

Development of Compact Accelerator-Based
Terahertz Radiation Source at Kyoto University

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Abstract

A compact accelerator-based terahertz (THz) radiation source has been successfully developed at Institute of Advanced Energy, Kyoto University. The system had been designed, constructed and could generate the intense THz radiation in the frequency range of 0.16 to 0.53 THz from the short bunch low-energy electron beam at 4.6 MeV. The compact accelerator-based THz radiation source consists of a 1.6 cells photocathode radio frequency (RF) gun, a solenoid magnet, a magnetic chicane bunch compressor, a short planar undulator, a triplet and doublet quadrupole and a beam dump. THz radiations are generated by injecting short electron bunches to the undulator. Electrons emit radiations in the forward direction with a high degree of phase coherence or called coherent undulator radiation (CUR) whose intensity is much higher than a random phase radiation. The system is simple, economic and compact with total length of 3.7 m and aims to use for basic researches and industrial applications.

During the development of the system, many research and technical works had been carried out. The system was designed by using the particle tracking simulation codes PARMELA and General Particle Tracer (GPT). PARMELA was used for the calculation of the beam properties at the RF gun exit for the magnetic chicane design. While GPT was used for the start-to-end tracking simulation. The photocathode RF gun was installed, commissioned and could generate the first electron beam in May 2015. The RF gun could provide the beam energy of 4.6 MeV and the relative energy spread of 1.3 % at the driven RF power of 9 MW and the laser injection phase of 30 degree. The maximum bunch charge reached up to 1.4 nC at the laser energy of 350 μ J. At the bunch charge of 50 pC, the beam emittances were 0.5 and 0.8 mm-mrad in the horizontal and vertical axis, respectively. The magnetic chicane bunch compressor employs four rectangular dipole bending electromagnets arranged in the longitudinal symmetric layout. The magnetic field of the bending magnet was calculated by using RADIA. The bunch compression characteristics of the chicane were investigated by the observing of the coherent transition radiation (CTR). The chicane successfully compressed the electron bunch at the laser injection phase less than 40 degree and the peak CTR intensity occurred at the laser injection phase of 24 degree. The estimated minimum bunch length by fitting the CTR spectrum to the spectrum of the Gaussian distribution was less than 1 ps at the R_{56} around - 45 mm. The THz radiation generated by the undulator had the frequency range from 0.16 to 0.53 THz with the bandwidth of 10%. The details of the design, the simulations and the measurement results are explained in this thesis.

Contents

Chapter 1 Introduction.....	1
1.1. Terahertz Radiation Overview.....	1
1.2. Coherent Undulator Radiation from a Short Electron Bunch.....	5
1.2.1 Electron Motion in Undulator.....	5
1.2.2 Spatial and Spectral Distribution of Undulator Radiation.....	7
1.2.3 Coherent Enhancement of Undulator Radiation.....	10
Chapter 2 Development Overview of Compact Accelerator-based Terahertz Radiation Source	12
2.1 Conceptual Design.....	12
2.2 Beam Line Components.....	14
2.2.1 Electron source.....	14
2.2.2 Bunch Compressor.....	17
2.2.3 Undulator.....	18
2.2.4 Beam Dump Bending Magnet.....	18
2.2.5 Focusing Magnet.....	19
2.3 Beam Line Layout.....	20
2.4 Beam Line Construction and Timeline.....	22
Chapter 3 Beam Line Components, Instrumentations and Control System.....	24
3.1 Photocathode RF-gun and Related System.....	24
3.1.1 Theory of Photoemission and Beam Dynamics.....	24
3.1.2 Photocathode RF gun	29
3.1.3 Laser System and RF System	31
3.1.4 Time Structure.....	36
3.1.5 Low and High Power Test.....	37
3.2 Bunch Compressor.....	40
3.2.1 Working Principle.....	40
3.2.2 Calculation of 1 st order Momentum Compaction Factor.....	47
3.2.3 Dipole Magnet of the Magnetic Chicane	49
3.2.4 Measurement of H-magnet Magnetic Field.....	52

3.3 Undulator	55
3.3.1 Undulator Specification.....	55
3.3.2 Measurement of Undulator Magnetic Field	56
3.4 Focusing and Steering Magnets.....	59
3.4.1 Solenoid magnet.....	59
3.4.2 Quadrupole magnet.....	61
3.4.3 Steering Magnet.....	65
3.5 Beam Instrumentation	66
3.5.1 Beam Profile Monitor.....	66
3.5.2 Bunch Charge Monitor	66
3.5.3 Energy Spectrometer.....	68
3.5.4 Michelson Interferometer	70
3.5.5 Terahertz Radiation Detector.....	73
3.6 Control System.....	77
 Chapter 4 Particle Tracking Simulation.....	 79
4.1 Tracking Simulation Codes.....	79
4.2 Start-to-end Tracking Simulation by GPT	82
 Chapter 5 Measurement of Beam Properties	 87
5.1 Beam Energy and Energy Spread.....	87
5.2 Beam Emittance.....	92
5.3 Bunch Charge	94
5.4 Dark Current.....	96
5.5 Laser Beam Size	98
 Chapter 6 Investigation of Bunch Compression Characteristics by Coherent Transition Radiation.....	 101
6.1 Transition Radiation	101
6.1.1 Theory of Transition Radiation.....	101
6.1.2 Coherent Transition Radiation from Short Electron Bunch.....	103
6.2 CTR Experiment and Results.....	104
6.2.1 Spatial Distribution	105

6.2.2 Total CTR Intensity	107
6.2.3 Bunch Compression Characteristics	108
6.2.4 Power spectrum of CTR	110
6.2.5 Estimation of Bunch Length	113
 Chapter 7 Measurement of Undulator Radiation	 116
7.1 Measurement Setup and Results.....	116
7.1.1 Spatial Distribution.....	118
7.1.2 Total Intensity.....	120
7.1.3 Power Spectrum	122
 Chapter 8 Conclusion.....	 129
List of Publications.....	132
Acknowledgement.....	136
References.....	137
Appendix.....	141
A. Input files of Simulation.....	141

Chapter 1

Introduction

1.1 Terahertz Radiation Overview

Over past a few decades, the study of Terahertz (THz) radiation or THz science gains a high interest in various fields of basic researches and industrial applications. THz radiation is an electromagnetic radiation whose frequency lies between microwave and infrared. The boundary of the THz regime is not strictly defined typically but refers to 100 GHz to 30 THz (see Fig.1.1). This regime knows as a *frequency gap* in the electromagnetic spectrum that difficult to generate by conventional electronics or optical devices. The frequency range of THz radiation corresponds to intermolecular vibration [1] a large molecule vibration such as a biological molecule that allows us to extend the study of the molecular dynamics beyond conventional infrared radiation techniques. Therefore, THz science is able to provide new information or methods of material analysis. For examples, THz time-domain spectroscopy (THz-TDS) technique [2] uses a short pulse of THz radiation to probe material properties. The materials effect on both amplitude and phase of the THz pulse. Therefore, the THz-TDS provide more information than the conventional Fourier-transform spectroscopy techniques which give only the amplitude information. THz radiation is suitably used as a pump pulse to excite the vibration of molecules in a pump-probe experiment [3] that allows studying of chemical reactions in a transient state. On the other hand, communication devices operating in THz frequency range can provide a higher data transmission rate than currently used in gigahertz frequency range. THz radiation is able to penetrate a non-conducting material such as envelopes, clothes, plastic packaging etc. Hence THz radiation is suitable for non-destructive and non-invasive inspection and can be used similar to x-ray in some case. THz radiation has less harmful to biological molecules than x-ray because it has low photon energy and is a non-ionized radiation.

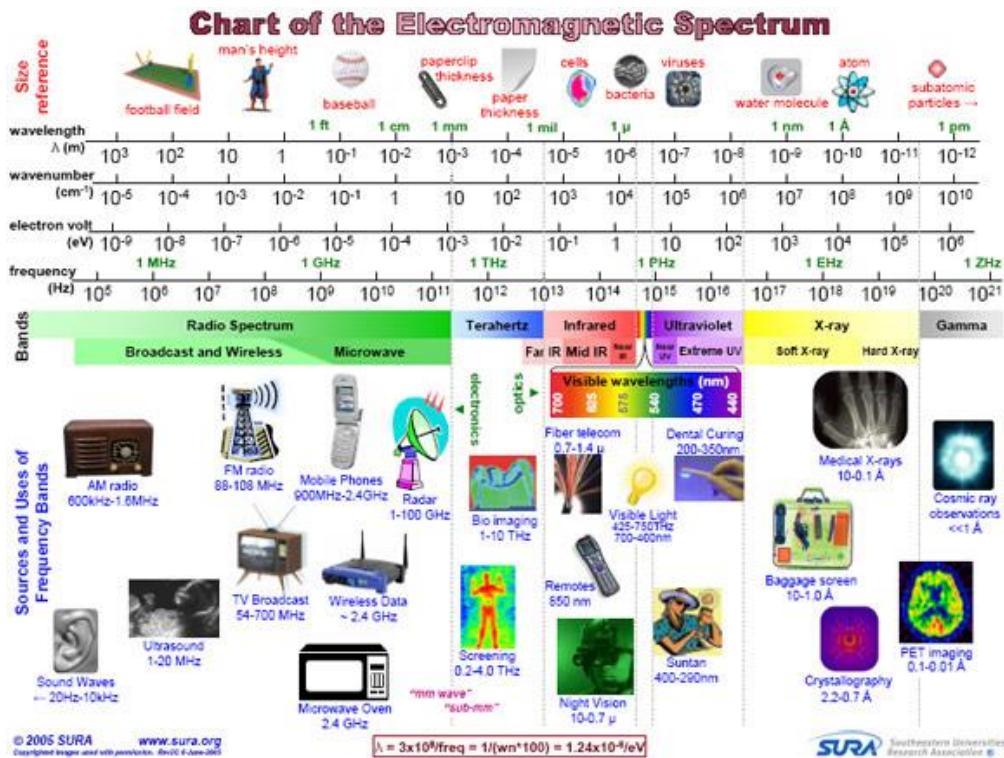


Figure 1.1: Electromagnetic spectrum and its utilization [4]

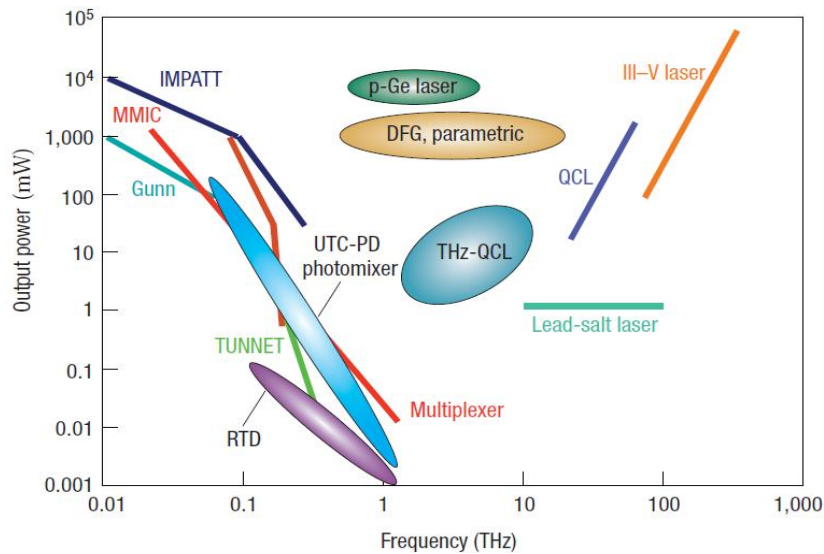


Figure 1.2: Schematic diagram of the THz emission power as a function of frequency. IMPATT; impact ionization avalanche transit-time diode, MMIC; microwave monolithic integrated circuit, TUNNET; tunnel injection transit time, Multiplexer; SBD frequency multiplier, Gunn; Gunn diode, UTC-PD; Uni-traveling-carrier photodiode, RTD; Resonance tunneling diode, QCL; Quantum cascade laser and DFG; Difference-frequency generation. The values of TUNNET and Multiplexer are indicated by the peak power and the others are indicated by the average power. [1]

Nowadays, there are many types of THz radiation sources have been invented and the diagram of the emission power of the sources as a function of frequency [1] is shown in Fig. 1.2. The solid line in the diagram is the conventional THz radiation sources. The sources can be categorized in two main groups. First, electronic devices which are specifically designed to operate at an ultra-high frequency are on the left side of the diagram. Second, the photonic devices developed towards low frequencies are on the right side of the diagram. The emission powers of these devices drop toward the THz frequency regime at around 100 GHz to 30 THz. The specially designed THz sources such as a p-type germanium laser (p-Ge laser), a nonlinear crystal for the different frequency generation (DFG) and the THz parametric generator can provide THz radiations but the emission powers limit in just a few watt. THz radiation is also very rare in natural. At the black body radiations at temperature 3000K, the fraction of the THz radiation is less than 1% of the total radiations. By these difficulties of the THz generation, the development of the THz radiation source is one of the main challenges in the THz science especially in a high power region.

An accelerator-based THz radiation source is a kind of sources that can provide THz radiation with a high power, a high brightness, a narrow bandwidth and a continuous tunable frequency. A charged particle beam, which is usually an electron beam, is accelerated until relativistic speed then able generates the THz radiations by several techniques. For examples, an electron beam bended by magnetic fields of a bending magnet and generate THz radiation by *Synchrotron Radiation* [5]. THz radiations are generated by a short bunched electron beam cross a non-uniform dielectric material such as vacuum-metal called *Transition Radiation* [6]. THz radiations generated by injecting an electron beam close to the grating surface are known as *Smith-Purcell Effect* [7]. An electron beam travels through the periodic magnetic fields and emits the THz radiation with a narrow bandwidth in forward direction called *Undulator Radiation* [8]. The idea of generating the THz radiations from the undulator was proposed in early fifties by Motz [9] on the emission of radiation by fast electrons passing through an undulator. In case of an electron bunch length shorter than a THz radiation wavelength, the undulator radiation become coherence or called *Coherent undulator radiation* (CUR) whose power is much higher than the incoherent ones. The examples of the machine employed this scheme are the SUNSHINE (Stanford University Short Intense Electron Source) facility [8] which can generate the radiation in the frequency range from 1 to 6 THz from the electron beam energy of 15 MeV and TELBE (Terahertz facility at ELBE) [10] can provide the radiation from 0.3 to 1.5 THz by 40 MeV beam. Over past decade, a small-scale accelerator systems operating by a few MeV modulated electron beam had been

proven that it has the potential to generate a high power THz radiation. The examples of the machines are FEL-CATS [11, 12] which is able to generate the radiation from 0.4 to 0.7 THz by 2.5 MeV beam. The facility at Peking University [13] which operates in the beam energy range of 2.4 to 3.1 MeV can provide the radiation in the range from 0.24 to 0.42 THz.

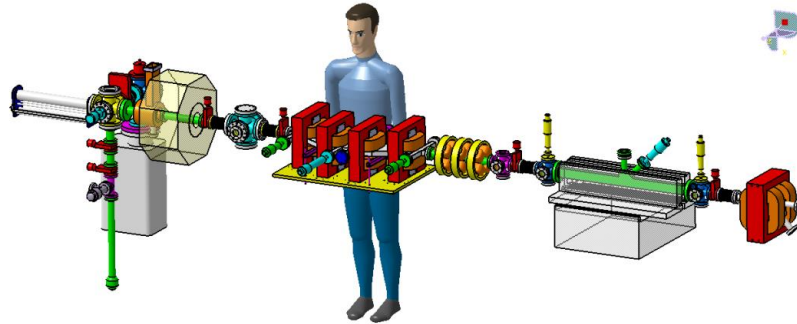


Figure 1.3: 3-dimensional model of the compact accelerator-based THz radiation source at Institute of Advanced Energy, Kyoto University.

We have also been developed a new compact accelerator-based THz radiation source at Institute of Advanced Energy, Kyoto University and the 3-dimensional model of the system is shown in Fig. 1.3. The project plans to generate high brightness and high power THz radiations in a longer wavelength range than the current operating mid-infrared free-electron laser (KU-FEL) [14]. At this first stage of the development, the goals are to design, construct and generate the THz radiation via CUR from a short bunch and low energy electron beam. This thesis explains the details of the design, the selection of the operating parameters, the component designs, the simulations and the measurements of the CUR.

The structure of the thesis starts with the Chapter 1 which is the introduction of the THz radiation and the theory of CUR. The overview of the system development is described in Chapter 2. Chapter 3 explains the related theories and details of beam line components, the instrumentations and the control system. Chapter 4 describes the particle tracking simulation by a numerical simulation code PARMELA [15] and GPT [16]. The measurements of the beam properties such as the beam energy, the bunch charge and the beam emittance are presented in Chapter 5. The bunch compression characteristics and the estimation of the bunch length by the observation of the coherent transition radiation (CTR) describe in Chapter 6. The measurement results and discussions of the undulator radiation are presented in Chapter 7. Finally, the conclusion is described in Chapter 8.

1.2 Coherent Undulator Radiation from a Short Electron Bunch

Undulator is a device which generates periodic magnetic fields to drive the electrons in a sinusoidal trajectory. Electrons travel inside the undulator and emit radiation due to the transverse acceleration by the magnetic fields. The radiations concentrate in the forward direction and the radiation wavelength observed in the laboratory frame appears contracted by the *Lorentz's transform* and *Doppler Effect*. The spectrum of radiation has a narrow bandwidth due to the longitudinal interference. In case of the electron bunch length is comparable to the radiation wavelength, radiations has a high degree of phase coherence or called *Coherent Undulator Radiation* (CUR). The intensity of CUR is proportional to the square of the number of electron. The schematic diagram of the electron traveling through an undulator is shown in Fig. 1.4. The characteristic of electrons traveling in an undulator and their radiations will be explained in the following.

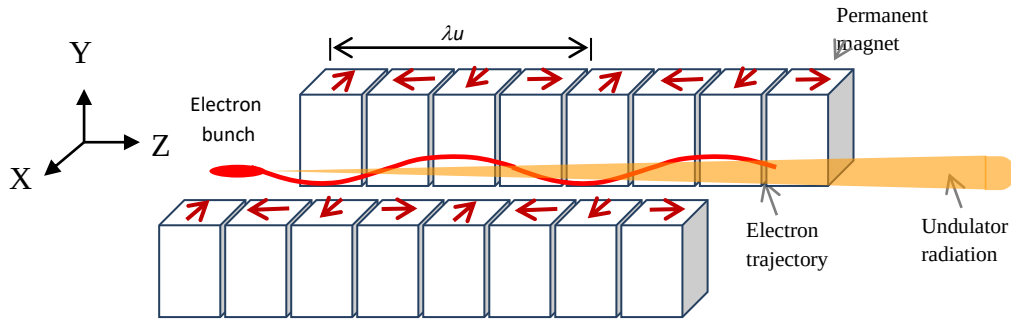


Figure 1.4: Schematic diagram of electron motion in a planar vertical deflection Halbach type undulator and the emission of undulator radiations.

1.2.1 Electron motion in an undulator

In this study, we consider an ideal planar vertical deflection undulator as the theoretical model. The magnetic fields between the undulator gap is assumed to be purely sinusoidal and only in the horizontal direction (X direction). The magnetic fields and the electron trajectory and the coordinate are illustrated in Fig. 1.5. The magnetic fields in the undulator gap can be expressed by

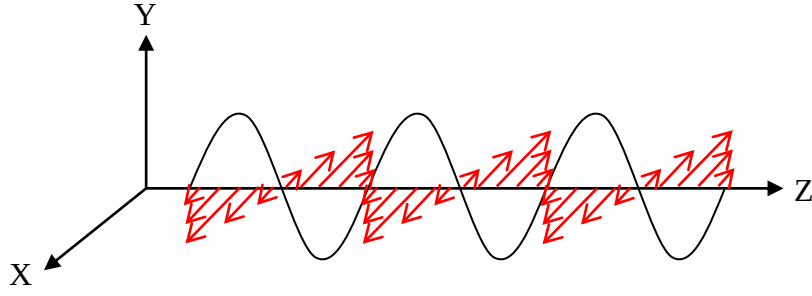


Figure 1.5: Magnetic fields (arrows) and electron trajectory (solid line) of the ideal planer vertical deflection undulator.

$$B_x = -B_0 \cosh(k_u x) \sin(k_u z) , \quad (1.1)$$

$$B_y = 0 , \quad (1.2)$$

$$B_z = -B_0 \sinh(k_u x) \cos(k_u z) , \quad (1.3)$$

where B_0 is the peak magnetic field, k_u is the undulator wave number $k_u = 2\pi/\lambda_u$ and λ_u is the undulator period length. Electrons traveling inside the undulator are only influenced by the magnetic fields. Electron trajectory in an undulator can be derived from the Lorentz force equation,

$$\gamma m_e \mathbf{v} = -e \mathbf{v} \times \mathbf{B} , \quad (1.4)$$

$$\ddot{y} = \frac{e}{\gamma m_e} B_x \dot{z} , \quad \ddot{z} = \frac{e}{\gamma m_e} B_x \dot{x} . \quad (1.5)$$

The above equations show that the electron motion is coupled between X and Y axes. We assume that the longitudinal velocity $\dot{z}$ is constant along an undulator $\dot{z} \approx \beta c$, then $\ddot{z} \approx 0$. The transverse electron trajectory along the center axis can be calculated by integrating Eq. 1.5 two times respected to the t and then yields

$$y(t) \approx \frac{e B_0}{\gamma m_e \beta c k_u^2} \sin(k_u \beta c t) , \quad (1.6)$$

$$y(z) = \frac{K}{\beta \gamma k_u} \sin(k_u z) , \quad (1.7)$$

$$K = \frac{eB_0}{m_e c k_u} = \frac{eB_0 \lambda_u}{2\pi m_e c} = 0.934 B_0 \lambda_u, \quad (1.8)$$

Where γ is the Lorentz factor, B_0 is the peak magnetic field on the undulator axis, m_e is the electron mass and c is the speed of light. K is the undulator strength parameter. In case of the K equal or less than one, the electron trajectories are nearly perfect sinusoidal trajectory and this device is called *Undulator*. The same structure device with the K larger than one is called *Wiggler* [17] which provides a higher magnetic field strength than the undulator. Electrons travel inside the Wiggler with distorted sinusoidal trajectories resulting in the radiations with many higher harmonics.

1.2.2 Spatial and Spectral Distribution of Undulator Radiation

The radiant intensity I of the spatial and spectral distribution of undulator radiation for a known trajectory electron can be calculated by the *Leinard-Weichert potential* [18]. The spatial distribution G_n and the spectral distribution H_n function of undulator radiation are given by

$$\frac{d^2 I}{d\Omega d\omega} = \frac{q^2 \gamma^2 N^2}{4\pi \epsilon_0 c} \sum_{n=1}^{\infty} G_n(K, \gamma\theta, \phi) H_n(K, \gamma\theta, \omega) \quad (1.9)$$

where

$$G_n(K, \gamma\theta, \phi) = \frac{4n^2}{A^2} \left\{ \left[S_1 \alpha \cos\phi - \left(S_1 + \frac{2}{n} S_2 \right) \frac{A}{2\alpha \cos\phi} \right]^2 + S_1^2 \alpha^2 \sin^2\phi \right\} \quad (1.10)$$

$$H_n(K, \gamma\theta, \omega) = \left\{ \frac{\sin[N\pi(\omega/\omega_1 - n)]}{\pi N(\omega/\omega_1 - n)} \right\}^2 \quad (1.11)$$

and

$$S_1 = \sum_{k=-\infty}^{+\infty} J_k(n\xi_z) J_{2k+n}(n\xi_x) \quad S_2 = \sum_{k=-\infty}^{+\infty} k J_k(n\xi_z) J_{2k+n}(n\xi_x) \quad (1.12)$$

$$\xi_z = \frac{K^2}{4A} \quad \xi_x = \frac{2K\alpha \cos\phi}{A} \quad A = 1 + \alpha^2 + \frac{K^2}{2} \quad \alpha = \gamma\theta \quad (1.13)$$

$$\omega_1 = \frac{2\gamma^2\omega_0}{1 + \gamma^2\theta^2 + K^2/2} \quad \omega_0 = \frac{2\pi c}{\lambda_0} \quad (1.14)$$

and q is the charge of particle, N is the number of undulator periods, Ω is the solid angle, ω is the angular frequency, ε_0 is the permittivity of free space, θ is the observation angle with respect to the undulator axis, ϕ is the angle about undulator axis, γ is the Lorentz factor, J_n is the Bessel function of the first kind of order n and λ_0 is the undulator period length. In the forward direction $\theta = 0$ and at the first harmonic $n = 1$, the fundamental frequency ω_{10} and fundamental wavelength λ_r can be expressed by,

$$\omega_{10} = \frac{2\gamma^2\omega_0}{1 + K^2/2}, \quad (1.15)$$

$$\lambda_r = \frac{\lambda_0}{2\gamma^2} \left(1 + \frac{K^2}{2}\right). \quad (1.16)$$

Then the spectral distribution equation can be simplified to

$$\left| \frac{d^2 I}{d\Omega d\omega} \right|_{\theta=0} = \frac{q^2 \gamma^2 N^2}{4\pi \varepsilon_0 c} F_n(K) \left\{ \frac{\sin[N\pi(\omega/\omega_{10} - n)]}{\pi N(\omega/\omega_{10} - n)} \right\}^2, \quad (1.17)$$

$$F_n(K) = \begin{cases} \frac{K^2 n^2}{(1+K^2/2)^2} \times \left[J_{\frac{n+1}{2}} \left(\frac{nK^2/4}{1+K^2/2} \right) - J_{\frac{n-1}{2}} \left(\frac{nK^2/4}{1+K^2/2} \right) \right]^2 & n = 1, 3, 5 \dots \\ 0 & otherwise \end{cases} \quad (1.18)$$

If an undulator is very long and N close to infinity, the spectral bandwidth $\Delta\omega$ become very narrow like δ -function at the center frequency ω_0 . For a finite N_u period undulator, the spectral bandwidth is inverse proportional to the number of period of the undulator and has a full width at half maximum $\Delta\omega$ of

$$\frac{\Delta\omega}{\omega_{10}} = \frac{1}{N_u} \quad (1.19)$$

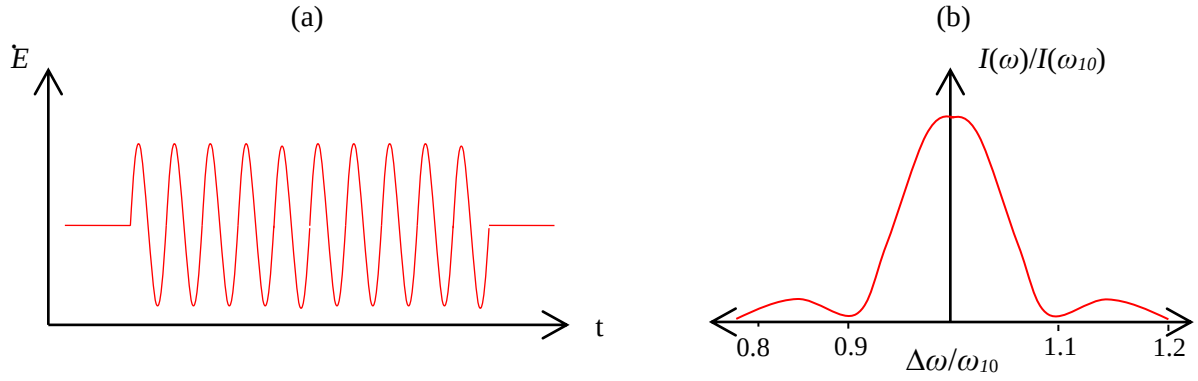


Figure 1.6 (a) Undulator radiation field wave train and (b) the spectral distribution of a 10-period undulator.

Figure 1.6 shows an ideal radiation field from a 10-period undulator and its spectral distribution. The number of cycle of the radiation field wave train has the same as the number of period of the undulator. The spectral distribution of the undulator radiation can be obtained by the Fourier transform of this field. The spectrum contains a main component at the center frequency and the smaller ones beside due to the finite length of the wave train. For actual beam, electrons enter an undulator with a transverse off-axis and a planar undulator focuses beam in the non-deflecting plane like a rectangular bending magnet. Consequently, the betatron function inside an undulator oscillates resulting in appearing of the off-axis radiation at the center axis. Therefore, the observed spectrum of the undulator radiation at the center axis becomes wider bandwidth as illustrated in the Fig. 1.7.

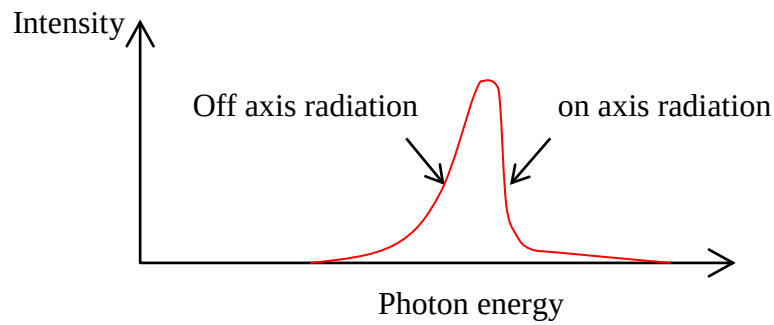


Figure 1.7 Spectral of the undulator radiation on the center axis.

1.2.3 Coherent Enhancement of Undulator Radiation

In case of many electrons, undulator radiation is the summation result of the individual emitted fields. The total undulator radiation electric field $E_{tot}(\omega)$ of N_e electrons with j number [8] can be calculated by

$$\vec{E}_{tot}(\vec{k}) = \vec{E}_{1e}(\vec{k}) \sum_{j=1}^{N_e} e^{i(\omega t_j + \vec{k} \cdot \vec{r}_{j\perp})}, \quad (1.20)$$

where E_{1e} is the field of a single electron, the t is the time of electron, the k is the wave number, the r is the vector in transverse and N_e is the number of electron. The total radiation power P_{tot} is proportional to the square of the field so

$$P_{tot}(\vec{k}) = P_{1e}(\vec{k}) \left| \sum_{j=1}^{N_e} e^{i\vec{k} \cdot \vec{r}_j} \right|^2, \quad (1.21)$$

where $\vec{r}_j = \vec{r}_{j\perp} + z_j \hat{z}$ locate at the j -th electron with respect to the first electron. The above equation can be rewritten in the continuum limit as

$$P_{tot}(\vec{k}) = P_{1e}(\vec{k}) N_e^2 \left| \int S(\vec{r}) e^{i\vec{k} \cdot \vec{r}} d^3r \right|^2, \quad (1.22)$$

where $S(\vec{r})$ is the probability distribution function in the 3-dimensional direction and $\int S(\vec{r}) e^{i\vec{k} \cdot \vec{r}} d^3r$ is the Fourier transform of electron distribution which is defined as the *form factor*. In the longitudinal direction (z axis), the form factor of a bunch with the normalized longitudinal distribution function $S(z)$ can be determined by

$$h(\omega) = \int S(z) e^{kz} dz \quad (1.23)$$

The form factor has the maximum value at one when a bunch has a zero bunch length. For an actual beam, the bunch length is not zero and particle distribution of can be any function. To simplify the calculation, we assume that the longitudinal particle distribution is the Gaussian distribution with the standard deviation σ_z . The form factor in the longitudinal direction of this bunch can be expressed by

$$f(k_z) = 1/\sqrt{2\pi}\sigma_z \int_{-\infty}^{+\infty} e^{-z^2/2\sigma_z^2} e^{ik_z z} dz = e^{-\sigma_z^2 k_z^2} \quad (1.24)$$

The energy radiated by a single electron E_{1e} of energy γmc^2 in the forward direction at the fundamental frequency ω_0 can be calculated by the Fourier transform of the N -period sine wave [8]

$$E_{1e}(\omega) \propto \int_0^{\frac{2\pi N}{\omega_{10}}} e^{i\omega_{10}t} e^{-i\omega t} dt = \frac{2\pi N}{\omega_{10}} \left(e^{-i\pi N \frac{\omega - \omega_{10}}{\omega_{10}}} \right) \left[\frac{\sin(\pi N(\omega - \omega_{10})/\omega_{10})}{\pi N(\omega - \omega_{10})/\omega_{10}} \right] \quad (1.25)$$

$$E_{1e} = \frac{Nq^2}{6\epsilon_0} \frac{2\pi}{\lambda_0} K^2 \gamma^2 \quad (1.26)$$

where q is the charge of electron and ϵ_0 is the permittivity of free space.

Chapter 2

Development Overview of Compact Accelerator-Based Terahertz Radiation Source

2.1 Conceptual Design

A compact accelerator-based THz radiation source at Institute of Advanced Energy, Kyoto University is a new machine and aim to generate the radiation in a longer wavelength regime than the current operating mid-infrared free electron laser (KU-FEL) [14]. The KU-FEL is able to provide the radiation in the wavelength range from 4 to 23 μm by using the 1.8 m long undulator with the optical resonator as the radiator and the beam energy range from 20 to 40 MeV. The bunch charge of the KU-FEL is limited at the maximum around 40 pC due to the back bombardment effect [19] of the thermionic cathode RF-gun. While the compact THz system plans to generate the radiation in the wavelength of a few hundred micrometers by low energy electron beam around 5 MeV with a higher bunch charges than KU-FEL. The development of the compact THz system is based on the KU-FEL facility by sharing the building, the RF power source, the controls and the measurement systems.

The research work of the compact THz radiation source has been started since 2008 [20]. The system with different configurations had been proposed and studied. For example, the numerical study of the THz radiation generation using the photocathode RF gun as the electron source was explained in [21]. The development of the multibunch photocathode laser drive system for the photocathode radio frequency (RF) gun driven was described in [22]. The seed THz FEL laser to a short planar undulator was studied in [23]. After the carefully considerations, we decided to fix the system configuration and started the construction in the end of year 2013. The main components consist of a 1.6-cell S-band BNL-type photocathode RF gun equipped with a solenoid magnet, a magnetic chicane bunch compressor, a triplet and a doublet quadrupole magnet, a planar Halbach type permanent magnet undulator, a beam dump and a photocathode drive laser system. All main components except the magnetic chicane have already existed before the start of construction. Only the magnetic chicane is a new component which was specifically designed for the compact THz system. The design of the chicane and the selection of the operating parameters had been performed in this study.

The system plans to generate THz radiations via CUR as explained in the section 1.1.2. The photocathode RF gun is used as electrons source and expect to provide a beam with a high bunch charge, a low emittance and a low energy spread. The bunch from the RF gun will be compressed by the magnetic chicane until its bunch length comparable to the CUR wavelength resulting in a higher CUR intensity. The frequency of the CUR also can be continuously tuned by adjusting the undulator gap. The target performances of the compact THz radiation source are listed in Table 1. The typical performances of the KU-FEL confirmed in July 2016 [14] are listed in Table 2.

Table 2.1: Target performances of the compact THz radiation source

Parameters	Values
Electron beam energy	4 to 5 MeV
Electron beam energy spread	1 %
Bunch charge	~ 200 - 300 pC
Compressed bunch length	~1 ps
Radiation wavelength	500 - 1500 μm
Spectrum bandwidth ($\Delta\omega/\omega$)	10%
Peak radiation power	$\sim 10^6$ W

Table 2.2: Typical performance of KU-FEL (July 2016).

Parameters	Values
Electron beam energy	20 to 40 MeV
Wavelength range	3.6 – 23 μm
Spectrum width	~ 3%
Macro-pulse repetition rate	1 – 2 Hz
Maximum macro-pulse energy	30 mJ @5 μm
Macro-pulse duration	~ 2 μs
Micro-pulse repetition rate	2856 MHz
Maximum micro-pulse energy	~ 5 μJ @5 μm
Micro-pulse duration	0.6 ps @12 μm (Qin et al. (2012))

2.2 Beam Line Components

This section describes the background, the concept design and the installation of the main components of the compact THz system. Technical details of each component are explained in the chapter 3.

2.2.1 Electron Source

Electron source for the compact THz system must be compatible with the current operating KU-FEL electron source which is the 4.5 cells S-band normal conducting thermionic cathode RF gun. The thermionic cathode RF-gun provides a beam with limited bunch charge and has low beam stability due to the back bombardment effect. Therefore, to overcome these limitations, the 1.6 cells BNL-type photocathode RF gun was selected as the electron source for the compact THz system. This gun was designed and manufactured by Japan High Energy Accelerator Research Organization (KEK) [24]. This RF gun is the last version of the development series and many improvements had been implemented such as using a frequency tuning by the deformation of the inner RF cavity wall, removing screws on the gun back plate, removing the laser injection port and finishing surface were extremely smooth by using a super-fine lathe diamond cut. These improvements allow achieving a high quality factor, a high acceleration field with a low dark current and a low break down rate. The same design guns were donated to Kyoto, Tokyo and Osaka University in 2008. The photocathode plug of this gun is exchangeable in order to change the cathode material. This gun has a solenoid magnet attached in front of the gun for the emittance compensation and the laser has to be injected from the front side to the cathode. The vacuum of the RF gun was maintained by two ionization pumps and two non-evaporative getter (NEG) pumps that provide the total pumping capacity of 380 L/s. The temperature of the RF gun during operation was controlled at 30 °C by the temperature control unit.

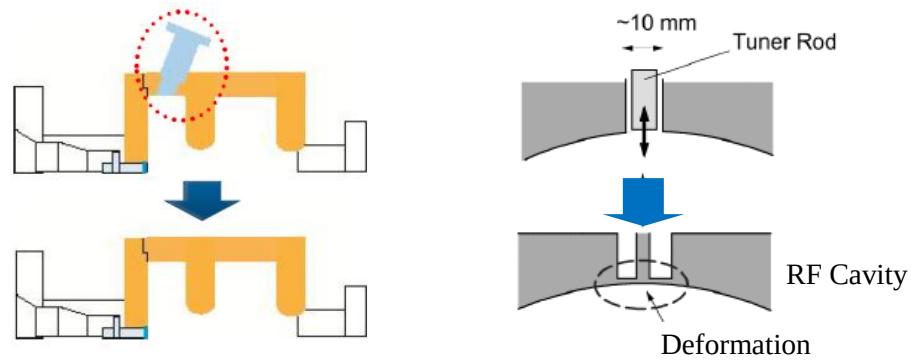


Figure 2.1: Photocathode RF gun improvements, cross section view along the axial show the removal of the laser injection port (left), cross section view along the radial plane at the frequency tuning plug, the frequency tuning deformation of the inner RF cavity wall (right).

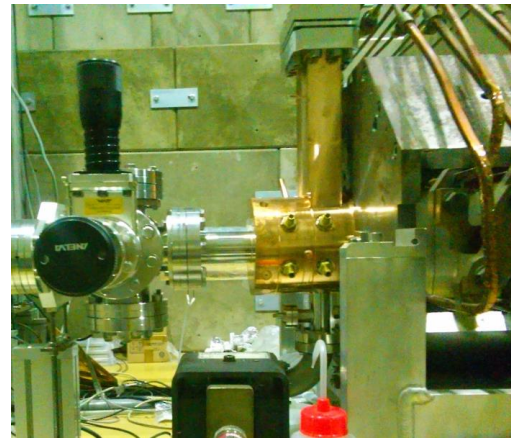
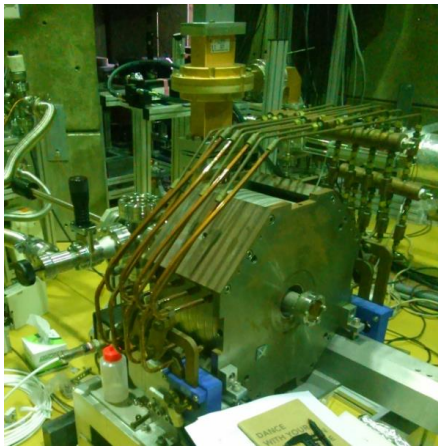


Figure 2.2: Photocathode RF gun before installation in the isometric view (left) and the side view (right).

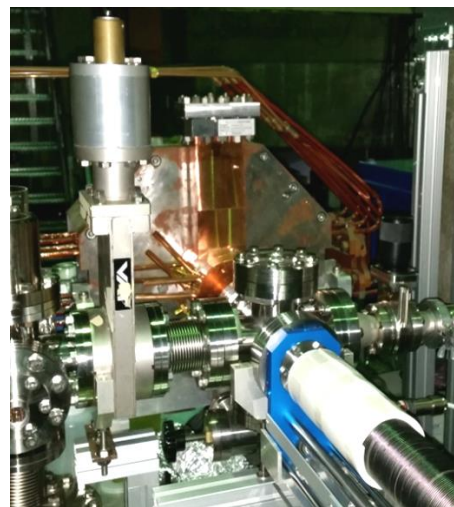


Figure 2.3: Photocathode RF-gun after installation in the front side (left) and the back side (right).



Figure 2.4: Top view of the photocathode RF-gun.

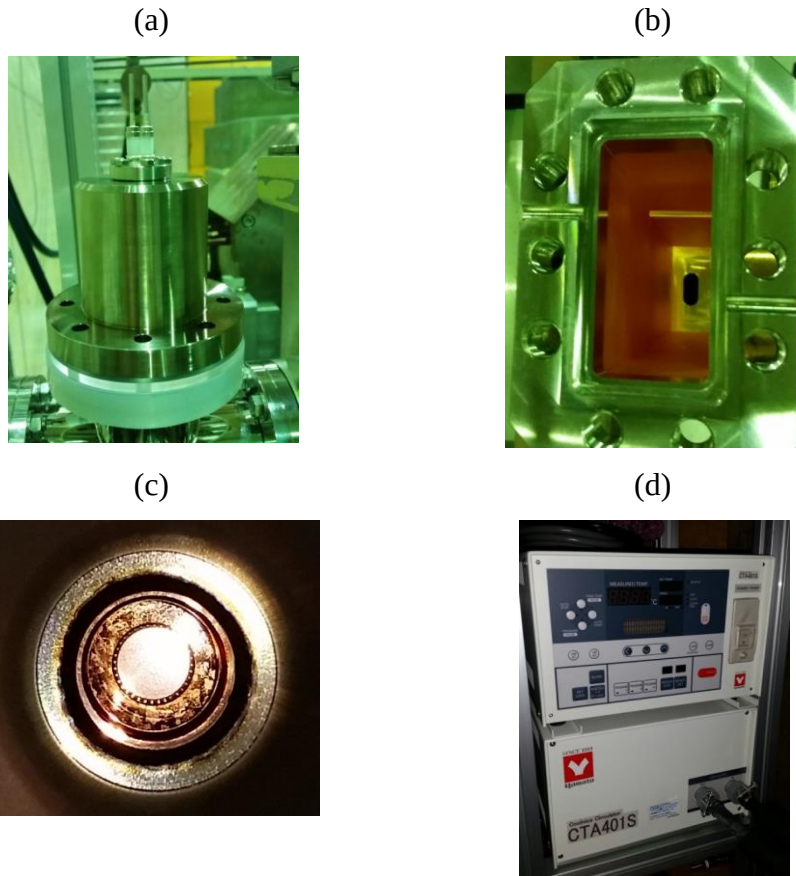


Figure 2.5: (a) Non evaporative getter (NEG) pump (b) Coupling hole between the waveguide and the RF gun cavity (c) the cathode plug (d) the temperature control unit

2.2.2 Bunch Compressor

To generate an intense CUR, a bunch length of electrons injected to an undulator must be as short as possible. The bunch length of the exiting bunch from the photocathode RF gun is not short enough limited by a laser pulse duration illuminated to the cathode and the acceleration characteristic. Therefore, a magnetic bunch compressor has to be employed for a further compression of the bunch from the RF gun. The magnetic bunch compressors create a dispersive beam inside that allows manipulating of a longitudinal phase-space of a bunch. Many types of magnetic bunch compressors can be used for longitudinal bunch compression such as an alpha magnet, an achromatic bending magnet, two bending magnets etc. The bunch compressor type selection

By considering many factors such as a layout of beam line, a size of bunch compressor, a flexibility of usage, we decided to use a magnetic chicane with four dipole rectangular bending magnets arranged in the longitudinal symmetric layout as the bunch compressor. The chicane was designed for operating in low beam energy regime for both compression and uncompression modes. The gap between the pole face of the magnet is 30 mm which is the same as the gap of the bending magnet of KU-FEL. The two magnets at the middle of the chicane can be moved in the horizontal direction for operating in the large deflection angle. The vacuum chamber was designed to allow the maximum beam deflection angle of 35 degree and has 8 ports for beam profile monitors, the energy slit and the vacuum evacuation port.

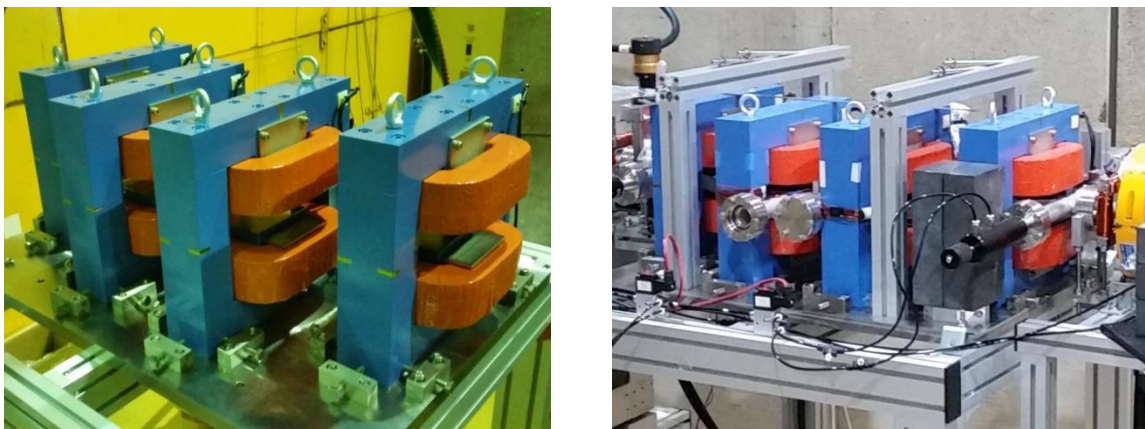


Figure 2.6: Magnetic chicane bunch compressor before (left) and after (right) installation.

2.2.3 Undulator

Undulator for the compact THz system was donated from National Institute of Advanced Industrial Science and Technology (AIST). The undulator is a vertical deflection planar Halbach type permanent magnet with the number of period of 10 and the period length of 70 mm. The undulator gap can be manually adjusted and the minimum undulator gap is limited by a vacuum chamber at 30 mm. The vacuum chamber is a new construction and has a retractable beam profile monitor port at the middle of the chamber. The screen of beam profile monitor was normal to the beam axis and the viewport 45 degree respected to the beam axis.

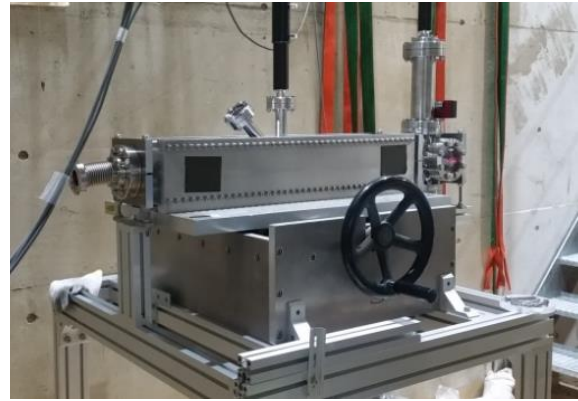
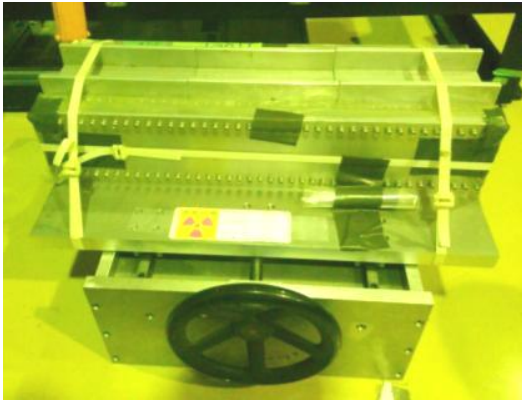


Figure 2.7: Vertical deflection planar Halbach type permanent magnet undulator before installation (left) and during the installation (right).

2.2.4 Beam Dump Bending Magnet

A beam dump bending magnet is a rectangular bending magnet to bend the beam in the vertical direction with the deflection angle of 45 degree. The magnet exists from previous research project with unknown conditions and specifications. The magnetic field distribution of the magnet had been measured to confirm the condition and the measurement results are explained in chapter 3 section 3.5. The vacuum chamber of the beam dump magnet is a new design and has two ports which are the on-axis port and the 45 degree deflection angle port.

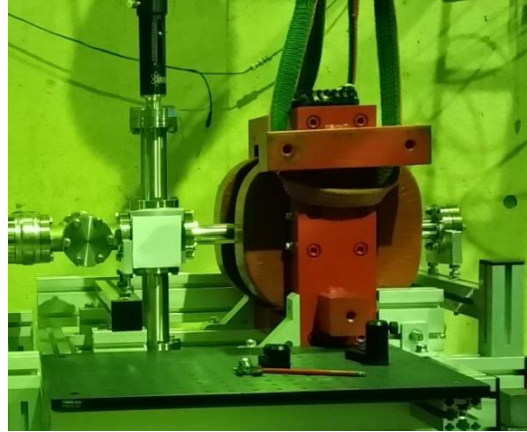


Figure 2.8: Beam dump bending magnet before installation (left) and during installation (right).

2.2.5 *Focusing elements*

Quadrupole focusing magnets were used for the beam focusing as triplet and doubled quadrupole. These quadrupole magnets exist from the previous research project with unknown condition. But the specifications of the magnet can refer to the document from manufacturer. The magnetic field was measured to confirm their conditions and the measurement results are shown in chapter 3 section 3.4.



Figure 2.9: Quadrupole magnet for the beam focusing.

