MAGNETIC FIELD MEASUREMENT OF UNDULATOR IN KU-FEL

M. Nakano, N. Okawachi, H. Zen, T. Kii, K. Masuda, H. Ohgaki#, K. Yoshikawa, T. Yamazaki
Institute of Advanced Energy, Kyoto University, Gokasyo, Uji, 611-011, Japan.

Abstract

An FEL system (KU-FEL) covering wavelengths from 4 to 13 μm is under construction at Institute of Advanced Energy, Kyoto University. The magnetic field of the undulator in KU-FEL has been measured. Measured magnetic field showed demagnetization in the downstream part of the undulator. By using the measured data, we have estimated the optimal parameters of both the electron beam and the optical cavity to enhance the FEL gains for the first lasing. In this optimized condition, though FEL gains decreased by a few % but, FEL powers were not much decreased, compared with those for the design field. Saturated FEL in 6-12 μm is expected from the recent studies in the macropulse width of the electron beam from the RF gun.

INTRODUCTION

KU-FEL system for bio/chemical researches in 4-13μm is under construction [1]. Figure 1 shows a schematic view of the system. The system consists of a 4.5 cell thermionic RF gun, a 3-m accelerator tube, a Halbach type undulator and an optical cavity. The RF gun and the accelerator tube have been installed and accelerated an electron beam up to 40 MeV. The undulator and the optical cavity will be installed within this year.

In parallel with the construction, in order to estimate the high FEL gains for the first lasing, we have optimized parameters of electron beam and optical cavity based on original design parameters of our undulator (shown in Table 1) [2]. However, demagnetization was anticipated since the undulator had been used for lasing experiments under the cooperation of FELI and University of Tokyo [3]. Then, we measured the magnetic field of the undulator. By using the date, we have optimized parameters of electron beams and the optical cavity and calculated realistic FEL gains and powers.

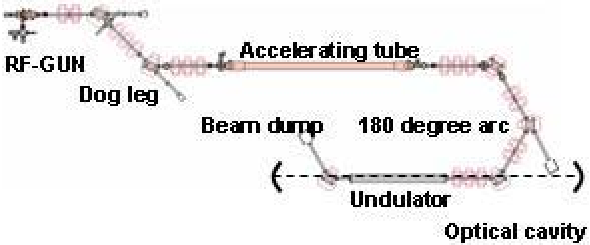

Fig. 1 . Schematic view of KU-FEL.

Table 1: Parameters of the original designed undulator of KU-FEL

Length	1.6 m
Period	40 mm
Number of period	40
Gap	26 - 45 mm
Maximum magnetic field	0.25 - 0.045 T
K-value	0.95 - 0.17

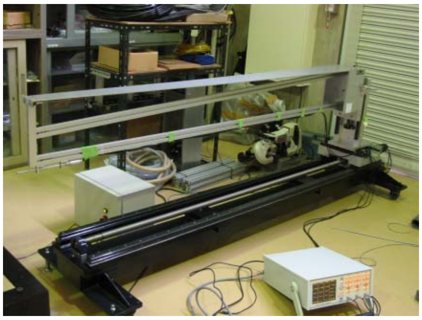

Fig. 2: Measurement device for magnetic field.

Table 2: Specification of measurement device

Moving stage	
Motor	Stepping motor
Resolution	0.01 mm
Operation range	2 m

Gauss meter	
Resolution	0.10%
Stability of temperature	0.040 %/K

MEASUREMENT OF MAGNETIC FIELD

The magnetic field of the undulator was measured in vertical and horizontal direction, using a Hall probe manufactured by F. W. BELL. The probe was driven by moving stage that run on a stepping motor (Fig. 2) and was moved on the central axis of the undulator by 1 mm step. Specification of the measurement device is shown in Table 2. Figure 3 shows the measured magnetic field of the undulator. The undulator error (shown in Fig. 4) is defined by following : *Error* = 1- $B_{p,exp}/B_{p,ideal}$, where $B_{p,exp}$ is the peak magnetic induction from fitting the measured date to sinusoidal function and $B_{p,ideal}$ is the peak value of the design magnetic field. Thus, the error is positive when there is demagnetization. The initial and end peak of the measured magnetic field of the undulator

