INVESTIGATION OF THE COHERENT CHERENKOV RADIATION USING TILTED ELECTRON BUNCH

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Abstract

Cherenkov radiation can be produced when the velocity of the charged particles are faster than the light in some medium. We investigated the coherent Cherenkov radiation using electron bunch tilting for matching the wave front of the Cherenkov radiation. The electron bunch was tilted by using rf transverse deflecting cavity. We tested several materials for the Cherenkov targets that have enough transmittance at the wavelength of THz region. As a result, high peak power THz was achieved using this novel technique. We will report the principle of this technique, the experimental results and future prospects at the conference.

INTRODUCTION

Radiation frequency of THz (10^{11}~10^{13}Hz) has a properties of both radio wave and light wave so that it considered to be useful in various field such as material science, medical, non-destructive inspection and so on. Recently, the high peak power THz pulse found to be usable for transforming the surface molecular because the frequency of the THz is same range to the vibration and rotation of the molecular.[1] The accelerator based THz source has an advantage in producing high peak power THz pulse. At Waseda University, we have the electron accelerator system based on a photocathode rf gun. The energy of the beam is up to 5.5 MeV, which is enough to produce THz radiation. We have been studying coherent THz generation by synchrotron radiation[2], transition radiation[3] and Cherenkov radiation[4]. In these generation methods, Cherenkov radiation was the most powerful source because the electrons interact with the medium inside the target.

Cherenkov radiation, which was firstly reported in 1944 [5], is produced when the velocity of electron is faster than the radiation in some medium. The radiation direction is not same with electron beam which determined by the electron velocity and the refractive index of the medium. This characteristic of Cherenkov radiation would disturb to achieve coherent radiation in whole part of the medium. To overcome this phenomenon, we employed to use electron bunch tilting. In this paper, we will report the principle of the coherent Cherenkov radiation by electron bunch tilting, experimental results of generation of the coherent Cherenkov radiation, and future prospective.

COHERENT CHRENKOV RADIATION BY ELECTRON BUNCH TILTING

The schematic of Cherenkov radiation is shown in Fig. 1.

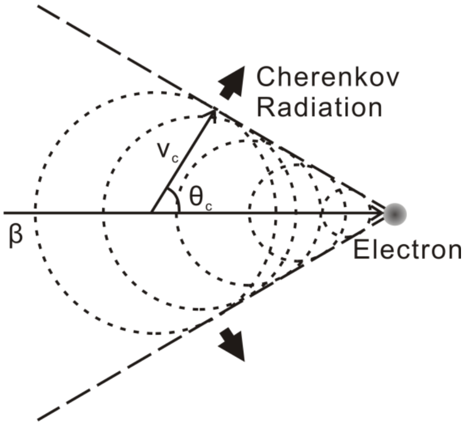

Figure 1: Schematic of Cherenkov radiation.

Cherenkov radiation radiates when the velocity of charged particle is faster than the radiation in the medium at an angle determined by the following:

$$\cos\theta_c = \frac{1}{n\beta} \tag{1}$$

where θ_c is radiating angle, n is the refractive index of the medium and β is the Lorentz factor of the electron. In order to achieve the coherent radiation, one will think how to produce the ultra-short electron bunch, which bunch length is much shorter than the radiation wavelength. Using such electron beam, the coherent Cherenkov radiation can be produced partially in the medium. However, if the medium is longer than the wavelength of the radiation, the radiations generated from the different position of the medium cannot be coherently overlapped. To overcome this phenomenon, electron bunch tilting can would be useful to enlarge the area of the medium, which contributes to generate the coherent radiation. The idea of the bunch tilting technique is originally tested in the laser terahertz generation by using wave front tilting. [6] We apply this idea to the electron bunch. Here we consider about the Cherenkov radiation from the tilted bunch. Fig. 2 shows the Cherenkov radiation from the tilted bunch. The left side of the Fig. 2 shows the Cherenkov radiation

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from the single electron. Electron radiates the Cherenkov radiation at the different position of the medium. Radiation from the different position never overlapped each other but they have relationship in phase and spatial position decided by the distance of the radiating position. If the electron bunch is smaller and shorter than the radiation wavelength, the Cherenkov radiation from the one position is the coherent radiation.

