WAKE FIELD POTENTIALS OF "DECHIRPERS"*

A. Novokhatski#, SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA

Abstract

A corrugated structure, which is used in "dechirper" devices, is usually a pipe or two plates with small corrugations (bumps) on the walls. There is a good single-mode description of the wake potentials excited by a relativistic bunch if the wave length of the mode is much longer than the distance between the bumps in the pipe. However, ultra-short bunches, which are now used in FELs, excite much higher frequency fields and the corresponding wake potentials will be very different from the single-mode description. We have made analyzes of these wake potentials based on a numerical solution of Maxwell's equations. It was confirmed that the behavior of the wake fields of ultra-short bunches in corrugated structures is not much different from the fields excited usually in accelerating structures where the wake potentials are described by the exponential function. We also carried out calculations for a similar device, that was installed and measured at the Pohang Accelerator Laboratory, Korea. We find very good agreement with the experimental results.

INTRODUCTION

The precise knowledge of the wake fields generated in different elements of free electron lasers (FEL) including accelerator, beam transport and undulators has become very important with increasing power and efficiency of X-ray production. Usually it is a "negative" effect. For example in Ref.[1] it is demonstrated how the wake fields generated in collimators may decrease the FEL performance. However the effect from wake fields can also be "positive" if this field is used to improve the energy spectrum. These wake fields can be generated in the accelerator (linac) or in special devices – "dechirpers". To our knowledge this word was introduced in ref. [2] for the first time.

There are several publications which have some sort of formula for the wake fields in corrugated structures. The references to these publications can be found in Ref. [3-4]. These formulas are derived from the assumption of a single dominating mode and the Green's function for the wake potentials is described as a damped cosine function. Although they referred to our 1997 publication [5], where we found a similarity to the wake fields in corrugated structures with the fields in a tube with a thin dielectric layer, the authors do not fully analyze the applicability of the single mode approach to describe wake fields of very short bunches. A corrugated wall structure is planned for use in the device that makes an additional energy loss along the very short bunches of the LCLS [4]. It now becomes very important to check how well a single mode approach can describe the fields, that are excited in corrugated structures and perhaps another description must be used. For the FEL application the dechirper has a small sized corrugation structure, of order of millimeters. Electron bunches in the FEL have a length of micron. If we scale the bunch length together with the structure size up ten times or more we will get geometry environments that are very similar to the linear accelerating structures. As we know, the wake fields in the accelerating structures are not described by a single mode. There is another description, which contains all modes. Such as the Green's function for the TESLA accelerating structure [6] or the SLAC accelerating structure [7]. We may assume that the wake potentials of a corrugated structure excited by short bunches are also described by this or a similar function. To check this assumption we calculated wake potentials of the corrugated structure using a computer code NOVO [8], which was specially designed to calculate wake fields of very short bunches. This code has been benchmarked based on a good agreement with the wake fields measured in the LCLS-LTU [9]. Recently the code was extended for the wake field calculations in rectangular beam chambers [10].

*Work supported by DoE Contract No. DOE-AC02-76SF00515
#novo@slac.stanford.edu

A DECHIRPER

As mentioned above, a dechirper takes energy from the beam through the interaction of the bunch electro-magnetic field with a metal corrugated structure. The practical design of the dechirper consists of two identical movable parallel plates (jaws) with corrugated walls in a form of the periodic set of planar diagrams. A schematic drawing of the dechirper is shown in Fig. 1. The dechirper, which is planned to be installed at LCLS, has the following parameters of the corrugated structure. The period is 0.5 mm, the thickness of a diaphragm is a half of a period and the transverse sizes of a diaphragm are: h=0.5 mm, Lx=12 mm. Definitions of the sizes are given in Fig. 1. The total length L of the corrugated structure is 2 m. The gap between two jaws is adjustable. The nominal gap is 1.4 mm.

