DIELECTRIC WAKEFIELD ACCELERATOR EXPERIMENTS AT THE SABER FACILITY *

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Abstract

Electron bunches with the unparalleled combination of high charge, low emittances, and short time duration, as first produced at the SLAC Final Focus Test Beam (FFTB), are foreseen to be produced at the SABER facility. These types of bunches have enabled wakefield driven accelerating schemes of multi-GV/m in plasmas. In the context of the Dielectric Wakefield Accelerators (DWA) such beams, having rms bunch length as short as 20 um, have been used to drive 100 um and 200 um ID hollow tubes above 20 GV/m surface fields. These FFTB tests enabled the measurement of a breakdown threshold in fused silica (with full data analysis still ongoing) [1]. With the construction and commissioning of the SABER facility at SLAC, new experiments would be made possible to test further aspects of DWAs including materials, tube geometrical variations, direct measurements of the Cerenkov fields, and proof of acceleration in tubes >10 cm in length. This collaboration will investigate breakdown thresholds and accelerating fields in new materials including CVD diamond. Here we describe the experimental plans, beam parameters, simulations, and progress to date as well as future prospects for machines based of DWA structures.

INTRODUCTION

Particle accelerators with field gradients orders of magnitude larger than existing, conventionally employed systems have long been promised. Recent experimental work has validated gradients in excess of 1 GV/m for a number of schemes including plasma wakefield accelerators (at over 10 GV/m) [2], and laser-driven wakefield-accelerators [3, 4, 5]. These advanced accelerators have applications in pushing the energy frontier and reducing the size and cost of machines in high-energy colliders, light-sources, and basic sciences. Conventional accelerators, based on metallic resonant-cavities, scale unfavorably to high gradients due to the need to simultaneously scale the power sources to higher frequencies. The transition from existing tens of MV/m gradients to GV/m gradients implies an attendant transition from GHz (microwave) driven to THz-powered structures. While high-power microwave sources are available and well developed, such sources do not exist in the so-called terahertz gap. Additionally, as resonant structures are scaled to higher gradient and hence smaller dimensions, the fabrication tolerances become increasingly smaller and beyond state-of-the-art. This lack of sources and practical limitations has pushed development of advanced accelerators either to still-shorter wavelengths as offered by lasers, or to beam-driven structures that rely on the wakefields produced by one electron bunch to drive a subsequent “witness” bunch.

Wakefield-driven accelerating-schemes can offer high gradients and conceptually simple geometries. The Dielectric Wakefield Accelerator (DWA) is one such approach (see Fig. 1) and employs a hollow dielectric-tube. A short (<1 ps) drive-bunch traverses the tube creating Cerenkov wakefields that propagate towards the dielectric boundary at the Cerenkov angle, and are reflected back towards the center axis, where a second bunch arrives and is accelerated [6]. The DWA solves the THz-power problem by using radiated fields from short electron-bunches, leveraging high-precision fabrication technology from developments in fiber optics, and provides a straightforward means of producing large on-axis accelerating fields.

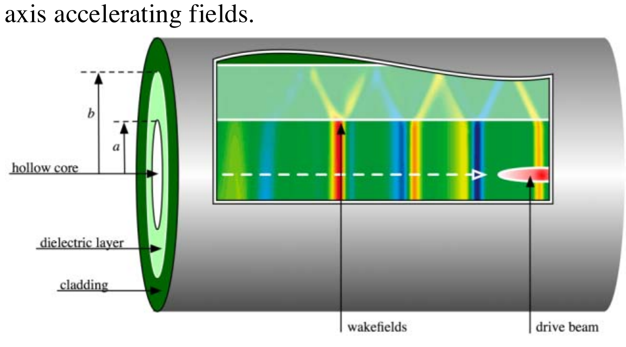

Figure 1: Conceptual drawing of the dielectric wakefield accelerator (DWA). A “drive” beam excites wakefields in the tube, while a subsequent “witness” beam (not shown) would be accelerated by the reflected wakefields (bands of color).

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WORK TO DATE

Accelerating schemes relying on material boundaries, including the DWA and conventional metallic cavities, are ultimately limited in their gradient by breakdown. Breakdown has been well studied in a number of scenarios. For metallic cavities, Fowler-Nordheim [7] emission can lead to breakdown. This and other breakdown phenomena are typically empirically represented by a Kilpatrick-like limit on the achievable gradient as a function of resonant frequency [8]. For laser driven structures breakdown is well measured for both short and long timescales (where heating and melting dominate) [9]. Prior to the earlier work of this collaboration [10], field gradients producible by particle beams in dielectrics were low (MV/m) and on a longer time-scale (>ps). The unprecedented combination of high charge, short bunch duration, and small transverse-size available at SLAC's Final Focus Test Beam (FFTB) enabled the GV/m fields of this experiment to be achieved.

