NUMERICAL EVALUATION OF OSCILLATOR FEL WITH MULTI-BUNCH PHOTO-CATHODE RF-GUN IN KYOTO UNIVERSITY*

Hideaki. Ohgaki#, Toshiteru Kii, Kai Masuda, Satoshi Sasaki, Takumi Shiiyama, Heishun Zen, Institute of Advanced Energy, Kyoto University, Gokasho, Uji, Kyoto 6110011, Japan
Ryunosuke Kuroda, National Institute of Advanced Industrial Science and Technology, Umezono 1-1, Tsukuba, Ibaraki 3058658, Japan
Masao Kuriki, Nobuhiro Terunuma, Junji Urakawa, High Energy Accelerator Research Organization, 1-1, Oho, Tsukuba, Ibaraki, 305-0801, Japan
Yoshio Kamiya, Masakazu Washio, Research Institute for Science and Engineering, RISE, Waseda University, 3-4-1, Okubo, Shinjuku-ku, Tokyo, 169-0072, Japan

Abstract

Numerical evaluations have been performed to install a photo-cathode RF-gun into an oscillator FEL system which has been developed in Kyoto University. The original FEL system was consisted of a 4.5-cell thermionic RF gun with S-band accelerator tube of 3-m to oscillate the mid-infrared FEL. The electron beam properties have been evaluated from an RF-gun to an FEL by using PARMELA and ELEGANT. On the other hand, the FEL parameters have been calculated with GENESIS which takes the optical cavity into account. The evaluated peak current of the electron beam was 10-50 times as high as those with the thermionic RF-gun. Since the oscillator FEL requires a multi-bunch electron beam, evaluation of the round-trip development of the FEL has been also performed by a 100 bunch train beam. The results showed that the FEL gain saturation was achieved within 3 round-trips.

INTRODUCTION

An infrared FEL (4-13 μm) facility for energy science is under construction at the Institute of Advanced Energy, Kyoto University [1]. The electron beam of 40 MeV and peak current of -10 A has been successfully accelerated by a linac system which consists of a 4.5-cell thermionic RF gun, a 'dog-leg' transport system, a 3m s-band linac, and a 180-degree arc bunch compressor [2]. Figure 1 shows the schematic view of the linac system which includes the photo-cathode RF-gun. To reduce the back-bombardment effect in the 4.5-cell RF gun, several attempts have been made, and the macro pulse duration of 5 μs has been achieved [3]. However, there still needs several efforts are needed both to extend the macro pulse duration and to increase the peak current to reach the FEL saturation [4]. Replacing the thermionic RF-gun to a photo-cathode RF-gun is the most promising way to obtain a high peak current electron beam. Therefore, we made a preliminary design study [5] and start to develop a 1.6-cell photo-cathode RF-gun [6]. Recently, the improved design of the

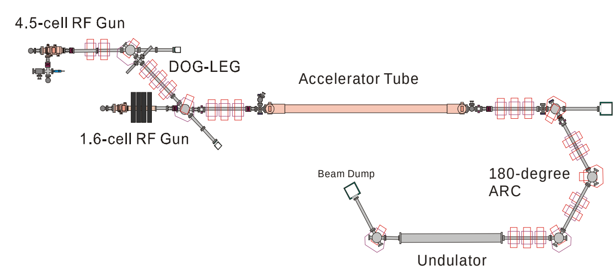

Figure 1: Schematic view of the KU-FEL driver linac.

