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Measurements of terahertz radiation generated using a metallic, corrugated pipe[☆]

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ABSTRACT

A method for producing narrow-band THz radiation proposes passing an ultra-relativistic beam through a metallic pipe with small periodic corrugations. We present results of a measurement of such an arrangement at Brookhaven's Accelerator Test Facility (ATF). Our pipe was copper and was 5 cm long; the aperture was cylindrically symmetric, with a 1 mm (radius) bore and a corrugation depth (peak-to-peak) of 60 μm. In the experiment we measured both the effect on the beam of the structure wakefield and the spectral properties of the radiation excited by the beam. We began by injecting a relatively long beam compared to the wavelength of the radiation, but with short rise time, to excite the structure, and then used a downstream spectrometer to infer the radiation wavelength. This was followed by injecting a shorter bunch, and then using an interferometer (also downstream of the corrugated pipe) to measure the spectrum of the induced THz radiation. For the THz pulse we obtain and compare with calculations: the central frequency, the bandwidth, and the spectral power—compared to a diffraction radiation background signal.

1. Introduction

There is great interest in having a source of short, intense pulses of terahertz radiation. There are laser-based sources of such radiation, capable of generating few-cycle pulses with frequency over the range 0.5–6 THz and energy of up to 100 μJ [1]. And there are beam-based sources, utilizing short, relativistic electron bunches. One beam-based method impinges an electron bunch on a thin metallic foil and generates coherent transition radiation (CTR). Recent tests of this method at the Linac Coherent Light Source (LCLS) have obtained single-cycle pulses of radiation that is broad-band, centered on 10 THz, and contains >0.1 mJ of energy [2]. Another beam-based method generates narrow-band THz radiation by passing a bunch through a metallic pipe coated with a thin dielectric layer [3–5].

Another, similar method for producing narrow-band THz radiation has proposed passing the beam through a metallic pipe with small periodic corrugations [6]. According to calculations, an ultra-relativistic beam excites a dominant synchronous mode in a properly designed corrugated structure which, in turn, generates a THz pulse. This method is the subject of the present report. We consider here round geometry which will yield radially polarized THz (studies of this idea in flat geometry can also be found [7]). We present results of measurements of the spectral properties of the radiation excited by the beam.

A corrugated structure that we call "TPIPE" was tested with beam at the Accelerator Test Facility (ATF) at Brookhaven National Laboratory. We first used a relatively long beam, with short rise time—compared to the wavelength of the radiation—to excite the structure, and then used a downstream spectrometer to infer the central wavelength of the radiation. Then for a shorter bunch, by means of an interferometer also downstream of the corrugated pipe, we measured the spectrum of the induced THz. Due to a background of diffraction radiation of the bunch field, we could obtain the relative strength of the THz signal to this background. Our experimental set-up was simple and not optimized for the efficient collection of the radiation (by e.g. the inclusion of tapered horns between the structure and the collecting mirror of the interferometer, as was done in Refs. [4,5]). As such, the present experiment should be considered a proof-of-principle experiment for generating THz using a round, corrugated, metallic structure.

Specifically, our goal in this work is to demonstrate a narrow-band THz signal downstream of TPIPE using the two measurement methods.

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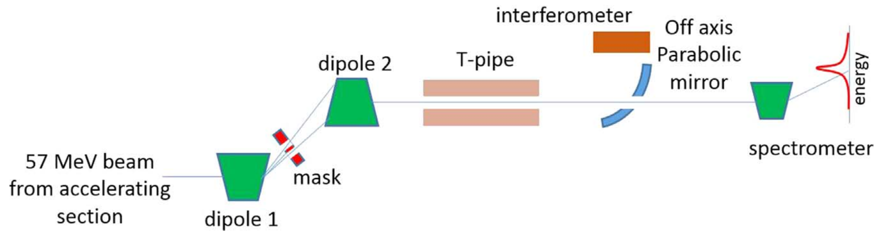

Fig. 1. Sketch of the experimental layout.

In addition, we measure, and compare with calculations, the central frequency of the pulse, the bandwidth, and the relative strength of the signal at the central frequency.

2. Experimental set-up

A schematic of the experimental layout is presented in Fig. 1. A 57 MeV electron beam was initially shaped using a mask [9] and then sent through TPIPE to generate a THz pulse. The beam leaves the structure directly followed by the THz pulse. At the exit of TPIPE the radiation pulse diffracts, and further downstream some of it is reflected by an off-axis parabolic mirror into a Michelson interferometer for characterization. The intensity of the THz signal collected is measured by an IRLabs General Purpose 4.2 K (liquid helium) Bolometer System. Note that the mirror is located 17.5 cm beyond TPIPE, and that in front of the mirror is a 12.5 mm radius iris, which limits the radiation that is collected. As for the electron beam, it passes through a 2.5 mm radius hole in the mirror, where it generates diffraction radiation, some of which also ends up in the interferometer. Finally, the electron bunch enters the spectrometer for characterization.

