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DEVELOPMENT OF AN ON-LINE BUNCH LENGTH MONITORING SYSTEM AT PLS-II USING AN ULTRAFAST PHOTODIODE

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Abstract

Users of time-resolving experiments at 3rd generation synchrotron light sources deem online bunch length and filling pattern monitoring as an important real-time diagnostic. We developed an on-line monitoring system that can measure bunch lengths and filling pattern using a photodiode, a wideband pre-amplifier, and a sampling digitizer. Two different methods were evaluated to reconstruct the bunch lengths: Gaussian deconvolution method as an approximation scheme and Fourier analysis as a method to restore the original signal by using the power transmission characteristics of the electronic devices in the system, including a bias-tee, a wide band amplifier and cables, as well as the photodiode. A bunch lengthening experiment has been conducted to compare and verify the results of those two methods of the photodiode and the result of the streak camera images by changing the overall gap voltage of the superconducting RF cavities. In this paper, we elaborate upon the said photodiode-based measurement techniques, and present the experimental results.

INTRODUCTION

Pohang Light Source (PLS-II) is a 3rd generation light source and is designed to form a bunch train with 470 RF buckets placed 2 ns apart in a synchrotron of 281.82 m (accelerated RF frequency of 500 MHz, harmonic number of 470). Since 2019, to support time-resolving experiments, PLS-II has applied filling-pattern profiling to operation by selectively injecting electron beams into each bucket to control the amount of charge for each bunch. The 1B diagnostic beamline uses a streak camera to observe longitudinal properties of the beam, such as electron beam filling pattern and bunch length. The streak camera has a high temporal resolution and sensitivity, and so is appropriate for fine longitudinal beam measurements; however, it can only manually monitor specific events due to its incapability of making continuous measurements.

Filling pattern measurement mainly uses a beam position monitor (BPM). However, BPM has low resolution, and the signal sum value from 4 pickups makes signal analysis difficult. To solve this problem, at the 2008 Australian Synchrotron, D. J. Peake measured the filling pattern using a photodiode [1]. During normal operation (250~400 mA) of the PLS-II storage ring, the average RMS bunch length is about 19~21 ps. A high-speed readout system is required to measure the single bunch length. Therefore, we built and tested a diagnostic device that continuously measures bunch length and filling pattern information using an ultrafast MSM (Metal-Silicon-Metal) photodiode.

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EXPERIMENTAL SETUP

The simple schematic diagram in Fig.1 (a) presents the filling pattern and bunch length monitoring system with the photodiode. An MSM photodiode (Hamamatsu G4176-03) with a rise time of 30 ps always observes the radiation produced by the bunch train. The optical signal is converted to an electric signal by the photodiode and passes through the Picosecond 5541A 26 GHz bandwidth bias tee and a wide bandwidth amplifier (Mini-Circuits ZX60-14012L) to amplify the low photocurrent. A Pico Technology Picoscope 9404-16, a sampling digitizer, was used as the readout device. Picoscope 9404-16 has a maximum 2.5 TS/s random sampling and 500 MS/s real-time sampling, and 16 GHz analog input bandwidth is suitable for filling pattern and bunch length measurement.

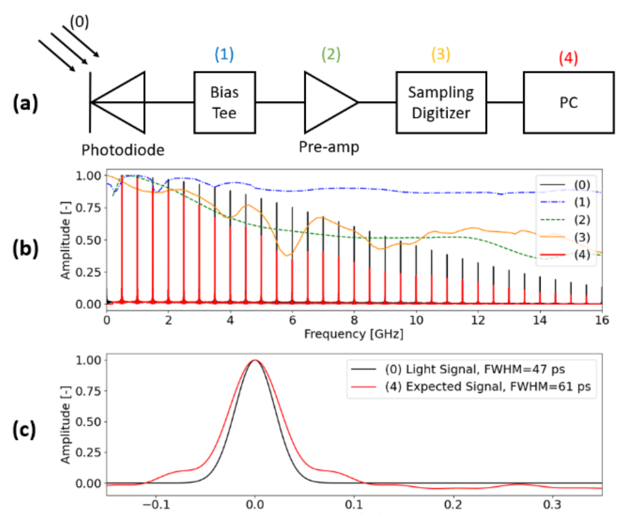

Figure 1: Experimental configuration and signal flow. Synchrotron radiation(0) is incident on the photodiode. The signal passed through the bias tee(1) and amplifier(2) is sampled by the sampling digitizer(3) then, the signal measured by the PC(4) is read. (b) When a Gaussian signal (0) with a standard deviation of 20 ps is input, the spectrum of the signal in (0), (4) and the gain of (1), (2), (3) electronics. (c) The original signal is distorted as it passes through the electronics.