2.3 Beam Line Layout

The compact THz system is located in the same accelerator room with KU-FEL. The available space is limited in the area of 5×8 m beside the KU-FEL linac. The beam line center height is 1.3 m above the floor and 1 m far from the wall.

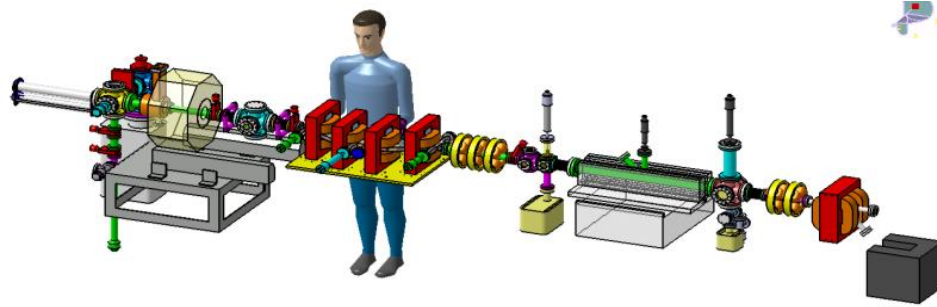


Figure 2.7: 3-dimension schematic view of the compact THz radiation source.

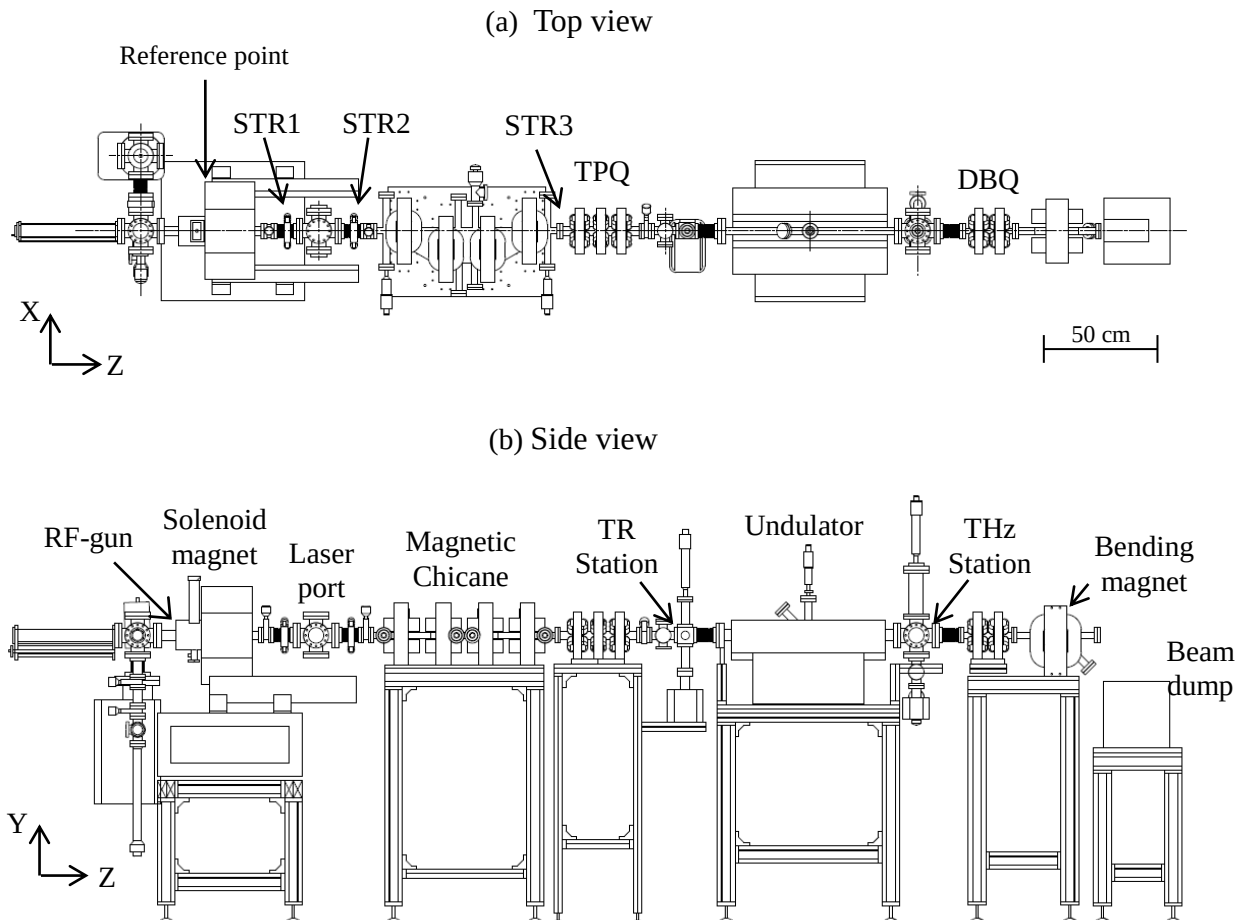


Figure 2.8: Beam line drawing of the compact THz radiation source system (a) top view and (b) side view (STR: Steering magnet, TPQ, DBQ: Triplet and doubled quadrupole magnet, TR: Transition radiation)

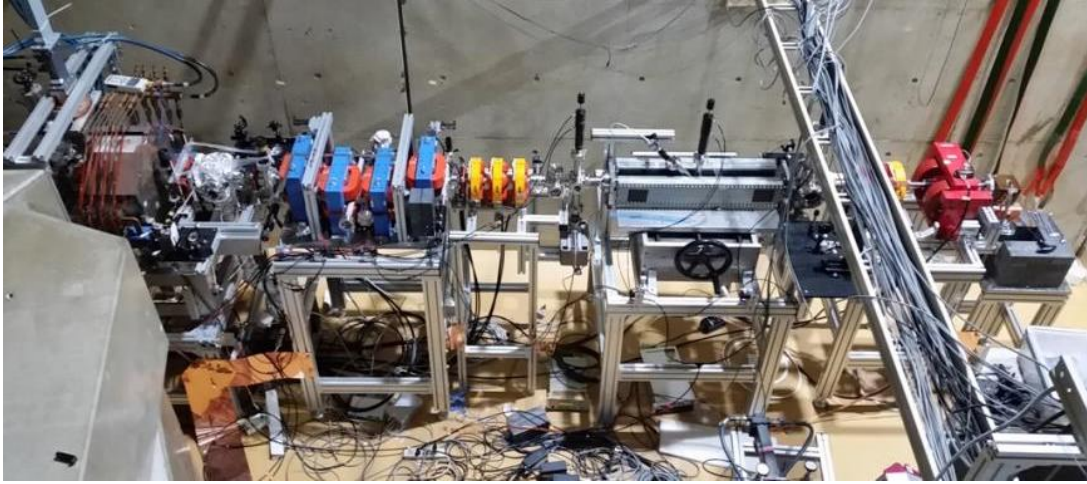


Figure 2.9: Complete beam line of the compact accelerator-based THz radiation source.

Table 2.3: List of the components and locations measured from the edge of solenoid magnet. (See Fig. 2.8 and the dimensions with mark * are values from calculation.)

Beam line components	Center position from the reference point (mm)
Cathode surface	- 124.54*
RF-gun	- 62.27*
Solenoid magnet	114
Steering magnet 1 (STR1)	360
Laser port	500
Steering magnet 2 (STR2)	670
Fluorescence Screen no.1	790
Chicane magnet no.1	875.5
Chicane magnet no.2	1065.5
Chicane magnet no.3	1255.5
Chicane magnet no.4	1445.5
Fluorescence Screen no.2	1520
Steering magnet 3 (STR3)	1610
1 st magnet of triplet quadrupole (TPQ)	1672
TR Station	2030
Undulator	2658
THz mirror	3162
1 st magnet doubled quadrupole (DBQ)	3435
Beam dump bending magnet	4240

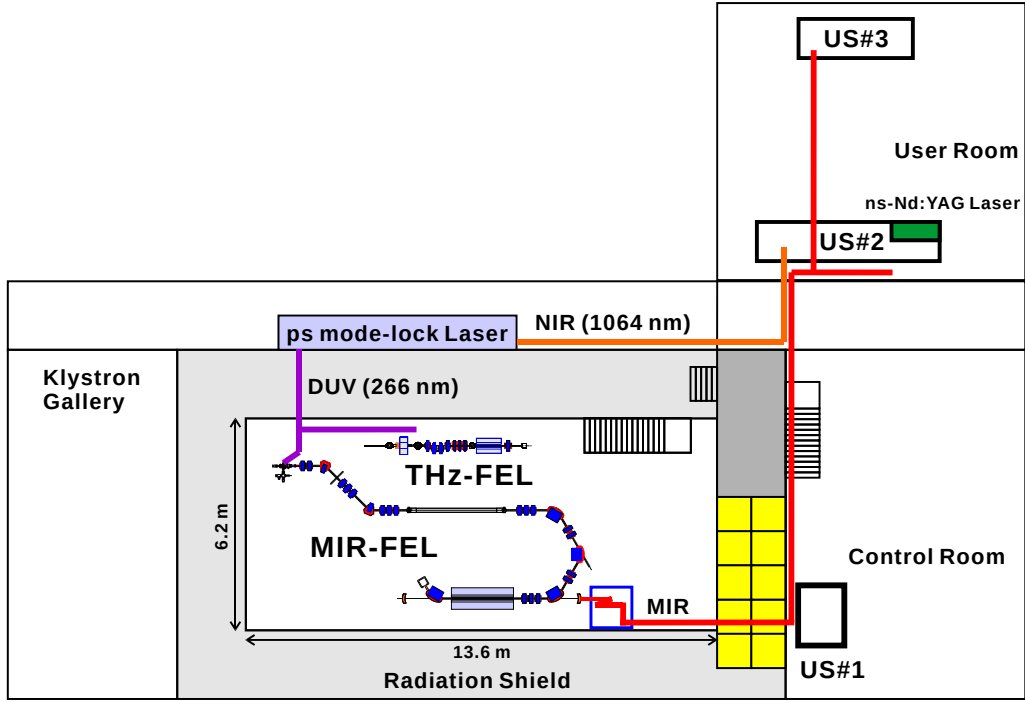


Figure 2.10: Layout of the compact THz system, the KU-FEL (MIR-FEL), the klystron room, the laser room, the control room and the user area.

2.4 Beam Line Construction and Timeline

The construction work of the compact THz system was started in the end of 2013. The waveguide and the RF circulator of the thermionic RF gun of the KU-FEL were disassembled and rearranged (see Fig. 2.11). The waveguide switch was added downstream the RF circulator for switching operation between the thermionic RF-gun of the KU-FEL and the photocathode RF gun of the compact THz system. The RF gun cooling system, the power supplies for the magnets and pneumatic actuators, the vacuum gauge and the control devices were placed on the radiation shield wall beside the beam line. The photocathode RF gun could generate the first photo-electron beam in May 2015 [25]. The magnetic chicane was installed in Feb 2016 and the bunch compression characteristic was investigated by the observing of the coherent transition radiation in Mar 2016 [26]. The undulator was installed in July 2016 and the first THz radiation was generated in Aug 2016 [27].



Figure 2.11: Waveguide after rearrangement, the waveguide switch (at the center of the figure) was installed downstream RF circulator (red) for the switching operation between the 4.5 cells thermionic cathode RF-gun and the photocathode RF-gun.

Chapter 3

Beam Line Components, Instrumentations and Control System

This chapter describes the details of the photocathode RF gun, the bunch compressor, the undulator, the magnets, the instrumentations and the control system including the measurement of their characteristics.

3.1 Photocathode RF-gun and Related System

A photocathode radio-frequency (RF) gun is an advanced electron sources which is able to produce high quality electron beams such as a high-current, a short bunch, a long macro-pulse duration and a low emittance. Unlike a thermionic cathode, electrons emerge from a cathode surface discontinuously by injecting laser pulses to the cathode surface. Therefore, the back bombardment effect [28] in which electrons are accelerated backward and heat up the cathode resulting in the limitation of emitted electrons of the thermionic cathode, can be completely avoided by injecting a laser pulse during the acceleration phase. Moreover, the temporal distribution of electrons can be manipulated by control of the laser distribution. A short and intense electron beam generated by this gun is suitable for accelerator based light source.

Photocathode RF-gun was first operated at Los Alamos National Laboratory [29] in early eighty. The theoretical study of the beam dynamics was proposed by Kim [30] and the extend study based on Kim's study was presented by Travier [31]. In this section, we describe a brief the theory, the beam dynamics, the parameter selection, the RF and the laser system of the photocathode RF-gun.

3.1.1 Theory of Photoemission and Beam dynamics

Photons can extract electrons from a metal surface by the photoelectric effect. The escape energy of electrons from materials is defined as the *work function* (Φ). The mathematical expression of the photoelectric effect is given by

$$E_k = hf - \Phi, \quad (3.1)$$

where E_k is the kinetic energy of electrons, h is the Plank's constant and f is the frequency of the photon. The processes of photoemission can be considered in the three independent steps known as *three step model* [32]. In this study, we consider only overall probability of the photons that can extract electrons from the metal surface. The ratio of the number of emitted electrons n_e to the number of incident photons n_p is defined as quantum efficiency QE,

$$QE = \eta = \frac{n_e}{n_p} = \frac{hv}{E_{laser}} q \quad (3.2)$$

The quantum efficiency is strongly depended on the surface condition of materials. A coating of the metal surface by alkaline metals such as Cs, Te can increase QE. QE reduces as a function of time due to the changing of the surface condition. For a given cathode, the quantum efficiency depends on the laser wavelength. A laser pulse with the wavelength of λ_L and energy W illuminates to a photocathode and then emitted charges Q can be calculated by

$$Q [\text{nC}] = \frac{\eta e W \lambda_L}{hc} = 8.07 \times 10^{-3} \eta [\%] W [\mu\text{J}] \lambda_L [\text{nm}] \quad (3.3)$$

External electric fields also effect to the emitted charges by interrupting the work function of materials known as *Schottky effect* [33]. The electric fields distorted the potential barrier of the cathode material resulting in the reduction of the work function. Thus, the quantum efficiency included Schottky effect can be written as

$$QE \propto (hv - \phi_0 + \alpha\sqrt{E})^2 \quad (3.4)$$

where α is the $= e (e/4\pi\epsilon_0)^{1/2} = 3.7947 \times 10^{-5} [e(\text{Vm})^{1/2}]$.

For the beam dynamic of the photocathode RF gun, we consider a simple pill box cavity structure known as the Brook Heaven National Laboratory (BNL) type [34] which is used for our system. This cavity type is easy to fabricate and the geometry can be scaled in the frequency range from 1.3 to 17 GHz. This cavity provides a low RF breakdown rate. The cut section view of BNL-type RF cavity is shown in Fig. 3.1.

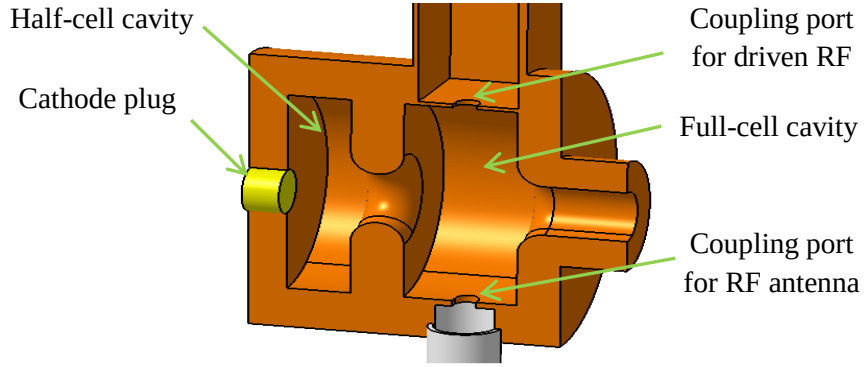


Figure 3.1: Cut section view of the BNL type RF gun

The RF gun of the compact THz system plans to operate at high accelerating electric fields in order to reduce the influence of the space-charge effect by the factor $1/\gamma^2\beta$. The peak field are limited by the field breakdown and depended on the driven RF frequency of the RF gun. The peak accelerating field can be estimated by Kilpatrick criterion [35] as

$$f_{RF}[\text{MHz}] = 1.64 E_K^2 \exp\left(\frac{-8.5}{E_K}\right) \quad (3.5)$$

where f_{RF} is the frequency of the driven RF and E_K is the Kilpatrick criterion peak field in MVm^{-1} . The above equation can be rewritten in the practical expression of the maximum accelerating gradient E_{0max} as a function of f_{RF} by

$$E_{0max}[\text{MV/m}] = 8.47 + 1.57\sqrt{f_{RF}(\text{MHz})} \quad (3.6)$$

In practical, the peak accelerating field may different from the calculation due to the different conditions of the RF gun such as a cavity structure or a surface roughness. The microwave propagates inside the cavity is formed as standing waves with the transverse magnetic field mode TM010 and the phase different between half- and full-cells is 180 degree or called π -mode. The longitudinal accelerating field $E_z(z)$ in the simple form can be expressed by

$$E_z(z) = E_0 \cos(kz) \sin(\omega t + \phi_0) \quad (3.7)$$

where E_0 is the maximum accelerating field amplitude, k is the rf wave number, $k=2\pi/\lambda$, λ is the wave length, ϕ_0 is the phase of the central particles when it leaves the cathode surface and

z is the longitudinal coordinate. The schematic diagram of the accelerating field and an electron bunch are illustrated in Fig. 3.2.

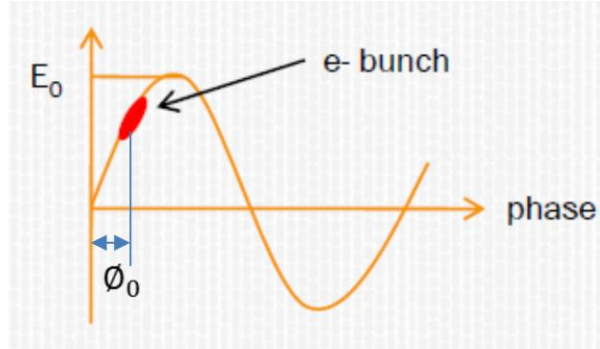


Figure 3.2 Accelerating electric fields of the RF gun and an electron bunch

From Fig. 3.2, energy of electrons within a bunch are modulated depend on their longitudinal position respected to the RF phase. The phase of electron bunch exiting the RF gun ϕ_∞ is shifted from the initial phase by $\phi_\infty = \omega t - kz - \phi_0$ and then the beam energy chirp of the electron bunch become

$$\frac{d\gamma}{dz} = \frac{eE_0}{2mc^2} [\sin\phi + \sin(\phi + 2kz)] . \quad (3.8)$$

The properties of the exiting beam from the RF gun $n + 1/2$ cells which n is the integer can be estimated by the practical formulas given by Travier [31]. These formulas assume that no radial and longitudinal expansion of a bunch occur during acceleration and the rms bunch length in term of angle of the rf phase σ_ϕ is less than $\pi/10$ which gives in practical unit as

$$\sigma_b[\text{ps}] \leq \frac{5 \times 10^4}{f[\text{MHz}]} \quad (3.9)$$

Then, the strength of the radiation field dimensionless parameter α is defined as

$$\alpha = 46.7 \frac{E_0[\text{MV/m}]}{f[\text{MHz}]} . \quad (3.10)$$

Then the maximum beam energy γ , the rms energy spread $\sigma_{\Delta\gamma}$, the rms relative energy spread $\Delta U/U$ in percentage, the space charge emittance ϵ_{sc} , the rf emittance ϵ_{rf} and the total emittance ϵ_{bd} can be calculated by

$$\gamma = 1 + (n + 0.5)\alpha\pi = 1 + 146.8(n + 0.5) \frac{E_0[\text{MV/m}]}{f[\text{MHz}]} \quad (3.11)$$

$$\sigma_{\Delta\gamma} = 2\pi\alpha f \sigma_z = 2.9 \times 10^4 E_0[\text{MV/m}] \sigma_b [\text{ps}] \quad (3.12)$$

$$\frac{\Delta U}{U} (\text{rms}) = \frac{\sigma_{\Delta\gamma}}{\gamma-1} = 2 \times 10^{-4} \frac{f[\text{MHz}] \sigma_b[\text{ps}]}{n+0.5} \quad (3.13)$$

$$\varepsilon_{rf}[\pi \text{ mm mrad}] = 2.73 \times 10^{-11} E_0[\text{MV/m}] f^2[\text{MHz}] \sigma_x^2[\text{mm}] \sigma_b^2[\text{ps}] \quad (3.14)$$

$$\varepsilon_{sc}[\pi \text{ mm mrad}] = 3.76 \times 10^3 \frac{Q[\text{nC}]}{E_0[\text{MV/m}] (2\sigma_x[\text{mm}] + \sigma_b[\text{ps}])} \quad (3.15)$$

$$\varepsilon_{bd}[\pi \text{ mm mrad}] = \sqrt{\varepsilon_{rf}^2 + \varepsilon_{sc}^2} \quad (3.16)$$

where σ_x is the rms transverse beam size determined by the laser pulse and limited by the iris radius between full- and half-cell of the RF cavity.

3.1.2 Photocathode RF Gun

The photocathode RF gun of the compact THz system is a 1.6-cells BNL type normal conducting RF gun and operates in S-band frequency of 2,856 MHz. The driven RF power couples to the gun through the iris at the full-cell cavity as shown in Fig. 2.5 (b). At the opposite side of the driven RF iris, the cavity has the same shape iris for the RF power monitoring antenna (see Fig. 3.1). The parameters of the RF cavity of the gun are listed in Table 3.1.

Table 3.1: Parameters of the photocathode RF gun RF cavity.

Parameters	Values
RF frequency	2,856 MHz
Number of cells	1.6 cells
Radius of cavity	41.565
Half-cell length	34.135
Full-cell length	90.405
Iris radius	12.496

The accelerating electric fields inside the RF cavity in π -mode calculated by SUPERFISH [36] is shown in Fig. 3.3. The peak of the accelerating fields occurs at the cathode surface and at the middle of the full-cell. The unnormalized longitudinal accelerating field amplitude on the center axis is shown in Fig. 3.4.

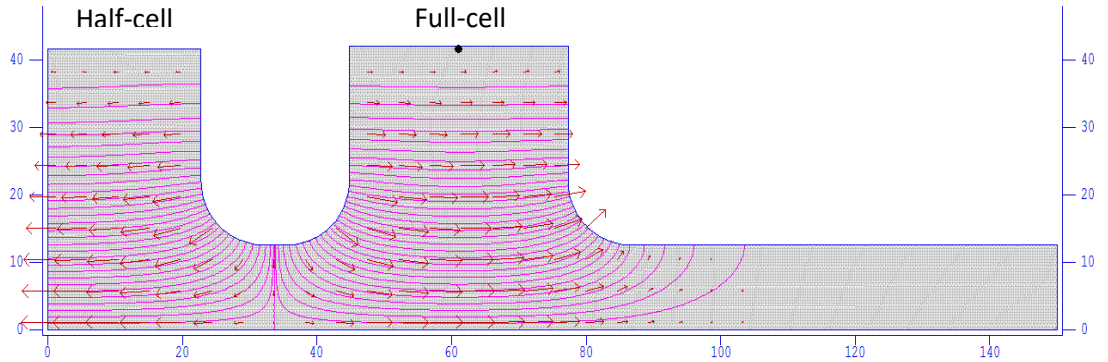


Figure 3.3: Accelerating electric fields calculated by SUPERFISH

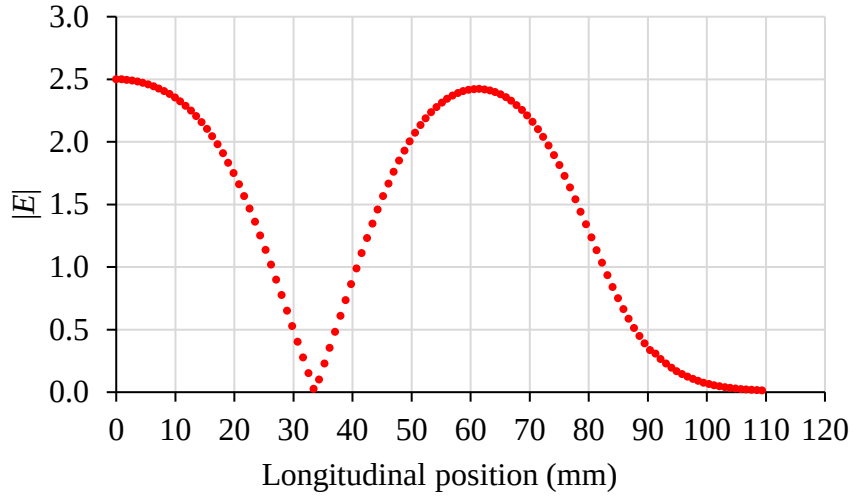


Figure 3.4: Unnormalized longitudinal accelerating field amplitude on the center axis

From the RF gun parameters, the calculated peak accelerating field E_{0max} corresponding to the RF frequency of 2,856 is 92.3 MV/m. In practical, the S-band RF gun can operate at the peak accelerating field up around 100 MV/m. At the transverse laser beam size of 0.5 mm and the laser pulse duration of 6 ps which are the measured values (see chapter 5), the exiting beam from the RF gun has the beam energy γ of 8.7, the relative energy spread $\Delta U/U$ of 0.97%. At the bunch charge of 50 pC, the RF and space charge emittance are 0.036π and 0.53π mm mrad and the total space charge of 0.53π mm mrad. A copper cathode was employed for the RF gun conditioning and all experiments. At the electric field 100 MV/m, the QE is around 0.014 % [37] and the maximum bunch charge calculated by Eq. 3.3 was 10.52 nC at the laser energy of 350 μ J. However, these values are just for the estimation of the beam properties of the RF gun. The measurements of the beam properties of the RF gun are described in the chapter 5.

3.1.3 Laser and RF system

Laser system

UV lasers system for the photocathode RF gun illumination [22] was separately developed from 2008. The concept of the laser system for the KU-FEL is to generate multi laser pulses that require synchronized frequency to the optical cavity of the KU-FEL. The main components of the laser system are a passively mode-locked Nd:YVO₄ oscillator with built-in acousto-optics modulator (Time bandwidth, GE-100-VAN-89.25MHz-CLX-Flexible AOM), a beam alignment control system (Aligna4D, TEM) , two laser diode pump amplifiers (REA5006-2P1,CEO), second harmonic generation (SHG) and forth harmonic generation (FHG) non-linear crystals, the Faraday isolators, the half wave plates, the quarter wave plates and the polarized beam splitters. Inside the oscillator, the neodymium-doped yttrium orthovanadate (Nd:YVO₄) laser diode generates a continuous laser at the wavelength of 1064 nm injecting to an optical cavity. The cavity consists of a concave mirror, flat mirrors set in a free-space. The optical cavity stores the laser energy and the cavity length was adjusted to a certain length to produce a short pulse yield from the interferences of the longitudinal modes. The change of the cavity length due to the temperature fluctuation was compensated by a feedback controlled piezo electric actuator. The flat mirror of the cavity made by a Semiconductor Saturable Absorber Mirror (SESAM) whose reflectivity dependence on laser intensity. The SESAM absorbs a low intensity light remain only a high intensity light pulse circulated inside the cavity. Acousto-Optics Modulator (AOM) was employed to modulate the amplitude of micro-pulse and control the macro-pulse length according to the waveform generated by the function generator. The schematic diagram of the laser oscillator is shown in Fig. 3.9. The schematic diagram of the laser system is shown in Fig. 3.10.

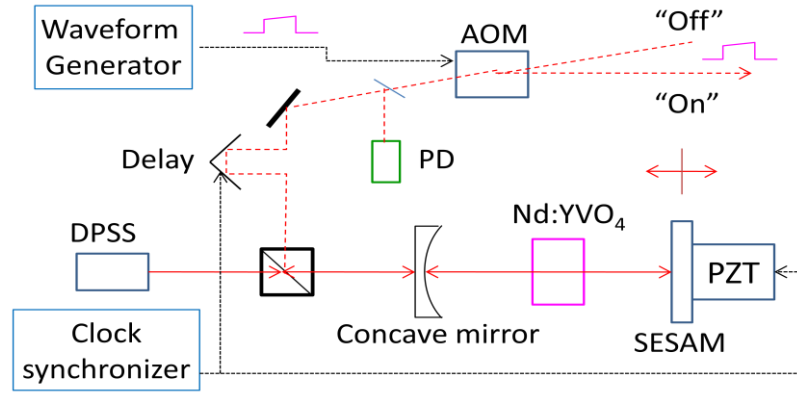


Figure 3.9: Schematic diagram of the passively mode-lock laser oscillator. The solid red line represents a continuous laser and the dash red line represents the pulse laser. (DPSS; Diode pump solid state, PD; Photodiode, PZT; Piezo electric actuator, AOM; Acousto-optics modulator, SESAM; Semiconductor saturable absorber mirror

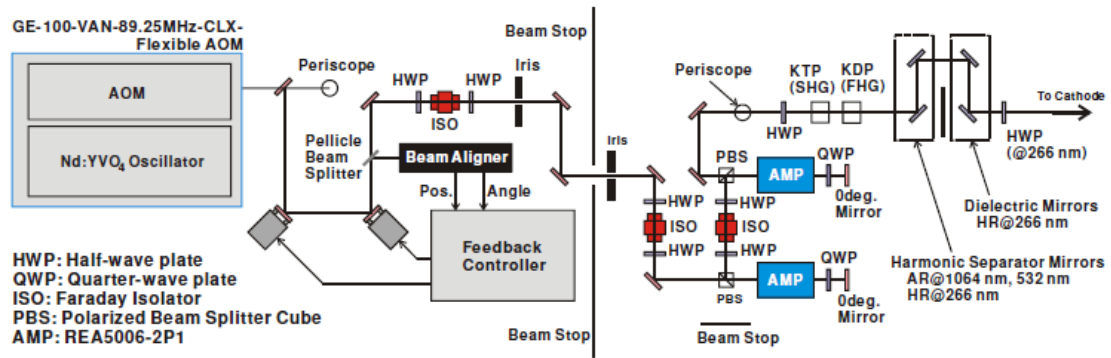


Figure 3.10: Schematic diagram of the laser system for the photocathode RF gun.

The laser exiting from the oscillator has a low stability because the dimensions of the resonance cavity changes due to the temperature fluctuation. Therefore, the temperature of the laser room is controlled at 23 °C and the two motorized rotatable mirrors controlled by a real-time feedback control system are employed to stabilize the laser beam alignment. The Faraday isolators which rotate the plane of polarization in 45 degree in the one pass were used with the half-wave plates in order to block a reflected light. The lasers are amplified by two laser diode pumped amplifiers arranged in series. The pair of non-linear crystals, potassium titanyl phosphate (KTP) crystal and potassium dihydrogen phosphate (KDP) crystal, were used for SHG and FHG, respectively. The laser light enters the crystal and generates nonlinear polarization waves which oscillate with twice the fundamental frequency.

The final wavelength is the fourth harmonic wavelength at 266 nm. The laser beam is transported to the gun by several UV enhanced aluminium mirrors.

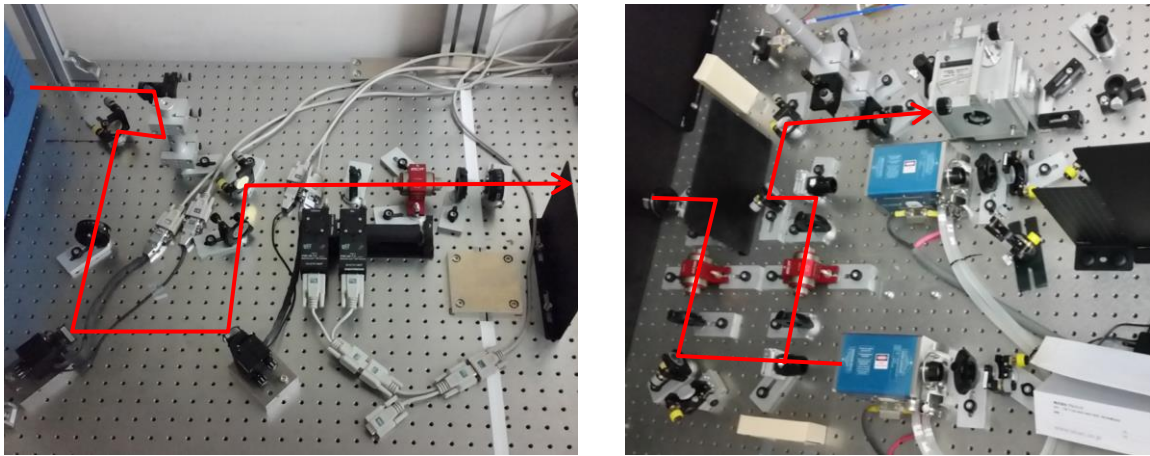


Figure 3.11: The laser system for the photocathode RF gun. (left) Beam alignment stabilizer, (right) laser amplifiers and SHG, FHG. The red line represents the laser beam path.

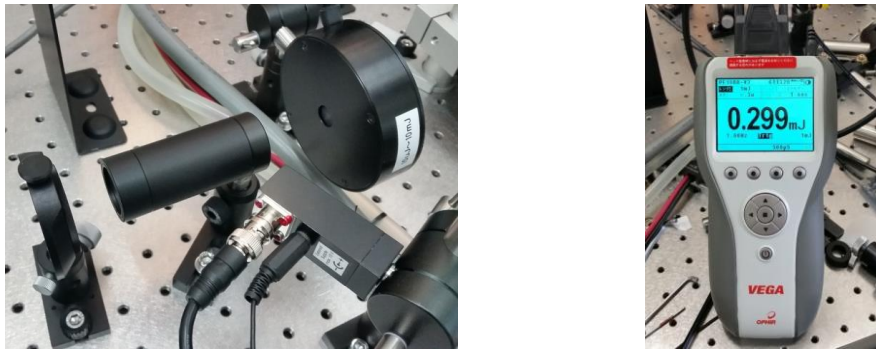


Figure 3.13: Photodiode detector (left) and the laser energy meter (right).

The laser pulse structure had been chosen to conform to the RF power source pulse and the optical resonator length of KU-FEL. The laser repetition rate of micro-pulse of 89.25 MHz is a 1/32 time of the S-band RF frequency of 2,856 MHz and the 3rd harmonic of the roundtrip frequency of the FEL light pulse propagate in the KU-FEL optical cavity. The repetition rate of macro-pulse is 10 Hz which is limited by the repetition rate of the RF power source driven the RF gun. The KU-FEL requires multipulse lasers for the photon-electron interaction in the optical oscillator. Meanwhile, the compact THz system requires at least a single pulse laser per macropulse because the system operates with a single pass. The parameters of the laser system are listed in Table. 3.2.

Table 3.2: Parameters of the photocathode RF gun laser system

Parameters	Values
Oscillator type	Passively mode-locked
Oscillator wavelength	1064 nm
Wavelength after FHG	266 nm
Repetition frequency of micropulse	89.25 MHz
Repetition of macropulse	10 Hz
Pulse duration (FWHM)	~ 6 ps
Optical transportation efficiency	82 - 92%

RF system

The photocathode RF-gun shares the RF power source with the existing 4.5 cells thermionic cathode RF-gun of the KU-FEL [14]. This source has the peak power of 10 MW and the maximum repetition rate of 10 Hz. The waveguide RF switch, which is installed downstream the circulator, is used for switching the RF power between these two RF-guns. The forward and reflected RF powers fed the photocathode RF gun are picked up by the coupled waveguide installed upstream the RF gun. The signals were attenuated by two 10 dB attenuator and the attenuation of the coaxial cables are -2.47 and -2.91 dB for the forwarded and reflected cable, respectively. Then the peak amplitude waveform was detected by the crystal detectors and read out by digital oscilloscope (Yogokawa, WE711 100MS/s). The block diagram of the RF and laser system is shown in Fig. 3.14.

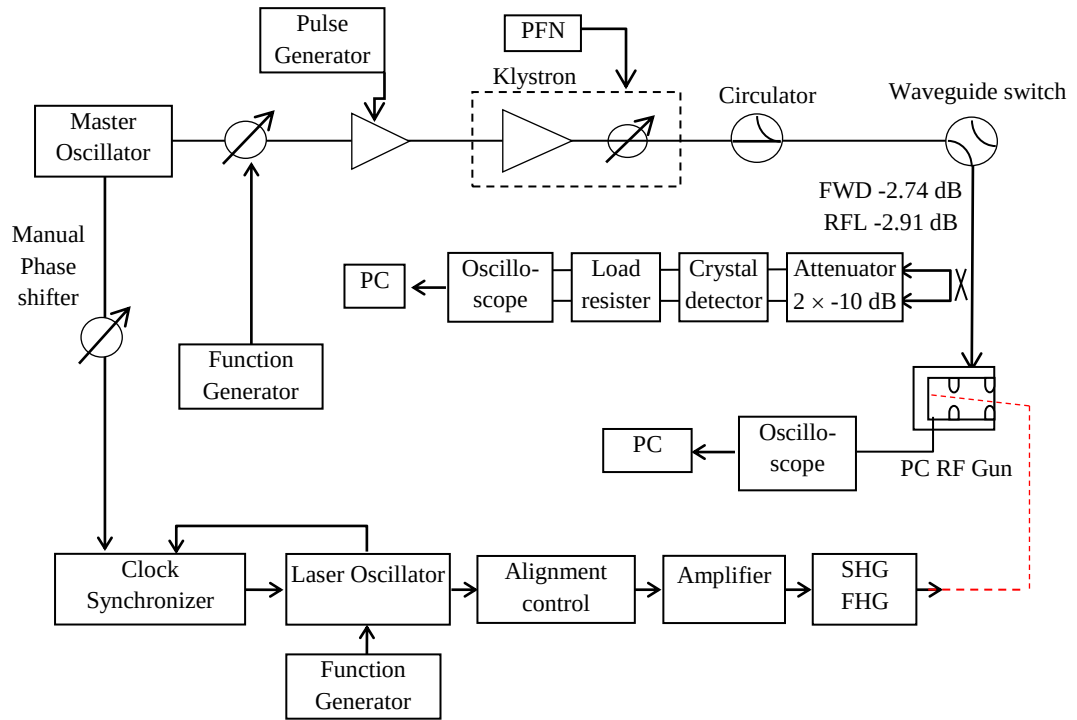


Figure 3.14: Diagram of the RF and the laser system for the photocathode RF gun (PFN: Pulse forming network, SHG: Second harmonic generation, FHG: Forth harmonic generation)

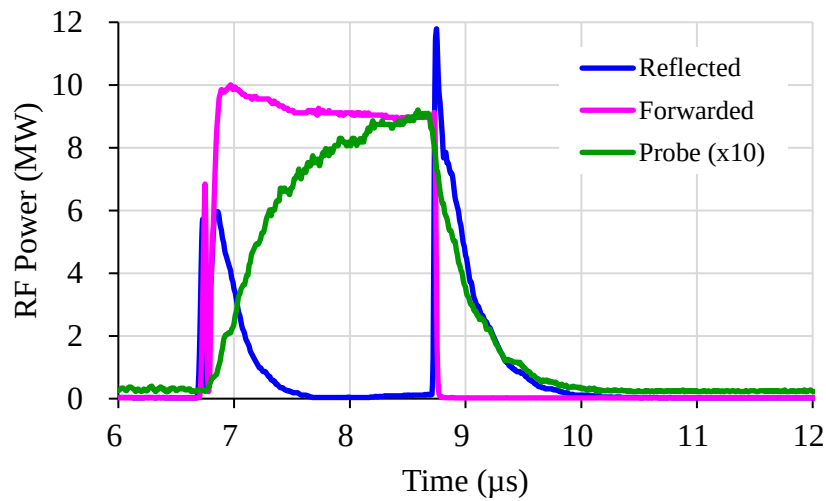


Figure 3.15: Measured RF wave form of the photocathode RF gun

Table 3.3 Parameters of the RF system

Parameters	Values
RF frequency	2,856 MHz
Peak power	~ 9 MW
RF Pulse duration	2 μ m
RF Pulse repetition rate	2 Hz

Because the CUR is generated with the single pass operation, the macropulse duration was set to a short duration at 2 μ s. The energy stored in the RF cavity reach the maximum within which the reflected RF power became close to zero. The laser pulse was injected at close to the end of macropulse which the energy stored in the RF gun is close to the saturation.

3.1.4 Time structure

The time structure of the RF pulses, the laser pulses and the definition of the laser injection phase are shown in Fig. 3.16. The RF pulse has frequency of 2,856 MHz (S-band) corresponding to the time period of 350.14 ps. The repetition rate of the macropulse was 2 Hz which provide the spacing between macropulse of 0.5 s. The laser pulse has the repetition rate of 89.25 MHz which has the time duration between pulses of 11.2 ns or 32 times longer than the RF pulse duration. Throughout this study, the macropulse duration of the RF pulse was set at 2 μ s and therefore the number of the laser pulse per macropulse was 178 pulses. The electron bunch time structure was the same as the laser pulse time structure. The relative phase between the zero crossing of the accelerating field and the end of the laser pulse was defined as the laser injection phase ϕ_L .

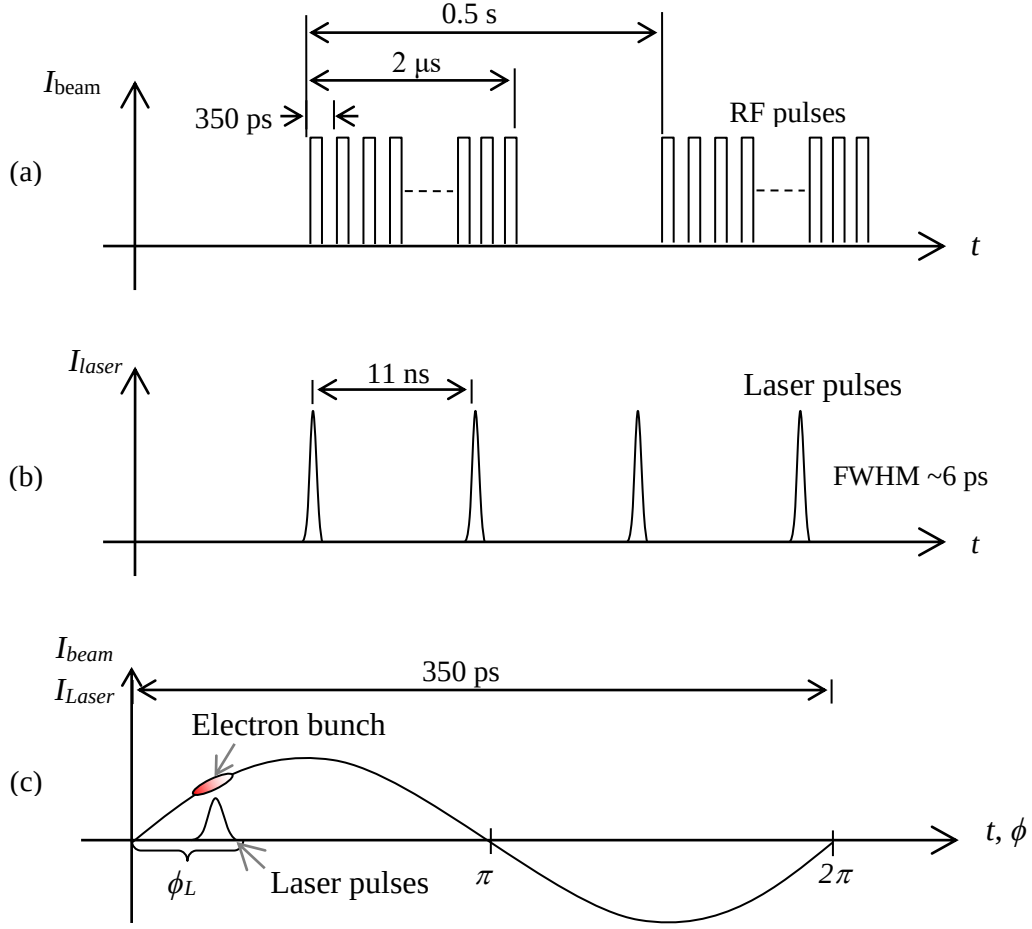


Figure 3.16: Time structures of (a) the RF pulse, (b) the laser pulse and (c) the definition of the laser injection phase (not to scale).

3.1.5 Low Power and High Power Test

The resonance characteristic of the RF cavity of the RF gun was measured in two conditions according to the driven RF power. At the resonance condition, the RF cavity stores a maximum power from the driven RF resulting in a minimum reflected RF power from the cavity. For the low power test, the spectrum analyzer (Agilent, N9320B) was used for the measurement of the resonance frequency. The spectrum analyzer connects to the RF cavity through a directional coupler and the waveguide coaxial adapter. The spectrum analyzer generate microwave signal and scan frequency in a specified range. The reflected signals pass through the reflecting port of the directional coupler and read out by the spectrum analyzer. The measurement was performed at the room temperature at 22 °C. The schematic diagram of the low power test is shown in Fig. 3.17.

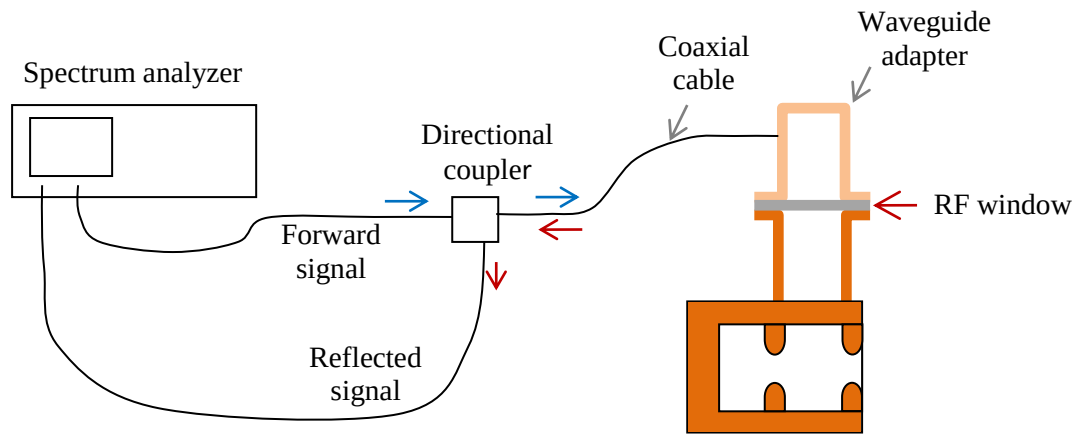


Figure 3.17: Measurement setup for the low power test of the photocathode RF gun

For the high RF power test, the RF gun was installed and connected the waveguide to the RF power source and the test was performed as the operating condition. The RF power fed to the cavity losses to heat due to the resistance of the cavity internal wall or called cavity wall loss. This heat causes the expansion of the RF cavity resulting in the shifting of the resonance frequency. Therefore, the temperature of the RF gun has to be carefully controlled.

Table 3.4 Low power and high power test of the photocathode RF gun

Parameters	High power test	Low Power test
Cavity Temperature :	30.0 deg. C	22.0 deg. C
Quality Factor of π -mode :	10700	11400
Coupling Coefficient of π -mode :	1.18	1.26
Resonance Frequency of π -mode :	2856.06 MHz	2856.46 MHz
Resonance Frequency of 0-mode :	2852.51 MHz	2853.05 MHz
Mode Separation :	3.55 MHz	3.41 MHz

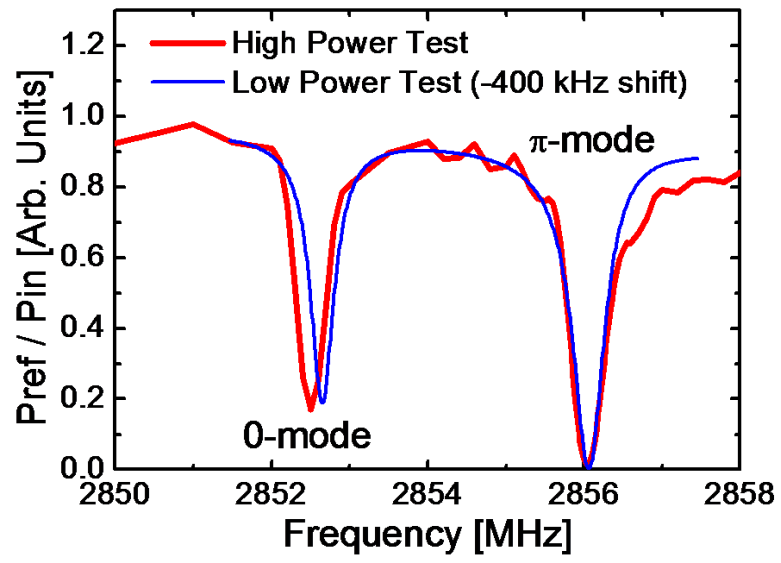


Figure 3.18: Low and high power test of the photocathode RF gun.

3.2 Bunch Compressor

Bunch compressor is a key component for manipulating a longitudinal phase-space of an electron bunch suitable for the CUR generation. As described in section 2.2.2, we decided to use a longitudinal symmetric magnetic chicane bunch compressor for the compact THz system. The working principle, the details of magnet design and the magnetic field measurement of the magnetic chicane are described in this section.

3.2.1 Bunch compressor working principle

A magnetic chicane bunch compressor for the compact THz system consists of four dipole rectangular bending electromagnets arranged in a longitudinal symmetric layout as shown in Fig. 3.19. An electron bunch generated by the RF gun travels in the magnetic chicane bunch compressor in the energy dependence path. Higher energy electrons are deflected in a smaller angle and travel in the inner path which has a shorter path length. While lower energy electrons are deflected in a larger deflection angle and travel in a longer path length. This allows the position of electrons can be relatively changed resulting in a shorter or longer bunch length at the chicane exit. This bunch compressor configuration is effective for a wide beam energy range from a few MeV to several GeV. The schematic of the chicane and the evolution of the longitudinal phase-space along the chicane are shown in Fig. 3.19.

