DEVELOPMENT OF COHERENT TERAHERTZ WAVE SOURCES USING LEBRA AND KU-FEL S-BAND LINACS*

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Abstract

In an infrared free-electron laser (FEL) facility using an S-band linac, a short-bunched electron beam is required to obtain a high FEL gain. Generally, the bunch length of the electron beam is compressed to 1 ps or less before interaction with the photons accumulated in the FEL resonator. This suggests that the electron beam dedicated to the FEL lasing is suitable for generation of high-peak-power coherent radiation in terahertz (THz) wave region. With the compressed electron beams the coherent THz-wave sources have been developed at Laboratory for Electron Beam Research and Application in Nihon University and mid-infrared FEL facility in Kyoto University. The observed energy has been higher than 100 μJ per macropulse in both infrared facilities.

INTORODUCTION

To increase a gain of a free-electron laser (FEL), high electron charge and short pulse width are required for the electron beam used in an infrared FEL facility. Although it is necessary to consider slippage of the electron beam in an insersion device, the root-mean-square (RMS) bunch length of the electron beam is often compressed to 1 ps or less before the insersion device.

Then, the electron beam in the infrared FEL facility is suitable for generating intense coherent radiation in a terahertz (TH) wave region, which lies between the microwaves and the infrared region. A lot of materials have unique absorptive and dispersive properties in the THz wave region [1]. Because the coherent radiation is broad band, it is useful for THz spectroscopy [2]. By combining the probe light of the coherent radiation with the pump light of the infrared FEL, it is expected to clarify dynamics of the molecular vibrations. Because the maximum electric field of the coherent radiation becomes more than 100 kV/cm, it can cause nonlinear optical effects in the THz region [3]. Multiphoton absorption will be also observed by using high-repetition coherent radiation.

Therefore, National Institute of Advanced Industrial Science and Technology (AIST) has developed intense THz-wave sources at infrared FEL facilities in cooperation with Nippon University and Kyoto University. We have already observed coherent synchrotron radiation (CSR) in both infrared FEL facilities. In this article, we will report the status and the new plan of the developments of the coherent radiation THz-wave sources.

THZ-WAVE SOURCES AT LEBRA

At the Laboratory for Electron Beam Research and Application (LEBRA) at Nihon University, an S-band linac is used to generate unique light sources. The electron-beam energy 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. The LEBRA has two monochromatic light sources, which are the infrared FEL in a wavelength region of 1–6 μm and the parametric X-ray radiation (PXR) in an energy region of 5–34 keV [4, 5]. The electron beam is transported from the S-band linac to the FEL straight section or the PXR straight section with the separate 90° arc sections, which can

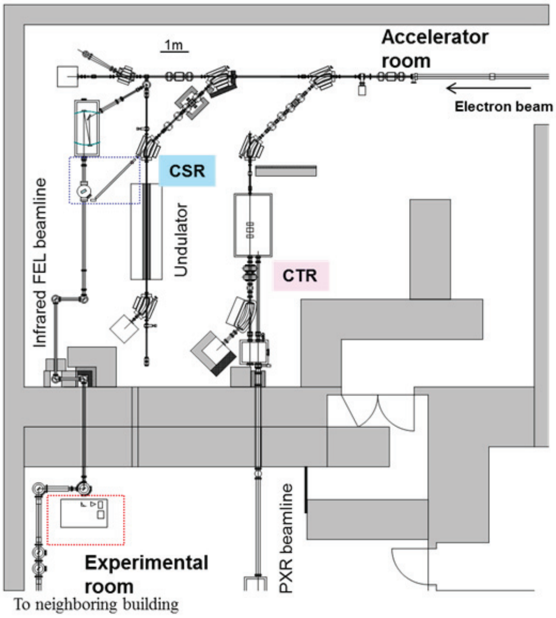

Figure 1: Layout of the experimental setup of coherent radiations at the LEBRA.

