ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB077

HIGH POWER TERAHERTZ CHERENKOV FREE ELECTRON LASER FROM A WAVEGUIDE WITH A THIN DIELECTRIC LAYER BY A NEAR-RELATIVISTIC ELECTRON BEAM*

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Abstract

Corrugated and dielectric structures have been widely used for producing accelerator based terahertz radiation source. Recently, the novel schemes of the sub-terahertz free electron laser (FEL) from a metallic waveguide with corrugated walls and a normal dielectric loaded waveguide driven by a near-relativistic (beam energy of a few MeV) picosecond electron beam were studied respectively. Such a beam is used for driving resonant modes in the waveguide, and if the pipe is long enough, the interaction of these modes with the co-propagating electron beam will result in micro-bunching and the coherent enhancement of the wakefield radiation. It offers a promising candidate for compact accelerator-based high power terahertz source which can be realized with relatively low energy and low peak-current electron beams. However the choices of the waveguide above is less effective in order to obtain high power with frequency around 1THz. In this paper, we propose to use the waveguide with a thin dielectric layer instead, and high power radiation (> 10 MW) around 1 THz is expected to obtain in the proposed structure according to the simulation results.

INTRODUCTION

Accelerator-based THz radiation sources are attractive for their remarkable advantage of high radiation power [1]. However, these facilities are large, expensive, and not readily available on a customized base for a broader community of researchers and industrial users. For achieving compact accelerator-based sources, lots of efforts have been made, and a promising way is to make use of the low energy beam and the radiators which have high shunt impedance and coupling efficiency [2].

When relativistic electron beams pass through the metallic pipes (or plates) with corrugations or dielectric structures, electromagnetic waves (wakefields) that propagate with the beams are excited. The waveguide eigen modes can be coherently excited by a beam whose length is a fraction of the wavelength or an appropriate spaced electron bunch train [3]. Yet it is not easy to generate ultra relativistic electron bunches or bunch trains with high peak current (high bunch charge and short bunch length) at low beam energy since the longitudinal space-charge effects might contribute to smearing out any structure in the temporal beam profile [4]. To give another option of excitation of the resonant mode, a novel scheme of sub-THz free electron laser (FEL) from a metallic pipe with corrugated walls driven by a near-relativistic (<10 MeV) picosecond electron beam was proposed and analyzed by using the Vlasov–Maxwell equations [5]. Such a beam is used for driving resonant modes in the pipe, and if the pipe is long enough, the interaction of these modes with the co-propagating electron beam results in micro-bunching and the coherent enhancement of the wakefield radiation. Furthermore, a one-dimensional (1D) numerical model which can fast track the total FEL process was developed in specialty and another sub-THz example which uses a normal dielectric loaded waveguide (DLW) was present [6].

In this paper, we propose to use the waveguide with a thin dielectric layer instead in order to promote the scheme up to obtain higher frequency. Comparing with the previous waveguide structures, the unique structure has the advantages of high group velocity to shorten the pulse length for improving the pulse power and high frequency while maintaining the efficient coupling .

THEORY

An electron beam entering a cylindrical waveguide with a thin dielectric layer ($d \ll a$) at the longitudinal coordinate $z = 0$ and moving along the pipe axis, the wakefields will be generated along with the beam and move at the group velocity v_g, as shown in Fig. 1.

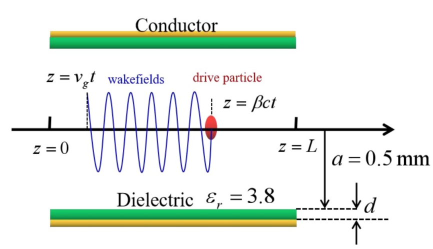

Figure 1: Definition of the geometry.

