NUMERICAL VALIDATION OF THE CLIC/SwissFEL/FERMI MULTI PURPOSE X BAND STRUCTURE*

M. Dehler, PSI, Villigen PSI, Switzerland
A. Candel, L. Lee, SLAC National Laboratory, Menlo Park, USA

Abstract

Currently an X-band traveling wave accelerator structure is fabricated in a collaboration between CERN, PSI and Sincrotrone Trieste (ST). PSI and ST will use it in their FEL projects, CERN will test break down limits and rates for high gradients. A special feature of this structure is two integrated wake field monitors monitoring the beam to structure alignment. The design used the classical approach to model individual components and to assume the overall behavior to be the simple superposition of the results. This technique is known to produce valid structure designs. To get a full view of the structure's properties, we followed that by a numerical electromagnetic simulation validation of the full structure to see effects such as internal reflections inside the structure or higher order dispersive terms. Using SLAC's high-performance electromagnetic code suite ACE3P, first results were obtained for the fundamental mode and the lower transverse modes.

INTRODUCTION

Both FEL projects, SwissFEL and Fermi-Elettra each require an X-band RF accelerating structure for optimal bunch compression at the respective injectors[1]. As CLIC[2] pursues a program for producing and testing X-band high-gradient RF structures, a collaboration between PSI, ST and CERN has been established to build a multi-purpose X-band accelerating structure.

Table 1: Specifications

Beam Voltage	30 MeV
Max. Power	29 MW
Iris diameter	9.1 mm (avg.)
Wake field monitors	up/downstream
Operating temp.	40 deg. C
Fill time	100 ns
Repetition rate	100 Hz

The structure has a $5\pi/6$ phase advance and an active length of 750 mm. RF power is coupled in an out using the SLAC mode launcher. Its purpose is not to test higher order mode damping. Also, the FEL projects do not need extremely low long range wakes, so no HOM damping is used. But minimizing transverse kicks due to single bunch wakes by a good structure to beam alignment is critical for the FEL performance, so that two wake field monitors with a theoretical resolution of 10 μm were included. Table 1 gives the basic specifications.

The design process used an uncoupled model for the accelerating mode: all components, power couplers, matching cells, accelerating cells are designed individually and the overall behavior is given by a simple superposition of all. A more refined equivalent circuit[3] was used to model transverse higher order modes and the wake field monitors.

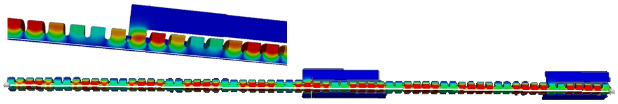

Figure 1: Cut through structure showing magnitude of electric field: bottom full structure, top zoom on a wake field monitor.

This approach produces valid structure designs, but gives only limited information about the behavior of the real structure. So a validation with modern high performance codes is needed to capture deviations in the behavior due to higher order effects not described by the design models and to have a final proof of principle for the structure. One example for a higher order effect is, that the two wake field monitors present sudden jumps in the otherwise smooth variation of the RF parameters over the structure and this shows up as additional internal reflections, standing wave patterns and probably lowered break down limits. Also, we have power couplers and special matching cells, which alter the dipole mode spectrum and influence the wake field.

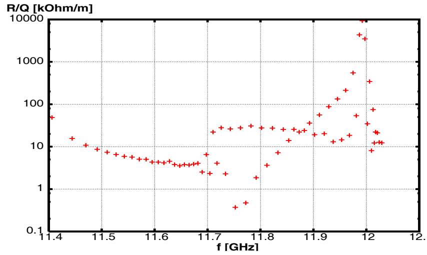

Figure 2: R/Q for modes in the fundamental band

The validation was done with the ACE3P, a family of massive parallel electromagnetic codes. We present results for the accelerating mode and the lower dipole bands and compare them with those from the simplified models.

THE ACCELERATING MODE

For the eigenvalue analysis with Omega3P[4], power couplers and matching cells were omitted in the calculation giving a 66 cell sub structure. Profiting from the double symmetry, a quarter of the geometry was discretized with 500'000 elements. Optimum accuracy was obtained by using third order basis functions resulting in an eigenvalue problem with approximately 10 million unknowns.

