BEAM ENERGY COMPENSATION BY RF AMPLITUDE CONTROL FOR THERMIONIC RF GUN AND LINAC BASED MID-INFRARED FEL

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Abstract

A mid-infrared FEL facility which consists of a thermionic RF gun, a traveling-wave type accelerator tube and a halbach type undulator was constructed for the energy science in Institute of Advanced Energy, Kyoto University. We found that the beam energy after the accelerator tube decreased from 26 to 23.5 MeV during macro-pulse duration (~4 μs), because the beam current increases from 65 to 120 mA due to the back-bombardment effect in the RF gun. To compensate the energy drop and to minimize the energy spread during the macro-pulse, the amplitude of RF power was controlled. As the result, the energy is found to be kept constant around 25 MeV during the macro-pulse duration, and the energy spread of the electron beam was greatly reduced from 6 to 0.8 percent in FWHM. The energy evolution agreed well with numerical calculation.

INTRODUCTION

A mid-infrared free electron laser (MIR-FEL, target wavelength: 3-14 μm) facility named KU-FEL (Fig. 1) based on a 4.5 cell S-band thermionic RF gun and a travelling-wave type accelerator tube with constant gradient structure was constructed for the energy science in Institute of Advanced Energy, Kyoto University [1]. The electron beam quality such as a constant beam energy, a constant bunch interval, a high peak current (> 10 A) and a longer than 3 μs macro-pulse duration is required for lasing KU-FEL. Due to the back-bombardment effect in the RF gun [2, 3], the bunch charge and the macro-pulse duration have in general a trade-off relationship, and the macro-pulse duration t was found to be limited to less than 1 μs at the undulator section when the charge per bunch was higher than 20 pC. To compensate the energy drop, the RF amplitude control by changing the klystron gain by changing the pulse shape of the klystron voltage was introduced to lengthen the macro-pulse duration [4]. As the result, we succeeded to produce an electron beam with over 60 mA in average current with a 4 μs macro-pulse duration at the entrance of the accelerator tube.

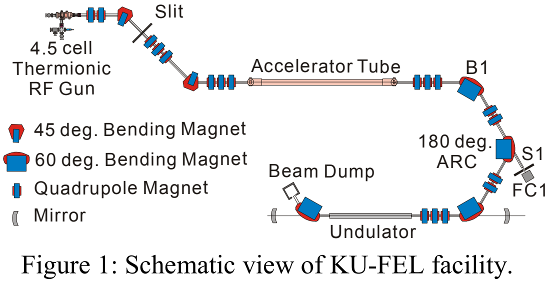

Figure 1: Schematic view of KU-FEL facility.

The inherent current increase in the RF gun, however, still limited the use of the linac for the FEL lasing. Due to the transient beam loading effect in the accelerator tube caused by the beam current increase during a macro-pulse, the beam energy after the accelerator tube was found to decrease and the energy drop is not suitable for the FEL build-up. The beam loading compensation was thus applied in the accelerator tube. In this paper, the energy decrease due to the transient increase of beam current and methods to compensate it are discussed.

EFFECT OF BEAM LOADING INCREASE IN ACCELERATOR TUBE

If we assume electrons on the crest of a periodically steady-state accelerating electric field, the energy gain δE of a single electron in a travelling-wave type accelerator tube with a constant gradient structure is described as [5]

$$\delta E = \sqrt{P(0) Z_{\mathrm{sh}} D (1 - \mathrm{e}^{-2\zeta})} - \frac{I Z_{\mathrm{sh}} D}{2}\left(1 - \frac{2\zeta\, \mathrm{e}^{-2\zeta}}{1 - \mathrm{e}^{-2\zeta}}\right), \quad (1)$$

where $P(0)$ denotes the RF power at the entrance of the tube, I the average beam current, Z_{sh} the shunt impedance, D the effective length and ζ attenuation parameter of the tube. The parameters of our accelerator tube are followings: Z_{sh} = 36.4 MΩ/m, D = 2.933 m, ζ = 0.62. These parameters substituting those in the Eq. 1 then give

$$\delta E = 8.71 \times 10^{3} \sqrt{P(0)} - 26.43 \times 10^{6} I \quad [\mathrm{eV}]. \qquad (2)$$

