EVALUATION OF LASING RANGE WITH A 1.8 M UNDULATOR IN KU-FEL

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Abstract

In KU-FEL (Kyoto University FEL) 12-13 μm FEL has been available by using a 40 MeV S-band linac and 1.6-m Halbach-type undulator. We are going to install 1.8-m undulator which was used in JAEA to extend the lasing range of KU-FEL. We measured the undulator field and evaluated the FEL gain to confirm the possible lasing range. The measured magnetic field showed large demagnetization in several %. Numerical evaluation of the lasing range has been carried out by using GENESIS1.3 and the result showed the expected FEL gain with 1.8-m undulator (10%) which was smaller than with 1.6-m undulator (20%). We simulated a sorting of 1.8-m undulator magnets and FEL gain was recovered to be (30%). Another candidate to increase FEL gain is narrowing the gap of the 1.6-m undulator from 25 mm to 20 mm. This resulted large increment of FEL gain (35%), which is larger than sorting result of 1.8-m (30%).

INTRODUCTION

We have studied and developed mid-infrared free electron laser (MIR-FEL) facility (KU-FEL) for advanced energy researches in Kyoto University. KU-FEL consists of a 4.5-cell thermionic RF gun, a 3-m accelerator tube, a beam transport system, a 1.6-m Halbach-type undulator and an optical cavity as shown in Fig. 1. The RF gun which operates at 2856 MHz (S-band) generates electron beam which has 5.2 μs macro-pulse duration and up to 9 MeV at exit. Electrons are accelerated up to 40 MeV at the accelerator tube. The 1.6-m undulator has period number of 40 and maximum *K*-value of 0.99. The optical cavity has total length of 4.52 m and consists of two Cu-mirrors coated with Au. Upstream mirror has 2.0-mm diameter coupling hole. The curvatures of the upstream and downstream mirror are 3.030 m and 1.872 m respectively. We have achieved FEL saturation at 13 μm [1,2].

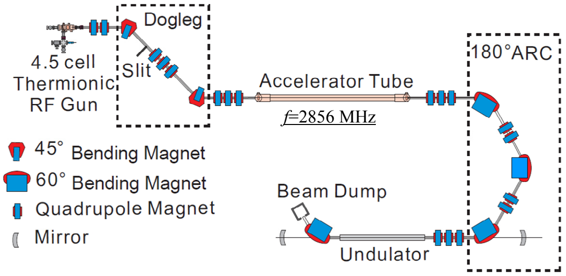

Figure 1: Schematic view of KU-FEL.

We plan to install Hybrid-type 1.8-m undulator to extend lasing range and increase FEL gain instead of Halbach-type 1.6-m undulator. We expect to increase FEL gain about twice larger than before [3]. The 1.8-m undulator parameters are listed in Table 1 and view of that is shown in Fig. 2.

For 1.8-m undulator, we redesigned the optical cavity which has total length of 5.042 m, and the upstream mirror has 1.0-mm diameter coupling hole. The curvatures of the upstream and downstream mirror are 2.456 m and 2.946 m respectively.

Table 1: Parameters of Hybrid-type 1.8-m Undulator

Total length	1.8 m
Period number	52
Undulator period	33 mm
Gap	15 – 100 mm
Maximum magnetic field	0.559 T
Maximum *K* value	1.72

Figure 2: Hybrid-type 1.8-m undulator.

MAGNETIC FIELD MEASUREMENT

The magnetic field of 1.8-m undulator was measured by 2-m linear stage and 3-D gaussmeter (LakeShore Cryotronics, Inc.). The probe of gaussmeter was attached the top of linear stage, and moved 1-mm step end to end of 1.8-m undulator. In one measurement, the system moved 1 mm, then halted 200 ms. After that we measured 5 times at intervals of 100 ms and took average of results. The magnetic field of 1.8-m undulator was measured at gap of 25 mm and is shown in Fig. 3.

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Maximum and average of peak field are 0.220 T and 0.212 T respectively. Measured magnetic field shows large de-magnetization from average field in order of about ± 3.5% as seen in Fig. 4. The position of the large de-magnetization corresponds to the place of the beam profile monitor. This suggests magnets of undulator suffered from the radiation.

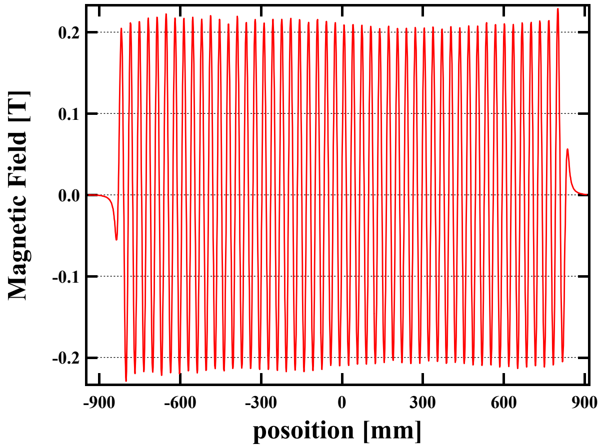

Figure 3: Magnetic field at gap = 25 mm.

