SIMULATION OF A NEW PHOTOCATHODE RF GUN IN KU-FEL

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Abstract

Upgrade project of Mid-infrared Free Electron Laser in Kyoto University (KU-FEL) has been started to achieve high peak power and ultra-short pulse operation by installing a new photocathode RF gun under the High-Repetition-Rate attosecond pulse source based on the High Harmonic Generation (HHG) project, Q-LEAP. A start-to end simulation was performed to optimize the magnet component of the accelerator and to evaluate an expected FEL performance. The 1.6-cell photocathode RF gun manufactured by KEK is expected to generate a 1-nC bunch charge beam. A beam compression study has been conducted and the RMS bunch length has been success-fully compressed to 0.42 ps which can generate a 1 kA of peak current. The FEL simulation using the optimized beam parameter shows that the FEL intra-cavity power can saturate at 10^9 Watts by only 5 roundtrips.

INTRODUCTION

The “Q-LEAP” project is the research project to develop the fundamental technology for high-repetition attosecond light sources driven by next-generation lasers and Free Electron Lasers. We aim to make the development and realization of a high repetition rate ultrashort pulse light source (10 MHz or higher) by generation of few-cycle pulses in the mid-infrared wavelength region using the existing FEL facility and performing high-order harmonic generation (HHG).

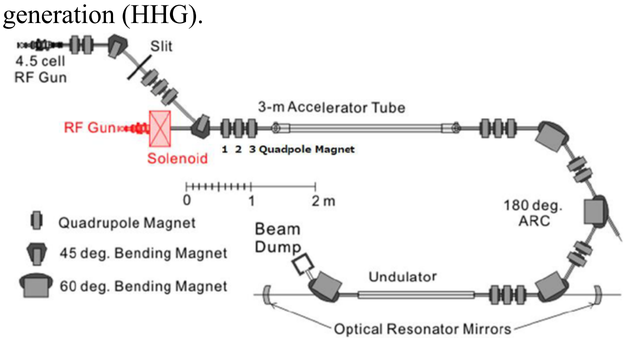

Figure1: Schematic view of KU-FEL.

At Institute of Advanced Energy, Kyoto University, an oscillator-type mid-infrared Free Electron Laser named as KU-FEL, which has been developed and covers the wavelength range from 3.5-23μm [1], joins the Q-LEAP project. To achieve a higher efficiency for an ultra-short pulse oscillation, a new photocathode RF electron gun has been introduced in KU-FEL [2]. Figure 1 shows the schematic view of KU-FEL including the new electron gun and solenoid magnet.

A beam simulation study on the electron beam and FEL with the 1.6-cell photocathode has been performed to evaluate the electron beam characteristics by the beam simulation code GPT [3] including the optimization of the accelerator component. FEL simulation is performed by using GENESIS [4] with an oscillator calculation.

ELECTRON BEAM SIMULATION

The beam simulation study from the RF gun to the end of accelerator tube has been conducted with a 1-nC bunch charge beam in 2021 [5]. The laser injection phase and the acceleration phase of the accelerator tube was investigated and the1-nC bunch charge beam can be successfully accelerated to be 28.5 MeV. In addition, beam parameter was also optimized at the exit of accelerator tube with the RMS emittance of 4.12 mm-mrad and RMS energy spread of 0.6% but the bunch length was very large, 2.14 ps, which can only obtain a peak current of 200A [5]. To achieve higher peak current with a high bunch charge beam, a bunch compression study is indispensable. In the KU-FEL facility, the electron beam can be compressed by a 180° arc section.

In the bunch compression simulation with the space-charge effect caused by 1-nC bunch beam, the relationship between RMS bunch length and several R56 parameter have been calculated and the result is shown in Fig. 2. We can perceive that when the R56 was set to be 0.1 m, the RMS bunch length was minimum at 0.42 ps and a 1011 A of peak current, which is 8.4 times higher than the previous condition with 4.5-cell thermionic cathode RF gun (photocathode operation) was achieved.

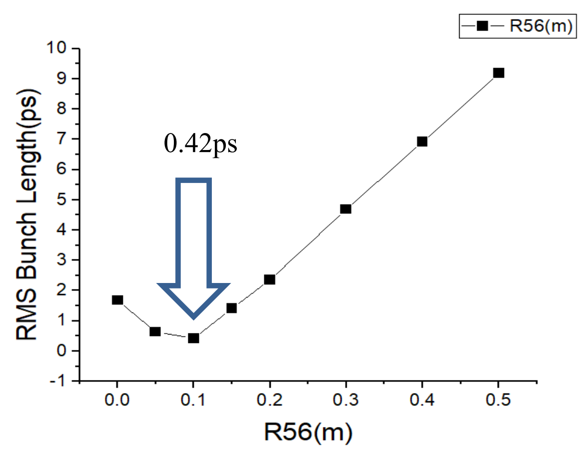

Figure 2: Relation of R56-RMS bunch length.

