DEVELOPMENT OF COMPACT THZ-FEL BASED ON LASER PHOTOCATHODE RF GUN SYSTEM

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Abstract

A compact THz-FEL has been developed based on a laser photocathode rf gun system at AIST. The rf gun has been improved using a Cs_2Te photocathode with a compact load-lock system. The multi-bunch electron generation has been performed with the rf gun and the multi-pulse UV laser system. The undulator radiation has been considered to generate THz-FEL in both cases of about 3 MeV and 40 MeV electron beam. The preliminary experiment of THz applications such as THz imaging has been carried out using a coherent synchrotron radiation in the THz region with 40 MeV electron beam.

INTRODUCTION

THz imaging technique using the laser-driven THz source has been developed at many other laboratories for detection of the illegal medicine, dangerous chemicals and so on [1]. However, in case of laser based THz source, the output power is very low so that the imaging analysis of it is not practical for the large illuminated area. Therefore, high power THz source based on the compact electron linac is required and it can perform the total inspections of the sealed letters and the carry-along items.

The terahertz (THz) self-amplified spontaneous emission (SASE) Free Electron Laser (FEL) has been considered based on an S-band compact electron linac at AIST [2]. The FEL will operate in the wavelength range of 100-300 μm, which corresponds to 1.5-3 THz using 40 MeV electron beam and a small undulator which has number of period of 20 and undulator period of 100 mm. The output power of the SASE-FEL is more than about 2 W with the narrow spectral width of 2-3 %, output stability of 2-3 % and pulse width of 5-10 ps (1σ). In this case about 40 MeV electron beam, the electron charge is required more than 1 nC/bunch × 100 bunches at repetition rate of 50 Hz. All of system is built in one research room about 10 meters square including an electron injector, an electron linac, quadrupole magnets, bending magnets, an rf source and a high power laser system. Figure 1 shows a top view photograph of the S-band compact electron linac. The injector consists of a laser photo-cathode rf gun which has the BNL type S-band 1.6 cell cavity with a Cs_2Te photocathode load-lock system and a solenoid magnet for emittance compensation. A compact load-lock system of Cs_2Te photocathode which total length is less than 1 m has been improved by corraborating with KEK and Waseda University. To generate multi-bunch electron beam, the compact all solid state multi-pulse UV laser system which is table-top size within 1 m × 0.7 m has been originally developed at AIST. The linac has two 1.5-m-long accelerator structures which is a 1/2 π mode standing wave structure. The electron beam can be accelerated up to about 42 MeV using the rf source of a 20 MW klystron. The high intense THz radiation source based on the electron linac has been also developed instead of a conventional laser based THz source.

On the other hand, we have also considered the much smaller system to generate THz-FEL using about 3 MeV electron beam generated from an rf gun and a compact undulator. The new photocathode rf gun has developed in corroborating with KEK. The compact rf source of about 4 MW klystron was installed for the rf gun into a mezzanine space in size of 3 meter squares which is indicated in the middle of Fig. 1. The designed THz pulse has high peak power in frequency range between 0.1 - 2 THz

In a preliminary experiment for THz applications, we have performed the generation of THz coherent synchrotron radiation using the 40 MeV ultra-short electron bunch with bunch length of less than 0.5 ps (rms) and developed the THz scanning imaging device

In this conference, we will report present status of our system for the THz-FEL and results of the preliminary experiment of THz scanning imaging.

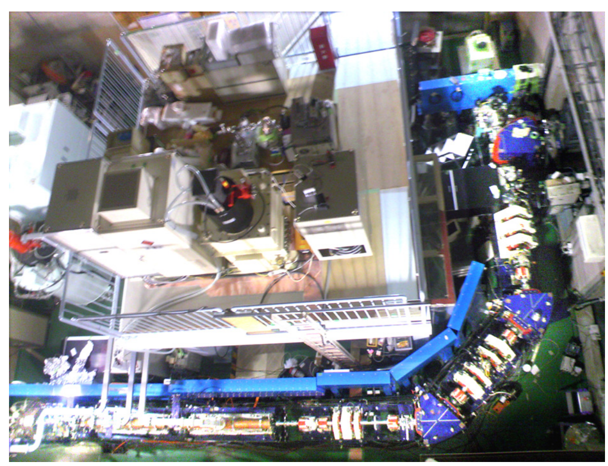

Figure 1: Top view photograph of S-band compact electron linac and mezzanine space for the compact THz FEL based on the photocathode rf gun.

