Investigation of electron energy spread effects on the intracavity MIR-FEL power at the PBP-CMU electron linac laboratory

S Sukara¹,²,³, H Ohgaki⁴ and S Rimjaem¹,²,³,*

¹ Master Degree Program in Physics, Faculty of Science, Chiang Mai University (CMU), Chiang Mai, Thailand
² Plasma and Beam Physics (PBP) Research Facility, Department of Physics and Materials Science, Faculty of Science, Chiang Mai University, Chiang Mai (CMU), Thailand
³ Thailand Center of Excellence in Physics, Ministry of Higher Education, Science, Research and Innovation, Bangkok, 10400, Thailand
⁴ Institute of Advanced Energy, Kyoto University, Kyoto, Japan

* E-mail: sakhorn.rimjaem@cmu.ac.th

Abstract. At the PBP-CMU Electron Linac Laboratory, the existing linear accelerator system is under developing to produce electron beams with suitable properties for generation of oscillator mid-infrared free-electron laser (MIR-FEL) and super-radiant terahertz (THz) undulator radiation. This work focuses on the simulation of the oscillator MIR-FEL with expected electron beam energy of 20 – 25 MeV to evaluate the required electron beam parameters. To achieve FEL saturation, the single-pass FEL simulation using the code GENESIS 1.3 was performed to estimate the laser wavelength, FEL gain and electron macro-pulse duration. In the simulation, electron beams with energy spread of 0, 0.5 and 1.0 %, and the electron peak current of 25 and 50 A were considered. As a result, the electron beam with energy of 20 – 25 MeV can produce the FEL wavelengths of 13.5 – 21.2 µm using a 1.6-m undulator with maximum undulator parameter of 1.07. The largest FEL gain is 216% when using electron beam energy and peak current of 20 ± 0% MeV and 50 A, which requires the electron macro-pulse duration of 1.6 µs to saturate FEL. Due to the possible macro-pulse duration at our facility of 6 µs, the operation of electron beam with energy spread of 0.5% and peak current of higher than 25 A is required to saturate FEL. Results from this single-pass simulation can be used as a based information for further practical consideration with multi-pass simulation.

1. Introduction

The electron linear accelerator (linac) laboratory of the Plasma and Beam Physics Research Facility, Chiang Mai University (PBP-CMU Electron Linac Laboratory: PCELL) is currently extending the accelerator system to produce an oscillator mid-infrared free-electron laser (MIR-FEL) and a super-radiant terahertz (THz) undulator radiation. Design of proper electron beamlines and numerical simulation to optimize electron beam properties are conducted parallelly with the simulation for radiation generation.
At our facility, electrons are generated from a thermionic cathode and accelerated in a 1.5-cell radio-frequency (RF) gun to have a maximum beam energy of 2 – 2.5 MeV [1]. The electron beam is further accelerated by a 3-m travelling-wave linac to gain the energy up to 25 MeV. Both the electron gun and the linac are operated with 2,856-MHz RF wave produced from two separated klystrons. The RF wave has a maximum pulse duration of about 6 µs [2]. Three bunch compressor systems; alpha magnet and 180° magnetic bunch compressors are respectively placed downstream the electron gun and the linac. Downstream the two 180° magnetic bunch compressors, there are two beamlines for generation of THz radiation and MIR-FEL. This paper focuses on the MIR-FEL simulation to estimate the possible FEL wavelength and electron macro-pulse duration from electron beam with energy of 20 – 25 MeV. The effects of different electron energy spread and peak current are considered in this work. The MIR-FEL is produced using a 1.6-m undulator system transferred from the KU-FEL facility [3] and an optical cavity. From the magnetic field measurement at our facility [4], the undulator has the average maximum undulator parameter (K-value) of 1.07 at the minimum undulator gap of 26 mm. The optical cavity was designed to have cavity length of the 4.72 m, which can contain 90 resonated laser pulses with the micro-pulse repetition rate of 2,856 MHz. The schematic layout of the accelerator and laser system is shown in figure 1.

Furthermore, the electron beam parameters used in simulations presented in this paper are estimated from specifications of our accelerator system and the KU-FEL first lasing operation with the 1.6-m undulator [5]. The expected electron beam and undulator parameters are listed in table 1. The K-value distribution calculated from the results of peak undulator magnetic field measurement in [4] is displayed in figure 2.

