RF pulse shape control in the compact linear collider test facility

Oleksiy Kononenko a,b,* , Roberto Corsini b

a SLAC National Accelerator Laboratory, 2575 Sand Hill Rd, Menlo Park, CA 94025, USA
b CERN, CH-1211, Geneva 23, Switzerland

ABSTRACT

The Compact Linear Collider (CLIC) is a study for an electron–positron machine aiming at accelerating and colliding particles at the next energy frontier. The CLIC concept is based on the novel two-beam acceleration scheme, where a high-current low-energy drive beam generates RF in series of power extraction and transfer structures accelerating the low-current main beam. To compensate for the transient beam-loading and meet the energy spread specification requirements for the main linac, the RF pulse shape must be carefully optimized. This was recently modelled by varying the drive beam phase switch times in the sub-harmonic buncher so that, when combined, the drive beam modulation translates into the required voltage modulation of the accelerating pulse. In this paper, the control over the RF pulse shape with the phase switches, that is crucial for the success of the developed compensation model, is studied. The results on the experimental verification of this control method are presented and a good agreement with the numerical predictions is demonstrated. Implications for the CLIC beam-loading compensation model are also discussed.

1. Introduction

The Compact Linear Collider (CLIC) is a study for a multi-TeV lepton linear accelerator aiming at colliding particles at an energy scale currently not accessible [1]. CLIC will be based on a novel two-beam acceleration scheme, where a high-current low-energy drive beam generates RF by passing through the power extraction and transfer structures (PETS), accelerating a low-current main beam up to 3 TeV. A schematic layout of CLIC is presented in Fig. 1.

To keep the luminosity loss below 1%, the root mean square (r.m.s.) bunch-to-bunch energy spread (σ) in the main beam must be below 0.03% [1]. However, if the accelerating RF pulse is not properly optimized, bunches gain a different energy due to the transient beam-loading effect. In contrast to the beam-loading compensation schemes for the klystron powered accelerators, see for instance [2,3], the CLIC RF pulse shape is determined by current modulations of the drive beam, that is combined to reach higher currents in the delay loop (DL) and two combiner rings (CR1 and CR2). It means that to minimize the energy spread in the main beam, a dedicated beam-loading compensation model must be employed.

This critical performance issue has been addressed [4] by developing the transient beam-loading model and the compensation method for CLIC, including the effect of higher-order modes [5]. The RF pulse shape, that reduces the energy spread down to the specification limit, was modelled by optimizing the drive beam phase switch times in the sub-harmonic buncher [6]. As shown in [7], controlling the pulse shape can also be helpful for the final conditioning of the CLIC main linac accelerating structures.

In this study, we benchmark the key feature of the compensation model experimentally and demonstrate the RF pulse control in the CLIC Test Facility 3 (CTF3) [8] by using the phase switches. The paper is organized as follows. Section 2 reviews the beam-loading compensation model for CLIC and discusses possible options to confirm the numerical predictions experimentally. Section 3 presents the RF power production model and the numerical pulse shape optimization procedure for CTF3. Section 4 demonstrates a control over the RF pulse shape with the phase switches and shows a comparison with the simulations. Finally, Section 5 concludes the paper.

2. Transient beam-loading compensation model

The CLIC injector delivers 140 μs-long drive beam with a bunch repetition frequency of 0.5 GHz [1]. Every 244 ns the sub-harmonic bunching system changes the phase by 180° switching from filling the odd to filling the even buckets and vice versa. The resulting 244 ns-long phase-coded sub-pulses are accelerated to about 2.4 GeV and interleaved with those of the next sub-pulse in the delay loop, see Fig. 2. Similarly, three of the resulting sub-pulses are merged in the CR1 and four of the

---

* Corresponding author at: SLAC National Accelerator Laboratory, 2575 Sand Hill Rd, Menlo Park, CA 94025, USA.
E-mail address: Oleksiy.Kononenko@slac.stanford.edu (O. Kononenko).

https://doi.org/10.1016/j.nima.2018.04.050
Received 10 April 2018; Accepted 24 April 2018
Available online 4 May 2018
0168-9002/© 2018 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).
new sub-pulses in the CR2. Finally, 24 trains with the bunch repetition frequency of 12 GHz are generated feeding 24 sectors of the CLIC decelerator, one 244 ns-long train per a sector.

