ELECTRON BEAM FOR COMPACT THZ FEL AMPLIFIER AT KYOTO UNIVERSITY*

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Abstract

Construction of a new compact accelerator-based terahertz (THz) radiation source at the Institute of Advanced Energy, Kyoto University will be soon completed and the first lasing is planned in Aug 2016. The system operates at a beam of 4.6 MeV generated by a 1.6 cells photocathode RF-gun. The bunch is compressed by a magnetic chicane bunch compressor, then injected to a short planar undulator for the THz radiation generation via a coherent synchrotron radiation (CSR). The characteristics of the compressed beam by the chicane were investigated by the coherent transition radiation (CTR) technique. As the results, the chicane could compress the bunch at the laser injection phase from 10 to 40 degree and the maximum compression is at the phase of 27 degrees. The suitable 1st momentum compaction, R_{56}, is between -43.6 and -51 mm and the final bunch length calculated by simulation is around 2 ps.

INTRODUCTION

A new compact high-power terahertz (THz) radiation source at the Institute of Advanced Energy, Kyoto University [1] is nearly complete. The system consists of a 1.6-cell S-band BNL-type photocathode RF-gun [2] equipped with an emittance compensation solenoid magnet, a magnetic chicane bunch compressor, and a triplet quadrupole magnets and the undulator. A Halbach type undulator is used as a radiator. The photocathode is illuminated by a picosecond UV lasers. The total length of the system is less than 5 m and located in the same accelerator room with Kyoto University Free-Electron Laser (KU-FEL) [3] to share the RF-power source and the picosecond UV laser [4]. At the 1st stage of the development, THz radiation will be generated from the undulator via coherent synchrotron radiations (CSR). The CSR occur when electron bunch has a shorter bunch length than radiation electrons emits the radiation. The picture and the schematic diagram of the system are shown in Fig.1 and 2.

The beam properties at the photocathode RF gun exit were measured in Mar 2015 [5]. The characteristic of the compressed beam was investigated by the coherent transition radiation technique in Apr 2016 [6]. The undulator has been installed in Jul 2016 and planned to generate the THz radiations in Aug 2016. The particle tracking simulation code General Particle Tracer (GPT) [7] was also used for the beam dynamics study. The accelerating electric field of the 1.6 cells photocathode RF-gun was calculated by SUPERFISH [8] and then was imported to GPT. The number of particle in the simulation was 200,000 particles. The space-charge effect was calculated by using "spacecharge3Dmesh" algorithm. The beam acceptances were defined according to the internal dimension of the vacuum chambers of the actual beamline. The particle travel out of the beam acceptance would be removed. This paper will present the RF-gun beam properties, the bunch compressor details, the compressed beam characteristics and the expected undulator radiation.

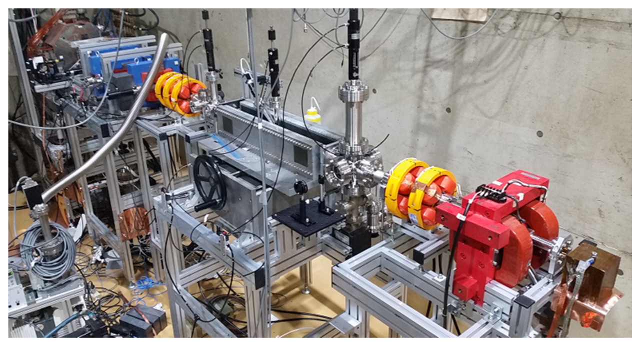

Figure 1: Beamline of the compact THz FEL amplifier.

PHOTOCATHODE RF GUN BEAM

Our 1.6 cells BNL type photocathode RF-gun is the revised model of the RF-gun developed by KEK [9]. The RF-gun has a high Q-value around 12,000 and can generate a high beam current and a high energy beam with a low transverse emittance. We plan to operate the RF-gun at a high energy as much as possible in order to reduce the influence of the space-charge effect. However, the maximum beam energy is limited by the RF power source and the structure of the RF-gun. The current available klystron for the RF gun has the maximum power of 9 MW that provides beam energy of 4.6 MeV. The accelerating field at the cathode surface calculated by GPT was 100 MV/m which is close to the maximum field limitation of the BNL type RF-gun at 120 MV/m [10].