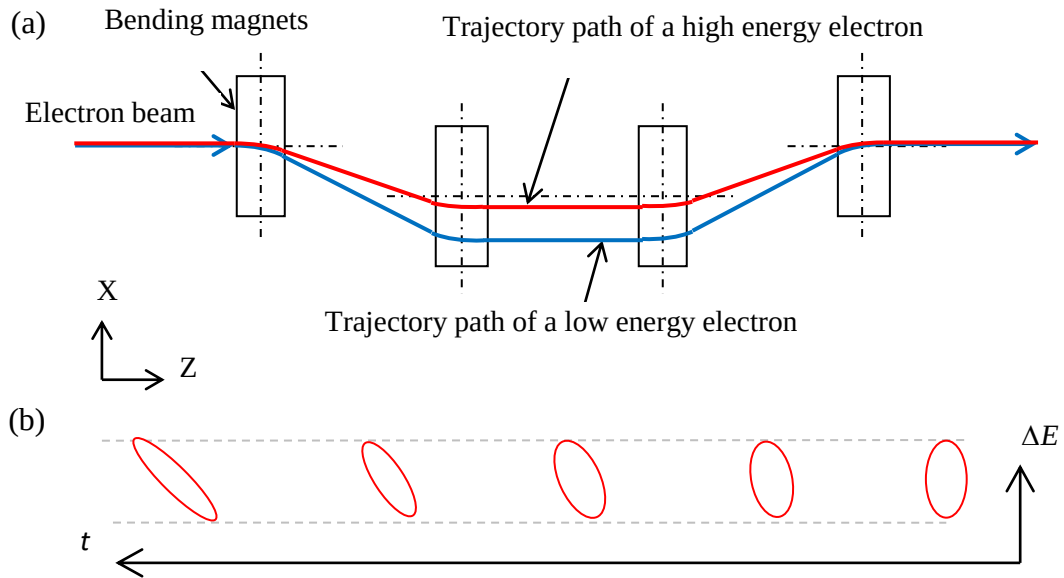


Figure 3.19: (a) Schematic of the magnetic chicane bunch compressor and travelling paths (b) energy-time phase space evolution along the chicane.

To describe the bunch compression characteristics, the phase-space coordinate is defined in a moving frame along the reference path as shown in Fig. 3.20. The phase-space transformation of an electron bunch passing a bunch compressor can be described by a first order linear matrix formalism [38] as shown in Fig. 3.21.

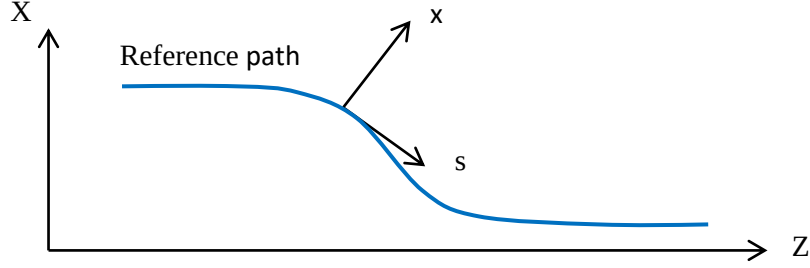


Figure 3.20: Definition of the phase-space coordination for the bunch compressor.

$$\begin{pmatrix} x_f \\ x'_f \\ y_f \\ y'_f \\ l_f \\ \delta_{E,f} \end{pmatrix} = \begin{pmatrix} R_{11} & R_{12} & 0 & 0 & 0 & R_{16} \\ R_{21} & R_{22} & 0 & 0 & 0 & R_{26} \\ 0 & 0 & R_{33} & R_{34} & 0 & 0 \\ 0 & 0 & R_{43} & R_{44} & 0 & 0 \\ R_{51} & R_{52} & 0 & 0 & 1 & R_{56} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_i \\ x'_i \\ y_i \\ y'_i \\ l_i \\ \delta_{E,i} \end{pmatrix}$$

Figure 3.21: First order linear matrix formalism of the magnetic chicane bunch compressor

The final electron bunch length l_f at the chicane exit can be calculated by $l_f = R_{51}x_i + R_{52}x'_i + l_i + R_{56} \delta_{E,i}$ where l_i is the initial bunch length x_i is the transverse position of electron, R_{51} , R_{52} and R_{56} are the matrix elements and $\delta_{E,i}$ is the relative energy spread. The first two terms are small and can be neglected. Thus, the bunch length change ds after pass through the chicane approximately become

$$l_f - l_i = ds = R_{56} \delta_{E,i}. \quad (3.17)$$

The matrix element R_{56} is the *first order momentum compaction factor* which is defined by the change of the total path length over relative energy spread. The R_{56} value can be positive or negative depended on the arrangement of magnets of a bunch compressor. To obtain a minimum bunch length at the chicane exit, the optimum R_{56} value have to match with the energy chirp h of a initial bunch which is defined by

$$h = d\delta / c dt_{t=0}. \quad (3.18)$$

where t is the time position of each electron and c is the speed of light. Then, the optimum R_{56} value is

$$R_{56} = -1 / h . \quad (3.19)$$

As Eq. 3.8, the energy chirp of a bunch strongly depends on the relative phase between an electron bunch and the RF phase or the laser injection phase. The energy chirp of the electron bunch at the RF gun exit was calculated by using the tracking simulation code and described the late part of this section.

In this study, we consider only the chicane with four dipole bending magnets arranged in the longitudinal symmetry as shown in Fig.3.19. For a mono-energetic beam, the diagram of the beam trajectory inside the chicane can be illustrated as Fig. 3.22.

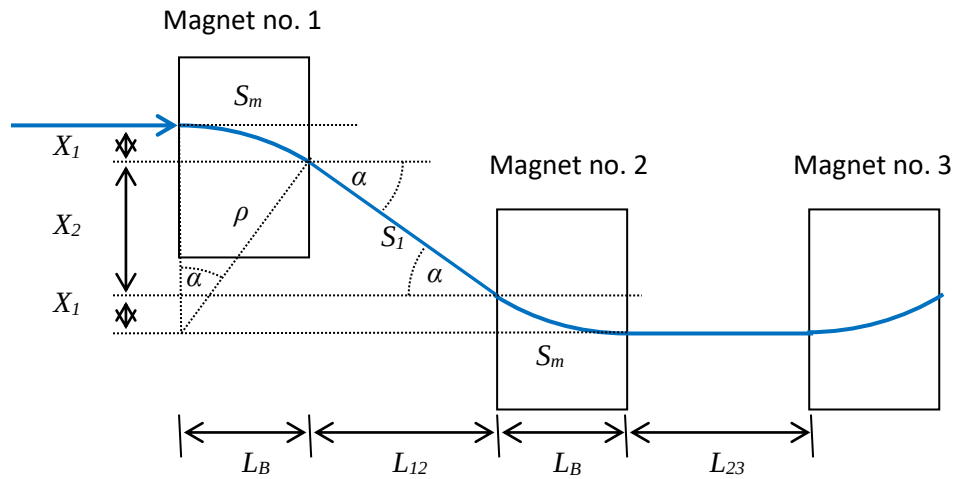


Figure3.22: Diagram of a mono-energetic beam trajectory inside the magnetic chicane

The deflection angle α is proportional to the total magnetic fields seen by electrons $\alpha = \frac{e}{p} \int B_y ds$ here B_y is the bending magnet magnetic fields and P is the momentum of electron. However for the chicane design, we assume that electrons are deflected only by the uniform magnetic fields within between the pole face of bending magnet and their trajectory is a part of circle with the radius of curvature ρ of

$$\rho = \frac{P}{qB_y} . \quad (3.20)$$

The total path length of the mono-energetic beam traveling through the longitudinal symmetric chicane depends on the deflection angle and the chicane geometry. The total path length L_{tot} can be calculated by

$$L_{tot} = 4 S_m + 2 S_{12} + L_{23} \quad (3.21)$$

where S_m is the curve path length inside the magnet no.1 S_{12} is the path length between the magnet no.1 and no. 2 and L_{23} is the path length between magnet no. 2 and no.3. The S_m equal to $\alpha\rho$ and the radius of curvature is $\rho = L_B / \sin \alpha$. Therefore, S_m can be rewritten as $S_m = L_B \alpha / \sin \alpha$. The S_1 is equal to $L_{23} / \cos \alpha$. Then the total path length can be calculated by

$$L_{tot} = 4L_B \frac{\alpha}{\sin \alpha} + 2 \frac{L_{12}}{\sqrt{1-(\sin \alpha)^2}} + L_{23} \quad (3.22)$$

The horizontal beam offset need to be considered to determine the width of the magnet and the vacuum chamber dimension. The maximum beam offset X_{max} occur at the middle of the chicane between the magnet no.2 and no.3 and can be calculated by

$$X_{max} = 2 X_1 + X_2 \quad (3.23)$$

$$X_{max} = 2 L_B \tan \frac{\alpha}{2} + L_{12} \tan \frac{\alpha}{2} \quad (3.24)$$

For a realistic beam, electron beams are non-monoenergetic beam. Electrons with a small energy deviation are bended by slightly different angle $\frac{\sin \alpha_1}{1+\delta_E}$ as shown in Fig. 3.23. The total path length of electron with small energy deviation can be obtained by substitute $\frac{\sin \alpha_1}{1+\delta_E}$ in Eq. 3.22.

$$L_{tot} = 4L_B \arcsin \left(\frac{\sin \alpha_1}{1+\delta_E} \right) \frac{\sin \alpha}{1+\delta_E} + 2 \frac{L_{12}}{\sqrt{1-(\sin \alpha)^2}} + L_{23} \quad (3.25)$$

Then, the R_{56} can be calculated by the differential of the above equation over the energy as

$$R_{56}(\alpha) \approx - \frac{1}{3} \left\{ (3L_{12} + 2L_B) + \frac{(L_{12}+L_B)^2(3L_{34}+2L_B)}{(L_{34}+L_B)^2} \right\} \alpha^2, \quad (3.26)$$

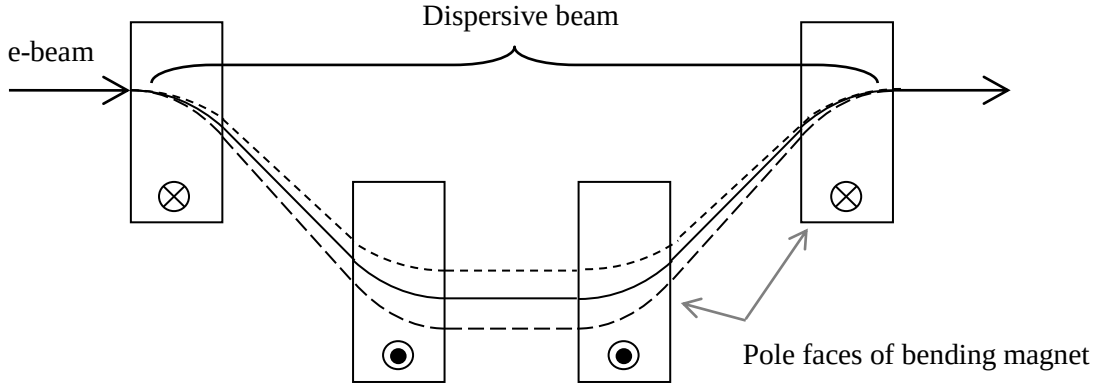


Figure 3.23: Diagram of a non-monoenergetic beam trajectory inside the chicane (top view). Dashed line represents the beam with the small energy deviation around the nominal beam energy (solid line).

where L_{12} is the distance between magnet no.1 and no.2, L_{34} is the distance between magnet no.3 and 4 and L_B is the magnet length. For the longitudinal symmetrical chicane, L_{12} equal to L_{34} then the Eq. 3.26 can be reduced to

$$R_{56}(\alpha) \approx -2\alpha^2\{(L_{12} + 2/3L_B)\}. \quad (3.27)$$

The energy chirp of the electron bunch exiting the RF gun (Eq. 3.8) was calculated by PARMELA [15] and the result is shown in Fig. 3.24. The 100,000 macroparticles were assumed to emerge from the cathode surface and used for the tracking calculation. The ahead 90 percent electrons within the exiting bunch which is the regime of the linear correlation in the longitudinal phase-space were used for the energy chirp calculation. It is obvious that the electron beam accelerated by the lower electric field and the larger acceleration phase has a smaller energy chirp. Then, the deflection angles of the magnetic chicane corresponding to the energy chirp of the initial bunch were calculated as shown in Fig. 3.25. The deflection angle of the chicane should be small as much as possible in order to avoid a strong focusing in the non-deflecting plane.

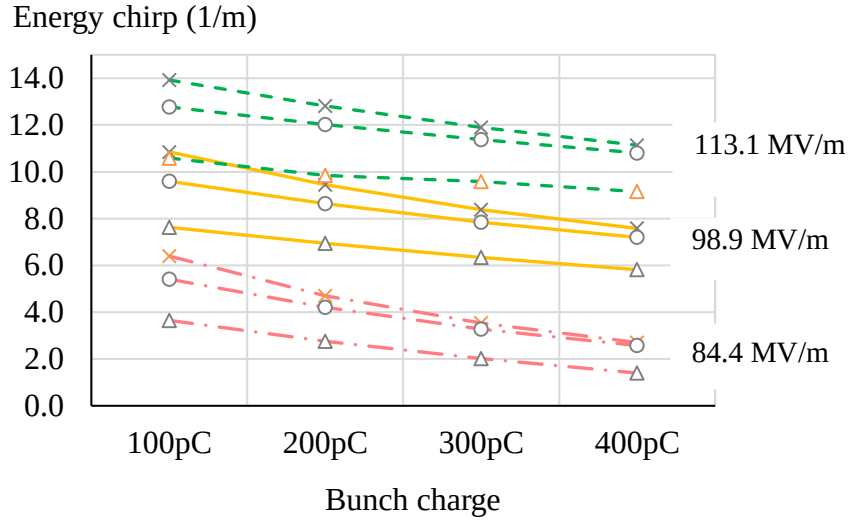


Figure 3.24: PARMELA calculation of the energy chirp of the electron bunch at the RF gun exit for the different peak accelerating fields of 84.4 (dashed line), 100 (solid line) and 113.1 MV/m (dot-dashed line) and the laser injection phase of 12 (cross mark), 16 (circle mark), and 20 degree (triangle mark).

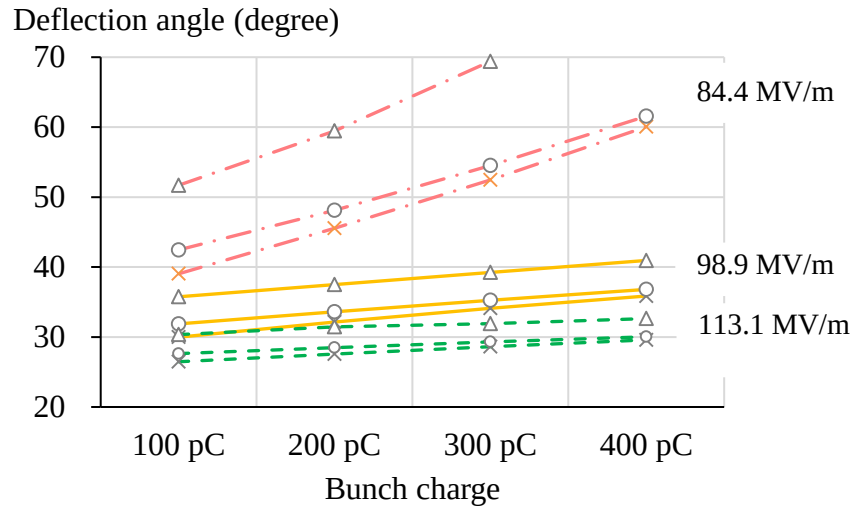


Figure 3.25: Calculation of the deflection angle of the chicane corresponding to the energy chirp in Fig 3.24. The descriptions of marks and lines are the same as Fig. 3.24.

The maximum beam deflection angle of the chicane was decided at 35 degree and the distance between centers of each magnet is 190 mm. The center of the 1st and 4th magnet aligns with the beam axis while the center of the 2nd and 3rd magnet can be moved in horizontal direction in order to large deflection angle. The vacuum chamber was designed for both no compression and compression operation mode. Correction coils was add to

compensate the magnetic field drop in the transverse off-center region of the 2nd and 3rd magnet (see 3.2.4). The descriptions of the magnetic chicane dimension are shown in Fig. 3.26 and the parameters of the magnetic chicane bunch compressor are listed in the Table 3.5.

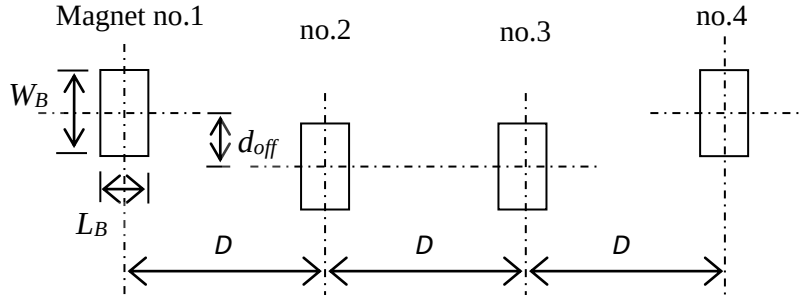


Figure 3.26: Descriptions of the magnetic chicane bunch compressor dimensions.

Table 3.5: Parameters of the magnetic chicane bunch compressor

Magnetic Chicane Parameters	Values
Dipole magnet geometry length (L_B)	65 mm.
Dipole magnet effective length (L_{eff} , see 3.2.4)	106.7 mm
Pole face width (W_B)	100 mm
Distance between the center of magnets (D)	190 mm
Pole gap	30 mm
Center offset of 2 nd and 3 rd magnet (d_{off})	82 mm
Deflection angle	35 deg. max
Number of turn per coil	190 turn
Maximum coil current	1969.6 A-turns
Maximum magnetic field	168 mT
Correction coils on 2 nd and 3 rd magnet	12 turns

3.2.2 Calculation of the 1st order momentum compaction factor

The R_{56} was calculated by using the tracking simulation code GPT (see chapter 4). A single electron with slightly different energies around the nominal beam energy of 4.6 MeV which is the beam energy at the operating condition (see chapter 5) was tracked through the chicane. Then the total travelling path length inside the chicane was calculated and plotted as a function of the relative energy. The plot was fit to the quadratic function and the coefficient of the linear term was the R_{56} value. The magnetic field of the magnetic chicane was varied from 70 to 105 mT corresponding to the chicane excited current of 4.4 to 6.6 A (see section 3.2.4). The trajectory and the beam offset in the horizontal axis are shown in Fig. 3.27. The total path length different as a function of the relative energy spread is shown in Fig. 3.28. The calculated R_{56} value by GPT and Eq. 3.27 are shown in Fig. 3.29.

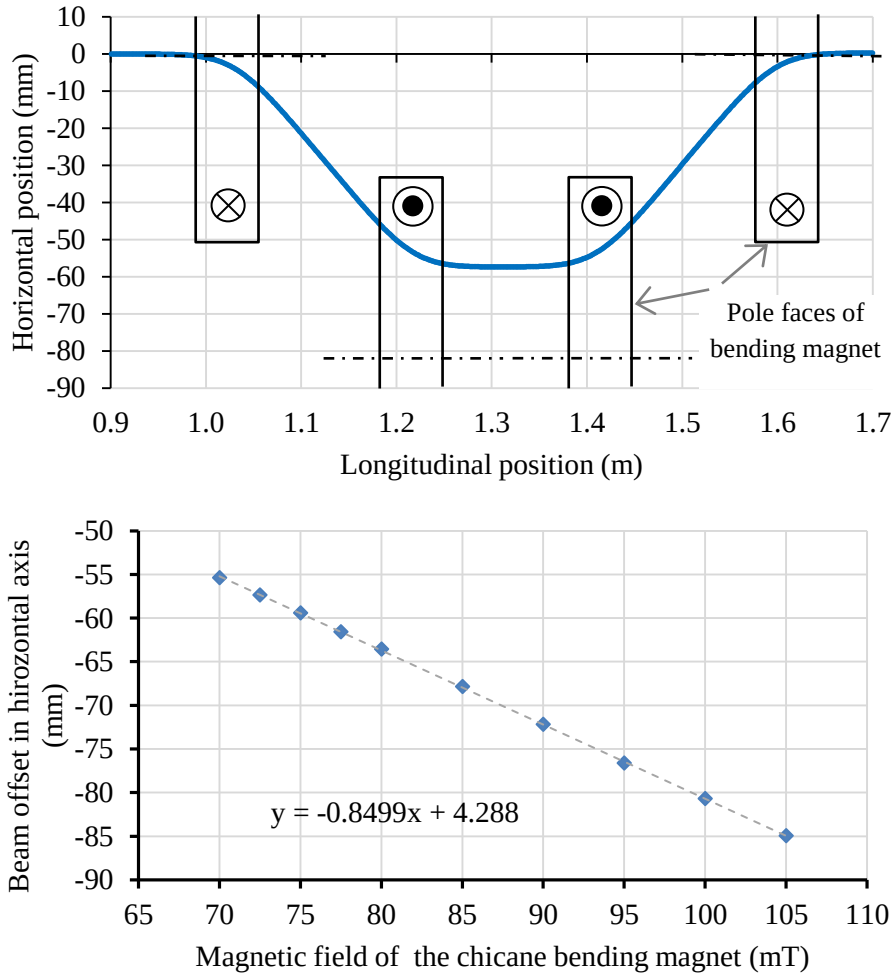


Figure 3.27: Trajectory of the electron with the energy of 4.6 MeV at the magnetic field of the bending magnet of 72.5 mT (upper) and the beam offset in the horizontal axis (lower).

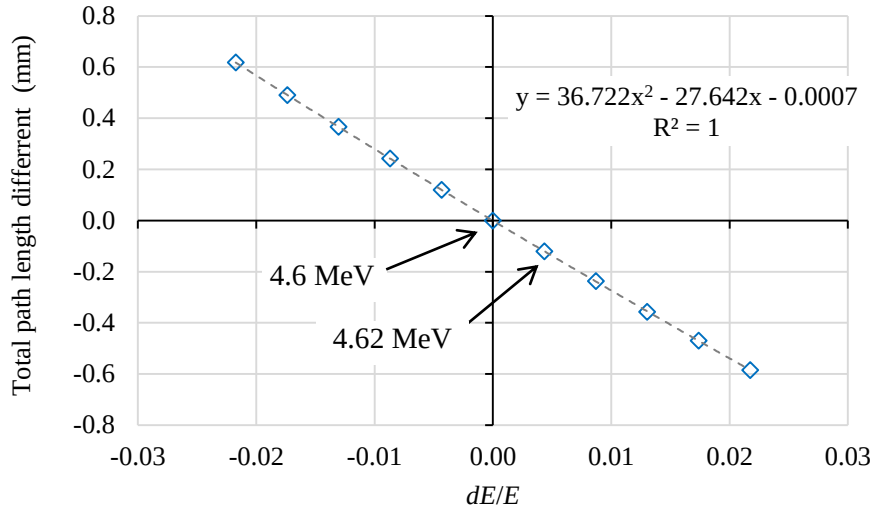


Figure 3.28: Total path different at the nominal energy beam energy of and the magnetic field strength of 72.5 mT by GPT calculation (diamond marks) and the fitted quadratic curve (dashed line).

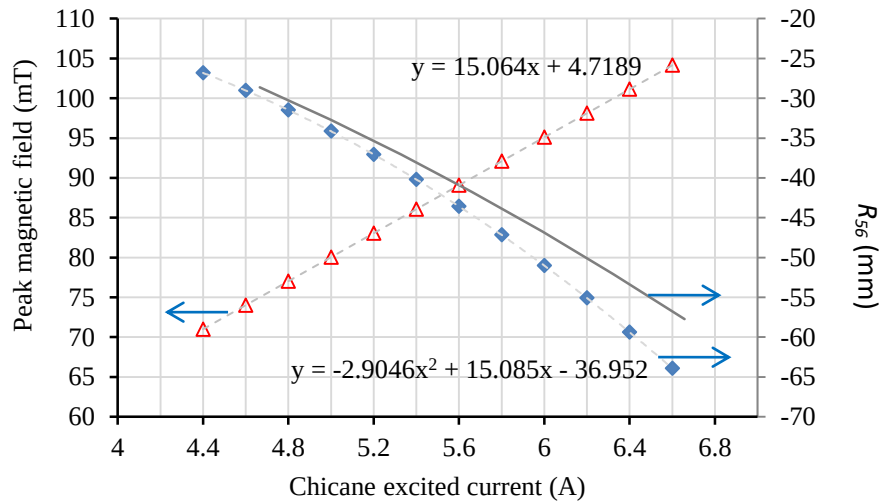


Figure 3.29: R_{56} values by the GPT calculation (diamond marks), by the Eq. 3.27 (solid line) and the measured magnetic fields (triangle marks) as a function of the excited current of the magnetic chicane bending magnet.

3.2.3 Dipole magnet of the magnetic chicane

A rectangular dipole bending electromagnets were used as the magnet of the magnetic chicane bunch compressor. This magnet is called “*H-magnet*” because the confined space by the yoke like an alphabet “H”. The H-magnet creates the vertical magnetic fields which bends beams in the horizontal direction. The magnetic field B_0 between the pole gap G can be calculated by Ampere’s law with the integral path as shown in Fig. 3.30. By assuming that the iron yoke has the very large permeability $\mu_r \gg 1$, the magnetic field at the center of the pole gap can be calculated by

$$B_0 = \frac{\mu_0 n I}{G} \quad (3.28)$$

where μ_0 is the permeability of free space, $4\pi \times 10^{-7}$ H/m or 1.2566×10^{-6} N/A², n is the number of coil turn and I is the coil excited current.

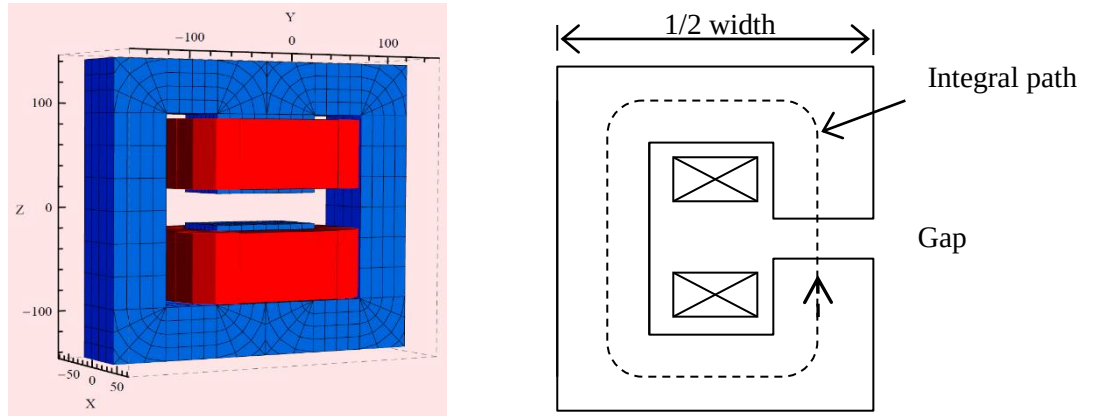


Figure 3.30: H-magnet model by RADIA and the integral path for the calculation.

The magnet dimensions were determined by the geometry of the magnetic chicane and are listed in Table. 3.6. The pole gap was designed to be the same as the KU-FEL bending magnet at 30 mm. An air-cooled polyester enamel coated copper wire (PEW) with the rectangular cross section of 2×5 mm was installed for each pole. The maximum current supplied to the coil was 12.1 A that provide the current density of $J = 12.1 / 10 = 1.21$ A/mm². This value is less than 2 A/mm² which is the maximum allowable current density for an air-cooled copper coil [39]. The calculated maximum magnetic field is $B_0 = \mu_0$

$(2 \times 190) \times 12.1 / 0.03 = 192.6 \text{ mT}$. The yoke made from steel SS400 and has the rectangular cross section of $50 \times 65 \text{ mm}$. The magnet is compact and symmetry along the vertical and horizontal middle plane. The drawing of the magnet is shown in Fig. 3.31 and the parameters of the magnet are listed in Table 3.6.

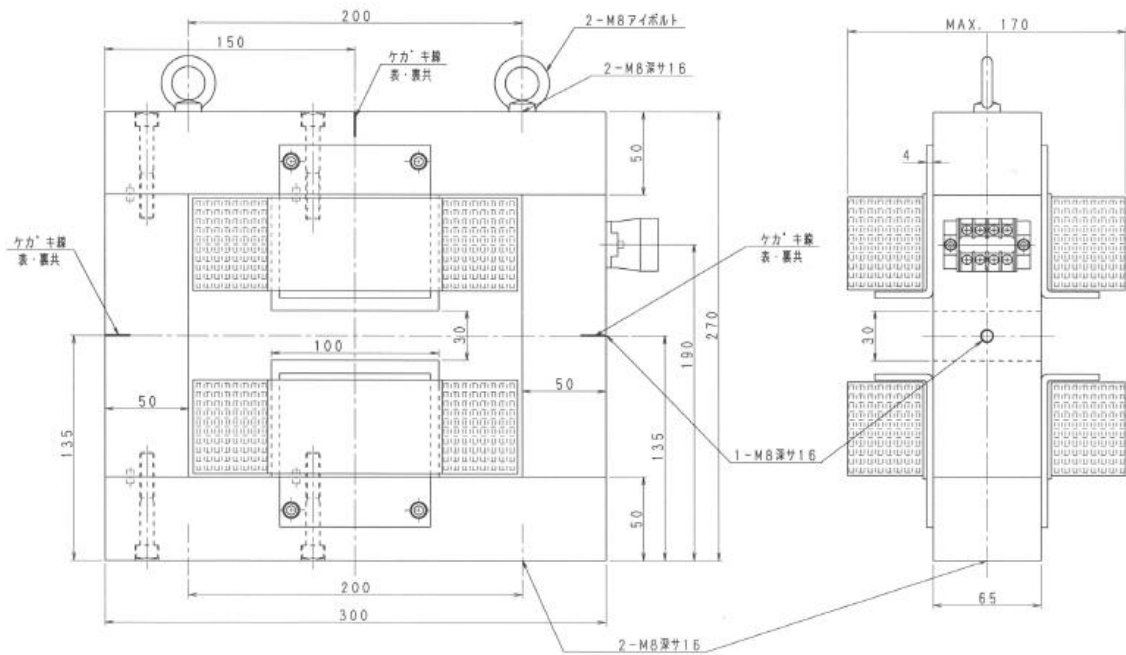


Figure 3.31: Drawing of the H-magnet of the magnetic chicane bunch compressor in the front view (left) and the side view (right).

Table 3.6: Specifications of the H-magnet.

Parameters	Values
Pole gap	30 mm.
Pole thickness	65 mm.
Pole width	100 mm.
Yoke cross section	$65 \times 50 \text{ mm}$.
Number of turn per coil	190 turn
Wire cross section	$2 \times 5 \text{ mm}$
Maximum coil current	12.1 A
Maximum current turns	2299 A-Turn
Maximum magnetic fields	192.6 mT

The characteristics of the magnetic fields were calculated by RADIA code [40] which is a 3D magnetostatics code to solve boundary magnetostatics problems. The calculation of the relation between the transverse magnetic field strength at the pole gap center and the supply coil current calculated by RADIA is shown in Fig. 3.33. As the result, the magnetic field strength at the pole gap center was linear proportional to the excited current until 5,000 A-Turn which exceeds the maximum design current at 2,299 A-turn. Therefore, the magnetic fields inside the yoke would not saturate although the maximum current was applied. The calculation by RADIA had a good agreement with the calculation by Eq. 3.28 as shown in Fig. 3.33. The calculations of magnetic field distributions are described in the magnetic field measurement section 3.2.4.

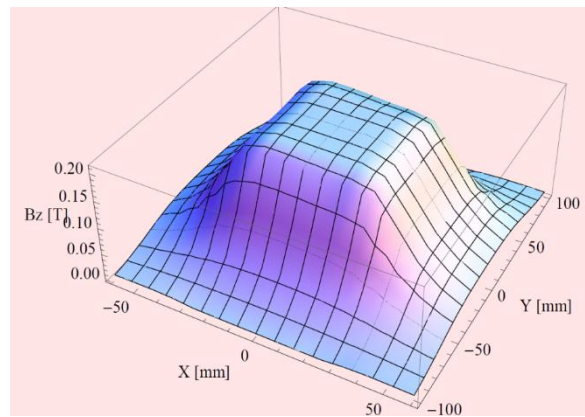


Figure 3.32: Magnetic field distribution result by RADIA surface plot in xz plane

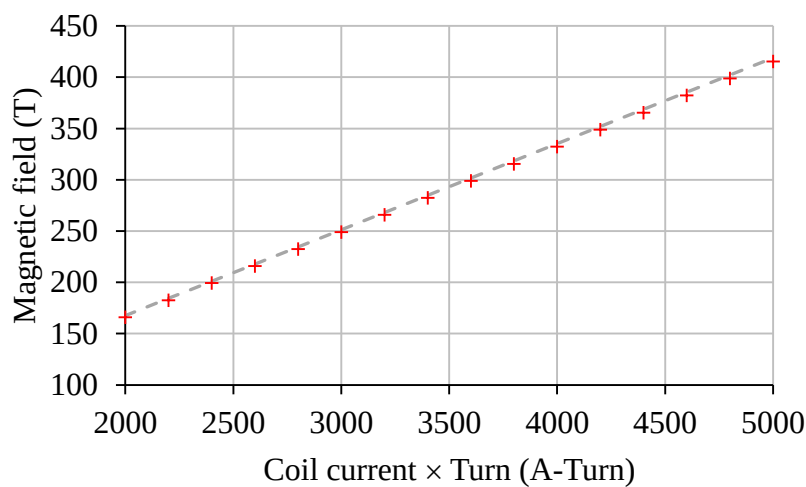


Figure 3.33: Magnetic field strength at the center of the pole gap as a function of the excited coil current calculated by RADIA (cross mark) and by the Eq. 3.25 (dashed line).

3.2.4 Measurement of H-magnet Magnetic Field

The distribution of the H-magnet magnetic fields was measured by a 3-axis magnetic Hall probe and the setup is shown in Fig. 3.34. The Hall probe was attached on the 3-dimensional translation stage and controlled by LabVIEW. The stages were moved in X, Y, Z axes with the interval step of 0.5, 0.2 and 0.1 cm and the total movement distance of 18.5, 8.0 and 2.2 cm, respectively. The magnet was excited by the DC current of 10 A. The normalized measured magnetic fields along Z and X direction are shown in Fig. 3.35.

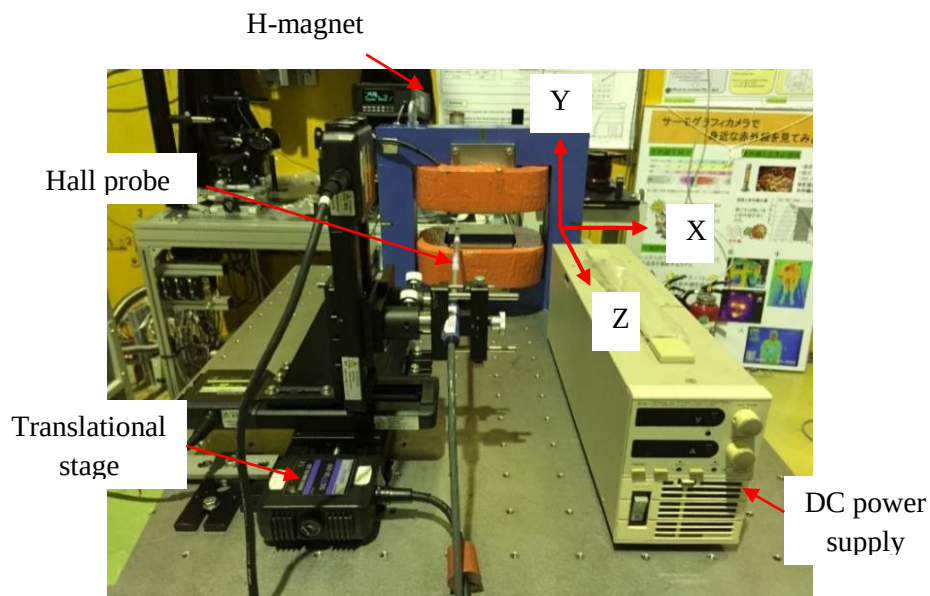


Figure 3.34: Measurements set up for the H-magnet magnetic fields

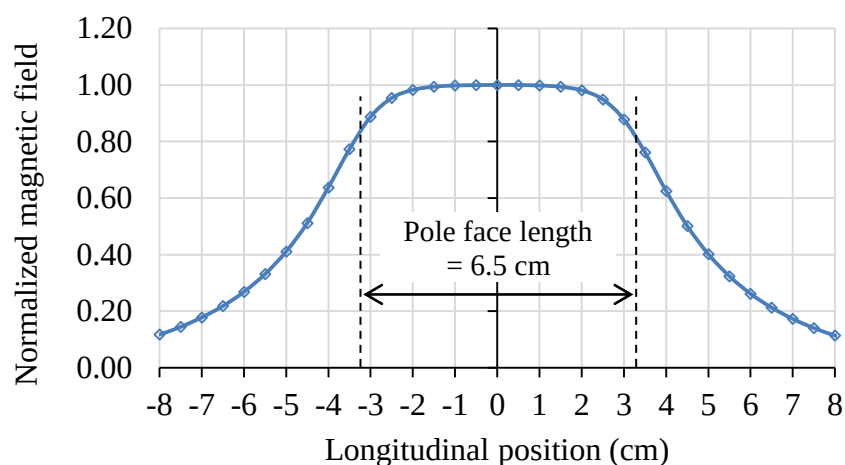


Figure 3.35: Normalized measured magnetic field of the H-magnet along the Z axis.

The measured magnetic field of the H-magnet has peak at the middle of the magnet with the value of 156.64 mT and the fringe fields extends over the pole face and reduce as a function of the distance. The effective length l_{eff} which defined by $l_{eff} = \int B_z dz / B_{max}$ here B_z is the transverse magnetic field along z direction and B_{max} is the peak magnetic field strength. The value of $\int B_z dz$ is 1678.89 mT-cm and the B_0 is 156.64 mT. Thus the effective length of the H-magnet is 10.67 cm.

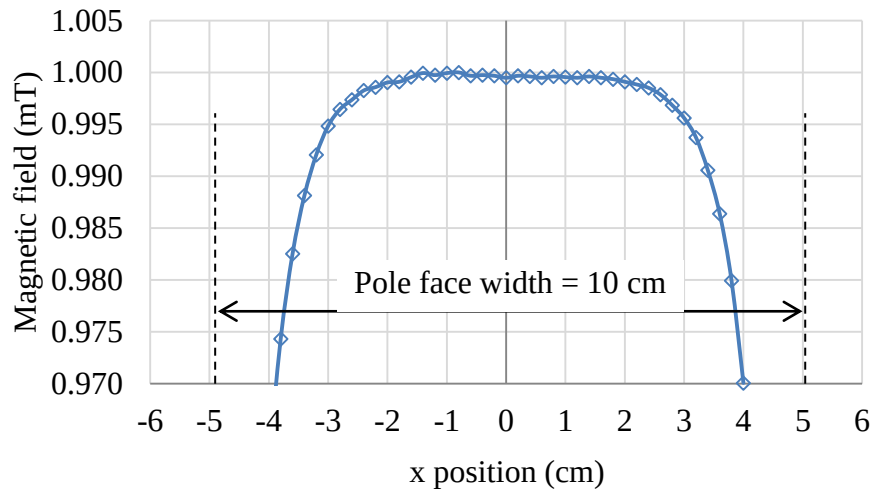


Figure 3.36: Normalized measured magnetic field of the H-magnet along the X axis

The distribution of the magnetic fields along the X axis of the H-magnet are uniform around the middle of the magnet ($x = 0$) as shown in Fig 3.36. The magnetic fields gradually drop toward the edge of the pole face and approximately 1% at the x position of ± 3.1 cm. When electrons travel in off-center trajectory through the H-magnet no.2 and 3. Electrons see the lower magnetic field from the magnets no.2, 3 than no.1, 4 resulting in the remaining of the dispersion and the transverse beam offset. To compensate this, two small correction coils were added at the one side of the yoke of the H-magnet no. 2 and 3 as shown in Fig. 3.37. Figure 3.38 show that the measured peak magnetic fields of H-magnet as a function of the exited current. The peak magnetic fields have proportional to the exited current and agree with the calculation by RADIA.

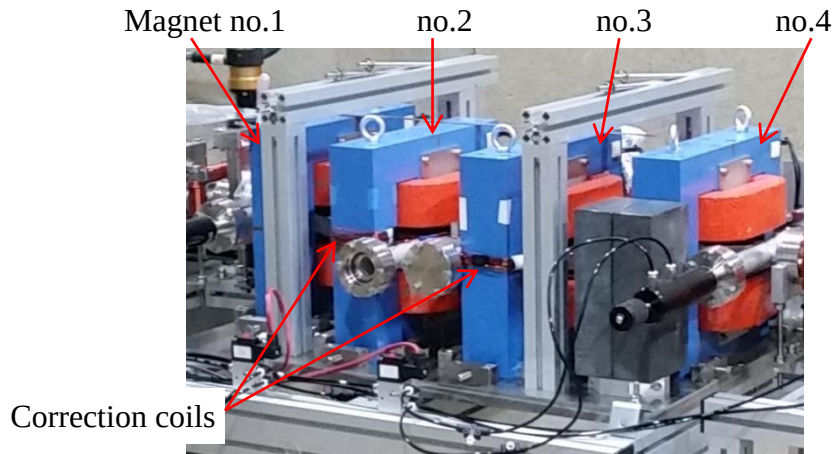


Figure 3.37: Two correction coils are installed at the chicane bending magnet no. 2 and 3.

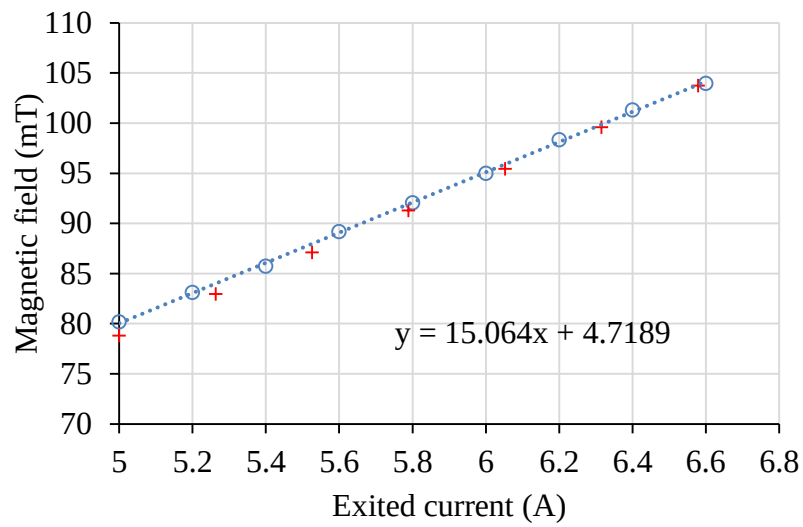


Figure 3.38: Magnetic field at the center of the pole gap of the H-magnet as a function of the exited current by the measurement (circle marks) and RADIA calculation (cross marks).

3.3 Undulator

3.3.1 Undulator Specification

Undulator of the compact THz radiation source is a vertical deflection planar Halbach type permanent magnet with the period length of 70 mm and the number of periods of 10. The undulator gap can be manually adjusted with the minimum gap of 30 mm limited by the vacuum chamber and the undulator parameters are listed in Table 3.7.

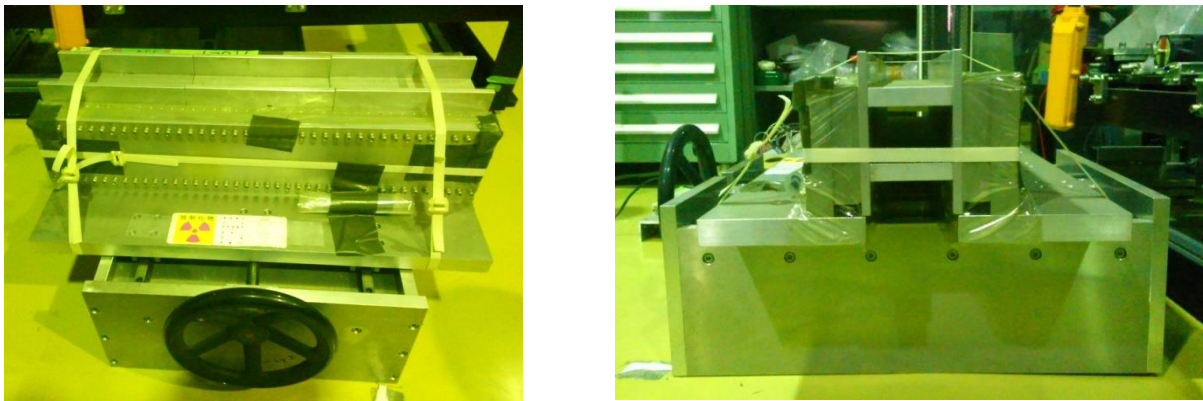


Figure 3.39: Undulator for the compact THz radiation source in the front view (left) and the side view (right)

Table 3.7: Undulator parameters of the compact THz radiation source

Undulator Parameters	Values
Number of period	10
Period length	70 mm
Total length	700 mm
Minimum gap	30 mm
Maximum magnetic field	0.43 T
Maximum undulator parameter (K)	2.8
Spectral bandwidth	10 %
Radiation frequency (Beam energy of 4.6 MeV)	0.17 – 0.55 THz

3.3.2 Measurement of Undulator Magnetic Fields

Undulator magnetic fields were measured by a Gauss meter (Lakeshore 460 3-channel Gauss meter) with using a 3 axis Hall probe. The meter has the resolution of $5 \frac{3}{4}$ digit and the accuracy of $\pm 0.10 \%$. The probe was mounted on the 2-m long translational stage driven by a servo motor with the maximum resolution of 0.01 mm. The movement of the stage and the read out of the measured values were controlled by LabVIEW. The set up of the undulator magnetic field measurement is shown in Fig. 3.40.

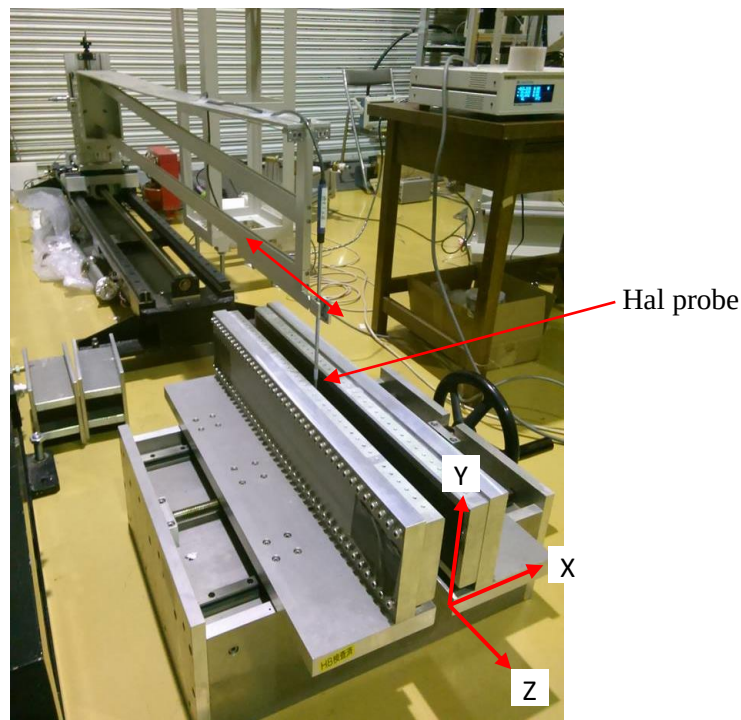


Figure 3.40: Measurement setup of the undulator magnetic fields



Figure 3.41: 3-Channels Gauss meter (Lakeshore 460)

The measurement result of the magnetic fields and the magnetic field amplitude error is shown in Fig. 3.42. The magnetic field has a peak at the period next to edge of the undulator. The magnetic field amplitude error ΔB was calculated by comparing the measured fields to the ideal fields (Eq. 1.1). The undulator magnetic field B_{real} including the ΔB can be expressed by

$$B(z) = B_0 (1 + \Delta B / B_0) \sin(k_u z) \quad (3.29)$$

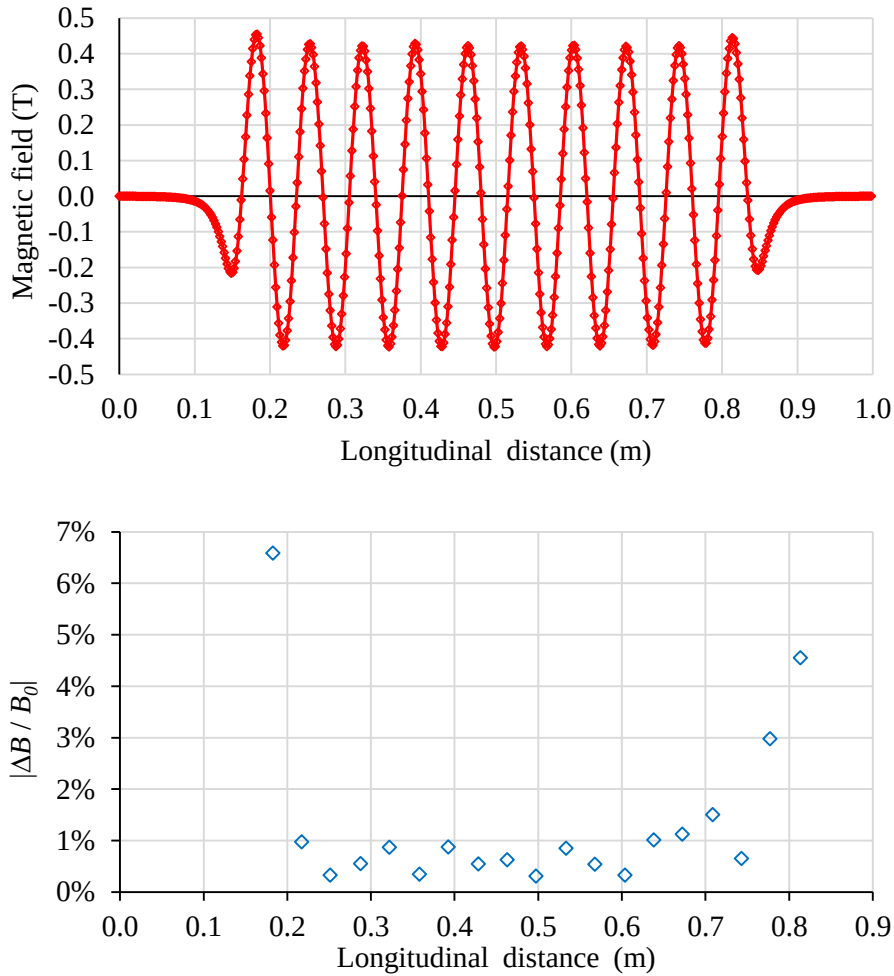


Figure 3.42: Measured magnetic field at the center axis at the undulator gap of 30 mm (upper) and the magnetic field amplitude error ΔB (lower).

