

SIMULATIONS STUDY OF TRANSVERSE WAKEFIELDS IN A DIELECTRIC WAKEFIELD ACCELERATION SCHEME*

B. Higuera Gonzalez^{†1}, G. Xia¹, The University of Manchester, Manchester, UK

T. J. Overton¹, T. H. Pacey¹, Y. M. Saveliev¹, ASTeC STFC Daresbury Laboratory, Daresbury, UK
¹also at The Cockcroft Institute, Daresbury, UK

Abstract

Novel acceleration schemes aim to address the need for higher acceleration gradients which enable to minimise the size and costs of particle accelerators. One of these novel accelerator schemes is the dielectric wakefield acceleration (DWA), where an electron bunch is accelerated by the longitudinal wakefields generated within a dielectric lined waveguide by a leading drive bunch with higher charge. The advantages of this novel acceleration method include high accelerating field strength, the simplicity of its structure and the stability of the wakefield generated which is synchronous with the electron bunch. However, the drive bunch propagation length, and hence the achievable energy gain, is limited by the effect of the transverse wakefields. These fields deflect the bunch towards the dielectric, leading to charge losses, a phenomenon commonly referred to as beam break-up (BBU) instability. This study uses simulations to investigate the transverse wakefields and their impact on the beam dynamics in a DWA scheme with drive and witness (main) bunches. The findings will be further explored experimentally at the CLARA facility in Daresbury Laboratory.

INTRODUCTION

Wakefields are generated within a dielectric-lined waveguide (DLW) through the emission of Cherenkov radiation as relativistic charged particles propagate through the structure [1]. The strength of these fields depends directly on the bunch charge, as they result from the convolution of the bunch's charge distribution with the wake potentials of the structure [2]. Initially, the longitudinal field within the bunch is decelerating, transitioning to an accelerating phase behind the bunch [3]. This property can be exploited to create a simple and efficient accelerating scheme by placing a lower charge main (witness) bunch at an optimal time delay behind the driving bunch [4, 5].

However, if a beam is offset from the centre between the dielectric plates, it excites dipole-like transverse fields that kick it towards the closer dielectric. This effect is strongest for the high-charge drive bunch, leading to BBU losses and reduced accelerating field strength [6]. Several schemes have emerged to minimise BBU [6-8]. In these proceedings, we have investigated compensating an offset in a DLW by introducing an opposite offset in a second DLW.

The methodology section will outline the simulation software, DLWs structure, and parameters used. This is followed by the results of two simulations sets: one with drive and main bunches, and the other with the drive bunch

alone. These results will be tested at CLARA (Compact Linear Accelerator for Research and Applications).

METHODOLOGY

The simulations presented here were performed using DiWaCAT (Dielectric Wakefield Calculator And Tracker) [9]. DiWaCAT has been benchmarked against the widely used CST code as well as experimental data [10], and has supported several simulation studies conducted by the DWA team at Daresbury Laboratory [11, 12].

Within DiWaCAT, the simulation process begins with the generation of a particle bunch distribution, consisting of uniform-charge macroparticles. Next, the wakefields within the planar DLWs are calculated using the transverse operator method [2], which involves convolving the single-particle wake potential with the bunch distribution. Finally, the bunch is tracked through the waveguide, with the option to drift it towards a virtual screen for analysis.

Dielectric Structure and Beam Parameters

Figure 1 presents a schematic diagram of the structure, which comprises two DLWs, each with a dielectric half-gap, a , and independently adjustable vertical positions, allowing for flexible control over the bunch offset. Both DLWs have a length, L , of 200 mm, a dielectric thickness, δ , of 200 μm , and a dielectric permittivity, ϵ_r of 3.75. The full gap, $2a$, was set at 2 mm for both DLWs.

