# HIGHER-ORDER MODES AND BEAM-LOADING COMPENSATION IN CLIC MAIN LINAC

O. Kononenko, A. Grudiev, CERN, 1211, Geneva, Switzerland

## *Abstract*

Compensation of transient beam loading is one of the major performance issues of the future compact linear collider (CLIC). Recent calculations, which consider the most important fundamental mode, have shown that the 0.03% limit on the rms relative bunch-to-bunch energy spread in the main beam can be reached by optimizing the RF power pulse shape for the TD26, the CLIC baseline accelerating structure. Here we perform an additional dedicated study of the influence of higher-order modes on the energy spread compensation scheme. It is demonstrated that taking these modes into account in the accelerating structure does not increase the rms energy spread in the main beam above the CLIC specification level.

## INTRODUCTION

In order to have a luminosity loss of less than 1% in CLIC [1] interaction point, the rms bunch-to-bunch relative energy spread in the main beam must be below 0.03% [2]. However, at the beginning of the bunch train each bunch gains a different energy due to the transient beam-loading effect. A new model to compensate for the transient beam loading in the CLIC main linac has been developed recently in [3]. It takes into account the exact 3D shape of the CLIC accelerating structures as modelled in commercial software HFSS [4] including couplers and the CLIC specific RF pulse generation scheme.

Unloaded and loaded voltages seen by the beam have been both calculated in [3] taking into account structure's frequency response for the port excitation and beam coupling impedance in the frequency range of 11.5-12.5 GHz. This corresponds to the bandwidth of the fundamental TM$_{01}$ mode in the CLIC baseline accelerating structure. In CLIC the power source is 11.994 GHz power extraction and transfer system (PETS) [7] so indeed only the fundamental mode will be excited by the feeding pulse at this frequency. On the other hand, the main beam travelling through the accelerating structure excites higher-order modes (HOM) up to the frequencies limited by the bunch length, which is 44 um in CLIC [1].

In this paper we investigate the influence of higher-order modes on the energy spread compensation scheme. We also perform a comprehensive comparison of the results obtained with HFSS results with those from the massively parallel electromagnetic code ACE3P [5] and the commercial software GdfidL [6].

## UNLOADED VOLTAGE

Unloaded voltage in the accelerating structure is calculated in HFSS using port excitation which is described schematically in Fig. 1 (top). Here we use ACE3P electromagnetic codes to benchmark HFSS results for the fundamental mode.

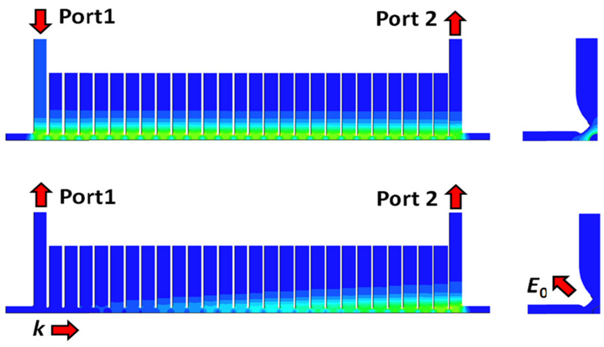

Figure 1: Electric field distribution for port (top) and plane wave (bottom) excitations.

We have simulated ¼ of the TD26 accelerating structure with magnetic walls on the symmetry planes and finite conductivity (copper) on the exterior in HFSS driven mode solver and s3p, the frequency domain solver for ACE3P. In Fig.2 the reflection parameter S$_{11}$ is presented as calculated in using both programs for 10 MHz bandwidth which includes the CLIC main linac operating frequency of 11.994 GHz.

