FEASIBILITY STUDY OF PHOTOCATHODE OPEARATION OF THERMIONIC RF GUN AT KU-FEL*

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Abstract

Kyoto University Free Electron Laser (KU-FEL) is an oscillator-type mid-infrared FEL driven by a compact linac which uses a thermionic RF gun. Recently we succeeded in a photocathode operation of the RF gun by using the thermionic cathode (LaB_6) as a photocathode material. Experiments of the photocathode and thermionic cathode operations were performed for a comparison of two different operation modes at the FEL wavelength of 11.7 μm. As the result, it was demonstrated that the photocathode operation enables us to generate around 6 times as high micro-pulse energy as thermionic cathode operation.

INTRODUCTION

Kyoto University Free Electron Laser (KU-FEL) has been developed for promoting energy-related researches at the Institute of Advanced Energy, Kyoto University [1]. The first lasing of KU-FEL was achieved in 2008 [2]. The initial wavelength range of the FEL was limited by FEL gain from 10 to 14 μm. Even with the limited wavelength range, the user experiments of the facility were started in 2009. In parallel with user experiments, intensive work has been conducted for extending the wavelength range and increasing its stability [3-7]. Thanks to those efforts, the wavelength range of KU-FEL has been extended to 5 – 20 μm and the power stability of KU-FEL has been drastically improved.

The facility was originally developed with an RF gun with a thermionic cathode since it did not require expensive laser sources for electron generation. However, the bunch charge of electron beam generated from the RF gun and macro-pulse duration of electron beam have trade-off relationship due to back-bombardment effect [8]. The bunch charge and macro-pulse duration under the normal operational condition of KU-FEL linac is less than 50 pC and 6.5 μs, respectively. Those values are sufficient for FEL lasing but not enough to obtain a high peak power output of the FEL. There was a user request for our facility to supply a higher peak power, lower macro-pulse energy and lower micro-pulse repetition rate to perform a nonlinear experiment in mid-infrared wavelength region because a sample can be easily destroyed by the FEL pulses generated by the thermionic operation of the RF gun where the FEL pulses have a high macro-pulse energy and a high repetition rate of micro-pulse. In order to fulfil the user's demand and extend performance of KU-FEL, we started preparation of the photocathode operation of the RF gun in KU-FEL at 2010. A multi-bunch UV laser has been developed for driving a photocathode [9].

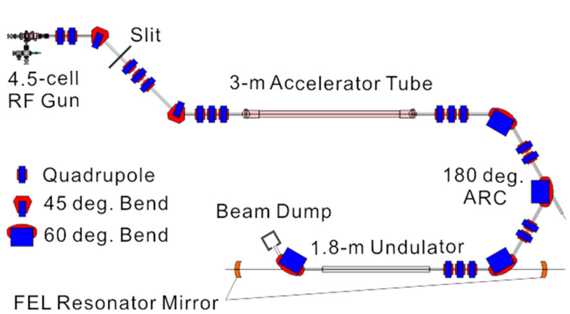

Figure 1: Schematic diagram of KU-FEL.

Table 1: Specifications of Main Components of KU-FEL

RF Gun	
Resonant Frequency	~ 2856 MHz
Coupling Coefficient	2.8
Quality Factor	12500
Structure	4.5-cell side couple
Accelerating Mode	π mode
Cathode	LaB_6 (100)
Cathode Radius	1 mm
Accelerator Tube	
Resonant Frequency	~ 2856 MHz
Structure	Constant Gradient Type Traveling-wave Tube
Accelerating Mode	2/3 π mode
Effective Length	2.9 m
Undulator	
Total Length	1.8 m
Number of Periods	53
Period Length	33 mm
Maximum K-value	1.35
FEL Optical Resonator	
Mirror Curvature	Upstream : 2.946 m Downstream : 2.456 m
Cavity Length	5.038 m
Roundtrip Frequency	29.75 MHz
Hole Diameter on Upstream Mirror	1 mm

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The first lasing of KU-FEL under the photocathode operation of the RF gun has been achieved in March 2015.

OPERATION MODE OF KU-FEL RF GUN

The KU-FEL consists of a 4.5-cell RF gun, a 3-m accelerator tube, a bunch compression arc, a 1.8-m undulator and an FEL optical resonator. The schematic diagram of the facility is shown in Fig. 1. The specifications of main components of KU-FEL are listed in Table 1.

