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CONSTRUCTION OF AN INFRARED FEL AT THE COMPACT ERL*

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Abstract

The compact Energy Recovery Linac (cERL) has been in operation at KEK since 2013 to demonstrate ERL performance and develop ERL technology. Recently KEK has launched an infrared Free-Electron Laser (FEL) project with a competitive funding. The purpose of this project is to build a mid-infrared FEL based on the cERL, and to use that FEL as a light source for creating the processing database required for industrial lasers. The FEL system is a single-pass FEL composed of two 3-m undulators and a matching section between them. The FEL was constructed from October 2019 to May 2020. The commissioning was completed successfully, and the target power of the project was almost achieved.

INTRODUCTION

In recent years, due to its light weight and low cost, there is an increasing demand for organic materials such as resins and engineering plastics as industrial materials to replace metals. However, the processing of organic materials is generally performed by machining, molding, or laser processing using a fixed-wavelength high-power laser such as a CO_2 laser or a fiber laser. On the other hand, organic materials have steep absorption peaks in the mid-infrared wavelength (5 - 25 μm) due to molecular vibration modes. These steep absorption peaks are used to specify the molecular structure in chemical analysis. Non-thermal processing utilizing this absorption characteristic is an ideal processing method for improving the processing efficiency from the existing laser processing. However, little information available for each organic material, such as optimum wavelength, power density and pulse width required for processing such as cutting and welding. In the mid-infrared region, there is no high-power tunable laser on either the short-wavelength side or the long-wavelength side of the CO2 laser, so there is no processing data of laser process. To create a database for efficient processing of organic materials, we need a high-power tunable light source operating in this wavelength region.

Currently, FEL [1, 2] is the only candidate for a high-power light source that meets this requirement. The High Energy Accelerator Research Organization (KEK) has started an FEL project with competitive funding from the New Energy and Industrial Technology Development Organization (NEDO). The purpose of this project is to construct an infrared FEL using the compact ERL [3], which is the test accelerator of ERL [4] in KEK, and to use the FEL as a light source to create the processing database required for industrial lasers. The FEL is also expected to be a demonstration machine for ERL-based FEL for future EUV lithography light sources [5]. This paper reports on the construction of the ERL-based infrared FEL at KEK.

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COMPACT ERL AT KEK

The cERL is a superconducting accelerator for the purpose of developing technologies necessary for the realization of next-generation ERL-based accelerators and demonstrating their performance. The cERL was commissioned in 2013 and has been in operation to date. The average beam current in CW operation increased by an order of magnitude each year, and an energy recovery operation with a beam current of 0.9 mA was achieved in 2016 [6].

Table 1: Design and Typical Operational Parameters of the cERL

Parameter	Design	Typical
Beam energy [MeV]	35	17.5-19.0
Injector energy [MeV]	5	3 – 4
Gun energy [keV]	500	←
Bunch repetition [GHz]	1.3	←
Average current [mA]	10	1
Operation mode	CW & Burst	←

We have utilized the cERL as a research platform for a laser Compton X-ray [7], THz radiation from ultra-short electron bunches [8, 9] and an EUV-FEL for next-generation lithography [5]. Recently, an irradiation beamline was newly installed in response to a commissioned research funded by a private company [10]. Here, we are engaged in research such as manufacturing tests of ^{99}Mo, which is a raw material for ^{99m}Tc, an RI for nuclear medicine, and physics and chemistry experiments for reforming and regenerating asphalt. Table 1 shows the design and typical operating parameters of the cERL. The repetition rate of the electron bunch in normal operation is 1.3 GHz. In FEL

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operation, the repetition rate becomes 81.25 MHz by exchanging the laser for the photocathode electron gun, and the bunch charge increases from 0.77 to 60 pC. The average current in CW mode under this condition is 5 mA. However, since the maximum average current is limited to 1 mA, the FEL will be operated in burst mode for a while.

