NUMERICAL STUDY ON THE OPTIMUM CAVITY VOLTAGE OF RF GUN AND BUNCH COMPRESSION EXPERIMENT IN KU-FEL

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Abstract

High peak current (~40 A) electron beams with the macro-pulse duration of 2-5 μs are required for the lasing of Kyoto University Free Electron Laser (KU-FEL). However, the bunch charge and macro-pulse duration in the facility have a trade-off relationship, and the bunch charge is limited to <30 pC when the macro-pulse duration is ~3 μs. Therefore, the optimization of operational condition of our thermionic rf gun and the bunch compression are necessary to achieve such a high peak current. Optimum field strength of our rf gun was surveyed by numerical simulation. The result indicates that the highest peak current is around 23 A with the average field strength of 24 MV/m. Under the same condition, bunch lengths of electron beams were measured by using a streak camera. The condition of bunch compression was also surveyed in experiment. The measured minimum bunch length was 2.0 ps, which was as short as the temporal resolution of the measurement system. Since the bunch charge was 14 pC, the highest peak current was estimated to be more than 7 A from the experimental result.

INTRODUCTION

A mid-infrared free electron laser facility (3-14 μm) named KU-FEL was constructed for the energy science in Institute of Advanced Energy, Kyoto University [1]. As shown in Fig. 1, the facility consists of an S-band 4.5 cell rf gun with a tungsten dispenser-type thermionic cathode, an energy filtering section (Dog-leg), a S-band accelerator tube (3 m), a bunch compression section (180-deg. arc), an undulator and an optical cavity. Electron beams were successfully accelerated up to 40 MeV [2]. However, due to the back-bombardment effect [3,4], the bunch charge and macro-pulse duration have a trade-off relationship and the bunch charge was limited to smaller than 30 pC with the macro-pulse duration of ~3 μs. Thus the bunch compression is necessary to obtain a peak current of

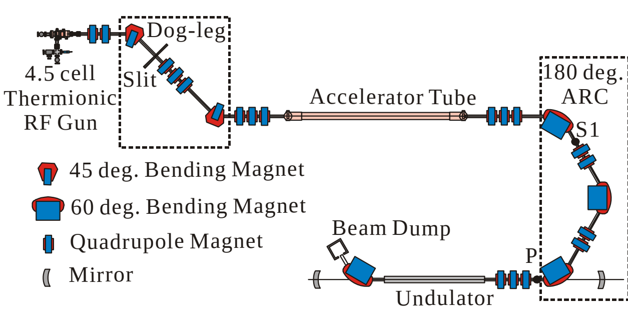

Figure 1: Schematic view of KU-FEL facility.

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~40 A, which is required to achieve the FEL saturation [5] in KU-FEL. Another feature of the gun is that the higher average current is available after energy filtering section if the higher electrical fields are induced to its cavities. On the other hand, the nonlinearity of longitudinal phase space distribution, which enlarges a bunch length during a bunch compression, increases if too high electrical fields induced. It means that there is the optimum operational condition of the field strength of rf gun to obtain the highest peak current. In this study, first, the optimum field strength of the gun was surveyed by numerical simulation. Second, the bunch length was measured and the optimum bunch compression condition was determined under the gun condition in experiment. PARMELA [6] was used for particle tracking from the gun to the undulator. And ELEGANT [7] was used to find the achromatic sets of quadrupole magnets of dispersive section in simulation and experiment. And the code was also used to calculate and control the R_{56} of the arc.

STUDY ON THE OPTIMUM FIELD STRENGTH OF RF GUN

Dependences of the longitudinal emittance and the average current on the average field strength of the first half cell of the 4.5 cell rf gun were shown in Fig. 2. The field strengths of other 4 cells are about twice higher than that of the first cell. The longitudinal phase space distributions at the entrance of the accelerator tube were shown in Fig. 3. As mentioned in the introduction, the higher average current is available after the energy filtering section if the higher field strength of the cells is induced. As shown in Fig. 2 and 3, however, the nonlinearity of the longitudinal phase space distribution and the corresponding longitudinal emittance rise up if too high electric fields (>25 MV/m) are induced. High bunch charge and low longitudinal emittace are required to obtain high peak current after bunch compression.

