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A STABLE DRIVE BEAM FOR HIGH GRADIENT DIELECTRIC WAKEFIELD ACCELERATION*

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Abstract

A high accelerating gradient, with stable beam transport, is necessary for the next generation of particle accelerators. Dielectric wakefield accelerators are a potential solution to this problem. In these proceedings, we present simulation studies of electron bunches in the self-wake regime inside a planar dielectric structure. This is analogous to driving beams in a dielectric wakefield accelerator. The transverse and longitudinal wake fields are investigated for dielectric plate gaps, various transverse beam sizes, and longitudinal bunch profiles. The effects of these on the stability of drive bunches, and acceleration of a witness bunch, are discussed in the context of electron bunches that can be produced with conventional linac RF technology.

INTRODUCTION

With conventional accelerating technology, using RF structures, the accelerating gradient for charged beams is limited. This is typically ~30-50 MV/m. A number of novel accelerating methods have been proposed to accelerate charged particles using electrical fields orders of magnitude larger than this, including plasma-based and structure based technologies. Dielectric Wakefield Acceleration (DWA), has been shown experimentally to accelerate electron beams with gradients of 300 MV/m [1], and sustain GV/m fields without breakdown [2].

Accelerating beams at these gradients, whilst maintaining beam quality, requires control of transverse effects. Inside a planar dielectric lined waveguide (DLW), as in Fig. 1, transverse fields are quadrupole like, de-focusing towards the dielectric plates, F_y, and focusing in the perpendicular direction, F_x [3]. These fields are significant, with an accelerating gradient ~GV/m, the transverse fields within the bunch are ~100 MV/m [4]. Fields of this strength make beam stability a significant issue; F_y is defocussing and will affect stable beam acceleration, leading to beam losses if not controlled. A number of procedures for reducing the transverse wakes have been suggested, including the use of elliptical beams which has been shown theoretically and confirmed experimentally to reduce transverse fields [3, 5].

MODELLING TECHNIQUE AND SOFTWARE

To simulate fields inside the planar DLW, software has been developed to implement the transverse operator method,

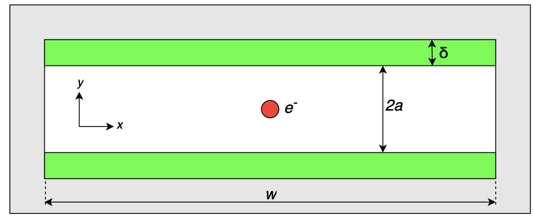

Figure 1: Diagram of the transverse profile of a planar DWA. For reference, silver is outer casing, green is the dielectric material, and white is vacuum.

as described in [6]. The field is given by the convolution of the Green's function (the wake potential W_i), and the beam charge density, $\rho(x, y, z)$. Solutions are calculated for the vacuum and dielectric regions.

The input beam for this software is generalised, given as either a 3D probability distribution function, with the beam generated within the code, or as an external beam file (i.e. from another simulation software). The code has been benchmarked against commercial codes, namely VSim [7] and CST [8], to ensure valid field calculations.

The field strength is directly proportional to the drive beam charge. Of importance is the ratio of longitudinal and transverse fields, and the ratio of peak decelerating and peak accelerating fields. F_y and F_x relate to the transverse forces orthogonal and parallel to the dielectric plate respectively. From the longitudinal field E_z, E_z^{dec} and E_z^{acc} are the peak decelerating (within the bunch) and accelerating fields (behind the bunch) respectively. We will define the stability ratio (S.R.) as

$$\text{S.R.} = \frac{E_z}{F_y}, \tag{1}$$

which will be given at a specific longitudinal position within the drive bunch (chosen to be ξ=0 throughout these proceedings). The transformer ratio, defined as

$$\text{T.R.} = \frac{E_z^{acc}}{E_z^{dec}}, \tag{2}$$

will relate to the peak decelerating field within the drive bunch and peak accelerating field behind the drive bunch. Throughout, F_y and F_x will be calculated at the transverse position $(x, y) = (0, +1\sigma_y)$ and $(+1\sigma_x, 0)$ respectively. E_z is always calculated at the beam centre, $(0, 0)$.

DIELECTRIC GAP

While increasing the dielectric half-gap, a, both longitudinal and transverse fields will reduce. The longitudinal field

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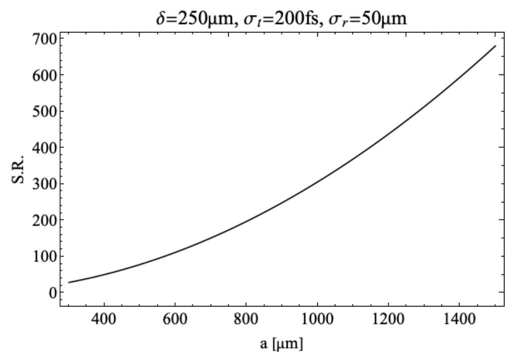

Figure 2: Stability ratio for a 200 fs bunch with varying dielectric half-gap.

