BEAM PROPERTIES FROM S-BAND ENERGY COMPENSATED THERMIONIC RF GUN AND LINAC FOR KU-FEL

Toshiteru Kii, Hideaki Ohgaki, Kai Masuda, Satoshi Sasaki, Takumi Shiiyama, Heishun Zen

Institute of Advanced Energy, Kyoto University, Gokasho, Uji, Kyoto 6110011, Japan

Abstract

Beam properties after the accelerator tube of the KU-FEL system were measured to ensure the potential of the energy compensation technique to compensate for energy degradation in a thermionic RF-gun. Small growth of energy spread and emittance were observed, and its influence to the FEL gain and evolution of output power were estimated. It was found that the influence due to the amplitude modulation was so serious, because the small increase of the energy spread drastically reduces FEL gain. In addition to the amplitude modulation, phase modulation will be required.

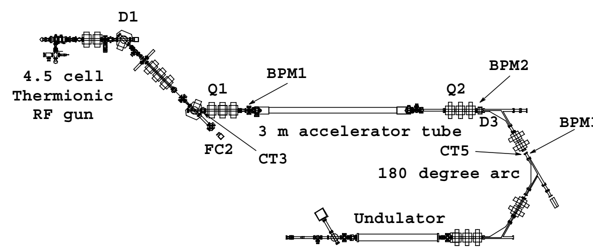

Fig. 1 Arrangement of the KU-FEL.

INTRODUCTION

An MIR-FEL facility, KU-FEL, has been constructed for application of the energy science[1]. The KU-FEL consists of a thermionic RF gun and a 3-m accelerator tube and an undulator to generate 4-13 μm FEL as shown in fig. 1. As an electron injector, we chose a thermionic RF-gun because of its compactness and an easy-handling feature. However, a serious problem of back-bombardment limits macro-pulse duration up to several micro seconds. Then, we have tested an energy compensation technique[2], which uses an amplitude modulated rf pulse using remotely controllable pulse forming network of the Klystron modulator, to reduce the influence of the back-bombardment, and successfully extracted energy compensated electron beam of 4.0 μsec macro-pulse duration and numerically expected to extract electron beam with constant energy up to 8.0 μsec[3,4]. On the other hand, the amplitude modulated RF pulse will give rise to phase difference between RF-gun and accelerator tube, because timing of RF output from Klystron will be shifted to earlier timing because the velocity of the electrons in the Klystron tube is changed during macro-pulse. Moreover, time-varying beam loading will increase beam emittance due to space charge effect. Therefore, we have studied influence of the beam properties, such as temporal current profile, energy spread and emittance, at the exit of the accelerator tube. We have also studied on a figure-of-merit of average beam current and pulse duration, because higher beam current reduces macro-pulse duration.

BEAM PROPERTIES

We have estimated the influence of the energy compensation technique from measurements of beam properties at the entrance and the exit of the accelerator tube. To estimate the influence of the technique clearly, two operational modes were selected. In the first mode, RF pulse of 3 μsec was fed to the RF-gun. Pulse duration after the first bending magnet was about 1.5 μsec. This mode was used to evaluate the beam properties without amplitude modulation. (Mode 1: Non-modulated mode) In the second mode, RF pulse of 7 μsec was fed. Pulse duration after the first bending magnet was about 5.2 μsec. This mode was used to evaluate the effect of the amplitude modulation. (Mode 2: Modulated mode) In these modes, average beam currents were set to around 30 mA, because if the electron beam with higher beam currents and shorter macro pulse duration is used as modulated mode, it is difficult to clear the differences between two modes.

Temporal Current Profile

Temporal profiles of the beam current at the entrance and the exit of the accelerator tube were measured using current transformers (CT3 and CT5 in fig. 1). As shown in figs. 2 and 3, acceleration was performed well in both modes. Although the most of electrons were accelerated in the modulated mode, macro-pulse duration was shortened after acceleration, and beam current was decreased by several percent in the latter part of the macro-pulse as shown in fig 3.

