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The Particle-Tracking Simulation of a New Photocathode RF Gun in the Free-Electron Laser Facility, KU-FEL

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Abstract: A project is underway that aims to generate attosecond pulses via high-harmonic generation in rare gases, driven by extremely short and highly intense pulses from free-electron-laser oscillators. For this purpose, it has been planned that a new photocathode RF gun, dedicated to high-bunch-charge operation, will be installed at the KU-FEL (Kyoto University Free Electron Laser) oscillator facility. In this study, RF guns with two different structures (1.6-cell and 1.4-cell) were compared, from the perspective of exploring the possibility of introducing bunch-interval modulation, which is important for achieving high extraction efficiency in the FEL oscillator. As a result, it was confirmed that the introduction of bunch-phase modulation would be possible only in the case of the 1.6-cell RF gun. After the structure of the RF gun was decided on, particle-tracking simulations were performed, to study the electron-beam parameters using the 1.6-cell RF gun and 1 nC bunch charge. The results showed that we could obtain the peak current of 1 kA without a large degradation of the other parameters.

Keywords: photocathode RF gun; high-bunch charge; free electron laser oscillator; particle-tracking simulation

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1. Introduction

A mid-infrared free-electron laser (FEL) facility named Kyoto University FEL (KU-FEL) has been developed [1]. The schematic diagram of KU-FEL is shown in Figure 1. The facility consists of a 4.5-cell thermionic RF gun, a 3 m traveling-wave-accelerator tube, a 1.8 m hybrid undulator, and a 5 m optical cavity. Detailed parameters of these components are reported elsewhere [2]. KU-FEL is routinely in operation, supplying intense and wavelength-tunable ultrashort pulses to internal and external users.

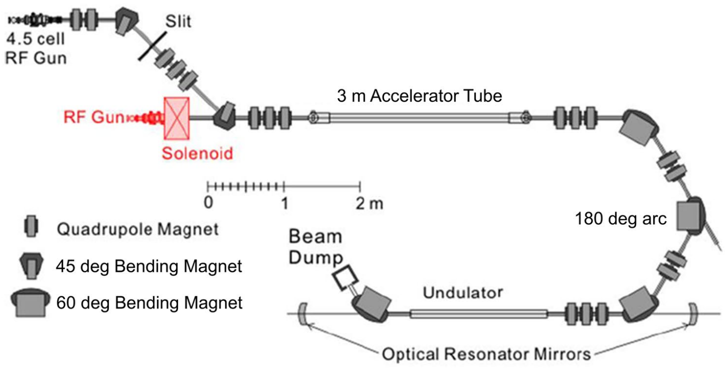

Figure 1. The schematic diagram of KU-FEL (Kyoto University Free-Electron Laser), including a new photocathode RF gun with a solenoid magnet dedicated to the high-bunch-charge operation (red-colored part).

