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INFRARED FREE-ELECTRON LASER PROJECT IN THAILAND

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Abstract

The infrared free-electron laser (IR FEL) project is established at Chiang Mai University (CMU) in Thailand with the aim to provide experimental stations for users utilizing accelerator-based coherent terahertz (THz) and mid-infrared (MIR) radiation. Main components of the accelerator system include a thermionic radio-frequency (RF) gun, an alpha magnet as a bunch compressor and energy filter, a travelling-wave RF linear accelerator (TW RF linac), a THz transition radiation (THz TR) station, two magnetic bunch compressors and beamlines for MIR/THz FEL. The system commissioning is ongoing to produce the beams with proper properties. Simulation results suggest that the oscillator MIR FEL with wavelengths of 9.5-16.6 µm and pulse energies of 0.15-0.4 µJ can be produced from 60-pC electron bunches with energy of 20-25 MeV. The super-radiant THz FEL with frequencies of 1-3 THz and 700 kW peak power can be generated from 10-16 MeV electron bunches with a charge of 50 pC and a length of 200-300 fs. Furthermore, the coherent THz TR with a spectral range of 0.3-2.5 THz and a pulse power of up to 1.5 MW can be obtained. The MIR/THz FEL will be used for pump-probe experiments, while the THz TR will be used in Fourier transform infrared (FTIR) and time-domain spectroscopy (TDS).

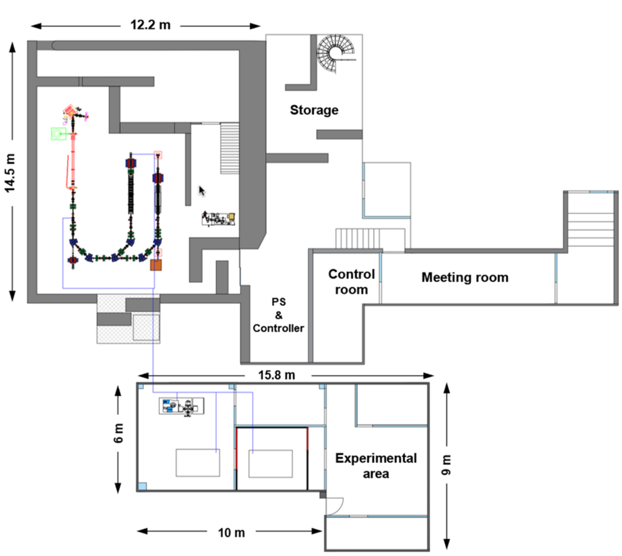

Figure 1: A layout of the IR FEL facility at PCELL consisting of areas for accelerator and experimental stations.

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INTRODUCTION

Ultrashort electron and photon pulses, especially in the femtosecond time scale, have become important tools for various applications in life science and materials science [1]. Accessibility to such short pulses is being offered at the PBP-CMU Linac Laboratory (PCELL) of the Plasma and Beam Physics (PBP) Research Facility, Chiang Mai University (CMU). At PCELL, we are especially interested in using ultrashort electron pulses to produce coherent THz radiation, MIR radiation and X-ray.

The establishment of the infrared free-electron laser (IR FEL) facility at PCELL includes the development of accelerator system, stations and beamlines for generating THz transition radiation (THz TR), MIR FEL, THz FEL, short-pulsed electron and X-ray as well as advanced experimental stations including FTIR spectroscopy, THz TDS and pump-probe experiments. This facility will be the first facility of its kind in Thailand and South-East Asia. The layout of the whole facility, including areas for the accelerator and the experiments is presented in Fig. 1. All buildings and infrastructure for both areas are already available and ready for installation of new accelerator components and experimental setups.

ACCELERATOR AND BEAMLINES

The accelerator system consists of a thermionic RF gun for producing electron beam with maximum kinetic energy of ~2 MeV, an alpha magnet for bunch compression and energy filtering, a TW linac for further accelerating the beam to reach energy in a range of 10 - 25 MeV. Two magnetic bunch compressors for MIR-FEL and THz-FEL beamlines are installed downstream the linac.

The advantage of PCELL facility comes from the original design of our electron accelerator system, which was constructed to produce electron beams with ultra-short bunch length in scale of femtosecond [2]. The electron beam with a bunch length as short as 180 fs was experimentally obtained [3]. Figure 2 shows the present setup of the accelerator system, radiation station and beamlines in the radiation shielding accelerator hall. Installation of beamline components is underway and it is expected to be completed in 2023. There are two stations for generating THz TR and short-pulsed electron/X-ray, and two beamlines for generating MIR and THz FEL.

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Figure 2: Current setup of the accelerator and beamlines.

