MIR-FEL WITH 4.5-CELL THERMIONIC RF-GUN

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Abstract

We have constructed a compact Mid-Infrared Free Electron Laser (MIR-FEL) facility, Kyoto University FEL (KU-FEL) for advanced energy researches. The KU-FEL, consisting of an S-band thermionic RF gun, a 3 m accelerator tube and a planer undulator, aims to generate 4-13 μm tunable FEL. The most serious problem in using the thermionic RF gun for FEL facilities is unstable beam loading owing to back-streaming electrons in the RF gun. In order to overcome the problem, we have developed beamloading compensation methods realized by amplitude modulated RF and slight detuning of the resonant frequency of the RF gun. The first lasing was successfully achieved on March, 2008 at 12.4 μm and the FEL power saturation at 13.6 μm was observed on May. 2008.

INTRODUCTION

A tunable and coherent light source in the MIR (mid-infrared) range is useful tool for a research on molecular dynamics, designing a functional material, which are key techniques for "sustainable energy science". Thus in the Institute of Advanced Energy, Kyoto University, we have developed a compact MIR-FEL (Free Electron Laser) facility[1] with a thermionic RF gun. A use of the thermionic RF gun is aimed to realize a cost effective, compact, easily operable FEL facility.

Facility Design

The FEL system has been constructed in the Laboratory for Photon and Charged Particle Research, Institute of Advanced Energy, Kyoto University. Schematic drawing of the FEL facility is shown in Fig. 1. Total area of the facility is 350 m^2 including klystron gallery, control room and experimental hall. In order to reduce a construction cost, height of a radiation shielding wall made of concrete is reduced to 2.5 m and stairs are used to access to the accelerator room instead of a shielding door. Part of the shielding wall consists of cubic concrete blocks of 1 m^3 which can be moved to install large devices in the accelerator room. The KU-FEL was constructed in 2006[2] and commissioning was started in Dec. 2007.

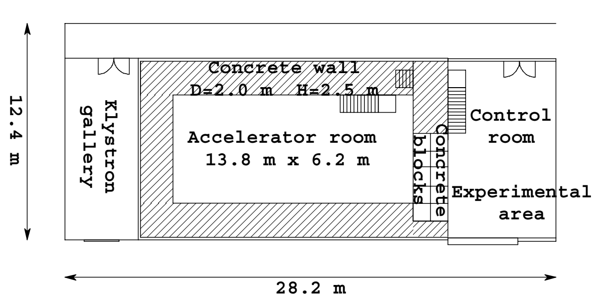

Figure 1: Schematic drawing of the KU-FEL facility.

KU-FEL System

The FEL system consists of an S-band 4.5 cell thermionic RF gun driven by a 10 MW klystron, a 3 m travelling wave accelerator structure driven by a 20 MW klystron, beam transport system, a Halbach type undulator of 1.6 m, and an optical resonator. Figure 2 shows a schematic drawing of the system. The FEL wavelength of from 4 to 13 μm is expected with electron-beam energy of from 20 to 40 MeV.

A thermionic RF gun is a key device for constructing economical and compact FEL facility, because it does not need any expensive multi-bunched stable short pulsed UV laser for a photocathode RF gun or additional beam bunching system for a DC RF gun. However, a serious problem of back-bombardment limits macro-pulse duration. The back-bombardment problem is described as follows. Some electrons which escape from acceleration phase change their direction in the RF gun. And the cathode surface temperature increases due to bombardment of the back-streaming electrons. As a result, the number of extracted electron increases, and the beam loading increases. Then the beam energy decreases. In case for our 4.5 cell thermionic RF gun, the maximum pulse duration which can pass the 'dog-leg' section shown in Fig. 2 was less than 1 μs, when the cathode temperature was set to extract the electron beam more than 100 mA at the exit of the 'dog-leg' section.

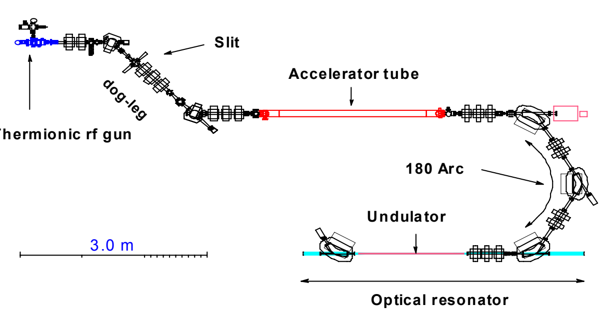

Figure 2: Layout of KU-FEL system.

