

# COMPENSATION OF TRANSIENT BEAM-LOADING IN CLIC MAIN LINAC

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## Abstract

Compensating transient beam loading to maintain a 0.03% rms relative beam energy spread is a key issue for the CLIC two-beam acceleration technique. The combination of short pulses, narrow bandwidth rf components and the limited number of rf pulse shaping “knobs” given by the drive beam generation scheme makes meeting this specification challenging. A dedicated model, which takes into account all stages of drive beam generation, including the delay loop and combiner rings, the single-bunch response of the power generation structure (PETS), the RF waveguide network transfer function and dispersive properties of the accelerating structure has been developed. The drive beam phase switching delays, resulting rf pulse shape, and finally the energy spread are presented.

## INTRODUCTION

In order to have luminosity loss less than 1% in CLIC interaction point, the rms bunch-to-bunch relative energy spread in main beam must be below 0.03% [1]. On the other hand, at the beginning of the bunch train, each bunch gains different energy due to the transient beam-loading effect. In this paper, a new method of calculating voltage in the accelerating structure of realistic geometries during the transient is described and the optimization of the rf pulse shape for CLIC main linac to compensate the transient beam-loading effect is presented.

The T24 CLIC accelerating structure prototype [2] has been analyzed, however the same method will be applied to the CLIC baseline structure [3].

## UNLOADED AND LOADED VOLTAGES

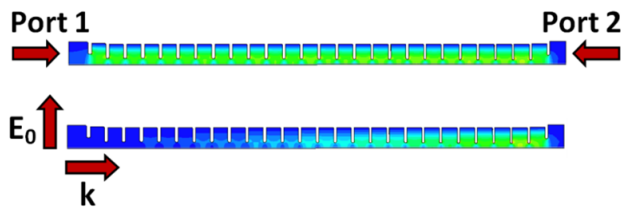


Figure 1: Electric field distribution in T24 structure calculated for two cases: port excitation (top) and plane wave excitation (bottom).

The frequency domain code HFSS [4] is used to calculate electromagnetic fields in T24 structure. Port excitation is used to calculate unloaded electromagnetic field as it is shown in Fig 1 (top). To calculate electromagnetic field excited by the beam an equivalent

current source on the structure’s axis is modelled by a plane wave excitation. To do this a plane wave with transverse polarisation is used. Corresponding electric field  $E_0$  and propagation vector  $k$  of the wave is shown in Fig. 1 (bottom). The unloaded accelerating voltage is calculated using electrical field obtained from the port excitation of the structure by the following formula:

$$V_{acc}(f) = \int_0^L E_z^{PORT}(f, z) e^{i\omega z/c} dz,$$

where  $L$  is the length of the accelerating structure,  $c$  – speed of light in vacuum. Using normalization for the fields determined from the plane wave excitation we calculate the beam coupling impedance:

$$Z_{pw}(f) = \frac{Z_0}{2\pi r E_0} \int_0^L E_z^{PW}(f, z) e^{i\omega z/c} dz,$$

where  $Z_0$  is the impedance of free space,  $r$  is the auxiliary geometrical parameter which comes from the HFSS model. The accelerating voltage for the power of 1 W and beam coupling impedance are presented in the Fig. 2 below.

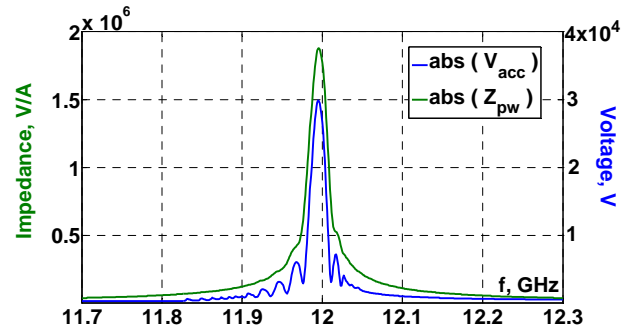


Figure 2: Accelerating voltage for the port excitation (blue) and beam coupling impedance (green) versus frequency.

Performing an inverse Fourier transform we convert accelerating voltage and coupling impedance to the structure time response  $r(t)$  and wake potential  $W(t)$ , respectively, which are presented in Fig. 3.

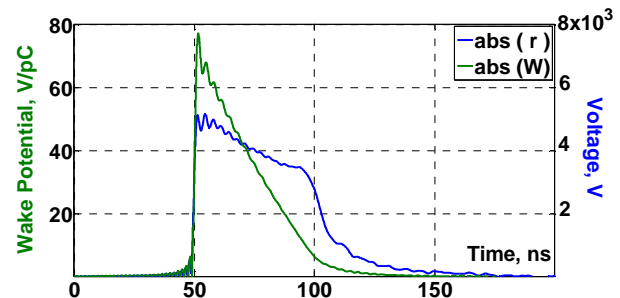


Figure 3: Envelopes of the time response function for the port excitation (blue) and wake potential (green).

