Wideband Diagnostics for Online Measurement of Temporal Information of Beams in a Storage Ring

Garam Hahn, Woojin Song, Yong-Seok Lee, Young-Do Joo, and Ji-Gwang Hwang

***Abstract*— One of the confronting challenges for storage-ring-based light sources to serve time-resolved experiments is online and quantitative measurements of temporal information such as bunch lengths, phases, and currents of stored bunches which are separated by 2 ns with a duration of tens of picoseconds. We demonstrated a compact online diagnostics which enables simultaneous measurements of such temporal information by directly observing the visible part of synchrotron radiation using a fast photodiode and wide bandwidth analog devices consisting of a bias tee, a preamplifier, a digitizer, and cables. A new dedicated signal analysis model capable of compensating for the nonlinear frequency response of the wideband device was developed and compared with a conventional Gaussian deconvolution method that assumes linear frequency responses and perfect Gaussian signal shapes in all calculations. As a result, we show that the new method with the online-diagnostics provides a better estimation of the pulse duration with smaller fit errors and it simultaneously matches the fit curve to the impulse response result of the system measured with a femtosecond laser. The minimum measurable bunch length and bunch current resolution of this system were estimated to be approximately 12 ps and 9 μA, respectively.**

***Index Terms*— Bunch length, fast photodiode, fill-pattern, numerical compensation (NC) algorithm, online-measurement, storage ring, wideband diagnostics.**

I. INTRODUCTION

THE advancement of accelerator-based light sources has driven the progress of modern science by serving high-brightness photons in various spectral ranges from Infrared to X-ray. It enables the observation of not only static structures of molecules or atoms but also veiled dynamic properties of matter. Particularly, contemporary research on complex fill-patterns [1], [2] in an electron storage ring has propelled to the forefront in investigations of MHz time-resolved experiments [3] with a temporal resolution of tens of picoseconds and sophisticated techniques with a hundred femtosecond resolution [4], [5], [6] while serving high brightness users simultaneously. For these fast time-resolved applications, it is crucial to quantify the temporal distribution of electron bunches which has a duration of tens of picoseconds with 2 ns spacing. To gauge the quantity precisely, many facilities utilized a synchro-scan streak camera which operates in synchronism with a repetition rate of the bunch which allows integration of photon intensities over many turns to mitigate statistical fluctuation on the measurement [7]. However, the instruments are expensive and fundamentally pertain to observing either the bunch-by-bunch motion of a single bunch or the turn-by-turn behavior of a bunch train over a few milliseconds [8], [9].

Here, we propose a compact diagnostic instrument based on a state-of-the-art metal-semiconductor-metal (MSM) photodiode that exploits a Schottky-barrier structure promising a rise time of tens of picoseconds. The proposed system overcomes the technical limits of the present beam diagnostics which can not observe bunch-by-bunch and turn-by-turn longitudinal motions over tens of thousands of turns. Particularly, this feature offers a special opportunity to measure the mode of coupled-bunch instability that may occur during the operation of a storage ring due to the gap changes of in-vacuum undulators. In addition, the system is capable of measuring the current of each bunch with a resolution of 9 μA, which enables synchrotron users to provide accurate information when conducting time-resolved experiments that require the detailed analysis of source information. The detector adopts broadband electronics which consists of a 12 GHz MSM photodiode, a 26 GHz bias tee, a 14 GHz amplifier, and a 16 GHz digitizer, to observe the input signal with minimum distortion for precisely measuring the temporal distribution of the electrons. However, the broadband electronics still impairs the initial distribution due to the nonlinear response of each component and the influence is nonnegligible when the bunch length approaches the cut-off frequency of the system. A dedicated robust algorithm is also established for retrieving the initial signal rapidly. It enables measurement of the temporal distribution of electron beams by an accurate reconstruction with a time resolution of a few picoseconds for an 11.5 ps long bunch. This compact instrument also measures a bunch charge, duration, and phase simultaneously. Furthermore, the diagnostics equipped with a real-time digitizer allow observing

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the turn-by-turn and bunch-by-bunch longitudinal dynamics which is important to study rapid beam instabilities in a machine.

