

## PRESENT STATUS OF FEL DEVELOPMENT IN KYOTO UNIVERSITY

Satoshi Sasaki, Heishun Zen, Takumi Shiiyama, Toshiteru Kii, Kai Masuda, Hideaki Ohgaki  
Institute of Advanced Energy, Kyoto University, Gokasho, Uji, Kyoto, Japan, 611-0011

### Abstract

We have constructed an infrared (4-13  $\mu\text{m}$ ) FEL facility for advanced energy researches in Kyoto University. The numerical studies on the expected FEL gain, which were based on the experimental measurements both of the undulator and of the electron beam parameters, were carried out. GENESIS code has been modified to simulate an oscillator FEL which took into account the chamber geometry and the mirror including hole coupling. Dependencies on a tilt angle and an offset of the mirror were evaluated by using this modified code, then for the first lasing the mirror parameter was optimized. At the present stage, we have installed the undulator and the mirror cavity. Measurements on spectrum of the spontaneous emission and electron beam characteristics were carried out. The measured spontaneous emission was consistent with the result of the calculation obtained with measured magnetic field of the undulator. Since the evaluated peak current of the electron beam was not enough for the lasing, LaB<sub>6</sub> cathode was ready to use.

### INTRODUCTION

We have studied and developed an infrared (4-13  $\mu\text{m}$ ) FEL facility (KU-FEL) for advanced energy researches in Kyoto University. The KU-FEL consists of a 4.5-cell thermionic RF gun, 3 m accelerator, beam transport, Halbach-type undulator, and optical cavity. The RF gun and the accelerator operate at 2856 MHz (S-band), and produce electron beams up to 40 MeV.

To optimize the optical cavity, we calculated the FEL gain with the measured magnetic field of the undulator[1]. However, the treatment of the loss in the vacuum chamber and the light output from the cavity was truncated on the assumption of simple Gaussian distributions in transverse direction. On this assumption, the tolerance of the alignment errors of the optical cavity mirrors could not be evaluated. In this study, we carried out calculations of the light propagation taking into account of the duct shape and reflection/transmission of the light at the mirror for optimization of the optical mirrors and evaluation of the misalignment tolerance. For this purpose, we have modified a calculation code, GENESIS1.3[2].

Based on the re-optimized parameters in these calculations, we have installed the optical cavity and undulator in the KU-FEL system. We then observed the spectrum of the spontaneous emission, and compared it with the SRW[3] calculation.

Aiming at a higher peak current, we replaced the tungsten cathode in the RF gun by a LaB<sub>6</sub> cathode. In this paper, the preliminary experimental comparison will be also reported.

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### FEL GAIN CALCULATION

#### Calculation Code

We had calculated the FEL gain and round trip development to optimize the optical cavity parameters, by using TDA3D[4], but it didn't take into account the duct shape, reflection on mirror, absorption, and transmission of the mirror. In addition, the detuning parameter can hardly be handled.

To cope with these problems in this study, we modified GENESIS1.3 code taking in the realistic duct shape. We simulated a realistic FEL gain by using the modified code. The duct shape taken in the calculation is shown in Fig.1. The parameters of the electron beam used in the FEL gain calculation were optimized for the measured undulator parameters, and are listed in Table 1. The undulator parameters are listed in Table 2.

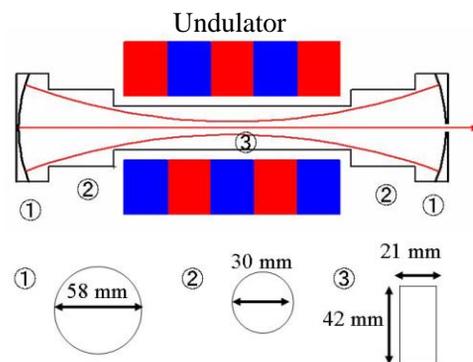


Figure 1: Duct shape

Table 1: Electron beam parameters

Emittance(x)	3.5 $\pi\text{mm-mrad}$
Emittance(y)	3.5 $\pi\text{mm-mrad}$
$\Delta E / E$	0.5 %
Beam size(x)	0.6 mm
Beam size(y)	0.4 mm
Twiss parameter $\alpha_x$	3.6
Twiss parameter $\alpha_y$	0
Beam energy	25 MeV