When the beam current I increases from 65 to 120 mA during macro-pulse duration, for example by the use of the RF gun in the KU-FEL, the second term of the Eq. 2 shows a unacceptable energy decrease from -1.7 to -3.2 MeV. The beam loading compensation in the tube is thus required to compensate this energy drop.

BEAM LOADING COMPENSATION FOR FEL DRIVER LINAC

There are methods to compensate the beam loading effect by using RF modulation, i.e. amplitude control [4, 6] and frequency or phase control [7]. In our case, a precisely even micro-bunch interval is required for the FEL build-up. A constant energy chirp is also preferred for a bunch compression to achieve a high peak current beam to enlarge an FEL gain. The frequency or phase control is not appropriate in these viewpoints, since it may change the interval and the energy chirp during the macro-pulse duration. There are two candidates of amplitude control methods; one is modulating the klystron gain by changing the pulse shape of the klystron voltage [4], and the other is the low level amplitude control using an IQ-modulator [6]. For klystron output

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control by the latter, a klystron and a driver amplifier should be used under unsaturated condition. Our klystron driver amplifier is not stable if it is used in the unsaturated condition. Hence we decided to use the klystron voltage modulation.

If this method is applied, the phase shift due to the change of the electron velocity in the klystron tube must be considered and compensated. Figure 2 shows the diagram of our RF system including two voltage-controlled phase shifters (Model: PS-3-2856, R&K Co., Ltd) and phase detectors (Model: PDU-NK02N-01, NIHON KOSHUHA Co., Ltd.) to measure and compensate the phase shift.

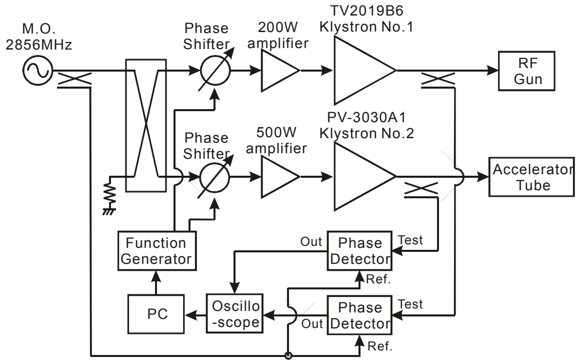


Figure 2: Schematic drawing of RF system.

EXPERIMENTS

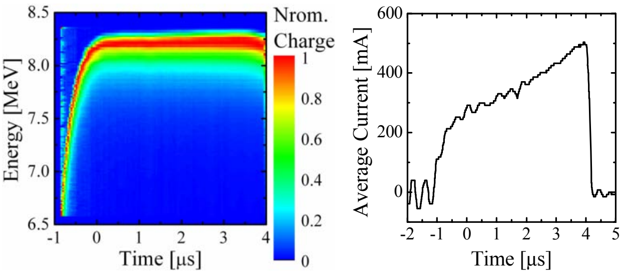
Energy distribution after the accelerator tube was measured to evaluate the energy drop due to the transient increase of beam current and to check the effectiveness of the compensation method. In this experiment, the RF phase evolutions of the RF powers fed to the gun and the tube were always measured and kept constant within a phase fluctuation less than 3 degree.

Beam Condition before the Accelerator Tube

The RF amplitude control for the RF gun was introduced and the output beam energy of the gun was adjusted to constant value as shown in Fig. 3 (a). Figure 3 (b) shows the current profile at the exit of the RF gun and the beam current is seen increasing from 250 to 500 mA in 4.5 μs. The electron beam goes through an energy filtering section, which consists of two bending magnets and a slit. After that section, the beam current was decreased to be about one fourth as much as before the energy filter.

