

# PRESENT STATUS OF KYOTO UNIVERSITY FREE-ELECTRON LASER FACILITY, KU-FEL\*

H. Zen<sup>†</sup>, T. Kii, H. Ohgaki, Institute of Advanced Energy, Kyoto University, Uji, Japan

## Abstract

There are two accelerator based infrared light sources in Kyoto University Free-Electron Laser (FEL) facility. One is a mid-infrared FEL covering the wavelength range from 3.4 to 26 micro-m driven by 40-MeV multi-bunch electron beams supplied from an S-band RF gun and an S-band linac. The other is a coherent undulator radiation covering the wavelength range from 0.1 to 0.4 THz driven by 3.6-MeV electron beam supplied from an S-band RF gun. Present status of those accelerator based infrared light sources is described in this paper.

## INTRODUCTION

Kyoto University Free-Electron Laser (KU-FEL) facility has two accelerator-based infrared light sources. A schematic diagram of the KU-FEL facility is shown in Fig. 1. One is a mid-infrared FEL (MIR-FEL) [1] covering the wavelength range from 3.4 to 26 μm and the FEL is driven by 40-MeV multi-bunch electron beams supplied from an S-band RF gun and an S-band linac. The other is a Terahertz Coherent Undulator Radiation (THz-CUR) [2] covering the frequency range from 0.1 to 0.6 THz driven by a 3.6-MeV electron beam supplied from an S-band RF gun. MIR-FEL and THz-CUR are open to international and domestic external users under the Joint Usage/Research Center for Zero Emission Energy Research program [3] of the Institute of Advanced Energy, Kyoto University. The history of number of the users and the operational time of the KU-FEL facility are shown in Figs. 2 and 3 respectively. The number of external user groups is 17 in the fiscal year 2023. The total operational time of KU-FEL in the fiscal year 2022

was around 450 hours, which is 47% of the maximum operational time per year (960 hours). Approximately 90% of the operational time was used for user experiments.

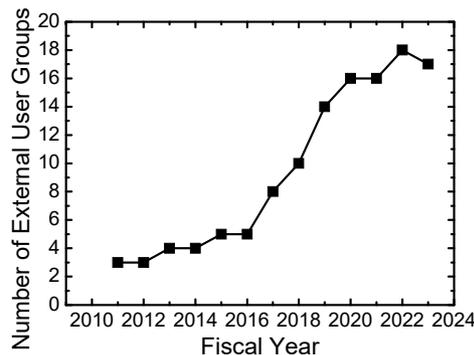


Figure 2: The history of number of external user groups.

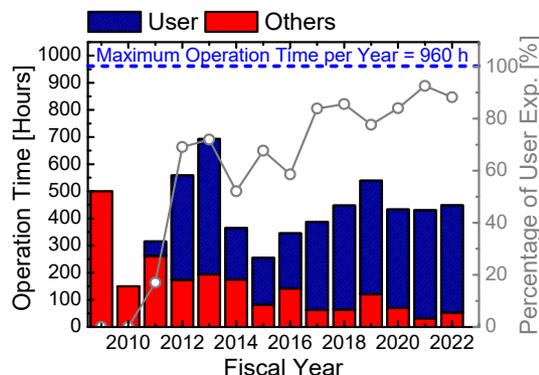


Figure 3: The history of operational time of KU-FEL.

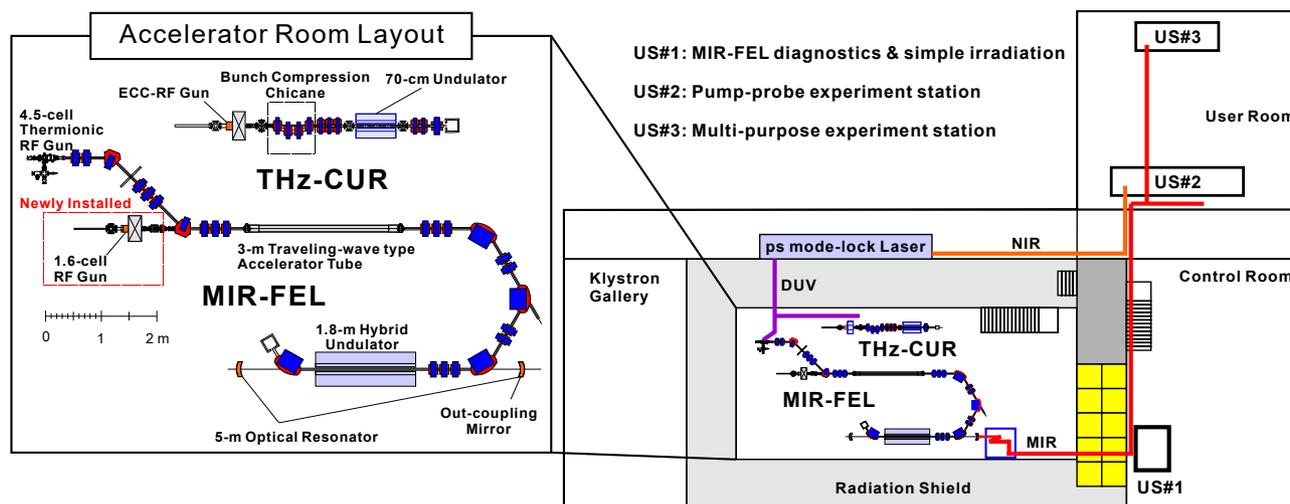


Figure 1: Schematic diagram of KU-FEL facility in May 2023.

