ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-TUPA82

TRANSVERSE STABILITY IN AN ALTERNATING SYMMETRY PLANAR DIELECTRIC WAKEFIELD STRUCTURE

W. Lynn*, G. Andonian, N. Majernik, S. O'Tool, J. Rosenzweig, UCLA, Los Angeles, CA, USA
S. Doran, SY. Kim, J. Power, E. Wisniewski, Argonne National Laboratory, Lemont, IL, USA
P. Piot, Northern Illinois University, DeKalb, IL, USA

Abstract

Dielectric Wakefield Acceleration (DWA) is a promising technique for realizing the next generation of linear colliders. It provides access to significantly higher accelerating gradients than traditional radio-frequency cavities. One impediment to realizing a DWA-powered accelerator is the issue of the transverse stability of the beams within the dielectric structure due to short-range wakefields. These short-range wakefields have a tendency to induce a phenomenon known as single-bunch beam breakup, which acts as its name implies and destroys the relevant beam. We attempt to solve this issue by leveraging the quadrupole mode excited in a planar dielectric structure and then alternating the orientation of said structure to turn an unstable system into a stable one. We examine this issue computationally to determine the limits of stability and based on those simulations describe a future experimental realization of this strategy.

INTRODUCTION

Since they were invented, accelerators have pushed the parameters of both energy and cost higher and higher over time. Dielectric Wakefield Acceleration (DWA) is proposed technique for decoupling these two parameters by introducing drastically higher accelerating gradients than traditional radio-frequency cavities and consequently significantly shortening the length of any planned accelerator. The general mechanism by which a DWA scheme operates, as seen in Fig. 1, is a "drive" beam is directed down a dielectric lined waveguide, historically cylindrical in shape, which excites wakefields which then accelerate a trailing "witness" beam [1, 2]. Experiments have demonstrated accelerating gradients in DWA structures in excess of 1 GeV/m [3, 4] which is extremely promising but these structures were relatively small when compared to the required multi-meter long accelerating regions required for a practical future accelerator [5].

A major limitation on the length of a DWA structure is the phenomenon known as single-bunch Beam Breakup (BBU) wherein the drive beam, in addition to generating a longitudinal accelerating wake, generates a short-range transverse deflecting wake that acts on itself [6]. In extreme conditions this wake can destabilize the drive beam significantly enough to strike the accelerator walls, completely defeating the purpose of the accelerator in the first place [7, 8]. Therefore, in order to make practical use of DWA based designs, BBU must be suppressed or at least mitigated.

* wlynn@physics.ucla.edu

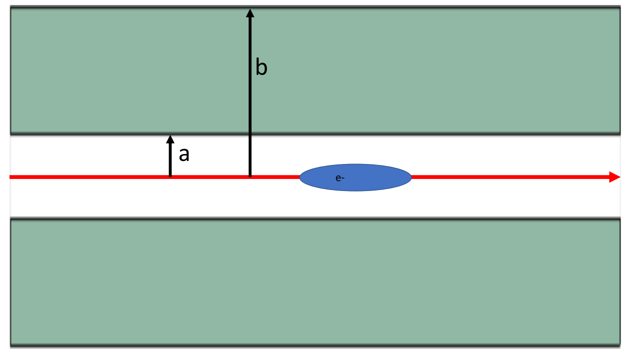

Figure 1: Schematic drawing of a basic DWA setup. Green is the dielectric material. Red is the beam axis and centerline. a is the distance from the centerline to the dielectric surface. b is the distance from the centerline to the exterior of the dielectric. Blue is the beam.

One proposed technique is to use an external magnetic Focusing and Defocusing (FODO) lattice to focus and correct the beam so that BBU effects do not destroy it. Unfortunately such a technique is inherently limited by the fact that in a cylindrical structure the longitudinal wakefields scale with a^{-2} but the transverse fields scale with a^{-3} ultimately capping the achievable accelerating gradient without inducing BBU [7].

Another approach is to abandon the cylindrical geometry and use a planar structure with a correspondingly planar beam. It has been shown that in the case of an infinitely wide beam in an infinitely wide planar structure the transverse wakefields vanish, unfortunately so do the longitudinal fields as well [8, 9]. Luckily, in the non-infinite case the transverse fields scale with σ_x^{-3} while the longitudinal fields scale with σ_x^{-1} implying that there exists a parameter region where the longitudinal fields are strong enough to be useful while the transverse fields are suppressed enough to not cause trouble [10]. Unfortunately while the primary deflecting fields are suppressed secondary quadrupole-like fields are not and are still strong enough to severely distort the tail of the beam leading to BBU [11].

