NUMERICAL STUDY ON THE UNDULATOR IN KU-FEL

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Abstract

The optimization of electron beam parameters and the design of the optical cavity have been numerically carried out in order to obtain high FEL gains in the KU-FEL facility. A FEL gain of up to 82 % has been reached for the FEL wavelength of 12 μm in the optimized conditions. The FEL power saturation in 8~12 μm wavelength can be expected with the optimized condition. However, it is still difficult to obtain in the FEL saturation below 6 μm wavelength with a macro-pulse duration of 3 μs or less. In addition, the calculated FEL gain increases with the normalized filling factor. Consequently, increasing the density of electron beam and the overlap between the electron beam and the laser is important to obtain a large FEL gain.

INTRODUCTION

We have constructed KU-FEL system for 4~13 μm FEL for bio/chemical energy researches at the Institute of Advanced Energy, Kyoto University [1]. The system consists of a thermionic RF gun, a 3-meter accelerating tube and 1.6-m undulator [2]. An electron beam with a macro-pulse duration of 3 μsec has been successfully accelerated to 30 MeV and studies on the beam characteristics have also been carried out [3]. We rebuilt the facility building for KU-FEL in 2004 [4] and reinstallation of the system has almost finished. The previous calculation showed, however, that the macro-pulse duration of the electron beam, 3 μsec would be too short to achieve the FEL saturation [5]. To deliver saturated FEL beams for the application purpose an optimization of the electron beam parameters and the optimized design of the optical cavity are crucial issues. In this paper, we will report on the optimization both of the electron beam parameters and of the optical cavity parameters by using numerical calculations.

BEAM OPTIMIZATION

KU-FEL system

The KU-FEL system mainly consists of an RF gun, an accelerating tube, and an undulator. Figure 1 is a schematic view of KU-FEL. The 4.5 cell thermionic RF-gun has been installed and generates electron beams with 3 μsec macro-pulse duration whose maximum energy is about 11 MeV. To extend the macro-pulse duration extensive studies have been carried out [6]. The S-band accelerator tube is 2.9 m in active length, and accelerates electron beam up to 40 MeV by using 20 MW RF power. The Halbach type undulator [7] is ready for system installation. The undulator length is 1.6 m, the period is 40 mm, the number of periods is 40, and undulator parameter, K-value, is 0.95~0.17.

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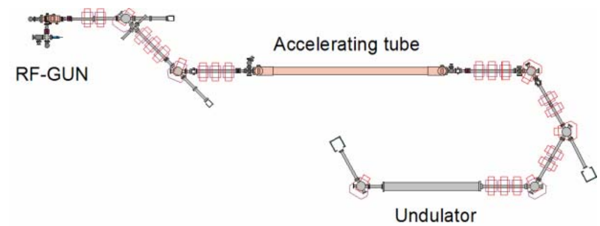

Figure 1: Schematic view of reinstalled KU-FEL system.

FEL gain and saturation

In this work, we used the axial symmetric 3D code TDA3D [8] to calculate FEL gain and saturation. Three typical electron beam energies, 25, 30, 35 MeV, are used for the calculation. Electron beam parameters, listed in Table1, are calculated by using PARMELA [9] and TRACE3D [10].

Since TDA3D code can not calculate the round trip development of the light, we made a supplemental code to simulate the round-trip development by subtracting the optical loss from the FEL gain in each pass. In this work, we assumed optical loss as 10% and calculated FEL saturation. After design of optical cavity, we used designed value to get more realistic calculation of the FEL saturation.

The cavity length of the KU-FEL is 4.305 m defined by the geometric condition (Figure 1) and the RF frequency of the RF gun and the accelerating tube. Therefore, 1 μsec of macro-pulse duration corresponds to 35 round-trips.

