MEASUREMENT OF COHERENT SMITH-PURCELL RADIATION USING ULTRA-SHORT ELECTRON BUNCH AT t-ACTS

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Abstract

The coherent Smith-Purcell radiation (SPR) emitted as a short electron bunch passes over a periodic metal surface is expected to be applied as a non-destructive beam diagnostic tool. The longitudinal profile of the electron bunch can be deduced by the measured spectrum of the coherent SPR, which is compared with the theoretical one for single electron. There are several theoretical models that explain the SPR mechanism, such as the surface current (SC) model and the van den Berg model. But the difference of estimation in radiation intensity between different models is not trivial, and also the experimental data to evaluate those validity is not enough. At test accelerator, t-ACTS, in Tohoku University we are conducting experimental research on coherent SPR in the terahertz frequency region using an ultra-short electron bunch of about 100 fs. As a result of the measurement, the reasonable response of the CSPR angular distribution with the change in bunch length in the 100 FS region was con-firmed. On the other hand, the observed angular distribution and the calculated results show different peak positions and shapes especially for the longer bunch length. From these results, we confirmed the usefulness of SPR as a non-destructive bunch length measurement, and we plan to conduct additional experiments to confirm the difference from the SC model.

INTRODUCTION

Smith-Purcell radiation is supposed to be applicable to non-destructive beam monitors [1-3]. It is also expected that a single shot measurement is possible and the measurement system can be constructed compactly. So far, most of the bunch length measurements by CSPR have been performed in the sub-ps region and no measurements have been made with bunch lengths less than 100 fs. In order to obtain the information of the longitudinal bunch shape (bunch form factor) in the frequency domain, the measured spectrum of coherent radiation has to be compared with the theoretical one. Although the SC model is widely used in many experiments in bunch length measurement, there are differences in the evaluation of radiation intensity between models [4], and thus it seems that the validity of a specific model has not yet been established. Therefore, we decided to conduct experiments to measure the bunch length in the fs region using SPR. CSPR was generated by an ultra-short electron bunch (80~150 fs) at t-ACTS and its angular distribution was compared with the calculation based on the SC model in order to investigate its practicality as a non-destructive bunch length monitor.

SMITH-PURCELL RADITAION

The Smith-Purcell radiation is obtained when electrons pass over a metal surface with a periodic structure [5]. SPR is characterized by a dispersion relation between the radiation wavelength and the radiation angle. The relationship between the radiation wavelength λ_n and angle θ is given by

$$\lambda_{\mathrm{n}} = \frac{d}{n}\left(\frac{1}{\beta} - cos\theta\right), \quad (1)$$

where β is v/c, d is the period length of the periodic structure, and n is the order of the radiation.

In the SC model [6], which explains SPR through the currents that are being induced on the surface of the grating by a charge passing near-by, the energy dI emitted per unit solid angle dΩ by a single electron passing at a distance h above the grating is given by

$$\left(\frac{dI}{d\Omega}\right)_1 = 2\pi q^2 \frac{Z}{l^2}\frac{n^2\beta^3}{(1-\beta cos\theta)^3} R^2 \exp\left(-\frac{2h}{\lambda_e}\right), \square \quad (2)$$

where Z is the length of the grating, q is the electron charge and R^2 is a grating factor depending on the shape of the grating. The quantity λ_e in the Eq. (2) is "evanescent wavelength" and defined by

$$\lambda_e \equiv \left(\frac{4\pi}{\gamma\beta\lambda_n}\sqrt{1+\gamma^2\beta^2\sin^2\theta\sin^2\phi}\right)^{-1}. \square \quad (3)$$

The intensity of the SPR decays with the distance between the bunch and the grating surface.

In the case of a bunch consisting of N_e electrons, the emitted energy per solid angle is given by

$$\left(\frac{dI}{d\Omega}\right)_{N_e} = \left(\frac{dI}{d\Omega}\right)_{sp} [N_e + N_e(N_e-1)f(\omega)]. \quad (4)$$

For the bunch length sufficiently shorter than the wavelength of radiation, the radiation is coherently enhanced and its intensity is proportional to the product of the square of N_e and the bunch form factor *f(ω)* as written in the Eq. (4). The bunch form factor *f(ω)* is defined as the Fourier transform of the longitudinal particle distribution within the bunch. From the dispersion relation between radiation angle and frequency, the angular distribution of CSPR reflects the form factor. Therefore, we can get the information of bunch length from the angular distribution

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of CSPR. The period of the grating used and the observation angle range need to be determined according to the desired bunch length region.

