OBSERVATION OF >GV/M DECELERATING FIELDS IN DIELECTRIC LINED WAVEGUIDES*

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Abstract

Recent experimental measurements of the energy lost to wakefields in a dielectric lined waveguide are presented. These measurements demonstrate average decelerating gradients on the order of >1 GV/m, for two different structures. The measurements were made at the Facility for Advanced aCcelerator Experimental Tests (FACET) at SLAC National Laboratory using sub-millimeter diameter fifteen-centimeter long quartz fibers of annular cross section. The unique extremely short, high charge, ultra relativistic beam at FACET (200 fs, 3 nC, 20 GeV) allows the use of dielectric wakefield structures of unprecedented size and length. In addition to experimental results, we support conclusions with simulation and theoretical work. This measurement builds on a large body of work previously performed using dielectric wakefield structures in an effort to provide high gradient accelerating structures for tomorrows linear colliders.

INTRODUCTION

Accelerator physicists are looking for technologies to increase the average gradient in new systems past the present limit of ~20 MVm^{-1} in traditional room temperature copper structures [1]. The end goal of such research is not only reduction in size of present and future accelerating complexes, from kilometers [2] to a kilometer or less, but for the creation of high energy, compact beam sources that pave the way for the next generation of radiation sources which operate in bands heretofore difficult to access, such as terahertz [3–5] and x-rays [6].

Such possible gradient increasing modalities include systems that produce modest increases in gradients, such as superconducting radio frequency structures at ~50 MVm^{-1} [1], and ones that produce massive gains in gradients, such as plasmas at ~100 GVm^{-1} [7]. An additional intermediate option is the use of dielectric lined waveguides, or Dieletric Wakefield Accelerators (DWA), capable of supporting fields on the order of ~5 GVm^{-1} [8]. We discuss here recent experiments designed to measure the decelerating gradient in cylindrical dielectric lined waveguides. Such measurements allow an estimate of the accelerating gradient behind the wake driving bunch to be made and allow studies of the effects of beam breakup instabilities [9]. We show here measured decelerating gradients of the GVm^{-1} level, which exceed previous measurements by two orders of magnitude [10, 11].

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EXPERIMENT

The experiment presented here threads an electron beam through a hollow, cylindrically symmetric dielectric structure [12]. As the beam passes through the dielectric structure it couples to the modes supported in the structure that have non-zero longitudinal electric field, $E_z \neq 0$. The experiment is conducted in two parts that allows the characterization of the beam-structure interaction. First, the radiation generated in the structure is spectrally characterized, which allows a description of the structure's reaction to the beam. Second, the average beam energy is measured both with and without the structure in the beam so that the beam's reaction to the structure can be described. A diagram of the experiment can be found in Figure 1.

Table 1: Structure Parameters divided by transverse geometry, a and b are in μm.

ρ_{in}/ρ_{out} = a/b	**450/640**	**400/600**	**200/300**
Length [cm]	10	15	15
λ [μm] (TM_{01})	760	760	430
$E_0[\frac{V}{m}]$	0.047	0.053	0.124

The structures used in this experiment are metal coated SiO2 and Quartz ($\epsilon_r = 3.8 - 3.9$) optical fibers of annular cross section with hollow inner channel of radius a and outer diameter of radius b. The dielectric thickness is the difference between these two radii. Other structure parameters can be found in Table 1. The fibers are purchased uncoated and unspooled, so as not to unintentionally introduce bends in the final product. The fibers are then cleaned and a small adhesion facilitating layer of aluminum is vacuum deposited to around 30 nm thickness. After aluminum, copper is vacuum deposited to 500 nm thickness followed by a sulfate base electroplating bath that increases the copper thickness to 20 μm. Finally the structures are cut to length using a diamond saw to produce the flat surfaces shown in Figure 2.

