OBSERVATION OF MULTI-GeV BREAKDOWN THRESHOLDS IN DIELECTRIC WAKEFIELD STRUCTURES*

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Abstract

An experiment designed to test the breakdown threshold of a dielectric subjected to the GV/m-scale electric-fields of an intense electron-beam has been completed. In this experiment at the Final Focus Test Beam (FFTB) facility, the 30 GeV SLAC electron beam was focused down and propagated through short fused-silica capillary-tubes with internal diameters of as little as 100 μm. The electric field at the inner surface of the tubes was varied from about 1 GV/m to 22 GV/m by adjusting the longitudinal compression of the electron bunch. We observed a sharp increase in optical emissions from the capillaries in the middle part of this surface field range which we believe indicates the transition between sustainable field levels and breakdown. If this initial interpretation is correct, the multi-GV/m surfaced fields that were sustained equate to on axis accelerating field of several GV/m.

INTRODUCTION

The accelerating field achievable in conventional radio frequency accelerators is ultimately limited by the breakdown of the metallic accelerating structure. It is well understood that the field sustainable in a cavity increases with the frequency of the cavity [1, 2]. Simply following this scaling by using ever higher frequency cavities is difficult due to the "THz gap"; the current lack of practical high power source between X-band microwaves ($\sim$ 11 GHz) and infrared lasers ($\sim$ 28 THz). Various studies have indicated that GV/m accelerating fields should be possible in dielectric laser accelerators [3] as long as the driving laser pulses are very short [4]. The difficulty with laser accelerators, however, is that they operate at very short wavelengths (e.g. 10.6 μm at 28 THz), which greatly complicates structure fabrication, beam injection, and beam phasing.

Dielectric accelerators can also be powered directly by high energy charged particle beams via wakefield excitation [5, 6], eliminating the need to generate high power electromagnetic waves, and can operate at essentially any wavelength since the accelerating wakefield wavelength is determine by the dielectric geometry. An electron-beam-driven dielectric-wakefield-accelerator is essentially a uniform dielectric tube coated on the outside with a heterogeneous, often metallic, cladding, see Fig. 1. When an intense electron beam passes through the center of the tube its electric field bends at the Cerenkov angle within the dielectric, reflects off the cladding boundary, and returns to the axis where it can be used to accelerate other particles. In the ideal limit, where the electron beam length (σ_z) is much smaller than the the inner dielectric radius (a), the on axis accelerating field ($E_{z,accel}$) is given by $E_{z,accel} \approx 2Q/a^2$, where Q is the beam charge. Maximizing the accelerating wakefield therefore requires maximizing Q while minimizing σ_z and a. It should also be noted that a must be chosen several times larger than the beam radius (σ_r) to prevent damage to the dielectric from the beam halo.

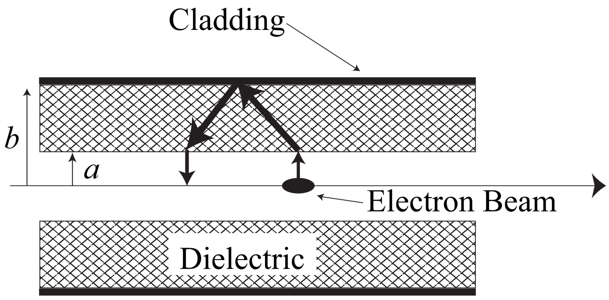

Figure 1: Schematic of the dielectric wake accelerator.

Dielectric wakefield accelerators have been studied in depth over the last several years, but their maximum fields have been limited to 10's of MeV/m by the lack of ultra-short drive beams. The recently achieved 20 μm pulse-length beams obtained at the Stanford Linear Accelerator Center (SLAC) Final Focus Test Beam (FFTB) facility [7] are sufficient to generate longitudinal fields in excess of 1 GV/m. We have used the FFTB beam to begin probing the GV/m regime of dielectric accelerators.

