DEVELOPMENT OF COMPACT THZ-FEL SYSTEM AT KYOTO UNIVERSITY

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Abstract

We are developing a compact accelerator based terahertz (THz) radiation source by free-electron laser (FEL) at the Institute of Advanced Energy, Kyoto University. The system consists of a 1.6-cell S-band BNL-type photocathode RF-gun, a focusing solenoid magnet, a magnetic bunch compressor, focusing quadrupoles and an undulator. The system will generates an ultra-short electron pulse in a few hundred femtoseconds shorter than radiation wavelength, expecting for a super-radiant emission from the undulator. The target radiation wavelength is 100 to 300 µm. A tracking simulation and optimization are performed by using PARMELA and General Particle Tracer (GPT) code. The FEL radiations are analyzed by a 1 dimensional FEL theory. The design parameters, simulation results and status are reported and discussed in this paper.

INTRODUCTION

A new compact terahertz radiation source is under the development at the Institute of Advanced Energy, Kyoto University. The system was designed to be simple, compact and economical aimed using for scientific researches or industrial applications. The system consist of a 1.6-cell S-band BNL-type photocathode RF-gun, a focusing solenoid magnet, a 4-dipole magnetic chicane bunch compressor, quadrupole magnets, a planar halbach undulator and a photocathode drive laser system. Currently, the RF-gun, the undulator and the laser system have been prepared. The magnetic chicane and the quadrupoles are newly designed components. The system is located in the same accelerator room with Kyoto University Free-Electron Lasers (KU-FEL) [1]. The schematic view of the proposed system is shown in Fig. 1.

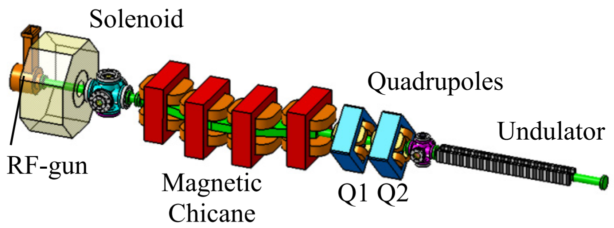

Figure 1: Schematic view of the compact THz-FEL system at Institute of Advanced Energy, Kyoto University.

BEAM DYNAMIC STUDY

The multi-particle beam dynamics was investigated by numerical simulation using PARMELA [2] and GPT [3]. Both codes track particles in the 6-dimensional phase space including the space-charge effect. The simulation of the RF-gun was performed by PARMELA. Then the results are converted to GPT file format and used as the input for the beam dynamics simulations from the RF-gun exit to the end of the undulator by GPT. The parameters of the system was optimized to provide the electron beam with a high peak current, a small beam size and a low energy spread suitable for the FEL radiation generation inside the undulator.

For the simulation of multi-particle beam dynamics, 10,000 macro particles per 2,856 MHz with the total charge of 100 pC are assume to be emitted from photocathode plug illuminated by the lasers.

Photocathode RF-gun

The 1.6-cell S-band BNL-type photocathode RF-gun, which was manufactured by KEK since 2008, is a new adoption component of the laboratory. The RF-gun performances have been studied by numerical simulations in [4]. In this study, this RF-gun numerical model is used.

The photocathode RF-gun is illuminated by a pico-seconds mode-locked Nd:YVO_4 UV laser system [5]. The laser system consists of an acousto-optic modulator, beam position stabilizer, two of double pass amplifiers, SHG and FHG crystals. The cathode plug was made from copper and loaded to the RF-gun by a load-lock system. The quantum efficiency (QE) of the cathode plans to be improved by coating the cathode surface with Cs and Te.

For the simulation, the RF-gun operates at a high accelerating condition with average accelerating voltage of 80 MV/m in order to reduce the space-charge effect. The accelerating field ratio between half-cell and full-cell are assumed to be 1:1. We made several calculations and concluded that the lasers are injected at a low accelerating phase which provides a lower energy spread and a better linearization of an energy chirp. The laser profiles are Gaussian distribution in both transverse and longitudinal with specified cut-off limits. The simulation parameters of the RF-gun are listed in Table.1.

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Table 1: The Photocathode RF-gun Parameters

RF-Gun Parameters	**Values**
Type	1.6-cell S-band BNL type photocathode
Accelerating field	80 MV/m (avg)
Bunch charge	100 pC
Solenoid field strength	1,800 G
Laser type	Forth harmonics of pico-seconds mode-locked Nd:YVO$_4$
Laser longitudinal length	rms 6.2 deg, max 12 deg
Laser transverse size	max radius 1 mm.
Laser injection phase	12 deg

Magnetic Chicane

The magnetic chicane bunch compressor which consists of 4-rectangular H-type dipole electromagnets is a newly designed. The chicane creates an energy dependent path inside where the path length of electrons with higher momentum is shorter than electrons with lower momentum. Consequently, the electron bunch become shortens in the longitudinal leading to increasing of the peak current. The schematic of the magnetic chicane is shown in Fig. 2.

