Journal of the Korean Physical Society, Vol. 57, No. 2, August 2010, pp. 344∼348

Research Activities on a MIR-FEL and Table-Top THz Generation in Kyoto University

H. Ohgaki,* T. Kii, K. Masuda, M. A. Bakr, K. Higashimura, R. Kinjo, K. Yoshida, S. Ueda and T. Sonobe
Institute of Advanced Energy, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan

Y. U. Jeong
Korea Atomic Energy Research Institute, Taejon 305-600, Korea

(Received 29 December 2009)

Free Electron Lasers (FEL), which could be useful for developing energy materials, have been exploited at the Institute of Advanced Energy, Kyoto University. A mid-infrared FEL has been developed, and FEL gain saturation at 13.2 μm was achieved for the first time in May 2008. A FEL beam characterization was performed. A macro pulse energy of 5 mJ/pulse and a peak power of about 3 MW were achieved. A FEL beam transport system was constructed in the user room. Furthermore a tabletop THz FEL amplifier for the spectral range from 150 to 300 μm, which consists of a photocathode RF gun and an undulator, has been proposed to strengthen the materials research. For evaluation of the proposed design, a start-to-end simulation was carried out. An output power of about 350 kW is expected with the proposed system.

PACS numbers: 41.60.Cr
Keywords: MIR-FEL, THz FEL amplifier, Start-to-end simulation
DOI: 10.3938/jkps.57.344

I. INTRODUCTION

Construction of a Mid-Infrared Free Electron Laser (MIR-FEL) facility (KU-FEL) at the Institute of Advanced Energy, Kyoto University (KU) was finished in 2006 [1]. We started FEL oscillation experiments in 2007 and succeeded in the first lasing at a wavelength of 12.4 μm in March 2008 [2]. A beam loading compensation method with an RF amplitude control in the thermionic RF gun was used to qualify the electron beam. To stabilize the RF phase shifts due to the time transient RF field in the RF gun, we developed a feed-forward RF phase control. Detuning method also was developed to sustain the macro-pulse length of the electron beam up to about 6 μs [3]. As a result, FEL gain saturation at 13.2 μm was observed for the first time at May 2008. In order to start application in renewable energy science, we have started to construction of the MIR beamline. For pilot applications of the MIR- FEL to optical properties measurements, an in-situ photoluminescence (PL) spectra measurement system for TiO_2 was installed to investigate the effects of FEL on the photoexcitation process, which may provide possibly gives rise to find more precise information on the photoelectric conversion mechanism.

The other research topic in our activities is related to THz radiations, which can be used beneficially for imaging, absorption spectrum measurements, and so on. Compared to coherent synchrotron radiation THz sources, the THz FEL has features such as high peak power, narrow spectrum bandwidth, and high coherency. However, the FEL facility generally needs a huge space. Therefore, a tabletop THz FEL system can make a great contribution to developments for THz light applications. Our previous paper [4] proposed a tabletop SASE-THz FEL amplifier. In this report, the evaluation of the THz FEL parameter by using a start-to-end simulation of the proposed THz FEL amplifier will be described in Section IV.

II. IR-FEL LASING EXPERIMENTS

The KU-FEL system consists of a thermionic RF gun driven by a 10-MW klystron, a 3-m accelerator tube driven by a 20-MW klystron, a beam transport system, and a Halbach-type undulator of 1.6 m. Figure 1 shows a diagram of the KU-FEL facility and the MIR-FEL beam transport line from the accelerator room to the application room.

A LaB_6 thermionic cathode of 2 mm in diameter was employed to produce a high-brightness electron beam. An achromatic transport system consists of a 45° bend-

