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PHYSICS GOALS OF DWA EXPERIMENTS AT FACET-II

J. B. Rosenzweig*, G. Andonian, H. Ancelin, A. Fukasawa, C. Hansel, G. Lawler, W. Lynn, N. Majernik, J. Mann, P. Manwani, Y. Sakai, O. Williams, M. Yadav
University of California, Los Angeles, CA, USA
S. Baryshev, Michigan State University, East Lansing, Michigan, USA
S. Baturin, Northern Illinois University, DeKalb, Illinois, USA
M. Hogan, B. O'Shea, D. Storey, V. Yakimenko
SLAC National Accelerator Laboratory, Stanford University, Menlo Park CA, USA

Abstract

The dielectric wakefield acceleration (DWA) program at FACET produced a multitude of new physics results that range from GeV/m acceleration to the discovery of high field-induced conductivity in THz waves, and beyond, to a demonstration of positron-driven wakes. Here we review the rich program now developing in the DWA experiments at FACET-II. With increases in beam quality, a key feature of this program is extended interaction lengths, near 0.5 m, permitting GeV-class acceleration. Detailed physics studies in this context include beam breakup and its control through the exploitation of DWA structure symmetry. The next step in understanding DWA limits requires the exploration of new materials with low loss tangent, large bandgap, and improved thermal characteristics. Advanced structures with photonic features for mode confinement and exclusion of the field from the dielectric, as well as quasi-optical handling of coherent Cerenkov signals is discussed. Use of DWA for laser-based injection and advanced temporal diagnostics is examined.

INTRODUCTION

Dielectric wakefield accelerators (DWA) have been under investigation for the last three decades, with progression in achieved accelerating gradient from the 10 MeV/m [1] to greater than the GeV/m level [2]. In proceeding to these very high gradients, a jump in frequency by an order of magnitude over pioneering work at the AWA [3], to greater that 0.2 THz has been necessitated. The most recent DWA in the high frequency and/or high gradient regime, taking place mainly at the ATF and FACET facilities, have produced a plethora of interesting results that pave the way to use of the DWA in advanced accelerator applications such as linear collider and X-ray FEL.

These previous investigations (many of which were accomplished in this collaboration) include a series of notable results, including:

- Use of planar dielectric structures with 1D photonic (Bragg reflector) design, exploring confinement without lossy metal boundaries [4].
- Extension of photonic structure design to three dimensions using a dielectric woodpile, to permit selective mode profile excitation [5].
- Observation of GeV/m deceleration and acceleration in long (up to 15 cm) structures, producing >100 MeV energy change in electron beam energy [6].
- Use of DWA structures for phase space manipulation, such as energy chirp compensation [7] and beam shaping [8].
- Discovery of high-field induced damping of THz wakefields in dielectrics [9].
- Demonstration of transverse wakefield suppression in slab-symmetric DWA with strongly transversely elliptical beams, while maintenance of GV/m-class field excitation [10].
- Demonstration of wakefield reconstruction methods using both coherent Cerenkov radiation [6], and a extension to energy loss measurements [11].
- Exploration of charge asymmetry in DWA with positron-excited wakes, as needed for potential linear collider applications [12].

The experiments reported above that investigated GV/m fields were performed at the SLAC FACET user facility by the E201 collaboration. These experiments are now to be followed by a dedicated program at the successor facility at SLAC, FACET-II [13] under the banner of the E321 collaboration. They address urgent issues in reaching and maintaining very large accelerating fields, while preserving the beam phase space quality and attendant stability in applications.

INITIAL PHASE EXPERIMENTS

First phase experiments will take place in a dedicated, newly repurposed chamber with a high level of vacuum achievable to permit co-existence with sensitive, nearby RF cavities. This infrastructure, described in a contribution to these proceedings by O. Williams *et al.* [14], will provide six-axis alignment of multiple structures, and will have beam positioning monitors and coherent Cerenkov radiation measurement [15] capabilities that use an optimized Vlasov

* rosen@physics.ucla.edu

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antenna [16] launching approach. This is discussed further by Yadav *et al.* [17], also in these proceedings. A rendered layout of the vacuum vessel is shown in Fig. 1.