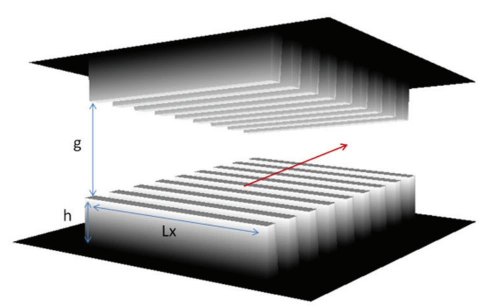

Figure 1: A schematic drawing of a dechirper. The red line shows a bunch trajectory.

ISBN 978-3-95450-134-2

We start with calculations to make a comparison with the single mode approach. We calculated wake potential of a relatively long bunch of 25 micron and for a relatively long range of distance after a bunch for a nominal gap. This wake potential is show in Fig. 2.

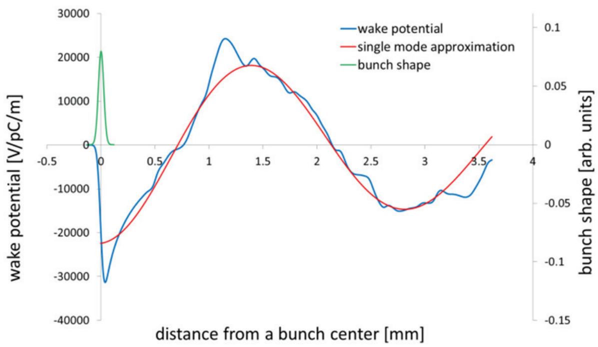

Figure 2: Wake potential (a blue line) of a 25 micron bunch passing through a 2 m rectangular corrugated structure with a full gap of 1.4 mm. The red line shows a single mode approximation. The green line shows the bunch charge distribution.

The shape of the wake potential seems to be easily fitted by a damped cosine function. This approximation is shown by a red line in Fig. 2. The frequency of this mode is 105.5 GHz or the wave length of this mode is 28.4 mm which is in agreement with calculations in Ref. [4]. However, as we can see from the plot, this fit does not give a good approximation at small distances: in the bunch region. For a shorter bunch such kind of approximation can bring much more mistake. Calculated wake potentials of 10 and of 5 micron bunches are shown in Fig. 3 by magenta and green lines. We can see a great difference in the shape of the wake potentials, which have a dependence upon the distance in this region of a bunch while the single mode approach gives an almost constant value (red line). In the Fig. 3 we also include a wake potential of a 25 micron bunch to show that all three wake potentials have a common part, which can be very well approximated by an exponential function (a pink line).

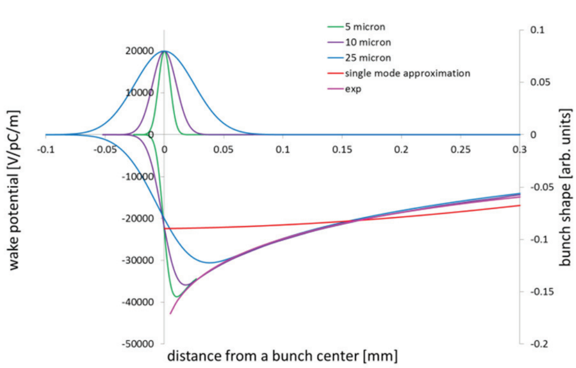

Figure 3: Wake potential of a 5 micron bunch (green line), 10 micron (magenta line) and 25 micron (blue line). The red line shows a single mode approximation and the pink line show the exponential function.

Based on this approximation we suggest using the following approximation of the Green's function for corrugated structures

$$w_{\parallel}(s) = A(g)\exp\sqrt{\frac{s}{s_0(g)}} \tag{1}$$

The fitting parameters $A(g)$ and $s_0(g)$ are functions of the gap size g (full gap). We can use this approximation as a Green's function to calculate wake potentials of bunches with any complicated charge distribution $q(s)$

$$W(s) = \int_{-\infty}^{s} q(s')w_{\parallel}(s-s')ds' \tag{2}$$

We show an example of a complicated bunch shape (two horn distribution) in Fig. 4. The bunch distribution is shown by the blue line. The "head" of the bunch is on the left.

