# HIGH FREQUENCY, HIGH GRADIENT DIELECTRIC WAKEFIELD ACCELERATION EXPERIMENTS AT SLAC AND BNL*

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### *Abstract*

Given the recent success of >GV/m dielectric wakefield accelerator (DWA) breakdown experiments at SLAC, and follow-on coherent Cerenkov radiation production at the UCLA Neptune, a UCLA-USC-SLAC collaboration is now implementing a new set of experiments that explore various DWA scenarios. These experiments are motivated by the opportunities presented by the approval of FACET facility at SLAC, as well as unique pulse-train wakefield drivers at BNL. The SLAC experiments permit further exploration of the multi-GeV/m envelope in DWAs, and will entail investigations of novel materials (e.g. CVD diamond) and geometries (Bragg cylindrical structures, slab-symmetric DWAs), and have an over-riding goal of demonstrating >GeV acceleration in ~33 cm DWA tubes. In the nearer term before FACET's commissioning, we are planning measurements at the BNL ATF, in which we drive ~50-200 MV/m fields with single pulses or pulse trains. These experiments are of high relevance to enhancing linear collider DWA designs, as they will demonstrate potential for efficient operation with pulse trains.

## INTRODUCTION

In recent years, high gradient dielectric wakefield accelerators (DWA)[1] have attracted significant attention for applications in high energy physics and advanced THz light sources. From the HEP viewpoint, the DWA is a promising path to improve acceleration gradients in structure-based accelerators in a revolutionary manner, by one-to-two orders of magnitude to over a GV/m. This is accomplished in the longer wavelength THz spectral region, which in comparison to laser-excited systems, requires ~100 micron as opposed to sub-micron apertures. As such, one may envision beams of much higher charge and relaxed emittance requirements that may pass through THz-scale structures. In addition, the microscopic breakdown dynamics of the dielectric have been observed experimentallly, in the ultra-fast context of wakefield excitation, to be more forgiving in the THz-mm regime relative to optical-IR, yielding multi-GV/m accelerating field before the onset of breakdown.

The DWA produces unprecedented high peak electromagnetic powers associated with these fields, and as such represents an absolutely unique approach to THz radiation production, in either single-mode or multi-mode scenarios. This method for generating coherent THz pulses, termed coherent Cerenkov radiation (CCR), yields not only quite high peak power, but can also give very narrow line widths. A comparison with a THz source based on coherent undulator radiation (super-radiant FEL) serves to illustrate these advantages: one may produce similar powers in a cm-scale DWA as a 1 m long FEL undulator, with narrower line-width.

In this paper we review the basic physical scenario behind the previous experimental efforts by the UCLA-centered collaboration on both GV/m level acceleration (at the SLAC FFTB) and THz generation (at the UCLA Neptune Laboratory). We present plans for follow-on experiments at the SLAC FACET facility that aim to demonstrate key aspects of GV/m-class DWA use in linear colliders and future light sources.

As both of these applications demand high efficiency and large through put of beam current, multiple pulses should be accelerated in a heavily beam-loading scheme. In order to accomplish this, one should modify the basic DWA structure to yield a low group velocity. We discuss this new type of design, and experimental tests now beginning at the BNL ATF.

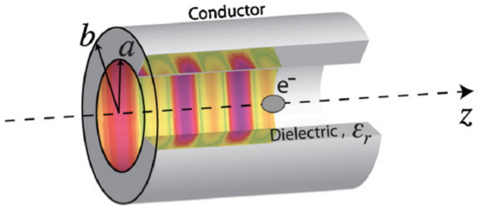

Figure 1: DWA scheme, with dielectric in region *a<r<b,* with conducing cladding, and evacuated beam hole.

## RECENT EXPERIMENTAL HISTORY

With the successful production of very short, focusable beams at the FFTB for plasma wakefield acceleration studies, it was realized in late 2005 that one could exploit such capabilities to explore a new, very high gradient regime of the DWA [2], which until that point had been tested at field levels <100 MV/m. This opportunity can be appreciated by writing a heuristic scaling of the decelerating fields associated with a beam in the DWA,

$$E_{z,dec} \cong \frac{eN_b}{\pi a \varepsilon_0 \left( a + \sqrt{\frac{8\pi}{\varepsilon_r - 1}} \varepsilon_r \sigma_z \right)} \qquad (1)$$

Where $N_b$ is the number of driving beam electrons, $\sigma_z$ is the beam rms pulse length, $\varepsilon_r$ is the relative dielectric permittivity, and $a$ is the inner radius of the dielectric annular region. For FFTB parameters ($\sigma_z$=50 μm, $N_b = 1.4 \times 10^{10}$, with $a$=50 μm, and $\varepsilon_r$=3.8) up to 12 GV/m deceleration field (27 GV/m surface field) was accessible. This impressive possible field led to a test-

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beam parametric study (varying the pulse length to control the peak fields) termed T-481 that determined that the threshold field value for breakdown was 13.8 GV/m on the dielectric surface, corresponding to 5.5 GV/m decelerating field [3].

