ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-TUPRI077

STABILIZATION OF MID-INFRARED FEL BY FEEDBACK CONTROLS

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Abstract

Stable electron beam position and energy are crucial for stable operation of Free Electron Laser (FEL) both in single-pass and oscillator configurations. In order to increase stability of FEL output power and wavelength, three feedback control loops based on beam position measurements have been introduced to an S-band linac driving the mid-infrared oscillator type FEL at Kyoto University. The beam position and energy of the electron beam have been successfully stabilized. The achieved stability of FEL output power was 10%-FWHM at the wavelength of 12 μm. The wavelength stability of the FEL was estimated to be 0.3%-FWHM from measured electron beam energy fluctuation.

INTRODUCTION

A mid-infrared FEL, named as KU-FEL, has been developed to promote energy related sciences at Institute of Advanced Energy, Kyoto University [1]. The FEL is an oscillator type FEL driven by a 40-MeV S-band linac, which consists of a thermionic RF gun, a 3-m traveling wave type accelerator tube, a 180-degree arc section for bunch compression and a 1.8-m hybrid undulator. The schematic drawing of the linac is shown in Fig. 1. The first lasing and power saturation have been achieved in 2008 [2, 3]. The achieved tunable range of the FEL is 5-20 μm [4].

Stabilities of electron beam position and energy are crucial to obtain stable FELs lasing. In case of oscillator type FEL, the fluctuation of beam position causes the fluctuation of output power of the FEL. The fluctuation of electron beam energy causes the fluctuation of lasing wavelength. The FEL power and wavelength must be stabilized to use FEL beam especially for spectroscopic applications.

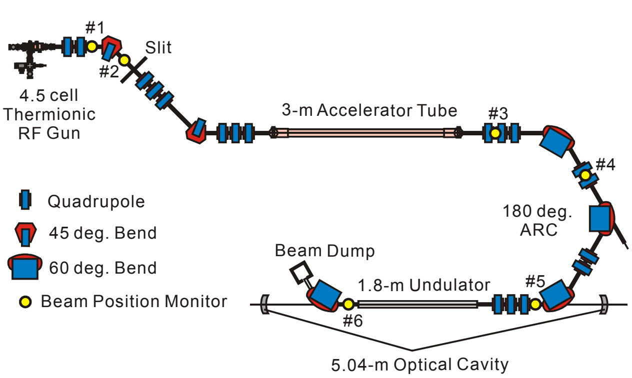

Figure 1: Layout of the KU-FEL driver linac.

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In order to measure the electron beam position and energy, we have introduced 6 Beam Position Monitors (BPMs) to the FEL driver linac [5]. The position of each BPM is shown in Fig. 1. Two feedback loops based on measured beam positions in the low energy section of KU-FEL have been already introduced [5]. Although those feedback controls drastically increased the FEL stability, FEL power stability (47%-FWHM [5]) and wavelength stability (~3%-FWHM [6]) were not high enough because there was no feedback system in the high energy section. In this work, we developed additional three feedback loops to obtain higher stability of the FEL power and wavelength.

FEEEDBACK CONTROLS

Three feedback loops have been added to the KU-FEL linac for improving the stability of the FEL power and wavelength. One is the beam energy feedback at the high energy section based on the horizontal beam position measured by BPM#4 in Fig. 1. Another is the feedback for the RF phase difference between the RF gun and the accelerator tube based on the vertical beam position measured by BPM#3. The other one is the feedback of horizontal beam position at BPM#3 for stabilizing the electron beam position at the entrance of bending magnet which used to measure the electron beam energy for the energy feedback. The details of those feedbacks are described in following subsections.

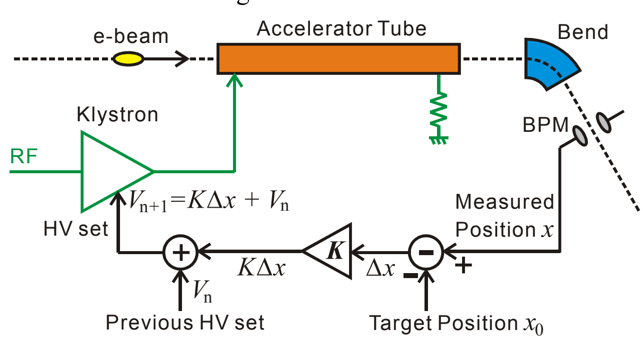

Figure 2: Schematic diagram of the energy feedback in the high energy section of the KU-FEL linac.

Energy Feedback in High Energy Section

In the KU-FEL, the RF gun and the accelerator tube are driven by two independent klystrons. The electron beam energy in the low energy section has been stabilized by changing the RF power fed to the gun according to the measured horizontal position at BPM#2 in Fig. 1 [5]. The same method is selected for the energy feedback in the high energy section. The schematic diagram of the feedback control system is shown in Fig. 2.