*E-mail: ohgaki@iae.kyoto-u.ac.jp; Fax: +81-774-38-3426

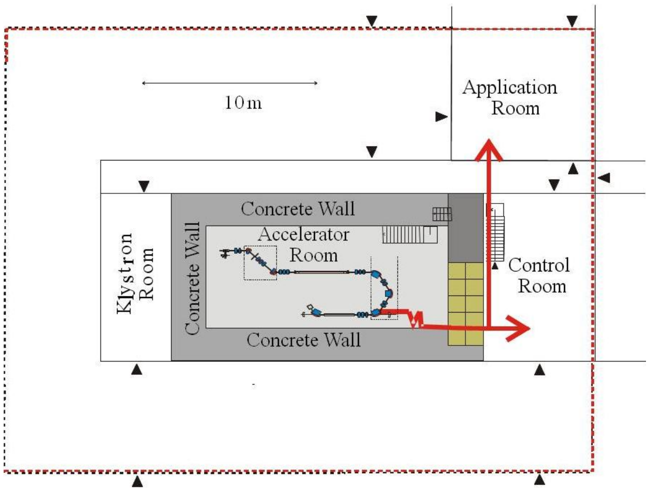

Fig. 1. Schematic view of the KU-FEL facility and the MIR-FEL beam transport line.

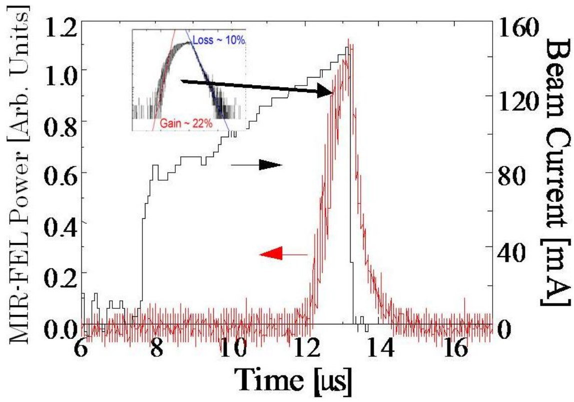

Fig. 2. Temporal profile of the beam current and the MIR-FEL power.

ing magnet and an energy slit, three quadrupole magnets and another dipole magnet, and it serves as an energy analyzer. The energy slit was set to select an electron beam with about a 3% energy spread. An S-band accelerator tube accelerates the electron beam to 40 MeV at a 20-MW RF power. For the saturation experiment, the electron beam energy was 23.9 MeV. The beam parameters were optimized to obtain the maximum FEL gain by the simulation code, GENESIS [5]. To achieve gain saturation in the MIR-FEL we used a beam loading compensation method with an RF amplitude control in the thermionic RF gun to generate an electron beam with a constant energy. We also developed and applied a feedforward RF phase control to stabilize the RF phase shifts during the macro-pulse.

The 180° arc designed for the bunch compressor was tuned to obtain a high peak current of the electron beam. Thus, the micropulse peak current was estimated from the simulation to be around 38 A. Two triplet quadrupoles located on both sides of the 180° arc worked as a beta-match component between the linac and the undulator. A planar-type undulator, which was used for the experiment in the collaboration between FELI and the University of Tokyo [6], was used. The undulator length was 1.6 m, the period was 40 mm, the number of periods was 40 and the undulator parameter K-value was varied from 0.99 to 0.17 by changing the gap of the undulator. In this experiment, we used a K-value of 0.99 to maximize the FEL gain in our system. The optical resonator consists of a pair of gold-coated Cu mirrors with 99.04% reflectivity, the upstream mirror of which has a coupling hole of 2 mm. The horizontal and the vertical normalized emittances measured were 4 πmm-mrad and 12 πmm-mrad at the undulator, respectively. Since the RF frequency was 2856 MHz in the KU-FEL linac, the cavity length was set to 4.516 m by using a set of five-axis mirror manipulators whose scanning resolutions in the longitudinal direction were 1 μm.

The FEL signal was measured with an HgCdTe (MCT) IR detector. Figure 2 shows the light output signal, as well as the electron beam current, during the experiment. The FEL gain was estimated from the exponential growth of the laser output signal to be 22%, and the optical loss was estimated from the decay of the laser output signal to be 10%, which includes detector response of about 100 ns. Therefore, the total FEL gain was 32%, as shown in Fig. 2. An approximately 10^7-W output power could be expected with a 4.5-μs buildup time, which corresponds to the electron beam used in the experiment. A 3D simulation with a modified GENESIS was performed from the RF gun to the FEL. In that simulation, a realistic geometry of the KU-FEL optical cavity, including the vacuum chamber, was taken into consideration. The results of these calculations indicated a total gain of around 31%, and this value agrees well with the experimental values.

