ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB155

STRONG QUADRUPOLE WAKEFIELD BASED FOCUSING IN DIELECTRIC WAKEFIELD ACCELERATORS

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Abstract

We propose here to exploit the quadrupole wakefields in an alternating symmetry slab-based dielectric wakefield accelerator (DWA) to produce second-order focusing. The resultant focusing is found to be strongly dependent on longitudinal position in the bunch. We analyze this effect with analytical estimates and electromagnetic PIC simulations. We examine the use of this scenario to induce beam stability in very high gradient DWA, with positive implications for applications in linear colliders and free-electron lasers.

INTRODUCTION

Dielectric Wakefield Accelerators are of major interest to anyone building or using accelerators since they promise to significantly decrease accelerator size and consequently cost. They promise this by providing significantly higher accelerating gradients than typical copper cavities. DWA schemes can generate accelerating gradients exceeding 1 GeV/m [1] whereas the International Linear Collider for example calls for a gradient of 31.5 MV/m [2]. Since DWAs are not limited to colliders such as the ILC but are also highly applicable to technologies such as the X-ray Free Electron Laser [3] which in turn is in high demand [4, 5] meaning there is significant opportunity to deploy DWA schemes.

Unfortunately one of the major limitations of DWAs is the instability of the drive bunch due to short-range wakefields resulting in Single Bunch Beam Breakup (SBBU). This instability threatens to limit the effectiveness of DWAs [6, 7] by imposing a maximum length on all such designs. An immediate solution comes in the form of the slab-symmetric DWA structure paired with an extremely high aspect ratio beam which eliminates the deflecting modes causing SBBU. Unfortunately completely eliminating all deflecting modes also eliminates the accelerating modes. Fortunately, the accelerating field scales with σ_x^{-1} while the deflecting force scales with σ_x^{-3} [8] so there is hope. The natural result of a slab-symmetric AWA is a quadrupole response since single particle wakes in such a structure are given by [9] as

$$W_\perp = -\frac{Q\pi^3\theta(\zeta)\zeta}{8a^3}\left(\operatorname{sech}\left(\frac{\pi}{4}\frac{\psi^*-\psi_0}{a}\right)\right)^2\tanh\left(\frac{\pi}{4}\frac{\psi^*-\psi_0}{a}\right), \tag{1}$$

where ζ is $z - ct$, θ is the Heavyside function, a is half the vacuum gap, and ψ is given by $x + iy$. The result of this is that for any real beam in a slab-symmetric structure there will be at least a quadrupole response.

In the limit $x \ll a$ and $y \ll a$ Eq. (1) can be deconstructed into

$$w_y \simeq \frac{Q\pi^4}{32a^4}y\zeta\theta(-\zeta) \tag{2}$$

$$w_x \simeq -\frac{Q\pi^4}{32a^4}x\zeta\theta(-\zeta) \tag{3}$$

and in event we consider a uniform current with the head of the beam at $\zeta = 0$ we can arrive at

$$w_x = -\frac{\lambda\pi^4}{64a^4}x\zeta^2, \tag{4}$$

where λ is the linear charge density. Since the focusing (and defocusing) are second order in ζ this is highly advantageous and leads directly into our proposed design. By repeatedly alternating the orientation of the structure relative to the beam we can turn these rather powerful deflecting modes to our advantage.

THE ALTERNATING SYMMETRY STRUCTURE AND SIMULATION SETUP

We studied the alternating symmetry structure via PIC simulations using CST Studio Suite. The simulations were focused exclusively on the beam-structure interaction and therefore did not consider any external forces such as focusing magnets or any information imparted on the beam by a theoretical upstream lattice. We modeled the structure within CST via simple blocks of silicon dioxide with a coating of perfect conductor on the significant outer face as seen in Fig. 1. The blocks are then arranged in parallel pairs with a variable distance vacuum gap between the uncoated dielectric faces. Each pairing is then arranged longitudinally at 90° to the previous pair creating the alternating symmetry. The full parameters for the geometry of the structure are given in Table 1.