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The difference of the horizontal beam position between the target position and that measured by BPM#4, Δx, is multiplied with K which determines the strength of feedback. Then the HV set of the klystron driving the accelerator tube is changed with $K\Delta x$.

RF Phase Difference Feedback

There are many possible sources of changing the RF phase difference between the RF gun and the accelerator tube because the two independent klystrons are used for driving the gun and the accelerator tube. In addition to the natural drift of the RF phase, the beam energy feedback system both in the low and the high energy section causes additional drift of the RF phase difference, because the applied voltages to the klystrons are varied for the energy stabilization as we described in previous sub-section. The change of the applied voltage to the klystron results the phase change of the amplified RF power because of change of the traveling time of the electron beam in the klystron.

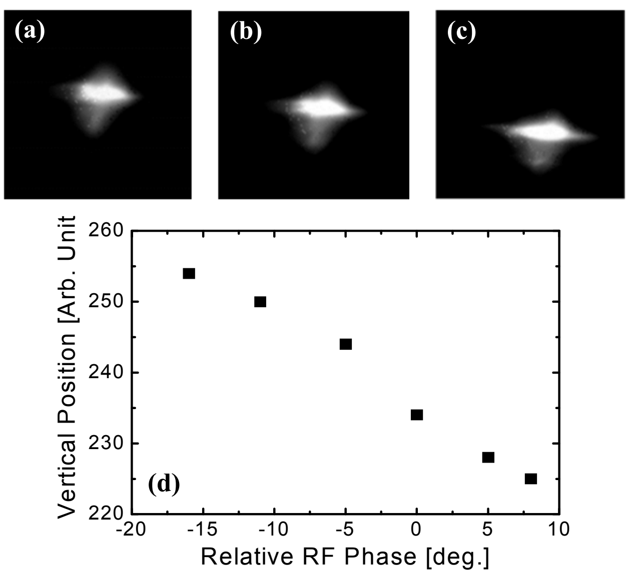

Figure 3: Measured beam profile after the accelerator tube (a) with the relative RF phase of -16 degree, (b) with -5 degree, and (c) with +8 degree. (d) Relationship between the vertical beam position and relative RF phase.

We employed a tricky method to observe the drift of the phase difference. A strong correlation between the vertical electron beam position at BPM#3 (shown in Fig. 1) and the RF phase difference has been observed as shown in Fig. 3. The reason of this correlation might be a phase dependent kick in the coupler cell of the accelerator tube or a phase dependent kick in the accelerator tube due to an off-axis electron beam injection [7]. Since this information directly gives us the phase relationship between the injected electron beam and the acceleration field in the accelerator tube, this can be the most reliable method to measure the phase difference when the electron beam position, angle and energy at the entrance of the accelerator tube are stabilized. We don't need to worry about thermal elongation of RF cables or waveguides.

The configuration of the feedback control system is almost the same as the energy feedback system. The vertical beam position after the accelerator tube is measured by BPM#3 and compared with the target position. In order to stabilize the beam position at BPM#3, a voltage controlled phase shifter equipped in the low power RF system of the klystron is adjusted with the same determination method as the energy feedback.

Horizontal Beam Position Feedback at BPM#3

As reported in the previous report, we have observed gradual shift and sudden change of vertical beam position at BPM#2, which is possibly caused by a charge up of the ceramic duct in the current transformer installed in the straight section of the RF gun [5]. We have observed almost same behaviour in the horizontal beam position at BPM#3. In order to stabilize the electron beam energy by the aforementioned beam energy feedback system, the incident condition of electron beam to the 1st 60-degree bending magnet should be stabilized. There is a horizontal steering magnet just after the current transformer and the steering magnet is used for compensating the horizontal kick in the ceramic duct based on the measured horizontal displacement of the electron beam at BPM#3. The configuration of feedback loop is similar to the energy feedback system shown in Fig. 2. In this feedback loop, the set value of the excitation current of the steering magnet is varied by the horizontal displacement.

EXPERIMENTAL RESULT

To measure the FEL lasing stability, the KU-FEL was operated at the electron beam energy of 8.4 MeV in the low energy section and 28.3 MeV in the high energy section. The lasing wavelength of the FEL was tuned to be 12 μm. All feedback systems were turned on. Temporal evolution of the applied voltage on the klystron used for driving accelerator tube, the applied voltage on the voltage controlled phase shifter, the excitation current of the horizontal steering magnet used for compensating the horizontal kick in the current transformer and corresponding BPM positions are shown in Fig. 4. In this experiment K values for the energy feedback, the phase feedback and horizontal beam position feedback were adjusted to -0.015 mm^{-1}, -0.04 V/mm and 0.3 A/mm, respectively. The time trend of FEL output power is shown in Fig. 4 (d).