#kii@iae.kyoto-u.ac.jp

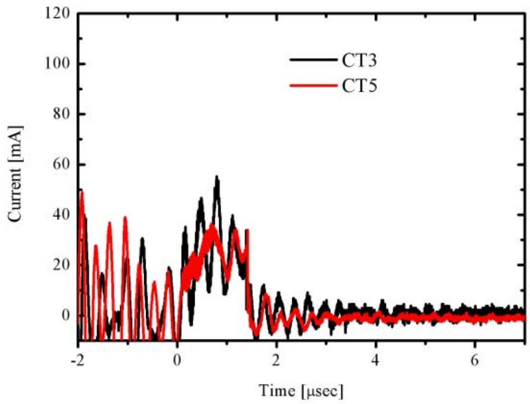

Fig. 2 Temporal profiles of the beam current for non-modulated mode measured at the entrance of the accelerator tube (CT3) and at the exit of the accelerator tube (CT5).

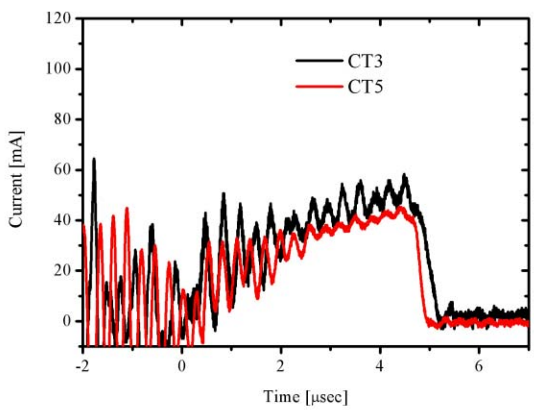

Fig. 3 Temporal profiles of the beam current for modulated mode measured at the entrance of the accelerator tube (CT3) and at the exit of the accelerator tube (CT5).

Energy Spread

Energy spreads were also measured. Before the accelerator, the first bending magnet (D1) and Faraday cup (FC2) were used. After the accelerator, the third bending magnet (D3) and the beam profile monitor (BPM3) was used. As shown in fig. 5, significant growth of the energy spread was observed after acceleration. Absolute value of the energy spread was expanded with modulated RF from 170 keV to 400 keV. It was probable that the phase differences between the stored RF in the gun and the injected RF to the accelerator tube changed the accelerating efficiency in the latter part of the macro-pulse. To estimate the order of the phase difference, phase dependence of the accelerated electron beam energy was measured. Energy difference of 500 keV corresponds to phase difference of about 5 degree around the crest of the phase dependence curve as shown in fig. 6. Therefore, phase difference of several degrees seems to be introduced by the amplitude modulation. FEL gains and power evolutions were also calculated using GENESIS[5] to estimate the influence of the energy spread. In these calculations, bunch length of 1.0 ps, beam energy of 25 MeV, energy spread of 0.5%, transverse emittance of 3.5π mm-mrad were assumed. The FEL power evolutions for electron beam with 0.5% and 1.0% energy spread are shown in fig. 7. As shown in fig. 7, the influence of the modulated RF input is quite serious due to the growth of the energy spread. The result indicates that the FEL gain rapidly decreases in the macro pulse. Phase modulation to the source RF of the Klystron will be effective to reduce expansion of the energy spread. It is important to measure the time evolution of the energy spread, to estimate the FEL power evolution precisely.

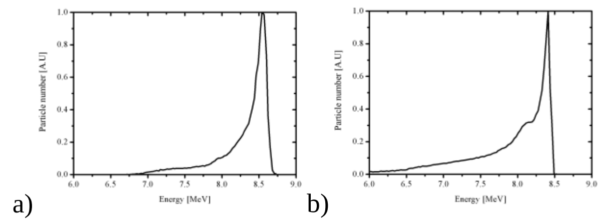

Fig. 4 Energy spread before the accelerator tube. a) Non-modulated mode b) Modulated mode

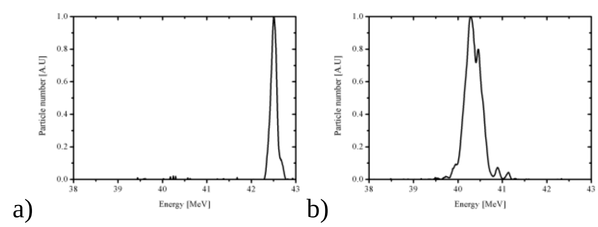

Fig. 5 Energy spread after the accelerator tube. a) Non-modulated mode b) Modulated mode

