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Applied Physics Express

LETTER • OPEN ACCESS

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To cite this article: Heishun Zen *et al* 2020 *Appl. Phys. Express* **13** 102007

Applied Physics Express 13, 102007 (2020) LETTER
https://doi.org/10.35848/1882-0786/abb690

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Record high extraction efficiency of free electron laser oscillator

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Received August 17, 2020; revised September 7, 2020; accepted September 8, 2020; published online October 1, 2020

The highest extraction efficiency (9.4%) of a free electron laser (FEL) oscillator has been achieved at the midinfrared FEL facility of Kyoto University. Because of the interaction between the electron beam and FEL electromagnetic field, a maximum electron energy decrease of 16% was observed. The measured energy decrease was consistent with the measured FEL spectrum. An FEL micropulse energy of ∼100 μJ with the expected few-cycle pulse duration at a wavelength of 11 μm was observed. This result is an important milestone for the high-extraction-efficiency FEL oscillator and will contribute to the strong-field physics of atoms and molecules. © 2020 The Japan Society of Applied Physics

The demands on intense and ultrashort midinfrared (MIR: 3–20 μm) or longwave-infrared (LWIR: 8–15 μm) lasers with wide wavelength tunability are rapidly increasing. These wavelength regions are attractive for the strong-field physics of atoms and molecules since the ponderomotive energy of a charged particle in a laser field scales with the square of the wavelength. One strong motivation for the development of these MIR lasers is attosecond light sources based on high harmonic generation (HHG). Reportedly, the 1.6 keV soft X-ray can be generated by HHG of the MIR femtosecond laser at a wavelength of 3.9 μm.[1)] In this paper, the cut-off energy of the HHG source can be extended by driving the HHG source with lasers having a longer wavelength. Recently, the development of an intense and few-cycle laser source in the LWIR was reported and used for the first demonstration of the ionization of atomic xenon in the LWIR region.[2)] Ultrafast and strong-field laser science is now being extended to the MIR/LWIR wavelength region.

The free electron laser (FEL) oscillator is a widely tunable intense laser operating in the MIR/LWIR region. The FEL oscillators convert the kinetic energy of high-energy electrons to the energy of electromagnetic waves through the FEL interaction. The conversion efficiency, called the extraction efficiency, is one of the key parameters of FEL performance since a higher extraction efficiency results in a higher micropulse energy. Moreover, the micropulse duration of the FEL is inversely proportional to the extraction efficiency in short-pulse FEL oscillators.[3)] An increase in the extraction efficiency is indispensable for the generation of millijoule-class micropulse energy with a few-cycle duration, which is required for strong-field physics. At present, the generation of millijoule and few-cycle pulses in FEL oscillators has been independently achieved by different facilities but not yet achieved simultaneously. The generation of millijoule pulses from an FEL oscillator was achieved by the regenerative-amplifier FEL at Los Alamos National Laboratory, driven by high-charge (4.5 nC) electron bunches. A maximum micropulse energy of 1.9 mJ with a central wavelength of 16 μm and a duration of ∼16 ps (∼300 optical cycles) was generated.[4)] The generation of a few-cycle pulse was achieved by an FEL in the Japan Atomic Energy Research Institute (JAERI-FEL) under the perfectly synchronized condition of the optical cavity length to the electron bunch interval at a wavelength of 23 μm and a micropulse duration of 255 fs (3.4 optical cycles) for the full width at half-maximum.[5,6)] The generated micropulse energy and corresponding peak power were 74 μJ and 290 MW, respectively.[6)] The highest extraction efficiency of an FEL oscillator was 9%, which was also achieved by the JAERI-FEL under perfect synchronization.[7)] The maximum micropulse energy, the shortest pulse duration and the highest extraction efficiency of MIR-FEL oscillators have not yet been clarified. To judge the applicability of MIR-FELs to strong-field physics, further research on the high-extraction-efficiency FEL oscillator must be carried out. For this purpose, as a starting point, an FEL oscillator that can have higher or similar extraction efficiency relative to that of the JAERI-FEL must be developed.

