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BEAM LOADING COMPENSATION IN THE MAIN LINAC OF CLIC

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Abstract

Compensation of multi-bunch beam loading is of great importance in the main linac of the Compact Linear Collider (CLIC). The bunch-to-bunch energy variation has to stay below 1 part in 10^3. In CLIC, the RF power is obtained by decelerating a drive beam which is formed by merging a number of short bunch trains. A promising scheme for tackling beam loading in the main linac is based on varying the lengths of the bunch trains in the drive beam. The scheme and its expected performance are presented.

1 INTRODUCTION

Multi-bunch beam loading is a strong effect in the main linac of CLIC. It needs to be compensated with help of the RF to avoid extreme variations of the beam energy along the pulse. Several approaches to solve the problem exist. All of them are based on manipulations of the drive beam which generates the RF power.

The first possibility is to reduce the bunch charge in the first part of the drive-beam pulse [1]. In this scheme, the first bunch has about $70\,\%$ of the nominal charge. The charge is then slowly increased from one bunch to the next until it reaches the nominal value. This charge ramp creates a ramp in the RF voltage. By carefully shaping the charge ramp, one can achieve beam-loading compensation. In principle, this compensation can be perfect. However, it may be very difficult to control the bunch charge with the required precision so as to achieve the required compensation of the gradient variation $\Delta G/G_0 \leq 10^{-3}$ (G_0 is the nominal gradient).

Another method is described in reference [2]. It achieves $\Delta G/G_0 \approx 2 \times 10^{-3}$. It requires additional hardware and may compromise the stability of the drive beam in the decelerator.

In a third option, presented in this paper, one creates a ramp in the current of the drive-beam pulse comparable to the first option. But instead of varying the bunch charge, one varies the number of bunches per unit length of the pulse. This can be achieved by modifying the drive beam in the drive-beam injector [3]. To understand this, it is necessary to understand the drive-beam generation, which is described below.

2 THE DRIVE-BEAM GENERATION

The drive beam is produced and accelerated at a frequency of about $937\,\mathrm{MHz}$. In the injector of the drive-beam linac, one has a sub-harmonic buncher which can be switched to fill either odd or even buckets. In the drive-beam accelerator, the beam then consists of short trains of bunches that fill every second bucket. The first train fills the odd buckets, the immediately following second train fills the even ones, and this pattern is then repeated [4]. The current in the drive-beam accelerator, and consequently the beam loading, therefore remains constant. After acceleration, the trains are separated using an RF-deflector running at half the linac frequency. The first train is deflected into a delay loop and merged with the second one in a second RF-deflector, see Fig. 1. The newly created pulses are separated by gaps that allow conventional deflectors to be switched on and off.

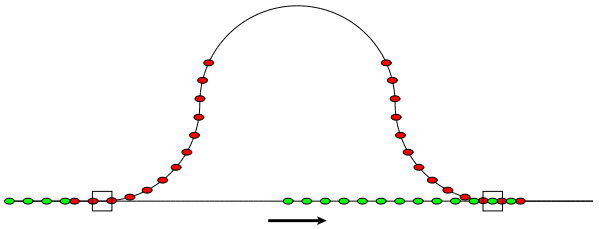

Figure 1: Schematic layout of the delay loop after the drive-beam accelerator in CLIC. The two RF-deflectors are shown as rectangles.

They are sent into two combiner rings [5]. These rings have a circumference equal to the distance between two pulses plus (or minus) a quarter wavelength. This allows to merge four pulses to form a single one, using an RF-deflector. The new pulse has four times as many bunches as each of the initial ones, with a distance between the bunches that is four times smaller. The bunches comprising the four pulses have been inter-leaved by this operation so that the first bunch of each of the initial pulses is one of the first four of the final pulse.

The first ring is followed by a second one, four times larger, which merges four of the pulses of the first ring. At the end, the bunch-to-bunch distance has been reduced from the initial $64\,\mathrm{cm}$ to only $2\,\mathrm{cm}$. In the following, each $64\,\mathrm{cm}$ long section of the beam pulse is called a bin and it contains 32 bunches. The bunches that were in the first bin of each initial train are in the first bin of the final pulse. The bunches that were in the second bin of an initial pulse are in the second bin of the final pulse, and so on.