A new research project was started in 2018, aiming to generate attosecond pulses by high-harmonic generation (HHG) in rare gases, driven by mid-infrared FELs [3]. During this project, KU-FEL was assigned to provide extremely-short-pulse FELs with a high enough peak power to drive HHG. To fulfil the required performance of the FEL beam, two major upgrades were planned. One was to realize the photocathode operation of the 4.5-cell thermionic RF gun. Since the cathode of the RF gun was made of LaB_6 single crystal, electrons could be generated not only by heating the cathode, but also by illuminating light whose photon energy was higher than the work function (2.36 eV) [4–9]. By using a ps-multipulse laser system developed in the KU-FEL facility [10,11], the electron-bunch charge was increased from <60 pC to ~200 pC with a reduced bunch-repetition rate (from 2856 MHz to 29.75 MHz). This upgrade enabled an increase in the extraction efficiency of KU-FEL from 5.5% to 9.4%, which is a record-high extraction efficiency [12]. Under the photocathode operation of the 4.5-cell RF gun, it was confirmed that the FEL micro-pulse energy and duration were ~100 μJ [12] and 150 fs (4.2 cycles at 10.7 μm), respectively [13]. The other upgrade was the introduction of a new photocathode RF gun dedicated to the generation of electron beams, with a bunch charge of 1 nC or even higher because of the available electron-bunch charge of the 4.5-cell RF gun being limited to ~200 pC due to the small cathode size (2 mm in diameter), the small inter-cavity irises (8 mm in diameter), the low on-cathode electric field (<30 MV/m), and the absence of a focusing solenoid. We expected that the increase in the bunch charge up to 1 nC, caused by introducing the new photocathode RF gun, would result in the extraction efficiency increasing to >20%, and the FEL micro-pulse duration reducing to less than two cycles based on the efficiency scaling on the normalized cavity loss shown in [3], and the inversely proportional characteristics of the pulse duration against the efficiency [14,15]. For this purpose, firstly, we studied the applicability of the dynamic cavity desynchronization method (DCD) [16] to 1.6-cell and 1.4-cell photocathode RF guns. The 1.6-cell RF gun has been used for various applications such as electron sources in high-gain single-pass FELs [17–19], THz coherent radiation sources [20–24], Compton X-ray sources [25], and ultrafast electron diffraction (UED) [26] following its invention [27]. The 1.4-cell RF gun has recently been proposed to generate high-brightness electron beams, and is considered to be used for a high-gain single-pass FEL driver linac [28] and UED [29]. In this paper, we will report on the result of the particle-tracking simulation that we conducted on the RF gun section to determine the structure of the RF gun. Next, we performed particle-tracking simulations from the RF gun to the entrance of the undulator, to investigate the available electron-beam properties at the undulator section of KU-FEL.

2. Methods and Parameters

A particle-tracking simulation software named General Particle Tracer (GPT) [30] version 3.1 was used for electron-beam-tracking simulations in this study. The inner cavity shape of the 1.6-cell and 1.4-cell RF guns were the same as those developed by High Energy Accelerator Research Organization (KEK) and Osaka University group [29,31] for ultrafast electron diffraction and microscopic imaging. These RF guns were optimized for high-repetition-rate operation by reducing the surface field on the iris part of the cavities, and by having a large difference (~15 MHz) between the resonant frequencies of π- and 0-modes. We also required these preferred features because the application of oscillator FEL lasing required electron beams with a long macro-pulse duration. The cavity structures used in the simulation are shown in Figure 2, with field-contour maps calculated by a Superfish code [32]. As shown in the figure, those cavities have elliptically shaped cavity structures, which contribute to reducing the surface field on the iris, and widening the mode separation.

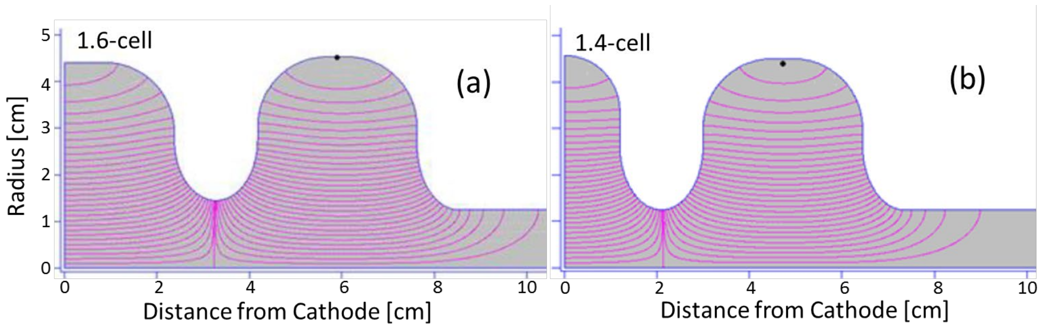

Figure 2. Structures of RF gun cavities: (**a**) 1.6-cell RF gun, (**b**) 1.4cell RF gun. These have cylindrical symmetry. (**a**,**b**) have the same coordinate scale. The black dots indicate the points of the RF excitation.