A pyroelectric energy detector was used for quantitative evaluation of the radiation energy per pulse. The voltage signal from the detector was amplified by using Multi-function optical meter, and the absolute pulse energy was around 4.6 mJ/macropulse.

The long term stability within 30 minutes and the fluctuation, in FWHM, in the energy histogram were measured. The results indicated that the the fluctuation was around 15%. The wavelength spectrum was measured by using a monochromator and MCT detector. The peak wavelength was around 13.2 μm, and the linewidth was 1.8% in FWHM. Table 1 shows the main parameter of the MIR-FEL.

III. BEAMLINE DESIGN

At first, we measured the beam profile of the MIR-FEL at the accelerator room to design the beamline by using an MCT detector. The beam size was about 4.5 mm (FWHM) 640-mm downstream of the outcoupling hole

Table 1. Main parameters of the FEL beam

Wavelength (μm)	13.2
σ_λ/λ (%)	1
Average Power (mW)	4.6
Peak Power (MW)	2*
Power Stability (%, 30 min.)	15

*assumed 1 ps pulse duration

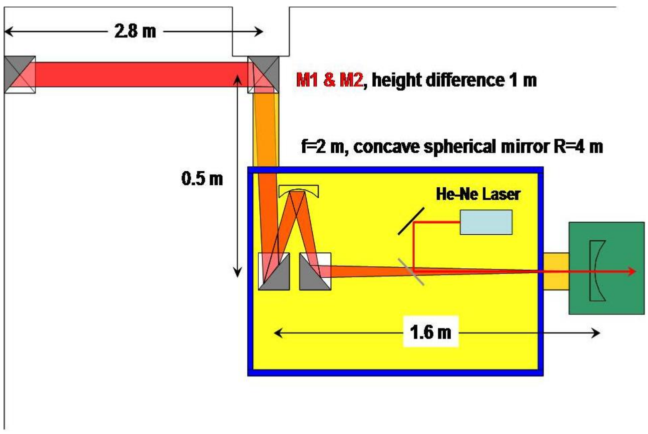

Fig. 3. Schematic drawing of the beam expander.

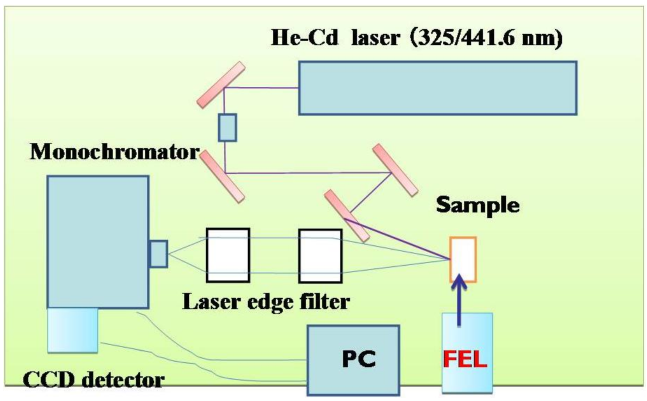

Fig. 4. A plane view of the optical measurement system for the pilot application of the MIR-FEL.

(2 mm in diameter). Therefore, the beam divergence is deduced to be 7 mrad. Then, the FEL output extracted from the optical cavity is converted to a parallel beam by using a concave spherical mirror with a focal length of 2 m, as shown in Fig. 3. The parallel beam is transported to the experiment room by deflections on 6 flat mirrors, and 3 additional flat mirrors are used to transport the beam to the application room. Actuators are used to adjust the angles of the mirrors to deflect the parallel beam. The parallel beam is passed through a PE pipe with a 60 mm diameter, which is filled with dry nitrogen to avoid laser power absorption by the water vapor.

As for a pilot application of the MIR- FEL to a renewable energy study, a new approach of material evaluation was developing at our research group. In this study, we focused on TiO_2, because it has been widely applied for renewable-energy-related materials, such as solar cells, and photoanode for splitting of water to produce hydrogen fuel. Especially, TiO_2 solar cells have several advantages, such as its low cost and nontoxicity of the raw material, compared with silicon solar cells. If TiO_2 solar cells with high photoelectric conversion efficiency are to be produced, it is important to understand the photoelectric conversion mechanisms by evaluating the energy bands structure in details. This ongoing study is aimed at a better understanding of the energy band structure of TiO_2 by use of in-situ photoluminescence measurement under the radiation of the MIR-FEL. Figure 4 shows a plane view of the developed measurement system.