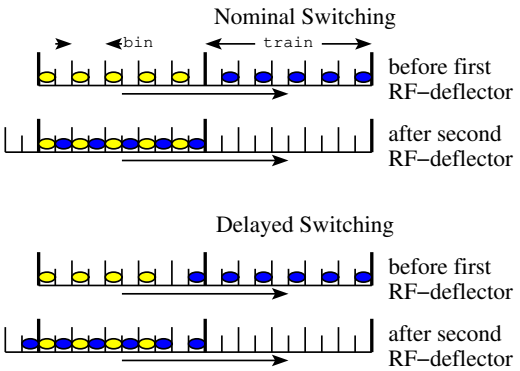

Figure 2: The scheme of delayed switching. In this example, each train contains 5 bins (an arbitray number chosen for better visibility). In the upper case the phase is switched at the nominal time, creating a rectangular pulse. In the lower case the phase switch is delayed to create a ramp.

3 DELAYED SWITCHING

In order to create a current ramp in the final pulse, the first few bins of this pulse must contain a smaller number of bunches than nominal. This in turn requires that some of the pulses after the delay loop have less than the nominal two bunches per bin. This can be achieved by delaying the switching of the sub-harmonic buncher. The effect of the nominal switching is illustrated in the upper part of Fig. 2. The two trains before the delay loop and the pulse after this loop are shown. In the delay loop, the bunches of the first train are delayed by one nominal train length. In the lower part of the figure, the sub-harmonic buncher is switched slightly later. The bunch that, in the nominal scheme, would have been the first one of the second train is therefore appended to the first train. The second train starts one bunch later than nominal. As a consequence, the pulse after the delay loop contains only one bunch in the first bin. The last bunch of the first train is appenended after at the end of the pulse.

The additional tail of the pulse creates no problem in the combiner ring, as long as the distance to the first bin of the next pulse is long enough to switch the ejection kickers of the rings on and off. In the drive-beam decelerator, the additional tail is not important, since it will just add a little tail to the RF-pulse produced in the power extraction and transfer structures (PETS).

The switching time can be individually chosen for each train, so a rather fine ramp in the final pulse can be created. This solution does not require any additional hardware; one must only be able to switch the sub-harmonic buncher at non-regular intervals.

4 NUMERICAL RESULTS

To achieve beam-loading compensation in the CLIC main linac, 11 of the 32 initial trains need to be delayed in the drive-beam linac. The maximum delay necessary is 11 bins. The gradient seen by the main-linac bunches can be

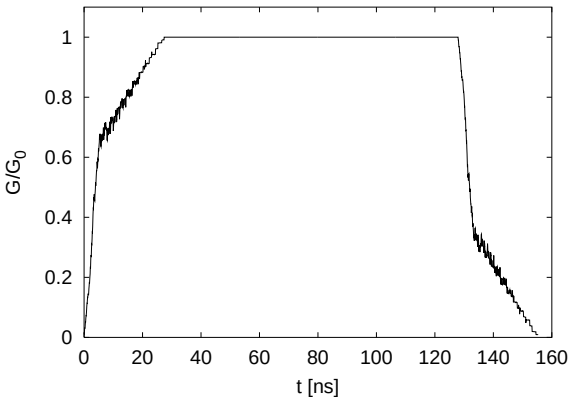

Figure 3: Shape of the RF pulse which is produced by the drive beam if delayed switching is applied.

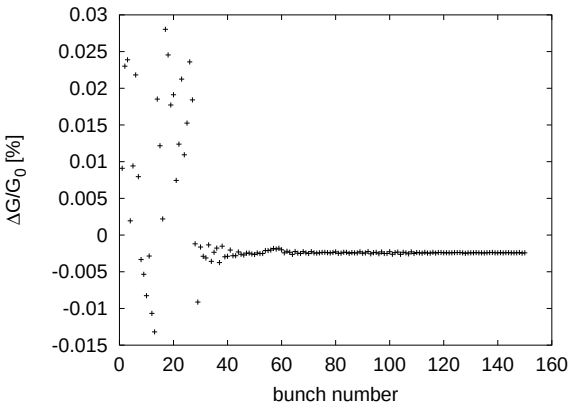

Figure 4: The deviation from the nominal gradient as seen by each bunch in the main linac.

simulated with ASTPC [6]. In this program, the transient effects in the PETS of the drive-beam decelerator, as well as in the main-linac accelerating structures are taken into account. Each structure is represented by a series of reflectors that are located at the cell boundaries. This makes it possible to simulate precisely the beam acceleration in the time domain.

The gradient errors depend on which of the trains are delayed. To find a good choice, a number of different delay patterns was created randomly. These were evaluated with the program and the best case was accepted. For this case, Fig. 3 shows the RF-pulse as it is produced by the PETS. This pulse leads to a bunch-to-bunch gradient error in the main linac that remains below $\Delta G/G_0 = 5 \times 10^{-4}$, see Fig. 4. This is better than the required precision of $\Delta G/G_0 \leq 10^{-3}$.

