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DESIGN AND SIMULATION OF THE MIR-FEL GENERATION SYSTEM AT CHIANG MAI UNIVERSITY

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Abstract

At the PBP-CMU Electron Linac Laboratory, the system to generate MIR-FEL using the electron linac has been developed. In this contribution, the design and simulation results of the MIR-FEL generation system are presented. The system is designed as the oscillator-FEL type consisting of two mirrors and a 1.6-m permanent planar undulator. The middle of the undulator is determined as the laser beam waist position. Both two mirrors are the concave gold-coated copper mirrors placing upstream and downstream the optical cavity, which has a total length of 5.41 m. The FEL is designed to coupling out at a hole with diameter of 2 mm on the upstream mirror. The optical cavity is optimized to obtain high FEL gain and high FEL power using GENESIS 1.3 simulation code. The electron beam with energy of 25 MeV is used in the consideration. As a result, the MIR-FEL with central wavelength of 13.01 µm is obtained. The optimum upstream and downstream mirror curvatures are 3.091 m and 2.612 m, respectively, which give the Rayleigh length of 0.631 m. This optical cavity yields the power coupling ratio of 1:1000 and the FEL gain of up to 40%. The extracted MIR-FEL peak power in 100 kW scale is obtained at the coupling hole. The construction of the practical MIR-FEL system is conducted based on the results from this study.

INTRODUCTION

At the Plasma and Beam Physics Research Facility, Faculty of Science, Chiang Mai University (PBP-CMU), the research team of the PBP-CMU Electron Linac Laboratory (PCELL) has developed an electron linear accelerator system (linac) to produce ultra-short electron bunches. The system has been upgraded to have a potential to accelerate electron beam with a kinetic energy of up to 25 MeV [1]. With this electron beam, we aim to produce free electron laser (FEL) in mid-infrared (MIR) and terahertz (THz) regimes using two undulator systems. The radiation generation system is separate into two sections; one for the MIR-FEL generation and the other is for the THz-FEL generation. The top-view layout of this system is illustrated in Fig. 1.

In this study, the MIR-FEL section is designed. In this section, there is a Halbach-type permanent magnet undulator with a length of 1.6 m [2] obtained from KU-FEL facility, Kyoto University, Japan, in 2018. It was used to generate the first MIR-FEL at the KU-FEL facility in 2007 using 25 MeV electron beam [3]. Then, this undulator was transferred to PCELL with the aim to generate the first MIR-FEL in South-East Asia region. The MIR-FEL generation at PCELL is designed as an oscillator type consisting of two concave mirrors at two ends of the MIR-FEL section. This paper presents the design of the optical cavity and optimization of the mirror curvatures to obtain high MIR-FEL output power and large FEL gain using a computer simulation. The FEL simulation code named GENESIS 1.3 [4] with the modified version from KU-FEL facility [5] is used for estimating the MIR-FEL power evolution in multi-round trips. The time-independent mode was applied assuming that the electron beam current in the longitudinal axis has a uniform and continuous distribution.

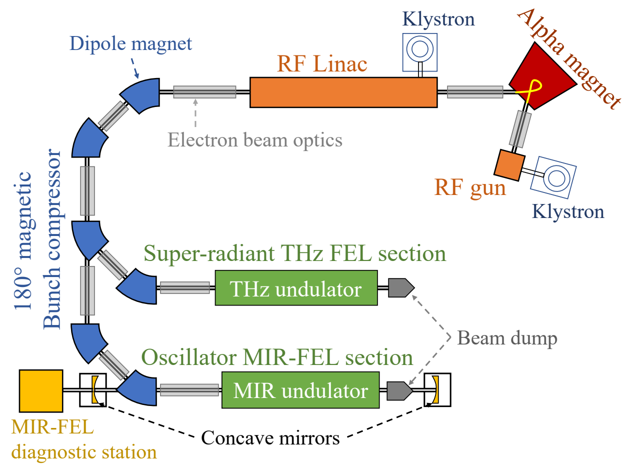

Figure 1: Layout of the accelerator system together with the MIR- and THz-FEL generation system at PCELL.

