PRESENT STATUS OF KYOTO UNIVERSITY FREE ELECTRON LASER

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Abstract

A vacuum duct was newly designed and manufactured to make the undulator gap narrower in order to increase the KU-FEL performance. The width of the undulator duct is 15 mm, but the minimum undulator gap is limited to 16.5 mm due to the small flexure of the duct. After replacing the old undulator duct whose minimum width was around 19.5 mm with new one, the tunable range of KU-FEL has been extended from 5-14.5 μm to 5-21.5 μm. The FEL gain higher than 60% has been observed at largely detuned optical cavity.

INTRODUCTION

An oscillator type Mid-Infrared Free Electron Laser (MIR-FEL) named as 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 effect in the gun [2, 3, 4, 5], we have achieved the first lasing [6], and power saturation in 2008 [7]. However, with trade off relationship between the bunch charge and macro-pulse duration limits the tunable range of the FEL (only 10 to 14 μm). In order to extend the tunable range, the optical cavity mirrors and the undulator have been replaced in January 2012. After those replacements, the tunable range of the FEL has been extended to 5 – 15 μm [8]. We have been still making efforts to increase the FEL gain and to extend the tunable range. For that purpose, we fabricated a new vacuum duct for our undulator, which has the horizontal width of 15 mm. At 15-mm gap, twice FEL gain than 19.5-mm gap (the minimum gap with the old undulator duct) is expected. Commissioning experiments with the new duct have been done in April 2013. The result of the experiment and upgraded performance of KU-FEL are reported in this paper.

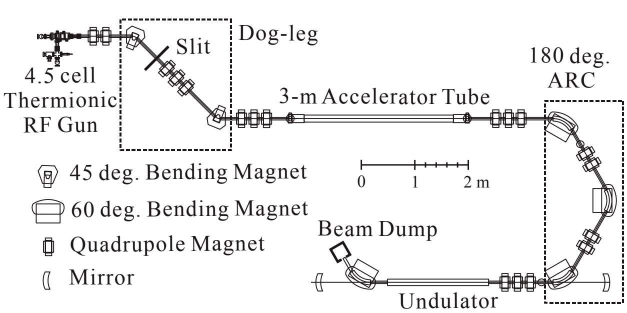

Figure 1: Schematic diagram of KU-FEL accelerator.

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KU-FEL DEVICE

Figure 1 shows the schematic diagram of KU-FEL device, which consists of a 4.5-cell thermionic RF gun, dog-leg section for an 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 and the optical cavity are shown in Table 1.

Table 1: Parameters of Undulator and Optical Cavity

Undulator		
Structure		Hybrid
Period length		33 mm
Number of periods		52
Maximum K-value		1.00 @ 19.5-mm gap* 1.56 @ 15-mm gap**
Minimum Gap		15 mm**
Optical cavity (upstream mirror has out-coupling hole)		
Mirror curvature	Upstream	2.984 m
	Downstream	2.503 m
Diameter of out-coupling hole		1 mm
Cavity length		5.0385 m
Reflectivity of one mirror		99.04%

* Minimum gap limited by old vacuum chamber
** Minimum gap limited by undulator mechanics

DESIGNING AND MANUFACTURING OF NEW UNDULATOR DUCT

As listed in Table 1, the minimum gap given by the undulator itself is 15 mm. Therefore, we decided to design a new undulator duct whose width is 15 mm. In order to give sufficiently high mechanical strength against air pressure, the thickness of undulator duct was selected as 2 mm. Then the clear aperture size in horizontal (gap side) direction was fixed as 11 mm. The vertical aperture was designed to have same size with old one, 56 mm. The comparison between the horizontal aperture size and 6σ–beam size of FEL beam are shown in Fig. 2. The 6σ–beam size in the optical cavity at the wavelength of 20 μm is comparative with the horizontal aperture of the vacuum duct at both ends of the undulator duct. Therefore, optical loss caused by diffraction at the vacuum chamber must be smaller than 1% even at the longest wavelength of our target, 20 μm.