II. EXPERIMENTAL SETUP

The temporal distribution of an electron bunch in a storage ring is mainly determined by magnetic lattice which defines the energy-dependent time-of-flight property, and radio frequency (RF) cavities that not only provide a focusing force in the longitudinal direction but also are used to recover beam energy lost by the emission of synchrotron radiation. Except for special cases, e.g., isochronous optics [10], [11] or bunch compression by high frequency cavities [12], [13], the rms temporal length of a bunch obtains in the range of 20–100 ps rms for a beam current of 1 mA and each bunch is separated by a few nanoseconds. Therefore, a state-of-the-art high-speed photodetector can be used to quantify temporal information accurately. In this study, a GaAs MSM photodiode (G4176-03, Hamamatsu) having a rise time of 30 ps with a dark current of 100 pA at a bias voltage of 7 V was utilized. These fast and high gain characteristics allow us to evaluate the bunch length, longitudinal phase as well as bunch current precisely. As shown in Fig. 1, the circuit is comprised of wide-bandwidth devices and is also designed with the simplest structure possible to analyze signal distortion.

Synchrotron radiation produced by a bending magnet is guided to the photodiode through optical elements such as mirrors and lens and converted to an electric signal. The converted signal passes through an analog circuit that is composed of bias tee (Picosecond 5541A) and amplifier (Mini-Circuits ZX60-14012L) for intensifying the signal to a readable level and is then sampled by a digitizer (Picoscope 9404-16) which has an analog input bandwidth of 16 GHz with an equivalent time sampling option, up to 2.5 TSa/s. The trigger signal provided by the accelerator timing system has a carrier frequency of 1 MHz. The typical noise of the device is 2.2 mV rms but this can be further suppressed down to an order of magnitude by averaging the statistical noise over a few hundred samples. The digital data is conveyed to a control PC to compute the fill pattern and bunch length and the results are serviced to the accelerator control network in the form of process variable on an Experimental Physics and Industrial Control System (EPICS) [14].

III. TEMPORAL DISTRIBUTION RETRIEVAL METHODS

Due to the distortion of an input signal by an impulse response of the analog circuit, the duration of the measured pulses using the photodiode gets longer than the real temporal size of electron beams in a storage ring. Therefore, it is necessary to implement such a technique to recover the original signal to gauge the bunch length as well as the phase information precisely. In this section, we compared two different approaches, analytic gaussian deconvolution (AGD) method in the time domain and numerical compensation (NC) method in the frequency domain, and proven that the latter method can push the resolution close to the technical limit.

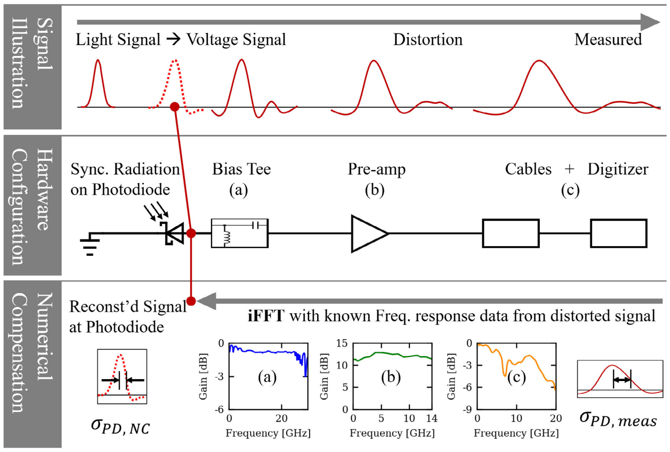

Fig. 1. Schematic of a wideband diagnostic system composed of MSM photodiode, bias tee (a), preamplifier (b), and digitizer (c) for measuring temporal information of electron beams in a storage ring.

