BUNCH LENGTH MEASUREMENT USING COHERENT CHERENKOV RADIATION

K. Kan, J. Yang, A. Ogata, T. Kondoh, K. Norizawa, Y. Yoshida
The Institute of Scientific and Industrial Research (ISIR), Osaka University, 8-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan

Abstract

A new method for bunch diagnostic based on multimode Coherent Cherenkov Radiation (CCR) was proposed. Generation of quasi-monochromatic terahertz (THz) using multimode CCR on the order of 0.1 THz was carried out. The intensity and frequency of CCR were measured directly by a Michelson interferometer and a bolometer.

コヒーレントチェレンコフ放射を用いた電子ビームパルス幅測定の研究

1. Introduction

Femtosecond electron bunches are key elements in the study of ultrafast reactions and phenomena in time-resolved pump-probe experiments involving the application of techniques such as ultrafast electron diffraction (UED) and pulse radiolysis. The time resolutions in UED and pulse radiolysis depend on the electron bunch length. In UED, an electron bunch is used as a probe source and ultrafast phenomena, such as laser-induced phase transients, are monitored using electron diffraction patterns. Pulse radiolysis also involves the use of an electron bunch and a laser; this technique is a powerful tool that can be used for the observation of ultrafast radiation-induced phenomena involving the mechanical motions of electrons and atomic nuclei in reaction mechanisms that are studied in physics, chemistry, and biology.

At Osaka University, a photocathode-based linear accelerator (linac) and a magnetic bunch compressor were constructed for femtosecond pulse radiolysis based on a femtosecond electron bunch. A picosecond electron bunch with a transverse emittance of approximately 3 mm-mrad was generated using a photocathode radio frequency (RF) gun by projecting a Nd:YLF picosecond laser onto a copper cathode. The electron bunch was accelerated up to 32 MeV by the booster linear accelerator with an optimal energy-phase correlation in the bunch (the acceleration of the bunch head was greater than that of the bunch tail) for compression of the bunch. Finally, the electron bunch was successfully compressed into femtoseconds, e.g., 98 fs in root-mean-square (rms) at 0.2 nC [1]. A femtosecond electron bunch has been used in pulse radiolysis in order to study the kinetics of solvated electrons with time resolution of femtoseconds.

In this paper, bunch diagnostic using multimode CCR was investigated. Multimode CCR was generated by a hollow dielectric tube covered by a metal and the electron bunch from the photocathode RF gun linac. The intensity and frequency of CCR were measured by a Michelson interferometer and a bolometer.

2. Experimental arrangement

The photocathode RF gun and multimode CCR measurement system are shown in Fig. 1. 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 light 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^{o} 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 27 MeV by a 2 m long S-band travelling-wave linac with a minimum energy spread. In the experiment, the picosecond electron bunch at the linac exit was used for multimode CCR generation. When the picosecond electron bunch moves on the axis of a hollow dielectric tube covered by a metal, partially periodic electric field, i. e. quasi-monochromatic THz, is induced as shown in Fig. 1. 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 25 mm downstream of the tube in the air. The CCR generated in the tube was reflected by an off-axis parabolic mirror (OAP1) with a focal length of 25 mm. The parallel THz light was separated by a beam splitter (BS) and one of the THz light was reflected by a moving mirror (M2). The mirror diameters except an off-axis parabolic mirror (OAP2) were <30 mm. The two THz light joined together at a 4.2K silicon bolometer. 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.

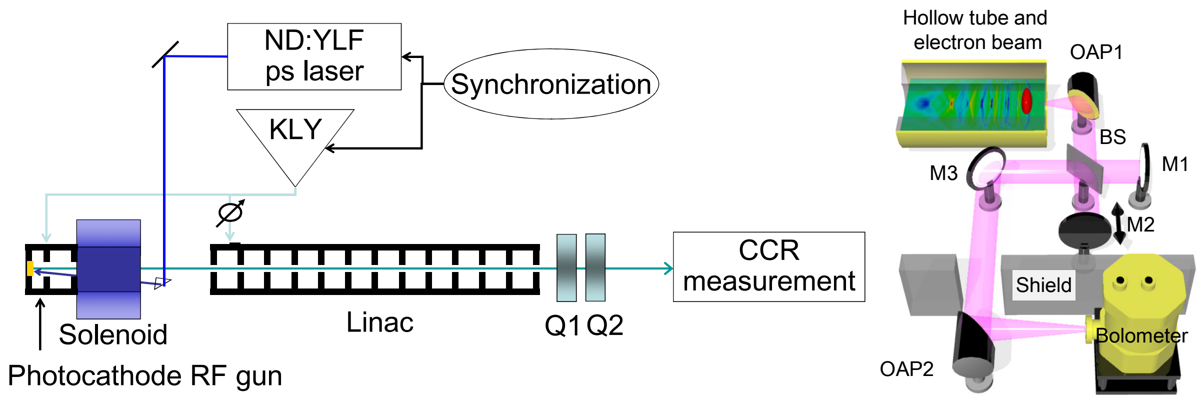

Figure 1: (Left) Photocathode RF gun linac. (Right)Diagram of multimode CCR and measurement system. OAP denotes an off-axis parabolic mirror; M, a plane mirror; BS, a beam splitter.

3. Results and discussions

3.1 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. An interferogram with data points of 128 and a time step of 1 ps 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 THz 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. A saturation was observed at a tube length of ≈150 mm. The nonlinear increase intensity would be caused by the EM field propagating through the electron bunch [2]. 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.

