Design of Compact THz-FEL system at Kyoto University

Suphakul Sikharin [1,*], Yusuke Tsugamura [1], Heishun Zen [1], Toshiteru Kii [1], Qika Jia [2] and Hideaki Ohgaki [1]

[1]Institute of Advanced Energy Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan
[2] University of Science and Technology China, Hefei, 230029, China
*sukarin.supakun.78z@st.kyoto-u.ac.jp

Abstract

A development of a compact terahertz (THz) radiation source by free-electron lasers (FEL) at the Institute of Advanced Energy, Kyoto University is ongoing. The system consists of a photocathode RF-gun, a focusing solenoid, a magnetic bunch compressor, a focusing quadrupole and an undulator. The system is designed to be simple, economical and compact which aim to use for scientific researches or industrial applications. The total length of the system is less than 5 m. The radiations are generated by ultra-short and intense electron pulses which are injected to a short undulator. Interactions between electron pulse and optical field are analyzed by 1-D FEL equations. A tracking simulation and optimization are performed by using PARMELA and General Particle Tracer (GPT) code.

INTRODUCTION

A new terahertz radiation source is under the development at the Institute of Advanced Energy, Kyoto University. The system would consist of a 1.6 cell BNL type photocathode RF-gun, a focusing solenoid magnet, a 4-dipole magnetic chicane bunch compressor, a triplet quadrupole magnet and a planar halbach undulator and a laser system. The system will be used for energy science researches or industrial applications. The system is designed to be simple, economic and compact with the total length less than 5 m. The schematic view of the proposed system is shown in Fig 1.

To investigate the beam dynamics, PARMELA or "Phase And Radial Motion in Electron Linear Accelerator" [1] code and GPT or "General Particle Tracer" code [2] have been used for the simulations of multi-particle beam dynamics from the RF-gun to the undulator and optimization of lattice parameters.

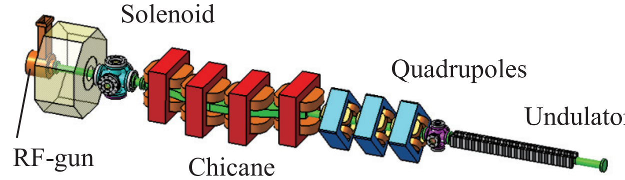

Figure 1: Schematic view of the compact THz-FEL at Institute of Advanced Energy, Kyoto University.

The magnets of the chicane were designed and simulated by using computer code RADIA [3].The FEL radiation power was estimated by the 1-dimensional FEL theory by considering in a short bunch case or called "super radiation". The system will be installed in the same accelerator room with Kyoto University Free-Electron Lasers (KU-FEL) [4].

BEAM DYNAMIC STUDY

The electron beam dynamics of the compact THz- FEL system has been studied by PARMELA and GPT codes. Both codes track particles in the 6-dimensional phase space and include the space charge effect. In this study, the longitudinal beam dynamics from the RF-gun to the undulator entrance was investigated by using PARMELA. Meanwhile, the transverse beam dynamics was optimized by using GPT. Because the undulator with vertical deflection, which will be used for the compact THz- FEL system, is only available in GPT.

Photocathode RF-gun

The 1.6 cell BNL type photocathode RF-gun, which was manufactured by KEK, is used to produce a high-brightness, short-bunch and low emittance electron beam suitable for the compact THz-FEL system. The RF-gun performances have been studied in [5]. The cathode plug was made from copper and loaded to the RF-gun by a load-lock system. The improvement of the quantum efficiency (QE) of the cathode is also studying by coating the cathode surface with Cs and Te. The photocathode RF-gun is illuminated by a pico-seconds mode-locked Nd:YVO4 UV laser system which consists of an acousto-optic modulator, beam position stabilizer, two of double pass amplifiers, SHG and FHG crystal.

For simulation, the previous RF-gun model [5] was used. The accelerating voltage and bunch charge are varied then investigate the exiting beam dynamics. We assumed that the ratio of the field strength of the half-cell and the full-cell was 1:1. The laser profiles were assumed to be the Gaussian shape in both transverse and longitudinal. The laser injection phase was selected at a lower phase which provides a lower energy spread. The RF-gun and laser parameters are shown in table 1.

