

# SIMULATION AND OPTIMIZATION OF INJECTOR SYSTEM FOR THE PRE-BUNCHED THz FEL

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## Abstract

A linac-based light source for generation of infrared free-electron laser is under the development at the Plasma and Beam Physics (PBP) Research Facility, Chiang Mai University, Thailand. The injector system of the facility consists mainly of an S-band thermionic cathode RF electron gun, a pre-bunch compressor in a form of an alpha magnet and a travelling-wave linac structure. Two 180-degree magnetic bunch compressors, which each system has 4 dipole magnets, quadrupoles and steering magnets, are installed downstream the injector system. Two separate radiation beamlines for mid-infrared (MIR) and terahertz (THz) free-electron laser (FEL) are located following the bunch compressor systems. In this contribution, we focus only on the coherent and high-power pre-bunch THz FEL that is generated from electron bunches with a femtosecond length. Electron beam dynamic simulations with program ASTRA were performed to obtain optimal electron beam properties. Optimization of the injector system for the THz FEL is thus presented. The simulated results show that the beam at the linac exit has a bunch length of 282 fs with a charge of 200 pC when the linac RF phase is 90° and the alpha gradient is 300 G/cm. This optimal condition will be used as an input for simulation in the 180-degree bunch compressor system and in the THz undulator magnet.

## INTRODUCTION

Nowadays, the THz radiation has been used in many applications due to its unique features. Since the THz wave can pass through non-metallic materials, reflected by metal and absorbed by liquid, it is suitably used in THz imaging for non-destructive analysis of different density materials e.g. investigation of chemical structures of pharmaceutical materials or imperfection observation of integrated circuits, semiconductor devices or electronic cards [1].

The frequency ranges of the THz radiation also correspond well with rotational and vibration modes of many bio-molecules. Therefore, it can be used to study the characteristics of intermolecular bonds such as hydrogen bonding, Van der Waals forces, and molecule-ion attractions by using the THz spectroscopy technique. Various applications of THz radiation lead to broad studies on development of THz light sources, detectors, and experimental techniques. An accelerator-based light source is one of the most powerful sources for producing the THz

radiation. Many accelerator centers and laboratories develop the THz light sources worldwide including free-electron lasers.

In typical FELs, the radiation emits when an electron bunch moving through magnetic field of an undulator magnet interacts with the radiation, which is produced in the first section of a long undulator or inserted from external seed laser. The co-propagating radiation modulates the longitudinal velocity of electrons and eventually the electrons are bunched, which is called the micro bunching process. Contradictory, in case of pre-bunched FELs, ultrashort and high-charged electron bunches are produced before injecting the beam into the undulator. When the electron bunches with a length of equal or shorter than the radiation wavelength travelling in the undulator magnetic field, the radiation will be coherently emitted. In this case, the radiation emitted from different undulator poles along the beam trajectory overlaps and interferes constructively. This leads to properly add up of the radiation in the forward direction and results in the enhancement of the radiation intensity that is proportional to the electron number squared.

The construction of the pre-bunched THz FELs from femtosecond electron bunches and the typical MIR FEL oscillator (as shown in Fig. 1) are underway at our laboratory. The accelerator system includes the injector part, the 180-degree bunch compressors, and radiation stations. However, this paper focuses only on optimization of the injector system for generation of the femtosecond electron bunches at the entrance of the THz undulator magnet. This system consists of a thermionic cathode RF electron gun, an alpha magnet and a travelling-wave linac structure. The optimization was divided into three parts; in the RF-gun, from the gun exit to the alpha magnet and from the alpha magnet to the linac. The optimal electron beam with small emittance, low energy spread, short bunch length, and high beam current is expected to achieve downstream the linac.

## METHOD

Properties of the radiation from charged particle beam depend significantly on the beam qualities. Numerical optimization of electron beam properties has to be done before installation of the accelerator components. Electron beam dynamic simulations throughout the injector system by using program ASTRA [2] were performed to determine the appropriate operational parameters of the

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pre-bunched THz FELs beamline. Considered parameters for the simulation are an RF gun electric field amplitude, a gradient of alpha magnet and a linac RF phase. These parameters were optimized to obtain shortest electron bunch length, maximum charge per bunch, lowest energy spread, and small transverse emittance at the linac exit.

Firstly, the electric field amplitude inside the gun was varied to achieve the electron bunch with the maximum kinetic energy of 2.5 MeV according to the designed performance of the RF gun [3]. After that, the electron

beam is properly guided to the alpha magnet by adjusting the fields of steering and quadrupole magnets. The gradient of the alpha magnet was then optimized from 200 G/cm to 400 G/cm. The beam exiting the alpha magnet moves forward to the linac that has an RF phase of 90° for maximum acceleration condition. Quadrupoles' and steerers' field were adjusted to achieve small emittance and low energy spread. For all magnets, three-dimensional (3D) magnetic field distributions are obtained from simulations with program CST EM Studio 2018 [4].

