DEVELOPMENT OF A HIGH-POWER COHERENT THz SOURCES AND THz-TDS SYSTEM ON THE BASIS OF A COMPACT ELECTRON LINAC

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Abstract

The high-power terahertz time-domain spectroscopy (THz-TDS) has been developed on the basis of a compact S-band electron linac at AIST, Japan. It is strongly expected for inspection of dangerous materials in the homeland security field. THz radiations are generated in two methods with the ultra-short bunch. One is THz coherent synchrotron radiation (THz-CSR). The other is THz coherent transition radiation (THz-CTR). In the preliminary experiment to obtain the characteristics of THz-CTR, it was observed that the focused THz-CTR had the donut profile in the transverse field due to its initial radial polarization. It was considered to be z-polarization at the focus point. In case of the THz-TDS experiment, THz-CTR was controlled to be linearly polarized with the polarizer and focused to an electro optical (EO) crystal to obtain a THz temporal waveform using EO sampling method. It leads to THz spectrum with Fourier transform. In this paper, we will describe details of our linac and results of the THz-CTR-TDS experiment.

INTRODUCTION

THz wave is electromagnetic wave located in 0.1-10 THz region. In the security field, it is a strong tool for inspection of explosives and illegal drugs because they have fingerprint spectrum in the THz region [1]. However, conventional laser-driven THz sources are still low-power sources to use in industrial fields. On the other hand, THz sources based on accelerators can generate a high-power THz pulse. We have developed generation of high-power THz coherent synchrotron radiation (THz-CSR) and coherent transition radiation (THz-CTR) at AIST. The THz radiation is emitted coherently when the electron bunch length is shorter than its wavelength (Figure 1).

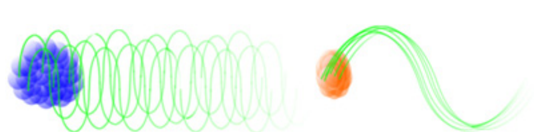

Figure 1: Emission images of incoherent (left) and coherent radiation (right).

This coherent radiation intensity ($I_{coh}(\omega)$) and incoherent radiation intensity ($I_{inc}(\omega)$) are expressed by the following formula,

$$I_{coh}(\omega) = \big(1 + (N-1)f(\omega)\big)I_{inc}(\omega) \qquad (1).$$

N is the electron number in a bunch, ω is the angular frequency and $f(\omega)$ is known as the bunch form factor. When the form is assumed to be Gaussian distribution, it is derived from

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

Here, σ_z is the electron bunch length. $I_{inc}(\omega)$ is calculated with SPECTRA code and $I_{coh}(\omega)$ is derived from equation (1). Figure 2 shows calculation results about the enhancement factor of CSR intensity as a function of its frequency with the 1 nC, 40 MeV electron bunch by changing the bunch length. As a result, it is required for THz coherent radiation that the electron bunch length is shorter than 1 ps. When the bunch length is enough short against wavelength, $f(\omega)$ comes up to 1. It is estimated that $I_{coh}(\omega)$ is N (10^9~10^{10}) times larger than $I_{inc}(\omega)$.

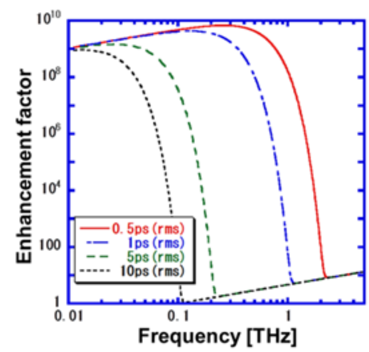

Figure 2: Enhancement factor of CSR as a function of its frequency by changing the bunch length.

S-BAND LINAC BEAM LINE

The S-band linac consists of Cs_2Te photocathode rf-gun & two S-band (2856 MHz) acceleration tubes. Figure 3 shows the layout of the beam line at AIST.

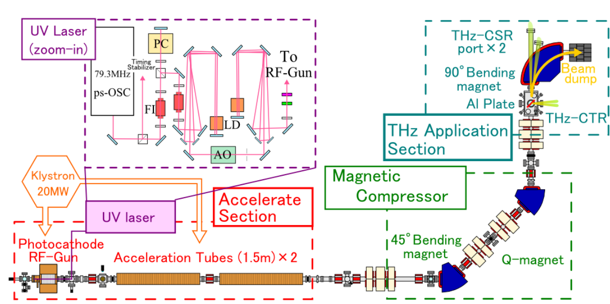

Figure 3: S-band linac beam line at AIST, Japan.

The injector is a BNL-type photocathode rf-gun, which generates 1 nC/bunch, 4 MeV electron beam. The acceleration tubes accelerate the electron beam up to about 40 MeV and the electron beam gets the linear energy chirp by adjusting rf phase at the acceleration tubes. The head and tail of the bunch correspond to high-energy and low-energy parts, respectively.

The magnetic bunch compressor is located downstream from the acceleration tubes. It consists of two 45-degree bending magnets and four Q-magnets (Figure 4).

