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# STUDY ON COHERENT THz RADIATION USING TILT CONTROL OF ELECTRON BEAM

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*Abstract*

When the velocity of the charged particles is faster than the light velocity in a medium, Cherenkov radiation is produced at an angle dependant on the refractive index of the medium. We can obtain coherent radiation by matching the tilt of the electron beam with the Cherenkov radiation angle, which is very useful as a high intensity THz pulse source. In this study, we use an rf transverse deflecting cavity, in order to give a tilt to electron beam. In our previous study, broadband THz pulse was generated by focusing the transverse size of the electron beam using quadrupole magnets. However, it is necessary for a more advanced light source to have monochromaticity and wavelength-tunability. Therefore, we tried to enhance only a specific wavelength by applying a periodic structure to the electron beam using multi slit. At the conference, we will report the principal of quasi monochromatic Cherenkov radiation, the experimental results and future prospects.

## INTRODUCTION

Terahertz (THz) radiation is electromagnetic waves that have a frequency range between 0.1 THz ~ 10 THz. In recent years, THz wave research has developed, and there are several THz light sources such as quantum cascade laser, intense laser based sources and accelerator based sources. With the development of THz light sources and detectors, research on THz applications has also progressed. THz wave has some unique characteristics such as low energy compared to X-ray and some specific absorption peak unique to the substance. Imaging and spectroscopy techniques that apply these features are researched in variety of fields including security, medicine, biology, and communication.

At Waseda University, we have been developing a new THz light source by coherent Cherenkov radiation using tilted electron beam. In our previous study, we used quadrupole magnets (Q-mag) to focus the electron beam and generate coherent radiation[1]. In this method, THz pulse has broadband frequency component depending on the electron beam size. In order to generate a monochromatic THz radiation, we introduced a periodic structure to the electron beam. THz pulses generated from the electron beam with periodic structure are composed of micro pulses that reflects the structure. Because only the frequency corresponding to that period is enhanced, a monochromatic pulse is generated. For this research, we have designed the multi slit for the electron beam spatial modulation and investigated the monochromatization of THz pulse.

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## GENERATION OF THZ RADIATION

### *Coherent Radiation*

In order to obtain intense radiation from the electron beam, it is significant to match the phase of the radiation wave from each electron. A measure of how well the phases are matched is called coherence. As shown in Fig. 1, when the traveling direction length of electron bunch (bunch length) is sufficiently shorter than the radiation wavelength, the phase of radiation is matched and there are many coherent components. On the other hand, incoherent radiation is produced when the bunch length is longer than the radiation wavelength. The total radiation intensity due to coherence is theoretically analysed, and the total radiation intensity is defined as:

$$P = p_0 N_e [1 + (N_e - 1) f(\lambda)] \quad (1)$$

where $P$ is the total radiation intensity, $p_0$ is the radiation intensity per electron, $N_e$ is the numbers of electrons and $f(\lambda)$ is called form-factor that represents the electron distribution in the bunch. The value of $f(\lambda)$ is in the range of $0 \leqq f(\lambda) \leqq 1$, and $f(\lambda) = 1$ if completely coherent and $f(\lambda) = 0$ if completely incoherent. Therefore, Eq. 1 can be written as:

$$P = \begin{cases} p_0 N_e & (incoherent) \\ p_0 N_e^2 & (coherent) \end{cases} \quad (2)$$

The total radiation intensity is proportional to the square of

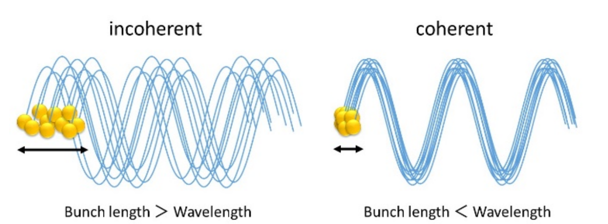


Figure 1: Radiation from the electron bunch longer and shorter than the wavelength of radiation.

the number of electrons as the coherent components increases[2].