Each of the combined multi-bunch trains consists of 12 odd and 12 even buckets. To ensure the constant charge per train, the beginning of the first odd and the end of the last even buckets should be fixed in the sub-harmonic bunched, leaving the other 23 phase switches available to control the length of each bucket individually. Adjusting the phase coding times is a “cheap” method to create a modulation of the drive beam current that finally translates into the modulation of the accelerating RF pulse. It was recently shown, that if these adjustments are properly optimized, the energy spread in the main beam could be minimized down to the CLIC specification level [4].
Fig. 4. The envelopes (left) of the unloaded voltage (blue) and the main beam induced voltage for a train of 312 bunches (green), voltage seen by the main beam (red); relative energy spread along the main beam, $\sigma = 0.025\%$, for the optimized CLIC pulse (right) as simulated in [4]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CTF3</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch repetition frequency (GHz)</td>
<td>1.5 / 3</td>
<td>0.5</td>
</tr>
<tr>
<td>Delay loop, combination factor</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Combiner ring #1, combination factor</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Combiner ring #2, combination factor</td>
<td>–</td>
<td>4</td>
</tr>
<tr>
<td>Total combination factor</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td>Number of phase switches per pulse</td>
<td>7</td>
<td>23</td>
</tr>
<tr>
<td>PETS power per ACS (MW)</td>
<td>20–70</td>
<td>63.1</td>
</tr>
<tr>
<td>RF pulse length, ns</td>
<td>140</td>
<td>244</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Main beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch repetition frequency (GHz)</td>
<td>1.5</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>1–226</td>
</tr>
<tr>
<td>Bunch charge (nC)</td>
<td>0.1–0.6</td>
</tr>
<tr>
<td>Injection energy (GeV)</td>
<td>0.177</td>
</tr>
<tr>
<td>Injection energy spread (%)</td>
<td>~1</td>
</tr>
</tbody>
</table>

In Fig. 3 the optimized adjustments to the nominal phase switch times and the resulting RF pulse are shown for CLIC as modelled in [4]. In Fig. 4 the unloaded voltage, the main beam induced voltage for a train of 312 bunches and the voltage seen by the beam are presented, also shown is the energy spread along the main beam minimized down to 0.025%.

To demonstrate the feasibility of the CLIC concept, the CLIC Test Facility 3 [8] was built at CERN by an international collaboration, see Fig. 5 for the detailed CTF3 layouts. At the end of 2016, CTF3 successfully completed its research program and was converted into the CERN Linear Electron Accelerator for Research (CLEAR) [9].

CTF3 included a drive beam injector with a sub-harmonic buncher operating at either 1.5 or 3 GHz, drive beam linear accelerator, delay loop which doubled the beam frequency and one combiner ring with a factor of four in the beam frequency multiplication. The combined drive beam could be sent to either the two-beam module (TBM) [10] with two PETses powering two TD26 accelerating structures (ACS) [11] each, or to the test beam line (TBL) [12] where 12 CLIC PETses were installed in series decelerating the beam down to 40%.

Unfortunately, the full-scale experimental verification of the CLIC beam-loading compensation model was not feasible in CTF3 because of the following reasons. First, the CTF3 RF pulse was significantly shorter than the one for CLIC (140 ns vs 244 ns), and the number of the phase switches to control its shape was only seven (23 in CLIC). Second, the total charge available for the main beam in CTF3 was not sufficient to produce the required beam-loading effect in the accelerating structures. Third, as CTF3 had no damping rings the energy spread in the probe beam was well above the CLIC specification value.

A detailed comparison of the CTF3 and CLIC parameters relevant for the experimental verification of the model is shown in Table 1.

On the other hand, the beam-loading effect was a recent focus of the breakdown studies in CTF3, see [13,14]. In that experiment the drive beam was diverted into the dogleg line, shown in Fig. 5, and sent into the CLIC prototype accelerating structures to investigate its effect on the breakdown rate. As a part of the studies, the CTF3 drive beam current was set up to approximately 1 A to match the current of the CLIC main beam and the beam-loading power was measured. The data were in a good agreement with the simulations based on the discussed model [4], see Fig. 4 in [13].

Along with the calculations of the beam-induced power, the key feature of the compensation scheme is the control over the RF pulse shape with the drive beam phase switches. In the next sections we benchmark this feature experimentally by taking into account the main beam pulse numerically and, based on the optimized phase-switch adjustments that minimize the energy spread, synthetize the required RF pulses in CTF3.
Fig. 6. Illustration of the phase coding in the sub-harmonic buncher (top) and the drive beam combination in the delay loop (bottom). The bunches in the odd (red) and even (blue) buckets are out of phase by 180°. The black vertical lines correspond to the nominal phase switch times and the red vertical line corresponds to the adjusted switch #3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 7. Illustration of the current evolution in the CTF3 combiner ring. The black vertical lines correspond to the nominal phase switch times and the red vertical line corresponds to the adjusted switch #3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
The drive beam combination profiles available in CTF3; the profile used for the pulse shape control experiment is bolded.