Experimental Setup

The energy distribution and its temporal evolution of the electron beam after the accelerator tube was measured by using the bending magnet B1, the faraday cup FC1 and the energy slit S1 of 5 mm width (their layout is shown in Fig. 1). The length between the bending magnet and the slit was ~1.8 m, and the energy resolution in this configuration was around 0.7 percent in FWHM.



(a) Energy Evolution (b) Current Profile

Figure 3: Beam properties at the gun exit with the RF amplitude control.

Experimental Result

Two conditions were examined in this experiment: one is the constant RF power (Fig. 4 (a)), the other is the amplitude controlled RF power (Fig. 4 (b)). Figure 4 (c) shows the current profile at the entrance and the injection timing of the beam to the tube. The beam current increased from 65 to 120 mA in 4 μs.

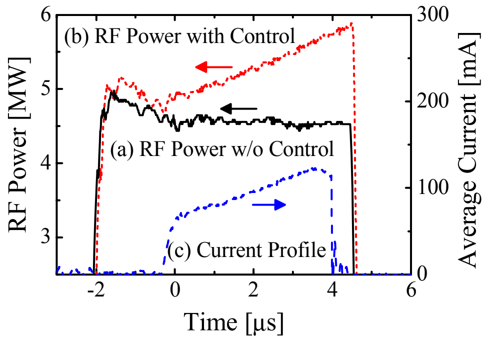
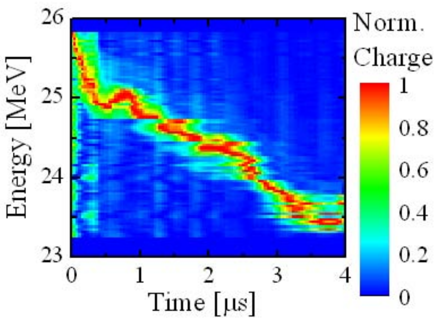
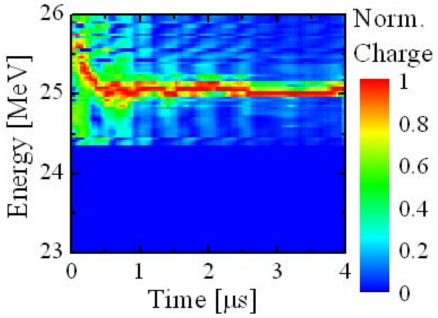


Figure 4: RF power evolutions with and without RF amplitude control and current profile at the entrance of the accelerator tube.

The results of energy measurements are shown in Fig. 5. Without the RF amplitude control, the beam energy decreased from 26 to 23.5 MeV during macro-pulse duration as shown in Fig. 5 (a). In contrast with RF amplitude control, as shown in Fig. 5 (b), the beam energy was found to be kept constant around 25 MeV except for the beginning of the macro-pulse. The origin of the energy change was considered to be the rapid beam loading change at the beginning of the macro-pulse. There could be several methods to compensate it, i.e. making use of the steep slope of the RF amplitude during filling time [8], and the fast RF amplitude control with IQ-modulator [6]. Figure 6 shows the energy profile with and without the RF amplitude control. The energy spread without the control was around 6 percent in FWHM which mainly came from the energy drop due to the transient increase of beam current. The energy spread was dramatically reduced to 0.8 percent in FWHM with the control. This value is almost same with resolution of the measurement and considered to be enough for our FEL build-up.



(a) Energy evolution without amplitude control



(b) Energy evolution with amplitude control

Figure 5: Beam energy evolution at the exit of the accelerator tube with and without the RF control.

