NON-LINEARITY CORRECTION OF SHOTTKEY DIODE THZ DETECTOR SYSTEM USING CSR BURST FROM STORAGE RING*

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Abstract

We show a practical method to calibrate non-linearity of Schottky diode detector for the short-pulsed THz radiation from the electron storage ring. A frequency distribution of pulse area was measured at three distances of the detector from the radiation source. Non-linearity correction function was obtained by a condition that the three distribution should be the same with non-linearity correction and reduction factor by the distance.

INTRODUCTION

It is known that a high peak current beam in electron storage ring emits burst of coherent synchrotron radiation (CSR) in THz region [1-7]. In comparison with the other methods to produce CSR in electron storage ring, this method supplies higher power and the CSR is easy to be obtained with no special expense. The high peak current is normally obtained in a single bunch or a few bunch operation. Despite these merits of CSR burst, it is not used for experiments. This is because the origin of the CSR burst is a fine time structure in the bunch due to longitudinal beam instabilities, therefore, the burst is not stable. However there had been no quantitative measurements on the bursting power. Then we investigated the time structure or fluctuation to know how unstable the burst is [8], hoping that the bursts would have an application with an appropriate time averaging. In that experiment we needed a fast THz detector so that to separate the burst at each revolution. The detector should have a large dynamic range because the CSR burst ranges for some tens of magnitudes.

There had been some kinds of detectors in THz region, such as Si bolometer, and Pyro element. The response of the fastest one among them was 1 MHz, which was slower than our requirement, 2.5 MHz. Recently developed superconducting hot-electron bolometer [9] had as fast rise time as 10 ps. It was used at electron storage ring BESSY-II [10], however, it was very expensive and not easy to be handled. Our choice was Schottky diode detector for sub THz detection, originally introduced to electron storage ring at BNL [2]. It is commercially available, not much expensive, faster than GHz, easy to use, and has large dynamic range if we apply appropriate non-linearity correction. This paper reports how we correct its non-linearity in our experiments.

The detector itself is as fast as its frequency of the radiation to be detected. It is faster than the recording electronics, an rf amplifier and a digital oscilloscope. In our experiment, the turn-by-turn CSR power was obtained as a short-pulsed signal and recorded by a digital scilloscope for as long as 10ms, roughly equals to the radiation damping time. The recorded signal width, 1.2 ns FWHM, was determined by an rf amplifier and much longer than the width of CSR itself, some tens ns. This means that we do not have accurate information on the pulse width, therefore, we cannot use non-linearity data obtained from DC radiation.

We will show a practical method to calibrate non-linearity of Schottky diode detector for the short-pulsed THz radiation from the electron storage ring. The non-linear correction should depend on the measurement system (analogue amplifier and others) and pulse shape of the radiation itself. This is why we had to use the THz pulse itself for the calibration. This non-linearity was calibrated by a set of measurements at three different distances from the light source point. We assumed that with a constant reduction factor by the distance, the distributions of the corrected CSR power should be the same.

MEASUREMENT IN SIMPLE CASE

Choice of Diode Detector

We used commercially available Schottky diode detector with horn (WR5.1ZBD; Virginia Diode Inc.), which was sensitive to a radiation of 0.14 - 0.22 THz. The signal from the diode was amplified (17dB; 10kHz - 1GHz band) and recorded by a digital oscilloscope (20Gs/s; 2GHz). Fig. 1 shows the typical recorded pulse shape. We observed no explicit dependence of pulse shape on the CSR power.

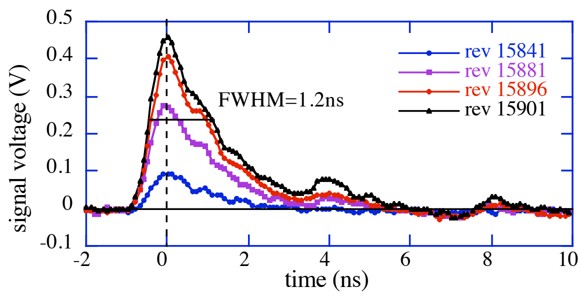

Fig. 1 Power dependence of the recorded pulse shape from WR5.1ZBD. Traces were the shape obtained at different revolutions. The origin of the second peak, 4ns (= 2 rf periods) after the main peak is not known.