In a previous research,[8)] high-extraction-efficiency lasing with an extraction efficiency of 5.5% was achieved at the MIR-FEL facility of Kyoto University, i.e. KU-FEL,[9)] driven by electron beams having a relatively low bunch charge (<60 pC). The goals of the present research are to achieve the highest FEL oscillator extraction efficiency and to show the possibility of applying the MIR-FEL to strong-field physics by increasing the electron bunch charge.

The experiments were conducted at KU-FEL.[9)] The electron beam energy was set at 28.5 MeV to drive the FEL oscillator at a wavelength of 11 μm, which was almost the same as in the previous experiment.[8)] The FEL was generated by the electron beam with 7 μs long macropulses containing ∼200 micropulses separated by 33.6 ns. The operation parameters are summarized in Table I.

The extraction efficiency of 5.5% reported in the previous paper[8)] was the record highest efficiency for an MIR-FEL driven by a normal conducting linac. High-efficiency lasing was achieved by introducing the dynamic cavity desynchronization (DCD) method.[10)] With the DCD method, we can switch the FEL lasing mode from the high-gain, low-saturation mode to the low-gain, high-saturation mode within a macropulse. The low-gain, high-saturation mode corresponds to superradiant FEL lasing under perfect synchronization.[8)] The extraction efficiency of the superradiant FEL oscillator is a function of the FEL gain parameter and loss, where the extraction efficiency can be increased by

Table I. The operation parameters used at KU-FEL during the experiment. The outcoupling hole, which was used to extract the intracavity FEL power, is located at the center of the upstream FEL cavity mirror.

Electron beam energy	28.5 MeV
Macropulse repetition rate	2 Hz
Macropulse duration of the electron beam	7 μs
Micropulse repetition rate	29.75 MHz
Structure of the undulator	Hybrid, Planer
Period length of the undulator	33 cm
Number of periods of the undulator	52
Undulator K-value	1.34
FEL wavelength	11 μm
Corresponding slippage length	572 μm
FEL cavity roundtrip loss	3.4%
FEL cavity length	5.0385 m
FEL cavity mirror curvature (upstream)	2.984 m
FEL cavity mirror curvature (downstream)	2.503 m
Diameter of the outcoupling hole	1 mm

enlarging the FEL gain or reducing the loss.[7)] Therefore, increasing the electron bunch charge for the higher FEL gain is a straightforward way to achieve an extraction efficiency surpassing the previous record.

The electron source at KU-FEL is a thermionic RF gun with a standing-wave 4.5-cell accelerating structure and a thermionic cathode made of LaB_6 with a radius of 1 mm. In the previous experiment, the maximum bunch charge was kept below 60 pC due to the serious back-bombardment effect.[11)] To increase the bunch charge, we upgraded the RF gun system to enable photocathode-mode operation in the FEL experiment. The LaB_6 cathode can be operated as a photocathode when the cathode is heated up to a temperature below the threshold of thermionic emission and illuminated by UV laser pulses.[12–16)] The RF gun was equipped with a multibunch 266 nm UV laser system for photocathode-mode operation.[17,18)] The macropulse energy, macropulse duration and micropulse repetition rate of the UV laser used in this study were ~5 mJ, 7 μs, and 29.75 MHz, respectively.

The extraction efficiency of the FEL was evaluated from the measurements of electron energy variation after the undulator, the same as in the previous work.[8)] We recorded macropulse current profiles with changing the dipole magnet field of the energy analyzer to scan the kinetic energy of the electrons reaching the Faraday cup through an aluminum slit. The evolution of the energy distribution in a macropulse can be constructed from the series of recorded current profiles. The change in electron energy due to the FEL interaction, which corresponds to the FEL efficiency, was calculated from the measurement results with and without FEL lasing. We used an intracavity beam shutter for the measurement without FEL lasing. In the FEL efficiency evaluation for the photocathode generating beam, we must subtract the background contribution owing to a non-laser-induced electron beam, which is inherently generated in the RF gun due to thermionic and field emission on the cathode. This background was recorded by preventing the UV laser from entering the cathode.