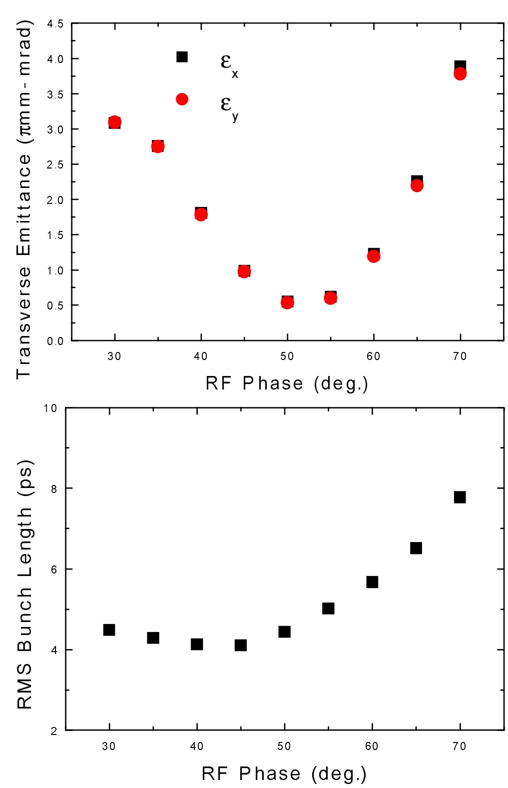

Figure 2: Transverse RMS emittance(a) and energy spread(b) of the electron beam from the gun as a function of the laser injection phase.

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#ohgaki@iae.kyoto-u.ac.jp
+present address: International Center for Elementary Particle Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

photo-cathode RF-gun has been installed in the linac in AIST and succeeded to generate 100-bunch electron beam. The beam charge of 1.5 nC/bunch has already been achieved. We are going to install the similar RF-gun system into KU-FEL system. Thus a start-to-end calculation with the photo-cathode RF-gun has been performed. For the electron beam a simulation has been made by PARMELA [7] and ELEGANT [8] from gun to undulator. On the other hand, the FEL parameters have been calculated by using GENESIS [9] which was modified to calculate an optical cavity. Then the FEL gain was compared with the present thermionic RF-gun based system.

1.6-CELL PHOTO-CATHODE RF-GUN

The improved BNL type 1.6-cell photo-cathode RF-gun [10] has succeeded in generation of a high brightness electron beam, about 1 πmm-mrad with 1.5 nC/bunch. A multi-bunch operation also succeeded with a 100 bunch UV drive laser and a Cs_2-Te cathode. This type of photo-cathode RF-gun manufactured in KEK will be installed into KU-FEL system. As is shown in figure 1, the 1.6-cell photo-cathode RF gun will be located at the upstream of the accelerator tube. The RF system will be shared with the existing thermionic RF-gun. Since the thermionic RF-gun operates 2856 MHz bunch train, a large average power FEL will be generated by the thermionic RF-gun. On the other hand, the photo-cathode RF-gun can generate a high peak power FEL but small average power FEL, because the bunch train is depends on the laser frequency of the laser (357 MHz).

The electron beam parameter from the 1.6-cell RF-gun has been evaluated by using PARMELA with the maximum electric field of 50 MV/m at the cathode surface which was given by an acceleration test in AIST. We also assumed that the ratio of the field strength of the half cell and regular cell was 1:1 which was measured with the test gun at KEK. The ratio of the field strength, which can be tuned from 0.8:1 to 1.3:1, and the maximum filed strength should be optimized for its' purpose, because the electric field for the cavity cell largely affects the property of the output beam. The driver laser parameters assumed here was a picosecond UV laser [11], whose beam profile was 0.7 mm at the cathode surface and the pulse duration was 6.0 ps. The Gaussian shapes were also assumed both for the transverse (1 mm cut-off) and for the longitudinal (12 ps cut-off) distribution to simplify the calculation. Figure 2 shows the transverse RMS emittance(a) and energy spread(b) of the electron beam from the RF gun as a function of the laser injection timing. We assumed 1 nC/bunch at the cathode surface in this paper.

It is clear that the transverse RMS emittance of 1 πmm-mrad and energy spread of 2% can be generated at the 45 degree of the laser injection phase at the gun exit. The solenoid field for the emittance compensation [12] which

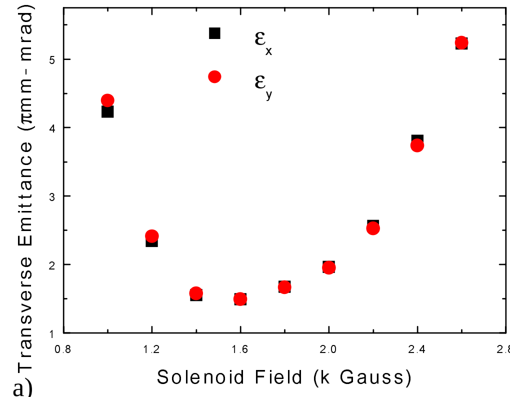

Figure 3: Transverse RMS emittance at the exit of the accelerator tube as a function of the solenoid field.

