PRODUCTION OF ULTRA-SHORT ELECTRON PULSE AND OBSERVATION OF COHERENT TRANSITION RADIATION AT T-ACTS, TOHOKU UNIVERSITY

T. Abe†, S. Kashiwagi, F. Hinode, T. Muto, K. Nanbu, K. Takahashi, I. Nagasawa, H. Saito,
Y. Shibasaki, C. Tokoku and H. Hama,
Research Center for Electron Photon Science (ELPH), Sendai, Japan

Abstract

A test-Accelerator as Coherent Terahertz Source (t-ACTS) project has been under development at Research Center for Electron Photon Science, Tohoku University. In order to generate a coherent radiation in terahertz (THz) region, it is necessary to produce sub-picosecond electron pulses. Velocity bunching scheme is employed for the short electron pulse production in t-ACTS. We experimentally confirmed the production of short electron pulse under 500 fs by measuring the bunch length using a streak camera. Coherent transition radiation in THz region was produced by which the short electron pulses pass through a vacuum-metal interface. Several radiation properties including spatial distribution, polarization and spectrum were measured and compared with theoretical calculations. The details of the beam experiment at t-ACTS are described.

INTRODUCTION

The intense coherent THz source is a powerful tool for many scientific fields such as biophysics and molecular science. The t-ACTS has been proposed as a test accelerator complex towards intense THz source at Research Center for Electron Photon Science, Tohoku University. The t-ACTS accelerator consists of a compact linear accelerator with a thermionic RF-gun and undulator [1]. The t-ACTS project employs the velocity bunching scheme in its compact linear accelerator to produce the femtosecond electron bunches for generating coherent radiation in THz region [2]. Demonstration of short bunch generation was performed and the bunch length was measured using a streak camera. The compressed beam is much shorter than the wavelength of THz radiation, and has a sufficient large form factor for coherent enhancement of radiation power.

COHERENT TRANSITION RADIATION

The total radiated power from an electron bunch of *N* electrons can be written as

$$\mathrm{P}(\lambda) = [N\{1 - f(\lambda)\} + N^2 f(\lambda)] \cdot P_0(\lambda), \tag{1}$$

where $P_0(\lambda)$ is the radiated power from a single electron. The function of $f(\lambda)$ is bunch form-factor for Gaussian bunch with rms bunch length σ_b and is given by

$$f(\lambda) = \left|\exp\left(-2\pi^2 \frac{{\sigma_b}^2}{\lambda^2}\right)\right|^2. \tag{2}$$

In case of that bunch length is shorter than the radiation wavelength and $f(\lambda)$ is not zero, the radiated power $P_0(\lambda)$ has a coherent term that is proportional to N^2.

Transition radiation is produced by the passage of charged particles through the boundary between media with different dielectric constant. In the case of that electron bunch passes through a perfect conductor tilted 45º, the backward transition radiation emitted at 90º with respect to the beam propagating axis. The angular distribution of radiation is given by contribution of both parallel and perpendicular polarization, which are

$$\frac{d^2W^{\parallel}}{d\omega d\Omega} = \frac{e^2\beta^2}{8\pi^3\varepsilon_0 c}\left[\frac{2\sin\theta - \sqrt{2}\beta\cos\phi}{\left(\sqrt{2} - \beta\sin\theta\cos\phi\right)^2 - \beta^2\cos^2\theta}\right]^2, \tag{3}$$

$$\frac{d^2W^{\perp}}{d\omega d\Omega} = \frac{e^2\beta^2}{8\pi^3\varepsilon_0 c}\left[\frac{\sqrt{2}\beta\cos\theta\sin\phi}{\left(\sqrt{2} - \beta\sin\theta\cos\phi\right)^2 - \beta^2\cos^2\theta}\right]^2, \tag{4}$$

where ω c ,v and β are the angular frequency of radiation, the speed of light, the electron velocity and v/c, respectively [3]. Symbol θ represents the angle between the direction of emitted radiation and the –z axis, while ϕ is the azimuthal angle defined in the x-y plane (interface) with respect to -x axis as shown in Fig. 1. Total radiation intensity can be expressed as $d^2W/d\Omega d\omega = d^2W^{\parallel}/d\Omega d\omega + d^2W^{\perp}/d\Omega d\omega$. From Eqs. (3) and (4), radiation intensity is proportional to frequency.

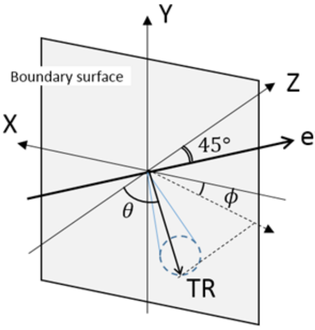

Figure 1: Geometry of calculation for transition radiation.