KU-FEL uses an optical cavity consisting of two spherical mirrors. The cavity has an outcoupling hole at the center of the upstream cavity mirror to extract the FEL power. The parameters of the optical cavity are summarized in Table I. The temporal profile of the extracted FEL pulses was measured by a high-speed pyroelectric detector (Model 420, Eltec Instruments) connected to a transimpedance amplifier (TIA60, Thorlabs). The macropulse energy of the FEL after passing through two KRS-5 windows was measured by using a pyroelectric sensor (ES145C, Thorlabs) connected to a digital energy meter (PM100D, Thorlabs).

In this experiment, the DCD parameters[10)] were tuned so that we had the highest FEL power at the end of the macropulse. The extraction efficiency measurement was performed under the optimized DCD parameters and optical cavity length.

The typical electron beam current and FEL power macropulse profiles measured by a current transformer and a fast pyroelectric detector are shown in Fig. 1. The total charge measured by the Faraday cup was 45 nC, including the non-laser-induced beam, with a total charge of 5.8 nC. The micropulse repetition rate and bunch charge of the non-laser-induced beam were 2856 MHz and 0.3 pC, respectively. The corresponding bunch charge of laser-induced electrons was 190 pC, which was more than 3 times the bunch charge under thermionic operation.[8)] The macropulse energy of the FEL measured after passing through two KRS-5 windows was 5.5 mJ, and the corresponding micropulse energy was 50 μJ.

The energy evolutions of the electron bunch in a macropulse with and without FEL lasing are shown in Fig. 2. Clearly, a large fraction of the electrons in bunches are greatly decelerated in the latter part of the macropulse. The maximum energy decrease was 16%. From the measured result of energy evolution, the average energy of the electron bunch at each moment in the macropulse can be calculated, as shown in Fig. 3(a). The average energy of the electron bunch was gradually reduced from 28.5 to 25.9 MeV. This large average energy decrease was induced by the FEL interaction. Because of the energy conservation law, the equivalent energy was transferred to the intracavity FEL field. After the relative change in the average energy of the electron bunch was calculated, the extraction efficiency of the FEL could be evaluated as shown in Fig. 3(b). At 6.6 μs, the extraction efficiency reached 9.4%, which is the world's highest recorded extraction efficiency observed in an FEL oscillator.

The high-efficiency lasing observed at KU-FEL was accompanied by FEL spectral broadening. Measured FEL spectra for the thermionic cathode operation and the photocathode operation are shown in Fig. 4. The electron beam

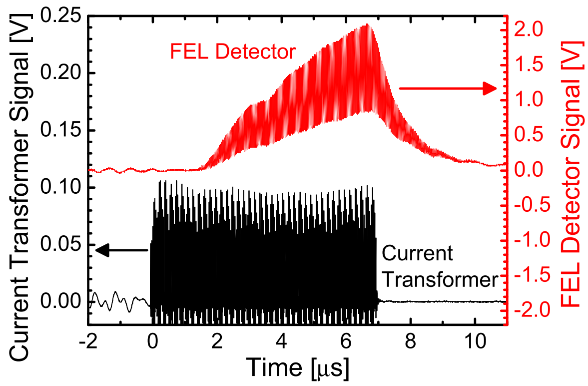

Fig. 1. (Color online) Typical temporal macropulse profiles of the electron beam measured by a current transformer, and the FEL power measured by a pyroelectric detector.

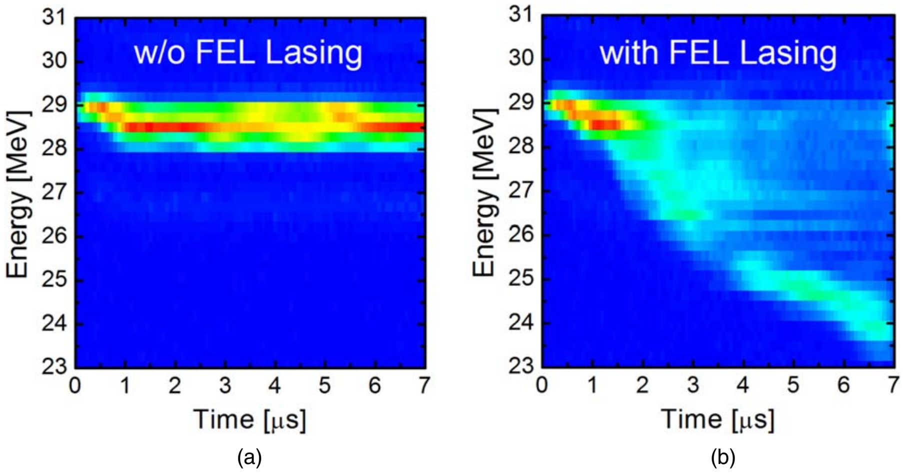

Fig. 2. (Color online) The measured evolution of the energy distribution in a macropulse. (a) Without FEL lasing. (b) With FEL lasing.

