SHORT RANGE WAKEFIELDS IN MAX IV AND FERMI LINAC

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Abstract

Ultra-short electron pulses suffer from transverse wake fields resulting in a degradation of the beam quality. Since transverse emittance is a crucial parameter for FEL drivers, a careful characterization of wakefields is necessary in the design and commissioning phase of a high-brightness linear accelerator.

In this paper we investigate the effect of transverse wakefields in the MAX IV linac. Estimations of the wakepotentials have been done with 2D modeling of the accelerating structures as well as with analytical models. In addition, electron beam effects caused by transverse wakes were studied at FERMI@Elettra [1] to verify the accuracy of the corresponding wakefield model in elegant [2].

INTRODUCTION

MAX IV Laboratory in Lund, Sweden, is now under construction. It will consist of a 300 m long S-band linac used for injection and top up of two storage rings and at the same time provide a high-brightness beam to a short pulse facility (SPF) [3]. A possible future extension for a free electron laser (FEL) is also considered.

An excellent beam quality is required for a high-brightness accelerator, hence the knowledge of beam quality degradation such as short range wakefields in the accelerating structures have to be carefully investigated. Results from simulations performed in a previous study [4], report negligible influence from the transverse wakefields on the beam quality, in the MAX IV linac. These simulations, however, were carried out using a wake model originally generated for LCLS at SLAC [5], as the accelerating structures of SLAC linac resemble the ones that will be used for MAX IV linac. Different from the LCLS, the beta functions in the main linac of MAX IV reaches higher values, owing to the fewer quadrupoles in the lattice, and it is therefore of special interest to find a more specific estimation of the wakefields to create a precise MAX IV model.

In this article we attempt to determine the short range wakefields in the MAX IV linac accelerating structures by using two different approaches. The first approach is an analytical approximation to obtain the short range wakefields in a simplified cavity structure. The analytical approximation is derived from high frequency impedance formula, which after Fourier transformation result in both longitudinal and transverse (dipole) wakefunctions [6, 7]. The second method is a numerical approach using ABCI, azimuthal beam cavity interactions [8], a program that computes wake potentials generated by a bunched beam passing through an axisymmetric structure.

Furthermore, we show experimental results obtained at FERMI@Elettra which are planned to be compared with the corresponding particle tracking from elegant, using wakefunctions calculated in [7].

WAKEFIELDS IN THE MAX IV LINAC

When a bunch of charged particles passes through a cavity structure it will create wakefields that will have an impact on the particle beam itself. This creates beam instabilities that decrease the beam quality considerably and in the worst case lead to beam break up. Wakefields can be classified into long and short range wakes. Bunch to bunch wake interaction, i.e. wakes created by a previous bunch affecting the following bunches, is called long range wakes, whereas short range wake describes the wakes generated within the same bunch, e.g. when the head of a particle bunch affects its own tail. Only the short range wakefields are taken into account in this article since the time between the bunches during operation in MAX IV is sufficient long to attenuate all long range wakes. From here on, all wakes are considered to be short range wakefields. Investigating the wakefields in MAX IV linac is particularly important, since the beta-functions tend to reach high values. The dipole wakes have a tendency to kick the bunch tail in a transverse direction and hence reduce the quality of the beam.

Analytical Study

The cavity model under consideration is purely periodic and cylindrical symmetric with the geometry of the cells specified in Fig. 1.

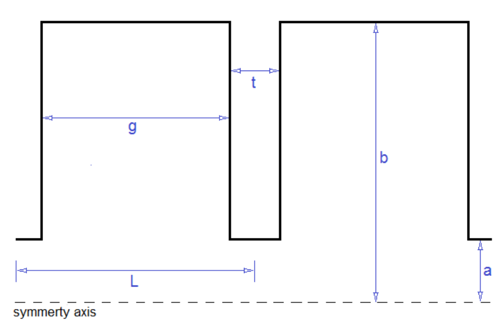

Figure 1: Geometry of the analytical cavity model with iris radius a, gap g, period L, thickness t and cavity radius b. The MAX IV accelerating structure is a constant gradient traveling wave structure composed by 156 cells with an iris radius decreasing from 14.5 to 11 mm along the beam direction. In our calculation we use the minor iris radius of 11 mm, the period L is 33.34 mm and the thickness t is of 5 mm.

