BEAM-DRIVEN DIELECTRIC WAKEFIELD ACCELERATING STRUCTURE AS A THZ RADIATION SOURCE*

A. M. Cook†, H. Badakov, R.J. England, J.B. Rosenzweig, R. Tikhoplav, G. Travish, O.B. Williams,
UCLA, Los Angeles, CA 90095, USA
M.C. Thompson, LLNL, Livermore, CA 94550, USA
A. Kanareykin, Euclid TechLabs, Solon, OH 44139, USA

Abstract

Experimental work is planned to study the performance of a beam-driven cylindrical dielectric wakefield accelerating structure as a source of THz coherent Cerenkov radiation (CCR). For an appropriate choice of dielectric tube geometry and driving electron bunch parameters, the device operates in a single-mode regime, producing radiation in the THz range. This source can potentially produce high power levels relative to currently available sources, with $\sim$50 μJ radiated energy per pulse achievable using the electron beam currently in operation at the Neptune advanced accelerator laboratory at UCLA ($\sim$13 MeV beam energy, $\sim$200 μm RMS bunch length, $\sim$500 pC bunch charge). Preparations underway for installation of the experiment are discussed.

INTRODUCTION

The concept of the beam-driven dielectric wakefield accelerator (DWA) has been studied in depth in recent years. The beam-driven accelerator concept in general is interesting because it is not necessary to apply external power in order to accelerate a beam, and because the structures can potentially produce very high accelerating gradients. While not affording accelerating gradients as high as those offered by plasma wakefield accelerators (PWFA) [1], the DWA may be an attractive alternative in some cases due to its relative simplicity of implementation and immunity to possible ion motion problems [2].

In the DWA scenario, a driving electron bunch travels in a hollow channel along the axis of a slow-wave structure such as a dielectric-loaded waveguide or dielectric capillary tube. Cylindrical or slab (Cartesian) geometries are typically considered. The driving bunch excites many modes in the structure via Cerenkov radiation which superimpose to create a wakefield that travels with a phase velocity equal to the velocity of the bunch. The wakefield can then accelerate a second witness electron bunch following at an appropriate distance behind the driving bunch. At the same time, the driving bunch is decelerated as it loses energy to the wakefield. The fundamental theorem of beam loading limits the magnitude of the accelerating gradient seen by the witness bunch to less than or equal to twice the decelerating gradient seen by the driving bunch, in the case of a symmetric driving bunch [3].

Experimental and theoretical work done by researchers at Argonne National Laboratory [4, 5], and work published more recently [6, 7, 8, 9], has predicted and measured the superposition of beam-driven wakefields in cylindrical dielectric structures. A recent preliminary experimental study by a UCLA/SLAC/LLNL collaboration has used the ultra-short, high-energy beam at the SLAC FFTB facility to explore the GV/m regime of dielectric accelerating structures. The study estimates, based on experimental observations, that longitudinal accelerating gradients in excess of 1 GV/m are sustainable in a fused silica DWA structure [10]. This result highlights the usefulness of the DWA concept in the future of high-energy linear accelerators, as the limits on accelerating gradients of conventional accelerator technology are being reached.

The experimental work described in this paper seeks to explore the performance of a cylindrical DWA structure as a THz radiation source. Theoretical and simulation results indicate that with an appropriate choice of dielectric structure geometry and driving electron bunch parameters, the wakefield radiation produced in the structure is narrowband relative to bending magnet radiation and lies in the THz range of the spectrum. The electron beam at the Neptune laboratory at UCLA is suitable as a drive beam for this experiment, with beam parameters nominally matching those required.

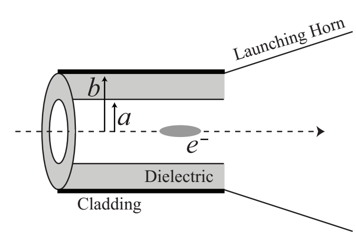

Figure 1: Cylindrical dielectric wakefield accelerating structure and CCR launching horn.

THEORY AND SIMULATION

The accelerating structure we will use in this experiment is a circular cylindrical capillary tube of uniform relative dielectric permittivity ε, illustrated in Figure 1. The dielectric is coated on the outside with a conducting cladding

* Work supported by the United States Department of Energy
† alancook@physics.ucla.edu

to ensure total reflection of the Cerenkov radiation at the boundary.

