DEVELOPMENT OF INTENSE TERAHERTZ–WAVE COHERENT SYNCHROTRON RADIATIONS AT LEBRA

N Sei[#] , H. Ogawa, Research Institute of Instrumentation Frontier, National Institute of Advanced Industrial Science and Technology, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan

K. Hayakawa, T. Tanaka, Y. Hayakawa, K. Nakao, K. Nogami, M. Inagaki, Laboratory for Electron Beam Research and Application, Nihon University, 7-24-1 Narashinodai, Funabashi, 274-8501, Japan

Abstract

To obtain an intense light source in the terahertz region, we developed coherent synchrotron radiation (CSR) using an S-band linac at Laboratory for Electron Beam Research and Application in Nihon University. Intense radiation was observed in the D-band region and it was confirmed to be the CSR. The two-dimensional distribution of the CSR was measured, and the CSR reflected in the vacuum chamber of the bending magnet was found to be emitted through the quartz window for a few tens of picoseconds.

INTRODUCTION

Nihon University and National Institute of Advanced Industrial Science and Technology have jointly developed intense terahertz-wave coherent synchrotron radiation (CSR) at Laboratory for Electron Beam Research and Application (LEBRA) in Nihon University. Because the electron beam of a linac used in an FEL facility must have a short bunch length and a high charge in order to saturate the FEL power, it is suitable for generating intense coherent radiation [1]. We measured an intense terahertz (THz) wave from LEBRA and confirmed it to be the CSR [2]. In this article, we report the characteristics of the observed CSR.

S-BAND LINAC AT LEBRA

The S-band linac at LEBRA consists of a 100 keV DC electron gun, prebuncher, buncher, and three 4 m long traveling wave accelerator tubes [3]. The electron beam accelerated by the linac is guided to an FEL undulator line by two 45-degree bending magnets. Energy of the electron beam can be adjusted from 30 to 125 MeV, and the charge in a micropulse is approximately 30 pC in full-bunch mode, where the electron beam is bunched in 350-ps intervals [3, 4]. The macropulse duration determined by the flat-top pulse width of the 20 MW klystron output power is approximately 20μs. The insertion device is a 2.4-m planar undulator with a maximum K value of 1.9. The length of the undulator period and number of the periods are 48 mm and 50, respectively. The electron beam in the undulator is removed from the FEL undulator line by a 45-degree bending magnet and loses its energy in a beam dump. Mirror chambers, each containing a metal mirror, are set at the ends of the FEL undulator line; the mirrors are 6.72 m apart. Fundamental FELs oscillate

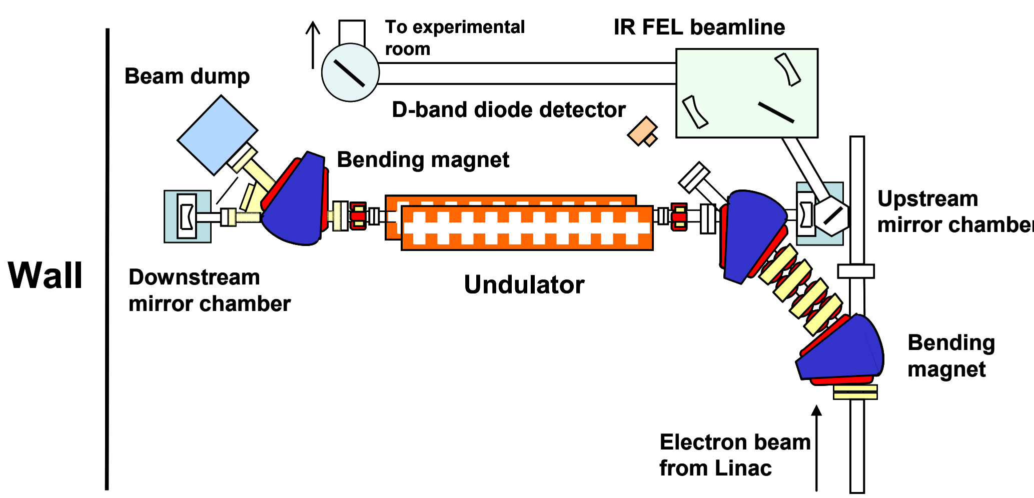

Figure 1: Outline of the CSR observation experiment at LEBRA.