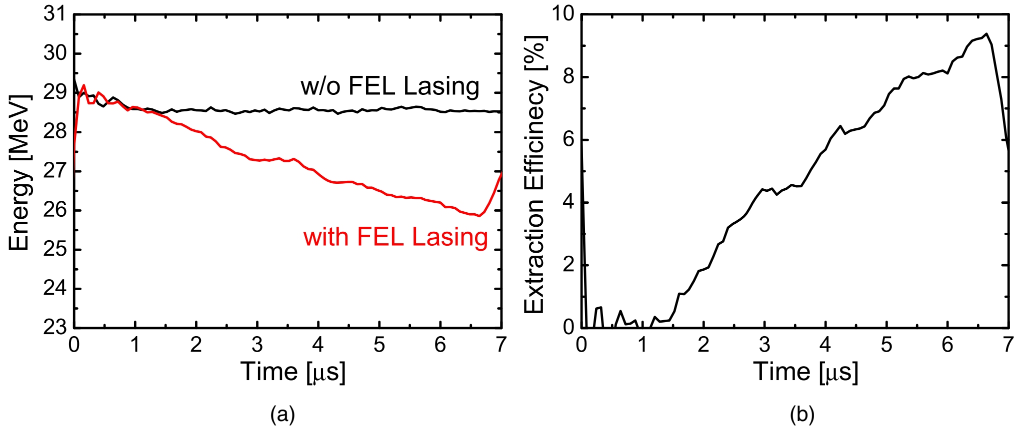

Fig. 3. (Color online) (a) The evolution of the average energy of the electron beam calculated from the results shown in Fig. 2. (b) The extraction efficiency of the FEL evaluated from the results shown in (a).

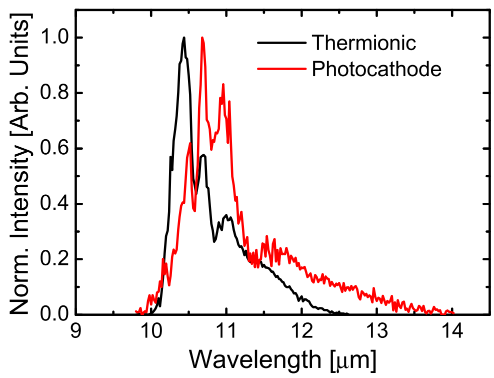

Fig. 4. (Color online) Typical FEL spectra with photocathode operation and thermionic cathode operation. These operations have the same initial electron beam energies.

energy without FEL lasing was the same in the two cases, but the wavelength spectrum of the photocathode operation was much wider than that of the thermionic operation. The FEL wavelength scales with γ^{-2}, where $\gamma = E_k/(m_0c^2) + 1$ is the Lorenz factor of the electron, in which m_0 is the electron rest mass and c is the velocity of light. The energy decrease of 16% leads to a resonant wavelength shift of +40%. The resonant wavelength calculated from a theoretical equation[19] without FEL lasing is 9.7 μm, and the expected wavelength with a +40% wavelength shift is 13.6 μm. The spectrum has a similar width to that of the above calculation, which suggests that the observed energy decrease is consistent with the measured spectral broadening. In the thermionic operation, we achieved an extraction efficiency of 5.5% and a maximum electron energy decrease of 9.5%.[8] These values are ~60% of the photocathode operation values. Therefore, the FEL bandwidth under thermionic operation was ~60% that under photocathode operation, as shown in Fig. 4.

