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NARROWBAND-FREQUENCY TERAHERTZ GENERATION FROM BEAM PIPE WITH HELIX WIRES

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Abstract

We studied through analysis and numerical simulations the use of a relativistic electron bunch to drive a metallic beam pipe with helix wire inside, for the purpose of generating narrowband-frequency terahertz radiation. We have shown that the frequency is related to the radius of the pipe and that of the wire, thus one can generate a narrow-band radiation pulse with frequency tunable through this scheme with different pipes and wires. The total energy of a few milli-Joules. The pulse length tends to be on the order of hundreds of picoseconds. We have also shown that, if the pipe radius is tapered along its length, the generated pulse will end up with a frequency chirp.

INTRODUCTION

The development of an accelerator-based Terahertz (THz) source could represent a real advancement for the scientific community [1], with important perspectives in different areas of fundamental research and applied physics, including applications in medical imaging, spectroscopy of solids and liquids, and chemical and security identification [2].

To generate THz radiation, the electron beam has to pass through a slow-wave structure, such as a corrugated metallic waveguide and a dielectric-loaded waveguide. The relativistic electron bunch generates radiation that follows the beam, which is also referred to as wakefield. The electron beam excites only modes with phase velocity equal to the velocity of beam, i.e., close to the speed of light c. With a sufficiently short (rms bunch length σ_z less than a radiation wavelength λ) driving beam, the radiation from the electron bunch is coherent [3].

In a recent experiment at FACET, a metallic beam pipe with round bore and small, rectangular corrugations is used to generate narrow-band radiation at 0.4 THz, with depth of corrugation $\delta = 60\mu$m and pipe radius $a = 1$mm the corrugated structure is 50 mm long, a 50 pC electron beam with $\sigma_z = 50\ \mu m$ has passed through the structure and transferred 1.2 uJ energy into the THz radiation [4]. Another example is a W-band flat metallic corrugated structure at around 0.1 THz driven by AWA bunch train, few millijoules of pulse energy with MW peak power was generated with 3 sub-bunches of 75 MeV, 500 μm long, 2 nC electron beam passing through a 12-cm long structure [5].

In this report, we design a simpler layout of a THz wakefield structure, which we call it as helix-wire pipe structure (HWP). This structure can be taken as a corrugated structure, with the wire diameter $2r$ is equivalent to the peak to peak depth of corrugation δ. Therefore, similar analytical estimates in corrugated structure can be applied for the HWP [6]. For the simulations, we employ electromagnetic design and analysis program CST, which computes the fields generated by an ultra-relativistic bunch in a structure in the time domain [7]. Simulations agree well with the theoretical analysis, which show that a 50-mm long HWP structure is able to generate mJ energy at THz freqeuncy when driven by 1nC electron beam, the gradient is in order of 100MV/m, and THz power is 10 MW The frequency from HWP is narrow-band frequency is tunable with wire diameter and pipe diameter We have also shown that, if the pipe radius is tapered along its length, the generated pulse will end up with a frequency chirp.

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BASIC DESIGN OF THE STRUCTURE

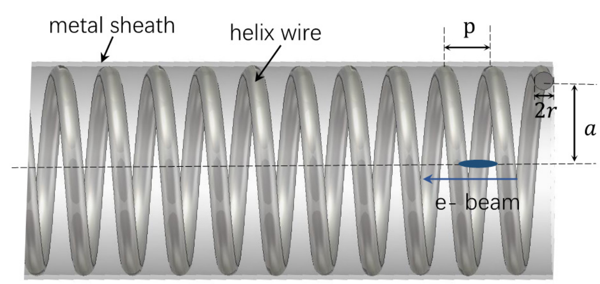

Figure 1: Basic design of the helix-wire pipe (HWP) structure, which is a helix wire inserted into a metal round pipe, the whole serves as a high impedance THz wakefield structure, parameters of the structure is listed in Table 1.

In our study, a metal round pipe with helix wire inside serves as the THz wakefield structure, the parameters are helix period p, wire diameter $2r$, pipe radius a and total length of the structure L_s, which are list in Table 1.

Table 1: Parameters of HWP Structure

parameter	DLW No.1
a	1.0 mm
r	0.1 mm
p	0.5 mm
L_s	50 mm

The wire diameter $2r$ in HWP is equivalent to the peak to peak depth of corrugation δ. Similar analytical estimates is applicable. Analytical formulas as following: the frequency $f = \frac{c}{\pi\sqrt{2ar}}$=0.2 [THz] only depends on the wire diameter and the pipe radius, while the group velocity v_g is also highly depend on the helix wire period parameter p,

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for structure in Table 1, $\beta_g = v_g/c = 0.54$, which predicted that the generated THz wakefield pulse duration $\tau_s = \frac{L_s}{v_g}(1-\beta_g)$=0.14 ns from the 5 cm long structure.

When excited by electron beam of 1nC Gaussian beam with rms bunch length 0.1 mm, the form factor of the beam $F(f) = e^{-(k^2\sigma_z^2/2)} = 0.9$, and the loss factor $\kappa = \frac{Z_0 c}{2\pi a^2} e^{-(k^2\sigma_z^2)} = 1.47 \times 10^{16}$ V/m/C. The THz wakefield gradient $E_s = 2\kappa q/1-\beta_g = 64$ MV/m and total power $U = q^2 \kappa L_{s/1-\beta_g} = 1.6$ mJ, THz power $P = U/\tau_s = 11.3$ MW, the theoretical wake function is:

$$w(s) = 2\kappa q L_s \left(1 - \frac{s}{\tau_s c}\right)(s < \tau_s c) \cdot \cos(ks) \quad (1)$$

Note that we have considered the group velocity enhancement effect, i.e., factor $1/(1-\beta_g)$, when calculate the wakefield gradient and the THz power, which comes from the compression of the travelling wave inside the structure [8].