<table>
<thead>
<tr>
<th>Initial bunch repetition frequency (GHz)</th>
<th>Combination factor</th>
<th>Final bunch repetition frequency (GHz)</th>
<th>Number of the phase switches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delay loop</td>
<td>Combiner ring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>1.5</td>
<td>2</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>1.5</td>
<td>2</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>1.5</td>
<td>2</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>–</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>–</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>–</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>–</td>
<td>4</td>
<td>12</td>
</tr>
</tbody>
</table>

3. Simulation of the optimized RF pulse shape in CTF3

3.1. RF power production model for CTF3

The CTF3 injector delivered 1.12 μs-long drive beam pulses with the bunch repetition frequency of either 1.5 or 3 GHz each. The 1.5 GHz odd and even buckets could be merged in the delay loop, increasing the beam frequency by a factor of two. The 3 GHz beams were combined by a factor of four in the ring resulting in the 12 GHz multi-bunch trains. A brief overview of the CTF3 drive beam combination profiles is presented in Table 2. Similar to CLIC, the CTF3 sub-harmonic bunching system [15] could flip the beam phase by 180°, defining if a particular sub-pulse was diverted to the delay loop or not. The frequency of the DL RF deflector was 1.5 GHz, so the phase switches had the required effect on 1.5 GHz beams only. When all the eight sub-pulses are combined in the both the delay loop and the combiner ring, the pulse length was reduced to 140 ns and the bunch repetition frequency was increased to 12 GHz resulting in the resonant power build up in decelerators. This combination profile is bolded in Table 2 and was used for the RF pulse shape control experiment.
In Fig. 6 the phase coding in the sub-harmonic buncher and the current multiplication (×2) in the delay loop are illustrated schematically for a sample 1.5 GHz pulse in CTF3. In Fig. 7 the steps of the current evolution (×4) in the combiner ring are presented. To demonstrate the way of creating the current ramp, the timing of the phase switch #3, that controls the end of the third and the beginning of the fourth buckets, is adjusted by a value of Δt, that is essentially a difference between the nominal switch time and the actual value.

After all the combinations, the 12 GHz 140 ns-long drive beam pulse is sent to the PETs decelerators and generates RF power. $U(t)$, the
The voltage induced by the beam in PETS, can be calculated as

\[ U(t) = \sum_{i=1}^{N_b} q(i) R(t + T_i) e^{2\pi i f_0 c t / \lambda} \]  

(1)

where \( N_b \) is a number of bunches in the drive beam, \( q(i) \) is the \( i \)-th bunch charge, \( R(t) \) is a single bunch response as simulated for PETS \([16, 17]\), \( T_i \) — time of the \( i \)-th bunch within the bunch train, \( f_0 \) — the CLIC nominal RF frequency of 12 GHz, \( c \) — speed of light in vacuum, \( \sigma_0 \) — the bunch length used for the bunch response simulation, \( \sigma_i \) — the measured \( i \)-th bunch length. The exponential term in Eq. (1) accounts for the realistic bunch form factor, see, for instance, Eq. (22) in \([18]\).

The beam-loading compensation tool \([4]\), developed for the CLIC RF pulse shape optimization and the energy spread minimization, has been extended to simulate the RF power production for CTF3 \([15]\). It takes into account the combination scheme, the phase, charge and bunch length variations along the drive beam as well as the phase switch times in the sub-harmonic buncher. By incorporating the measured drive beam properties into Eq. (1), this tool was used to simulate the RF pulse shapes for the CTF3 experiment.

### 3.2. Simulation of the RF pulse shape for the CTF3 experiment

When the buncher phase flips by 180° every 140 ns and the 1.5 GHz 1.12 μs-long drive beam pulse goes through the both the delay loop and the combiner ring, a 12 GHz 140 ns-long pulse with the peak current of about 25 A is generated. Passing through PETS the beam can generate a 140 ns-long RF pulse with up to 70 MW of power per accelerating structure in TBM. As the rise time plus the filling time of the TD26 structure is roughly 90 ns, the time available for the beam acceleration in CTF3 is only 50 ns. The CLIC main beam frequency is 0.5 GHz, so for the purpose of the experiment, we optimize the energy spread numerically for 100 bunches only. This is in contrast to 312 bunches for CLIC that has a longer RF pulse.