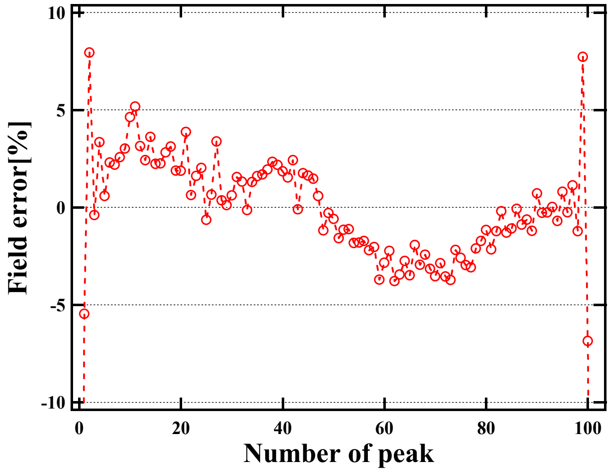

Figure 4: Magnetic error at gap = 25 mm.

FEL GAIN CALCULATION

Calculation Code

FEL gain was calculated by using GENESIS1.3 [4] which can take into account the duct shape (diffraction losses). The original version of GENESIS1.3 can only calculate 1-pass FEL gain. Therefore we modified the GENESIS code which calculates multi-pass gain by using the previous output data as the next input data. We take into account the light from the undulator which travels in free space and reflects a couple of mirrors, and return undulator.

Calculation was done using optimized electron beam parameters which are based on experimental data of KU-FEL. Electron beam parameters are listed in Table 2 and duct shape for 1.8-m undulator is shown in Fig. 5.

Table 2: Electron Beam Parameters

Normalized emittance (x)	3.5 πmm-mrad
Normalized emittance (y)	3.5 πmm-mrad
Energy spread	0.5%
Beam size (x)	0.6 mm
Beam size (y)	0.4 mm
Twiss parameter α_x	4.8
Twiss parameter α_y	0
Beam energy	20 – 40 MeV

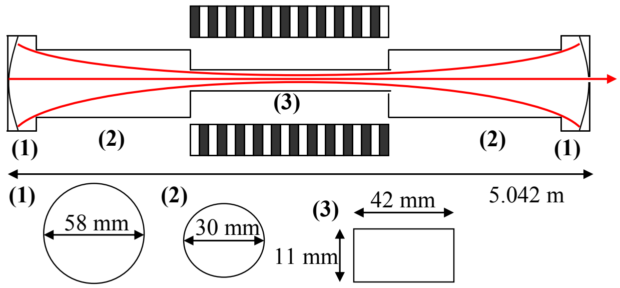

Figure 5: Duct shape for 1.8-m undulator.

FEL Gain for 1.8-m Undulator

Since FEL gain shows the maximum value at gap of 15 mm, calculation was done at gap of 15 m and energy of electron beam was chosen 20, 25, 30, 35 and 40 MeV. The magnetic field data at gap of 15 mm was extrapolated from the measurement with the gap of 25 mm, and the maximum and the average of peak field are 0.559 T and 0.539 T, respectively. For comparing, calculations were done 3 cases, 1.8-m ideal field, 1.8-m measured field and 1.6-m measured field data. Electron beam trajectories of each case were adjusted by steering magnets so that electron beam and radiation interacts around the central axis of the gap. Fig. 6 displays the results.

Since FEL gain with the 1.8-m measured was smaller than that with1.6-m, we assumed uniform random sorting of 1.8-m undulator magnets ±3.5% from average peak field and calculated FEL gain. This result is shown in Fig. 6 as well.

According to the calculations, the FEL gain of 1.8-m measured magnetic field is 10% which is smallest. The FEL gain of the sorting magnetic fields is 30% which is larger than that of the 1.6-m measured (20%). To reveal the origin of the small gain of 1.8-m undulator, 1-pass gain was calculated with wavelength around 25 μm and results are shown in Fig. 7.

The FEL gain with the measured magnetic field has 2-peaks which correspond to smaller and larger field of the average peak field. On the other hand, the FEL gain with the sorting magnetic field doesn't split and larger than the measured one. Consequently, 1.8-m undulator needs to sort or shimming to obtain an enough FEL gain.

