IMPROVEMENT OF KU-FEL PERFORMANCE BY REPLACING UNDULATOR AND OPTICAL CAVITY

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Abstract

An upgrade project of the MIR-FEL facility developed in the Institute of Advanced Energy, Kyoto University has been in progress since 2010. The project consists of two topics; one is replacement of undulator and the other is replacement of the optical cavity mirrors. Those replacements were accomplished in January 2012. After the upgrade, we have so far succeeded in FEL lasing from 5 to 14.5 μm. Details of upgrade project and design work on a new optical cavity is reported in this paper. In addition, the results of the commissioning of a newly installed undulator and optical cavity is reported.

INTRODUCTION

An oscillator type Mid-Infrared Free Electron Laser (MIR-FEL) named the KU-FEL has been developed in Institute of Advanced Energy, Kyoto University, for aiding energy related sciences [1]. A 4.5-cell thermionic RF gun is employed as the electron source. After introduction of some cures of back-bombardment effects in the gun [2, 3, 4, 5], we have achieved first lasing [6], and laser saturation in 2008 [7]. However, a trade off relationship, caused by back-bombardment effects, between the bunch charge and the macro-pulse duration, limited the tunable range of the FEL to only 10 to 14 μm. An upgrade project for extending the tunable range of the FEL was started in 2010. The project consists of two topics. One is replacement of undulator and the other is replacement of optical cavity mirrors, which were newly designed in this work. In January 2012, those replacements were accomplished. After the upgrade, the tunable range of the FEL was extended to 5 – 14.5 μm.

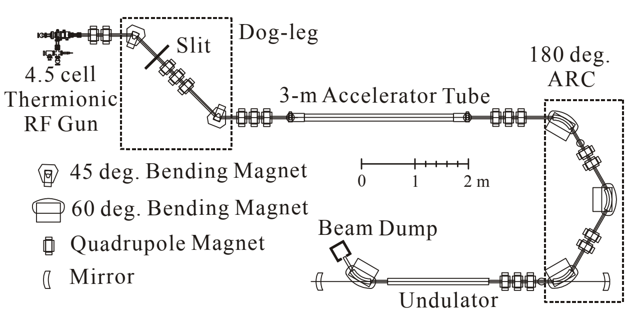

Figure 1: Schematic diagram of KU-FEL accelerator.

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KU-FEL DEVICE

Figure 1 shows a schematic diagram of the KU-FEL device, consisting of a 4.5-cell thermionic RF gun, a dog-leg section for energy filtering, a 3-m accelerator tube, a 180-degree arc section for a bunch compression, an undulator and an optical cavity. Parameters of the undulator (undulator #1) and the optical cavity before upgrade are shown in Table 1.

Table 1: Parameters of Undulator and Optical Cavity Before the Upgrade

Undulator #1 (until Dec. 2011)		
Structure		Halbach
Period length		40 mm
Number of periods		40
Maximum K-value		0.99
Optical cavity (upstream mirror has out-coupling hole)		
Mirror curvature	Upstream	3.03 m
	Downstream	1.87 m
Diameter of out-coupling hole		2 mm
Cavity length		4.513 m
Reflectivity		99.04%

UPGRADE PROJECT

An upgrade project was started in 2010. The objective of this upgrade was an extension of the wavelength range of the FEL. The project consists of two topics. One is replacement of undulator and the other is replacement of optical cavity mirrors.

Replacement of Undulator

The operation of the ERL-FEL developed in JAEA [8] was terminated in 2009. We were able to obtain the undulator (undulator #2) used for the ERL-FEL and install it into KU-FEL. Parameters of the undulator are listed in Table 2.

The undulator #2 has a shorter period length, larger number of periods and almost the same maximum K-value compared with undulator #1. The larger number of periods contributes to enhanced FEL gain for the same wavelength.

