INJECTOR SYSTEM FOR LINAC-BASED INFRARED FREE-ELECTRON LASER IN THAILAND

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Abstract

A possibility to develop a compact linac-based Infrared free-electron laser (IR FEL) facility has been studied at Chiang Mai University (CMU) in Thailand. Characteristics of the emitted FEL light and reliability in operation of the FEL system are determined by the properties of the electron injector, the undulator, and the optical cavity. The proposed injector system for the future IR FEL is based on the electron linear accelerator system at the Plasma and Beam Physics Research Facility at CMU (PBP-CMU). Numerical and experimental studies to adjust the existing system to be able to drive the IR FEL have been performed. The results of preliminary studies and the proposed parameters for the injector and the FEL system are concluded in this contribution.

INTRODUCTION

Linac-based free-electron lasers (FELs) have recently gain interest worldwide in the accelerator and particle beam community as the new generation light source, which can be utilized in numerous applications. Characteristics of the output FEL radiation are determined by the properties of the electron beam and the undulator, where the light is emitted. Since the FEL light sources require electron beams of high quality, the development and optimization of the injector system are important.

Electromagnetic radiation in the infrared wavelength regime, especially the far-infrared (FIR) or THz radiation, is of a great interest source for applications in various fields [1-4]. A possibility to develop an infrared free-electron laser (IR FEL) is studied at the Plasma and Beam Physics Research Facility, Chiang Mai University (PBP-CMU). At this initial stage, we concentrate on the development of an FEL covering the THz radiation wavelength around 50-200 µm. Study of the FEL radiation in the mid-infrared (MIR) and near-infrared (NIR) regime will be considered in the future.

In order to develop the FEL system, optimization of both injector and FEL system is ongoing. In this paper, we concentrate on an overview of the project and preliminary optimization of a thermionic based electron radiofrequency (RF) injector to produce electron beams with properties yielding the requirements for an IR FEL.

PROPOSED IR FEL FACILITY

Generally, an IR FEL facility consists of an injector system for generating and accelerating electron beam, an undulator magnet for FEL lasing and an optical cavity for amplifying the FEL radiation output power. For the considered injector system of the proposed IR FEL at CMU, we plan to make use of the existing linac system as much as possible while maintaining its functionality as the femtosecond electron and photon pulse facility.

The proposed IR FEL system shown in Fig. 1 consists of an injector system, an accelerating structure, a 180° achromat section, an undulator magnet and an optical cavity. The injector system combines a thermionic cathode RF-gun and an alpha magnet as a magnetic bunch compressor. The accelerating structure is an S-band travelling wave SLAC-type linac, which can be used to accelerate an electron beam to reach a maximum energy of about 30 MeV. The injector system, the linac structure, beam steering and focusing elements as well as beam diagnostic instruments upstream the achromat section will be modified from the existing PBP-CMU linac system [5]. The undulator magnet is a planar type with a length of 1.67 m. The optical cavity composes of two symmetric spherical mirrors with a coupling hole on one of the mirrors. Some parameters of the undulator and the optical cavity used in preliminary FEL optimization are listed in Table 1.

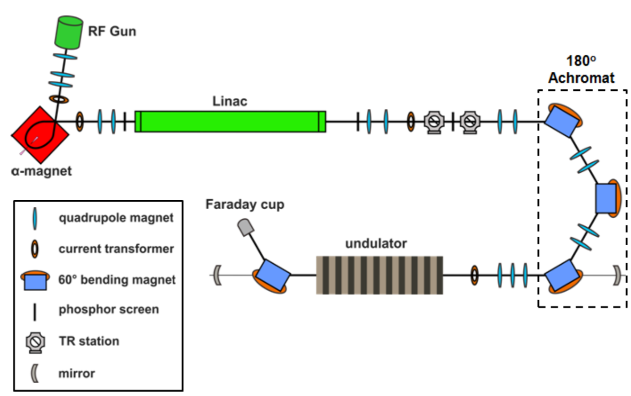

Figure 1: Schematic layout of the possible IR/THz FEL system at Chiang Mai University, Thailand.