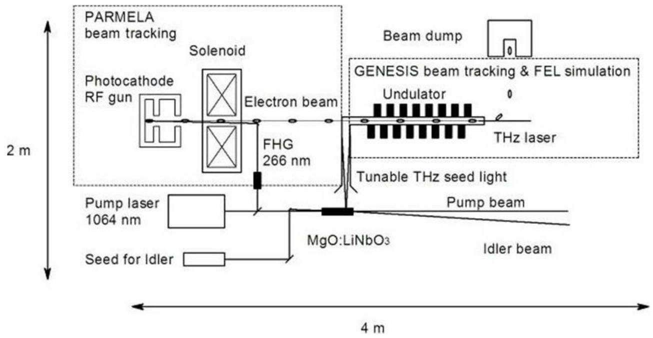

Fig. 5. Schematic view of the THz FEL amplifier.

IV. START-TO-END SIMULATION OF THE TABLETOP THZ FEL AMPLIFIER

The proposed tabletop SASE-THz FEL amplifier consists a BNL-type 1.6-cell photocathode RF gun, a focusing solenoid, 1.6-m long undulator with 80 periods, and a THz-wave parametric generator [7] with wide tunability used as a seed light, as shown in Fig. 5. Generally, a seed FEL can achieve a narrower spectrum than a shot noise amplifier. Therefore, our basic design adopted a parametric generator driven by the pump laser that excites the photocathode of the electron gun at the same time.

For the start-to-end simulation from the RF gun to the undulator entrance, we used the simulation code Parmela [8]. The electron beam was generated from the 1.6-cell photocathode RF gun. During the simulation, we assumed that the pump laser had a 10 ps (FWHM) pulse duration and that the laser spot radius at the cathode surface was 0.7 mm (FWHM). To miniaturize the whole system, we used an emittance compensation solenoid for beam focusing at the center of undulator. We confirmed that there was no serious degradation of the beam emittance in this case. The distance from photocathode to the undulator entrance was set to be 0.8 m. For an

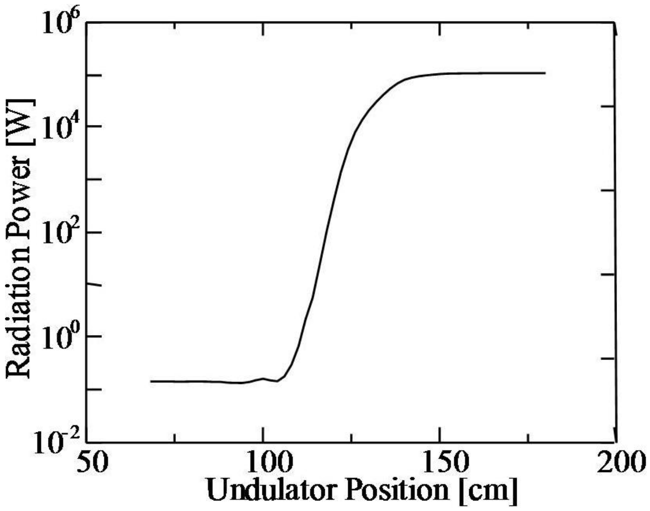

Fig. 6. Calculated FEL power for a 1-nC/bunch beam current.

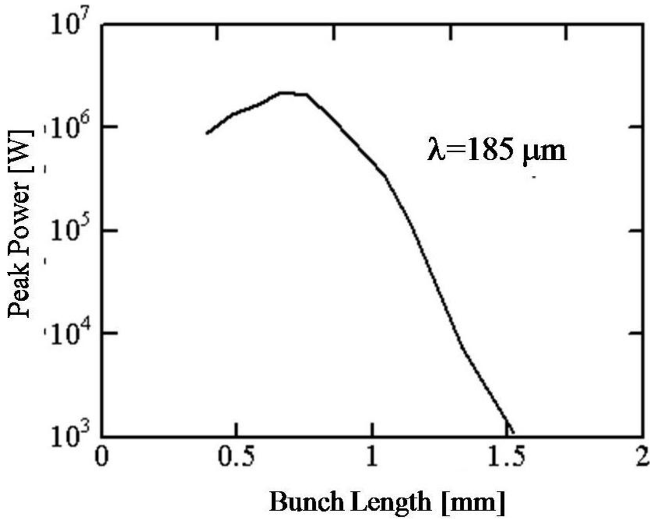

Fig. 7. Calculated FEL peak power at different electron bunch lengths.