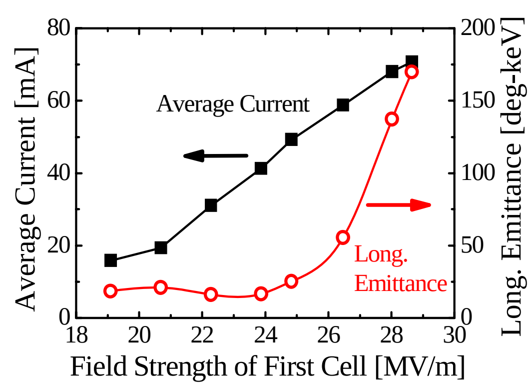


Figure 2: Longitudinal emittance and average current as a function of the field strength of first half cell.

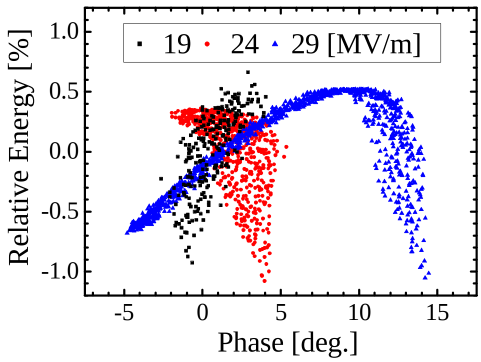


Figure 3: Longitudinal phase space distribution at the entrance of accelerator tube (simulation).

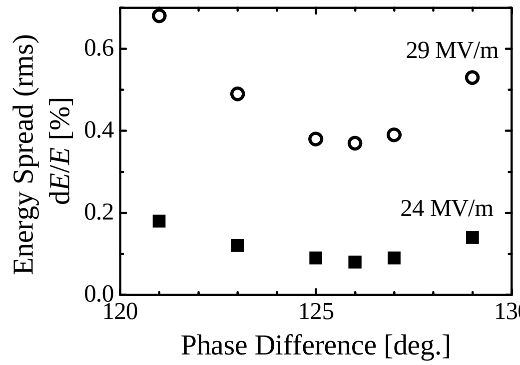


Figure 4: Energy spread as a function of phase difference between the rf gun and the accelerator tube.

There are two candidates of the field strength for the highest peak current. One is around 24 MV/m which have the smallest longitudinal emittance with a medium bunch charge. The other is 29 MV/m which have the highest bunch charge with the largest longitudinal emittance.

Due to the transient energy drop by the back-bombardment effect, in practical experiment, there is a trade-off relationship between the average current and the macro-pulse duration after the energy filter, which means that the macro-pulse duration decreases if the average current increases. Table 1 shows the typical parameters of electron beams that have the highest average currents with the macro-pulse duration of 2.4 μs under the 24 and 29 MV/m conditions. In this numerical study, beam parameters were adjusted to those shown in Table 1.

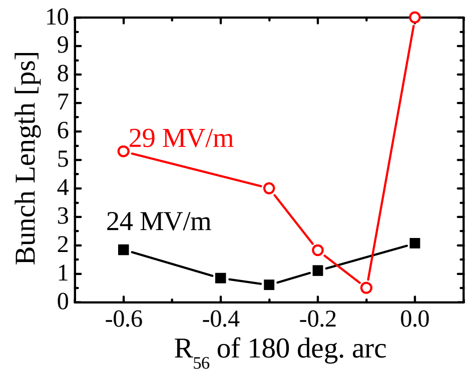


Figure 5: Bunch length as a function of R_{56} of the 180 deg. arc.

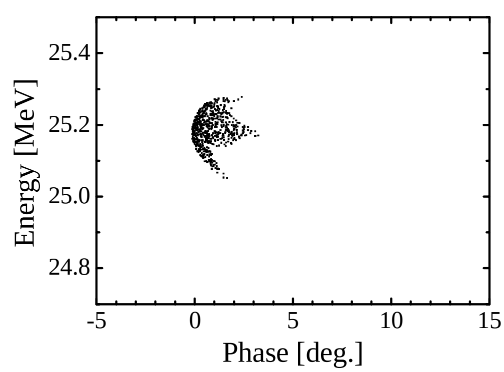
Table 1: Typical parameters of the electron beam under the 24 and 29 MV/m conditions.

