Pulse Shaping and Beam-Loading Compensation with the Delay Loop

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Abstract

In the drive-beam accelerator of the compact linear collider (CLIC) the trains fill every second bucket. If the bunches in the one train occupy even buckets they will occupy odd ones in the next train and vice versa. This encoding is achieved by a phase switch at the injector. An RF-kicker running at half the linac frequency and a delay loop are used to separate the trains after the acceleration. This paper shows how the delay loop and the phase switch can be used to compensate the main-linac beam loading. It is also possible to shorten the final pulse which would otherwise be fixed by geometry.

1 Introduction

In CLIC, a drive beam is used to generate the RF-power necessary to accelerate the main beam. This drive beam is produced and accelerated at a low frequency of about 937 MHz. In this accelerator, the beam 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, the pattern is then repeated [1]. The current in the linac, and consequently the beam loading, remains therefore constant. After acceleration, the trains can be 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 to switch on or off conventional deflectors, see Fig. 2. The pulses are sent into so-called combiner rings [2]. These rings have a circumference equal to the distance between two pulses plus or minus a quarter wavelength. This allows to merge four pulse to form one—using an RF-deflector. The first ring is followed by a second one of four times the size which overlays four of the pulses of the first ring.

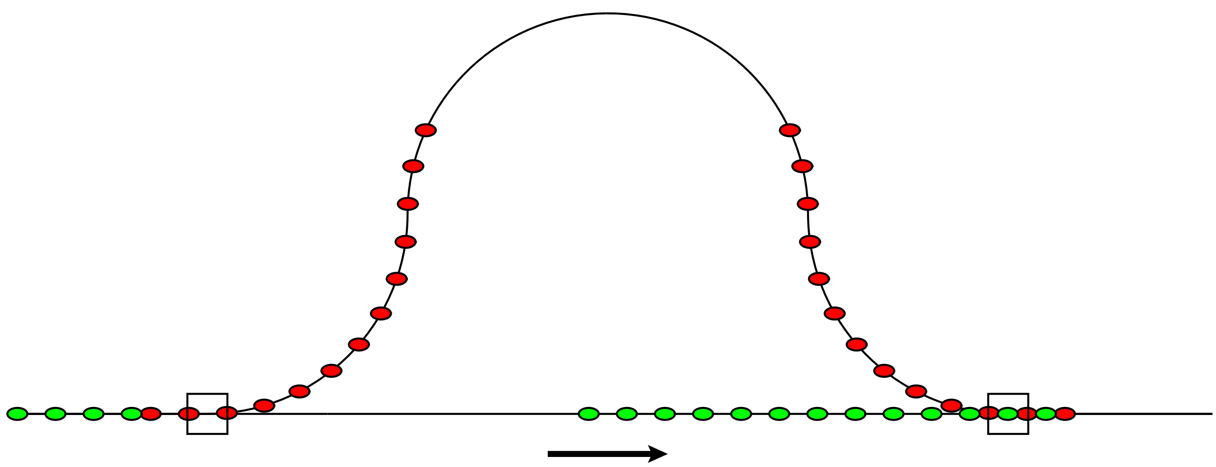

Figure 1: Schematic layout of the delay loop after the drive-beam accelerator in CLIC. The positions of the two RF-deflectors are marked with rectangles.