In electron beam and FEL optimizations, we consider two scenarios. The first one is studying the FEL radiation in the case of the electron beam whose bunch length is longer than the radiation wavelength. The other one is for the case of the electron beam whose bunch length is shorter than the radiation wavelength.

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Table 1: Parameters of Undulator and Optical Cavity Used in FEL Calculations

Parameter	Value
Undulator type	Planar
Undulator length	1.67 m
Number of period	22
Period length	7.7 cm
K-parameter	0.4 -1.52
Optical cavity length	5 m
Infrared reflectivity of optical cavity	95%

The FEL radiation due to the interaction between optical fields and an electron beam with a bunch length longer than the radiation wavelength has been studied using the numerical code GENESIS 1.3 [6]. As an example, the electron beam with an rms bunch length of a few ps has been considered. Preliminary required beam parameters used in the simulations for the radiated wavelength of 100 µm are shown in Table 2. With the aforementioned parameters, the expected FEL power is on the order of tens of megawatt as shown in Fig. 2. The numbers of round trips needed to accumulate the radiation amplification until reaching the saturation condition are about 60 and 80 turns for the cases of no loss and with 5% loss in the optical cavity, respectively. The undulator parameter (K) of 1.52 has been used in the simulation. With the optical cavity length of 5 m, the electron macropulse length of about 3 µs is required. Due to the back-bombardment effect, the available macropulse length of electron beam exiting the thermionic RF-gun at the PBP linac system is about 1-2 µs. Therefore, the modification of the RF power system may be required.

Table 2: Beam Parameters Use in GENESIS Simulations

Parameter	Value
Beam energy	15 MeV
Relative energy spread (rms)	0.5%
Longitudinal rms bunch length (σ_z)	2 ps
Bunch charge (Q_b)	30 pC
Peak current (I_p)	30 A
Normalized beam emittance (ε_x,ε_y)	3π mm-mrad
Beam size (σ_x,σ_y)	0.3 mm
Twiss parameters (β_o,α_o)	0.7, 0.3

For this conventional FEL scenario, the alpha magnet will serve only as the energy filter element. From the optimization of the electron distribution at the RF-gun exit, the electrons at the head of the bunch with high energy level form a quasi-monogenetic beam. Therefore, compression in the alpha magnet for this useful part the bunch can be neglected. Some small energy spread will be induced during the post acceleration of the electron beam in the linac leading to the electron distribution suitable for the bunch compressor downstream the linac. The 180° achromat is used as both turn around section and as the magnetic bunch compressor. Electron beam optimizations for this case are presented in another contribution [7].

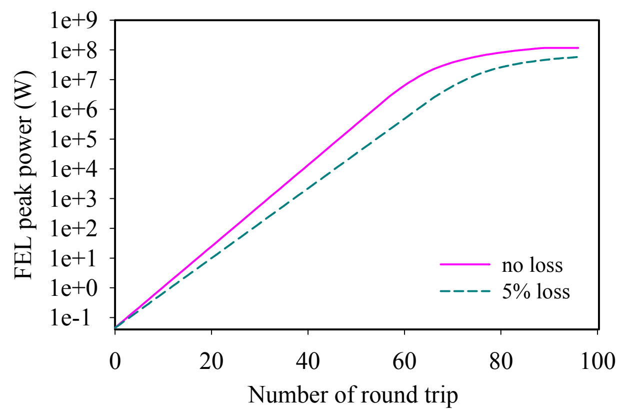

Figure 2: Simulated radiation power evaluation at the radiation wavelength of 100 µm for the electron rms bunch length of 2 ps without and with 5% power loss in the optical cavity.

The FEL mechanism in case of electron beams with bunch length shorter than the radiation wavelength has been studied and reported in [8]. This scenario is known as the pre-bunched FEL. The study results show that the saturation mechanism in the pre-bunched FEL seems to be different from the conventional FEL. The saturated peak power in this case is much higher than that for the long electron bunches. It has been proposed that to generate the THz light with the pre-bunch FEL, the electron beam with the bunch length less than 100 fs is required [8, 9].