---

ohgaki@iae.kyoto-u.ac.jp

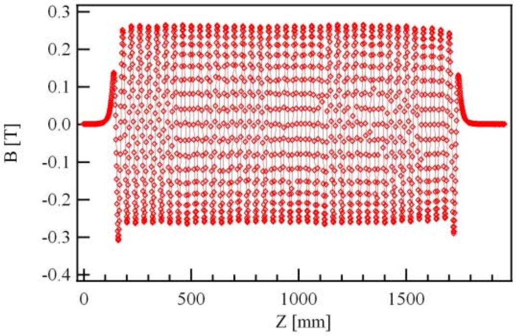

Fig. 3: Measured magnetic field of the along the central undulator axis.

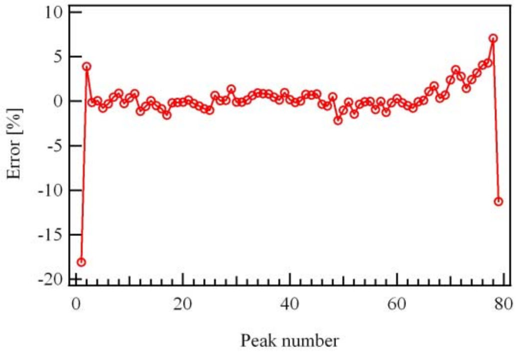

Fig. 4: Undulator error as a function of peak number.

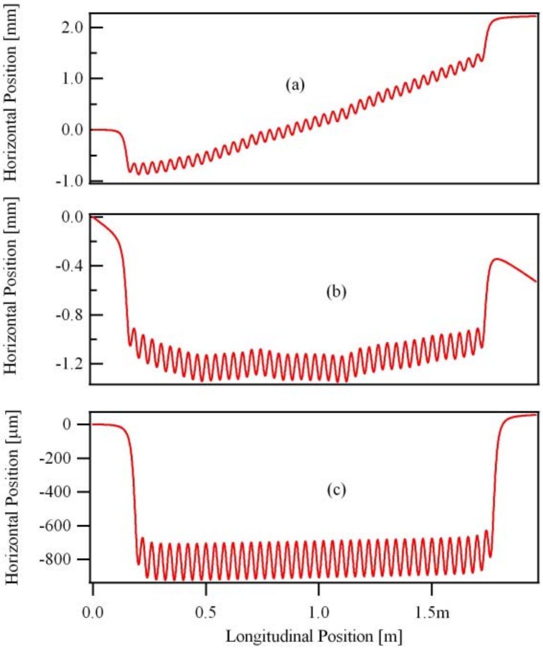

Fig. 5: (a) and (b) is horizontal trajectories calculated from the measurement without and with deflection at the entrance of the undulator, respectively. (c) is a horizontal trajectory calculated from the design.

is not considered as peak number: the number of peak field is 79. Figure 3 and Fig. 4 clearly show a demagnetization in the downstream part, peak number 70-78 in Fig.4. The gap is narrower (25.5 mm) than the original design, because we have modified the undulator in order to make the gap variable. Thus, the maximum value of peak magnetic field and K-value are 0.26 T and 0.99, respectively.

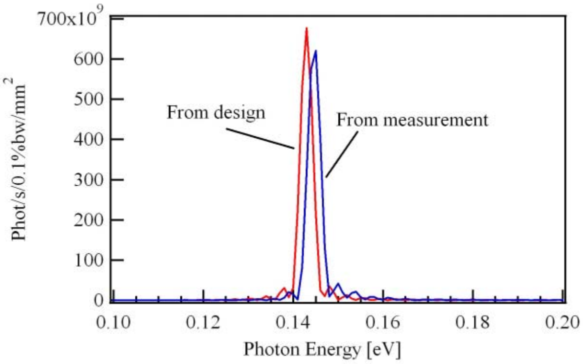

Fig. 6: Calculated spectrum of spontaneous radiation.