![Figure 1. The non-scaled schematic layout of the accelerator and laser system at PCELL including the THz and MIR-FEL beamlines.](image1)

![Figure 2. The K-value distribution of the 1.6-m undulator measured at PCELL.](image2)

| Table 1. Expected electron beam and 1.6-m undulator system parameters. |
|---------------------------------------------------------------|
| **Electron beam parameter** | **value** | **Undulator parameter** | **value** |
| Electron energy | 20 - 25 MeV | Undulator period | 40 mm |
| Energy spread (ΔE/E) | 0.5% | Number of period | 40 |
| Macro-pulse duration | < 6 µs | Undulator length | 1.6 m |
| Micro-bunch duration (FWHM) | ≤ 2 ps | Undulator gap | 26 - 45 mm |
| Bunch charge | < 100 pC | Peak magnetic field | 0.29 - 0.0045 |
| Normalized transverse emittance | 3 πmm.mrad | K-value | 1.07 - 0.17 |
| Radial transverse beam size (RMS) | 1 mm |  |  |
2. Time-independent GENESIS 1.3 simulation and results

The MIR-FEL simulation was performed with the computer code called GENESIS 1.3 [6], which calculates the interaction between electrons and radiation fields in the undulator magnetic field based on the differential Maxwell’s equations. In this work, the single-pass time-independent simulation is used to estimate the possibility of the MIR-FEL generation with the parameters in table 1.

The possible FEL wavelength, the radiation amplification and the electron macro-pulse duration were examined with the K-value distribution in figure 2. The maximum K-value provides the largest FEL amplification, which is appropriate to find the FEL lasing point. Furthermore, a uniform rectangular undulator duct geometry with vertical and horizontal width of 4.22 and 2.08 cm is included in the simulation to consider the diffraction loss.

2.1. FEL wavelength investigation

In all simulations reported in this paper, the parameters in table 1 were used in the simulation input while the electron energy spread was changed to 0%, 0.5% and 1.0%. Firstly, the FEL wavelength was investigated. In the simulation, the electron-radiation interaction is growing from a single input radiation wavelength. Thus, the FEL wavelength, which gives the maximum FEL gain at different beam energy (20 – 25 MeV), was calculated by slightly changing the radiation wavelength from the spontaneous radiation wavelength. The FEL wavelength was selected from the case with maximum amplified radiation power at the undulator exit. The FEL wavelength investigation was displayed in figure 3, which shows that the FEL wavelengths are longer than the spontaneous undulator radiation (dashed line) of about 3% – 5% and the electron beam with larger energy spread provides longer FEL wavelength. As a result, the MIR-FEL wavelength of 13.5 – 21.2 µm can be produced from the 1.6-m undulator for the electron beam energy of 20 – 25 MeV.

![Figure 3. The FEL wavelength for electron beam energy of 20 – 25 MeV at various energy spreads (solid line) compared with the spontaneous radiation wavelength with the K-value of 1.07 (dashed line).](image)

2.2. Intracavity radiation gain and evolution time consideration

We calculated the intracavity radiation gain from the single-pass simulation, which is defined by the increasing ratio of the radiation power from the undulator entrance to the exit. In this case, the effect of diffraction loss by undulator duct was included in the gain value. The relation is given by

\[ G = \frac{P_f \cdot P_i}{P_1}, \]

where, \( P_i \) and \( P_f \) are the radiation power at the undulator entrance and exit, respectively. The single-pass gain value can be applied to calculate the amplified radiation power in the further roundtrips to reach the saturation point. The calculation is under the assumptions of the constant gain without radiation loss by optical mirrors and FEL outcoupling. The amplifield radiation power and the number of roundtrips can be calculated from

\[ P_n = (G - 1)^n \times P_1, \]
where, $P_n$ is the $n^{th}$-roundtrip radiation power, $n$ is the number of roundtrip and $P_i$ is the initial radiation power. In this case, the spontaneous undulator radiation power (0.127 W) was used as the initial power. In addition, the saturated radiation power was partially extracted from the total electron beam power that was assumed to be 6% of the total electron beam power. This value was estimated based on the multi-pass simulation at KU-FEL [7]. Then, the evolution time to reach the FEL saturation was calculated from the travelling time in a roundtrip multiplied by the number of roundtrip that achieves the saturation point. For the single roundtrip in the 4.72-m optical cavity, the travelling time of the optical radiation is 31.5 ns. Furthermore, The electron macro-pulse duration was evaluated from the evolution time calculation. In common S-band normal-conducting accelerator, the RF filling time of around 1 μs must be subtracted from the available macro-pulse of RF wave [8]. Thus, the required RF macro-pulse duration should be 1 μs longer than the evolution time to reach the FEL saturation.

### 2.3. Result of intracavity radiation gain and evolution time investigation

The radiation gain simulation was performed with the electron energy of $20 - 25$ MeV and energy spread of 0%, 0.5% and 1.0%. The estimated electron bunch charge of less than 100 pC and micro-bunch length of 2 ps were used. The electron peak currents of 50 A and 25 A were taken into account for the simulation. Figure 4 shows the intracavity radiation gains in single roundtrip. The gain value slightly drops when the electron energy increases. The results with energy spread of 0% have the largest radiation gain, while the cases with more energy spread provide less gain. In addition, the interaction of the radiation with electron beam of 25-A peak current provides significantly less radiation gain than the 50-A peak current case. The maximum value is 216.8% for the beam of 20 ± 0% MeV and the peak current of 50 A, while the minimum gain value is 12.5% for the beam of 25 ± 1.0% MeV and the peak current of 25 A.

