OBSERVATION OF NARROW-BAND TERAHERTZ COHERENT CHERENKOV RADIATION FROM A DIELECTRIC STRUCTURE*

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Abstract

We report experimental observation of narrow-bandwidth pulses of coherent Cherenkov radiation produced when a sub-picosecond electron bunch travels along the axis of a hollow cylindrical dielectric-loaded waveguide. For an appropriate choice of structure properties and driving beam parameters, the device operates in a single-mode regime, producing radiation in the THz range. We present measurements showing a narrow emission spectrum peaked at 367 ± 3 GHz from a 1 cm long fused silica capillary tube with sub-mm transverse dimensions, closely matching predictions. We demonstrate a 100 GHz shift in the emitted central frequency when the tube wall thickness is changed by 50 μm. Calibrated measurements of the radiated energy indicate up to 10 μJ per 60 ps pulse for an incident beam charge of 200 pC, corresponding to a peak power of approximately 150 kW.

INTRODUCTION

As a relativistic electron bunch travels along the vacuum channel in a cylindrical dielectric-lined waveguide (DLW), it drives coherent Cherenkov radiation (CCR) wakefields [1] that are confined to a discrete set of modes due to the presence of the conducting outer boundary [2]. The waveguide behaves as a slow-wave structure, supporting modes with phase velocity equal to the beam velocity that are thus capable of efficient energy exchange with the beam. With a sufficiently short (RMS bunch length σ_z less than a radiation wavelength λ) driving beam containing N electrons, the coherent radiation power at the relevant longer wavelengths is enhanced by a factor proportional to N over incoherent radiation [3]. This coherent excitation process offers a simple and effective energy conversion method, allowing creation of sources producing unprecedented peak power in the THz spectral region.

Investigation of DLW structures for the purpose of converting the energy in an electron beam into electromagnetic radiation [4, 5] has centered on particle acceleration (dielectric wakefield accelerators) [6, 7, 8] and microwave/THz/IR generation (Cherenkov masers/FELs) [9]. With regard to the latter, studies have achieved amplification of microwaves and THz radiation through both seeded and self-amplified free-electron maser processes driven by continuous and microbunched beams in cm-scale structures. This paper presents work based on a different excitation scenario, analogous to the superradiant FEL regime [10], in which a short beam drives a coherent wakefield without a gain process or instability. Our measurements demonstrate the generation of high-peak-power THz pulses in a small-scale DLW structure driven by a single sub-picosecond bunch of electrons. Appropriate choice of the structure's transverse geometry allows the short beam to radiate coherently into a very narrow bandwidth with a design-selectable central frequency.

The dispersion equation describing the eigenfrequencies of the structure, for the ideal case of azimuthally symmetric TM_{0n} modes, is given by [11, 12]

$$\frac{I_1(k_n a)}{I_0(k_n a)} = \frac{\varepsilon_r k_n}{\kappa_n} \frac{J_0(\kappa_n b)Y_1(\kappa_n a) - Y_0(\kappa_n b)J_1(\kappa_n a)}{Y_0(\kappa_n a)J_0(\kappa_n b) - Y_0(\kappa_n b)J_0(\kappa_n a)}, \quad (1)$$

where k_n and κ_n are the transverse wavenumbers in the vacuum and dielectric regions respectively, ε_r is the relative permittivity of the material, and $n = 1, 2, 3...$ indexes the solutions to the transcendental equation. $J_m(x)$ and $Y_m(x)$ are Bessel functions of the first and second kinds of order m, and $I_m(x)$ is the modified Bessel function of the first kind. For a given driving electron bunch length, the DLW tube dimensions (a, b) can be chosen such that only the fundamental TM_{01} mode wavelength is long enough to be coherently enhanced, thus selecting a single, dominant operating frequency.