To increase the efficiency of the oscillator FEL, the DCD method [16] should be introduced, as the available macro-pulse duration of the electron beam in KU-FEL is limited to ~7 µs [12,33]. The build-up time and the saturation power of oscillator FELs strongly depend on the synchronized condition between the optical pulse circulating in the optical cavity, and the electron bunch supplied from an electron linac. Under the slightly desynchronized condition, a short build-up time can be obtained with low saturated power. Under the perfectly synchronized condition, the highest-saturated power can be obtained, but a long build-up time is required. In the DCD method, the bunch-spacing in an electron-beam macro-pulse was introduced, to switch the synchronized condition from the slightly desynchronized condition to the perfect synchronized condition, to have a short build-up time and a high saturation power at the same time. Since the repetition rate of the mode-locked laser oscillator in the ps-multipulse laser system cannot be modulated, and the repetition rate of electron emission from the cathode is fixed, it is not clear whether the bunch-spacing modulation necessary for the DCD method can be introduced or not when a photocathode RF gun with an arbitrary structure is used as an electron-beam source. As experimental evidence, we were able to obtain bunch-spacing modulation in the case of the photocathode operation of a 4.5-cell RF gun by modulating the RF field excited in the gun cavity. To examine the capability of DCD in the 1.6-cell and 1.4-cell RF guns, we studied the arrival-time modulation of the electron bunch using these two RF guns depending on the laser-injection timing under the fixed generated-electron-beam energy conditions.

After the gun structure was selected, particle-tracking simulations, from the cathode to the undulator entrance, were performed. The schematic diagram showing the geometry simulated is shown in Figure 3. A solenoid magnet for focusing electron-beam and emittance compensation [34] was attached to the RF gun. Next, triplet quadrupole magnets (TQ1) were used to adjust the focusing condition of the electron beam, and to pass through the 3 m traveling-wave accelerator tube. In the accelerator tube, the electron-beam energy was accelerated to 28.5 MeV. Then, triplet quadrupole magnets (TQ2) were used to adjust the focusing condition of the electron beam, and to pass through the 180 deg arc section, which consisted of three sector-type 60 deg bending magnets and two doublet quadrupoles. In the arc section, the electron-bunch length was reduced by magnetic-bunch compression, with the combination of the slight off-crest acceleration in the accelerator tube. The longitudinally compressed electron beams were sent to triplet quadrupole magnets (TQ3) to adjust the focusing condition of the electron beam in the undulator. The 180 deg arc section needed to satisfy achromatic conditions with different first-order momentum compaction factors. To discover the proper combination of the two doublet quadrupoles, we used a matrix calculation code developed by Miyajima, KEK [35].

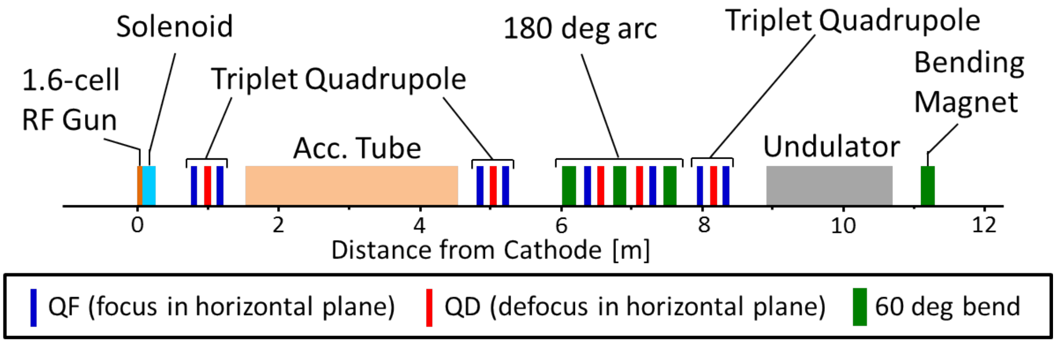

Figure 3. Schematic diagram of the geometry simulated in the tracking simulation. The tracking simulations were performed from the cathode in the 1.6-cell RF gun to the entrance of the undulator. QFs and QDs are quadrupole magnets.