### *Cherenkov Radiation*

Cherenkov radiation is electromagnetic radiation generated like a shock wave when the velocity of charged particles exceeds the phase velocity of light in the medium. Charged particles induce polarization in the medium and when it returns ground state, electromagnetic waves are emitted. The schematic of Cherenkov radiation is shown in

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Fig. 2. The condition of Cherenkov radiation is expressed as follows:

$$\beta > 1/n \quad (3)$$

where $\beta = v/c$ is the relative velocity of electron to the speed of light and $n$ is the refractive index of the medium. The direction in which the radiation wave propagates depends on the refractive index, and Cherenkov radiation angle is determined by the following equation:

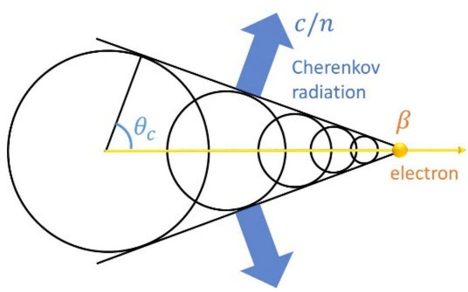


Figure 2: The diagram of Cherenkov radiation.

$$\cos\theta_c = 1/n\beta \quad (4)$$

### Phase Matching by Tilted Electron Beam

When the target medium is irradiated by nontilted electron beam, the wavefront from the head of electron bunch and the wavefront from the tail don't overlap, and coherent radiation cannot be obtained. However, if electron beam is tilted to Cherenkov angle, the radiation at each position in

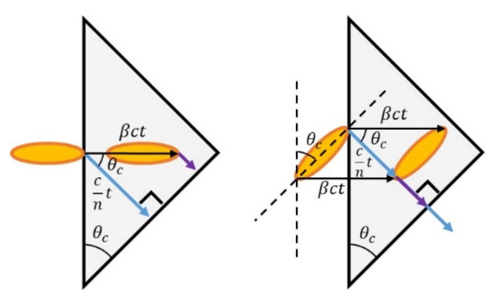


Figure 3: Phase matching of Cherenkov radiation from the tilted electron bunch.

the medium is phase matched. The schematic of phase matching by tilted electron beam is shown in Fig. 3.

The electron beam travels through the medium of refractive index $n$ by $\beta ct$ in $t$ seconds. Then, the light emitted in the first position travels through the medium in the direction of the Cherenkov angle by $ct/n$. Thus, obviously from Fig. 3, the condition for overlapping radiation at each position is expressed as the following:

$$\beta ct\cos\theta_c = ct/n \quad (5)$$

Since the Cherenkov angle is expressed by $\cos\theta_c = 1/n\beta$, phase matching is completed by tilting the electron beam to the Cherenkov angle, so that Eq. 5 is always satisfied

### Monochromatization by Spatial Modulated Electron Beam

The coherence in coherent Cherenkov radiation due to electron beam tilt is determined by the beam size of the electron beam. Therefore, broadband radiation in the wavelength range sufficiently shorter than the size of the electron beam can be obtained. In order to generate quasi-monochromatic pulse, a periodic structure is given to the electron beam. As shown in Fig. 4, the electron beam is spatially modulated by passing through the multi slit. The radiation pulse emitted from the electron beam with a periodic structure are constituted by micropulses having intervals corresponding to the period. Accordingly, only the frequency corresponding to the period is enhanced, and quasi-monochromatic THz radiation is obtained.

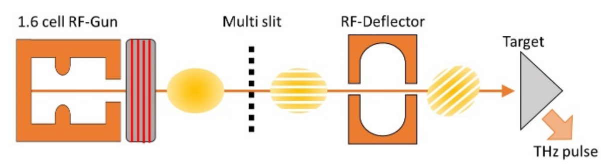


Figure 4: Generation of monochromatic THz pulse by spatial modulated electron beam.

## EXPERIMENTAL SETUP

### Beamline Layout

The beamline used in this experiment is shown in Fig. 5. Electron beam with maximum energy of 5 MeV is generated by the 1.6 cell photocathode rf-gun at a resonance frequency of 2856 MHz. The electron beam is modulated with a multi slit just before the rf-deflector, then tilted to the angle same as the Cherenkov angle, and irradiated to the target medium. As for the target, TOPAS (cyclic olefin copolymer) which has a small change in refractive index in the THz band and a small absorption of THz radiation was used[3]. The generated THz pulse is collected using a THz lens and measured by quasi-optical detector (QOD) in

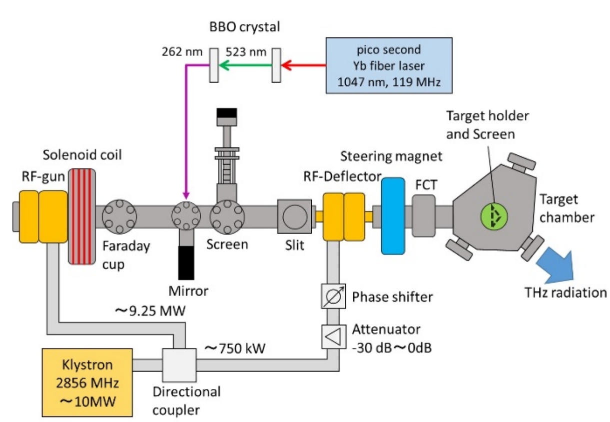


Figure 5: Experimental setup of monochromatic coherent terahertz radiation using electron beam tilting.

