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Investigation of Electron Beam Parameter in Seeded THz-FEL Amplifier using Photocathode RF Gun

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Abstract

Simple, compact, and powerful seeded terahertz-free electron laser (THz-FEL) which consists of a photocathode radio-frequency gun, a focusing solenoid, an undulator and a THz wave parametric generator has been designed. A start-to-end calculation has been performed by using the particle tracking code PARMELA and the FEL gain simulation code GENESIS1.3. To obtain a higher FEL gain, we searched a better condition of the electron beam parameter and the seed light. In the present design scheme, the FEL peak power was calculated to be 3 kW at the FEL resonant wavelength of 179 μm. Since the power of the seed light was 0.20 W, the light power was amplified almost 10^4 times.

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Keywords: Electron beam parameter; Free-electron laser; Terahertz radiation; Photocathode RF gun

1. Introduction

THz radiation is an electromagnetic radiation in the wavelength range from millimeter wavelength to far infrared. Recently, the industrial application of THz radiation has attracted attention, because THz radiation can penetrate fabrics and plastics, and make no damage on tissue and DNA. Therefore, there are so many application targets such as medical diagnosis, discrimination drug and explosive in the mail, and

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so on, of THz imaging [1,2]. Powerful and wavelength-tunable THz sources are required for these applications. It is known that Free Electron Lasers (FELs) are the most powerful and wavelength-tunable radiation sources in the THz region. However, it has a problem that FEL facility generally needs a huge space and a high cost. Therefore, we have proposed a table-top seeded THz-FEL amplifier in the previous work [3]. This system consists of a 1.6-cell photocathode radio-frequency (RF) gun, a focusing solenoid, an undulator, a drive laser for exciting the cathode, and a THz-wave generator as shown in Fig. 1. A Brookhaven National Laboratory type 1.6-cell photocathode radio-frequency (RF) gun which has succeeded in generation of a high quality electron beam will be installed as an electron source [4]. Generally, a seeded FEL can achieve a narrower spectrum than a shot noise amplifier type FEL. Therefore, our conceptual design was adopted to use a THz-wave parametric generator caused by the drive laser that excites the photocathode of the electron gun at the same time.

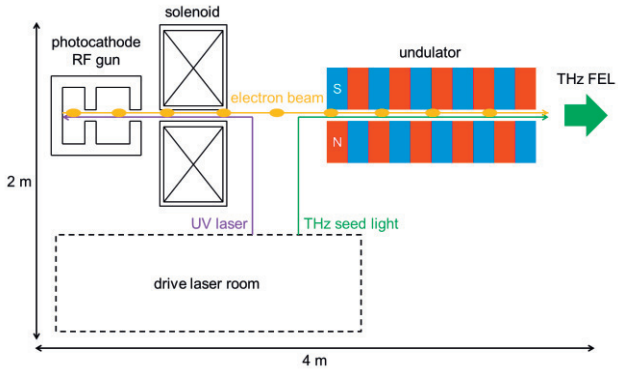

Fig. 1. Conceptual drawing of the table-top seeded THz-FEL amplifier

However, there are challenges to realize our concept, i.e. the slippage problem in a long wavelength FEL [3]. Therefore we plan to set up a test machine to examine the proposed design by using the exiting FEL facility, KU-FEL [5]. In this paper, we describe an optimization of the electron beam parameters of the test machine by using numerical simulations.

2. Beam Tracking Simulation

We calculated electron beam properties from the RF gun to the exit of the solenoid by using simulation code PARMELA [6]. During the simulation, a bunch charge of 1.0 nC/bunch was assumed to be generated from the RF gun by exciting the photocathode with a drive laser. We assumed that the drive laser had Gaussian temporal and spatial distributions, whose rms pulse duration was 6.2 ps and rms beam size was 1.38 mm at the cathode surface.

