STUDY OF BUNCH LENGTH MEASUREMENT BY FORWARD COHERENT SMITH-PURCELL RADIATION

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Abstract

A bunch length monitor with non-destructive and single-shot capabilities using the Coherent Smith-Purcell Radiation (CSPR) is under development at the Research Center for Electron Photon Science, Tohoku University. Since the angular distribution of CSPR reflects the longitudinal bunch length, it is expected that measurements of the peak position of the emission angle can be used to discriminate changes in the bunch length, which making it possible to monitor relative bunch length fluctuations. A concept of the monitoring system and the status of preliminary measurements for development are presented.

INTRODUCTION

So far, the attempts for a bunch length measurement using the coherent radiation have been studied by many researchers, with the radiation sources including the Smith-Purcell Radiation (SPR) [1-4]. For reliable bunch shape measurement with CSPR, it is necessary to know a grating factor accurately. The grating factor is a complicated function that depends on the grating geometry and the radiation angles, which is generally obtained only numerically, and the obtained results depend on the model used and are not clear so much [5]. Apart from the absolute bunch shape measurement, non-destructive and single-shot measurement would be useful for beam control in accelerators, even if it could only monitor relative fluctuations of the overall bunch length. Such application may be found in next-generation plasma-based accelerators, which can produce ultra-short bunch with the fs level but tend to be less stable from shot-to-shot [6]. It is expected that such monitor can be realized by adopting SPR. It is also worth noting that, in CSPR spectrum measurement, a compact measurement system can be constructed, because a separate spectrometer is not required unlike other radiation such as transition radiation. We aim to study experimentally whether such application of CSPR is possible at a test accelerator, t-ACTS, which can stably generate a short bunch beam less than 100 fs in average by applying the velocity bunching to a multi-bunch beam from a thermionic RF-gun. In the following, we describe the concept for monitoring the relative bunch length variation and then present the status of preliminary measurements for the development.

BUNCH LENGTH VARIATION MONITOR

Smith-Purcell Radiation

SPR is obtained when electrons pass over a metal surface with a periodic structure [7] and has a characteristic

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relationship between the radiation wavelength λ_m and the polar observation angle θ;

$$\lambda_m = \frac{d}{m}\left(\frac{1}{\beta} - \cos\theta\right) \quad (1)$$

where β is v/c, d is the period length of the periodic structure, and m is the order of the radiation. In the Surface Current (SC) model [8] the energy dI emitted per unit solid angle $d\Omega$ by a single electron passing at a distance h above the grating is given by

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

where Z is the length of the grating, q is the electron charge and R^2 is the grating factor. The quantity λ_e in Eq. (2) is "evanescent wavelength" and defined with the azimuthal angle ϕ by

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

Bunch Length Variation Monitor Using CSPR

Since the emission angle of SPR has a dispersion relation as shown in Eq. (1), the change in bunch length can be observed as the difference in peak position in the angular distribution of CSPR intensity. Figure 1 (a) shows an example of the angular distribution for the various bunch lengths calculated based on the SC model, with $d = 600$ μm, $h = 500$ μm, and beam energy and charge of 20 MeV and 10pC, respectively. The grating period affects not only the radiation intensity but also the shape of angular distribution through the grating factor, so it must be determined in consideration of actual experimental conditions. The 600 μm period in this preliminary measurement was determined by two points: the magnitude of the change in peak angle when the bunch length was changed, and the limitation of the angular range for detecting radiation in the current setting. The single-shot measurement can be realized by placing multiple detectors on the circumference with different
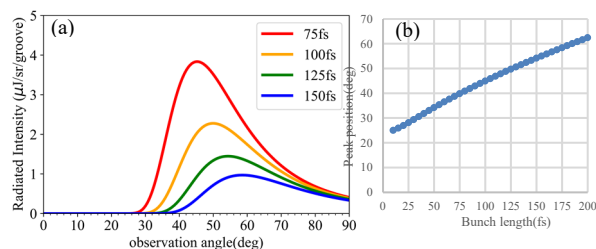

Figure 1: Calculated angular distribution of SPR for various bunch length; 75fs, 100fs, 125fs, and 150fs(a) and dependence of the bunch length on the peak position of emission angle of CSPR (b).

emission angle and measuring them simultaneously. Figure 1 (b) shows the dependence of bunch length on the peak emission angle for the case in t-ACTS. If the peak angle can be measured with a resolution of 5 degrees, a bunch length difference of 25 fs can be distinguished.