A. Analytic Gaussian Deconvolution

This conventional method, assuming that all basis functions are Gaussian shapes, deconvolutes the measured signal by using an impulse response and well-defined jitters. The validity of this method has been proven by previous studies [15], [16], [17]. These studies show that it has an advantage in terms of computing speed since the method assumes a linear time-invariant (LTI) system which is intuitive and straightforward. For a LTI system, the output signal $y(t)$ can be expressed in the convolution integral form as

$$y(t) = x(t) \times h(t) = \int_{-\infty}^{\infty} x(\tau) h(t-\tau) d\tau \tag{1}$$

where $x(t)$ is the input signal and $h(t)$ is the impulse response function [18]. When several electronic devices such as a photodiode h_{PD}, a bias tee h_{BT}, and an amplifier h_{Amp} are connected in series, the impulse response function of the entire system can be interpreted based on the associative property as

$$h_{\mathrm{sys}} = h_{\mathrm{PD}} \times h_{\mathrm{BT}} \times h_{\mathrm{Amp}} \times \cdots \tag{2}$$

Using (1) and (2), the original signal can be retrieved by the decomposition of two Gaussian functions [19]. Therefore, the standard deviation of the input signal σ_{real} can be expressed

$$\sigma_{\mathrm{real}}{}^2 = \sigma_{\mathrm{PD,meas}}{}^2 - \sigma_h{}^2 \tag{3}$$

where $\sigma_{\mathrm{PD,meas}}$ is the rms length of the output signal and σ_h is the rms length derived from the impulse response function of the entire system $h_{\mathrm{sys}}(t)$.

For the LTI system, that the impulse response function remains a constant, the length of the output signal should approach σ_h when the input pulse is close to a delta function. Such relation can be verified by calculating correlations between the measured pulsewidth $\sigma_{\mathrm{PD,meas}}$ and real pulsewidth σ_{real}. The absolute length can be robustly confirmed by a streak camera with a high temporal resolution for various bunch lengths in a storage ring.

We performed a bunch lengthening experiment in the PLS-II storage ring by changing overall acceleration gap voltage. Bunch lengths, $\sigma_{\mathrm{PD,meas}}$ by the photodiode circuit and σ_{real}

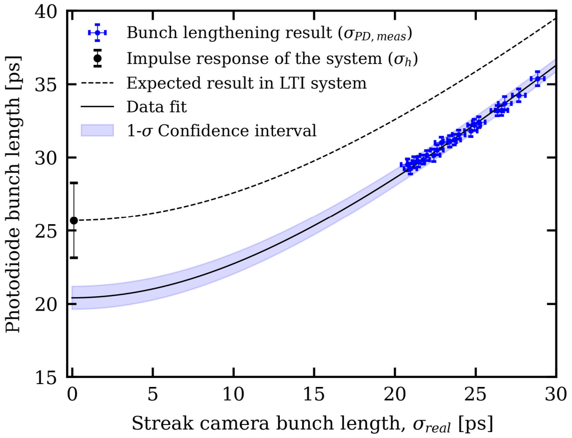

Fig. 2. Pulselength measured by the diagnostic system as a function of absolute bunch length in a storage ring. The absolute bunch length has been defined by a streak camera which has a temporal resolution of 2 ps rms.

by the streak camera with a temporal resolution of 1 ps, were measured simultaneously during the experiment. The result is shown in Fig. 2 which indicates the impulse response of the system as $\sigma_h = 20.43 \pm 0.81$ ps. However, the calibration curve does not match the impulse response of the system σ_h which was carried out using a short laser pulse with a duration of 100 fs which can be considered as the Dirac delta function compared to the rise time. A mitigation of the discrepancy was tried by putting an additional constant term both inside and outside of the square root of the fit form which can be induced by the change of frequency response function of the photodiode in time. This indicates that the AGD model cannot reliably predict regions with no data points, making it an improper model for measuring a short bunch in a storage ring. In addition, the minimal pulselength of 20.43 ps estimated from the calibration curve is not even practical.