The DWA program at SLAC was interrupted due to the loss of the FFTB facility to the demands of the LCLS. As such, the next round of experiments, which were to extend the materials damage threshold measurements and collect and charaterize the CCR. Due to delays in replacement of the FFTB capabilities, these experiments were moved to the UCLA Neptune Laboratory, where a >11 MeV, $\sigma_z = 200\ \mu$m with $Q$~200 pC is available after chicane compression. This beam was used to excite several differing DWA tube geometries in only the fundamental mode ($k_0\sigma_z \cong 1$), illustrating the tunability of the central CCR wavelength in the THz spectral region, and very narrow linewidth operation [4].

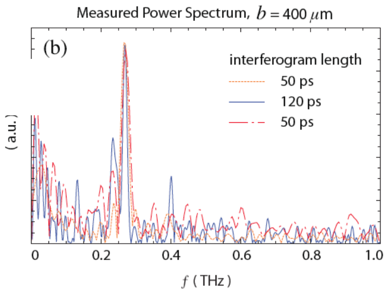

Figure 2: FFT of autocorrelated CCR measurements from Neptune DWA tests, for differing interferogram lengths.

## FUTURE EXPERIMENTS AT FACET

With the imminent construction of the FACET facility for advanced accelerator research at SLAC, the possibilities for further high gradient DWA experiments are again promising. The beam at FACET [5] will have similar parameters to those found at the FFTB: $Q$=3-5 nC, $U$=25 GeV, $\sigma_z \geq 20$ μm, $\sigma_r \geq 10$ μm, with the shortest pulses being accompanied by large energy spread.

The T-481collaboration has been extended to embrace this new agenda at FACET, and has received approval at E-169 to proceed with experimental planning. As this approval was based on a previous version of the facility, the collaboration must renew this approval in the coming months. The basic proposed work includes the following:

- **Coherent Cerenkov radiation measurements**: Investigations of the THz CCR signal in the spectral range will be extended to include harmonics, as an independent measure of the fields in the dielectric, and as a bunch length diagnostic.
- **Materials**: Previously only fused silica tubes were tested; additional materials including CVD-fabricated diamond will be explored.
- **Coating**: The metallic coating used on the tubes in T-481 were vaporized by pulsed heating. In future tests use dielectric cladding/Bragg fibers will be explored.
- **Varying tube geometry**: Custom DWA tubes with varying diameters will be used, allowing breakdown limits to be explored at fixed beam parameters. Short, 1 cm tubes were used in T481. E-169 will employ a range of lengths from 1-33 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 acceleration:** Longer fibers (10-33 cm) will allow for the direct measurement of energy change to the beam due to wakefield acceleration and deceleration. This will be done with single mode DWA operation, with long beams in which the trailing part of the beam is accelerated. An example using a $Q$=3 nC, $\sigma_z$ = 74 μm beam, in a 33 cm long DWA tube with $a$=50 μm, $b$=118 μm, $\varepsilon_r$=3.8 has been simulated with OOPIC; the results are given in Fig. 3.
- **Transverse beam stability studies:** Parametric studies of beam steering and focusing to deduce the deleterious effects of deflection modes on transverse beam stability.
- **Two-beam experiments**: Observation of narrow band acceleration using separate witness/drive beams.
- **Slab-symmetric structures**: Use of slab-symmetric wake structures, to test longitudinal coupling and purported diminishing of transverse wakefields [6].

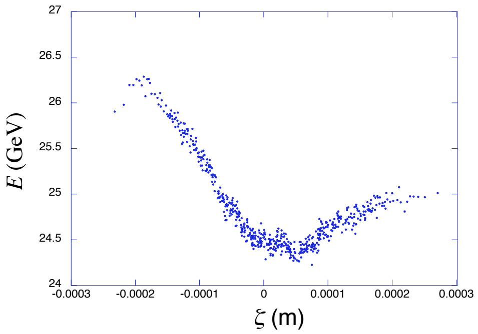

Figure 3: OOPIC simulations of longitudinal phase space in 33 cm, > 3GV/m DWA experiment at FACET.

## MULTIPULSE DWA, BNL EXPERIMENTS

We note that two of the points given above concern significant changes in the simple DWA geometry shown in Fig. 1. Similar to the Bragg radial profile mentioned for transverse mode confinement, we have recently investigated structures with longitudinal periodicity, in order to diminish the wake group velocity to near zero.

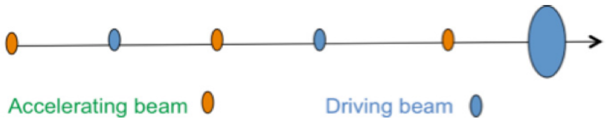

Figure 4: Scheme for beam loading and energy replacement in a DWA with interspersed pulse trains.