Since the short-range transverse response of a planar dielectric structure to an on-axis particle is inherently quadrupole-like [10] it makes sense to attempt to leverage this effect instead of attempting to suppress it. The technique to leverage this quadrupole-like response is simply to abandon the flat beam concept and rotate the dielectric structure 90° periodically along the length of the interaction as seen in Fig. 2 [9, 12–14]. This alternates the direction of the focusing and defocusing elements of the transverse wakes re-

ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-TUPA82

sulting in a net effect analogous to a magnetic FODO lattice, and longitudinally it recovers all of the "lost" accelerating gradient when compared to the flat beam case. In this paper we describe a proposed experiment of this final "Alternating Symmetry" DWA scheme of periodically rotating a planar dielectric structure to be conducted at the Argonne Wakefield Accelerator (AWA) facility and simulations to support it.

PROPOSED EXPERIMENT

We propose to experimentally test the viability of the alternating symmetry DWA technique for transversely stabilizing a drive beam and avoiding BBU using the AWA beamline. The proposed beam statistics are listed in Table 1. Since the object is strictly to examine the effect of the short-range transverse wakefields, the beam will be focused to a waist at the mouth of the structure and then allowed to evolve ballistically with the exception of the momentum kicks imparted by the wakefields. We will then image the beam 0.5 m downstream of the structure exit and compare it to the beam when the structure jaws are fully retracted as a baseline. We also will measure the beam emittance, energy, and longitudinal profile after the structure and compare them to a no-structure baseline. We will scan the structure gap in both the x and y directions from 1 mm to fully open to demonstrate the effect of the alternating symmetry scheme and the beam charge to vary the coupling between the beam and the structure.

The dielectric slabs themselves will be prepared at UCLA where they will undergo machining and the deposition of metal on the surface opposite that of the beam. The dielectric slab properties are described in Table 2. After preparation the slabs will be retained and aligned mechanically inside the vacuum chamber by a strongback for each set of slabs in each orientation. The strongback holds it's own set of slabs in alignment with each other and then, through the use of precision rods within the chamber, is itself aligned to the other sections as seen in Fig. 3. Motion control will be provided via vacuum compatible linear actuators that mount to the back side of the strongbacks and are powered by stepper motors.

Table 1: Beam Parameters

Beam Parameters	
Energy (U)	60 MeV
Charge (Q)	2 nC
Length (σ_z)	640 µm
Width (σ_x)	100 µm
Height (σ_y)	100 µm
Horizontal Emittance (ϵ_x)	5 µm rad
Vertical Emittance (ϵ_y)	5 µm rad

SIMULATIONS

We have simulated the result of the beam described in Table 1 passing through the structure described in Table 2 using CST Microwave Studio's Particle In Cell (PIC) solver [15]. The simulation used open boundary conditions to avoid spurious reflections and higher density meshing along the beam axis to better capture particle behaviour. The beam was generated from ideal beam parameters and then imported into the PIC simulation, it does not include effects from the AWA lattice although such simulations are planned in the future. Some results of the simulations can be seen in Figs. 4 and 5 which show the expected beam images downstream of the structure and numerically how the beam ellipticity changes as a function of the structure gaps respectively. The simulated YAG images clearly show the stability of the alternating scheme when compared to the non-alternating version with the fact that the full structure result is virtually indistinguishable from the no-structure result. The strength of this effect is quantified by the ellipticity plot which shows that the transverse shape of the beam is directly affected by the ratio of the gaps.

