GENERATION OF COHERENT UNDULATOR RADIATION USING EXTREMELY SHORT ELECTRON BUNCH AT t-ACTS, TOHOKU UNIVERSITY

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Abstract

An accelerator test facility, t-ACTS, was established at Research Center for Electron Photon Science, Tohoku University, in which an intense coherent terahertz (THz) radiation is generated from an extremely short electron bunch. Velocity bunching scheme in a traveling-wave accelerating structure is employed to produce the short electron bunch. 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 developed to produce intense coherent THz radiation. Properties of the radiation from the THz undulator such as an electric field of the radiation, the spectrum and, angular distribution were numerically investigated based on the parameters of short electron bunch and the THz undulator. By optimization of bunch compression, it is possible to extract a coherent radiation of fundamental mode excluding higher-order modes. The detail of the numerical studies for the coherent undulator radiation and a preparation of beam experiment are reported.

INTRODUCTION

The generation of relativistic and sub-picosecond electron pulses allows the direct production of high intensity, coherent, narrow-band terahertz (THz) radiation by passing the electron pulse through an undulator [1]. Using the coherent and narrow-band THz radiation, we can produce various polarization states. Such a THz source is useful for various scientific research and applications.

The accelerator system of t-ACTS consists of an S-band thermionic rf gun, alpha magnet with energy collimation, a 3m-long accelerating structure, 2.5m-long linearly-polarized undulator with 25 periods. The compressed beam is much shorter than the wavelength of THz radiation, and it has a sufficient large form factor for enhancement of coherent radiation power.

EXTREMELY SHORT ELECTRON BUNCH GENERATION

Velocity bunching scheme proposed by Serafini and Ferrario is employed for extremely short electron pulses production [2]. An electron bunch, which is slightly slower than the velocity of light, is injected into the accelerating structure. Since the phase velocity of RF in the accelerating structure is equal to the speed of light, the electron bunch slips backward to the direction of crest phase and starts to accelerate as rotating its longitudinal phase space. The bunch length after acceleration strongly depends on the initial distribution in longitudinal phase space of electron beam and the injection phase into accelerating structure. To manipulate the longitudinal distribution of electron bunch, we have developed an S-band thermionic cathode RF gun, which has two independent cells named ITC (Independently Tunable Cells) RF gun. According to a numerical simulation, ~50 fs bunch can be produced by using the t-ACTS accelerator configuration. Beam experiment of velocity bunching has been carried out by observing sub-picosecond electron pulse using a streak camera. We experimentally confirmed the production of short electron pulse under 500 fs in this measurement [3].

TERAHERTZ UNDULATOR

Undulator is powerful tool for narrow-band radiation source. Radiation wavelength depends on the electron beam energy and undulator parameters. To produce the THz radiation, electron beam energy should be lower, while K-value and period length have to be large. 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. 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 and 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 44~110 mm. In actual experiment, minimum gap is set to 54 mm to keep an aperture for installation of beam pipe. The peak of magnetic field strength is 0.41 T at gap = 54 mm. This undulator produces the terahertz radiation and its wavelength is 300~136 μm (1.0~2.2 THz) with 19 MeV electron beam.

UNDULATOR RADIATION FROM SHORT ELECTRON BUNCHES

An electric field and spectrum of radiation were calculated from an electron beam and the undulator parameters. The Lienard Wiéchert potential describes the electromagnetic effect of a moving charge. The electric field generated by moving electron is derived by following equation [4, 5],

$$\boldsymbol{E}(t) = \boldsymbol{E}_v(t) + \boldsymbol{E}_a(t) = \frac{e}{4\pi\varepsilon_0}\left[\frac{(1-\beta^2)\cdot(\boldsymbol{n}-\boldsymbol{\beta})}{R^2(1-\boldsymbol{n}\cdot\boldsymbol{\beta})^3} + \frac{\boldsymbol{n}\times\{(\boldsymbol{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}}\}}{cR(1-\boldsymbol{n}\cdot\boldsymbol{\beta})^3}\right]_{ret} \quad (1)$$

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where R and $\boldsymbol{n}$ are the distance and direction, respectively, from the electron to the observation point. In Eq. (1), the suffix *ret* means that the equation is computed at the retarded time *t'* related to the observer time *t* by *t' = t - R(t')/c*. First term, which depends on the velocity of electron, is neglected. Because the velocity field is much smaller than the acceleration field. The spectral of radiation is given by

$$\frac{d^2I}{d\omega d\Omega} = \frac{e^2}{4\pi\varepsilon_0 c}\left|\frac{1}{2\pi}\int_{-\infty}^{\infty}\frac{\boldsymbol{n}\times\{(\boldsymbol{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}}\}}{(1-\boldsymbol{n}\cdot\boldsymbol{\beta})^2}e^{i\omega(t-\boldsymbol{n}\cdot\boldsymbol{r}(t)/c)}dt\right|^2 \quad (2)$$

A magnetic field of undulator was derived by a three-dimensional magnetic field calculation program with magnetic charge method [6], and the electron trajectory in the magnetic field is calculated with relativistic equation of motion using the Runge-Kutta method.