In all simulations, the RMS pulse duration, and the transverse size of the UV laser irradiated on the cathode, were assumed to be 2.4 ps and 1 mm with Gaussian distribution, respectively [36].

3. Results and Discussions

3.1. Study on the Availability of the DCD Method

First, the basic properties of the electron beam generated from the 1.6-cell and 1.4-cell RF guns were checked. The obtained average energy and energy spread for the 1.6-cell and 1.4-cell RF guns are shown in Figure 4. In the simulation, the field strength on the cathode was set to 120 MV/m. As shown in Figure 4a, the 1.6-cell RF gun could generate a low-energy-spread electron beam when the laser-injection phase was in the region from 0 to 45 degrees. In the case of the 1.4-cell RF gun (Figure 4b), electron beams with low energy spread could be generated when the laser-injection phase was in the region from 65 to 85 degrees. Only these limited laser-injection-phase conditions were useful for oscillator FEL lasing.

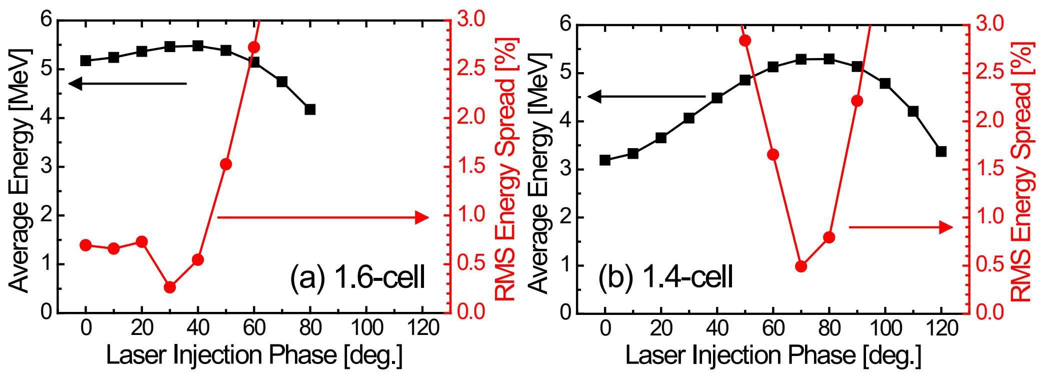

Figure 4. Dependences of the average energy and the RMS energy spread on the laser-injection phase: (**a**) 1.6-cell RF gun, (**b**) 1.4-cell RF gun.

For the oscillator FEL utilizing DCD, the electron-beam energy should be kept constant even with the modulation of the laser-injection phase. This can be done by modulating the amplitude of an RF pulse fed to the RF gun, together with the phase modulation of the RF pulse. Therefore, the dependence of the arrival time at 500 mm downstream from the cathode was checked by adjusting the cathode surface field to have a fixed average energy of 5.5 MeV and 5.2 MeV, for 1.6-cell and 1.4-cell RF guns, respectively. In the simulation, the timing of laser irradiation on the cathode was defined as time equal to zero, and the RF phase of the half-cell of the RF guns was varied, to see the dependence of the arrival time on the laser-injection phase. The results are shown in Figure 5. In the case of the 1.6-cell

RF gun, the arrival time of the electron bunch demonstrated a strong dependence on the laser-injection phase. On the contrary, in the case of the 1.4-cell RF gun, the dependence of the electron-bunch arrival time on the laser-injection phase was small. This feature of the 1.4-cell RF gun would be quite good for ultrafast electron diffraction (UED) [26] or microscopic imaging [37] applications, as timing jitter between the laser and the RF field did not cause arrival time jitter of the electron bunch on the sample. However, our application, driving oscillator FEL, requires the modulation of the bunch-arrival time or interval to use DCD. Therefore, we decided to use a 1.6-cell RF gun as a newly installed photocathode RF gun in KU-FEL.