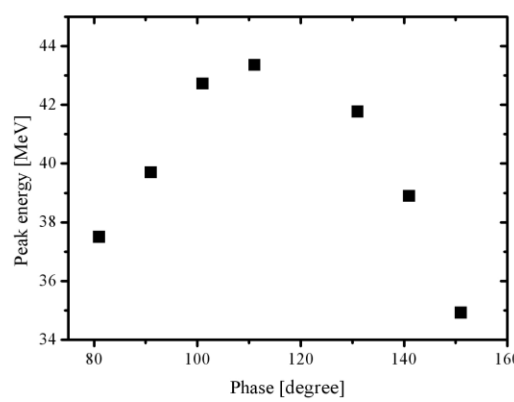

Fig. 6 Phase dependence of the peak energy of the accelerated electron beam.

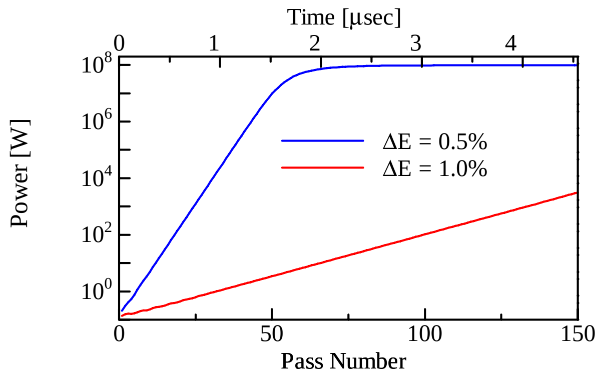

Fig. 7 FEL power evolutions for different energy spread.

Beam Emittance

Beam emittances were also measured using phase space tomography method. Although when we apply the tomography method to the electron beam with energy spreads, estimated emittance will be overestimated[6], in these experimental condition, energy spreads were less than 2.0%, thus the tomography method was effectively worked. Phase space distributions before and after the accelerator were measured using quadrupole magnets (QM1, QM2) and beam profile monitors (BPM1, BPM2). Reconstructed phase space distributions are shown in figs. 8 and 9. As shown in figs. 8 and 9, main components of the electron beams become fuzzy when the modulated RF were used.

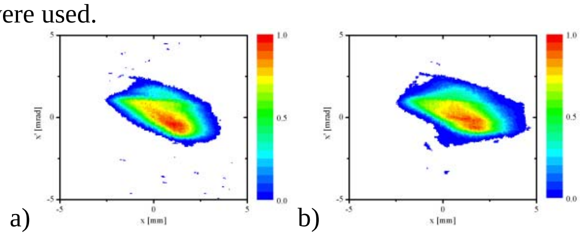

Fig. 8 Phase space distribution in x dimension before the accelerator. a) Non-modulated mode b) Modulated mode.

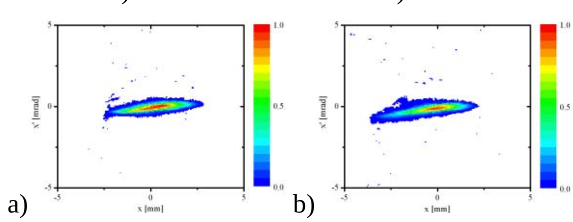

Fig. 9 Phase space distribution in x dimension after the accelerator. a) Non-modulated mode b) Modulated mode.

The evaluated rms emittances after the accelerator were increased by about 40% with modulated RF pulse as shown in table 1. To estimate the influence of the modulation, FEL power evolutions were calculated. As shown in fig. 10, the influence of the emttance growth is small. In these calculations, bunch length of 1.0 ps, beam energy of 25 MeV, energy spread of 0.5 %, transverse emittance of 3.5π and 10.0π mm-mrad were assumed.

Table 1. Evaluated beam emittances at the entrance and the exit of the accelerator tube.

mode	Emittance @ entrance [π mm mrad]	Emittance @ exit [π mm mrad]
1	x : 4.0 , y : 0.9	x : 2.5 , y : 2.5
2	x : 4.5 , y : 1.0	x : 3.3 , y : 3.5

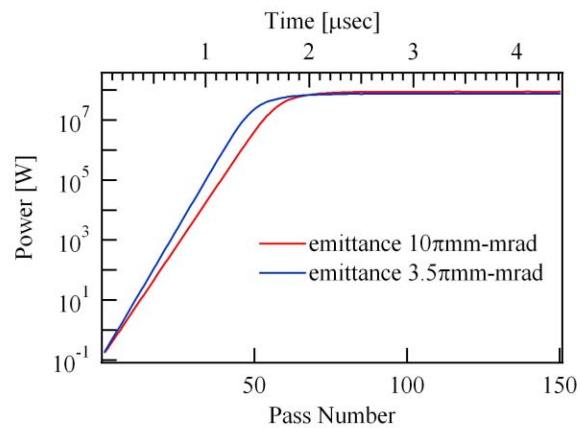

Fig. 10. FEL power evolutions for the electron beam with different emittance.