SIMULATION RESULTS

THz Wakefield Generation

CST particle tracking studio is used to get the electric field and the spectrum from the Fast Fourier Transform (FFT) algorithm, results are shown in Fig. 2. A drive beam of 1 nC with 0.1mm rms. bunch length is used to go through the structure, and the monitor is posited at Z=52 mm.

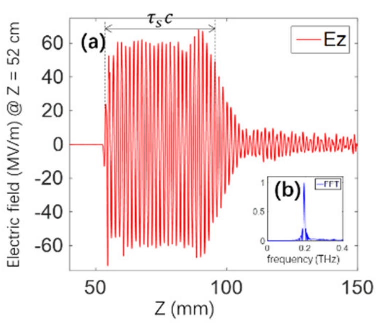

Figure 2: (a) Simulated THz electric field at monitor (position Z=52 mm); (b) FFT of the electric field.

As Fig. 1 (a) shows, the generated Terahertz is about 64 MV/m, and radiation pulse length is about 42.6 mm which equal to $\tau_s c$ as theory results. The FFT results in Fig. 1 (b) shows the frequency of the wakefield is 0.2 THz, which also agree with the formula above.

We also applied wakefield studio in CST to get the wake function and the wake impedance of the HWP driven by electron beam of 1 nC with 0.1 mm rms bunch length. Results are shown in Fig. 3, in Fig. 3 (a) we have also compared the simulation (red curve) with theoretical analysis of wake function envelope from equation (1) (blue curve), they agree well with each other. The wake impedance in Fig. 3 (b) is FFT of the wake function in Fig. 3 (a), which centred at 0.2 THz with a high quality, which also demonstrated the narrow band of the THz wakefield radiation.

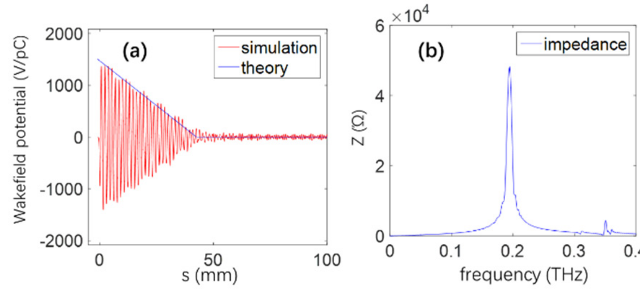

Figure 3: (a) Simulated wake function from CST (red curve) and the theoretical envelope of wake function (green curve); (b) simulated wake impedance from CST.

Frequency Tenability

As the theory predicted that the frequency of HWP structure follows formula of $f = c/\pi\sqrt{2ar}$. We do parameter scan to build different models and use CST to compute the centroid frequency, results are shown in Fig. 4.

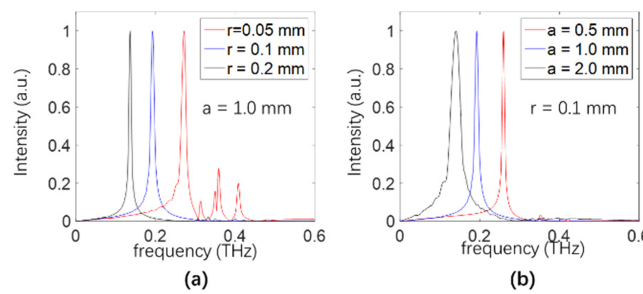

Figure 4: Simulated frequency with different parameters of the HWP structure. (a) different helix wire radius r with same pipe radius a=1 mm (b) different pipe radius a with same helix wire radius r=0.1mm.

Simulations demonstrate that the frequency is related to the root mean square of both pipe radius and helix wire radius. Thus, provided a new method to process THz wakefield structures with different frequency.

Figure 5 shows preliminary results on frequency spectrum of tapered HWPs with parameter a uniformly varies along the tubes, one is from 0.1 mm to 0.5 mm (red curve) and one is from 0.1mm to 0.2 mm (blue curve). The length of the structure is 50 mm. Results shown a relatively broad band frequency compared to the uniform pipe, which implies that the frequencies are chirped, and should be compressed this is followed by a properly designed dispersive device—analogous to what is done in chirped pulse amplification (CPA) in high power lasers—the pulse can then be compressed. This chirped THz generation based on taper HPW is simpler to process compared to that based on normal round corrugated structures, in which the depth of corrugation is varied along the pipe as designed in Ref. [6].

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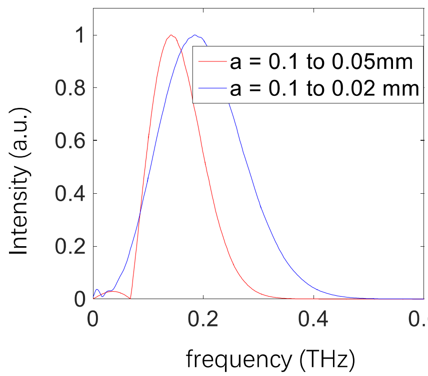

Figure 5: Preliminary results on frequency spectrum of HWPs with parameter a uniformly varies along the tubes, one is from 0.1 mm to 0.5 mm (red curve) and one is from 0.1mm to 0.2 mm (blue curve).

SUMMARY

We designed a HPW structure for THz wakefield/radiation generation, which is a metallic beam pipe with helix wire inside. Theoretical analysis and simulations show the frequency is related to the radius of the pipe and that of the wire, the frequency is narrow-band and tunable with structure parameters. The total energy is a few milli-Joules, and gradient is 100 MV/m when driven by 1nC electron beam. Primary results also shown that the HPW is suitable for chirped THz generation.

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