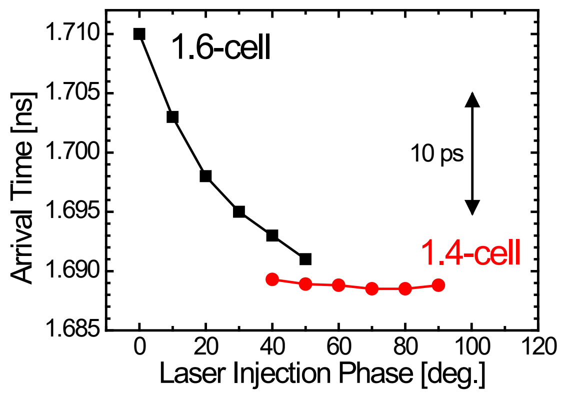

Figure 5. Arrival time dependence on the laser-injection phase. The laser-injection timing is defined as the time equal to zero, and the RF phase at that time is varied.

3.2. Study on the Electron-Beam Properties at the Undulator

Particle-tracking simulations, and optimization of the parameters of the solenoid magnet, quadrupole magnets, and traveling-wave accelerator tubes, were performed to study the available electron-beam properties at the undulator with a 1.6-cell RF gun. The schematic diagram of the electron accelerator, and the geometry used in the particle-tracking simulation, are shown in Figures 1 and 3, respectively. The laser-injection phase on the cathode was 40 degrees, which was fixed in the following simulations, since the highest electron-beam energy and low-energy spread can be obtained under the condition. It is also known that a low emittance beam can be obtained with the injection phase [38]. The electron-beam energy after the traveling-wave accelerator tube was adjusted to 28.5 MeV, by adjusting the electric-field strength in the traveling-wave tube. The optimized properties are shown in Table 1. The RF phase of the accelerator tube at the time of electron-bunch injection was adjusted to have a slight time–energy correlation, to perform magnetic-bunch compression in the 180 deg arc section, with the first-order momentum-compaction factor (R_{56}) of 0.1 m. Then, the normalized field gradient of the doublet quadrupole magnets in the 180 deg arc section were 44.69 and -31.30 m^{-2}, for focusing and defocusing quadrupole magnets, respectively. In the table, we also list, for comparison, the properties of the electron beam with the photocathode operation of the 4.5-cell RF gun, obtained by the particle-tracking simulation [38]. Compared with the results for the 4.5-cell RF gun, the peak current was largely increased without large degradation of other properties. The RMS emittance was increased from 4.7 to 5.8 mm-mrad, but this would not have a large impact on the FEL performance, as the targeted FEL wavelength was rather long (>8 μm). The energy spread of the 1.6-cell RF gun with the 1 nC bunch charge was half-tripled from that of the 4.5-cell RF gun with the 120 pC bunch charge. These parameters strongly depend on the strength of the solenoid magnet.

Table 1. The optimized electron-beam parameters at the undulator.

Beam Parameter	1.6-Cell RF Gun	4.5-Cell RF Gun [39]
Bunch Charge	1 nC	120 pC
RMS Bunch Length	0.42 ps	0.43 ps
Peak Current	1011 A	120 A
RMS Energy Spread	1.1%	0.4%
RMS Normalized Emittance	5.8 mm-mrad	4.7 mm-mrad

Some representative calculation results of the evolution of the RMS emittance and the energy spread, with different field strengths of the solenoid magnet, are shown in Figures 6 and 7. In this calculation, all parameters except the solenoid strength were fixed. As one can see in the figures, there is a trade-off relationship between the emittance and the energy spread. This is due to the transverse–longitudinal coupling through a strong space-charge effect in the electron bunch. When the RMS emittance is small after the bunch compression, the electron-beam size can be small. Due to the small beam size, the high peak current, and the not-so-high beam energy, the space-charge effect becomes stronger, and induces growth in the energy spread. A good balance between the energy spread and the RMS emittance to have maximum FEL power will be found in experiments.