For a single particle, the longitudinal wakefield inside the vacuum chamber can be mathematically expressed by the following equation

$$E_z(r,z,s) = 2\kappa q I_0\left(\frac{kr}{\beta\gamma}\right)\cos\left(\frac{k}{\beta}(s-z)\right)e^{-\alpha_c(s-z)},$$
$$\text{when } s\left(1-\frac{v_g}{\beta c}\right) < z < s, \quad (1)$$

* Work supported by National Natural Science Foundation of China (11705198,11775216,11805200), Fundamental Research Funds for the Central Universities (No. WK2310000082 and No. WK2310000090)

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ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB077

where z is the observation position, s and q are are respectively the drive particle position and charge, $I_0(x)$ is the modified Bessel function of the first kind, γ is the Lorentz factor, κ and k are the loss factor per unit length and wave number associated to the mode supported by the structure respectively, α_c is defined by $\alpha_c = \alpha_0 v_g/(\beta c - v_g)$ and α_0 is the field attenuation per unit waveguide length. The mode parameters can be obtained by following the methodology as described in [7] or determined with help of wakefield codes [8].

As an example of a structure with $a = 0.5$ mm, $d = 20$ um or 10 um, and the relative permittivity $\epsilon_r = 3.8$ (the dielectric material: fused silica) , the mode parameters in Eq. (1) as the function of the electron energy are shown in Fig. 2. Comparing with the normal dielectric loaded waveguide, the waveguide with a thin dielectric layer has a higher frequency up to around 1 THz while maintaining the efficient coupling factor and besides a high group velocity which can shorten the pulse length to improve the pulse power. In the following section, we will show that these characters will contribute to a much better FEL performance.

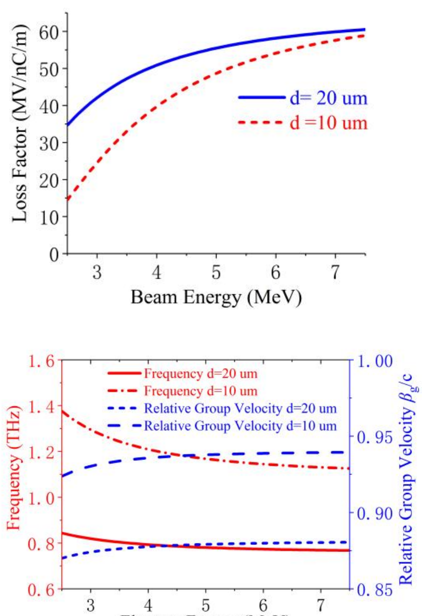

Figure 2: Loss factor, frequency and the group velocity as a function of the electron energy.

When it comes to a long electron beam at several MeV and a long dielectric pipe, the interaction of the wakefield with the co-propagating electron beam will result in beam energy modulation, micro-bunching and the coherent enhancement of the wakefield radiation. The analytical approach in [5] can provide the crude estimates of the expected parameters of such FEL process. The Pierce parameter, gain length and saturation power are given respectively by

$$\begin{cases} \rho = \frac{1}{2}\left(\frac{2\kappa I}{k_w \gamma k I_A}\right)^{1/3} \\ P_{sat} \approx \rho \gamma m c^2 \frac{I}{e} \end{cases}, \quad (2)$$

where I is the beam current and the new variable k_w (an analog of the FEL undulator wave number) is defined by the equation $k_w/k = (\beta c - v_g)/\beta c$.

SIMULATION RESULTS

To study the radiation, the one-dimensional (1D) numerical model developed in [6] is used, whose validity for simulating this kind type of FEL process has been confirmed by the particle in cell (PIC) simulations.

For simplicity and direct comparison with the example using the normal dielectric loaded waveguide [6], we also assume that an electron beam has an uniform temporal distribution with time length 10 ps and beam current of 100 A; the beam energy is chosen at 5.4 MeV. Such an electron beam can be generated directly by the photocathode rf gun. The parameters of the waveguide structure are the same as the example in the above section and its mode parameters are plotted in Fig. 2. Assume that the loss tangent of the dielectric is 3×10^{-3} and the conductor is made of copper whose conductivity is 5.81×10^7 S/m. The corresponding attenuation coefficients are $\alpha_c = 21.44$ m^{-1} and $\alpha_c = 41.24$ m^{-1} for $d = 20$ um and $d = 10$ um respectively.