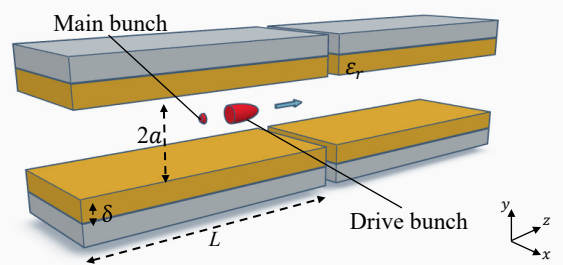


Figure 1: Schematic diagram of the accelerating structure setup. Both structures have a length $L = 200$ mm, dielectric thickness $\delta = 200$ μm , and relative permittivity $\epsilon_r = 3.75$. The half gap a and the vertical beam offset are variable.

For the corresponding experiment at CLARA, a mask will be used to collimate a Gaussian bunch, creating the drive and main bunches [13]. In this way, the drive bunch corresponds to the first half of the original Gaussian bunch, while the main bunches are longitudinal sections of the tail, each 200 fs long. These conditions have been simulated using original collimated bunch parameters consistent with expected CLARA specifications [13], as summarised in Table 1.

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[†] beatriz.higuera@postgrad.manchester.ac.uk

Table 1: Beam Parameters

Beam parameter	Value
RMS Bunch Length	1.5 ps
RMS Transverse Size	50 μm
Average Energy	250 MeV
Total Charge	250 pC
Normalised Emittance	1 mm mrad
Full Energy Spread	12 MeV

RESULTS

For the BBU studies, two different sets of simulations were performed. The first set included both the drive and main bunches to obtain the combined wakefields generated, including beam loading and to assess the impact of transverse fields on both bunches. The second set focused exclusively on the drive bunch, aiming to investigate potential methods for BBU compensation.

Combination of Drive+Main Bunches

We calculated the longitudinal wakefield for three different offset conditions: no offset, a 150 μm offset, and a 250 μm offset. In each case, the same offset was applied to both DLWs. Figure 2 presents the resulting longitudinal wakefields, where the accelerating peak consistently appears at approximately 2.75 ps for all cases. However, the field strength increases with offset, as expected, since larger offsets excite higher-order modes.

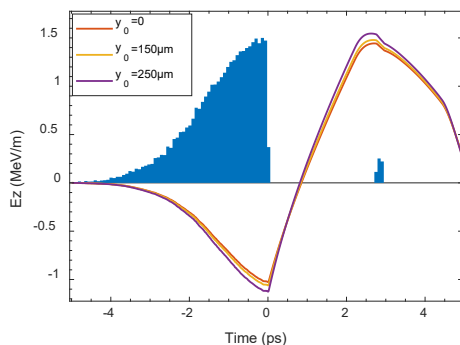


Figure 2: Longitudinal wakefield for aligned and offset (150 μm and 250 μm) bunches, with accelerating field peak at ~ 2.75 ps. The longitudinal profiles of the drive and main bunches are included in blue for reference.

Once the optimal main bunch delay for maximum acceleration was identified, we assessed the transverse wakefields excited at this point. These fields, normalised to their peak strength, are shown in Fig. 3. The results indicate that the dipole-like transverse fields (F_y) are effectively cancelled at the optimal delay for acceleration, while the quadrupole-like fields ($Q_y = dF_y/dy$) are cancelled earlier due to their higher frequency. In contrast, the drive bunch experiences both dipole-like and quadrupole-like transverse

fields, with their strength increasing towards the tail, leading to BBU as the bunch propagates through both DLWs.

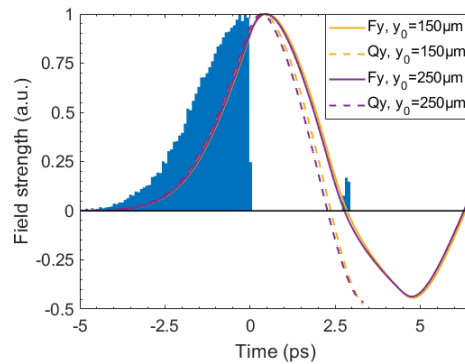


Figure 3: Dipole-like (F_y) and Quadrupole-like (Q_y) transverse fields for 150 μm and 250 μm offsets. The longitudinal profiles of the drive and main bunches at optimal time delay are included in blue for context.