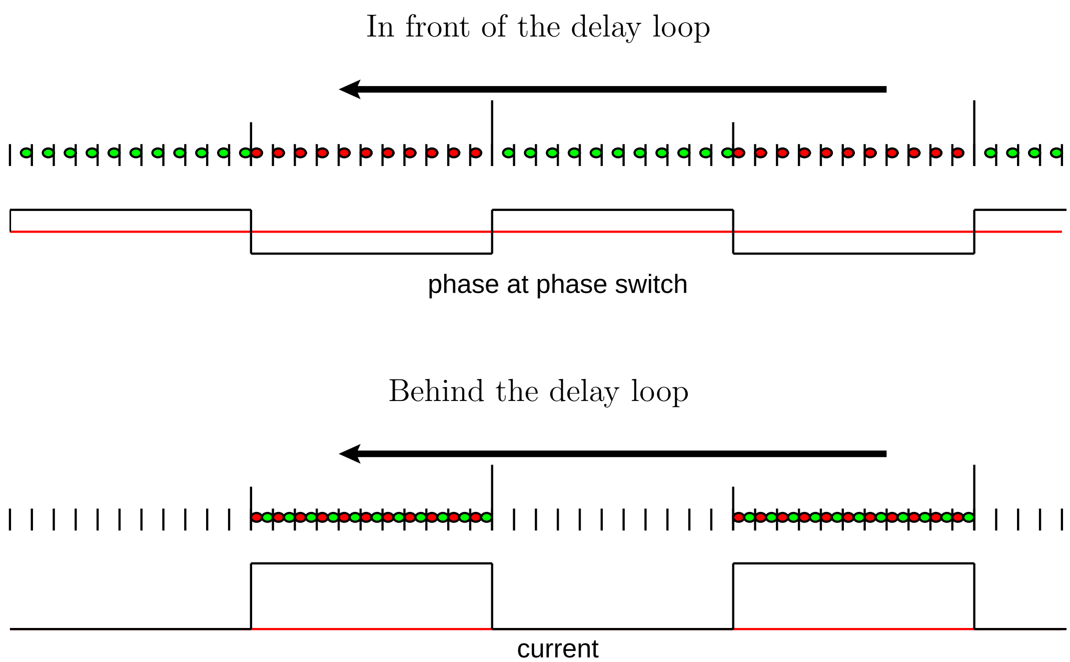

Figure 2: Nominal use of the delay line in order to achieve a rectangular pulse.

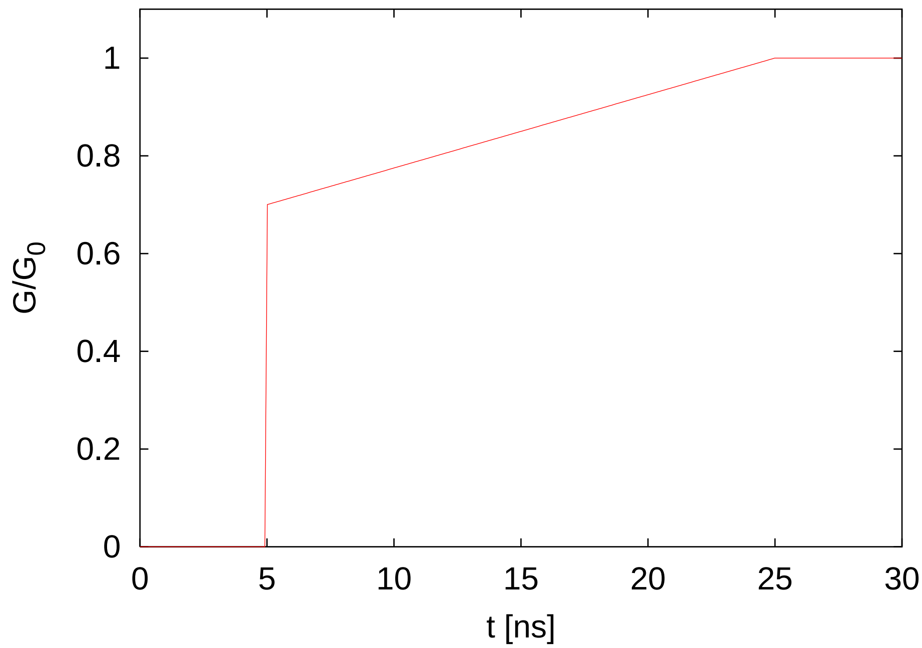

Figure 3: A generic example of the RF-pulse necessary to compensate the main-linac beam loading.

