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BEAM DYNAMICS AND DRIVE BEAM LOSSES WITHIN A PLANAR DIELECTRIC WAKEFIELD ACCELERATOR *

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Abstract

Beam-driven dielectric wakefield accelerators (DWA) have the potential to provide accelerating gradients in the GV/m range. The transverse dynamics in such devices need to be understood to avoid instabilities over long transport distances and facilitate beam matching to specific applications (e.g. FELs). This presentation details simulation studies of the magnitude of beam-breakup instability (BBU) in planar dielectric lined waveguides (DLWs). These are for DWA drive beams, with high charge and momentum that can be produced at current facilities. Using a series of perpendicular DLW segments has been proposed to control instabilities over larger distances. Using self-developed software, the beam dynamics of a drive beam within a DLW are simulated and the magnitude of beam losses along a DLW of varying lengths calculated and beam quality preservation investigated. Methods to reduce transverse instabilities have been explored, and the impact of these on the length of a possible DWA acceleration stage are investigated. An acceleration stage with m-scale length, consisting of multiple alternating planar DLWs, is suggested and preservation of beam quality along this distance is shown.

INTRODUCTION

Dielectric wakefield acceleration (DWA) is a method suggested to produce high gradient acceleration of charged particles at future facilities. DWA exploits the Cherenkov radiation generated by a drive beam of charged particles inside a dielectric lined waveguide (DLW) to accelerate a trailing main (witness) bunch [1].

DWA experiments have shown that electron bunches produced by conventional accelerators can excite fields of upto 850 MV/m before strong damping is observed [2], with charge symmetry demonstrated between electron and positron drive bunches [3]. Witness electron bunches have been accelerated with gradients of 300 MV/m [4]. Shaping the drive beam longitudinally, it is possible to increase the transformer ratio (accelerating to decelerating field ratio) [5]. Whilst this comes at the expense of the maximum accelerating field obtainable it does increase the efficiency of main bunch acceleration [6].

Experimental and theoretical studies of dielectric wakefield acceleration have either focused on cylindrical DLWs [4,7,8], or planar structures with just a single orientation [9]. Planar structures have been suggested as potentially advantageous due to the transverse fields being approximately quadrupole-like. This allows for the use of alternating, horizontal and vertical (H+V), akin to a FODO cell, to control transverse beam size while propagating through the structure [10, 11]. In these proceedings, simulations of drive beams in planar structures are presented. Beam losses in a single planar DLW determine the total length of acceleration that can be maintained, and a H+V setup is then used to determine the extent to which beam quality can be preserved.

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SIMULATION METHODOLOGY

A fully three-dimensional greens function approach has been used for these studies. Beams generated with initial parameters, or beams from other accelerator simulation tools, can be used as inputs and beam dynamics within a DLW calculated using a Boris pusher method [12]. Fields are calculated using the transverse operator method outlined in [13], which have been bench-marked against commercial codes CST and VSim. By specifically modelling DWA effects this increases efficiency compared to the commercial alternatives, allowing for computational time to be reduced by orders of magnitude. The number of modes used for each calculation is automatically chosen to ensure full convergence, and thus all higher order fields are automatically included.

SINGLE STAGE DYNAMICS

Beam and structure parameters, listed in Table 1, have been chosen to match those expected for a drive beam at a future DWA accelerator and achievable at current facilities. A beam is chosen with 2 nC charge and 1 GeV/c beam momentum to generate large longitudinal fields and facilitate ~m scale transportation. Beams with a larger charge density towards the tail are needed for a higher transformer ratio. For a maximal transformer ratio, a longer bunch with a 'double-triangular' or 'doorstop' shape would be used [14, 15]. We have chosen to simulate a highly skewed gaussian (with skewness $\alpha = -4$), so any beam losses at the tail are immediately evident.