From Eq. 1.5, the 1st integration of the magnetic field multiply by the factor $e / \gamma m_e$ give the transverse velocity of electrons and the trajectory can be obtained by the 2nd integration of the magnetic field multiply by the factor $e / \gamma m_e \beta c$. The transverse velocity and trajectory is shown in Fig. 3.43. Note that we applied angle kick to an incident electron in order to obtain the exiting trajectory with parallel direction to the axis.

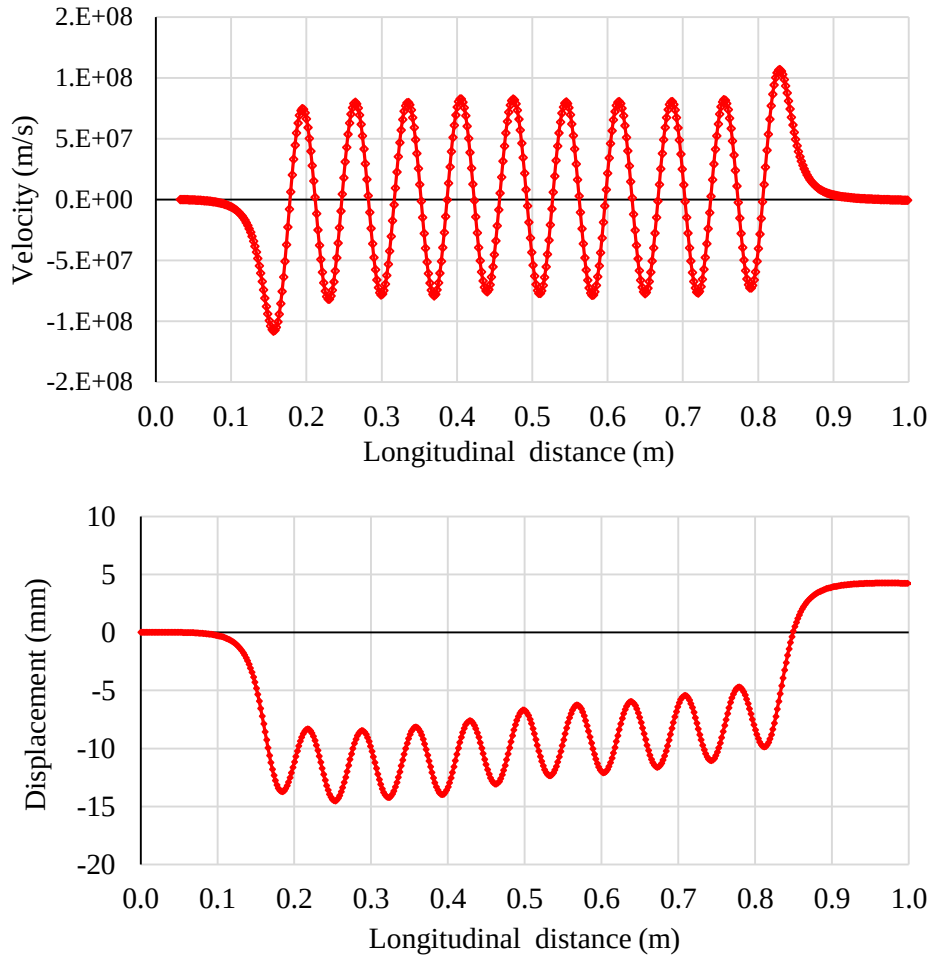


Figure 3.43: Calculation of the electron transverse velocity (upper) and trajectory (lower).

At the gap of 30 mm, the measured peak magnetic field at the center between poles is 0.43 T and the maximum undulator parameter K is 2.8 corresponding to the radiation frequency of 0.17 THz. The calculated undulator parameter and the undulator radiation frequency as a function of the undulator gap are shown in Fig. 3.44.

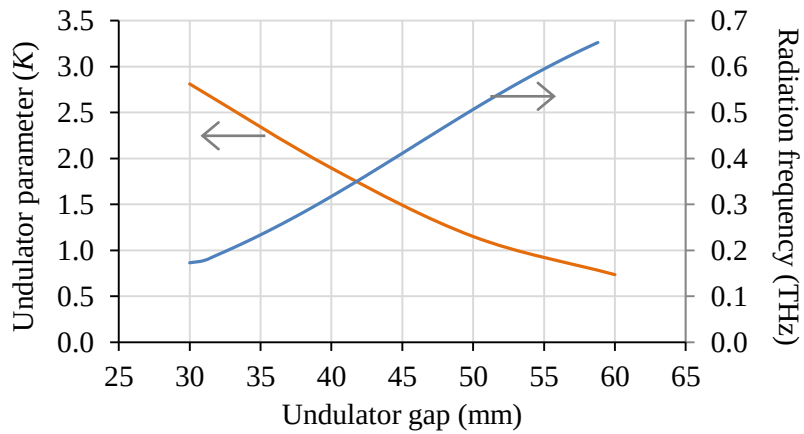


Figure 3.44: Undulator parameter and radiation frequency as a function of the undulator gap.

3.4 Focusing and Steering Magnets

3.4.1 Solenoid magnet

Solenoid magnet attached in front of the RF-gun was designed and manufactured by Japan Advanced Industrial and Science Technology (AIST) [41]. The solenoid magnet was employed for the emittance compensation of the photocathode RF gun beam. The magnet made from a hollow rectangular water cooled copper coil formed in a pancake shape. The several pancake coils which alternate with the iron plates were stacked together and covered by a stainless steel case. The total length of solenoid is 22 mm. The DC current power supply of the solenoid magnet has the maximum current of 200A. The four normal close temperature sensors with the open circuit temperature at 80 degree and the cooling water flow switch were connected in series for the power supply interlock system.

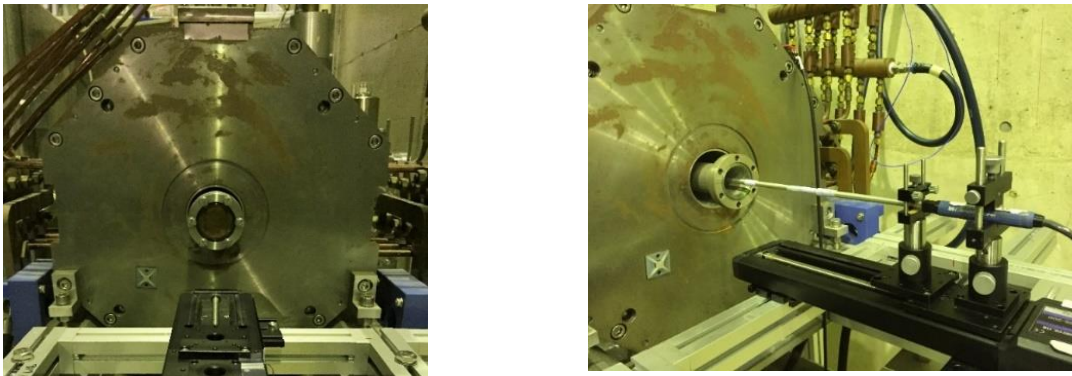


Figure 3.45: Front view of the solenoid magnet (left) and the set up of the solenoid magnetic field measurement (right).

The longitudinal magnitude field of the solenoid magnet was measured by using 3-axes Hall probe attached on the translation stage and the applied current was 100 A. The setup of the magnitude field measurement of the solenoid magnet is shown in Fig. 3.45. The measurement result of the longitudinal magnetic field B_z as a function of the position are shown in Fig. 3.46. The longitudinal magnetic field at the center of the magnet as a function of the exiting currents is shown in Fig. 3.47.

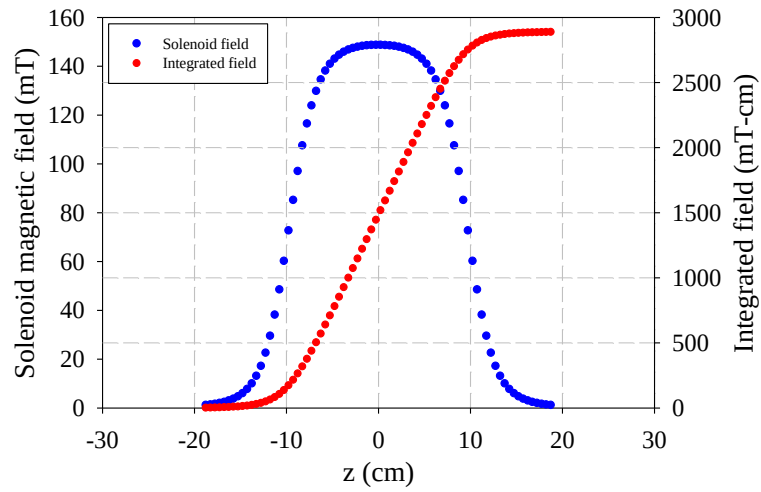


Figure 3.46: Measured longitudinal magnetic fields and its integration as a function of longitudinal position with the excited current of 100 A.

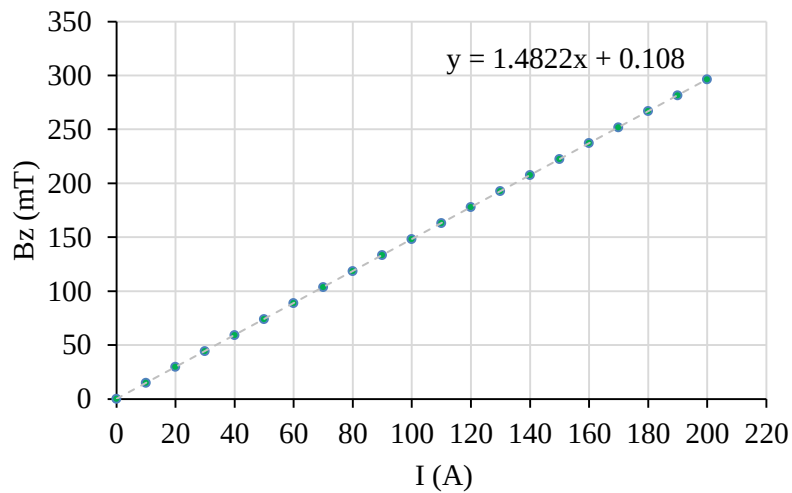


Figure 3.47: Measured peak longitudinal magnetic field as a function of the excited currents.

As the result, the maximum measured magnetic fields are 148.65 mT at the center of the magnet. The peak magnetic field at the center of the magnet was proportional to the exciting current and the relation can be written as

$$B_z [\text{mT}] = 1.4822 I [\text{A}] + 0.108 \quad (3.29)$$

where B_z is the longitudinal magnetic field magnitude and I is the excited current of the solenoid magnet. To calculate the effective length, the integration of the longitudinal field

along the z-axis at the applied current of 100 A are shown together in Fig. 3.47. The effective length l_{eff} of the solenoid magnet is the integral magnetic fields along longitudinal direction $\int B_z dz$ divided by peak magnetic field B_0 as

$$l_{eff} = \int B_z dz / B_0 \quad (3.30)$$

The value of $\int B_z dz$ is 2886.14 mT-cm and the B_0 is 148.66 mT. Therefore, the effective length of the solenoid magnet is 19.41 cm.

3.4.2 Quadrupole magnet

Quadrupole magnet is a beam focusing device which comprises with two pairs of magnetic poles and confines by a yoke and the same polarity poles are placed in the opposite side. Quadrupole magnet is able to focus beam in one direction while defocus in another orthogonal direction. The transverse magnetic fields B_x , B_y of the quadrupole magnet is linear proportional to the distance from the magnet center and can be expressed by

$$B_x(x, y) = g_y y \quad , \quad B_y(x, y) = g_x x \quad (3.31)$$

where g_x and g_y is the magnetic field gradient $g_x = \partial B_x / \partial x$, $g_y = \partial B_y / \partial y$. The longitudinal magnetic field is maximum at the center of the magnet and gradually decreases toward the edge of the pole face and rapidly decrease extends over the pole face. The effective length of the quadrupoles is defined by integral of the magnetic fields in longitudinal direction $\int B_z dz$ divided by the peak magnetic field. The picture of the quadrupole magnet is shown in Fig. 3.48. The dimension of the quadrupole magnets is listed in Table 3.8.



Figure 3.48: Quadrupole magnet (front view)

Table 3.8 Dimensions and properties of the quadrupole magnet.

Parameters	Values
Aperture	34 mm
Pole face width	40 mm
Magnetic yoke width	40 mm
Magnetic yoke thickness	15 mm
Total height	210 mm
Magnetic coil size	74 mm
Number of coil turn	168 turns
Maximum applied current	6 A

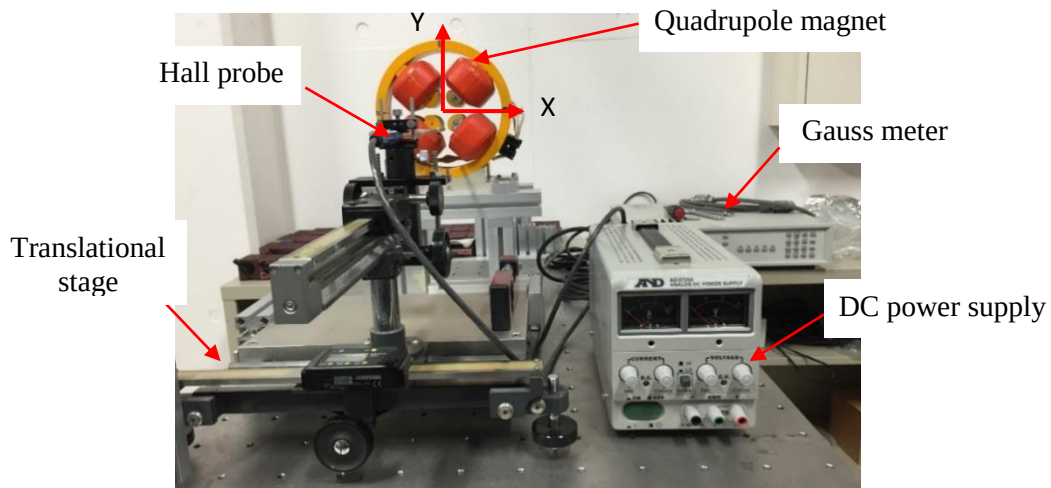


Figure 3.49: Set up of the quadrupole magnetic field measurement.

The measurement of the magnetic fields of the quadrupole magnet was performed by using the 3-axes Hall probe and read out by the 3-channel Gaussian meter and the set up is shown Fig. 3.49. The probe was mounted on the translation stage and its position was read out by digital linear scales. The center of the magnet is defined as $(x,y,z) = (0,0,0)$. The measured magnetic fields along the horizontal and vertical axis of the quadrupole magnet are shown in Fig. 3.50 and 3.51. As the results, the measured fields are proportional to the distance from the center and the magnetic field strength at the same distance from the center is similar for in horizontal and vertical directions.

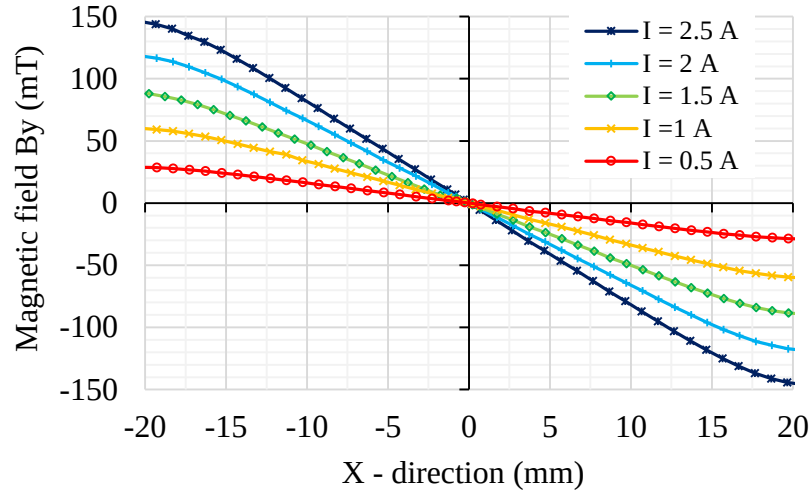


Figure 3.50: Measurement result of the vertical magnetic field along X axis.

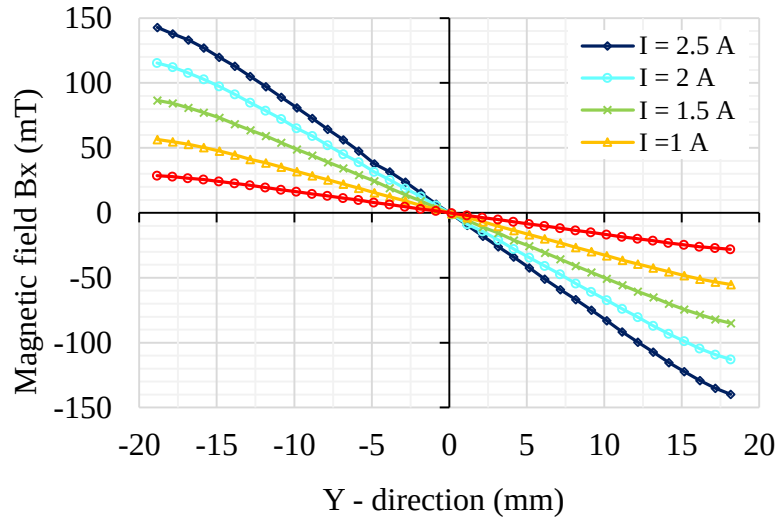


Figure 3.51: Measurement result of the horizontal magnetic fields along Y axis.

The magnetic field gradients as a function of the excited current in the horizontal and vertical axis are shown in Fig. 3.52. The magnetic field gradients were calculated at 5 mm far from the center of the magnet in both directions. The results show that the field gradients are proportional to the excited current. The measured magnetic fields in the longitudinal direction are shown in Fig. 3.53. The measured $\int B_z dz$ and g_x are 169.36 mT and 2.97 mT/mm. The effective length of the quadrupole magnet $\int B_z dz / g_x$ is 57.03 mm.

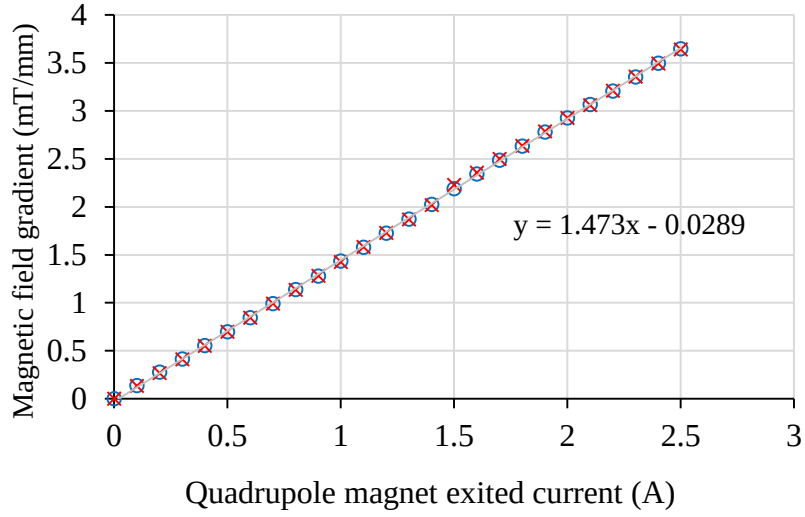


Figure 3.52: Magnetic field gradient of the quadrupole magnet by the measurements (cross mark) and the calculation (circle mark).

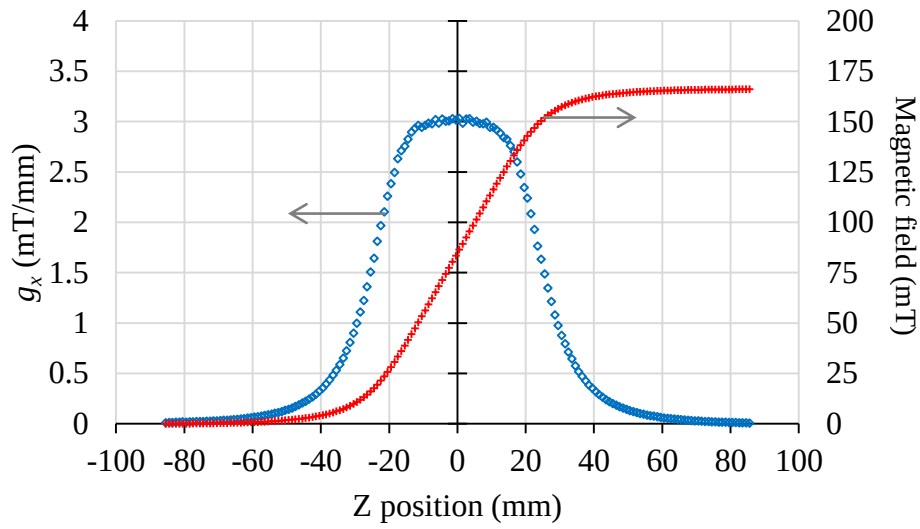


Figure 3.53: Measurement results of the longitudinal magnetic fields (diamond marks) and its integration (cross marks).

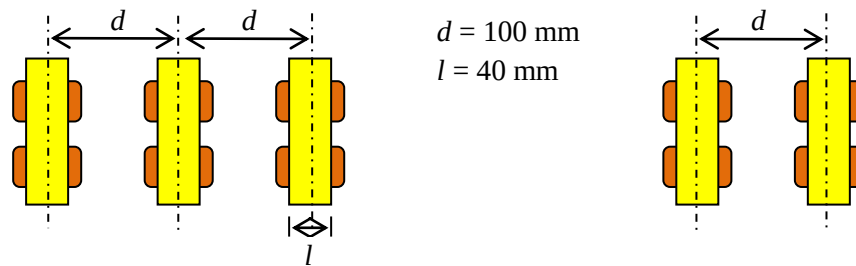


Figure 3.54: Diagrams of the triplet (left) and the doubled (right) quadrupole magnet.

3.4.3 Steering magnet

Three steering magnets were used for adjusting the beam direction along the beam line (see Fig. 2.8). The 1st steering magnet was made by the four quadrupole coils with unknown specification but it could perform properly. The 2nd and 3rd steering magnet was made by four pieces of a 15×15 mm cross-section iron connecting in the square shape as shown in Fig. 3.55. Coated copper wire winding has 78 turns for each coil and opposite coil is connected in series to generate both vertical and horizontal magnetic fields. Two DC power supplies with the maximum current of 3 A were used for each steering magnet. The polarity of coils can be switched by using the magnetic relays as shown in Fig.3.56. The maximum magnetic field strength can be calculated by Eq. 3.25 and the integral path for the calculation as shown in Fig. 3.55. The calculated maximum magnetic field is $B_0 = \mu_0 NI/G = 4\pi \times 10^{-7} (78)(3)/(0.065) = 4.52 \text{ mT}$ at the excited current of 3A.

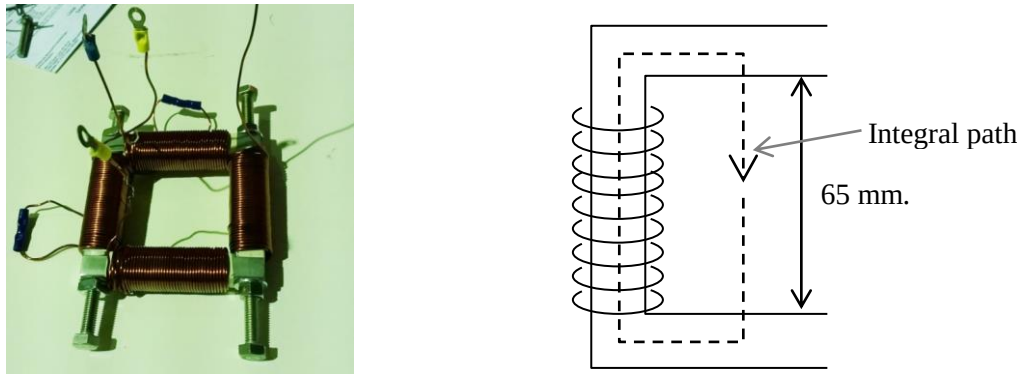


Figure 3.55: Steering magnet (left) and the schematic diagram for the magnetic field calculation (right).

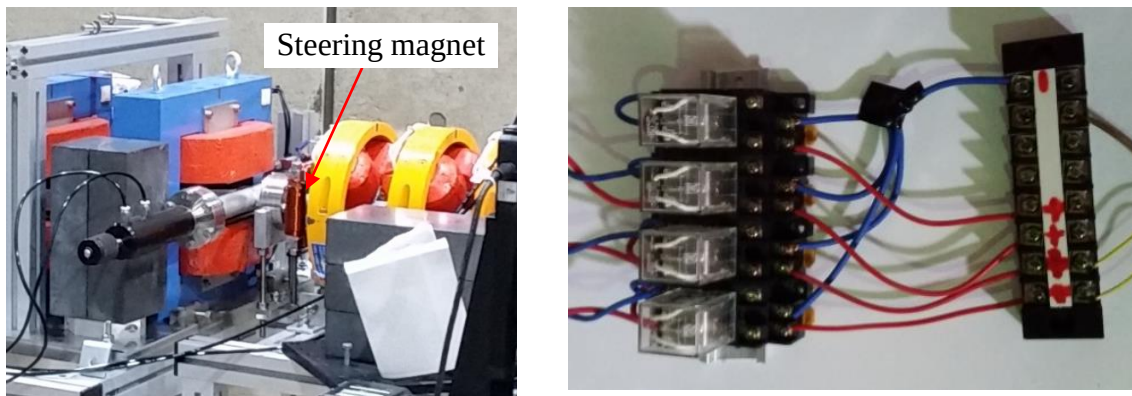


Figure 3.56: Steering magnet downstream the chicane (left) the magnetic relays for switching of the steering magnet polarity (right).

3.5 Beam Instrumentations

3.5.1 Beam Profile Monitor

The transverse electron beam profile was observed by a fluorescent screen which emit visible lights when expose to electron beams. Four beam profile monitors were installed along the beam line where are at upstream and downstream the chicane, the TR station and the middle of the undulator. The beam profile monitors at the upstream and downstream the chicane has the dimension of 10 x 10 mm and tilted in 45 degree respected to the beam axis. The beam profile at the TR station has the dimension of 30 × 30 mm is attached back side of the aluminum foil and arranged in 45 degree to the beam axis. The beam profile at the middle of the undulator magnet is normal to the beam axis. All screens were observed by the CCD camera (EASLER, acA640) using the lens and the extension tubes. The camera is connected to the control system network. The image properties such as gain, exposure time and maximum can be adjusted by the real-time image processing software by using LabVIEW.

3.5.2 Bunch Charge Monitor

Faraday cup is a simplest device for a destructive measurement of a particle charge. A Faraday cup made from a block of conducting material typically designed in a cup shape in order to capture all charge particles and prevent scattering of particles. The time resolution of charge measurement by Faraday cup can be very high up to several GHz that allow measuring a time structure of a short bunched beam in picoseconds scale. The usage of the Faraday cup is limited only for a low-energy beam because a high energy beam has a high penetration which requires a very thick block material and a heat dissipation system for a Faraday cup. The amount of capture charges can be obtained by measuring a signal by oscilloscope. The relation between the measured voltage signal $U(t)$ and the bunch charge Q can be expressed by

$$Q = \int I(t) dt = \int U(t) / R dt \quad (3.32)$$

where $I(t)$ is the current signal and R is the impedance of the measurement system. The schematic diagram of the bunch charge measurement by Faraday cup is shown in Fig. 3.57.

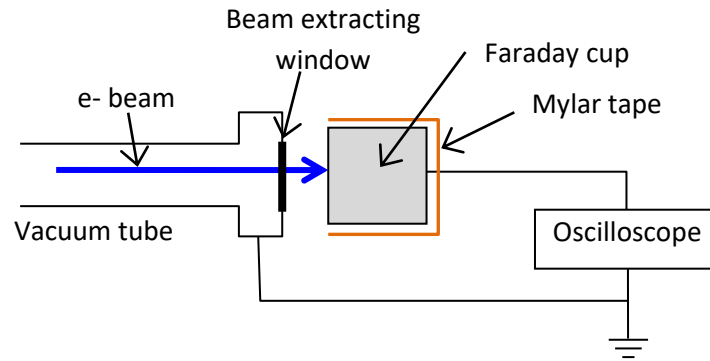


Figure 3.57: Schematic diagram of the bunch charge measurement by a Faraday cup

An out-of-vacuum carbon Faraday cup with the dimension of $10 \times 10 \times 10$ cm was used for the bunch charge measurement of the compact THz system. Carbon material is suitable for Faraday cup because it has low atomic number that provide low back scattering electron [42]. The cup was covered by a mylar tape for the faces which did not exposed to the beam to prevent lose of electrons. The cup was placed at the end of the beam line downstream the beam extracting window and connected to the ground through the 200 GHz oscilloscope (IWATSU, DS-5624A). The signals from the faraday cup were monitored and the bunch charge was calculated by the integration of the measured signal.

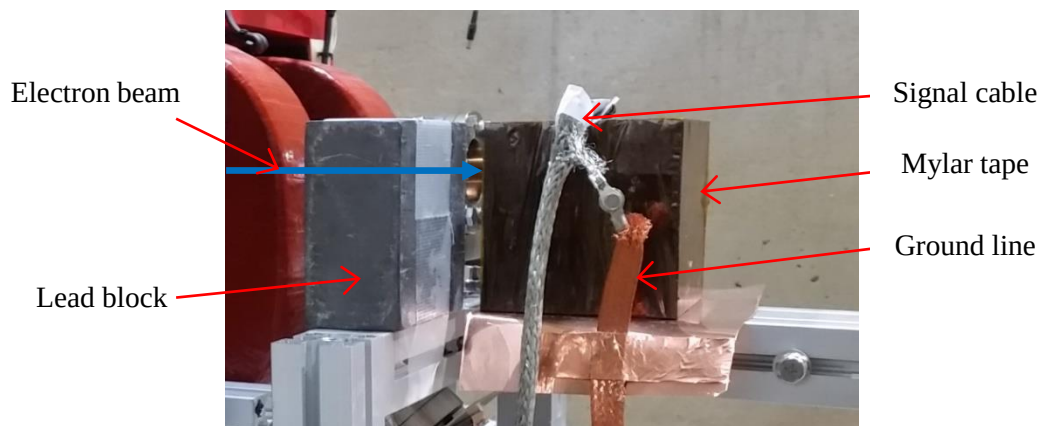


Figure 3.58: Carbon Faraday cup for the bunch charge measurement

3.5.3 Energy spectrometer

Beam energy and spread of electron beams can be simply determined by measuring the angle of deflection of the beams in known magnetic fields. The total deflection angle α_{tot} of electron beam depends on the momentum p of electron and the total magnetic fields $\int B_z ds$ seen by electrons. The relation of these parameter can be derive from the Lorentz force and can be expressed by

$$p = \frac{e}{\alpha_{tot}} \int B_z ds \quad (3.33)$$

where e is the charge of electron. The beam energy E is then given by

$$E = \sqrt{p^2 c^2 + (m_0 c^2)^2} \quad (3.34)$$

In case of non-monoenergetic electron beams, the exiting beam from a bending magnet becomes wider in the deflection plane due to the deflection angle dependence on their energy or *dispersive beam*. The low energy electron beam deflects with an angle larger than high energy ones. The beam size σ_y of the dispersive beam can be calculated by

$$\sigma_y = \sqrt{\beta_y \varepsilon_y + D_y^2 \sigma_E^2} \quad (3.35)$$

where β_y is the vertical beam envelope function, ε is the beam emittance, D is the dispersion function of the bending magnet, $D(z) = 2\sin(\alpha/2)z$, here z is the distance from the magnet center and α is the deflecting angle. The quadrupole magnet is usually placed in front of the bending for focusing the beam. Therefore, the energy spread σ_E can be calculated by

$$\sigma_E \approx \sigma_x / D_x \quad (3.36)$$

The beam dump bending magnet (Fig. 3.59) was used as the energy spectrometer for the beam energy and the energy spread measurement. The magnet is the rectangular bending electromagnet with the pole length of 100 mm, the pole width of 100 mm and the pole gap of 50 mm. The magnet deflect beam in the vertical direction to the beam dump. The magnetic

fields of the bending magnet have been measured by 3-axis Hall probe and the 3-channel Gauss meter (Lakeshore, 460). The maximum magnetic field at the excited current of 5.5A is 89.9 mT. The distribution of the magnetic field is shown in Fig. 3.60 and Fig. 3.61. The effective length of the bending magnet calculated by Eq. 3.30 is 18.39 cm.

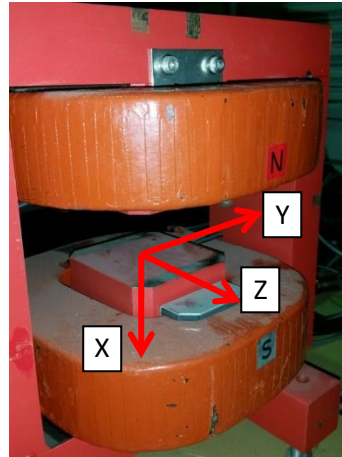


Figure 3.59: The beam dump bending magnet.

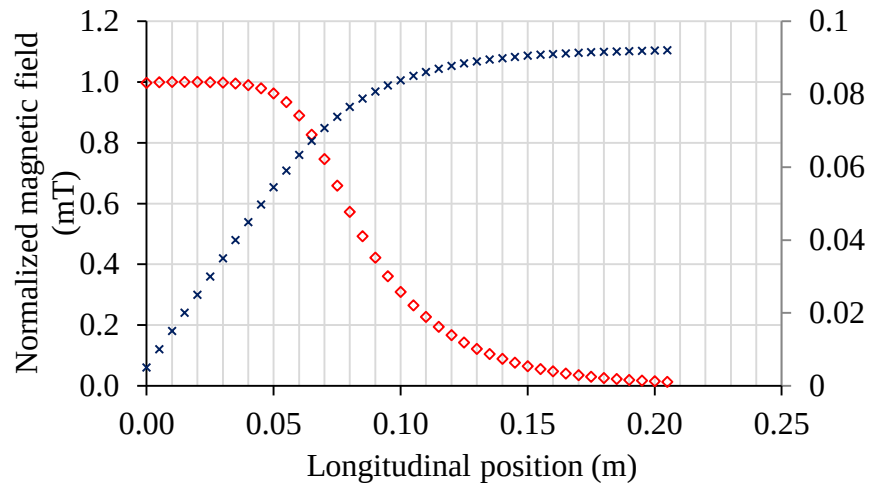


Figure 3.60: Normalized magnetic field (diamond mark) along the longitudinal position (Z axis) and the integration of the magnetic fields (cross mark).

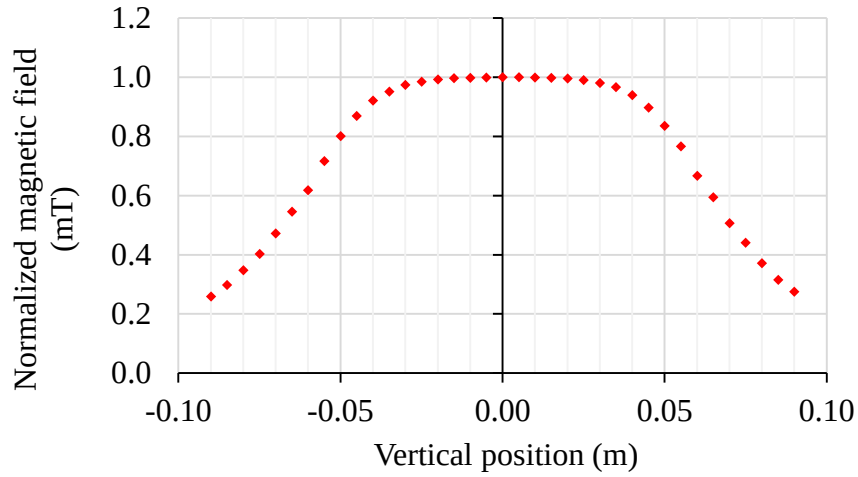


Figure 3.61: Normalized magnetic field along the vertical position (Y axis)

3.5.4 Michelson interferometer

A Michelson interferometer is an optical device which split incident lights in two parts therefore sometime it referred as a two beam interferometer. In this study, the interferometer was used for analyze the radiation spectra of a coherent transition radiation (chapter 6) and the undulator radiation (chapter 7). The schematic diagram of the Michelson interferometer is shown in Fig. 3.62.

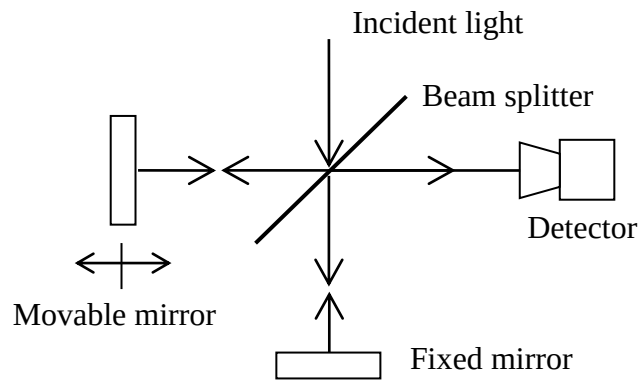


Figure 3.62: Schematic diagram of a Michelson Interferometer.

The Michelson interferometer consists of a beam splitter, a fixed mirror, a movable mirror and a detector. The incident lights are split into two beams by the beam splitter which arranged in the oblique angle of 45 degree respected to the incident light axis. One beam reflect back to the beam splitter by a fixed mirror while another one reflect back a movable

mirror which create a path length different δ . Then, the both reflected beams are recombined again and their amplitude are interfered each other. If the path length of the two beams is equal ($\delta = 0$). The two beams are recombined with constructive interference and the autocorrelated amplitude reaches the maximum. When the path length difference equal to the half wavelength of the incident light, the autocorrelated amplitude becomes zero due to the destructive interference. The detected signal intensity dependence on the path difference or an interferogram $S(\delta)$ [43] can be expressed by

$$S(\delta) \propto \int |TRE(t + \frac{\delta}{c}) + RTE(t)|^2 dt, \quad (3.37)$$

$$S(\delta) = 2 \int |RT|^2 E(t) E^* \left(t + \frac{\delta}{c} \right) dt + 2 \int |RTE(t)|^2 dt. \quad (3.38)$$

where R and T are the reflection and transmission coefficient of the beam splitter, $E(t)$ is the time-varying electric field, t is the time, and c is the speed of light. The first term is an autocorrelation of the radiation pulse while the second term determines the baseline whose intensity is half of the maximum value. An interferogram is the result of many frequency components contained in the light. These frequency components can be analyzed by Fast Fourier Transform (FFT) resulting in the radiation power spectrum $I(\omega)$ expressed by

$$I(\omega) = |E(\omega)|^2 \propto \int_{-\infty}^{+\infty} S(\delta) e^{i\omega\delta/c} d\delta \quad (3.39)$$

where $E(\omega)$ is the electric field in the frequency domain. However, the measured spectrum is strongly depend on the R, T value in the form of $|R(\omega)T(\omega)|^2$ called *beam splitter efficiency*. The beam splitter efficiency has specific frequency dependence depending on the refractive index and thickness. At a curtain frequency, the beam splitter efficiency drop to zero due to the destructive interference occurs by multiple internal reflections between the surfaces of a beam splitter called *thin film interference* [44]. A measured spectrum is also distorted by optical components of the measurement system such as absorption of a medium (air or filled-gas) $F_{med}(\omega)$, a frequency response of a detector $F_{det}(\omega)$, a diffraction limited spectral transmission at a low frequency $F_{diff}(\omega)$ and source size effect on radiation $F_{source}(\omega)$. To obtain a correct spectrum, all these factors need to be carefully considered. The spectrum dependent factor $F(\omega)$ of the measurement system that can be expressed by

$$F_{meas}(\omega) = F_{bs}(\omega) F_{med}(\omega) F_{det}(\omega) F_{source}(\omega) \quad (3.40)$$

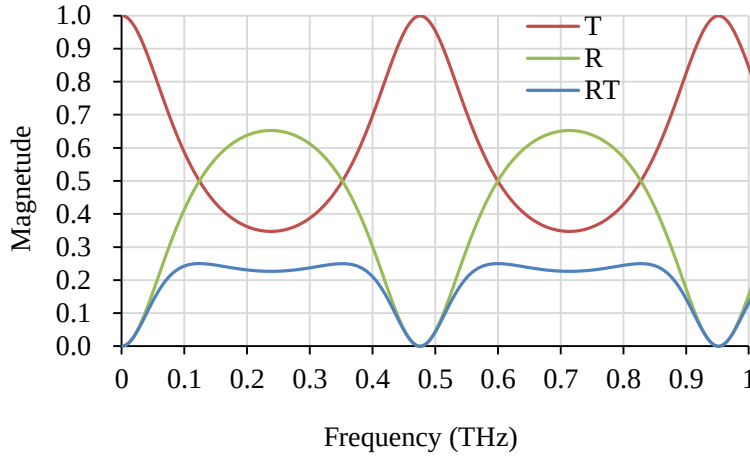


Figure 3.63: Magnitude of transmission T , reflection R and product of RT of sapphire beam splitter for the coherent transition radiation experiment. The RT drop at 0.475 THz due to the multiple internal reflections inside the beam splitter.

The measurement of the continuous time-domain signal is always done by sampling a signal over a given period of time resulting in a series of discrete signal. The sampling period time, t_{sam} , has to be shorter than a half of a signal period. Otherwise the measured signal cannot reconstruct an actual signal. The inverse of the sampling period time is the sampling frequency, $f_{sam} = 1/t_{sam}$. The upper limit on the frequencies obtained from the Fourier transform is known as *Nyquist frequency* (F_{Nyq})

$$F_{Nyq} = F_{sam} / 2 \quad (3.41)$$

The sampling frequency of a Michelson interferometer is determined by the scan step of a movable mirror. For example, the moving step of the movable mirror is 0.1 mm equivalent to the optical path different of 0.2 mm. The calculated sampling frequency is $c/0.2 \text{ mm} = 2.997 \times 10^8 / 0.2 \times 10^3 = 1.5 \times 10^{12} = 1.5 \text{ THz}$. Therefore, the maximum frequency which obtains from Fourier transform or Nyquist frequency is 0.75 THz.

Time window T_{win} which is defined as a total time period of measured radiation can be calculated from a total optical path different length of an interferogram or two times of the total moving range L_{tot} of a movable mirror

$$T_{win} = 2 \times L_{tot} / c . \quad (3.42)$$

For example, the total moving range of the movable mirror is 7 mm which equal to the total optical path different length of interferogram of 14 mm. The time window is $14 \times 10^{-3} / c = 14 \times 10^{-3} / 2.997 \times 10^8 = 46.7$ ps.

The spectral resolution comes from the limitation of the Fourier transform of the finite length of discrete time-domain data. The Fourier transform of this data give the spectrum with main component and many smaller components. The spectral resolution I_{reso} can be determined by the inverse of time window

$$I_{reso} = 1 / T_{win} \quad (3.43)$$

For the example, the total movable range of the movable mirror of 7 mm has the time window of 46.7 ps that provides the spectral resolution of $1 / 46 \text{ ps} = 21.4 \text{ GHz}$. To obtain a high resolution, the time window total movable range of a movable mirror should be as long as possible.

3.5.5 Terahertz detector

Two small-size room-temperature detectors were used for the measurements of THz radiation intensity of the coherent transition radiation (chapter 5) and the undulator radiation (chapter 6). The brief theories and the specifications of the detectors are described in this section.

Pyroelectric detector

Pyroelectric detector is a thermal detector which converts energy of an incident radiation pulse to electricity by the *pyroelectricity effect* [45]. The detector made by a pyroelectric crystal whose molecule has electrical asymmetry acting like a dipole arranged randomly resulting in neutral electric fields. When the incident radiations illuminate on a crystal, radiation absorption cause the crystal temperature change and a polarization current is generated. The pyroelectric detector can be considered as a combination of a capacitor and a generator. Time response of the detector is not so fast typically in the order of hundred microsecond and therefore it cannot measure the radiation energy of an individual

microbunch. The amplitude of the output signal from the pyroelectric detectors is proportional to the temperature change of the pyroelectric material and the area of the detector. The pyroelectric detector has a uniform spectral characteristic in a wide frequency range. The equivalent circuit and the typical signal waveform of the pyroelectric detector are shown in Fig. 3.64.

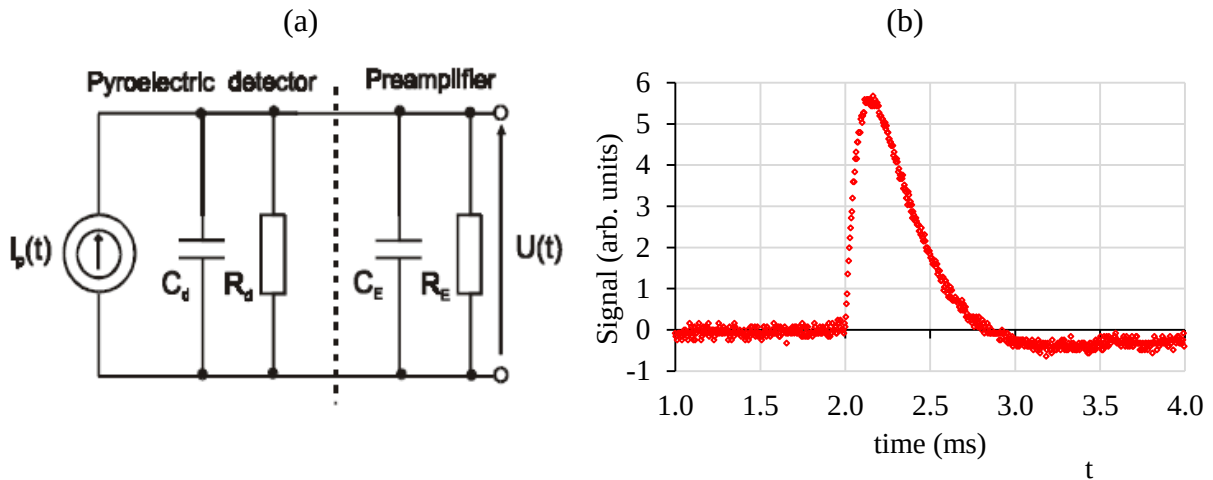


Figure 3.64: (a) Equivalent circuit of the pyroelectric detector with pre-amplifier and (b) typical signal waveform of a pyroelectric detector.

The pyroelectric detector used in this study was manufactured by PHLUXi (PHLUXi, PYD-1-018) [46]. The detector has a fast response, a broad spectral response from THz to UV and no cooling required. The specifications of the detector are listed in Table. 3.9. However, these values were measured with the pulse laser at the wavelength of 1064 nm, the pulse repetition rate of 300 Hz and the pulse duration of 100 μ s. The performance of the detector might differ in the THz radiation regime. Unfortunately, the detector calibration in the THz radiation regime had not been performed during this study. Therefore, all measured values presented in this study were the relative values.

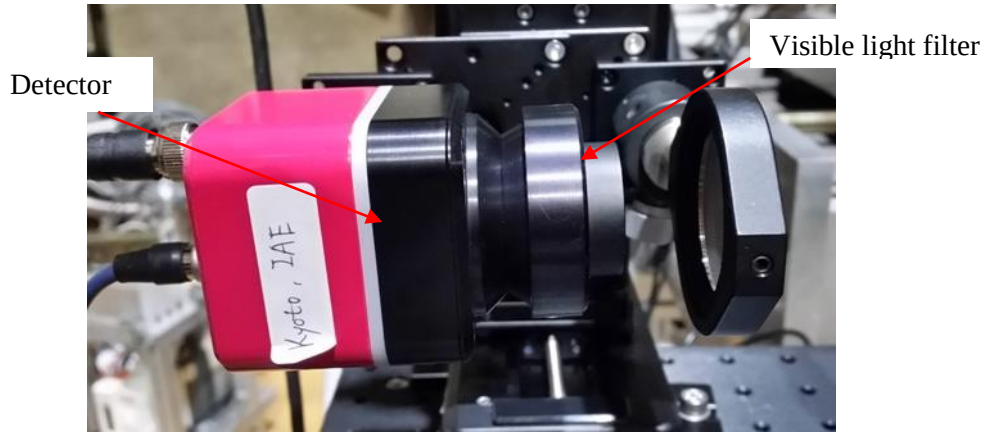


Figure 3.64: Pyroelectric detector attached with the visible light filter and lens.