Beam optimization

The electron beam parameter used in the original gain calculation was not completely matched to the matching condition [11], $\alpha_{x,y}=0$ and $\beta_{x,y}=1/k_{x,y}$, because PARMELA calculation was slightly different from TRACE3D. Therefore, we have tried to change the

Table 1: Electron beam parameters before injected into the undulator.

macropulse duration	3	μsec
beam energy	25~35	MeV
peak current	40	A
normalized emittance in x	11.3	πmm-mrad
normalized emittance in y	10.1	πmm-mrad
energy spread	0.5	%
beam size in x (original value)	0.570	mm
beam size in y (original value)	0.820	mm

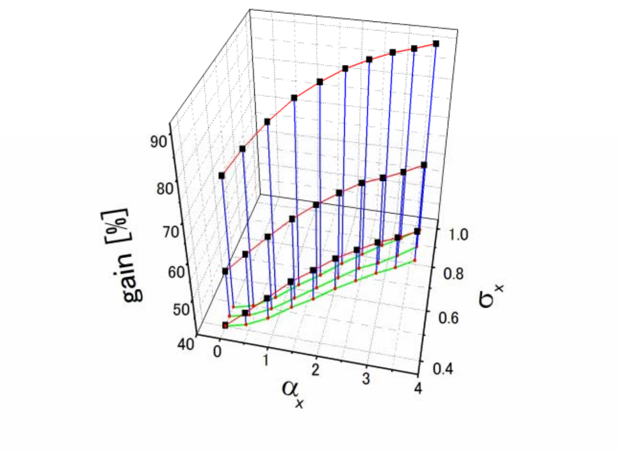

Figure 2: FEL gain as a function of α_x and σ_x with σ_y=0.35 mm

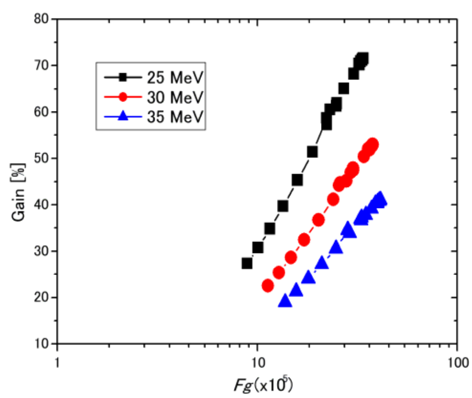

Figure 3: Relation between F_g and FEL gain. FEL gain increase exponential function of F_g in proportion.

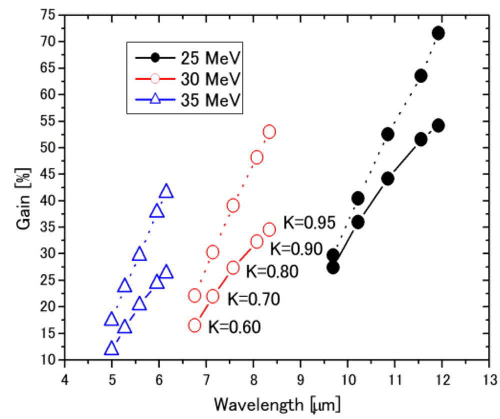

Figure 4: FEL gain of original beam (solid line) and optimized beam (broken line)

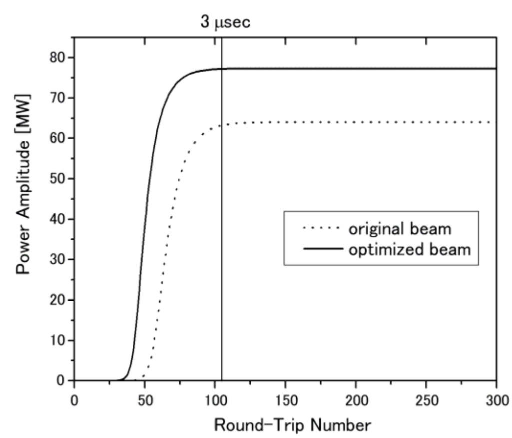

Figure 5: FEL saturation in 12 μm. FEL power with original beam can not saturate, but that with optimized beam achieves saturation.