INTENCE COHERENT THZ SOURCE

THz Undulator

The wavelength of the undulator radiation as THz radiation can easily be calculated from

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$$\lambda \cong \frac{\lambda und(1+K^2/2+\gamma^2\theta^2)}{2\gamma^2}$$

Here, γ is the Lorentz factor, K the wiggler strength, θ the angle of observation, λ_{und} the undulator period. We calculated the undulator radiation in rage of THz region with 3 MeV electron beam generated from the rf gun and the compact undulator with λ_{und} = 20 mm. Figure 2 shows undurater radiation as a function of K value with each electron energy (1.5, 2.0, 2.5, 3.0 and 3.5 MeV). The dot line also indicates undulator radiation with K = 1 by changing electron energy in range between 1 MeV and 3.5 MeV. It is found that the THz radiation with tunable wavelength can be generated using the rf gun and the compact undulator.

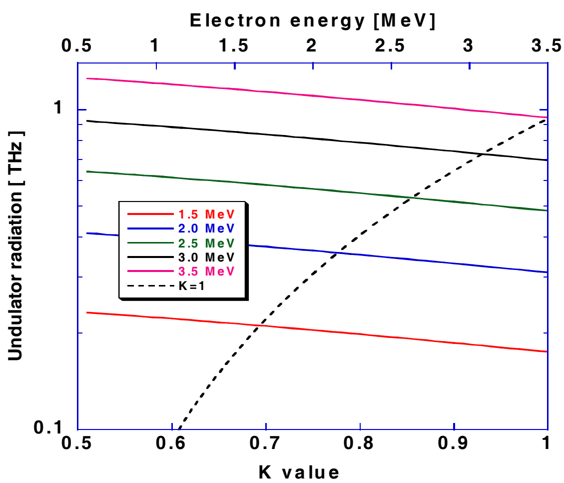

Figure 2: THz Undulator radiation using rf gun.

Coherent THz Generation

In a preliminary experiment for THz applications, we have performed the coherent THz generation using the 40 MeV ultra-short electron bunch with bunch length of less than 0.5 ps (rms) [3-4]. Synchrotron radiation less than critical frequency ω_c is coherently emitted from a ultra short electron bunch (σ_z). Its frequency is expressed by

$$\omega_c = \pi c/\sigma_z \qquad (2).$$

The total photons (I_{tot}) with both of incoherent and coherent radiation are derived from equations

$$I_{tot} = I_{inc}(1+(N-1)f(\omega)) \qquad (3), \text{and}$$

$$f(\omega) = e^{-\frac{(\omega\sigma_z)^2}{2}} \qquad (4).$$

Here, I_{inc} is the photons of incoherent radiation, N is the number of electrons in the bunch and $f(\omega)$ is the fourier transform of the longitudinal electron density for Gaussian bunches with bunch length σ_z [5].

In Fig. 3, the enhancement factor as a function of frequency was calculated by changing the electron bunch length from 0.5 ps to 10 ps with 1 nC and 30 MeV against the incoherent synchrotron radiation yield of about 0.1 THz which is normalized to 1. In this experiment, our rf detector is a W-band rf detector (WiseWave FAS-10SF-01) which has a sensitive range of 0.075 THz – 0.11 THz so that the requirement of the electron bunch length is less than about 5 ps (rms).