Results of magnetic field measurements of undulator #2 were reported in FEL 2011 [9]. Large amplitude fields errors (± 3.5%) were observed in the measurements and

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reported at the conference. However, we found a misalignment of measurement system. A field error of ± 1.0%, as shown in Fig. 2, was measured after correcting the misalignment. Such a field error does not seriously degrade the FEL gain.

Table 2: Parameters of a Newly Installed Undulator That Had Already Been Used for the ERL-FEL in JAEA

Undulator #2 (from Dec. 2011)	
Structure	Hybrid
Period length	33 mm
Number of periods	52
Maximum K-value	1.05*
Minimum Gap	20 mm*

*with present vacuum chamber. Mechanical limit of the minimum gap is 15 mm. Then K-value will be higher than 1.5.

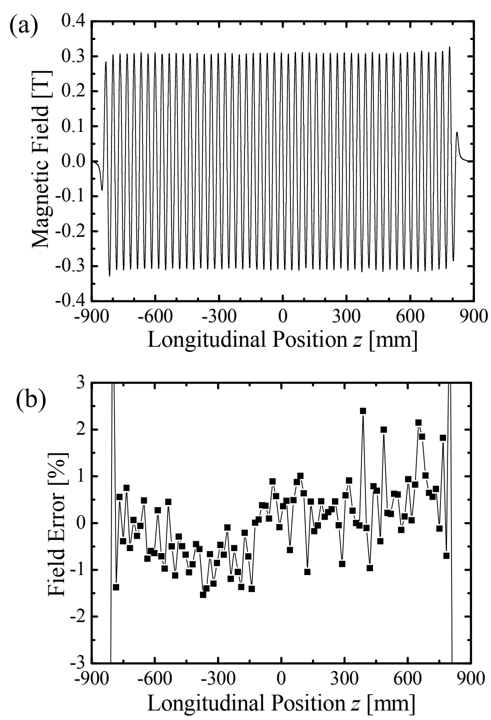

Figure 2: Measured magnetic field (a) and field error (b) of undulator #2 at the undulator gap of 20 mm.

Replacement of Optical Cavity Mirrors

Since the optical cavity was designed for first lasing of our facility [6, 7], the mirror curvatures were chosen to have a moderate FEL gain and a higher tolerance to misalignment of cavity mirrors. Since then, we designed the cavity mirrors to have a higher FEL gain and a lower tolerance to the mirror misalignment.

Another possible improvement to achieve lasing at shorter wavelength is reducing the size of the out-coupling hole, because the diameter of the out-coupling hole was selected to be 2 mmϕ, under the expectation of a higher gain than achieved. This made the optical losses too high at short wavelengths.

We are planning to introduce a photocathode RF gun in our drive linac system and the drive laser for the photocathode RF gun is under development [10]. The repetition rate of the mode-locked oscillator has already been selected as 89.25 MHz, which is the 32nd sub-harmonic frequency of the accelerator RF (2856 MHz). Therefore, the cavity length was changed to 5.0385 m. In this cavity length, three FEL pulses are stored when the photocathode RF gun frequency is used.

DESIGN OF NEW OPTICAL CAVITY

As mentioned previously, replacement of optical cavity mirrors offered the possibility of extending the tunable range of the KU-FEL. For that purpose, the optical cavity was redesigned using GENESIS1.3 [11] modified for oscillator calculations [12]. The calculation was done in time-independent mode.

At first, we chose the diameter of out-coupling hole as 1 mm in order to extend tunable range to shorter wavelengths.. We decided to put the undulator #2 at the same entrance position as the previous undulator (#1) and set the waist position of the optical cavity at the centre of the undulator. The geometry of cavity mirrors and the undulator is shown in Fig. 3. When the waist position is fixed, mirror curvatures are uniquely determined from g-parameter ($g = (1 - L/R_1)(1 - L/R_2)$), which indicates the stability of optical cavity. Here L, R_1 and R_2 are cavity length, curvature of upstream mirror and curvature of downstream mirror, respectively. The relationship between g-parameter and mirror curvatures is listed in Table 3.

