ISBN: 978-3-95450-179-3 doi:10.18429/JACoW-FEL2017-TUP067

STUDY ON CHERENKOV LASER OSCILLATOR USING TILTED ELECTRON BUNCHES *

K. Sakaue†, WIAS, Waseda University, Tokyo, Japan
M. Brameld, Y. Tadenuma, R. Yanagisawa, M. Washio, RISE, Waseda University, Tokyo, Japan
R. Kuroda, Y. Taira, AIST, Ibaraki, Japan
J. Urakawa, KEK, Ibaraki, Japan

Abstract

We have been studying a coherent Cherenkov radiation by using tilted electron bunches. Bunch tilting can enhance the radiation power about 10 times due to the wavefront matching of radiations. Recently, we investigated that this technique can produce high peak power THz pulses with sufficient pulse energy. The resulting pulse energy was more than 30 nJ/pulse and peak power was about 10 kW. Introducing the oscillator cavity with two concave mirrors can achieve lasing using tilted electron bunches. In the calculation we present, 1 μJ/micro-pulse and 100 μJ/macro-pulse broadband THz pulses are expected to achieve, which is powerful THz source compared with the existing THz FELs. In this conference, we will report the experimental results of coherent Cherenkov radiation, calculated results towards lasing and future prospective.

INTRODUCTION

Radiation in the terahertz (THz) frequency range is recognized to be useful for material science, medical use and other applications. The most useful feature of THz radiation its absorption spectrum of particular materials. This is the absorption of the vibration and/or rotation of molecules. Recently, the high peak power THz pulse was found to be useful for transforming the surface molecular using specific absorption [1]. The accelerator based THz source has an advantage in high peak power THz pulse generation with monochromatic and wavelength tunability. have useful properties. The photon energy of the THz radiation is several meV so that our electron accelerator system based on photocathode rf gun with 5-MeV energy is enough for the THz generation.

We have been studying on the coherent THz generation with Cherenkov radiation process [2]. In order to enhance the THz radiation power, we employed an electron bunch tilting. The relativistic electrons radiate a Cherenkov radiation when the velocity of electron is faster than the light in the medium at certain angle. Fig. 1 shows the schematic of Cherenkov radiation from electron (left) and tilted electron bunch. Electron radiates the Cherenkov radiation at several points in the medium but each radiation cannot be interacted with each other. When the electron bunch is perpendicular to the Cherenkov angle (right), radiation from different points of the medium can coherently overlap and enhance the pulse intensity [2].

* This work was supported by a research granted from The Murata Science Foundation and JSPS KAKENHI 26286083.
† kazuyuki.sakaue@aoni.waseda.jp

We successfully measured and enhanced the THz power, then started to design the oscillator cavity for lasing by Cherenkov radiation. This paper reports on the experimental results of coherent Cherenkov radiation, design and calculated results for constructing a laser, and future prospective.

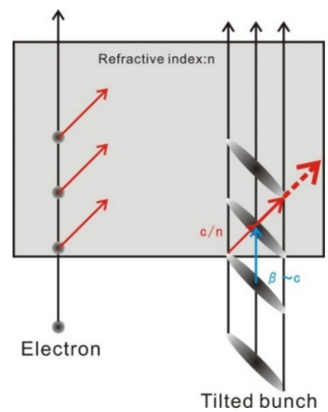

Figure 1: Generation of Cherenkov radiation from a tilted electron bunch.

EXPERIMENTS OF COHERENT CHERENKOV RADIATION

Experimental setup

Figure 2 shows the experimental setup of coherent Cherenkov radiation by electron bunch tilting. Electron bunch is produced by photocathode rf electron gun with energy of 4.5 MeV. Electron bunch is passed through the solenoid magnet for emittance compensation and focused by the quadrupole magnets. The focus size is the key parameter of the form factor in this experiment. After the quadrupole magnets, we installed an rf transverse deflecting cavity for tilting the bunch. Tilting angle can be controlled by regulating the rf power for the rf deflector.

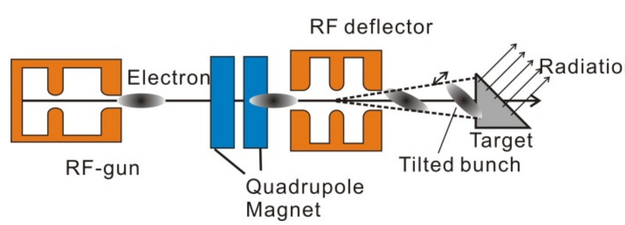

Figure 2: Experimental setup of coherent Cherenkov radiation by electron bunch tilting.

ISBN: 978-3-95450-179-3 doi:10.18429/JACoW-FEL2017-TUP067

After the rf deflector, the target medium of Cherenkov radiation is installed. We employed the target made by TOPAS [3], which has transmittance and uniform refractive index in THz range. The refractive index of TOPAS is 1.52 in the THz frequency. The resulting Cherenkov angle is 48.9 degrees. The radiation is extracted through the vacuum window and guided to the measurement system. We used a schottky barrier diode (SBD), the THz power meter and the time domain spectroscopy (TDS) system using EO sampling method [4].