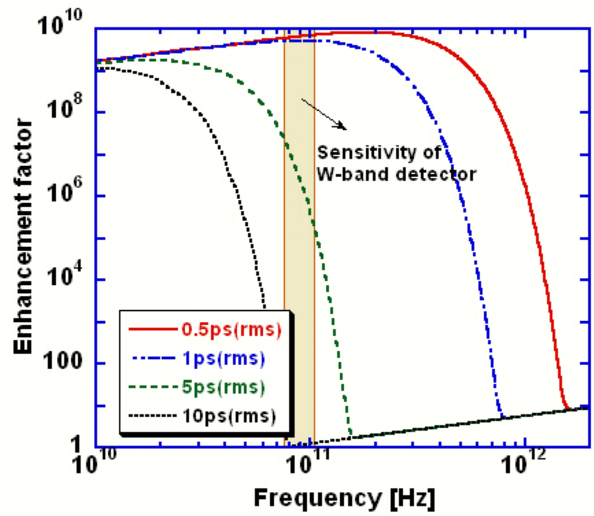

Figure 3: Enhancement factor of CSR as a function of frequency by changing electron rms bunch length (0.5 ps, 1 ps, 5 ps, 10 ps).

Table 1: Design Values of the Coherent THz Source

Electron beam	
Max. Energy	30 ~ 42 MeV
Charge per bunch	1 nC – 2 nC
Energy Spread for compression	~ 5%
Bunch length (after compression)	300 fs (rms)
Bunch number	1 – 100
Rep. rate	10 Hz ~ 50 Hz
THz pulse	
Frequency	0.1 – 2 THz
Pulse energy	65 nJ
Peak power	25 kW
Rep. rate	10 – 50 Hz
Pulse width	700 fs (rms)

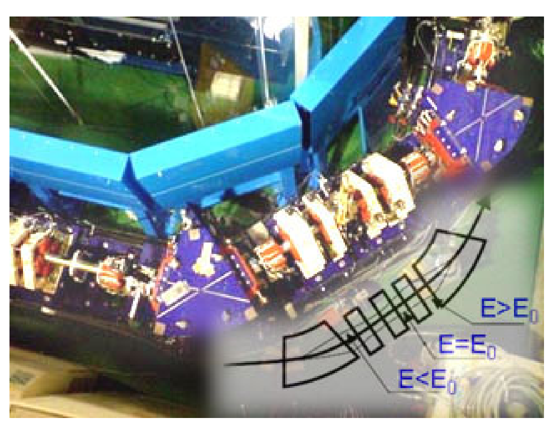

Figure 4: Achromatic arc section for bunch compression.

The coherent synchrotron radiation (CSR) was generated using an ultra short and high charge electron bunch. The achromatic arc section consists of two 45-degree bending magnets and 4 Q-magnets for the bunch compression. Figure 4 shows the achromatic arc section for the bunch compressor. The 90 degree bending magnet was located after the Q-triplet downstream from the achromatic arc section and CSR experiment was performed at 20 degree direction in the 90 degree bending magnet which had the curvature radius of 300 mm. Figure 5 shows the setup of the detection of 0.1 THz CSR. The CSR was extracted from a crystal quarts window located at 20 degree direction in the 90 degree bending magnet and collected by the parabolic antenna and passed through a W-band wave guide (WR-10), an E-bend and an attenuator and guided to the W-band rf detector which signal of 500 mV corresponded to 1 mW for about 0.1 THz radiation. To generate the THz CSR, the bunch length was compressed less than 1ps using Q-magnets in the achromatic arc section as it was measured with the rms bunch length monitor using two-frequency analysis technique [6]. The THz CSR pulse is extracted from a z-cut quartz window for THz applications. Typical electron beam parameters for the THz CSR generation and our expected THz specification were described in Table 1.

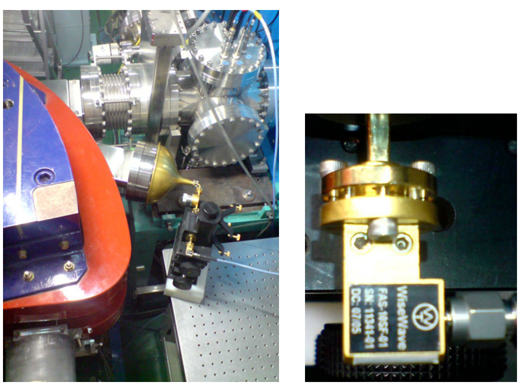

Figure 5: Setup of THz measurement at 90degree bending magnet with W-band rf detector