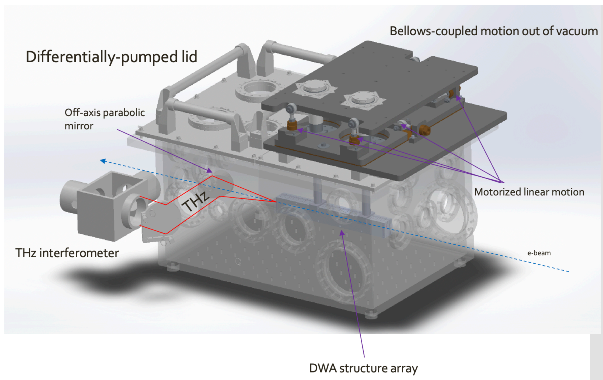

Figure 1: Rendering of vacuum vessel design for hosting DWA experiments at FACET-II.

With the advent of higher quality beams to be available in FACET-II, we can address new frontiers in key issues in DWA physics and technology. In particular, the much-improved emittances (and eventual production of asymmetric, “flat-beam” emittances) should enable passage of the beam through long, high-gradient structures, up to 50 cm in length. The beams (driver and witness) at FACET-II are operated nominally at 10 GeV, with rms bunch lengths as low as 20 microns and up to 2 nC of charge.

We aim to observe up to 0.5 GeV of energy change in such structures with slab symmetry. These investigations will quantify beam breakup and attendant emittance growth from dipole and quadrupole-like transverse modes that are a general feature of slab-symmetry [18, 19]. These experiments will employ drive beams of varying ellipticity, and include observation of witness beam acceleration. These studies will permit the identification of trade-off curves between achievable gradient and transverse stability.

The first phase of experiments will also use dipole wakes as a benefit to beam measurements, in the introduction of passive streaking for femtosecond beam characterization. By off-axis passage of the beam, coupling to transverse mode adds transverse-longitudinal correlation similar to a RF sweeper cavity.

One of the major surprises uncovered at FACET in E201 was the onset of high-field-induced conductivity above 700 MV/m axial fields, observed through the damping of the CCR-based wakefield reconstruction [9]. These studies ascribed the onset of conductivity to promotion of electrons to the conduction band, where their keV ponderomotive energy permitted an avalanche of ionization. In order to explore the validity of this model, we plan studies on high field damping effects using low loss tangent materials such as CVD diamond and alumina. Alternative damping models, such as material changes due to pulsed heating at boundary of metal and dielectric, will be explored first phase experiments.

The initial phase experimental campaign is foreseen to last 18 months.

NEXT GENERATION EXPERIMENTS

In the future, the E321 agenda will expand to embrace advanced structure designs. For example, the woodpile structure used in previous experiments at the ATF showed interesting photonic properties that can be exploited at the GV/m field level. The cylindrical pieces that make up the woodpile, which creates a broad stop-band about the operating frequency, can be arrayed to orient themselves to show only a round surface to the accelerating field. This can strongly suppress, by a factor of nearly $\varepsilon/\varepsilon_0$, the field that penetrates the dielectric. This is a notable improvement over previous longitudinally invariant structures, which permit the entire axial field at the boundary to enter the dielectric. The attenuation of field penetration should permit a significant increase in peak axial field achieved before the threshold for high-field-induced conductivity is encountered.

Further, the photonic structure we are developing (see Fig. 2) is a hybrid between the woodpile (which provides confinement in the horizontal direction) and a dielectric laser accelerator-inspired structure. This central region permits a fast group velocity, low stored energy per unit length, and the ability to radiate higher order modes for fast damping.