Consequently, the intracavity saturated FEL powers extracted from the electron beam energy of $20 - 25$ MeV are 30 – 37.5 MW and 60 – 75 MW for the peak currents of 25 and 50 A, respectively. The saturation power is used to calculate the laser evolution time and the results are shown in figure 5. Overall, the required evolution time is longer for electron beam with higher energy, larger energy spread and lower peak current. In the case of 50-A electron peak current, the shortest and the longest evolution times are 0.6 and 2.7 μs for electron beams of $20 ± 0$% MeV and $25 ± 1.0$% MeV, respectively. For the 25-A electron peak current case, the shortest and the longest evolution times are 1.0 and 5.2 μs. The longest evolution time of 5.2 μs is used to estimate the electron macro-pulse duration, which is 6.2 μs for an electron energy of $25 ± 1.0$% MeV and a peak current of 25 A. In case of the electron with energy spread of 0.5% and peak current of 25 A, the required evolution time is 2.6 – 3.5 μs. Whilst the operation with the peak current of 50 A requires 0.9 – 0.12 μs to reach the saturation point. For our RF system

![Figure 4](image1.png)  
*Figure 4. The intracavity radiation gain in single pass with electron beam parameters listed in table 1.*

![Figure 5](image2.png)  
*Figure 5. The evolution time of radiation amplification to reach the saturation point with electron parameters listed in table 1.*
with possible electron pulse duration of about 6 µs, the electron beam with energy of 20 – 25 MeV, energy spread of 0.5% and peak current of at least 25 A is acceptable to achieve FEL saturation.

3. Conclusion
The single-pass time-independent GENESIS 1.3 simulation was performed to investigate the possible MIR-FEL wavelength and electron beam pulse duration for the PCELL facility. The results reveal that the possible FEL wavelength of 13.5 – 21.2 µm can be obtained using the maximum K-value of 1.07 and the electron beam energy of 20 – 25 MeV. The laser wavelengths are longer than the spontaneous radiation by 3% – 5% for the electron energy spread of 0% – 1.0%. The energy spread and electron peak current have strong effect on the radiation power amplification. The simulation results suggest that the electron beam in practical operation should have energy spread of 0.5% and electron peak current of more than 25 A to saturate the FEL power.

However, the investigation of radiation amplification from the single-pass FEL simulation has several assumptions. Practically, the radiation gain is not constant in roundtrips. It would gradually decrease at the beginning and sharply fall to zero when it reaches the saturation point. In addition, the radiation power might be loss due to the optical mirror reflections and the radiation outcoupling, which can reduce the radiation gain in the cavity. Thus, the practical power evolution time should be longer than the results shown in this work. For more realistic results, the multi-pass simulation with optical cavity parameters that includes the effects from the inconstant radiation gain and the individual saturation power at different beam parameters should be conducted. The consideration of the optical cavity loss by the mirrors and hole couplings will also be included. Furthermore, the propagation of the radiation inside the optical cavity corresponding to the mirror curvatures should be considered for the calculation of the electron-radiation interaction.

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References
[1] Rimjaem S, Kusoljariyakul K and Thongbai C 2014 Nucl. Instrum. Methods Phys. Res. A 736 10
[2] Nakano M, Okawachi N, Zen H, Kii T, Masuda K, Ohgaki H, Yoshikawa K and Yamazaki T 2006 Proc. Free Electron Laser 2006 (Berlin) p 660
[3] Rimjaem S 2006 Generation of Far Infra-red Radiation from Relativistic Electron Beams (Chiang Mai: Chiang Mai University) p 123
[4] Kongmali K 2018 Simulation and Measurements of The Permanent Undulator Magnetic Field (Chiang Mai: Chiang Mai University) p 16
[5] Ohgaki H, Kii T, Masuda K, Higashimura K, Kinjo R, Zen H, Yoshikawa K, Yamazaki T and Jeong Y U 2008 Proc. Free Electron Laser 2008 (Gyeongjii) p 4
[6] Reiche S 1999 Nucl. Instrum. Methods Phys. Res. A 429 243
[7] Sasaki S, Zen H, Shiiyama T, Kii T, Masuda K and Ohgaki H 2007 Proc. Free Electron Laser 2007 (Novosibirsk) p 394
[8] Wiedemann H 2007 Partical Accelerator Physics Third Edition (Berlin, Springer) p 563