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compress the RMS bunch length to 1 ps or less. The macropulse duration determined by the flat-top pulse width of the 20 MW klystron output power is approximately 20 µs. However, the width of the flat-top pulse is adjusted to be 5 µs or less to avoid heating damage of a silicon crystal for PXR generation. Layout of the experimental setup at the LEBRA is shown in Fig. 1.

Although the bunch length is minimized at the FEL straight section, there is no view port to extract the CSR at the downstream bending magnet. In the PXR straight section, the electron beam is not operated in the long macropulse mode. Then, we developed the CSR beam at the upstream bending magnet in the FEL straight section at first. Because the RMS bunch length was calculated to be approximately 2 ps at the upstream bending magnet, we expected that the intense CSR was emitted in a frequency range of 0.1–0.3 THz. We observed intense THz wave beam extracted from a fused-quartz vacuum window with using a D-band diode detector (Millitech Inc., DXP-06), and we confirmed that it was the CSR beam by measuring dependency of the intensity on the electron charge of the micropulse and the two-dimension distributions of the horizontally and vertically polarized radiations [6]. The energy of the CSR beam extracted from the vacuum window was approximately 0.4 µJ per macropulse.

Because ionizing radiation generated due to the relativistic electron beam of the linac in the accelerator room, we transport the CSR beam to an experimental room by using the infrared FEL beamline. To match the profile of the CSR beam to that of the infrared FEL beam, we used a thin $LiTaO_3$ crystal substrate in the infrared FEL beamline. It has an average reflectance of 67% in the frequency range of 0.1–0.3 THz and an average transmission of 75% in the wavelength range of 0.5–5 µm. The energy of the transported CSR was 50 nJ per macropulse, and it was available at frequency range of 0.1–0.3 THz [7]. The qualities of the THz-wave beam were sufficient to be used in evaluation of the bunch length, imaging experiments, and spectroscopy [8]. Figure 2 shows a transmission imaging of a banded agate with a thickness of 6 mm by using the CSR beam. It is noted that a druse and bands in the banded agate cause interference of the CSR. The CSR beam can be applied with the infrared FEL beam, and a preliminary experiment of two color spectroscopy have been already conducted with the CSR and infrared FEL beams at the LEBRA.

To obtain more powerful THz waves, we have undertook developments of new coherent radiation sources. In the PXR straight section, there is a device of transition radiation to observe the profile of the electron beam. Because it is located behind the silicon crystal, it does not avoid to generate the PXR beam. Moreover, the RMS bunch length can be compressed to 1 ps or less. As shown in Fig. 3, intensity of coherent transition radiation (CTR) is more than 100 times as high as that of the CSR. The CTR energy is expected to be more than 1 mJ per macropulse. Because the CTR can be handled as a point light source, it is easy to transport the CTR beam to the experimental room. Then, an alumina fluorescent screen was replaced with a 50–µm titanium film, and characteristics of the CTR were investigated. We have already observed intense THz waves which has a maximum at a frequency of 0.3 THz. The energy of the intense THz waves was much higher than 0.1 mJ per macropulse. The THz waves can be simultaneously used with the PXR beam, so that we plan to transport the intense THz waves with using the PXR beamline. The identity of the intense THz waves will be reported in the near future.

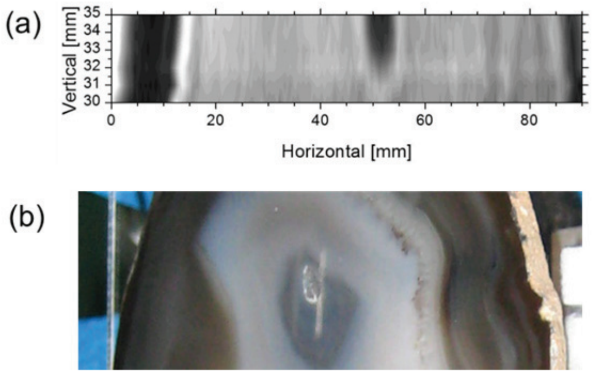

Figure 2: (a) Transmission imaging of a banded agate with using the CSR beam and D-band diode detector and (b) photograph of the banded agate.