FACET

While we will show later that the fields in the structure approach several GVm^{-1} it is still desirable to achieve as large of an energy shift as possible after passing through the structure. To that end the high energy beam available at the Facility for Advanced aCcelerator Experimental Tests (FACET) at SLAC National Laboratory provides naturally long beta functions, thus extending the interaction without the need of a focusing channel to keep the beam in the structure. In addition to high beam energy, FACET offers

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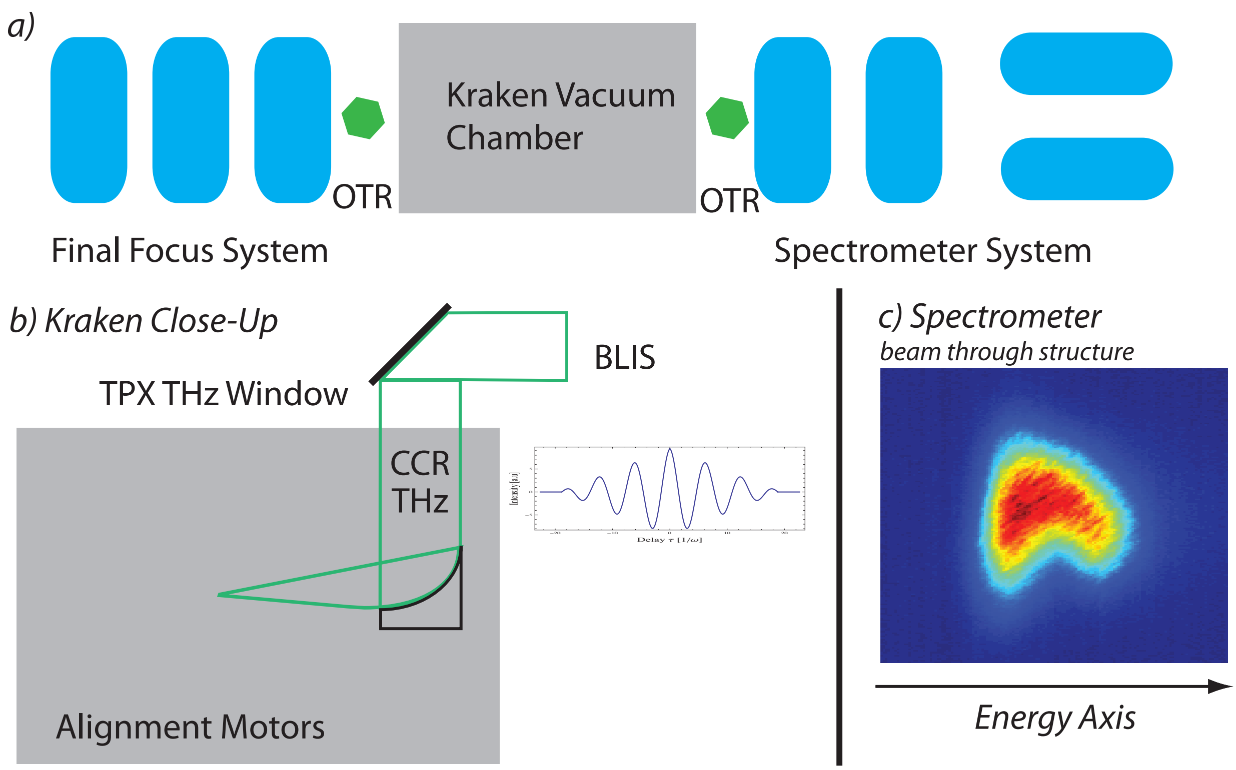

Figure 1: A graphical representation of the experimental set up at FACET. a) Shows the optical set up; quadrupole magnets are shown in orange and teal, dipoles in blue and the beam in red. There are Optical Transistion Radiation screens both upstream and downstream of the experimental vacuum chamber, the so-called "Kraken", to facilitate alignment to the structures. b) The layout in and around the vacuum chamber. A series of seven high precision vacuum motors are used to align the structure to the beam with the help of a green laser set to the beam path. The Coherent Cerenkov Radiation (CCR) generated in the structure is impedance matched to free space by a horn (not shown) and collected and collimated by a three inch off-axis parabolic (OAP) mirror. Once collimated the CCR is transported out of vacuum through a TPX window and then to a scanning Michelson interferometer (BLIS). An example of a trace produced by the interferometer is shown. c) A sample of images from the spectrometer light imaging system. Top is the beam after passing through the structure, bottom is structure free transport.

exceptionally high peak beam currents by providing upwards of 3 nC of charge in beams as short as 20 μm. A summary of the relevant beam parameters can be found in Table 2.