Thermionic Cathode Operation

The cathode temperature is increased to around 1900 K to have enough amount of thermionic electron emission from the cathode. In this operation mode, electrons are continuously supplied from the cathode and directly accelerated by time-varying RF field. In this situation, some electron cannot reach to the next cavity before changing the electric field direction are decelerated back and some of them hit the cathode. Those electrons are called as back-bombarding electron. The back-bombarding electrons dispose their energy to the cathode and the cathode temperature is significantly increased during a macro-pulse. Then the emission current from the cathode is increased and electron beam energy drops in the macro-pulse due to the increase of beam loading. These consequent phenomena have been called as the back-bombardment effect. Some countermeasures have been introduced to mitigate the back-bombardment effect in the RF gun [3, 7, 10]. Thanks to those countermeasures, electron beams having the maximum bunch charge of 50 pC

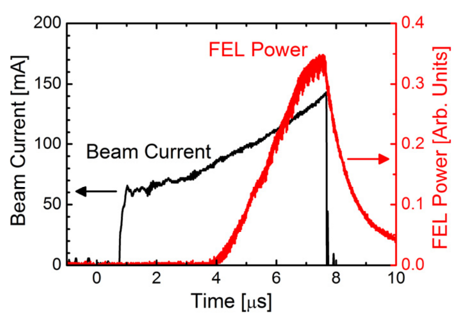

Figure 2: Typical temporal evolution of electron beam current and FEL power under thermionic cathode operation of KU-FEL.

Table 2: Main Parameters of KU-FEL under the Thermionic Cathode Operation

Wavelength Range	5 – 20 μm
Max. Macro-pulse Energy	30 mJ @9 μm
Max. Micro-pulse Energy	5 μJ @9 μm
Typical Macro-pulse Duration	~ 2 μs
Micro-pulse Duration	0.6 ps-FWHM*
Max. Peak Power	~ 8 MW
Typical Spectral Width	~ 3%-FWHM

*Measured at 12 μm [11]

and the macro-pulse duration of 6.5 μs have been generated at KU-FEL. In the thermionic cathode operation, the repetition rate of electron micro-pulse is equal to the RF frequency of the RF gun, 2856 MHz. The typical macro-pulse structures of the electron beam measured at the final beam dump and the FEL output power are shown in Fig. 2. As one can obviously see that the electron beam current was continuously increase during the macro-pulse. Even with this ramping up current condition, we could keep the electron beam energy constant by ramping up the RF power fed to the RF gun and accelerator tube [12].

The main parameters of KU-FEL under the thermionic cathode operation are listed in Table 2. The wavelength range where we can obtain FEL macro-pulse energy higher than 1 mJ is from 5 to 20 μm.

Photocathode Operation

The photocathode operation of KU-FEL has been performed using same cathode with the thermionic operation. In case of photocathode operation, the cathode temperature was decreased to around 1400 K to reduce the thermionic electron emission from the cathode and UV laser pulses were irradiated to the cathode to obtain photoelectron emission. Then electrons are supplied from cathode only when the laser pulse is irradiated to the cathode, i.e. electron emission timing is controlled by the laser. A multi-bunch UV pico-second laser system has been developed for the photocathode operation of the RF gun [9]. A feasibility study has been conducted under the final electron beam energy of 23.8 MeV and corresponding FEL wavelength of 11.7 μm. In this experiment, the micro-pulse repetition rate of UV pico-second laser was 29.75 MHz, micro-pulse number of 120, and each micro-pulse had 26 μJ. The laser injection angle onto the cathode was around 70 degree and the polarization direction of the laser was adjusted to have highest quantum efficiency on the cathode. In this experiment, measured maximum quantum efficiency was around 4×10^{-4}, which was strongly depended on the laser injection phase. This implies that the Schottky effect on the photoelectron emission process is dominant effect for this cathode. The laser injection phase was adjusted to 10-20 degree since the electron beam energy spread was small (< 5%). The result is shown in Fig. 3. As shown in the figure, electron beam

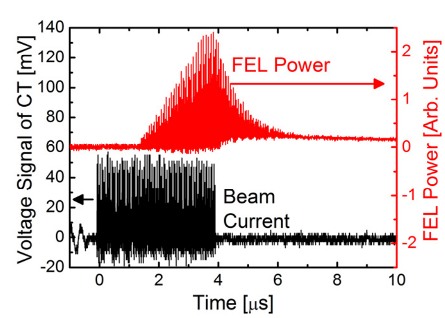

Figure 3: Temporal evolution of electron beam current and FEL power under photocathode operation of KU-FEL.