Experimental and theoretical results have shown that transverse fields can be mitigated by using an elliptically shaped beam [9, 16]. We will compare the feasibility of a beam shaped in this way to a symmetric (circular) drive beam. Behind the drive bunches, these beam and structure parameters lead to peak accelerating fields of 78 MV/m and 62 MV/m for the circular and elliptical beams respectively.

In a realistic machine, small uncertainties in the initial beam position cannot be avoided. In Fig. 1, the charge transported in a single DLW stage is shown for the elliptical and

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Table 1: Beam and Structure Parameters

Property	
Total Beam Charge	2 nC
Beam Momentum	1 GeV/c
Total Bunch Length	2.5 ps
Gaussian Skewness, α	-4
Vertical Beam Width, σ_y	50 µm
Horizontal Beam Width, σ_x	50 µm (Circular) 500 µm (Elliptical)
Normalised Emittance, $\epsilon_{x,y}$	1 mm mrad
Vacuum Half-gap, a	500 µm
Dielectric Thickness, δ	250 µm
Dielectric Permitivity, ϵ	4

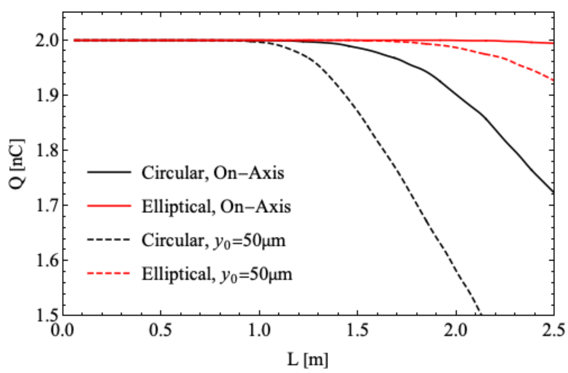

Figure 1: Charge transported along a single planar DLW, for the circular and elliptical beams both on-axis and offset 50 µm from structure centre.

circular beams. With a 50 µm offset towards the dielectric, beam-breakup instability (BBU) is seen with an elliptical beam at 2 m, and 1 m for the circular beam. Although BBU development due to beam offset from the axis is a stronger factor in beam losses than the beam defocussing at the tail caused by quadrupole-like wakefields as evident from Fig. 2, the latter cannot be neglected. Focusing and defocusing fields are not symmetric for elliptical beams [17], thus complicating (if not preventing) the configuration of perpendicular stages to maintain beam properties over a long distance. To demonstrate the effectiveness of the H+V configuration in controlling the transverse beam dynamics, we will use the circular beam in the following sections.

SINGLE H+V SECTION

For a single pair of H+V structures, the ideal scenario is for the output beam parameters to equal the input beam parameters. Symmetry between the two transverse planes and a decreased variation in parameters are also important for predictable beam behaviour. These conditions are affected by the structures lengths as demonstrated in Fig. 3 where two cases are presented: each DLW section of 20 cm and 50 cm length. At the exit from a second 20 cm long DLW structure, the beam sizes in both planes differ from initial parameters by only a few micrometers. With 50 cm structures, the increase

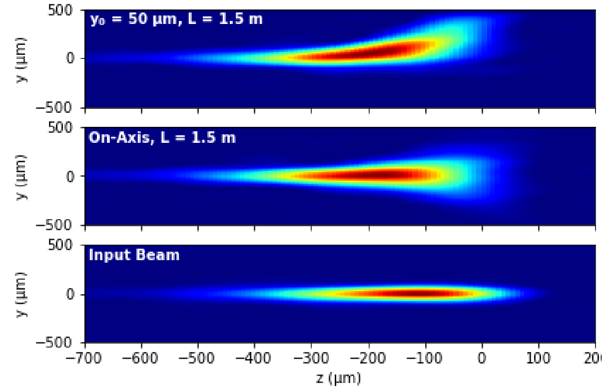

Figure 2: Vertical and longitudinal macroparticle positions 1.5 m into a single DLW stage for the circular beam, with initial position on-axis and with a small offset. The input beam is also shown. The bunch head is on the left.

in beam sizes is significantly larger and beam envelopes in both planes are evidently asymmetric. The same applies to the evolution of the projected normalized emittance as shown in Fig. 4. Again, the shorter DLW sections appear to be a preferred choice given the fact that, at the exit, the emittance returns to approximately the initial value. We will therefore consider the shorter 20 cm stages for long distance acceleration.

