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RESEARCH OF COHERENT EDGE RADIATION GENERATED BY ELECTRON BEAMS OSCILLATING FREE-ELECTRON LASERS

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Abstract

We have been studied far-infrared coherent radiation with an S-band linac at Laboratory for Electron Beam Research and Application (LEBRA) at Nihon University. We have already developed a couple of terahertz-wave sources based on coherent synchrotron radiation and coherent transition radiation, which have been applied to spectroscopic research. Moreover, we developed coherent edge radiation (CER) at the downstream bending magnets in the FEL sections. Because the edge radiation has an annular shape distribution characterized by the asymmetric first-order Laguerre-Gaussian mode, the CER can be extracted from an optical cavity of the FEL system without a diffraction loss of the FEL beam. The root-mean-squared bunch length of the electron beam was evaulated by measuring the CER spectra, which was about the same level as the FEL micropulse width. Although the infrared FELs at LEBRA had a long slippage length, the FEL energy became higher as the bunch length was shorter. The CER intensity can be a guidepost enhancing the FEL power because of the existence of their correlation.

INTRODUCTION

Generally, a high electron-density beam is required for free-electron laser (FEL) oscillations in FEL facilities. In order to realize the high electron density, an electron beam is compressed to shorten the electron-bunch length in a straight section where an insertion device for the FEL oscillation is installed. The bunch length is an important parameter because it affects not only the FEL gain evaluation but also the detuning curve and the FEL pulse width [1]. Power of coherent radiations generated by the short electron bunch become high in the terahertz (THz) region [2]. Recently, generation and measurement techniques for THz waves have been improved, and evaluation of the bunch shape using the coherent radiation has been performed by various methods. We also developed coherent radiation sources at Laboratory for Electron Beam Research and Application (LEBRA) and at Kyoto University Free Electron Laser (KU-FEL), and used them for the evaluation of the bunch length [3–5].

However, in order to avoid influence on the FEL oscillation, coherent radiation generated in a straight section where the FEL is amplified has not been conventionally used for a measurement of the bunch length. Then, we focused on coherent edge radiation (CER) which could be extracted from the straight section without growing a diffraction loss [6]. We inserted a mirror chamber, which could extract the CER generated at the downstream bending magnet in the FEL straight section, into the optical cavity at LEBRA, and observed the CER in the THz region during the FEL oscillations. In this article, the estimated and measured characteristics of the CER beam at LEBRA are discussed.

COHERENT EDGE RADIATION

Edge radiation is electromagnetic waves emitted by charged particles due to the velocity change at an end of a bending magnet in the direction of movement. Because it is relativistic dipole radiation with longitudinal acceleration, it has a hollow spatial distribution with radial polarization [6]. It is more intense than the synchrotron radiation in the infrared region, and the energy of the CER for a typical electron bunch of an S-band linac is several tens nJ. Therefore, it is possible to extract the high-power CER in the THz region from the FEL optical cavity without damaging the FEL oscillations. The dependence of the CER spectrum on the radiation angle is not significant, so that the influence of a hole-coupled mirror on the spectrum of the extracted CER beam can be corrected by calculation.

Preliminary experiments on the characteristics of the CER beam were conducted at the infrared FEL facility KU-FEL [7]. Resonator-type FELs in a wavelength region of 3.5–23 μm have been developed using an S-band linac and an 1.8-m planar undulator at KU-FEL [8]. The CER generation experiments were conducted using the electron beam with the energy of 28 MeV and the macropulse duration of 7 μs. The averaged charge of a micropulse of the electron beam was approximately 35 pC. The CER beam generated at the entrance of the downstream bending magnet with the radius of curvature of 338 mm in the FEL straight section was extracted from the FEL optical cavity by a plane mirror

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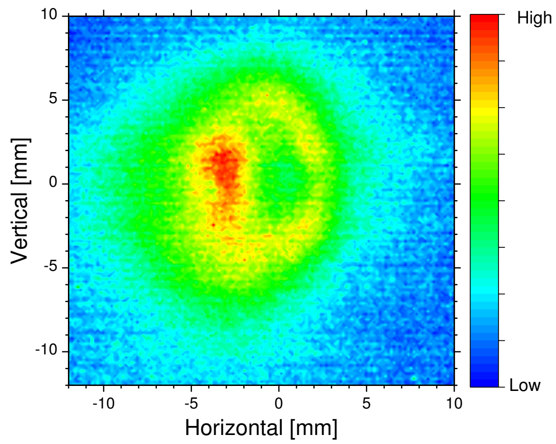

Figure 1: Observed CER profile at KU-FEL. The electron beam moves from the center to the left.