*#sei.n@aist.go.jp

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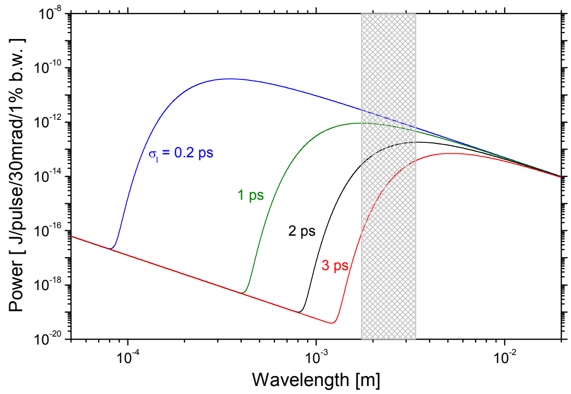

Figure 2: Calculated spectra of CSR emitted in the bending magnet. The gray mesh zone expresses a wavelength region where the D-band diode detector can measure electromagnetic radiation.

at wavelengths of 1–6 μm. The FEL beam, transmitted through a hole coupling in the upstream mirror, is converted to a parallel beam by aspherical mirrors. It is transferred from the accelerator room to the experimental rooms and used in dental and biological applications. An additional high-speed grid pulser having a pulse width of 600 ps was recently introduced in the electron gun [5]. The operation mode using this pulser is called burst mode, and a few high-charge micropulses (0.3–0.5 nC per micropulse) can be accelerated at intervals of 22.4 or 44.8 ns.

COHERENT SYNCHROTRON RADIATION EXPERIMENTS

After an electron bunch passes through the two 45-degree bending magnets in front of the undulator, its length can be compressed from 3 to 1 ps using a magnetic compressor. However, there is no optical beam window to extract the CSR in the FEL undulator line. Thus, we observed the CSR emitted at the entrance of the second 45-degree bending magnet, where the calculated bunch length was approximately 2 ps in full-bunch mode. On the other hand, the bunch length in burst mode was slightly longer than that in full-bunch mode. Figure 1 shows the outline of the CSR observation experiment. Although the CSR is emitted along the electron-beam orbit in a bending magnet chamber 24 mm high, its solid angle which was incident on a transfer pipe (diameter, 20 mm; length, 265 mm) was 0.065 radians. Figure 2 shows calculated spectra of the CSR emitted in the 45-degree bending magnet with micropulse charge of 30 pC. The CSR power has a maximum at wavelength of around 3.5 mm. In addition, it is sensitive to the bunch length in a wavelength region of 1-3 mm. The CSR passed through the transfer pipe and was extracted through a quartz window from the vacuum to the atmosphere. The electron-beam energy was set to 100 MeV in the CSR observations.

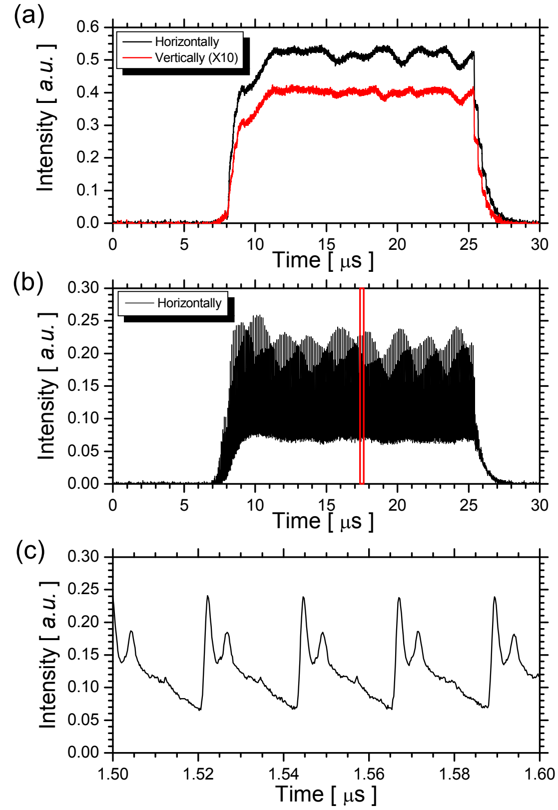

Figure 3: Measured power evolutions of the THz-wave radiation in full-bunch mode (a) and burst mode (b). Figure (c) is expansion on the red frame in (b).