To shape the beam we started by accelerating it off-crest in the accelerating section, in order to create a linear correlation between the longitudinal bunch coordinates z and energy E. When the beam passes through a dipole magnet ("dipole 1" in Fig. 1) it becomes horizontally dispersed as in an energy spectrometer. A transverse mask is placed after the first dipole to block electrons of certain energies. A second dipole of opposing sign ("dipole 2") restores the beam to its original state, minus, however, the electrons that were blocked. Due to the E-z correlation of the beam, the image in the downstream spectrometer also carries information about the beam's longitudinal shape. Therefore, distances on the spectrometer image can be related to longitudinal distances within the beam.

3. Calculations

3.1. Central frequency of THz pulse

Consider a metallic beam pipe with a round bore and small, rectangular (in longitudinal view) corrugations (see Fig. 2). The parameters are period p, (full) depth of corrugation δ, corrugation gap g, and pipe radius a; where we consider small corrugations (δ, p) $\ll a$ and also $\delta \gtrsim p$. Let us here assume $p = 2$ g. It can be shown [6] that a short, relativistic bunch, on passing through such a structure, will induce a wakefield that is composed of one dominant, synchronous mode, of wave number $k \approx 2/\sqrt{a\delta}$, relative group velocity $v_g/c \approx 1 - 2\delta/a$, with c the speed of light, and loss factor $\kappa \approx Z_0 c/(2\pi a^2)$, with $Z_0 = 377\ \Omega$. In addition to the effect on the beam, a radiation pulse of the same frequency, with a uniform envelope (with a relatively sharp rise and fall) of full length $\ell = 2\delta L/a$ (L is pipe length) will follow the beam out the downstream end of the structure. One can see that, in order to generate a pulse of frequency ~1 THz, both the bore radius and the corrugation dimensions must be small; with $a \sim 1$ mm, then $\delta \lesssim 10\ \mu$m. For a=1 mm, $\delta = 60\ \mu$m, the pulse frequency $f \approx 0.4$ THz. If, in addition, the pipe length is L=5 cm, then the full radiation pulse length, $\ell = 6$ mm.

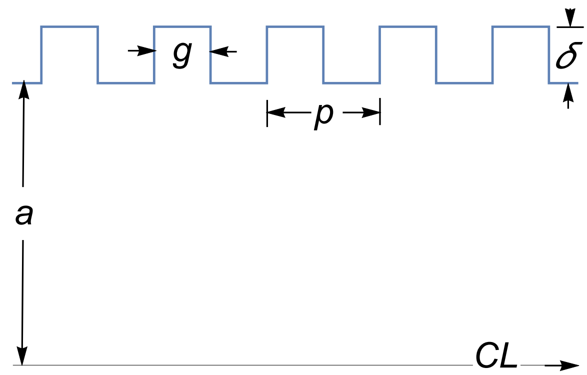

Fig. 2. Idealized geometry of the corrugated structure. The sketch shows five periods, given in cylindrical coordinates (r *vs.* z). The beam is meant to pass through on the axis, denoted by "centerline" (CL) in the plot. For efficient generation of THz radiation, one wants (δ, p)$\ll a$ and requires $\delta \gtrsim p$.

TPIPE was machined from two rectangular blocks of high purity copper, each of dimension 2 cm by 1 cm by 5 cm on a side. Two 1-mm (radius) cylindrical grooves were first machined in the long direction in each block. One groove in each block was meant to remain smooth, for the null test of the experiment. The other groove was further machined, to give it corrugations. Originally, the goal was to have rectangular corrugations (in longitudinal view) with period ~250 μm and (total) depth of corrugation ~60 μm. However, rectangular corrugations of such small size are difficult to make; thus, a rounded profile was obtained using a 50 μm (radius) milling bit. When the machined blocks were measured at SLAC, it was determined that the corrugations actually had a period of 231 μm and a depth of corrugation of 72 μm; furthermore, the radii of the "irises" and the "cavities" (in longitudinal view) were not identical, and were $r_1 = 91$ μm and $r_2 = 41$ μm, respectively (see Fig. 3, the blue curve). As the final step, the two copper blocks were diffusion bonded at SLAC to yield one block with two cylindrically symmetric bores, one corrugated and one smooth.

We performed time-domain simulations with the 2D Maxwell equation solving program ECHO [8]. We used a Gaussian bunch, with $\sigma_z = 90$ μm, and let it pass through an entire 5-cm-long TPIPE structure. For the model used in the ECHO simulations, we used circular arcs (brown curves in Fig. 3) of radius $r_1 = 91$ μm and angular extent $\theta = \pi/2$ (for the irises), and of radius $r_2 = 41$ μm and angular extent $\theta = 2\pi/3$ (for the cavities), and connected them by straight lines (in red). The final structure has period $p = 231$ μm and a depth of corrugation of 72 μm. We see that the model gives a good approximation to the measured shape of TPIPE (the blue curve).

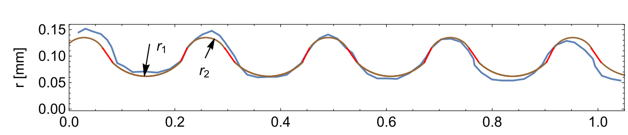

Fig. 3. A rough digitization of the measured geometry of TPIPE's corrugations (blue curve). The model used in ECHO simulations is also shown: arcs (brown curves) of radii $r_1 = 91$ μm and $r_2 = 41$ μm are connected by straight lines (in red), to give a structure with a period $p = 231$ μm and a depth of corrugation of 72 μm.