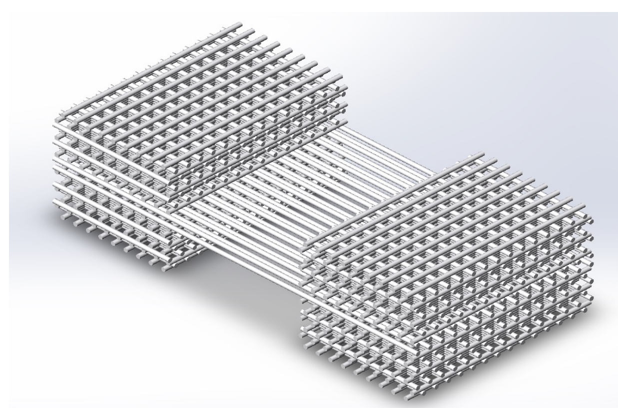

Figure 2: Optimized hybrid woodpile photonic structure for DWA experiments, permitting mode control and HOM damping.

This structure still employs a wide geometry, with the idea of suppressing wakes by use of strongly elliptical beams [20]. This approach is still susceptible to the quadrupole-like instability, which is the subject of current experiments by the collaboration at the AWA. We intend to address the stabilization of beam propagation by utilizing the strong quadrupole fields (up to 200 kT/m in planned FACET-II experiments) associated with a tight, round beam that propagates in a slab-structure with alternating symmetry.

Such as structure is shown in Fig. 3; the periodicity in FACET-II experiments is chosen be be 3 cm, with a 400 mi-

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cron gap. These parameters are chosen to provide strong second order focusing which increases with distance from the head of the beam. This behavior has been modelled in simulation, as illustrated in Fig. 4. It can be seen that the quadrupole instability is stabilized, and the beam propagates with tight focusing.

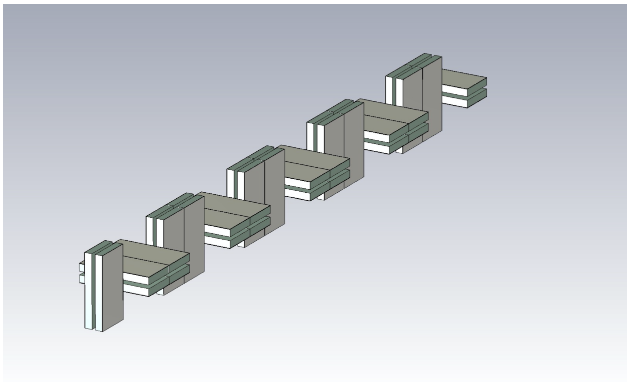

Figure 3: Simple slab DWA with structures rotated 90 degrees periodically to obtain second order quadrupole focusing.

We note that the implementation of wake-based focusing is an essential feature of plasma wakefield acceleration, but has not yet been proposed for DWA. As the predicted second-order focusing has a strong time dependence, we are currently exploring its use for stabilizing the dipole instability, employing a form of BNS damping similar to that arising from an applied RF quadrupole [21]. These issues are explored in detail in a paper in these proceedings by W. Lynn *et al.* [22].

SUMMARY AND FUTURE DIRECTIONS

With a basis in a greater than one decade record of successful investigations in DWA physics techniques, the E321 collaboration is poised to begin a new chapter at FACET-II. The program of DWA research outlined above is rich in possibilities, emphasizing the physics that is encountered when attempting to reach GeV/m gradients in dielectric structures. These experiments aim at ambitious acceleration goals, with one GeV modules in reach by the end of the E321 program. Such acceleration, being reached only after meter-scale propagation, necessitates beam transverse stability, which we are actively investigating. New schemes based on innovations in structure geometry will be essential in this effort.

Looking to the future, it is hoped that positrons will be available at FACET-II. In this case one can test the charge asymmetry at field levels that would provoke nonlinear material response (*e.g.* high-field conductivity) where the sign of the exciting field may be important.