THz Transition Radiation (THz TR) Station

The electron beam with ultrashort bunches allows us to apply the transition radiation technique for producing the coherent THz transition radiation (CTR), which is generated when electron beam passing through an interface between two media with different dielectric constants. A thin Al-foil is used as a radiator, which can be considered as a vacuum-conductor interface. The radiator is tilted at 45º facing the electron beam direction, thus, emitting backward TR perpendicular to the beam axis. At a wavelength about or longer than the electron bunch length, the TR radiation becomes coherent.

At our facility, it was experimentally shown that the THz TR obtained from 8-MeV electron bunches with a length of 300 fs covers the spectrum range of 5 - 60 cm^{-1} (0.15 - 1.80 THz) and the 10-MeV electron bunches with a length of 200 fs provide the spectrum range of 5-80 cm^{-1} (0.15-2.4 THz) [4, 5]. Currently, the RF system of the linac has been upgraded and electron beams with maximum energy of about 20 - 25 MeV are expected. The THz TR with broader spectral range (0.3 – 2.5 THz) and higher output pulse power (up to 1.5 MW) is aimed. Table 1 shows expected parameters of electron beam and THz TR produced from our system.

Table 1: Parameters of Electron Beam and CTR [6]

Parameter	Value
Beam energy (MeV)	22
Bunch charge (pC)	60
Electron bunch length (fs)	200 - 300
Frequency (THz)	0.3 - 2.5
Pulse energy (μJ)	0.17 - 0.25
Peak power (MW)	0.9 - 1.5

MIR-FEL and THz-FEL Beamlines

To extend the capability of our facility, two 180º-magnetic bunch compressors consisting of dipole, quadrupole and steering magnets are installed downstream the THz TR station. Two separate radiation beamlines for MIR and THz FEL are located following the bunch compressor systems. The FEL can be produced by various techniques. At our facility, two techniques are employed.

The first technique called "the oscillator FEL" is used to generate the MIR FEL. The main components of this beamline are a permanent undulator magnet and an optical cavity, which consists of two gold-coated copper mirrors placing at the two ends of the undulator [7]. The MIR FEL pulses are extracted from the optical cavity through a coupling hole in the upstream mirror and transported from the accelerator hall to the experimental area. The MIR FEL with tunable wavelength of 9.5 - 16.6 μm is expected to be produced from the 60-pC electron beam with energy of 22 to 25 MeV. The simulated FEL pulse energy is in a range of 0.15 - 0.4 μJ.

Another technique called the "pre-bunch FEL" or the "super-radiant FEL" is used to generate the THz FEL. In this beamline, ultrashort electron bunches with high peak current are produced before injecting them into the field of electromagnetic undulator. The microbunching process does not occur in this case since the electron bunches already have a length of equal or shorter than the radiation wavelength. The THz radiation is coherently emitted from electrons in the bunch. The radiation emitted from different undulator poles along the beam trajectory overlaps and interferes constructively. This leads to properly add up of the radiation in the forward direction and results in the enhancement of the radiation intensity that is proportional to the electron number squared.

The beam dynamic simulation results suggest that the 50-pC electron bunch with energies of 16 and 10 MeV will have rms bunch lengths of about 200 and 300 fs at the undulator entrance, respectively. This will yield the THz FEL with tunable frequency in a range of 1 - 3 THz. The maximum radiation peak power of about 700 kW is expected at 1 THz. Specifications of electron beam and radiation for MIR and THz FEL are listed in Table 2.

Table 2: Electron Beam and Radiation Parameters for MIR and THz FEL at PCELL [7, 8]

Parameter	MIR FEL	THz FEL
Beam energy (MeV)	22 -25	10 - 16
Bunch charge (pC)	60	50
Electron bunch length (fs)	200	200 - 300
Wavelength (μm)	9.5 – 16.6	100 - 300
Frequency (THz)	18.1 – 31.6	1 - 3
Radiation pulse length (ps)	~1	0.2 - 0.3
Pulse energy (μJ)	0.15 – 0.4	0.07
Peak power (MW)	≤ 0.4	≤ 0.7

Short-pulsed Electron/X-ray Irradiation Station

Since the accelerator system at PCELL is capable to produce ultrashort electron bunches, it has potential to conduct the study of "FLASH radiotherapy experiment". The experimental set up will be installed at the end of the accelerator straight section for irradiation with

- short-pulsed electron beam with energy of 6 - 25 MeV, 1 - 4 μs macropulse, 0.3 - 1.0 ps microbunch and high current (variable),
- short-pulsed parametric x-radiation with energy of 10-35 keV while using 15 to 20 MeV electron beam and a Si- crystal at observation angles of 10º - 45º.

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EXPERIMENTAL STATIONS

The THz TR and MIR/THz FEL produced from our system will be employed as the light source for THz-FTIR spectroscopy, THz TDS and pump-probe experiment.