<sup>†</sup> zen@iae.kyoto-u.ac.jp

## MIR-FEL

The MIR-FEL in KU-FEL facility is normally operated with the thermionic cathode operation of the 4.5-cell RF gun equipped with a LaB<sub>6</sub> cathode. The gun can also be operated as a photocathode RF gun by irradiating multi-bunch UV lasers on the cathode because of the low work function of the cathode [4]. The typical performances of MIR-FEL under those two operation modes are summarized in Table 1. On one hand, under thermionic operation, MIR-FEL can provide FEL pulses with a micro-pulse repetition rate of 2856 MHz. On the other hand, under the photocathode operation, the micro-pulse repetition rate is reduced to 29.75 MHz. However, electron beams with a higher bunch charge than the thermionic cathode operation can be used for FEL lasing in the case of the photocathode operation. The maximum bunch charge in the case of the thermionic operation is around 60 pC and that in the case of the photocathode operation is around 200 pC. The higher bunch charge enables us to obtain higher gain and higher extraction efficiency. In the thermionic and photocathode operations, the extraction efficiencies of 5.5% [5] and 9.4% [6] have been achieved, respectively. The micro-pulse duration and shape have been measured and reported [7]. As a result, the micro-pulse duration under the thermionic operation was determined as 230 fs at the lasing wavelength of 10.3  $\mu\text{m}$ . And the micro-pulse duration under the photocathode operation was determined as 150 fs at the lasing wavelength of 10.7  $\mu\text{m}$ . At the same time, we confirmed that FEL pulses have the Burnham-Chiao ringing, i.e., sub-pulses and  $\pi$ -phase jumps between ringing pulses [7].

Table 1: Typical performances of MIR-FEL under the thermionic and photocathode operation of the 4.5 cell RF gun.

|                            | Thermionic                   | Photocathode               |
|----------------------------|------------------------------|----------------------------|
| Wavelength Range           | 3.4-26 $\mu\text{m}$         | TBD                        |
| Max. Macro-pulse Energy    | $\sim 60$ mJ                 | $\sim 4.5$ mJ              |
| Macro-pulse duration       | @10 $\mu\text{m}$            | @9 $\mu\text{m}$           |
| Macro-pulse rep. rate      | $\sim 2$ Hz                  | $\sim 3.5$ Hz              |
| Max. Micro-pulse energy    | 10 $\mu\text{J}$             | 40 $\mu\text{J}$           |
| Micro-pulse duration [7]   | @10.3 $\mu\text{m}$          | @10.7 $\mu\text{m}$        |
| Micro-pulse rep. rate      | 2856 MHz                     | 29.75 MHz                  |
| Max. extraction efficiency | 5.5% @11.6 $\mu\text{m}$ [5] | 9.4% @11 $\mu\text{m}$ [6] |

Recently, the origin of complex beam profiles observed in KU-FEL has been determined as the airy pattern, which is inherently generated when a hole-coupling was used [8]. A simple and efficient way to make the beam profile fundamental Gaussian mode has also been introduced.

MIR-FEL has three user stations. User station 1 (US#1) is dedicated to MIR-FEL diagnostics and simple irradiation experiments. User station 2 (US#2) is dedicated to pump-probe experiments. User station 3 (US#3) is dedicated to multi-purpose use. Detailed explanations of those stations can be found on the website [9].

### Improvement of Transport Efficiency

Until 2018, the demand to have higher FEL intensity is not high. Therefore, the optics used in the MIR-FEL transport line is not optimized to have high transport efficiency. However, after a project to realize high-harmonic generation in gas targets by MIR-FEL [10] was approved in the fiscal year 2018, there was increasing demand for higher FEL intensity. To fulfil this demand, we modified the configuration of the FEL transport line as shown in Fig. 4. In the old setup, two KRS-5 windows with an incident angle of  $\sim 0$  degrees were used. One KRS-5 window was the vacuum window to separate the ultra-high-vacuum environment required for electron accelerators from the atmosphere. The other KRS-5 window was used for the injection of a visible guide laser and for monitoring the macro-pulse shape of the FEL. Each KRS-5 window has  $\sim 70\%$  transmittance. Therefore,  $\sim 50\%$  of energy loss occurred in this transport optics. In the new setup, the number of KRS-5 windows in the main FEL beam path was reduced from 2 to 1. The angle of the KRS-5 window used for the vacuum window was changed from 0 to 45 degrees to have a P-polarized injection condition. The transmittance of MIR-FEL is increased from 70 to 85.5% by changing the incident angle and P-polarized injection condition. The surface reflection of the vacuum window is used for the injection of the visible guide laser and monitoring of the macro-pulse shape of the FEL. Therefore, no additional KRS-5 window is needed in the main FEL beam path. By this modification, an increase of FEL intensity with the factor 1.74 ( $1/0.7 \times 0.855/0.7$ ) can be expected. After changing the setup, the FEL intensity increase with the expected factor has been confirmed.