Table 1: The Photocathode RF-gun Parameters

RF-Gun Parameters	**Values**
RF-Gun Type	1.6 cell BNL type photocathode
Accelerating field	110 MV/m
Bunch charge	100 pC
Solenoid field strength	1800 G
Laser type	pico-seconds mode-locked Nd:YVO4
Laser longitudinal length	rms 6.2 deg, max 12 deg
Laser transverse size	max radius 1 mm.
Laser injection phase	12 deg

At the above conditions, the beam at the solenoid magnet exit has the average energy of 9.4 MeV, the RMS energy spread of 0.104 MeV, the bunch length at FWHM of 5 ps, the peak current of 125 A. The energy time phase space and current profile at the solenoid exit are shown in fig.2 and fig 3.

Magnetic Chicane

The magnetic chicane bunch compressor is a new designed component which consists of 4-rectangular H-type dipole electromagnets. The chicane creates

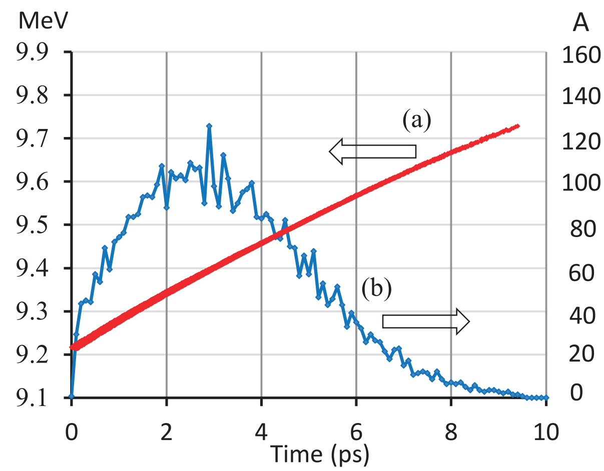

Figure 2: Energy time phase space (a) and current profile (b) at the RF gun exit.

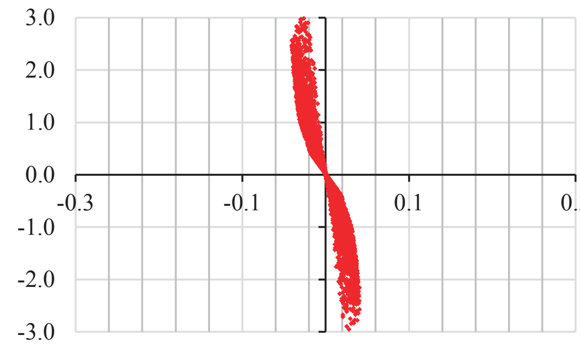

Figure 3: Transverse phase space in x-x' at the RF gun exit.

an energy dependent path inside where the path of an electron with higher momentum is shorter than an electron with lower momentum. Consequently, the electron bunch become shortens in the longitudinal which lead to the peak current getting higher. The energy slits are added between 2nd and 3rd magnet to removed undesired electrons which do not contribute to the FEL radiation.

The magnet has the geometry length of 75 mm and the distance between magnets is 125 mm. The deflection angle of the chicane can be varied from 0 to 30 degree which corresponds to the 1st order momentum compaction (R_{56}) of 0 to -130.1 mm. The optimized chicane parameters for the beam at the RF-gun condition in the table 1 are shown in the table 2.

Table 2: The Optimized Magnetic Chicane Parameters

Parameters	**Values**
Magnetic chicane	
Type	4 dipole magnet H-Type rectangular
Defection angle	21 degree
1st order momentum compaction (R_{56})	-51 mm.
Energy filter (MeV)	min 9.3, max 9.57
Peak magnetic field	0.158 T
Coil current	1886 A-turns

At the undulator entrance, the electron bunch length at FWHM becomes 0.14 ps and the bunching factor is 0.68. The peak current is up to 400 A and the rms energy spread is 0.63%. The rms beam size in horizontal and vertical is 0.2 mm and 1.2 mm. The energy time phase space and the current profile at the exit of the undulator entrance are shown in fig.4 and fig.5.