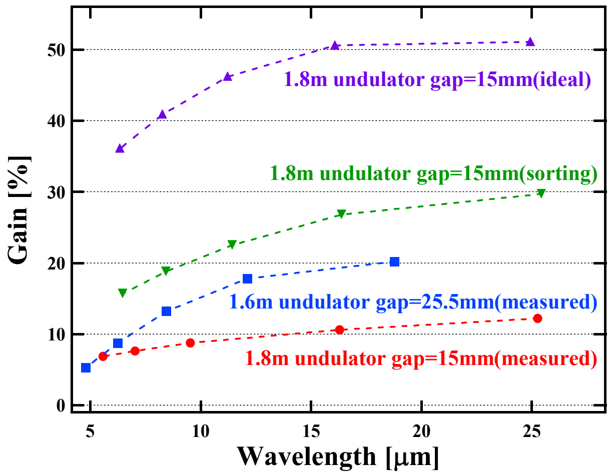

Figure 6: FEL gain results.

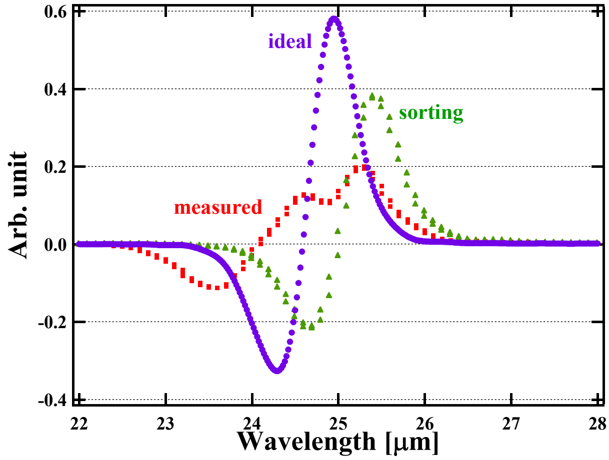

Figure 7: 1-pass gain.

FEL Gain for 1.6-m Undulator

FEL gain of 1.8-m undulator was smaller than expected. Therefore we considered another method to increase FEL gain. The gap of 1.6-m undulator can be narrower (<25.5 mm) mechanically. Then I assumed gap = 15, 20 and 25.5 mm and exchange to optical cavity of 1.8-m's. This optical cavity of 1.8-m was designed for 1.8-m undulator and also for photo cathode RF gun that we want to install in the future. Magnetic field was calculated by

$$B_0 = 1.95 \exp\left[-\frac{\pi L_{\mathrm{gap}}}{\lambda_{\mathrm{u}}} \right] \qquad (1)$$

where B_0, L_{gap} and λ_{u} are average peak field, gap length and undulator period respectively [5]. Equation (1) was carried out by Halbach field equation and field measurement data at gap = 25.5 mm. According to Eq. 1, B_0 of gap = 15 and 20 mm are 0.600 T and 0.405 T respectively. FEL gain was calculated and shown in Fig. 8.

This result suggests lasing range of KU-FEL would extend by 1.6-m undulator with narrowing gap. Expected lasing ranges of 15 and 20 mm gaps are 12 – 40 and 7-27 μm with electron energy of 20-40 MeV. Since our target lasing range is from 5 to 20 μm, we can use 20-mm gap.

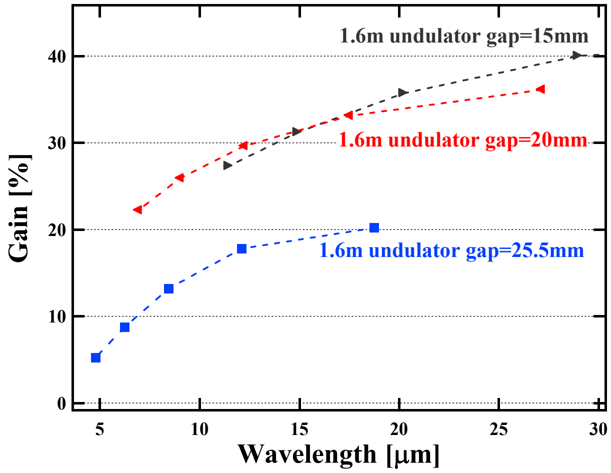

Figure 8: FEL gain (1.6-m undulator).

CONCLUSION

We measured magnetic field of Hybrid-type 1.8-m undulator which was used in JAEA. The magnetic field shows large de-magnetization of about ±3.5% from average peak field. FEL gain calculation using measurement data has been carried out and the result shows that the FEL gain of 1.8-m undulator is smaller than that of the existing 1.6-m one. However if we unify the magnetic field by sorting or shimming, FEL gain would be larger than 1.6-m one.

Another candidate to increase gain is narrowing the gap of 1.6-m undulator by replacing the thinner duct. When the gap is narrowed, the expected FEL gain is increase. The expected lasing range at 20-mm gap will be 7-27 μm.

These results suggest us narrowing the gap of 1.6-m undulator is a short method to increase FEL gain and extend lasing range. However, we should evaluate several methods to recover the FEL gain with 1.8-m undulator for seeking the best method.

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