THz-FTIR Spectroscopy

THz-FTIR is the most basic technique that utilizes the typical wide radiation spectrum in a MIR wavelength between 2 to 30 µm and a FIR wavelength between 30-1000 µm. The THz-FTIR spectrometer displayed in Fig. 3 including an external light source input port with matching optics is already available at our facility. The THz TR with wavelengths 120 - 1000 µm (0.3 – 2.5 THz) will be transported from the accelerator hall to this input port. With such a high radiation intensity than a Hg-lamp in a conventional THz-FTIR spectrometer, measuring liquid samples will be easier with higher transmitted/reflected signal. Since the THz TR is a coherent broadband radiation with radial polarisation, we can use essential design optics to select the polarization before transporting it into the FTIR spectrometer. Then, the measurement on polarization respond of materials can be conducted.

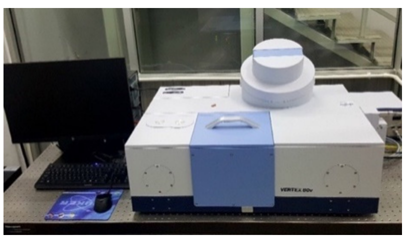

Figure 3: Bruker Vertex 80v FTIR spectrometer with a light source input port for THz TR.

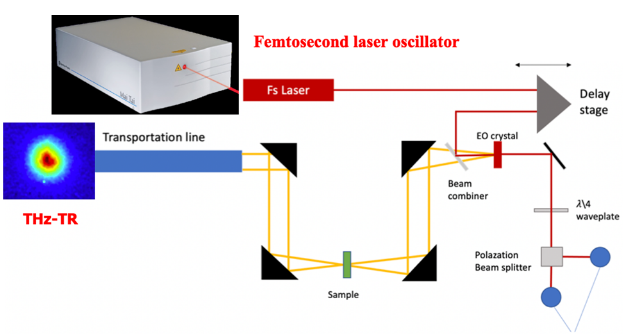

Figure 4: A diagram showing major components in the planned THz TDS setup at PCELL.

THz Time-domain Spectroscopy (THz TDS)

Another interesting technique is the THz TDS, which provides information of the sample's effect on both amplitude and phase of the THz radiation. The THz TDS is ideal for studying low-energy dynamics in matters such as inter- and intramolecular vibrations and phonon modes. The THz TDS system using the THz-TR together with an available femtosecond laser at PCELL will be developed. The synchronization between the repetition rates of the commercial femtosecond laser and the THz TR is very challenged. A diagram of the planed THz TDS setup is shown in Fig. 4. Similar systems are under the development at the TeraFERMI laboratory using also the THz TR and at the AIST laboratory using the coherent synchrotron radiation (CSR) [9 -11]

MIR and THz FEL Pump-probe Spectroscopy

The study of chemical processes in extremely short timescales lies in the area of femtochemistry, which was made possible with the use of short-pulsed lasers [12-13]. The appropriated technique used for studying ultrafast molecular processes is a "pump-probe spectroscopy". In this technique, an ultrashort laser pulse is split into two portions; a pump beam and a probe beam, with time delay between them. The pump beam is used to excite the sample, leading to a non-equilibrium state whilst the probe beam is used to monitor the pump-induced changes in optical properties, e.g., transmittance and reflectance, of the sample. Measuring the optical properties as a function of time delay between the arrival of pump and probe pulses provides information about relaxation of the sample. A picture illustrating a working principle of pump-probe spectroscopy using the MIR/THz FEL is shown in Figure 5.

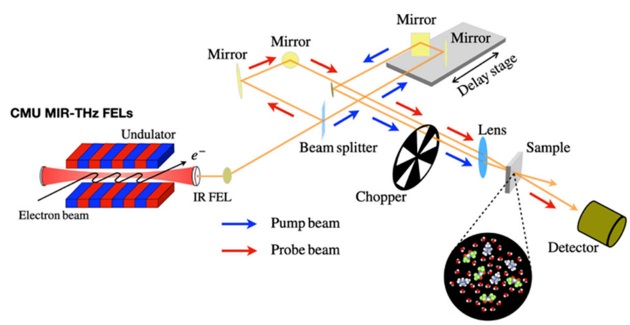

Figure 5: A drawing of a single-colour pump-probe spectroscopy using MIR/THz FEL as a light source.

CONCLUSION

An accelerator-based IR/THz FEL facility is under the construction at Chiang Mai University, Thailand. This project was officially launched in 2019 and planned to be ready for applications in 2024. Development of experimental stations using THz-FTIR spectroscopy, THz TDS, and pump-probe experiment is proceeded. The proof-of principle experiments using these stations are dedicated to "Astrochemistry experiment", "perovskites" and "metal oxides" for application in solar cell and "ionic liquids" for potential application in energy storage. The ultimate goal of this facility is to become the first user IR/THz FEL facility in South-East Asia that opens for all researchers from Thailand and Asian. It will provide experimental stations and advanced tools for frontier researches and applications in material science, biotechnology and medicine.

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