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We had the other detector (DXP-08; Millitech Inc.), which was sensitive to a radiation of 0.10 - 0.14 THz. Its response to a much high power pulse was not normal as shown in Fig. 2. The second peak, which shape was not deformed, looked good for the measurement but we do not know its origin, therefore we should not. We gave up using this detector because a non-linearity correction was impossible.

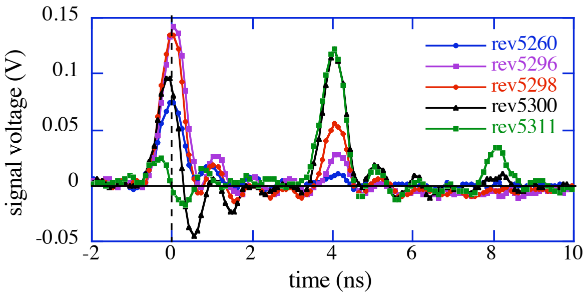

Fig. 2 Power dependence of the recorded pulse shape from DXP-08. For the low-power signal, The area of the main peak was proportional to that of the second peak. At above the threshold, the shape of the main peak was deformed to a bi-polar (or differential) shape shown at rev5311.

Electron Storage Ring

The electron storage ring for the measurement was NewSUBARU (NS), 1.5 GeV synchrotron radiation ring at the SPring-8 site. It was operated with single-bunch, top-up mode at 1.0 GeV during this measurement. Normally the rf acceleration voltage (V_{RF}) at 1 GeV is 100 kV and the linear momentum compaction factor (α) is 0.0012. The natural bunch length, the revolution period, the synchrotron oscillation period and the longitudinal damping time are 17 ps (standard deviation), 396 ns, 200 µs and 12 ms. Fig. 3 shows the typical time structure from one shot of measurement.

Measurement

With a single shot, the signal for 10 ms (=25250 revolutions) was recorded. The results gave relative radiation power for every revolution from the same bunch. The pulse area A_P for each revolution was calculated from the data. Fig. 3 shows example of the results.

RF phase modulation

When the radiation pulse is longer the non-linearity correction should be smaller for the same pulse area, because the peak is lower. This case was realized by applying rf phase modulation with frequency of twice of the synchrotron oscillation ($2fs$) [11]. In this case the radiation power was also modulated with frequency of $2fs$.

We applied the modulation so that to make the bunch structure shown in Fig. 4. The CSR was emitted when the bunch was separate, which means that the pulse width of the original CSR was longer than that of the normal case.

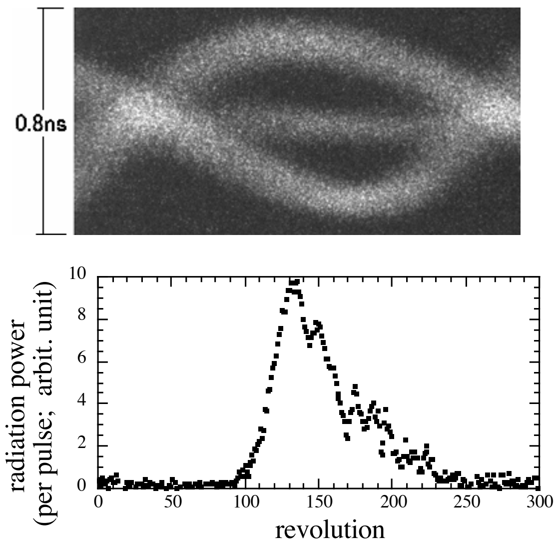

Fig. 4: Three bunches in a bucket (above image) and the CSR timing (below). The vertical axis of the above image is the rf phase.

CALIBRATION OF NON-LINEARITY

We recorded the radiation at three distances, 6 shots (151500 pulses) for each. The fist step of the analysis was to make distribution function of the un-corrected power of pulses. When the un-corrected distribution function $n(A_P)$ dA_P gives the number of pulses which area was between A_P and A_P+dA_P, the integrated distribution $N_A(A_P)$ is defined by