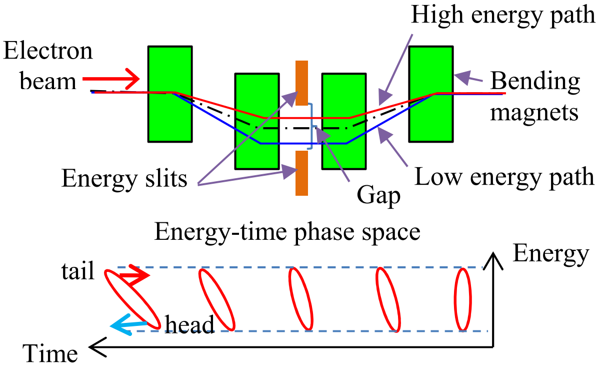

Figure 2: Schematic of the magnetic chicane.

Table 2: The Magnetic Chicane Parameters

Magnetic Chicane Parameters	**Values**
1st order momentum compaction (R_{56})	-113.5 mm.
Deflection angle	29.5 deg.
Energy slits - Slit width	2 mm
- Offset from centre	112.2 mm
Magnets - Geometrical length	75 mm.
- Distance between magnets	125 mm
- Magnetic field	0.168 T
- Coil current	1969.6 A-turns

The energy slits consist of two metal plates whose positions can be adjusted in horizontal axis. The slits are placed between the 2nd and 3rd magnet to remove electrons which do not contribute to the FEL radiation. The deflection angle of the chicane can be varied from 0 to 35 degree. The optimized chicane parameters given by simulation corresponding to the RF-gun parameters are shown in Table. 2.

Undulator and THz-radiation

The undulator for the compact THz-FEL is a planar Halbach type, an adjustable gap and a deflection plane in vertical. Since the electron bunch will be shorter one and the radiation wavelength is very long in our case, the slippage effect is significant which cause FEL interaction only a few period of the undulator. Therefore the short undulator period of 10 has been chosen. The quadrupoles are installed upstream the undulator to focus an electron beam to the undulator. The undulator parameters are listed in Table. 3. The THz-radiations are generated by injecting an ultra-short electron bunch to the undulator. When the electron bunch length is significantly shorter than the FEL wavelength, each individual electron moves sinusoidal and emits the radiation in almost the same phase called "super-radiation". The power of super-radiation, P_{sr}, can be estimated by the 1-dimensional FEL theory [6]

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

where l_b is the bunch length, λ_s is the undulator resonance wavelength, b is the bunching factor $b = \left|\langle e^{i\theta} \rangle\right|$ 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.

Table 3: The Undulator Parameters

Undulator Parameters	**Values**
Type	Plannar Halbach
Number of period	10 periods
Period length	70 mm.
Undulator gap	40 mm.
Peak magnetic field	0.275 T
Undulator parameter (K)	1.802
FEL resonance wave length	244 µm
Quadrupole magnetic field gradient (T/m)	Q1 = 1.4, Q2 = -2

SIMULATION RESULTS

For the RF-gun section, PARMELA simulation has been performed to obtain the electron bunch with a linear energy chirp which is suitable for the bunch compression by the chicane. The energy time phase-space, the current profile and the transverse phase-space the electron bunch at the RF-gun exit are shown in Figs. 3 and 4. The FWHM bunch length and the peak current are 4 ps and 24.4 A. The transverse phase spaces of both horizontal (x axis) and vertical (y axis) are the same.

At the undulator entrance, GPT simulation has been performed to optimize the chicane parameter. The FWHM bunch length reduces to 0.4 ps, the peak current is up to 90 A and the bunching factor is 0.26. The bunch

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charge reduces to about half of the initial bunch charge because of the energy slits. The energy time phase-space, the current profile and the transverse phase-space at the the undulator entrance are shown in Fig. 5, 6. The electron beam properties are listed in Table 4.

