PHASE SPACE MANIPULATION OF SUB-PICOSECOND ELECTRON BUNCHES USING DIELECTRIC WAKEFIELD STRUCTURES*

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Abstract

Dielectric lined waveguides have drawn interest due to their application as high gradient accelerating structures, in both externally driven and wakefield schemes. We present simulation studies of sub-picosecond electron bunches interacting with dielectric structures in the self-wake regime. The parameter space for a tunable, sub-millimeter aperture, terahertz frequency structure is investigated. The potential application as a longitudinal phase space dechirper is demonstrated, with specific application to CLARA at Daresbury Laboratory. The impact of transverse effects is considered and minimised. The resulting FEL output is simulated.

INTRODUCTION

Metallic grating dechirpers have been proven to work operationally at LCLS; both improving the performance and giving increased control over the free electron laser (FEL) output [1]. Dielectric lined waveguides (DLWs) have been shown to reduce longitudinally correlated energy spread (chirp) [2], by utilising the short-range decelerating wakefield.

Bunches with large negative chirp (the tail of the bunch has a higher energy than the head) are used in FELs where the chirp allows for longitudinal compression to sub-ps bunch duration in magnetic chicanes. However, the chirp increases the photon bandwidth and reduces the power output of the FEL. A DLW dechirper provides a potentially attractive option to passively reduce the chirp of bunch in a small space.

This paper considers the use of a tunable DLW to improve the performance of the CLARA FEL at Daresbury Laboratory. CLARA has several beam modes [3,4], so a tunable DLW wakefield dechirper has the additional attraction that the strength of interaction can be altered by changing specific DLW parameters, allowing it to respond to varying machine or experimental conditions. We analyse the use of thin dielectric layers to reduce the spread of the core of the bunch, and consider the effect of transverse wakes.

WAKEFIELD MODELLING IN DLW

Beam-wakefield interactions can be simulated using electromagnetic particle in cell (EM-PIC) codes. However utilising EM-PIC in 3D can be computationally prohibitive. For the simple geometry shown in Fig. 1 success has been had

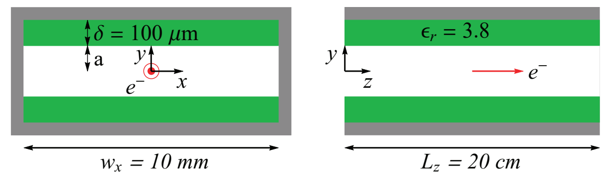

Figure 1: (Colour) Diagram of coordinate system and key parameters for dechirper structure, with quartz layers in green and metallic walls in grey. Left, front view structure. Right, profile view.

in forming analytical models for the wakefield based on decomposition into longitudinal section electric (LSE) and longitudinal section magnetic (LSM) modes [5]. These analytical models have been implemented in the space charge tracking code Impact-T [6], and validated against the EM-PIC code VSim whilst providing two orders of magnitude speed improvement [7]. The 3D PIC space charge calculation implemented in Impact-T is particularly important for dechirper design as bunch dynamics are affected by both the significant self field and short range wakefield. Therefore the semi-analytic approach of Impact-T provides a useful design tool for the DLW dechirper. One limitation of this code is that the bunch profile must be transversely symmetric about the vertical axis. Impact-T is used for all wakefield simulations presented in this paper.

DECHIRPER DESIGN

Longitudinal Field Profile

The dechirper is used to reduce the energy spread of the bunch by decelerating the tail of the bunch more than the head. For the flat-top profile bunches in [2] this is achieved by using a thick dielectric layer to produce a multimode wakefield which is approximately linear across the longitudinal profile of the bunch. For Gaussian-like bunches it is advantageous to use thinner dielectric with a non-linear longitudinal wakefield. There are two reasons for this: only the central region of the bunch lases efficiently, so the wakefield only needs to be linear in this region, and also there is an increase in wakefield amplitude. This is illustrated in Fig. 2, with the notation used to describe the parameters of the DLW shown in Fig. 1. We consider the lasing region of the bunch as the longitudinal FWHM of the charge distribution, and refer to parameters associated with this as "core" parameters. In this case the function of the dechirper is to linearise the longitudinal phase space in the core of the bunch, and ignore the head and tail sections.

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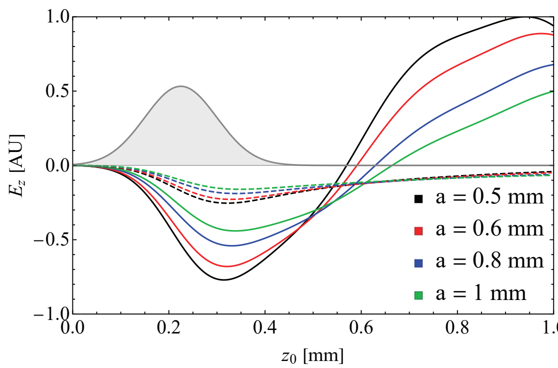

Figure 2: (Colour) Comparison between wakefield excited by a Gaussian bunch (grey) in a DLW using analytical equations [7]. The solid lines use δ =100 µm and dashed lines use δ =1500 µm, the bunch charge is constant.