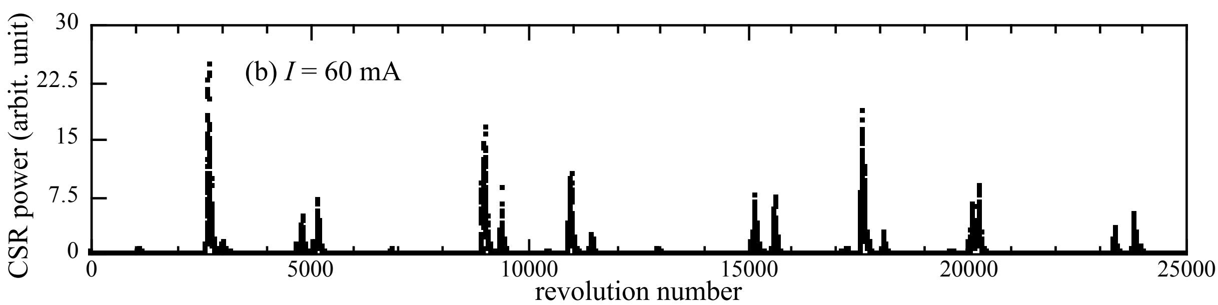

Figure 3: Examples of observed time structure of CSR burst in 10ms with normal ring parameters.

$$N_A(A_P) = \int_{A_P}^{\infty} n(A)dA. \qquad (1)$$

We used a range of non-linear response of the detector and the pulse power P_P was given by a function of A_P. This function is what we want. We assumed that with a constant reduction factor by the distance k_D, the distributions of CSR power should be the same. This factor was not always proportional to the square of the distance because of the absorption of radiation by air.

We found that the exponential non-linearity correction function with one free parameter, k_E,

$$P_P = A_P Exp[k_E \times A_P] \qquad (2)$$

satisfied the above condition. Fig.5 (a) and (b) show N_A without and with the non-linearity correction. N_A at three distances meets with appropriate k_D and with the non-linearity correction. The simple exponential function with one free parameter gave better agreement than any polynomial function with three free parameters.

The correction function was obtained for the normal case and the case with the 2*fs* modulation. The parameters of the correction function are listed in Table I. The distance factor k_D were the same for two cases but the exponential factor k_E was not. This was reasonable because the pulse width would have been smaller with the modulation.

With the non-linearity correction, the dynamic range of the system, determined by the oscilloscope, was enlarged by about a factor of ten.

Table I Parameters for the corrction functions. Three values of k_D are for the measurement with the distances between the light source point to the detector.

machine condition	k_E	k_D
normal	.009	1, 5.8, 11.5
2*fs* modulated	.005	1, 5.8, 11.5

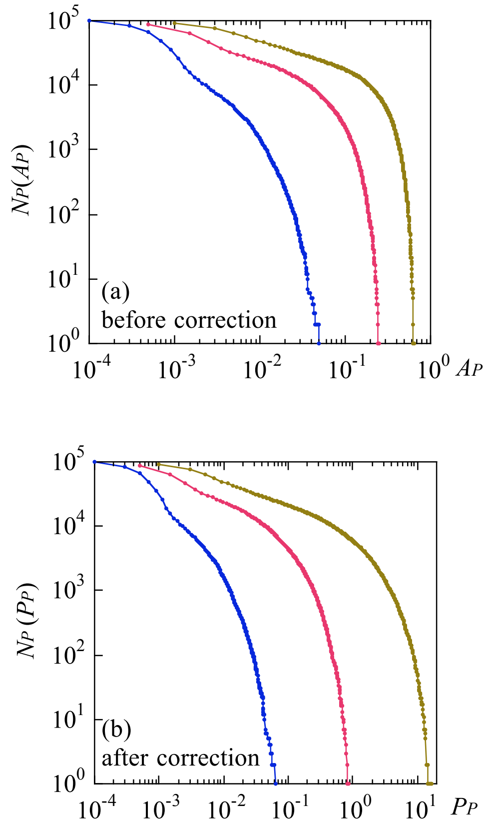

Fig. 5 The distribution function obtained at three different distances from the light source point, (a) without and (b) with the non-linearity correction.

DISCUSSION

This correction was practical because it includes the effect of the frequency range and non-linearity of the measurement system, the rf amplifiers and the oscilloscope.

Through the analysis we had assumed that the original pulse shape of the radiation with the same machine condition were the same. This assumption was not perfect, therefore the correction was not perfect especially for the case with 2*fs* modulation. For more accurate correction we should find a correction function at each sliced modulation phase. However, the present rough correction is enough for our purpose. The pulse with high power radiation almost determined the fluctuation of the power, which would have emitted at the similar condition.

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