DESIGN OF MIR-FEL GENERATION SYSTEM

Figure 2 presents the layout and positions of the optical mirrors and the 1.6-m undulator for the MIR-FEL system at PCELL. The middle of the undulator is determined as the laser waist position where the laser beam has the smallest transverse size. The total length of the optical cavity is 5.405 m that contains 102 FEL pulses with repetition rate of 2,856 MHz. Both two concave mirrors are gold-coated copper mirror that have the reflectivity of 99%. At the center of the upstream mirror, there is a hole with diameter of

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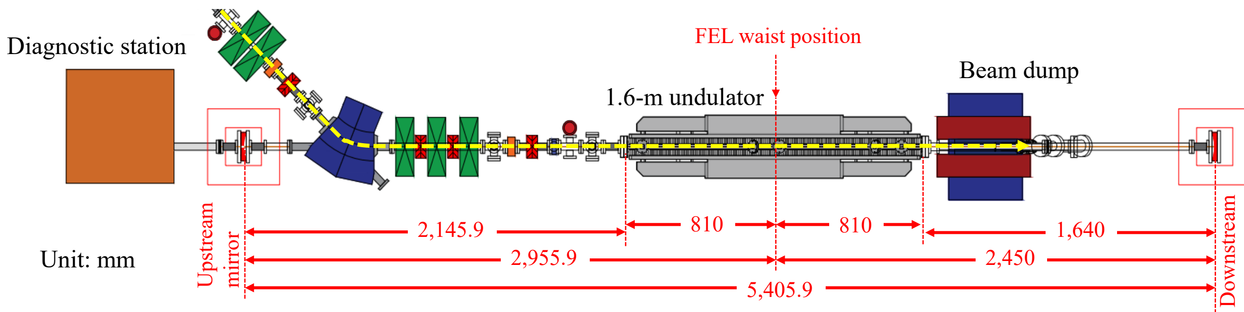

Figure 2: Top-view layout of the MIR-FEL section at PCELL.

2.0 mm suggested by [5] to extract the MIR-FEL out of the optical cavity to the diagnostic station. The electron beam is transported from the accelerator to the MIR-FEL section via a 180° bunch compressor, and finally dumped at the beam dump. Between the bunch compressor and beam dump, the electron beam is designed to move through the undulator to radiate and interact with the radiation in the cavity. The path of the electron beam is illustrated as the dashed yellow line in Fig. 2. In this study, the expected electron beam with kinetic energy of 25 MeV is used, where its parameters are listed in Table 1. The 1.6-m undulator has 40 periods of magnetic fields with and the period length of 4.00 cm. The magnetic field distribution was measured at PCELL, which yields the maximum value of 0.29 T. This distribution is calculated to the rms undulator strength (K_{rms}) at peak positions, which has the average value of 0.756. These parameters are used in the FEL simulation to investigate the FEL wavelength and the MIR-FEL lasing condition.

The FEL simulation is initialized by the electron beam parameter at the undulator entrance and the initial undulator radiation with a single wavelength. The initial radiation peak power is set as the spontaneous power of about 0.1 W. Theoretically, the calculated spontaneous radiation wavelength for this system is 12.6 µm. However, the FEL simulation with the uniform K_{rms} distribution of 0.756 results that the radiation power is dropped when the electron beam passes through the undulator. Then, the radiation wavelength is surveyed to obtain the radiation power gain condition. Consequently, the FEL simulation with a wavelength of 13.01 µm provides the highest gain. This wavelength is determined as the central FEL wavelength in this system and used for the further FEL simulation in this study.

Table 1: Parameters of the Expected Electron Beam at MIR-FEL Section

Parameter	Value
Kinetic energy	25.0 MeV
Energy spread	±0.5 %
Macro-bunch duration	≤ 5 µs
Bunch charge	100 pC
Peak current	50 A
Normalized emittance in x-axis	3 mm·mrad
Normalized emittance in y-axis	3 mm·mrad
Rms beam size in x-axis	1 mm
Rms beam size in y-axis	1 mm

The FEL simulation with the undulator strength distribution is performed. It results that the radiation power gain cannot be obtained because of the electron beam off-axis in the horizontal direction by the non-uniform K_{rms} distribution. Therefore, the horizontal deflecting angle of the electron beam trajectory is optimized. Consequently, the electron beam at the undulator entrance should have the horizontal deflecting angle of 2.04 mrad to obtain the highest radiation power gain. In the next step, the mirror curvatures of both two mirrors are considered to provide a high-power and high-gain MIR-FEL output.

MIRROR CURVATURE OPTIMIZATION

The mirror curvatures are optimized by using the Gaussian propagation calculation, where the curvature corresponds to the radiation wavefront curvature. This is varied by the Rayleigh length when the laser wavelength is fixed at 13.01 µm. The relation between the mirror curvatures and the Rayleigh length is shown in Fig. 3(a). These values are conducted in the FEL simulation in multi-round trips scheme. Since the electron macro-pulse duration at PCELL is limited to be less than 5 µm and the light traveling time in a round trip is approximately 36 ns, the FEL simulation of 140 round trips is conducted. As a result, the radiation power rises exponentially and reaches the saturation power in 10 - 100 MW scale.