To optimize the electron beam for FEL generation, the RMS emittance, beam size were calculated by changing the parameter of triple quadruple magnets before and after the arc section. According to the simulation result, magnetic field gradient of the three quadrupole magnets before arc section QAC21,22,23 was set to be 1.375, -2.75 and 1.375

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T/m and the magnets after the arc section QUND1,2,3 were set to be 3.5, -7, 3.5 T/m which can get the minimum average radius of 0.96 mm at the entrance of the undulator.

Finally, the magnetic field strength of the solenoid which located at the exit of the photocathode RF gun has been tuned. The solenoid magnetic field strength was originally set to be 2006 Gauss [5] and to get the smaller average beam size at the undulator, the magnetic field strength was increased to 2069 Gauss, 2131 Gauss and 2194 Gauss.

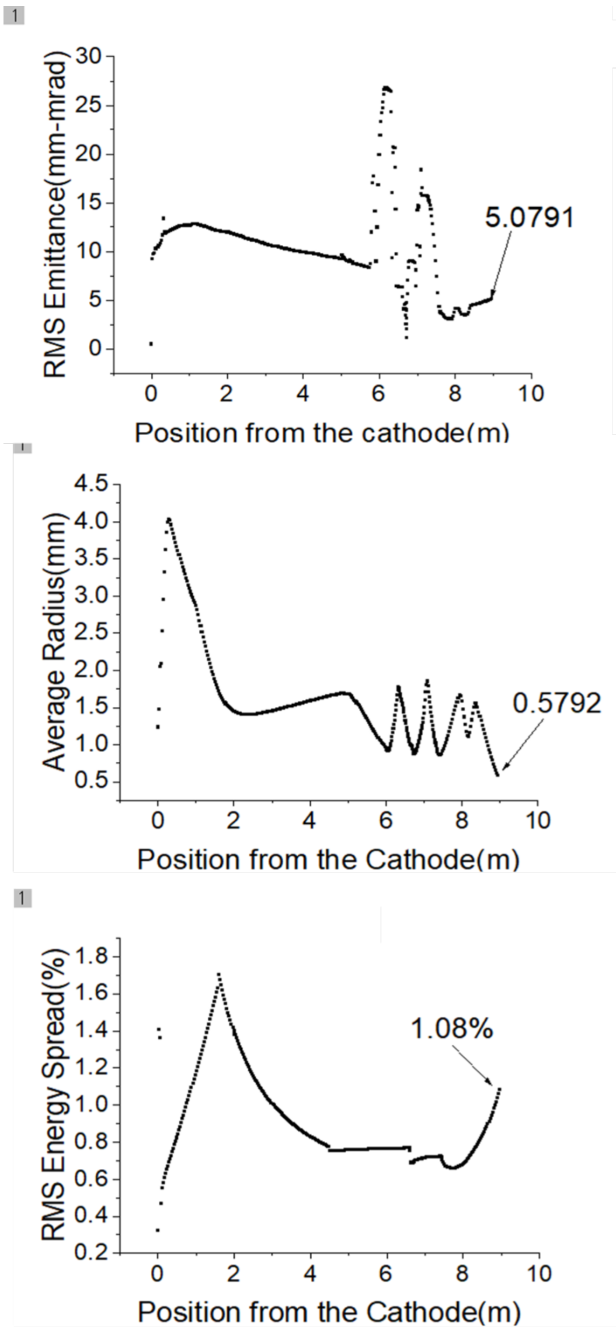

Figure 3: RMS Emittance(up), Average Radius(mid), RMS Energy Spread(down) with magnetic field strength at 2069 GAUSS.

The result shows that the smaller average radius is obtained when the magnetic field is 2069 Gauss and 2131 Gauss, but once it rises to 2194 Gauss, both the emittance and radius were increased significantly. Considering the three parameters of RMS emittance, average radius and the RMS energy spread, the magnetic field strength with 2069 Gauss was chosen (Fig. 3). Tables 1 and 2 show the beam parameter with 4.5-cell thermionic cathode RF gun (photocathode operation) [6] and the new 1.6-cell photocathode electron gun at the entrance of the undulator, respectively.

Table 1: Beam Parameter of 4.5-Cell Thermionic Cathode RF Gun (Photocathode Operation) at the Entrance of the Undulator

4.5-cell thermionic cathode RF gun (Photocathode operation)	
Bunch charge	120pC
RMS bunch length	0.43ps
Peak current	120A
RMS energy spread	0.4%
RMS emittance	4.68mm-mrad

Table 2: Beam Parameter of New 1.6-Cell Photocathode RF Gun at the Entrance of the Undulator

1.6-cell photocathode RF gun	
Bunch charge	1nC
RMS bunch length	0.42ps
Peak current	1011A
RMS energy spread	1.08%
RMS emittance	5.08 mm-mrad

FEL SIMULATION

KU-FEL consists of a 1.8-m Hybrid-type undulator whose parameter is shown in Table 3. The FEL simulation with the new photocathode RF gun (Table 2) was performed using GENESIS1.3.