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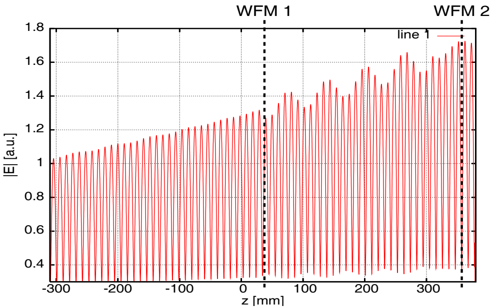

Figure 3: Absolute electric field of main accelerating mode on axis

Figure 1 shows the structure with the magnitude of the electric field of the accelerating mode indicated in the color shading and figure 2 the spectrum of the fundamental monopole band. The main accelerating mode with an R/Q near 10 kΩ/m has a computed loss free resonance frequency of 11.99235 GHz. Including conduction losses via the power loss method lowers it further to f=11.9912 GHz, which corresponds extremely well to the design frequency of f=11.991648 GHz. The deviation is only 450 kHz – a relative error less than $4 \cdot 10^{-5}$!

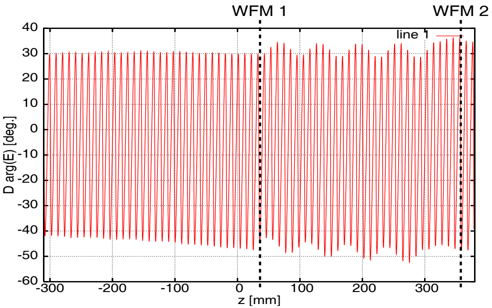

Figure 4: Phase error of electric field through the structure

Figures 3 and 4 show the on axis distribution of amplitude and the phase advance error of the main accelerating mode. The simulation does not include any attenuation, so the increase in amplitude from the beginning to the end is to be expected. The global variation of the phase error is excellent, the phase drift over the whole length is minimum (The fast oscillation per cell is an artifact due to the fact, that we subtracted a simple linearly varying phase advance).

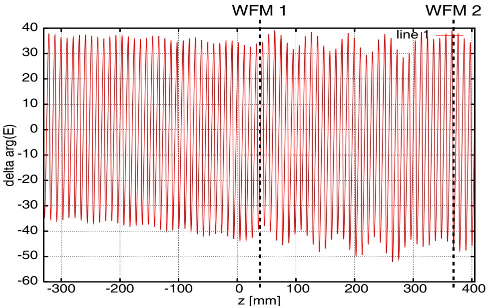

Figure 5: Phase error of electric field through the structure when driving it via the power couplers

A quite interesting thing to note is the standing wave pattern between both wake field monitors, which appears in the amplitude as well as the phase error. These reflections are probably due to higher order effects as different multipolar components in the eigen fields. They cancel out mutually, so that the standing wave does not extend beyond the region between the monitors. Including conduction losses and computing the structure as driven via the input port does not change the picture as can be seen in figure 5.

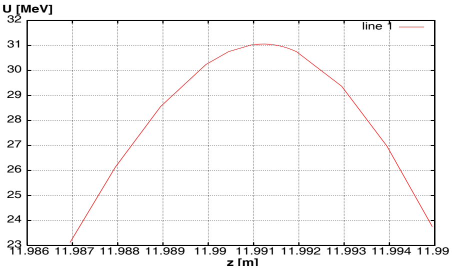

Figure 6: Beam voltage versus frequency at nominal power (29 MW)

As mentioned, we did an analysis of the scattering parameters using S3P[5]. The full structure including power couplers and matching cells was modeled and also wall losses were taken into account. Due to internal restrictions in the code, we were only able to use second order basis functions, at a price of a somewhat higher error. Figure 6 plots the variation of the beam voltage with the frequency. Conforming to specification, a nominal input power of 29 MW produces an acceleration of 31 MeV. Including the attenuation gives a constant on axis gradient throughout the structure and both amplitude (not shown) and phase error (Fig. 5) show the reflective behavior of the wake field monitors seen already with Omega3P.

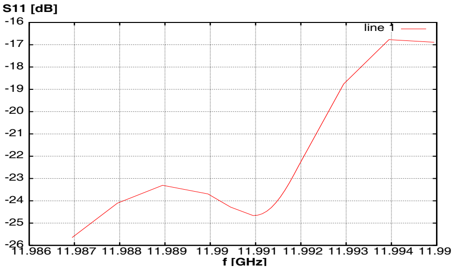

Figure 7: Input match versus frequency

The computed match (Fig. 7) of -24.7 dB is actually poorer than the design value, but still acceptable. The exact source of this deviation is still unknown.