To go further in our studies, it is necessary to provide more direct experimental measures of the electromagnetic wake properties in the DWA.

NEXT STEPS

With the demise of the FFTB facility at SLAC, a new facility with similar capabilities has been designed — SABER (South Arc Beam Experiment Region). This facility was proposed to be built in the Instrument Section in the SLC South Arc tunnel, and was intended for experiments requiring compressed, focused, high-energy beams of electrons or positrons.

Table 1: Proposed DWA parameters for SABER, with short pulse for breakdown studies, and long pulse for observation of acceleration/deceleration.

Parameter	Short Pulse	Long Pulse
Beam Energy	25 GeV	
Beam Charge	3 nC	5 nC
Energy Spread (FWHM)	< 2% (0.6 GeV)	< 0.28% (0.070 GeV)
Beam Length (σ_ζ)	≥20 μm	≤150 μm
Beam Radius (σ_ρ)	<10 μm	
In. Dielec. Rad., a	100 μm	
Out. Dielec. Rad., b	175 μm	
Dielec. Perm., ε	~ 3	
Dielec. Length, L_d	10 cm	
Peak E_z, acc.		1.1 GV/m
Peak $E_{r,surface}$		2.2 GV/m
Max. Gain (10 cm)		0.11 GeV

Following on the success of T-481, the E169 experiments described here were proposed to take place at the SABER facility and would have involved three phases. The first phase would be a detailed breakdown study including exploration of a large range of design parameter space, materials, and cladding designs; and, quantifying of the fields by measurement of the coherent Cerenkov radiation. The second experimental phase would attempt to directly observe acceleration and deceleration of particles in 10 cm length fibers. The third phase — once the SABER facility is well characterized and fully operational — would involve significant acceleration, building on the results and expertise gained in the initial two phases, by using tubes in the range of one meter.

The specific goals of the proposed DWA studies at SABER can be listed:

- **Coherent Cerenkov Radiation (CCR) measurements**: Investigations of CCR in the THz spectral range will serve as a measure of the fields in the dielectric, and as a bunch length diagnostic.
- **Materials**: In T-481, only fused silica tubes were tested; additional materials including CVD-fabricated diamond [11] will be explored.
- **Coating**: The thin metallic coating used on the tubes in T-481 proved inadequate to withstand ohmic heating due to induced currents. Use of dielectric cladding will be explored at SABER.
- **Varying tube diameters**: T-481 used off-the-shelf fused silica tubes which were available in 100 μm and 200 μm IDs, and fixed 350 μm OD. In E169 we plan to have several custom diameters fabricated, allowing the breakdown limit to be explored at fixed beam parameters.
- **Varying tube length**: Short, 1 cm tubes were used in T-481. The SABER experiments will use lengths from 1 to 10 cm with the ultimate goal of pursuing a 1 m long DWA module. They will also allow the dependence of breakdown on time of exposure to high gradient wakefields.
- **Direct observation of beam changes:** Longer fibers will allow for the direct measurement of momentum change to the beam due to wakefield acceleration and deceleration, and may also produce notable changes in the transverse centroid due to transverse wakes (see Figure 3).
- **Preparation**: Alternative fiber preparation techniques will be considered and tested. Different methods of cladding removal and tips polishing (*e.g.* diamond cleaving) to eliminate debris contamination in the tube bore will be employed.

The study of the coherent Cerenkov radiation (CCR) emitted from fused silica fibers is a central part of this experimental work, as it directly probes the wake-field excitation process, giving an independent measurement of the wake-field strength. The CCR measurements can be one of the first efforts undertaken at SABER since they require only reproduction of the FFTB electron beam parameters. The total energy lost to emission of CCR may be estimated as $U_{\check{C}} \cong Q_b E_{z,dec} L_d / 2$, where L_d is the length of the tube. For L_d=1 cm, Q_b = 3 nC, and $E_{z,dec}$=2 GV/m, we estimate that 30 mJ of CCR will be emitted. The CCR radiation emitted at the downstream fiber end will use metallic cones (e.g. horns) as a means of impedance matching to free space, and directing the radiation in a forward cone.

For 10 cm structures, and the longer beam listed in Table 1, the initial FWHM energy spread is ~85 MeV, and thus the induced energy change in the beam of ~110 MeV is easily resolvable. One may also observe transverse wake effects. An initial 20 μm (~4σ) offset in the beam centroid may produce, in diamond tubes, a transverse wake force of 200 MeV/m, or an integrated transverse kick over 10 cm of 20 MeV. This corresponds to an angle of 80 μrad, which is a bit smaller than the angles due to emittance (140 μrad for β^*=5 cm).

