GENERATION OF COHERENT UNDULATOR RADIATION AT ELPH, TOHOKU UNIVERSITY

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Abstract

A test accelerator as a coherent terahertz source (t-ACTS) has been under development at Tohoku University, in which an intense coherent terahertz (THz) radiation generated by an extremely short electron bunch [1]. Velocity bunching scheme in a traveling accelerating structure is employed to generate femtosecond electron bunches [2]. Spatial and temporal coherent radiation in THz region can be produced by the electron bunches with small transverse emittance. A long-period undulator, which has 25 periods with a period length of 10 cm and a peak magnetic field of 0.41 T, has been also developed and installed to provide intense coherent THz undulator radiation. By optimizing the bunch length, we found that it is possible to generate a coherent undulator radiation that contains only the fundamental wave from numerical studies. Beam experiment was performed to generate and observe the coherent undulator radiation from extremely short electron bunches. Coherent undulator radiation from 2.6 to 3.6 THz was demonstrated. The preliminary results of the experiment will be reported in this paper.

INTRODUCTION

The relativistic and sub-picosecond electron pulses allows direct production of high intensity, coherent, narrow-band terahertz (THz) radiation by passing the electron beam through an undulator [1]. Using the coherent and narrow-band THz radiation, the various polarization states can be produced for scientific research and applications.

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

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

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 it is given by

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

As the compressed electron bunch is shorter than the radiation wavelength, $f(\lambda)$ is not zero and the radiation power from the electron bunch $P(\lambda)$ has a coherent term that is proportional to N^2.

The accelerator system of t-ACTS consists of a specially designed S-band RF gun [3], an alpha magnet with energy slit, a 3m-long accelerating structure, 2.5m-long linearly-polarized undulator with 25 periods. We experimentally confirmed the production of short electron bunch by measuring the bunch length using a streak camera and analysing spectrum of coherent transition radiation in THz region [4-6]. Generation of coherent undulator radiation is studied and demonstrated at t-ACTS.

UNDULATOR RADIATION FROM SHORT ELECTRON BUNCHES

An electric field and spectrum of undulator radiation can be calculated from an electron beam motion and the undulator parameters. The Lienard Wiéchert potential describes the electromagnetic effect of a moving charge. To obtain the electron beam motion, a magnetic field of undulator is derived by a three-dimensional magnetic field calculation program with magnetic charge method [7], and the electron trajectory in the undulator field is calculated with relativistic equation of motion using the Runge-Kutta method. The radiation field and spectrum are calculated for Gaussian bunch with σ_t = 100 fs. An electron energy, K-value and number of periods of undulator were 30 MeV, 3.88 and 25, respectively. Wavelength of fundamental radiation was approximately 120 μm (2.5 THz). Figure 1 shows the electric fields and spectrum of undulator radiation, respectively. By adjusting the bunch length relative to wavelength of fundamental radiation, the higher harmonics can be supressed and the time profile of the electric field become almost sinusoidal wave as in case of σ_t = 100 fs.

We evaluate the intensity of coherent undulator radiation for the case of 100 fs Gaussian bunch. Macropulse duration is 2.0 μs and it contains about 5700 microbunch. Radiation wavelength for fundamental is 120 μm (2.5 THz) and the pulse duration of the radiation is 10 ps

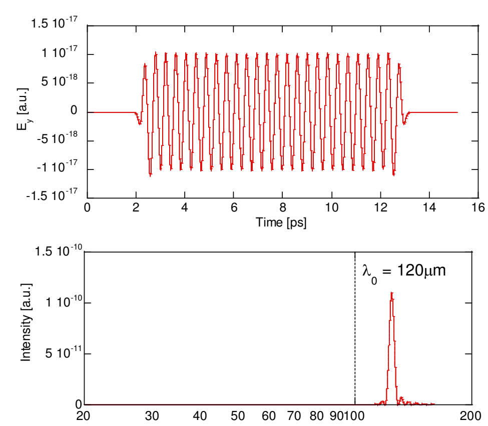

Figure 1: Electric field (up) and radiation spectrum (down) of undulator radiation from Gaussian bunch of σ_t=100 fs.

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containing 25 wave cycles. The radiation energy in a micropulse and macropulse are 8.4 nJ and 48 μJ, respectively.

