SINGLE BUNCH WAKEFIELDS IN THE CERN-PSI-ELETTRA X-BAND LINEAR ACCELERATOR

M. El Ashmawy, G. D'Auria, Sincrotrone Trieste ELETTRA, Italy.
R. Zennaro, G. Riddone CERN, Switzerland.
M. Dehler, J.-Y. Raguin, Paul Scherrer Institut, Switzerland

Abstract

FERMI@ELETTRA and PSI-XFEL are 4th Generation Light Sources that require high quality electron beam at the entrance of the undulator chains. In this context, a specially developed X-band structure with integrated alignment monitors will be used to mitigate the nonlinearities in the longitudinal phase space due to the second order RF time curvature and the second order momentum compaction term of chicane compressor. The knowledge of the transverse and longitudinal short range wakefields in the X-band structure is essential to evaluate the beam quality in terms of longitudinal energy spread and transverse kick spread. We have used the ABCI code to numerically evaluate the transverse and longitudinal wake potentials for short bunches in this structure.

INTRODUCTION

FERMI@ELETTRA [1] and PSI-XFEL [2] are single pass FEL facilities in the spectral range 100 - 4 nm and 7 - 0.1 nm respectively. Both facilities foresee an ultra short and high quality electron beam needed at the entrance of the undulators. However, due to the RF time curvature of the main accelerating sections a non-linearity over the longitudinal profile of the electron bunch energy is introduced which in turn impedes the compression process in magnetic chicane leading to sharp temporal spikes in the beam current that affect the FEL process. An effective and functional method to compensate for the effect of non-linearity is to use an accelerating structure working at frequency of high harmonic of the main accelerating linacs and operating in the decelerating regime, see e.g. [3]. For that reason an X-band (12 GHz) structure is currently under development in the framework of collaboration between CERN-PSI-ELETTRA [4] and one structure will be installed on the FERMI linac before the first bunch compressor [5]. Although the X-band structure will enhance the beam quality from some point of view, on the other hand the same structure could degrade the beam quality due to the wakefields excited by the electron beam. Accordingly, the short range transverse and longitudinal wakefields should be carefully considered. In that concern, we have used ABCI code [6] to study the longitudinal and transverse wakefields behaviours for electron bunches of different rms lengths (σ: 75 – 1000 μm) travelling along the X-band structure.

X-BAND STRUCTURE

The X-band structure understudy is ≈ 1m long (73 cells) integrated with two alignment monitors in addition to two mode launchers. Fig.1 shows a cut view of the X-band structure.

* mostafa.ashmawy@lycos.com

Figure 1: Cut view of X-band structure showing the mode launchers and wakefield monitors.

LONGTITUDINAL WAKES

Longitudinal Wake Function

The longitudinal wake potentials of Gaussian bunches with different rms bunch lengths ranging from 75 μm – 1000 μm are evaluated numerically using ABCI. Fig.2 shows the simulation results which indicate that the longitudinal wake fields of all bunches tends to follow a common envelope function after a certain distance from the bunch centre. Such envelope function (shown by black dashed line in Fig. 2 (left) is known as the longitudinal wake function.

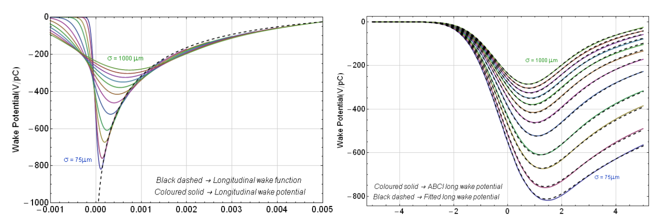

Figure 2: Left: longitudinal wake potentials (solid lines) and the longitudinal wake function (dashed line) of the X-band structure. Right: Numerical (solid lines) and analytical (dashed lines) longitudinal wake potentials normalized to rms σ of the electron bunch

Accordingly, the wake potential at any bunch length of interest could be easily found analytically by the convolution of that bunch with the wake function. By fitting the envelope of all wake potentials of different bunches we have obtained the following equation of the wake function w_l:

$$w_l = a_0 e^{\left(-\sqrt{z/b_0}\right)} + c_0 z^{d_0} \qquad V/pC \qquad (1)$$

Where a_0 = -1415, b_0 = 0.0004572, c_0 = 4500 and d_0 = 0.97. It is worthy to note that the first term in Eq.1 represents the analytical approximation of the longitudinal wake function of the TW accelerators suggested in Ref. [7] which is not in complete agreement with the data obtained by ABCI for our case specially at long bunches. The second term has been added to Eq.1 in order to approximate the analytical model of the wake function on a wider range of electron bunch lengths on one hand and to enhance the accuracy of the analytical model on the other. Fig.2 (right) shows the longitudinal wake potential obtained by ABCI and those obtained analytically using the Eq.1. The figure shows that the analytical model of the wake function represented by Eq.1 approximates very well the longitudinal wake function for a wide range of different rms bunch lengths ranging from 75 μm – 1000 μm.