2 Beam-Loading Compensation in the Main Linac

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. The goal is to keep the maximum final bunch-to-bunch energy variation below one part in 1000. In the bunch train, the beam loading reaches a steady state after the fill time of a main linac structure. For the bunches before this, the multi-bunch beam loading has to be simulated by a ramp in the RF-pulse. A generic example is shown in Fig. 3. Here, the RF-field has to start at 70 % of the nominal value and then to increase linearly within 20 ns to the nominal value.

Several different approaches to solve the problem exist. The charge in each bunch can be increased during the first part of each train, this creates a current ramp in the final pulse [3]. In this case the preceding train needs a tail of bunches with decreasing charges to keep the drive-beam current in the drive-beam accelerator constant [1]. It may be very difficult to control the bunch charge with the required precision. Another option may be partial filling of the main linac structures. In this case one adjusts the timing of the pulse in such a way, that when the first main-beam bunch arrives at a structure, it is only partially filled. In the following, the more and more complete filling of the structure increases the gradient, while the beam loading reduces it. So the two effects partially cancel.

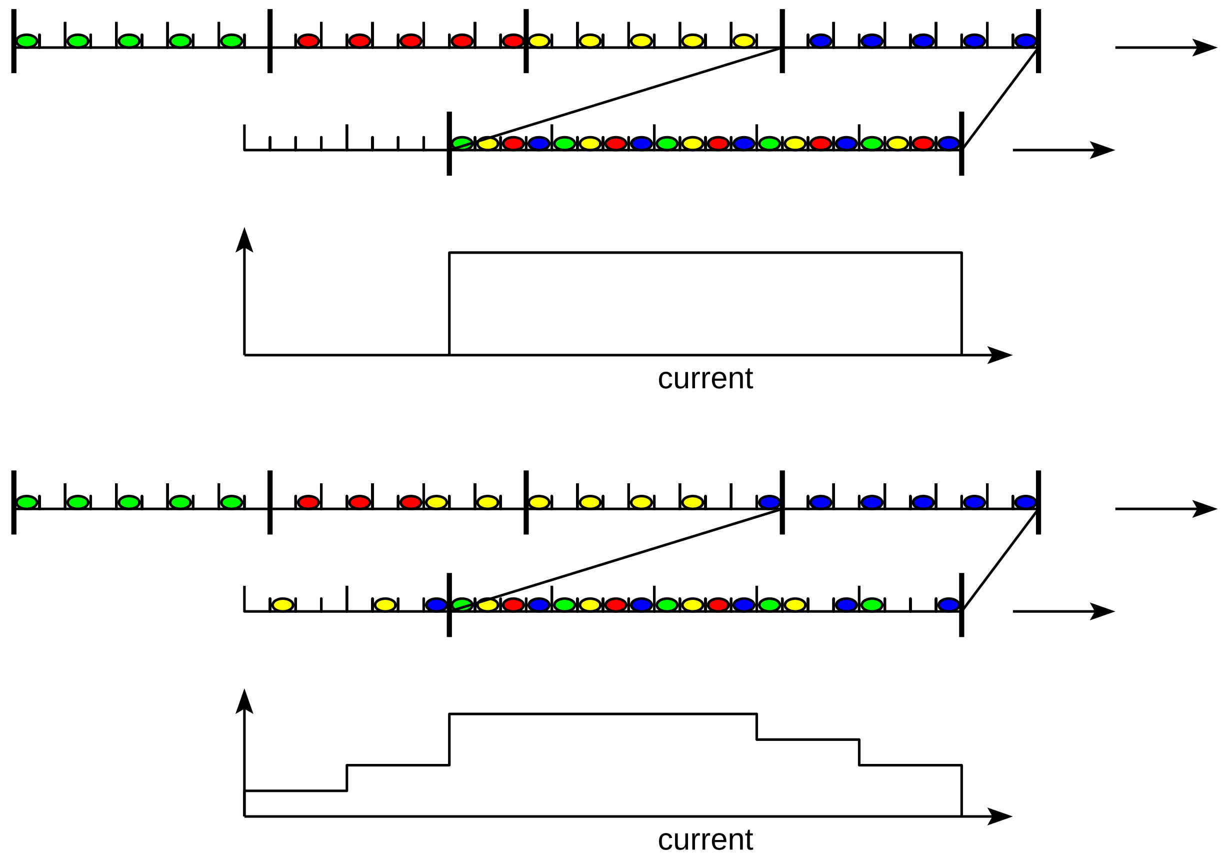

Figure 4: The scheme of the delayed switching. In the upper case the phase is switched at nominal times, creating a rectangular pulse. In the lower case the phase switch is delayed to create a ramp.