ANALYSIS METHOD

Single bunch length is about 20 ps, and when converted to a frequency band, the bandwidth (-3 dB) is about 10 GHz. The high frequency broadband signal is difficult to accurately measure bunch length because the bandwidth and time constant of electronics are distorting the original

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signal. Figure 1(b) shows the signal distortion process by bandwidth in a bunch length monitoring system. The length and waveform of the gaussian signal change as in (c) due to the gain of bias tee, amplifier, scope, and cable.

The impulse response function was used as the deconvolution kernel for original signal restoration. Assume an input signal(synchrotron radiation) is x(t) and the readout signal is y(t), y(t) can be expressed as a convolution of x(t) and the system response function h(t):

$$y(t) = x(t) * h(t) = \int x(\tau)h(t-\tau)d\tau . \qquad (1)$$

Assuming that both the input signal and the system response function are Gaussian pulses since Gaussian has semigroup properties, the standard deviation of each signal in Eq. (1) is,

$$\sigma_y^2 = \sigma_x^2 + \sigma_h^2, \qquad (2)$$

where σ_y^2, σ_x^2, and σ_h^2 is standard deviation of y, x, and h, respectively.

System response function h(t) consists of the response of N electronics by

$$h(t) = \sqrt{\sum_{i=1}^{N} h_i^2(t)}.$$

However, since information on $h_i(t)$ of each electronics is not required, we can obtain the basis function from the overall system response. If x(t) is a delta function, Eq. (1) is

$$y(t) = x(t) * h(t) = \delta(t) * h(t) = h(t). \qquad (3)$$

Therefore, we measured the RMS length of the basis function h(t) to be 29 ps using a femtosecond laser. It means that if we measure an electron beam length with 20 ps, a scope shows a bunch length with 35 ps by Eq. (2).

As a method of correcting signal distortion due to the gain characteristics of electronics shown in Fig. 1(b), the loss due to attenuation was compensated for using the scattering parameter. In this method, the necessary information is the forward voltage gain in the circuit, so S_{21} of each part was measured using a vector network analyser. The analog bandwidth of the sampling digitizer was estimated by inputting a constant input power using a signal generator and converting the output voltage measured by the digitizer to calculate the attenuation. Fig. 1(b) shows the gain measurement of each electronic including sampling digitizer. Here, we can see attenuation is large at a specific frequency. This underestimates the input power at some frequencies of the broadband signal, resulting in a distorted signal.

Next, a streak camera was used to verify the deconvolution method and to calibrate the results measured by the photodiode. In PLS-II storage ring, jitter of the main RF is about 70 fs, jitter of ¼ rf divider is 465 fs, and Fig. 2(a) shows that 1 sigma length of point spread function of the streak camera is about 3.75 ps. These values were used to find the basis function of the streak camera. Fig. 2(b) is an image taken by accumulating bunch trains under the RF gap voltage of 3 MV and 200 mA operating conditions in the PLS-II storage ring, and the average bunch length is 22 ps.