located at 0.56 m from the CER emitting point. The effective area where the plane mirror could reflect the CER beam was 20×20 mm^2. The observed CER spectrum was almost in agreement with the calculated one with the root-mean-square (RMS) bunch length of 0.19 ps in consideration of the diffraction loss of the measurement system. The energy of the extracted CER beam was approximately 0.10 mJ per macropulse, which was sufficient for measuring a profile of the CER beam by a THz camera. Figure 1 showed the measured CER profile which was reduced to one third by a polytetrafluoroethylene lens. The measured CER profile had a hollow structure resembling the first-order Laguerre-Gaussian mode with asymmetric intensity in horizontal direction. It roughly agrees with the calculated one for the effective area of the plane mirror. It was also showed that RMS bunch length evaluation could be estimated by measuring the CER intensity with ultrafast diode detectors at multiple frequencies. We demonstrated that the CER beam could be evaluated according to the theory and was promising for the electron bunch evaluation immediately after the FEL interaction.

DEVELOPMENT OF CER AT LEBRA

The S-band linac at the infrared FEL facility LEBRA has three 4-m long traveling wave accelerator tubes and accelerates the electrons up to 125 MeV [9]. The macropulse duration determined by the flat-top pulse width of the 20 MW klystron output power is approximately 20 µs. The repetition frequency of the electron beam is 2 Hz for the FEL experiments. The electron beam is guided to an FEL straight section by two 45° bending magnets. It passes through a 2.4-m planar undulator and is guided to a beam dump by a 45° bending magnet. The length of the undulator period and number of the periods are 48 mm and 50, respectively. Mirror chambers are set at the ends of the FEL straight section, and the distance of the mirrors are 6.72 m. Fundamental FELs oscillate at wavelengths of 1–6 µm. As shown in Fig. 2, an observation system for the CER beam generated at the downstream bending magnet was constructed in the FEL optical cavity. The vacuum chamber of

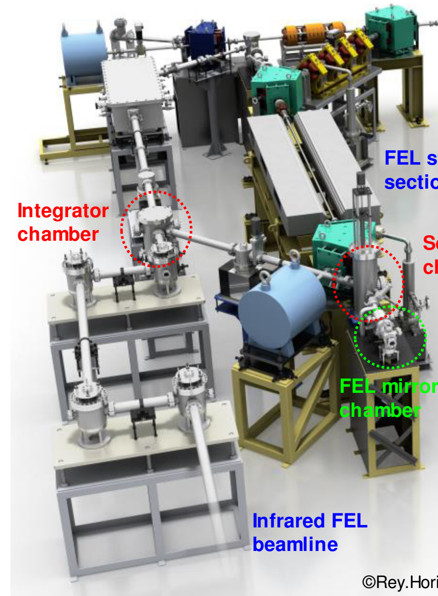

Figure 2: Layout of the CER beamline at LEBRA.

the downstream bending magnet has been improved, and the CER beam emitted in the horizontal angle of 38.1 mrad and the vertical angle of 23.5 mrad can be directly extracted from the vacuum chamber without reflecting on the inner surface of the vacuum chamber. In order to extract the CER beam from the FEL optical cavity without the FEL oscillation, a separator chamber was installed between the downstream bending magnet and the mirror chamber. A normal concave mirror and a hole-coupled concave mirror could be inserted on the axis of the FEL beam in the separator chamber. The effective diameter of the mirrors is 74 mm, and the diameter of the hollow is 25 mm, which is almost same as the diameter of the FEL mirror. The CER beam is deflected 135° by the mirror and transports to the infrared FEL beamline. An integrator chamber, which has been moved from the coherent synchrotron radiation beamline, has been set at the intersection of the CER beamline and the infrared FEL beamline. In the integrator chamber, a sapphire substrate deposited with Indium Tin Oxide (ITO) on a surface, which reflects 80% or more of electromagnetic waves at frequencies below 1 THz, can be inserted into the axis of the FEL beam. Because the ITO transmittes the infrared light, we can use the THz-wave CER and the near-infrared FEL on the same optical axis in the experimental room.

The ideal characteristics of the CER beam can be derived using the Liénard-Wiechert potential. Figure 3 shows a calculated two-dimensional distribution of the CER beam at the bunch length of 0.23 ps and the electron energy of 57 MeV. In this figure, a boundary where the CER beam can be transported to the integrator chamber without colliding on the vacuum chambers and a circumference of the hollow part are indicated by red and blue lines, respectively. It is noted that the maximum of the CER intensity passes through the hollow-coupled mirror even in the low-energy electron beam operation. However, the effective diameter of the mirror is large, so that the extraction efficiencies for