The achieved compensation is not very good within each decelerator. Different timings have to be chosen for each decelerator to achieve reasonable overall compensation. A third option is based on phase modulation of the drive-beam bunches in the ramp [4]. Here, the bunches of the final pulse are shifted longitudinally. The odd bunches are shifted forward, the even ones backward. This reduces the output power but leads to stronger transverse wakefield effects.

Another possible solution is delayed switching from one train to the next. For simplicity, it is assumed that the switching from odd to even buckets or vice versa is done instantly, which may be achievable [5]. A short charge ramp, in which the bunch charge in the first train decreases while it increases correspondingly in the second, does not change the conclusions. In the nominal case, the resulting pulse would be rectangular. The upper part of Fig. 4 shows this, under the assumption

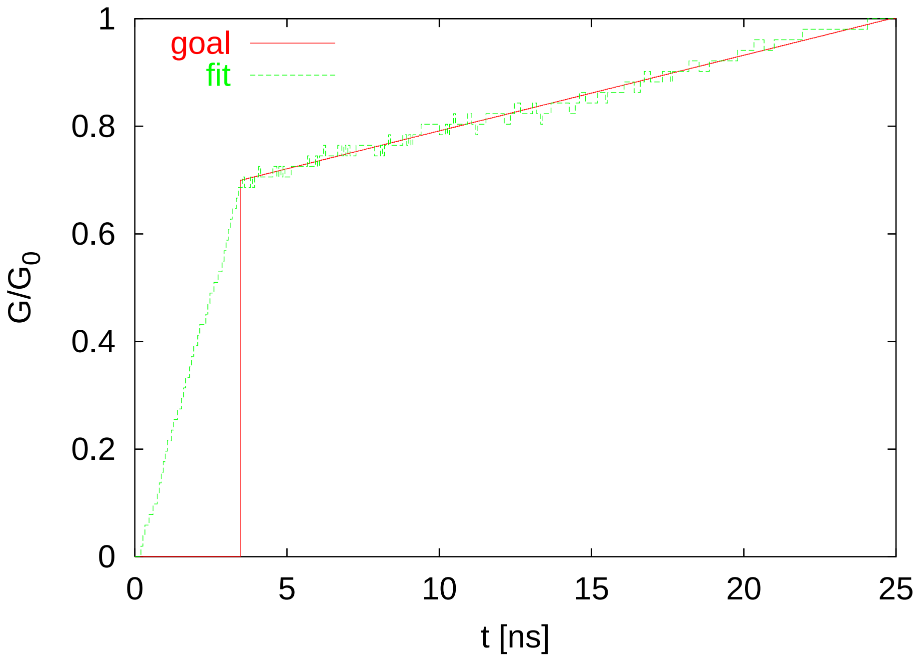

Figure 5: The pulse created by delayed switching.

that one uses only one combiner ring which folds only by a factor of two. If one however delays the switch after some of the trains, in the example the first and second one, one obtains a different shape. The bunches before the switch will be appended to the previous train and consequently to the tail of the final pulse. In the train after the switch, the first few bunches will be missing and therefore also a few in the first part of the final pulse. The result is a ramp in current in the pulse that is created by changing the bunch density rather than the charge per bunch, see the lower part of Fig. 4. The additional tail is of no concern, it will pass the drive-beam decelerator after the main beam.

