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# COHERENT EDGE RADIATION SOURCES IN LINAC-BASED INFRARED FREE-ELECTRON LASER FACILITIES

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## Abstract

National Institute of Advanced Industrial Science and Technology has been studied far-infrared coherent radiation at Linac-based infrared free-electron laser (FEL) facilities in collaboration with Nihon University and Kyoto University. Generally, it is possible to extract information about the electron bunch by observing the coherent radiation. To clarify the relationship between the FEL interaction and the coherent radiation, we developed coherent edge radiation, from which the bunch length could be evaluated, in FEL straight sections.

## INTRODUCTION

In order to oscillate an FEL, it is necessary to estimate characteristics of an electron beam in a straight section in which an undulator is installed. The bunch length of the electron beam related to the electron density is a significant parameter which characterizes behavior of the FEL. The bunch length influences not only the gain but also the pulse width of the FEL and the cavity-length detuning curve [1]. Observing the behavior of the bunch length in the straight section with the undulator is useful for understanding the FEL physics.

Observations of spectra of coherent radiation generated by the electron bunch are suitable for monitoring the bunch length of a short-pulse electron beam. However,

FEL pulses exist on the electron-beam orbit in the straight section with the undulator. A target for transition radiation cannot be inserted into the straight section. Hence, the transition radiation cannot be used to generate coherent radiation. The usage of synchrotron radiation is unlikely because the radiation power becomes weak away from the axis of the electron-beam orbit. Diffraction radiation can be extracted for the spectral measurement without losing the FEL oscillations. However, the spectrum of the diffraction radiation depends on the aperture diameter of the diffraction element. Because it is necessary to enlarge the aperture for long-wavelength FELs, conditions in which the diffraction radiation can be applied for a bunch length measurement are limited. Therefore, we used the coherent edge radiation (CER) generated by the downstream bending magnet in the FEL straight section. Because edge radiation has an annular shape distribution as the asymmetric first-order Laguerre-Gaussian ( $LG_{01}$ ) mode [2], the CER can be extracted from the optical cavity without a diffraction loss of the FEL beam. In the terahertz (THz) region, where the edge radiation becomes coherent, the intensity of the edge radiation is much higher than that of the synchrotron radiation. In this paper, CER sources at Kyoto University Free Electron Laser (KU-FEL) [3] and at Laboratory for Electron Beam Research and Application (LEBRA) in Nihon University [4] are discussed.

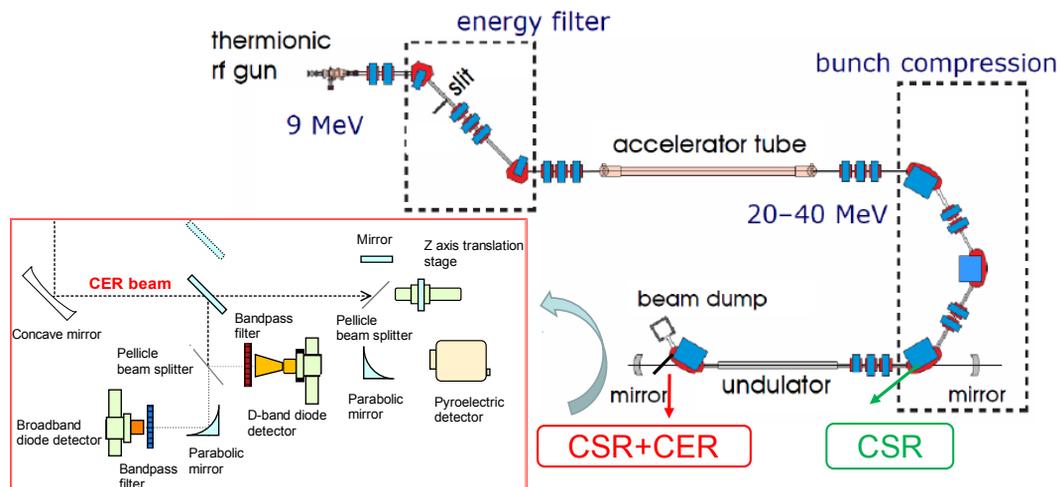


Figure 1: Schematic layout of the CER source and the measurement system at KU-FEL.