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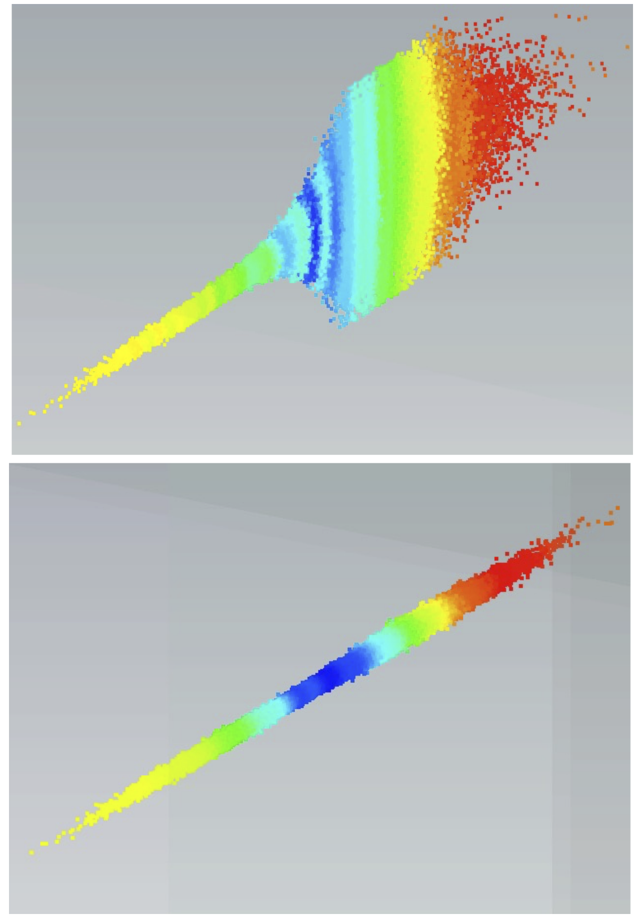

Figure 4: Top: final transverse spatial distribution after propagation in simple slab from CST simulation, displaying quadrupole instability. Bottom: final distribution after traversal of alternating symmetry structure, showing strong focusing.

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REFERENCES

[1] W. Gai *et al.*, "Experimental demonstration of wake-field effects in dielectric structures", *Phys. Rev. Lett.*, vol. 61, pp. 2756–2758, 1988. doi:10.1103/PhysRevLett.61.2756

[2] M. C. Thompson *et al.*, "Breakdown Limits on Gigavolt-per-Meter Electron-Beam-Driven Wakefields in Dielectric Structures", *Phys. Rev. Lett.*, vol. 100, p. 214801, 2008. doi:10.1103/PhysRevLett.100.214801

[3] J. Shao *et al.*, "Development and high-power testing of an *X*-band dielectric-loaded power extractor", *Phys. Rev. Accel. Beams*, vol. 23, p. 011301, Jan. 2020. doi:10.1103/PhysRevAccelBeams.23.011301

[4] G. Andonian *et al.*, "Planar-Dielectric-Wakefield Accelerator Structure Using Bragg-Reflector Boundaries", *Phys. Rev. Lett.*, vol. 113, p. 264801, 2014. doi:10.1103/PhysRevLett.113.264801

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB071

[5] P. D. Hoang *et al.*, "Experimental Characterization of Electron-Beam-Driven Wakefield Modes in a Dielectric-Woodpile Cartesian Symmetric Structure", *Phys. Rev. Lett.*, vol. 120, p. 164801, 2018. doi:10.1103/PhysRevLett.120.164801

[6] B. D. O'Shea *et al.*, "Observation of acceleration and deceleration gigaelectron-volt-per-metre gradient dielectric wakefield accelerators", *Nature Communications*, vol. 7, pp. 1–7, 2016. doi:10.1038/ncomms12763