The unloaded voltage in the accelerating structure is calculated for the arbitrary pulse by convoluting the pulse signal  $p(t)$  and time response  $r(t)$ :

$$V_{unloaded}(t) = conv(p(t), r(t)),$$

while the beam voltage is expressed in the terms of the wake potential of the whole bunch train:

$$V_{beam}(t) = q * \sum_{n=1}^{N_B} W(t + T_B),$$

where  $q$  is the bunch charge,  $N_B$  is the number of bunches in the train,  $T_B$  is the time between the bunches. Loaded voltage can now be determined from the relation:

$$V_{loaded}(t) = V_{unloaded}(t) + V_{beam}(t, T_{inj}),$$

where  $T_{inj}$  is the injection time of the beam.

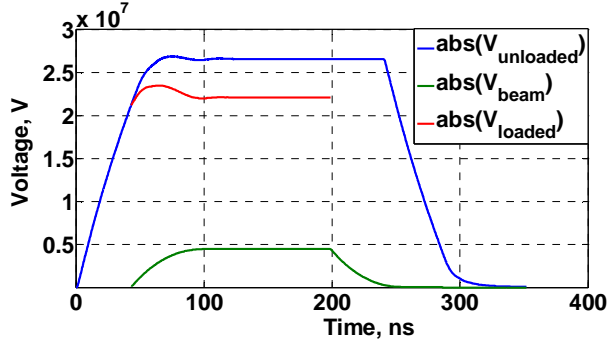


Figure 4: Envelopes of the unloaded voltage for a rectangular pulse of 240 ns (blue), envelope of the beam voltage for a train of 312 bunches (green) and loaded voltage in the main beam (red).

The unloaded voltage for a rectangular pulse of 240 ns and the CLIC nominal input power for 100 MV/m average loaded accelerating gradient operation, beam voltage for the train of 312 bunches of  $3.7 \cdot 10^9$  particles and the corresponding loaded voltage are shown in the Fig. 4. In this case, the relative energy spread can be minimized by optimizing injection time  $T_{inj}$  down to the level of 6% only. Clearly the CLIC specification for the energy spread could not be met if a rectangular pulse is used.

## CLIC PULSE SHAPE OPTIMIZATION

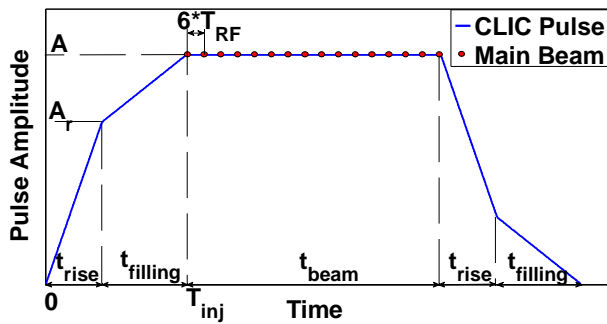


Figure 5: Schematic pulse shape for CLIC.

In order to better compensate bunch-to-bunch energy spread induced by the transient beam-loading effect a special pulse shape is used. In Fig. 5, the CLIC pulse shape is shown schematically. Here a ramp during the

filling time  $t_{filling}$  is used to perform the transient beam-loading compensation, whereas the rise time  $t_{rise}$  is introduced to take into account the transient related to the accelerating structure bandwidth. Since in CLIC [1] this pulse is generated in Power Extraction and Transfer Structure (PETS) by the drive beam, the voltage is simply proportional to the drive beam current, and the voltage modulation comes from drive beam current modulation.

In Fig. 6, the envelope of a single drive beam bunch response for PETS calculated in time domain using GdfidL [6] is shown. Parasitic reflections in the PETS on/off mechanism cause the appearance of a tail in the bunch response function. In order to investigate its influence on the energy spread, two cases have been investigated: main part of the PETS response from 0 to 2 ns (see green square in Fig. 6) without the tail and the full PETS bunch response including the tail.

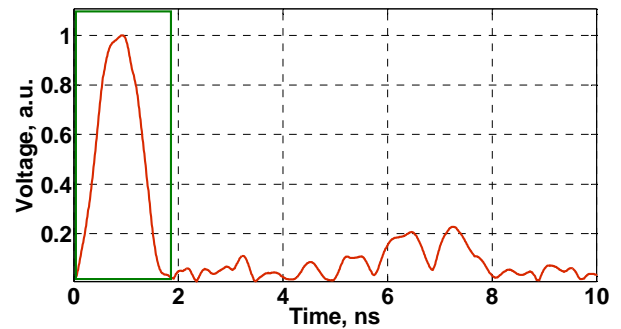


Figure 6: Envelope of the single drive beam bunch response.