---

† abe@lns.tohoku.ac.jp

ISBN 978-3-95450-147-2

GENERATION OF SHORT ELECTRON BUNCHES

The system for velocity bunching is simple and compact; it does not require special apparatus. In this bunching scheme, an electron beam, whose velocity is slightly slower than phase velocity of RF field ($\beta < c$), is injected into traveling-wave accelerating structure at appropriate phase. Electron distribution in the longitudinal phase space is deformed during phase slip, so that the bunch is compressed and accelerated simultaneously through the accelerating structure. When the injection beam has flat distribution in the longitudinal phase space with small energy spread and the injection phase is around the correct RF zero-cross, the electron bunch is compressed efficiently. To manipulate the longitudinal phase space distribution of electron beam we have developed a specially designed S-band RF gun named ITC (Independently Tunable Cells) RF gun [4]. A suitable longitudinal beam phase space for velocity bunching can be produced using the ITC RF gun.

Proof of principle experiment of velocity bunching was performed at t-ACTS [5]. In order to measure the bunch length, the optical transition radiation was observed using a streak camera for various injection phases at the accelerating structure. Although measured bunch length was shortened as the injection phase approached to zero, it didn't change around the zero-phase. In this measurement system, it was found out time resolution was limited around 400 fs due to intrinsic time resolution of streak camera and wavelength dispersion in optical transport line. However, at least, the minimum bunch length of about 450 fs was obtained.

CHARACTERIZATION OF COHERENT TRANSITION RADIATION

Measurement Setup

Transition radiation was generated from short electron bunches which parameters listed in Table 1. An alminium coat mirror with 30 mm diameter was installed at a radiator downstream of accelerating structure and it was tilted by 45° with respect to the beam propagating axis, and then the backward transition radiation is emitted perpendicularly to beam axis. Transition radiation extracted through a diamond window of 300 μm thickness and an intensity was measured using pyroelectric detectors (PYD-1 [PHLUXi], THZ1I-BL-BNC [Gentec-EO]) and Schottky barrier diode (DET-10, DET-16 [Millitech]) as well.

Table 1: Electron Beam Parameters

Macropulse length	~2.0 μs
Number of bunch	~5700 bunches/macropulse
Beam energy	30~50 MeV
Bunch charge	3 ~ 4 pC
Bunch length (σ_z)	0.1~ 2 ps

Spatial Distribution and Polarization

Spatial distribution of transition radiation was measured by scanning detector position across the radiation axis. Polarization components in both the horizontal and the vertical were measured by installing a wire grid polarizer (GS57207, wire diameter: 10 μm, period: 25 μm, SPECAC) in front of the pyroelectric detector. Figure 2(a) and 2(b) show calculated horizontal and vertical polarized components of radiation from Eqs. (3) and (4). Figures 2(c) and 2(d) are measured each polarized components respectively, and these spatial profiles are well consistent with the distribution that is expected from the Fig. 2(a) and 2(b). Figure 2(e) shows sum of two components, which is in good agreement with spatial profile of the radiation measured without the wire grid (Fig. 2(f)).

Radiation Spectral Distribution

A Michelson interferometer was installed to obtain an interferogram of transition radiation as shown in Fig. 3. In the Michelson interferometer, the radiation is splitted into two parts by a Mylar film beam splitter. A part of each pulse travels through the beam splitter towards to the pyroelectric detector. The detector signal is recorded as a function of the mirror position or the optical path difference of two pulses. As the pass length difference becomes close to the electron bunch length, the radiation field of two pulses overlap. Therefore the detector signal increases up to twice compared to the case of no overlap of the

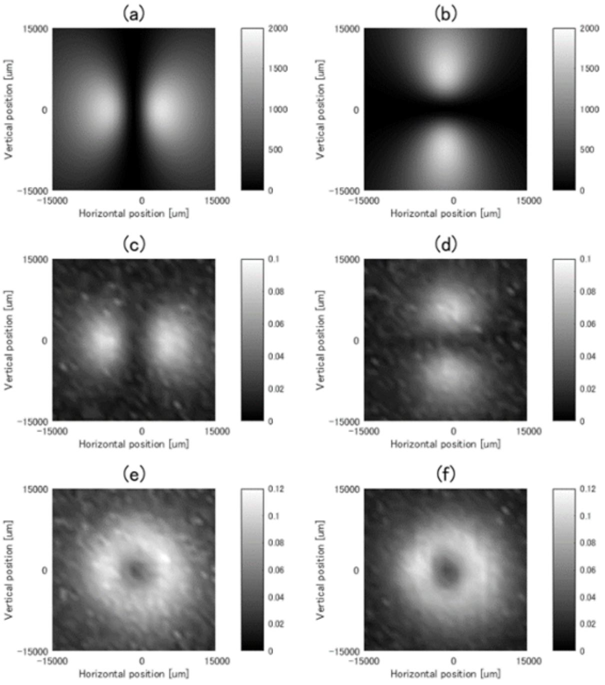

Figure 2: Spatial distribution of radiation. (a), (b) Calculated spatial profiles of horizontal and vertical polarized radiation. (c), (d) Measured spatial profiles of horizontal and vertical polarized radiation. (e) Sum of the horizontal and vertical polarized components. (f) Measured spatial distribution w/o wire grid polarizer.

two pulses. Entire interferometer system is enclosed (Fig. 3) and continually purged with dry nitrogen to avoid the strong absorption of THz by water vapor.