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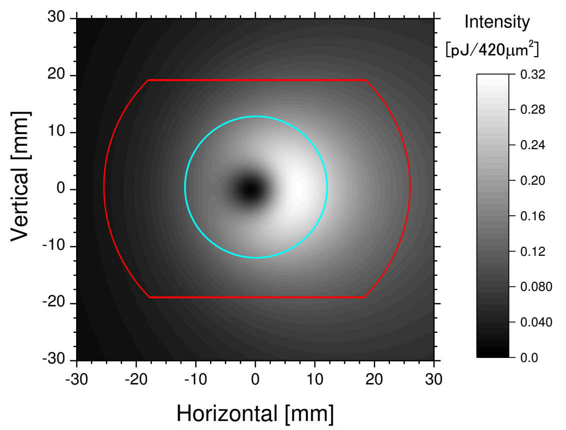

Figure 3: Calculated CER profile at the concave mirror in the FEL optical cavity. The electron beam moves from the center to the right.

the CER beam are 35% or more for the hole-coupled concave mirror and approximately 60% for the normal concave mirror at the electron-beam energy of 57 MeV. The energies of the CER beam extracted from the FEL optical cavity are calculated to be 0.19 mJ for the hole-coupled concave mirror and 0.30 mJ for the normal concave mirror at the micropulse charge of 27 pC and the macropulse duration of 18.1 μs. The ratio of the spectrum of the CER beam extracted by the hole-coupled concave mirror to the spectrum of the whole CER is gently changing in a frequency region of 0.1–3 THz. By considering the frequency dependency, it is possible to evaluate the bunch length using the observed CER spectrum.

OBSERVATION OF THE CER BEAM DURING THE FEL OSCILLATIONS

Before the transport CER beamline was completed, we observed the CER beam extracted into the atmosphere through a crystal quartz window located between the separator chamber and the integrator chamber. The CER experiments were performed at the electron energy of 57 MeV. The gap of the undulator was set to be minimum ($K = 1.9$). When the concave mirrors in the separator chamber were completely pulled out of the FEL optical cavity, the FEL oscillated with the energy of 1.5 mJ per macropulse at a wavelength of 5.4 μm. The FEL energy did not change even when the hole-coupled concave mirror was installed into the FEL optical cavity. It was confirmed that the hole-coupled concave mirror did not increase the cavity loss for the FEL beam.

The CER energy was measured by a calibrated THz power sensor (3A-P-THz; Ophir Optronics) in the atmosphere. The measured energies per macropulse using the hole-coupled concave mirror and the normal concave mirror were 0.17 and 0.25 mJ, respectively. Considering the transmission of approximately 0.8 for the crystal quartz in the frequency region of 0.1–3 THz, the measured CER energies were almost in agreement with the calculated ones. Therefore, we demonstrated that high-intensity CER beam could be extracted without damaging the FEL oscillation. We measured spectra of the CER beam using a Michelson-type interferometer and a THz energy meter (THz-10; Sensor und Lasertechnik GmbH) [7]. The RMS bunch length evaluated from the measured CER spectrum considering the absorption by the atmosphere was approximately 0.2 ps. It was observed that the FEL energy became higher as the bunch length was shorter even if the bunch length was shorter than the slippage length under the perfect synchronism of the optical cavity. We found a phenomenon that the CER spectrum modulated during the FEL oscillation and analysed the data of the CER spectra under various FEL conditions. After these experiments, the concave mirrors were replaced by toroidal mirrors.

CONCLUSION

We have developed a system that can observe CER generated by an electron beam immediately after FEL interaction without damaging an FEL beam at the infrared FEL facility LEBRA. A separator chamber, which could insert a hole-coupled concave mirror and a normal concave mirror on the axis of the FEL beam, was installed between the downstream bending magnet and the FEL mirror chamber. And the hole-coupled concave mirror could extract the CER beam from the FEL optical cavity without increasing the diffraction loss of the FEL beam. The CER beam extracted from the FEL optical cavity can be transported to the experimental room using the infrared FEL beamline. The measured CER energies with the hole-coupled concave mirror and the normal concave mirror were almost in agreement with the calculated ones. Moreover, we found a phenomenon that the CER spectrum modulated during the FEL oscillation. It is possible to observe the evolution of the electron-beam micropulse by measuring the CER spectra. In the near future, we plan to observe the correlation between the CER spectra and FEL power in detail.

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REFERENCES

[1] G. Dattoli *et al*., Nucl. Instrum. Methods Phys. Res., A, **285** (1989) 108.
[2] G. L. Carr *et al*., Nature **420** (2002) 153.
[3] N. Sei *et al.,* J. Phys. D: Appl. Phys. **46** (2013) 045104.
[4] N. Sei *et al.,* J. Opt Soc. Am B **31** (2014) 2150.
[5] N. Sei *et al.,* Jpn. J. Appl. Phys. **56** (2017) 032401.
[6] O. Grimm, *TESLA-FEL Report* **2008-05** (2008).
[7] N. Sei *et al.,* Phys. Lett. A **383** (2019) 389.
[8] H. Zen *et al*., Phys. Procedia **84** (2016) 47.
[9] T. Tanaka *et al.*, Nucl. Instrum. Methods Phys. Res., A, **528** (2004) 486.