Using the beam-loading compensation tool, the energy spread was optimized down to 0.02% for the injection time of 88.054 ns. In Fig. 8 the phase switch adjustments and the resulting RF pulse are presented. The unloaded and the beam-induced voltages as well as the accelerating voltage seen by the beam are shown in Fig. 9.

The calculated phase switch times were set up in the CTF3 control system to shape the drive beam current and, as a result, the RF pulse generated.

### 4. RF pulse shape control experiment in CTF3

A detailed description of the CTF3 machine can be found in \([19]\). For the purpose of the experiment we measured current with the beam position monitors (BPM) installed right next to the delay loop as well as in the transfer lines (TL), combiner ring, TBL and TBM, see Figs. 10 and 11. Details on various monitor designs used in CTF3 can be found in \([20–22]\).

The control system allows setting up each phase switch individually and to generate a “rectangular” pulse, the phase of the drive beam had to flip every 140 ns. By introducing the adjustments, shown in Fig. 8 (left), on top of the nominal switch times, we generated 1.12 μs-long phase-coded pulse at 1.5 GHz. In Fig. 12 the resulting drive beam current as well as its typical evolution in the delay loop and the combiner ring are presented.

First, the RF power production of the combined beam was studied in TBL. This was useful from the benchmarking point of view, as TBL consisted of a series of 12 identical PETSees, see Fig. 13.

In Fig. 14 the beam current, as measured before and after TBL, is compared with the one simulated from the initial (uncombined) pulse combining the beam by a factor of eight numerically. The pulse shapes agree pretty well except for the discrepancy in the amplitude due to the beam losses. As the losses were almost uniform along the beam, for the RF pulse shape simulations they were taken into account through the linear scaling.

The drive beam, passing through TBL, generates RF power in a series of decelerators \([23]\). Based on Eq. (1) and the measured beam properties, the RF pulse in the TBL PETSees was simulated from the numerically combined current and from the current as measured before TBL. In Fig. 15 the comparison of the simulations against the measurements is shown for the TBL PETSe8. The results are in a fair agreement confirming the expected effect of the adjustments to the nominal phase switch times in the sub-harmonic buncher. Stability of the shape was confirmed by calculating the standard deviation for a set of the generated RF pulses, also plotted in Fig. 15.

To study the RF pulse propagation through the accelerating structures, the drive beam was sent to TBM, see Fig. 16 for the corresponding layout and \([24, 25]\) for the details on the instrumentation.

The TBM PETSees are twice longer than the ones installed in TBL, so the appropriate single bunch response was used in Eq. (1) to model the RF power production. Taking into account the s-matrices as calculated for the TD26 accelerating structure \([5]\), the pulse transmission through the accelerating structures was simulated and compared with the data. In Fig. 17 the transmitted RF pulse is shown as simulated and as measured in the TBM ACS2 at the time when the beam losses in CTF3
Fig. 12. The phase variation along the drive beam as measured in the linac (dashed blue); beam currents as measured after the linac (blue), after the delay loop (green), in the combiner ring (red) and after the combiner ring (magenta). The nominal (black crosses) and the coded (red crosses) phase switch times are shown on the time axis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 13. Beam instrumentation in TL2 and the beginning of TBL (left) as well as at the end of TBL (right), BPM’s and PETSe’s used for the measurements are highlighted.

Fig. 14. Drive beam current as measured before (blue) and after (green) TBL as well as the one simulated by numerically combining drive beam current assuming no losses (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

were moderate. The calculation shows a good agreement with the data demonstrating feasibility to manipulate the RF pulse shapes in the accelerating structures with the seven phase switches only.

5. Conclusions

The CLIC beam-loading compensation model has been further advanced to CTF3 by taking into account the corresponding drive beam
combination scheme and the measured phase, charge and bunch length variations. The beam effect in the accelerating structure was taken into account numerically and the phase switch timings were optimized to model the energy spread minimization in the main beam.

The phase switches were adjusted according to the simulations and the RF pulse shapes synthetized in CTF3 were in a good agreement with the numerical predictions for both the decelerators and the accelerating structures. This demonstrates the feasibility of a reasonable RF pulse shape control even with only the seven knobs available. As in CLIC the number of switches is 23, the control can be even more precise.

Even though the full scale experiment on the beam-loading compensation was not possible in CTF3 due to the obvious limitations of the
machine, the method of controlling the pulse with the phase switches shows a great potential for the transient compensation scheme as well as for the final conditioning of the accelerating structures in CLIC.

Acknowledgements

The authors are grateful to the CTF3 and the CLIC RF structure development teams for their invaluable help during the experiment.

References