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DEMONSTRATION OF GIGAVOLT-PER-METER ACCELERATING GRADIENTS USING CYLINDRICAL DIELECTRIC-LINED WAVEGUIDES*

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Abstract

We present here the results of measurements made showing 1 G V m^{-1} accelerating fields using a hollow dielectric-lined waveguide. The results are comprised of measurement of the energy loss of a high charge (3 nC) ultrashort (200 fs), ultra relativistic (20 GeV) beam and concomitant auto-correlation interferometeric techniques to obtain the frequency content of simultaneously generated coherent Cherenkov radiation (CCR). Experiments were conducted at the Facility for Advanced aCcelerator Experimental Tests (FACET) at the SLAC National Laboratory using metal-coated sub-millimeter diameter, ten-centimeter long fused silica tubes. We present simulation and theoretical results in support of the conclusions reached through experiment. These results build on previous work to provide a path towards high gradient accelerating structures for use in compact accelerator schemes, future linear colliders and free-electron lasers.

BACKGROUND

Present accelerator technology, the product of five decades of theoretical and experimental studies [cite SLAC design report], have slowed in progressing towards the longitudinal fields necessary for future high energy particle colliders [1,2]. While theoretically capable of producing the particles and energies necessary for future collider experiments, present technology is limited by its physical size as well as its budgetary size. Due to these limitations, and on general principle, it is necessary to explore other "advanced" technologies for accelerating charged particles. These advanced systems include technologies like plasmas, dielectrics and inverse free electron lasers. This publication focuses on the use of cylindrical dielectric lined waveguides as a method for accelerating electrons.

The use of dielectrics as accelerators of charged particle beams generally falls into two categories. The first is a dielectric structure which is powered by an external source, such as a laser [3]. This modality is similar to a traditional RF cavity driven by an external source, such as a klystron. The second use of dielectrics as an accelerator is as a Dielectric Wakefield Accelerator (DWFA), a method which takes advantage of the fact that good accelerators are also good decelerators. In such a system a "driving" particle beam is sent through a structure, transferring energy from the beam to the structure in the form of a wakefield. A "witness" bunch is then sent through the structure and gains energy, if it is phased properly with respect to the driving beam.

This experiment builds on previous work [4–6] by showing unprecedented gradients and lifetimes in dielectric lined waveguides. The experiment presented here consist of electron beam energy loss and Coherent Cherenkov Radiation autocorrelation measurements. Such measurements constitute a characterization of the coupling of the beam to the structure, and through well known relations [7], establishes an accelerating gradient on the order of 1 GV m^{-1}. Additionally, the experimental data shows structure lifetimes, at such intense gradients, exceeds many tens of thousands of electron pulses. Demonstration of long lifetimes in accelerator components is necessary for a future system to be taken seriously by the accelerator community.

EXPERIMENT DESCRIPTION

The characterization of the beam-structure interaction has two facets. First, in order to quantify the energy given up by the beam to the structure, the change in energy of the beam after traversing the structure is measured. Second, an autocorrelation measurement of the radiative wakefield generated by the beam passing through the structure verifies that the structure is reacting as expected to the presence of the beam. Specifically, an autocorrelation trace is used to determine the electromagnetic mode composition of the dielectric structure under experiment. This measurement is similar to recording the radio frequency pulse characteristics during operation of an S-band accelerating structure.

The structure, shown in Fig. 1, is an annular dielectric silicon-dioxide fiber coated with a metallic outer layer. This metallic layer is used to develop and confine the mode generated by the passing electron beam. The inner diameter of the structure is 450 µm while the outer diameter is 640 µm. For the experiment presented here the structures were ten-centimeters in length. The phase velocity of the wakefield generated by the driving beam is necessarily in phase with the driving beam itself, thus for beams close to the speed of light the witness beam does not dephase with respect to the wakefield and structure length is limited by available drive beam energy and the ability to transport the beam through the structure.