EXPERIMENTAL SETUP

Experimental Apparatus

Figure 2 shows the experimental setup. Mechanical actuators allow the aluminium (Al) coat mirror to be inserted in beamline to generate the transition radiation and to reflect the undulator radiation. The actuators with Al coat mirror are shown as PRM(TR) in Fig. 2. One Michelson interferometer (M1) was installed to measures the bunch length at the beam line upstream of the undulator and another (M2) was installed to measure the undulator radiation. The transverse beam size was measured using beam profile monitors (PRM) with phosphor screen and CCD camera. Diamond window with 300 μm thickness is employed to extract THz radiation. Measurements of the radiation in THz region are done using pyroelectric detector (THZ1I-BL-BNC [Gentec-EO]).

Extremely Short Bunch Generation

In velocity bunching, a bunch length after acceleration strongly depends on the initial distribution in longitudinal phase space of electron beam and the injection phase into accelerating structure. In this experiment, the beam injection phase into the accelerating structure was adjusted to produce short electron bunch by maximizing a radiation power of coherent transition radiation (CTR) at the diagnostic section. From the spectrum of the CTR, the electron bunch was compressed down to 100 fs, approximately. In this experiment, beam energy, bunch charge of micropulse, macropulse length and number of bunches in macropulse are 30 MeV, 3~4 pC, 2.0 μs and 5700, respectively.

Terahertz Undulator

We have developed the THz undulator, which is a planer undulator of Halbach type made only of permanent magnet (Nd-Fe-B) blocks with TiN coating [8]. The longitudinal magnetized blocks were installed at both ends of the undulator to align the injection axis with the oscillation axis of beam. The undulator gap changes horizontally, therefore the electron beam oscillates in vertical plane. The period length of the undulator and the number of periods are 100 mm and 25, respectively. Each magnet block size is 110×65×25 mm^3. The gap can be changed in the range of 54~110 mm and a minimum gap is limited for installation of beam pipe. The peak of magnetic field

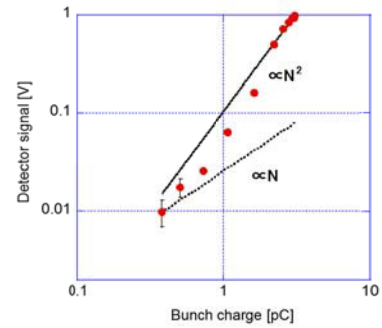

Figure 3: Beam current dependence of the undulator radiation. The solid and dashed lines indicate the expected quadratic and linear dependence, respectively.

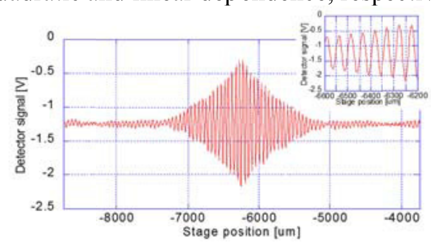

Figure 4: Measured interferogram of undulator radiation.

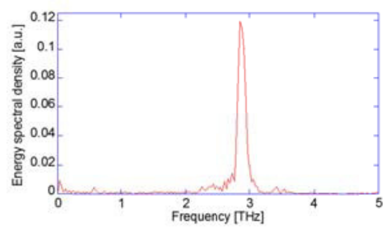

Figure 5: Frequency spectrum of undulator radiation with K=3.38.

strength is approximately 0.41 T at 54 mm of gap. A magnetic field of the undulator provide a natural focusing for electron beam, and the focusing strength is determined by the strength of undulator field and beam energy. The natural focusing is one significant issue for THz undulator. To keep a small beam size of electron beam in the undulator, Twiss parameter of injection beam should be optimized to compensate the natural focusing.

CHARACTERIZATION OF COHERENT UNDULATOR RADIATION

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 shown in Eq. (1). To analyze the coherence of the emitted undu-

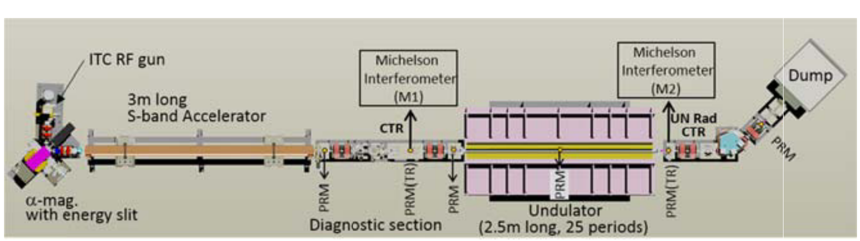

Figure 2: Beam line layout of experimental apparatus.