In this study, the electric field of the RF gun was changed at 40-80 MV/m, and the laser injection phase was changed at 10-80 degrees which allowed us to deliver more than 90% of the accelerated particles at the exit of the RF gun. The beam properties of beam energy, energy spread, peak current, and normalized emittance at the exit of the solenoid were investigated. These results as a function of the laser injection phase at the different RF electric field are shown in Figs. 2 (a)-(d). It is clear that the laser injection phase less than of 50 degree should be adopted because a small rms normalized emittance (~4.5 πmm-mrad) and a narrow energy spread (less than of 4%) with a high peak current (85-210 A) can be

obtained. The beam energy needed for the aiming FEL radiation wavelength can be derived by the resonant condition from the following formula:

$$\lambda_R \cong \frac{\lambda_u}{2\gamma^2}(1+\frac{K^2}{2}), \tag{1}$$

$$K = \frac{eB_u\lambda_u}{2\pi mc} \approx 93.36 B_u \lambda_u, \tag{2}$$

where λ_R is radiation wavelength, λ_U is undulator period length, γ is Lorentz factor, e is elementary charge, B_U is peak magnetic field of the undulator, m is electron mass, and c is speed of light. As is shown in Fig. 2 (a), the FEL radiation wavelength of 130-600 μm (0.5-2.3 THz) can be generated by the expected beam energy of 3.1-7.2 MeV.

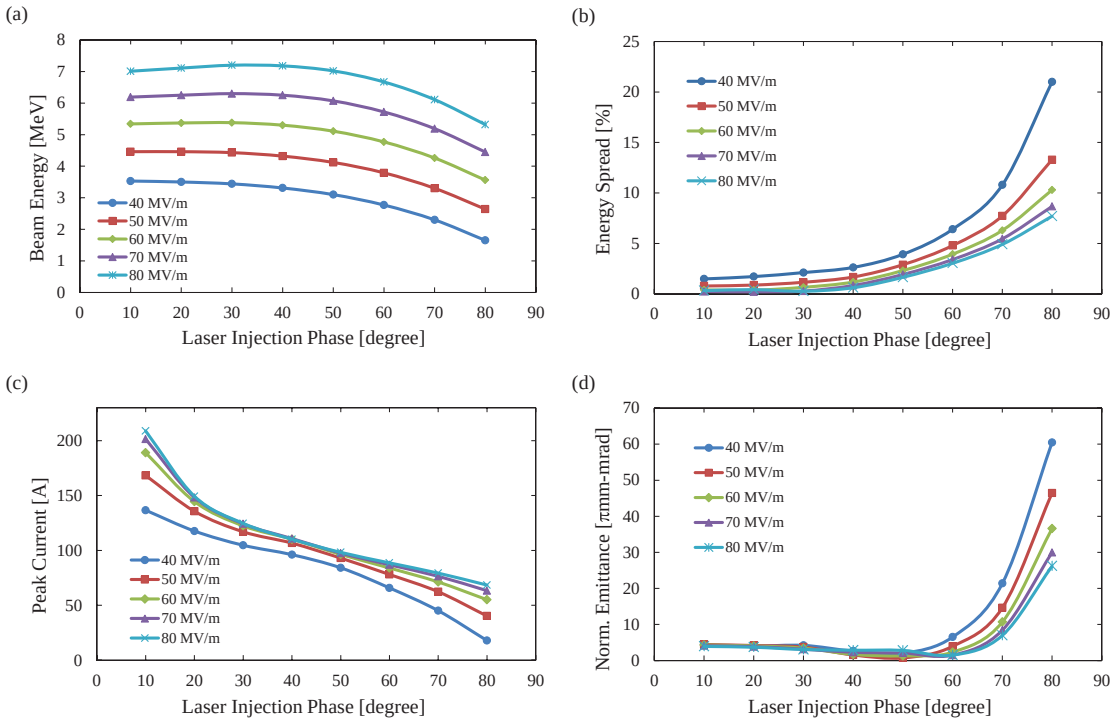

Fig. 2. Electron beam properties as a function of the laser injection phase at the exit of the solenoid
(a) beam energy (b) energy spread (c) peak current (d) normalized emittance

3. Searching for Optimum Condition

FEL gain was calculated by using the 3D time-dependent simulation code, GENESIS1.3 [7]. The electron beam parameters calculated by PARMELA were used together with the undulator parameters in GENESIS1.3. We temporary assumed to employ the undulator which was used to generate the mid-

infrared FEL in Kyoto University until last year [8]. The undulator parameters are shown in Table 1. The total length of undulator is 1.6 m, and the undulator gap is 20 mm. In this study the diffraction loss of the optical radiation was not included.