This vertical field effect can also be observed in Fig. 4, which compares the energy spectra of the drive and main bunches with and without an offset. In these plots, the bunch head is on the left and the tail on the right. When an offset is present, the drive bunch is clearly deflected towards the closer dielectric layer. Although the main bunches also experience a transverse kick, the one corresponding to the maximum energy gain, located at the peak of the longitudinal field (highlighted in yellow), maintains its position.

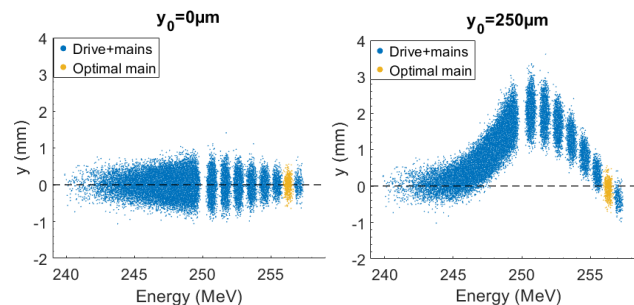


Figure 4: Particles distribution in a vertical plane after 5 m drift, with no offset (left) and with a 250 μm offset (right). The drive bunch followed by shorter main bunches is shown as blue scatter, with the bunch head on the left. The optimally timed main bunch for acceleration is highlighted in yellow, showing no transverse kick.

BBU in Drive Bunch

As observed in the above simulations, BBU primarily affects the drive bunch due to its higher charge and the fact that the transverse fields responsible for BBU are minimised at the optimal time delay, where the main bunch should be positioned. Therefore, the focus is on controlling BBU in the drive bunch to preserve the strength of the longitudinal accelerating field. For this, an initial offset of $y_1 = 200 \mu\text{m}$ is introduced in the first DLW (DLW1), while the transverse fields and beam dynamics are studied for various offsets, y_2 , in the second DLW (DLW2).

Figure 5 illustrates the offset required in DLW2 to cancel the vertical field generated in DLW1. The results show that the vertical field after DLW2 is effectively cancelled when an opposite offset is applied, matching the offset in DLW1 but with the opposite sign.

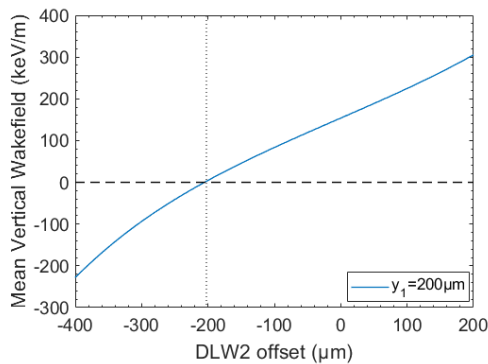


Figure 5: Mean vertical wakefield in DLW2 as a function of a y_2 when $y_1 = 200 \mu\text{m}$. The vertical wakefield is compensated when the same offset as in DLW1 is introduced but with opposite sign.

However, the drive bunch enters DLW2 with a vertical momentum induced by the transverse fields in DLW1. To compensate for this kick and minimise BBU instability, it is necessary to introduce a greater vertical field in DLW2 to cancel this momentum. Figure 6 shows the required y_2 to cancel this vertical momentum. As expected, the offset must be greater than $-200 \mu\text{m}$ to generate a compensating vertical field, eliminating the momentum gained in DLW1.