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lator radiation, the signal of the pyroelectric detector was recorded as a function of the electron beam current measured using a fast current transformer (FCT) at the entrance of the undulator. The beam current was varied using mechanical slit which located downstream of the accelerating structure. In Fig. 3, the radiation intensity is plotted as a function of the microbunch charge. The solid line shows what is expected for a coherent radiation ($\propto N^2$). The output power clearly increases as the square of the bunch charge, confirming the occurrence of coherent undulator radiation.

Frequency Spectrum

The frequency spectrum of the undulator radiation was measured in Michelson interferometer (M2). As the optical path length of one arm of the interferometer is varied by changing mirror position, the interferometer generates the interferogram of the radiation pulse. Entire of interferometer system is enclosed and continually purged with dry nitrogen to avoid the strong absorption of THz wave by water vapor. Figure 4 shows the measured interferogram, moving the mirror in 5 μm steps over 5 mm. This interferogram indicates that coherent undulator radiation was being produced. Figure 5 shows a frequency spectrum of the undulator radiation and a frequency resolution of the spectrum was 29.97 GHz. Center frequency of the radiation was approximately 2.88 THz (λ = 105 μm) and a frequency spread was 0.13 THz (FWHM).

By changing undulator gap, the frequency shift of the undulator radiation was investigated. The frequency of the radiation as a function of undulator strength parameter is shown in Fig. 6. The curve fitting was carried out for the measured data to find beam energy. Derived beam energy from the fit was 31.1 MeV agreeing with the measured 30 MeV in this experiment.

Spatial Distribution and Polarization

Spatial distribution of undulator radiation was measured by scanning detector position across the radiation axis. For this measurement, the pyroelectric detector was located 1.6 m from the center of the undulator. Polarization components in both the vertical and horizontal were measured by installing a wire grid polarizer (GS57207, wire diameter: 10 μm, period: 25 μm, SPECAC) in front of the pyroelectric detector. Frequency of measured undulator radiation was approximately 2.7 THz with K = 3.8.

Figure 7 shows the measured vertical and horizontal polarized components of the undulator radiation. The radiation intensity of vertical polarized component is much stronger than horizontal one. The measured horizontal polarization profile has an intensity peak at center of the distribution. This peak would not be a coherent transition radiation generated at the Al mirror, since the transition radiation has angular divergence ($1/\gamma$) and there is no intensity peak on the radiation axis [6]. Central peak in the horizontal polarization will be due to the transverse emittance of the electron beam. The spatial distribution and polarization properties of the coherent undulator radiation are under investigation.

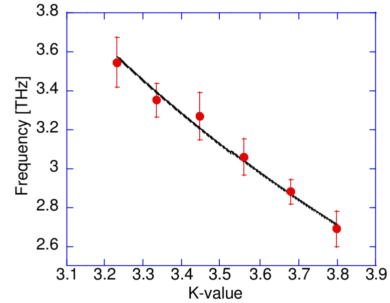

Figure 6: Radiation frequency as a function of undulator strength parameter, fit by the resonance equation.

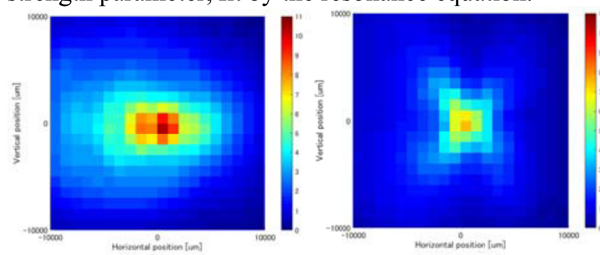

Figure 7: (Left) Vertical and (Right) horizontal polarized components of spatial profile of the undulator radiation.

CONCLUSION

The coherent undulator radiation from extremely short electron bunch has been observed in the 2.6-3.6 THz range. The measurement results showed the properties of coherent radiation such as the radiation intensity having quadratic dependence for the bunch charge and the features interferogram. The vertical and horizontal polarization components of the coherent undulator radiation were also measured using a wire grid polarizer; we continue to investigate the polarization properties of the coherent undulator radiation. Further research for the coherent undulator radiation will lead to new applications of THz light.

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