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having constant beam current and 4-μs macro-pulse duration could be generated. The total charge of electron beam was measured as around 18 nC by a Faraday cup located at the final beam dump shown in Fig. 1. The bunch charge was evaluated as 150 pC from the total charge and number of electron micro-pulses. The bunch charge under photocathode operation was 3 times as much as the maximum bunch charge under the thermionic operation. The FEL macro-pulse energy was measured as 0.8 mJ by a pyroelectric detector. Then the micro-pulse energy was evaluated as 13 μJ.

For comparison, the performance with the thermionic cathode operation has been examined at the same electron beam energy and FEL wavelength. As the result, the FEL macro-pulse energy was measured as 13 mJ and the micro-pulse energy was evaluated as 2 μJ. These experimental results are summarized in Table 3. The macro-pulse energy of FEL under the photocathode operation was one-sixteenth of that under the thermionic cathode operation. Since the micro-pulse repetition rate was one-ninety-sixth, the micro-pulse energy under the photocathode operation was around 6 times as high as that under the thermionic cathode operation. Moreover, in case of photocathode operation, only one optical pulse was stored and amplified in the optical resonator. As aforementioned, higher peak power, lower macro-pulse energy and lower micro-pulse repetition rate is preferred for nonlinear optical experiments. A figure of merit (FOM) for the nonlinear experiments can be defined as

$$\mathrm{FOM} = \frac{E_{\mathrm{micro}}}{E_{\mathrm{macro}}} \quad (1)$$

where E_{micro} and E_{macro} are FEL micro-pulse energy and FEL macro-pulse energy, respectively. In case of single pulse laser, FOM is equal to unity. FOM is also listed in Table 3. In case of photocathode operation, FOM was around 1.6×10^{-2} and this value was around two order of magnitude higher than that of thermionic cathode operation, 1.5×10^{-4}.

The RF gun doesn't have focusing solenoid and the acceleration field on the cathode is not so high (<30 MV/m). Therefore, it is not easy to increase the electron bunch charge higher than 150 pC since the RF gun strongly suffered from electron beam defocusing due to the space charge effect around the cathode. We can possibly increase the micro-pulse energy or FOM by increasing the number of micro-pulse and optimizing the size of the out-coupling hole of the optical resonator mirror.

CONCLUSION

Photocathode operation of the thermionic RF gun has been studied in KU-FEL. A LaB_6 cathode which has been used as the thermionic cathode in the gun was used as the photocathode in this study. Experiments have been conducted under the thermionic cathode operation and photocathode operation at the FEL wavelength of 11.7 μm with the electron beam energy of 23.8 MeV. As the result, the FEL micro-pulse energy of the thermionic cathode operation and photocathode operation were 2 μJ and 13 μJ, respectively. Around six times higher micro-pulse energy than thermionic cathode operation can be generated under the photocathode operation. Moreover, when we consider the figure of merit for nonlinear experiments, which is given as (Micro-pulse energy of FEL) / (Macro-pulse energy of FEL), two order of magnitude higher FOM can be achieved by the photocathode operation. Therefore, we can conclude that the photocathode operation of thermionic RF gun at KU-FEL is feasible for nonlinear optical experiments in the MIR wavelength region.

Table 3: The Electron Beam Properties and FEL Performances under the Thermionic Cathode Operation and Photocathode Operation

	Thermionic	Photo-
Electron Bunch Charge	< 50 pC	150 pC
Electron Beam Macro-pulse Duration	6.5 μs	4 μs
Number of FEL Pulses in Optical Resonator	96	1
Micro-pulse Repetition Rate	2856 MHz	29.75 MHz
Macro-pulse Duration	2 μs	2 μs
Macro-pulse Energy, E_{macro}	13 mJ	0.8 mJ
Micro-pulse Energy, E_{micro}	~2 μJ	~13 μJ
Figure of Merit for Nonlinear Experiments ($E_{\mathrm{micro}}/E_{\mathrm{macro}}$)	1.5×10^{-4}	1.6×10^{-2}

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