Beam diagnostic based on coherent Cherenkov radiation using dielectric tube

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Abstract

Beam diagnostic for electron bunch length using spectrum analysis of multimode terahertz (THz) -wave on the order of 0.1 THz was investigated. The multimode THz-wave was generated by coherent Cherenkov radiation (CCR) using hollow dielectric tubes and femtosecond/picosecond electron bunches. The spectra of multimode THz-wave depended on electron bunch length, which was measured by a streak camera, resulting in a possibility of a new beam diagnostic based on CCR and a bunch form factor.

誘電体管コヒーレントチェレンコフ放射によるビーム診断の研究

1. Introduction

Ultrashort, e. g. femtosecond [1] or picosecond, electron bunches are used in accelerator physics applications such as free electron lasers (FELs), laser-Compton X-ray, and pulse radiolysis [2]. On the other hand, electron bunches with short bunch lengths are also useful for electro-magnetic (EM) radiation production in terahertz (THz) range because the inverse of 1 ps bunch length corresponding to the frequency of 1 THz. A shorter electron bunch can emit EM radiation of higher frequency according to the bunch form factor, which is described by the Fourier coefficients of the bunch distribution [3]. Furthermore, the radiation intensity at lower frequency than the inverse of the bunch length is proportional to the electron number, e. g. $\approx 10^9$ at 1 nC. As the result, an intense THz-wave can be generated by such electron bunches. In the studies on EM radiation emitted from electrons, Cherenkov radiation (CR) has been studied since the 1930s [4] and radiation yield dependence on wavelength and angular distribution was reported. In the 1990s, the bunch form factor [3] and angular distribution of coherent transient radiation (CTR) from electron bunches were measured experimentally. Recently, not only monochromatic THz-wave [5] but also multimode one [6,7] of <0.4 THz were generated by coherent Cherenkov radiation (CCR). Another THz-wave generation method, which utilized a periodic electron bunch distribution, generated narrow-band THz-wave up to ≈0.86 THz for a bunch length diagnostic [8]. Alike THz-wave generated by a laser, that generated by an accelerator would be useful to a probe light, which monitors conductivity due to quasi-free electrons, or imaging for medical and security use.

In this paper, generation of multimode THz-wave using multimode CCR on the order of 0.1 THz was investigated. The multimode CCR was generated by a hollow dielectric tube covered by a metal and femtosecond/picosecond electron bunches from a photocathode RF gun linac. Finally, beam diagnostic for electron bunch length using spectrum analysis of multimode THz-wave was proposed.

2. Experimental arrangement

The photocathode RF gun linac and SPR measurement system are shown in Fig. 1. The details of the linac are discussed in references [9,10,11]. Figure 1(a) shows the linac system. The electron bunch was generated by a 1.6-cell S-band (2856 MHz) RF gun with a copper cathode and a Nd:YLF picosecond laser. The pulse width of the UV pulse from the laser was measured to be 5 ps in FWHM as a Gaussian distribution. The UV light was projected onto the cathode surface at an incident angle of approximately 2° along the electron beam direction. The beam energy at the gun exit was 4.2 MeV. The picosecond electron bunch produced by the RF gun was accelerated up to ~32 MeV by a 2 m long S-band travelling-wave linac with an optimal energy-phase correlation for the bunch compression, in which the head electrons of the bunch have more energy than the bunch tail. Finally, the energy-phase-correlated electron bunch is compressed into femtosecond by rotating the phase space distribution in the magnetic bunch compressor, which is constructed with two 45°-bending magnets (B1 and B2), four quadrupole magnets (Q3, Q4, Q5, and Q6), and two sextupole magnets (S1 and S2). The femtosecond electron bunch was obtained by adjusting the energy modulation in the linac, e. g., compressed bunch length of ~0.2 ps in rms measured by a streak camera at a bunch charge of ~40 pC and a linac phase of 97.5°.