The effect of misalignment of cavity mirrors under the condition of different g-parameters was examined and results are shown in Fig. 4. From the experience of FEL operation, we know that we can set the mirror position and angle with ±0.1-mm and ±0.1-mrad accuracy. Thus we decided to use the g-parameter higher than 0.7 and lower than 0.9 in this upgrade.

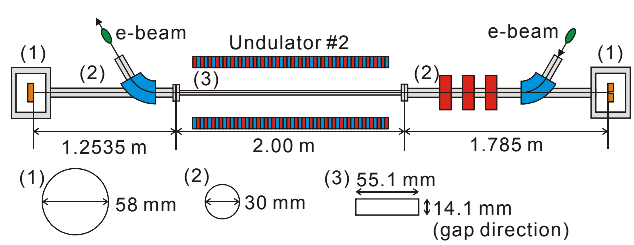

Figure 3: Geometry of the undulator and cavity mirrors.

Table 3: Relationship Between g-parameter and Mirror Curvatures with the Cavity Length of 5.0385 and Fixed Waist Position at Undulator Centre

g-parameter		0.54	0.70	0.90
Curvature [m]	Upstream	3.414	2.984	3.179
	Downstream	2.364	2.503	1.979

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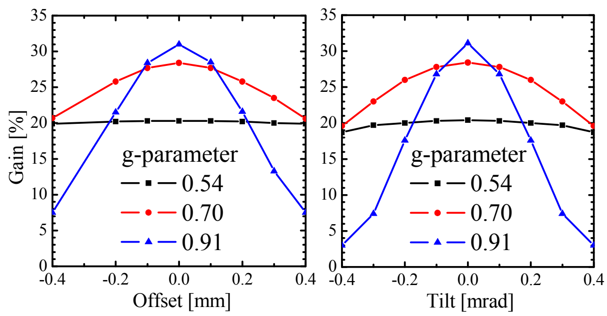

Figure 4: Effect of cavity misalignment under the condition of different g-parameters at 5.8 µm.

Next the dependences of gain and saturation intracavity power on the *g*-parameters was examined. The results are shown in Fig. 5. The gain was monotonically dependent on the *g*-parameter. However, the saturation power has peak at $g = 0.75$. From this result, the cavity condition $g = 0.75$ was selected and then upstream and downstream mirror curvatures were determined to be 2.946 and 2.456 m, respectively.

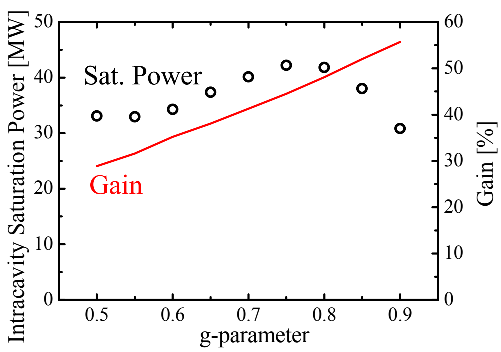

Figure 5: Dependences of gain and saturation intracavity power on g-parameter at 23 µm.

ESTIMATION OF NET FEL GAIN

The FEL gain and the optical loss of the cavity were estimated by simulations using the modified GENESIS 1.3 in time-independent mode. In the calculation, the measured magnetic field shown in Fig. 2 and size of vacuum duct shown in Fig. 3 were taken into account. The electron beam parameters, which were obtained from various measurements [13], are shown in Table 4.