Table 2: Parameter of Halbach type undulator

total length	1.6 m
Repetition	40
period	4 cm
gap	25.5 - 45 mm
Maximam magnetic field	0.26 - 0.0045 T
K value	0.99 - 0.17

### Set Up of the Optical Cavity

Firstly, the mirror curvatures were designed in the viewpoint of FEL lasing stability as follows. Parameters of the optical cavity were once optimized to obtain the highest FEL gain by using TDA3D with aforementioned truncations, and FEL gain was 87% under the electron beam condition of 25 MeV, while the resultant stability has not been evaluated. By using the modified GENESIS1.3, we calculated FEL gain under the same conditions, and FEL gain was 49%. The reason why FEL gain decreased was due to the diffraction loss.

The stability was then evaluated by using the modified GENESIS1.3 and as the result it was found that the optical cavity was unstable for FEL lasing. The g-parameter was found to be 0.93, We thus re-optimized the parameters of the optical cavity by the use of modified GENESIS1.3, to obtain a g-parameter of ~0.5. As the result, we have selected the curvature of the upper mirror of 3.03 m, the down mirror of 1.87 m, the the rayleigh length of 0.7 m, and beam waist of 1.1 m (see Table 3).

Secondly with the specification of the mirrors, the misalignment tolerance was the evaluated. The results of the mirror offset and tilt dependency are shown in Fig. 2. Here, Dm means down mirror, and Um means upper mirror. X and Y are the direction the mirrors offset and tilt. The FEL gain is seen to decrease ~10% with respect to the ideal alignment when the offset is 0.4 mm or the tilt angle is 400  $\mu$ rad. In comparison, with the original mirror parameter, the FEL gain is found to decrease by 30%, as shown in Fig.3. The re-optimized parameters are thus found to lead to a much better misalignment tolerance.

Finally, concerning the diameter of mirror hole, we simulated the FEL gains for the diameters of 1, 2 and 3 mm $\phi$ , and the results are summarized in Table 4. As of the numerical treatment of the out-coupling hole, we found that the discontinuity of the optical fields on the edge of the hole results in a numerical problem[5]. So, we rather treated the out-coupling as transpiration. As shown in Table 4, the FEL gain for 3 mm $\phi$  hole is found to be about a half of that for 1 mm $\phi$ . In comparison, the gain decrease for the 2 mm $\phi$  hole is tolerable, and the FEL output is more than two times higher than that for 1 mm $\phi$ . We thus chose the mirror diameter of 2 mm $\phi$ .

The optimized mirrors were then installed in the optical cavity of the KU-FEL. The picture of the mirror is shown in Fig. 4, and the reflectivity is shown in Table 3.

Table 3: Parameters of the optical cavity

Substance	Au coated Cu mirror
Rayleigh range	0.7 m
Beam waist position	1.1 m
infrared reflection	99.04%
down mirror curvature	1872 mm
upper mirror curvature	3030 mm
Cavity length	4.513 m

Table 4: FEL gain dependence on mirror hole diameter

diameter	Gain(%)	Output(MW)	Pass number for saturation
1mm $\phi$	44	2.0	70
2mm $\phi$	37	4.9	75
3mm $\phi$	24	4.8	100