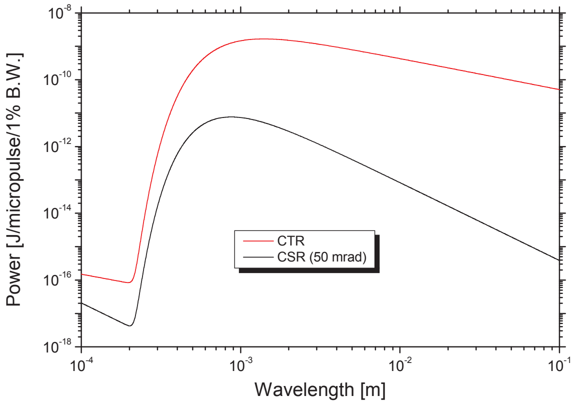

Figure 3: Calculated spectra of the CTR (red line) and CSR (black line) with the RMS bunch length of 0.5 ps at LEBRA. The radiation angle which CSR can be integrated is assumed to be 50 mrad.

THZ-WAVE SOURCES AT KU-FEL

At a mid-infrared FEL facility named as KU-FEL, which is located in Institute of Advanced Energy, Kyoto University, an S-band linac is also used to generate high peak-power light sources [9]. The KU-FEL consists of a 4.5-cell thermionic RF gun, a dog-leg section for an energy filtering, a 3-m accelerator tube, a 180° arc section for a bunch compression, an undulator, and an optical cavity. Recently, a photocathode gun has been developed

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as an exchangeable electron source. A schematic layout of the KU-FEL is shown in Fig. 4. A pulse width of the klystron is approximately 8 µs. However, when the pulse width becomes longer than 3us, the electron-beam qualities are influenced during the macropulse duration by back-bombardment effect. Although the electron energy is maintained fixedly by changing the high voltage of the klystron modulator, the electron charge of the micropulse changes from 20 to 40 pC. The FELs oscillate in a wavelength region of 5–22 µm, and the maximum energy of the FEL is 33 mJ per macropulse [10].

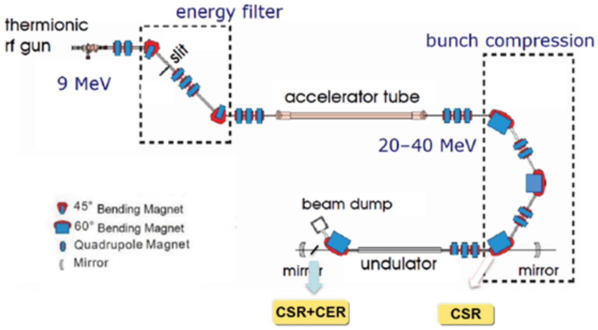

Figure 4: Layout of the experimental setup of coherent radiations at the KU-FEL.

The RMS bunch length of the electron beam in the KU-FEL can be compressed to 1 ps or less in the undulator section. However, a vacuum window to extract radiation is far from the downstream bending magnet, and an inner diameter of a vacuum pipe between the vacuum window and the bending magnet is narrow. The radiation angle which synchrotron radiation emitted from the downstream bending magnet can be extracted from the vacuum window is only 30 mrad. Then, we started to develop CSR at upstream bending magnet, which has a vacuum window at a bending angle of 30°. The radiation angle which synchrotron radiation emitted from the upstream bending magnet can be extracted from the vacuum window is 100 mrad. A fused silica with a diameter of 38 mm and a thickness of 3.5 mm is inserted in the vacuum window.

