LONG RANGE WAKEFIELDS IN THE SwissFEL C-BAND LINAC

A. Citterio, M. Aiba, R. Zennaro,
Department Large Research Facilities, Paul Scherrer Institute, 5232 Villigen, Switzerland

Abstract

The SwissFEL main linac consists of more than hundred constant gradient C-band accelerating structures which boost the beam energy from 410 MeV at the injector to the fina nominal energy of 5.8 GeV. With a repetition rate of 100 Hz, two bunches per pulse can be accelerated with a spacing of 28 ns to feed simultaneously two different FEL arms [1]. Rising of the long range wakefields both longitudinal and transverse, could affect this multibunch operation, causing degenerative effects on the quality of the second bunch. A direct computation of the longitudinal and transverse wakes by means of time domain simulations is compared with a model based on the computation of the dispersion curves of the wake modes by frequency domain simulations. A good agreement is obtained for both the synchronous frequency and impedance of all the main modes contributing to the wakefields Moreover, the total longitudinal wake at 28 ns is below the tighter tolerances required by the beam dynamics, so that neither Higher Order Modes (HOMs) nor beam loading require compensation. The effects on the beam of the long range transverse wakefield are also negligeable.

INTRODUCTION

The C-band accelerating structures are divided in 25 RF modules, each module being composed of four, 2 m long accelerating structures, one pulse compressor, one 50 MW, 3 µs pulse length klystron and one solid state modulator [2]. The bunch operation modes include the single bunch and the two-bunch mode.
In order to defin the bunch distance to be used in multibunch regime, the frequencies of the SwissFEL injector and C-band linacs must be taken into account. The SwissFEL booster linac, composed of six constant-gradient $2\pi/3$ travelling-wave accelerating structures, was originally designed to operate at the S-band European frequency of 2997.912 MHz. The C-band linac instead will operate at the American C-band frequency of 5712 MHz, this choice being dictated by the large availability in the market of the klystrons and RF components at this frequency. Thus, the minimum bunch distance will correspond to a common subharmonic between the American C-band frequency and a modifie European S-band frequency which doesn't move away too much from the design European frequency, allowing to operate again with the current European S-band booster linac. The common base frequency chosen is 142.8 MHz, corresponding to a minimum bunch distance of 7 ns and a new European S-band frequency of 2998.8 MHz.

Due to the frequency constraints, the two bunches will be separated by a multiple of 7 ns, the fina operating distance being determined by the design of the switching magnet, power requirements and wakefields In order to keep the nominal 53 MeV energy gain per accelerating structure with a 40 MW klystron output power and 3 µs pulse length (nominal setting before the switch yard), the pulse compressor operations, especially if done by phase modulation and detuning, require more power for larger bunch spacing. With this criteria, a 28 ns bunch distance corresponds to the maximum bunch spacing wich satifie the power requirements in pulse compressor operation, allowing also a simple design of the switching magnet. The effect of the long range wakefield for such a separation will be analyzed in the next sections.

MODEL COMPUTATION

The C-band accelerating structure consists of 110 cells, including the two coupling cells, and operates at 5712 MHz with a $2\pi/3$ phase advance. The wall cells are double rounded, the iris radius varies from 7.259 mm to 5.614 mm, the cell radius from 22.473 mm to 22.004 mm. The cells have elliptical-shaped irises to decrease the peak surface electric fiel [1]. In a quasi-coupled approximation [3], wakefield generated by the leading bunch acting on the second trailing bunch can be regarded as a sum on modes, each one of them has its particular fiel pattern and oscillates with its eigenfrequency ω_s:

$$W = 2 \sum_{modes} \sum_{cells} K_{s,i} \cdot exp\left(j\omega_{s,i} t \cdot \left(1 + \frac{j}{2Q_{s,i}}\right)\right) \quad (1)$$

For each mode, the longitudinal and transverse synchronous kicks, $K_{s,l}$ and $K_{s,t}$ respectively, are define as:

$$K_{s,l} = \frac{\left|\int E_z(z) \cdot e^{jkz} dz\right|^2}{4U} \text{ [V/pC]} \quad (2)$$

$$K_{s,t} = \frac{\left|\int E_z(r_0, z) \cdot e^{jkz} dz\right|^2}{kr_0^2 \cdot 4U} \text{ [V/pC/mm]} \quad (3)$$