We have previously shown that it is possible to generate electron bunches with an rms bunch length of less than 100 fs [10]. With this short bunches, the intense THz radiation from coherent Transition Radiation (TR) is expected to cover the wave number ranging from 5 cm^{-1} to 400 cm^{-1}. For this scenario, the alpha magnet will be used as a magnetic bunch compressor prior to the post acceleration by the linac. It will also be used as an energy filter utilizing its energy scrapers. The 180° achromat system for this case will be a turn-around section to save the space of the accelerator tunnel. Therefore, we can choose the position of the current experimental station to be the entrance of the 180° achromat. Then, the achromat section can be an isochronous magnetic system, which the beam characteristics before entering and after exiting the achromat system remain unchanged.

Since the FEL mechanism of the pre-bunched FEL cannot be simulated by using the well-known numerical

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codes e.g. GENESIS, a further methodical study is required. The interaction between the electron beam and the optical fields in this case will be investigated and reported in the future.

ELECTRON BEAM OPTIMIZATIONS FOR PRE-BUNCHED FEL

Longitudinal Beam Dynamic Simulations

The FEL performance depends on both the longitudinal and transverse properties of the electron beam. Beam dynamics simulations using the code PARMELA [11] and BCompress [12] were performed to study the optimal longitudinal electron beam parameters suitable for driving the FEL. The transverse properties have been studied using the beam envelope optics code Particle Beam 2003 [13].

PARMELA simulations were performed to investigate electron beam dynamics inside the RF-gun including effects of the space-charge force. Results of optimization of the thermionic RF-gun for producing the femtosecond electron bunches for the linac-based FIR (THz) radiation source have been reported in [10]. The revised study for the injector system of the IR FEL has been performed based on some available information from the previous study. In PARMELA simulations, we assume that the cathode emits the uniform electron beam with 100,000 macro-particles at an emitted current of 2.9 A per 2856 MHz RF cycle. Therefore, each macro-particle represents a charge of 10.15 fC. Starting from these specifications, we assume that the entrance of the isochronous achromat system begins at the current TR station. Electron bunches will travel through the achromat section and reach the entrance of the undulator with unchanged longitudinal properties. The particle distribution in the energy-time phase spread of a single bunch with the kinetic energy of about 15 MeV is shown in Fig. 3.

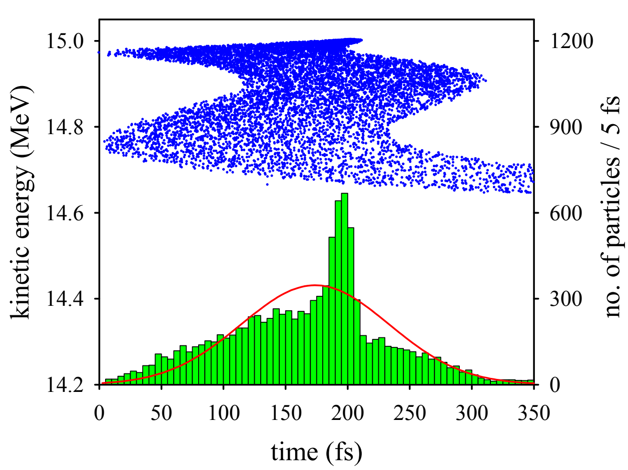

Figure 3: Simulated particle distribution in energy-time phase space of a single bunch at the entrance of the 180° acromat with histogram fitted by a Gaussian distribution with σ_z of 50 fs.

The relation between the relative rms energy spread of electrons and the bunch charge has been studied by selecting a fraction of the electron bunch using energy slits inside the alpha magnet vacuum chamber. A portion of electrons with different relative energy spreads are compressed differently inside the alpha magnet. By adjusting the alpha magnet gradient in the simulation, we can obtain the relationship between the energy spread and the bunch charge, which the results are shown in Fig. 4 for the case of an electron bunch length of 50 fs and 100 fs.

