PRESENT STATUS OF INFRARED FEL FACILITY AT KYOTO UNIVERSITY*

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Abstract

A mid-infrared Free Electron Laser (FEL) named KU-FEL has been developed for promoting energy related research at the Institute of Advanced Energy, Kyoto University. KU-FEL can cover the wavelength range from 3.5 to 23 µm and routinely operated for internal and external user experiments. Recently a THz Coherent Undulator Radiation (CUR) source using a photocathode RF gun has been developed as an extension of the facility. As the result of commissioning experiment, it was confirmed that the CUR source could cover the frequency range from 0.16 to 0.65 THz. Present statuses of these infrared light sources are reported in this paper.

INTRODUCTION

An oscillator type Mid-Infrared Free Electron Laser (MIR-FEL) named as KU-FEL has been developed at the Institute of Advanced Energy, Kyoto University for promoting energy related research [1]. The FEL succeeded in its first lasing [2] and power saturation [3] in 2008. At that time, the tunable range of the FEL was not so wide (only 10 to 14 µm) because of the limited gain of the FEL and macro-pulse duration of the electron beam. In order to extend tunable range, the optical cavity mirrors and the undulator have been replaced in January 2012. Then the tunable range of KU-FEL has been extended to 5 – 15 µm [4]. The narrowest undulator gap has been reduced from 20 to 15 mm by replacing the vacuum duct of undulator section in 2013. As the result of commissioning experiment, it was confirmed that KU-FEL could cover the wavelength range from 5 to 21.5 µm [5]. After the replacement of the vacuum duct of the undulator, some efforts to optimize the operation parameter of KU-FEL have been made and now the tunable range was extended 3.5 – 23 µm.

Now, KU-FEL is routinely operated for internal and external user experiments. The layout of KU-FEL facility is shown in Fig. 1. There are three user stations available. The user station #1 is the FEL beam diagnostics and simple irradiation station. In this station, an MIR-monochromator, MIR-detectors, pyroelectric energy meters and some focusing optics are available. The user station #2 is the pump-probe experiment station. In the pump-probe station, ns-Nd:YAG laser (1064, 532 and 266 nm), ps-Nd:YVO$_4$ laser (1064 and 532 nm), and a closed-cycle cryostat with optical windows are available. Users can perform the pump-probe experiment of solid samples with the lowest sample temperature of 12 K with various combinations of MIR-FEL and those solid state lasers. At this station, MIR induced mode-selective phonon excitation experiments of solid samples have been performed [6-8]. The station #3 is intended for multi-purpose application. There is an optical table and users can construct their experimental setup on the table.

In order to satisfy the user who wants to perform some nonlinear spectroscopy in MIR region, the photocathode operation of the KU-FEL has been demonstrated [9]. It was confirmed that the peak power of the FEL can be significantly increased by the photocathode operation with a significant reduction of the average power.

Recently, a THz Coherent Undulator Radiation (THz-CUR) source using a photocathode RF gun has been developed as an extension of the facility [10]. When the electron bunch length is shorter than the radiation wavelength, the radiations from each electron are coherently superposed. In the condition, the radiation intensity can be intense and the radiation has good longitudinal coherence. This radiation is called as “coherent” radiation. In the case of undulator radiation, it is called as CUR. In the THz region, some CUR sources have been developed so far [11-13]. Our THz-CUR source consists of a 1.6-cell photocathode RF gun, a bunch compression chicane, and 0.7-m Halbach type undulator. The total length of the machine is about 5 m. The THz-CUR source shares a photocathode driving laser system [14] and an RF source with a 4.5-cell RF gun of KU-FEL. The construction and commissioning of THz-CUR source were finished in August 2016. The layout of THz-CUR source is also shown in Fig. 1.

MIR-FEL

The oscillator type MIR-FEL named as KU-FEL consists of a 4.5-cell thermionic RF gun with a LaB$_6$ thermionic cathode which generates multi-bunch electron beams with the energy of 8.4 MeV, a dog-leg energy filtering section, a 3-m traveling-wave type accelerating structure, a bunch compressing 180-deg. arc section, a 1.8-m hybrid undulator, and a 5-m optical cavity. The typical characteristics of KU-FEL under the thermionic cathode operation are listed in Table 1. The available macro-pulse energies of KU-FEL measured at the user station #1 are shown in Fig. 2.