EXPERIMENT

t-ACTS

The multi-bunch electron beam generated by a specially designed rf-gun (ITC-RF gun [9]) and an alpha magnet can be compressed to very short bunch less than 100 fs by further applying velocity bunching in a 3m long accelerating structure [10]. Table 1 shows the beam parameters in t-ACTS. The SPR chamber is located 2 m downstream from the exit of the accelerating structure.

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)	80~100fs

Experimental Setup

Before demonstrating the single-shot measurement, we first perform a preliminary measurement to make sure that the response of the bunch length can be observed properly. For this purpose, a single detector was scanned over an emission angle of about 30 to 90 degrees in the experiment. Another purpose of this preliminary experiment is to investigate the effects of background caused by the beam. A sawtooth-shaped grating with a pitch of 600 μm and an inclination angle of 12 degrees was prepared. The frequency of the SPR emitted from this grating at an observation angle of 60 degrees is estimated to be 1THz. The number of grooves of the grating is 20. This grating block was mounted on the movable base to adjust the distance between the beam and the grating surface. A screen for observing the position and profile of the beam is installed on the same movable base. Figure 2 shows the layout to measure the angular distribution of the CSPR. To cover a wider angular range than our previous measurement [11], a Z-cut quartz window with an effective diameter of 100 mm was prepared as shown in Fig. 2 (a). 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 was moved to scan the angle from 32 to 90 deg, keeping the optical path length to 300 mm as shown in Fig. 2 (b). For the measurement of the frequency spectrum of CSPR, entire system was replaced to the Michelson interferometer as shown in Fig. 2 (c). Interferometer can be also moved from 60 to 32 degrees to measure the spectrum at each

emission angle. A background measurement was made by replacing the grating with a "blank" block which has the same geometry, but no grooves on the block surface.
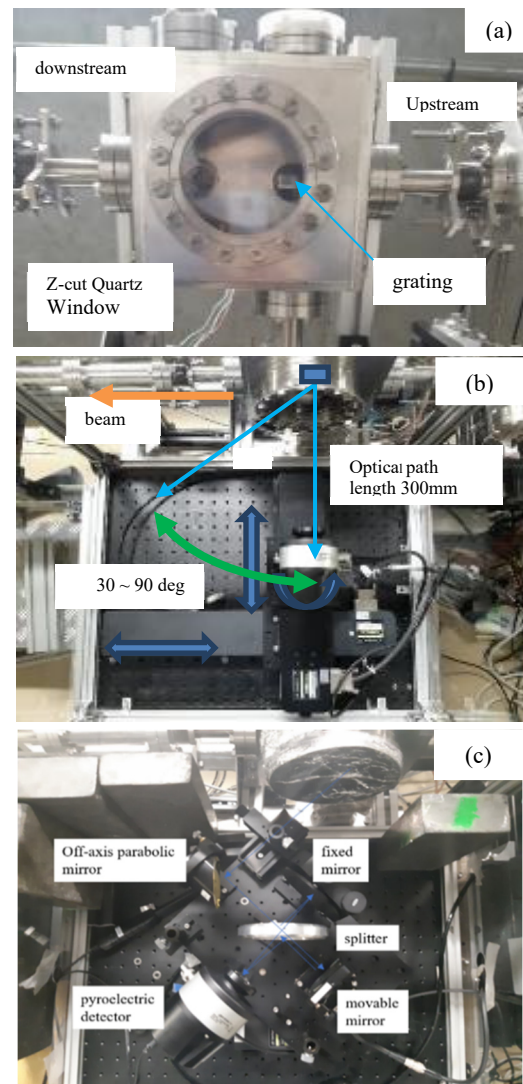

Figure 2: SPR measurement system the front (a) and top view (b), and Michelson interferometer (c).

MEASUREMENT

Figure 3 shows the angular distributions measured with the 600 μm period grating and the blank block. Comparing the radiation intensities from both blocks, we can deduce that the background contribution, including the diffraction radiation generated at the edges of the grating block, is about 10%. Since the transverse beam size at the grating position is less than one-fifth of the beam-grating distance of 0.5 mm, the background due to beam loss at the grating block was less significant than at other positions. As shown in Fig. 1 (a), the decrease of the signal intensity in the smaller emission angle less than 45 degrees looks consistent with the bunch form factor of 100 fs bunch length, but there observed the unexpected structure in the angular distribution. Since there is no similar structure in the BG distribution, CSPR seems to have such a distribution. To confirm the wavelength dependence of the emission angle,
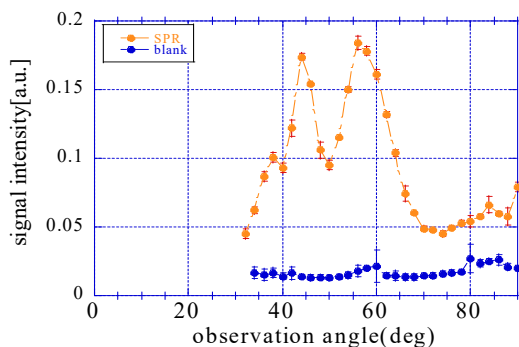
Figure 3: Measured angular distributions with the 0.6 mm period grating and the blank block.