[7] S. Antipov *et al.*, "Experimental Demonstration of Energy-Chirp Compensation by a Tunable Dielectric-Based Structure", *Phys. Rev. Lett.*, vol. 112, p. 114801, 2014. doi:10.1103/PhysRevLett.112.114801

[8] G. Andonian *et al.*, "Generation of Ramped Current Profiles in Relativistic Electron Beams Using Wakefields in Dielectric Structures", *Phys. Rev. Lett.*, vol. 118, p. 054802, 2017. doi:/10.1103/PhysRevLett.118.054802

[9] B. D. O'Shea *et al.*, "Conductivity Induced by High-Field Terahertz Waves in Dielectric Material", *Phys. Rev. Lett.*, vol. 123, p. 134801, 2019. doi:10.1103/PhysRevLett.123.134801

[10] B. D. O'Shea *et al.*, "Suppression of Deflecting Forces in Planar-Symmetric Dielectric Wakefield Accelerating Structures with Elliptical Bunches", *Phys. Rev. Lett.*, vol. 124, p. 104801, 2020. doi:10.1103/PhysRevLett.124.104801

[11] R. Roussel, G. Andonian, J. B. Rosenzweig, and S. S. Baturin, "Longitudinal current profile reconstruction from a wakefield response in plasmas and structures", *Phys. Rev. Accel. Beams*, vol. 23, p. 121303, 2020. doi:10.1103/PhysRevAccelBeams.23.121303

[12] N. Majernik *et al.*, "Positron Driven Dielectric Wakefields", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper TUPAB093, this conference.

[13] V. Yakimenko *et al.*, "FACET-II facility for advanced accelerator experimental tests", *Phys. Rev. Accel. Beams*, vol. 22, p. 101301, 2019. doi:10.1103/PhysRevAccelBeams.22.101301

[14] O. Williams *et al.*, "Interaction Region Design for DWA Experiments at FACET-II", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper MOPAB137, this conference.

[15] A. M. Cook *et al.*, "Observation of Narrow-Band Terahertz Coherent Cherenkov Radiation from a Cylindrical Dielectric-Lined Waveguide", *Phys. Rev. Lett.*, vol. 103, p. 4, 2009. doi:10.1103/PhysRevLett.103.095003

[16] S. Vlasov and I. Orlova, "Quasioptical Transformer Which Transforms the Waves in a Waveguide Having a Circular Cross Section into a Highly Directional Wave Beam", *Radiophysics and Quantum Electronics*, vol. 17, pp. 115–119, 1974. doi:10.1007/BF01037072

[17] M. Yadav *et al.*, "Efficient, High Power Terahertz Radiation Outcoupling From a Beam Driven Dielectric Wakefield Accelerator", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper MOPAB147, this conference.

[18] S. S. Baturin and A. D. Kanareykin, "New method of calculating the wakefields of a point charge in a waveguide of arbitrary cross section", *Phys. Rev. Accel. Beams*, vol. 19, p. 051001, 2016. doi:10.1103/PhysRevAccelBeams.19.051001

[19] 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, p. 121302, 2018. doi:10.1103/PhysRevAccelBeams.21.121302

[20] A. Tremaine, J. Rosenzweig, and P. Schoessow, "Electromagnetic wake fields and beam stability in slab-symmetric dielectric structures", *Phys. Rev.*, vol. E56, pp. 7204–7216, 1997. doi:10.1103/PhysRevE.56.7204

[21] V. V. Danilov, "Increasing the transverse mode coupling instability threshold by RF quadrupole", *Phys. Rev. ST Accel. Beams*, vol. 1, p. 041301, 1998. doi:10.1103/PhysRevSTAB.1.041301

[22] W. J. Lynn, G. Andonian, N. Majernik, and J. B. Rosenzweig, "Strong Quadrupole Wakefield Based Focusing in Dielectric Wakefield Accelerators", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper THPAB155, this conference.