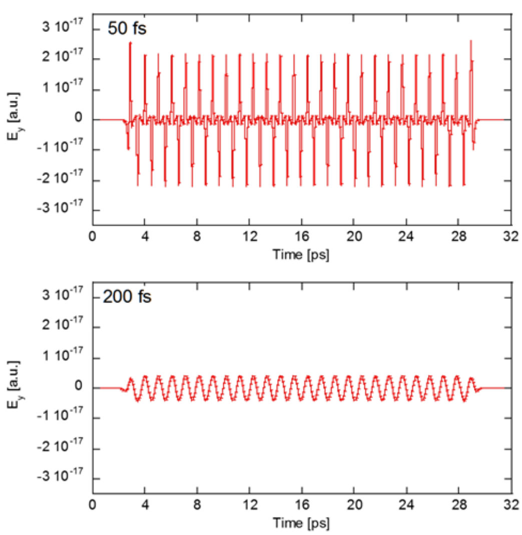

Figure 1: Electric fields of undulator radiation from Gaussian bunch with σ_t = 50 fs (up) and 200 fs (down).

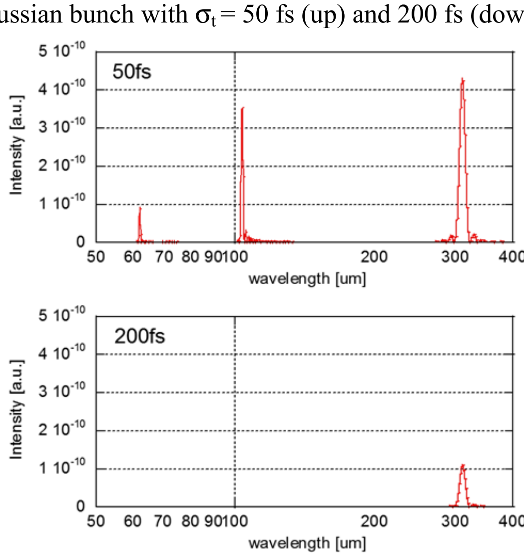

Figure 2: Radiation spectrum for Gaussian bunch with bunch length σ_t = 50 fs (up) and 200 fs (down).

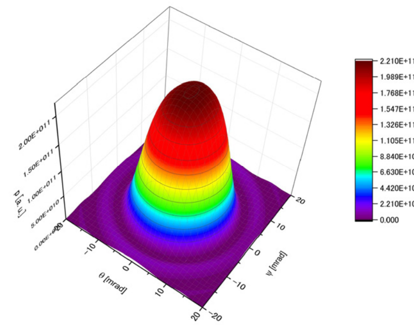

Figure 3: 3D-plot of the angular distribution of undulator radiation for fundamental mode.

Spectrum of undulator radiation can be derived by the Fourier transform of the electric field. The radiation field and spectrum were calculated for the Gaussian bunch with σ_t = 50 fs and 200 fs. An electron energy and K-value of undulator were 19 MeV and 3.88, respectively. Wavelength of fundamental radiation was approximately 310 μm (0.97 THz). Figure 1 and 2 show the electric fields and spectrum of undulator radiation, respectively. In the case of 50 fs bunch, the radiation spectrum includes higher harmonics. By adjusting the bunch length relative to wavelength of fundamental radiation, the higher harmonics of radiation can be supressed and the time profile of electric field became almost sinusoidal wave as in the case of σ_t = 200 fs.

The angular distribution for the fundamental mode of undulator radiation was calculated with E = 19 MeV and K = 3.88 [7]. Figure 3 shows 3-D plot of the angular distribution for the fundamental mode. The angular spread of the undulator radiation (σ_U) is less than 10 mrad. The divergence of radiation is not so large, however we need to consider carefully about an optical transport system including a vacuum window for THz radiation.

PREPARATION OF BEAM EXPERIMENT

Experimental Setup

Figure 4 shows the experimental setup. Mechanical actuators allow Al coat mirror to be inserted in beamline to generate transition radiation and reflect the undulator radiation. The actuators with Al coat mirror are shown as PRM(TR) in Fig. 4. One Michelson interferometer (M1) has been installed to measures the bunch length before the undulator and another (M2) will be 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.