Table 3.9: Specifications of the pyroelectric detector PHLUXi PYD-1-018

Specifications	Values
Wavelength region	300 nm to 300 μm
Sensor size	ϕ 1 mm
Frequency response	300 Hz maximum
Maximum pulse width	200 μs
Rise time	350 μs
Sensitivity (@ 1064 nm)	12 MV/J
Noise level	1 nJ
Maximum measured energy	10 μJ

Schottky zero-bias barrier diode detector

Schottky zero-bias barrier diode is a semiconductor diode formed by a metal-semiconductor junction. The SBD diode has a very fast switching action, low forward voltage drop and does not require an external power source. The response of the SBD diode detector is so fast in the order of nanosecond and able to see an individual waveform of the radiation. The SBD detector used in this study was manufactured by Millitech (Millitech, DET-05-RPFW0). The detector is compact, has a high sensitivity and operates in the G-band frequency range (140 to 220 GHz) [47]. The output voltage of the SBD detector is linear for the input power level below -10 dBm. At the 1 M Ω load impedance, the sensitivity of the detector is the 220 mV/mW with the flatness of $\pm$ 2.5 dB. This detector was installed in a

short G-band rectangular waveguide with the cross section of 0.65×1.3 mm. Therefore, the detector can detect radiations in a direction of polarization. The SBD detector, the sensitivity and the measured THz signal waveform by the SBD detector are shown in Fig. 3.65.

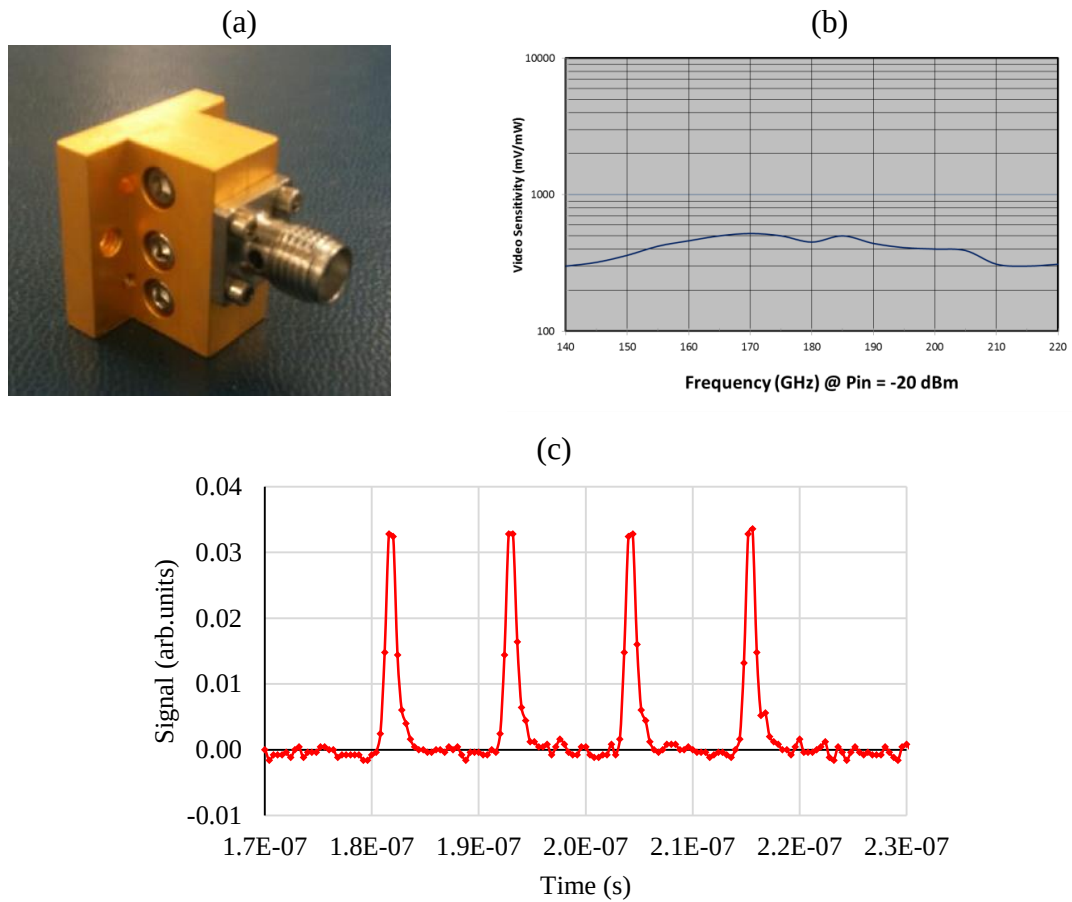


Figure 3.65: (a) SBD detector, (b) the sensitivity of the Millitech SBD detector model DET-05-RPFW0 and (c) the measured THz signal waveform.

3.6 Control system

The control system of the compact THz system was developed based on KU-FEL control system which uses LABVIEW as the control software and National Instrument as the interface hardware. The system is the network distributed control with Server - Client architect by using *ActiveX Channel Access* [48] as the communication protocol. Each controlled parameters were defined as *Process variables* whose values were sent throughout the network. The power supplies of all magnets were set to the output current mode and controlled by the external voltage in the range from 0 to 10 volt. A 16-channels analog output control module (National Instrument, NI 9264) was used as the voltage output module for the control of the magnet power supplies. The pneumatic actuators which used for the retraceable beam profile screens, the retraceable THz mirror and the laser shutter were controlled by the two 8-channels solid-state relay modules (National Instrument, NI 9485). The current of the power supplies were read by a 32-channels analog input module (National Instrument, NI 9205). All modules were mounted in the 8-slots ethernet data acquisition chassis (National Instrument, cDAQ-9188) and the chassis connect to the control computer via the local area network connection.

Table 3.10: List of the power supplies and the processes variables for the magnets.

Magnets	Power Supply Manufac., Model, Max Cur.	Process variables (Set variables)
Solenoid	KIKUSUI, PAT40-200, 200A	COMFEL:SOL:MAG:SET
Steering no.1 Hor	KIKUSUI, PMC18-3A, 3A	COMFEL:STRG:HOR:SET
Steering no.1 Ver	KIKUSUI, PMC18-3A, 3A	COMFEL:STRG:VER:SET
Steering no.2 Hor	TEXIO, PA10-5B, 5A	COMFEL:STRG2:HOR:SET
Steering no.2 Ver	TEXIO, PA10-5B, 5A	COMFEL:STRG2:VER:SET
Chicane bending	TAKASAGO, EX-375L2, 25A	COMFEL:CHI:MAG:SET
Chicane trim coils	KENWOOD, PMC18-5B, 5A	COMFEL:CHI:TRIM:SET
Steering no.3 Hor	TEXIO, PA10-5B, 5A	COMFEL:STRG3:HOR:SET
Steering no.3 Ver	KENWOOD, PMC18-5B, 5A	COMFEL:STRG3:VER:SET
Quadrupole no.1	TAKASAGO, TPO18-3D, 3A	COMFEL:QUAD:NO1:SET
Quadrupole no.2	TAKASAGO, TPO18-3D, 3A	COMFEL:QUAD:NO2:SET
Quadrupole no.3	TAKASAGO, TPO7-5D, 5A	COMFEL:QUAD:NO3:SET
Beam dump bending	TAKASAGO, EX-375L2, 25A	COMFEL:DUMP:SET

Table 3.11: List of the process variables for the shutter, the screens and the mirror.

Actuators	Process variables (Set variables)
Laser shutter	COMFEL:RLY:SHUTTER:SET
Chicane screen 1	COMFEL:RLY:CHISCRN1:SET
Chicane screen 2	COMFEL:RLY:CHISCRN2:SET
TR radiator	COMFEL:RLY:OTR:SET
Undulator screen	COMFEL:RLY:UNDSCRN:SET
THz mirror	COMFEL:RLY:THZMIRR:SET

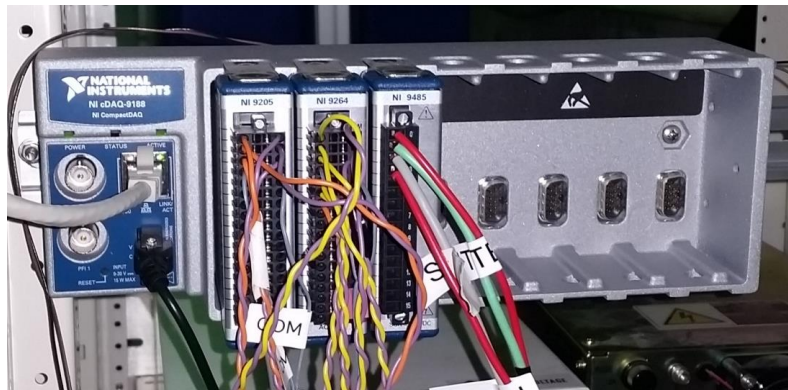


Figure 3.66: Ethernet data acquisition chassis (NI cDAQ-9188) and the control modules.

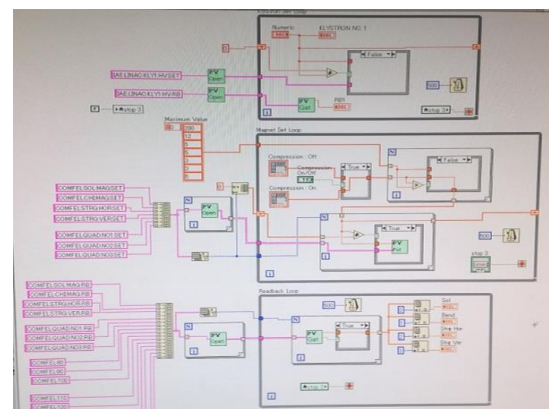
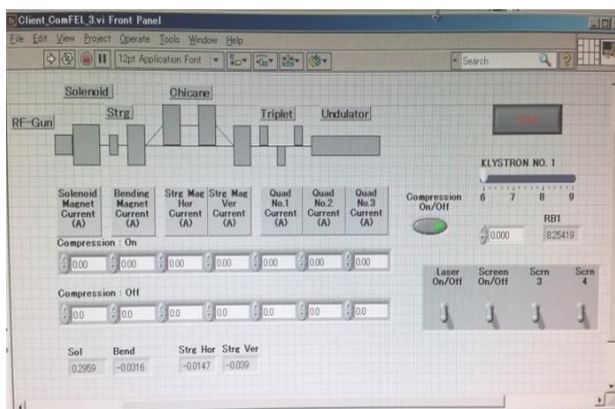


Figure 3.67: Control panel (left) and the control program (right) of the compact THz system.

Chapter 4

Particle Tracking Simulation

In this chapter, we explain the beam dynamics simulation to study the beam properties by using the particle tracking simulation code PARMELA and GPT. The results of PARMELA were used for the magnetic chicane design (section 3.2). The GPT was used for the start-to-end simulation. The discussions of the calculation results refer to chapter 5 and 6.

4.1 Tracking Simulation Codes

PARMELA

The code PARMELA [15] or the “Phase And Radial Motion in Electron Linear Accelerators,” was originally written by Kenneth R. Crandall in 1980 at Los Alamos laboratory, USA. Later, Lloyd Young modified the code for another application and prepared a working manual for his version. The PARMELA code has been improved continuously and verified the accuracy from various users worldwide. PARMELA can be used to simulate several types of charged particle with the options for including either 2D or 3D space-charge effects. PARMELA uses the right-handed curvilinear coordinate system, which the beam moves in +z direction and +x is referred to the right while +y is pointing up and tracks particle in 6 dimensional phase-spaces. External files such as accelerating electric fields or static magnetic fields created by an external code e.g. POISSON/SUPERFISH [49] can be imported and included in the input file of PARMELA. The default output file of PARMELA is TAPE2.T2 which contains 6 dimensional coordinates of particles at the exit of each beam line element. The graphical output of PARMELA is also available by using the post-processor *Pargraf* or *Tabplot*.

The numerical study of the beam properties at the RF gun exit by using PARMELA has been performed and reported in [50]. For this study, PARMELA was used for calculation of the energy chirp at the RF gun exit which was used for the design of the magnetic chicane (see section 3.2). 100,000 macroparticles were assumed to emit from the cathode surface. The average accelerating voltage was varied of 60, 70 and 80 MV/m equivalent to the peak accelerating voltage of 84.4, 98.9 and 113.1 MV/m. The laser injection phases were varied

from 12, 16 and 20 degrees. The beam properties at the RF gun exit are shown in Fig. 4.1 and the calculation results of the energy chirp refer to Fig. 3.24 and 3.25 in section 3.2.1.

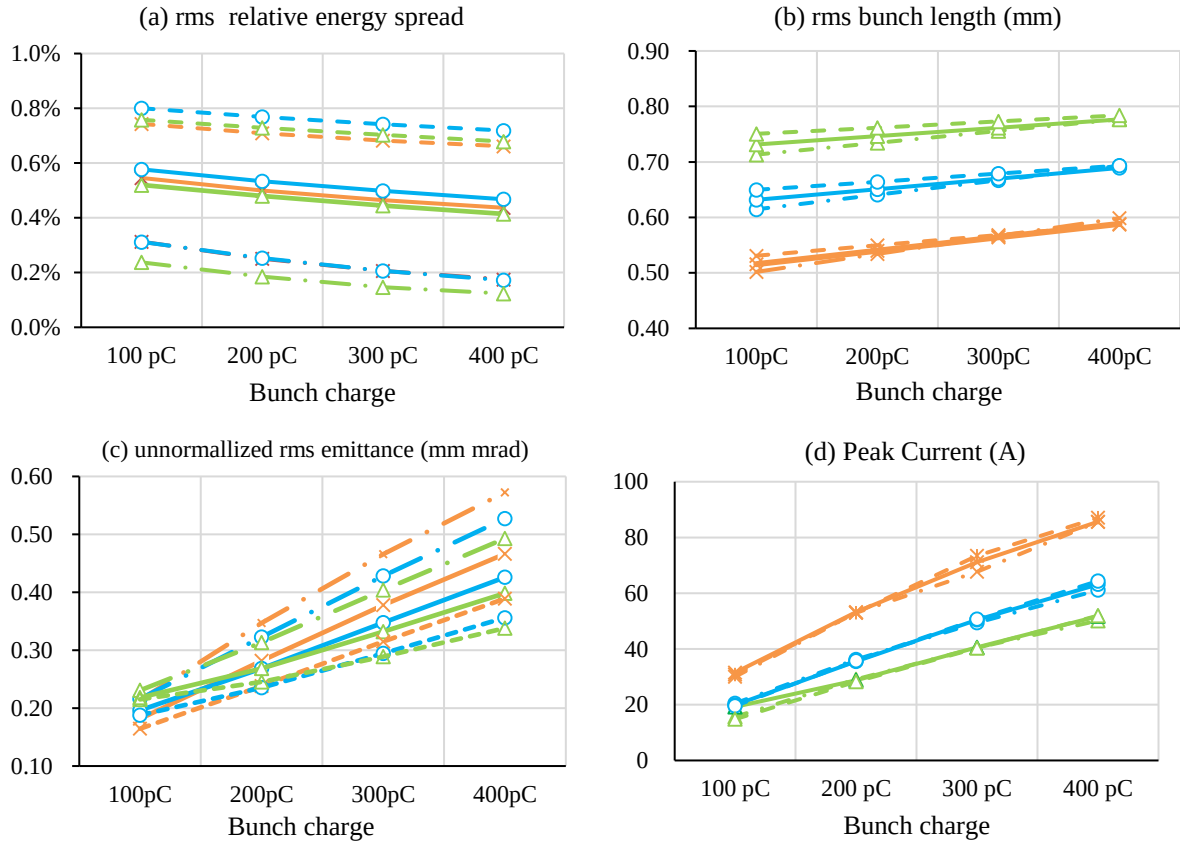


Figure 4.1: PARMELA calculation results of the beam properties at the RF gun exit. The single dot dashed, solid and dash lines represent the average accelerating voltage of 60, 70 and 80 MV/m, respectively. The cross, circle and triangle marks stand for the accelerating phase of 12, 16 and 20 degrees, respectively.

General Particle Tracer

General Particle Tracer or GPT [16] is the commercial software from Pulsar Physics [51] which was initially developed for the design of the FELIX accelerator at FOM-Rijnhuizen [52]. The GPT solve the particle's equations of motion by a fifth order Runge-Kutta method with adaptive step size control in the time domain. The adaptive step size mechanism automatically adjusts the size of the integration steps as function of the electromagnetic field gradients. Thus the computing time can kept to a minimum while the calculation still has a high accuracy. The GPT code is completely 3-dimension including a space-charge effect suitable for the calculation of low beam energy which is the space-charge

effect dominant regime. Beam line components can be positioned in anywhere and oriented in any direction in the 3D space. The code also includes the functions for a parameter optimization, a data-analysis, a pre- post- processing and a plotting. These functions make convenient for the beam line design. The code is also fully documented and all details of elements can refer to the manual. The input file for the tracking simulation of the compact THz radiation source is shown in the appendix A.

In this study, we used the GPT for the calculation of the longitudinal phase-space along the beam line and the start-to-end tracking simulation. The GPT was run on Window environment and the computer was a desktop personal computer (PC) with 3.4 GHz 6-core Intel Core i7-4930K CPU processor. The number of particles of the simulation is mainly limited by the calculation model of the space-charge effect. The most accurate space-charge calculation of the GPT is the *spacecharge3D* model which calculates all Coulomb forces and Lorentz transforms for each pair-wise interaction. We used this model because at near the cathode surface the bunch has low energy and large energy spread which require the calculation of the individual Lorentz factor. But the disadvantage of this model is a long calculation time which scale to the square of the number of particles. Therefore, we limited the number of particles for the simulation at 10,000 macroparticles. The distributions of the laser pulse illuminated to the cathode surface can be set by defining of the initial released time distributions (*settdist*). The initial released particle distributions in the transverse and longitudinal direction were Gaussian distribution with the rms radius of 0.5, the maximum radius 1 mm and the rms pulse length of 2.5 ps (FWHM pulse length of 6 ps)[53]. Because the zero laser injection phase of GPT is defined by the phase between the center of the laser pulse and the zero cross of the RF which is different from the definition in section 3.1.4. Thus, we introduced the phase offset parameter (*phOffset*) to adjust the GPT laser injection phase to close to the laser injection phase definition. The accelerating fields of the RF gun as shown in Fig. 3.4 which were calculated by SUPERFISH [49] were converted to the GPT input file by using the command *FISH2GDF*. The solenoid magnet element used a homogeneous solenoid without thickness approximated as a circular current sheet (*bzsolenoid*). The kinetic energy of electrons which emerge from the cathode surface was 0.16 eV which corresponding to the laser wavelength of 266 nm and the work function of copper of 4.5 eV and calculated by Eq. 3.1. Due to the Schottky effect that interrupt the material work function resulting in a lower the quantum efficiently as explained in the section 3.1.1, the bunch charge need to be adjusted for each the laser injection phase according to the measurement result. The positions of all beam line elements were indicated by the standard

orthonormal right-handed Cartesian coordinate system or called *world coordinate system* (wcs) in GPT. The bending magnet of the magnetic chicane, the quadrupole magnet and the undulator used the GPT elements which are *rectmagnet*, *quadrupole* and *unduplan*, respectively. The particles which are far away from the bunch center with three times of the standard deviation of the bunch distribution were removed by using the command *stdxyzmax*.

4.2 Start-to-end Tracking Simulation by GPT

For the start-to-end simulation, we emphasized on the calculation of the longitudinal phase-space along the beam line in order to investigate the bunch compression characteristic. The longitudinal phase-spaces of the electron bunch generated by the Gaussian distribution laser pulse with the FWHM pulse duration of 6 ps, the laser injection phase of 24 degrees, the maximum accelerating field of 100 MV/m and the R_{56} of -44.6 mm are shown in Fig. 4.2. As the results, the bunch could not be compressed by the chicane. Conversely, it expanded longitudinally when passed through the chicane. Because the most of the electrons concentrated at the center of the bunch and induced the strong space-charge force which rotated the longitudinal phase-space. The bunch before entering the chicane (see Fig. 4.1(b)) had very small energy spread.

For continuing of this study, we assumed that the laser distribution was a uniform with the total pulse duration of 6 ps. The longitudinal phase-space of the 50 pC bunch at the RF gun exit with the different laser injection phases are shown in Fig. 4.3 and the beam properties are list in the Table.4.1. The longitudinal phase-spaces of the electron bunch are shown in Fig. 4.4 and 4.5. As the results, the longitudinal phase-spaces of the laser injection phase less than 40 degrees were suitable for the compression by the chicane. When the compressible bunch passed through the chicane, the electrons at the head and the tail of the bunch moved to the center of the bunch. The electron distribution of the final bunch became like a Gaussian distribution function.

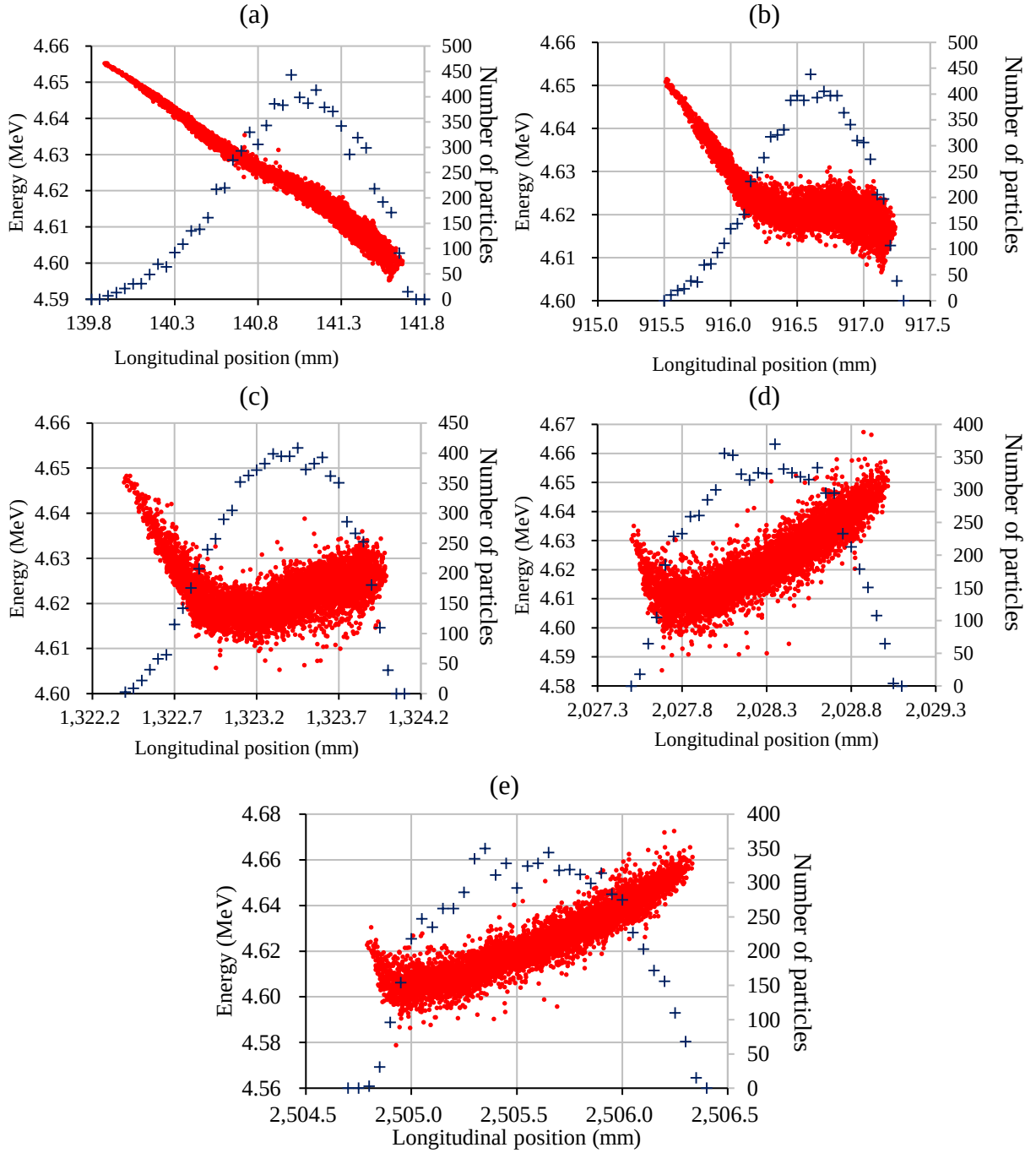


Figure 4.2: Longitudinal phase-spaces of the electron bunch generated by the Gaussian distribution laser pulse at the laser injection phase of 24 degree at (a) the RF gun exit, (b) the entrance, (c) the middle, (d) the exit of the chicane and (e) the undulator center. The point and cross marks stand for the macroparticles and the count of particles within the distance of 0.05 mm, respectively.

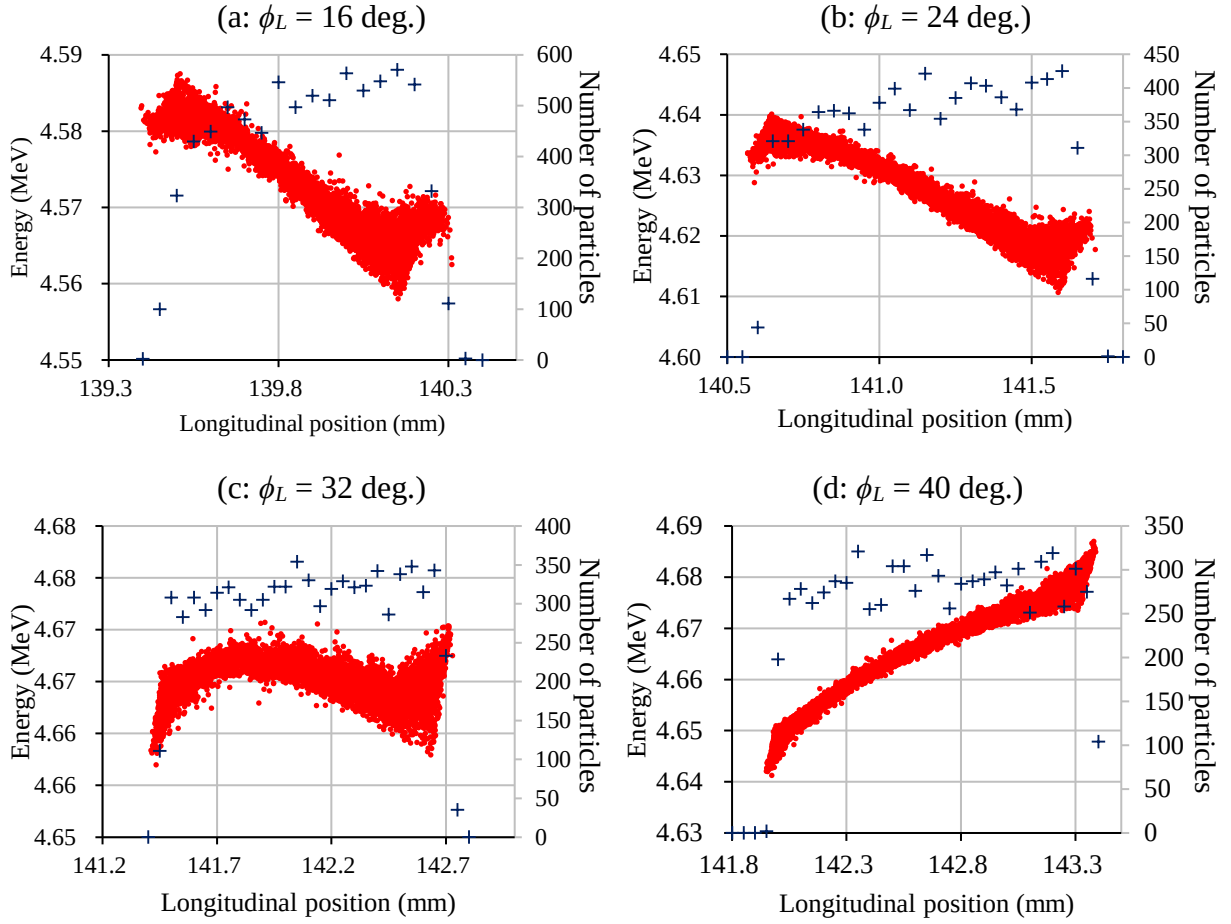


Figure 4.3: Longitudinal phase-spaces of the electron bunch generated by the 6 ps uniform laser pulse at the RF gun exit with the laser injection phase ϕ_L of (a) 16, (b) 24, (c) 32 and (d) 40 degrees. The description of the marks is the same as Fig. 4.2.

Table 4.1: GPT calculation of the beam properties at the RF gun exit.

Beam properties	Laser injection phases (degree)			
	16	24	32	40
Beam energy (MeV)	4.57	4.63	4.67	4.67
Relative rms energy spread %	0.14%	0.14%	0.04%	0.2%
FWHM bunch length (mm, ps)	0.73, 2.41	0.98, 3.25	1.25, 4.17	1.37, 4.58

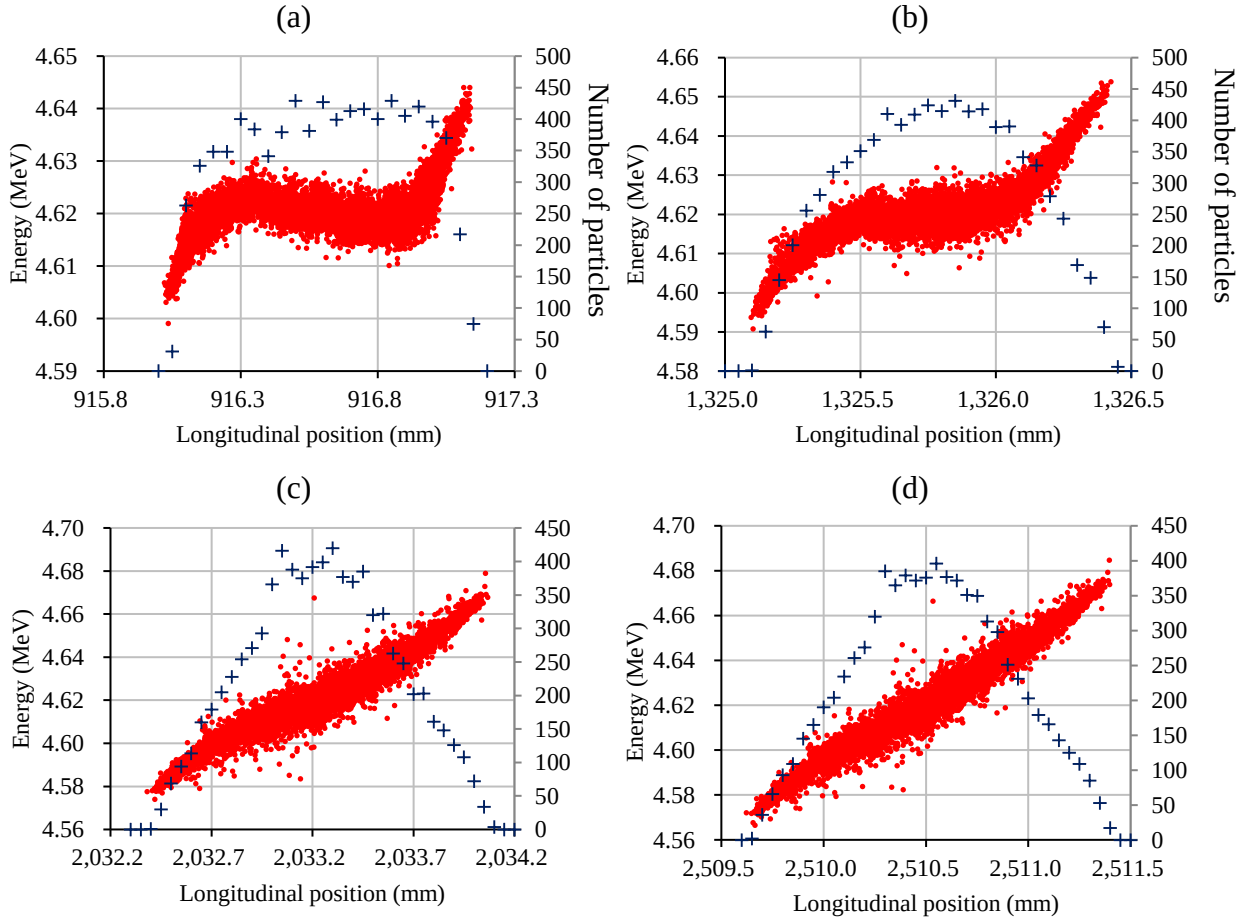


Figure 4.4: GPT calculation of the longitudinal phase-space at the R_{56} of -34.1 mm (a) the chicane entrance, (b) the middle of chicane, (c) the TR station and (d) the middle of the undulator. The description of marks is the same as the Fig. 4.2.

For the transverse beam properties, the GPT calculations were performed with the condition of the CUR experiment (chapter 7). The laser injection phase was 30 degree. The exited current of the solenoid magnetic field was 131A which provided the magnetic field of 194 mT (see section 3.4.1) and the calculated current-turn of the GPT solenoid element (*bzsolenoid*) was 159,000 A-turn. The exited current of the magnetic chicane was 5.8 A which provide the peak magnetic field of 93 mT (see section 3.2.4). The exited currents of the quadrupole magnet were 0.9, 1.6 and 0.9 A which provide the magnetic field gradient of 1.3, -2.3 and 1.3 T/m (see section 3.4.2, minus mean defocusing in X axis), respectively. The rms beam size along the beam line calculated by GPT is shown in Fig. 4.5. As the result, the maximum rms beam size was around 1.5 mm and the rms beam size in the undulator was less than 1 mm.

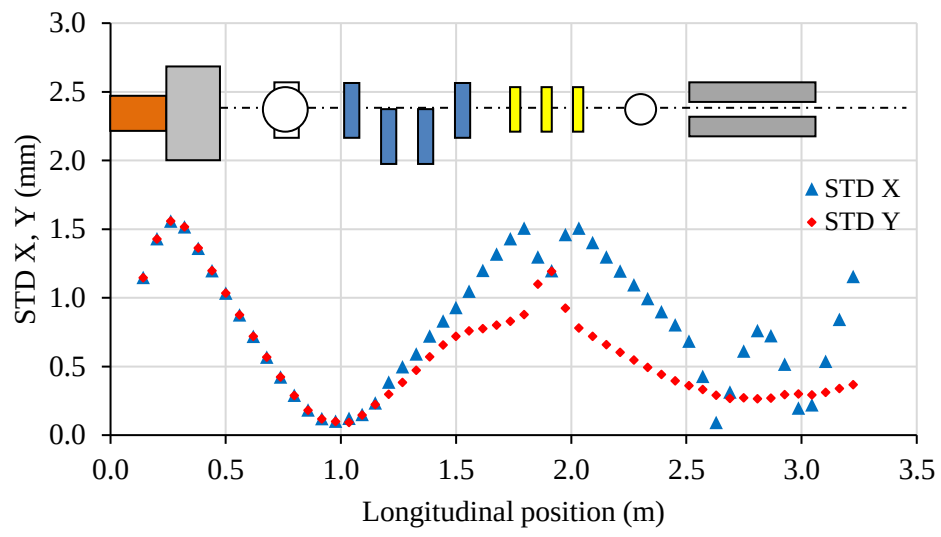


Figure 4.5: GPT calculation of the rms beam size of the CUR experiment.

Chapter 5

Measurements of Beam Properties

In this chapter, the details and results of the measurements of electron beam properties generated by the photocathode RF gun are explained. The measurements of the electron beam properties were separately studied and reported in [54]. The main parameters for all measurements are listed in the Table 5.1.

Table 5.1 Parameters for the measurements of the electron beam properties

Parameters	Values
RF Frequency	2,856 MHz
RF pulse duration	2 μ s
RF pulse peak power	5.6 to 9 MW
Photocathode material	Copper
Laser wavelength	266 nm
Laser repetition rate	89.25 MHz
Number of laser pulse per macropulse	1 to 4 pulses
Laser pulse duration (FWHM)	$\sim$ 6 ps
Laser beam size at cathode (Hor., Ver.)	0.4, 0.5 mm

5.1 Beam energy and energy spread

The beam energy and energy spreads were measured by using the beam dump bending magnet as described in 3.5.4. The measurement was performed with the beam line shown in Fig 5.1. The beams were bended by the bending magnet in the vacuum chamber with the deflection angle of 45 degrees and then extracted through the 20 μ m thick titanium film extracting window. The carbon faraday cup was placed in the air downstream to the beam extracting window for measuring the bunch charge. A lead slit with the thickness of 7 mm and 1.5 mm gap was put behind the extracting window. The slit gap centre was 175 mm in the horizontal and 165 mm far from initial beam axis center in the vertical away from the bending magnet center. The setup diagram of the measurement is shown in Fig. 5.2. To

determine the beam energy, the measured transverse magnetic fields of the bending magnet as shown in Fig. 3.60 and 3.61 were imported to the GPT and then particles were tracked through the bending magnet. The magnetic field of the bending magnet was varied and then energy of the particles which passed through the energy slit center was observed. The GPT tracking simulation through the bending magnet is shown in Fig. 5.3. The measured magnetic fields and the GPT calculation of the beam energy as a function of the bending magnet excited current are shown in Fig. 5.4.

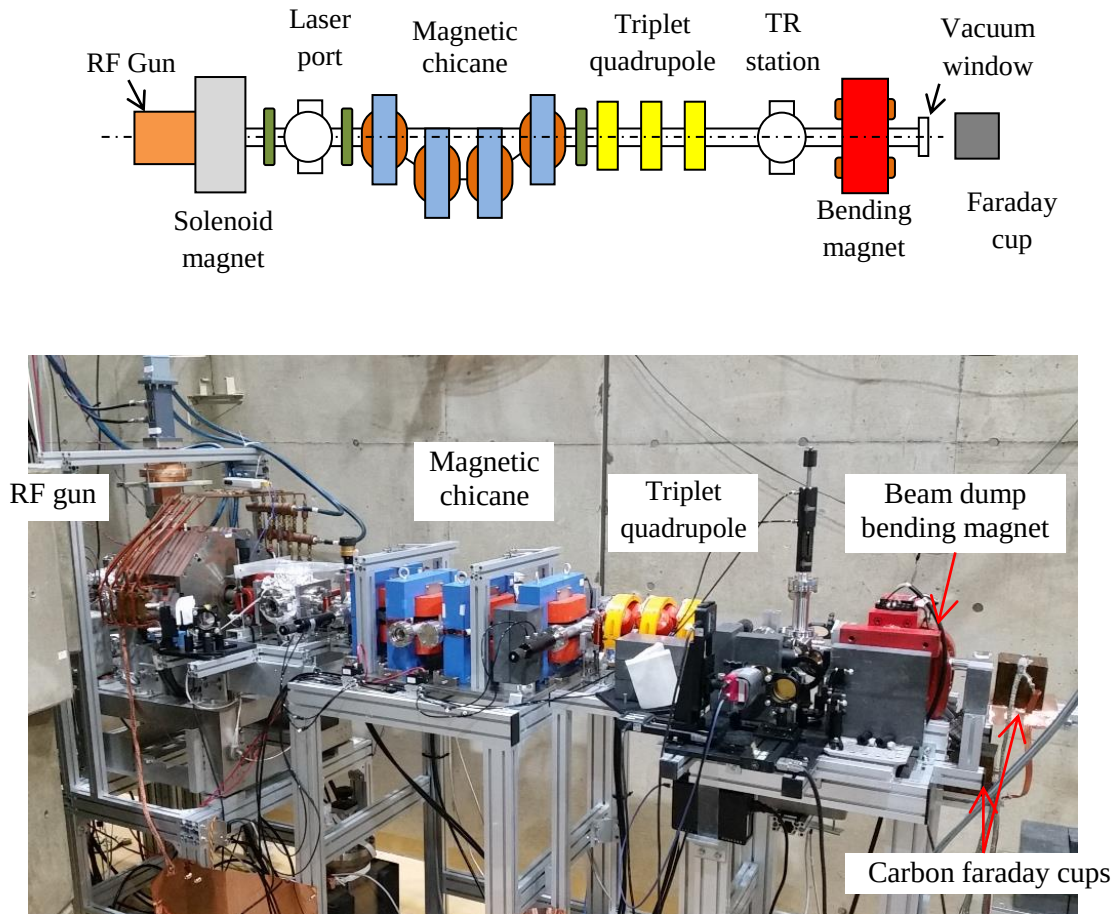


Figure 5.1: Beam line was used for the beam energy and energy spread measurement, the top view diagram (upper) and the isometric view (lower).

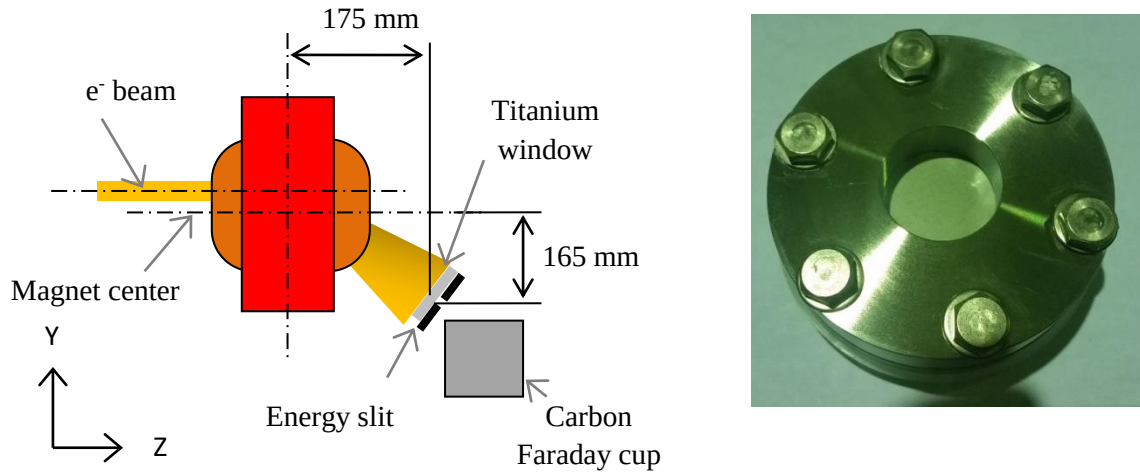


Figure 5.2: Schematic diagram of the beam energy spread measurement (left) the beam extracting window made by the 20 μm -thick titanium film (right).

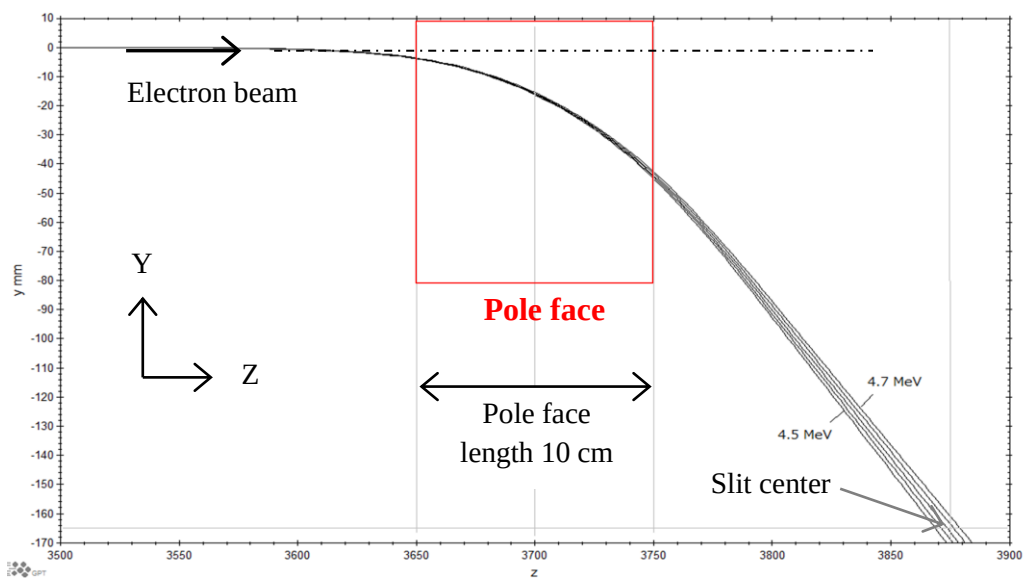


Figure 5.3: GPT tracking simulations of the single electron with the different energy from 4.5 to 4.7 MeV through the beam dump bending magnet.

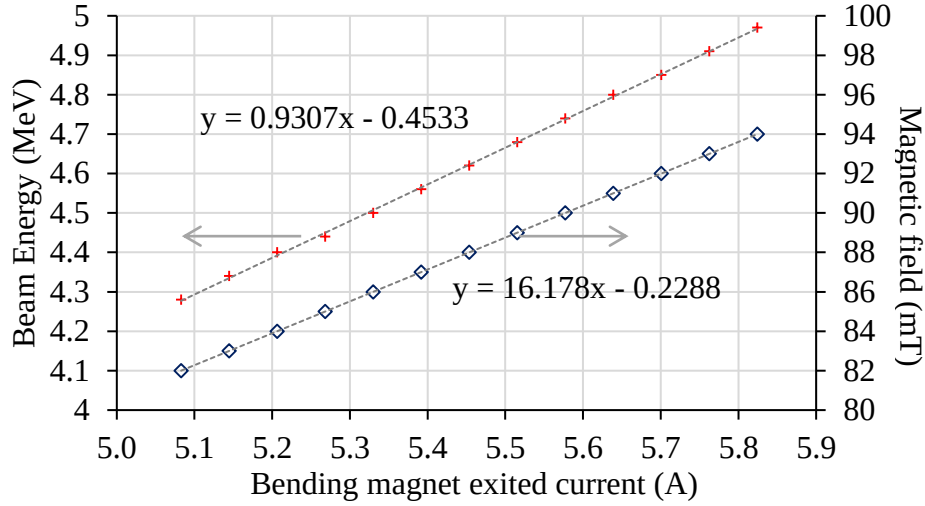


Figure 5.4: Measured magnetic field (diamond marks) and the beam energy (cross marks) corresponding to the excited current of the bending magnet calculated by GPT.

The measurements of the beam energy were performed at the RF power of 9 MW with the four laser pulses and the total pulse energy of 300 μJ per macropulse. The measurement and the GPT calculation results are shown in Fig. 5.5. As the results, the beam had the maximum energy of 4.8 MeV at the phase of 40 to 50 degree and the maximum bunch charge of 280 pC at the phase 60 degree. The beam energy at the operating laser injection phase of 20 - 30 degree was around 4.6 MeV. The beam energy rapidly decreased at the phase higher than 70 degree due to the acceleration behind the RF crest phase.

The GPT calculation was performed at the same condition as measurement and the maximum accelerating voltage at the cathode surface was 100 MV/m. The GPT result had a good agreement with the measurement result at the low laser injection phase. At the higher laser injection phase, the GPT result had a lower energy

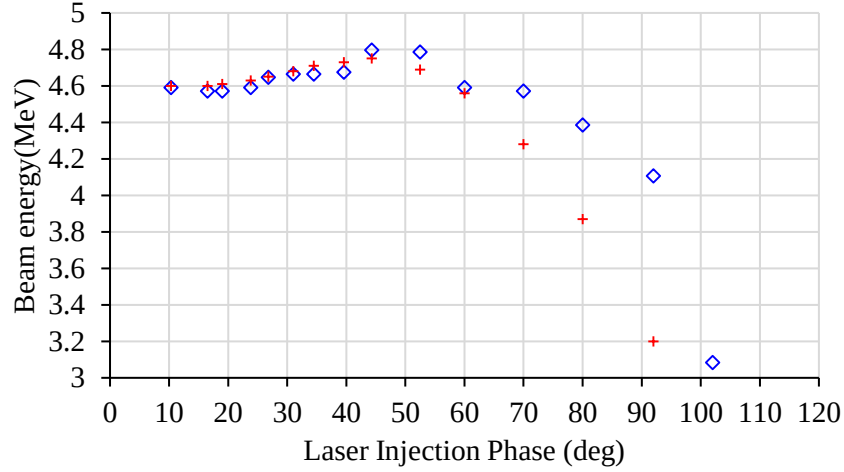


Figure 5.5: Measured beam energy (diamond marks) by the beam dump bending magnet and the GPT calculation (cross marks) as a function of the laser injection phase.

The beam energy spread was measured at the RF power of 9 MW, the laser energy of 124 μJ with 4 pulses per macropulse and the laser injection phase of 30 degree which was used for the CUR generation (Chapter 7). The triplet quadrupole was adjusted to focus the beam at the extracting window. The filtered bunch charge by the energy slits was measured by the faraday cup at the 45 degree deflection port and the result is shown in Fig.5.6.

The GPT calculation result was a lower energy spread of 0.7%. We have not identified the reason of discrepancy between the experimental results and the simulation. By fitting the measurement result to Gaussian distribution curve, the nominal beam energy is deduced to be 4.63 MeV and the rms energy spread is 0.059 MeV which corresponds to the relative rms energy spread of 1.27%. The energy resolution of the measurement system is 0.04 MeV or 0.86%.

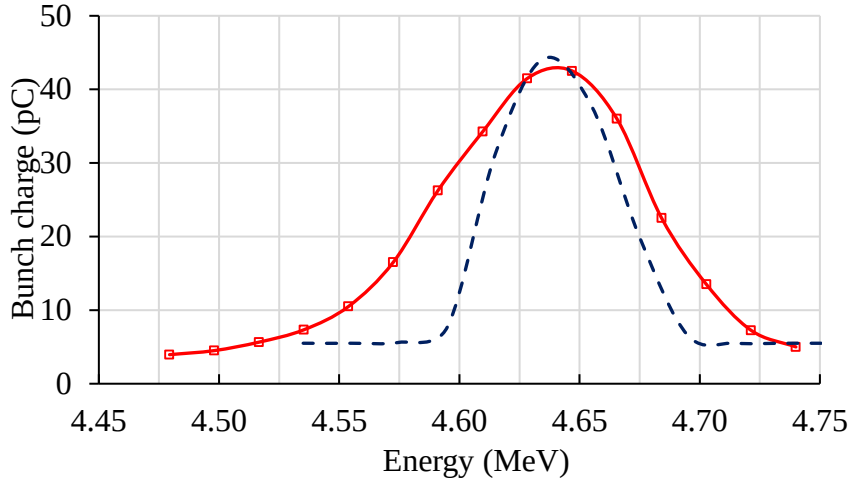


Figure 5.6: Filtered bunch charge as a function of the beam energy (solid line) measured by the Faraday cup at the 45 degree deflection port and the GPT calculation (dashed line).