Experimental results

Here we show the measurement results of coherent Cherenkov radiation experiment. Firstly, we detected the THz pulses by SBD. Figure 3 shows the measured THz waveform.

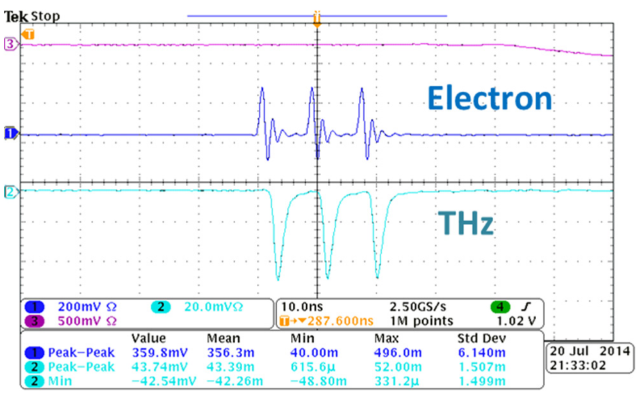

Figure 3: THz waveform detected by SBD (aqua) and electron bunch waveform by a current transformer (blue).

As shown in Fig. 3, three electron bunches produced three THz pulses. Our accelerator system can produce multi-bunch beam up to 200 bunches/train so that introducing oscillator cavity will realize the lasing.

As a next step, we measured the pulse energy of THz pulse. The resolution of the THz power meter is in the μW range, thus we used the multi-bunch beam to measure the average power and then divided by the number of pulses. Table 1 shows the results of this measurement.

Table 1: Results of Pulse Energy Measurement by THz Power Meter

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

Comparing the total band pulse energy, electron bunch tilting increased the pulse energy more than 7 times. The other columns are the measurement using band pass filters (BPFs). These results indicate that the THz pulse has a broad band spectrum and larger intensity in the low frequency part.

In order to confirm the THz spectrum, we employed a TDS system using EO sampling method. TDS systems measure the waveform of the THz pulse directly and its Fourier transformation corresponds to the spectrum of the THz pulse. The detail of the TDS system utilized in our experiment is can be found in [4]. We used ZnTe crystal as an EO crystal and a Yb fiber laser as a probe. Figure 4 shows the measured results in the time domain (top) and frequency domain (bottom).

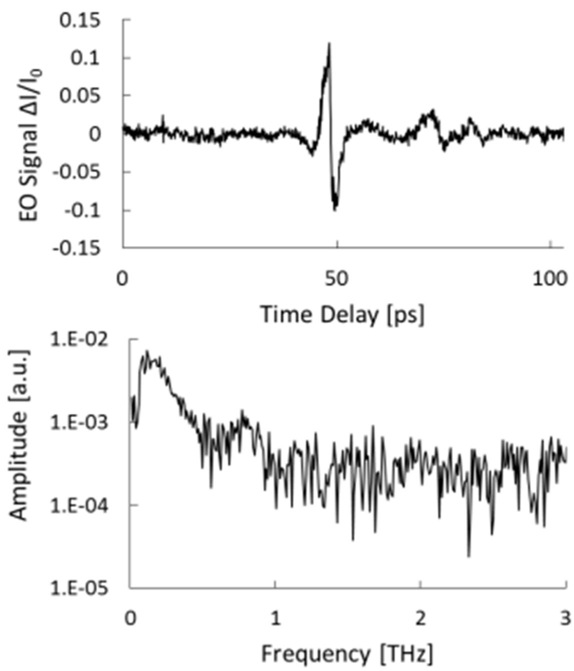

Figure 4: Measurement results of TDS system in time domain (top) and frequency domain (bottom).

The waveform in time domain has the single cycle property, a broad band spectrum. In the frequency domain, the THz pulse has a broad band spectrum up to 1 THz, the upper limit of the frequency determined by the system configuration. A combination of ZnTe 1 mm thick and Yb fibre laser would limit the sensitivity up to 1 THz. From the beam size before tilt, we expect that the THz pulse may include frequency content up to 3 THz.

CALCULATIONS OF CHERENKOV LASER OSCILLATOR

After the successful results of coherent Cherenkov radiation via electron-bunch tilting, we designed two different systems that could lase using an oscillator cavity. The first type is a normal TOPAS target with an output coupler oscillator. A sketch of this configuration, called NORMAL, is shown in Figure 5. The other is a high peak-power type with low losses and can extract a single pulse though a laser-plasma mirror. A sketch of this configuration, called HIPEAK, is shown in Figure 6.

ISBN: 978-3-95450-179-3 doi:10.18429/JACoW-FEL2017-TUP067

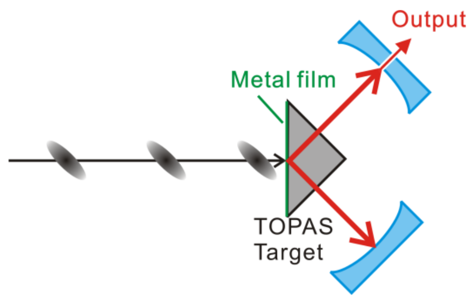

Figure 5: Designed laser oscillator type NORMAL.