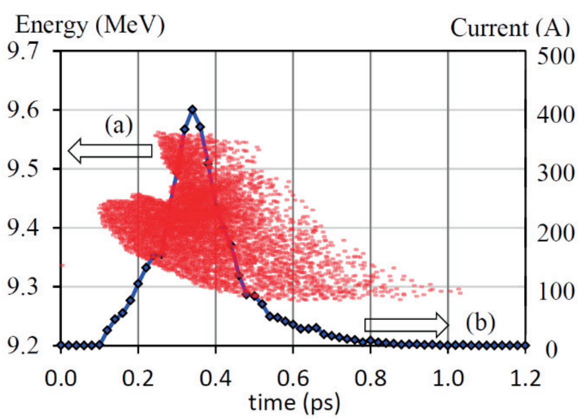

Figure 4: Energy time phase space (a) and current profile (b) at the undulator entrance.

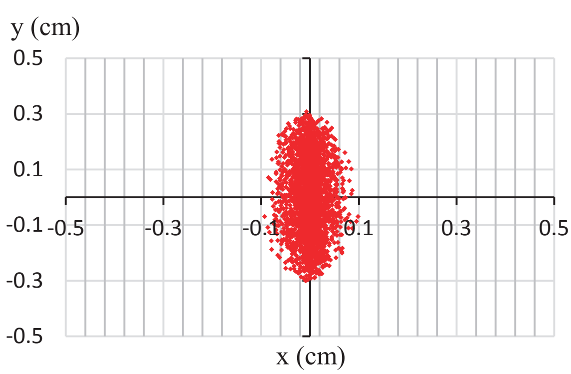

Figure 5: Particle distributions in transverse x-y plane at the undulator entrance.

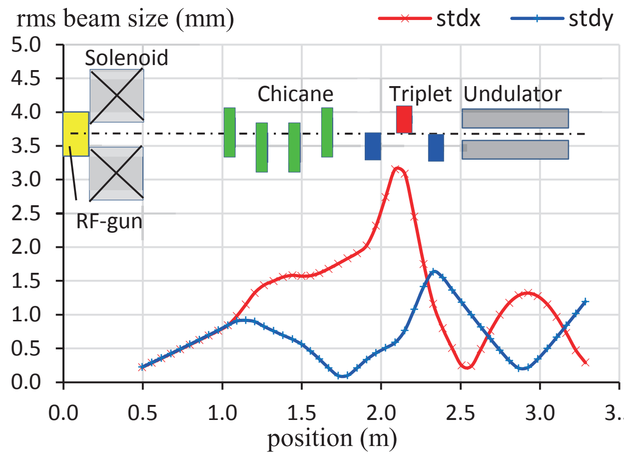

Figure 7: RMS beam size by GPT simulations.

Undulator and THz-radiation

The THz-radiations of the compact THz-FEL are generated by injecting an ultra-short electron bunch to the undulator. Each individual electron moves sinusoidal and emits the radiation in almost the same phase or called "super radiation". In this case, the electron bunch length has to be significantly shorter than the undulator resonance wavelength. The super radiation power of the ultra-short bunch can be estimated by the 1-dimensional FEL theory [6].

$$P_{sr} < (4\pi \frac{l_b}{\lambda_s} b)^2 \rho^3 P_e$$

where *Psr* is the super radiation power, l_b is the bunch length, λs is the resonance wavelength, b is the bunching factor $b = |\langle e^{i\theta} \rangle|$ where θ is the phase of the electrons inside the FEL radiation wave, ρ is the FEL parameter and P_e is the power of the electron beam.

For the compact THz-FEL, the undulator is the plannar halbach type with the deflection in the vertical. The undulator has 10 periods with the period length of 70 mm and adjustable gap. At the gap of 40 mm, the peak magnetic field is 0.275 T, the rms undulator parameter is 1.27, the resonance wavelength is 244 µm. From the beam parameters at the entrance of the undulator, the FEL parameter is 0.035 and the estimated FEL radiation power is about 0.21 MW.

CONCLUSION AND OUTLOOK

The beam dynamics of the compact THz-FEL has been investigated by numerical simulation. The electron bunches at the undulator entrance have average energy of 9.41 MeV, energy spread of 0.63%, bunch length of 0.14 ps and peak current of 400 A. Such a beam will provide the super radiation power of 0.21 MW for the wavelength of 244 μm.

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