The cathode of the RF-gun is exchangeable and the copper cathode was used for the measurement of the beam properties. The cathode was illuminated by a picoseconds UV laser with the wavelength of 266 nm. The measured laser pulse duration at the full width half maximum (FWHM) is 5.6 ps. The laser pulse length determines the initial bunch length. Shorter bunch length has a higher longitudinal space-charge effect leading to the easier longitudinal bunch deformation and a longer final bunch length. The summary of the beam properties is shown in Table 1.

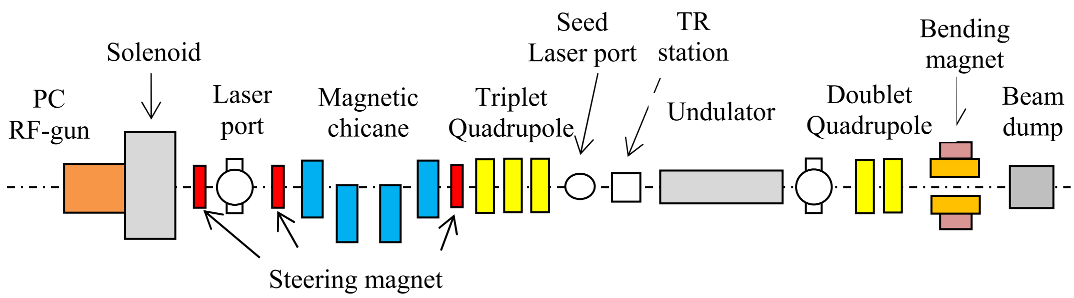

Figure 2: Schematic diagram of the compact THz FEL amplifier.

BUNCH COMPRESSOR

The magnetic chicane bunch compressor has been commissioned in Mar 2016. The chicane consists of four H-type rectangular electromagnet dipole magnets arranged in a symmetric layout as shown in Fig. 2. The magnets have the pole thickness of 65 mm, pole width of 100 mm, pole gap of 30 mm, and each pole equipped with a 190 turn air-cooled rectangular cross-section copper coil. The distance between the centers of the magnets is 190 mm. The maximum beam deflection angle is limited by the vacuum chamber dimension at 35 degrees. The bunch compression is determined by the 1st order momentum compaction (R_{56}), which is defined by the path length different in the dispersive section over the relative energy spread, $R_{56} = ds/d\delta$. The R_{56} was calculated by tracking a single particle using GPT. For the beam energy of 4.6 MeV, the calculated R_{56} is in the range from -26.8 to -63.9 mm corresponding to the chicane exciting current from 4.4 to 6.6 A. The measured magnetic field and the calculated R_{56} are shown in Fig. 3.

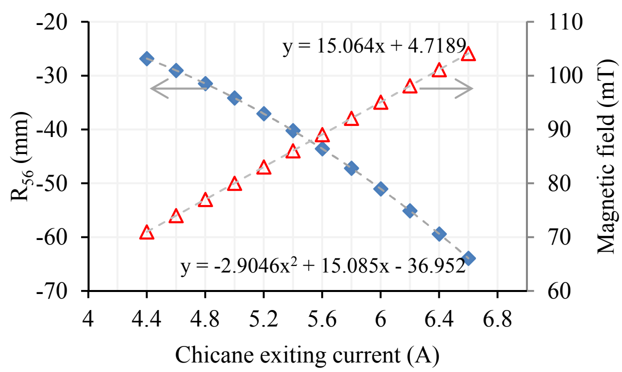

Figure 3: The measured magnetic field at the pole gab center and the 1st order momentum compaction factor of the beam energy of 4.6 MeV as a function of the chicane exciting current.

COMPRESSED BEAM PROPERTIES

The compressed beam properties have been diagnosed by the coherent transition radiation (CTR) technique [11]. The CTR was generated by an aluminium foil with thickness of 11 µm arranged in 45 degree to the beam direction. The backward CTR extracted perpendicular to the beam through the natural z-cut quartz window. The CTR intensity was measured by a pyroelectric detector (PYD-1-018, PHLUXi) equipped with lens and visible light filter. Figure 4 show the dependency of the CTR intensity on the laser injection phase for the both uncompressed and compressed bunch at the R_{56} of -26.8 mm. The measurement was performed at the laser energy of 300 µJ per macro-pulse (4 pulses). The chicane can enhance the CTR intensity at the laser injection phase from 10 to 40 deg. The bunch charges did not lose in the chicane during the compression which had been confirmed by the measurement.