OPERATION POINT OF THE THERMIONIC RF-GUN

Although the FEL gain becomes larger when extracted beam current is increased, the influence of the back-bombardment becomes larger, and then the macro pulse duration becomes shorter. In case for our RF gun, maximum beam current is about 120 mA, but the pulse duration is limited to less than 500 nsec. On the other hand, if the extracted beam current is limited to 30 mA, the pulse duration is reached up to 5 µsec. To find the better operational point, power evolution of the FEL for various average beam current was estimated. In these calculations, bunch length of 1.0 ps, beam energy of 25 MeV, transverse emittance of 3.5π mm-mrad were assumed. As shown in fig. 11, the FEL gain is sensitive to the average beam current. Therefore, we have tested to increase average beam current. As shown in fig. 12, we successfully extracted electron beam of 50 mA with pulse duration of 3.5 µsec.

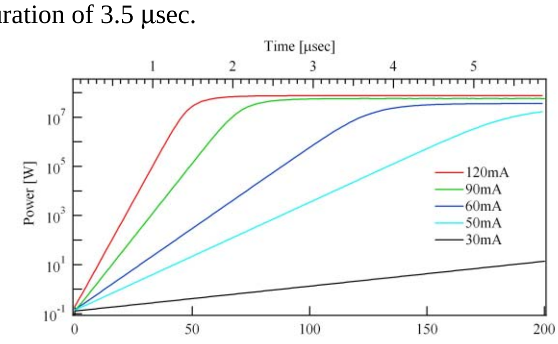

Fig. 11. Estimated FEL power evolutions for various average beam currents using GENESIS.

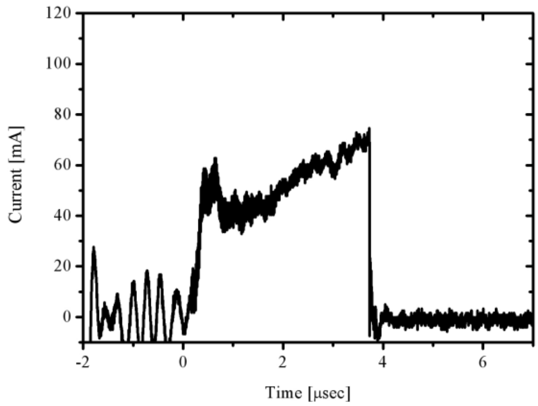

Fig. 12 Temporal profiles of the beam current with 50 mA of average current.

CONCLUSION

Beam property measurements were carried out to evaluate the performance of the energy compensation technique using amplitude modulated RF pulse applied to the thermionic RF gun in KU-FEL system and the influence of the amplitude modulation. It was found that the energy compensation technique was effective for extract the electron beam with longer macro pulse, but the influence to the energy spread was quite serious. To achieve the first lasing of the KU-FEL, an RF phase modulation will be required in addition to the amplitude modulation. The better operational point was also surveyed for higher FEL output. The new operating mode of 50 mA and 3.5 μsec was successfully found.

REFERENCES

[1] T. Yamazaki, et al., Free Electron Laser 2001 (2002), II13-II14.
[2] T. Kii, et al, Proceedings of the 26th International Free Electron Laser conference, (2004) 443-446.
[3] T. Kii, et al., AIP Conference Proceedings Volume 879, SYNCHROTRON RADIATION INSTRUMENTATION: Ninth International Conference on Synchrotron Radiation Instrumentation, (2006) 248-251.
[4] N. Okawachi, et al., Proceedings of International Conference on Free Electron Laser, (2006) 664-667.
[5] S. Reiche, "GENESIS 1.3 User Manual", (2004).
[6] H. Zen, et al., Proceedings of International Conference on Free Electron Laser, (2006) 668-671.