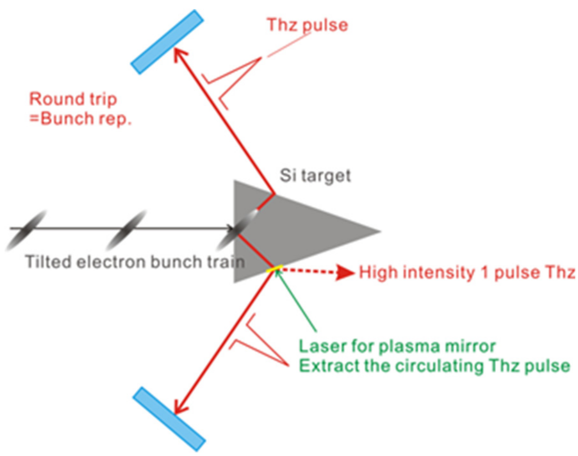

Figure 6: Designed laser oscillator type HIPEAK.

For a normal type oscillator, we employed TOPAS target as we used in the experiment. In order to make a closed loop, one surface of the TOPAS has metal coat. The refractive index of TOPAS is not high so that we simply configured the oscillator. The output coupler is employed for one mirror to match with the round-trip loss of the oscillator. We assumed one pass energy gain is 33 nJ as we measured above. The calculated result is shown in Fig. 7.

Considering the practical use of THz pulses, high peak power THz radiation is the most useful. Thus, we designed the high peak power oscillator. Figure 6 illustrates the configuration of HIPEAK oscillator. We employed a Si target, which is low absorption in the medium. In addition, the THz pulse is extract/inject to the medium by a Brewster's angle in order to minimize the loss. The round-trip loss is less than 2%.

The key point of this oscillator is the extraction by the laser. We use the Si semiconductor target and the injection is not perpendicular to the medium. If we make mirror surface at the time which the oscillator is saturation, the maximum pulse energy can be extracted. The laser plasma mirror is a well-known technique for the semiconductors [5]. Then we can obtain the single, high peak-power THz pulse using the HIPEAK oscillator. It should be noted that we assumed in the calculation that the single pass gain of Si was same with TOPAS.

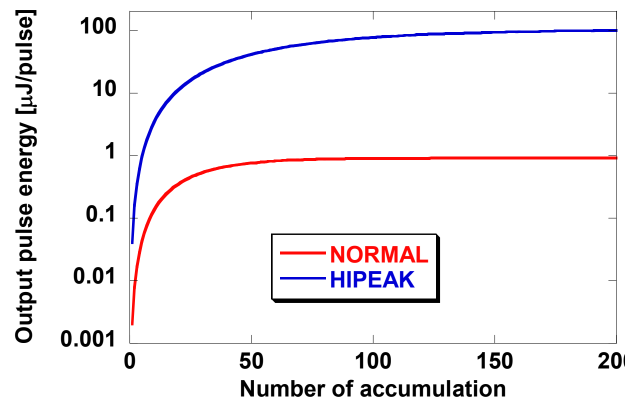

Figure 7: Calculated results of lasing by coherent Cherenkov radiation by two types of oscillator.

Figure 7 shows the calculated results of lasing by two types of oscillator shown in Figs 5 and 6. In Fig. 7, the red line shows the result of NORMAL oscillator. We used 200 multi-bunch beams for the calculation. The NORMAL type utilizes the output coupler, so the oscillator is saturated around 100 bunches. The resulting pulse energy was about 1 μJ. The output THz pulse is multi-pulse so that the macro pulse energy will be more than 100 μJ. The blue line in Figure 7 shows the result of HIPEAK oscillator. The vertical axis indicates the single pulse energy extracted by the plasma mirror. The output pulse energy exceeds about 100 μJ around 200 pulse stacks in the oscillator. This pulse energy would be one of the most powerful THz pulse, which is produced by the accelerator consists of the rf electron gun alone.

CONCLUSIONS

We demonstrated the coherent Cherenkov radiation via electron-bunch tilting. A THz pulse of about 10 kW peak power was obtained by this technique. This technique can be utilized for lasing using an oscillator cavity. A calculation of the oscillator cavity is presented in this paper. We designed two types of oscillator which can achieve as much as 100-μJ pulse energy by the electron gun alone. We are planning to construct the oscillator and expect to realize the very high peak-power THz source in the near future.

REFERENCES

[1] H. Hoshina *et al.*, *Sci. Rep.*, vol. 6, p. 27180 (2016).

[2] K. Sakaue *et al.*, in *Proc. of IPAC'17*.

[3] P. D. Cunningham *et al.*, *J. Appl. Phys.*, vol. 109 (2011) 043505.

[4] R. Yanagisawa *et al.*, in *Proc. of IPAC'17,* THPAB119.

[5] A. Y. Elezzabi *et al.*, *Opt. Lett*,. vol. 19, p. 898 (1994).