the beam-loading is not constant only where one switches from odd to even, or even to odd buckets. The first half of each train is sent into a delay line, using an RF-deflector at the end of the linac, running at half the linac frequency. The second half is deflected to the other side and passes with no delay. The delay line is adjusted to interleave the two halves of the train to form one, with every bucket filled. This train has the length of an initial half train and is followed by a gap of the same length.

While this solves the problem in the case of constant charge per bucket, the beam-loading compensation in the main linac requires that each half-train starts with a charge ramp. The charge is thus increasing over the first few bunches. This would also create a significant variation in beam-loading (Fig. 1c). This is solved by adding a tail of bunches to the previous half-train which overlaps the ramp (Fig. 1d). This is feasible since different buckets are used for consecutive half-trains. The charge in the tail can be adjusted to make the beam-loading constant.

If the injector is only able to vary the charge per bunch slowly along the train, a longer ramp and a longer tail would be required, see Fig. 1e. In the following simulations, it is assumed that the charge rises linearly from zero to full intensity over the 20 bunches in the ramp and decreases, also linearly, in a tail of the same length.

The flat top of each train contains 47 bunches each with a charge of $q \approx 17.6\,\mathrm{nC}$ [2]. The total pulse ($92\,\mu\mathrm{s}$) is thus sufficient to feed 20 drive beam decelerator sectors.

3 COMPRESSION

The initial bunch length is assumed to be about $\sigma_z = 4\,\mathrm{mm}$ at an energy $E_i = 50\,\mathrm{MeV}$ with an energy spread of $0.75\,\%$ (L.Rinolfi [3]). While this spread is partly correlated with the longitudinal position, in the following it is assumed to be completely incoherent—to be pessimistic.

A simple calculation of the achievable compression was performed using a linear approximation. Since the exact longitudinal wakefield was not available, the values derived for an S-band structure [4] were used. The longitudinal wakefield amplitude $\hat{W}_L$ scales as $\hat{W}_L \propto f^2$ with the acceleration frequency f. The ratio of aperture a to wavelength λ is also different, here the scaling $\hat{W}_L \propto (\lambda/a)^2$ was used as an approximation.

In order to avoid large energy losses due to coherent synchrotron radiation in the combiner rings and in the bends into the decelerator, the bunch length in these sections has to be at least $\sigma_z = 2\,\mathrm{mm}$ (R. Corsini [3]). The final compression is therefore done afterwards. For the compression two different approaches are possible. One can either compress the bunch to a length of $\sigma_z = 2\,\mathrm{mm}$ inside the linac (preferably at low energy) and do the final compression after the bends. Or one can compress the bunch inside the linac in several stages as much as possible. Then it has to be uncompressed at the end of the linac to $\sigma_z = 2\,\mathrm{mm}$. Finally it has to be compressed again after the bends.

An example of the first approach uses an RF-phase for the beam of $\Phi_{RF} = -12°$. The first compression is done at $E \approx 100\,\mathrm{MeV}$, achieving the required $\sigma_z = 2\,\mathrm{mm}$. The final compression step at the decelerator entrance yields $\sigma_z = 290\,\mu\mathrm{m}$ and an RMS energy spread of $\sigma_E = 18\,\mathrm{MeV}$ (case 1). Without wakefields (case 2) one would reach $\sigma_z = 340\,\mu\mathrm{m}$ and a final energy spread of $\sigma_E = 8.5\,\mathrm{MeV}$—this shows the relative independence of the result on the wakefield model.

Using the second approach, the bunch is compressed as much as possible at three positions along the linac, then uncompressed to $2\,\mathrm{mm}$, and recompressed after the bends (case 3). The bunch length achievable with this method is $\sigma_z \approx 170\,\mu\mathrm{m}$. This is significantly shorter than in for case 1 and the final energy spread of $\sigma_E = 13.4\,\mathrm{MeV}$ is also smaller. If the RF-phase is set to $\Phi_{RF} = 0°$ after the first two compression steps (case 4) one can still achieve $\sigma_z \approx 200\,\mu\mathrm{m}$ with an energy spread of $\sigma_E \approx 11.4\,\mathrm{MeV}$. Figure 2 shows the phase space distribution after the final compression for this case.

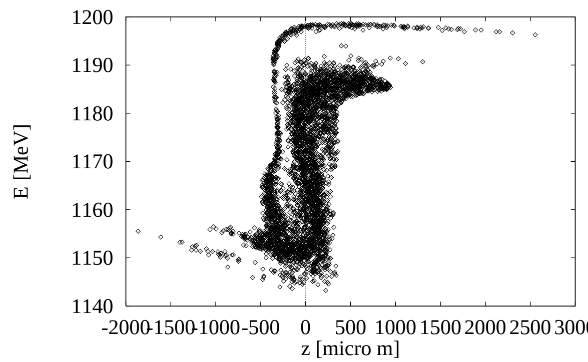

Figure 2: The phase space distribution of the particles after the last compression step in case 4. The particles represent different charges.

Table 1: Deviations from nominal values that result in a longitudinal shift of the bunches of about $10\,\mu\mathrm{m}$.

case		1	2	3	4
$\Delta G/G_0$	$[10^{-4}]$	0.45	0.4	0.5	0.4
$\Delta E_i/E_{i,0}$	$[10^{-4}]$	0.8	16	0.9	0.8
$\Delta\Phi_{\mathrm{RF}}$	$[0.1°]$	0.12	0.1	0.12	0.12
$\Delta q/q_0$	$[10^{-2}]$	0.2	—	0.25	0.2

Energy variations of the bunches are transformed into longitudinal position errors by the bunch compression. These energy variations can be caused by variations of the initial beam energy E_i, the acceleration gradient G, the RF-phase and the bunch charge. Table 1 shows the size of these variations that lead to a longitudinal shift of $10\,\mu\mathrm{m}$. The differences in gradient and RF-phase are assumed to be constant along the accelerator, not random errors.