Radiation spectrum of transition radiation can be derived from Fourier transform of the interferogram. Figure 4(a) shows measured interferogram using the Michelson interferometer, and the optical path length was varied by 20 µm per step. Figure 4(b) shows the transition radiation spectrum produced with short electron bunches. Frequency resolution of the spectrum was 125 GHz in this measurement. Injection phase for velocity bunching was adjusted so as to make the bunch becomes shortest. Broadband radiation is observed shown as Fig. 4(b), and which higher frequency reaches to around 3.5 THz.

Radiation Intensity and Bunch Charge

One of peculiar properties of coherent radiation from electron bunch is the radiation intensity is proportional to the square of the number of electrons in a bunch as indicated by Eq. (1). Intensity of transition radiation was measured using Schottky barrier diode which has 35 GHz of bandwidth at a center frequency of 0.1 THz. Microbunch charge was controlled using mechanical slit which located downstream of the accelerating structure. In Fig. 5, the radiation intensity is plotted as a function of the microbunch charge, which shows a good agreement with the theoretical N^2curve.

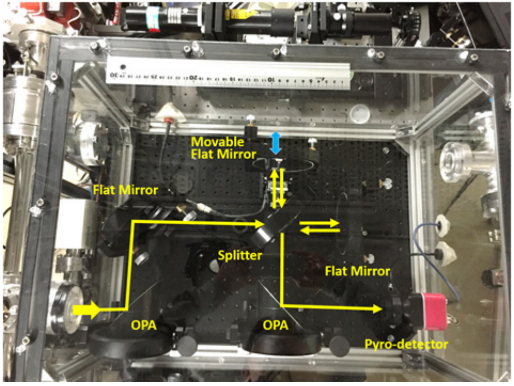

Figure 3: Setup of Michelson interferometer.

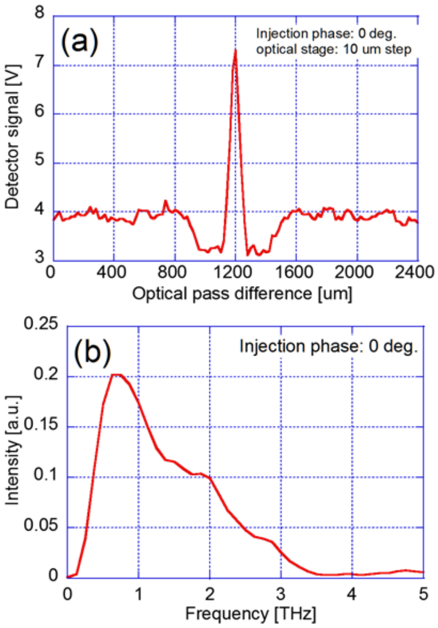

Figure 4: (a) Measured interferogram of transition radiation and (b) Radiation spectrum.

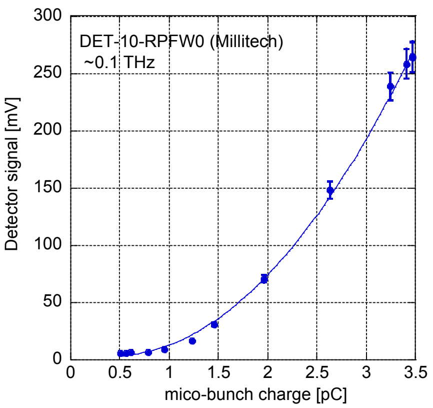

Figure 5: Intensity of transition radiation as a function of microbunch charge. Solid line shows the quadratic dependence expected for coherent radiation.

CONCLUSION

Demonstration of velocity bunching for short electron bunch production was performed at t-ACTS, Tohoku University. We confirmed generation of sub-picoseconds electron bunches and measured bunch length was shortened according as the injection phase approaches to zero. Coherent transition radiation generated by the short electron bunches was observed and characterized experimentally. Spatial distribution of the horizontal and vertical polarized components was observed by the measurement. In spectrum measurements using a Michelson interferometer, the broadband spectrum at z region was derived from the interferogram. Both the interferogram and spectrum suggest attainment of an extremely short electron bunch around 100 fs. Bunch length can be directly measured from the width of the interferogram, however the evaluation of the measurement system, such as frequency dependence of beam splitter and so on, is not fully completed. We will perform to calibrate the system based on a Blackbody source.

ACKNOWLEDGEMENT

This work is partly supported by Grant-in-Aid for Scientific Research (B) 25286084, MEXT, Japan.

REFERENCES

[1] H. Hama et al., New J. Phys. 8 (2006) 292.

[2] L. Serafini, and M. Ferrario, AIP Conf. Proc. 581, 87.

[3] M.L. Ter-Mikaelian, High-energy Electromagnetic Process in Condensed Media, Wieley, New York, 1972.

[4] F. Hinode et al., Proc. of IPAC'10, (2010) 1731.

[5] S. Kashiwagi et al., Proc. of LINAC2014, (2014) 1178.