FEL with a wavelength of 150-300 μm, the beam energy needed was calculated to be 4.6 - 6.7 MeV. By using a Parmela simulation, we estimated bunch length, peek current, and energy at the entrance of the undulator to be 3.47 ps, 115 A, and 6.25 MeV, respectively, for a bunch charge of 1.0 nC/bunch with the electric field of 70 MV/m in the RF gun.

The FEL gain was calculated by using the 3D time-dependent simulation code GENESIS. Beam parameters calculated by Parmela were taken for the FEL simulation. During GENESIS calculation, the THz FEL radiation, whose beam waist was 3.5 mm (rms), was assumed to propagate in waveguide mode inside the undulator. Entire power of seed light which was produced by THz-wave parametric generator was 0.20 W. It should be noted that the power of the seed light, which entered waveguide, was limited at 0.13 W because of diffraction. Therefore, the beam waist of seed light was set to the undulator entrance to input maximum seed light. Although the pulse length of the electron bunch was 1.04 mm (rms), the slippage length reached 23 mm in the free space mode for a FEL wavelength of 185 μm, an undulator period 2.0 cm, and undulator period number of 125. From the pulse length of the electron bunch and the FEL wavelength, the FEL interaction occurred only in 12 undulator periods, which corresponds about 25 cm in length. Therefore, the FEL simulation was performed by using the time-dependent mode in GENESIS to treat the slippage effect correctly.

The FEL peak power was calculated to be 350 kW as shown in Fig. 6, at an FEL wavelength of 185 μm. Since the power of the seed light was 0.20 W, the light power was amplified almost 10^6 times in this case. The light energy per FEL pulse was estimated to be 4 μJ by integration of the radiation power. To estimate the saturation power, we put a seed power of 200 W into the calculation. As a result the peak power at the FEL power saturation was 9.0 MW. This result shows that the FEL with a 0.20- W seed did not reach saturation in our original design because of a long slippage length with a short electron pulse. Since a stable FEL power is required from view point of FEL applications, FEL power saturation is preferable.

To get higher FEL gain, we investigated the electron bunch length dependency on the FEL power. The electron bunch length can be changed by changing the length of the laser pulse that is injected to photocathode or by changing the input phase of the RF field in the RF gun. We assumed the former method here. When the input laser pulse length from 5.0 to 15.0 ps, the Parmela calculation showed a bunch length was changed from 1.27 to 5.07 ps (0.38 - 1.52 mm (rms)). It should be noted that the beam energy did not change significantly for these conditions. Then, the FEL gain simulation was done with the corresponding bunch length. The undulator period number was kept at 80. The calculated FEL peak powers for different bunch lengths are shown in Fig. 7. The FEL wavelength was set to 185 μm in each calculation. The FEL peak power increased to 2.2 MW for a bunch length of 0.66 mm. This clearly shows that shortening the bunch length is effectively increasing the FEL gain. However, the saturated FEL peak power could not reach the expected saturated power of 9.0 MW which was deduced from the calculation with a seed laser power of 200 W. As is shown in Fig. 7, the energy spread of the electron beam increases as the bunch length increases. Due to the S-band RF acceleration and the laser injection phase of 40 degrees, the acceleration voltage is altered in both ends of the longitudinal front and of the end of the electron bunch. And thus, they do not contribute to the FEL interaction when the electron bunch gets longer. On the other hand, the energy spread was decreased from 0.80 to 0.47% by decreasing the electron

