WAKEFIELD COMPUTATIONS FOR A CORRUGATED PIPE AS A BEAM DECHIRPER FOR FEL APPLICATIONS*

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Abstract

A beam "dechirper" based on a corrugated, metallic vacuum chamber has been proposed recently to cancel residual energy chirp in a beam before it enters the undulator in a linac-based X-ray FEL. Rather than the round geometry that was originally proposed, we consider a pipe composed of two parallel plates with corrugations. The advantage is that the strength of the wake effect can be tuned by adjusting the separation of the plates. The separation of the plates is on the order of millimeters, and the corrugations are fractions of a millimeter in size. The dechirper needs to be meters long in order to provide sufficient longitudinal wakefield to cancel the beam chirp. Considerable computation resources are required to determine accurately the wakefield for such a long structure with small corrugation gaps. Combining the moving window technique and parallel computing using multiple processors, the time domain module in the parallel finite-element electromagnetic suite ACE3P allows efficient determination of the wakefield through convergence studies. In this paper, we will calculate the longitudinal, dipole and quadrupole wakefields for the dechirper and compare the results with those of analytical and field matching approaches.

INTRODUCTION

In order to cancel the residual energy chirp in a beam before it enters the undulator in a linac-based FEL, a beam dechirper whose design consisting of periodic corrugations on the chamber walls has been proposed [1]. Such a dechirper is a passive device as it uses the longitudinal wakefield generated by the beam transit to compensate for the energy difference within the beam. The dechirper can be installed in machines such as LCLS-II where a superconducting linac will be used for beam acceleration and the wakefields generated in the superconducting cavities are not strong enough to dechirp the beam.

The original dechirper proposed for the light source NGLS was a round corrugated metallic pipe. The wakefields for the round geometry have been calculated using an analytical approach and formulas are available. Later, a flat rectangular geometry with corrugations on two parallel metallic plates was adopted and a dechirper was built and tested [2] at the injector test facility (ITF) for the PAL-XFEL in Korea [3]. The rectangular geometry has the advantage that the separation of the plates can be adjusted for different machine operation conditions. Formulas for the wakefields obtained by the analytical approach have been worked out recently for the rectangular case [4, 5]. Furthermore, numerical method using field matching in the frequency domain has been developed [4], which is believed to be more accurate than the analytical method.

The analytical approach is a good approximation when the depth and period of the corrugation are small compared with the separation of the plates. The corrugations in the dechirper being tested at PAL are small with respect to the chamber dimensions, but it is desirable to perform direct simulation by 3D electromagnetic code to verify the validity of the analytical approximation. This work focuses on numerical simulation using the finite-element electromagnetic code suite ACE3P [6] to calculate the wakefields of the dechirper and compare them with the analytical and field matching approaches. In addition to determining the longitudinal wakefield that is used to cancel the energy chirp of the beam, the dipole and quadrupole wakefields that kick and defocus the beam and hence increase its emittance will also be evaluated.

THE DECHIRPER MODEL

A sketch of the geometry of the dechirper is shown in Fig. 1. The corrugation is defined by the period p, the gap g, and the depth h. These corrugation parameters are fractions of a millimeter in size. The corrugations are located at the top and the bottom of the rectangular chamber with half height a and half width w. In order to provide sufficient longitudinal wakefield, the height of the dechirper needs to be small enough (on the order of millimeters), which is small compared with the chamber width, and the length of the dechirper needs to be long enough (on the order of meters). The dimension parameters of the dechirper tested at PAL are a = 3 mm, p = 0.5 mm, g = 0.3 mm, and h = 0.6 mm. In practice, a is adjustable from $2a$ = 5 mm to 28 mm. The validity of the analytical approximation is when p, $h \ll a$ and the corrugation depth h is much larger than its period p. It can be seen that the corrugation dimensions are about an order of magnitude smaller than the dechirper height. A direct 3D numerical simulation is required for cross check of the analytical calculation.