B. Numerical Compensation

The AGD technique has the obvious drawback of only being applicable to systems with Gaussian impulse response functions. Therefore, it leads to a substantial misreading of the bunch length for non-Gaussian systems, particularly, when the pulse duration approaches the measurement limit of the system (see Fig. 2). It highly demands a dedicated algorithm for reliably recovering the initial distribution to push the measurement accuracy close to its resolution frontier where the bunch length in a modern storage ring is established. The nonflat and arbitrarily shaped frequency response characteristics of RF devices connected in series, from the photodiode to the digitizer, create the distortion of the original waveform. The AGD technique is inappropriate for recovering such localized signal characteristic changes in the frequency domain. Here, we propose a robust and reliable algorithm to meticulously retrieve the temporal information of the electron bunches measured by a wide bandwidth system as previously elaborated in Fig. 1.

This approach is based on an NC scheme that treats the distortion in the frequency domain by utilizing the characteristic frequency response of all devices employed. The frequency response of the entire system is yielded by the product of the frequency response of each device, for instance, the transmission parameters of the bias tee and the preamplifier are taken from the datasheet and the transmission parameters of the cables and the digitizer are measured using the well-calibrated instruments. An overall frequency response of the serially connected photodiode circuit was calculated as

$$R(\omega) = R_1(\omega) \cdot R_2(\omega) \cdot R_3(\omega) \tag{4}$$

where R_1 is the frequency response (transmission parameters) of the cables and the digitizer, R_2 is the normalized voltage gain of the preamplifier, and R_3 is the transmission parameters of the bias tee. We applied the overall frequency response function to the Fourier-transformed time-series data $\mathbf{F}(h(t))$, which is distorted, to compensate by using

$$h'(t) = \mathbf{F}^{-1}\left[\frac{\mathbf{F}(h(t))}{R(\omega)}\right] \tag{5}$$

where $h'(t)$ is recovered time-series waveform, $h(t)$ is measured waveform, and $\mathbf{F}$ and $\mathbf{F}^{-1}$ denote Fourier transform and inverse Fourier transform, respectively. The recovered waveform $h'(t)$ represents a signal of the photodiode that cannot be directly measured without a bias tee in experiments. We applied this procedure to the time-series data of the laser impulse experiment to get an impulse response function of the photodiode, which is 24.44 ps.

Since the frequency response of the photodiode is not numerically defined, we applied a data-fitting method similar to AGD to obtain the bunch lengths. The form is

$$\sigma_{\mathrm{PD,NC}} = \sqrt{\sigma_{\mathrm{real}}{}^2 + \sigma_h{}^2} + c \tag{6}$$

where, the σ_h is 53.8 ps and c is -29.0 ps. Contrary to the results of the AGD method, the NC method yields a calibration curve that agrees well with both the slope and interception point. The constant shift term c is not intuitively and physically interpreted, but it could be originated by a change of frequency response function of the photodiode in time in a single pulse excitation and deexcitation.

Based on the calibration curve shown in Fig. 3, the shortest bunch length that can be measured in the proposed system with the NC method is about 11.5 ps. On the contrary, the value cannot be defined when using the AGD method due to the inconsistency of the calibration curve and the impulse response. In addition, data-fit errors of the calibration curve of the NC method show smaller than the AGD method for the same data in all ranges. Therefore, we determined that the NC method was more appropriate for analyzing temporal information in this system. However, the reliability of this technique strongly relies on the accuracy of the measured frequency response for each RF element and the response functions should be updated when the configuration is modified.

IV. FILL-PATTERN MEASUREMENT

Contemporary storage-ring-based light sources facilitate a hybrid filling pattern with a Top-Up operational mode

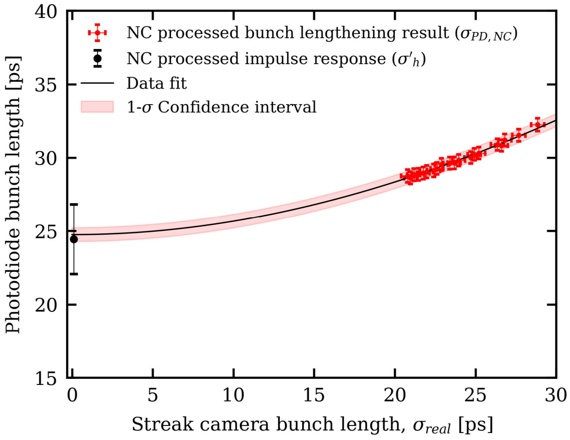

Fig. 3. Comparison of pulselength measurements of numerically compensated signal and streak camera image as shown in Fig. 2. The shortest measurable bunch length with the NC method is about 11.5 ps. It can be estimated from the intersection between the vertical interception obtained from the laser measurement and the linear extrapolation of the calibration curve.