We simulated a "control"structure as well to demonstrate the effect of the alternating symmetry scheme. This structure is identical to the alternating symmetry structure except all of the pairs of dielectric slabs are parallel to each other as seen in Fig. 2.

The beam used to drive the structures was generated externally via Mathematica and then imported into CST to avoid accidental binning of the particles in time. The beam parameters are given in Table 2.

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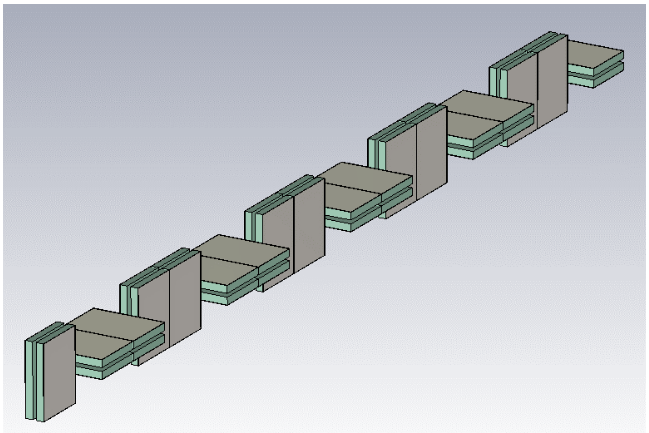


Figure 1: The Alternating symmetry structure simulated in CST. Each "cell" of the structure is composed of two mirrored dielectric slabs made of Silicon dioxide and coated with a perfect conductor on their outer face with a vacuum gap between them.

Table 1: The Geometric Parameters of the Alternating Symmetry Structure Seen in Fig. 1

Gap	1 mm
Cell length	30 mm
Slab thickness	2 mm
Dielectric constant	3.75
Number of "cells"	9

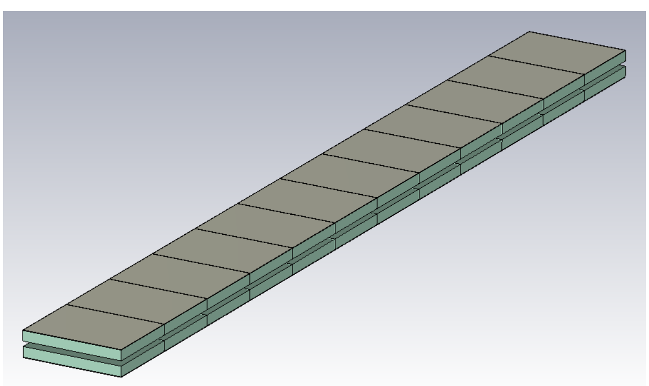


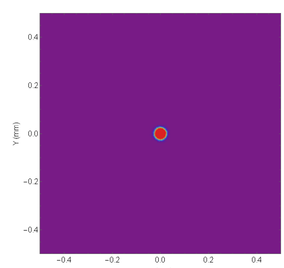
Figure 2: The control structure. Identical to the structure in Fig. 1 except there is no rotation between dielectric "cells".

Table 2: The Parameters of the Beam Used to Drive the Dielectric Structures. The Beam is Mono-Energetic

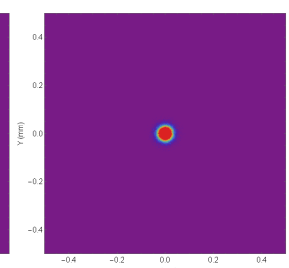
Energy	**40 MeV**
Charge	1 nC
σ_x	10 µ m
σ_y	10 µ m
σ_z	600 µ m
ϵ_{Nx}	0.05 µ m Rad
ϵ_{Ny}	0.05 µ m Rad