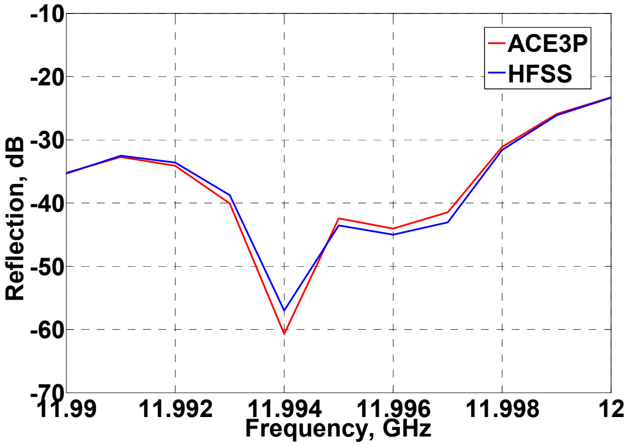

Figure 2: Reflection coefficient s$_{11}$ calculated in HFSS and ACE3P for port excitation.

The complex magnitude of the longitudinal component of electric field along the beam axis is presented in Fig.3, while in Fig. 4 E$_z$ is shown in the complex plane. Since there is an uncertainty in the field phase on the port we have selected the appropriate zero phase. As illustrated, there is a good agreement between HFSS and ACE3P frequency domain solvers and the difference is at the level of several percents.

ISBN 978-3-95450-115-1

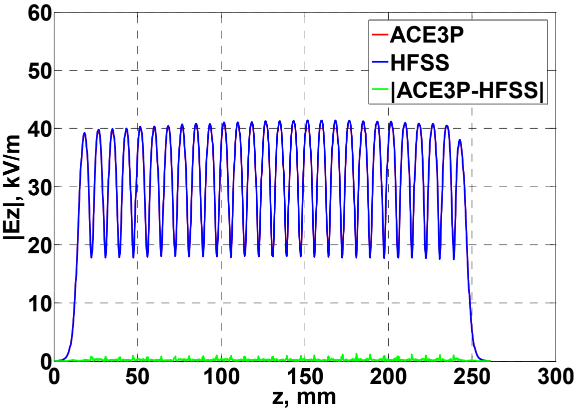

Figure 3: Complex magnitude of the longitudinal component of electric field calculated in HFSS and ACE3P.

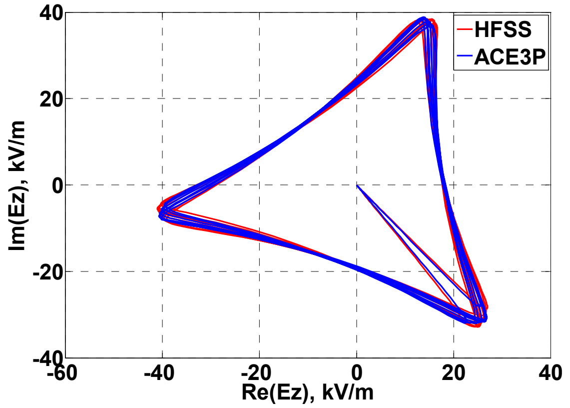

Figure 4: $E_z$ in complex plane calculated in HFSS and ACE3P.

## BEAM-LOADING

To take into account higher-order modes excited by the beam, we have used the plane wave excitation in HFSS described in [3] in detail and illustrated in Fig. 1 (bottom). We have also used ACE3P and GdfidL to benchmark these results in time and frequency domains. Basic parameters of the performed simulations are gathered in the Table 1.

Table 1: Simulation Setup

| Software | Exterior | Bunch, sigma | Domain |
|---|---|---|---|
| HFSS | Copper | - | Frequency |
| ACE3P | PEC | 1mm | Time |
| GdfidL | PEC | 1mm | Time |

In Fig. 5 we present beam coupling impedances as calculated in HFSS, ACE3P and GdfidL for the 12-26 GHz frequency range. The first monopole HOM band has been identified between 23.5 and 26 GHz and presented in Fig. 6. It can be seen that ACE3P results are slightly different from the HFSS/GdfidL ones. Effect of detuning can also be clearly observed in this Fig 6.

