ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-TUPME036

SIMULATION STUDY ON ELECTRON BEAM ACCELERATION USING COHERENT CHERENKOV RADIATION

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Abstract

Beam diagnostics for electron bunch length using spectrum analysis of multimode terahertz (THz) -wave have been studied in ISIR, Osaka University. The multimode THz-wave was generated by coherent Cherenkov radiation (CCR) using hollow dielectric tubes and femtosecond/picosecond electron bunches. In this study, numerical calculation of acceleration and deceleration of electron beam using multimode THz-wave was carried out.

INTRODUCTION

Picosecond and femtosecond electron bunches are applied to the development of high-quality and intense light sources for applications in accelerator physics such as free electron lasers [1,2] and laser-Compton X-rays [3,4]. Such electron bunches can be also applied to time-resolved experiments involving the application of techniques such as ultrafast electron diffraction [5] and pulse radiolysis [6,7,8,9] with femtosecond or picosecond time resolutions. Short electron bunches are useful for electro-magnetic radiation production in terahertz (THz) range because of the inverse of 1 ps corresponding to the frequency of 1 THz. Schemes of THz generation using electron beams are investigated in coherent transition radiation (CTR) [10,11,12,13], Smith-Purcell radiation [14], and coherent Cherenkov radiation (CCR) [15,16] for several applications, e.g., beam diagnoses, probe sources, and beam acceleration. CCR utilizes a hollow dielectric tube and electron beam, and generates monochromatic or multimode THz waves. Recently, THz generation based on a modulation of electron beam are investigated to obtain narrowband THz pulses [17,18]. In the application of THz waves to beam acceleration, demonstration of a planar structure for accelerating structure was reported [19]. If beam acceleration based on THz waves using a kind of structure is realized, efficient beam acceleration would be developed by effective usage of THz waves emitted by electron beams. Conversely, if beam deceleration is possible, schemes of compact THz source would be developed based on an amplification of THz waves as shown in free-electron lasers. In the both acceleration and deceleration, the conservation of energy balances the energy of electron beam and THz waves.

In this study, simulation study on electron beam acceleration based on CCR using hollow dielectric tubes and femtosecond/picosecond electron beams was conducted. Numerical calculation of acceleration and deceleration of the beam was carried out to understand the effect of THz waves on the electron beam.

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SIMULATION AND ANALYSIS

Figure 1 shows the geometry in the simulation and field map of longitudinal electric field. In this scheme, two electron beams travelled through a hollow dielectric tube. The front electron beam is used for the generation of multimode THz waves based on CCR. Acceleration and deceleration of the back electron beam was calculated. CCR is one of techniques for the generation of multimode THz waves, i.e., discrete spectral components. A short electron beam moving through a metal-wrapped hollow dielectric tube induces multimode THz waves as shown in Fig. 1. This slow-wave structure of a hollow dielectric tube supports fundamental and higher modes with phase velocity equal to the beam velocity, which is approximately equal to the light speed in this study. Numerical simulation was conducted using OOPIC code (Tech-X) which calculates THz waves induced by the front electron beam travelling through a tube and effect of electric field on the back electron beam.

In the simulation, bunch charge of each electron beam was fixed to 100 pC/pulse. The tube wall thickness was fixed to 0.5 mm. Delay time of the back electron beam with respect to the head electron beam t_d, was adjusted at <25 ps. The beam energy and radius were 30 MeV and 0.25 mm in root mean square (rms), respectively. The back electron beam travelled through a path of 50 mm, which is a length of acceleration or deceleration. In the simulation, difference in energy between the front and back electron beams was calculated. The dependence of acceleration on the inner radius a and bunch length was investigated by changing the delay time which corresponded to the accelerating phase in the multimode THz wave.

In the analysis of simulation results, frequency components induced by the front electron beam was taken into account because acceleration depends on the both frequency components and phase of THz wave. Theoretical frequency of CCR depends on the hollow dielectric tube conditions and agrees well to the experimental frequency. Assuming azimuthally symmetric transverse magnetic (TM) mode along the tube axis is

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induced, the frequency of TM_{0n} mode can be expressed as [15,16, 20]

$$\frac{s}{k\varepsilon}\frac{I_1(ka)}{I_0(ka)}=\frac{\psi_0}{\psi_1}, \tag{1}$$

where I denotes the modified Bessel function of the first kind; k and s, the radial wave numbers in the vacuum and dielectric regions; ε, the permittivity of the dielectric region; a and b, the inner and outer radii of the tube; Ψ_0 and Ψ_1 [20], functions composed of the Bessel functions and the tube radii. The theoretical discrete frequencies of TM_{0n} modes were calculated numerically for the fused silica tube with the relative permittivity (ε) of 3.8. At this point, energy gain E_g is defined as follows:

$$E_g = E_b - E_f, \tag{2}$$

where E_b and E_f denote the energy of back and front electron beam, respectively. Acceleration and deceleration can be expressed by the theoretical frequencies of n-th mode ω_n and the delay time of the back electron beam t_d as follows:

$$E(t_d)=\sum_n a_n \cos(\omega_n t_d), \tag{3}$$

where E and a_n denote the fitting function and fitting parameter for n-th mode. This equation expresses superposition of multimode THz waves. If higher frequency components become larger for the energy gain as a function of the delay time, distortions are shown according to Eq. (3).

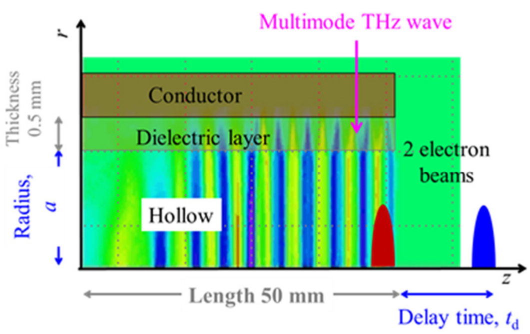

Figure 1: Geometry in the calculation. A field map of longitudinal electric field induced by the front electron beam is shown.