electron beam size, σ_x and σ_y, and Twiss parameter, α_x. On the other hand, α_y is fixed to 0 in this work, because the y-plane has a natural focussing from the undulator field. The other beam parameters are also fixed to the values used in the original calculation [5]. Figure 2 shows the FEL gain as a function of α_x and σ_x. Table 2 is a result of optimized beam parameters. To evaluate the parameter search process, we define the normalized filling factor, F_g, as an evaluation function.

$$F_g = \frac{F.F}{\langle\sigma_x\rangle \cdot \langle\sigma_y\rangle} \tag{1}$$

$$F.F = \frac{\int_{-L/2}^{L/2} s_{EB} \cdot s_{Laser} dz}{\int_{-L/2}^{L/2} s_{EB} dz \cdot \int_{-L/2}^{L/2} s_{Laser} dz} \tag{2}$$

$$\sigma_{x,y} = \sqrt{\varepsilon_{x,y}\beta_{x,y}} \tag{3}$$

$$s_{EB} = \sqrt{\sigma_x^2 + \sigma_y^2} \tag{4}$$

where $<\sigma_{x,y}>$ is average electron beam size, ε_x and ε_y are normalized emittance in each x-x' plane and y-y' plane, L is undulator length, and $s_{EB}(z)$ and $s_{Laser}(z)$ are RMS electron beam size and FWHM radius of laser, respectively.

Figure 3 shows the relation between F_g and FEL gain. As is shown in the figure, the calculated FEL gain shows exponential function of F_g. Consequently, to obtain a large FEL gain it is clear that increasing both the density of the electron beam and the overlap between electron beam and laser at the same time is important.

Figure 4 and Figure 5 display the FEL gain and gain saturation using optimized electron beam parameters and those of original calculations as a comparison. As is shown in figures, the expected FEL gains have been enhanced by electron beam optimization. However, in short wavelength, below 8 μm, we still can not reach enough saturation. It should be noted that Figure 4 indicates that the FEL gain decreases drastically when undulator parameter, K-value decreases. Thus we should change the beam energy to choose the FEL wavelength and only use undulator gap for fine tuning.

Optical cavity optimization

Table 2: The optimized beam parameters for the highest FEL gain in each beam energy

	25	30	35	MeV
σ_x	0.74	0.68	0.58	mm
σ_y	0.35	0.35	0.35	mm
α_x	2.4	2.4	2.0	
α_y	0	0	0	
gain	71.57	52.98	41.07	%

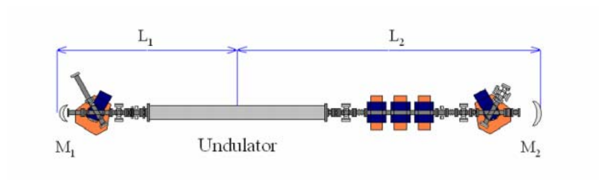

Figure 6: Undulator and optical cavity in KU-FEL. L_1 is 1.605 m, L_2 is 2.70 m, R_1 (the curvature of M_1) is 1.72 m, and R_2 is 2.77 m.

As shown in previous section, not enough FEL saturation can be obtained by the electron beam optimization. To obtain a further enhancement in FEL gain, optimization in optical cavity is one of effective method. To optimize the optical cavity we calculated the optical loss as a function of Rayleigh range, z_R. The optical loss of the laser is analytically calculated assuming the Gaussian beam optics [12] and expressed as following

$$\Delta t = 1 - \int_0^{L_z} \int_{-\phi(z)/2}^{\phi(z)/2} \frac{1}{\sqrt{2\pi} w(z)} \exp\left[-\frac{x^2}{2w(z)^2} \right] dx dz \quad (4)$$

where Δt is optical loss, $\phi(z)$ is diameter of the beam duct at position z, $w(z)$ is the RMS beam size of the laser, and L_z is cavity length. Out coupling is also calculated as a Gaussian distribution for laser. We assume the hole coupling and hole radius is derived from 5% out couple in 12 μm wavelength.

