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GENERATION OF COHERENT THz TRANSITION RADIATION FOR TIME DOMAIN SPECTROSCOPY AT THE PBP-CMU ELECTRON LINAC LABORATORY

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Abstract

The accelerator system at the PBP-CMU Electron Linac Laboratory (PCELL) of the Plasma and Beam Physics (PBP) Research Facility is used to generate terahertz (THz) coherent transition radiation (CTR). Due to broad spectrum, it can be used as a light source for THz time-domain spectroscopy (TDS) to measure both the intensity and phase of the THz signal. This contribution presents the generation of THz-TR produced from 10 – 25 MeV electron beams. Compressed electron bunches with a length in femtosecond scale are used to generate the THz-TR employing a 45°-tilted aluminum (Al) foil as a radiator. The radiation properties including angular distribution and radiation spectrum are measured at the TR station in the accelerator hall and at the TDS station in the experimental area. The radiation spectral range covering up to 2.3 THz with a peak power of 0.5 – 1.25 MW is expected. The collection efficiency and influence of optical components on the radiation properties were studied. The results show that the considered effects have a significant impact on the TR properties. Results from this work will be used in the TR characterization that is needed to be interpreted carefully.

INTRODUCTION

THz radiation is an electromagnetic wave with a frequency range of $(0.3 - 3) \times 10^{12}$ Hz. This frequency range corresponds to rotational and vibration modes of many molecules. Therefore, it can be used to study, e.g., characteristics of intermolecular bonds by using THz spectroscopic technique [1–4]. One of the most promising sources for THz spectroscopy is linac-based coherent THz radiation from ultrashort electron bunches [5–9]. With an electron bunch as short as femtosecond scale, the radiation emitted from all electrons in the bunch add up coherently and has high intensity, which is proportional to the number of electrons in the bunch squared. The shorter electron bunches provide the broader THz radiation spectrum with higher radiation intensity. At PCELL, CTR has been generated from electron bunches with a length of about 200 fs [10–13]. The features of intense, coherent and broadband spectral range of THz-TR leads to the interest on using it as a light source for THz-TDS, which has the advantage to measure both the intensity and phase of electric fields from THz radiation. This allows us to determine not only the absorbance of the sample, but the complex refractive index [14]. The design and development of the THz-TDS system at PCELL require several aspects, which are generation and characterization of THz-TR, transportation of the THz-TR from the radiation station in the accelerator hall to the application room where the TDS system will be located. In this study, we report the characterization of the CTR produced from short electron bunches with an average energy in a range of 10 – 25 MeV. The radiation properties including radiation spectrum and angular distribution are investigated. Furthermore, we evaluated some effects that affect the transmission efficiency in the Michelson interferometer for radiation spectrum measurement.

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METHODOLOGY

At our facility, a train of electron bunches is generated from a thermionic cathode radio-frequency (RF) electron gun with a maximum kinetic energy of about 2 – 2.5 MeV. The electron bunches are then accelerated by an RF linear accelerator (linac) to reach kinetic energy of about 8 – 25 MeV. The electron bunches are compressed to have a bunch length of 100 – 300 fs at the CTR experimental station downstream the linac by using an alpha magnet and velocity bunching process in the linac. At the CTR station, an Al foil with a thickness of 25 µm and a diameter of 24 mm is used as a radiator by placing it 45° with respect to the electron beam direction. The backward TR is emitted at the radiator surface and is collimated by a goal-coated parabolic mirror placing at its focal point in the vacuum chamber below the center of the radiator. The collimated radiation is then guided to pass through a high density polyethylene (HDPE) window as shown in Fig. 1. The radiation then enters the measuring system. The HDPE window has a diameter of 32 mm and a thickness of 1.25 mm. The radiation spectrum is measured using the Michelson interferometer. The CTR with a spectral range of upto 2.3 THz and a peak power of 0.5 - 1.25 MW is expected.

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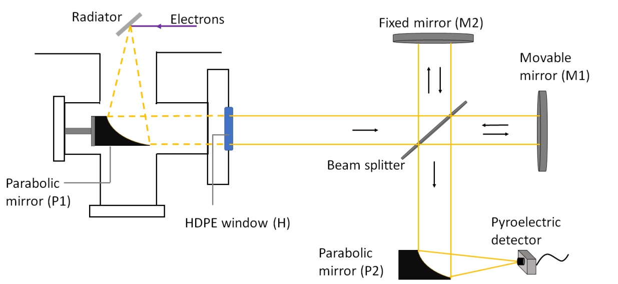

Figure 1: The setup for backward CTR generation and Michelson interferometer for radiation spectrum measurement.