Gun	Field Strength of First Cell [MV/m]	24	29
Gun Exit	Peak Energy [MeV]	7.5	9
	Average Current [mA]	320	320
	Macro-pulse Duration [μs]	3.3	3.3
After Dog-leg	Average Current [mA]	40	70
	Macro-pulse Duration [μs]	2.4	2.4

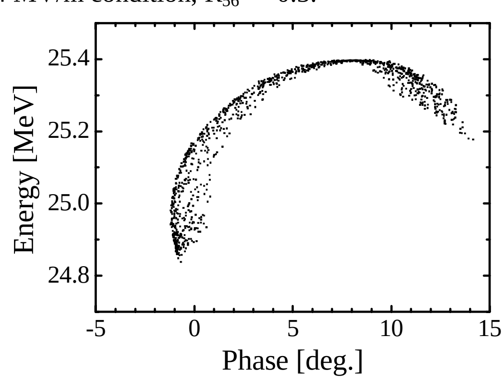
Bunch Compression

The bunch compression properties under the 24 and 29 MV/m condition were examined by numerical simulation. The energy after the accelerator tube was set to about 25 MeV by adjusting field strength. Under both of the two conditions, the energy spread is minimal when the phase difference between the gun and the tube set to 126 deg. as shown in Fig. 4. An energy chirping is essential for the bunch compression and we gave the energy chirp by selecting the phase difference of 121 deg.

Dependences of the bunch length on R_{56} with energy chirping are shown in Fig. 5. The bunch length was evaluated by the least square fitting of Gaussian distribution to the temporal distribution. The longitudinal phase space distributions under the minimum bunch length condition are shown in Fig. 6, and the temporal



(a) 24 MV/m condition, R_{56} = -0.3.



(b) 29 MV/m condition, R_{56} = -0.1.

Figure 6: Longitudinal phase space under the minimum bunch length condition.

profiles are shown in Fig. 7. The peak current was also evaluated by the Gaussian fitting and the results are shown in Table 2. As you can see in Fig. 6 and Fig. 7, all the electrons are bunched well under the 24 MV/m condition, and the electrons are not bunched well under the 29 MV/m condition. Thus the peak current under the 24 MV/m condition was higher than 29 MV/m condition as shown in Table 2, even though the total bunch charge was lower.

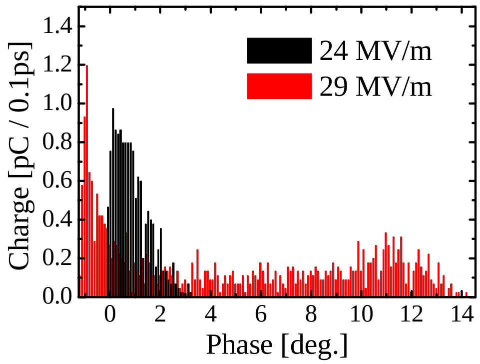


Figure 7: Temporal distributions with the minimum bunch length condition.

Table 2: Results of numerical simulations.

Field Strength of First Cell [MV/m]	24	29
Total Bunch Charge [pC]	14	25
Bunch Length [ps]	0.6	0.5
Peak Current [A]	23	16

BUNCH LENGTH MEASUREMENT AND BUNCH COMPRESSION

The bunch length measurements and the bunch compression were carried out to determine the optimum condition of bunch compression in experiment under the 24 MV/m condition. In experiment, the beam parameters before the accelerator tube were same with ones shown in Table 1. The central energy after the tube was adjusted to 25 MeV, and the phase difference between the gun and the tube was adjusted to the condition that the horizontal beam size at the beam profile monitor S1 in Fig. 1 became minimal.

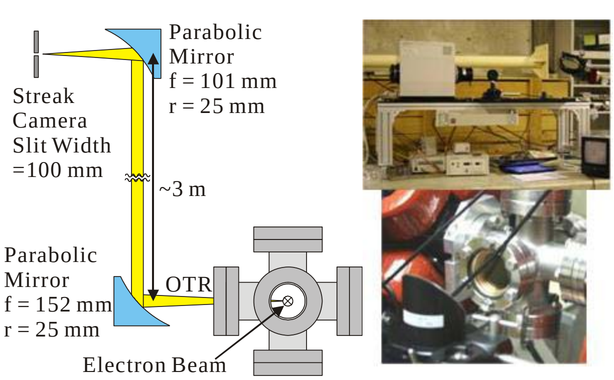


Figure 8: Setup of optics and streak camera.