When the beam head reaches at 200 mm, the phase space distribution is shown in Fig. 3. To characterize the temporal structure and micro-bunching of the electron beam, the bunch form factor $B(k) = < \exp(jk_z s) >$ evolution as with the beam head position is shown in Fig. 3. In order to study the effect of the group velocity on the bunch form evolution, the simulation results in which the group velocity is set to be negative infinity are also presented. This setting is approximately correct for particle tracking if the the beam density changes slightly during the newly generated wakefield sweeping over the total beam. As seen from Fig. 4, a high group velocity will lengthen the saturation distance because it will take a long time for the wakefield generated by the front electrons to enhance the micro-bunching of the behind ones, but the micro-bunching process inside the whole beam is more consistent, thus it will achieve a greater maximum bunch factor finally.

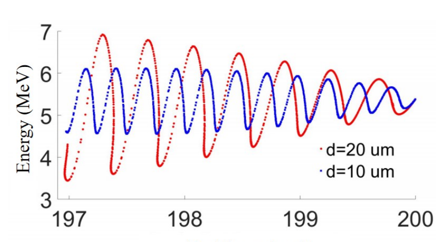

Figure 3: Beam phase space distribution at $t = 0.2$ m/c.

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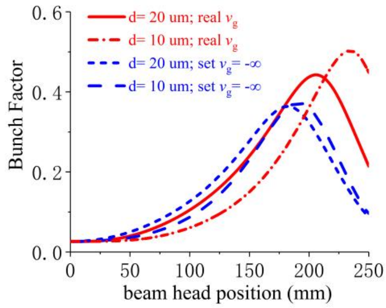

Figure 4: Bunch form factor evolution as with the advancement of the beam.

The instantaneous pulse power generated by the beam can be written approximately as [9]

$$P = \frac{Q^2 B^2 \kappa}{1/v_g - 1/\beta c}, \tag{3}$$

where Q is the total beam charge and the denominator in Eq. (3) represents the growth of the pulse time length with the advancement distance of the beam. Thus a high group velocity which can shorten the pulse length will contribute to greatly improve the pulse power.

Figure 5 shows the maximum power flow and the total energy flow versus the longitudinal position. The maximum power is 16.6 MW at 0.77 THz for d = 20 um and 27.9 MW at 1.16 THz for d = 10 um. By using the Eq. (2), it estimates the saturation power of 9.5 MW and 8.9 MW for d = 20 um and d = 10 um respectively. Figure 6 shows the power flow vs time at at the cross sections where the maximum power and pulse energy are achieved respectively.

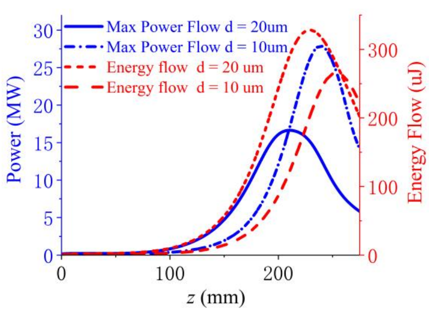

Figure 5: Maximum power flow and total energy flow versus the longitudinal position.

Recently, a new type of dielectric loaded waveguide structure named separated dielectric loaded waveguide (SDLW) [9] is proposed which can greatly increase the group velocity while slightly the other mode parameters comparing to the ordinary DLW. For generating the sub-THz radiation, if we use the separated DLW to replace the ordinary DLW in [6] with the other conditions remaining the same, the maximum pulse power can also reach tens of MW, while it is about 6 MW using the ordinary DLW.

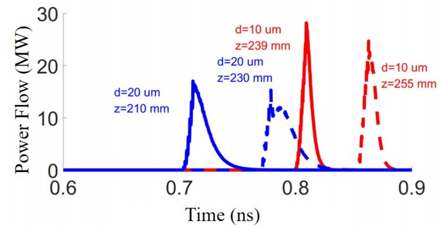

Figure 6: Power flow vs time at at the cross sections where the maximum power and pulse energy are achieved respectively.

CONCLUSION

In summary, we studied terahertz Cherenkov free electron laser from a waveguide with a thin dielectric layer by a near-relativistic electron beam. According to the analytical and simulated results, it showed that the usage of the unique waveguide structure could promote the scheme up to obtain high radiation power (> 10 MW) and frequency around 1 THz.

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