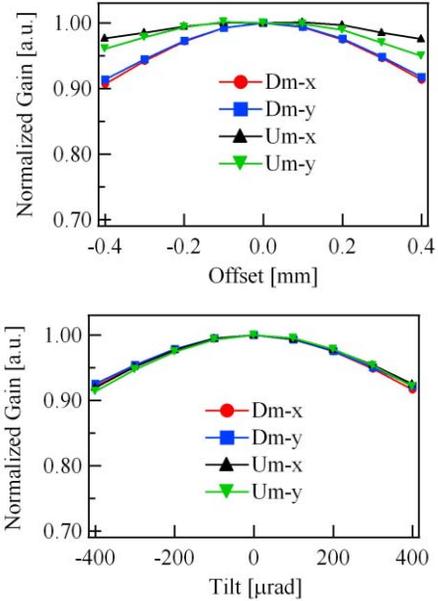


Figure 2: Influence of mirror misalignment of 0.5 g-parameter

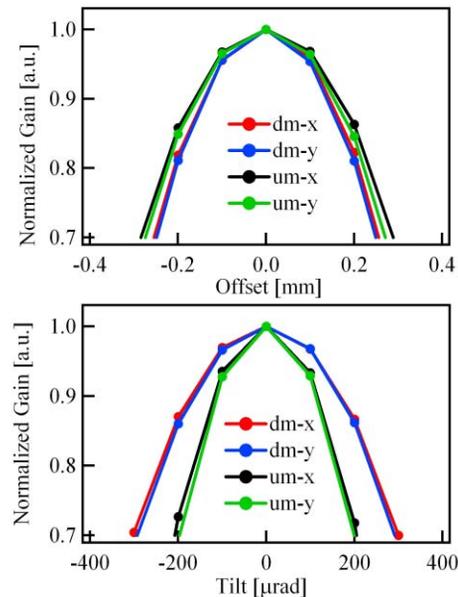


Figure 3: Influence of mirror misalignment of 0.93 g-parameter

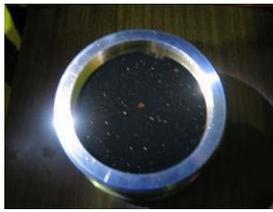


Figure 4: Au coating mirror

The FEL power evolution calculated by modified GENESIS1.3 under electron beam condition of 25 MeV is shown in Fig. 5. For comparison, the preliminary result by the use of TDA3D on same condition is also shown in Fig. 6.

At the present stage, the macro-pulse length of electron beam is about 3  $\mu\text{s}$  in KU-FEL, so it is necessary for electron beam peak current to be 40 A in order to realize FEL lasing.

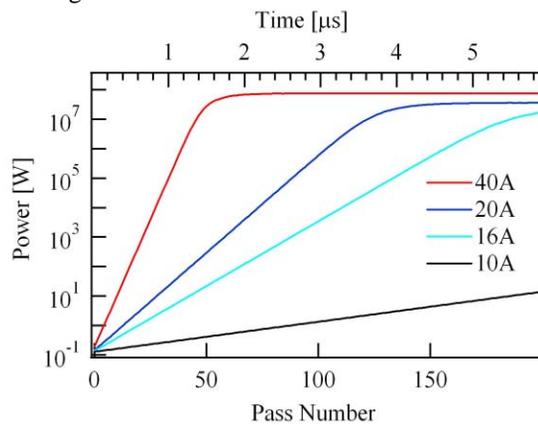


Figure 5: FEL power evolution calculated by GENESIS1.3

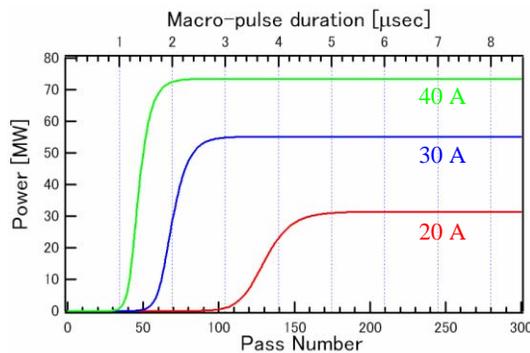


Figure 6: FEL power evolution insufficient on mirror and diffraction losses.

## MEASUREMENTS

### Measurement of Spontaneous Emission

We measured the spectrum of spontaneous emission using an InSb detector (Judson, J15D12) and a monochromator (Digikrom, DK240). We extract the light from the downstream of the mirror chamber, and then focus it on the entrance of the monochromator by a parabolic mirror. The experimental setup is shown in Fig.7.

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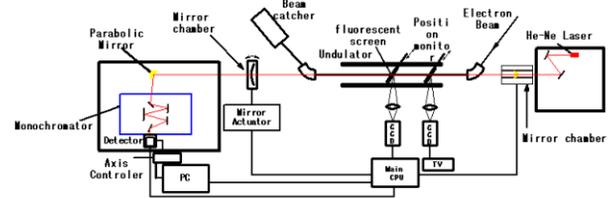


Figure 7: Experimental setup

We observed the spectrum of spontaneous emission, under the condition of the electron beam energy of 29.5 MeV. The electron beam condition is shown in Table 1 except for energy, and the observed spectrum is shown in Fig. 8. The spectrum shows a peak at 9.2  $\mu\text{m}$ , and its FWHM is 270 nm. The undulator parameters are listed in Table 1, and the spectrum calculated by SRW by using these parameters is also shown in Fig. 8 as the dotted line. The observed spectrum shows exactly the same peak wavelength as the calculation, and the FWHM also agrees well with the calculation, considering that the FWHM by the calculation doesn't include resolution of the monochromator, 100 nm.