Table 1. Undulator parameters

Undulator period length λ_u	*40 mm*
Number of undulator period	*40*
K value	*0.99*
Peak magnetic field intensity	*0.265 T*

3.1. Dependence on the waist position of the seed light

During this simulation, the whole power of the seed light assumed to be produced by the THz-wave parametric generator was set to be 200 mW. It is known that the seeded FEL is directly related to the energy modulating process by the seed light. To investigate an effect of the seed light, we changed the waist position of the seed light from -0.2 to 0.8 m in a free space. The waist position of 0 and 0.8 m are located at the entrance and the center of the undulator. The Rayleigh length was adjusted respectively to make the maximum value of the FEL peak power by changing the waist size. The FEL peak power as a function of the waist position at the exit of the undulator is shown in Fig. 3. The FEL peak power was normalized on the basis of the maximum value at the waist position of 0.05 m. It was noted that the energy modulation was generated by the seed light near the entrance of the undulator than the overlapped effect between the electron beam and the seed light (filling factor). We found that the best condition of the waist position and the Rayleigh length for the seed light was 0.05 and 0.1 m, because the seed light only works as an initial energy modulator for the electron beam and the FEL radiation amplified by the spontaneous radiation from the modulated electron beam itself.

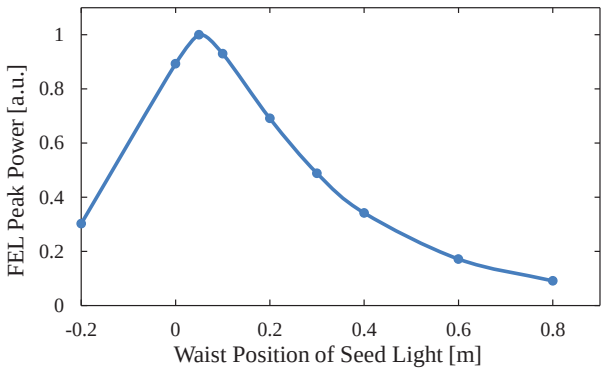

Fig. 3. Calculated FEL peak power at the different waist position of the seed light

3.2. Investigation of the electron beam parameters

It is well known that the peak current, the energy spread and the emittance are the most important to generate FEL efficiently under the interaction between the electron beam and the light. In this meaning a high peak current with a narrow energy spread and a small emittance is preferable. Therefore we

calculated the FEL peak power as a function of four parameters (peak current, energy spread, and normalized emittance of x, y direction) to evaluate the dependence of each parameter. The results are shown in Figs. 4 (a)-(d) when the waist positions of the seed light are 0.05, 0.4 and 0.8 m. The FEL peak power was normalized on each graph. Consequently it is a clue to optimize the laser injection phase and to decide the system configuration like a bunch compressor.

The peak current and the normalized emittance are derived by the following formulae:

$$I_{\text{peak}} = \frac{q}{\sqrt{2\pi}\sigma_{\text{e,t}}} \approx \frac{q}{2.5\times\sigma_{\text{e,t}}}, \tag{3}$$

$$\sigma_{\text{x}} = \sqrt{\frac{\beta_{\text{x}}\varepsilon_{\text{n,x}}}{\gamma}}, \sigma_{\text{y}} = \sqrt{\frac{\beta_{\text{y}}\varepsilon_{\text{n,y}}}{\gamma}}, \tag{4}$$