This refinement is necessary if one wishes to use the DWA for a linear collider (LC), for example. In order to have high efficiency, one should not throw away the majority of the stored energy in the accelerator structure after loading the wake wave with a single beam pulse. It is also difficult to maintain phase space quality and a high transformer ratio when attempting to extract a large amount of stored energy with a single pulse.

Instead, as is customary in standard LC design [7], one should use pulse trains. In the wakefield accelerator case, there should be a driving train and an accelerating train that are interspersed, so that the modest energy extraction from a relatively low charge beam can be restored with a subsequent small charge pulse. In this scenario, one may substitute a single large charge driving beam with a train of smaller $Q$, small emittance beams that are easier to compress [8] to the needed $\sigma_z$. One may even use a train of smaller $Q$ pulses to replace the large charge bunch that initiates the drive sequence with a train of small $Q$ bunches. In this way one may also have more focusable beams, that can be used to scale DWA operation to shorter wavelength and higher gradient (*cf.* Eq. 1).

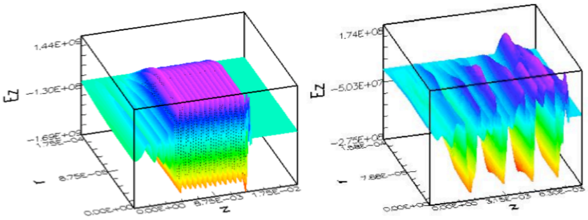

Figure 5: left) Wakefields in a standard DWA; (right) wakefields in a periodic DWA. Propagation in standard case indicated by lack of field near the left boundary.

In order to implement this scheme, however, one should diminish the group velocity $v_g$ to near zero, so the EM energy does not exit the structure during the pulse train. A method for accomplishing this has been studied at UCLA, where the value of $\varepsilon$ is alternated periodically in $z$. In order to set $v_g$ to zero, we begin the analysis by defining, in analogy to particle optics, a phase advance $\mu$ in the vector $\left(E_z, \partial_z E_z\right)$, and set it to $\pi$. With this prescription we have identified a structure made of alternating $SiO_2$ and diamond and simulated its performance in OOPIC (Fig. 5). We are currently studying methods of creating such periodic DWA structures with industrial partner RadiaBeam Technologies under SBIR support.In order to test the physics of multi-pulse excitation, we will take advantage of the method developed at the BNL ATF for creating a multiple pulse train out of a single pulse of electrons by mask collimation of a chirped beam at a high dispersion point in the beamline [9].

An OOPIC simulation of the experiment currently underway at the ATF, using a metallic-coated, uniform $SiO_2$ DWA tube structure ($a$=100 $\mu$m, $b$=150 $\mu$m) is given in Fig. 6. Four drive pulses with $Q$=25 pC resonantly excite fields to above 55 MV/m, and a 5th witness beam is staggered to test the acceleration fields.

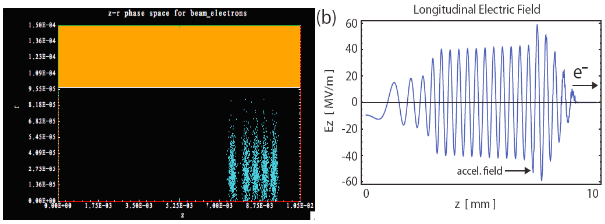

Figure 6: (left) Beam and dielectric geometry in OOPIC simulation of pulse-train experiment at BNL ATF; (right) $E_z$ associated with the multi-pulse excitation.

Initial testing at the ATF has begun recently. DWA tubes have been fabricated at UCLA installed at the point in the beamline where a well-focused beam is available. The energy loss/gain associated with single pulse wakes consistent with simulations have already been observed from a single short pulse. In addition, copious CCR signal was observed The creation of the pulse train using the mask technique has been tested, with both signs of the chirp used. It has been found that by correction of transport nonlinearities one could obtain a variety of pulse length for both positive and negative chirps. A FFT of the 4-pulse train obtained in an optimized case is shown in Fig. 7. The width of the peak about 207 μm indicates a nearly transform limited case — uniform, periodic train.

Further tests with the full pulse train systems, including energy gain and loss in SiO2 and diamond tubes, are planned in the coming months. The diamond tube installation will require very high field permanent magnet quadrupoles to permit 100 μm aperture beam passage.

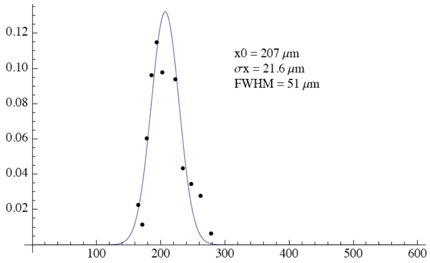

Figure 7: (left) Beam and dielectric geometry in OOPIC simulation of pulse-train experiment at BNL ATF; (right) $E_z$ associated with the multi-pulse excitation.

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