TRANSVERSE WAKE FIELDS

In the design, transverse wakes as well as the wake field monitors signals were modeled with an equivalent circuit[3], where a double chain of LC resonators describes the two lowest dipole bands. In the following, we look at the quality of the results for the wakes and beam impedances.

We started with an eigenvalue analysis of the structure omitting the mode launchers. The signal outputs of the

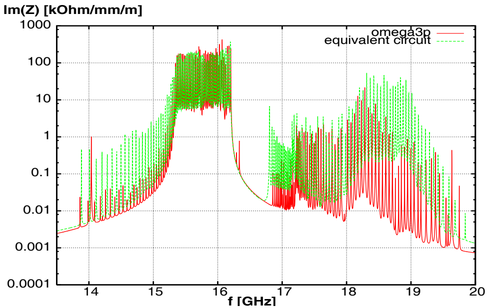

Figure 8: Imaginary transverse beam impedance versus frequency

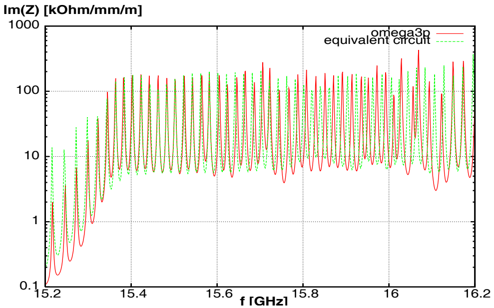

Figure 9: Imaginary transverse beam impedance versus frequency (Zoom)

wake field monitors were shorted electrically. Systematic differences between the equivalent circuit and the numerical model are the use of matching cells instead of standard ones and the shorted monitor waveguides. Given the computed resonant frequencies, kick and quality factors, the beam impedance was computed.

Figure 8 shows the comparison with the equivalent circuit model. A well known effect is the overestimation of the impedance in the upper dipole band between 16.8 and 20 GHz by the equivalent circuit. Standing waves in the shorted wake field monitor outputs produce additional resonances near e.g. 14 and 16.4 GHz.

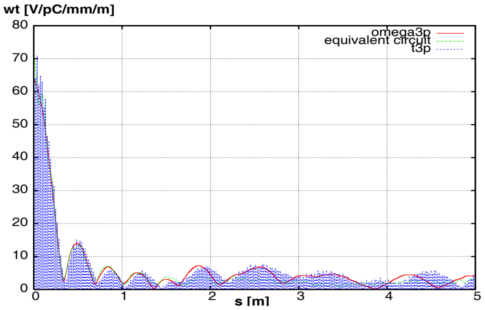

Figure 10: Comparison of wake functions

The dominant contribution for the wake comes from the lower band, the corresponding impedance is plotted in figure 9. We see how the matching cells at the extremes of the structure affect mainly the dipole modes at the lower and upper end of the spectrum. Amplitude and location of the resonance peaks fit very well in the middle, whereas to the sides, deviations become more and more pronounced.

For the comparison of the wake functions, we added a wake field computation using T3P. The full structure, including power couplers and matching cells, was calculated. The signal outputs of the wake field monitors were terminated with general purpose absorbing boundary conditions. The bunch length used in the simulations was 0.8 mm r.m.s. and results were scaled up accordingly to be comparable to the wakes generated from the beam impedance calculation.

Figure 10 compares all results. The main difference between the Omega3P runs and the equivalent circuit is in the magnitude of the second dipole band, from $s = 1.6m$ on the curves start to diverge. The wake field computation adds damping by the wake field monitors and the power couplers, plus we see contributions from third and higher order dipoles. The computed wakes fits the results from Omega3P very well with minor divergences after $s = 3.7m$.

CONCLUSION AND OUTLOOK

Using the high-performance electromagnetic code suite ACE3P, we performed an in depth validation of the design of the new multi purpose CLIC/PSI/FERMI X Band structure. With the exception of a slightly disappointing, yet still acceptable, power input match, results for the accelerating mode are excellent. The accuracy of the resonant frequency will essentially be determined by mechanical tolerances and not the approximation errors of the design process. Higher order effects such as internal reflections from the wake field monitors were visible, but not at a critical level. The agreement of transverse impedances and wakes with those obtained from an equivalent circuit model is good, adding e.g. couplers into the simulation did not create new dramatic effects.

The validation is continuing. The next steps are to calculate the response of the wake field monitor and to look at the effect of internal misalignments in the structure on wakes and the wake field monitor resolution.

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