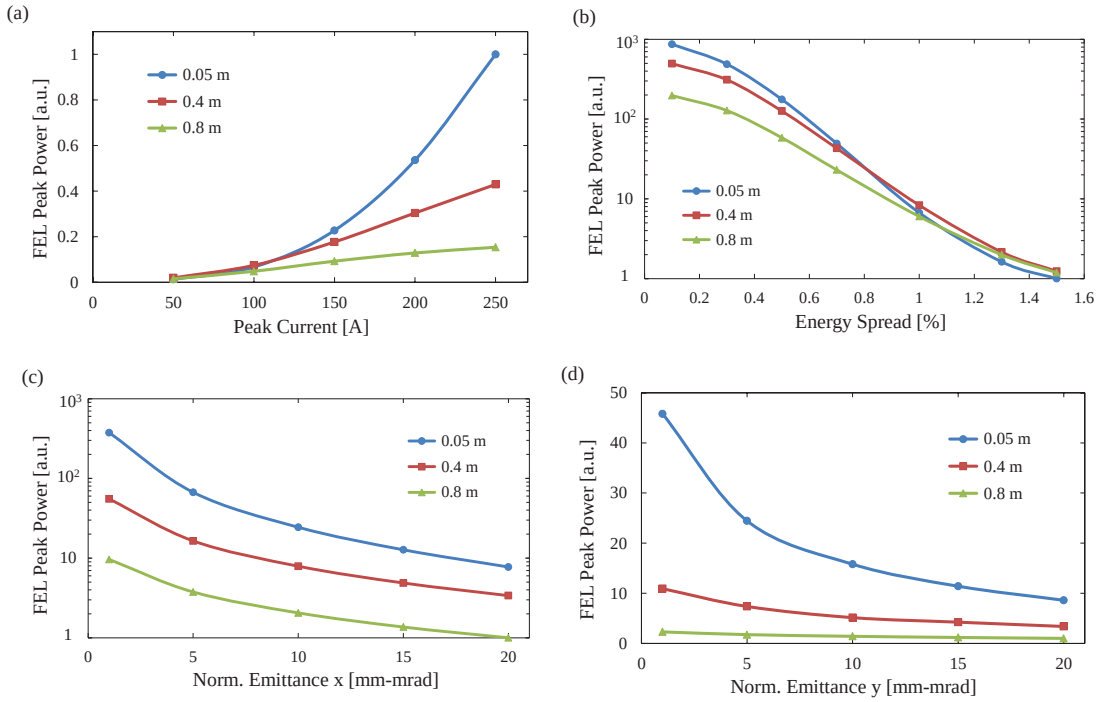

Fig. 4. Calculated FEL peak power as a function of each parameter
(a) peak current, (b) energy spread, (c), (d) norm. emittance) for the different waist position

where I_{peak} is peak current, q is bunch charge, $\sigma_{\text{e,t}}$ is rms bunch length, σ_{x}, σ_{y} are rms beam sizes, β_{x}, β_{y} are beta functions, and $\varepsilon_{\text{n,x}}$, $\varepsilon_{\text{n,y}}$ are normalized emittances. To examine the peak current dependence as shown in Fig. 4 (a), the rms bunch length was changed with keeping the bunch charge of 1 nC. To examine the normalized emittances dependence as shown in the Figs. 4 (c), (d), the beta functions were adjusted to make the maximum value of the FEL peak power. On this condition, the highest FEL peak

power was obtained at the waist position of 0.05 m. As seen in Figs. 4 (a)-(d), the energy spread is the most critical factor for obtaining the higher FEL gain.

4. Performance of amplifier

4.1. Numerical calculation of the present design

In the previous section, we discussed the FEL peak power dependence on each electron beam parameter. As the result we adopted the electron beam parameter in the laser injection phase of 10 degree for a bunch charge of 1.0 nC/ bunch with the electric field of 70 MV/m in the RF gun. And also, Twiss parameters of α and β function were adjusted to make the maximum value of the FEL peak power. The parameters of the electron beam and the undulator are shown in Table 1, 2.

Table 2. Electron Beam Parameters used in GENESIS1.3

Horizontal Emittance $\varepsilon_{n,x}$	*4.11 πmm-mrad*
Vertical Emittance $\varepsilon_{n,y}$	*3.75 πmm-mrad*
Horizontal Beam Size σ_x	*1.24 mm*
Vertical Beam Size σ_y	*0.423 mm*
Twiss Parameter α_x	*1.68*
Twiss Parameter α_y	*0.10*
RMS Energy Spread	*0.239%*
Beam Energy E_k	*6.19 MeV*
RMS Pulse Length (RMS Bunch Length)	*1.98 ps (0.59 mm)*
Peak Current	*201 A*
Resonant Wavelength	*179 μm*

The temporal distributions of the FEL power at the exit of the undulator and the beam current at the entrance of the undulator are shown in Fig. 5. The FEL peak power was calculated to be 3 kW at the FEL radiation wavelength of 179 μm. Since the power of the seed light was 0.20 W, the light power was amplified almost 10^4 times in this case. The light energy per the FEL pulse was estimated to be 15 nJ by integration of the radiation power.

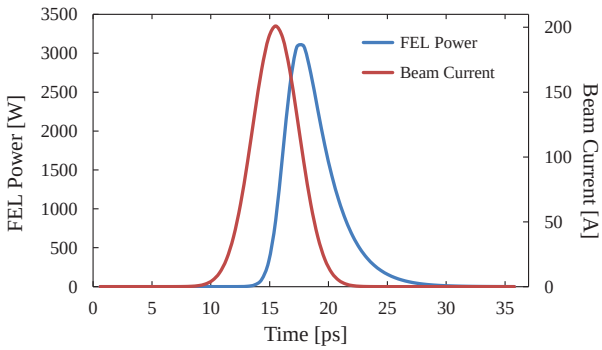

Fig. 5. Temporal distribution of the FEL power at the exit of the undulator and the beam current at the entrance of the undulator

4.2. Optimization of the undulator parameters

In the previous section, the FEL power still couldn't reach to the power saturation. Therefore we optimized the undulator parameters to estimate the best performance of this amplifier.