In the experiment, not only the picosecond electron bunch at the linac exit but also the femtosecond one at the compressor exit was used for multimode THz-wave generated by CCR as shown in Fig 1(b). When such electron bunches move on the axis of a hollow dielectric

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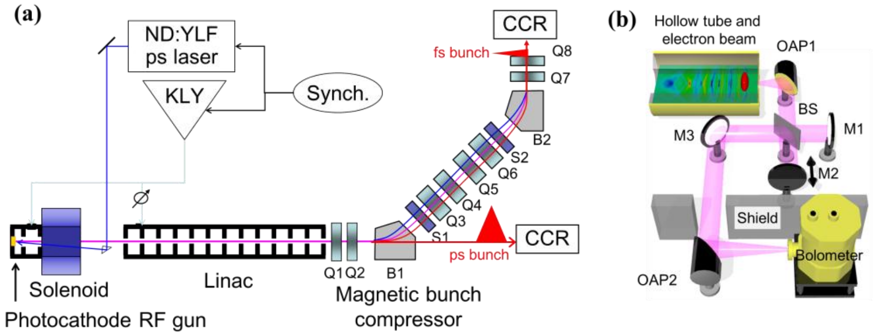

Figure 1: (a) Photocathode RF gun linac with a magnetic bunch compressor of an achromatic arc. (b) Diagram of multimode CCR and measurement system. OAP denotes an off-axis parabolic mirror; M, a plane mirror; BS, a beam splitter.

tube covered by a metal, partially periodic electric field, i.e., multimode THz-wave, is induced as shown in Fig. 1(b). This slow-wave structure of the hollow dielectric tube supports modes with phase velocity equal to the beam velocity, which contain fundamental and higher modes. The inner and outer radii of the tube, made of fused silica, were 5 mm and 7 mm, respectively, resulting in the tube wall thickness of 2 mm. The hollow tube was covered by a copper conductive tape for a metal boundary condition, which reflects and stores EM radiation in the tube. In order to measure the intensity and frequency of CCR, a Michelson interferometer was set downstream of the tube in the air. The distance between the tube exit and an off-axis parabolic mirror (OAP1) was fixed to the effective focal length of the mirror from a viewpoint of collimating. The THz-wave was separated by a beam splitter (BS) and one of the THz light was reflected by a moving mirror (M2). The two THz light joined together at a 4.2K silicon bolometer (Infrared Laboratories Inc.). The intensity and frequency of CCR were analyzed by the fast Fourier transform (FFT) of an interferogram, which is a dependence of the bolometer output on the moving mirror (M2) position.

3. Results and discussion

3.1 Analytical frequency of TM mode

The frequency of multimode CCR depends on the hollow dielectric tube conditions. Assuming azimuthally symmetric Transverse Magnetic (TM) mode along the tube axis is induced, frequency of TM_{0n} mode can be expressed as [5,7,12]

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

where k and s denote the radial wave numbers in the vacuum and dielectric regions; a, the inner radius of the tube; Ψ_0 and Ψ_1 [12], functions composed of the inner and outer radii and Bessel functions of the first and second kinds. If Eq. (1) is satisfied, phase velocity is equal to the beam velocity. The theoretical frequencies of TM_{0n} modes were calculated for the tube with the relative permittivity of 3.8 and the inner and outer radii of 5 mm and 7mm.

3.2 Dependence on tube length

In the multimode CCR experiment, the dependence of the intensity on the tube length was investigated as shown in Fig 2. In this experiment, the picosecond electron bunch at the linac exit was used. An interferogram with 128 data points and 1ps time step was measured for the FFT calculation. Figure 2(a) shows the interferograms for three different tube lengths. The periodic oscillation from a 150 mm long tube decayed more slowly than that from a 50 mm long tube because the tube length decided the energy of CCR stored in the tube. Figure 2(b) shows the frequency spectra for three different tube lengths. Analytical frequency of TM_{0n} mode was also shown as crosses. All the spectra indicated sharp peaks at frequencies of 0.09 and 0.14 THz, which corresponded to TM_{03} and TM_{04} modes, respectively. The absence of the lower modes, e. g. TM_{01} or TM_{02}, would be caused by the frequency characteristics of the bolometer and the beam splitter, the mirror diameters, and the loss in the fused silica. The intensity increased nonlinearly at a tube length of >100 mm. Saturation was observed at a tube length of ~150 mm. The saturation would be caused by the balance between the EM radiation production due to beam energy loss and the dielectric loss in the fused silica.

