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A HIGH-EFFICIENCY DIELECTRIC WAKEFIELD ENERGY BOOSTER FOR CLARA

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Abstract

Structure-based wakefield acceleration, using dielectric-lined or corrugated waveguides, is a novel acceleration method currently being explored by several research groups globally. This technology facilitates the transfer of energy from a high-charge drive beam to a lower-charge main bunch with high accelerating gradients. In this study, we propose an energy booster for the Compact Linear Accelerator for Research and Applications (CLARA) at Daresbury Laboratory, utilising dielectric wakefield acceleration (DWA). Our simulation study optimises the drive beam and structure to achieve maximal energy efficiency across varying main beam energies, enabling the delivery of a main beam with adjustable charge and final energy. Additionally, we have considered the stability of both the accelerated and drive beams, selecting the geometry and layout of accelerating structures to maximise accelerated beam quality and mitigate the development of beam breakup instability in the drive beam.

INTRODUCTION

Beam-driven novel acceleration methods, whether structure-based or plasma-based, are being proposed as methods to extend or upgrade existing accelerator facilities as well as for the development of new facilities. Structure wakefield acceleration (SWFA) structures, using dielectric or metallic corrugated waveguides, are increasingly used for beam manipulation and diagnostics at current facilities, such as energy dechirpers [1, 2] and passive streakers [3, 4], and experiments have demonstrated acceleration with gradients up to 320 MV/m and GV/m fields without breakdown [5, 6]. SWFA is being developed for use at proposed and upcoming facilities, such as at the Argonne Wakefield Accelerator [7], and tested at multiple facilities worldwide.

The Compact Linear Accelerator for Research and Applications (CLARA) at Daresbury Laboratory is a 250 MeV accelerator currently being commissioned, with Phase-2 of operation planned to begin in late-2025. CLARA is built with the goal of researching accelerator technology, including novel acceleration techniques and FEL related technologies, and accelerator related topics such as medical and industrial applications [8]. Previous experimental exploitation at CLARA was with a maximum 35 MeV, and a maximum 100 pC, between 2018 and 2021. Phase-2 involves increasing the maximum energy to 250 MeV and charge to 250 pC, for delivery to the Full Energy Beam Exploitation (FEBE) experimental hutch [9]. FEBE is designed for user experiments with two experimental chambers and capability to characterise output beams from experiments up to 2 GeV. A dielectric wakefield dechirper will be installed prior to the FEBE dog-leg to control the longitudinal phase space, and a removable dielectric wakefield streaker is planned for longitudinal diagnostics in the FEBE hutch [10]. The layout of CLARA is shown in Fig. 1.

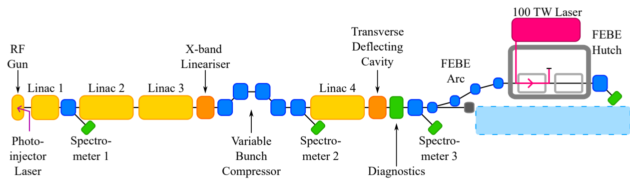

Figure 1: Schematic of the CLARA Phase-2 beamline [9]. The straight-on beamline considered for a DWA booster is highlighted in light-blue.

The aim of CLARA as an accelerator test facility requires a flexible accelerator capable of delivering electron bunches with tuneable parameters. With this in mind, we considered the use of a dielectric wakefield accelerator (DWA) energy booster. This booster would allow for the delivery of electron beams with energies between 250 MeV and 1.5 GeV and bunch charge inversely proportional to energy. In these proceedings, we will present a proposed acceleration cell and accelerator layout. We will then demonstrate the ability of such a layout to accelerate the main bunches to varying final energies with the associated efficiency of drive beam energy extraction. Finally, we will present an example beam transport through a single acceleration cell, demonstrating the preservation of beam quality for both drive and main beams.

CLARA BOOSTER STRUCTURE

The DWA energy booster considered in these proceedings uses a set of planar dielectric-lined waveguides (DLWs), with alternating orientations. This horizontal+vertical (H+V) setup has been investigated and shown to mitigate quadrupole-like wakefields, conserving beam quality over long propagation distances [11, 12]. These DLWs are laid out as in Fig. 2, with alternating single- and double-length DLWs to avoid the development of overall focusing/defocusing.

Transverse wakefield effects are minimised by reducing the length of each DLW. Controlling the gap and position of every DLW becomes impractical as the length of each DLW decreases and number of DLWs increases. It is more

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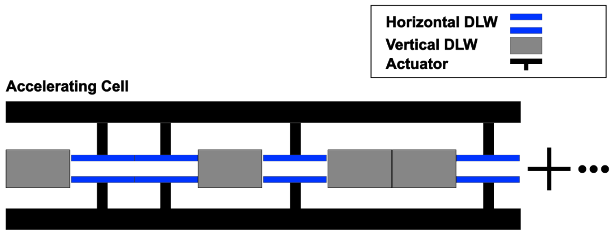

Figure 2: Schematic of a DWA acceleration cell, using a H+V setup, with the layout shown repeating indefinitely.

practical to connect DLW plates of the same orientation to a single actuator, with 4 actuators to control the DLW gap and position.