Dechirper Parameter Selection

The dielectric used is quartz as it is readily available and can be machined to the parameters required. For all cases considered the relative permittivity is given as $\epsilon_r = 3.8$ and is assumed to be isotropic and frequency independent, in the frequency range considered. To reduce the footprint of the dechirper in the CLARA lattice, we restrict the length $L_z = 20$ cm. The structure width is set $w_x = 10$ mm in order to have a large transverse aspect ratio and minimise coupling to LSE modes [7]. Additionally we fix δ =100 µm, to provide a balance between wakefield linearity and strength across the bunch core for varying a. Integrated CLARA beam parameters were used to create a 6D Gaussian input bunch. The input bunch parameters are given in Table 1, where E denotes mean energy, σ_t an RMS bunch length, $\sigma_{x,y}$ RMS transverse sizes, and $\epsilon_{x,y}$ projected normalised emittances. Using these parameters the value of a is scanned and the resulting energy spread shown in Fig. 3, with the optimum at $a = 0.5$ mm. However, the projected emittances in this case were $\epsilon_x = 5.08$ mm mrad and $\epsilon_y = 6.51$ mm mrad. These values would be highly detrimental to FEL performance and lead to $a = 0.6$ mm being selected for less severe transverse effects. Figure 4 demonstrates the effect of the dechirper with initial and final longitudinal phase spaces and energy distribution. The integrated beam parameters are summarised in Table 1.

TRANSVERSE EFFECTS

The transverse emittance growth from a single, "straight", dechirper (Table 1) is prohibitive for efficient FEL operation and should be < 1 mm mrad. This projected emittance growth is caused by the quadrupole component of the LSM modes acting on the bunch, and is also evident from the change in $\sigma_{x,y}$. One method to reduce the projected emittance growth is to adopt the two dechirper system as used at LCLS [1]. Here the dechirper is split in half and each piece is oriented orthogonally to the other. In this way the longitudinal dynamics are preserved and the emittance growth is near cancelled [8]. This horizontal and vertical configuration is

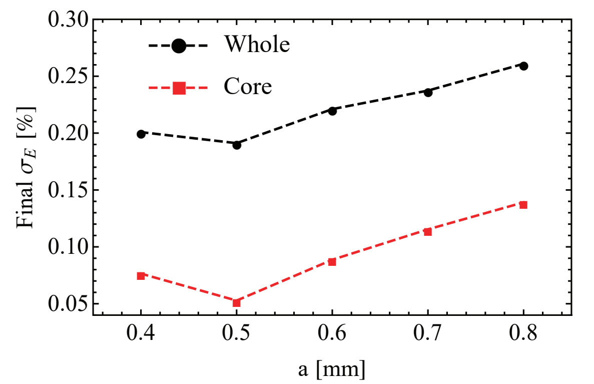

Figure 3: Variation of whole and core energy spread with dechirper half gap a.

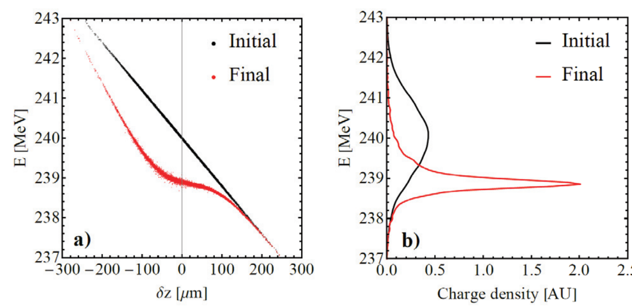

Figure 4: (Colour)Initial and final results for simulation of dechirper shown in Fig. 1 with $a = 0.6$ mm. a) Longitudinal phase space, head of bunch on right. b) Energy distribution.

termed H+V. This was simulated using two 10 cm dechirpers with a 1 cm gap in between. The emittance growth for the H+V method is shown in Fig. 5 , using the initial bunch parameters given in Table 1. The H+V method reduces the emittance growth to within acceptable range, with final values of $\epsilon_y = 0.83$ mm mrad and $\epsilon_x = 0.83$ mm mrad.