In formulas 2 and 3, $E_z(r_0, z)$ is the electric fiel at a displacement r_0 from the axis, U is the energy stored in the mode and $k = \omega_s/c$.
The wakefiel analysis takes into account the 108 regular cells of a single C-band accelerating structure, neglecting the effect of the input and output J-type couplers. In fact, because they are not symmetric on the longitudinal plane, they cannot be simulated whitout considering the full geometry of the structure, with a considerable growth of the

simulation time. The approximated geometry will cause an obvious overestimation of the wake envelope, trapping the wakes inside the structure instead of fl wing through the couplers. This conservative approach in the evaluation of the wake envelope is applied also to the Eq. 1, where the losses, represented by the quality factor Q_s, are not considered. This choice is dictated by the comparison between a computation model using HFSS simulations [4] and Particle Studio wake simulations [5], which don't foresee losses. The time decay of the wakes presented in the next section is then determined only by the synchronous frequency distributions. The results about the longitudinal wakefield will be however postprocessed in a fina step introducing a Q factor equal to 10500 ($\sim Q$ of the fundamental mode), constant for each Higher Order Mode (HOM), showing a negligeable gain in the wake envelope at 28 ns. The most relevant HOM passbands in the frequency domain were obtained performing at firs HFSS simulations: for f ve accelerating cell geometries (cells n. 1, 25, 53, 80, 108), the dispersion curves at f ve relevant phase advances were computed by a polynomial fit The intersection points of the corresponding synchronous line indicate the synchronous frequencies of the Eq. 1. These frequencies will be used for further HFSS simulations to get the synchronous kicks and phase advances. A the end of the process, the synchronous frequency and kick distributions are known and the wake envelope can be represented by the Eq. 1. The results obtained, referred to a point-like beam size, are finall compared with a Particle Studio simulation in a fin mesh, where their spectra are normalized to the frequency dependent form factor in a post-processed step.

RESULTS

Longitudinal Wakefields

Taking advange of symmetry considerations, one quarter of a single C-band accelerating structure was simulated in Particle Studio. For the longitudinal wake evaluation, a mesh of $93.5 \cdot 10^6$ tetrahedral cells with 0.2 mm edge length was used. The simulated beam bunch has a gaussian profil with a size of $\sigma_z = 1.5$ mm. Figures 1 and 2 show the total longitudinal wake envelope and its frequency spectrum (fundamental mode and HOMs) obtained for both computation methods. At 200 pC, the nominal σ_z at the entrance of the firs linac is 124 µm.

The pulse-to-pulse stability requirement at 200 pC operation regime for the first most critical, C-band Linac is $6 \cdot 10^{-5}\ \Delta V/V$ [6]. In terms of wakefiel this corresponds to a charge fluctuatio of 5.3%, which is much less than the expected pulse-to-pulse charge instability ($\leq 1\%$).
The HOMs contribute to the wakes with 7 bands up to 33 GHz. Filtering from the Fig. 1 the fundamental mode, it is possible to obtain the HOM envelope. Their sum is shown in Fig. 3.

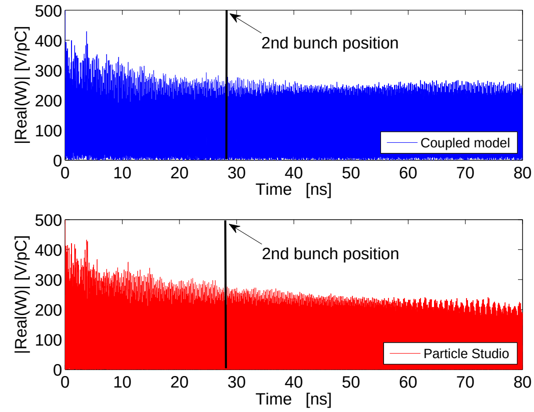

Figure 1: Time behaviour of the long range longitudinal wakefield for fundamental mode plus HOMs computed by fittin dispersion curve method (blue line) and Particle Studio (red line). The critical wakefiel corresponding to the nominal 1% of charge fluctuatio is equivalent to 1590V/pC.

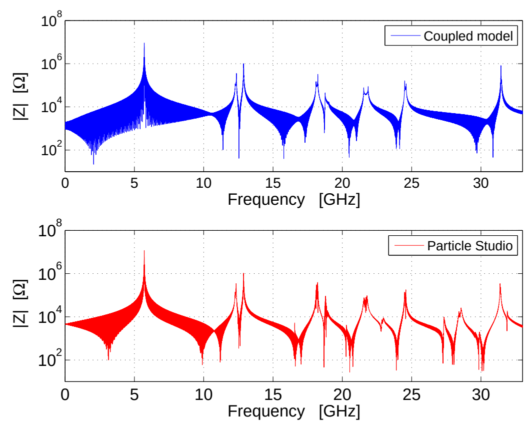

Figure 2: Impedance spectrum of the long range longitudinal wakefield produced by fundamental mode plus HOMs.