Characterization of Electron Beam

Acceleration phase was tuned to make the minimum bunch length. Microbunch charge and energy of electron beam were 4 pC and 30 MeV, respectively. The transverse emittance was measured by quadrupole scan downstream of accelerating structure using PRM(TR). Normalized emittance were $\gamma\varepsilon_x = 2.2\pm0.2$ πmm mrad and $\gamma\varepsilon_y =$

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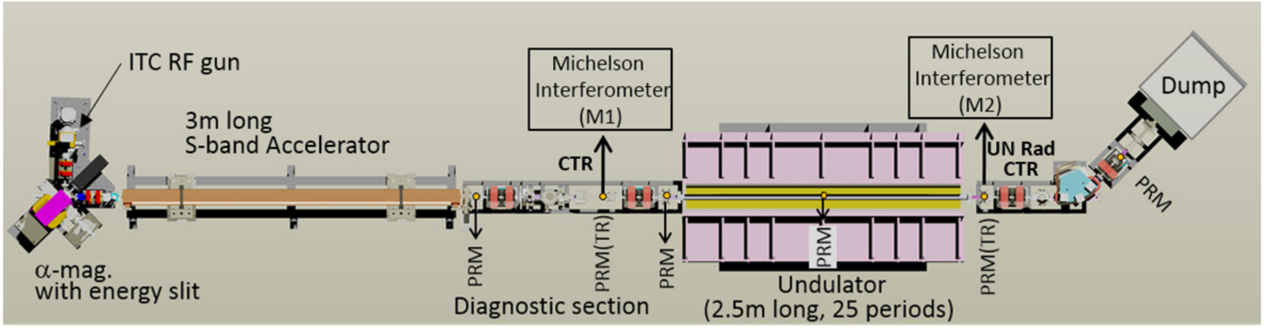

Figure 4: Beam line layout for coherent undulator radiation measurement.

9.4±0.7 πmm mrad, and Twiss parameter are α_x / α_y = -9.9±2.0 / -10.2±0.4 and β_x / β_y = 19.4±4.0 m / 10.8±0.4 m. Measured vertical emittance was four times larger than one in horizontal. The cause of this difference is currently under investigation.

Michelson interferometer was installed to diagnostic section to measure a bunch length and a radiation spectrum of transition radiation. The radiation spectrum was obtained from the Fourier transformation of the interferogram. In preliminary experiment, we could observe coherent transition radiation and the frequency of radiation reached to around 3.5 THz. The spectrum suggests us that the electron beam is shorten to around 100 fs [8].

Optics Matching for Injection Beam

A magnetic field of the undulator provide a natural focusing for electron beam and the focusing strength is determined by a strength of undulator field and beam energy. The natural focusing is one significant issue for THz undulator. To keep a small beam size in the undulator, Twiss parameter should be optimized to compensate the natural focusing. The natural focusing k_x is 8.62 m^{-2} for B_u = 0.41 T and E_b = 30 MeV, and the matching condition at the entrance of undulator in horizontal and vertical directions are α_{x0} = 0, β_{x0} = 0.341 and α_{x0} = 1.73, β_{x0} = 2.89, respectively. From the results of quadrupole scan, we tried to found an optics setting for four quadrupoles before the undulator. Figure 5 shows the β-functions along the beamline from accelerator exit to entrance of undulator with matching condition. We confirmed that it is possible to transport the electron beam and to match the beam parameters at entrance of undulator.

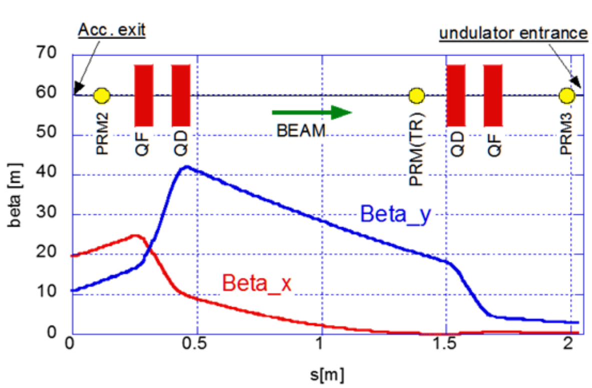

Figure 5: Beta functions along the beamline.

Expected Coherent Undulator Radiation

We evaluate an intensity of coherent undulator radiation using measured electron beam parameters. Macropulse duration is 2.0 μs and it contains about 5700 microbunch. The length of microbunch (σ_z) is assumed to 100 fs. The undulator gap and peak magnetic field are 54 mm and 0.41 T.

Radiation wavelength for fundamental is 120 μm (2.5 THz) and the pulse duration of radiation is 10 ps including 25 wave cycles. Time profile of the electric field of radiation is almost sinusoidal wave. The radiation energy of micropulse and macropulse are 8.4 nJ and 48 μJ, respectively.

CONCLUSION

We are conducting development of accelerator based coherent THz source at t-ACTS. Short electron bunch have been produced by velocity bunching, and the coherent transition radiation from the short bunch have been observed and its spectrum was measured. Numerical studies for coherent undulator radiation were also performed using t-ACTS parameters. It was found that it is possible to obtain the coherent undulator radiation of only fundamental excluding higher harmonics by adjusting the appropriate bunch length. As preparation of beam experiment, we characterized the electron beam and the condition of injection beam into undulator was defined from measured beam parameters. After the construction of second interferometer (M2), we will implement the experiment to observe coherent undulator radiation.

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