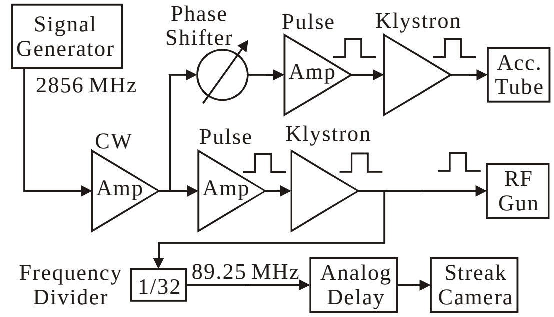


Figure 9: Trigger diagram for the streak camera.

Experimental Setup

A mirror target to generate optical transition radiations (OTRs) from electron beams was inserted at the position P in Fig. 1, and the OTRs were transported to and focused on the entrance slit of a streak camera (HAMAMATSU C6138S) by a pair of parabolic mirrors as shown in Fig. 8. The focusing mirror enables to minimize the deterioration of temporal resolution with the least weakening of the OTR. The slit width of streak camera was limited to over 100 μm due to weak OTRs, and we use 50 ps full scale range. Then, the temporal resolution was around 2.0 ps.

The trigger diagram for the streak camera is shown in Fig. 9. The trigger signal was generated by using a frequency divider (1/32) from rf power fed to the rf gun in order to synchronize the trigger signal with the electron beam.

Result and Discussion

Figure 10 shows the typical result of the bunch length measurement and it was integration of 10 shots. When the temporal profiles were integrated, the mean of each temporal profile were aligned in order to mitigate the deterioration of temporal resolution due to timing jitter (~10 ps) of the trigger signal.

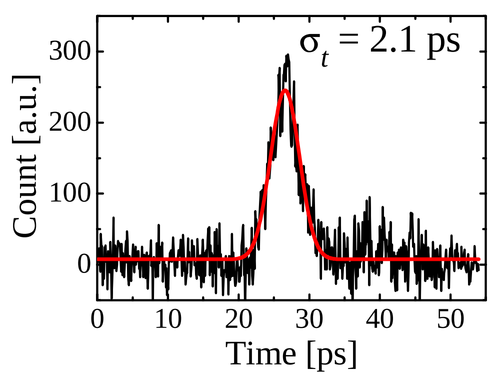


Figure 10: Typical result of the bunch length measurement. This result was integration of 10 shots.

Dependences of measured bunch lengths on R_{56} of 180-deg. arc section were shown in Fig. 11. These results are also integration of 10 shots. The minimum bunch length was around 2.0 ps with R_{56} = -0.3, -0.4. The result was as short as the temporal resolution of this measurement limited by slit width of the streak camera. Therefore, the actual bunch length must be shorter than 2.0 ps. The peak current of electron beam was measured to be more than 7 A, since the bunch length was shorter than 2.0 ps and the bunch charge was 14 pC. Higher temporal resolution is required to discuss shorter bunch lengths and to shorten the bunch length under 2.0 ps.

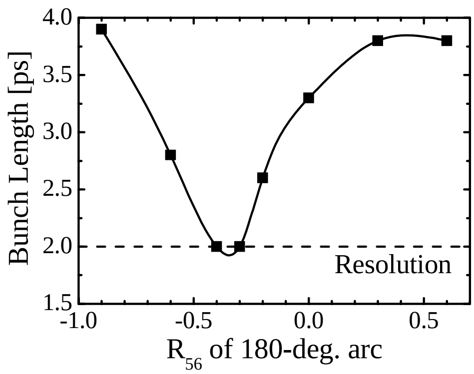


Figure 11: Experimental result of dependences of bunch lengths on R_{56} of 180-deg. arc section.

CONCLUSION

The optimum cavity voltage of our thermionic rf gun was studied by numerical simulation. The result indicated that the field strength of first cell should be around 24 MV/m to obtain high peak current in present setup. The highest peak current was about 23 A under the condition. The bunch length measurement and bunch compression were performed under the optimum condition. The measured minimum bunch length was 2.0 ps when R_{56} was -0.3, -0.4. The minimum bunch length was as short as the temporal resolution of measurement system. Thus the peak current was estimated to be more than 7 A in this experiment. Higher temporal resolution is required to discuss shorter bunch length and to obtain higher peak current. And now, we are preparing a configuration which enables us measurements with higher temporal resolution.

The peak current about 23 A is not enough to achieve FEL saturation [5] in KU-FEL, even if we could shorten the bunch length to 0.6 ps in experiment. To obtain higher peak current, we are now preparing a LaB_6 cathode [8] and a triode-type rf structure [9,10].

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