Table 2: Dielectric Structure Parameters

Structure Parameters	
Dielectric constant (ϵ)	3.75
Half-gap (a)	0.5 mm
Dielectric thickness	5 mm
Dielectric slab length	40 mm
Dielectric slab width	40 mm
Structure length	160 mm

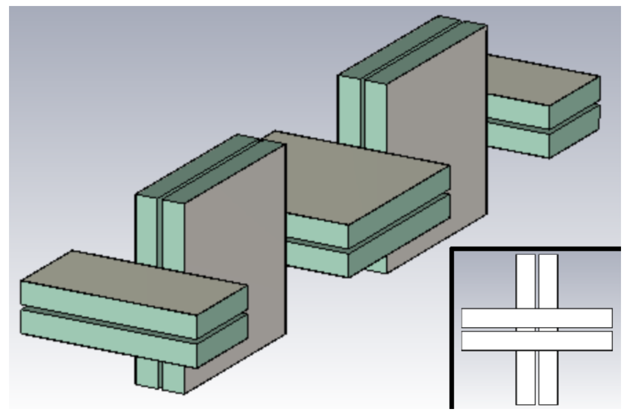

Figure 2: A cartoon depiction of the proposed dielectric structure orientation and layout. The beam travels between the sets of slabs, diagonally across the image. An on-axis view is provided in the insert with the beam path being into the page through the small square at the center of the structure.

CONCLUSION

In this paper we have described an approachable experiment to study the alternating symmetry DWA scheme which is a valuable goal because it provides a potential path towards realizing DWA on previously unavailable scales due BBU. After this experiment, one potential future direction

ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-TUPA82

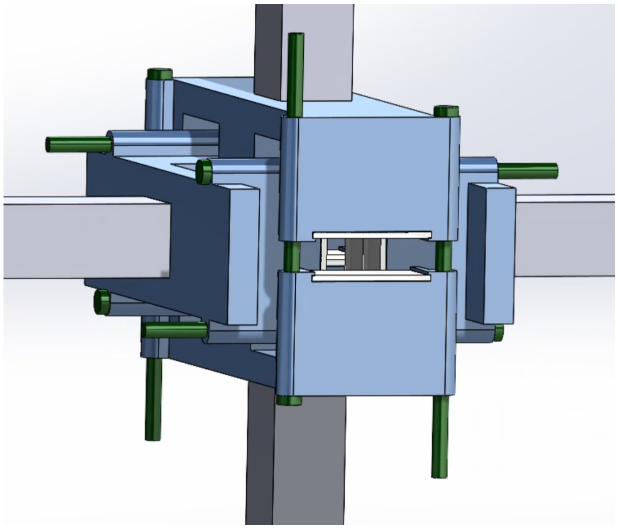

Figure 3: An example of the mechanical support and alignment mechanism for the dielectric structures. The strongbacks which retain and align the slabs are colored blue, the alignment rods are colored green, and the dielectric slabs themselves are white. The grey columns connect the strongbacks to the linear actuators.

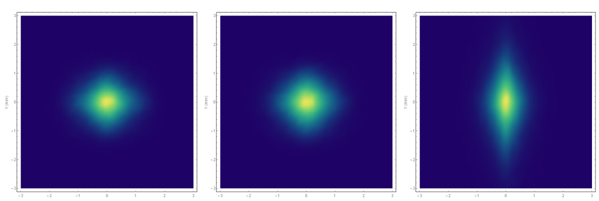

Figure 4: Simulated images of the beam on a downstream YAG after passing through the structure and a half-meter drift space. On the left, the beam without the structure. In the center, the beam with both sets of slabs inserted. On the right, the beam with the gap in the x-direction much larger than the y-direction.

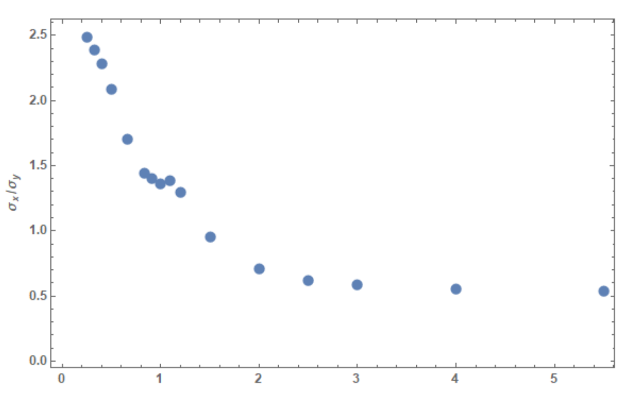

Figure 5: A plot of the beam ellipticity σ_x/σ_y as a function of the ratio of the gap in the x-direction to the gap in the y-direction. First y-gap was scanned while the x-gap was held fixed at 1mm and then the same for the x-gap.

could be implementing such a large scale DWA interaction complete with a magnetic lattice to control the head of the beam.