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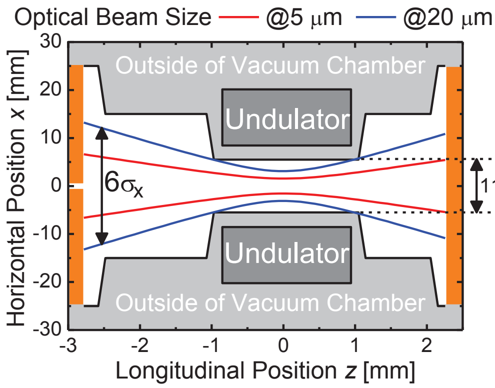

Figure 2: Physical geometry of the undulator, optical cavity mirrors (orange rectangles), vacuum chamber and optical beam in horizontal plane (gap side). The optical beam size was given by transverse mode calculation of ideal optical cavity having the parameters listed in Table 1. In the calculation, effect of the coupling hole is not taken into account.

At first, a test model of the rectangle vacuum chamber shown in Fig. 3 was manufactured. For reducing the manufacturing cost, two L-shaped stainless steel (SUS304) plates were welded to make a long rectangle vacuum duct. By polishing the welded part, flat surface can be obtained and this manufacturing way does not increase the minimum gap of undulator.

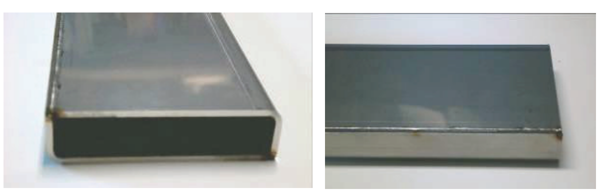

Figure 3: Photo of the test model for rectangle chamber.

The final drawing of newly designed undulator vacuum duct is shown in Fig. 4. The total longitudinal length is 2 m. The duct has 6 small ports for beam profile monitors. Three alumina fluorescence screens with 2 mm hole are inserted from the port #1-3. The fluorescence induced by electron beam are observed by a CCD camera from the port #4-6.

The new undulator duct was manufactured by Japanese company, Shinseiki. After welding all components, magnetic annealing was performed to make sure that the undulator duct is non-magnetic and does not make any perturbation of magnetic field of the undulator. Then the company performed the electrolytic polishing treatment to make the inner surface smooth and clean.

INSTALLATION OF NEWLY MANUFACTURED UNDULATOR DUCT

In April 2013, the old undulator duct was replaced with newly manufactured one. After the installation, the minimum undulator gap was checked. Unfortunately, we could not close the undulator gap narrower than 16.5 mm because of small flexure of the new duct. The K-value of the undulator with 16.5-mm gap is calculated to be 1.34 from the magnetic field measurement. In Fig. 5, the photo of undulator with the new duct is shown.

Figure 5: Photo of the undulator with new vacuum chamber.

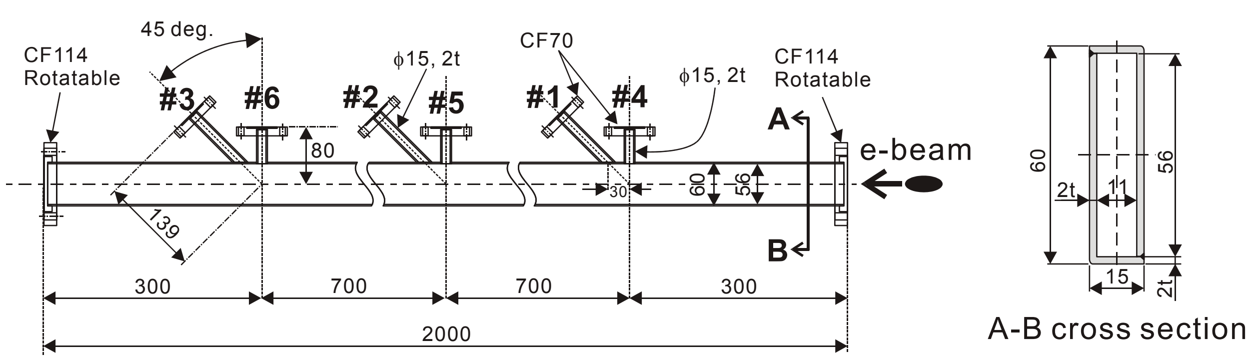

Figure 4: Final drawing of newly designed undulator vacuum duct.

COMMISSIONING

Initial Checking

At first, the electron beam was sent to the undulator section with 80-mm gap condition, i.e. fully opened gap. The electron beam profiles at the three profile monitors were checked. The electron beam profiles on CRT display are shown in Fig. 6. We confirmed that the horizontal electron beam size is smaller than 6 mm in the undulator. At the same time, transmission of the electron beam was also checked and we confirmed that there was no significant beam loss at the undulator section.