## COHERENT EDGE RADIATION SOURCE AT KU-FEL

KU-FEL consists of an S-band 4.5-cell thermionic RF gun, an energy filtering dog-leg section, a 3 m accelerator tube, a 180° arc section, and a 1.8-m hybrid planner undulator with the number of periods of 52. The maximum energy of the electron is 40 MeV and the maximum duration of the electron-beam macropulse is approximately 8  $\mu$ s. The charge of the micropulse increases from 20 to 50 pC due to back-bombardment effects on the thermionic RF gun [3]. The root-mean-square (RMS) bunch length of the electron beam was designed to be 1 ps or less in the FEL straight section using the magnetic compression of the 180° arc section. The tunable range of the FEL wavelength is from 3.5 to 23  $\mu$ m.

Coherent synchrotron radiation (CSR) was observed at the upstream bending magnet in the straight section [5]. The angle between the CSR beam and the straight section was 30°. Because the solid angle to pass CSR without impinging a vacuum pipe was as large as 0.10 rad, the measured CSR energy was 55  $\mu$ J per macropulse of the electron beam. The RMS bunch length evaluated from the measured CSR spectrum was approximately 1.4 ps. The electron bunch was not sufficiently compressed, so that it was necessary to measure the bunch length in the straight section.

We, therefore, observed the CER at the downstream bending magnet in the straight section. Figure 1 shows a schematic layout of the CER source at KU-FEL. The CER beam was extracted from the optical cavity by inserting a deflection mirror tilted by 45° to the optical axis in the horizontal plane. The effective area of the deflection mirror that was projected onto the plane perpendicular to the optical axis was 20 mm square. The distance from the light source of the downstream bending magnet to the deflection mirror was 0.56 m. The electron beam generated the intense CER at the upstream and downstream bending magnets. However, because the inner sizes of the rectangular undulator vacuum duct were only 11 mm in horizontal and 56 mm in vertical direction, the CER generated at the upstream bending magnet in the THz region did not directly arrive at the deflection mirror. Generally, the electron beam also generated the CER at both ends of an undulator. However, regarding the undulator at KU-FEL, the magnetic field was designed to gradually disappear at the ends of the undulator in order to avoid a walkoff of the electron-beam trajectory. The magnetic field at the end of the undulator was much lower than that at the bending magnet. Then, it was expected that only the CER generated at the downstream bending magnet was observed as a THz-wave beam.

The profile of the THz beam was observed by a pyroelectric THz camera in air. The electron-beam energy was 28 MeV and the macropulse duration was 7  $\mu$ s. The profile measured with a polytetrafluoroethylene lens had a hollow structure resembling the LG<sub>01</sub> mode with the asymmetric intensity in horizontal direction, and it roughly agreed with the calculated CER profile at the deflection

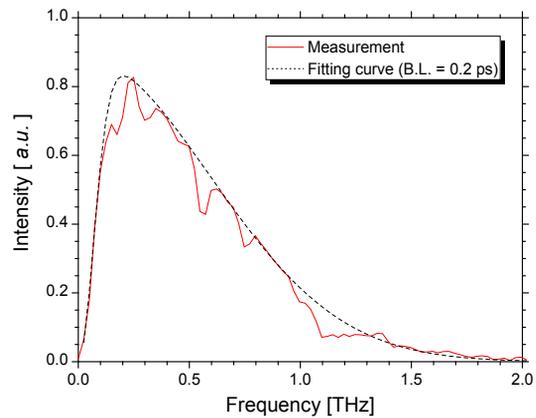


Figure 2: Spectrum of the CER beam at KU-FEL.

mirror. Then, it was confirmed that the observed THz beam was the CER beam generated at the downstream bending magnet. The power of the THz-wave beam was evaluated to be 0.10 mW considering the sensitivity of the THz camera.

CER spectra were measured by using a Michelson-type interferometer. Figure 2 shows the CER spectrum in the operation condition that the FEL output power was maximized. The RMS bunch length evaluated from the measured CER spectrum was approximately 0.2 ps, so that it was clarified that the electron bunch was sufficiently compressed. Because a rectangular mirror was used to extract the CER beam from the optical cavity as the deflection mirror, the measurement of RMS bunch length was impossible on FEL oscillations. A mirror having a hole-coupled structure can solve this problem. We planned to use a hollow mirror at LEBRA.