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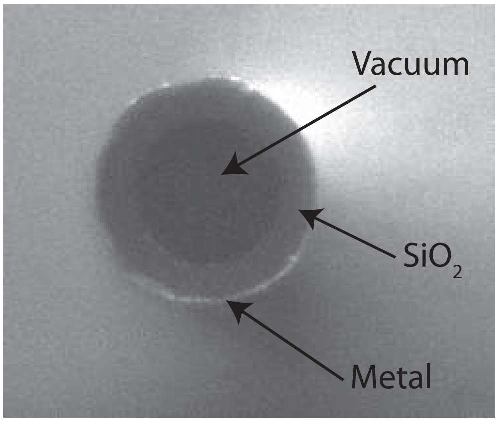

Figure 1: Picture of a structure used in the presented experiment. The aluminum and copper metal jacket varies (deliberately) from 12 µm to 25 µm.

A diagram of the experiment is detailed in Fig. 2. In the diagram the salient details of the experiment are shown. Of particular interest is the method for aligning such small structures to the beam at FACET in a non-destructive fashion. The alignment is performed by marking the beam position on beam position screens upstream and downstream of the experimental chamber. A laser with a spot size of 40 µm at the interaction point is then positioned on the beam marks and the structure is aligned to the laser vector.

FACET

To achieve as long an interaction as possible, without the aid of external guiding mechanisms like focusing channels, it is necessary to use a beam with as high an energy as possible. High beam energy results in a small geometric emittance which allows for large beta functions. With a beam energy of 20.35 GeV, the Facility for Advanced aCcelerator Experimental Tests (FACET) at SLAC National Laboratory provides the highest energy electron test beam in the world. Other beam parameters for the facility are listed in Table 1.

Table 1: FACET Beam Parameters

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

Since the magnitude of the decelerating wakefield $E_{z,dec}$ is proportional to $\frac{Q^2}{\sigma_z}$, ensuring a robust structure-beam interaction requires a high current electron bunch. FACET is capable of providing 3 nC of charge in a bunch length of around 20 µm, approximately 20 kA of current. Such high currents allow the generation of wake fields on the scale measured in this experiment, 0.5 GeV to 1.0 GeV.

MEASUREMENT

For this experiment, the relatively small difference between the nominal beam energy and the beam energy after traversing the structure necessitates a statistical approach to the energy shift measurement. In this case the number of measurements of the centroid beam energy should exceed five hundred measurements in order to reduce the confidence intervals used to determine the energy loss to a level which renders the measurement significant. The measurement proceeds in a simple measure and bin process where a histogram of the two scenarios is constructed and their means compared.

To ensure the measurement is due to wakefield coupling in the dielectric structure it is necessary to quantify other sources of energy loss in this experiment. The sources of energy loss are expected to be coherent diffraction radiation, from entering and exiting the structure, and energy transferred to the wakefield in the structure as coherent cherenkov radiation. In the limit that the $A << \gamma\lambda_{rad}$, where A is the structure aperture, diffraction radiation can be modeled as transition radiation. The resulting calculation yields an expected energy loss of 25 mJ. The energy give up by the beam to the dielectric structure is seen to be split between the dominant TM_{01} mode and the higher order TM_{02} mode. No coupling to HEM modes is observed.

With the spectral content of the radiation known and the energy exchange between the beam and the structure quantified a description of the beam-structure interaction can be given. This description allows the determination of the potential gradient behind the driving bunch, via the aforementioned fundamental theorem of beam loading. To support such a deduction, self-consistent simulations using the commercial code VORPAL [8] are performed to verify beam-mode coupling and other dynamic characteristics of the interaction. The simulations are shown to agree well with both theoretical solutions to Maxwell's Equations in the waveguide as well as measurements made at FACET.