The DLW parameters have been chosen to minimise the excitation of higher-order modes (i.e. closer to a single-mode approximation) to maximise the achievable transformer ratio. Therefore, a thin dielectric (150 µm thick) with a low dielectric permittivity (quartz, $\epsilon_r = 3.75$) has been chosen. With planar DLWs the dielectric gap is adjustable, allowing for the same acceleration length independent of final energy. For these proceedings, we have considered a single 150 µm vacuum half-gap in all cases.

SIMULATION RESULTS

The 3D wakefields excited in the DLWs have been calculated using DiWaCAT, an open-source dielectric wakefield calculator and beam tracker which has previously been benchmarked against experimental results [13, 14].

The final main beam energy is determined by both the transformer ratio (TR), and the accelerating gradient. The TR, defined as the ratio of maximum accelerating gradient (within the main bunch) to maximum decelerating gradient (within the drive bunch), sets a limit on the maximum energy to which the main beam can be accelerated before the drive beam energy is fully extracted. If the acceleration length is constant, the acceleration gradient also sets a limit on the main bunch final energy.

The efficiency of the accelerator is the ratio of total energy transfer from drive to main beam, given by

$$\eta = \frac{Q_m \langle E_m \rangle}{Q_d \langle E_d \rangle}, \tag{1}$$

where Q_d and Q_m are the drive/main bunch charges, and $\langle E_d \rangle$ and $\langle E_m \rangle$ are the average drive beam decelerating gradient and main beam accelerating gradient respectively. The factors in Eq. (1) illustrate that a perfectly efficient wakefield accelerator is analogous to a transformer, converting a high current (charge) and low voltage (energy) input into low current and high voltage output.

Tuneable Main Beam Energy

Ideally, the drive beam energy would be fully depleted at the end of the acceleration length. Using the setup in Fig. 2, if the drive bunch is depleted before the end of the acceleration length, those remaining DWA cells can be set with a large gap to prevent it from interacting with the beam.

The drive and main beam profiles are chosen by optimising for both a specific transformer ratio and maximising the energy transfer efficiency. This ensures that the maximum total energy is extracted. The starting point for the optimisation is the doorstop profile defined in [15]. Solutions which result in an RMS acceleration gradient spread greater than 5% in the main bunch are excluded.

Three main bunch energies have been considered: 500 MeV, 1 GeV, and 1.5 GeV. At the start of the booster, the main and drive bunch energies are both 250 MeV, so the required transformer ratios are 1, 3, and 5 for each final energy. The fields excited for each TR are shown in Figs. 3, 4, and 5 respectively. Values for the fields excited in each case are listed in Table 1. A 150 µm half-gap produces a ~10-20 MV/m accelerating gradient in all cases, demonstrating the need also to change the gap to keep a constant total acceleration length. In practice, the length required to reach over 1 GeV at these gradients would be limiting. These energies would likely require higher beam charges to be feasible, with the accelerating gradient directly proportional to drive beam charge whilst efficiency remains constant. For a total acceleration length of 20 m, 1 GeV, and 1.5 GeV final energies would require ~1 nC, and ~1.5 nC drive beams respectively; main bunch charges scale with drive charge.

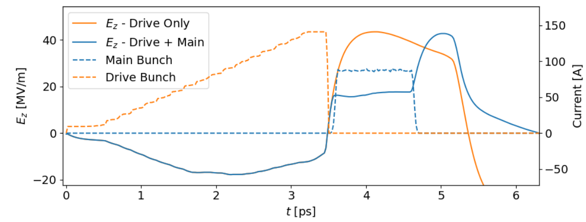

Figure 3: Longitudinal fields (left axis) and current profiles (right axis) for TR = 1.

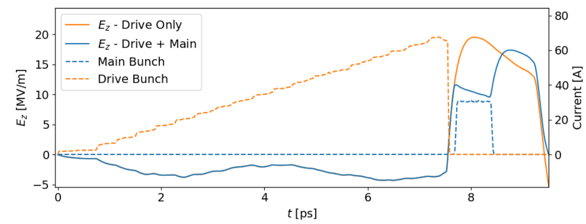

Figure 4: Longitudinal fields (left axis) and current profiles (right axis) for TR = 3.

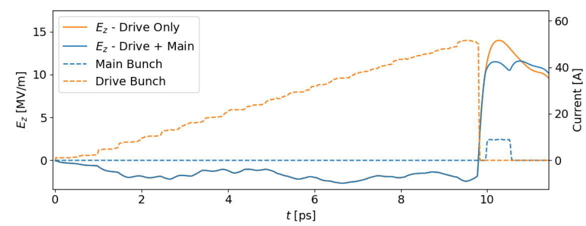

Figure 5: Longitudinal fields (left axis) and current profiles (right axis) for TR = 5.

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Table 1: Field parameters for each optimised transformer ratio (TR) presented. E_d and E_m refer to drive/main beam field respectively.