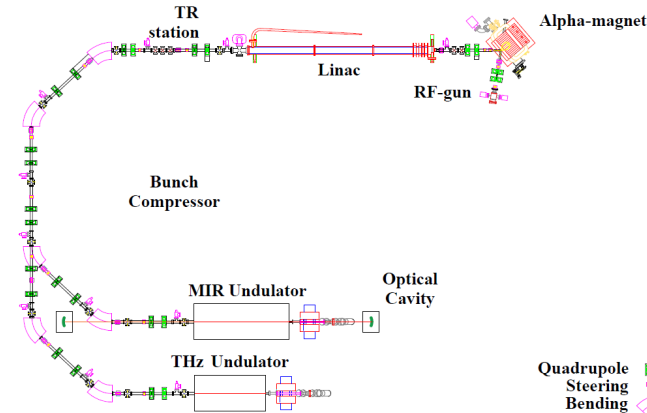


Figure 1: Schematic drawing of the infrared free-electron laser sources at the PBP Facility.

## RESULTS AND DISCUSSION

### Simulation in RF-gun

Electrons with no energy spread and non-zero emittance are emitted uniformly from the cathode surface with the average current of 2.6 A over an RF period. An initial kinetic energy of 0.165 eV was defined for a cathode temperature of 1000°C. An initial number of macro-particles is 350,000 with a total charge of 910 pC. We applied the 3D RF field distribution of the RF-gun obtained from the program CST EM Studio 2012 in the simulation [3]. The electric field amplitude inside the gun was optimized to obtain the electron bunch with the kinetic energy of 2.5 MeV.

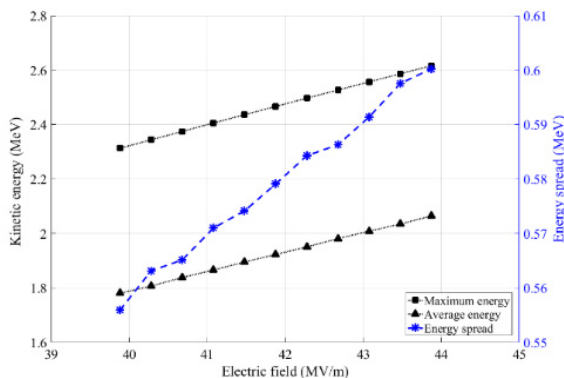


Figure 2: Dependency of maximum energy, average energy and energy spread of electron bunch at the gun exit as a function of electric field at the center of the full cell.

Results of electric field variation shown in Fig. 2 obviously indicate that the electrons gain higher energy for

higher electric field. The energy spread of the beam is large at high electric field due to time-varying feature of the RF field. The maximum electron energy of 2.5 MeV is achieved at the field amplitude of 42.3 MV/m. About 75% of the particles are lost inside the RF-gun. An electron bunch exiting the RF-gun has a charge of 224 pC, an average energy of 2 MeV and an energy spread of 0.62 MeV.

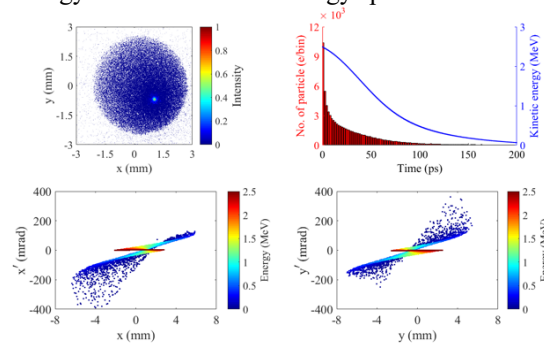


Figure 3: Transverse beam distribution, longitudinal distribution and transverse phase spaces of electron bunch at the gun exit for the field amplitude of 42.3 MV/m.

The transverse beam distributions in Fig. 3 show that the beam centroid is off-axis due to the influence of the asymmetric field distribution inside the gun cavities [3]. Electrons with high kinetic energy are accommodated at the head of the bunch and have nearly zero divergence.

### Simulation from RF-gun Exit to Alpha Magnet

After leaving the gun, the beam was directed to the alpha magnet by using steering magnets. Two quadrupoles were used to minimize the transverse size and divergence of the

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electron beam as shown in Fig. 4 (top left) to prevent emittance growth and bunch length enlargement [5].

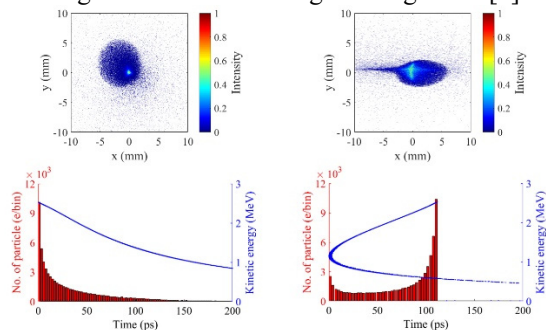


Figure 4: Distributions of electron bunch at the alpha magnet entrance (left) and exit (right).