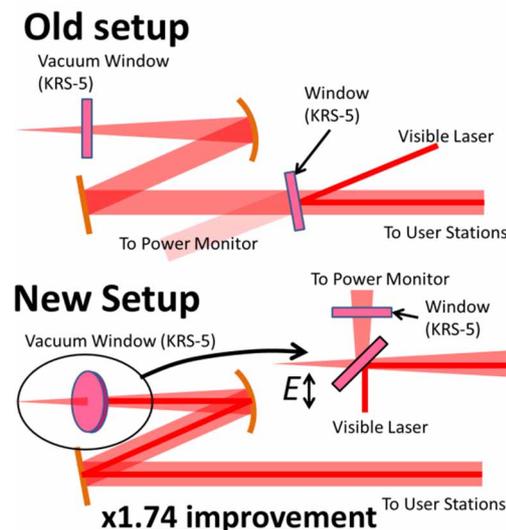


Figure 4: Old and new setup in the MIR-FEL transport line.

## THZ-CUR

THZ-CUR consists of an S-band RF gun, a solenoid magnet, a bunch-compression chicane, quadrupole magnets, and an undulator. The schematic diagram of THZ-CUR is shown in Fig. 1. Initially a 1.6-cell RF gun was used as the electron source of THZ-CUR [11]. We confirmed the saturation behaviour of the intensity against the bunch charge because of bunch elongation induced by the strong space charge effect [12]. Countermeasures to avoid saturation (longitudinal and transverse profile manipulation) have been proposed [13]. The properties of THZ-CUR with the 1.6-cell photocathode RF gun are summarized in Table 2 [2].

By using quasi-monochromatic intense THz radiations from THZ-CUR in the KU-FEL facility, an efficient and fast switchable method to control the polarization state of the THz beam has been developed [14].

Table 2: The properties of THZ-CUR with the 1.6-cell photocathode RF gun.

| Parameters              | Value                     |
|-------------------------|---------------------------|
| Frequency range         | 0.16-0.65 THz             |
| Typical bandwidth       | ~10%                      |
| Max. Micro-pulse energy | ~1 $\mu\text{J}@0.16$ THz |
| Micro-pulse duration    | 60 ps@0.16 THz            |
| Max. peak power         | 38 kW@0.33 THz            |

In 2019, the 1.6-cell RF gun was replaced with an Energy Chirping Cell attached RF gun (ECC-RF gun) [15] in collaboration with Dr. Sakaue, University of Tokyo. In the case of the 1.6-cell RF gun, a small energy chirp introduced by the small difference of acceleration gradient in the bunch length was used to introduce the energy chirp for the magnetic bunch compression in the chicane. The small energy chirp can easily be reduced by a strong space charge effect when the bunch charge is high. Since the ECC-RF gun has a specially designed energy chirping cell that introduces strong energy chirp, a shorter bunch length than that of the 1.6-cell RF gun can be expected. Commissioning experiments have been performed and the properties of the THZ-CUR using the ECC-RF gun have been examined [16]. Since ECC spends some part of RF energy fed to the gun for introducing energy chirp, the electron beam energy after the gun was reduced from 4.6 to 3.3 MeV when the 1.6-cell RF gun was replaced with the ECC-RF gun. The lowest frequency of the THZ-CUR source was reduced from 0.16 to 0.08 THz. The highest frequency observed in the commissioning experiment was 0.4 THz. We consider higher frequency than 0.4 THz can be generated but the highest frequency of THZ-CUR with the ECC-RF gun has not been examined yet.

## FUTURE PERSPECTIVE

A new 1.6-cell RF gun dedicated to the high-bunch-charge operation of MIR-FEL have been installed. Commissioning experiments using a copper cathode has been

performed and FEL lasing with electron beams generated from the gun having a 60-pC bunch charge with 4- $\mu\text{s}$  macro-pulse duration has been achieved. The cathode will be exchanged with CsTe coated Molybdenum cathode and high-bunch-charge operation up to 1 nC will be possible. This upgrade will enable us to obtain extraction efficiency beyond 20% and 1-mJ class micro-pulse energy of the MIR-FEL.

The THZ-CUR will be modified to oscillator configuration to demonstrate the bunched FEL concept [17] and its application to THz acceleration of electron beam. Our proposal was approved and machine modification will be performed in the fiscal year 2023.

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