The shortest wavelength of KU-FEL (3.5 µm) is limited by the maximum available electron beam energy and the undulator period length which are 40 MeV and 33 mm, respectively. We can generate FEL with bit shorter wavelength by increasing available electron beam energy of the facility. The reason why the longest wavelength is

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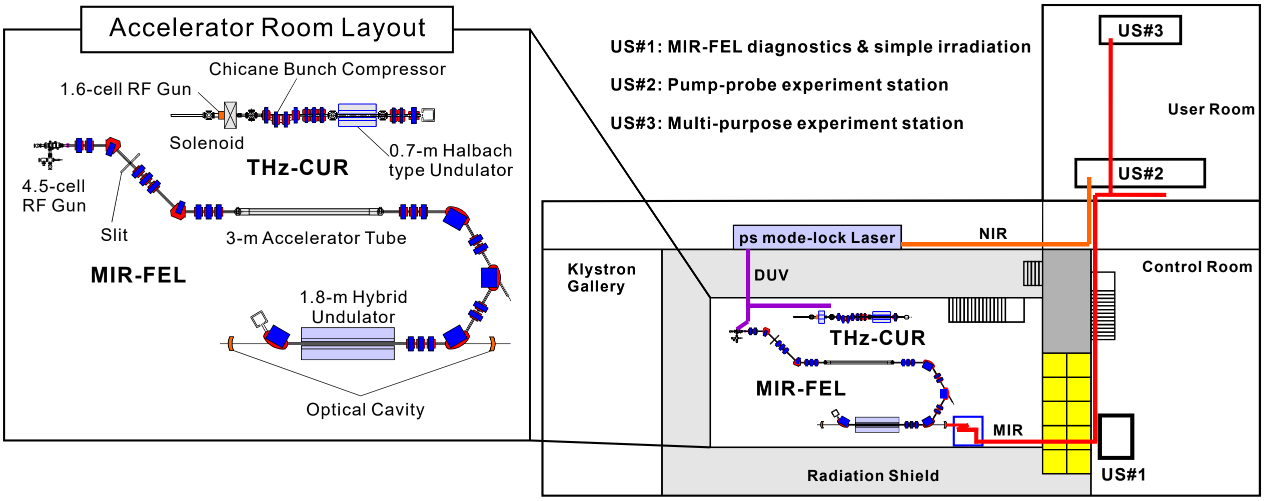

Figure 1: Layout of the infrared FEL facility in August 2017.

limited to 23 μm is not well understood. The resonant wavelength of the undulator and KU-FEL can be longer when the electron beam energy is reduced. We have tried several times to achieve FEL lasing at the wavelength of 24 μm by reducing the electron beam energy. However, we could not observe FEL lasing at this wavelength. For further investigation of the reason, a fast pyroelectric detector (ELTEC, Model 420) was introduced for measuring the round-trip loss of the optical cavity. The measured temporal evolution of FEL macro-pulse at the wavelength of 19.5 and 23 μm are shown in Fig. 3. The decaying slopes of the measured waveforms were analyzed and the optical cavity losses were determined as 6% and 8% for 19.5 and 23 μm, respectively. As one can see in the figure, the waveform of 23-μm condition has faster-rising slope than that of 19.5-μm. It implies that the FEL gain of 23-μm condition was higher than that of 19.5-μm condition. The round-trip loss of the optical cavity tends to increase as the wavelength of the FEL gets longer. However, this slow increase of the round-trip loss of the optical cavity seems to be not the critical factor which limits the tunable range of KU-FEL.

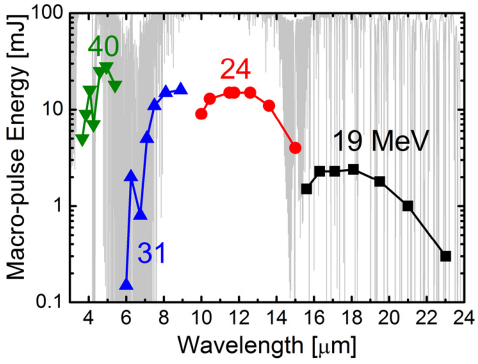

Figure 2: The available macro-pulse energy of KU-FEL at the user station #1.

In other facilities, it was reported that the FELs with an optical cavity having partial waveguide have specific wavelength where the phase difference of two transverse optical modes is π and the FEL lasing gets difficult [16]. The shortest specific wavelength λ_0 can be given by:

$$\lambda_0 = \frac{b^2}{2L}\,, \tag{1}$$

where b and L denote the height and longitudinal length of vacuum duct inserted in the undulator, respectively. At KU-FEL, the height b is 11 mm and length L is 2 m. Then using Eq. (1), the specific wavelength is 30.25 μm. The specific wavelength calculated was not so different from the longest wavelength limit of KU-FEL. This might be the reason why the KU-FEL cannot achieve lasing at 24 μm. Some efforts to understand the reason for the longest wavelength limit are being undertaken.

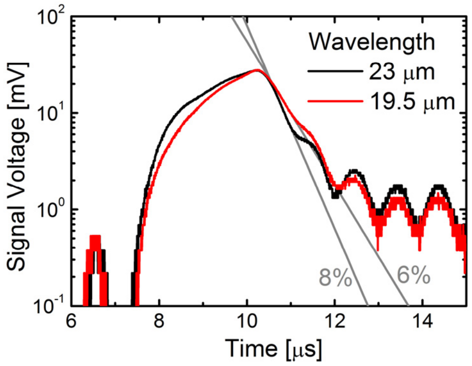

Figure 3: Temporal evolution of FEL macro-pulse at the wavelength of 19.5 and 23 μm.