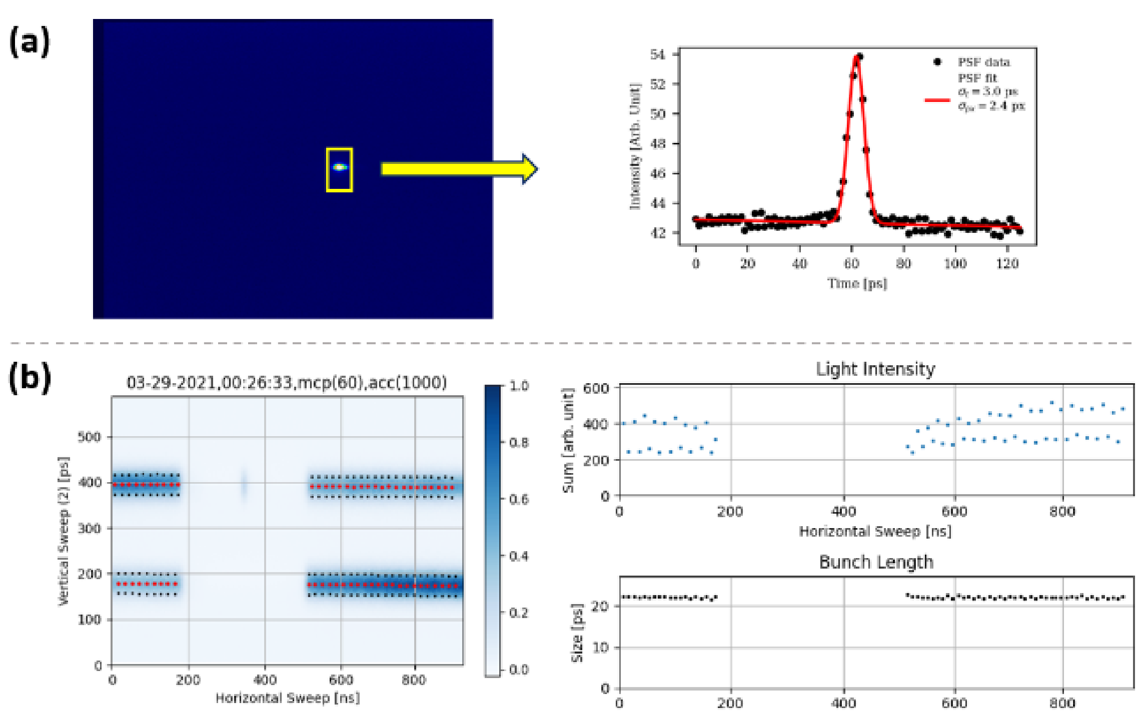

Figure 2: (a) Streak camera focus mode image (left) and PSF obtained by fitting the data (right). (b) Data obtained by accumulating 1000 images of synchrotron radiation by a bunch train with a total length of 1us (left) and each electron bunch length (right).

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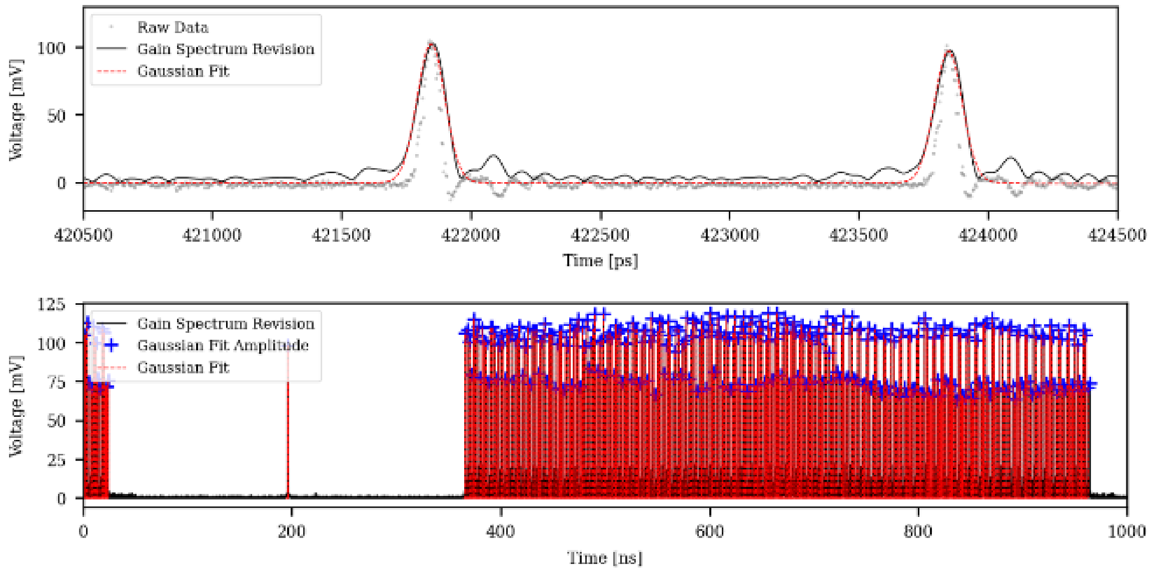

Figure 3: A picture of measuring the filling pattern (above) of a 1us-long bunch train under the 3 MV, 200 mA operating condition using a photodiode and an enlarged part of the filling pattern (below). The gain is compensated (black line) for the data sampled at 250 kS/se (gray dot) and then processed through Gaussian fitting (red dash line).

EXPERIMENTAL VERIFICATION

The signal measured by the photodiode is restored to the original signal using signal analysis, and the result is shown in Fig. 3. The sampling digitizer data do not show a Gaussian distribution as expected. Therefore, the gain (see Fig. 1(b)) compensates for the measured signal, and the resulting profile is Gaussian-fitted. The processed signal shows the filling pattern well in the graph below in Fig. 3.

We conducted experiments to verify and calibrate the analysis method by changing the electron beam bunch length in the PLS-II storage ring. Two parameters were varied in order to change the bunch length: the main RF cavity gap voltage and the beam current [2][3]. In normal operation, when the gap voltage decreases, the bunch length becomes longer [4], so we measured the bunch length by changing the total gap voltage from 3 MV to 2.2 MV at 200 kV intervals. Figure 4 shows the bunch length measured with a streak camera, and the bunch length increases when the gap voltage is lower.