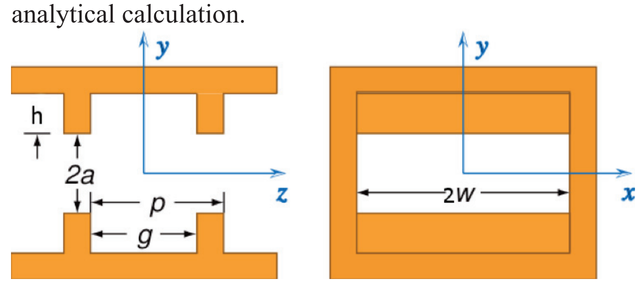

Figure 1: Sketch of the geometry of the dechirper.

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NUMERICAL APPROACH

The 3D numerical simulation is performed using the time domain module T3P of the code suite ACE3P. The wakefield computation in T3P is facilitated by the following simulation capabilities. First, T3P runs on computers at NERSC computing facility, which provides massively parallel computation to achieve fast computing speed. Second, a moving window technique for unstructured grids implemented in T3P confines short-range wakefield computation to the region of the mesh around the moving beam, thus substantially enhancing the computation efficiency. It should be pointed out that while it is straightforward to implement the moving window technique in the FDTD method with regular rectangular grids, its implementation in the finite-element method using unstructured grids is rather non-trivial [7, 8]. It requires careful mapping of field quantities when transferring the solution from the current window to the next one, especially under the computation environment where multiple computer processors are used.

Despite the above-mentioned computational advantages, simulating the full dechirper of meters long and with large chamber *w/a* aspect ratio is still challenging, if not infeasible. Fortunately, the wakefield will reach steady state after a certain catch-up distance, and the reflection from the sides of the chamber will be negligible when *w/a* is larger than a certain value. Therefore, a reduced model with much smaller length and width than the actual device can be used to obtain accurately the wakefield per unit length of the dechirper. Because of symmetry, only a quarter of the reduced model as shown in Fig. 2 is needed for T3P calculation.

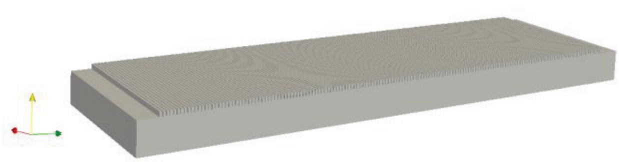

Figure 2: One quarter of the vacuum region of the dechirper model with corrugations situated on a half of the top plate used for T3P simulation. The full model is obtained by reflection with respect to the horizontal and vertical planes.

Figure 3 shows three snapshots of the beam transit in the dechirper with 160 corrugations. The computation at each time step in T3P is confined only in the colored region when the moving window technique is employed in following the transiting beam. Thus the computation domain is only a small fraction of the model, which drastically reduces the computation time.

Convergence studies have been performed by varying the number of corrugations and the width of the chamber, respectively. It was found that when the number of corrugations reaches 160, the longitudinal wakefield per unit length does not change. Fig. 4 shows the comparison of the longitudinal wakefields for a model with 144 and 160 periods. It can be seen that the two curves are almost the same. In a similar manner, when the chamber *w/a* aspect ratio is greater than about 2.5, the wakefield remains unchanged. In all the following numerical simulations, the dechirper model has 160 corrugations and *w/a* of the rectangular chamber is 3.