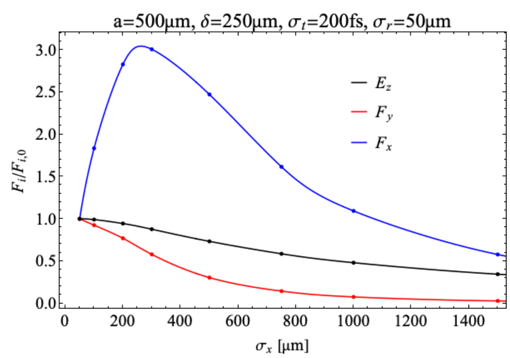

Figure 3: The 3D fields with varying beam width, σ_x. The fields are normalised to the fields for a circular beam, $F_{i,0}$.

reduces at an faster rate, therefore increased dielectric gap does increase the stability of the bunch, for a given accelerating gradient as shown in Fig. 2. Between a=500 µm and 1 mm the stability ratio increases by a factor of 3.9, with decelerating gradient decreasing by a factor of 3.1.

The field strength increases linearly with drive beam charge. Increasing both beam charge and dielectric gap, a constant accelerating gradient can be achieved, and defocusing force can be decreased.

ELLIPTICAL/FLAT DRIVE BEAM

Wider beams can be used to reduce transverse fields. By increasing the horizontal width of the bunch, coupling to higher-order modes is reduced [3]. When compared to the fields with a round bunch, reduced defocusing fields are seen with increased σ_x in Fig. 3. This pattern matches experimental results [5]. This displays a potential way to mitigate transverse forces and increase drive beam stability. The accelerating gradient decreases at a slower rate, so high fields could be obtained with lower de-focusing fields. For example, at σ_x=800 µm, F_y is 15% the value for a circular beam, whilst the longitudinal field is still 60% the value for a circular beam.

Larger focusing than de-focusing, as shown in Fig. 3 does reduce the symmetry of the system. Having symmetric fields would allow for planar plates to be used perpendicular to each other to balance fields in each direction. This "horizontal and vertical" (H+V) setup has been previously proposed, and can be viewed similarly to a FODO cell [9]. FODO-like behaviour is no longer true if the fields are not equal or not quadrupole-like. The shape of the focusing force in the horizontal direction for wider beams will determine this.

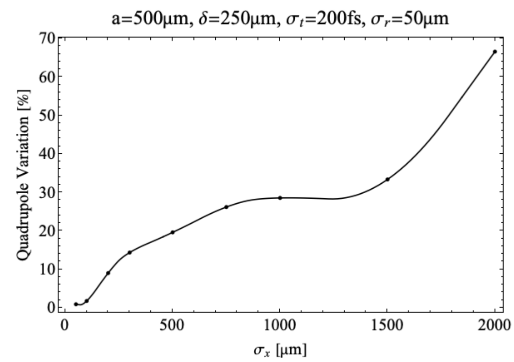

Figure 4: The percentage variation from quadrupole behaviour for bunches of varying beam widths, σ_x. A positive variation relates to F_x smaller than expected for purely quadrupole-like fields.

Beam Optics

For the fields to remain quadrupole-like, and therefore able to take advantage of a H+V setup, the transverse force must remain proportional to the distance from the beam centre. Therefore, the ratio of $F_x(\sigma_x)$ to $F_y(\sigma_y)$ should be equal to the ratio of σ_x to σ_y. The variation from this relationship grows with beam width, shown in Fig. 4. Reduced focusing, compared to a quadrupole magnet, would require a the H+V DLWs with different lengths to ensure the different focusing and de-focusing do not lead to a growth in beam size.

The variation in force across the transverse profile determines whether the Gaussian profile is maintained. For the Gaussian transverse profile to be maintained, the transverse force must be purely quadrupole-like (i.e. $F_x \propto \Delta x$). For a circular beam, the focusing force is directly proportional to the distance from beam centre as expected, see Fig. 5. This relationship is not maintained for wider bunches, with reduced focusing at the beam edges. Increased focusing at the centre will relate to increased kurtosis. Kurtosis could be corrected by sextupole magnets, but cannot be counteracted by a DLW in the same way as quadrupole-like fields.

LONGITUDINAL BUNCH PROFILE

Symmetrical longitudinal bunch profiles, have a transformer ratio limited to 2 [2]. If the bunch length of a driving beam is comparable to the fundamental mode wavelength, a non-symmetrical beam can increase this [10, 11]. The particle distribution function (PDF) for a skew-Gaussian beam is given by

$$f(x) = \phi(x)(1 + \mathrm{erf}(\frac{\alpha x}{\sqrt{2}})), \quad (3)$$

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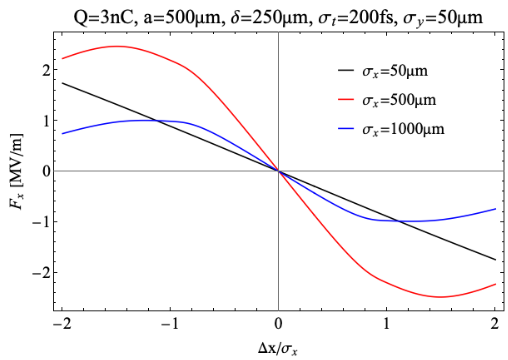

Figure 5: F_x across the horizontal bunch profile for 200fs bunches for a number of beam widths.