After above confirmation, we closed the undulator gap down to 19.5 mm which was the narrowest undulator gap before replacement of the undulator duct. And the electron accelerator conditions were adjusted to have same condition with user operation before the replacement. After that, we immediately got FEL lasing at the wavelength of around 11 µm. Then the loss of the optical cavity was found to be 3.2%, which was as same as the previous one.

(a) upstream (b) center (c) downstream

Figure 6: Electron beam profiles in undulator. At the center, electron beam passed through the hole on the fluorescence screen. The diameter of the hole is 2 mm in horizontal and 1.4 mm in vertical direction.

Checking the Wavelength Tunable Range

Next, we started checking the tunable range and available FEL output pulse energy with varying the electron beam energy and the undulator gap. The results are shown in Fig. 7. As shown in the figure, the maximum FEL macro-pulse energy of 33 mJ was achieved at the wavelength of 9 µm with the e-beam energy of 30 MeV. In addition, the tunable range of KU-FEL was confirmed to be from 5 to 21.5 µm. The wavelength tunability given by varying the undulator gap was larger than 2 µm.

At the experiment, the FEL lasing wavelength, undulator gap, electron beam energy were recorded and those relationship are plotted in Fig. 8. The undulator K-values of each undulator gap were calculated from the FEL lasing wavelength and e-beam energy, and compared with K-value given by magnetic field measurement. The results are shown in Fig. 9. The K-value calculated from the lasing wavelength and the e-beam energy shows higher value than the K-value given by the field measurement. Since the e-beam energy is calculated from the strength of the 1st bending magnet of 180-degree arc section in Fig. 1, accuracy of the e-beam energy is not so good. If we calibrate the real e-beam energy as 5% lower than that calculated from the bending magnet strength, the K-value calculated from the lasing wavelength and calibrated e-beam energy shows good agreement as shown in Fig. 9.

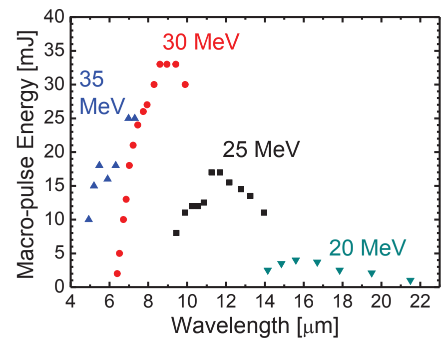

Figure 7: FEL macro-pulse energy with different electron beam energy and undulator gap. The macro-pulse energies were measured at the exit of optical cavity just after passing through KRS-5 vacuum window. The undulator gap was varied from 16.5 to 23 mm.

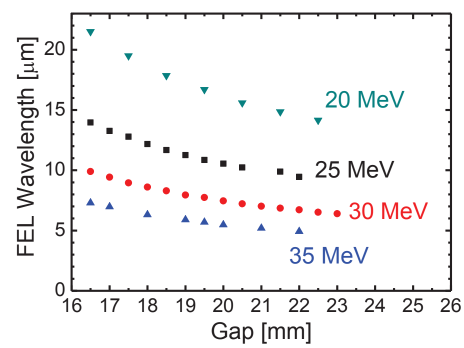

Figure 8: Relationship between the FEL lasing wavelength, undulator gap and electron beam energy. The electron beam energy was determined from the field strength of the 1st bending magnet in 180-deg. arc section in Fig. 1.

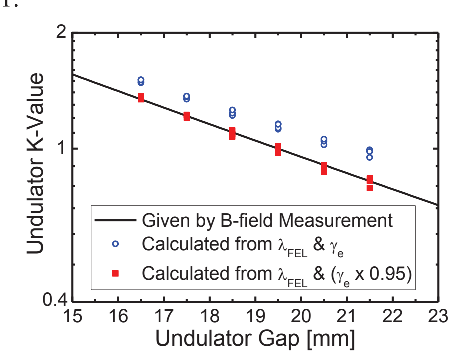

Figure 9: Relationship between the undulator gap and K-value. Black line is given by the result of magnetic field measurement. Blue open circle is calculated from FEL lasing wavelength and e-beam energy calculated from bending magnet strength. Red dot is calculated from the lasing wavelength and 5% lower e-beam energy than Blue open circle.