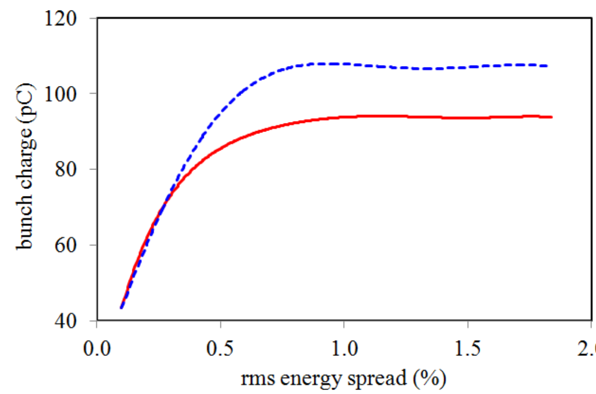

Figure 4: Simulated bunch charge as a function of relative rms energy spread for the electron bunch length of 50 fs (dash line) and 100 fs (solid line).

Results of the bunch compression study using the alpha magnet show that with a relative energy spread of below 0.7%, the bunch charge increase proportionally to the energy spread. Then, it stays constant with the bunch change of about 93 pC and 107 pC for the rms bunch length of 100 fs and 50 fs, respectively. This can be explained that with the rms energy spread larger than 0.7% the selected bunch contains some electrons with lower energies, which are not properly compressed inside the alpha magnet. Only the high energy electrons are compressed and form the condense distribution at the head of the bunch. Preliminary study results show that it is possible to produce the electron beam with the bunch length about or shorter than the suggested requirement for the pre-bunched FEL [8].

Optimization of Beam Transport Line

The beam envelope along the beam transport line from the RF-gun exit to the entrance of the achromat has been studied and optimized. Initial transverse beam parameters are estimated from the PARMELA distribution at the RF-gun exit with the rms beam size of 2.5 mm and the normalized beam emittance of 3.8 π mm-mrad. By carefully optimizing the parameters of each component along the beamline, we achieved the final beam at the entrance of the 180° achromat with the properties suitable for the FEL system. The proposed beam optics of the injector system is illustrated in Fig. 5. Some optimized

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beam transverse parameters are shown together with longitudinal properties in Table 3.

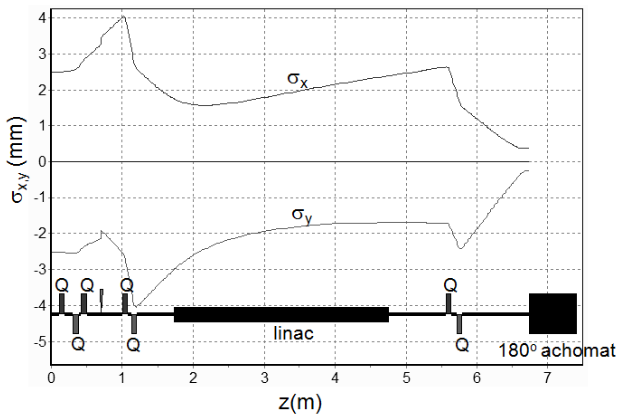

Figure 5: Simulated beam envelops from the exit of the RF-gun to the entrance of 180° achromat.

Table 3: Typical Parameters at the PBP Linac System and Optimized Electron Beam Parameters Using Beam Optics and Beam Dynamics Simulations

Parameter	**Value**
Microbunch repetition rate	2856 MHz
Macropulse repetition rate	1 -10 Hz
Current macropulse width	1-2 μs
Beam energy	15 MeV
Energy spread (rms)	0.7%
Minimum longitudinal rms bunch length (σ_z)	50 fs
Bunch charge (Q_b)	107 pC
Peak current (I_p)	844 A
Normalized rms emittance (ε_x, ε_y)	3.8 π mm-mrad
Horizontal beam size (σ_x)	0.394 mm
Vertical beam size (σ_y)	0.321 mm

CONCLUSION

The specifications of the injector system for the proposed IR FEL facility at Chiang Mai University in Thailand have been studied. Simulation and numerically studies showed that it is possible to use the existing linac system to produce electron beams with the specifications suitable for the IR FEL lasing requirements. The electron beam with a few ps bunch length can be used for the conventional IR FEL oscillator, while the electron beam with the bunch length less than 100 fs is considered for the pre-bunched FEL. By properly adjusting machine parameters, the 15 MeV electron beam with the minimum rms bunch length of 50 fs, a bunch charge of 107 pC and a peak current of 844 A can be produced. Further study will be performed to accumulate the useful information for technically modifying the current linac setup at Chiang Mai University to serve as the injector system for the future IR FEL.

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