Table 3: Parameters of Hybrid-Type 1.8-m Undulator

KU-FEL Undulator	
Total length	1.8m
Period number	52
Undulator period	33mm
Minimum Gap	15mm
Maximum magnetic field	0.559T
Maximum K value	1.72

First, to find the maximum FEL amplification wavelength, the one-pass gain calculation was conducted. The result is shown as the black curve in Fig. 4. The highest gain of FEL (307%) is obtained at the wavelength of 12.285 μm.

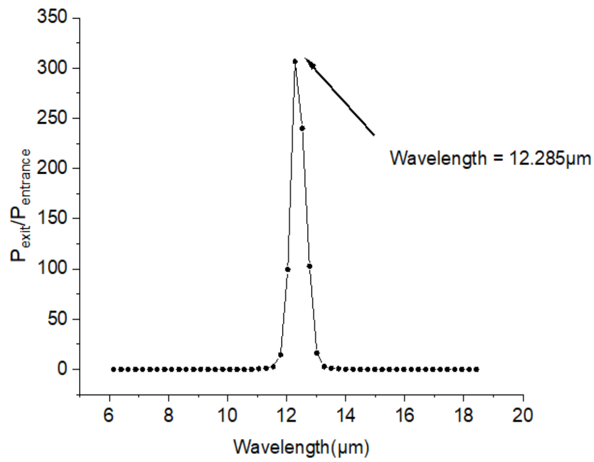

Figure 4: FEL wavelength investigation.

Second, for the trajectory correction in the x-axis, the collector strength parameter CX was investigated as shown in Fig. 5. As the result, the minimum summation of $(\Delta x)^2$ occurs when CX= -40.7.

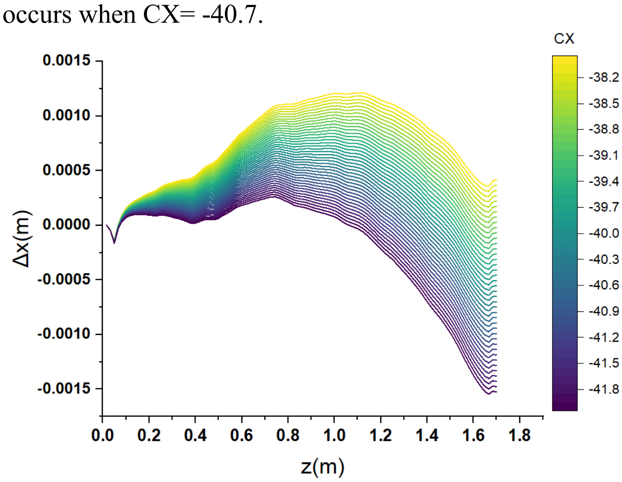

Figure 5: Electron beam trajectories for different CX values.

Finally, the multi-pass time-independent simulation using Genesis 1.3 is performed to calculate the FEL gain.

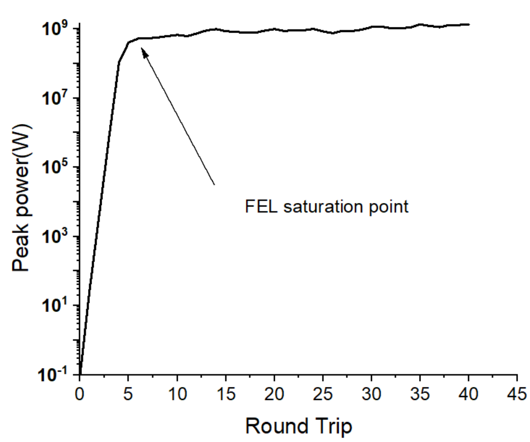

Figure 6: Peak power evolution of multi-pass time-independent simulation (Undulator Gap:16mm).

The evolution of FEL peak power with the round-trip is demonstrated in Fig. 6. The result shows that the FEL peak power is saturated by 5 round-trips with 10^9 Watts.

CONCLUSION

The beam simulation from the exit of acceleration tube to the entrance of the undulator and the FEL simulation was conducted with the new 1.6 cell photocathode RF gun with 1-nC bunch charge beam whose maximum acceleration energy is 28.5 MeV. The RMS bunch length was successfully compressed to 0.42 ps which can achieve a 1011 A peak current by optimization of the arc section component. The FEL simulation result proves that the FEL intra-cavity power can saturate at 10^9 Watts by only 5 roundtrips that is higher FEL gain than that of the 4.5-cell thermionic cathode RF gun with the photocathode operation. The installation of the new 1.6 cell photocathode RF gun will be finished at the end of 2022 and the beam commissioning is scheduled in early 2023.

REFERENCES

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