## COHERENT EDGE RADIATION SOURCE 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 [4]. 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-

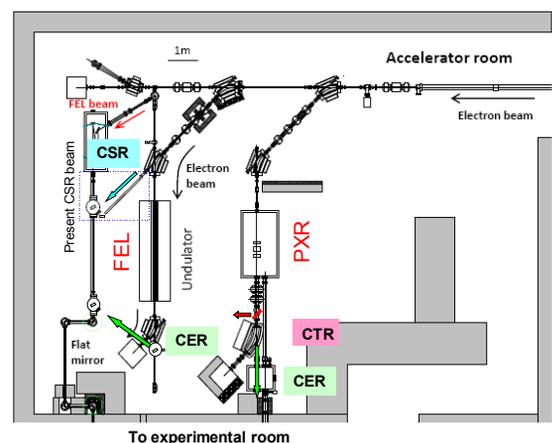


Figure 3: Coherent radiation sources at LEBRA.

ps intervals. The accelerated electron beam is allocated to two straight sections by bending magnets. Each straight section is used for the infrared FEL and parametric X-ray radiation (PXR). The schematic layout of LEBRA is shown in Fig. 3. The electron beam is guided to a FEL straight section by two 45° bending magnets. 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. Mirror chambers, each containing a metal mirror, are set at the ends of the FEL straight section. The mirrors are 6.72 m apart. Fundamental FELs oscillate at wavelengths of 1–6  $\mu\text{m}$ .

A few coherent radiation sources have been developed at LEBRA. In the FEL straight section, CSR generated at the entrance of the second 45° bending magnet was observed [6], and it was transported to the experimental room using the FEL beamline [7]. Because the electron bunch was not sufficiently compressed, the measured CSR energy was as low as 1  $\mu\text{J}$  per macropulse of the electron beam. Then, a thin titanium screen was installed instead of an alumina fluorescent plate used for the profile monitor in the PXR straight section, and coherent transition radiation (CTR) source was developed. The measured CTR energy was as high as 1 mJ per macropulse [8]. Moreover, the CTR beam was transported to the experimental room using the PXR beamline and was applied to imaging experiments on biological samples in the THz region. A CER beam generated at the downstream bending magnet was observed in the PXR straight section. The RMS bunch length evaluated from the CER spectrum was approximately 0.2 ps, and it was expected that the electron bunch was also compressed to the same length even in the FEL straight section.

To investigate effects of the FEL interaction on the electron bunch in the FEL straight section, a deflection mirror system was inserted between the downstream bending magnet and the downstream optical cavity mirror. This mirror system can switch with a hole-coupled concave mirror or a normal concave mirror and without the mirrors under remote control. The effective diameter of the mirrors was 60 mm and the inner diameter of the hole was 25 mm. Considering the inner shape of the downstream bending magnet chamber, the extraction efficiency for the CER was approximately 30% for the hole-coupled concave mirror and 60% for the normal concave mirror in the electron-beam energy of 57 MeV. By using the hole-coupled concave mirror, we succeeded in observing the CER on FEL oscillations for the first time. Figure 4 shows the CER power extracted to the air with the hole-coupled concave mirror at the electron-beam energy of 57 MeV. The measured power was 0.35 mW at the macropulse duration of 18  $\mu\text{s}$  and the macropulse repetition of 2 Hz. The wavelength of the FEL was 5.4  $\mu\text{m}$  and the FEL macropulse energy measured was 1.5 mJ in the experimental room. The RMS bunch length evaluated from the measured CER spectrum was 0.2 ps or

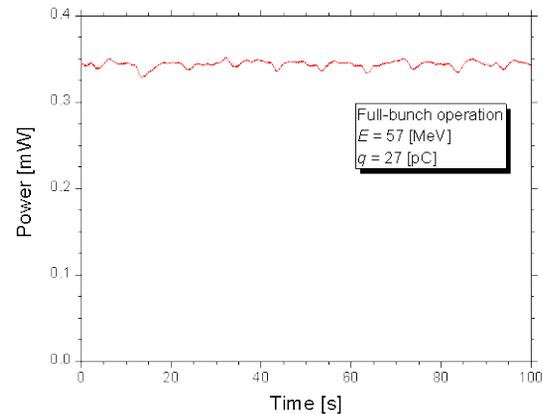


Figure 4: Measured CER power on FEL oscillations.

less. It was confirmed that the FEL energy was 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 plan to measure the correlation between the CER spectrum and the evolution of the FEL macropulse.

## CONCLUSION

Intense CER sources have been developed at the FEL facilities KU-FEL and LEBRA. Despite using the small mirror to extract the CER beam from the optical cavity at KU-FEL, the output power of the CER beam was 0.10 mW in air. The RMS bunch length evaluated from the measured CER spectrum was approximately 0.2 ps, so that it was clarified that the electron bunch was sufficiently compressed. At LEBRA, the hole-coupled mirror was used to extract the CER beam from the optical cavity. The CER was observed on FEL oscillations for the first time. We will study influence of FEL oscillations on the electron bunch by measuring the CER with the constructed observation system in addition to a new development of coherent Cherenkov radiation [9].

## APPENDIX

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