5.2 Beam emittance

Beam emittance is defined as the area occupied by particle beams in the phase space divided by π . The emittance is conserved under the conservative force such as a transverse magnetic field according to Liouville's theorem [55]. The rms transverse emittance can be calculated by

$$\varepsilon_x = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2} \quad (5.1)$$

where x is the transverse displacement and x' is the angular displacement $x' = p_x / p_y$, p is the particle momentum in transverse direction. The transverse emittance depends on the beam energy and can be reduced by the acceleration. The energy-independent emittance or normalized beam emittance is defined as

$$\varepsilon_{norm} = \varepsilon \beta \gamma \quad (5.2)$$

where β is the normalized speed of electron to the speed of light and γ is the Lorentz factor. The low emittance beam is required for the compact THz system to generate the high brightness radiation. The beam emittance can be measured by several methods such as quadrupole scan method [56], tomographic method [57] and slit scanning method [58]. For our system, the beam generated by the photocathode RF gun has low energy spread therefore

the quadrupole scan method is suitable for the measurement of the beam emittance. The set up for the beam emittance measurement is shown in Fig. 5.7. The last magnet of the triplet quadrupole magnet, which has the effective length of 57 mm was used for the quadrupole scan method. The distance from the photocathode to the center of the quadrupole magnet and the screen is 1100 mm and 1275 mm, respectively. The gradient of the quadrupole magnet was varied and then the images of the beam profile were observed by the fluorescence screen no.1. The rms beam size was calculated by fitting to the Gaussian distribution function. The measurement was performed at the bunch charge of 53 pC and the injection phase of 40 deg. The results of the beam emittance as a function of the excited current of the solenoid magnet and the bunch charges are shown in Fig. 5.8 and 5.9. The minimum beam emittance was around the solenoid current of 135 A by the measurement and 132A by the GPT calculation.

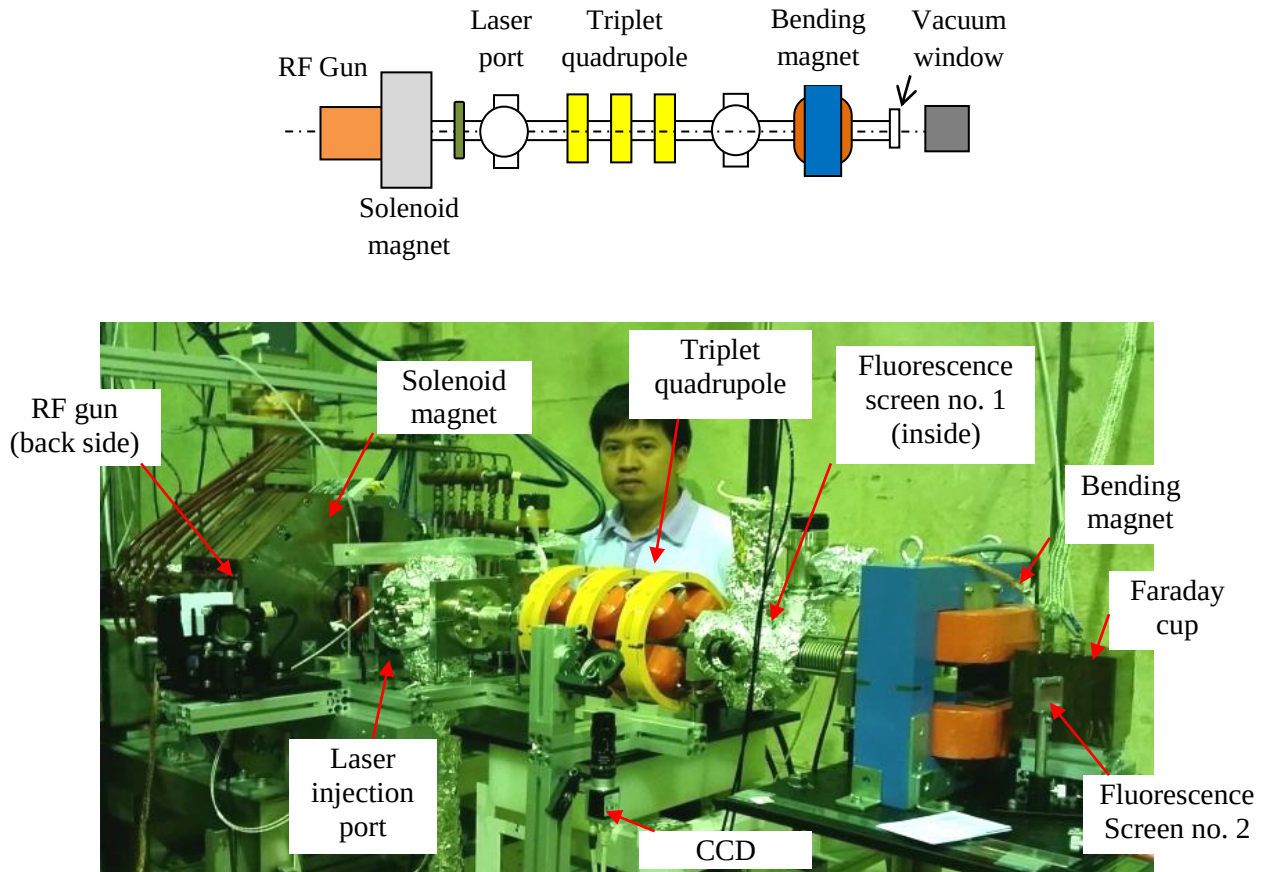


Figure 5.7: Beam line for the beam emittance measurements.

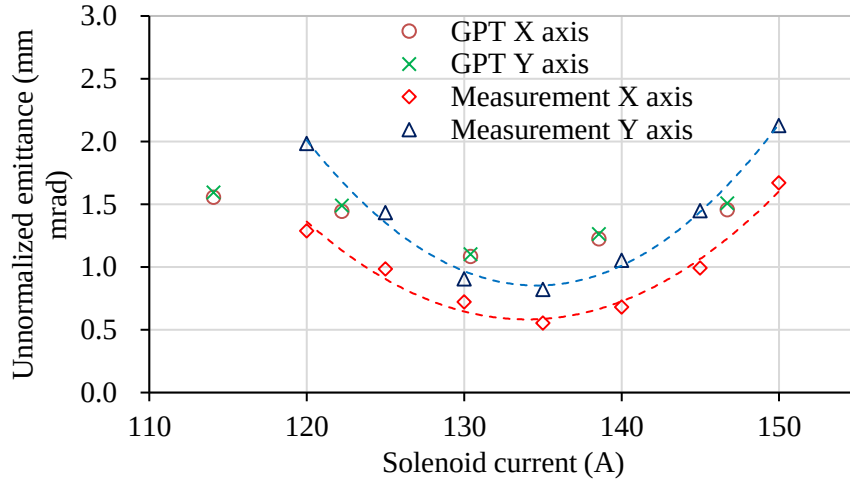


Figure 5.8: Unnormalize rms emittance as a function of the excited current of the solenoid magnet at the bunch charge of 53 pC and the injection phase of 40 deg and the GPT calculation at the same condition.

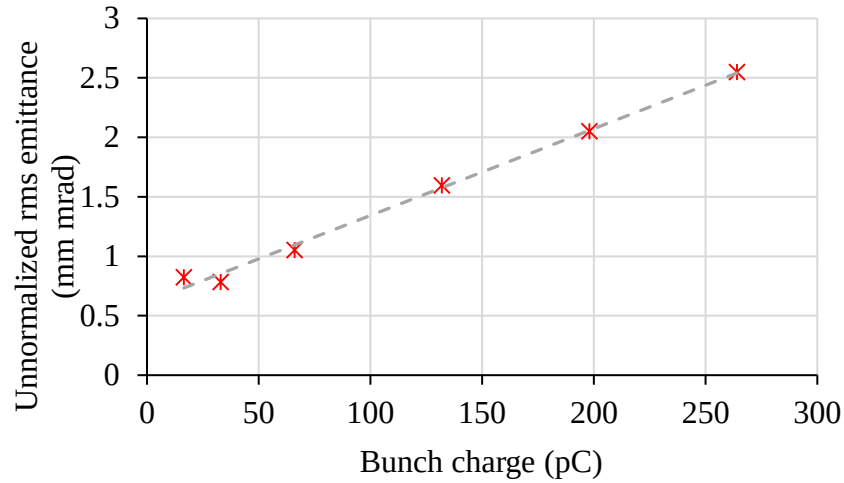


Figure 5.9: Unnormalize rms emittance as a function of the bunch charges at the solenoid gradient of 1926 G and the laser injection phase of 40 deg.

5.3 Bunch charge measurement

Bunch charge was measured as a function of the laser injection phase and the laser energy. The setup of the measurement is shown in Fig. 5.10. A 10 cm cubic out-of vacuum carbon Faraday cup (see section 3.5.2) was employed as the charge detector and placed downstream the 0.2 mm-thick copper beam extracting window. Faraday cup was connected

to the ground through the 200 GHz oscilloscope (IWATSU, DS-5624A) by a coaxial cable. The read out voltage signals were calculated by integration of the current signal over a time period as explained in 3.5.2. A ferrite bead was added to the signal cable to reduce noise signals to the oscilloscope.

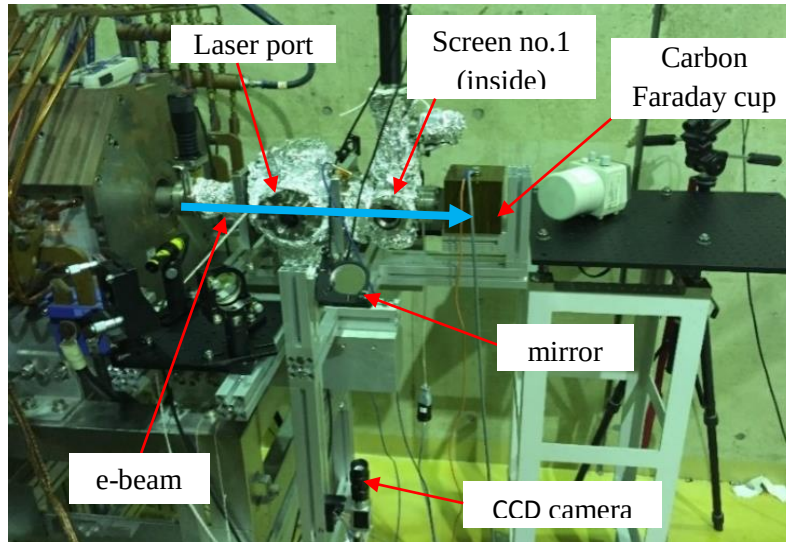


Figure 5.10: Setup for the bunch charge measurement.

The measurement was performed at the RF power of 9 MW and the number of laser pulses per macropulse was varied from 1 to 4 pulses. The measurement and the GPT calculation results are shown in Fig. 5.11. As the results, the bunch charge increase proportionally from zero at the laser injection phase of zero degree until the peak bunch charge at around 70 to 80 degree. Then the bunch charge rapidly drops at the laser injection phase higher than 70 degree due to the bunch has large energy spread that could not be focused by the solenoid magnet. The maximum measured bunch charges reached 1.4 nC at the laser energy of 350 μ J. The GPT calculation with laser injection power of 75 μ J result also has the same tendency with the measurement results. Due to the Schottky effect (section 3.1.2), the bunch charge at the low laser injection phase by the GPT calculation is less than the measurement result.

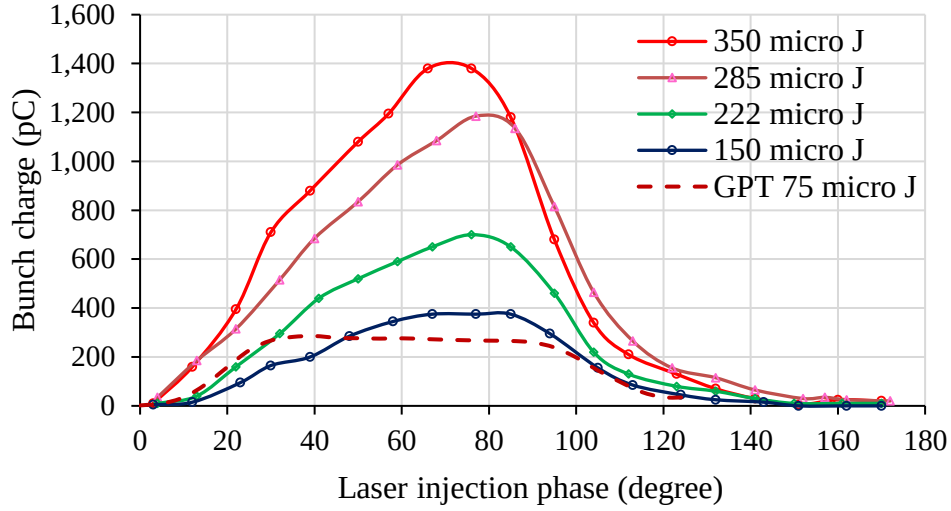


Figure 5.11: Electron bunch charge dependence on the laser energy and the laser injection phase by the measurement (solid lines) and the GPT calculation (dashed line).

5.4 Dark current measurement

Dark current causes by the field emission from the imperfection microstructures of a cathode surface, internal surface of the RF cavity or small dust particles inside the RF cavity. The dark current depends on a surface finish, accelerating field strength and a macropulse duration. The dark current limits the maximum accelerating field strength of the RF gun and causes a serious problem in a long operating RF gun. The dark current was measured by using the same beam line as the bunch charge measurement as shown in Fig. 5.10. The magnetic field strength of the solenoid magnet was adjusted for focusing the dark current beam to the screen and Faraday cup. The results of the dark current as a function of the driven RF power for the RF gun and the solenoid magnetic fields are shown in Fig. 5.12 and Fig. 5.13. The images of the dark current on screen no.1 are shown in Fig. 5.14. As the results, the dark current is proportional to the driven RF power of the RF gun. The maximum dark current was up to 70 pC at the magnetic fields of the solenoid magnet of 1770 Gauss.

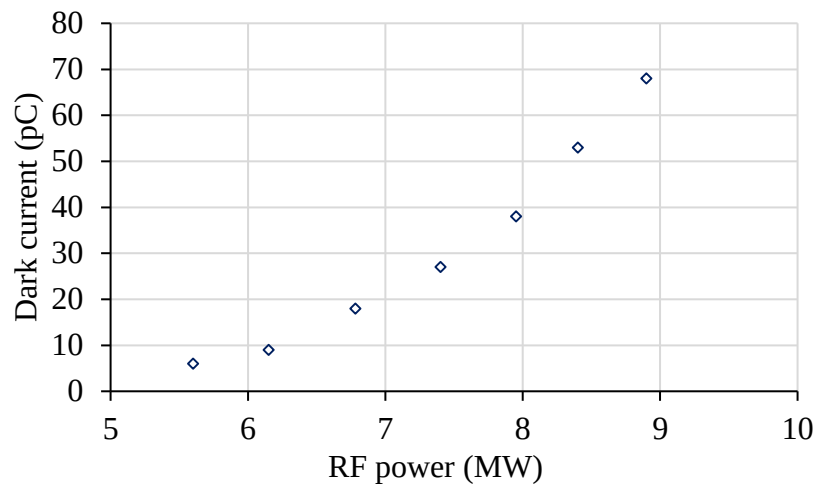


Figure 5.12: Measured dark current as a function of the driven RF power of the RF gun.

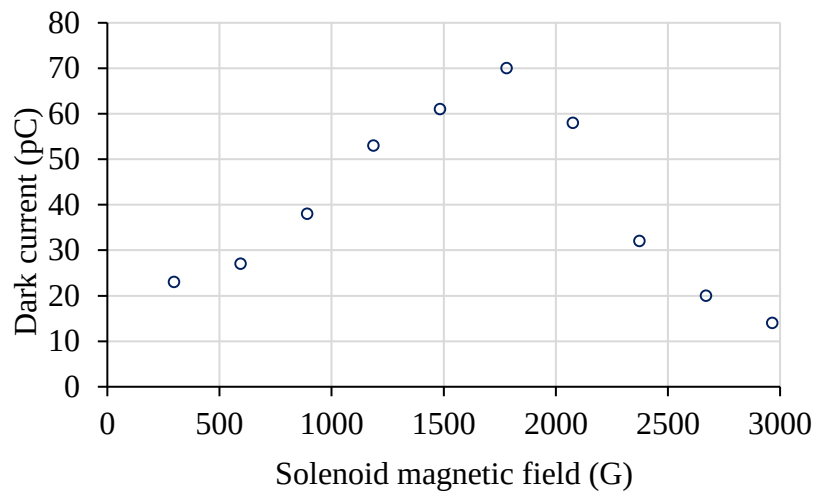


Figure 5.13: Measured dark current as a function of the longitudinal magnetic field of the solenoid magnet at the driven RF power for the RF gun of 9 MW.

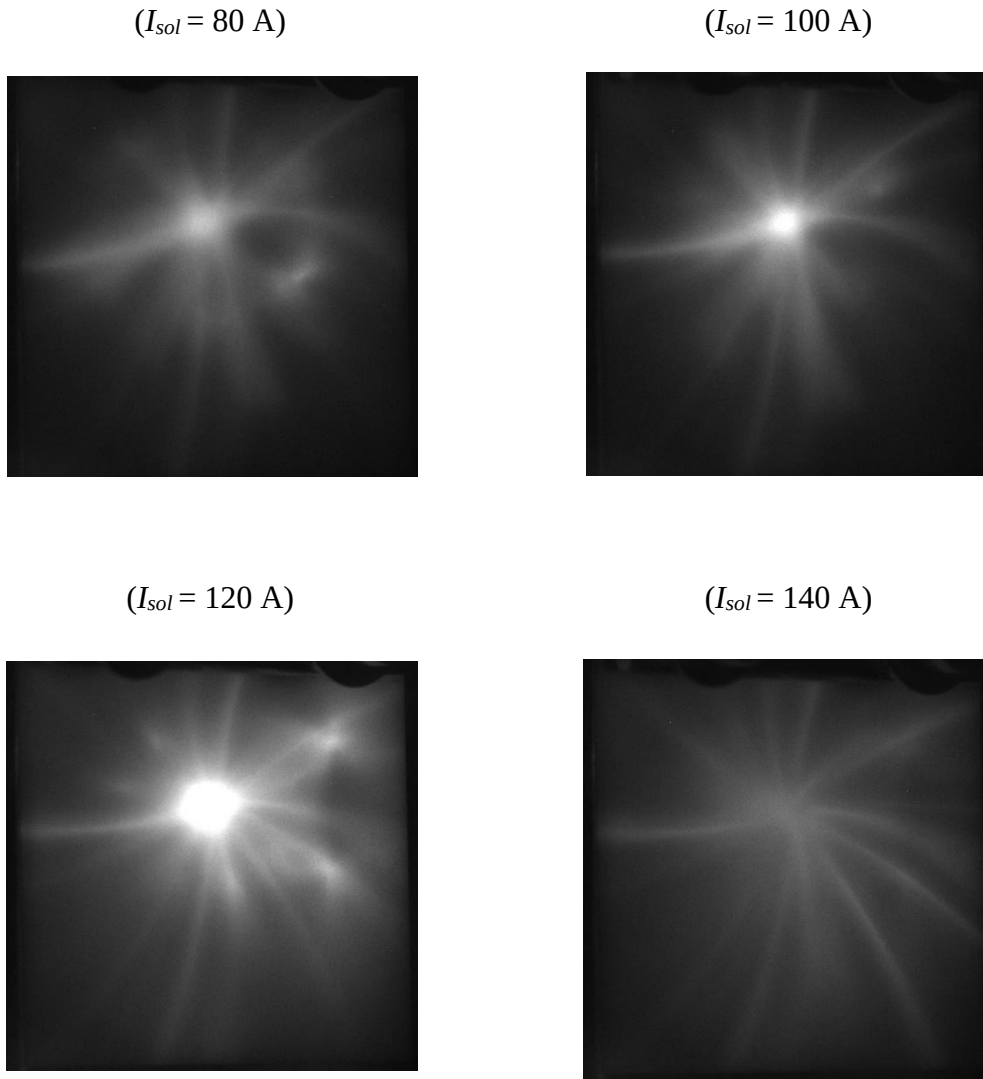


Figure 5.14: Dark current images on the fluorescence screen with the different excited current of the solenoid magnet.

5.5 Laser beam size measurement

Laser beam size at the cathode surface was measured in order to confirm the transportation and focusing of the laser beam. The measurement was performed by using a scanning aperture technique or known as a knife edge technique [59]. A sharp edge of knife cut a laser beam in the transverse direction and then the energy of remain part was measured. The measured energy as a function of the knife position can be used for the calculation of the transverse laser beam profile. Two laser energy meters (Gentec, QE8SP-I-BL) were used as a main detector and a reference detector for the measurement. The setup of the laser beam size

measurement is shown in Fig. 5.15. The knife position was located ~800 mm far from the mirror no. 3 which equal to the distance from the mirror no.3 to the cathode surface. The knife was mounted on the manual translational stages and moved with 0.1 mm interval in the horizontal and vertical directions.

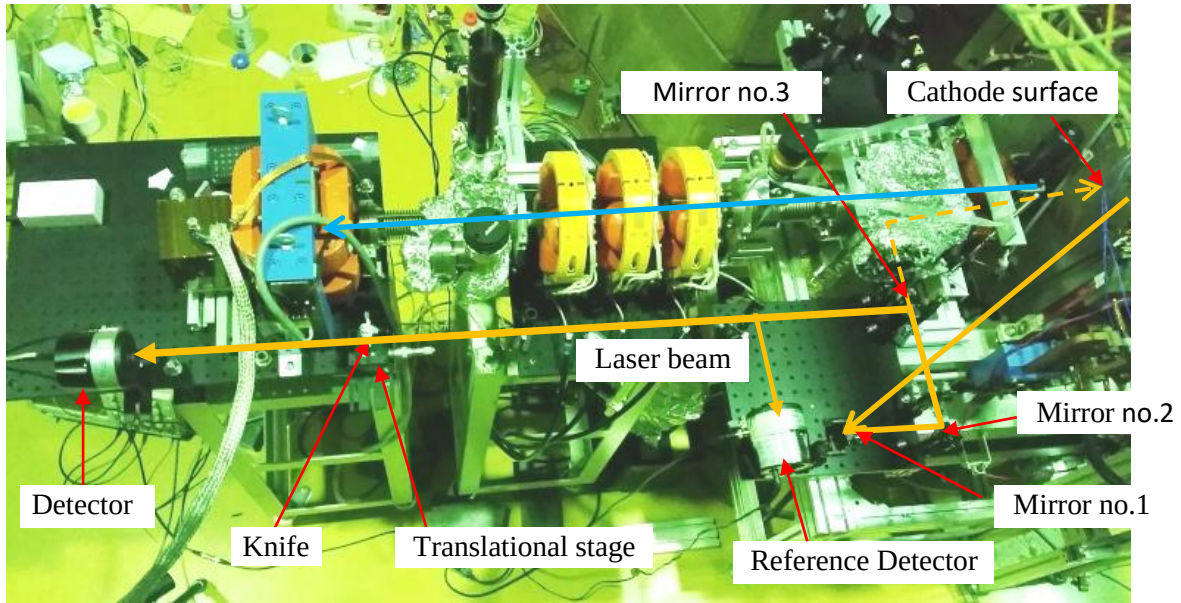


Figure 5.15: Set up of the measurement of the laser beam size by the knife edge technique. The solid line represents the laser beam for measurement.

The transverse laser profiles were assumed to be the Gaussian distribution in both horizontal and vertical axes. The measured results were normalized and then fit to the integration of the normalized Gaussian distribution or called error function which can be expressed by

$$\text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt \quad (5.3)$$

The measured laser beam energies as a function of the knife position in the horizontal and vertical direction are shown in Fig. 5.16 and 5.17. The calculated vertical and horizontal laser beam size were 0.5 and 0.4 mm, respectively.

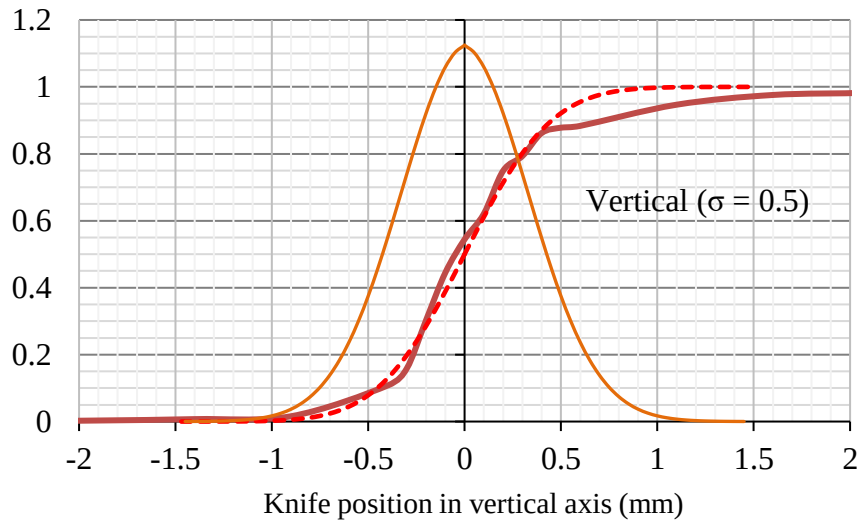


Figure 5.16: Normalized measured laser energy (thick solid line), the fitted error function (dashed line) and the differential of the fitted error function (thin solid line) as a function of the knife position in vertical axis.

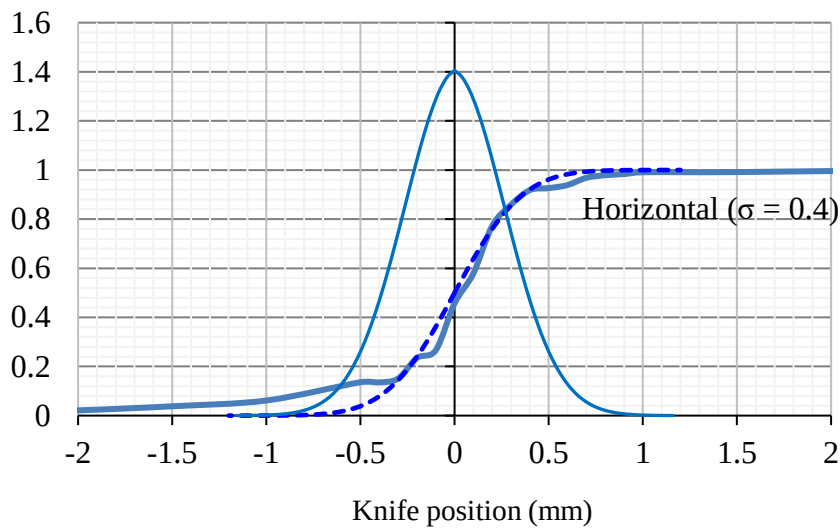


Figure 5.17: Normalized measured laser energy (thick solid line), the fitted error function (dashed line) and the differential of the fitted error function (thin solid line) as a function of the knife position in horizontal axis.

Chapter 6

Investigation of Bunch Compression Characteristic by Coherent Transition Radiation

In this chapter, we investigated the characteristics of the magnetic chicane bunch compressor and compressed electron beam by observing of the properties of coherent transition radiation (CTR). The bunch length of the compressed bunch was also estimated and compared to the simulation result.

6.1 Transition Radiation

Transition radiation (TR) occurs when electrons cross a boundary of media with different dielectric constants. TR was first predicted theoretically by Ginzberg and Frank [6] in 1945. The shape of the TR pattern is a hollow cone in the both forward and backward directions. The TR has a broad spectrum range up to X-ray regime and their intensity is also frequency independence. Due to the emission process of TR is very fast, the TR can be used for a sub-picosecond electron bunch diagnostic by observing of its spectrum. This method is called the frequency-resolved technique which was proposed by Barry [60] and first successfully applied by Lihn [61].

6.1.1 Theory of Transition Radiation

Theory of transition radiation can be considered as a collision problem of two-charged-particles which are an electron and its image charge. When an electron travel across the boundary between vacuum ($\varepsilon = 1$) and a perfect conductor ($\varepsilon = \infty$), the perfect conductor act like a mirror and a positive image charge which moves in the opposite direction. An electron and its image charge collide each other at the boundary where their velocity changes instantaneously and the radiations are generated. The schematic diagram of an electron and the transition radiation pattern is shown in Fig. 6.1. TR energy radiated per unit angular frequency per unit solid angle [62] can be calculated by

$$\frac{d^2 W}{d\omega d\Omega} = \frac{e^2 \beta^2}{\pi^2 c} \frac{\sin^2 \theta}{(1 - \beta^2 \cos^2 \theta)^2} \quad (6.1)$$

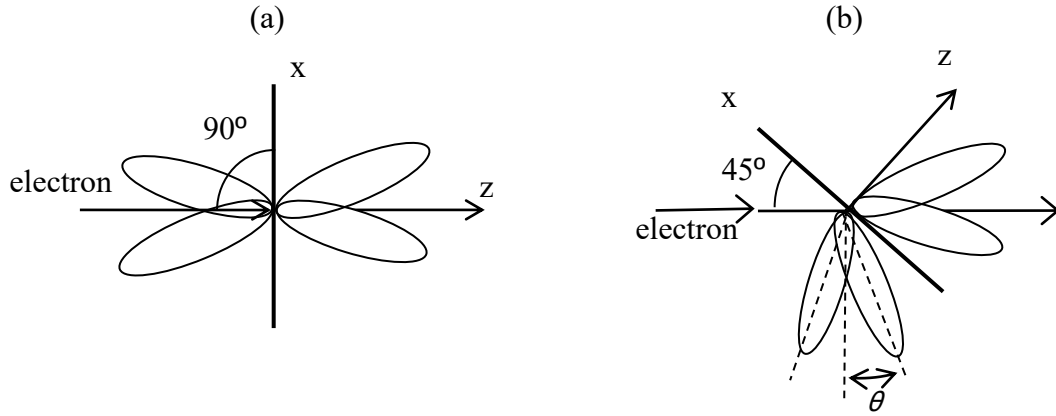


Figure 6.1: Schematic diagram of the transition radiation with (a) the normal incident and (b) the oblique incident of 45 degree.

The TR does not emit in the on-axis direction ($\theta = 0$) and the radiation intensity reaches its maximum at $\sin \theta = 1 / (\beta\gamma)$, where β is the normalized velocity to the speed of light, γ is the Lorentz factor. For relativistic electrons ($\beta \rightarrow 1$ and $\gamma \gg 1$) the angle is as small as $\sin \theta \approx \theta$. Therefore, the maximum intensity occurs at $\theta \approx \pm 1/\gamma$. In this study, the incident angle was set at 45 degree and the backward TR would be observed through the THz window. The two components of backward TR which are parallel and perpendicular to the beam axis can be expressed by

$$\frac{dW_{\parallel}}{d\Omega d\omega} = \frac{e^2 \beta^2}{2\pi^2 c} \left[\frac{2 \sin \theta - \sqrt{2} \beta \cos \phi}{(\sqrt{2} - \beta \sin \theta \cos \phi)^2 - \beta^2 \cos^2 \theta} \right]^2, \quad (6.2)$$

$$\frac{dW_{\perp}}{d\Omega d\omega} = \frac{e^2 \beta^2}{2\pi^2 c} \left[\frac{\sqrt{2} \beta \cos \theta \sin \phi}{(\sqrt{2} - \beta \sin \theta \cos \phi)^2 - \beta^2 \cos^2 \theta} \right]^2, \quad (6.3)$$

where θ is the angle between the direction of emitted radiation and ϕ is the azimuthal angle defined in the xy-plane with respect to $-x$ axis.

6.1.2 Coherent Transition Radiation from Short Electron Bunch

The total TR intensity can be derived by superimposing of individual radiation fields emitted by each electron in the bunch. The total radiation intensity from a bunch of N_e electron [62] can be calculated by

$$I_{tot}(\omega) = I(\omega) [N_e + N_e(N_e-1)|f(\omega)|^2], \quad (6.4)$$

where $I_e(\omega)$ is the radiation intensity from a single electron and $f(\omega)$ is the form factor (see section 1.2.3). The form factor in the forward direction can be reduced to

$$h(\omega) = \left| \int e^{ikz} h(z) dz \right|. \quad (6.5)$$

where k is the radiation wave number, $k = \omega/c = 2\pi/\lambda$, $h(z)$ is the normalized distribution function of electrons in the longitudinal direction and z is the longitudinal position. In case of a long bunch length, each electron emits radiations in random phase resulting in the incoherent transition radiations whose intensity is proportional to N_e . For a short bunch length, radiations have a high degree of phase coherence called coherent transition radiation (CTR) whose intensity is much higher and proportional to N_e^2 . The CTR spectrum is only determined by the longitudinal distribution of an electron bunch or the bunch form factor. The CTR spectra can be analyzed by using Michelson interferometer as explained in 3.5.5. The relation between CTR and the form factor [62] can be expressed as

$$I(\omega) = \text{FT} \{I(\delta)\} \propto |R(\omega)T(\omega)\tilde{E}(\omega)|^2 \propto |h(\omega)|^2. \quad (6.6)$$

where $I(\delta)$ is the interferogram, $R(\omega)$ and $T(\omega)$ are the reflectance and the transmittance of the beam splitter and $E(\omega)$ is the electric fields of incident light.

6.2 CTR Experiment and Results

The beam line for the CTR experiment is shown in Fig. 6.2. The RF and the laser parameters were as shown in Table 5.1. A 11 μm -thick aluminum foil arranged in tilt 45 degrees respected to the beam direction was used as the CTR radiator. A fluorescence screen was attached at behind of the aluminum foil to observe the beam position. The backward CTR was extracted to air through a 4 mm-thick Z-cut natural crystal quartz window (Fuji Ideck, TF70) with the aperture diameter of 33 mm. The quartz window has a flat frequency response in a wide range and over terahertz regime [63].

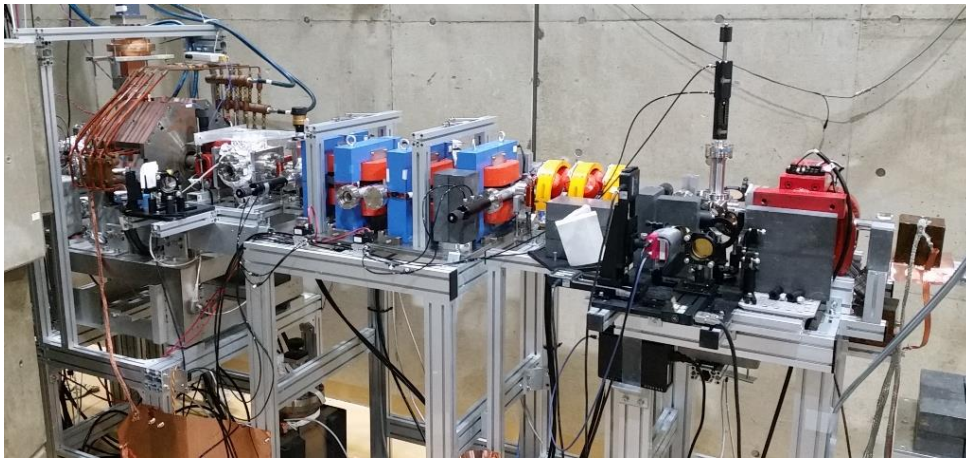


Figure 6.2: Beam line for the coherent transition radiation experiment.

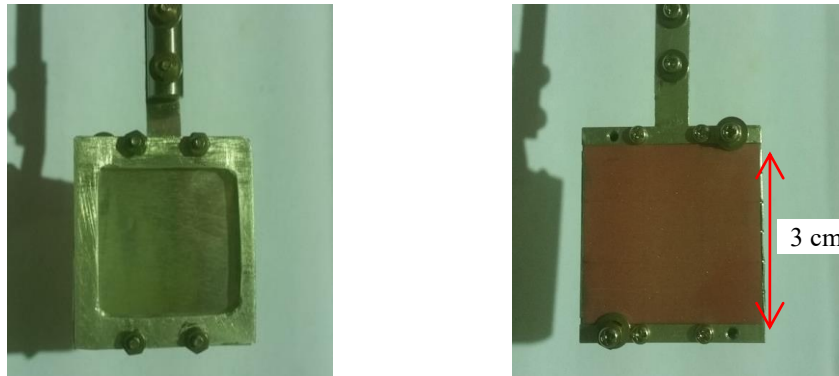


Figure 6.3: CTR radiator made from aluminum foil with the thickness of 11 μm (left). The fluorescence screen was attached at the back side of the holder (right).

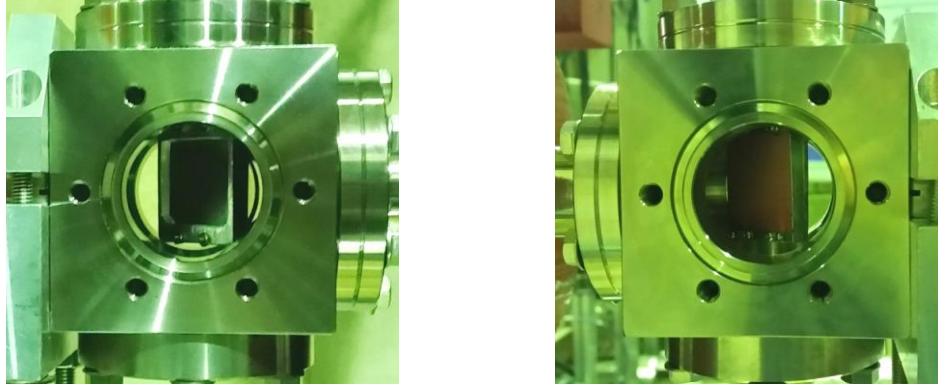


Figure 6.4: Transition radiation experiment station before the THz window installation, aluminum foil (left) and fluorescence screen (right).

The two small-size uncooled detectors were used for the CTR detection which are a Schottky-barrier zero bias diode (SBD) detector (Millitech, DET-05-RPFW0) and a pyroelectric detector (PHLUXi, PYD-1-018). The details of the detectors are explained in 3.5.5. The signals measured by the detectors were recorded by a 1GHz oscilloscope (Tektronix, DPO4104). A 10 cm cubic out-of-vacuum carbon was employed as a Faraday cup for the bunch charge measurement and placed at the end of the beam line. The bunch passed through a copper window with the thickness of 0.2 mm and the signal was read by a 200 MHz oscilloscope (Iwatsu, DS-5624A). The input impedance for the both CTR and bunch charge measurement was set at 1 M Ω . The magnet power supplies, the actuators, the translational stages, the cameras and the waveform measurement were performed under the network distributed control system by LabVIEW.

6.2.1 Spatial Distribution

The spatial distribution of the CTR was measured to ensure that the main part of the backward CTR was efficiently extracted through the quartz window. The intensity mapping was performed by scanning the SBD diode detector across axes. A 25 dB gain pyramidal horn antenna (Ducommun, ARH-1025-02) was attached to the detector to obtain higher detected CTR signals. The detector was mounted on the two translational stages (Sigmakoki, SGSP20-85) and scanned with 2 mm intervals in the horizontal and vertical directions. The distance from the centre of the CTR radiator to the SBD detector was approximately 135 mm and the setup is shown in Fig. 6.5.

The measurement was performed at the beam energy of 4.6 MeV, the RF pulse duration of 2 μs and the laser pulse energy of 133 μJ and 4 pulses per macro-pulse. Figure 6.6 shows the results of the spatial distributions of the CTR in vertical and horizontal polarization. The results demonstrated that CTR was properly extracted and the clearly exhibit the lobe structure characteristic of CTR. The distance between peaks was about 30 mm which equal to the open angle of 6.3 deg. This was close to the calculated open angle of the CTR, which inverse of the Lorentz factor, $1/\gamma$, at 5.7 deg.

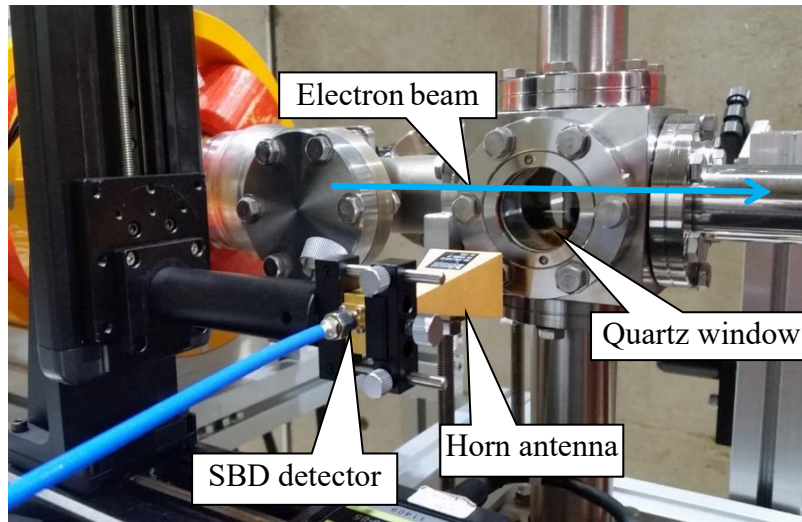


Figure 6.5: Setup of the CTR spatial distribution measurement

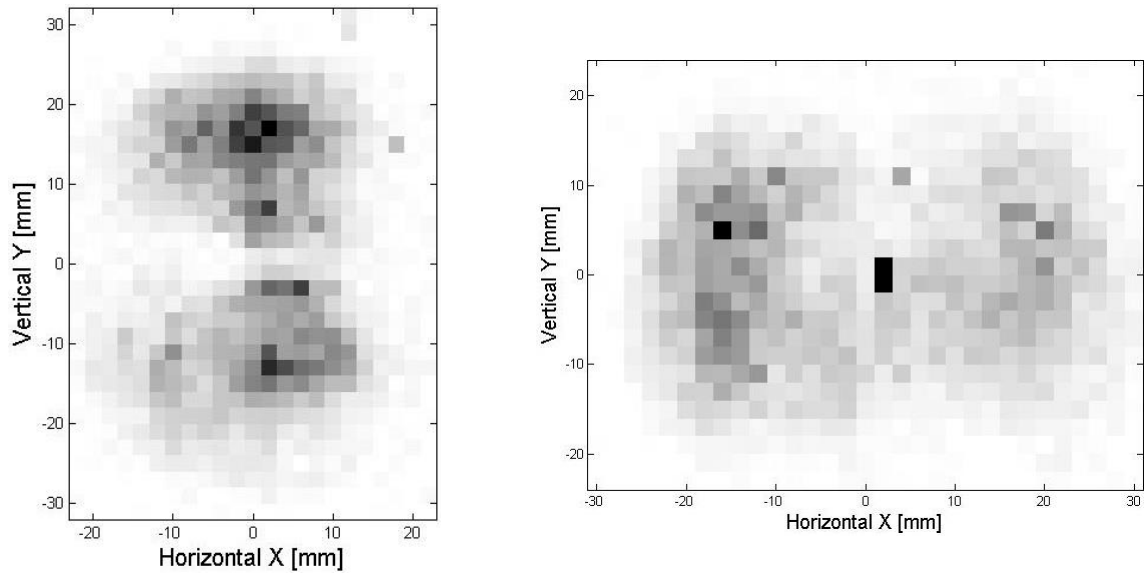


Figure 6.6: Measurement result of spatial distribution of coherent transition radiation.

6.2.2 Total CTR Intensity

The total intensity was measured by using focusing optics to collect extracted CTR to the detector. The 2-inch off-axis gold-coated parabolic mirror (Thorlabs, MPD249-M-01) with the focal length of 106.5 mm was employed to focus the CTR into parallel beam. Then the gold-coated flat mirror (Thorlabs, PF20-03-M01) reflected the CTR radiation to the second off-axis parabolic mirror which focused the beam to the detector. The pyroelectric detector was placed next to the parabolic mirror at the focal length distance. The focal point was aligned to the detector by the two-dimensional scanning in the normal plane against the beam. The setup of the CTR intensity measurement is shown in Fig. 6.7.

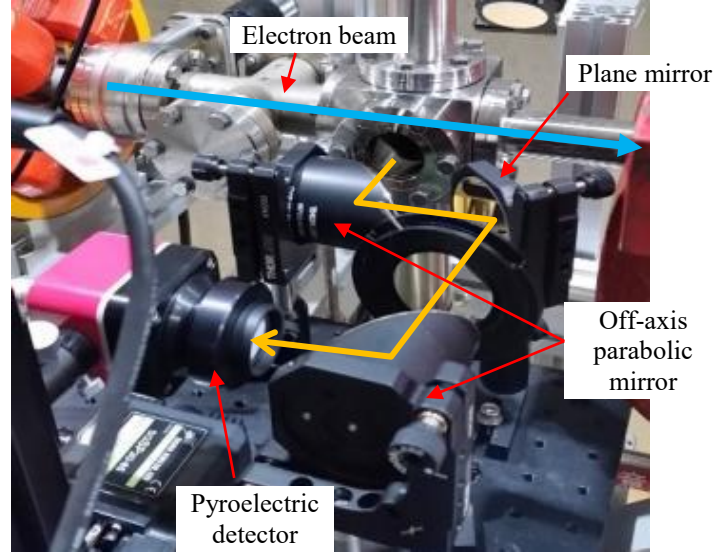


Figure 6.7: Set up of the OTR intensity measurement

The CTR intensity dependence on the square number of electron N_e^2 is shown in Fig. 6.8. The measurement was performed at the RF power of 9 MW, the laser energy up to 300 μJ per bunch, the laser injection phase of 30 deg and the chicane exiting current of 5.8 A equivalent to the R_{56} of - 47.1 mm. As the result at the N_e^2 less than 5.63×10^{18} , the CTR intensity was proportional to the square number of electrons. But at the higher N_e^2 , the CTR intensity was not the same tendency as at the low N_e^2 and the bunch length seems lengthen due to the space charge effect resulting in the lower CTR intensity than expected.

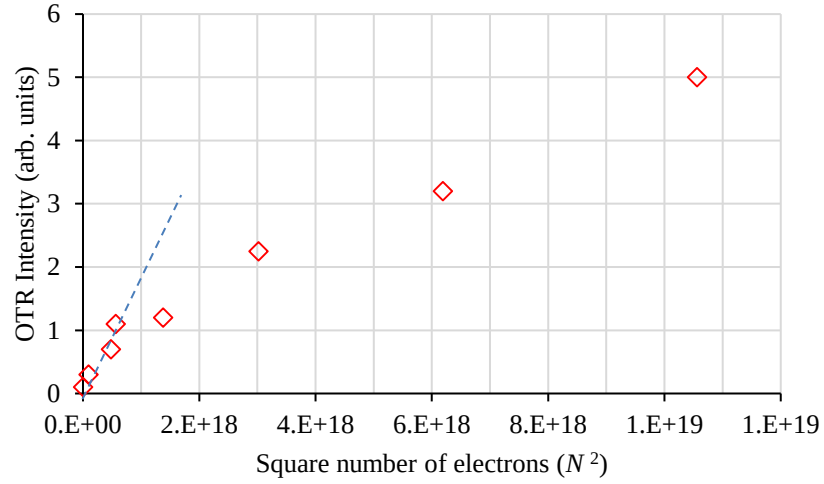


Figure 6.8: CTR intensity as a function of the square number of electrons.

6.2.3 Bunch compression characteristic

The bunch compression characteristic was investigated by the observation of the total CTR intensity. The initial energy-time phase space was adjusted by varying the laser injection phase from 0 to 110 degrees in order to find the suitable phase for the given R_{56} value. The chicane was operated in two conditions which were turn-off and -on corresponding to the R_{56} values of 0 and -26.8 mm, respectively. The turn-on R_{56} value was just for the study of the bunch compression characteristic and not optimum for the compression to the minimum bunch length. The optimum R_{56} value for the bunch compression was investigated and explained in section 6.2.5. The bunch charge was also measured to confirm the number of electron in each laser injection phase. The number of the laser pulses and the laser energy were 300 μJ with 4 pulses per macropulse. The measurement result of the bunch charge and the CTR intensity as a function of the laser injection phase are shown in Fig. 6.9 and 6.10.

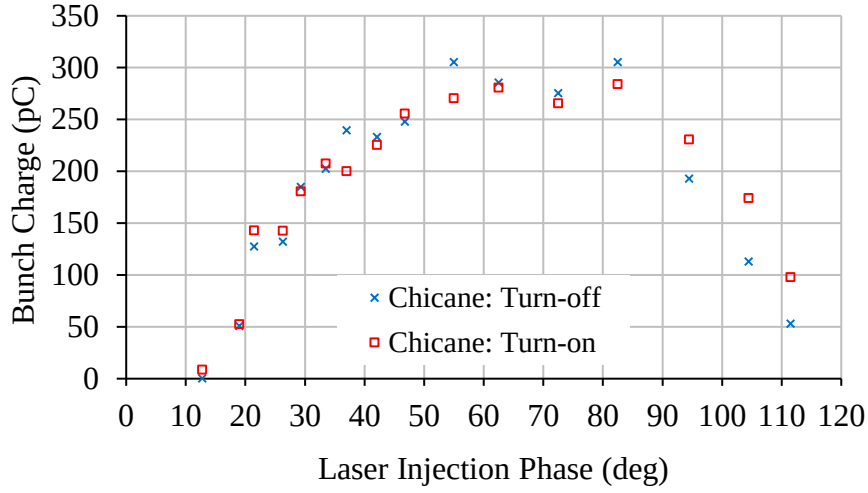


Figure 6.9: Measured bunch charge as a function of the laser injection phases.