As mentioned above, before this study was carried out, the highest extraction efficiency of an FEL oscillator was 9%, which was achieved by the JAERI-FEL under perfect synchronization.[7] Since the FEL gain is greatly suppressed under perfect synchronization, the operation condition was considered to be realized only with FELs driven by superconducting accelerators to provide electron beams with very long macropulses (>100 μs). However, in the present research, with the introduction of the DCD method,[10] FEL lasing similar to the perfectly synchronized condition was achieved, and a higher extraction efficiency than that of the previous research was obtained with a much shorter macropulse duration (~7 μs). This result is an important milestone for an FEL oscillator driven by a normal conducting accelerator, which can provide only a short macropulse duration (<30 μs).

The experimentally obtained micropulse energy after two KRS-5 windows was 50 μJ. Since the transmittance of one

KRS-5 window in this wavelength region is ~70%, the expected micropulse energy before those windows was 100 μJ, which can be made possible by using windows with an antireflection coating. Although we did not measure the pulse duration in the experiment, we deduced a few-cycle FEL pulse generation from the observed extraction efficiency and the scaling of the extraction efficiency and the pulse duration in short-pulse FEL oscillators.[3] The energy and duration of the obtained FEL pulses are comparable with those of a solid-state laser applied for strong-field studies of atoms at LWIR wavelengths, 80 μJ, 2.8 cycle at 8.9 μm.[2]

Next, we evaluate the FEL pulse energy stored in the optical cavity from the outcoupled micropulse energy. The outcoupling ratio of the cavity was calculated to be 1.2% from the cavity geometry with an assumption of a perfect TEM_{00} beam inside the cavity. From the outcoupling ratio, the micropulse energy inside the optical cavity was calculated to be 8.3 mJ. We should note that the intracavity FEL pulse energy obtained in the experiment, 8.3 mJ, exceeds the kinetic energy of the electron bunch, 5.4 mJ. The instantaneous power of the intracavity FEL pulse also exceeds the electron beam power even with a conservative assumption, i.e. the FEL pulse length is equal to the bunch length. Analytical studies have been developed to describe FEL physics in the low-gain, high-gain and superradiant regimes.[3,20–22] In these studies, the gain and efficiency of the lasing, the bandwidth and the duration of the obtained FEL pulses were derived with a perturbation analysis, assuming that the FEL power normalized by the gain parameter is much smaller than the electron beam power. In the present study, we achieved an FEL efficiency exceeding the analytical prediction under the condition that the above assumption does not hold. The experimental results will stimulate future development of the FEL theory and simulation codes applicable to the nonperturbative regime.

In conclusion, the highest MIR-FEL oscillator extraction efficiency (9.4%) was achieved at KU-FEL. A large fraction of electrons was efficiently decelerated by the FEL interaction. The maximum energy decrease of electrons was observed to be 16%. The measured FEL spectrum had a bandwidth consistent with the measured electron energy spread. The observed micropulse energy after two KRS-5 windows was 50 μJ, corresponding to a pulse energy of 100 μJ after the outcoupling hole. From the cavity outcoupling ratio, the intracavity micropulse energy was evaluated to be 8.3 mJ, which exceeds the total kinetic energy of the electron bunch. The achieved FEL performances are comparable with the performances of the solid-state laser used for ionizing xenon atoms.[2] We can use the outcoupled FEL pulses for the strong-field physics of atoms and molecules in the LWIR region.

The obtained results strongly encourage us to further increase the electron bunch charge, which can be accomplished by introducing a new RF gun dedicated to photocathode operation with a high bunch charge. This gun with a high-quantum-efficiency photocathode will enable us to generate an electron beam with a bunch charge of 1 nC and a longer macropulse duration (~10 μs). This upgrade will contribute to a further increase in the extraction efficiency of the FEL and enable the generation of millijoule-class MIR-FEL micropulses, which will be a new platform to explore the frontier of FEL oscillators and the strong-field physics in the LWIR region. Moreover, the experimental results provide motivation for studying FEL physics and simulations in the nonperturbative regime. The outcome of these future studies in addition to the present results will contribute to the realization of a high cut-off energy and high-repetition-rate HHG sources based on MIR-FEL oscillators driven by CW electron accelerators.[23]

Acknowledgments This work was supported by the MEXT Quantum Leap Flagship Program (MEXT Q-LEAP) Grant Number JPMXS0118070271.

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