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SIMULATION STUDY OF A PLANAR DIELECTRIC-LINED WAVEGUIDE STRUCTURE FOR MANIPULATION OF FEMTOSECOND HIGH BRIGHTNESS ELECTRON BEAM IN LONGITUDINAL PHASE SPACE

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Abstract

In many advanced accelerator facilities such as e+e-- linear colliders and high gain free electron lasers, magnetic bunch compressors are often used for enhancement of beam brightness. However, the energy chirp (correlated energy spread) introduced into the beam by the chirper linac remained after bunch compression is undesirable in some applications. In this report, we present our study of a planar dielectric-lined waveguide (DLW) structure that can be used to remove the remaining energy chirp after bunch compression. As revealed from ELEGANT [1] simulation of a 250 MeV high brightness driver linac system for the proposed EUV FEL test facility in NSRRC, a correlated beam energy chirp of about 42 keV/μm is left after bunch compression. We successfully used a 1-m long corrugated pipe dechirper to remove this energy chirp in ELEGANT simulation. However, fabrication of this 1-m long corrugated pipe structure is not an easy task. In order to save space and simplify mechanical design, we are considering the possibility to use planar DLW structures as dechirper. Wake potential due to this DLW dechirper has been calculated by Computer Simulation Technology (CST) software [2]. The wake potential by a short Gaussian bunch as calculated by CST is de-convoluted to obtain the corresponding wake function of the structure. The effect of the dechirper on beam distribution can then be studied by particle tracking using this wake function in ELEGANT. We expect the performance of the optimized 20-cm DLW dechirper design will be equivalent to the 1-m long corrugated pipe. Using this technique, wake functions of more sophisticated electromagnetic wave structures can be obtained and used in particle tracking code for parameter optimization.

INTRODUCTION

A 66.5-200 nm FEL facility driven by a 250 MeV high brightness electron beam has been proposed in National Synchrotron Radiation Research Center (NSRRC). The baseline design is a 4th harmonic HGHG FEL that utilize 266-800 nm optical parametric amplifier (OPA) as seed [3-4]. The 200-250 pC drive beam is delivered by a high brightness linac system equipped with a 60 MeV photoinjector and a 100 MeV magnetic bunch compression system using nonlinear optics. A pair of 5.2-m constant-gradient traveling-wave rf linac structures energized by a single 35 MW pulsed klystron/SLED system are used to boost the compressed beam to nominal energy in an efficient way. It is worth noting that the photoinjector has now been operational for generation of THz superradiant spontaneous undulator radiation (THz SSUR) for some pilot user experiments. In previous simulation study, a 1-m corrugated pipe had been used to reduce the correlated energy spread of the drive beam [5]. The pipe radius is 1.25mm and width of gap is 0.25mm. Period and depth of corrugate groove is 0.5mm. Fig. 1 depicts the electron distribution of the drive beam in longitudinal phase space when the compressed beam passes through such corrugated pipe dechirper. The expected performance of the dechirper has been achieved according to ELEGANT simulation. However, besides relatively high fabrication cost, the space occupied by the dechirper is considered to be too long to fit into the 38-m bunker at the NSRRC Accelerator Test Area (ATA). Furthermore, such configuration is not practical because of its beam aperture is not adjustable.

In this study, we propose to use a new process to verify the desired phase space distribution of particle by combining CST wake field solver and ELEGANT. This method provides a feasibility way to design beam energy dechirpers with complicated electromagnetic structures. As a demonstration of this method, a prototype of flat DLW dechirper structure which have the same performance as a 1-m corrugated pipe dechirper but a much more compact size can be designed for the NSRRC 250 MeV drive linac without tedious analytic calculations.

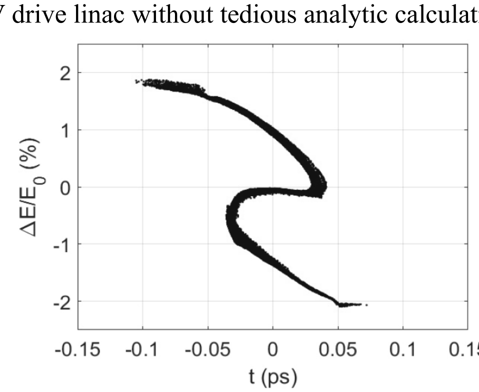

Figure 1: Longitudinal phase space distribution of electrons at driver linac exit. A 1-m corrugated pipe dechirper has been added into the system after the main linac in ELEGANT simulation [3].