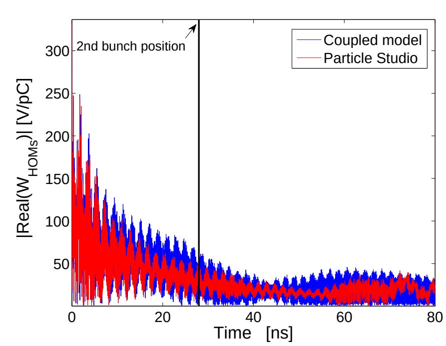

Figure 3: HOM contribution to the long range longitudinal wakefields

Transverse Wakefields

Concerning the transverse wakefields one quarter of accelerating structure was meshed in Particle Studio with

$38.8 \cdot 10^6$ cells with a 0.2 mm edge length. The transverse wakes were generated by a beam bunch with gaussian profil ($\sigma_z = 2$ mm) moving at 1 mm offset from the geometrical axis. As usual, the wake envelope and impedance, plotted in Figures 4 and 5, are normalized to the form factor.

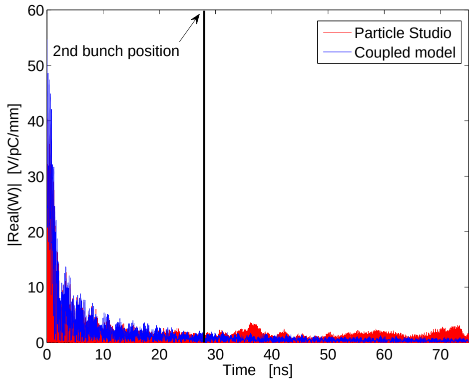

Figure 4: Time behaviour of the long range transverse wakefields

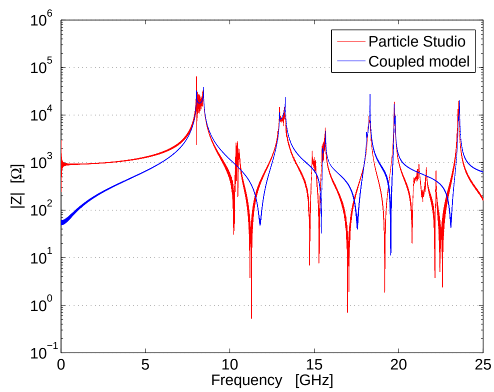

Figure 5: Impedance spectrum of the long range transverse wakefields

Six relevant bands fil the frequency spectrum up to 25 GHz. To keep a conservative approach to the Fig. 4, at 28 ns a trailing charge experiences a transverse wake of 5 V/pC/mm. In order to check the effect of such a transverse wake, a simulation was performed in MADX tracking the leading and trailing bunches. A random displacement to C-band cavities was introduced with 100 µm rms. Then, at the switch yard, the statistics of the position of the second bunch relatively to the firs one was collected, showing a distribution with $\sigma = 6$ µm.

The σ in Fig. 6 refers to a static approach where the charge of the bunch doesn't change. If, however, 1% of charge fluctuatio is taken into account, a factor 100 is gained, so that 60 nm is obtained for the beam jitter, which is largely inside the tolerances.

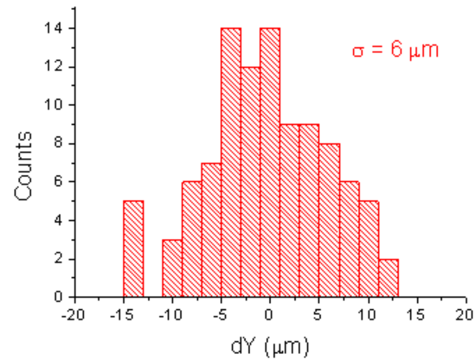

Figure 6: Relative position of the trailing bunch under the effect of a 5 V/pC/mm transverse wakefields

AKNOWLEDGEMENTS

This wakefiel analysis tooks advantage of stimulating discussions and precious suggestions by M.M. Dehler, his contribution being very useful to understand and to properly face up to a so important topic.

CONCLUSION

The two computation methods show a very good agreement for both the longitudinal and transverse wakefields both for the synchronous kick and frequency distributions. Eq. 1, usually referred to the transverse wakes, is a good approximation also for the longitudinal case. The beam dynamic constraints are satisfie by the current C-band Linac design, the HOMs being neglectable at 28 ns. Moreover, the beam loading effect requires no compensation, simplifying the pulse compressor operation.

REFERENCES

[1] R.Ganter et al. SwissFEL CDR, report n.10-04, V19, 3.3.2011

[2] R. Zennaro, J. Alex, M. Bopp, H. Braun, A. Citterio, H.R. Fitze, M. Pedrozzi and J. -Y. Raguin, "Conceptual Design of the C-band Module for the SwissFEL", Linac2010, Tsukuba, September 2010, TUP001, p. 392.

[3] K.L.F. Bane, R.L. Gluckstern, "The Transverse Wakefiel of a Detuned X-band Accelerator Structure", SLAC-PUB-5783, March 1992.

[4] `http://www.ansoft.com/products/hf/hfss/`.

[5] `http://www.cst.com/Content/Products/PS/Overview.aspx`.

[6] S. Reiche, private communication.