IR-FEL BASED ON COMPACT ERL

The infrared FEL (IR-FEL) developed by KEK covers a wavelength of 10 to 20 µm as a mid-infrared light source for investigating the processing characteristics of organic materials. As the FEL for that purpose, we chose the single-pass FEL [11] instead of the proven resonator type FEL [12-14] used in ERL.

In general, a high-quality high-peak current beam and a long undulator are required to realize lasing with a single-pass FEL. Since the cERL cannot be expected to have a very high-peak current, an undulator of at least 7 to 8 m is required to reach the power saturation of FEL using a planar type undulator. Since the output power that must be achieved under the contract with NEDO is 1W class when operating in CW mode, we decided the required undulator length to 3 m and the number units to two. Figure 1 shows the layout of the cERL after modification for IR-FEL. These undulators were installed in the south-straight section of the cERL.

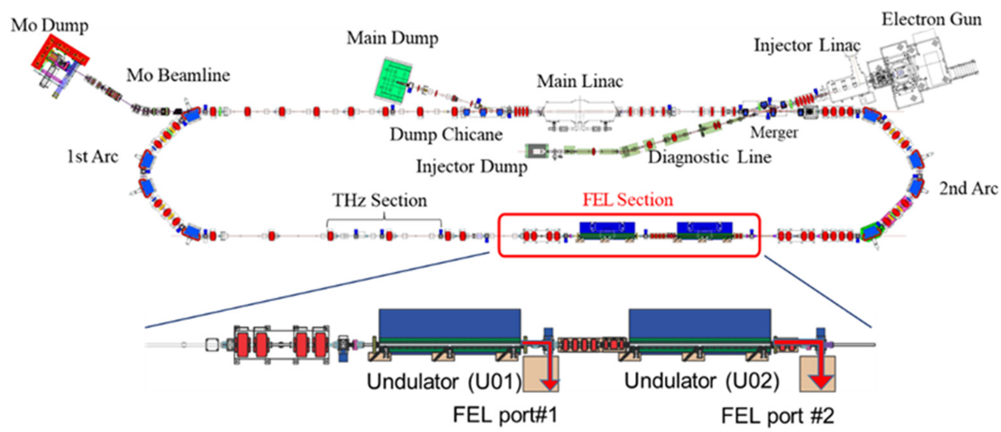

Figure 1: Layout of the cERL after modification for IR-FEL (upper) and enlarged drawing of the undulators installed in the south-straight section (lower).

Undulators

Due to the relatively low beam energy of the cERL, a shorter period length of the undulator is required to obtain FEL amplification at wavelengths of 10 to 20 µm. Furthermore, a small magnetic pole spacing (gap) is required to obtain a sufficient K-value with such a shorter period length. On the other hand, a small gap causes beam loss and radiation. These effects cannot be ignored in CW operation of the cERL. In consideration of the FEL power at the wavelengths and the beam loss in CW operation, we have selected a combination of a period length of 24 mm and a gap of 10 mm.

Figure 2: Fixed gap planar undulators installed in the cERL.

Figure 2 shows two undulators installed in the south-straight section of the cERL. These undulators are fixed gap planar undulators with the function of Adjustable Phase Undulator (APU) [15]. The lower magnet array can slide in the beam axis direction, and the wavelength of the FEL can be adjusted by changing the phase difference between the upper and lower magnet arrays. The magnet material is Ne-Fe-B, and the K-value is 1.4 when the phase difference is zero. The undulator has 124 periods, and a total length of 3 m. The undulator weighs about 4 tons. The structure without the gap variable mechanism greatly contributed to the cost reduction and weight reduction. After commissioning in June 2020, the undulators were tapered by sandwiching shims of different thickness in the mounting of the upper magnet array.

Vacuum Duct and Monitors

The undulator is equipped with an aluminum extruded vacuum duct. The opening of the vacuum duct is an ellipse with a horizontal width of 50 mm and a vertical length of 7.8 mm (Fig. 3). The vacuum duct has three small beam profile monitors. Ce doped YAG crystal is used as the scintillation screen. These screens are moved in and out through the ICF34 ports at a 45-degree angle to the beam axis (Fig. 4).