[20], [21] to serve high-brightness and time-resolved experiments simultaneously. The filling pattern typically composed of a high-current single bunch in the center of a few hundred nanoseconds dark gap for generating X-ray pulses with an MHz repetition rate, followed by standard multibunches each of milliampere current separated by 2 ns. Even for the Top-Up operation, the beam current of each bunch varies in the last two digits since the electrons are lost naturally due to Coulomb interaction within a bunch and are replenished every few minutes to maintain the current level (see Fig. 4).

A capacitive stripline detector which assesses the induced current on the exposed electrodes to the electrons is widely employed to gauge the quantity. However, the device can not achieve a high resolution since the inevitable nonlinear response introduces nonnegligible errors for off-centered beams and the bandwidth is also limited. Since the diode-based monitor supports the bunch-resolved option and has a linear response with respect to the input power which is proportional to a bunch charge, the monitor can be utilized for the beam current measurement. A previous study on the fill-pattern monitor based on a fast photodiode in Australian Synchrotron [22] has demonstrated qualitatively that the resolution of current measurements is superior to a capacitive stripline detector. However, the noise level of their detector constrains the resolution down to a bunch charge of 36 pC which is the signal-to-noise (SNR) of roughly 3.0. In our study, the standard deviation of the background level is measured to be 0.31 mV and the amplitude of the signal is 100.81 mV for a beam current of 1.0 mA. Therefore, the resolution of the beam current measurement is 9.25 μA which corresponds to a bunch charge of 8.6 pC. The output signal level varies sensitively depending strongly on the alignment of the optics because the diode has a limited active area of 200 μm^2.

The wideband detector system allows not only to distinguish each bunch's motion in tens of picoseconds but also to observe the relatively slow beam motion that arises in several

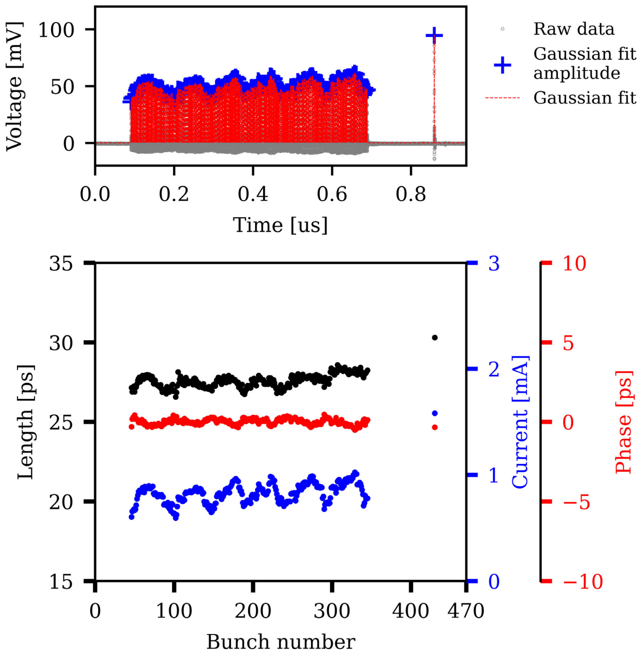

Fig. 4. Fill-pattern, bunch length, and phase with 250 mA Top-Up mode. PLS-II storage ring has a 1.58 mA high current bunch in the middle of a 340 ns dark gap and a 600 ns-long bunch train with a current of 0.83 mA separated by 2 ns. The data was sampled with an equivalent sampling method with a sampling speed of 250 GSa/s (gray dot) and processed using a compensation algorithm illustrated in Fig. 1.