As one can see in Fig. 4 (a-c), the horizontal beam position at BPM#4, i.e. beam energy in the high energy section, the vertical beam position at BPM#3 and the horizontal beam position at BPM#3 were successfully stabilized by newly introduced feedback systems. The stabilized electron beam successfully generated a stable output power of the FEL as seen in Fig. 4 (d). The stability of the FEL power was 10%-FWHM and shot-by-shot fluctuation was dominant. Such shot-by-shot

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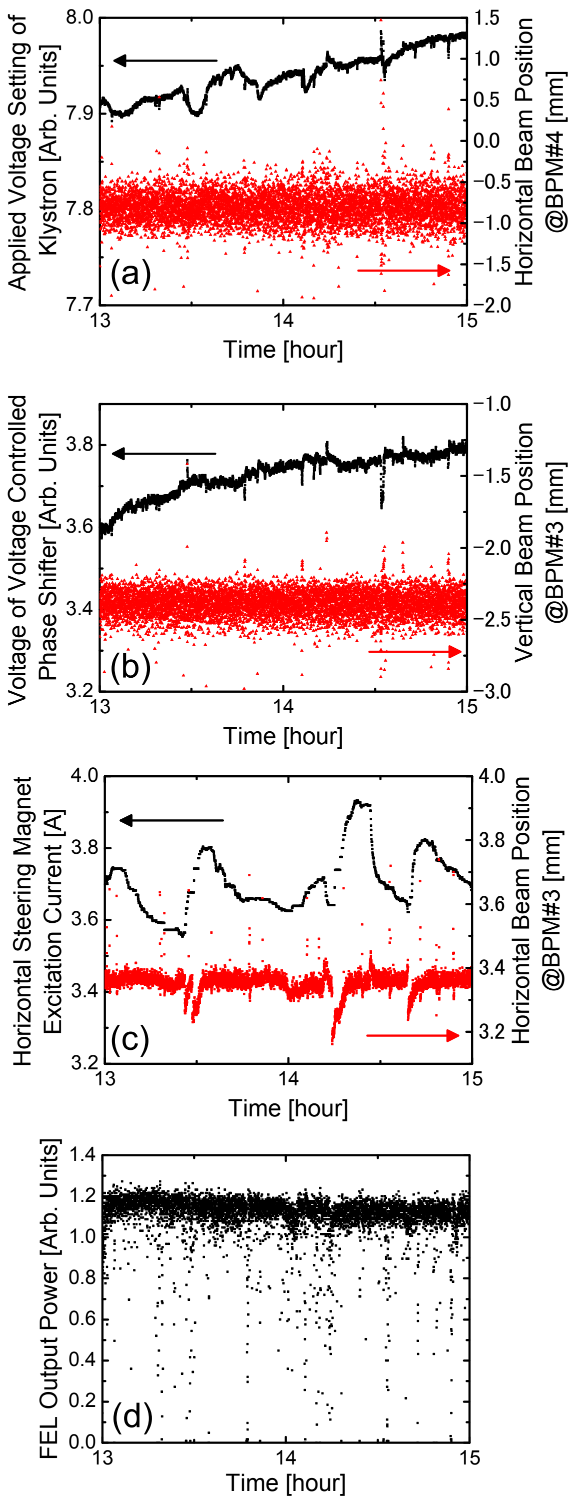

Figure 4: Time trend of (a) the klystron voltage and the horizontal beam position at BPM#4, (b) the voltage of voltage controlled phase shifter and the vertical beam position at BPM#3, (c) the current of horizontal steering magnet and the horizontal beam position at BPM#3, (d) FEL output power.

fluctuation cannot be stabilized by the feedback systems which we have introduced in this time. In addition, one can see some sudden power drops in Fig. 4 (d) which were caused by discharge in the RF gun. In order to increase the stability furthermore, we need to find sources of the shot-by-shot fluctuation and remove them.

The wavelength stability of FEL with the feedback systems has not been measured yet. However, that can be estimated from the horizontal beam position fluctuation at BPM#4. The measured horizontal beam position fluctuation was 0.4 mm-FWHM. At the BPM#4, horizontal dispersion was around 120 keV/mm. Then the energy fluctuation was 48 keV-FWHM. The wavelength stability was estimated as 0.3%-FWHM.

CONCLUSION

Three feedback loops have been introduced to stabilize the electron beam position and energy in the driver linac of KU-FEL. The electron beam position and energy were successfully stabilized and, then, the output power of the FEL was stabilized. The stability of the output power of the FEL was 10%-FWHM. The wavelength stability of the FEL was estimated to be 0.3%-FWHM from the measured electron beam energy fluctuation. The shot-by-shot fluctuation, which cannot be suppressed by the introduced feedback method, is the main source of the remained fluctuation. In order to increase the stability furthermore, we need to find the sources of the shot-by-shot fluctuation and remove them.

ACKNOWLEDGMENT

The author thanks KEK-ATF staff for their great help to implementation of the BPM system. This work is partially supported by The Collaboration Program of the Laboratory for Complex Energy Processes, Institute of Advanced Energy, Kyoto University.

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