RESULTS AND DISCUSSION

Collection Efficiency and TR Angular Distribution

Transition radiation from an electron is originated at the point of incidence and is emitted in a radiation cone. With 45° incidence, the angular distributions of backward TR with different electron beam energies are illustrated in Fig. 2. For this case, the angular distribution are slightly asymmetric in horizontal cross section and this asymmetry is reduced with higher electron energy. As seen from Fig. 2, the radiation

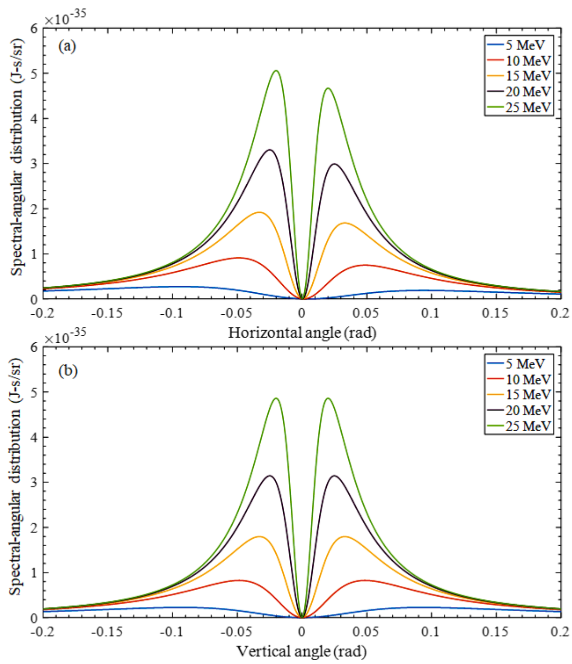

Figure 2: Backward angular distributions of TR for various electron energies with (a) horizontal cross section and (b) vertical cross section.

from electron with low energy has large opening angle and it becomes smaller when the electron has higher energy. The radiation opening angle are ±49 mrad and ±20 mrad for electron energies of 10 and 25 MeV, respectively. When observing the radiation, it is collected over a solid angle. The collection efficiency is increased with the increasing of acceptance angle θ_a and reaches 100% of total radiation when the acceptance angle is $\pi/2$. The radiation has maximum intensity around the angle of $1/\gamma$. However, a large fraction of radiation is emitted at larger angle. The collection of the radiation within an experimental acceptance angle is therefore important.

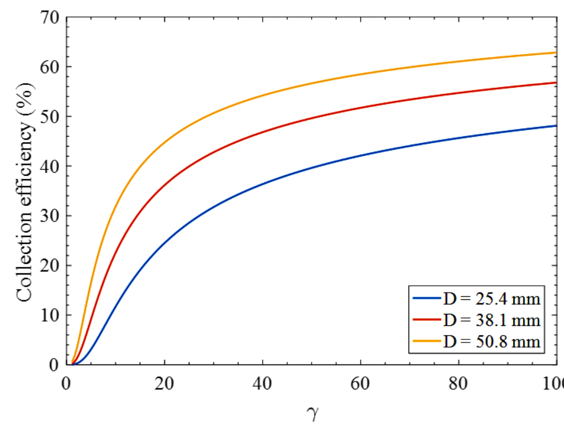

Figure 3: Collection efficiency of transition radiation as a function of electron beam energy (γ) with different parabolic mirror diameter (D).

For the setup to transport the TR to the measuring system, a parabolic mirror is used to collect the diverse radiation to become a parallel beam. The acceptance angle is then limited by size and position of the mirror. This mirror has a diameter of 25.4 mm and is placed at its focal point of 76.2 mm. The experimental acceptance angle is equal to 0.165 rad. The radiation of 25.03 % and 39.61 % of the total radiation intensity is collected for electron with energy of 10 MeV and 25 MeV, respectively. To study the influence of the mirror size, the collection efficiencies at different size of mirror are plotted as a function of electron energy in term of γ as indicated in Fig. 3. At a fixed position of parabolic mirror, the acceptance angle is increased when the mirror size is increased. For the parabolic mirror with the diameter (D) of 25.4 mm, the efficiency is lower than 50 % for all energies. Thus, the plan to improve the collection efficiency by increasing the size of mirror is considered at PCELL.

Evaluation of CTR Spectrum

Michelson interferometer is used for measurement of radiation spectrum and electron bunch length. The effect that must be considered is the diffraction due to finite aperture in the radiation propagation. Then, the size of mirrors used in the interferometer is optimized to find the best performance of the system. The energy transmission of the radiation through the Michelson interferometer is calculated by using Fraunhofer diffraction, assuming circular apertures [15]. The energy transmission can be considered as a ratio of energy contained within the second surface and the total energy [16]. As shown in Fig. 1, from the diagram, the radiation from the first parabolic mirror "P1 (diameter of 25.4 mm)" travels through the HDPE window, then it enters the Michelson interferometer. The radiation impinges on