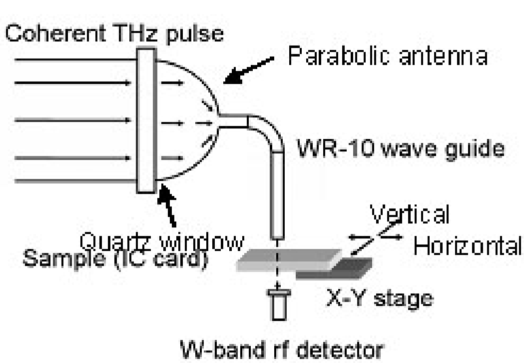

Figure 6: Setup of THz transmission imaging using THz CSR pulse with W-band waveguide, detector and X-Y sample stage.

THz Scanning Imaging System

The THz transmission imaging as the preliminary experiment for THz applications has been demonstrated using the THz CSR with the W-band rf detector[7]. Figure 6 shows the setup of the imaging experiment with the THz CSR. The THz pulse is extracted from the quartz window (z-cut) located at 20 degree direction in the 90 degree bending magnet and collected by the parabolic antenna. The THz pulse passes through a W-band waveguide (WR-10) with an E-bend waveguide and it is guided to the W-band rf detector (WiseWave FAS-10SF-01) whose sensitive area is 1mm $\times$ 2mm with sensitive range of 0.075 - 0.11 THz. Its signal of 500 mV corresponds to 1 mW. In this experiment, the imaging sample was selected an integrated-circuit (IC) card with about 50 $\times$ 85 mm2 in size and 1 mm thickness in taking account of the previous report[8]. The THz imaging of a left part of the IC card with area of about 50 $\times$ 35 mm2 has been performed with a scanning step of 600 μm and scanning time of 5 hours. Figure 7 shows results of the THz imaging. It is found that its resolution of the THz imaging is limited by the W-band waveguide aperture of 1 mm $\times$ 2 mm. The resolution is only decided its aperture size so that the tapered waveguide is possible to reduce the imaging resolution. The THz CSR is mostly polarized to the horizontal direction due to the bending direction of the electron beam, and the linear polarity become strong by passing through the waveguide. As a result, the difference of the transmission images between the X-ray and the THz imaging was clearly observed due to the circuit lines direction against the THz polarization like an effect with a wire grid polarizer. The edge interference of the IC card was also observed in the THz imaging because of its high coherency.

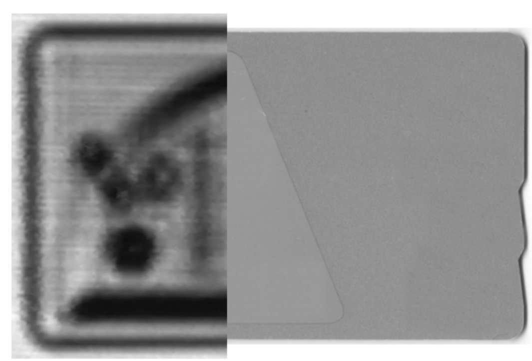

Figure 7: THz transmission image of the left part of IC card with area of 50 $\times$ 35 mm^2.

SUMMARY

The THz-FEL has been considered based on an S-band compact electron linac at AIST [2]. The FEL will operate in the wavelength range of 100-300 μm, which corresponds to 1.5-3 THz using 40 MeV electron beam and a small undulator which has number of period of 20 and undulator period of 100 mm. We have also considered the much smaller system to generate THz-FEL using about 3 MeV electron beam generated from an rf gun and a compact undulator. It is found that the THz radiation with tunable wavelength can be generated using the rf gun and the compact undulator.

For the preliminary experiment for THz applications, the generation of the THz coherent synchrotron radiation (CSR) in the 90 degree bending magnet has been successfully performed using the electron bunch which has the energy of 40 MeV. The THz transmission imaging of the IC card has been also successfully demonstrated with the W-band rf detector. As a result, it is found that the THz imaging characteristics was observed and also found that its intensity and stability are good performance for THz applications.

In near future, we will complete the all components installation and preparation for the THz-FEL and start the investigation of the un-researched materials in the frequency range of 0.1 – 2 THz.

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