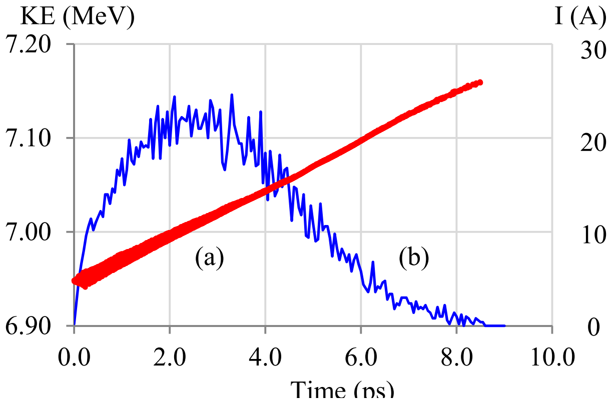

Figure 3: Energy time phase-space (a) and current profile (b) at the RF-gun exit (PARMELA simulation results).

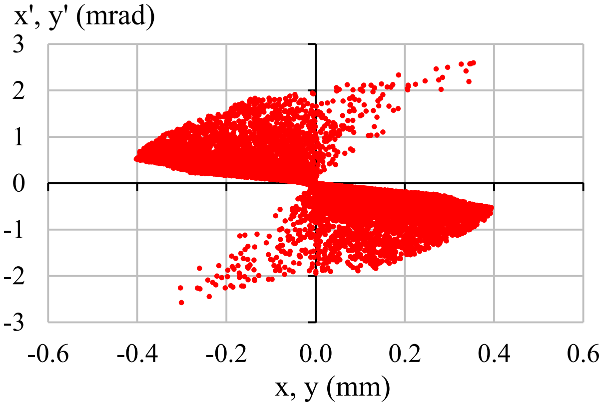

Figure 4: Transverse phase-space in x-x′ and y-y′ at the RF-gun exit (PARMELA simulation result).

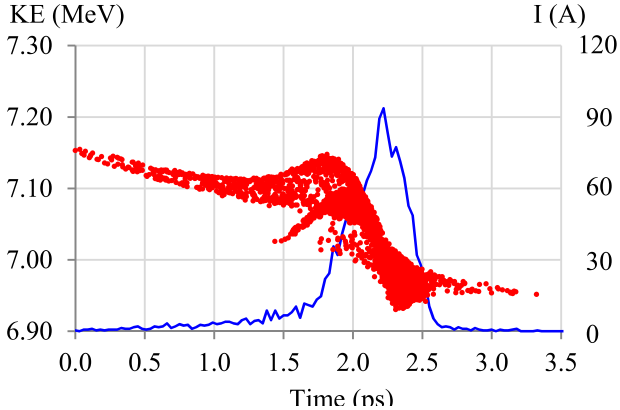

Figure 5: Energy time phase-space (a) and current profile (b) at the undulator entrance.

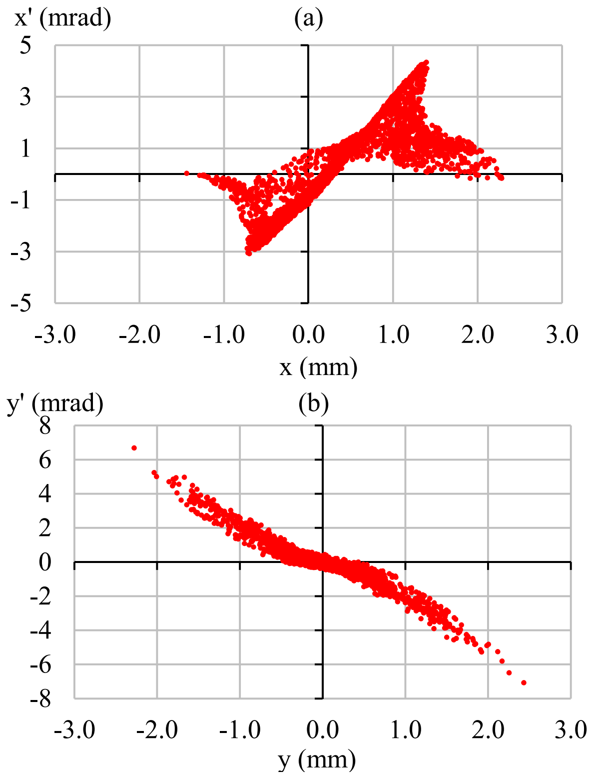

Figure 6: Transverse phase-space in x-x′ (a) and y-y′ (b) at the undulator entrance (GPT simulation result).

The rms beam size, transverse and longitudinal normalized rms emittances of the whole system are shown in Figs. 7, 8 and 9. The undulator has a strong focusing in horizontal (non-deflection plane) and no focusing in vertical (deflection plane). The average horizontal and vertical rms beam sizes of the beam inside the undulator are 0.59 mm and 0.32 mm, respectively.