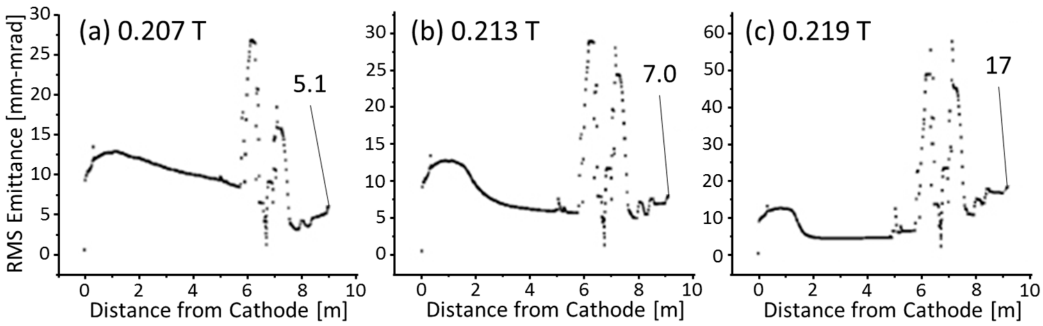

Figure 6. The evolution of RMS normalized emittance along the beamline with different solenoid strength: (**a**) 0.207 T, (**b**) 0.213 T, and (**c**) 0.219 T.

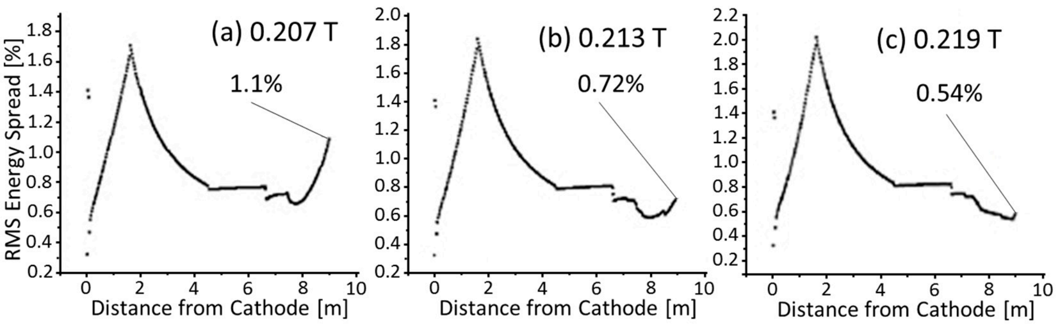

Figure 7. The evolution of RMS energy spread along the beamline with different solenoid strength: (**a**) 0.207 T, (**b**) 0.213 T, and (**c**) 0.219 T.

The obtained parameters are very promising with regard to increasing the extraction efficiency of KU-FEL. At the moment, the 1.6-cell RF gun has already been fabricated, and the low-power and high-power testing of the gun has been accomplished.

4. Conclusions

A project is underway that aims to generate attosecond pulses via the HHG in rare gas driven by mid-infrared FEL oscillators. For generating extremely short and highly intense pulses from the FEL oscillator KU-FEL, the new photocathode RF gun dedicated to high-bunch-charge operation has been installed in KU-FEL. In this work, photocathode RF guns with two different structures (1.6-cell and 1.4-cell) were compared from the viewpoint of the applicability of the DCD method, which is important for achieving high extraction efficiency, with electron beams having short macro-pulse durations. As a result, it was confirmed that the introduction of the DCD method would be possible only with the 1.6-cell RF gun. Therefore, we decided to use the 1.6-cell RF gun in our project.

Next, particle-tracking simulations, from the cathode to the entrance of the undulator, were performed, to check the electron beam properties available with the 1.6-cell RF gun and the bunch charge of 1 nC. As a result, the peak current of ~1 kA without serious degradation of other parameters was confirmed. It was also found that there would be a trade-off relationship between the energy spread and the emittance. The optimum working point would be found through experiments.

We achieved FEL lasing with an electron beam provided by the new 1.6-cell RF gun with a copper cathode, which generated low bunch charge (~60 pC), in March 2023. The cathode will be replaced by Cs_2Te with high quantum efficiency, so that the operation with a high bunch charge can be accomplished in the near future.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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Conflicts of Interest: The authors declare no conflict of interest.

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