This solution does not require any additional hardware, one must only be able to use the fast switch at non-regular intervals.

In Fig. 5 a simple demonstration of the performance of the scheme is shown. The goal for the shape of the RF-pulse is the generic example of Fig. 3. By delaying 10 of the 32 trains a shape very similar to the task was achieved.

More detailed calculations, that take also the main linac structure into account, show that the maximum difference in gradient seen by any two bunches is of the order of $4 \cdot 10^{-4}$ [6]. It does not cause a problem, if the switch is slower, such that the trains have a small charge ramp at the head and the tail. This can even improve the performance of the compensation scheme. Also by using different switch patterns for consecutive drive-beam sectors the performance can still be improved.

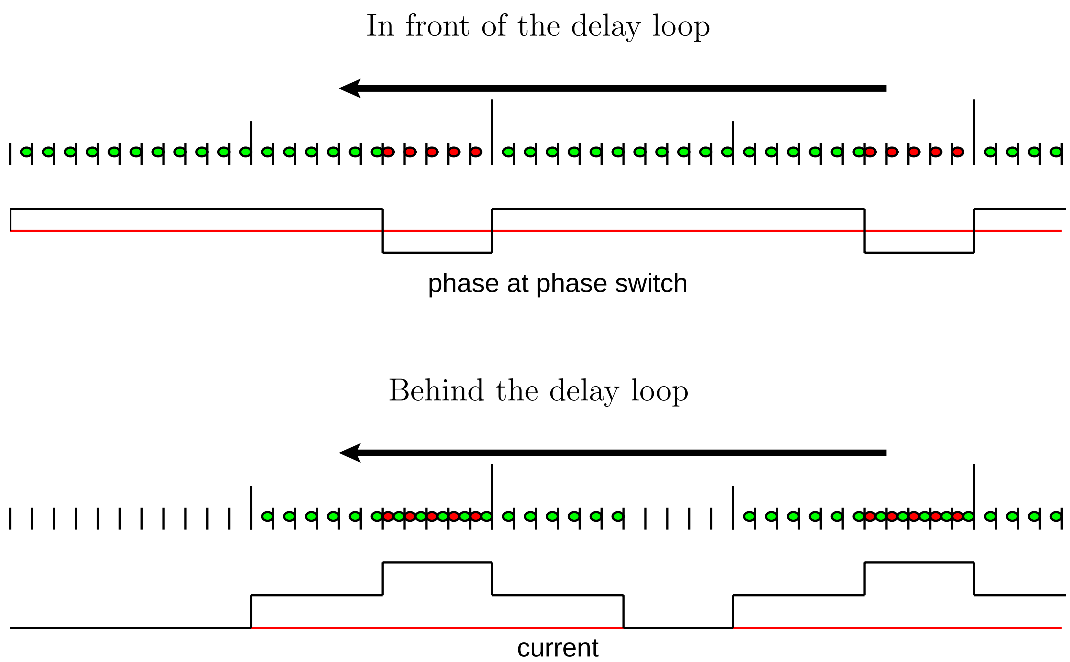

Figure 6: Use of the delayed switching to shorten the high power pulse.

3 Changing the Pulse Length

In order to condition the structures, it is useful to be able to vary the pulse length. With klystrons this is straightforward. In the case of CLIC, the pulse length is in principle fixed by the combiner rings. While the pulse accumulated in the ring may be shorter than the nominal one, this leads to gaps in the beam in the drive beam accelerator. This turns the beam loading compensation in the accelerator impossible.

Two main options exist to solve the problem. The first one can be used if the pulse length should be changed only slightly compared to the nominal value. The second one can be used, if the change should be more drastic. In the following, only the effect of the delay loop is shown for illustrating the priciples. The rings mainly increase the current and frequency of the pulse, but do not alter the pulse shape too much.