The RMS bunch length was calculated to be 1–2 ps at the radiation point in the upstream bending magnet. Therefore, the maximum of the CSR spectrum was expected to be in a wavelength region of 0.1–0.2 THz, so that we used a G-band diode detector (Millitech Inc., DXP-05) to investigate evolution of THz waves extracted from the vacuum window. As shown in Fig. 5, we observed intense THz waves, of which macropulse structure was different from that of core monitor signal. The intensity of the THz waves was almost proportional to the second power of the charge up to 6 pC when the macropulse width was 2.8 µs. We measured two-dimensional distributions of the coherent THz waves, and it was found that it almost accorded with the two-dimensional distributions of synchrotron radiation at a frequency of 0.14 THz. Then, the intense THz waves were confirmed to be the CSR. Figure 5 suggests that the bunch length of the micropulse changed during the macropulse duration. We measured energy of the CSR extracted from the vacuum window by a pyrodetector (Gentec-EO Inc., QE8SP-I-MT-BNC) which was set on a two-dimensional moving stage, and it was approximately 55 µJ per macropulse. The CSR spectrum was measured by a simple Michelson interferometer, and it was clarified that the maximum was in a frequency region of 0.1–0.2 THz. The detailed characteristics of the CSR beam will be report in another paper [11].

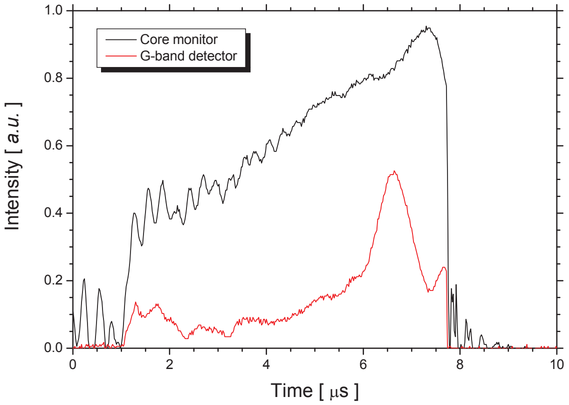

Figure 5: Evolutions of core monitor signal (black line) and CSR intensity measured be G-band diode detector (red line) during the macropulse duration.

Although the radiation angle in the downstream bending magnet is small, the CSR power at the entrance of the downstream bending magnet is higher than that at the observation point in the upstream bending magnet. We also expected to observe coherent edge radiation (CER) at the vacuum window near the downstream bending magnet [12]. Then, we measured profiles of a THz-wave beam with a Teflon lens and a pyroelectricity camera (Ophir Optronics Solutions Ltd., Pyrocam IV), which was located 0.7 m from the entrance of the downstream bending magnet. As shown in Fig. 6, the measured profile had nonuniform hollow structure. This experimental result suggests that the CSR and CER were emitted from

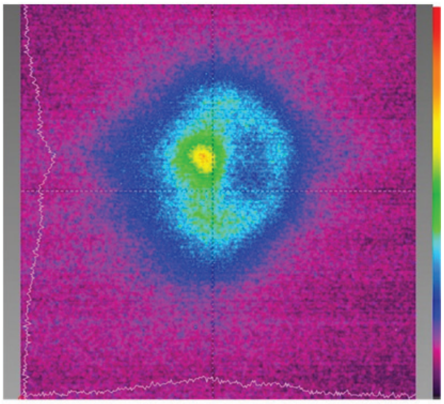

Figure 6: Measured profile of the intense THz waves emitted from the entrance of the downstream bending magnet in the undulator section.

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the entrance of the downstream bending magnet. The THz-wave energy extracted from the vacuum window was measured by the pyrodetector, and it was 100 µJ or more. As the infrared FEL system with the storage ring NIJI-IV at the AIST has developed quasi-monochromatic X-ray beams via FEL-Compton backscattering [13, 14], FEL facilities have potential to develop complex light sources. We plan to clarify the characteristics of the intense THz waves.

CONCLUSION

We have developed intense THz-wave sources by using short-pulse electron beams in the infrared FEL facilities. At the LEBRA, the CSR emitted from the upstream bending magnet in the FEL straight section was transported to the experimental room by using the FEL beamline. It was applied to the imaging experiments and spectroscopy with the infrared FELs. The new CTR, of which energy is 1 mJ per macropulse or more, is under development in the PXR straight section. At the KU-FEL, the CSR with energy of 55 µJ per macropulse has been developed in the upstream bending magnet of the undulator section. The more powerful THz-wave source is under development in the downstream bending magnet. We will advance pioneering studies in which the intense THz waves are used with the infrared FEL or the PXR.

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