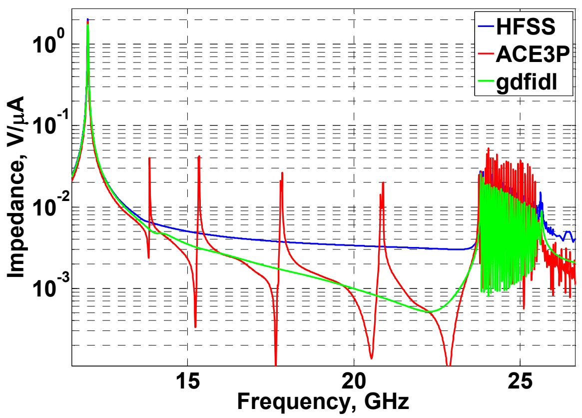

Figure 5: Beam coupling impedance as calculated in HFSS, ACE3P and GdfidL.

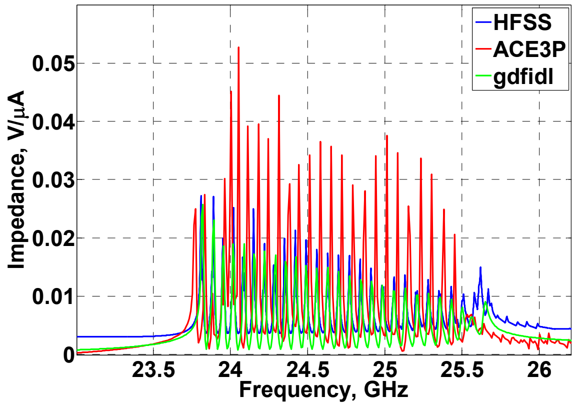

Figure 6: Beam coupling impedance for the first monopole HOM band.

In Fig. 7 we show envelope of the longitudinal wake as calculated in ACE3P and GdfidL. For HFSS we present convolution of wake function with 1 mm sigma bunch.

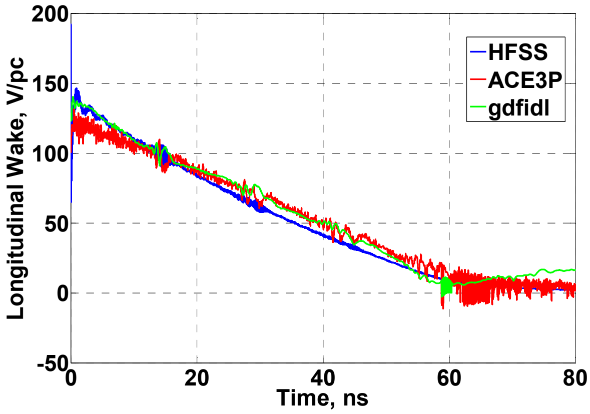

Figure 7: Envelope of the longitudinal wake for HFSS, ACE3P and GdfidL.

It can be seen that HFSS and GdfidL are consistent during the first 20ns, while ACE3P and GdfidL are in better agreement from 20ns up to filling time of the TD26 structure (around 60ns) since they both have no Ohmic losses included in the simulation setup. It worth also to mention that the GdfidL wake (green line in Fig.7) starts to rise after the filling time of the structure. We believe this to be a result of a mismatch of the coupler cells caused by the finite mesh size, 50 um in this case.

In order to investigate energy spread in CLIC caused by the ACE3P and gdfidl wakes an additional dedicated study which involves simulations with the copper exterior is required.

## BEAM-LOADING COMPENSATION

Here we consider an RF pulse shape developed in [3] to compensate for the energy spread in main beam to the CLIC required 0.03% energy (see Fig. 8). This pulse has been derived for 1 GHz bandwidth of the simulated beam coupling impedance in HFSS and is defined by the optimized buncher delays [3] and CLIC specific drive-beam generation scheme [1].