EXPERIMENT

t-ACTS

At t-ACTS (test Accelerator as Coherent THz Source) facility, ultra-short electron beams of less than 100 fs can be generated by velocity bunching method, and the R&D works for terahertz light sources and beam monitors are conducted based on this ultra-short electron bunch [7]. In the velocity bunching method, the bunch length can be adjusted by the injection phase of the beam to the accelerating structure. The t-ACTS linac consists of a thermionic rf gun, an alpha magnet with an energy filter and a 3 m traveling-wave accelerating structure. Table 1 shows the beam parameters. A diagnostic section for measuring bunch length by observing the coherent transition radiation (CTR) spectrum using a Michelson interferometer is provided downstream of the accelerating structure, and a grating that generates SPR is installed 1 m downstream of it, 1 m upstream of the SPR chamber.

Table 1: Beam Parameters

Macro-pulse duration	~2.0 μs
Number of bunches	~5700 (per macro-pulse)
Beam energy	20 MeV
Beam emittance	~3 πmm mrad
Bunch charge	3 ~10 pC
Bunch length (σ_t)	80~100 fs

Experimental System

Figure 1 shows the layout to measure the angular distribution of the CSPR. The electron beam passes near the grating surface in the chamber, and then the generated CSPR is extracted through the TPX window. In order to reduce the absorption of THz waves by water the entire optical system outside the vacuum was purged with dry air. CSPR was detected by pyroelectric detector THZ5I-BL-BNC (Gentec-EO), which has high sensitivity and wide bandwidth in the terahertz frequency region. For the measurement of the angular distribution of the CSPR, this THz detector can be moved to scan the angle from 66 to 96 deg, keeping the optical path length to 400 mm. For the measurement of the frequency spectrum of CSPR, whole system was replaced to the Michelson interferometer.

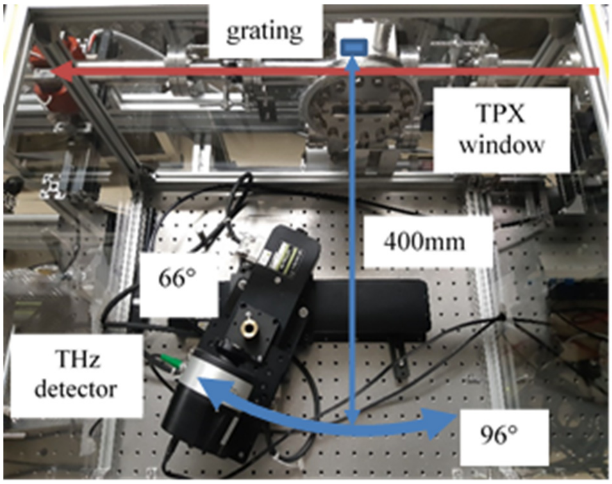

Figure 1: SPR measurement system.

The grating block was made of aluminum alloy and fabricated to have a pitch of 200 μm as shown in Fig. 2. The inclination angles of the gratings G1 and G2 are 12 degrees and 30 degrees, respectively. The wavelength of the SPR emitted from G1 at an observation angle of 90 degrees is 1.5 THz. The number of grooves is 60. This block was mounted on the movable base to adjust the distance between the beam and the grating surface as shown in Fig. 2 (lower).

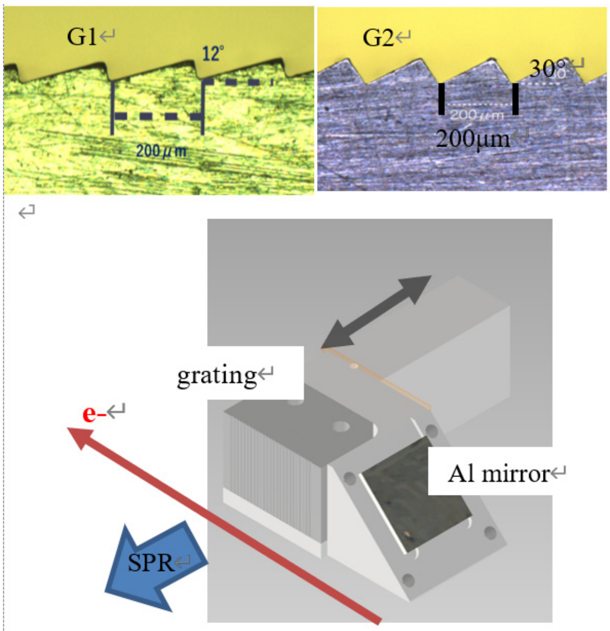

Figure 2: Grating profile of G1 and G2 (upper) and movable system (lower).

MEASUREMENT

Figure 3 shows the measured CSPR spectrum for the grating G1. The interferogram of CSPR emitted at the 90 degrees direction is shown in Fig. 3 (left). The corresponding frequency spectrum is also shown in Fig. 3 (right). The measured frequency of CSPR is about 1.53 THz, which is well consistent with the expectation for the SPR from the grating with a period length of 200 µm.