Table 4: Electron Beam Parameters Used for Gain Estimation

Energy Spread (FWHM)	511 keV
Peak Current	40 A
Normalized Emittance (*x* and *y*)	3.5 π mm-mrad
Beta Function (β_x, β_y)	2.67 m, 2.18 m
Twiss parameter(α_x, α_y)	5.22, 0.00
Macro-pulse Duration	5.2 µs
Bunch Length (FWHM)	2.0 ps

Figure 6 shows the estimated net gain at the minimum undulator gap (K = 1.05). In the figure, the estimated net gain with the undulator #1 and the old optical cavity is also plotted for comparison. One can easily find that the net gain at shorter wavelength was greatly increased. The main reason for this net gain increment is the smaller size of the out-coupling hole.

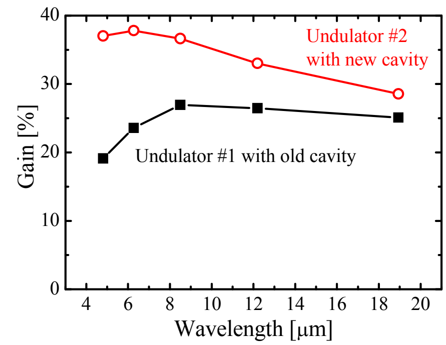

Figure 6: Net gain of undulator #2 with new optical cavity and undulator #1 with old optical cavity.

COMMISSIONING RESULTS

The commissioning of the KU-FEL with newly installed undulator and the optical cavity was started at the end of January 2012. After a week of searching for the cavity length, the lasing condition of the cavity length was found. Another week was required for adjusting the mirror cavity alignment and the electron beam trajectory in the undulator. Finally, we succeeded in achieving the power saturation of our FEL around 10 µm.

We have already checked the tunable range of upgraded system. Figure 7 shows the spectrum of KU-FEL at different electron beam energies. We could achieve laser power saturation at wavelengths from 5 to 14.5 µm.

Typical FEL parameters after the upgrade are listed in Table 5. The macro-pulse duration of the optical pulse is around 2 µs and then more than 5700 micro-pulses are included in one macro-pulse. We were worried about small output power due to the smaller out-coupling hole, but the highest macro-pulse energy of 15 mJ has been recorded around the wavelength of 10 µm. This pulse energy is sufficient for many application experiments.

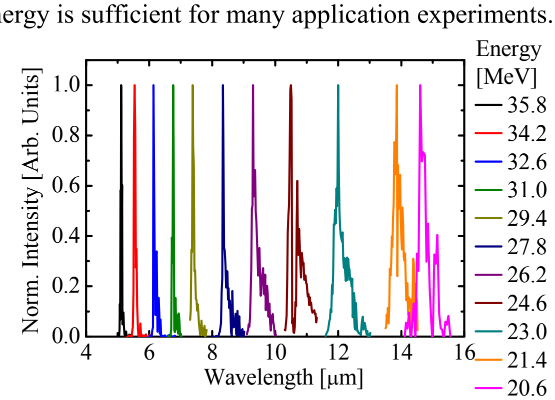

Figure 7: Spectrum of KU-FEL with various electron beam energy.

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Table 5: Measured Typical FEL Parameters After Upgrade

Wavelength	5 – 14.5 μm
Spectrum width	~ 3%
Macro-pulse duration	~ 2 μs
Macro-pulse energy	1 – 15 mJ
Micro-pulse duration	< 0.7 ps [14]

The micro-pulse duration of FEL has been measured by means of autocorrelation. The measurement was done at the wavelength of 12 μm and showed that the micro-pulse duration is shorter than 0.7 ps [14].

CONCLUSION

We have started an upgrade project of the MIR-FEL developed in the Institute of Advanced Energy, Kyoto University. The project consists of two topics; one is replacement of the undulator, and the other is replacement of the optical cavity mirrors. An undulator previously used for the ERL-FEL in JAEA was installed in the KU-FEL. A new optical cavity with higher *g*-parameter than the previous cavity and with a smaller out-coupling hole, has already been installed.

After commissioning of the newly installed undulator and the optical cavity, the tunable range of the KU-FEL was successfully extended from 10 – 14 μm to 5 – 14.5 μm.

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