Photocathode operation

A LaB_6 single crystal is used as the thermionic cathode installed in the 4.5-cell RF gun. The cathode can also be used as a photocathode. A multi-bunch ps-DUV laser system [14] has been developed for the photocathode operation of the 4.5-cell RF gun and KU-FEL. In 2015,

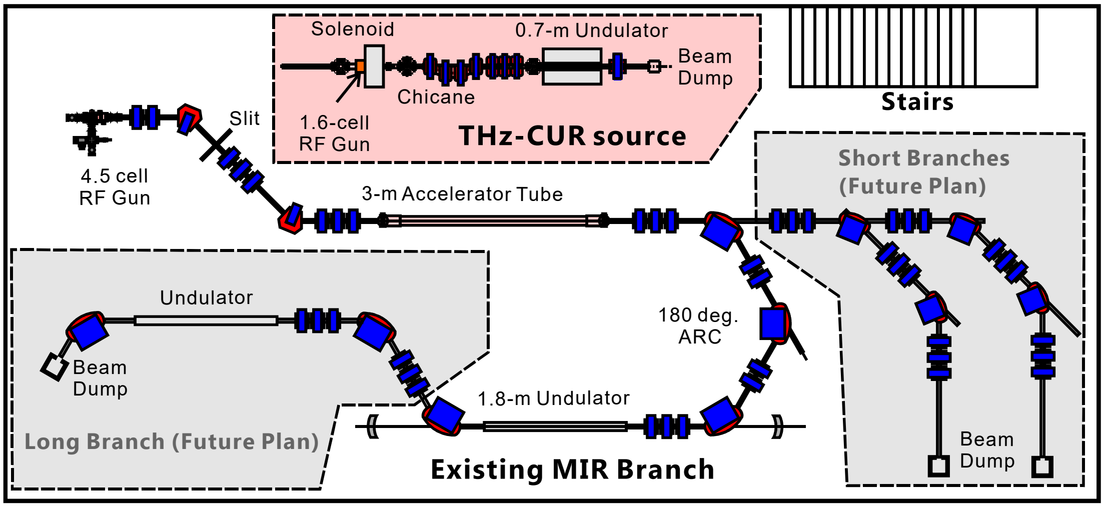

Figure 4: Possible arrangement of new beamlines in the infrared FEL facility at the Institute of Advanced Energy, Kyoto University.

we conducted some commissioning experiments and achieved the photocathode operation of KU-FEL [9].

Under the photocathode operation condition, the bunch charge was approximately 150 pC, which was three times as high as that of thermionic operation. Then the micro-pulse energy was increased from 2 to 13 µJ at the FEL wavelength of 11.7 µm. At that time, the macro-pulse energy of KU-FEL with photocathode operation was around 0.8 mJ, which is much smaller than that of thermionic operation (13 mJ). It is because of the difference of micro-pulse repetition rate; 29.75 MHz for photocathode operation and 2856 MHz for thermionic operation. The photocathode operation can realize the condition of FEL with low average power and high peak power. This condition is good for nonlinear optical experiments where the peak fluence of the laser beam is important.

THz-CUR SOURCE

Since a more detailed report will be available in these proceedings [17], here we only show some brief results obtained by the commissioning experiments of THz-CUR source. As the result of the commissioning experiments, it was confirmed that the THz-CUR source could cover the frequency range from 0.16 to 0.65 THz by using short bunch electron beam with the energy of 4.6 MeV. The peak power of the THz-CUR source was measured to be higher than 20 kW. The THz-CUR intensity dependencies on the electron bunch charge were measured at various undulator gap conditions. As a result, saturation of THz-CUR intensity was observed. The saturation could be caused by the bunch lengthening and emittance degradation due to strong space charge effect. For real user experiments, a THz transport line should be constructed.

FUTURE PERSPECTIVE

The MIR-FEL can now cover the wider range than its initial target wavelength range (5–20 µm). Although there are some remained study subjects such as the limitation of the longest wavelength, introduction of photocathode operation to user experiments, and further optimization of the operation conditions, it is reasonable to mention the future upgrade of the facility. The possible arrangement of additional beamlines is shown in Figure 4. A similar configuration has been reported in the previous report [18] but some descriptions are updated. As shown in the figure, there is some space to install a long branch and two short branches. An undulator can be installed in the long branch. The target wavelength could be THz region. There are two possible schemes to generate monochromatic THz beam; one is the CUR and the other is the oscillator FEL. The CUR does not require optical cavity and is much simpler in operation and realization than the oscillator FEL. So, we may start from CUR. One of the short branches can be used for coherent THz generation using various schemes such as coherent transition radiation [19, 20], Vavilov-Cherenkov radiation from a grating pair [21], and resonant coherent diffraction radiation [22]. The other short branch can be used for electron beam irradiation and other interesting applications.

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