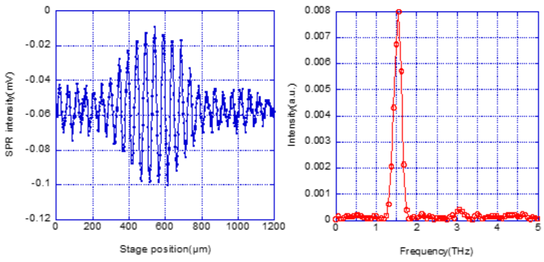

Figure 3: Interferogram (left) and corresponding spectrum (right) of measured CSPR.

The measurement results of the bunch length dependence of the CSPR intensity are as follows. The upper graph in Fig. 4 shows the calculated angular distributions for the Grating G1 based on the SC model. In the calculation, the bunch length was varied from 110 to 160 fs as shown by the different color lines.

The lower left graph in Fig. 4 shows the angular distributions of CSPR from G1 measured at different bunch length. The lower right graph in Fig. 4 is normalized by the strength at 192 fs. The SPR intensity in the shorter wavelength region more decreases than longer part as the bunch length increases, thus the overall behavior regarding the bunch length response looks consistent with the expectation. This suggests that the CSPR observation can be applied to bunch length monitoring in the THz region.

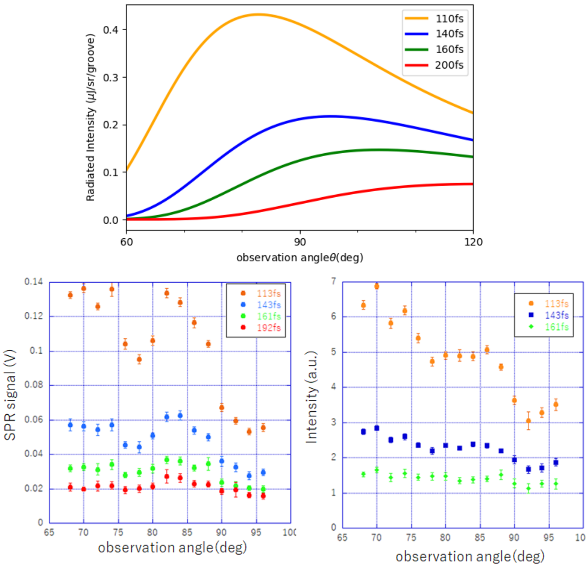

Figure 4: Angular distributions for the SC model (upper) and measurement results for grating G1 (lower).

However, looking at the angular distribution, there is a discrepancy between the measurement and the model calculation. The background that affects the measurement is important because the signal intensity of the SPR is generally very weak. The background of the coherent diffraction radiation from the edge of the grating block may have a significant effect. We fabricated the dummy block without grating, and the additional measurement is now under preparation to confirm the effect of the diffraction radiation.

Figure 5 shows the results of measuring the angular distribution of CSPR from gratings with of different inclination angles. The measurement results are normalized to the maximum value in the angular distribution for G1 calculated by the SC model. According to the calculation by the surface current model, the intensity for G2 was expected to be several times that for G1, but the measured signal strengths were similar level to each other. In the derivation of the bunch form factor, it is essential to evaluate the spectrum by model calculation, so further measurements are required to confirm the validity of the SC model calculation.

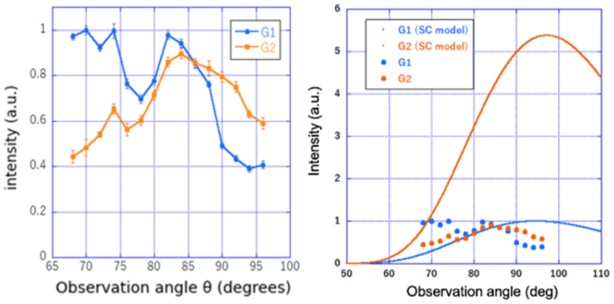

Figure 5: SPR measurement results using gratings G1 and G2 with different inclination angles (left) and Comparison with calculation results of SC model (right).

CONCLUSION

Coherent Smith-Purcell radiation has a definite advantage of the beam nondestructive and single shot capability for the beam monitor.

We observed CSPR in the terahertz frequency region from the ultra-short electron bunches with the bunch length of about 100 fs and confirmed the expected response of the intensity distribution with respect to the bunch length. However, the measurement also shows some disagreements with the SC model calculation, so that the additional measurements are under the preparation. Since the signal intensity of CSPR is rather weak, the background of diffraction radiation from the edge of the grating block may have a large effect, and preparations for additional measurements are underway. Improving the measurement system is also an issue to check the validity of the SC model calculation, thus the SPR chamber are going to be replaced to cover the wider range of observation angle.

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