BEAMLOADING COMPENSATION

In case of a low-gain resonator linac FEL, which consists of an undulator and a couple of mirrors, an

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spontaneous radiation emitted from electron bunch is amplified by the FEL interaction with following electron bunches. Thus, macropulse duration of the electron beam is quite important to obtain saturated FEL output. In case for the KU-FEL, the required pulse duration was at least 3 μs [3]. In order to obtain the long-pulse electron beam, we have developed and applied several techniques to reduce the back-streaming electrons and to reduce the influence of the back-bombardment.

Transverse Magnetic Field on the Cathode Surface

Application of transverse magnetic field on the cathode surface[4] is the most popular technique to reduce the back-streaming electrons. We have applied the transverse magnetic field of about 10 G using a dipole magnet located behind the RF gun[5]. Although the temperature increase during the macropulse was reduced, the effect was not enough to obtain the electron beam longer than 1 μs, because too large magnetic field also diverge the extracted electron beam and the electrons were lost in the RF gun.

Amplitude Modulation to the Input RF

In order to compensate the energy degradation due to the cathode heating by the back-streaming electrons, we applied amplitude-modulated RF pulses to the RF gun[6] and the accelerator tube. Remotely tunable reactors in a pulse forming network (PFN) of a klystron modulator[7] were used to form the optimized RF pulse shape. Phase advance due to the change of the velocity of the electrons in the klystron tube was carefully compensated by using a electric phase shifter. The block diagram of the RF supply system is shown in Fig. 3. The temporal evolutions of the applied voltage to the klystron for the RF gun, the input and reflected RF pulse from the RF gun, and the beam current at the exit of the RF gun are shown in Fig. 4. Although the transverse magnetic field was applied on the cathode surface, the extracted current increased from 200 to 500 mA. In this condition, the RF amplitude was changed from 6.4 to 8.0 MW during the macropulse. The temporal evolutions of the energy distribution extracted from the RF gun with and without modulated RF input are shown in Figs. 5 a), b). The energy degradation during the macropulse due to the increase of the beamloading was successfully compensated. The energy degradation was reduced from 10 to 0.7 %.

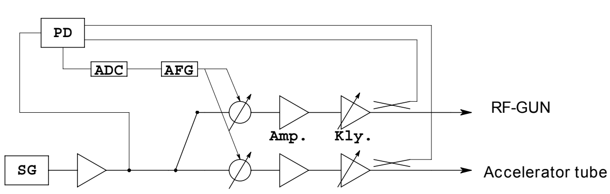

Figure 3: Block diagram of the RF system. The RF phase and the amplitude are independently controlled for the RF gun and the accelerator tube.

As the results, the first lasing of the KU-FEL at 12.4 μm was successfully observed[8]. The same RF amplitude modulation method was also introduced to the accelerator tube. The energy degradation after the accelerator tube was also reduced from 6.0 to 0.8 % as shown in Figs. 6 a), b). The macropulse duration was extended by the amplitude modulation technique from 0.8 to 4.0 μs.

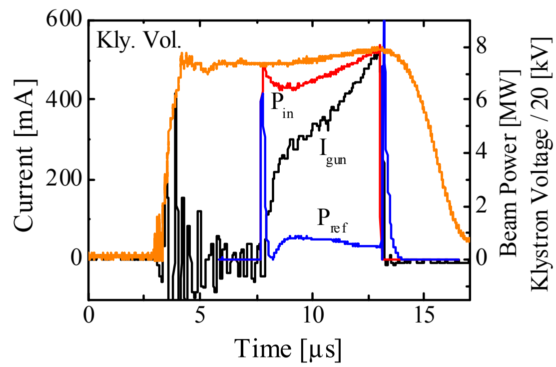

Figure 4: Temporal profiles of the klystron voltage (Kly. Vol.), input RF to the RF gun (P_{in}), extracted current from the RF gun (I_{gun}), and reflected RF from the RF gun (P_{ref}).

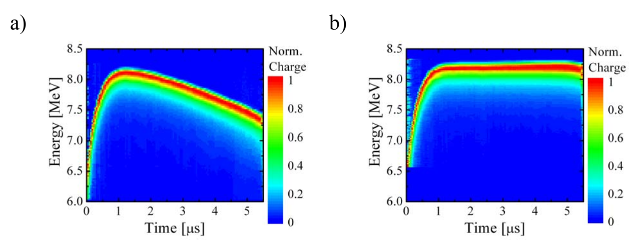

Figure 5: Temporal evolutions of the energy distribution extracted from the RF gun. a): flat RF b): modulated RF.