CONCLUSION

The FACET facility at SLAC has allowed the measurement of heretofore unobserved gradients in dielectric wakefield structures and has shown the ability of these structures to survive such sustained gradients for many tens of thousands of pulses. These measurements pave the way for future drive-witness experiments to sample the wakefield left behind such high current bunches and, due to the nature of the radiation generated and its wavelength, the generation of terahertz radiation pulses of unprecedented energy [9]. Future work is required to demonstrate the ability to guide beams through such structures for lengths much longer than a β function in order to make a low energy drive beam, high energy witness beam scenario feasible.

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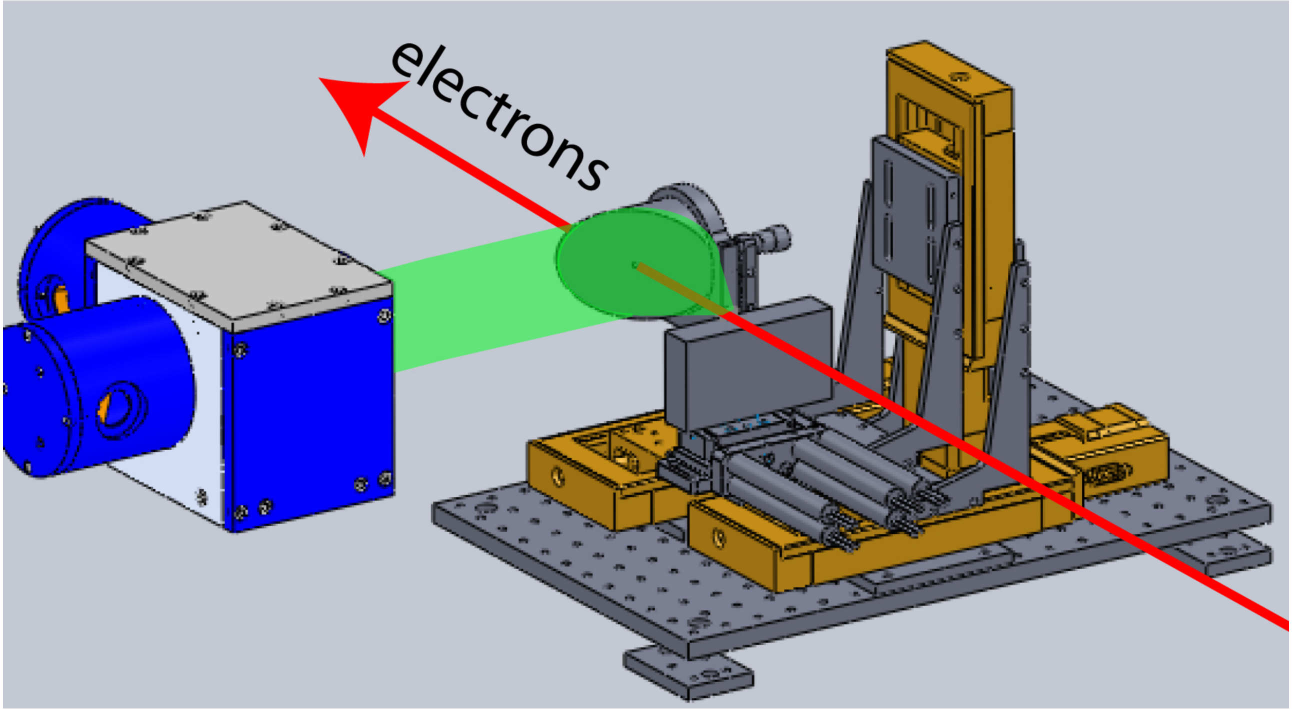

Figure 2: SolidWorks rendering of the experiment chamber at FACET. The electron beam path is shown in red and the Coherent Cherenkov Radiation (CCR) path is shown in green. CCR is generated in the dielectric lined waveguide and coupled to an aluminum horn for transmission to free space. The radiation is then captured and collimated by a three inch off-axis parabolic mirror designed to completely occlude the solid angle subtended by the coupling horn.

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