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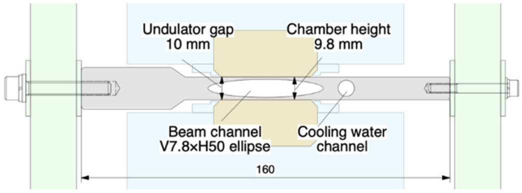

Figure 3: Cross section of the undulator beam duct. The undulator duct is made of extruded aluminum pipe with an opening of H50 mm x V7.8 mm.

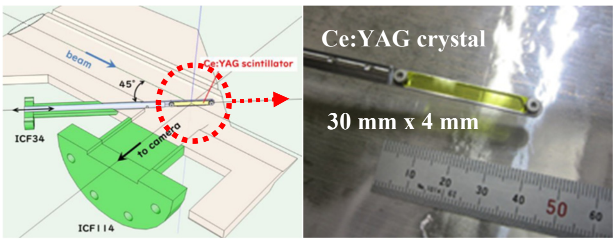

Figure 4: Newly developed small beam profile monitor using ICF34 port.

Matching Section Between Undulators

The distance between the two undulators is 2.3 m, and an FEL extraction system for separating the FEL radiation from the electron beam and extracting it into the air, four Q-magnets, and a chicane electromagnet [16] are installed there. The FEL radiation is extracted by a perforated gold-coated SUS mirror attached to a two-stage screen holder (Fig. 5). The hole diameter is 8 mm, and the electron beam is transported downstream through this hole, and only the FEL radiation is reflected in the 90-degree direction and extracted into the air through KRS-5 vacuum windows. The same system is also installed downstream of the second undulator. The electron beam envelopes in the horizontal and vertical planes must be optimized to minimize the average beam size in the undulators. The Q-magnets are used for matching the electron beam to the designed envelopes. The chicane is used to control the micro-bunching formed in the electron bunch by the FEL interaction at the first undulator and to enhance the optical amplification at the second undulator.

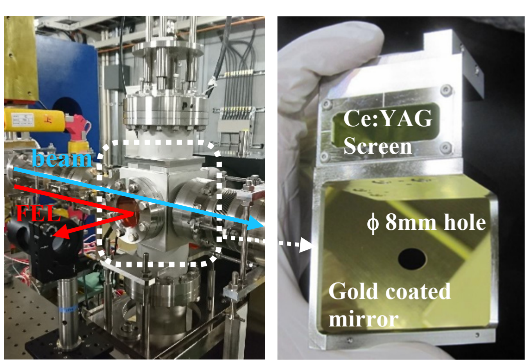

Figure 5: FEL extraction system (left) and the perforated gold-coated SUS mirror for reflecting FEL radiation (right).

Expected FEL Performance

Assuming an electron beam with an energy of 17.5 MeV, a charge of 60 pC/bunch, a bunch length of 1 ps (fwhm) with a gaussian shape, normalized emittances of 3 mm mrad, and an energy dispersion of 0.1%, an FEL output with a maximum energy of 0.1 µJ/pulse can be expected at a wavelength of 20 µm. If the IR-FEL is operated in CW mode with an 81.25MHz repetition rate, the average FEL power is expected to be up to about 10 W. However, due to the difficulty of achieving the target beam quality at low beam energy where the space charge effect cannot be ignored, we set the target FEL power in the project to 1 W.

Commissioning

The IR-FEL was constructed in the cERL at KEK from October 2019 to May 2020. The FEL commissioning was performed in two periods, June to July 2020 and February to March 2021. In the later FEL experiments, the target FEL power of the project was almost achieved due to the undulator tapering and/or beam quality improvement [17], and several types of sample irradiation experiments were conducted.

CONCLUSION

The ERL-based single-pass IR-FEL was constructed in the cERL at KEK. The commissioning was completed successfully, and the target power of the IR-FEL project was almost achieved while operating in burst mode. Our next goal is to demonstrate high-reptation lasing of the IR-FEL in the CW operation.

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