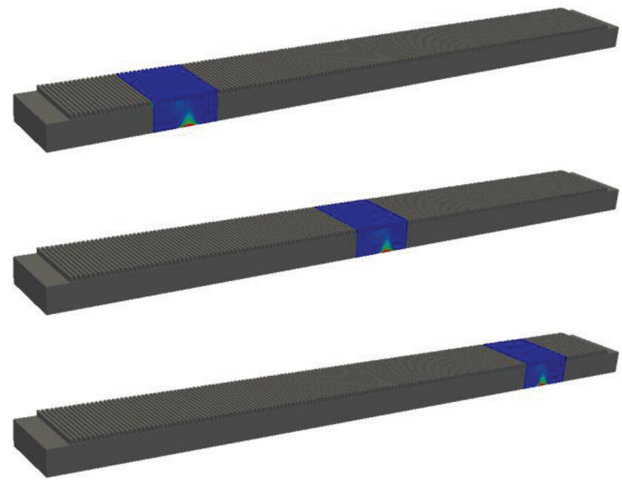

Figure 3: Snapshots of beam transit in the dechirper with 160 corrugation periods. The beam comes in from the left boundary at the origin (the lowest corner) and moves to the right. The colored region in each snapshot indicates the moving window at the corresponding time.

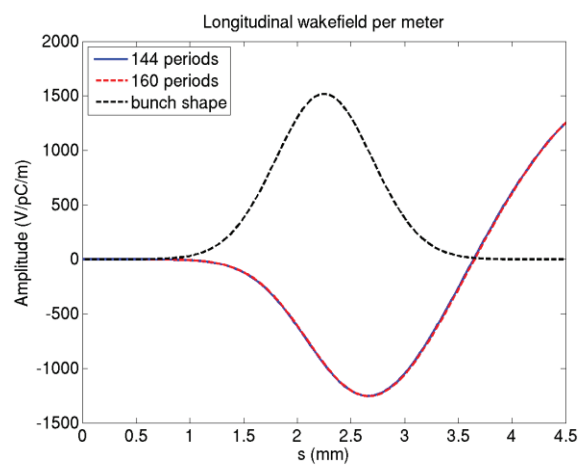

Figure 4: Longitudinal wakefield per unit length of the dechirper with 144 and 166 corrugations.

WAKEFIELDS OF DECHIRPER

The dimensions of the PAL dechirper have been listed in a previous section. To calculate the wakefields of the dechirper, a Gaussian bunch with $\sigma = 0.45$ mm is used, which corresponds to the rms beam size at the PAL test facility. Choosing appropriate boundary conditions at the symmetry planes in the quarter model shown in Fig. 2, one can determine the monopole and quadrupole wakefields with the beam transiting on the axis in a single T3P run, and the dipole wakefield with the beam transiting at an offset position in the vertical direction using different boundary conditions in another T3P run. The total transverse wakefield in the vertical direction is the sum of the dipole and quadrupole components and is given by

$$W_y = y_d W_{yd} + y_w W_{yq},$$

where W_{yd} and W_{yq} are the dipole and quadrupole wakefields, and y_d and y_w are the positions of the drive and witness particles, respectively. The wakefields are expressed in terms of per meter length so that the values