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Table 1: Breakdown Experiment Parameters

Beam Charge (Q)	3 nC
Beam Energy	30 GeV
Beam Radius (σ_r)	10 μm
Beam Length (σ_z)	100 - 20 μm
Inner Dielectric Radius (a)	50 and 100 μm
Outer Dielectric Radius (b)	162 μm
Dielectric Relative Permittivity (ε)	~ 3
Peak Decelerating Field	8 GV/m
Peak Field at Dielectric	22 GV/m

BREAKDOWN THRESHOLD OBSERVATIONS

The primary goal this experiment was to assess dielectric material survivability. The parameters for our experiment, which is based upon the unprecedented combination of high charge, short pulse duration, and small spot size available in the SLAC FFTB beam, are listed in Table 1. The peak electric field values in Table 1 are derived from OOPIC simulations [8]. The ability to drive surface fields up to 22 GV/m virtually guaranteed that we would be able to break down the dielectric.

Since the experiment uses dielectric tubes with 100 and 200 μm IDs, we limited the tube length to about a cm in order to mitigate alignment issues. The energy gained or lost by beam particles was therefore only on the order of 10 MeV, while the full energy spread of the highly compressed FFTB beam is several GeV. Consequently, energy changes were not resolvable in this experiment. The primary signature of high field wakes was the detection of dielectric breakdown.

This dielectric wakefield experiment is unique in that it produced fields comparable to those in earlier laser breakdown studies. We are particularly interested in differentiating material breakdown in wake-excited, relatively long wavelength (> 50 μm photon) systems, as compared with optically (laser) excited systems. In the case of optically excited fields, the breakdown limit for a pulse of the same duration as that generated by the electron beam wake is about 1.1 GV/m in fused silica [4, 9].

The dielectric tubes for this experiment were modified from off-the-shelf synthetic fused silica capillary tubing ($\varepsilon \cong 3$), which we procured in 100 and 200 μm ID sizes. Samples were prepared from this bulk product by cutting pieces to length, removing the outer polyimide jacket, polishing the cut ends, and coating the outside of the tube with vapor deposited aluminum. Groups of ten samples were packaged together for the experiment in modular mounting blocks. The 1 cm wide, by 5 cm long, by 0.5 cm high mounting block also has an optical transition radiation (OTR) screen for locating the beam orbit. Our methodology for aligning the experiment was to move the dielectric tubes onto the established beam orbit rather than trying to steer the beam through the tubes. In practice, this alignment technique seemed to work very well, although we could not rule out beam halo scrapping in the 1 cm long dielectric tubes. We intended to check for scrapping by monitoring the x-rays such scrapping would produce, but discovered that our x-ray detector was too insensitive. Alignment procedures will be further refined and use better x-ray diagnostics in future runs of the dielectric wake experiment. Once beam propagation through the dielectric tubes was established, we began to vary the wakefield magnitude by adjusting the beam pulse length and search for an optical signal of breakdown on a side view telescopic camera. This experiment was repeated for samples with different tube IDs. Individual tube samples were systematically exposed to different field levels for varying periods of time for a later study of differences in material damage.

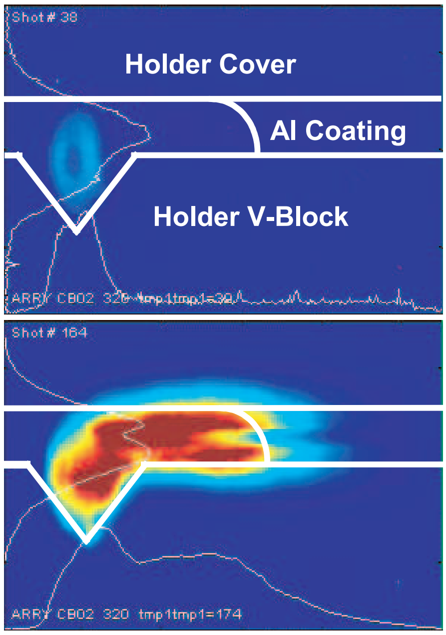

Figure 2: Visible light images (displayed with the same scaled-to-intensity color map) of a 100 μm ID fiber tip as the electron beam pulse current is ramped up. In the top image, the electron beam pulse length is long ($\sigma_z \sim 100$ μm) and the fiber end glows faintly with incoherent optical wavelength emissions. The various boundaries of the fiber holder, which is viewed at an angle of 45° from the beam axis, are also illustrated along with the area in which the fiber's aluminum coating blocks optical emissions. In the bottom frame, the electron beam is near its minimum pulse length ($\sigma_z \sim 20$ μm) and a breakdown event has occurred producing a large flash of visible light.