The method described achieves a constant amplitude of the accelerating field in the main linac. The main beam is, however, not accelerated on the crest of the RF wave, but at a small phase in the main part of the linac, $\Phi_{RF} = 6°$. At the end of the acceleration, this phase is even larger, $\Phi_{RF} = 30°$. Since the amplitude is increased in the RF phase and the beam loading is in phase with the beam, this

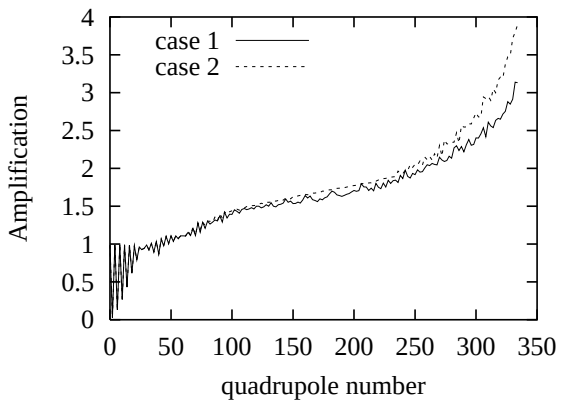

Figure 5: The maximum amplification of an initial beam jitter along the decelerator. The case of a rectangular current pulse (case 1) is compared to the one with a ramp in bunch number (case 2).

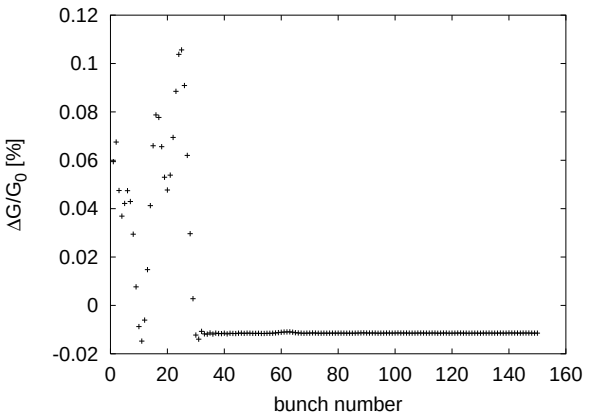

Figure 6: Deviation from the nominal gradient, as seen by the main-beam bunches in CTF3.

leads to an effective phase shift of the total accelerating field during the first part of the main-linac pulse. In order to prevent this, one can think of shifting the delayed trains before they are merged with the other ones. The shift has to be such that the bunches are in phase with the main beam. In this case, not only the amplitude but also the acceleration phase is maintained.

5 SIMULATION OF THE DRIVE BEAM

To estimate the impact of the beam-loading compensation on the stability of the drive beam in the decelerator, simulations are performed using PLACET [7]. A lattice is chosen in which each six-waveguide structure feeds three main linac structures.

As a measure of the stability, the maximum amplification of an initial jitter is used, which is determined as follows: in the simulation, each bunch is cut into slices. The beam is offset and then tracked through the decelerator. The maximum offset that the centre of any slice reaches, divided by the initial offset, is the maximum amplification. Figure 5 shows this amplification of a transverse jitter along the drive-beam decelerator. If no transverse wakefields were present, the final amplification factor would be $A = \sqrt{10}$ from the adiabatic undamping of the motion. As can be seen, a rectangular current pulse (case 1) is close to this case. The bunch ramp increases the amplification somewhat (case 2). This seems tolerable. Most of the effect is due to the trailing bunches.

If the delayed trains are shifted in phase, so as to prevent phase shift of the acceleration field, the wakefield effects in the drive-beam decelerator may become worse. The simulation shows that also in this case, the jitter amplification is almost the same as without the shift; they could not be distinguished in the plot. The method therefore seems to be practical. But other methods, such as a slow phase change along the train, might achieve the same result.

6 APPLICATION TO CTF3

Delayed switching could also be used in CTF3, the new CLIC Test Facility, which will be constructed at CERN. In this case, the switching time will be longer, about $4\,\mathrm{ns}$. Since only ten pulses are merged to form the drive beam, one only delays three of them. Again, different cases were searched for an optimum. The achieved compensation is very good, about $\Delta G/G_0 \approx 1.2 \times 10^{-3}$, see Fig. 6.

7 CONCLUSION

The method presented, to compensate the beam loading in the main linac, achieves the required precision of better than one part in 1000. It is very simple, can be adjusted to different switching times, and requires no additional hardware. It seems to be the method of choice for CLIC.

8 REFERENCES

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