BEAM TRAJECTORY AND SPONTANEOUS RADIATION

Evaluation of beam trajectory and spontaneous radiation is an effective method to verify the measurement of the magnetic field. At first, We calculated electron beam trajectories at 30 MeV with the measured magnetic field and the designed field by using SRW [4]. Vertical displacement of the electron beam in the undulator shown in Fig. 5 (a) is 2 mm so that overlap between electron beam and laser is too poor. In order to compensate this, we are going to set a steering magnet before the undulator. The beam trajectory thus deflected at an angle of 1.4 mrad is shown Fig. 5 (b). Figure 5 (c) shows a beam trajectory calculated from the designed field. Fig 6 shows calculated spectra of spontaneous radiations. The radiation intensity calculated from the measured magnetic field is reduced by 9 %, and the spectrum is shifted to longer wavelength and shows asymmetric distribution, compared with that from the design field.

FEL GAIN CALCULATION

We previously reported on FEL gains based on designed magnetic field of undulator (Table 1) [2]. On the other hand, by using the measured magnetic field instead of the designed one, FEL gains have been recalculated to estimate realistic gains, which will be compared in the following.

The axial symmetric 3D code TDA3D [5] was used to calculate FEL gain and saturation. In addition, the undulator period was forced to be 39. This is because the number of peak magnetic field for TDA3D is defined as double of the undulator period while the undulator period in KU-FEL is 39.5.

At the 180-degree arc between the accelerator tube and the undulator shown Fig. 1, we can control the electron beam parameters for the optimization. Among the

Table 3: Fixed parameters of electron beam

Peak current	40 A
Normalized emmitance in x	11 πmm-mrad
Normalized emmitance in y	10 πmm-mrad
Energy spread	0.50%

Table 4: The optimized beam parameters

Beam energy (MeV)	25	30	35
Beam size in x (mm)	0.65	0.60	0.55
Beam size in y (mm)	0.33	0.36	0.36
Twiss parameter α_x	1.9	2.0	1.9
Twiss parameter α_y	0	0	0

Table 5: Optimized optical parameters

Beam energy (MeV)	25	30	35
Rayleigh range		0.40 m	
Beam waist position		0.60 m	
Wavelength (mm)	12.3	8.6	6.3
Out coupling (%)	4.0	2.5	0.8
Diffraction loss (%)	5.6	6.0	7.0
Total loss (%)	9.6	8.5	7.8

electron beam parameters, a peak current, a transverse emittance, and an energy spread, which are evaluated by PARMELA [6], are fixed (Table 3) during the calculation. The other electron beam parameters, electron beam sizes and Twiss parameters, are optimized to obtain the maximum FEL gains in three electron beam energies, 25, 30, 35 MeV. Electron beam sizes are RMS values. Twiss parameter α_y is set to zero due to the natural focusing of the undulator field. Table 4 shows the beam parameters optimized to the measured magnetic field of the undulator.

Optimization of the parameters of the optical cavity is also essential to enhance the FEL gains. We also optimized the optical parameters, Rayleigh range and beam waist position, for three electron beam energies. Table 5 shows the optimized optical parameters. The optical cavity of the KU-FEL system has been designed taking into account the diffraction loss and the out coupling. The laser field is assumed to be the Gaussian in the calculation optical loss. The out coupling hole is 1 mmϕ located at the upstream mirror. As the result, the curvature of upstream mirror is calculated to be 2.58 m and that of downstream mirror is 1.92 m. Table 5 also shows the diffraction loss and out coupling of the designed optical cavity. From the setup condition of the optical cavity, shown in Fig. 7, the beam waist position is not at the center of the undulator but is shifted to upstream in order to reduce the diffraction loss at upstream chamber (30 mmϕ). FEL gains with optimization of both of electron beam and of optical cavity are shown in Table 6. The realistic FEL gains are lower by a few % than those based on the design magnetic field distribution.