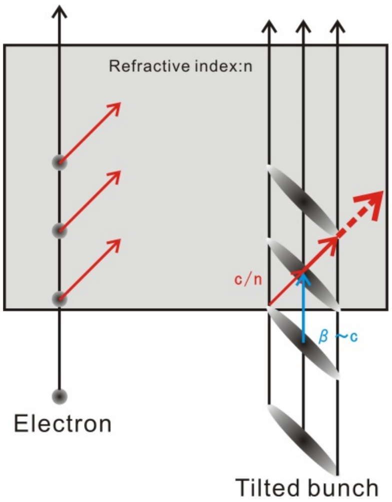


Figure 2: Cherenkov radiation from the tilted electron bunch.

Then we think to enlarge the area of coherent Cherenkov radiation of the medium by using electron bunch tilting. The right part of the Fig. 2 shows the Cherenkov radiation from the tilted electron bunch. The Cherenkov radiation radiates at certain angle determined by the Eq. (1) from the head of the bunch. The radiation passes in the medium with the velocity of c/n. On the other hand, the electrons pass with almost velocity of light. Radiation can keep overlapping with the latter electrons if electron bunch was correctly tilted. The point of this coherent Cherenkov radiation is small beam size before tilted. The beam size from the view of radiation angle is much smaller than the radiation wavelength, coherent Cherenkov radiation can be produced. The correct tilting angle of the bunch for the coherent radiation is the Cherenkov angle described in Eq. (1).

EXPERIMETAL SETUP

The experimental setup for coherent Cherenkov radiation experiment is illustrated in Fig. 3.

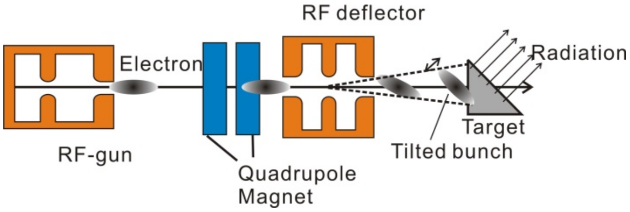
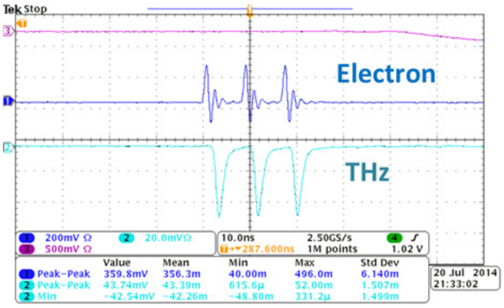


Figure 3: Experimental setup for coherent Cherenkov radiation by using tilted electron bunch.

Our accelerator system is based on laser photocathode rf gun. The gun is S-band, 1.6 cell type rf gun cavity. The photocathode is Cs-Te and the picosecond UV pulse produces photo-electrons. The resulting bunch length is 2~3 ps in rms, which is longer than the THz wavelength. The electron beam energy is up to 5.5 MeV with low emittance (2~3πmmmrad). The solenoid magnet is located right after the gun to compensate the emittance and then qudrupole magnets for focusing electron on the target are installed. For tilting the bunch, the rf transverse deflecting cavity (rf deflector) is used. Our rf deflector is also S-band 2 cell TM_{120} mode rf deflector specially designed for the ultra-short electron bunch measurement. [7][8] The rf power and phase of rf deflector can be adjusted using rf variable attenuator and phase shifter independently. The regulation of rf power can change the electron bunch tilting angle at the Cherenkov target. The rf power can change from 0 to 750 kW by the attenuator, which is enough for this experiment. At the target position, the profile monitor screen is also installed to measure the initial beam size and bunch tilting angle. As a target, we prepared TOPAS polymer [9] and highly resistive silicon, which have enough transmittance for the THz radiation. First experiment of this technique, we decided to generate THz radiation. The refractive indexes are 1.52 of TOPAS and 3.4 of Si in the whole THz region. The refractive index determines the radiation angle, so we expect that the broadband THz radiation would be generated by this technique. After the target, the THz detectors are installed for measuring the THz pulses. We used quasi-optical detector (QOD) , THz power meter, and Time Domain Spectroscopy (TDS) system for characterizing the THz pulse.

RESULTS AND DISCUSSIONS

Firstly, we observed the THz radiation by electron tilting Cherenkov radiation. In Fig. 4, detected THz pulses by the QOD is shown with the signal of electron bunches detected by the fast current transformer (FCT) located before the rf deflector.



	Value	Mean	Min	Max	Std Dev
1 Peak−Peak	359.8mV	356.3m	40.00m	496.0m	6.140m
2 Peak−Peak	43.74mV	43.39m	615.6µ	52.00m	1.507m
2 Min	−42.54mV	−42.26m	−48.80m	331.2µ	1.499m

Figure 4: Electron beam signal detected by FCT (blue: top) and THz pulse signal by QOD detector (aqua: bottom).