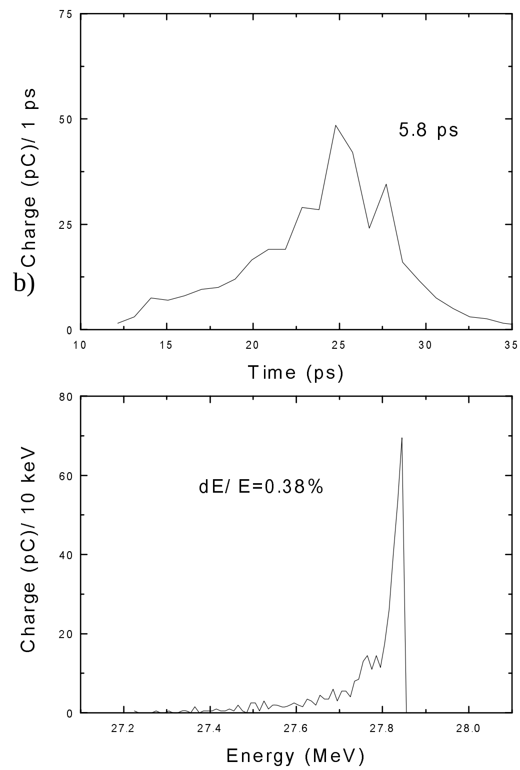

Figure 4: Time distribution (a) and energy distribution (b) at the exit of accelerator tube. The RF phase of the accelerator tube was chosen to 'on crest mode'.

was the same geometric configuration of ref. 13. The field distribution was calculated by using POISSON. As shown in fig.3 the transverse emittance of 1.5 πmm-mrad is obtained from the accelerator tube with the solenoid field of 1600 Gauss. Figure 4 also shows the bunch length(a) and the energy spread(b) of the electron beam from the accelerator tube with the RF-phase of 125 degrees where the smallest energy spread was obtained.

The achromatic 180-degree arc section was tuned both for the matching condition of the undulator parameter and for the bunch compression condition with matrix element, R_{56}, by using ELEGANT. Figure 5 shows the bunch length(a) and the energy spread (b) of the electron beam at the entrance of undulator. As is shown in fig.5 (a) the bunch length successfully reduced below 1 ps, but more than half of the electrons are spread away from the main bunch. This is due to a non-linear relation between phase and energy at the exit of the accelerator tube since the RF phase, 125 degrees, was located at RF crest. We call this operation mode as ‘on crest mode’. Thus we also calculated with the RF phase at 132.5 degrees where the relation between phase and energy was close to a linear one. We call this operation mode as ‘energy chirp mode’. Figure 6 shows the bunch length (a) and energy spread (b) of the electron beam at the entrance of undulator with RF phase of 132.5 degrees. As the results the bunch length was reduced from 0.8 ps to 0.23 ps and the peak current was increased from 443 A to 2.46 kA.

The expected parameters of the electron beam from 1.6-cell photo-cathode RF-gun were listed in table.1. Consequently, the photo-cathode RF-gun would generate 10-50 times large peak current electron beam to the thermionic RF-gun which generated 40 A peak current of the electron beam [5].