Figure 7 shows the FEL gain as a function of Rayleigh range, z_R, at 12 μm wavelength. As is shown in the Figure 7, the optimized z_R is 0.37 m without optical loss. Taking the optical loss into account, however, z_R = 0.425 m is an optimized condition. We also calculated how beam waist position changes FEL gain, but the effect is few percent. Consequently we put the beam waist position at the center of the undulator. Consequently, by optimization of optical cavity the expected FEL gain is 82% including the optical loss. As shown in Figure 6, the designed optical cavity is asymmetric. The distance from the undulator center to the downstream mirror, L1, is 1.72 m and that of upstream, L2, is 2.77 m. The curvature of mirrors is calculated analytically and out coupling hole of 1mmϕ is located at upstream mirror. Table 3 shows parameters of the designed optical cavity and total optical loss.

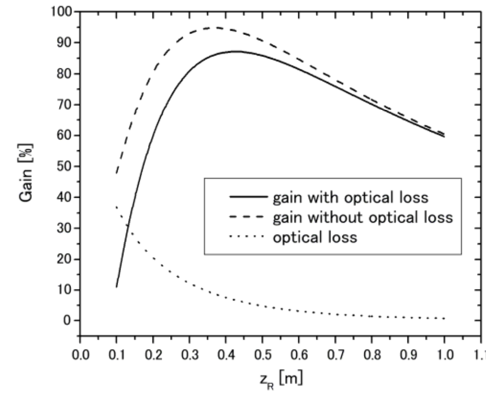

Figure 7: FEL gain with optical loss. Electron beam is optimized condition in 12 μm wavelength.

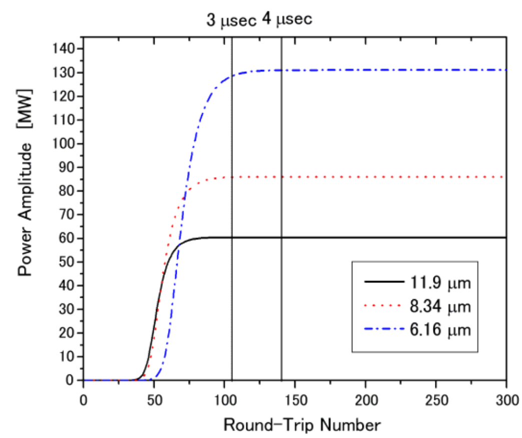

Figure 8: Optimized FEL saturation including optical loss.

By using calculated optical loss, the FEL saturation with optimized electron beam and designed optical cavity is shown in Figure 8. As shown in Figure 8 we can expect FEL saturation in 8~12 μm, however, it is still difficult to saturate below 6 μm with 3 μs macro-pulse duration. By using 4 μs macro-pulse duration of electron beam, as is shown in Figure 8, 6 μm FEL can be expected to saturate.

SUMMARY

The optimization of the electron beam properties and the design of the optical cavity are carried out by numerical simulations to obtain high FEL gains in the KU-FEL system. The FEL gain with the optimized condition is enhanced from 52% to 82% in 12 μm wavelength. The calculated FEL gain shows an exponential increase as a function of the normalized filling factor.

Consequently, increasing the density of the electron beam and the overlap between the electron beam and the laser are important to obtain a large FEL gain. In addition, the undulator gap spacing should be used for a fine tuning of the wavelength adjustment. Additionally the FEL power saturation in 8~12 μm wavelength can be expected by using the optimization of the electron beam and the optical cavity. However, it is difficult to reach the FEL saturation below 6 μm in wavelength with the macro-pulse duration of less than 3 μs. Efforts to extend macro-pulse duration in the RF gun is crucial in KU-FEL system.

Table 3: Parameters of the designed optical cavity.

Beam energy	25	30	35	MeV
wavelength	11.9	8.32	6.14	μm
R_1		1.72		m
R_2		2.77		m
optical loss in upstream beam duct	6.63	2.79	1.05	%
optical loss in downstream beam duct	2.48	0.296	0.025	%
out coupling (1mmϕ center hole)	5.00	5.98	6.96	%
Total loss	14.1	10.1	8.04	%

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