SIMULATION RESULTS

Effect of Bunch Length and Inner Radius

Figure 2 shows the energy gain as a function of the delay time. Effect of bunch length on the energy gain is shown in Fig. 2(a). The simulation was conducted at bunch length of the both electron beams of 1000, 500, and 200 fs. In this case, inner and outer radii of the tube were fixed to 1 and 1.5 mm, respectively, i.e., tube wall thickness of 0.5 mm. Offset of each data set was adjusted for comparison. Oscillations in energy gain were observed in each case due to the delay time. Shorter electron beam can induce higher modes according to bunch form factor [11] and previous experimental studies [15,16]. The energy gain was fitted using Eq. (3) and agreed to the fitting curves. Components of higher mode a_n increased due to short beam, and distortion of energy gain as a function of the delay time was observed. The energy gain was maximized by short beam due to superposition of multimode waves. Effect of inner radius on the energy gain is shown in Fig. 2(b). The tube radii also affected on the energy gain. In this case, bunch length was fixed to 200 fs. The tube wall thickness was fixed to 0.5 mm. Small tube radius increased energy gain due to increase in accelerating field in the tube. Increase in energy gain in experiments would require a usage of thin tubes although acceptance of electron beam depends on inner radius.

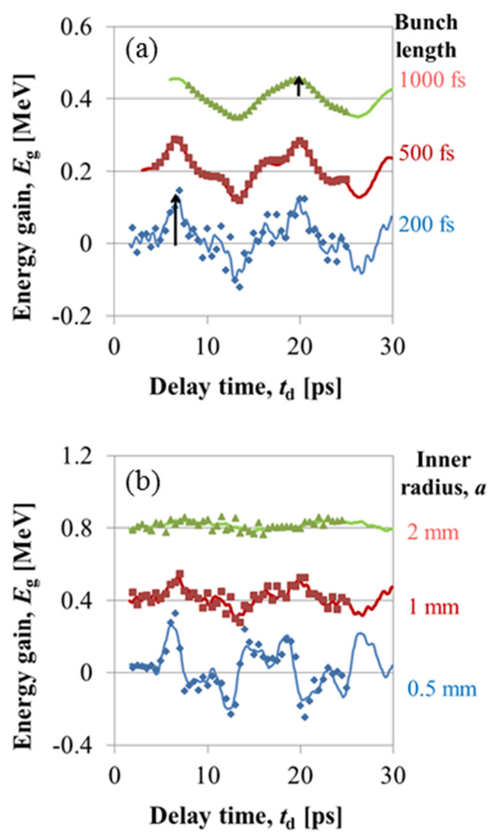

Figure 2: (a) Energy gain as a function of delay time for 1000, 500, and 200 fs bunch lengths with only the offsets adjusted for comparison. (b) Energy gain as a function of delay time for 2, 1, and 0.5 mm inner radii. The tube wall thickness was a constant of 0.5 mm. Lines denote the fitting results using Eq. (3) in each figure.

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Distribution of Electron Beams

Figure 3 shows the distribution of electron beams in the case of maximum energy gain in these parameters. Electron bunch length of 200 fs and inner radius of 0.5 mm were used. Energy gain, i.e., difference between the back and front electron beams, was obtained as 0.3 MeV at a path of 50 mm corresponding to ~6 MeV/m. However, the initial condition of energy was 30 MeV, and effective acceleration was 0.1 MeV as shown in Fig. 3. According to the simulation, shorter electron bunch had more effects of deceleration on itself due to electric field emitted by itsself. Optimization of the ratio of charges would be required for effective acceleration of electron beams using multimode THz waves. In the future, generation of 2 electron beams [8] based on photocathode-based linac will be used for the investigation of beam acceleration.

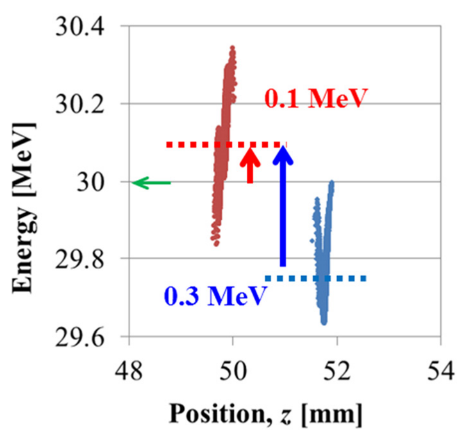

Figure 3: Distribution of electron beams in the case of maximum energy gain. Electron bunch length of 200 fs and inner radius of 0.5 mm were used.

CONCLUSIONS

Simulation study on electron beam acceleration based on CCR using hollow dielectric tubes and femtosecond/picosecond electron beams was conducted. Energy gain of the back electron beam depended on the bunch length and inner radius of the tube. The maximum energy gain was obtained as 0.3 MeV at a path of 50 mm corresponding to ~6 MeV/m. Effective acceleration would be also optimized by the ratio of beam charges. In the future, generation of 2 electron beams and beam acceleration using THz waves will be investigated.

ACKNOWLEDGMENT

We thank the staff of the research laboratory for quantum beam science at the Institute of Scientific and Industrial Research, Osaka University, for the experimental setup. This work was supported by KAKENHI (21226022, 23109507, and 25870404), research (Generation of high-power THz wave) funded by AIST, and a Grant for Basic Science Research Projects was received from The Sumitomo Foundation.

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