Table 6: Comparison of the optimized FEL gains of the measurement with those of the design

Beam energy (MeV)	25	30	35
Gain of design undulator (%)	89	65	49
Gain of real undulator (%)	87	64	49

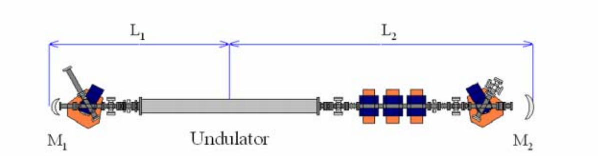

Fig. 7: Undulator and optical cavity in KU-FEL. L_1 is 1.605 m, L_2 is 2.70 m, R_1 (the curvature of M_1) is 1.92 m, and R_2 is 2.58 m.

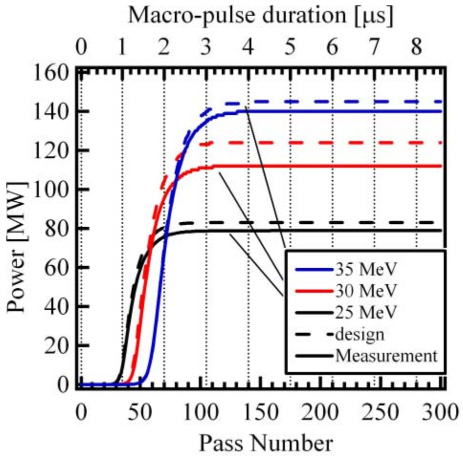

Fig. 8: FEL power as a function of pass number in each beam energy.

By using the above optimized conditions, we have estimated the evolution of the FEL power with the TDA3D modified to take into account the successive development of the laser power after round-trip. The optical loss is subtracted from the FEL gain in each pass. Figure 8 shows that FEL power from the measured magnetic field decreases by about 5 %.Then the numbers of round-trips necessary for saturation increase by about round-trips to reach gain saturation by 0.2 µm, compared with those from the design ones.

The injector in KU-FEL is a thermionic RF gun which have a disadvantage of back bombardment, so that macropulse duration has been restricted to 4 µs. However, since we have estimated macropulse duration is up to 8 µs [7], FEL saturation in each energy is expected.

SUMMARY

The measurement of the magnetic field of the KU-FEL undulator has been carried out. The electron beam trajectory in the undulator and the spontaneous radiation have been evaluated with measured magnetic field. The beam displacement is about 2 mm for 30 MeV electron beam. However, it can be reduced to 0.2 mm with a steering magnet placed just before the undulator. By using the measured magnetic field, the beam parameters and the optical parameters were optimized to obtain the maximum FEL gain. Calculation of FEL gain and FEL gain saturation have been performed. Although FEL gains show a few % decrease and thus the times to reach FEL saturations with the measured magnetic field are slightly longer than these with the design field, FEL saturation is expected in the wavelength region of from 6 to 12 μm.

REFERENCES

[1] T. Yamazaki, et al., Proc. Free Electron Laser Conf. 2001 (2002) II–13.
[2] T. Fukui, et al, Proc. Free Electron Laser 2005 (2006).
[3] E. Nishimura, et al., Nucl. Instrum. Methods, A341(1994) 39.
[4] O. Chubar, et al., Proc. of EPAC98, p.1177, 1998.
[5] J.S. Wurtele T.M. Tran. Computer Physics Comm., Vol.54, p.263, 1989.
[6] L. M. Young, James H. Billen : LA-UR-96-1835 (2002).
[7] N. Ohkawachi, et al., “Production of electron beam with constant energy by controlling input power into a thermionic RF gun”, in these proceedings.