ACKNOWLEDGEMENTS

This work was funded by the Department of Energy Office of Science Graduate Student Research Program as well as grants DE-SC0017648, DE-SC0017648 and DE-SC0018656.

REFERENCES

[1] G. A. Voss and T. Weiland, "Particle acceleration by wake fields," DESY, Tech. Rep., 1982. https://cds.cern.ch/record/138105

[2] W. Gai *et al.*, "Experimental demonstration of wake-field effects in dielectric structures," *Phys. Rev. Lett.*, vol. 61, no. 24, p. 2756, 1988. doi:10.1103/PhysRevLett.61.2756

[3] M. Thompson *et al.*, "Breakdown limits on gigavolt-per-meter electron-beam-driven wakefields in dielectric structures," *Phys. Rev. Lett.*, vol. 100, no. 21, p. 214 801, 2008. doi:10.1103/PhysRevLett.100.214801

[4] B. O'Shea *et al.*, "Observation of acceleration and deceleration in gigaelectron-volt-per-metre gradient dielectric wakefield accelerators," *Nat. Commun.*, vol. 7, no. 1, pp. 1–7, 2016. doi:10.1038/ncomms12763

[5] T. Behnke *et al.*, "The international linear collider technical design report-volume 1: Executive summary," 2013. doi:10.48550/arXiv.1306.6327

[6] A. Kanareykin, W. Gai, C.-J. Jing, A. L. Kustov, J. G. Power, and P. Schoessow, "Beam Breakup Instabilities in Dielectric Structures," in *Proc. PAC'07*, Albuquerque, NM, USA, Jun. 2007, pp. 4300–4302.

[7] C. Li, W. Gai, C. Jing, J. G. Power, C. X. Tang, and A. Zholents, "High gradient limits due to single bunch beam breakup in a collinear dielectric wakefield accelerator," *Phys. Rev. Spec. Top. Accel Beams*, vol. 17, no. 9, p. 091 302, 2014. doi:10.1103/PhysRevSTAB.17.091302

[8] A. Tremaine, J. Rosenzweig, and P. Schoessow, "Electromagnetic wake fields and beam stability in slab-symmetric dielectric structures," *Phys. Rev. E*, vol. 56, no. 6, pp. 7204–7216, 1997. doi:10.1103/PhysRevE.56.7204

[9] L. Xiao, W. Gai, and X. Sun, "Field analysis of a dielectric-loaded rectangular waveguide accelerating structure," *Phys. Rev. E*, vol. 65, no. 1, p. 016 505, 2001. doi:10.1103/PhysRevE.65.016505

[10] S. S. Baturin, G. Andonian, and J. B. Rosenzweig, "Analytical treatment of the wakefields driven by transversely shaped beams in a planar slow-wave structure," *Phys. Rev. Accel. Beams*, vol. 21, no. 12, p. 121 302, 2018. doi:10.1103/PhysRevAccelBeams.21.121302

[11] E. Simakov, G. Andonian, S. Baturin, and P. Manwani, "Limiting effects in drive bunch beam dynamics in beam-driven accelerators: Instability and collective effects," *J. Instrum.*, vol. 17, no. 05, P05013, 2022. doi:10.1088/1748-0221/17/05/p05013

ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-TUPA82

[12] D. Y. Shchegolkov, E. I. Simakov, and A. A. Zholents, "Towards a practical multi-meter long dielectric wakefield accelerator: Problems and solutions," *IEEE Trans. Nucl. Sci.*, vol. 63, no. 2, pp. 804–811, 2016. doi:10.1109/TNS.2015.2482820

[13] T. J. Overton, T. H. Pacey, Y. M. Saveliev, and G. X. Xia, "Beam Dynamics and Drive Beam Losses Within a Planar Dielectric Wakefield Accelerator," in *Proc. IPAC'22*, Bangkok, Thailand, 2022, pp. 641–644. doi:10.18429/JACoW-IPAC2022-MOPOMS010

[14] D. Y. Shchegolkov, E. I. Simakov, and A. Zholents, "Simulation Studies of BBU Suppression Methods and Acceptable Tolerances in Dielectric Wakefield Accelerators," in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 2685–2688. doi:10.18429/JACoW-IPAC2015-WEPJE007

[15] Dassault Systèmes, *CST Studio Suite*, 2020. https://www.cst.com/