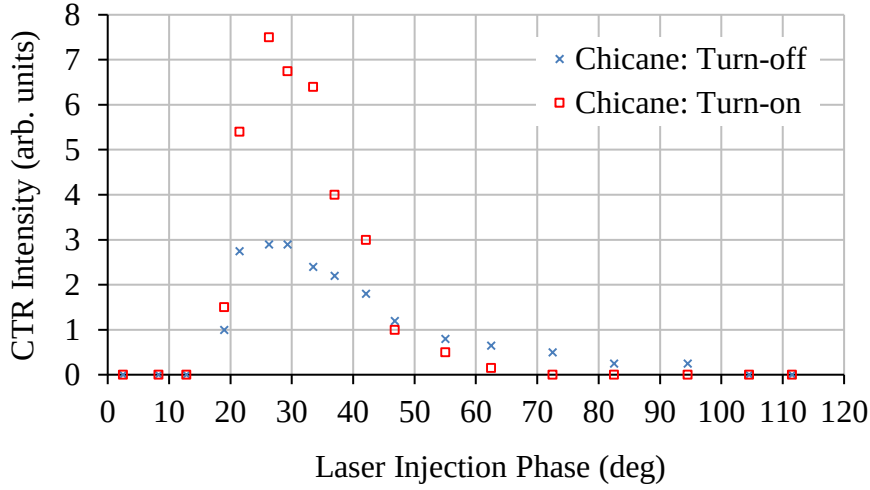


Figure 6.10: Measured CTR intensity dependence on the laser injection phases of the chicane turn-off and -on ($R_{56} = 0$, -26.8 mm).

As the results, the bunch charge of the turn-off and -on chicane had almost no difference. It means that electrons did not lose in the bunch compression section. The bunch charge gradually increased from zero at the phase of 0 degree until peak of 280 pC or 1.75×10^9 electrons at the phase around 50 degree, nearly constant at the laser injection phase from 50 to 75 deg and decreased at the higher phase. From Fig. 6.10, the measured CTR intensity was very sensitive to the laser injection phases especially in case of the turn-on chicane. The CTR intensity rapidly increased at the laser injection phase of 20 deg until reach the peak at around 25 to 30 degree. The compressible bunch was in the laser injection phase range less than 45 degree where the CTR intensities were enhanced. The enhancement of the CTR intensity due to the bunch compression depends mainly on the laser injection phase rather than the bunch charge. It means that the form factor mainly contributed to the

enhancement of CTR intensity. At the phase of the peak CTR intensity, the correlation between the initial energy-time phase space and the bunch compression was optimal that provided the bunch with minimum bunch length and the maximum form factor for the given R_{56} . The peak CTR intensity could be enhanced up to the factor of 2.6 compared to the chicane turn-off. At the laser injection phase over 45 degrees, the initial energy-time phase space of the bunch was flipped upside-down due to acceleration behind the RF-crest (see Fig. 4.1 d). Such a bunch has the large energy spread and long bunch length that provided the low CTR intensity. Moreover, the bunch expands longitudinally when passed through the chicane resulting in the lower CTR intensity compared to the intensity of the chicane turn-off.

6.2.4 Power spectrum of CTR

The power spectrum of CTR was measured in order to find the optimum R_{56} value which provides the minimum bunch length at a given laser injection phase. The measurement was performed by vary the R_{56} from - 31.5 to - 68.7 mm while the laser injection phase was fixed at 30 degree. The laser energy was 150 μ J with 4 pulses per macropulse. To ensure that the particle did not lost in the chicane by its focusing in the non-deflecting plane, the longitudinal magnetic field strength of the solenoid magnet was varied 169, 181 and 194 mT. The bunch charges for the different solenoid magnetic fields and R_{56} has been measured as shown in Fig. 6.11. The results show that the bunch charges did not lost in the bunch compression and were between 86 to 100 pC. The CTR interfereogram measured by the Michelson interferometer with averaged over 10 measurements are shown in Fig 6.12. The interferograms were shifted in vertical for clearly seen the lines and the measurement of the uncompressed bunch were not performed because the signals were too weak. The power spectra of CTR corresponding to the measured interfereograms and calculated by Fast Fourier Transform are shown in Fig. 6.13.

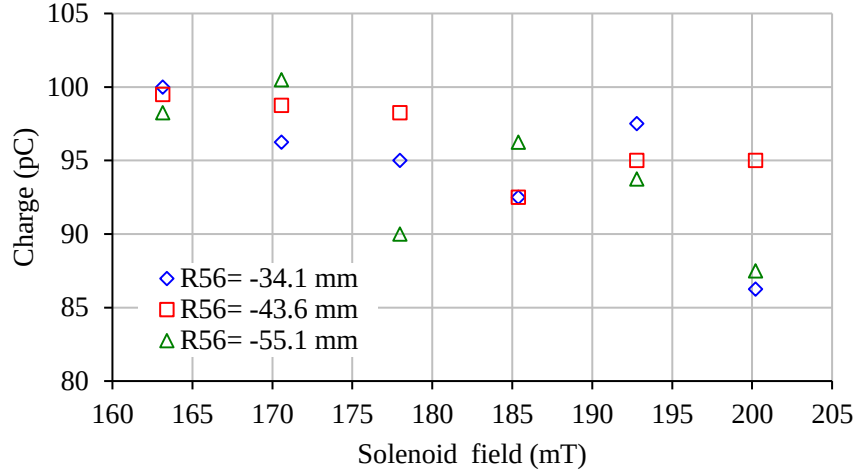


Figure 6.11: Bunch charge dependence on the solenoid magnetic field and the R_{56} .

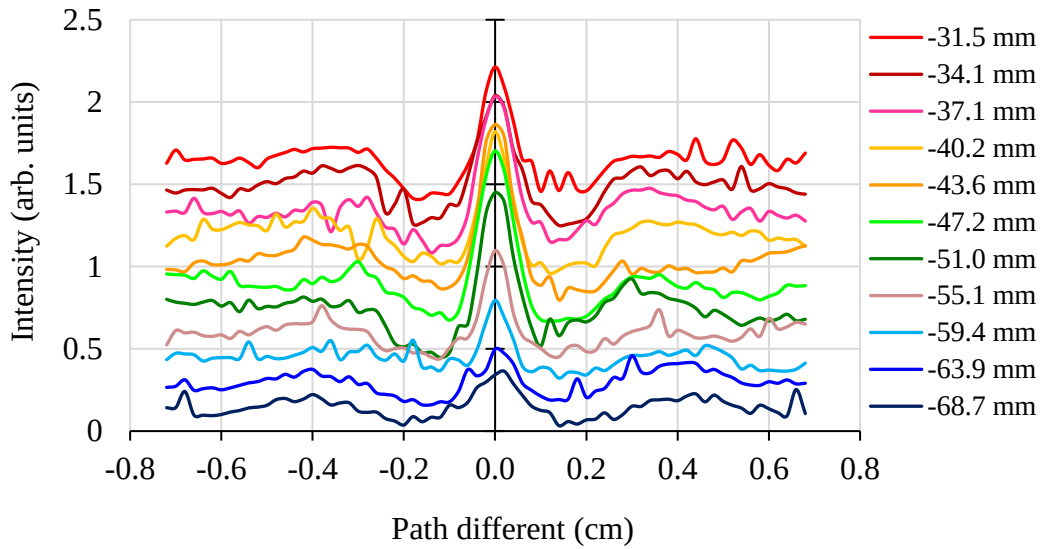


Figure 6.12: Measured interferograms of the different R_{56} .

As the results, the spectra contain not only the CTR ones, but also the effect of the frequency dependence of all optical components of the measurement system as mentioned in Eq. 3.40. The drop of the power spectrum in the low-frequency region causes by the decreasing of the beam splitter efficiency. From the Fig. 3.63, the efficiency RT of the sapphire beam splitter rapidly drops at the frequency lower than 0.08 THz. The low frequency components also loss by the diffraction due to the limited aperture. The absorption by the water content in air had no influence in this frequency range because it occurs at the frequency of 0.56 THz [64]. The quartz window and the mirrors have flat frequency responses. The cross-correlation signature of the detector, which results in the oscillating of the power spectrum, also did not appear in the result. We could conclude that the most of the

CTR spectrum contains the frequency components lower than 0.25 THz and the peak of the spectrum is around 0.08 THz.

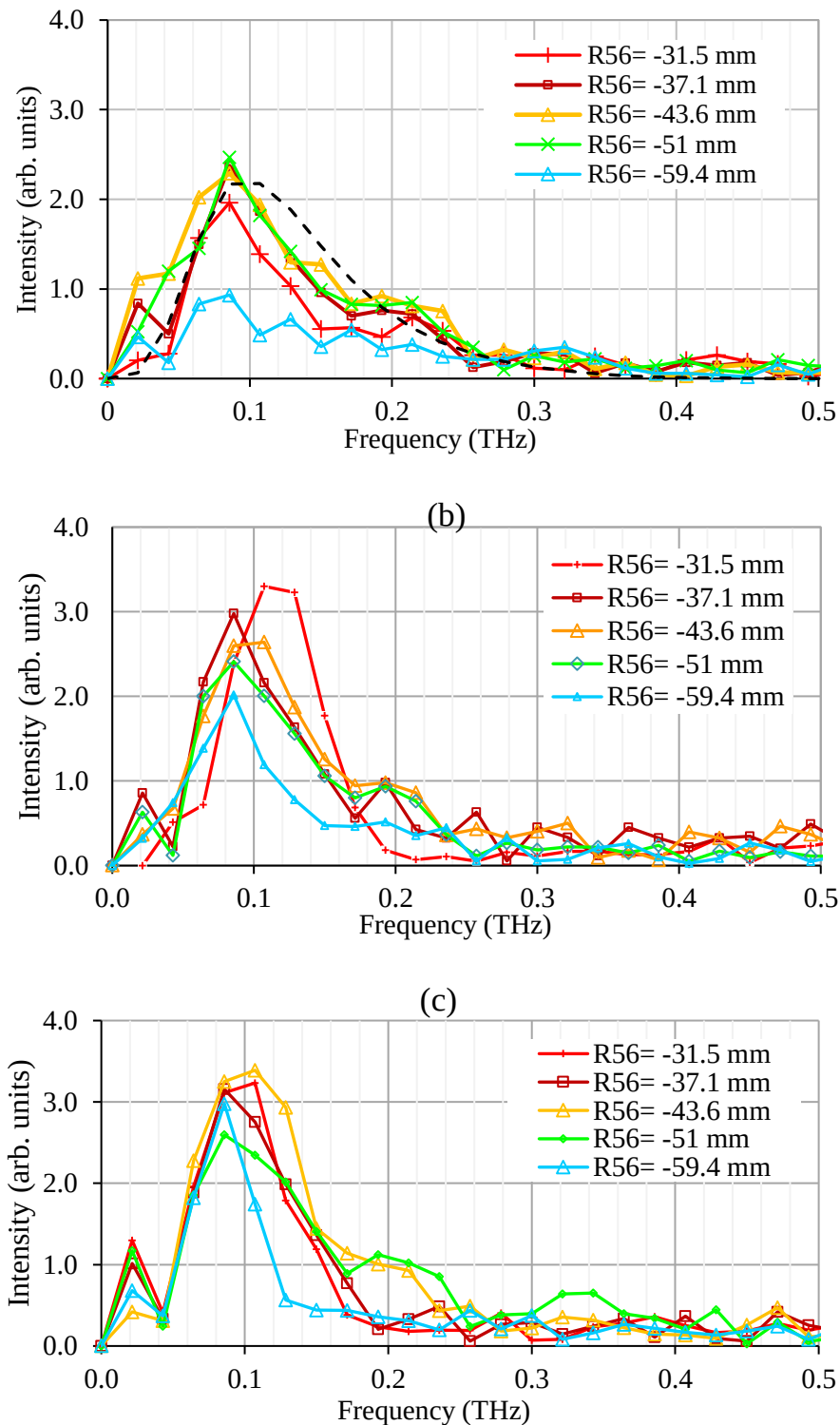


Figure 6.13: Power spectra of the CTR with the different R_{56} with the solenoid magnetic field of (a) 196, (b) 181 and (c) 169 mT. (Dashed-line; the spectrum of Gaussian distribution bunch with the rms bunch length of 1 ps)

6.2.5 Estimation of Bunch length

In this study, the rms bunch length was roughly estimated by fitting the measured CTR spectrum to the spectrum of a known particle distribution. We assumed that the longitudinal bunch distribution was a Gaussian distribution. Then the measured CTR spectra were fitted to the Gaussian power spectrum $C \cdot e^{-\omega^2 \sigma^2}$ where C is the constant, ω is the angular frequency and σ is the rms bunch length in the function of time. The fitting was performed by the least squares fit method at the frequency range higher than the 0.08 THz where the spectrum had less distortion by the beam splitter. The effect of the non-uniform beam splitter efficiency was also compensated by divided the measured spectrum by the normalized beam splitter efficiency. The low frequency suppression of the radiation power spectrum was considered only by the spectral efficiency drop of the beam splitter. The example of the fitted Gaussian spectrum is shown in Fig. 6.14. The estimated rms bunch lengths from the CTR spectrum and the GPT calculation as a function of R_{56} is shown in Fig. 6.15. The GPT calculation was performed with the uniform laser pulse with the total pulse duration of 6 ps, the laser injection phase of 30 degrees, the total bunch charge of 50 pC and the solenoid magnetic field around 169 mT. By the simulation study, the solenoid magnet had small influence to the minimum bunch length condition.

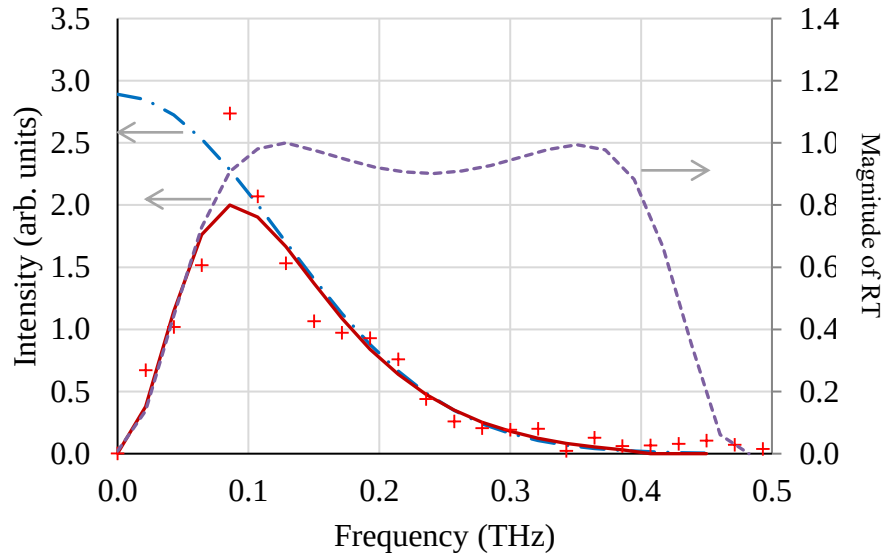


Figure 6.14: Fitted Gaussian spectrum (solid line) of the measured spectrum (cross marks, $R_{56} = -47.1$ mm.) is the product between the Gaussian spectrum (dot-dashed line, $C = 2.72$, $\sigma = 0.87$ ps) and the normalized beam splitter efficiency (dashed line).

As the results, the measurement results clearly show that the minimum bunch length was occurred at the R_{56} around -45 mm and the longitudinal phase space by the GPT calculation is shown in Fig. 6.16. The different beam focusing by the solenoid magnet gave the same tendency of the estimation results. The minimum bunch length calculated by GPT occurred at around -35 mm. The absolute values between the measurement and the calculation were also different almost the factor of two and the measurement result was more sensitive to the change of R_{56} than the calculation result.

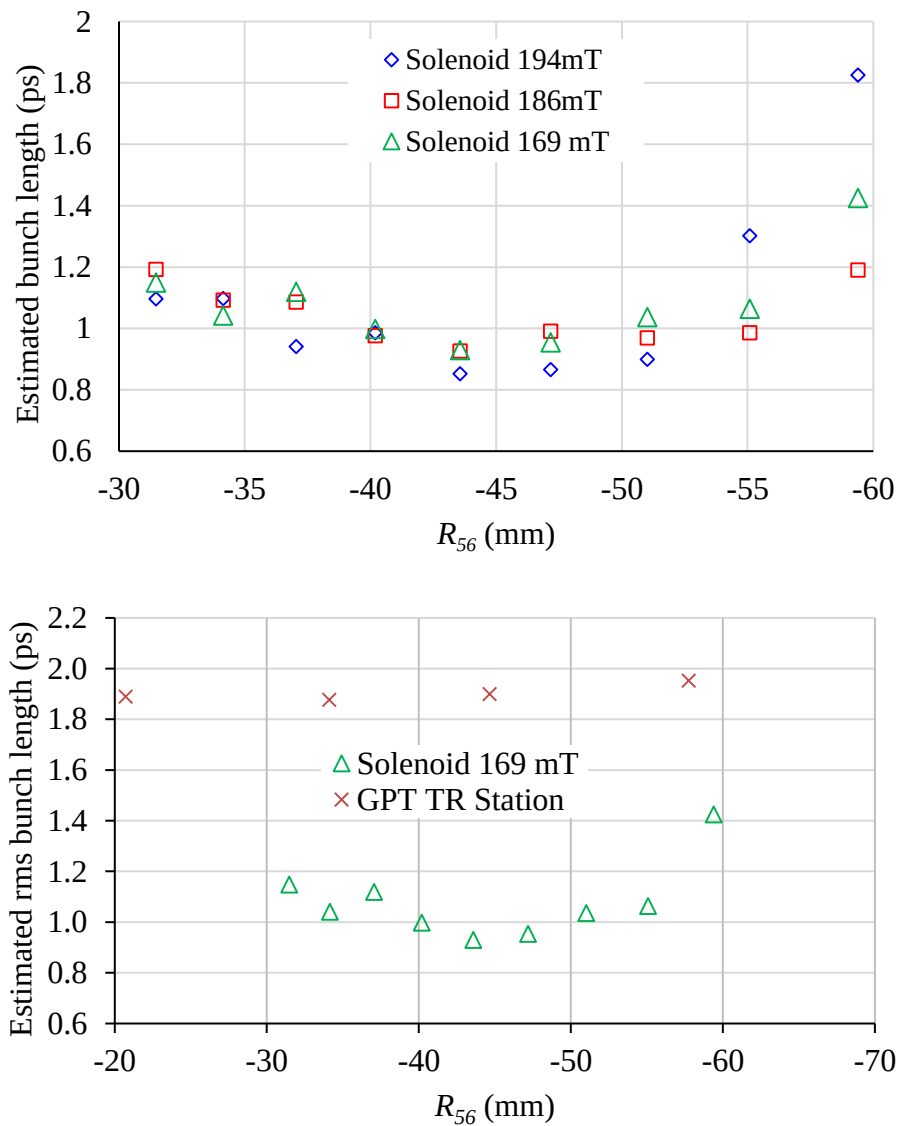


Figure 6.15: Estimated rms bunch length by the CTR spectra (upper) and the comparison of the estimated bunch length between by the CTR spectrum and the GPT calculation (lower).

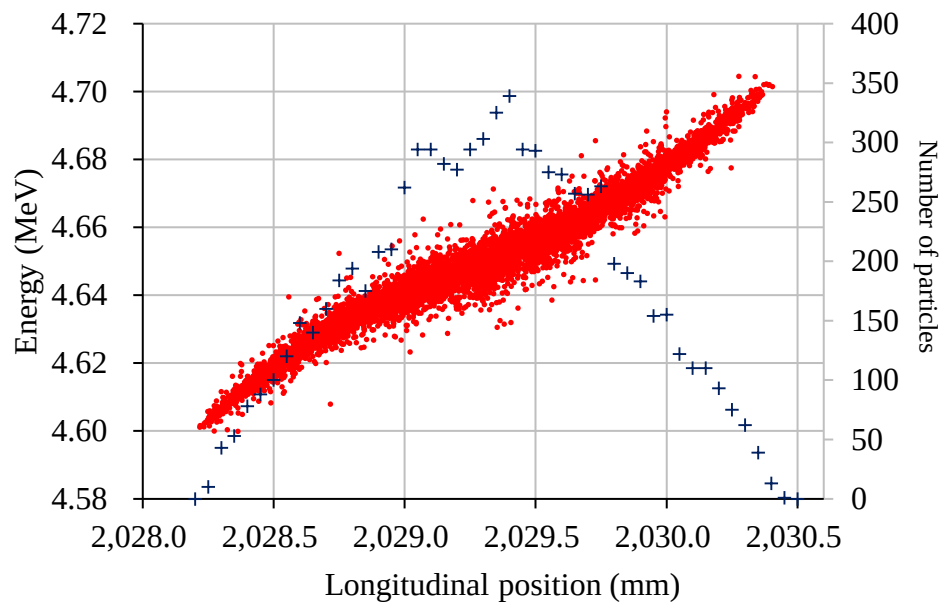


Figure 6.16: GPT calculation of the longitudinal phase-space at the R_{56} of -44.6 mm at the TR station.

Chapter 7

Measurement of Undulator Radiations

This chapter explains the details of the measurements and the results of the undulator radiation of the compact THz system. The measurements were performed at the maximum bunch compression condition as described in the chapter 6 to generate the coherent undulator radiation. The uncompressed condition measurements were also performed.

7.1 Measurement Setup and Results

THz radiations from the undulator reflected out of the accelerator vacuum chamber by a retractable THz mirror made by a titanium film with the thickness of $50\text{ }\mu\text{m}$ installed in a 6-crosses chamber downstream the undulator. The schematic diagram of the undulator and the THz mirror is shown in Fig. 7.1. The film was attached on a circular aperture aluminum holder with the aperture diameter of 54 mm arranged in the 45 degree respect to the electron beam direction and 480 mm far from the middle of the undulator. The fused silica with the aperture diameter 65 mm was employed as a THz window and the distance from the mirror to the window was about 120 mm. The beam profile monitor is installed at the middle of the chamber. The cross section of the undulator vacuum chamber was a rectangular with the internal dimension of $26 \times 48\text{ mm}$. The maximum open angle limited by the vacuum chamber is 7.1 deg in the vertical axis.

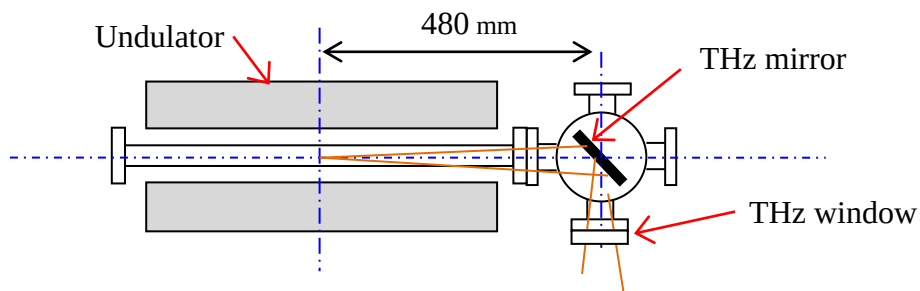


Figure 7.1: Schematic diagram of the extraction of the undulator radiations (top view).

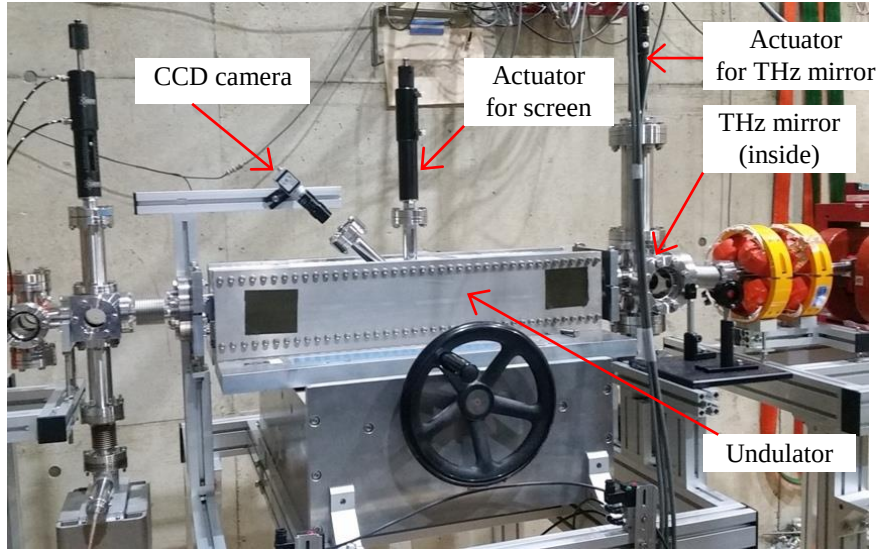


Figure 7.2: Photo of the undulator in the beam line.

Two types of small-size uncooled detectors which were the same detectors as the CTR experiment (chapter 6) were used for the THz radiation detection. First, a Schottky zero-bias barrier diode (SBD) detector (Millitech, DET-05-RPFW0) has the frequency range from 140 to 220 GHz (see section 3.5.5). Second, a pyroelectric detector (PHLUXi, PYD-1-018) equipped with the built-in lens and the visible light filter (see section 3.5.5). The detector has not been calibrated in the THz frequency range. The signals from the detectors were recorded by a 1 GHz oscilloscope (Textronics, DPO4104).

For the radiation measurement, the driven RF power for the PC RF gun was at 9 MW that provide the beam with the beam energy around 4.6 MeV. The number of laser pulse was adjusted from 1 to 4 pulses per macropulse to obtain proper detected signal by detectors. The magnetic chicane bunch compressor operated in two conditions which were turn-on and turn-off compression. The DC current of 5.8 A supplied to the chicane dipole magnets for the turn-on compression that provided the R_{56} of - 47.1 mm. The solenoid magnet attached in front of the RF-gun, the steering magnets, the small correction coil of the chicane dipole magnets and triplet quadrupole magnets were adjusted to obtain the highest detected signal from the detectors, i.e. highest radiation intensity.

7.1.1 Spatial Distribution

The spatial distributions of the undulator radiation were measured by scanning the SBD detector in two-dimensions without focusing optics. The scanning plane was normal to the extracted THz beam with the distance approximately of 140 mm from the center of the THz mirror. The detector was mounted on two translational stages (Sigmakoki, SGSP 20-85) and scanned with 4 mm interval in both horizontal and vertical directions. The measurement setup of the spatial distribution of the undulator radiation is shown in Fig. 7.3.

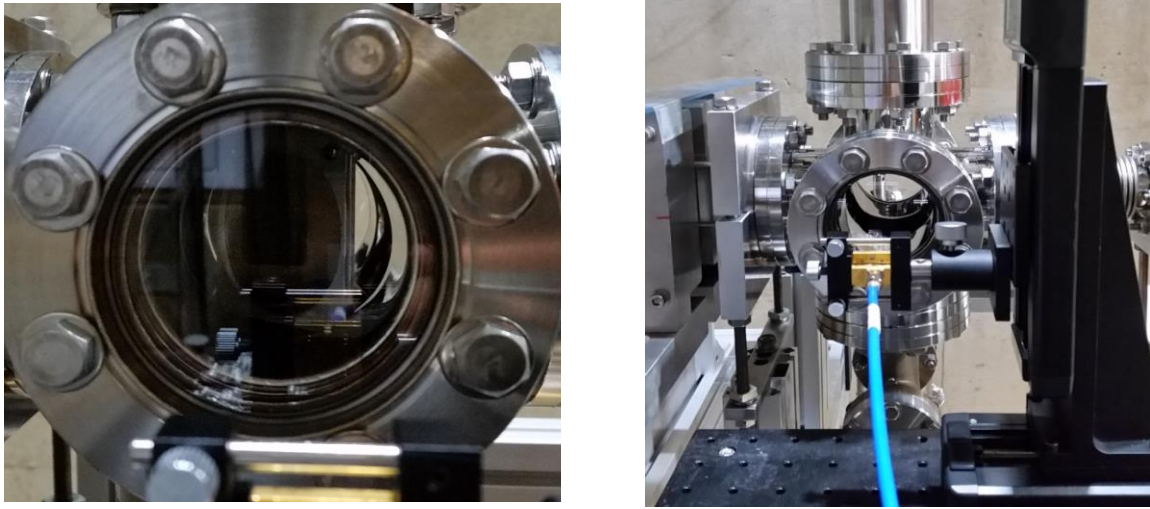


Figure 7.3: Measurement setup of the spatial distribution of the undulator radiation. THz mirror at move-down condition (left) and the setup of the SBD detector (right).

The spatial distribution measurements were performed at the laser injection phase of 20 deg and the R_{56} was fixed at - 47.1 mm. The undulator gap was varied to 30 mm (the minimum), 35 mm (the gap at the highest frequency response of the SBD detector) and 180 mm (the largest). These gaps had the undulator parameter K of 2.8, 2.3 and 0 and the calculated central frequencies of the radiation ω_0 of 0.17, 0.23 and 0.86 THz, respectively. The number and the energy of the laser pulse per macropulse were 4 pulses and 300 μJ . The results of the spatial distribution measurement are shown in Fig. 7.4. Note that all shown results were the radiations with the vertical polarization which is the same as the deflection direction of electron inside the undulator. The radiation with the horizontal polarization was also measured but the signal was very weak. As the results, the radiation from the compressed bunch concentrated in the narrow cone at the beam center and aligned to the center of the THz mirror (Fig. 7.4 a). The radiation from the uncompressed bunch was very

weak (Fig. 7.5 b). At the gap of 30 and 35 mm, the calculated opening angle K/γ of the radiation cone corresponding to the beam energy of 4.6 MeV ($\gamma \approx 10$) were 16 and 13.1 deg that larger than the acceptance angle of the mirror at around 6 deg. Therefore, only the center part of the radiation could be reflected by the mirror. But the other part of the radiation might be reflected by the internal side of the 6-cross chamber as clearly seen in Fig. 7.4 b. In case of the largest undulator gap at 180 mm (Fig. 7.5 a), the CUR could not be observed but the detected radiation was a coherent transition radiation in the vertical polarization, which emitte by the surface of THz mirror (Ti film) when electron bunch was injected to the film.

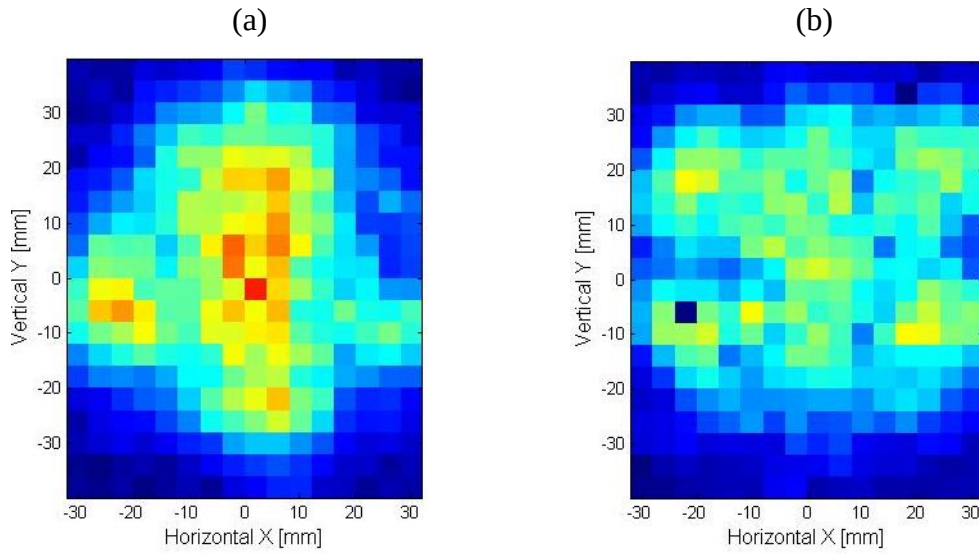


Figure 7.4: Spatial distribution of the undulator radiation at (a) the gap of 30 and (b) 35 mm.

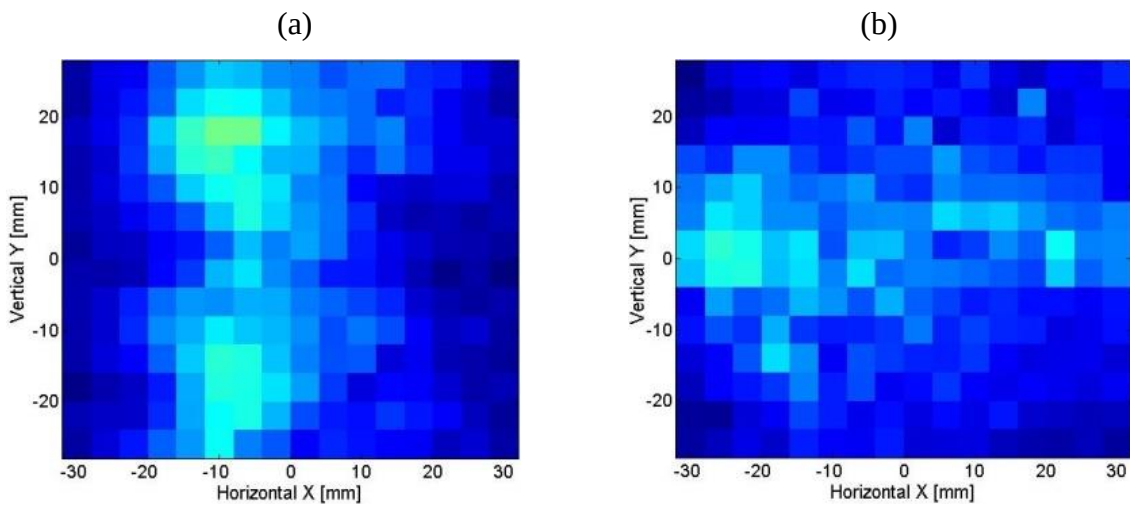


Figure 7.5: Spatial distribution of the undulator radiation at (a) the gap of 180 mm and (b) the uncompress bunch at the gap of 30 mm.

7.1.2 Total Intensity

The total intensity was measured by using a focusing optics to focus whole extracted beam to the pyroelectric detector. A plano-convex polytetrafluoroethylene lens or Teflon lens (Thorlabs, LAT115) with the 3 inch diameter and the focal length of 115 mm was employed and placed next to the THz window. The detector was aligned to the focal point by means of the translation stage. The setup of the total intensity measurement is shown in Fig.7.6.

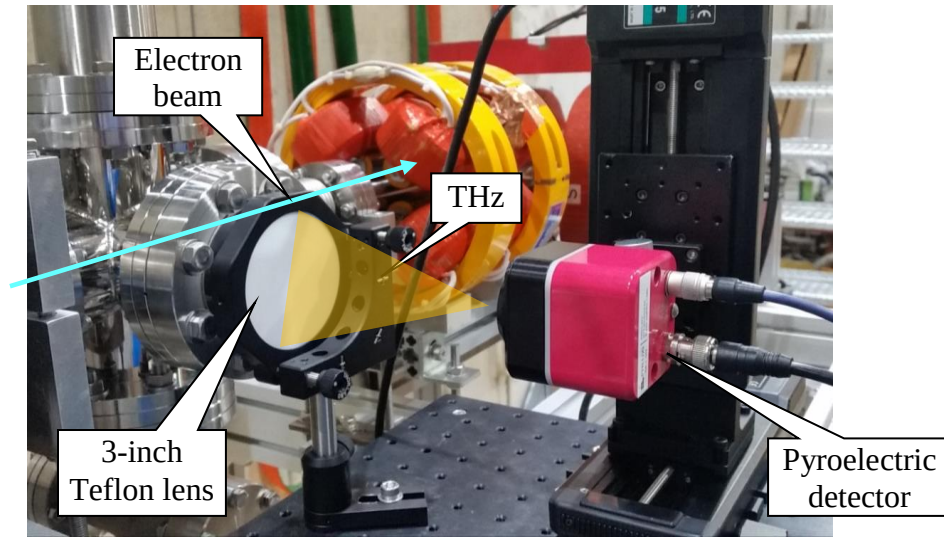


Figure 7.6: Measurement setup of the total undulator radiation intensity.

The measurement results of the bunch charges and the radiation intensities dependence on the laser injection phases of the uncompressed and compressed conditions are shown in Fig. 7.7 and 7.8. The measurement was performed with the number and the energy of the laser pulse per macropulse of 4 pulses and 300 μJ , respectively. The measured bunch charge of both compression conditions had almost the same for a given laser injection phase and undulator gap. But the CUR intensity of the compressed bunch was significantly higher than the uncompressed bunch. It means that the chicane successfully compressed the bunch and enhanced the form factor resulting in a higher CUR intensity. The peak intensity occurred at the phase around 15 to 25 degrees, where the bunch had suitable initial longitudinal phase space correlated with the compression at the R_{56} of -47.1 mm. The factor of the intensity enhancement reached up to 7.5, 4, and 8.3 at the undulator gap of 30, 40 and 50 mm, respectively. These values are higher than the factor of the CTR experiment value at 2.6 because the R_{56} value of the CUR experiment ($R_{56} = -47.1$ mm) was optimal for the bunch compression resulting in the shorter bunch length than the CTR experiment ($R_{56} = -26.8$ mm).

The CUR from the larger undulator gap had smaller intensity compared to the narrower one, because the form factor of the same bunch became smaller at a higher frequency. The peak CUR intensity of the compressed bunch at the undulator gap of 40 mm seems lower than expect. This might caused by poor adjustment of the beam condition such as beam focusing or beam direction during the measurement.

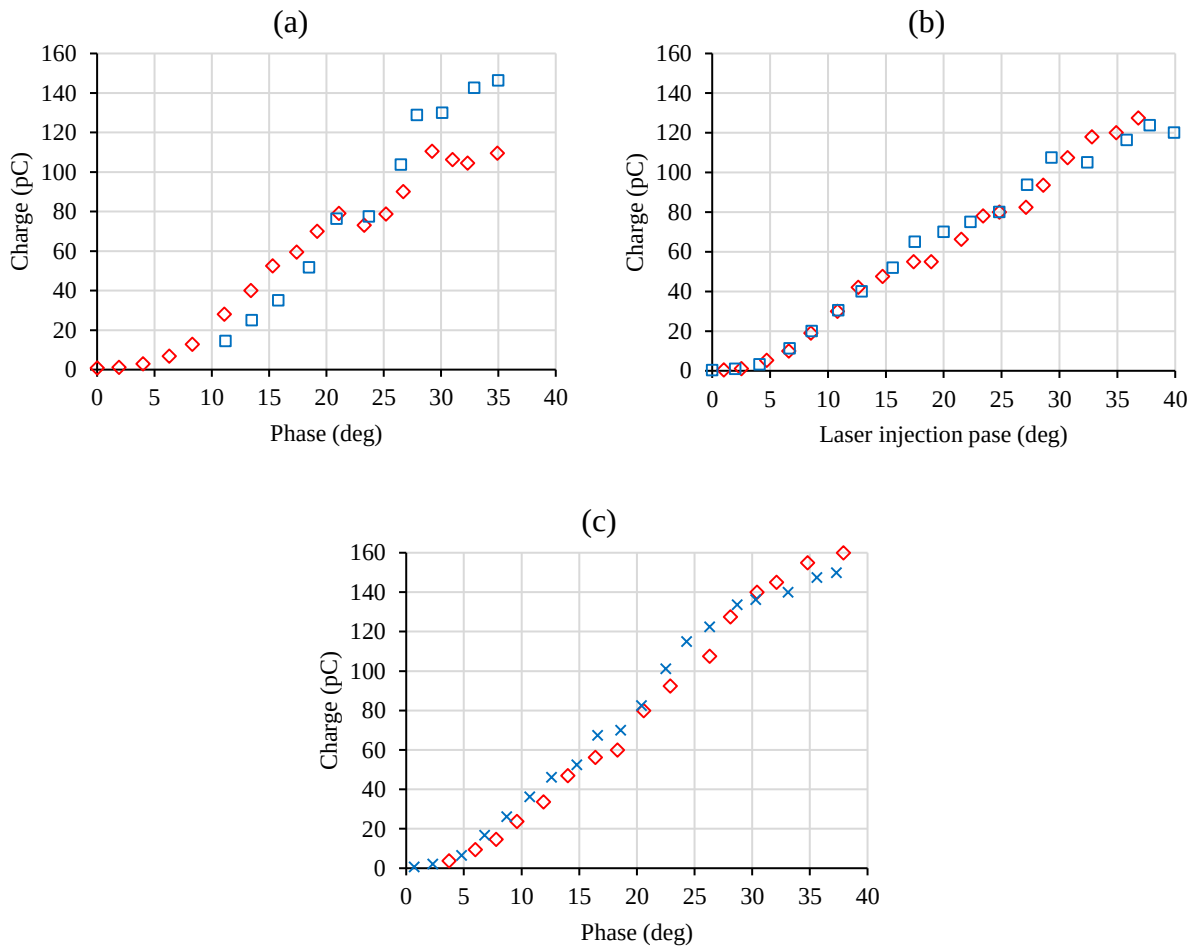


Figure 7.7: Measured bunch charge at the undulator gap of (a) 30, (b) 40 and (c) 50 mm of the compressed bunch (diamond marks) and uncompressed bunch (cross marks).

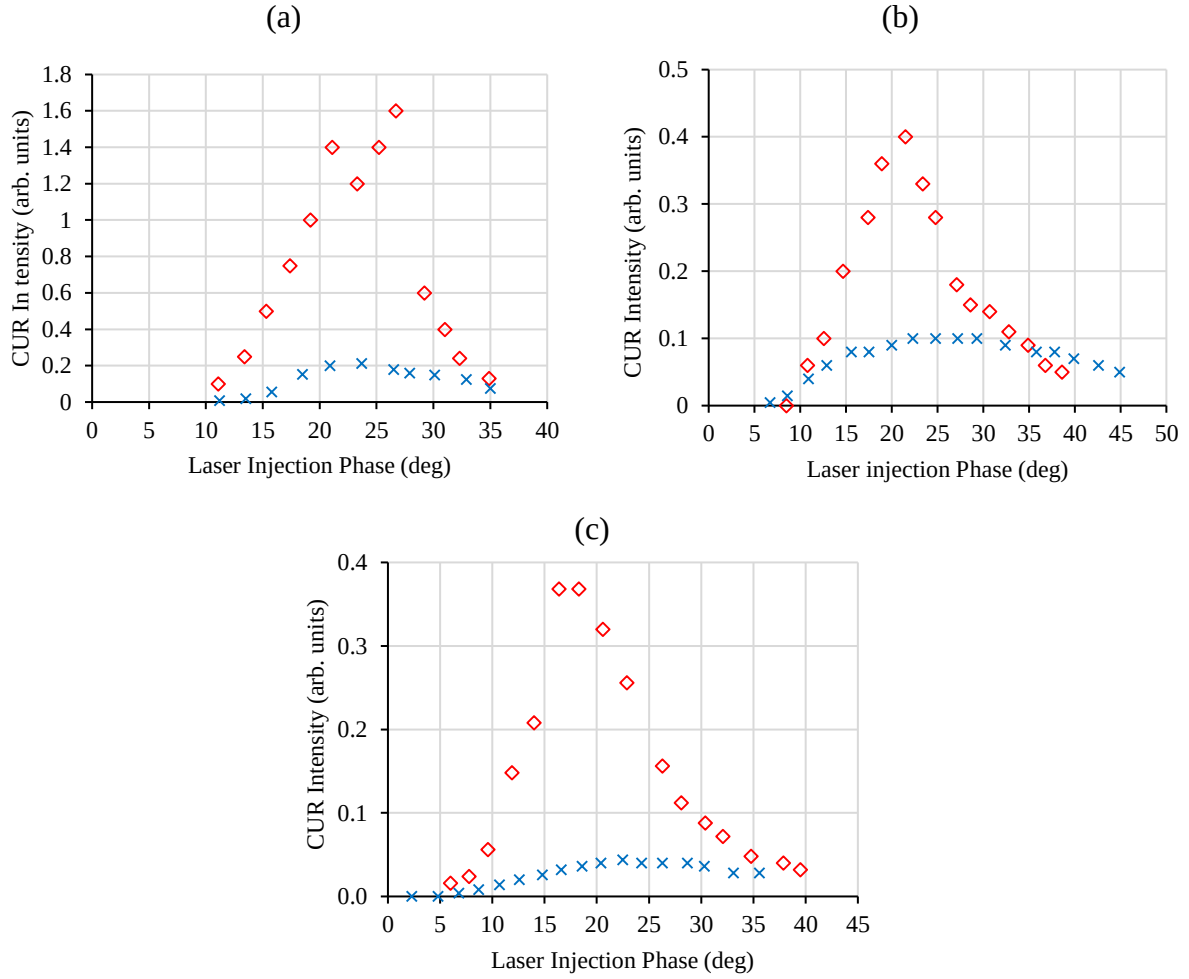


Figure 7.8: Undulator radiation intensity at the undulator gap of (a) 30, (b) 40 and (c) 50 mm of the compressed bunch (diamond marks) and uncompressed bunch (cross marks).

7.1.3 Power Spectrum

The setup of an in-air Michelson interferometer (section 3.5.4) for the power spectrum measurement is shown in Fig. 7.9. Two focusing lens which were the 3-inch and 2-inch diameter Teflon lens (Thorlabs, LAT115, LAT75) with the focal length of 115 and 75 mm were utilized for reducing the THz beam size suitable for the interferometer. The fixed and movable mirrors of the interferometer were 2-inch gold-coated flat mirror (Thorlabs, PF20-03-M01). For measuring the interferograms, the movable mirror position was varied from -8 to 8 mm with the step size of 0.1 mm. The total optical path different was 32 mm and the time window was 106.7 ps and the frequency resolution was 9.37 GHz.

Two types of the beam splitter which were a 100 micron-thick sapphire beam splitter and an inconel coated pellicle beam splitter with the thickness of 2 micron were used. Due to the efficiency drop of the sapphire beam splitter at around 0.5 THz, this beam splitter was

used for the measurement at the frequency less than 0.4 THz while the inconel coated beam splitter was used at the frequency more than 0.4 THz. The combined beams exiting the interferometer were focused by the 2-inch Teflon lens with the focal length of 50 mm (Thorlabs, LAT50). The pyroelectric detector with the built-in lens was mounted on the translation stages and aligned to the focusing point of the combined beam.

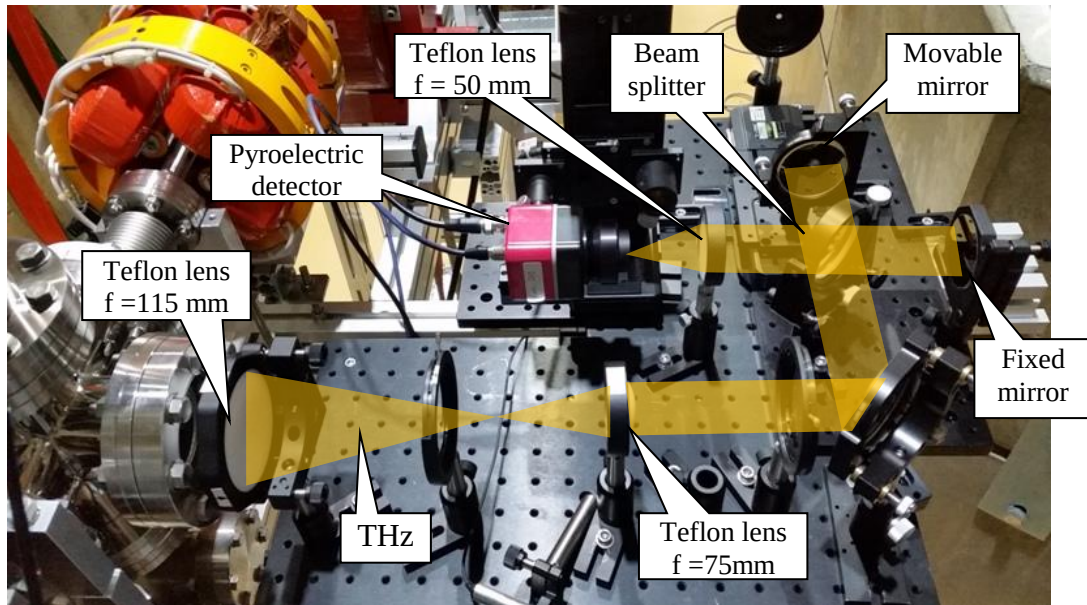


Figure 7.9: Setup of the Michelson interferometer for the power spectrum measurement.

The autocorrelation intensity dependencies as a function of path difference or interferograms measured by the Michelson interferometer for the undulator gap from 30 to 55 mm are shown in Fig. 7.10. Note that the interferograms are shifted in vertical for easier seeing the lines. The measurement was performed only for the compressed bunch because the signal had strong enough to detect. The undulator radiation spectra calculated by Fast Fourier Transform corresponding to the interferograms are shown in Fig. 7.11.