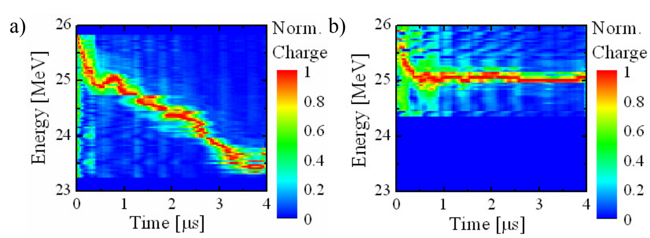

Figure 6: Temporal evolutions of the energy distribution at the exit of the accelerator tube. a): flat RF b): modulated RF.

RF Detuning in a Thermionic RF Gun

Although the macropulse duration was successfully increased, the FEL power was not saturated due to the inadequate macropulse duration, because the tuning range of the RF amplitude was limited to about 20% due to the mechanical limitation of the variable reactors of the PFN circuit. Thus we have introduced new beamloading compensation method which is realized by feeding a RF power with slightly higher frequency than the resonant frequency of the gun[9]. The energy degradation due to the reduction of the cavity voltage was successfully mitigated, and the macropulse duration at the undulator section was extended from 4.2 μs to 5.5 μs as shown in Fig. 7. In this case, the detuning was 290 kHz.

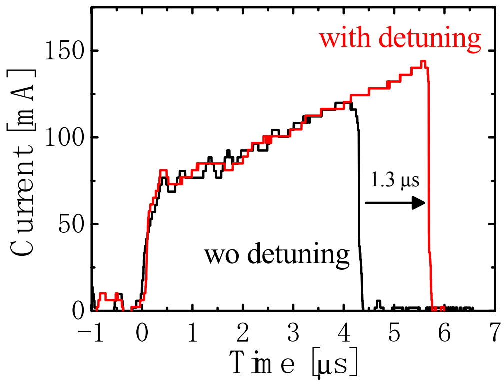

Figure 7: Current profiles of the electron beam at the undulator section. The detuning of 290 kHz was applied.

FEL Performance

A lasing experiment has been carried out using the optimized electron beam. The beam parameter under the lasing experiment is shown in Table 1. The FEL wavelength was 13.2 μm. The temporal evolutions of the FEL output and the current profile at the undulator section are shown in Fig. 8. At the end of the macropulse, power saturation of the FEL was observed. The peak FEL power was expected to be about 2 MW when we assumed the optical pulse duration was 1 ps. The FEL gain and the optical loss were evaluated as 22 % and 11 % respectively from the power evolution of the FEL output.

Table 1: Electron Beam Parameters in the Saturation Experiment

Parameter	Value
Energy (MeV)	24
σ_E/E (%)	0.8
Bunch length (ps in rms)	2
Macropulse length (μs)	5.5
Average current (mA)	115

CONCLUSION

We have constructed a compact MIR FEL facility, KU-FEL consisting of an S-band thermionic RF gun, a 3 m accelerator tube and a planer undulator. A serious back-bombardment problem in using the thermionic RF gun for FEL facilities was successfully solved by the energy compensation techniques. The first lasing of the KU-FEL was achieved by the RF amplitude modulation for the RF gun. By introducing a new detuning method realized by feeding a RF power with slightly higher frequency than the resonant frequency of the RF gun, the macropulse duration reached to 5.5 μs and the FEL power saturation at 13.6 μm was successfully obtained.

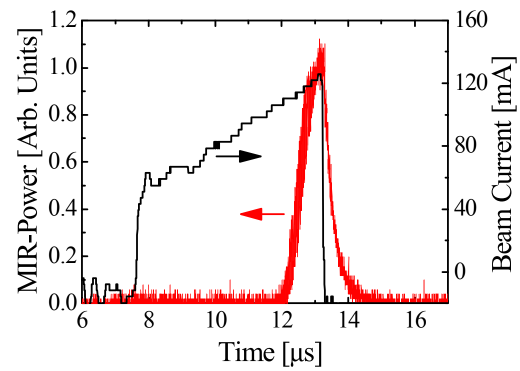

Figure 8: Current profile of the electron beam at the undulator section and power evolution of the FEL output.

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