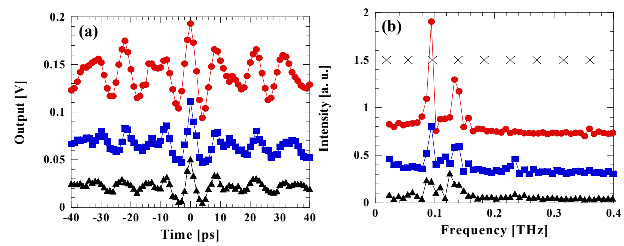

Figure 2: (a) Interferograms for 150, 100 and 50 mm tube lengths with offsets and factors adjusted for comparison. (b) Frequency spectra for 150, 100 and 50 mm tube lengths with offsets and factors adjusted. The theoretical frequencies of TM_{0n} modes (cross) according to Eq. (1) were shown.

3.2 Dependence on bunch charge

The bunch charge decides not only the intensity of EM radiation but also the bunch length due to initial space charge effect at the cathode surface. Figure 4(a) shows the interferograms near the centerburst position for three different bunch charges. The tube length was fixed to 150 mm. The 150 mm long tube enabled a measurement at a bunch charge of <10 pC. The interferograms at bunch charges of 15 and 8 pC were sharpened compared with that at a bunch charge of 150 pC. The information regarding the overall intensity of the spectrum is represented by only a few measurements near the centerburst position because of the separated THz traveling the same path length. It is obvious that a higher mode CCR is included at bunch charges of ≤15 pC, although the intensity decreases. Figure 4(b) shows the frequency spectra for three different bunch charges. The other higher mode, e. g. 0.36 THz (TM_{09}), was observed successfully at a bunch charge of ≤15 pC. Figure 4(c) shows the intensities for TM_{03}, TM_{04} and TM_{09} modes as a function of the bunch charge. The intensity of TM_{03} mode increased nonlinearly at a high bunch charge. The intensity of TM_{04} mode also increased, however, the increasing rate did not agree to that of TM_{03} mode. The intensity of TM_{09} mode was maximized at a bunch charge of 8 pC. Thus, the increasing rate of each mode due to the bunch charge was not a constant. It is expected that the CCR intensity at a different mode reveals the bunch form factor, which changes drastically in THz region.

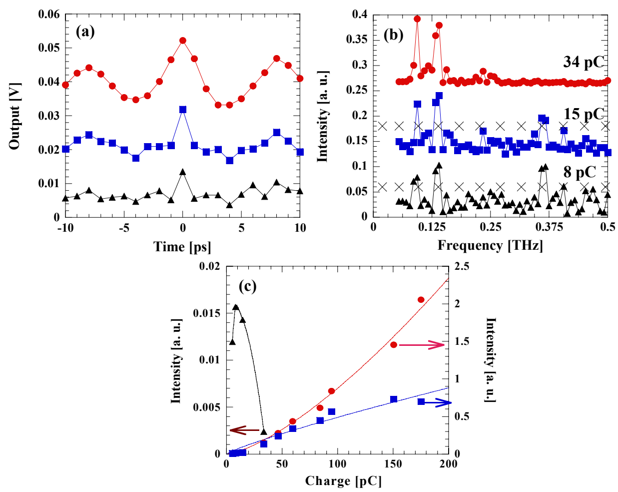

Figure 3: Interferograms near the centerburst position for 34, 15 and 8 pC bunch charges with offsets and factors adjusted for comparison. (b) Frequency spectra for 34, 15 and 8 pC bunch charges with offsets and factors adjusted for comparison. The theoretical frequencies of TM_{0n} modes (cross) were shown. (c) Intensities for TM_{03}, TM_{04} and TM_{09} modes as a function of the bunch charge.

3.3 Other CCR tube

CCR using the other tubes was also carried out. The wall thickness of the fused-silica tube decides the frequency discreteness of TM mode as shown in Fig. 4. The optimization of tube inner/outer radius would give comprehensive understanding to bunch form factor. This would be also an advantage for saving measurement time because of frequency resolution.

4. Conclusions

In conclusion, bunch diagnostic using multimode CCR was investigated. The CCR intensity at a different mode would reveal the bunch form factor, which changes drastically in THz region. An investigation of the bunch form factor using CCR spectra would be applied to a bunch length measurement. The flexibility of designing frequency would indicate the potential for other applications, e.g., analyzing light in pulse radiolysis, inverse Cherenkov radiation in metamaterials, and, non-invasive imaging.

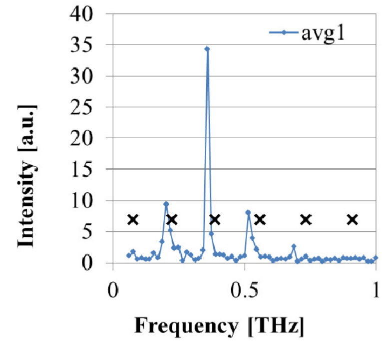

Figure 4: CCR from a tube with inner radius/ outer radius/ tube length of 1/1.5/150 mm. The theoretical frequencies of TM_{0n} modes (cross) were shown.

Acknowledgement

We thank the staff of the Radiation Laboratory in ISIR, Osaka University for the linac operation. We also thank Dr. Ryoichi Hajima (JAEA), Dr. Masao Kuriki (Hiroshima Univ.), Dr. Masanori Hangyo (ILE, Osaka Univ.), Weihua Jiang (Nagaoka Univ. of Technology), and, Shouichi Sakakihara (ISIR, Osaka Univ.) for their extensive advice and discussion on this work.

References

[1] J. Yang et al.,Nucl. Instr. and Meth.A 556, 52 (2006).
[2] B. W. J. McNeil et al, Optics Communications 163, 203 (1999).