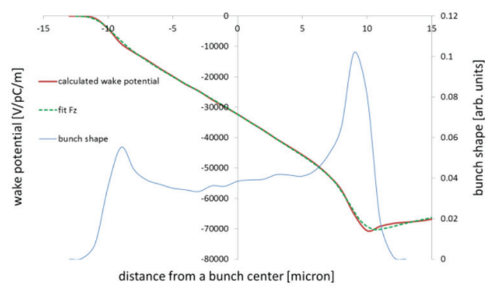

Figure 4: Comparison of the wake potential calculated using a computer code (red line) and calculated using a Green's function (green line) for a two horn bunch passing a dechirper with a 1 mm gap.

The comparison of the wake potentials calculated using a computer code (red line) and using a convolution with a Green's function (green line) is also shown in Fig. 4. We can conclude based on this good agreement, that we can use the above mentioned Green's function (1) to calculate wake fields in the dechirper. In these calculations the gap was 1 mm. It is interesting to note that the wake potential of a two horn bunch has two slopes. According to Fig. 4 we can compensate a possible energy chirp of the main part of a bunch, but the energy chirp of the second horn will be not compensated.

We made wake field calculations for different gaps in order to find approximate values for $A(g)$ and $s_0(g)$. We have found that a more or less good approximation (±5%) for A and s_0 over the range of gaps from 1 to 2 mm to be the following:

$$A(g) \approx A_0 L \frac{Z_0 c}{g^2} \qquad s_0(g) \approx g\sqrt{\frac{g}{L}} \tag{3}$$

with parameters: $A_0 \approx 0.85 \quad L \approx 55\ mm$.

ISBN 978-3-95450-134-2

TRANSVERSE WAKE FIELD

The main purpose of the dechirper is to introduce energy loss along the bunch. While interacting with a longitudinal force, which is responsible for the energy loss or gain, the particles of the bunch may also interact with a transverse force. We calculate the integral of the transverse forces (transverse kick) when a bunch is in the center of the dechirper in the vertical as well as is in the horizontal direction. A two dimensional plot of the vertical and horizontal kicks is shown in Fig. 5. The orientation of the dechirper jaws is as shown in Fig. 1.

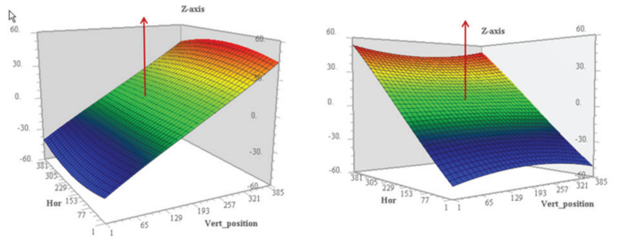

Figure 5: Integrated vertical and horizontal force distribution when a bunch trajectory lies in the center, between the jaws and in the middle of the diaphragms of the dechirper. Red arrows show the bunch trajectory.

It can be seen that the dechirper acts as a quadrupole lenses: defocusing in the direction of the jaws and focusing in the perpendicular direction. In general, we may represent the Green's function of the transverse kick using a Tailor expansion. In the vertical direction we have:

$$w_y(s,y) = w_y^0(s,y_1) + \\ + \sum_{n=1} \frac{\partial^n}{\partial y^n} w(s,y)|_{y=y1} (y-y_1)^n \quad (4)$$

When the leading particles have no offset $y_1 = 0$ and $w_y^0(s,0) = 0$ due to symmetry, then the first important term is the first derivative

$$w_y(s,y) = w_y^1(s)y = \frac{\partial}{\partial y} w_y(s,y)|_{y=0}\, y \quad (5)$$

A vertical gradient of the wake fields acting on the bunch particles will be a convolution of this function and the bunch charge distribution. We calculate this gradient for a 10 micron bunch moving through a dechirper with a gap of 1.4 mm. Fig. 6 shows this calculation. We have found that the transverse Green's function, which defines the vertical gradient, can be approximated by the following formula:

$$\mathrm{w}_{\mathrm{y}}^1(s) \approx \frac{1}{\Delta(g)} \frac{s}{s_0(g)} w_\parallel(s) \quad (6)$$

The parameter $\Delta(g)$ is approximately 2.2 mm for gaps of 1-2 mm. One can check how well this formula describes a vertical gradient. In Fig. 6 a green dashed line shows the vertical gradient calculated using Green's function (6). We get very good agreement in the bunch region.