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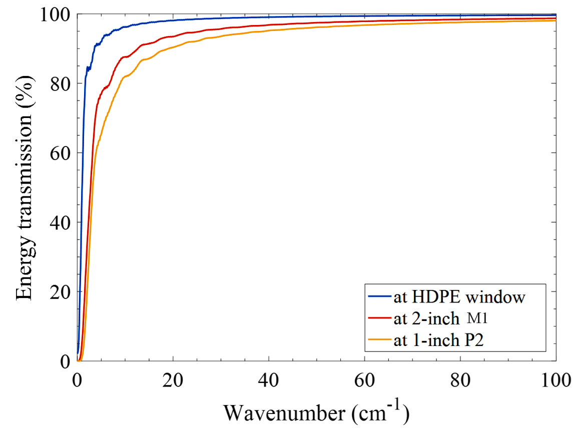

Figure 4: Energy transmission through the original setup (set 1) versus the radiation wavenumber.

flat mirrors "M1 (diameter of 50.8 mm)" and "M2 (diameter of 50.8 mm)", then reflected back to the beam splitter before collected by the parabolic mirror "P2 (diameter of 25.4 mm)" onto the detector. The HDPE window is placed at distance 76.2 mm away from P1. The flat mirror M1 is placed in Michelson interferometer with the distance from HDPE window of 367.3 mm. The distance between the flat mirror M1 and the parabolic mirror P2 is 215.9 mm. The calculated energy transmissions based on the above setup are shown in Fig. 4.

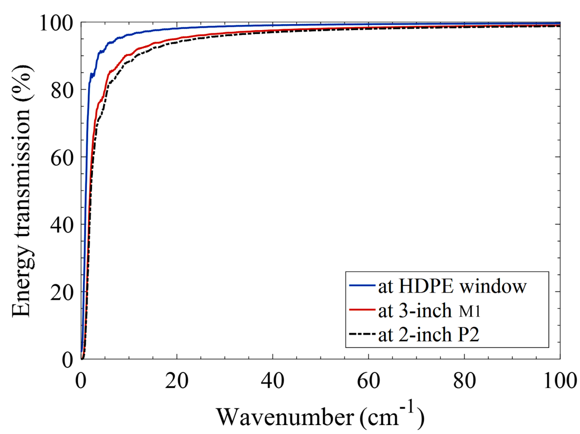

Figure 5: Energy transmission through the setup with improved design (set 2) versus the radiation wavenumber.

The energy transmission at HDPE window, flat mirror M1 and parabolic mirror P2 is determined with respect to the total energy on parabolic mirror P1. On the last surface, we found that the energy more than 80% are obtained for wavenumber higher than 10 cm^{-1}. The low frequency is suppressed due to the diffraction caused by optical components. The main suppression can be seen from the flat mirror resulting from the long traveling distance from P1 and the small size of the flat mirror. To improve the energy transmission, the size of M1 and P2 mirror are increased since we cannot reduce the distance from P1 to M1 as limited by the length of vacuum pipe.

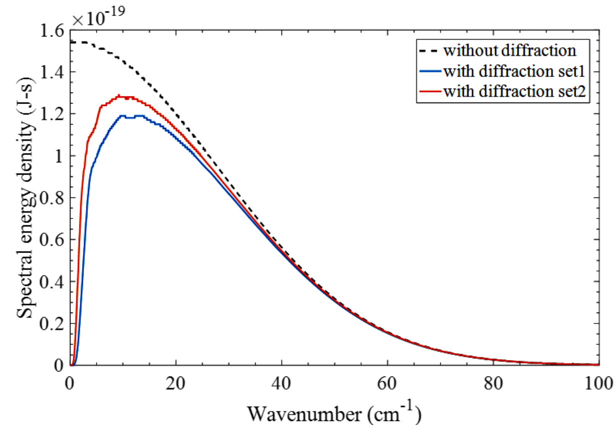

Figure 6: Coherent transition radiation spectra showing the effect of mirror diffraction for electron beam with energy of 10 MeV and bunch length of 40 μm.

For new P2 having diameter of 50.8 mm (2 inches) and new M1 having diameter of 76.2 mm (3 inches), the energy transmission values are shown in Fig. 5. In the improved design, the energy higher than 90% can be transmitted for wavenumber higher than 10 cm^{-1} (0.3 THz). This also means the low-frequency suppression is reduced. The CTR spectra comparing effect of optical instruments are shown in Fig. 6. The spectra were calculated by using 10 MeV electron beam with a bunch length of 40 μm and ignoring the effect from transverse beam size. By increasing the size of M1 and parabolic mirror P2, the spectrum has less cutoff at low wavenumber.

CONCLUSION

THz CTR is generated at PCELL by using femtosecond electron bunches of 8 – 25 MeV. The emitted radiation has high intensity and the spectrum is broad covering up to 2.3 THz. The backward TR transverse profile is asymmetric along the horizontal direction due to the 45° tilted radiator. The collection efficiency in term of electron energy is calculated and found that it increases with higher energy of electron because the radiation has smaller angular distribution. The efficiency can also be improved by increasing the mirror size. For radiation spectrum evaluation, the frequencies lower than 0.3 THz are suppressed due to mirror diffraction in the interferometer.

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