CIRCULAR DLW DECHIRPER

In the past 20 years, the concepts of using cylindrical DLW as wake-field accelerators or beam dechirpers have

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been studied thoroughly [6-8]. We can calculate the analytic wake function based on the previous analytical results. According to Ng's paper [7], analytical solution of the longitudinal wake field of a point charge can be expressed as follows:

$$E_{z0}(r,z,t) = -\frac{4q}{\varepsilon ab}\sum_{\lambda}\frac{xp_0}{\left(\frac{d}{dx}\right)D_0(x)} * \cos\frac{x*s}{a\sqrt{\mu\varepsilon-1}}|_{x=x_\lambda} \quad (1)$$

where

$$D_0(x) = xP_0'(x) + \frac{x^2\xi}{2\epsilon}P_0(x),$$
$$P_0 = J_0(sa)Y_0(sb) - Y_0(sa)J_0(sb),$$
$$P_0' = J_0(sa)Y_0'(sb) - Y_0(sa)J_0'(sb)$$

a and b are the outer and inner radii of the DLW dechirper respectively. The different between the two radii is the thickness of potential dielectric material (see Fig. 2). $\boldsymbol{x_\lambda}$ is the λth positive zero of the analytic function $D_0(x)$. ξ = b/a is the ratio of inner radius to the outer radius of the dielectric material.

By using this wake function in ELEGANT, we can calculate the effect of a circular DLW dechirper on the distribution of particles in phase space. After optimization of structure parameters, we come up with a 200 mm prototype DLW dechirper which has the same effect on beam as a 1-m corrugated pipe (see Table 1).

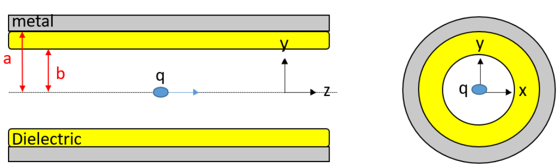

Figure 2: Geometry of a circular DLW structure.

Table 1: Optimized geometry of the circular DLW structure in this simulation study.

Parameter	Values
a	0.9 mm
b	0.8 mm
Dielectric Constant	3
Total DLW Length	200 mm

Fig. 3 shows the effect of circular DLW structure on longitudinal phase space particle distribution. The tail of bunch experiences more energy loss than its head. Thus, the correlated energy spread of the bunch has been removed.

DETERMINATION OF WAKE FUNCTION

As discussed in the last section, wake function of the circular DLW structure has to be found analytically. After the wake function is obtained, one can import it into particle tracking software (e.g. ELEGANT) to understand the impact of DLW on the phase space distribution of particles.

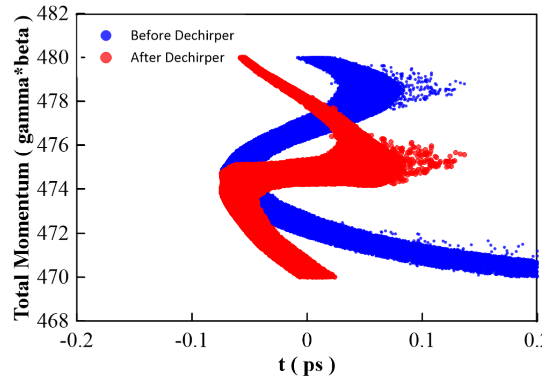

Figure 3: Comparison of the particle phase space distributions for a compressed beam before (blue dots) and after (red dots) the dechirper.

An alternative method to determine the wake function of an arbitrary structure is to use the commercial software CST to calculate the wake potential driven by a short Gaussian beam. Longitudinal wake potential is a convolution integral of wake function and line charge density as expressed as follow:

$$W_\lambda(s) = \int_0^\infty W(s')\lambda(s\text{-}s')ds' \quad (2)$$

One can reverse the process to obtain the wake function by de-convolution of wake potential calculated by CST with a Gaussian drive beam. That is:

$$W(s) = \mathcal{F}^{-1}\left\{\frac{\mathcal{F}\{W_\lambda(s)\}}{\mathcal{F}\{\lambda(s)\}}\right\} \quad (3)$$

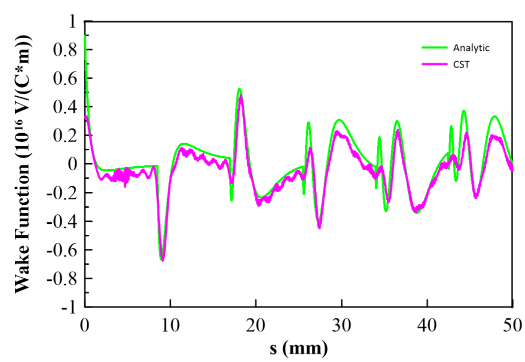

Figure 4: A comparison of wake functions obtained from analytical theory and from CST wake potential solver.

Wave functions by analytical theory and CST in Fig.4 are imported into ELEGANT to simulate their effects on particle distributions. As shown in Fig.5, the two distributions are almost overlap with each other. The alight difference may come from the resolution of CST calculation. If there are more hardware resources, the result of CST will be closer to the analytical solution. The feasibility of this method has proved to be adequate.