4 LATTICE

The lattice of the drive beam accelerator consists of simple FODO-cells with a constant quadrupole spacing of $3.9\,\mathrm{m}$. The phase advance per cell is about $116°$. One $3.1\,\mathrm{m}$ long accelerating structure, consisting of 29 cells, and a beam position monitor (BPM) are placed between two quadrupoles. The iris radii of the cells of the structure vary from 42.2 to $54.4\,\mathrm{mm}$. The initial beam energy after the injector is $50\,\mathrm{MeV}$.

5 STABILITY

To evaluate the beam stability, simulations with PLACET [5] were performed for the first 2000 bunches assuming initial transverse emittances of $\epsilon_x = \epsilon_y = 100\,\mu\mathrm{m}$. Each of the 29 cells of a structure is simulated using its two most important transverse modes. Three cells were calculated with ABCI (L. Thorndahl [3]) at a frequency $f = 3\,\mathrm{GHz}$ and frequencies and loss factors of the modes were derived by interpolation. A short model structure using a single cell size has been built (L. Thorndahl [3]).

Due to the length of the pulse the structures have to be damped to avoid beam breakup. The measured upper bound of the damping Q of the transverse mode is $Q \le 100$. The limit was due to the experimental setup, calculations for perfect loads predict $Q \approx 11$ (M. Luong [3]).

In the simulations each bunch is cut longitudinally into 21 slices. Using an undetuned structure with $Q = 100$ leads to an amplification of an initial beam jitter by a factor 15 for some of these slices. A reduction to $Q = 20$ reduces this to a factor of less than 2.

Detuning the structures by varying the iris radii from 42.2 to $54.4\,\mathrm{mm}$ reduces the amplification factor to less than 2 for a damping of $Q = 100$. Figure 3 shows the final positions of the slices after the linac. Within the region of constant charge, the bunch to bunch variations are relatively small, while in the transient parts where the trains overlap they are significantly larger. From train to train the variations are also small. Using the detuned structures, even a damping of $Q = 500$ does not increase the amplification factor significantly.

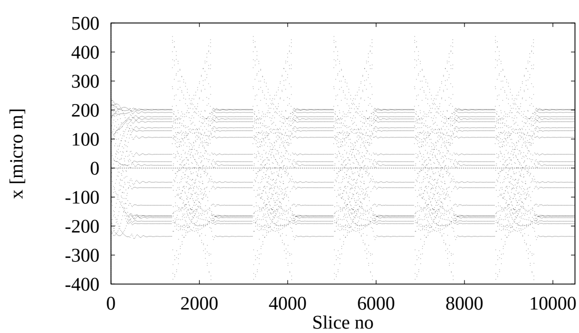

Figure 3: The final slice position for detuned structures with $Q = 100$. Each bunch is cut longitudinally into 21 slices, the first 500 bunches are plotted. The horizontal lines visible, are formed by equivalent slices of successive bunches. The slices of each bunch are filling the space between the minimum and maximum position.

An uncorrelated jitter of the quadrupoles of $\sigma_{quad} = 1\,\mu\mathrm{m}$ leads to a small movement of the beam of less than 0.06σ for any slice at the accelerator exit. The simple ATL-law is used to estimate the sensitivity to ground motion. In this model, the relative transverse offset Δy of two points, separated by a distance L, is given after a time T by $(\Delta y)^2 = ATL$. The value of the constant A is site dependent and can have a value of less than $A = 0.5 \cdot 10^{-6}\,(\mu\mathrm{m})^2/(\mathrm{sm})$[6]. For a test case, the maximum offset after $T = 10^5\,\mathrm{s}$ of any slice was 0.02σ and the average was 0.01σ without any feedback or steering. The linac is thus insensitive to ground motion.

The fast beam-ion instability [7] can also increase the beam emittance. A charged beam can ionise the rest gas in an accelerator. An electron beam will deflect the electrons that are set free in this process towards the outside. The positive ions however are accelerated towards the beam centre. In an unbunched beam they would oscillate. If in a bunched beam the ion oscillation frequency is smaller than the bunch frequency, the ions will be trapped. For the drive beam accelerator this condition is fulfilled. At the moment, simulations of this effect are not available for the drive beam, and analytic formulae [7] give no clear indication of importance of the problem.

6 ALIGNMENT AND STEERING

The initial position errors for quadrupoles are assumed to be $\sigma_{quad} = 500\,\mu\mathrm{m}$ and for beam position monitors and structures $\sigma_{BPM} = \sigma_{struct} = 100\,\mu\mathrm{m}$.

Already with a simple one-to-one steering the total emittance growth along the linac was found to be $3.5\,\%$ in a test case. The maximum position deviation of a slice from the beam centre at the linac exit was about 0.2σ.

7 CONCLUSION

The drive beam accelerator seems to be very stable if detuned and damped accelerating structures are used. Initial beam jitter is amplified by less than a factor 2 for any particle. The alignment tolerances are rather relaxed even when only simple steering is used for correction. The fast beam-ion instability remains to be investigated in detail.

8 REFERENCES

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