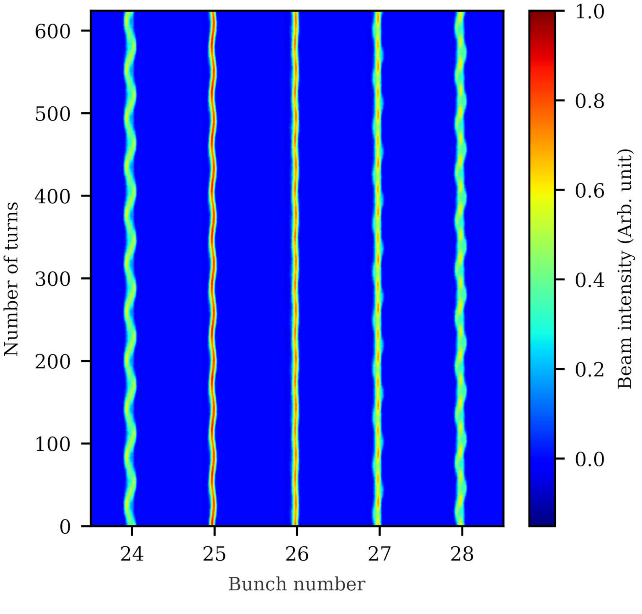

Fig. 5. Longitudinal turn-by-turn motion of unstable electron beams in the MLS of the Physikalisch-Technische Bundesanstalt in Berlin. The unstable beams were intentionally generated by pushing the beam to extreme conditions. It obviously shows the coupled bunch instability in a storage ring. A few bunches are selected for 600 turns ($\sim$ 100 μs) to reveal the various motions explicitly. Each bunch number stands for 2 ns spacing.

milliseconds. This unique feature enables the inspection of longitudinal coupled-bunch instabilities which is inconceivable for other diagnostics such as a streak camera, photon counting unit, and a stripline monitor. The beam experiment is carried out in the metrology light source (MLS) of the

Physikalisch-Technische Bundesanstalt in Berlin [23], [24] while the machine was intentionally on the longitudinally unstable condition. It is measured using the diagnostics system with a real-time digitizer with a bandwidth of 12.5 GHz which yields the data up to 1.25 ms for a sampling speed of 100 GSa/s. Fig. 5 evidences that the instrument offers a unique opportunity to observe the turn-by-turn motion of each bunch that occurs from the gigahertz to the subkilohertz regime. Notably, it enables quantitative evaluation of the beam motion in terms of its frequency and amplitudes which allows investigation of the source of the instability. Since this application is quite costly for data taking, transfer, storage, and analysis, the operation mode is not suitable for providing current and temporal information during such experiments that demand the beam information during a sample scanning which takes place in the order of tens of seconds. But we can provide a dedicated operation mode for observing instability during beam commissioning or sophisticated experiments such as postmortem with a special trigger setting.

V. CONCLUSION

We have proposed a compact optical diagnostics for measuring temporal information of electron beams in a storage ring using the visible part of synchrotron radiation. Since the duration of an electron bunch in a storage ring is normally tens of picoseconds, it demands a wideband detector system to mitigate the signal distortion caused by the impulse response of the devices. Therefore, this does call for research and development for fast optical diagnostics opted with the wideband detector system which consists of a 12 GHz MSM photodiode, a 26 GHz bias tee, a 14 GHz amplifier, and a 16 GHz digitizer. We demonstrated a dedicated algorithm to retrieve the temporal distribution which enables the measurement of a bunch length and current with a temporal resolution of 1.2 ps rms at a bunch length of 20 ps and a current resolution of 9 μA. This diagnostics can measure a bunch length down to 11.5 ps. The temporal resolution is statistically estimated by using Monte Carlo simulations based on impulse response, bunch profile, overall frequency response, random digitizer noise, and revolution trigger jitter. Particularly, the wideband system offers a special opportunity to observe bunch-by-bunch and turn-by-turn longitudinal motions, which were not possible with contemporary instruments such as the streak camera and photon counting diagnostics.

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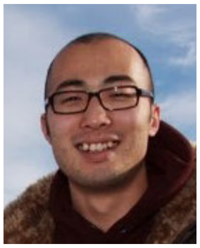

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