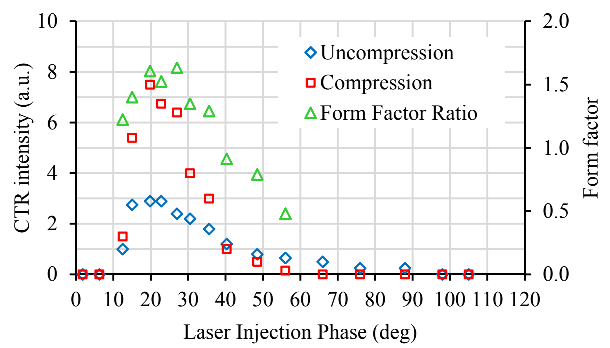

Figure 4: The CTR intensity at the R_{56} of -26.8 mm as a function of the laser injection phase.

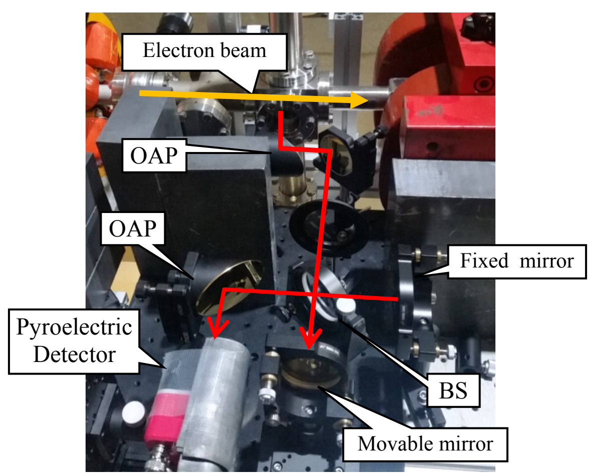

Figure 5: The setup of the Michelson interferometer, the red line represent the CTR radiation path, OAP: Off-axis parabolic mirror, BS: Beam splitter.

The CTR spectrums were measured by Michelson Interferometer whose set up is shown in Fig. 5. We used a sapphire with thickness of 100 μm as a beam splitter. Two 2-inch flat gold-coated mirrors were used for both arms of the interferometer. Two off-axis parabolic mirrors with the focal length of 106.5 mm were used to collimate the CTR from the extracting window and focus the autocorrelation signal from the interferometer to the detector. The movable mirror was moved with 0.1 mm step equivalent to the sampling frequency of 1.5 THz. The measurement of the CTR spectrum was performed at the laser injection phase of 30 degree, the solenoid magnetic field of 192 mT and the laser energy of 300 μJ per macro-pulse (4 pulses). The power spectrum of the CTR after subtraction of the DC components is shown in Fig.6. The most of the CTR spectrum is less than 0.25 THz. The best compression condition for this beam seems to be in the R_{56} range from -43.6 to -51 mm which contain a high frequency component than the other R_{56} range.

The particle distribution in the longitudinal phase space at the R_{56} of -47.1 mm and the same condition as the CTR spectrum measurement calculated by GPT is shown in Fig.7. The bunch profile was almost flat and a long spike shape at the bunch head cause by the longitudinal phase space deformation by the space-charge effect. The comparison of the normalized power spectrum measurement at R_{56} of -47.1 mm between the measured CTR and the GPT simulation is shown in Fig. 8.

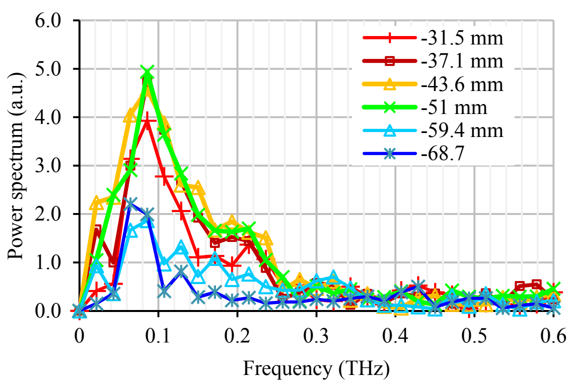

Figure 6: The power spectrum of the CTR for the different R_{56} at the solenoid magnetic field of 192 mT.