3.1 Small Change of the Pulse Length

The method of the delayed switching, as described above, can be used to create a pulse in which the nominal current is reached only for a short time. In the simplest case, one can choose the train that is sent through the delay loop to be much longer than the other one, see Fig. 6. The final pulse will then start at half the nominal current, have a short period with nominal current, and another

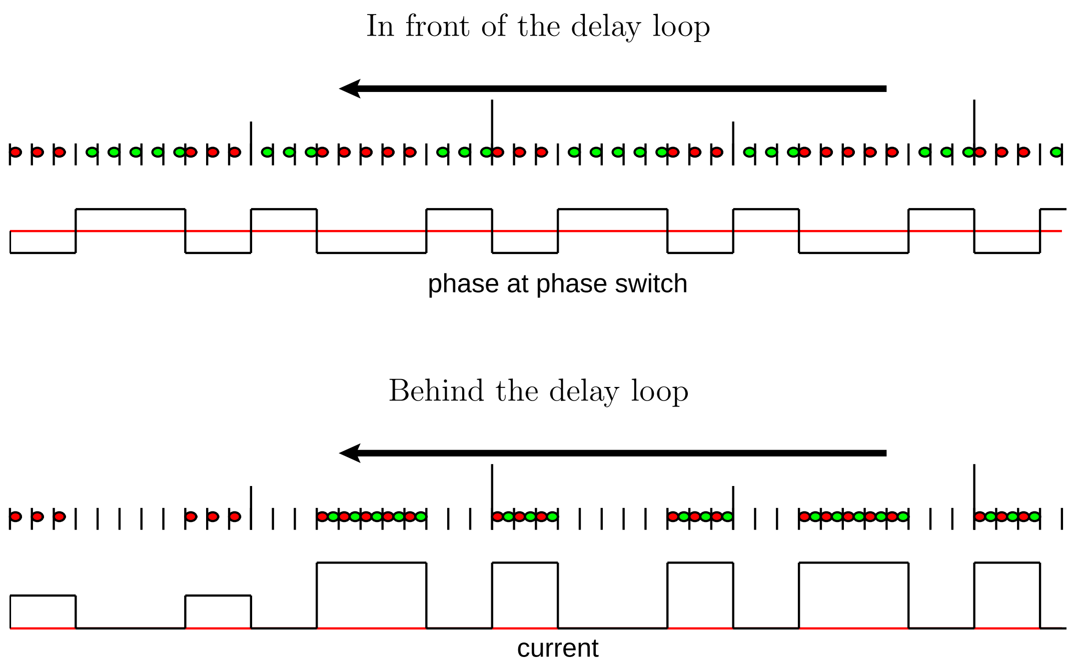

Figure 7: The triple switching system. The phase switch is used twice within each train and once between trains.

one with half the nominal current again. The length of the full current part of the pulse is equal to the gap between pulses after the delay loop. This gap has be to large enough to allow one to switch a transverse deflector either on or off. Therefore, one can achieve a minimum pulse length τ at full current that is equal to the rise (or fall) time of the extraction kicker of the ring τ_r.

3.2 Very Short Pulse

One may want to have an even shorter pulse or one may want to avoid the initial and final part of the pulse obtained with the above method. In this case, one does not switch only between two trains, but also twice within each train. This creates the pattern in Fig. 7, which leads to a pulse shape after the delay loop that contains large gaps. If the gaps are wide enough to allow a deflector to be switched on or off, it is possible to extract only one of the three created sub-pulses. The maximum pulse length is then $\tau = \tau_0 - 2\tau_r$, the minimum $\tau = 0$. Here, τ_0 is the nominal pulse length.

4 Conclusion

Compensation of the main-linac beam loading is very important in CLIC. Good compensation of the beam loading can be achieved by use of the delay line and the phase switch that separates the consecutive trains. If this switch is triggered slightly later than nominal for a number of trains, one can obtain a current ramp in the final pulse. This ramp can compensate the beam loading. In addition, the pulse length can be reduced in order to allow conditioning of the main-linac structures with full power but a shorter pulse. Both methods do not require additional hardware, if a fast phase switch exists.

References

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