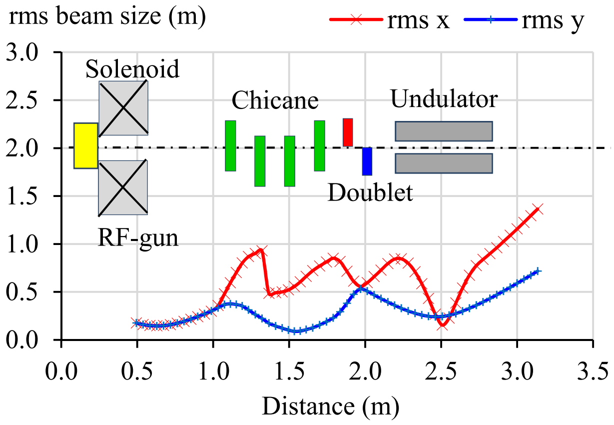

Figure 7: RMS beam size (GPT simulation results).

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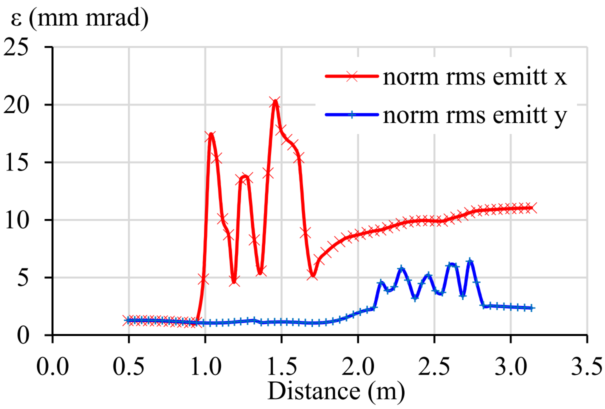

Figure 8: Transverse normalized rms emittance (GPT simulation results).

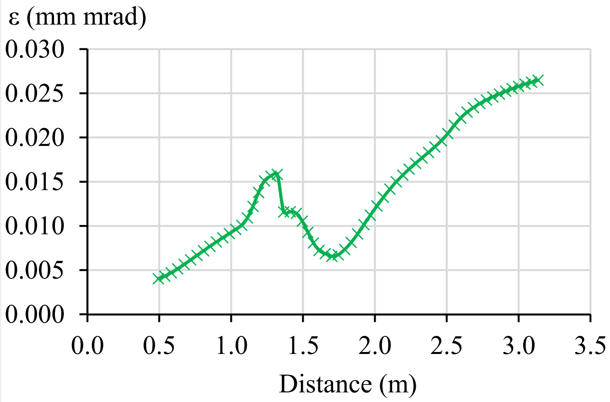

Figure 9: Longitudinal normalized rms emittance (90% of particles of the bunch, GPT simulation results).

Table 4: Summary of the Electron Beam and the THz Radiation Properties

Parameters	**Values**
RF-gun exit	
Beam energy - Average	7.02 MeV
- Maximum	7.15 MeV
- Minimum	6.94 MeV
RMS Energy spread	0.61 %
Bunch length (FWHM)	4 ps
Bunch charge	99.9 pC
Peak current	24.4 A
RMS beam size (mm)	$\sigma_x = 0.17$, $\sigma_y = 0.17$
Normalized RMS emittance (mm mrad)	$\bar{\varepsilon}_x = 1.27$, $\bar{\varepsilon}_y = 1.29$
Undulator Entrance	
Beam energy	
- Average	7.04 MeV
- Maximum	7.15 MeV
- Minimum	6.93 MeV
Energy spread	0.89 %
Bunch length (FWHM)	0.4 ps
Bunch charge	48.6 pC
Bunching factor	0.26
Peak current	93.7 A
RMS beam size (mm)	$\sigma_x = 0.66$, $\sigma_y = 0.46$
Normalized RMS emittance (mm mrad)	$\bar{\varepsilon}_x = 8.9$, $\bar{\varepsilon}_y = 2.2$
THz-radiation	
Radiation wavelength	244 µm
FEL parameter	0.0243
Super-radiation power	0.078 MW

CONCLUSION

The multi-particle beam dynamics of the compact THz-FEL has been investigated by the numerical simulations. The electron bunch at the undulator entrance has the average energy of 7.04 MeV, the energy spread of 0.89%, the bunch length of 0.4 ps, the peak current of 93.7 A, the bunching factor of 0.26 and the average rms beam radius inside the undulator of 0.67 mm. The calculated FEL parameter is 0.0243. Such a beam will provide the super-radiation power of 0.078 MW for the wavelength of 244 µm. A seeding FEL scheme [7] is also under consideration to obtain a high power FEL.

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