It was interesting to find that the Green's function for the gradient of horizontal kick has the same form like (6) but with a negative sign.

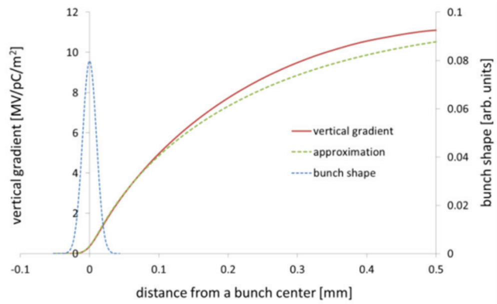

Figure 6: Vertical gradient of the transverse wake fields of a 10 micron bunch (red line), approximation of the vertical gradient (green dashed line) and bunch charge distribution (dotted blue line).

PAL-ITF EXPERIMENT

The single mode approach was also been used for calculating the wake fields in order to make a comparison with the experimental measurement of the corrugated dechirper in Pohang Accelerator Laboratory [2]. They found a 20% difference. They concluded the bunch charge must have been 150 pC instead of measured 200 pC. We decided to check this statement even the bunch length in the experiment was relatively large - 0.67 mm. The geometry of the corrugated structure can be found in Ref. [2]. It has the same period of 0.5 mm as the SLAC dechirper, but with a little bit thicker diaphragms. The main difference is a larger transverse size (*Lx*=50 mm), which allows using it with larger gaps.

We calculated wake potentials for an experimentally measured bunch distribution. Fig. 7 shows this distribution and corresponding wake potential for a gap of 6 mm. It is interesting to note that again the wake potential has two slopes for a two horn bunch, so there will not be full compensation of the chirp in the dechirper. Comparing the computed wake potential, we find good agreement with the shape of the measured wake potential, which is presented in the right middle plot of Fig. 5 in Ref. [2].

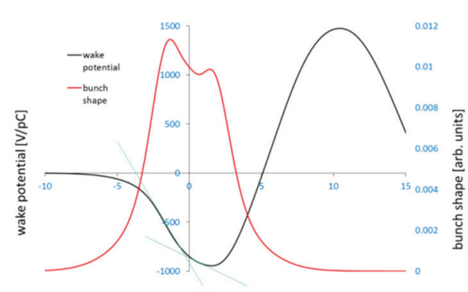

Figure 7: The shape of the experimentally measured two horn bunch (red line) and the corresponding wake potential (black line). Light green lines show two slopes.

ISBN 978-3-95450-134-2

We also calculated the loss factor as a function of the gap size. The results for the relative energy loss of a 70 MeV bunch with a charge of 150 pC (green line with red triangles) and 200 pC (black line with blue stars) are shown in Fig. 8.

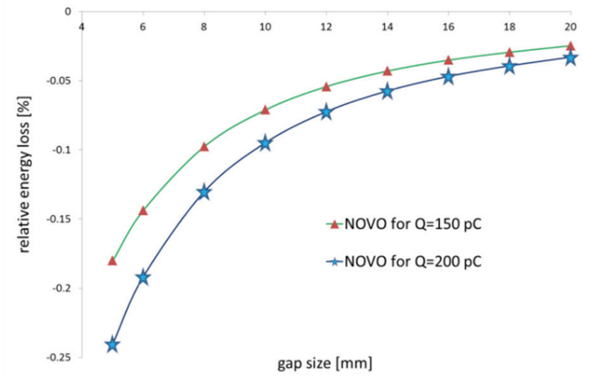

Figure 8: Relative energy loss of a bunch with a charge of 150 pC (green line with red triangles) and 200 pC (black line with blue stars).