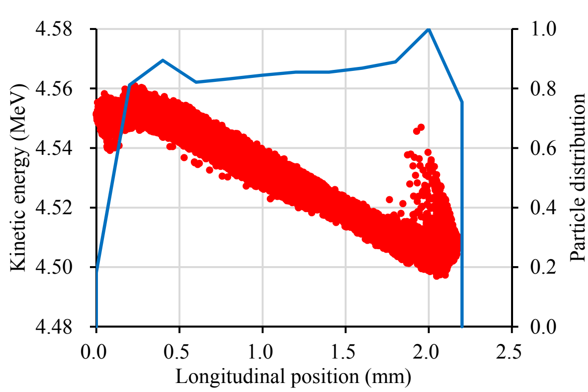

Figure 7: The Particle distribution in the longitudinal phase space by the GPT simulation at the R_{56} of -47.1 mm.

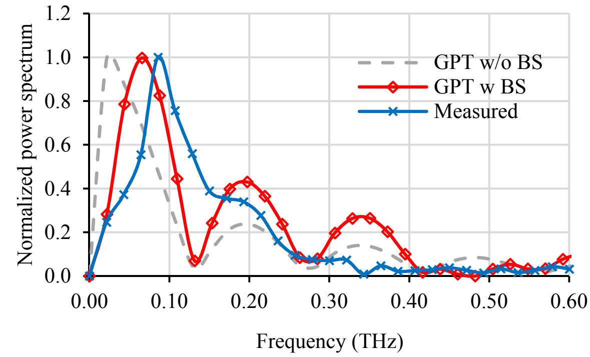

Figure 8: The normalized power spectrum of the measured CTR (cross mark) and the electron bunch by the GPT simulation with (square mark) and without (dash line) the beam splitter efficiency.

Table 1: Parameters of the Compact THz FEL Amplifier

Parameters	Values
Electron beam	
Maximum energy	4.6 MeV
Maximum bunch charge (Laser energy 350 μJ)	1.4 nC
Minimum normalized transverse emittance (Horizontal / vertical at 50 pC)	6π / 8π mm mrad
rms energy spread	1.3 %
Compressed bunch length (Simulation at R_{56} -47.1 mm)	~2 ps or 0.6 mm.
Undulator	
Type	Halbach (planar)
Period length (λ_u)	70 mm
Number of period (N)	10
Peak magnetic field (gap 30 mm)	0.43 T
Maximum undulator parameter (K)	2.7
Output radiation (expected)	
Maximum wavelength (λ_0)	1,600 μm
Radiation cone half-angle (γ^{-1})	5.7 deg
Maximum pulse length ($N\lambda_0$)	16 mm

The undulator specifications are shown in Table 1. The undulator radiation wavelength, which can be calculated by $(\lambda_u/2\gamma^2)(1+K^2)$ where λ_u is the undulator period length, γ is the Lorentz factor and K is the undulator parameter. At the maximum undulator parameter of 2.7, the radiation wave length is longest at 1.6 mm. The bunch length of the compressed bunch is shorter than the radiation wavelength. Therefore, the CSR will be able to generate from the undulator under this beam condition.

CONCLUSION

The beam properties for the compact THz FEL amplifier at Kyoto University have been investigated. The photocathode RF-gun can generate the beam energy of 4.6 MeV at the driven RF power of 9 MW. At this beam energy, the 1st momentum compaction, R_{56}, of the chicane is in the range from -26.8 to -63.9 mm corresponding to the chicane exciting current from 4.4 to 6.6 A. The chicane is able to compress electron bunch from the laser injection phase from 10 to 40 degree investigated by the coherent transition radiation technique. The maximum compression of the chicane is at the laser injection phase of 27 degree and the R_{56} range from -43.6 to -51 mm.

From the simulation, the electron bunch was deformed due to the longitudinal space-charge effect leading to the long final bunch length around 2 ps or 0.6 mm. But the bunch length is still shorter than the undulator radiation wavelength at 1.6 mm. Therefore the high power CSR from the undulator will be expected.

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