First, when we increased the peak magnetic field (K value) of the undulator from 0.2 to 2.0, the increase of the FEL peak power was estimated. The FEL peak power and the radiation wavelength as a function of the K value of the undulator are shown in Fig. 6. The red dot indicates the calculated value in the previous section. The relation between the K value and the radiation wavelength can be determined from Eq. (1). As seen in Fig. 6, the FEL peak power was saturated using the K value more than of 1.8. In this calculation the radiation wavelength was 319 μm, and the FEL peak power was almost 45 kW at K value of 1.8.

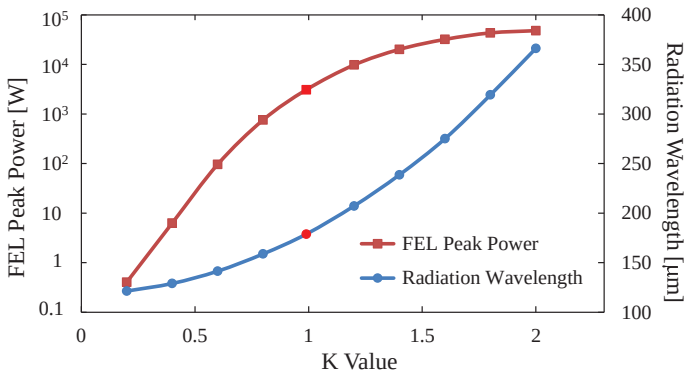

Fig. 6. Calculated FEL peak power and radiation wavelength as a function of K value of the undulator

Second, increasing the undulator period number for further micro-bunching inside the undulator, the increase of the FEL peak power was estimated. From the result of Fig. 6, we compared the FEL peak power of the existing undulator which had the K value of 0.99 with the optimized undulator which had the K value of 1.80. When we varied the number of the undulator period from 10 to 80 or 100 keeping the other parameter constant, the result is shown in Fig. 7. The red dot indicates the calculated value in the previous section. As shown in Fig. 7, the FEL peak power increased to almost 1.0 MW in each undulator. However, the FEL gain was saturated in the different number of the undulator period. Increasing the K value of the undulator, it was possible to make the undulator length shorter in obtaining the same FEL gain. Therefore we propose to use the undulator which has the stronger magnetic field (K = 1.8) and the shorter length (60 periods).

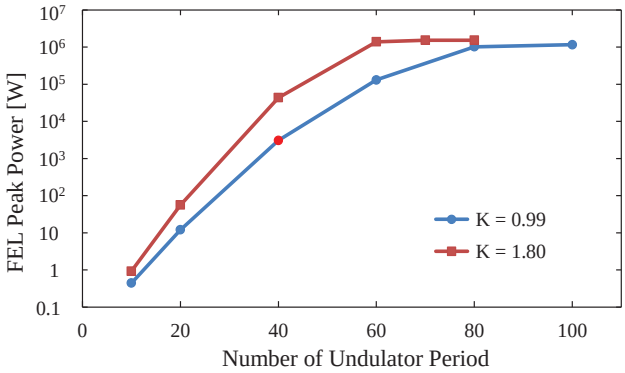

Fig. 7. Calculated FEL peak power as a function of the number of the undulator period

5. 5. Conclusion

A start-to-end calculation has been performed to estimate the FEL gain using a photocathode RF gun and the existing undulator. To obtain a higher FEL gain, we searched a better condition of the electron beam parameter and the seed light. As a result, it was a critical factor to adopt the narrow energy spread and focus the seed light at the entrance of the undulator. In the present design scheme, the FEL peak power was calculated to be 3 kW at the FEL resonant wavelength of 179 μm. Since the power of the seed light was 0.20 W, the light power was amplified almost 10^4 times. However, the FEL power couldn't reach to the power saturation. Therefore when we optimized the K value of the undulator from 0.99 to 1.80, and the undulator period number from 40 to 60, the FEL gain increased to be 10^3 times compared to using the existing undulator. Further studies on system design including an electron bunch compressor are required.

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