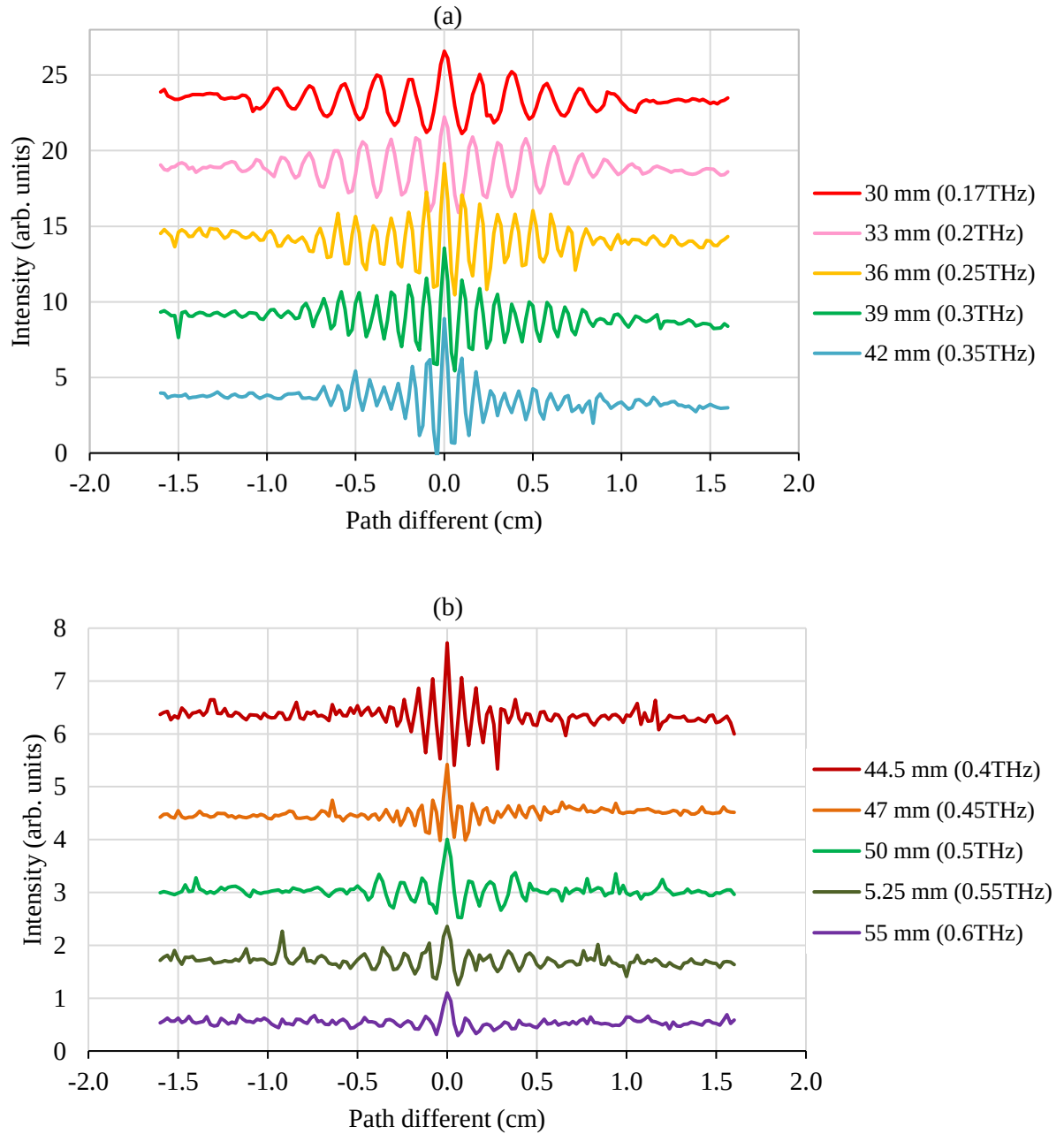
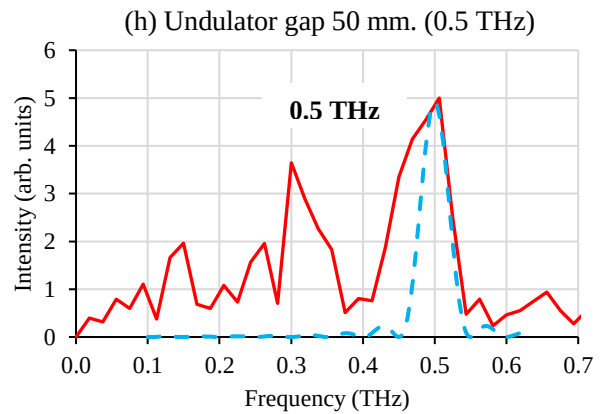
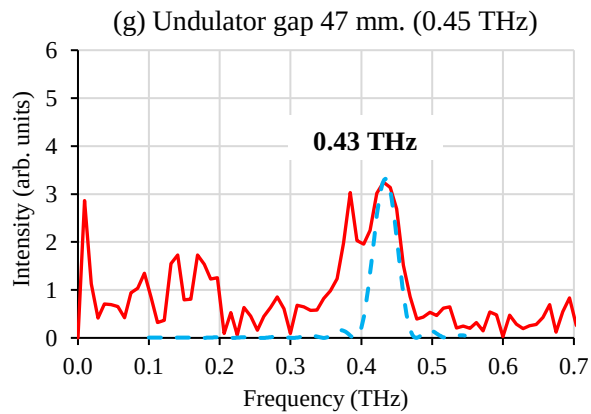
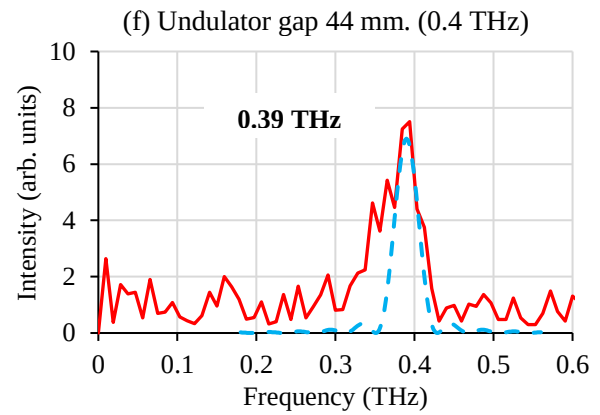
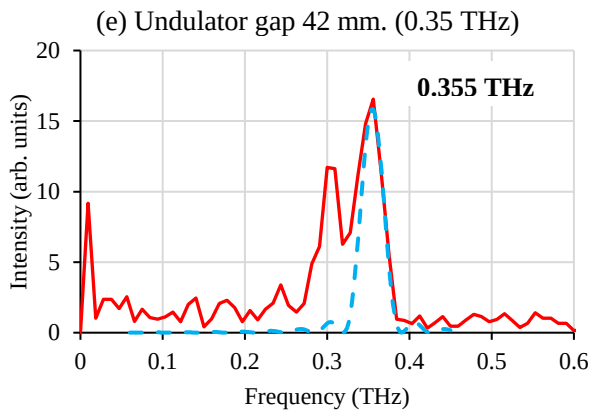
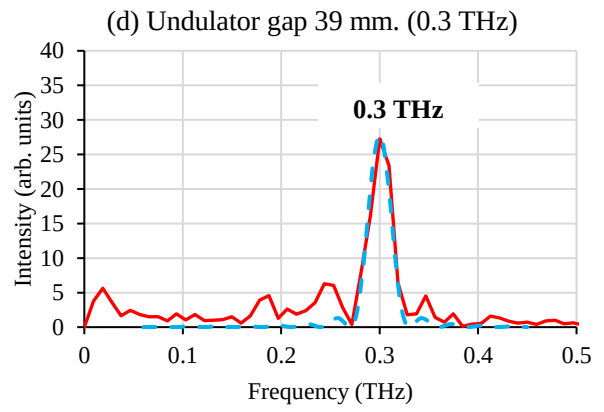
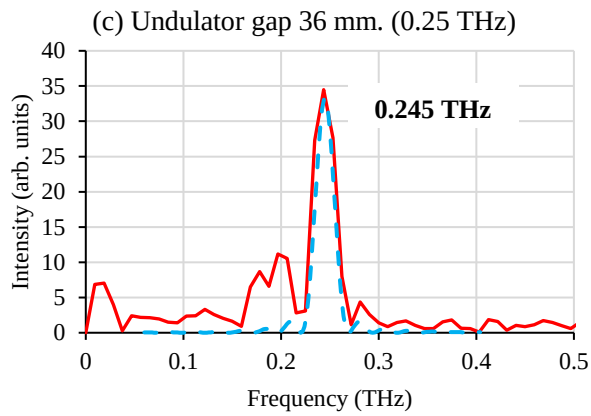
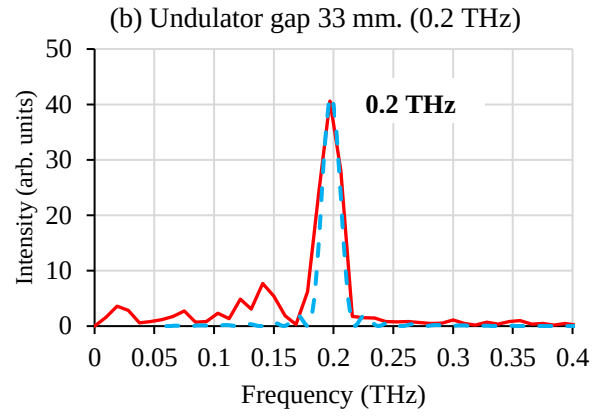
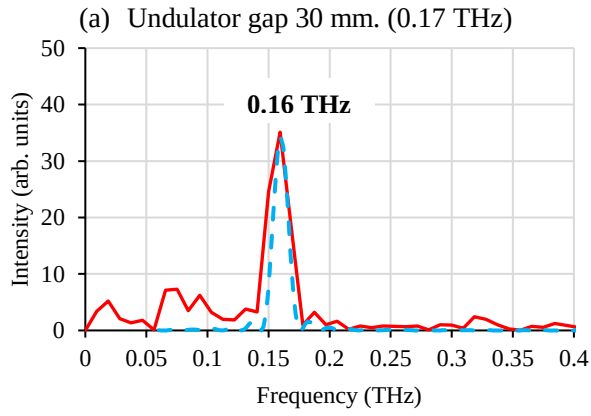


Figure 7.10: Measured interferograms by the Michelson interferometer for the compressed bunch with the undulator gaps of (a) 30 to 42 mm and (b) 44.5 to 55 mm.

As the results, the central frequencies of CUR were in the range from 0.16 to 0.53 THz and the FWHM bandwidth was approximately 10% agreed with the calculation. The spectra contained smaller components at the frequency lower than the central frequency. This might be the off-axis radiation as described in 1.2.2. The peak CUR intensity was at 0.2 THz. The highest frequency that could be distinguished from the noise floor was 0.53 THz.



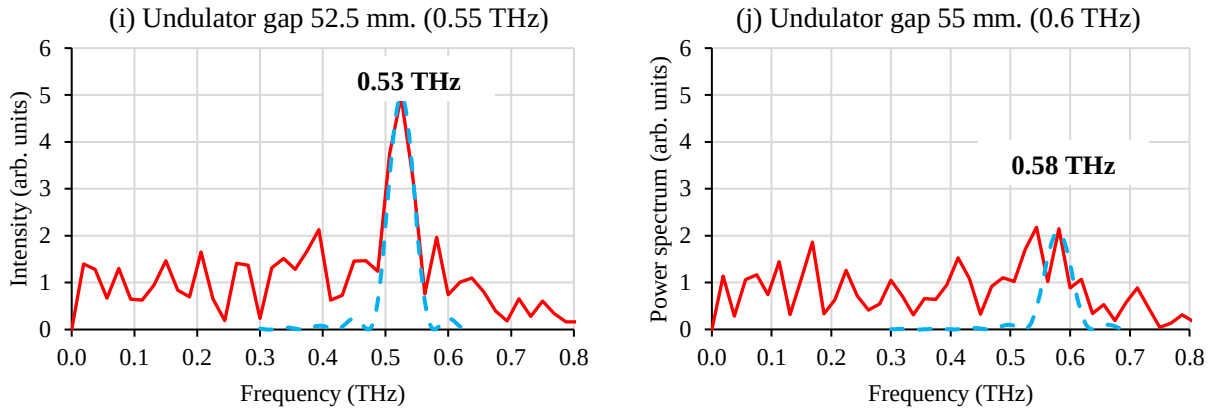


Figure 7.11: Power spectrum of the CUR for the different undulator gaps 30 to 55 mm. The frequencies in the bracket are the calculated central frequencies and the measured central frequencies are shown in the graph (solid lines; the measured spectra, dashed lines; the calculated spectra)

The comparison between the central frequencies by the measurement and the calculation is shown in Fig. 7.12, the peak CUR intensity as a function of the frequency is shown in Fig. 7.13 and the longitudinal phase-space in the undulator section is shown in Fig. 7.14. As the results, the measured CUR frequencies have a good agreement with the calculation. The peak CUR intensities were getting lower at the higher frequency due to the decreasing of the form factor at the high frequency.

The stability of the CUR intensity at the undulator gap of 30 and 55 mm (0.16 and 0.53 THz) are shown in Fig. 7.14 and 7.15. The drift of the CUR intensity was observed at the undulator gap of 30 mm. By fitting the intensity to the normal distribution function, the intensity deviations of the undulator radiation at the undulator gap of 30 and 55 mm are 0.296 and 0.134 equivalent to the relative rms intensity deviations of 8.9 % and 13 %, respectively.

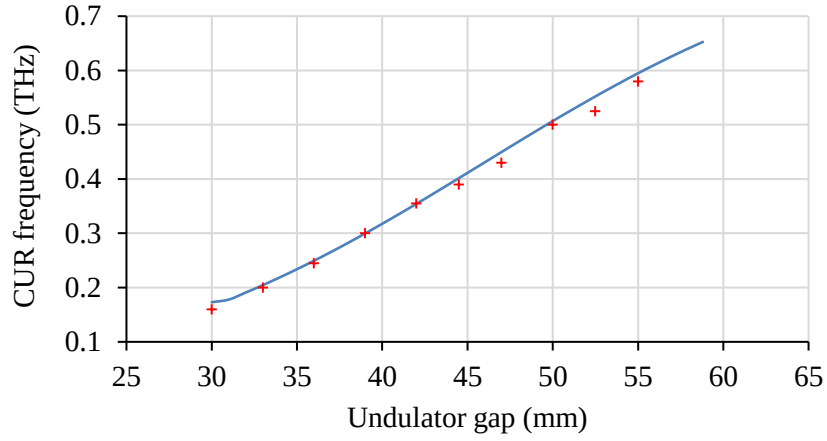


Figure 7.12: Central frequency of the CUR by the calculation (solid line) and the measurement (cross marks)

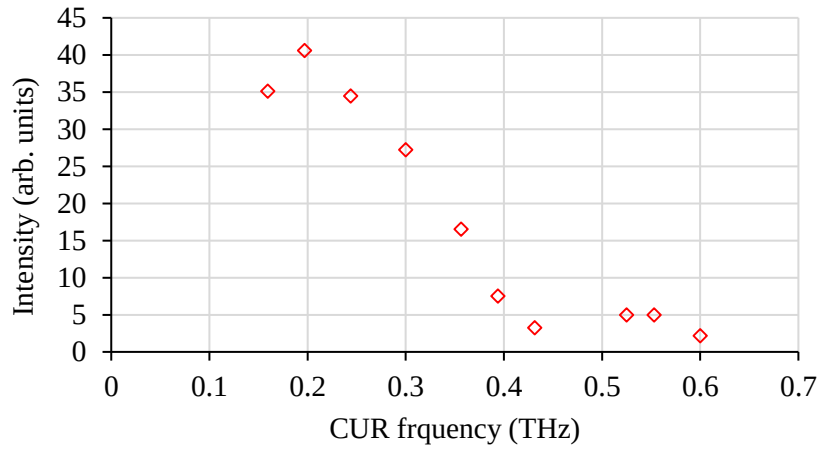


Figure 7.13: Measured peak CUR Intensity as a function of the radiation frequency.

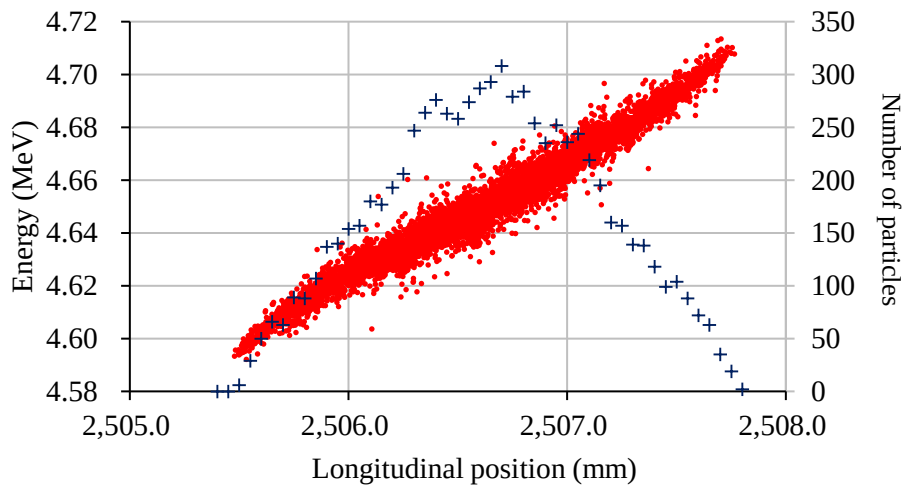


Figure 7.14: GPT calculation of the longitudinal phase-space at the middle of the undulator ($R_{56} = -44.6$ mm, the laser injection phase = 30 degrees and the bunch charge = 70 pC)

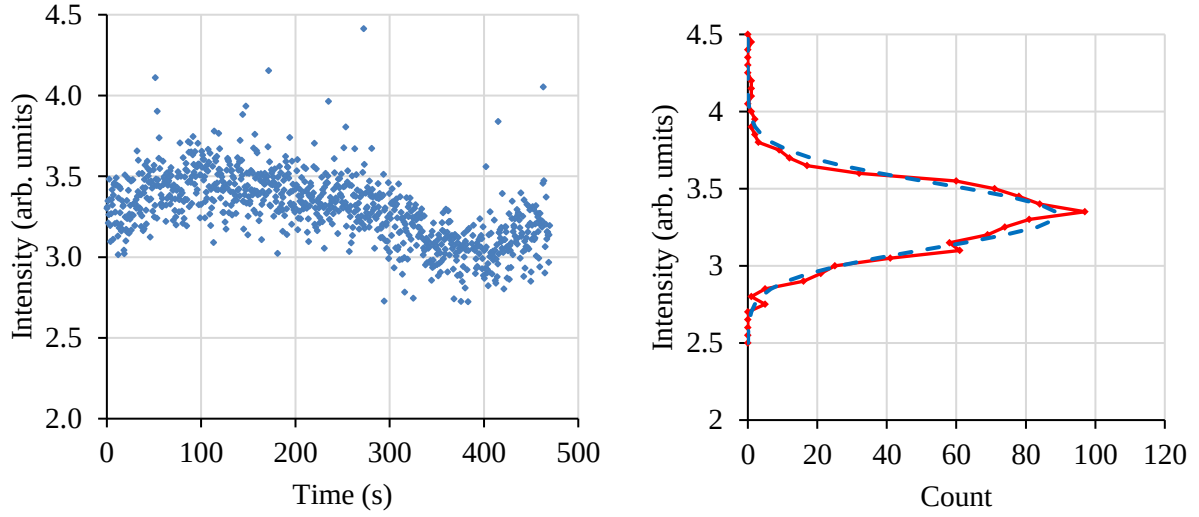


Figure 7.14: Measured CUR intensities (left) at the undulator gap of 30 mm as a function of time and the intensity histogram (right).

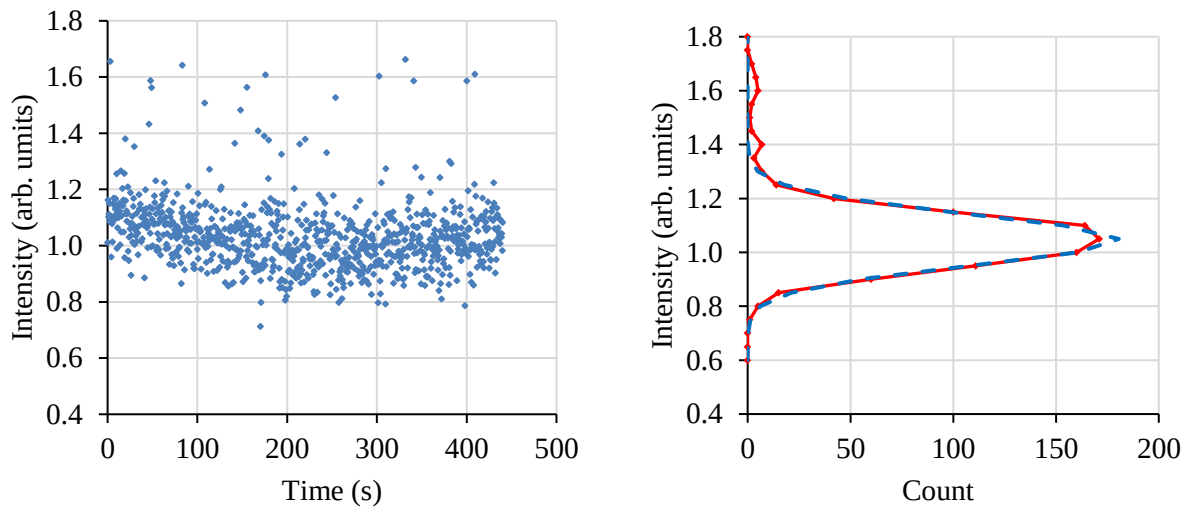


Figure 7.15: Measured CUR intensities (left) at the undulator gap of 55 mm as a function of time and the intensity histogram (right).

Chapter 8

Conclusion

The accelerator-based compact terahertz radiation source at Institute of Advanced Energy Kyoto University has been successfully developed and the first commissioning of the system was performed in Aug 2016. This thesis explain the conceptual design, the related theories, the details of the components, the simulation and the measurement results of the first terahertz radiation. The system could generate the terahertz radiation in the frequency range from 0.16 to 0.53 THz from the vertical deflection planar Halback type undulator with 10 periods and the period length of 70 mm. The peak magnetic field was 0.43 T at the undulator gap of 30 mm and the maximum undulator parameter of 2.8. The undulator radiations has high degree of phase coherence or called coherent undulator radiation (CUR) generated by a short bunch electron beam. The electron beam was generated by the 1.6 cell BNL type photocathode RF gun and compressed the magnetic chicane bunch compressor. The photocathode RF gun was first generated the electron beam in May 2015 and the magnetic chicane was successfully operated in Mar 2016. The characteristic of the chicane and the compressed electron beam properties have been investigated by the coherent transition radiation (CTR) technique. The electron beam properties, the bunch compression characteristics and the undulator radiation properties are summarized as follow.

Electron beam properties

- Beam energy generated by the photocathode RF gun depends on the driven RF power and the laser injection phase ϕ_L . The maximum beam energy was 4.8 MeV at the driven RF power of 9 MW and the ϕ_L of 45 to 50 degrees. At the operating condition at the ϕ_L of 30 degrees, the beam energy was 4.6 MeV and the relative beam energy spread was 1.3%.
- The bunch charge had the maximum at 1.4 nC at laser energy of 350 μ J. Bunch charge graduated increase from zero at the ϕ_L of zero degree to the maximum. The dark current was maximum at 70 pC.
- The beam emittance was measured by the quadrupole scan method and at the bunch charge of 50 pC, the measured beam emittance in the horizontal and vertical direction was 5.0, 7.5 mm mrad, respectively.

Bunch compressor characteristics

- The R_{56} value calculated by the simulation code GPT was in the range from -26.8 to -59.3 mm corresponding to the excited current of the bending magnet of the chicane from 4.4 to 6.4 A.
- The magnetic chicane bunch compressor could compress the electron bunch at the ϕ_L less than 40 degrees and the ϕ_L for the maximum compression was around 20 to 30 degrees.
- The spectrum of the CTR had the frequency lower than 0.24 THz and the main peak at 0.08 THz with the smaller peak at 0.2 THz.
- The maximum compression condition estimated by fitting the CTR power spectrum to the spectrum of Gaussian distribution bunch was at the R_{56} around -45 mm.
- The estimated minimum rms bunch length was less than 1 ps at the laser injection phase of 30 degree and the bunch charge of 98 pc.

Undulator radiation properties

- The undulator radiation had the frequency in the range from 0.16 to 0.53 THz corresponding to the undulator gap from 30 to 52.5 mm.
- The undulator radiation intensity depended on the frequency and has the maximum intensity at the frequency of 0.2 THz.
- The compressed bunch provided the higher CUR intensity than the uncompressed bunch by the factor of 7.5 and 8.3 at the undulator gap of 30 and 50 mm, respectively.
- The spectrum bandwidth of the undulator radiation was approximately of 10%.
- The radiation intensity had the relative deviation of 8.9 % and 13 % at the undulator gap of 30 and 55 mm, respectively.

Problems

We found the discrepancies between the tracking simulation and the measurement result. In the simulation, the electron bunch generated by the Gaussian distribution laser pulse with the FWHM pulse duration of 6 ps could not be compressed by the magnetic chicane due to the strong space-charge effect. But the CTR and CUR experiment results show that the chicane successfully compressed the electron bunch resulting in the higher CTR and CUR intensity. This may cause by the non-linear effect of the photoemission process of the cathode material. The further investigation of this issue is needed for better understanding of the beam

dynamic of the system. The bunch lengthening has been observed at a high bunch charge because of the strong space-charge effect which resulted lower CUR intensity. Curing methods have to be studied to mitigate the space-charge.

Future work

The measurements in this study were performed in the first commissioning of the system. Some performances have not been investigated in details yet. The first priority of the future measurements is the absolute power of CUR measurement. The other recommended measurements are the CUR intensity dependency on the bunch charge, the beam energy spread at the high laser injection phase, the minimum bunch length measurement by the other techniques, the transverse beam size along the beam line, etc. We also recommend to improvement of the performances, stability and usability of the system such as the precise adjustment of the beam line alignment, the remote control for the laser energy adjustment and the undulator gap adjustment, the feedback control the CUR intensity stability etc. The optical transportation line for the THz radiation to the user area is also need to be constructed.

In conclusion, the compact accelerator based THz radiation source has been successfully constructed and CUR has been generated. The performance of the THz source could be improved by further study on above mentioned issues.

List of Publications

List of First authorship publications

Journal Publications

- 1) Sikharin Suphakul, Kantaphong Damminsek, Heishun Zen, Toshiteru Kii, Hideaki Ohgaki, “Beam Dynamics Investigation for the Compact Seeded THz-FEL Amplifier”
Energy Procedia 89, 2016, pp 373-381.
- 2) Sikharin Suphakul, Heishun Zen, Toshiteru Kii, Hideaki Ohgaki, “Measurement of Coherent Undulator Radiation of Compact Terahertz Radiation Source at Kyoto University”
Int J Magnetics Electromagnetism 3, 2017, 008.
- 3) Sikharin Suphakul, Heishun Zen, Torishi Kii, Hideaki Ohgaki, “Investigation of Bunch Compressor and Low-Energy Electron Beam Characteristics by Coherent Transition Radiation”, Nucl. Instrum. Meth. in Phys. A (Submitted)

Conference Proceedings

- 1) Suphakul Sikharin, Yusuke Tsugamura, Heishun Zen, Toshiteru Kii, Qika Jia and Hideaki Ohgaki, “Design of Compact THz-FEL system at Kyoto University”, Proceeding of 11th Annual Meeting of Particle Accelerator Society of Japan, Aomori, 2014, pp.1393.
- 2) Suphakul Sikharin, Kantaphong Damminsek, Heishun Zen, Toshiteru Kii and Hideaki Ohgaki, “Electron Beam Generation by a Photocathode RF-gun at Kyoto University”, Proceeding of 12th Annual Meeting of Particle Accelerator Society of Japan 2015, Fukui, pp. 386-390.
- 3) S. Suphakul, H. Zen, K. Morita, K. Torgasin, K. Masuda, T. Kii, H. Ohgaki, “Electron Beam for Compact THz FEL Amplifier at Kyoto University”, Proceeding of 13th Annual Meeting of Particle Accelerator Society of Japan, 2016, Chiba, pp. 39 – 42.

4) S. Suphakul, T. Yusuke, H. Zen, T. Kii, and H. Ohgaki, “Development of Compact THz-FEL System at Kyoto University”, Proceedings of 36th International Free Electron Laser Conf., Basel, Switzerland, 2014, pp. 501 – 504.

5) S. Suphakul, H. Zen, K. Morita, K. Torgasin, K. Masuda, T. Kii, H. Ohgaki, “Generation of Short Bunch Electron Beam from Compact Accelerator for Terahertz Radiation”, Proceedings of International Particle Accelerator Conference, 2016, pp.1757-1759.

List of Contributed Publications

Journal Publications

1) H. Zen, S. Suphakul, T. Kii, K. Masuda, H. Ohgaki, “Present Status and Perspective of Long Wavelength Free Electron Laser at Kyoto University”, Physics Procedia 84, 2016, pp. 47 – 53.

2) K. Torgasin, K. Morita, H. Zen, K. Masuda, T. Katsurayama, T. Murata, S. Suphakul, H. Yamashita, T. Nogi, T. Kii, K. Nagasaki and H. Ohgaki “Thermally Assisted Photoemission Effect on CeB₆ and LaB₆ for Application as Photocathodes”, Phys. Rev. Accel. and Beams 20, 2017, pp. 073401.

Conference Proceedings

1) H. Zen, S. Suphakul, T. Kii, H. Ohgaki, “Development of Photocathode Drive Laser System for RF Guns in KU-FEL”, Proceedings of 36th International Free Electron Laser Conference, Basel, 2014, pp. 828-831.

2) K. Damminsek, S. Rimjaem, C. Thongbai, S. Suphakul, H. Ohgaki, H. Zen, “Electron beam properties of compact seeded terahertz FEL amplifier at Kyoto University”, Proceeding of the 37th International Free Electron Laser Conference, Daejeon, 2015, pp. 85-88.

3) T. Murata, H. Zen, T. Katsurayama, T. Nogi, S. Suphakul, K. Torgasin, T. Kii, K. Masuda, H. Ohgaki, K. Yoshida, K. Hachiya, “Development of Phonon Dynamics Measurement System by MIR-FEL and Pico-second Laser”, Proceedings of 37th International Free Electron Laser Conference, Daejeon, 2015, pp. 615-617.

4) K. Morita, H. Zen, K. Masuda, K. Torgasin, T. Katsurayama, T. Murata, S. Suphakul, H. Yamashita, T. Nogi, T. Kii, K. Nagasaki, H. Ohgaki, “Photoemission Properties of LaB6 and CeB6 Under Various Temperature and Incident Photon Energy Conditions”, Proceedings of 7th International Particle Accelerator Conference, Busan, 2016, pp. 2088-2090.

5) H. Zen, K. Morita, T. Murata, T. Nogi, S. Suphakul, K. Torgasin, T. Kii, K. Masuda, H. Ohgaki, R. Kuroda, “Feasibility Study of Photocathode Operation of Thermionic RF Gun at KU-FEL”, Proceedings of 7th International Particle Accelerator Conference, Busan, 2016, pp. 754-756.

List of Oral presentations

1) Suphakul Sikharin, Yusuke Tsugamura, Heishun Zen, Kai Masuda, Toshoteru Kii, Hideaki Ohgaki, “Design of Compact THz-FEL system at Kyoto University”, Annual Meeting of Atomic Energy Society of Japan 2014, Tokyo, 2014.

2) Suphakul Sikharin, Yusuke Tsugamura, Heishun Zen, Kai Masuda, Toshoteru Kii, Hideaki Ohgaki, “Design of Magnetic Chicane for Compact THz-FEL system”, Fall Meeting of Atomic Energy Society of Japan 2014, Kyoto, 2014.

3) Sikharin Suphakul Yusuke Tsugamura, Heishun Zen, Toshiteru Kii, Kai Masuda, Hideaki Ohgaki, “Expected THz-CSR Radiation performance of a short undulator”, Annual meeting of Atomic Energy Society of Japan 2015, Ibaraki, 2015.

4) Sikharin Suphakul, Kantaphong Damminsek, Heishun Zen, Kai Masuda, Toshoteru Kii, Hideaki Ohgaki, “Construction of Compact Seeded THz FEL system at Kyoto University”, Fall meeting of Atomic Energy Society of Japan 2015, Shizuoka, 2015.

5) Sikharin Suphakul, Heishun Zen, Toshiteru Kii, Hideaki Ohgaki, “Development of Compact Seeded Terahertz Free Electron Lasers”, The 6th International Symposium of Advanced Energy Science, 2015.

6) Sikharin Suphakul, Heishun Zen, Toshiteru Kii, Hideaki Ohgaki, “Simulation and Performance Test of Photocathode RF-gun at Kyoto University”, 2015 RF Gun Workshop meeting, Kyoto, 2015.

7) S. Suphakul, H. Zen, K. Morita, K. Torgasin, K. Masuda, T. Kii, H. Ohgaki, “Electron Beam for Compact THz FEL Amplifier at Kyoto University”, 13th Annual Meeting of Particle Accelerator Society of Japan, 2016, Chiba, 2016.

8) Sikharin Suphakul, Heishun Zen, Kenichi Morita, Konstantin Torgasin, Kai Masuda, Toshiteru Kii, Hideaki Ohgaki, “Measurement of Undulator Radiation from Compact THz FELs at Kyoto University”, 7th International Symposium of Advanced Energy Science, , 2016, Kyoto, 2016.

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References

- [1] M. Tonouchi, “Cutting-edge terahertz technology”, *Nature Photonics* 1, 2007, pp. 97-105
- [2] S. E. Ralph and D. Grischkowsky, “THz Spectroscopy and Source Characterization by Optoelectronic Interferometer”, *Appl. Phys. Lett.* 60, 1992, pp. 1070-1072.
- [3] G. Khitrova, “Theory
- [4] Website: www.sura.org
- [5] A. Hofmann, “Theory of synchrotron radiation”, SSRL ACD-note 38, Stanford Synchrotron Radiation Laboratory, 1986.
- [6] V. Ginsburg and I. Frank, “Radiation of a uniformly moving electron due to its transition from one medium into another”, *Journal of Physics* 9, 1945, pp 353.
- [7] S. J. Smith and E. M. Purcell, “Visible Light from Localized Surface Charges Moving across a Grating”, *Phys Rev* 92, 1953, pp. 1069.
- [8] D. Bocek, “Generation and Characterization of Superradiant Undulator Radiation”, SLAC-PUB-7016, 1995.
- [9] H. Motz, “Application of the Radiation from Fast Electron Beams”, *J. Appl. Phys.* 22, 1951, pp. 527.
- [10] B. Green et al., “High-Field High-Repetition-Rate Sources for the Coherent THz Control of Matter”, *Nature Photonics*, Scientific Report, DOI 10.1038/srep22256.
- [11] A. Doria et al., “Enhanced coherent emission of THz radiation by energy-phase correlation in a bunched electron beam”, *Phys. Rev. Lett.*, vol. 93, 2004, pp. 264 – 801.
- [12] G.P. Gallerano, A. Doria, E. Giovenale and G. Messina, “Coherence effects in FEL radiation generated by short electron bunches”, *Nucl. Instrum. Meth. A* 358, 1995, pp. 78 - 81
- [13] X. Wen et al., *Nucl. Instrum Meth. Phys. Res. A* 820, 2016, pp. 75–79.
- [14] H. Zen et al., “Present Status and Perspective of Long Wavelength Free Electron Laser at Kyoto University”, *Physics Procedia* 84, 2016, pp. 47 – 53
- [15] L.M. Young, “PARMELA”, LANL Technical Note LA-UR-96-1835, 2002.
- [16] S.B. Van der Geer et al., in *Proceeding of the 6th European Particle Accelerator Conference*, Stockholm, 1998, pp. 1245.
- [17] G. Brown, K Halback, J. Harris and H. Winick, “Wiggler and Undulator Magnets”, *Nucl. Instrum. Meth. A* 208, 1983, pp. 65-77.

- [18] S. Krinsky, “Undulator for the 700 MeV VUV-ring”, Nucl. Instrum. Meth. A 172, 1980, pp. 73-76.
- [19] C.B. McKee and J.M.J. Madey, Nucl. Instrum. Meth. A296, 1990, 716-719.
- [20] T. Kii, “Design Study on THz Seeded FEL Using Photocathode RF Gun and Short Period Undulator”, Proceedings of 30th International Free Electron Laser Conference, Gyeongju, 2008, pp. 196-199
- [21] H. Ohgaki et al., “Numerical Evaluation of Oscillator FEL with Multibunch Photocathode RF-GUN in Kyoto University”, Proceedings of 29th International Free Electron Laser Conference, Novosibirsk, 2007, pp. 390-393.
- [22] H. Zen et al., “Development of Photocathode Drive Laser System for RF Guns in KU-FEL”, Proceedings of 36th International Free Electron Laser Conference, Basel, 2014, pp. 828-831.
- [23] M. Bakr et al., “Design and Numerical Simulation of THz FEL Amplifier in Kyoto University”. Proceedings of 34th International Free Electron Laser Conference, Nara, 2012, pp. 520-522
- [24] N. Terunuma et al., “Improvement of an S-band RF gun with a Cs₂Te photocathode for the KEK-ATF”, Nucl. Instr. Meth. Phys. Res. A 613, 2010, pp. 1–8
- [25] K. Damminsek et al., “Electron beam properties from a compact seeded terahertz amplifier at Kyoto University”, Proceedings of FEL2015, 2015, pp. 85-88.
- [26] S. Suphakul et al., “Generation of Short Bunch Electron Beam from Compact Accelerator for Terahertz Radiation”, Proceedings of International Particle Accelerator Conference, 2016, pp.1757-1759.
- [27] S. Suphakul et al., Measurement of Coherent Undulator Radiation of Compact Terahertz Radiation Source at Kyoto University”, Int. J Magnetics Electromagnetism 3, 2017, pp. 008
- [28] M. A. A. Bark Arby, “Studies on the Reduction of Back Bombardment Effect in Thermionic RF Guns using Different Cathode Material”, Ph.D. Thesis Kyoto University, 2013.
- [29] J. S. Fraser, R. L. Sheffield and E. R. Gray, “High-brightness Photoemitter Development for Electron Accelerator Injectors,” Proceeding of AIP Conf., vol. 130, 1985, pp. 598-601.
- [30] K. J. Kim, “RF and Space-charge Effect in Laser-driven RF Electron Guns”, Nucl. Instrum Meth. Phys. Res. A 275, 1989, pp. 201-218.

- [31] C. Travier, "An Introduction to Photo-injector Design", Nucl. Instrum Meth. Phys. Res. A 340, 1994, pp. 26-39.
- [32] H. Y. Fan, "Theory of Photoelectric Emissions from Metals", Phys. Rev., vol. 68, 1945, pp. 43-52.
- [33] W. Schottky, "Über den austritt von elektronen aus glühdrähten bei verzögernden potentialen," Annalen Physik, vol. 44, 1914, pp. 1011-1032.
- [34] D.T. Palmer et al., "Commissioning Result of the Next Generation Photoinjector", BNL-63808, 1997.
- [35] W. D. Kilpatrick, "Criterion for vacuum sparking designed to include both RF and DC", Rev. Sci. Instrum., vol. 28, 1957, pp. 824-826.
- [36] L.M. Young, J.H Billen, POISSON/ SUPERFISH, Technical Note No. LA-UR-96-1834 Los Alamos National Laboratory, 1999.
- [37] T. Rao and D. H. Dowell, "An Engineering Guide to Photoinjectors", ISBN: 978-1481943222, 2013, pp. 171
- [38] F. Stulle, A Bunch Compressor for small Emittances and high Peak Currents at the VUV Free-Electron Laser, Ph.D Thesis, University of Hamburg, 2004.
- [39] T. Zickler, "Basic design and engineering of normal-conducting, iron-dominated electromagnets" CERN accelerator School CAS 2009 CERN-2010-004, pp. 65-102
- [40] P. Elleaume and O. Chubar and J. Chavanne, "Computing 3D Magnetic Field from Insertion Devices" Proceeding of PAC97 Conference, 1997, pp. 3509-3511.
- [41] Website: \ www.aist.go.jp
- [42] K. Wille, "The Physics of Particle Accelerators", ISBN 0 19 850550 7, Guildford & King's Lynn, pp. 259-260.
- [43] C. Settakorn, "Generation and use of coherent transition radiation from short electron bunches", Ph.D. Thesis, Stanford University, California, 2001.
- [44] Website: <https://www.britannica.com/science/light/Thin-film-interference>
- [45] M. Poulter, "Pyroelectric Organic Thin Films", Ph.D. Thesis, University of Oxford, UK, 1992.
- [46] Website: <http://phlux.com/English4.html>
- [47] Website: <http://www.millitech.com/MMW-MixerDetector-DET.htm>
- [48] K.U. Kasemir, "Integrating LabVIEW into a distributed computing environment", Proceeding of the 8th Int. Conf. ICALEPCS, California, 2001, pp. 548
- [49] L.M.Young, J.H. Billen, POISSON/SUPERFISH, Technical Note No. LA-UR-96-1834, Los Alamos National Laboratory, 1999.

- [50] K. Shimahashi, "Investigation of Electron Beam Parameterin Seeded THz-FEL Amplifier using Photocathode RF Gun", *Energy Procedia* 34, 2013, pp. 863 – 870
- [51] Website: <http://pulsar.physics.nl>
- [52] P.W. van Amersfoort et al., "The Electron Accelerator for FELIX", *Proceeding of Linear Accelerator Conference, Virginia USA, 1988*, pp. 305-307.
- [53] H. Zen, private communication.
- [54] K. Damminsek et al., "Electron beam properties of compact seeded terahertz FEL amplifier at Kyoto University", *Proceeding of the 37th Free Electron Laser Conference, Daejeon, 2015*, pp. 85-88.
- [55] H. Wiedermann, "Particle Accelerator Physics", Third Edition, ISBN-13 978-3-540-49043, Springer-Verlag Berlin, Heidelberg, 2007, pp. 155.
- [56] M.G. Minty, and F. Zimmermann "Measurement and Control of Charged Particle Beam" Springer-Verlag Berlin, Heidelberg, 2003, pp. 113-114.
- [57] M. Sarstedt, R. Becker, H. Klein, A. Masser, J. Miller R. Thomas and M. Weber "Beam Diagnostic Using an Emittance Measurement Device" *Nuclear Instrument and Methods in Physics Research B* 99, 1995, pp. 721-724.
- [58] H. M. Hudson and R.S. Larkin, "Accelerated Image Reconstruction using Ordered Subsets of Projection Data", *IEEE transaction and Medical Imaging* 13, No.4, 1994, pp. 601-609.
- [59] J. Magnes et al., "Quantitative and Qualitative Study of Gaussian Beam Visualization Techniques", *arXiv:physics/0605102 [physics.optics]*, 2006.
- [60] W. Barry, "An autocorrelation technique for measuring sub-picosecond bunch length using coherent transition radiation", *Proceeding of Workshop on Advanced Beam Instrumentation, Tsukuba, 92-1, 1991*, pp. 224-235.
- [61] H. C. Lihn, D. Bocek, P. Kung, C. Settakorn, and H. Wiedemann, "Measurement of subpicosecond electron pulses", *Phys. Rev. E* 53, 1996, pp. 6413-6418.
- [62] C. Settakorn, "Generation and use of coherent transition radiation from short electron bunches", *Ph.D. Thesis, Stanford University, California, 2001*.
- [63] Website: <http://www.fuji-ideck.co.jp/>
- [64] Y. Yang et al., Measurement of the transmission of the atmosphere from 0.2 to 2 THz, *Opt. Express* 19, 2011, pp.8830-8838.

Appendix

A. Input files of Simulation

1) PARMELA input file

```
run 1 1 2856. 0.0 1e-5 2
title
1.6cell RF-GUN, n1C, sigma=0.0689 mm, 6.24 deg.

input 9 59999 .3 0.1 80 8 12
cathode 0. 0.3 1 0. 0.0

cell 3.4135 1.25 1 180 -70 10 1 -1
cfield 10
KEK-GU03.t7

cell 9.0405 1.25 1 0 -70 20 1 -1
cfield 20
KEK-GU05.t7
drift 37.55 2 1
poisson 0 1 0 0 0 0 1
SHI-SOL2.t7
```

2) GPT Input file

```
# ***** Simulation of 1.6 cells BNL Photocathode RF-Gun *****
# ***** By Sikharin Institute of Advanced Energy, Kyoto University *****

# ***** Initial parameters *****

nps = 50000 ;                # Total particles
Qtot = -53e-12 ;            # Total charge (C)
setparticles("beam", nps, me, qe, Qtot ) ;

spacecharge3Dmesh();
# spacecharge3D();           # Space charge calculation
# setrmacrodlist( • beam • , • u • ,0.00001,0);    # For space charge calculation

# ***** *** Injection Laser : Transverse properties *****
r = 0.5e-3 ;                 # RMS radius (mm)
maxr = 1e-3 ;                # max radius (mm)

setrxydist("beam", "~g", 0, r,0,3);    # Radial distribution : Gaussian
#setrxydist("beam", "~u", maxr/2, maxr); # Radial distribution : Uniform
setphidist("beam", "~u", 0, 2*pi) ;     # Angle distribution : Uniform
```

```

# ***** Injection Laser : Longitudinal properties *****
# Particle-release time (Temporal distribution)
# tlen = 2.5e-12 ;          # RMS pulse length (s) 2.548e-12 // FWHM = 6 ps
# mlen = 3 ;              # max laser pulse length (sigma)
# settdist("beam","~g", 0,tlen,mlen,mlen) ; # Gaussian laser pulse center at t=0

ulen = 6e-12 ;          # Uniform laser pulse length (s)
settdist("beam","~u",0,ulen) ; # Uniform laser pulse center at t=0

# ***** Remove particle *****
stdxyzmax(3,3,3) ;      # Remove particle far away from center
zminmax("wcs","I",0,3.8); # Remove particle infront of min, after max position
Rmax("wcs","z",0.62454,0.008, 0.01); # Remove particle at Laser mirror
Rmax("wcs","z",1.79654, 0.0125,0.2); # Remove particle at Triplet quadrupole
Rmax("wcs","z",2.3, 0.015, 0.2);

# ***** Initial beam with no energy spread (Photocathode) *****
Eo = 0.16;             # Start KE = hf - work fcn = 4.66
tout(2e-9,4e-9,2e-10); # Max simulation time and steps
screen( "wcs","I", 0.12454); # Output at RF-Gun exit for BL tracking
                                # (data at end of output gdf file)

# ***** RF Cavity *****
# map25D_TM(ECS,mapfile.gdf, r,z, Er,Ez, Bphi,fac, k,phi,w);

k=0 ;
Ecathode=101;          # Electric Field at Cathode (MV/m)
ffac=Ecathode/2.5;     # Multiplication factor for the electromagnetic field
                        # at Cathode devide by SUPERFISH peak field
phase=40;              # RF phase (deg)
phOffset=-5;           # Set phase to same as measurment Unif 6ps -> -5 deg
offphi=(phase+phOffset-90)/180*pi; # RF phase offset (rad)
rmax("wcs","z",0.1, 0.0122,0.03); # RF-gun aparture r=12.2 mm

map25D_TM("wcs","z",0,"outsf72.gdf","R","Z","Er","Ez","H",ffac,0,offphi,2*pi*2856e6);

# ***** Solenoid Magnet *****
# bzsolenoid(ECS, R,L,nI) # current 131A,193mT, nI= 159000
nI=190000 ;            # 181mT, nI= 149500 / 169 mT, nI = 148400
bzsolenoid("wcs","z",0.23854, 0.029,0.216,nI); # Actual R=0.029, L=0.216

# ***** Magnetic Chicane and Energy slits *****
ffld = 66.66 ;         # fringe field = 2/gap gap = 0.03 m
bfld = 0 ;             # max magnetic field [T] 5.8A = 0.092 T /4.4A = 0.071 T
chwdth = 0.1 ;         # Width of rectangular magnet
chlgt = 0.065 ;        # Length of rectangular magnet
choffs = -0.082 ;      # No.2,3 Offset magnet from bean center
chcent = 1.00004 ;     #1 magnet center position
d = 0.19 ;             # Distance between chicane magnet

```

```

slit=-0.082 ;      # Offset of energy slits
xwidth = 0.1 ;     # Width of energy slits
trim = 0.3 ;       # Trim field [mT]

rectmagnet("wcs", 0, 0, chcent, 1,0,0, 0,1,0, chwidth, chlgth, -bfld, 0, ffld, 0) ;
rectmagnet("wcs", choffs, 0, chcent+d, 1,0,0, 0,1,0, chwidth, chlgth, bfld+trim/1000, 0, ffld, 0);
#multislit("wcs", slit, 0, chcent+d*1.5, 1,0,0, 0,1,0, xwidth, 0.01, 0.01, 0.2, 1);
rectmagnet("wcs", choffs, 0, chcent+d*2, 1,0,0, 0,1,0, chwidth, chlgth, bfld+trim/1000, 0, ffld, 0);
rectmagnet("wcs", 0, 0, chcent+d*3, 1,0,0, 0,1,0, chwidth, chlgth, -bfld, 0, ffld, 0) ;

# ---- Quadrupole // quadrupole(ECS,L,G) with out fringe field
# Positive : Focus in y / Negative : Focus in x

Q1= -1.3; -0.74 ;  # Magnetic field gradient [T/m]
Q2= 2.3 ; 0.5;
Q3= -1.3 ; -0.29;
quadrupole("wcs","z",1.79654, 0.055, Q1 ) ;
quadrupole("wcs","z",1.89654, 0.055, Q2 ) ;
quadrupole("wcs","z",1.99654, 0.055, Q3 ) ;

# ---- Undulator // unduplan(ECS,Nu,lamu,Bu,trim1,trim2)
Bu= 0.2 ;          # Vertical Deflection
UnPe = 0.07 ;      # Undulator Period
NumPe = 10 ;
# unduplan("wcs", 0,0,2.78254, 0,1,0, -1,0,0, NumPe,UnPe,Bu, 0.25,0.75) ;

# Beam dump
bdwidth = 0.09 ;   # Bending magnet width
bdlgth = 0.12 ;    # Bending magnet length
bdBfld= -0.088 ;   # -0.15326
b1 = 40 ;          # fringe field = 2/gap gap = 5 cm
b2 = 0 ;           # second order fring field correction
dl2 = 0.026 ;      # Fring field offset from edge 0.026
bdoffset = -0.036 ; # Vertical offset

# rectmagnet("wcs", 0,bdoffset,3.91454, 0,1,0, -1,0,0, bdwidth,bdlgth,bdBfld, dl2,b1,b2) ;

# Beam dump field 3D mapping // map3D_B(ECS, mapfile.gdf, x,y,z, Bx,By,Bz, Bfac)
# maxB = 88 ;      # Max magnetic field in mT
# map3D_B("wcs", 0,bdoffset,2.2, 1,0,0, 0,1,0,"BDField.gdf","x","y","z","Bx","By","Bz",maxB);

```