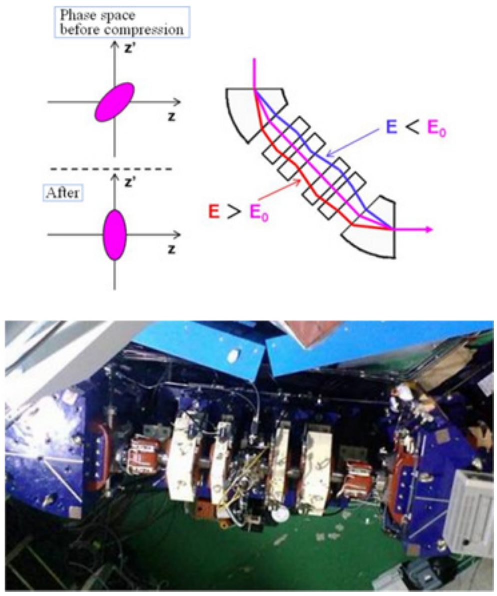

Figure 4: Magnetic bunch compressor.

The magnetic bunch compressor separates the electron orbits into many paths according to the energy. The high-energy and low-energy electrons pass along the long path and the short path, respectively after optimising magnetic fields of Q-magnets for the bunch compression. The electron bunch length is compressed into less than 1 ps from 3 ps for generation of THz coherent radiation [2]. The electron bunch is focused to the Al plate to generate THz-CTR. In case of THz-CSR, the electron bunch is bended by 90-degree bending magnet. The electron beam parameters are described in Table 1.

Table 1: The Electron Beam Parameters

Energy	40 MeV
Energy spread	< 5 %
Bunch length	< 1 ps
Charge per bunch	1 nC
Rep. rate	10 Hz
Beam size (rms)	< 100 μm

CHARACTERISTICS OF THz-CTR

The transition radiation is generated by the electron bunch crossing between two media of different dielectric constants. Its angular dependence of intensity $I_{tr}(\theta)$ is described by the formula,

$$I_{tr}(\theta) = \frac{e^2}{4\pi^3\epsilon_0 c}\frac{\beta^2 sin^2\theta}{(1-\beta^2 cos^2\theta)^2} \quad (3).$$

Here, θ is the angle of observation from the central axis direction of the transition radiation, ϵ_0 is the dielectric constant in vacuum, c is the speed of light, e is the elementary electric charge and β is the ratio of the velocity of electron beam to c. Figure 5 shows the scheme of transition radiation and it indicates forward and backward radiation. Figure 6 shows the calculation result of the angular dependence when the electron bunch has energy of 40 MeV. As a result, the divergence of the transition radiation is calculated to be approximately 12.5 mrad = $1/\gamma$. (γ is Lorentz factor.)

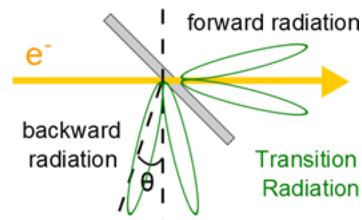

Figure 5: Scheme of transition radiation.

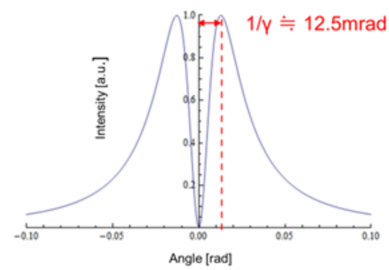

Figure 6: Angular dependence of transition radiation.

In this experiment, the THz coherent transition radiation (THz-CTR) is generated by the short electron bunch passing through the Al thin plate inclined 45 degree against the electron beam axis. The backward THz-CTR is extracted to the atmosphere from the vacuum through a quartz window.

As a preliminary experiment, the THz-CTR electric field profile was measured by scanning the 0.1 THz detector with X-Y-Z stage. The detector is Schottky diode which has higher sensitivity against horizontal polarization than vertical polarization. Two THz flat-convex lenses were used for diffraction limited focusing. The first lens is for collimating THz-CTR and the second one is for focusing.

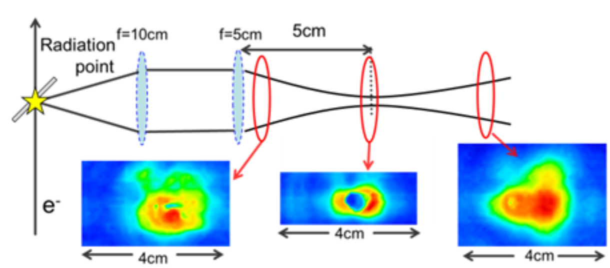

Figure 7: Profile changes of the THz-CTR electric field.

Figure 7 shows results of profile changes of the THz-CTR electric field. The donut profile was clearly observed at the focus point in Figure 7. The diameter of this hole size is about 3 mm. It is larger than the hole size which is estimated to be < 0.25 mm depended on $1/\gamma$ in Figure 6.