Loss Factor and Energy Spread.

Once the analytical longitudinal wake function is obtained it is easy to find the relevant longitudinal wake integrals i.e. the longitudinal loss factor K_l and the rms energy spread E_l defined by the following two equations:

$$K_l = \int_{-\infty}^{\infty} \lambda(z)\, W_l(z) dz \qquad V/pC \qquad (2)$$

$$E_l = \sqrt{\int_{-\infty}^{\infty} \lambda(z)\, \left[W_l(z) - K_l\right]^2 dz} \qquad V/pC \qquad (3)$$

Where W_l is the longitudinal wake potential obtained by the convolution of the electron bunch distribution *λ(z)* with the analytical wake function given by Eq.1. Fig.3 shows the loss factor and energy spread obtained numerically by ABCI and those obtained analytically by equations 1-3 as a function of the rms bunch length. Excellent agreement between the numerical data and analytical model is observed at all bunch lengths.

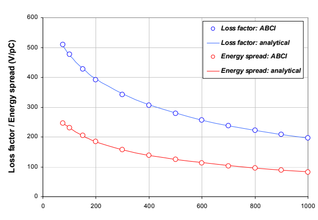

Figure 3: Loss factor (blue) and energy spread (red) obtained numerically by ABCI (circles) and those obtained analytically (lines) of the X-band structure.

TRANSVERSE WAKES

Transverse Wake Function

By the same manner, the transverse wake potentials of Gaussian bunches with different rms bunch lengths (σ: 75 – 1000 μm) are evaluated numerically using ABCI; such wake potentials are shown in Fig.4 (left). Again, the simulation results indicate that the transverse wake potentials tend to follow a common envelope function after a certain distance from the bunch centre and such function (shown by black dashed line in Fig. 4 left) is known as the transverse wake function which can be used to find the wake potential of any bunch length of interest. By fitting the envelope of the wake potentials we obtained the transverse wake function, w_T, as:

$$w_T = a_1\left(1-\left(1+\sqrt{\frac{z}{b_1}}\right)e^{-\sqrt{\frac{z}{b_1}}}\right)+c_1 z^{d_1} \qquad V/pC/m \qquad (4)$$

Where a_1 =76935, b_1 = 0.000288, c_1 = -4932100 and d_1 = 1. Similarly, the first term in Eq.4 represents the analytical approximation of the transverse wake function of the TW accelerators suggested in Ref. [7]. The second term has been added to Eq.4 for the same reasons aforementioned in the longitudinal case. Fig. 4 (right) shows the transverse wake potentials obtained by ABCI and those obtained analytically using Eq. 4. It is obvious that the analytical model (Eq.4) approximates very well the transverse wake function for bunch lengths ranging from 75 μm – 1000 μm.

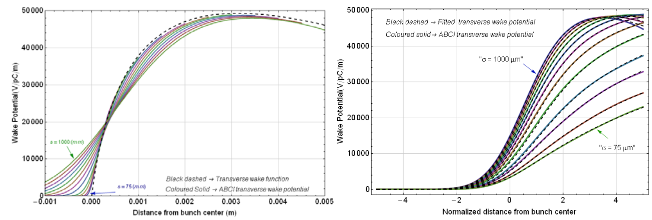

Figure 4: Left: transverse wake potentials (solid lines) and the transverse wake function (dashed line) of the X-band structure. Right: Numerical (solid lines) and analytical (dashed lines) transverse wake potentials normalized to rms σ of the electron bunch

Kick Factor and Kick Spread.

Using the analytical transverse wake function (Eq. 4) one can find the relevant transverse wake integrals i.e. the transverse kick factor K_T and the rms kick spread E_T that are defined by the following two equations:

$$K_T = \int_{-\infty}^{\infty} \lambda(z)\, W_T(z) dz \qquad V/pC/m \qquad (5)$$

$$E_T = \sqrt{\int_{-\infty}^{\infty} \lambda(z)\, \left[W_T(z) - K_T\right]^2 dz} \qquad V/pC/m \qquad (6)$$

Where W_T is the transverse wake potential obtainable by the convolution of the electron bunch distribution *λ(z)* with the analytical wake function given by Eq. 4. Fig.5 shows the kick factor and kick spread obtained numerically by ABCI and those obtained analytically by equations 4-6 as a function of the rms bunch length.

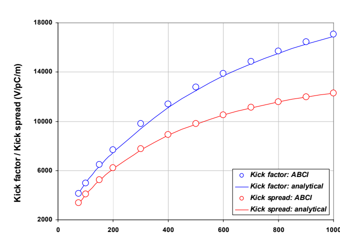

Figure 5: Kick factor (blue) and kick spread (red) obtained numerically by ABCI (circles) and those obtained analytically (lines) of the X-band structure.

Very good agreement between the numerical data and the analytical model is observed at all bunch lengths.