Table 1 Evaluated Electron Beam Parameters

	Thermionic RF gun[5]	Photo-Cathode RF-gun	
		On Crest mode	Energy Chirp mode
Emittance (πmm-mrad)	11.3(H) 10.1(V)	5.02(H) 5.01(V)	4.42(H) 3.03(V)
Energy Spread (%)	0.40	0.054	0.86
Bunch Length (ps)	1.8	0.80	0.23
Peak Current (A)	40.0	443	2,460

OSCILATOR FEL DRIVEN BY 1.6-CELL PHOTO-CATHODE RF-GUN

The FEL gain with the 1.6-cell photo-cathode RF-gun has been calculated by using above evaluated electron beam parameters. The undulator and optical cavity parameters used here are listed in ref. 4. The 1-pass FEL gains with the ‘on crest mode’ and with the ‘energy chirp mode’ were calculated as 8.8×10^4% and 7.6×10^7% in 12.1 μm wavelength. On the other hand, the 1-pass FEL gain with the thermionic RF-gun was 38%. The 1-pass gain was extremely enhanced even with the ‘on crest mode’ because of its’ large peak current, more than 400 A. Although a large energy spread in the ‘energy chirped mode’ a huge peak current, 2.4 kA, brought a huge 1-pass gain.

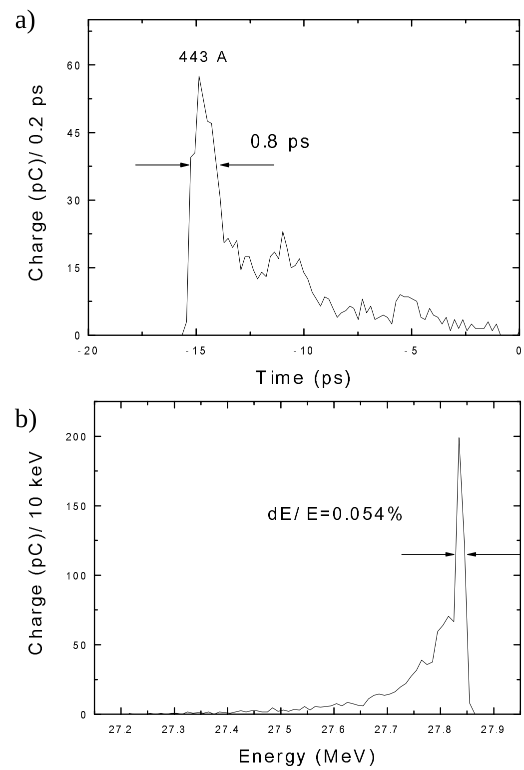

Figure 5: Time distribution (a) and energy distribution (b) at the undulator. The RF phase was ‘on crest mode’.

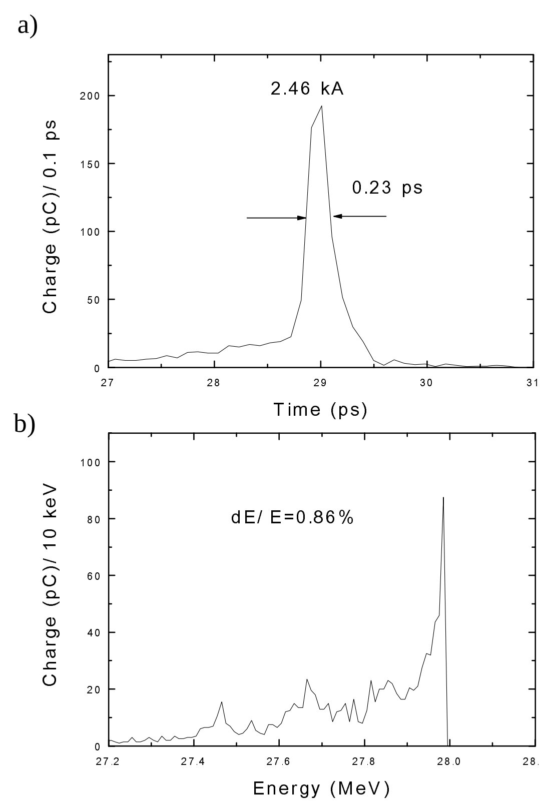

Figure 6: Time distribution (a) and energy distribution (b) at the undulator. The RF phase was ‘energy chirped mode’.