Subsequently, the MIR-FEL gain at the exponentially increasing of radiation power is investigated as well as the saturated intracavity power and extracted power at mirror hole. They are plotted against the Rayleigh length in Fig. 3(b) as the normalized values. The graph shows that the optical cavity with long Rayleigh length yields high extracted FEL power but low FEL gain, while the intracavity FEL power remains constant. Due to high extracted power and high gain is needed, it is challenge to select the optimum point. Hence, the multiplying weight (M) of the FEL gain and the extracted power is examined for assisting the optimization. The M value must be the maximum to present high-power and high-gain FEL conditions as required. The evaluation of M value is presented in Fig. 3(c), where the data are fitted

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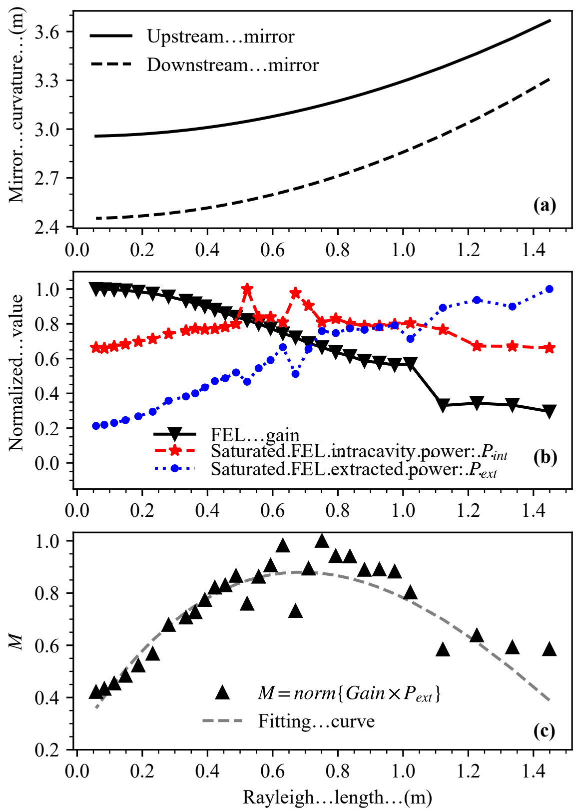

Figure 3: Relations of Rayleigh length to (a) the upstream and downstream mirror curvatures, (b) FEL gain, saturated intracavity and extracted powers, and (c) the multiplying weight M between FEL gain and extracted power.

by the 3rd-order polynomial. The trend of M value suggests that the peak at the Rayleigh length is about 0.6 - 0.7 m.

Finally, the optical cavity parameters with the Rayleigh length of 0.631 m is selected for the MIR-FEL optical cavity at PCELL. The upstream and downstream mirror curvatures are 3.091 m and 2.612 m, respectively. In this cavity, the evolution of the intracavity and extracted MIR-FEL powers in 140 round trips are investigated as presented in Fig. 4 together with the FEL gain percentage. It reveals that the MIR-FEL peak power increases exponentially with the gain percentage of 40% and reaches the saturated MIR-FEL intracavity peak power of about 100 MW within 3 µs. The saturated extracted FEL power at the mirror hole is about 100 kW, which yields the FEL power coupling ratio of about 1:1000.

SUMMARY

The MIR-FEL optical cavity with the cavity length of 5.41 m is designed and optimized using GENESIS 1.3 simulation program to obtain high FEL output power and high FEL gain. The electron beam with energy of 25-MeV is used in the FEL simulation. The optimum upstream and downstream mirror curvatures are 3.091 and 2.612 m, respectively. This cavity provides the MIR-FEL with the central wavelength of 13.01 µm and the power gain of up to 40%. The MIR-FEL is extracted at the 2.0-m coupling hole with the saturated peak power in 100 kW scale within 3 µm and the coupling ratio of 1:1000. This optical cavity design is adopted to the construction of the MIR-FEL section. However, this study is based on the time-independent mode, which neglects the longitudinal distribution of the electron beam. Thus, the further FEL simulation with GENESIS 1.3 code will be performed in the time-dependent mode to concern the longitudinal distribution of electron beam as in actual situation.

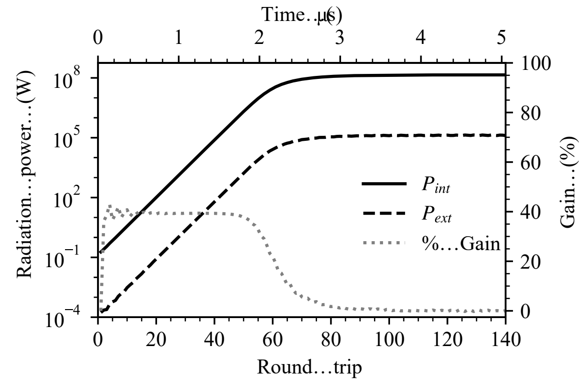

Figure 4: FEL power evolution in the intracavity and at the mirror hole of the MIR-FEL with the optimum parameters of the optical cavity.

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