The drive beam generation complex in CLIC [1] consists of injector, drive beam accelerator, delay loop and two combiner rings. Possible beam-loading compensation schemes are described in [5] and it is shown that the most efficient and cost-effective solution for CLIC is to modify the drive beam in the drive beam injector. It is also shown in [5] that the delayed switching allows to create a current ramp and hence to obtain the pulse shape which is necessary for the compensation. Since drive beam combination factor in CLIC is 24, there are 23 switching times  $T_{SWITCH}$  in the drive beam injector [1]. To find the optimum combination of switching time delays which give the best energy spread in the main beam the following goal function is minimized:

$$\max_{n=1, N_B} |V_{loaded}(t_n(T_{inj}), T_{SWITCH}) - \langle V_{loaded} \rangle| \rightarrow 0,$$

where  $t_n$  is the time for the  $n$ -th bunch. This function gives us  $N_B$  energy constrains which depend on switching times and injection time. Since it is a complicated (and significantly nonlinear) function of the switching times, we cannot apply any deterministic algorithms for its minimization. It is also complicated to make an exhaustive search, because possible number of the different CLIC pulses greater than  $10^{24}$ .

In such cases probabilistic (for example, genetic [7]) algorithms can be applied effectively and at the same time the computational efforts for the calculation of the goal function can be significantly reduced. Hence an effective

discrete model to calculate the goal function avoiding the full convolution calculation has been introduced. Moreover, a special genetic-like optimization algorithm has been developed for the energy spread minimization.

This optimization procedure has been applied and the results are presented below. The required level of 0.03% for the rms relative energy spread  $\sigma_E/\langle E \rangle$  has been achieved for the shortened PETS bunch response fixing  $T_{inj}$  to about 80 ns. Optimal switching time delays (difference between  $T_{SWITCH}$  and nominal 240 ns switching times) are shown in the Fig. 7.

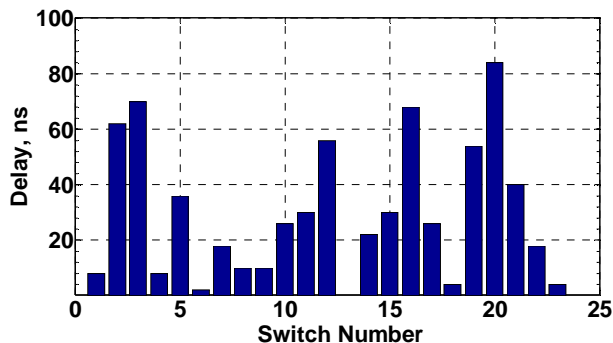


Figure 7: Switching delays for the optimal pulse generation.

The CLIC optimized pulse shape, which is determined by these delays and final relative energy spread  $\Delta E/\langle E \rangle$  in the main beam, are presented in the Fig. 8 and 9, respectively. Fig. 9 demonstrates that the relative peak to peak energy spread is around 0.08 % while the rms energy spread  $\sigma_E/\langle E \rangle$  is approximately 0.03 %.

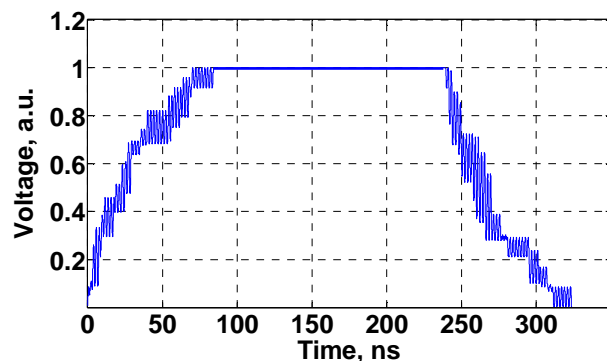


Figure 8: Envelope of the voltage for the CLIC optimized pulse.

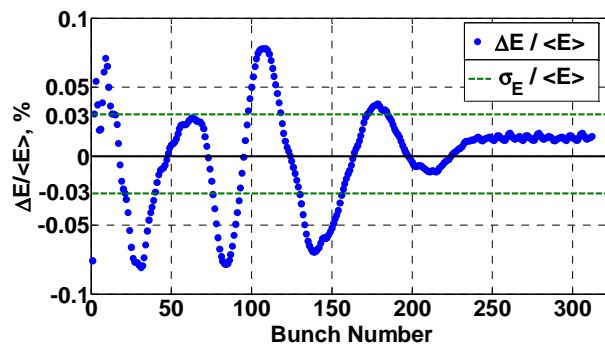


Figure 9: Optimized relative energy spread along the bunch train.

The same level of  $\sigma_E/\langle E \rangle$  was reached in the case of the full PETS bunch response including the tail caused by parasitic reflections from the PETS on/off mechanism however for different re-optimized switching time delays.

## CONCLUSIONS

A new method of calculating voltage during the transient caused by beam-loading in the accelerating structure of realistic geometries is presented. The optimization of the rf pulse shape for CLIC main linac to compensate the transient beam-loading effect on the bunch-to-bunch energy spread is developed. The results for the CLIC pulse shape optimization are presented showing that the rms relative energy spread of 0.03% required in CLIC has been achieved.

## ACKNOWLEDGEMENTS

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