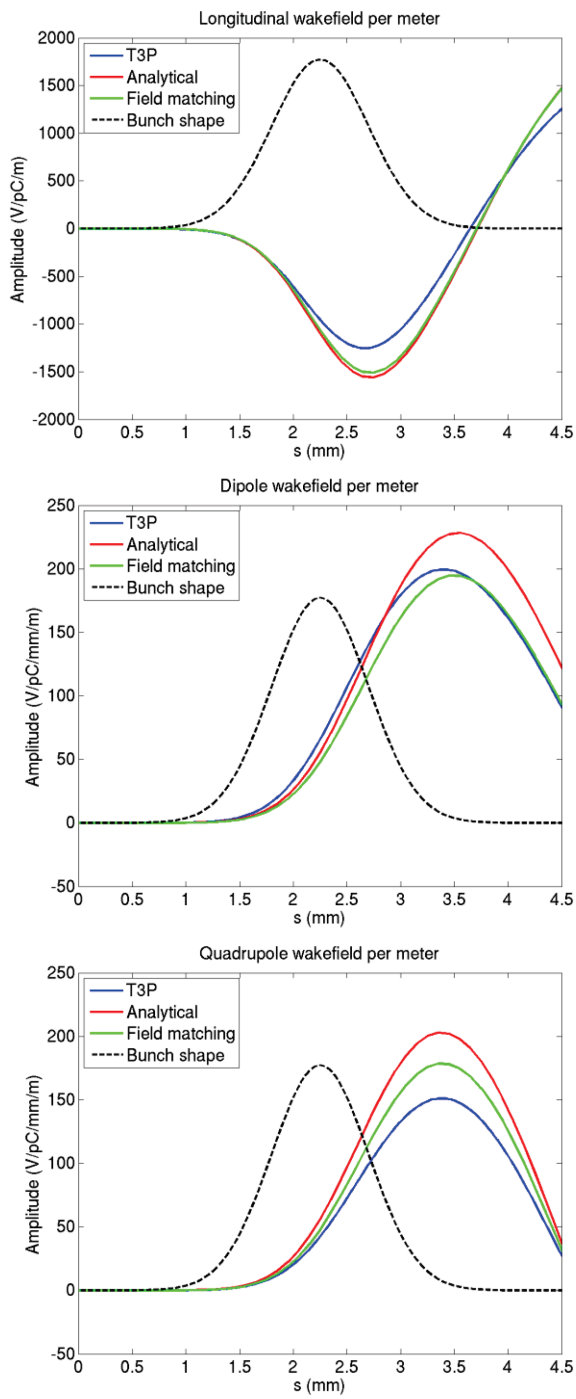

Figure 5: (Top) Longitudinal, (Middle) dipole, and (Bottom) quadrupole wakefield per meter length of the dechirper obtained by the analytical, field matching and numerical approaches.

for the actual dechirper can be readily obtained by multiplying with its length. In each of the monopole, dipole and quadrupole calculations, the T3P numerical results are compared with those evaluated by the analytical and field matching approaches.

Figure 5 shows the longitudinal, dipole and quadupole wakefields obtained by T3P numerical calculation, the analytical and field matching approaches. The loss factor obtained by numerical calculation is 821 V/pC/m, and the kick factors for the dipole and quadrupole components are 75 V/pC/mm/m and 52 V/pC/mm/m, respectively. In comparing the results of different approaches, Table 1 list the ratios of the loss or kick factors for any two of the approaches. In general, the analytical and field matching approaches agree with each other within 10%, while the numerical approach agrees either with the analytical approach or the field matching approach within 10-20%, depending on individual cases. This indicates that while analytical formulas render a fast means to determine the wakefields in a dechirper, in particular in exploring the parameter regime during the initial design phase, it is always desirable to further quantify the results with numerical methods for the final design.

Table 1: Comparison of the ratios of the loss factor or kick factors obtained by the analytical, field matching and numerical approaches.

Wake	FM/ Analytical	Numerical/ Analytical	Numerical/ FM
Monopole	0.97	0.84	0.87
Dipole	0.87	1.08	1.25
Quadrupole	0.86	0.73	0.85

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REFERENCES

[1] K.L.F. Bane and G. Stupakov, Nucl. Instrum. Meth. A **690** (2012) 106.
[2] H.-S. Kang, "Control of Electron Beam Longitudinal Phase Space with a Novel Compact De-chirper," FEL 2013, August 26-30, Manhattan, NY.
[3] S.J. Park et al., "Construction of Injector Test Facility (ITF) for the PAL XFEL," Proc. IPAC 2013, Shanghai, China, WEPWA043, p. 2220 (2013).
[4] K.L.F. Bane and G. Stupakov, Phys. Rev. ST Accel. Beams **6** (2003) 024401.
[5] G. Stupakov, private communications.
[6] https://confluence.slac.stanford.edu/display/AdvComp/Materials+for+cw11
[7] L.-Q. Lee et al., J. Comput. Phys. **229** (2010) 9235.
[8] C.-K. Ng et al., "High Fidelity Calculation of Wakefields for Short Bunches," talk given at PAC 2011, March 28 – April 1, New York, USA.

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