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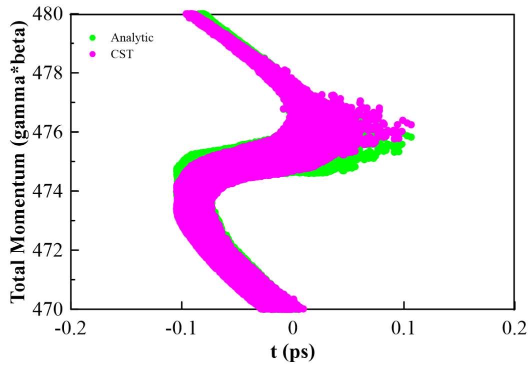

Figure 5: Particle phase space distributions obtained by ELEGANT with the analytical (green) and CST derived wake functions.

FLAT DLW SIMULATION

Using the proposed method, we designed a flat DLW dechirper (Fig. 6) with dimensions and dielectric constant shown in the Table 2. Wake potential is calculated by CST with short Gaussian beam. Then, by the deconvolution process, the wake function is imported into ELEGANT for particle tracking. Fig. 7 shows that the effect on particle distribution is similar to the circular DLW dechirper. Fig. 8 shows that most particle concentrated at a specific beam energy showing that correlated energy spread has been removed largely. It is worth noting that the flat dechirper structure is longer than the circular dechirper because the impact of the wake field on the particles is greatly reduced from in horizontal direction. Length of flat dechirper is about two times long than circular dechirper. The advantage of using flat dechirpers is their capability of gap adjustment.

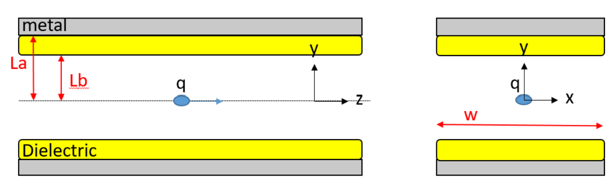

Figure 6: Geometry of flat DLW dechirper. La is outer width and Lb is inner width of flat dechirper. w is the width in horizontal direction.

Table 2: Optimized Dimensions of the Circular Dielectric Lined Waveguide Structure in this Simulation Study

Parameter	Values
La	2 mm
Lb	0.6 mm
w	70 mm
Dielectric Constant	3
Total DLW Length	400 mm

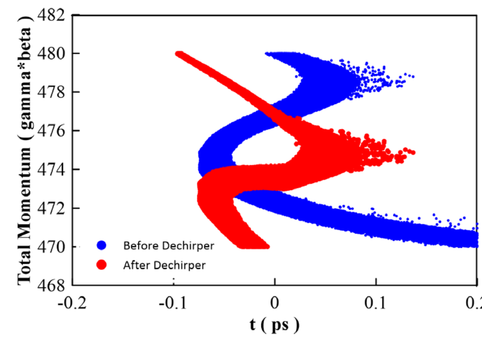

Figure 7: Particle phase space distributions before the flat DLW dechirper (blue dots) and after the dechirper (red dots).

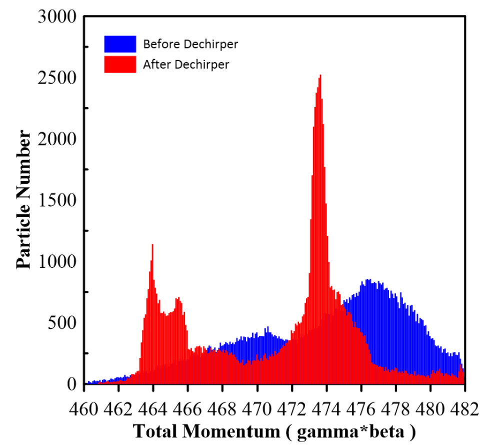

Figure 8: Particle number for different energy level

CONCLUSION

In this paper, analytic wake function of circular DLW dechirper is calculated for verification of its effectiveness as a dechirper with ELEGANT. A 200 mm long circular DLW dechirper has proven to have similar performance as a 1-m long corrugated pipe dechirper. We have demonstrated that the proposed deconvolution method is adequate for derivation of the correct wake function which can be used in particle tracking with ELEGANT. This method has been employed to design a new flat DLW dechirper. Table. 3 is a comparison of the length required for different dechirper structures that provide similar performance. DLW dechirpers have much shorter lengths size than corrugate.

Table 3: Optimized Dimensions of the Circular DLW Structure in this Simulation Study

Dechirper (for removing 1% energy spread)	Length
Corrugate Pipe	1000 mm
Circular DLW	200 mm
Flat DLW	400 mm

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