The magnitude of the decelerating wakefield seen by the driving electron bunch as it travels along the axis of the structure is given approximately by the simple formula

$$eE_{z,\text{dec}} \approx -\frac{4N_b r_e m_e c^2}{a\left\{\sqrt{\frac{8\pi}{\varepsilon-1}}\varepsilon\sigma_z + a\right\}}, \tag{1}$$

where N_b is the number of electrons in the bunch, r_e is the classical electron radius, c is the speed of light, σ_z is the RMS bunch length, and a is the inner radius of the dielectric tube. This formula is based on a Gauss' Law heuristic approach and does not take into account the finite thickness of the dielectric wall nor the reflective cladding at the boundary, but gives satisfactory agreement for use as an estimation tool. We see that the decelerating field, and thus the energy extracted from the driving bunch, varies directly with the bunch charge and inversely with the inner radius a and the RMS bunch length σ_z. We can use this decelerating field value to estimate the energy lost by the drive bunch in the structure, which is the total energy per pulse of CCR.

Based on geometrical arguments, the wavelength of the n^{th} mode excited in the structure can be approximated by the formula

$$\lambda_n \approx \frac{4(b-a)}{n}\sqrt{\varepsilon - 1}, \tag{2}$$

where n =1, 2, 3... is the mode number and b is the outer radius of the bulk dielectric material. The energy in each spectral line is approximately proportional to n down to a roll-off wavelength at $\lambda \approx \sqrt{2\pi}\sigma_z$ [11]. For an appropriate combination of driving bunch length and tube configuration (b, a, ε) the structure can be driven in a largely single-mode regime, creating a radiation pulse that is relatively narrow band, as simulation results show.

OOPIC Simulation

The particle-in-cell code OOPIC [12] was used to simulate the interaction of the electron beam with the dielectric structure and to explore the experimental parameter space. Parametric scans of the tube inner and outer diameters were conducted in order to determine a geometric configuration ideal for THz production. The results of one such scan are plotted in Figure 2, along with comparison data calculated using the heuristic formula of Eq. 2 and an analytic approach used in Ref. [4]. The tubes used in this experiment will have outer radii in the range of 325 - 400 μm, and the inner radius will be fixed at 250 μm.

Fourier analysis of the OOPIC data produced for a tube with ID = 500 μm / OD = 700 μm (Figure 3) clearly shows a spike in the CCR power spectrum in the THz range. The inset in the figure represents a lineout of the longitudinal electric field on-axis and shows the strongly sinusoidal nature of the wakefield excited by the driving electron bunch in this single-mode regime.

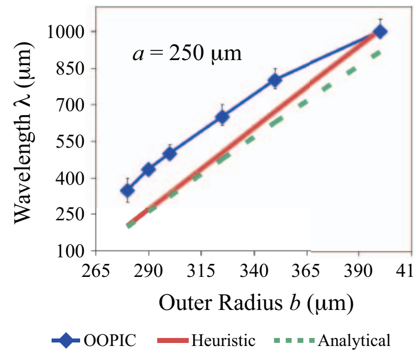

Figure 2: Central wavelength of emitted Cerenkov radiation as a function of outer tube radius.

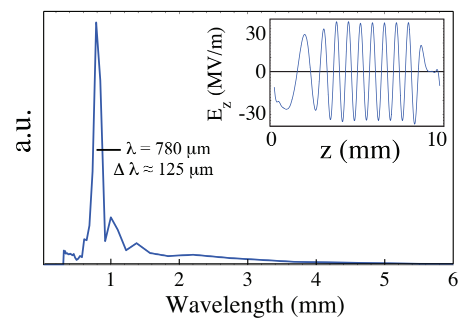

Figure 3: Power spectrum of emitted Cerenkov radiation, calculated numerically from the longitudinal on-axis electric field lineout shown in inset. The horizontal axis in the inset represents the whole length of a 1 cm dielectric tube, and electron bunch moves from left to right. Plots are derived from OOPIC data. Spectrum contains artifacts from discrete Fourier transform algorithm.