which is the definite feature of SPR, the spectrum was measured while changing the observation angle of a Michelson interferometer. Figure 4 shows an example of the interferogram taken at the observation angle of 60 degrees, which results in a nearly monochromatic radiation spectrum.
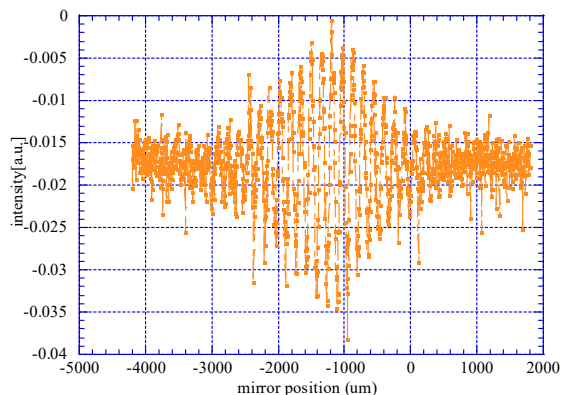

Figure 4: Example of interferogram taken at the observation angle of 60 degrees.

Figure 5 shows the measured spectra for the observation angles at 45, 50, and 60 degrees. The intensity of fundamental mode for 50 degrees is smaller than the others, while the second-order harmonic has a larger amplitude. Figure 6 shows the angular distribution of the total power of the peaks in the SPR spectrum, measured by sweeping the interferometer from 32 to 60 degrees at 2.5-degree steps. The solid line shows the fundamental mode only and the second-order harmonic is included for the dotted line. The angular distribution measured by the interferometer reproduces the same structure as shown in Fig. 3. It was also found that the second harmonic also has a different distribution from the SC model. The observed dispersion relation of the emission angle supports that the observed radiation is CSPR. However, it is unclear whether the experimental setup causes this structure of the angular distribution, or the evaluation based on the SC model is not valid for our current setup. To solve this cause, we are currently considering the preparation of new gratings with a different geometry, and modification of the layout so that the SPR

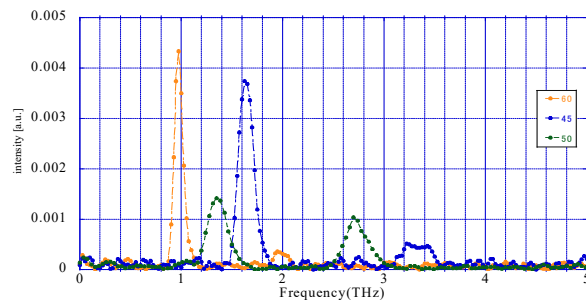does not pass through the vacuum window at a shallow incident angle, etc.

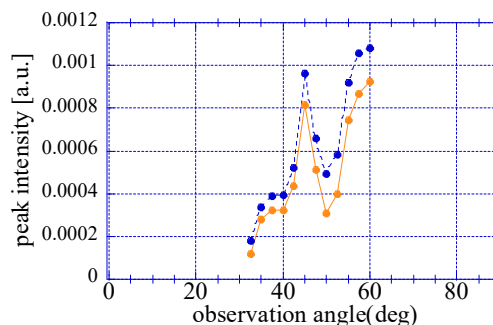Figure 5: Measured spectra for the observation angles at 45, 50, and 60 degrees.

Figure 6: Angular distribution of total power of peaks in SPR spectrum. The solid line shows the fundamental mode only and the second-order harmonic is included for the dotted line.

CONCLUSION

In this study, we are trying to apply a method which can monitor the relative bunch length fluctuations by simply measuring the peak of the emission angle of CSPR. In the preliminary measurement, we observed the angular distribution of CSPR and found that the decrease of the radiation intensity in the smaller emission angle is consistent with the bunch form factor of 100 fs bunch length, apart from the unexpected structure in the distribution. Modifications to the experimental setup are currently under consideration to investigate the cause of the unexpected angular distribution, and then the response of the bunch length to the radiation spectrum will be confirmed in that setup. Further research will be carried out with a view to applying it to monitors for fs-level ultra-short bunches expected in the laser-based accelerators.

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