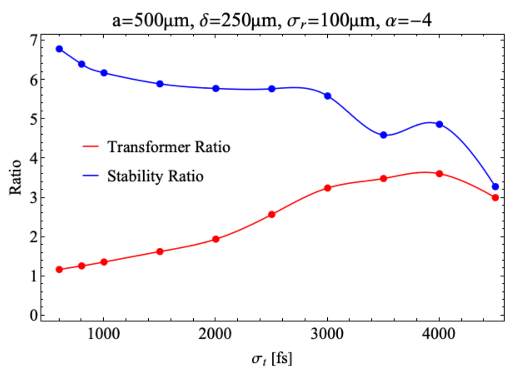

Figure 6: The transformer and stability ratio for increasing bunch length, for a skew-Gaussian bunch with α = -4.

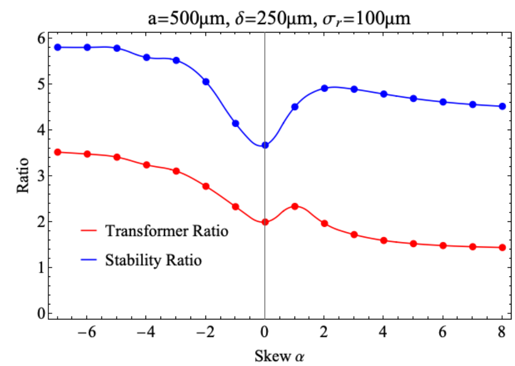

Figure 7: The transformer and stability ratio for increasing skewness, for a bunch with σ_t = 3 ps.

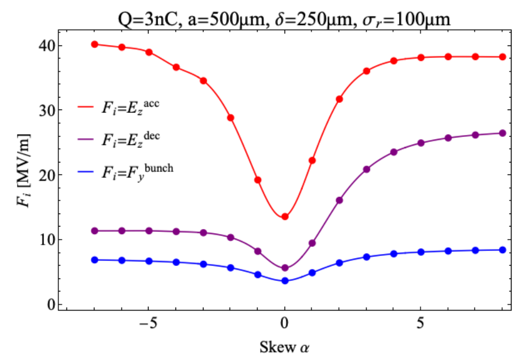

Figure 8: Fields calculated for a 3nC, σ_t = 3 ps, bunch for varying skewness.

where $\phi(x)$ is the normal distribution, erf() is the "error function", and α is the skewness. Increased positive α moves the peak current closer to the head of the bunch.

The relationship between the bunch length and T.R. has been explored for fixed structure parameters, shown in Fig. 6, with a maximum T.R. = 4 (double the maximum for a symmetric beam). Bunches longer than 4 ps contain both acceleration and decelerating phases within large parts of the bunch which would make them unsuitable. As the T.R. increases, the S.R. of the bunch decreases. T.R. increases faster than S.R. decreases, therefore the transverse force for a given accelerating gradient decreases.

The skewness of the profile affects the efficiency and stability of acceleration. An increased negative skewness leads to a higher transformer ratio, shown in Fig. 7. This should be expected as a result of increased non-symmetry. The stability ratio approximately follows the transformer ratio. As seen in Fig. 8, the increase in T.R. are due to large increases in accelerating gradient whilst decelerating gradient increases by less than 10%. For positive α, the deceleration force increases along with accelerating gradient. Increased α relates to large current at the beam head, so fields are similar to a short, pulse-like bunch.

Elliptical Skew-Gaussian Beams

With both the longitudinal and transverse beam profile able to increase the transformer ratio and stability ratio respectively, combining the two would allow for acceleration over longer distances with greater control. The same behaviour seen with a Gaussian beam with σ_t = 200 fs, is seen with a skew-Gaussian bunch with σ_t = 2.5 ps. The transformer ratio remains almost constant with increasing width. From σ_x = 50 μm to 2 000 μm, the stability ratio increases by an order of magnitude, from 5.95 to 59.0. In the same space, the transformer ratio decreases by 11%, from 3.53 to 3.12. Due to the potential growth in beam size and kurtosis, the transport of such beams requires future study.

CONCLUSION

Tailoring the longitudinal and transverse beam profile, both the stability of a drive beam and transformer ratio can be optimised. Using a highly skewed/triangular beam, a high transformer ratio can be achieved with a beam of bunch length comparable to the fundamental wavelength of the structure. For a target accelerating gradient, the transverse profile can be tailored to ensure maximum stability for that given accelerating gradient. Optimising for bunch length, structure gap, and transverse profile provides a suitable beam for high-gradient acceleration over larger distances. Future work on the optimisation and the transport of beams with high stability and transformer ratios will determine the feasibility of such an approach.

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