To calculate a round-trip development in an oscillator FEL, we modified GENSIS which treated the light propagation in an optical cavity including an optical loss in vacuum duct, mirror surface, and hole coupling [4]. The multi-bunch electron beam, a 100-bunch, has already been achieved by a 100 bunch UV laser system which was based on 357 MHz mode-locker [6]. However, we should note that our cavity length of the undulator is 4.51 m and round-trip frequency is about 33.2 MHz. Therefore about 10 round-trips can be used for the FEL amplification. So we assumed 10-round-trips, about 0.3 µs in macropulse, in this calculation. The round-trip development is shown in fig.7. As is shown in fig.7 FEL saturations are achieved with a few round-trips for both operation modes. The peak output powers were 10 MW with 'on crest mode' and 400 MW with 'energy chirped mode'. The average FEL energies were also calculated as 0.44 mJ/macro-pulse for 'on crest mode' and 4.6 mJ/macro-pulse for 'energy chirped mode'. On the other hand, the saturated output power of 2.4 MW can be obtained after 70 round-trips with the thermionic RF-gun system. The average FEL energy can be calculated as 10 mJ/macro-pulse for 3 µs macropulse length which corresponds to the 100 round-trips. To increase the average energy with a photo-cathode RF-gun, the bunch train should be increased. A 300-bunch train, 1 µs macro-pulse duration, should be the next target for the development of the photo-cathode RF-gun to replace the thermionic RF-gun completely.

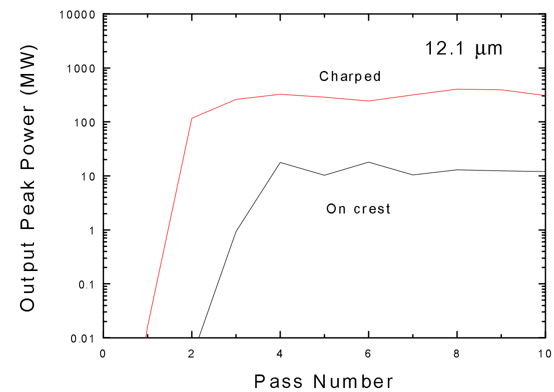

Figure 7: Round-trip development of the FEL output power.

CONCLUSION

An improved BNL type RF-gun, which has already been succeeded in generation of 100 bunch, about 1 πmm-mrad with 1.5 nC/bunch electron beam in AIST-RISE, will be installed in an oscillator FEL system. The FEL system was originally designed with a 4.5-cell thermionic RF gun with a 180-degree arc worked as a bunch compressor to oscillate the mid-infrared FEL in Kyoto University. To evaluate the FEL performance with the photo-cathode RF-gun we made a start-to-end calculation by using PARMELA, ELEGANT and GENESIS which has been improved to take an optical cavity into account.

The evaluated peak current of the electron beam at the undulator was 443 A when the RF phase was tuned to obtain the minimum energy spread, dE/E=0.054%, of the electron beam. When the RF phase was tuned for energy chirped beam, dE/E=0.86%, the peak current of the electron beam was 2.46 kA. Since the thermionic RF-gun generated 40 A electron beam, 10-50 times large peak current was obtained by the photo-cathode RF-gun.

The output power of 12.1 µm FEL, 400 MW, will be saturated within 3 round-trips with the energy chirped beam. On the other hand, the saturated output power of 2.4 MW can be obtained after 70 round-trips with the thermionic RF-gun system. We should note that only 10 round-trips can be used for the FEL amplification when we assumed a 100-bunch electron beam. Therefore, the evaluated average energy of the FEL was 4.6 mJ/macropulse which was smaller than that with a thermionic RF-gun, 10 mJ/macropulse.

Consequently a high brightness electron beam from the photo-cathode RF-gun will generate 100 times high peak power of FEL. However, the average power of FEL with the photo-cathode RF-gun will be smaller than that with thermionic RF-gun when we assume a 100 bunch train for the electron beam. Further developments for generating a longer multi-bunch beam are required to replace a thermionic RF-gun into a photo-cathode RF-gun, completely.

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