We confirmed that the radiation intensity was maximum at the electron beam angle was equal to the Cherenkov angle. Also, replacing the band-pass filter, the THz pulse has broadband spectrum.[4]

Then, we measured the THz pulse energy by the THz power meter. The pulse energy was still low so that we operated our accelerator with the 50 bunches mode, then we divided by 50 to calculate the 1 pulse energy of THz pulse. The measurement results are listed in Tab. 1.

Table 1: Measured Pulse Energy of the THz Pulse Generated by the Tilted and Un-tilted Electron Bunch

	Tilted	Un-tilted
Total band	33.2 nJ	4.5 nJ
0.3±10% THz	10.6 nJ	-
0.6±10% THz	4.0 nJ	-

As shown in Table 1, the pulse energy of the THz was more than 30 nJ/pulse in total bandwidth, which is enough for the detection. The spectrum of the THz pulse has larger low frequency part than the high frequency by using BPF measurement. Comparing with the un-tilted result, the electron bunch tilting enhances the pulse energy about 7.4 times.

Finally, we performed a TDS measurement by the EO sampling method. The detail of the system is described in Ref. [10]. We use an Yb fiber laser system for the detection and ZnTe crystal for the EO crystal. The probe laser and the THz pulse are focused on the EO crystal at the same pass. Delaying the laser pulse timing provides the electric field of the THz pulse. The measured THz pulse waveform and its Fourier transformation are shown in Fig. 5.

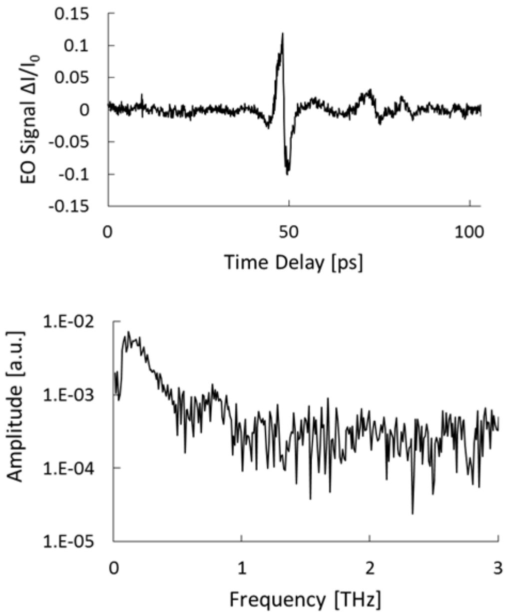


Figure 5: THz pulse waveform detected by the EO sampling (top) and spectrum of the THz (bottom).

As shown in Fig. 5, the THz pulse was a single cycle pulse, which means that the THz pulse has broad spectral bandwidth and the phase of the waves were matched each other i.e. coherent radiation. The pulse duration was about 4 ps in FWHM. Calculating the peak power by the pulse duration and pulse energy above, we have succeeded in generating near 10 kW peak power THz pulse using this technique. According to the spectrum of the THz pulse (Fig. 5 bottom), the THz pulse has broadband spectrum (0.1-1 THz), however, our EO sampling system has detection range up to 1 THz thus we believe that THz pulse has higher frequency component.

On the other hand, we tested the Si target for the radiator. The result was not good compared with the TOPAS target. We could observe the THz pulse by the QOD detector but could not by power meter and EO sampling because the THz intensity was not enough. The density of the Si is 2.4 times larger than TOPAS so that the penetration depth of the electron is much shorter. Therefore, we think the area of generating coherent radiation was not enough for the Si target to generate the enough pulse energy.

SUMMARY

We evaluated the coherent Cherenkov radiation by electron bunch tilting. As a radiator, lower density medium would be useful for the relatively low energy electron beam. The pulse energy, waveform, and spectrum were measured by power meter and TDS technique, respectively. Near 10 kW peak power THz pulse was produced using electron bunch tilting, it would be useful for the THz surface modification experiment.

In near future, we will replace the probe laser system for the EO sampling to enlarge the sensitivity frequency range in order to confirm the whole spectrum of the THz pulse. After that, as shown in Fig. 4, we can produce multi-bunch electron beam and multi-pulse THz pulse. It would be possible to demonstrate the laser oscillation using this technique to adopt the optical cavity. The laser oscillation will increase the pulse energy more than 10 times in the calculation. Then we are planning to application researches such as surface modifications by using high peak power THz pulses.

ACKNOWLEDGEMENT

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