Table 2: FACET Beam Parameters

Parameter	**Value**	**Unit**
Beam Energy	20.35	GeV
Charge	3	nC
Transverse Size at IP	30x30	µm
Bunch Length	20-50	µm
β^*	0.15x2.5	m

BEAM-MODE COUPLING

To model the beam-mode coupling we use conservation of energy to write the single particle coupling to the TM_{0n} modes as [13, 14],

$$E_0 = e v_z I_0(k\rho_0)\frac{1}{\int_A \left[\frac{S_z - v_z u}{E_0^2}\right] \mathrm{d}^2x}, \tag{1}$$

where A is the transverse surface containing the particle. To expand this to a full beam of r.m.s. length σ_z, r.m.s transverse size σ_ρ and axial offset ρ_0 we find that the convolution is,

$$E_z(z) = \frac{E_0 N_e}{\sqrt{2\pi}\sigma_z}\int_{-\infty}^{z} \mathrm{d}s e^{-ik_z(z-s)} e^{-\frac{s^2}{2\sigma_z^2}} * e^{\frac{-\rho_{off}^2}{2\sigma_\rho^2}} e^{\frac{\sigma_\rho^2}{2}\left(k^2+\frac{\rho_{off}^2}{\sigma_\rho^4}\right)} I_0(k\rho_{off}). \tag{2}$$

If ρ_0 is taken to be on the order of σ_ρ and both are small compared to the vacuum channel radius a, i.e. we assume all the charge is contained inside the vacuum channel near

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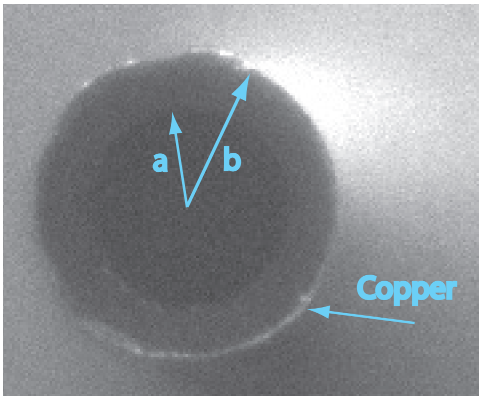

Figure 2: An image of one of the ends of a structure similar to the ones used in this experiment. The inner radius a is vacuum while the outer radius b is the structure diameter. In this case a = 200 μm and b = 300 μm. The reflective outer surface is the copper coating used to contain the mode, which is approximately 20 μm thick.

the axis of symmetry, we arrive at,

$$E_z(z) = \frac{E_0 N_e}{2} e^{-ik_z z} e^{-\frac{k_z^2 \sigma_z^2}{2}} * \left[1 + \mathrm{Erf}\left(\frac{z}{\sqrt{2}\sigma_z} - \frac{ik_z \sigma_z}{\sqrt{2}}\right)\right]. \quad (3)$$

Finally it is seen that if we examine the wakefield for positions much longer than σ_z that the field reduces to $E_z \simeq E_0 N_e$. This method can be expanded to include all modes the beam can excite, where $\sigma_z \ll \lambda_{mn}$. If this is done for the smallest of the structures presented in Table 1, keeping the first four TM_{0n} modes we see that the peak field behind the bunch can be in excess of 3 GVm^{-1}.

If we were to calculate the total energy transferred from the beam to the Cherenkov wakefield we convolve the beam distribution with its wakefield and would end up with an energy exchange proportional to N_e^2. Thusly, dielectric lined waveguides offer the potential for high energy pulses at wavelengths in the terahertz regime. For the experimental parameters presented in Table 2, calculations run from 100 mJ in the largest radius structure to almost a joule in the smallest.

CONCLUSION

We have shown here it is possible to generate gradients far in excess of those present in warm radio frequency structures, recommending such structures as a possible method for creating high energy compact accelerating systems. To continue to pursue dielectrics it is necessary to further study the excitation of higher order HEM_{mn} modes which consist of potentially unstable transverse forces of a magnitude comparable with the longitudinal gradient. Furthermore it is necessary to explore methods which can reduce the deleterious nature of said transverse fields [15].

Using the radiation generated in the terahertz regime by dielectric lined waveguides required complete characterization of the radiation after emission from the waveguide. The exact behavior of the dielectric materials used to produce the radiation is an open question, more so under such intense fields. It is seen that the radiation generated is spectrally consistent with theory and attempts to measure absolute energy produced are under way.

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