The CSR was detected by a Schottky D-band diode detector (Millitech Inc., DXP-06) with a pyramidal horn whose opening was 11 and 17 mm in the vertical and horizontal directions, respectively. This detector can measure electromagnetic radiation at frequencies range of 0.09–0.17 THz. The nominal sensitivity of the diode detector is 5 mV/10 μW for a cw source. The CSR components with vertical and transverse polarization can be measured by rotating the detector by 90 degrees. The output signal of this detector was led to an experimental room 30 m away and was measured using an oscilloscope with an analog bandwidth of 500 MHz. The rise-time of the measurement system was 1.3 ns, so we could not distinguish individual micropulses in full-bunch mode.

RADIATION POWER

Intense THz-wave radiation was observed in both modes. Figure 3 shows the power evolutions of the THz-wave radiation measured by the detector system, which was located 0.53 m from the quartz window. In full-bunch mode, the wave form of the power evolution was similar to that of the electron-beam macropulse regardless of the polarization. On the other hand, evolution of the radiation power could observe for the individual micropulse in burst bunch mode. The interval and charge per pulse of the high-speed grid pulser were 22.4 ns and 0.6 nC, respectively. It is found that at least two peaks appeared

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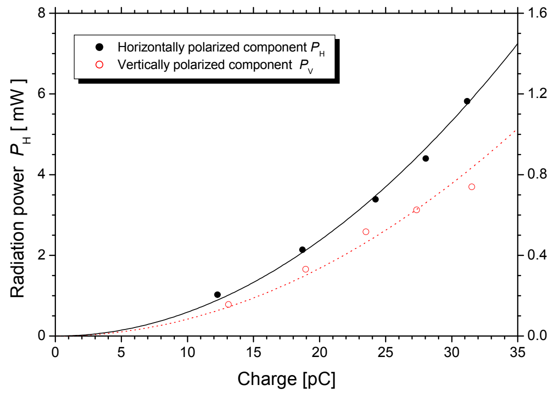

Figure 4: Measured dependence of radiation power on the electron-beam charge in full-bunch mode. The solid and dotted lines are quadratic curves fitting the data for the horizontally and vertically polarized radiation, respectively.

on the temporal structure in the interval [6]. The first peak corresponded to the intense radiation that arrived at the transfer pipe directly after it was generated in the vacuum chamber of the bending magnet. The second peak appeared approximately 5 ns after the first peak and corresponded to the intense radiation reflected repeatedly in the chamber and emitted through the transfer pipe. As shown in Fig. 3(c), the power evolution was an exponential decay after the second peak.

If this radiation was coherent, its power was proportional to the second power of the charge of the electron-beam micropulse. However, the bunch length in burst mode increases as the charge increases. The radiation power in the D-band region would be influenced by the bunch length as shown in Fig. 2. Thus, we investigated the relationship between the radiation power and the charge in full-bunch mode. Figure 4 shows the measured dependence of the radiation power on the electron-bunch charge. It is noted that the radiation power was almost proportional to the second power of the charge regardless of the polarization. This experimental result demonstrates that the radiation beam was coherent. When a quartz lens with an effective diameter of 46 mm was located 280 mm from the quartz window, the radiation power of the horizontally polarized component was 23 mW at 0.09–0.17 THz. Thus, the measured power of this radiation per macropulse was approximately 0.4 μJ in this frequency region. The width of a micropulse was much smaller than the rise-time of the measurement system.

EVOLUTION OF TWO-DIMENSIONAL DISTRIBUTION

Because the coherent radiation was reflected in the vacuum chamber of the bending magnet, the coherent radiation power extracted from the quartz window had temporal structure in burst mode. In the next step, we investigated the two-dimensional distribution of the coherent radiation. The diode detector, which was set on