The transverse beam distribution at the alpha magnet exit (Fig. 4 top-right) shows that the electron bunch is vertically focused after moving through the magnet. The longitudinal phase space of electrons at the alpha magnet entrance (Fig. 4 top-left) is then properly compressed after passing through the alpha magnet. High-energy electrons at the head of the bunch firstly enter the alpha magnet and travel with longer paths than lower energy electrons positioned at the bunch tail. Eventually, some low energy electrons catch up the high-energy ones and depart earlier from the magnet resulting in the clockwise rotation of longitudinal phase space at the magnet exit (Fig. 4 bottom-right).

### Simulation from Alpha Magnet to Linac

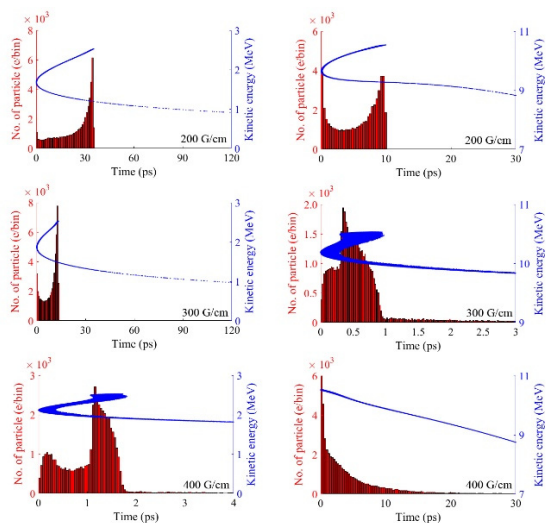


Figure 5: Longitudinal distributions of electron bunches at the linac entrance (left) and exit (right).

After exiting the alpha magnet, the transverse properties of electron beam are controlled with two quadrupoles and two steerers for directing the beam to center of linac with nearly zero divergence. Electrons in the bunch are accelerated in the linac with slightly different phases depending on their positions in the bunch. Thus, the magnetic field gradient of the alpha magnet has to be adjusted to achieve the shortest bunch length downstream

the linac. The linac gradient was adjusted to obtain the average beam energy of 10 MeV at the linac phase of  $90^\circ$ .

Electron beam distributions at the linac exit (Fig. 5) have different longitudinal phase spaces for different alpha magnet gradients. With the gradient of 300 G/cm, the electron bunch at the linac entrance has a proper longitudinal distribution for optimal velocity bunching in the linac. This leads to the shortest electron bunch length downstream the linac. The alpha magnet gradient of 200 G/cm provides under-compression beam at the linac exit while the gradient of 400 G/cm provides the over-compress condition.

The 3D distribution, longitudinal distribution and transverse phase spaces of electron bunch at the linac exit for the alpha gradient of 300 G/cm are shown in Fig. 6. The energy spectrum of electron bunch approaches the Gaussian distribution with energy spread of 0.41 MeV and 90% of electrons in the bunch occupies in the kinetic energy range of 9.9 -10 MeV. The Gaussian fitting bunch length is 282 fs with a charge of 200 pC. The horizontal and vertical emittance are 0.77 and 0.83 mm.mrad, respectively.

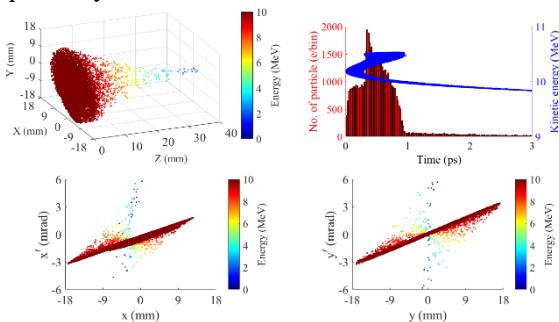


Figure 6: 3D electron bunch distribution, longitudinal distribution and transverse phase spaces at the linac exit for the alpha magnet gradient of 300 G/cm.

## CONCLUSION

The ASTRA beam dynamics simulation of the injector system was done to determine the appropriate parameters for the THz-FELs beamline. The electric field amplitude in the full-cell of the RF-gun was optimized to be 42.3 MV/m to produce the electron beam with the maximum energy of 2.5 MeV. Low-energy electrons located off-axis at the bunch tail have smaller transverse size and larger divergence than the high-energy electrons accumulated in the head of the bunch. A well correlation between energy and time of electrons in the bunch is suitable for the bunch compression in the alpha magnet. The optimal alpha magnet gradient to obtain the shortest bunch length and high charge at the linac exit is 300 G/cm. For the linac RF phase of  $90^\circ$ , the beam with an average kinetic energy of 10 MeV, a bunch charge of 200 pC and a bunch length of 282 fs can be achieved. The transverse emittances are small and below 1 mm.mrad. Further electron beam optimization will be conducted in 180-degree bunch compressor system

to obtain the proper beam properties at the entrance of the THz undulator magnet.

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