ISBN 978-3-95450-115-1

Assume a charge q that moves with the speed of light on axis through the structure specified above. At a distance s behind the driving charge, a test particle will experience a certain wakefield, which can be estimated analytically. According to [6, 9], the longitudinal and transverse wakefunctions from a 1 C point-like charge in a periodic structure can be expressed as:

$$w_L(s) \approx \frac{Z_0 c}{\pi a^2}\phi(s)e^{-\sqrt{s/s_1}} \quad (1)$$

$$w_x(s) \approx \frac{4Z_0 c s_2}{\pi a^4}\phi(s)\left[1-(1+\sqrt{s/s_2})e^{-\sqrt{s/s_2}}\right] \quad (2)$$

where $\phi(s)$ is a step function, Z_0 is the impedance of free space, c is the speed of light and where

$$s_1 = 0.41\frac{a^{1.8}g^{1.6}}{L^{2.4}},\, s_2 = 0.17\frac{a^{1.71}g^{0.38}}{L^{1.17}}$$

where s_1 and s_2 are valid for $s/L \leq 0.15$, $0.34 \leq a/L \leq 0.69$ and $0.54 \leq g/L \leq 0.89$.

It is important to highlight that these equations are only valid for very short distances s i.e. roughly the length of a bunch, approximately 0.3 mm. The longitudinal and transverse wakefields generated from equation (1) and (2) are shown in Fig. 2. The wakefields shows the force a particle feels at a distance s behind the test particle. The effect of the longitudinal wakefields are inversely proportional to the distance, whereas the effect of the transverse wakefields increases with the distance. It appears the wakefunctions depend largely on the iris radius.

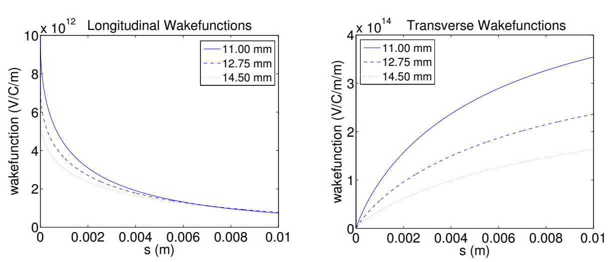

Figure 2: Analytically calculated longitudinal and transverse wakefunctions versus the distance s after the test charge. The wakefunctions are generated for different iris radius: 11, 12.75 and 14.5 mm.

Numerical Study

In ABCI, Maxwell's equations are solved directly in the time domain for a distribution of charged particles passing through an axisymmetric structure. A multi-cell model with the same parameters as specified in Fig. 1 is created. The number of cells is carefully chosen so as to obtain a steady state form of the wake functions. The number of cells N can be expressed as:

$$N = \frac{L_c}{L} = \frac{a^2}{2\sigma L}$$

where L_c is a catch up distance. In this case N=6.

In ABCI, the particle bunch is assumed to have a Gaussian particle distribution with a standard deviation, σ, of 0.3 mm i.e. 1 ps.

The resulting wake potentials generated by ABCI are shown in Fig. 3. The longitudinal and transverse wakepotentials show the force a particle experiences at a distance s behind a distribution of particles.

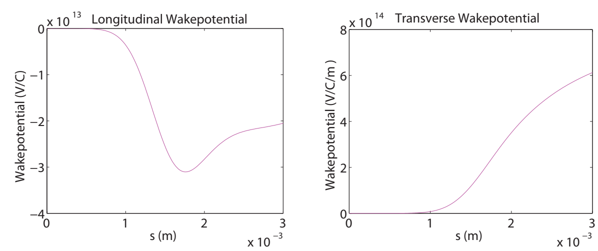

Figure 3: Wakepotentials at a distance s after the test distribution simulated with ABCI. The multi-cell model consists in this case of six cells with iris 11 mm.

Comparison of Approaches

To compare the analytical and the numerical approach, a convolution between the wakefields in Fig. 2 (iris 11 mm) and the same Gaussian pulse used in ABCI is executed. The same procedure is repeated for the wakefields originally generated for SLAC. Wakepotentials of the analytical and SLAC model are hence obtained. Figure 4 and Fig. 5 shows the longitudinal and the transverse wakepotentials for all three methods, respectively. Since the analytical approach is valid only for small distances s, a zoom covering the typical range of a compressed MAX IV pulse ($\approx$ 1 ps) is shown. As it can be seen in Fig. 4 and Fig. 5, the wakepotentials are well overlapping at short distances from the test distribution, however, at increasing distance the resemblance diminishes.