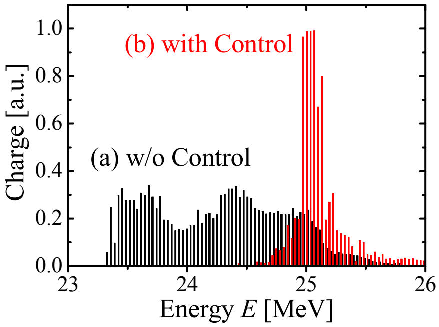


Figure 6: Bulk energy distribution with and without the RF amplitude control.

Discussion

The energy decrease due to the transient increase of the beam current was numerically calculated by using Eq. 2. In this calculation we assumed a constant beam energy of 8.2 MeV at the entrance of the accelerator tube. The experimental results agreed well with the results of the calculation as shown in Fig. 7 except for the difference of the absolute value of the beam energy between the calculation and the experiment under “with amplitude control” condition. The origin of the energy difference may come from the difference of the RF phase, because this calculation did not include the effect of phase difference. Figure 8 shows the optimized RF pulse shape which was numerically calculated from the beam current profile. In this calculation, we set the target energy gain to 17.6 MeV. It was also consistent with the experimental condition of the RF power as shown in Fig. 8. This result indicates that the optimum condition of the RF pulse shape can be calculated from the beam current evolution.

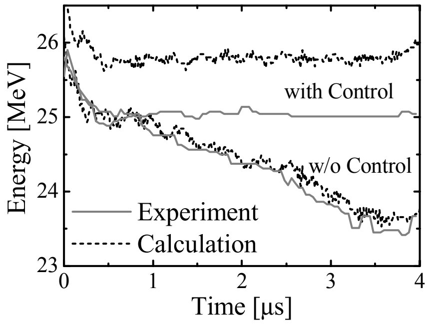


Figure 7: Peak energy evolution with and without the RF amplitude control.

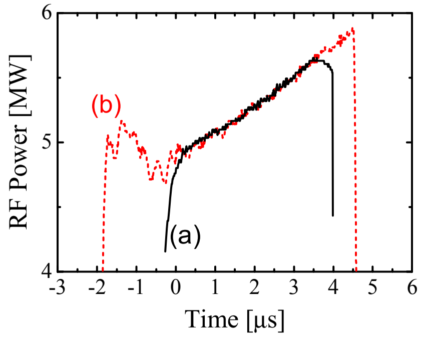


Figure 8: Comparison of RF power. (a) Optimum RF pulse shape for the energy compensation calculated from beam current evolution. (b) RF pulse shape of experiment.

CONCLUSION

The energy decrease during the macro-pulse duration due to the transient increase of the beam current was measured and compensated by using the RF amplitude control. When the current increased from 65 to 120 mA, the energy decreased from 26 to 23.5 MeV. With the RF amplitude control, the energy drop was eliminated except for the beginning of macro-pulse. The energy spread was reduced from 6 to 0.8 percent in FWHM by the control and this property was enough for the build-up of our mid-infrared FEL. The experimental results agreed well with the results of the numerical calculation with the analytical equation of energy gain in the accelerator tube. The optimum RF pulse shape was also calculated and it was consistent with the experimental condition. This result indicates that the optimum RF pulse shape can be calculated by the beam current evolution.

REFERENCES

[1] T. Yamazaki et al., Proc. of the 23rd Int. FEL Conf., and the 8th FEL User Workshop, pp.II13-14 (2002).
[2] C. B. McKee, et al., NIM, A 304 p.386 (1991).
[3] K. Masuda, et al., NIM A 483 p.315 (2002).
[4] T. Kii, et al., Proc. of FEL 2006, p.664 (2006).
[5] L.Schächter, “Beam-Wave Interaction in Periodic and Quasi-Periodic Structure”, Springer, p.316, 1996.
[6] M. Satoh, et al., NIM, A 538 p.116 (2005).
[7] S. Kashiwagi et al., Proc. of the 18th Int. Linac Conf., Genova, p.848 (1996).
[8] J. W. Wang, SLAC-Report-339 (1989).