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Checking the FEL gain

The FEL gain measurement was performed at the wavelength of 11 μm with two undulator gap conditions, 16.5 and 19.5 mm. For the gain measurement, Mercury Cadmium Zinc Telluride (MCZT) detector, PDI-2TE-10.6 made by Vigo System was used. The time constant of this detector is less than 3 ns and which is enough fast for FEL gain measurement. Since we are using the thermionic RF gun as our electron source and suffered from quite strong back-bombardment effect, it is difficult to change the macro-pulse duration of electron beam. In addition, e-beam current increases within the macro-pulse. This means the FEL gain possibly increases during the macro-pulse. Those effects make the accurate FEL gain measurement difficult. In this time, we just measured the time constant of a part of rising edge of the FEL macro-pulse and estimated the FEL gain.

Results of gain measurement together with detuning curve are shown in Fig. 10. The FEL gain was high in shorter cavity length and higher than 60%. The FEL gain with 16.5-mm undulator gap condition was about 1.5 times higher than that with 19.5-mm undulator gap at the relative detuning length of -25 μm.

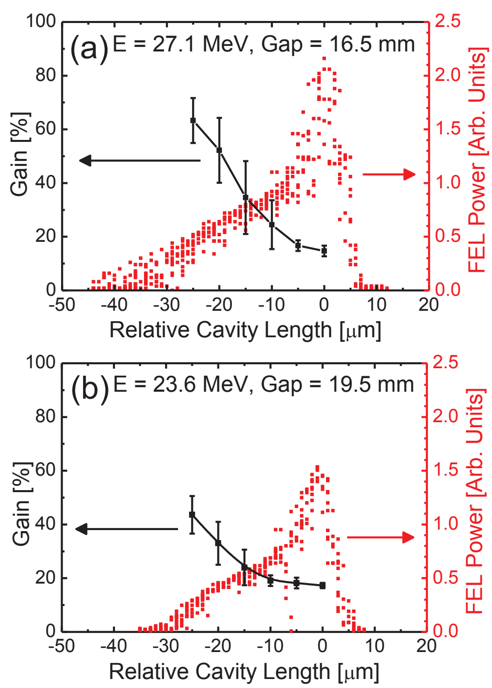

Figure 10: Measured FEL gain and FEL power at different detuning condition. (a) e-beam energy = 27.1 MeV, undulator gap = 16.5 mm. (b) e-beam energy = 23.6 MeV, undulator gap = 19.5 mm.

CONCLUSION

The new undulator duct whose horizontal width is 15 mm has been designed and manufactured. We expected to close the undulator gap down to 15 mm with the new duct. Unfortunately, the minimum gap was found to be 16.5 mm because of small flexure of the duct. The maximum K-value is increased from 1.00 to 1.34 by replacing the undulator duct. After the installation, commissioning work has been performed. We had no significant electron beam loss with narrower undulator duct and no significant increase of loss of optical resonator at the FEL wavelength of 11 μm. By the commissioning work, we confirmed that the tunable range was extended from 5-14.5 μm to 5-21.5 μm. In addition, we calibrated the e-beam energy from the relationship of the lasing wavelength, undulator magnetic field and e-beam energy. The FEL gain at largely detuned condition was higher than 60% at the FEL wavelength of 11 μm and the minimum undulator gap condition.

FUTURE WORK

There are some rooms of improvement to make KU-FEL better. One is reducing undulator gap down to 15 mm by correcting the small flexure of the undulator duct or replacing the undulator duct with narrower one. Another is increasing the out-coupling hole size to have higher output power, because the FEL gain seems to be sufficiently high.

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REFERENCES

[1] T. Yamazaki, et al., Proc. of 23rd Int. Free Electron Laser Conference, pp. II-13-14, 2002.
[2] C.B. McKee, J.M.J. Madey, Nucl. Instr. and Meth. A 296 (1990) p.716.
[3] T. Kii, et al., Nucl. Instr. and Meth. A 528 (2004) p.408.
[4] H. Zen, et al., Proc. of EPAC08 (2009) p.1329.
[5] H. Zen, et al., IEEE Trans. on Nucl. Sci., Vol. 56, No. 3, pp.1487-1491.
[6] H. Ohgaki, et al., Jpn. J. Appl. Phys. 47 (2008) pp.8091-8094.
[7] H. Ohgaki, et al., Proc. of FEL2008 (2008) pp.4-7.
[8] H. Zen, et al., Proc. of FEL2012 (2013) pp.449-452.

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