The bunch length measurement result obtained without signal processing is shown in Fig. 5 (a). The fitting curve meets on the y-axis because when the bunch length decreases, it is predicted to saturate to a constant value due to the basis function h(t) of Eq. (3). The y-intercept is 25 ps, which is shorter than the length of the basis function of 29 ps. On the other hand, the distribution of the measured values in the normal operation section with a bunch length of 20-25 ps is dense, and when the length measured with a streak camera is 22 ps, the measured value of the photodiode is 29.90±0.15 ps. Fig. 5 (b) shows the result of applying the deconvolution method to the raw data in Fig. 5 (a). Here, the distortion was corrected with a basis function and the resultant data points were fitted with a linear curve, whose y-intercept was found to be about -15 ps. After gain and basis function correction, the distribution of the measured values becomes wider and the error range is also larger than (a) image one. However, the bunch length of the photodiode is 22.05±0.96 ps in the bunch length 22 ps measured with a streak camera, which is a good prediction value.

We explore the discrepancy in the two graphs and y-intercept mismatching. The gain was measured separately for each component and used for a bunch lengthening experiment and basis function measurement, so there is a possibility that the spectrum can be changed. For example, the result of compensating the gain by FFT of the filling pattern shown in Fig. 3 increased excessively in the vicinity of 6 GHz, and the attenuation was relatively large above 11 GHz. Another cause is that the optical gain of the photodiode, which has the longest rise time in the circuit and is expected to have a large effect on signal distortion, is not considered. We expected that the basis function measurement would show the characteristics of the photodiode well, but the predicted values did not fit well as shown in Fig. 5. Therefore, a more accurate method of correcting the characteristics of the photodiode should be considered.

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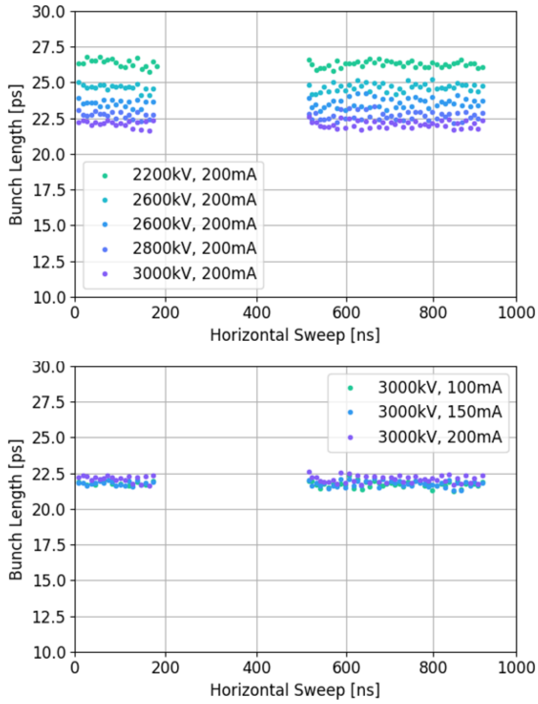

Figure 4: Changes in bunch length according to varying RF gap voltage (above) and beam current (below) measured with a Streak camera. When the total RF gap voltage is increased from 2.2 MV to 3 MV, the average bunch length in each condition decreases to 26.3, 24.7, 23.6, 22.7, and 22.1 ps.

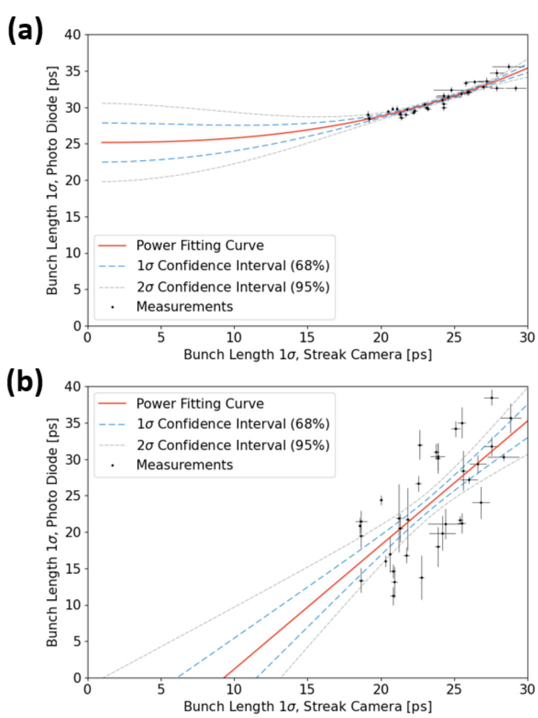

Figure 5: Bunch length measured by a photodiode and streak camera when RF gap voltage and beam current are changed. (a) Bunch length obtained directly from raw data without signal processing. (b) Bunch length calculated by applying the deconvolution method (gain and basis function correction).

CONCLUSION

In this paper, we design and test a system that can continuously measure filling patterns and bunch lengths in PLS-II storage rings. Several methods were used to recover the original signal to measure the exact bunch length. Bunch length measurement using a photodiode is an inexpensive and simple method. Since the calibration results were well measured up to the operating range, on-line measurement results will be provided to beamline users.

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