MODELING AND SIMULATIONS

Simple analytic models bolstered by particle in cell codes serve to predict the outcome of the SABER experiments. Adjustment of the bunch length is both the mechanism for achieving high wakefields and for parameterizing the experiments. An approximate expression for the decelerating field in a DWA clearly shows the bunch length dependency:

$$eE_{z\mathrm{dec}} \cong -\frac{4N_b r_e m_e c^2}{a\left[\sqrt{\frac{8\pi}{\varepsilon-1}\varepsilon\sigma_z}+a\right]}, \quad (1)$$

where a is the inner radius of the hollow dielectric tube, σ_z is the rms bunch length, r_e and $m_e c^2$ are the classical radius and the rest energy of the electron, respectively, and ε is the relative permittivity (dielectric constant) of the dielectric tube. For the high charge ($N_b = 3\times10^{10}$), ultra-short, low physical emittance, 25 GeV beams at SABER, both a (set minimally by transverse beam size) and σ_z can be accessed in experiments at the level of 100 μm or less. Thus, fields > 10 GV/m can be produced during these experiments (see Figure 2).

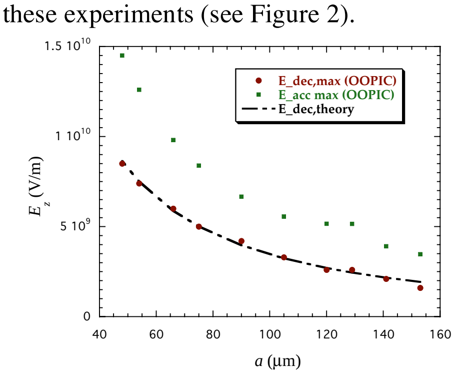

Figure 2: Dependence of longitudinal fields on a in OOPIC Cerenkov wake simulations, with b/a=3, ε=3, and beam parameters Q=3 nC, σ_z=20 µm, σ_r = 10 µm, beam energy 30 GeV, with predictions of Eq. 1.

The OOPIC [12] simulations of Figure 2 verify quite well the predictions of Eq. 1 concerning the maximum decelerating field. This figure also illustrates that, as is typical of wakefields driven by symmetric drive beams, the peak accelerating field behind the beam is ≤2 times the decelerating field.

The evolution of the beam through the wakefield can also be modeled with OOPIC which pushes particles self-consistently with the fields. One may evaluate the fields, as in Figure 3, by filtering the high frequency components of the intra-beam wake that arise from a numerical artifact of the finite spatial mesh.

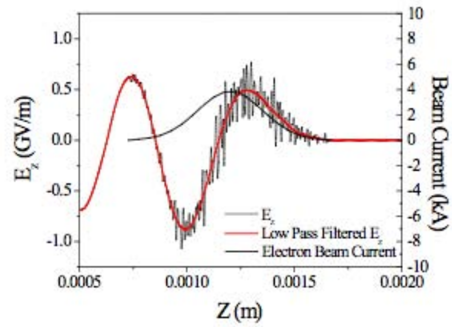

Figure 3: OOPIC simulation results for the parameters in Table 1, with longest beam (150 µm), in DWA acceleration experimental case (10 cm tube). In this scenario $\sigma_z > a$ which leads to broad sinusoidal wakefields which overlap with the driving beam.

CONCLUSIONS

The measurements from these SABER experiments would significantly advance the state of knowledge on dielectric wakefield accelerators. By having characterized the breakdown threshold for multiple materials, having measured the coherent Cerenkov emission, and having shown direct energy exchange with the beam, these experiments would prove the viability of dielectric-tube wakefield accelerators with GV/m accelerating gradients.

Next phase measurements, if successful, will demonstrate substantial, high-gradient acceleration of beams thus opening the possibility of colliders and compact, high energy machines based on dielectric-tube wakefield structures.

REFERENCES

[1] M. C. Thompson, *et al.*, these proceedings.
[2] M. J. Hogan, *et al.*, Phys. Rev. Lett. 95, 054802 (2005).
[3] C. G. R. Geddes, *et al. Nature* **431**, 538–541 (2004).
[4] S. P. D. Mangles, *et al. Nature* **431**, 535–538 (2004).
[5] J. Faure, *et al. Nature* **431**, 541–544 (2004).
[6] W. Gai, *et al.* Phys. Rev. Lett. **61**, 2756 (1988).
[7] R. H. Fowler, L. Nordheim, Proc. Roy. Soc., v. 119, n. A781, p. 173, 1928
[8] W. D. Kilpatrick, Rev. Sci. Instrum. **28**, 824. (1957).
[9] B. C. Stuart, *et al.*, J. Opt. Soc. Am. B 13, 459 (1996).
[10] M. C. Thompson, *et al.*, to be submitted to PRL.
[11] A. Kanareykin, *et al.*, Proc. AAC-2006, pp. 320-330.
[12] D. L. Bruhwiler *et al.*, Phys. Rev. ST Accel. Beams 4, 101302 (2001).