RESULTS

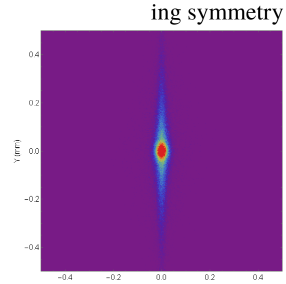
We obtained our results by exporting the beam periodically during the simulation. This allowed us to examine the beam dynamics throughout the structure but we primarily focused on the beam as it exited the structure to simulate the data given by a YAG screen if this were a real experiment. One of the major indicators that we examined was the transverse profile of the beam, both longitudinally integrated and slicewise in z. The longitudinally integrated trace-spaces are presented in Figs. 3 and 4. It is immediately visually obvious that the alternating symmetry scheme has had a significant effect on the survival of the beam. In Fig. 4c the tail of the beam is filling the entire gap of the structure and losing particles which is not desired. Numerically, σ_y of the beam at the exit of alternating symmetry structure is 15 µm and 123 µm at the exit of the control structure. Similarly, σ_x at the exit of the alternating symmetry structure is 15 µm and 18 µm at the exit of the control structure. The alternating symmetry structure clearly preserves the beam quite well without sacrificing anything other than complexity of design.



(a) At the entrance to the structures.



(b) At the exit of the alternating symmetry structure.



(c) At the exit of the control structure.

Figure 3: XY trace spaces of the beam at the start of the structures and at the end of both the alternating symmetry structure and control structure.

DISCUSSION

The alternating symmetry geometry appears to be a valuable step forward in combating beam breakup in dielectric wakefield accelerators. It solves an immediate issue with current designs and is within current manufacturing capabilities but it is likely not the final answer. As manufacturing techniques improve, we are interested in exploring further

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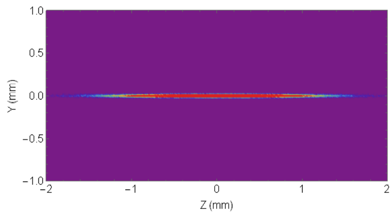
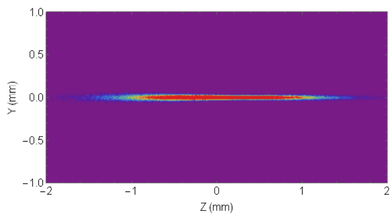
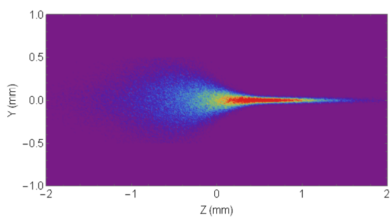


(a) At the entrance to the structures.



(b) At the exit of the alternating symmetry structure.



(c) At the exit of the control structure.

Figure 4: ZY trace spaces of the beam at the start of the structures and at the end of both the alternating symmetry structure and control structure.

designs such as Fig. 5. These designs require more exotic methods to produce such as improved additive manufacturing and grinding/polishing techniques. They also present interesting simulation challenges due to the difficulty in properly meshing continuously warped surfaces without causing a major decrease in computational efficiency. Ultimately though, the alternating symmetry solution promises significant advantage and should be studied in further depth.

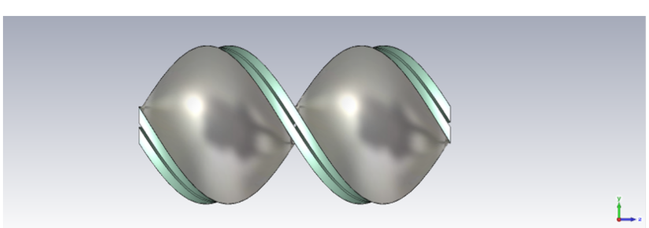


Figure 5: A continuously varying slab structure composed of the same material as Fig. 1 but with a different symmetry condition.

ACKNOWLEDGEMENTS

This work was supported by DOE HEP Grants DE-SC0017648, DE-SC0009914 and National Science Foundation Grant No. PHY-1549132.

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