EXPERIMENT

The experimental layout is shown in Figure 4a. A compressed electron bunch, with parameters shown in Table 1, is focused strongly by a permanent magnet quadrupole (PMQ) triplet and passes through a dielectric capillary tube. Upon exiting the tube, the bunch is recollimated by a second PMQ triplet and then steered 90 degrees upward to a beam dump by a permanent magnet dipole. The CCR emitted in the dielectric tube travels through the magnet assemblies and is eventually directed out of the vacuum box by an off-axis parabolic mirror. The electron bunch compression is achieved using an upstream magnetic chicane.

Table 1: Neptune beam parameters.

σ_z	200 μm
σ_r	50 μm
charge	500 pC
energy	13 MeV

This experiment will make extensive use of existing infrastructure at UCLA Neptune, as the quadrupole and

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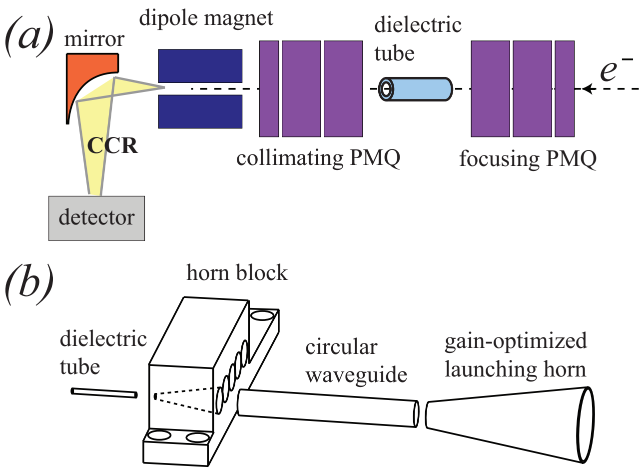

Figure 4: (a) Top-view schematic of experimental setup. (b) Layout of radiation transport.

dipole permanent magnet assemblies have been built and tested for a previous experiment [13]. All of the necessary detector and diagnostic apparatus are also readily accessible, as is the motion control and alignment equipment.

Measurement Goals

The quantities to be measured in this experiment are the total energy and the autocorrelation of the CCR pulse. The total pulse energy will be measured on a per-shot basis using a golay cell detector. A more sensitive measurement may also be taken using a liquid helium-cooled bolometer. A simple calculation of the energy lost by the driving bunch indicates that $\sim$50 μJ of Cerenkov radiation should be emitted as the bunch traverses the tube. Based on an estimation of the transition radiation energy emitted from the tube end, the CCR signal is expected to be 3 to 5 times greater than the incoherent background signal.

The autocorrelation will allow us to calculate the power spectrum and verify that the radiation is peaked in the THz range. It will be taken as a multi-shot measurement using a Michelson-type interferometer. The interferometer may be used with either the golay cell detector or the cyrogenic bolometer.

The dielectric material will be fused silica, chosen for its ubiquitous availability and ideal dielectric constant ($\varepsilon = 3.8$ for THz). We also plan to take measurements using CVD diamond tubing ($\varepsilon = 5.5$) [14].

Experimental Issues

A challenge in the experimental design is how to effectively transport the CCR from the dielectric tube to the diagnostics. Difficulty arises because the location of the tube holder assembly in the tight space between PMQ triplets does not allow a mirror to be placed directly at the exit of the tube. The somewhat rapidly diverging cone of THz radiation must be transported through the recollimating magnets and the dipole magnet before it can be directed out of the vacuum box by the parabolic mirror. The problem is addressed by placing sections of guiding conducting boundary along the beam path after the dielectric tube, as shown in Figure 4b. A launching horn is placed at the dielectric tube exit, as shown in Figure 1, which matches the radiation into a circular waveguide that runs inside the length of the recollimating PMQ. A second launching horn is located at the end of the circular waveguide, extending into the dipole magnet. The extent of the horn into the dipole is limited by the amount of clearance required for the electron beam to bend upward into the beam dump. The flare angle of the final horn is chosen to optimize the antenna gain, subject to this constraint.

SUMMARY

Simulation results indicate that single-mode operation of a DWA structure in the THz regime can be achieved with reasonable choices of dielectric structure geometry and driving electron beam parameters. We estimate that $\sim$50 μJ per pulse of CCR at THz wavelengths can be produced using the beam currently in operation at the UCLA Neptune laboratory. Preparations are underway to begin installing this experiment in the later part of 2007.

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