Parameter	**TR = 1**	**TR = 3**	**TR = 5**
Q_m [pC]	92.5	21.4	5
Total Drive Length [ps]	3.5	7.5	9.8
Maximum E_m [MV/m]	19.50	12.16	11.83
$\langle E_m \rangle$ [MV/m]	17.72	10.31	11.39
Maximum E_d [MV/m]	16.48	4.10	2.14
$\langle E_d \rangle$ [MV/m]	12.48	3.13	1.34
Efficiency, η [%]	52.54	28.14	19.31
RMS σ_{E_m} [%]	2.82	1.38	3.49

The achievable efficiency depends on the transformer ratio and energy spread. Maintaining the accelerating gradient required for a higher TR requires a lower charge main beam to avoid a large impact on the field, reducing efficiency. Similarly, a high charge main beam cancels a large amount of the accelerating field. If this cancellation is too strong the energy spread increases, setting a limit on efficiency. The optimisation performed here shows 55% energy transfer efficiency for the energy doubler, 28% for TR = 3, and 19% efficiency for TR = 5. The main bunch profile shape was kept constant; optimisation of this could bring efficiency gains and decreased energy spread increase.

Example Beam Transportation

Beam transport through a 0.5 m section of a DWA booster has been simulated using DiWaCAT, for the energy doubler (TR = 1) and 250 pC drive beam. Wakefields were calculated at the start of each DLW with the beam tracked through each 1.25 cm long DLW. Quadrupole-like wakefields present a challenge for beam transport. These fields introduce longitudinal variation in Twiss parameters in both drive and main bunches, introducing difficulties in terms of beam optics matching with conventional magnets between cells. Beam quality degradation is worsened by large transverse beam sizes or large divergence through DLWs. These features break the symmetry of transport through alternating structures, reducing wakefield cancellation and seeding beam-breakup instability.

The parameters for the input beam are listed in Table 2 (L = 0 m). The beam profile for TR = 1 requires longitudinal beam shaping, with ongoing development in this area at CLARA using photocathode laser shaping. Parameters at the end of the simulation, L = 0.5 m, are listed in Table 2. The main bunch acceleration matches expectations from the field calculation, with an average energy gain 1.56× the average drive beam energy loss and 1.44× the maximum deceleration. Emittance growth is seen, a result of longitudinal variation in beam parameters despite mitigation using the H+V geometry.

The horizontal phase spaces at the start and end are shown in Fig. 6, and longitudinal phase spaces shown in Fig. 7. Whilst the projected emittance has not significantly grown, the transverse momentum has grown over the acceleration length and the beam focused horizontally. Large divergence should be avoided, requiring regular beam optics between cells to 'reset' the beam and ensure effects degrading beam quality are not seeded. The emittance growth could be reduced by further reducing the length of each DLW, or increasing the dielectric gap (at the cost of accelerating gradient). Increasing the dielectric gap reduces the ratio of transverse to longitudinal wakefield strength [16].

Table 2: Beam (Drive+main) Parameters for the Simulation Input (L = 0 m) and L = 0.5 m

Parameter	**L = 0 m**	**L = 0.5 m**
Mean Energy (Drive) [MeV]	250.00	242.42
Mean Energy (Main) [MeV]	250.00	261.84
RMS Energy Spread (Main)	0.400%	0.677%
$(\epsilon_{x,n}, \epsilon_{y,n})$ [mm mrad]	(1.0, 1.0)	(1.66, 2.16)
RMS (σ_x, σ_y) [μm]	(10, 10)	(4.45, 17.64)

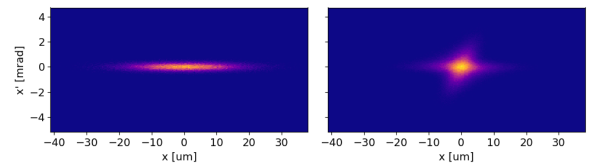

Figure 6: Horizontal phase space for the simulated beam at the start (left) and end (right), at L = 0.5 m.

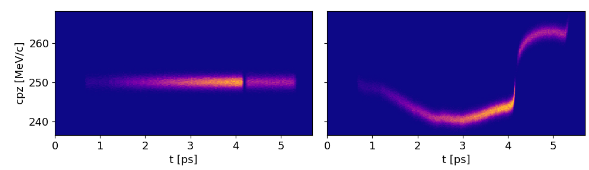

Figure 7: Longitudinal phase space for the simulated beam at the start (left) and end (right), at L = 0.5 m. The head of the drive beam is at the left of each plot.

CONCLUSIONS

In conclusion, we have shown that a dielectric wakefield booster at CLARA has the potential to accelerate beams with a tuneable final energy, delivered by optimising drive bunches for a target transformer ratio. We have considered beam transport for a section of a 20 m long CLARA energy doubler and demonstrated beam quality conservation and potential issues with beam transport. Increased bunch charge would be required to feasibly reach >1 GeV final energies. Increased bunch charges would also improve beam transport by allowing for larger dielectric gaps, resulting in lower relative transverse wakefields.

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