At the focus point, THz-CTR is thought to be longitudinally polarized (called z-polarization) due to radial polarization which is initial polarization of THz-CTR (Figure 8). The Schottky diode cannot detect z-polarization because electronic fields are cancelled in transverse direction. However, it is not suitable for THz-TDS system using electro optical (EO) sampling method. The EO crystal is pumped by THz-CTR. The refractive index ellipsoid of the crystal depends on the polarization of the THz electric field [3]. In case of the EO sampling method, the polarization of THz-CTR should be horizontally polarized. Therefore, we controlled it to horizontal polarization with a half-shade plate as a polarizer.

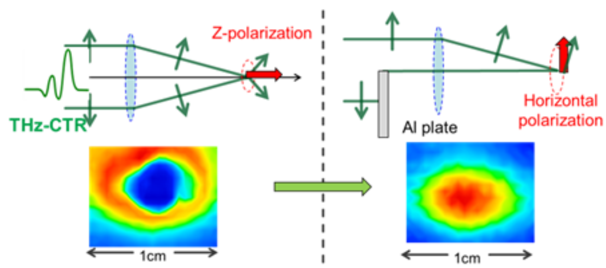

Figure 8: Polarization control of THz-CTR.

THz-TDS SYSTEM

The THz-TDS is based on the EO sampling methods with the pump-probe technique. The THz spectrum is obtained by Fourier transform of the measured temporal THz waveform. Figure 9 shows the schematic diagram of the THz-CTR-TDS system with EO sampling method.

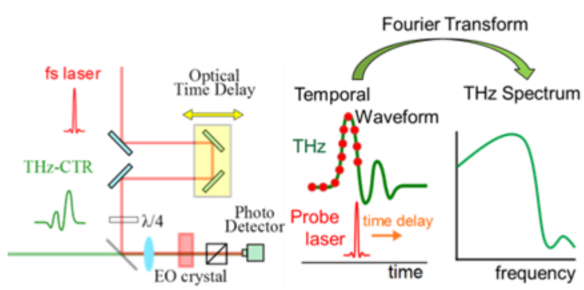

Figure 9: Schematic diagram of THz-CTR-TDS system with EO sampling method.

When the probe laser and THz pulse pass through the EO crystal at the same time, the complex refractive index of the crystal is changed by the THz electric fields. The polarization of the probe laser is also changed. We measured the intensity difference between the p- and s-polarization of the probe laser with a photo detector. The difference corresponds to the intensity of THz electric field. The THz temporal waveform is obtained with the pump-probe technique using optical time delay stage and the THz spectrum is calculated by Fourier transform.

Figure 10 shows the picture of the experimental setup. In this experiment, THz-CTR is controlled to horizontal polarization such as Figure 8 and focused to the 5 mm-thickness (1, 0, 0) oriented ZnTe crystal as a EO crystal. The measured frequency range and signal intensity depend on the thickness [4]. It is realized to make a temporal overlap in the EO crystal between the probe laser and optical transition radiation (instead of THz-CTR) with a same optical photo-detector.

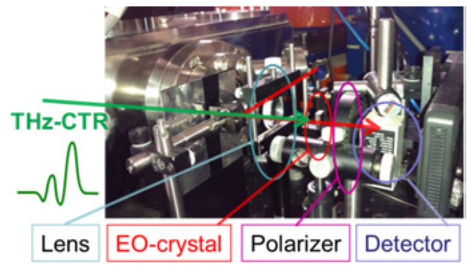

Figure 10: Experimental setup of the THz-CTR-TDS system with EO sampling method.

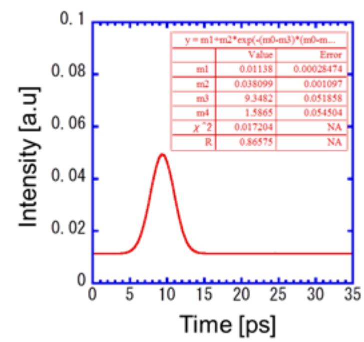

Figure 11: Measured THz temporal waveform (Gaussian fitted).

The Gaussian fitted THz temporal waveform has been successfully obtained in Figure 11. The measured THz pulse length has been estimated to be about 1.6 ps (rms). It is larger than the expected value (= the electron bunch length, 0.5 ps) due to the time jitter between the probe laser and THz pulse and the finite frequency response of EO crystal depending on its thickness.

CONCLUSIONS

The high-power THz wave has been generated using coherent transition radiation (CTR) with polarization control for THz time domain spectroscopy (THz-TDS) with the S-band compact linac at AIST. The THz-CTR-TDS System has been constructed with EO sampling method. As a result, the THz temporal waveform has been successfully measured with this system. In the next step, we will reduce the jitter and optimize the thickness of the EO crystal in order to improve the stability of this system and to extend the measured spectral range. In near future, we will apply the THz CTR-TDS system to investigation of un-researched materials.

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