It should be noted that the large projected emittance growth for a straight dechirper is a result of a longitudinally correlated transverse phase space rotation. In contrast, slice emittance remains largely unchanged as demonstrated in Fig. 6. The H+V configuration is a system which ro-

Table 1: Initial Bunch Parameters and Results of Simulations of the Dechirper Using Parameters in Fig. 1 and $a = 0.6$ mm; Values given as *Whole (Core)*

Parameter	Initial	Final
E (MeV)	240 (240)	239 (239)
Charge (pC)	250 (192)	250 (192)
σ_t (fs)	250 (159)	250 (159)
σ_E (%)	0.38 (0.24)	0.22 (0.08)
σ_x (µm)	100.2 (100.4)	80.3 (81.4)
σ_y (µm)	100.2 (100.3)	126.5 (122.8)
ϵ_x (mm mrad)	0.75 (0.75)	3.24 (2.60)
ϵ_y (mm mrad)	0.75 (0.75)	3.86 (2.40)

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ISBN 978-3-95450-182-3

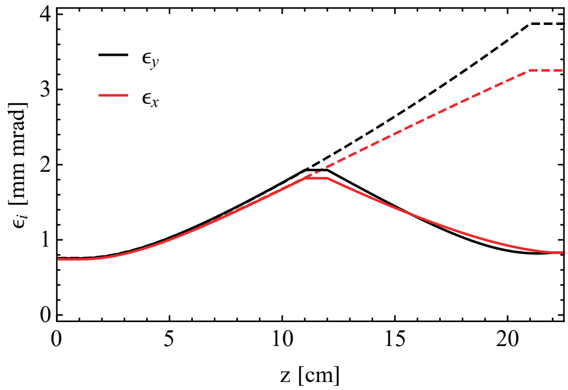

Figure 5: (Colour) Projected emittance for whole of bunch with propagation through dechirper, for H+V dechirper setup (solid lines) and single DLW case (dashed lines).

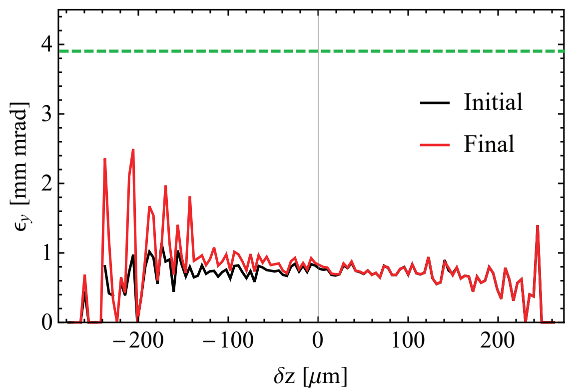

Figure 6: (Colour) Vertical slice emittance along bunch length using 15 fs slices for a straight dechirper with a = 0.6 mm. Dashed green line showing final projected emittance.

tates the transverse phase space along the bunch in the first module, and then counteracts this rotation in the second. Therefore it only cancels projected emittance growth if the emittances are approximately equal in both planes at the end of the first module. Figure 5 demonstrates this is the case for a = 0.6 mm after 10 cm.

IMPACT ON FEL PERFORMANCE

In order to assess the final impact on CLARA, simulations were carried out in the Genesis FEL code [9]. The bunches were matched to the undulator section of the lattice. Figure 7 shows the pulse energy growth through the FEL in the SASE regime. The H+V case demonstrates a 31% increase in pulse energy, whereas the straight case shows a 53% reduction. Therefore whilst the slice emittance has not significantly changed in the straight case, it is still important to control the projected emittance. The beam matching could be altered in order to improve the straight case performance, but it is not expected to improve beyond the H+V case.

SUMMARY

We have demonstrated that a 20-centimetre long DLW dechirper could reduce the chirp of bunches on CLARA. The

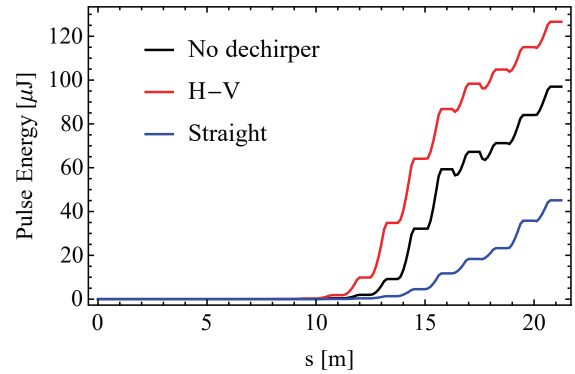

Figure 7: (Colour) FEL simulation for CLARA with dechirper half-gap set a = 0.6 mm. Case without dechirper uses initial parameters from Table 1.

transverse projected emittance growth has been minimised through a two stage H+V configuration. Furthermore we have demonstrated this system could offer the FEL a power increase of 31%.

Future work will include start to end modelling in CLARA and the assessment of bunch offsets and structure misalignment. Preparations are currently being made for a small scale experiment on tunable DLW wakefield interactions using the CLARA Phase 1 installation (45 MeV beam).

ACKNOWLEDGEMENT

T. Pacey would like to thank Drs. D. Mihalcea at Fermilab and J. Qiang at LBNL for their assistance in running Impact-T and the DLW wakefield package, and P. Williams at STFC/ASTeC for CLARA beam parameters.

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