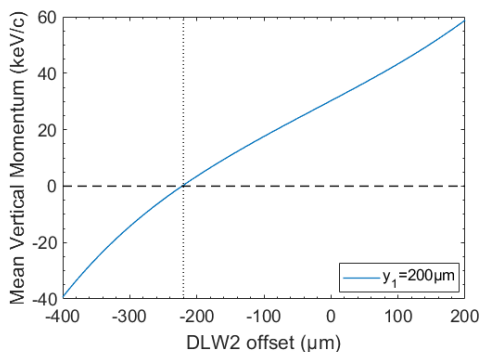


Figure 6: Mean vertical momentum at the end of DLW2, as a function of DLW2 offset, y_2 . Dashed lines illustrate the point where vertical momentum is cancelled, $y_2 = -220 \mu\text{m}$.

The same optimal offset for DLW2 was identified when examining the vertical position of the bunch at a downstream screen. Figure 7 shows the mean vertical position of the drive bunch at the end of DLW2 and after 3 m and 5 m of drift, as a function of y_2 . The results indicate that the bunch remains steady, regardless of the drift length, when $y_2 = -220 \mu\text{m}$. However, the mean bunch position is not precisely at zero, reflecting the vertical displacement acquired as the bunch travelled through DLW1. Although the vertical momentum was compensated in DLW2, this initial displacement remains.

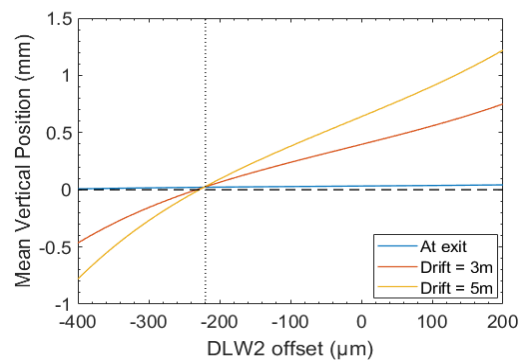


Figure 7: Mean vertical position of drive bunch when $y_1 = 200 \mu\text{m}$ as a function of y_2 (DLW2 offset).

For clearer visualisation of the kick compensation, Fig. 8 presents the vertical momentum as a function of time on the left, and the transverse bunch distribution after a 5 m drift, on the right. The vertical momentum increases towards the bunch tail when the same offset is applied in both DLWs. However, when a compensating offset is introduced in DLW2, the mean vertical momentum is cancelled, restoring it to a state similar to that of a perfectly aligned bunch. The transverse bunch distribution confirms that the bunch maintains a similar profile when the offsets are correctly compensated.

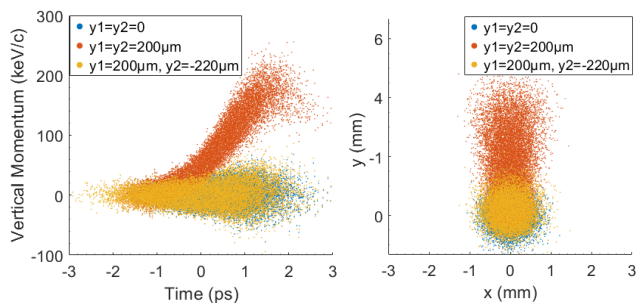


Figure 8: Mean vertical momentum along the bunch (left) and transverse bunch distribution (right) for aligned, compensated, and not compensated misalignments.

CONCLUSIONS

This study investigates the transverse fields in a dielectric wakefield acceleration (DWA) scheme, which cause beam break-up (BBU) instability. The main bunch is placed behind the drive bunch at an optimal time delay to experience the maximum accelerating field. Simulations show that the acceleration peak and cancellation of dipole-like transverse fields occur at the same time delay.

However, the transverse fields increase in strength towards the tail of the drive bunch, leading to beam losses that limit the bunch's propagation and, consequently, reduce the strength of the accelerating field. These simulations demonstrate that the transverse fields generated due to misalignments in a DLW, can be compensated by adjusting the transverse offset in a contiguous DLW.

These findings set the stage for future simulation and experimental studies at CLARA to develop a practical dielectric wakefield acceleration scheme that minimizes BBU instability.

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