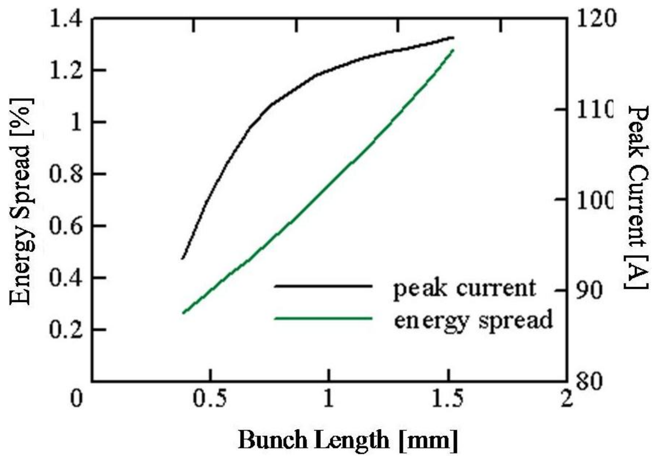

Fig. 8. Calculated peak current and energy spread of different bunch length electron beams with different laser pulse lengths.

bunch length.

However, excessive bunch shortening decreases the FEL gain. As shown in Fig. 8, the peak power of the FEL decreased when the electron bunch length was shorter than 0.66 mm (rms). There are two possible explanations for this gain decrease. One is that by shortening the electron bunch length, an interaction between the FEL and the electron bunch decreases when the slippage effect becomes dominant. The other is that, as shown in Fig. 8, the electron peak current decreases when the electron bunch length is shortened. The electron charge is linear to the laser pulse length, but the electron bunch length isn't linear in the laser pulse length. Consequently, optimization of the electron bunch length is required for the FEL power saturation.

V. CONCLUSIONS

We have been developed the MIR-FEL facility for renewable energy science in IAE, Kyoto University (KU). An amplitude-modulated RF power, beam loading compensation system and a phase stabilization system in both the thermionic RF gun and the accelerator tube were developed and applied in the KU-FEL. As a result, we succeeded in achieving FEL gain saturation at 13.2 μm with our FEL device. The FEL gain estimated from the temporal profile was around 32%. The beam profile was measured, and a beam transport line has been designed and constructed.

The preliminary measurements of the FEL at the control room indicated that we succeeded in transporting the FEL beam from the accelerator room to the experiment room. We will extend the beamline to the application room and start experiments on MIR-FEL applications in renewable energy research.

A start-to-end simulation has been performed to evaluate the original design of the tabletop THz-SASE FEL. The result shows that FEL amplification can be seen in the proposed design. However, due to the slippage effect with a long wavelength FEL, FEL power saturation could not be achieved. To achieve FEL power saturation, the simulation showed that shortening the electron bunch length contributed to obtaining a large FEL gain. The FEL peak power reached 2.2 MW at a bunch length of 0.66 mm, because a shorter electron bunch has less energy spread. However, an excessively short bunch the FEL gain loses because the slippage effect becomes dominant. Therefore, optimization of the bunch length is important for a THz SASE FEL amplifier. Further research on system design, including a bunch compressor, is required.

REFERENCES

[1] H. Zen, T. Kii, K. Masuda, H. Ohgaki and T. Yamazaki, Infrared Phys. Technol. **51**, 382(2008).
[2] H. Ohgaki, T. Kii, K. Masuda, H. Zen, S. Sasaki, T. Shiyama, R. Kinjo, K. Yoshikawa and T. Yamazaki, Jpn. J. App. Phys. **47**, 10, 8091 (2008).
[3] H. Zen, H. Ohgaki, T. Kii, K. Masuda, S. Sasaki, T. Shiyama, R. Kinjo, K. Yoshikawa and T. Yamazaki, IEEE Trans. Nucl. Sci. **56**, 3, 1487 (2009).
[4] T. Kii, K. Higasimura, H. Zen, R. Kinjo, K. Masuda and H. Ohgaki, *Prceedings of the 30th Free Electron Laser Conference* (*FEL2008*) (Gyeongju, Korea, 26 August 2008), pp. 196-199.
[5] S. Reiche, GENESIS v1.3 User's Manual.
[6] E. Nishimura *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **341**, 39 (1994).
[7] K. Kawase, H. Minamide, K. Imai, J. Shikata and H. Ito, Appl. Phys. Lett. **80**, 195 (2002).
[8] L.M. Young, J. H. Billen and Parmela, LA-UR-96-1835, 2001.