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which a Schottky diode is broadened by a lens. The measurement of quasi-monochromatization was performed by inserting band pass filter (BPF) before QOD.

### *Design of Multi Slit*

The multi slit was designed for the target frequencies of 0.2 THz and 0.3 THz. The slit width was fixed to 0.5 mm and the period was changed corresponding to the frequency. The period of 0.2 THz slit and 0.3 THz is 1.3 mm and 0.8 mm, respectively. The value of slit period was calculated taking into consideration the deflection by the rf-deflector and the change of speed of light in the medium.

## RESULTS AND DISCUSSIONS

### *Beam Profile and Solenoid Current Relationship*

A solenoid coil was used for the beam adjustment. The electron beam profile on the target depends on the solenoid current. Since the periodic structure on the target is very significant in monochromatization, the beam period was analysed from the beam profile image, and the corresponding frequency was determined. The result is show in Fig. 6. It was found that the solenoid current corresponds to the assumed frequency near 110 A at each slit.

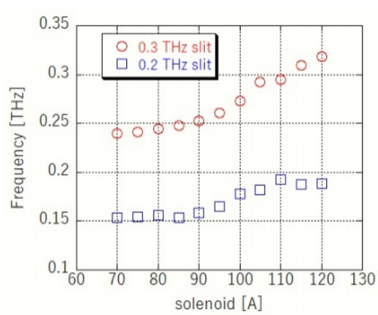


Figure 6: Corresponding frequency to solenoid current relationship.

### *THz Intensity and Beam Angle Relationship*

The angle of the electron beam was changed by controlling the rf-power applied to the rf-deflector. The electron beam charge was about 100 pC and BPF of 0.2 THz, 0.3 THz, and 0.5 THz was placed in front of the QOD. Fig. 7 represents the relationship between THz intensity and the beam angle. THz intensity was maximum at near 49° which corresponds to the Cherenkov angle. Furthermore, the assumed frequency was enhanced at each slit, and we have successfully confirmed the quasi-monochromatization.

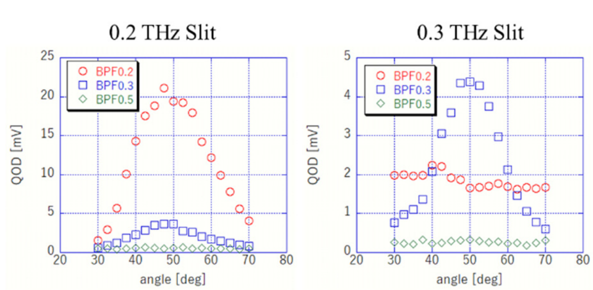


Figure 7: THz intensity and beam angle relationship.

### *Quasi-Monochromatization Measurements*

In order to evaluate the monochromatization, THz pulse intensity was measured when the solenoid current was changed using BPF of 0.2 THz, 0.3 THz, and 0.5 THz. The charge of the electron beam after the multi slit was adjusted to be constant at about 100 pC, and the angle of the electron beam is matched to the Cherenkov angle. The results are shown in Fig.8. The results that the assumed frequency is enhanced was obtained when the solenoid current is near 110 A.

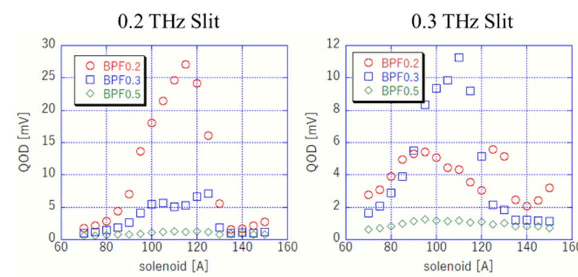


Figure 8: The results of quasi-monochromatization for 0.2 THz slit (left) and 0.3 THz slit (right).

## CONCLUSION

We succeeded in adding a periodic structure to the electron beam by multi slits. Since beam profile at the target position was changed by the solenoid coil current used for beam focusing, we analysed the corresponding radiation frequency from the electron beam profile image. In the frequency measurement of THz pulse using BPF, the expected frequency was enhanced for the two slits. We can say that the quasi-monochromatization was successfully demonstrated as we expected.

In near future, we will conduct beam tracking simulation for producing optimum electron beam and design better slit. Furthermore, in order to perform precise spectrum evaluation, a laser system for time domain spectroscopy is underdevelopment.

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