The electromagnetic simulation code OOPIC PRO [13] was used to conduct a design study of the dielectric structures, taking as free parameters a, b, ε_r, and σ_z. Fig. 2a shows the simulated longitudinal electric field E_z at $r = 0$ plotted along the length of the structure for the ideal case of an azimuthally symmetric beam traveling on the axis, illustrating the excitation of additional modes as the outer radius increases to accommodate longer wavelengths; the scaling of these mode frequencies with b is shown in Fig. 2b.

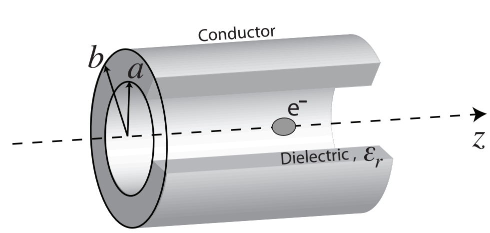

Figure 1: Cutaway diagram of a cylindrical dielectric-lined waveguide structure.

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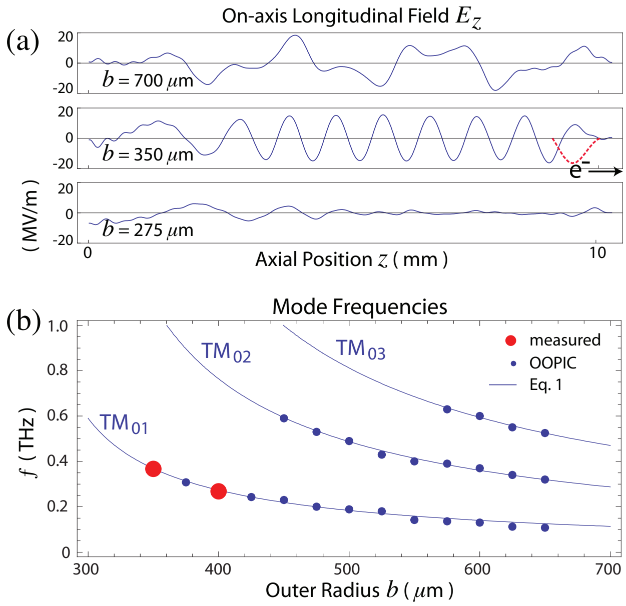

Figure 2: (a) OOPIC simulation of longitudinal wakefield E_z on tube axis vs. position along tube, for increasing b with fixed a and σ_z. (b) Scaling of mode frequencies with b, for constant a = 250 μm and σ_z = 200 μm.

MEASUREMENTS

The ideal tube design for this experiment is one that can support single-mode operation at a THz frequency and emits a maximum amount of energy, while maintaining compatibility with electron beam properties. The applicable beam parameters, belonging to the Neptune advanced accelerator laboratory at UCLA, are listed in Table 1. The minimum bunch length achievable by the Neptune chicane compressor system has been measured at $\sigma_z = 165 \pm 15$ μm (550 fs). This restriction informed the choice of radii (a, b) combinations of (250,350) μm and (250,400) μm, for which the TM_{01} mode has a wavelength long enough to be coherently excited by our beam according to Eq. 1. A tube length of 1 cm was chosen to maximize the radiated energy while still allowing passage of the electron bunch through the structure.

The dielectric tubes used in the measurements were obtained from 10 cm lengths of drawn fused silica ($\varepsilon_r = 3.8$) capillary, a material chosen for its universal availability. The tubing is first coated in an outer layer of gold ~ 1 μm thick with a ~ 50 Å chromium adhesion layer underneath, and then cleaved into 1 cm lengths. The Cr layer is necessary to prevent flaking of the Au coating during cleaving.