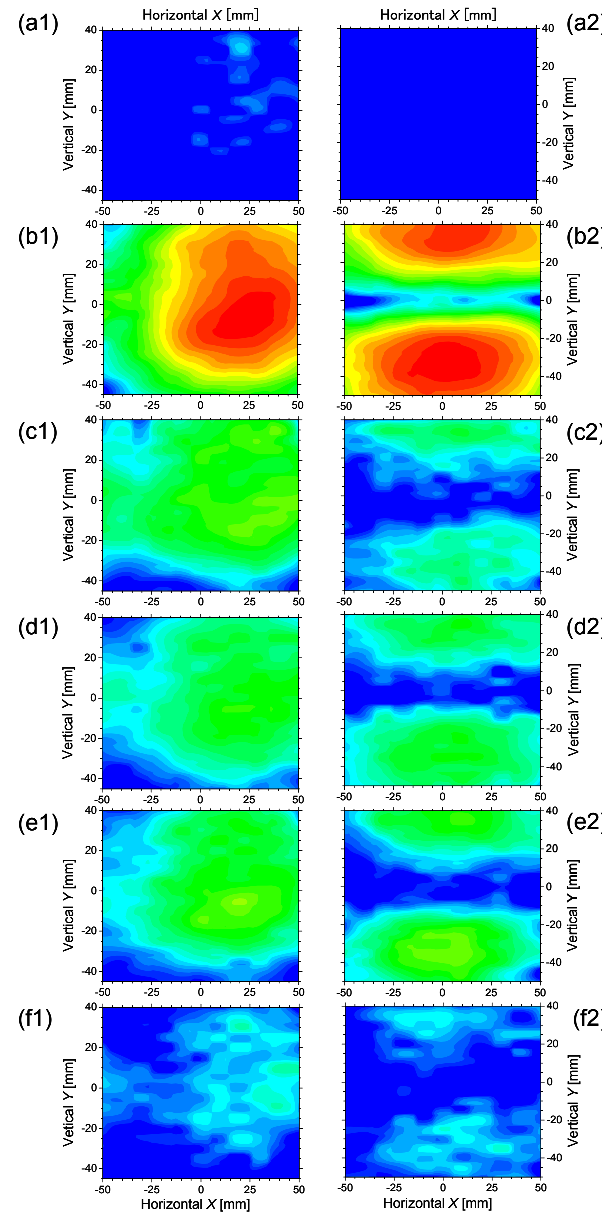

Figure 5: Two-dimensional mapping of (a1–f1) the hollizontally and (a2–f2) the vertically polarized components of the coherent radiation power. Time went from (a) to (f), and the time interval per frame was 4 ns.

an X–Y axis translation stage in an area of 100×85 mm^2, was located 0.53 m from the quartz window. The coherent radiation power was measured in 5-mm steps in the horizontal and vertical directions. To improve the spatial resolution, a metal slit (horizontal size, 8 mm; vertical size, 4 mm) was attached in front of the pyramidal horn. Figure 5 shows the evolution of the mapping of the coherent radiation power in the interval of 22.4 ns. The origin was on an axis of the electron-beam orbit between the two bending magnets. The electron beam moved from the origin in the positive direction on the X axis in the bending magnet. As shown in Fig. 5(b1), the center of the power in the horizontally polarized component shifted

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+25 mm along the X axis owing to the electron-beam orbit in the bending magnet. The shift was slightly smaller for the reflected radiation as shown in Fig. 5(e1). For the vertically polarized component, peaks appeared at an elevation angle of ±66 mrad from the quartz window. According to synchrotron radiation theory, the vertically polarized component of the synchrotron radiation at 0.14 THz, which was the center of the D-band region, exhibits maxima at an elevation angle of ±76 mrad [7], which agrees roughly with the observed angle. Thus, this radiation was identified as CSR. When the distance between the detector and the window was much larger than the diameter of the transfer pipe, the two-dimensional distribution of the vertically polarized component of the CSR appeared to be that of plane emission from the window.

It is found that intense radiation was emitted from the quartz window after the electron beam passed through the bending magnet. The radiation was CSR accumulated in the vacuum chamber of the bending magnet, and it caused high energy photons by Compton backscattering with the electron beam [8].

CONCLUSIONS

We developed an intense THz wave using an S-band linac at LEBRA. The radiation power of the THz wave was proportional to the second power of the charge in the electron micropulse. We measured the two-dimensional distribution of the intense THz wave; its vertically polarized component had roughly the same vertical distribution as the synchrotron radiation. Thus, the wave was identified as CSR. The evolution of the CSR power was measured in burst mode, and the CSR reflected in the vacuum chamber of the bending magnet was found to be emitted through the quartz window for a few tens of picoseconds. We plan to transport the THz-wave CSR to an experimental room using the infrared FEL beamline. Innovative applications are expected to use both the CSR and infrared FEL synchronously.

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