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].

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Total length</td>
<td>1.8 m</td>
</tr>
<tr>
<td>Period number</td>
<td>52</td>
</tr>
<tr>
<td>Undulator period</td>
<td>33 mm</td>
</tr>
<tr>
<td>Gap</td>
<td>15 – 100 mm</td>
</tr>
<tr>
<td>Maximum magnetic field</td>
<td>0.559 T</td>
</tr>
<tr>
<td>Maximum K value</td>
<td>1.72</td>
</tr>
</tbody>
</table>

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.

Figure 3: Hybrid-type 1.8-m undulator.

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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.

**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 with 1.6-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

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**Table 2: Electron Beam Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalized emittance (x)</td>
<td>3.5 πmm-mrad</td>
</tr>
<tr>
<td>Normalized emittance (y)</td>
<td>3.5 πmm-mrad</td>
</tr>
<tr>
<td>Energy spread</td>
<td>0.5%</td>
</tr>
<tr>
<td>Beam size (x)</td>
<td>0.6 mm</td>
</tr>
<tr>
<td>Beam size (y)</td>
<td>0.4 mm</td>
</tr>
<tr>
<td>Twiss parameter $\alpha_x$</td>
<td>4.8</td>
</tr>
<tr>
<td>Twiss parameter $\alpha_y$</td>
<td>0</td>
</tr>
<tr>
<td>Beam energy</td>
<td>20 – 40 MeV</td>
</tr>
</tbody>
</table>
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.

\[ B_0 = 1.95 \exp \left( -\frac{\pi L_{\text{gap}}}{\lambda_u} \right) \]  

(1)

where \( B_0 \), \( L_{\text{gap}} \) and \( \lambda_u \) 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 \( \mu \)m with electron energy of 20-40 MeV. Since our target lasing range is from 5 to 20 \( \mu \)m, we can use 20-mm gap.

**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

\[ B_0 = 1.95 \exp \left( -\frac{\pi L_{\text{gap}}}{\lambda_u} \right) \]  

(1)

where \( B_0 \), \( L_{\text{gap}} \) and \( \lambda_u \) 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.

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**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 \( \mu \)m.

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.

**REFERENCES**