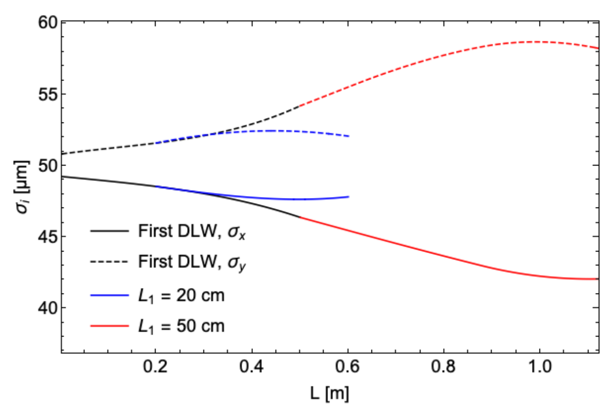

Figure 3: Horizontal (solid) and vertical (dashed) beam sizes through a H+V section, for a first horizontal section 20 cm and 50 cm long.

LONG DISTANCE ACCELERATION

Two configurations of multiple DLWs have been considered: with the first and final sections half the length of other sections, or each section of equal length. Simulations show that the beam size is kept more consistent using a first and final section 10 cm long. Differences in normalised emittance at the end of the 2 m are less pronounced: horizontal RMS emittance, ϵ_x is 4.4 and 5.3 mm mrad for L_1 = 10 and 20 cm respectively. As shown in Fig. 5, variations in beam size from focusing and defocusing through each section are not pronounced enough to show obvious betatron-like oscillations that would be expected with longer sections.

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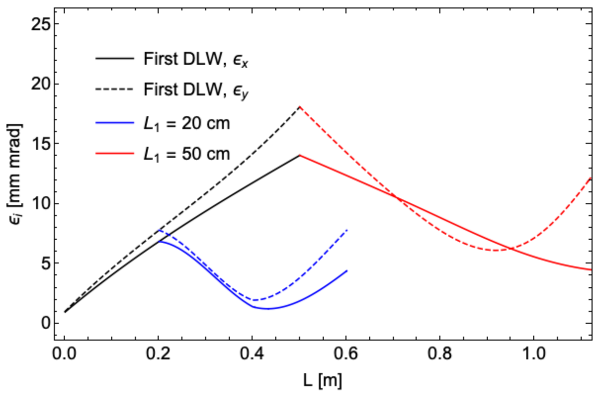

Figure 4: Horizontal (solid) and vertical (dashed) normalised RMS emittance through a H+V section, for a first horizontal section 20 cm and 50 cm long.

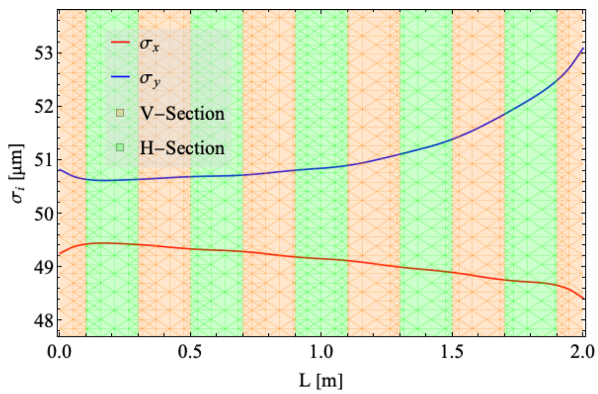

Figure 5: Horizontal and vertical beam sizes through 2 m of alternating horizontal (green) and vertical (orange) sections. N.B. measurements are taken at the end of each section.