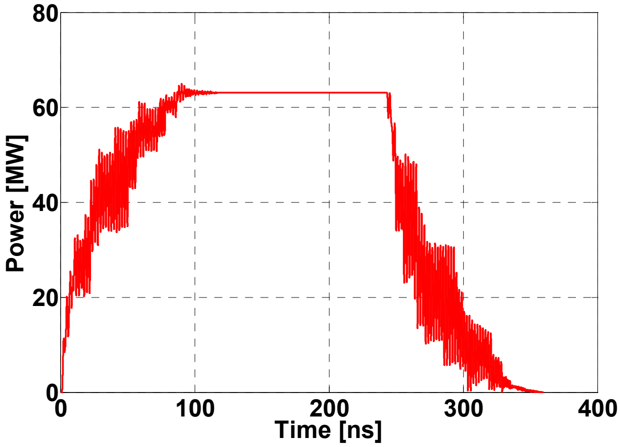

Figure 8: Input power of the CLIC optimized pulse.

In Table 2 we show rms of the relative bunch-to-bunch energy spread in the main beam for this optimized pulse shape and fixed injection time of about 88ns for the fundamental mode (0.6 and 1 GHz bandwidths) and including the first monopole HOM band (30 GHz bandwidth). In Fig. 9 we also present relative bunch-to-bunch energy spread along the main beam. It can be seen that higher-order modes have almost no impact on the beam-loading compensation scheme and rms of the energy spread stays within the CLIC required 0.03% level even without any additional pulse shape/injection time optimization.

Table 2: RMS of the relative bunch to bunch energy spread versus coupling impedance bandwidth simulated in HFSS

| Bandwidth, GHz | rms(ΔE) /<E>, % |
|---|---|
| 0.6 | 0.0257 |
| 1 | 0.0253 |
| 30 | 0.0280 |

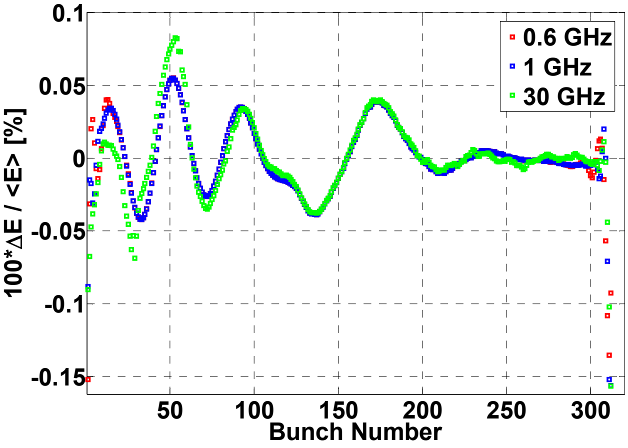

Figure 9: Energy spread in the main beam taking into account only fundamental mode (0.6 GHz and 1GHz bandwidth's) and including higher-order modes (30GHz bandwidth).

## CONCLUSIONS

A comprehensive benchmark is performed for the unloaded voltage and for the longitudinal beam coupling impedances and wakes in the TD26 accelerating structure. The technique developed in [3] has been applied to investigate the effect of the higher-order modes on the beam-loading compensation scheme for CLIC. It was demonstrated that the first monopole HOM band still can be fully compensated by the RF pulse shape derived for the fundamental mode only. Modes with the frequencies higher than 30 GHz will have even smaller impedances and hence almost no impact on the energy spread on the level of 0.03%.

## ACKNOWLEDGMENT

Authors are grateful to A. Candel, C. Ng and K. Kwok for their help and support in using ACE3P codes.

## REFERENCES

[1] CLIC Study, http://clic-study.org
[2] F. Tecker, Report No. CLIC-Note-764, 2008.
[3] O. Kononenko and A. Grudiev, Transient beam-loading model and compensation in Compact Linear Collider main linac, Phys. Rev. ST Accel. Beams 14, 111001 (2011)
[4] Ansoft HFSS, http://www.ansoft.com/products/hf/hfss/
[5] ACE3P electromagnetic codes, http://www.slac.stanford.edu/grp/acd/ace3p.html
[6] The GdfidL Electromagnetic Field Simulator, http://www.gdfidl.com
[7] I. Syratchev, D. Schulte, E. Adli, and M. Taborelli, Proceedings of the 22nd Particle Accelerator Conference, Albuquerque, NM, 2007 (IEEE, New York, 2007), pp. 2194–2196.