A schematic of the experiment is shown in Fig. 3. The incoming compressed electron beam is focused strongly into a dielectric tube by a triplet of permanent magnet quadrupoles. Downstream of the tube, the rapidly diverging beam and emitted CCR propagate collinearly to a 90-degree off-axis parabolic mirror (OAP), where the electron beam is dumped and the radiation is collimated out of the vacuum chamber into a radiation detection apparatus. Circular waveguide elements immediately following the tube serve to control the diverging THz beam and ultimately direct the radiation forward from a horn antenna toward the OAP mirror. The strongest source of background is coherent transition radiation (CTR) produced when the electron beam strikes the OAP and coherent diffraction radiation (CDR) emitted as it passes the end of the tube; the signal-to-noise ratio of CCR to CTR/CDR is established at roughly 9:1 by comparing the signal when the beam passes through a steel "dummy tube" to that from a dielectric tube.

Table 1: Experimental Parameters

bunch charge	Q	200 pC
bunch length	σ_z	165 μm
bunch radius	σ_r	80 μm
β-function		1 cm
beam energy		10 – 11 MeV
dielectric inner radius	a	250 μm
dielectric outer radius	b	350/400 μm
dielectric tube length	L	1 cm
dielectric constant	ε_r	3.8

Measurement of the CCR power spectrum was accomplished by autocorrelating the radiation pulse and applying discrete Fourier transform analysis to the data. An example of the raw autocorrelation data, taken using a standard Michelson interferometer in conjunction with a cryogenically cooled Si bolometer detector, is shown in Fig. 4a. The data is clearly oscillatory over a relatively long timescale, in stark contrast to the typical lone central peak characteristic of the broadband autocorrelation that would arise from the CTR/CDR background. Spectra from two dielectric structures of differing outer radii, shown in Fig. 4b, indicate narrow emission peaks close to the design frequencies of 368 and 273 GHz. The measured frequency results are summarized and compared with analytical and computational predictions in Table 2, with error estimates quoted as the standard deviation of central frequency values from several autocorrelation scans. The strong coupling of the

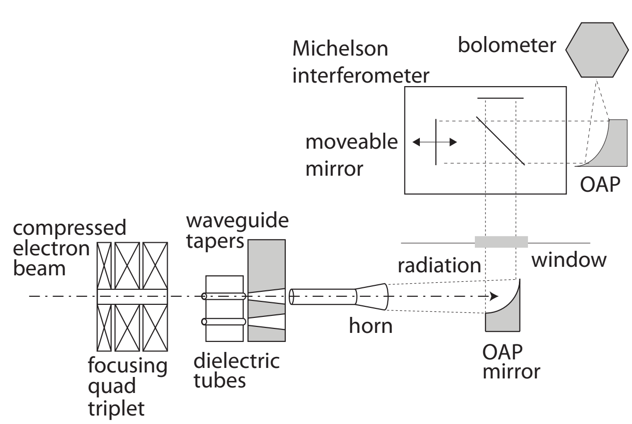

Figure 3: Schematic of experimental setup.

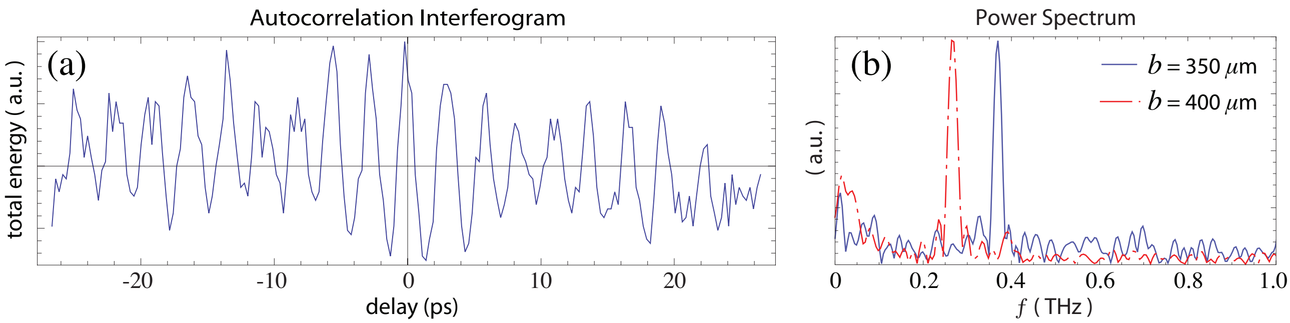

Figure 4: (a) Typical measured autocorrelation interferogram of radiation from b = 350 μm tube. (b) Measured power spectra, calculated by discrete Fourier transform, of radiation from b = 350 and 400 μm tubes.