Transverse fields are quadrupole-like, however the strength of the quadrupole field varies along the bunch. Quadrupole magnets cannot be used to cancel the transverse fields in the same way that a series of H+V sections can. Each longitudinal slice is affected by an approximately quadrupole-like field which is compensated with alternating DLWs. This can be seen in Fig. 6, where transverse phase spaces are shown for the central longitudinal beam slice at the entrance, after the first pair of DLWs and at the end of the 2 m channel. The slice emittance is practically unchanged. It is worth noting that unless a slice is infinitely thin longitudinally there will be growth in slice emittance due to longitudinal variation in transverse field strength. For sufficiently short 160 fs slices, the RMS slice emittance at the centre of the beam increases by less than 1% across the 2 m.

Transverse fields are not fully compensated for two reasons: higher-order (non-quadrupole) fields, and asymmetries in the beam profile. Higher-order fields cause curvature at the beam edges after the final section (seen in Fig. 6). Shown in Fig. 7, the projected horizontal phase space changes insignificantly from start to end. However, a small focusing effect can be seen in the final horizontal phase

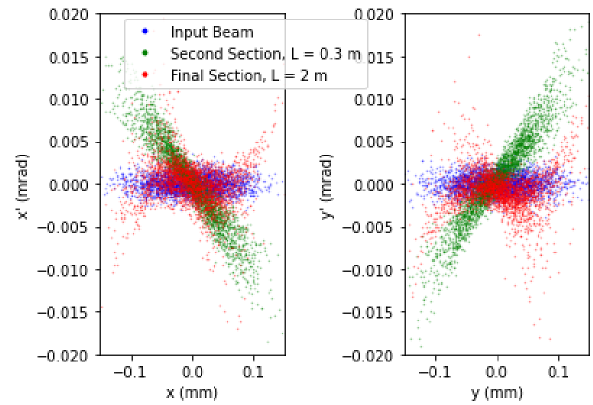

Figure 6: Horizontal and vertical phase space for the central of 11 longitudinal slices, at the end of the first vertical section, the final section, and initial phase space for this slice.

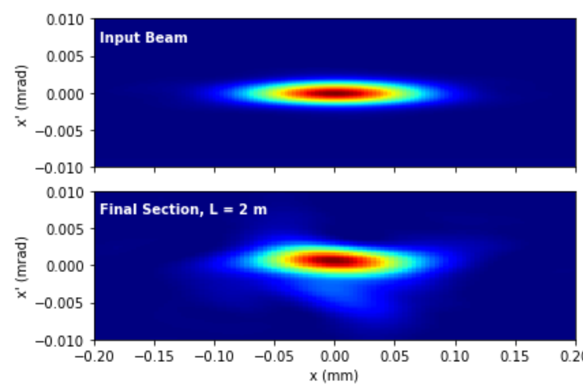

Figure 7: Projected horizontal phase space for the input beam and after 2 m.

space. The equivalent defocusing is observed in the vertical plane. These effects are however minimal and account to only a few μm beam size changes in both planes. This is likely due to the random variation in initial beam widths.

CONCLUSIONS

BBU instability is a main factor in limiting the length of an DWA structure, due to drive beam losses. The strength of the transverse kick off-axis (and therefore acceleration length) is proportional to charge, inverse vacuum gap cubed, and inverse beam momentum. We have demonstrated that the effects of the quadrupole wakefields can be effectively eliminated by using multiple perpendicular DLW stages. Beam quality can be maintained with a circular beam in this setup, unlike with an elliptically shaped beam that is able to mitigate for BBU losses. Using a H+V setup with an elliptical beam is, in principle, possible but presents a more complex problem subject to dedicated further study. With BBU sufficiently suppressed, the H+V setup can be used to extend this concept beyond the 2 m shown here.

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