While analysis of the collected data is still preliminary, the observations seem to indicate a clear breakdown threshold. Most of the observations were of 100 μm ID fibers and they consistently showed that the visible light output of the fibers jumped up sharply near the short end of the beam pulse length range, Fig. 2. This bright flash was clearly visible on both the side view telescopic camera and a wide-angle top-view general observation camera. The initiation

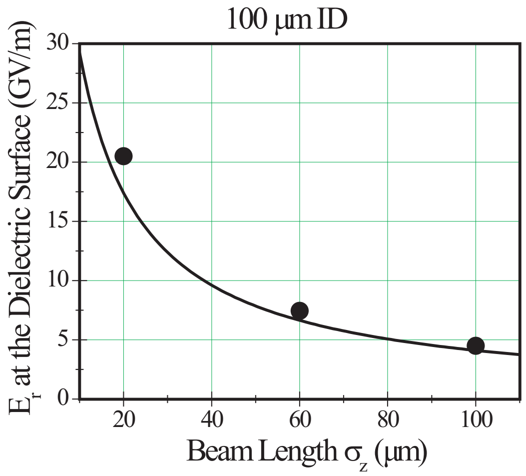

Figure 3: Radial electric field at the inner surface of a 100 μm ID fused silica capillary tube as a function of electron beam pulse length. The black line is the prediction of Eq. 1 and the dots are the results of OOPIC simulations.

of breakdown discharges is the most likely explanation for the optical radiation increase. The visible wavelength light recorded at long pulse length / low fields is probably due to a combination of incoherent cerenkov radiation, incoherent transition radiation, and scintillation. Once a breakdown occurs, however, the light from these mechanisms is small compared to the visible emissions from the plasma formed during the breakdown event. It is clear from the observations that breakdown events start to occur after the beam has been compressed below about the midpoint of its range. For an ultra-relativistic beam ($\gamma \gg 1$) it is fairly straightforward to calculate the radial field on the surface of the dielectric $E_{r,surface}$ to first approximation through simple application of Gauss' law. Such an analysis yields the expression

$$E_{r,surface} = \frac{1}{\epsilon_0} \frac{Q}{(2\pi)^{3/2} a\sigma_z + \frac{\sqrt{\varepsilon-1}}{\varepsilon}\pi a^2} \left[\frac{\mathrm{V}}{\mathrm{m}}\right], \quad (1)$$

where all quantities are in SI units, $\epsilon_0 = 8.854$ x 10^{-12} F m^{-1} is the permittivity of free space, and ε is the dielectric constant. This result compares well to those of more sophisticated analytical theories [10, 11]. Using Eq. 1 to plot the surface fields at the dielectric verses the beam pulse length, Fig. 3, we find that the breakdown threshold should be ≥ 3 GV/m. OOPIC simulations indicated that this range of surface fields corresponds to ≥ 1.5 GV/m on-axis accelerating field in the wake.

Further analysis of the data will allow us to precisely quantify the breakdown field and determine how much variation there is among the exposed fused silica capillary tubes. In addition to a more careful analysis of the visible light observations and associated beam parameters, we also intend to examine the dielectric tubes with various diagnostics to detect structural damage from the breakdown events. We hope to be able to correlate the number of breakdown events a particular tube experienced to the degree of pitting or other forms of damage that are evident in the post-mortem examination. The full results of this experiment will be reported elsewhere [13]. A second phase of the experiment is planned to measure the coherent Cerenkov radiation emitted by the fiber as an independent indicator of field strength [12] and directly measure deceleration within the beam. This work is being planned for the proposed SABER facility at SLAC [14].

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