Table 2: Comparison of measured TM_{01} mode frequencies with analytical and computational predictions for different tube sizes.

	$b = 400$ μm	$b = 350$ μm
measured	268 ± 2 GHz	367 ± 3 GHz
OOPIC	266 GHz	365 GHz
analytical	273 GHz	368 GHz

beam to the TM_{01} mode excitation through the large longitudinal electric field on-axis appears to dominate any contribution of higher-order modes. A shift of $\sim$ 100 GHz in the central frequency is observed between tubes, which matches well with predictions and demonstrates effective tunability. The 3 dB bandwidth of the central peak observed in each spectrum is $\sim$15 – 50 GHz, depending on the length of the autocorrelation scan. We infer that the measured bandwidth of the spectral peaks is limited by the observation time and is not an indication of an inherently broadened radiation process.

The total CCR energy emitted was measured by removing the interferometer device and focusing the radiation directly into a calibrated Golay cell detector. For an incident bunch charge of $\sim$200 pC, these measurements detect up to 10 μJ of energy per pulse after subtraction of background (compared to $\sim$15 μJ estimate). This corresponds to a peak power of $\sim$150 kW for a radiation pulse 60 ps long.

CONCLUSION

While the structures used in here are designed to operate at under 0.5 THz, availability of a shorter electron beam ($\sigma_z < 25$ μm) would enable use of tubes designed for frequencies well above 1 THz. For example, the SLAC LCLS beam ($Q = 0.5$ nC, 14 GeV) [14] in conjunction with an HDPE tube of dimensions (a, b) (50,80) μm would produce $\sim$50 MW of peak power at $f = 1.8$ THz.

This study represents a successful adaptation of the previously proven Cherenkov maser concept to the realm of ultra-short electron beams such as are available in state-of-the-art user facilities around the world. While the radiated energy and frequency achievable in our measurements were limited by available beam parameters, the results prove the potential of this method to produce tunable, narrow-band, multi-megawatt peak-power THz radiation in existing modern electron accelerators.

REFERENCES

[1] J. V. Jelley, *Cherenkov Radiation and Its Applications* (Pergamon Press, 1958).

[2] J. D. Jackson, *Classical Electrodynamics, 3rd Ed.* (Wiley, New York, USA, 1999).

[3] J. Nodvick and D. Saxon, Phys. Rev. **96**, 180 (1954).

[4] V. L. Ginsburg, Dokl. Akad. Nauk **56**, 253 (1947).

[5] C. T. M. Chang *et al.*, J. Appl. Phys. **41**, 4493 (1970).

[6] W. Gai *et al.*, Phys. Rev. Lett. **61**, 2756 (1988).

[7] J. G. Power *et al.*, Phys. Rev. ST Accel. Beams **3**, 101302 (2000).

[8] M. C. Thompson *et al.*, Phys. Rev. Lett. **100**, 214801 (2008).

[9] E. Garate *et al.*, Nucl. Inst. and Meth. A **259**, 125 (1987).

[10] A. Gover *et al.*, Phys. Rev. Lett. **72**, 1192 (1994).

[11] H. P. Freund and A. K. Ganguly, Nucl. Inst. and Meth. A **296**, 462 (1990).

[12] T.-B. Zhang *et al.*, Trans. Plasma Sci. **26**, 787 (1998).

[13] D. L. Bruhwiler *et al.*, Phys. Rev. ST Accel. Beams **4**, 101302 (2001).

[14] J. Arthur *et al.*, SLAC report R-0521 (1998).

[15] M. Naftaly and R. E. Miles, J. Appl. Phys. **102**, 043517 (2007).