INDUCED ENERGY SPREAD AND DEFLECTION ANGLE

As a case of study, we will consider the nominal parameters of the electron bunch at the entrance of the X-band structure of the FERMI@ELETTRA linac to evaluate quantitatively the effect of the longitudinal and transverse wakefields; where the actual bunch distribution is considered instead of an ideal Gaussian one which will be anyhow considered in parallel just for comparison. The electron bunch at the entrance of the X-band structure is approximately 4.65 mm in length with average energy 180 MeV and charge of 0.8 nC. Fig. 6 (up) shows the actual bunch distribution compared to the Gaussian one of the same length and charge; the other two subfigures are for the longitudinal and transverse wake potentials for the bunch distributions shown in Fig. 6 (up).

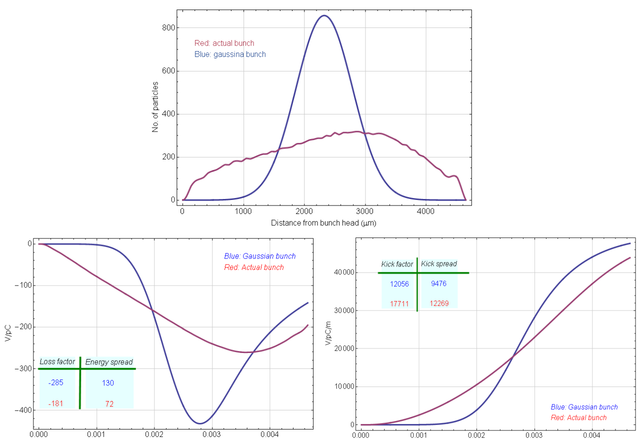

Figure 6: Longitudinal and transverse wake potentials of 4.65 mm electron bunch of Gaussian distribution (blue) and actual distribution (red). Both distributions are normalized to 1 pC.

As shown, the change in the bunch distribution causes a significant change in the wake potentials although both distributions have the same charge quantity; this in turn changes the associated wakes integrals. In the Gaussian bunch case, the effect of the wake potentials takes place dominantly at the centre of the bunch and thereafter, while in the actual bunch case the wake potential effect is observable along the entire bunch except the very start of the bunch head according to causality principle. However, particles near the tail of the bunch are still the most affected by wake potentials. The longitudinal energy spread and the transverse deflection angle induced into the actual electron bunch could be calculated by using equations 7 and 8 respectively:

$$\Delta E(z) = Q\, W_l(z) / E_0 \quad (7)$$

$$\Theta(z) = Q\, W_T(z) / E_0 \quad (8)$$

Where ΔE is the induced energy spread, $\Theta(z)$ is transverse deflection angle, Q is the total bunch charge, and E_0 is the bunch energy at the entrance of the X-band structure. W_l (z) and W_T (z) are the longitudinal and transverse wake potentials obtained either numerically or by the convolution of the wake functions with the bunch distribution. Substituting the electron bunch parameters in equations 7 and 8 one can get Fig.7.

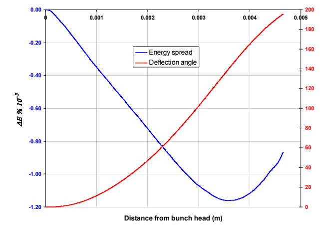

Figure 7: Induced energy spread and deflection angle due to wake potentials along the 4.65 mm electron bunch at FERMI@ELETTRA FEL.

CONCOLUSION

Longitudinal and transverse wake fields for different bunch lengths along the CERN-PSI-ELETRRA X-band structure have been calculated using ABCI code. The numerical results were used to derive approximate analytical models to evaluate the wakefields of the actual bunch parameters at FERMI@ELETTRA FEL. The results showed that there are significant discrepancies between the ideal Gaussian bunch and the actual bunch although both bunches have the same charge. Finally, induced energy spread and the deflection angle along the real bunch have been evaluated.

ACKNOLEDGEMENT

The authors undertook this work with the support of the ICTP programme for Training and Research in Italian Laboratories, Trieste, Italy

REFERENCES

[1] Swiss FEL, http://fel.web.psi.ch/

[2] FERMI@Elettra Conceptual Design Report;

[3] P. Emma "X-Band RF Harmonic Compensation for Linear Bunch Compression in the LCLS" SLAC-TN-05-004, LCLS-TN-01-1, (2001)

[4] M. Dehler, J.-Y. Raguin, A. Citterio, A. Falone, W. Wuensch, G. Riddone, A. Grudiev, R. Zennaro, "X-band rf structure with integrated alignment monitors", Phys. Rev. ST Accel. Beams, 12, 062001 (2009).

[5] G. D'Auria et al. "The X-band system for the FERMI@ELETTRA FEL project" this proceeding.

[6] ABCI website: http://abci.kek.jp/abci.htm

[7] K. Bane, "Short-range dipole wakefields in accelerating structures for the NLC", SLAC-PUB-9663, LCC-0116, (2003).