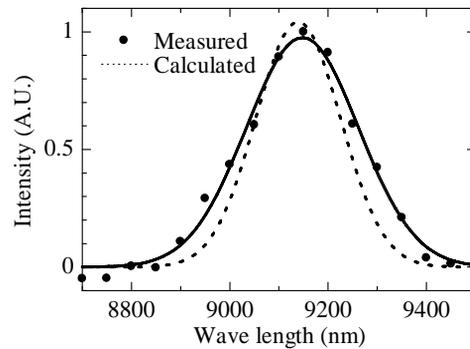


Figure 8: Measured and calculated spectrum of the spontaneous emission

### FEL Lasing Experiments

We then started FEL lasing experiments of 11  $\mu\text{m}$  wavelength with an electron beam energy of 26.5 MeV, macro-pulse length of 3  $\mu\text{s}$ , average current of 40 mA. The reasons for the choice of 11  $\mu\text{m}$  are as follows. On one hand, a lower energy electron beam shows in general a higher FEL gain. Furthermore, in the KU-FEL linac, lower energy operation of the RF gun is found to lead to a higher peak current[6]. On the other hand, the InSb detector loses sensitivity rapidly for  $\sim 13 \mu\text{m}$  or longer.

We then carried out experiments aiming at FEL lasing. We succeeded in accumulating the spontaneous emission, but neither FEL amplification nor saturation is observed at this moment.

The peak current of the electron beam of  $\geq 7$  A is estimated by the bunch length measurement[6]. According to the numerical calculations in the previous chapter, the sum of the diffraction loss and mirror loss exceeds the amplification if an electron beam if 7 A peak current.

Aiming at a higher peak current, we replaced the tungsten cathode in the RF gun by a LaB<sub>6</sub> cathode. An experimental comparison showed that a LaB<sub>6</sub> cathode lead to a higher peak current than a tungsten cathode in an RF gun[7], probably because a LaB<sub>6</sub> cathode is less sensitive to the back-bombardment effect.

Our preliminary test with a LaB<sub>6</sub> cathode when the RF gun operated at 9 MeV, showed that we obtained a 120 mA average current and 2.5 μsec macro-pulse length, which is encouraging compared with 70 mA and 3 μsec by the tungsten cathode.

In the next stage, we will operate the RF gun at 7.5 MeV, which is known as the best operational condition for the optimal peak current at the undulator [6]. Under this operational condition, the peak current by the tungsten cathode was  $\geq 7$  A. According to the current enhancement by the LaB<sub>6</sub> cathode, we can expect an enhanced peak current of  $\geq 12$  A. The expected FEL gain is  $\sim 5.0\%$ , and the FEL amplification would be  $\sim 100$ .

### SUMMARY

We modified the calculation code, GENESIS1.3, to calculate the FEL gain taking into account the duct shape and mirror, while we applied a truncation in the out-coupling treatment for numerical stability. In order to consider mirror out-coupling hole realistically, we must modify the calculation code further.

By using modified GENESIS1.3, we optimized the parameter of the optical cavity, and set up the experimental equipments. For these parameters, we calculated the expected FEL gain. As the result, we found that if the peak current of electron beam is 40 A, and macro-pulse length is 3 μs, 12 μm FEL saturation will be achieved on the electron beam condition of 25MeV.

The spectrum of spontaneous emission was measured. The results agreed well with calculation.

At present, we have not achieved an FEL lasing, mainly due to the limitation of the peak current and macro-pulse duration, i.e. the back-bombardment effect in the RF gun. Against this adverse effect, preliminary tests showed that the use of the LaB<sub>6</sub> cathode would lead to a higher peak current than a dispenser type one. By the LaB<sub>6</sub>, 12 A peak current is expected, and the corresponding FEL gain is 5%. Under this condition, we will be able to observe an FEL amplification.

### REFERENCES

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