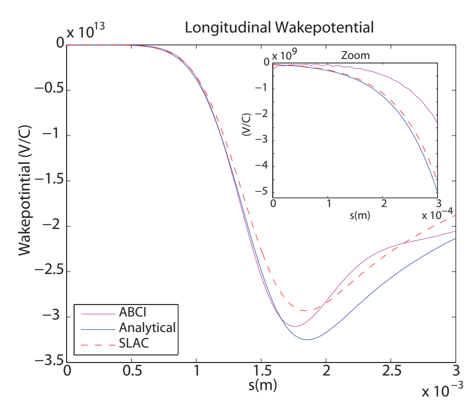

Figure 4: Comparison between ABCI, analytical and SLAC longitudinal wakepotential calculations.

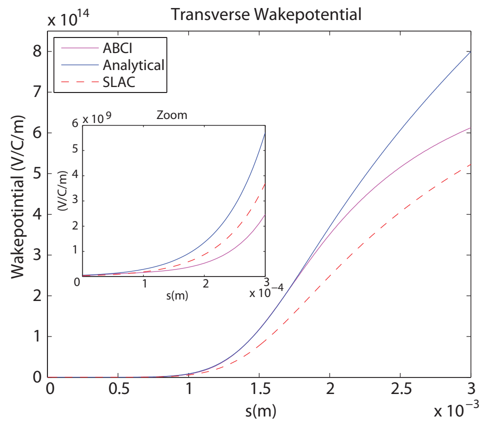

Figure 5: Comparison between ABCI, analytical and SLAC transverse wakepotential calculations.

PARTICLE TRACKING AND EXPERIMENTAL RESULTS

Experiments at FERMI@Elettra

To investigate whether the calculated approaches of the wakefields gives realistic result, we want to compare simulation with measurements from an already existing linac. Experiments were carried out at FERMI@Elettra. The main linac accelerator at Fermi consists of four linac sections transporting the beam to an undulator hall where FEL-radiation is generated and transported to the experimental areas [1]. The beam of charge 0.1 pC was displaced 1.5 and 3 mm of axis, respectively, in all five linac structures in section 4 in order to enhance the effect caused by the wakefields on the electron beam. A transverse deflecting cavity was then used to get the transverse particle positions on a screen downstream. With no compression, the bunch length was approximately 3.3 ps. Snapshots from the screen when the beam is on axis and displaced 1.5 and 3 mm, is visualized in Fig. 5. The tail of the beam receives a strong transverse kick from the dipole wakefields.

Particle Tracking with Elegant

The experiment with the FERMI linac is now to be simulated in elegant. For simplicity reasons, the entire cavity structure in the last section will be moved to simulate the displacement of the beam. The beam will be collected at the same corresponding screen as in the measurements. The cavities will be displaced 0, 1.5 and 3 mm off axis, and density plots and a comparison with Fig. 5 can be performed. Investigations are ongoing to obtain result from this study in a near future.

SUMMARY AND CONCLUSION

A comparison between analytical and numerical acquired longitudinal and transverse wakefields has been performed. Additionally, results from experiments carried out at FERMI@Elettra distinctly showed the influence of the

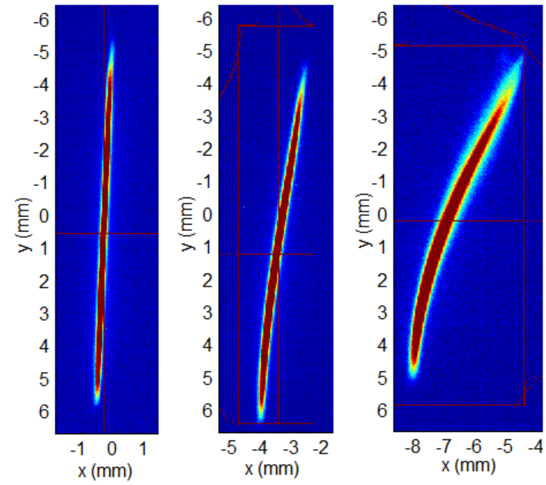

Figure 6: Measured beam profiles for different displacement of the beam (0, 1.5 and 3 mm from left to right respectively). For a misaligned beam the effects form the transverse wakefields are visible in the tail of the bunch.

transverse wakefields on the electron beam.

Wakepotentials from analytical theory, ABCI simulations and wakefields provided by SLAC seem to agree. For the range covering a typical MAX IV bunch length the three different methods appear to overlap roughly within a factor of two, however, the approaches deviates for increasing distances from the test distribution. Fortunately, the deviation occurs at the distance where the bunch has already passed the generated wakefields.

The experiments at FERMI showed clearly that the dipole wakefields kicks the tail of the beam in the transverse direction. The more the beam was misaligned the more obvious kick is observed. Beam tracking studies using elegant are still ongoing and will hopefully show the same tendency.

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ISBN 978-3-95450-115-1