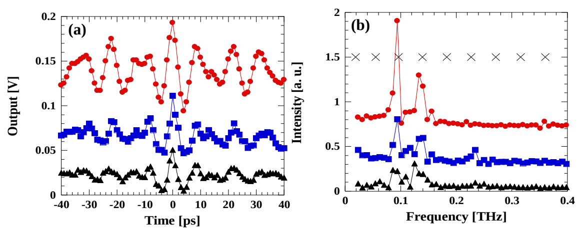

Figure 2: (a) Interferograms for 150, 100 and 50 mm tube lengths with offsets and factors adjusted for comparison. (b) Frequency spectra for 150, 100 and 50 mm tube lengths with offsets and factors adjusted. The theoretical frequencies for TM_{0n} modes (cross) according to Eq. (1) were shown.

3.2 Dependence on bunch length

The spectra of multimode THz-wave depends on electron bunch length from a view point of a bunch form factor [3], which indicates that shorter electron bunch can emit THz-wave of higher frequency. The tube length was fixed to 150 mm because of intensity as mentioned in Sec. 3.2. Furthermore condition of bunch compression was varied by the linac phase, which changed energy-phase correlation of electron bunch. Bunch charge was fixed to 45 pC to avoid saturation of bolometer output. When bunch charge was decreased by the linac phase, the bolometer output was increased, e.g., intensity factor of ~8 at bunch lengths of 1.3 ps and 0.21 ps. In order to investigate dependence of spectra of THz-wave on bunch length, electron bunch length was also measured by a femtosecond streak camera. Streak camera detected Cherenkov light in air by imaging using 2 lenses of focal length of 300 mm and a band pass filter of 480 ±5 nm. Figure 4 shows the dependence of spectra on bunch length. Short bunch length induced higher order of CCR, e.g., TM_{09} (0.36 THz) and TM_{017} (0.72 THz) modes at a bunch length of 0.21 ps. On the other hand, intensity ratio of lower modes, e.g., TM_{03} and TM_{04}, would be changed by a spectrum of incoherent radiation [3] at a bunch length of 0.21 ps. According to spectra of CCR and bunch length measurement using a streak camera, a new bunch length measurement using spectrum analysis of CCR would indicate a possibility of a new beam diagnostic based on a bunch form factor.

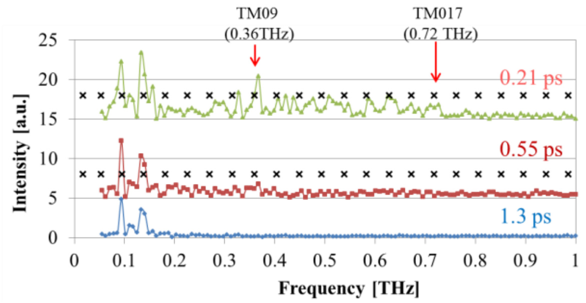

Figure 3: Frequency spectra for 0.21, 0.55, and 1.3 ps bunch lengths. Factors and offsets were adjusted for comparison. The theoretical frequencies for TM_{0n} modes (cross) according to Eq. (1) were shown.

4. Conclusions

Beam diagnostic for electron bunch length using spectrum analysis of multimode THz-wave based on CCR was investigated. Picosecond electron bunches induced TM_{03} (0.09 THz) and TM_{04} (0.14 THz) modes. The intensity of CCR was maximized at a tube length of 150 mm. When bunch length was compressed to ~0.2 ps, TM_{09} (0.36 THz) and TM_{017} (0.72 THz) modes were also observed. A new bunch length measurement using spectrum analysis of CCR would indicate a possibility of a new beam diagnostic based on a bunch form factor.

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