Comparison with a plot in Fig. 6 of Ref. [2] shows that our calculations for a 200 pC bunch are in better agreement with the experimental measurement than for a bunch of 150 pC. We also have good agreement for the focusing effect in the horizontal direction (Fig. 9) and the vertical transverse kick (Fig. 10) for a bunch charge of 200 pC. In these calculations we assume that the total distance to the screen (where the transverse position is measured) is 5.25 m, which is the sum of the distance from the end of the dechirper to the screen (4.75 m) plus half of the dechirper length (0.5 m). One can compare our result with the right plot of Fig. 9 in Ref. [8] and find very good agreement. The calculated vertical position of the bunch due to an offset position of the bunch in the dechirper (red line in Fig. 10) is also in very good agreement with the measurement data (Fig. 8 in Ref. [2]).

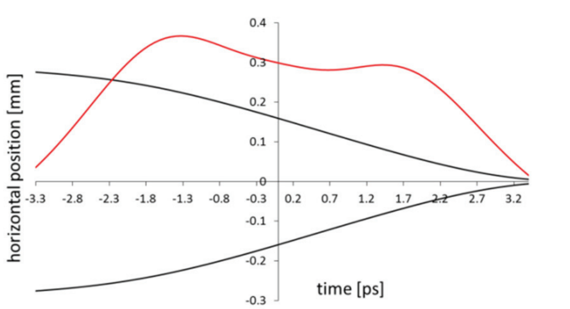

Figure 9: Horizontal position of the bunch boundary particles (black lines) downstream of the dechirper for a bunch charge of 200 pC. The red line shows the bunch charge distribution.

A blue line in Fig. 10 shows the energy loss of the bunch. It can be seen that the losses increase with the offset of the beam.

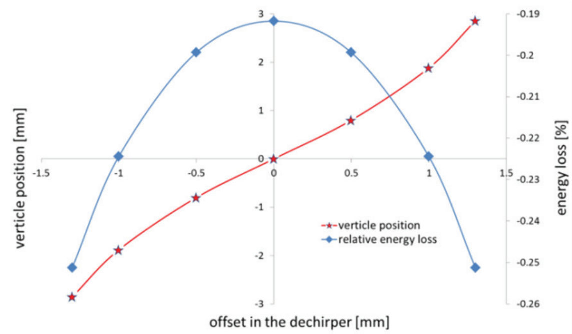

Figure 10: Vertical position of the bunch downstream of the dechirper (red line with red stars) and energy loss (blue line with diamonds) as a function of the vertical offset in the dechirper for a gap of 6 mm. The bunch charge is 200 pC.

To understand the reason for the difference between the wake potential calculated by our code and the single mode approach used for wake field calculations in Ref. [2], we carried out calculations of shorter bunches for this dechirper to derive the Green's function. We found that the difference came from the difference of Green's function at small distances. This difference is important even for a bunch length of 0.67 mm.

ACKNOWLEDGMENT

The author would like to thank Mike Sullivan for help and valuable comments, Axel Brachmann, Rick Iverson, Yunhai Cai, Paul J. Emma, Zhirong Huang and Franz-Josef Decker for support and interest in this work, and physicists of the Beam Physics Department for useful discussions.

REFERENCES

[1] A. Novokhatski et al., Phys. Rev. ST Accel. Beams 17, 124401 (2014).
[2] P. Emma et al., Phys. Rev. Let. 112, 034801 (2014).
[3] K. L. F. Bane and G. V. Stupakov, Phys. Rev. ST Accel. Beams 6, 024401 (2003).
[4] Z. Zhang et al., Phys. Rev. ST Accel. Beams 18, 010702 (2015).
[5] A. Novokhatski and A. Mosnier, in Proceedings of the 1997 Particle Accelerator pp. 1661–1663.
[6] A. Novokhatski and A. Mosnier, DAPNIA/SEA-96-08, 1996.
[7] A. Novokhatski Nuclear Instruments and Methods in Physics Research A684 (2012), 46–51.
[8] A. Novokhatski, SLAC-PUB-11556, 2005.
[9] A. Novokhatski, in Proceedings of the 31st (FEL09), Liverpool, UK.
[10] A. Novokhatski, Phys. Rev. ST Accel. Beams 14, 060707 (2011).

ISBN 978-3-95450-134-2