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Monitoring the charge bunch-by-bunch for the SSRF storage ring: Development and application

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Abstract Bunch charge uniformity controlling is very important for top-up operation of the storage ring. In order to monitor filling pattern and measure the bunch charge precisely, a PXI waveform digitizer-based data acquisition system has been developed to retrieve bunch charge information from BPM pickup signals. An effective sampling rate is extended to 400 GHz by waveform rebuilding technology, which overlays multi-turn data into single turn with real time sampling rate of 8 GHz. An on-line evaluation indicates that resolution and linearity of the charge measurement are better than 0.5% at input range of 0.5–12 nC.

Key words Beam diagnostics, Bunch charge monitor, Filling pattern, Top-up, SSRF

1 Introduction

Top-up operation mode of the storage ring is to be used at SSRF to minimize the dependence of beam current on machine parameters, The variation of bunch charges is required to be less than 10%. Thus, a precise bunch charge and filling pattern monitoring is necessitated. Table 1 shows that the BCM (beam charge monitor) specification can be achieved by directly sampling BPM (beam position monitor) pickup signal[1–3] or synchrotron radiation signal[4].

Table 1 SSRF BCM Specifications.

Parameters	Specifications
Analog bandwidth	≥ 250 MHz
Data updating rate	≥1 Hz
Bunch charge resolution	Better than 1%
Interface	EPICS CA

The SSRF storage ring adopts the technique of the button BPM pickups and the PXI (PCI eXtensions for Instrumentation) waveform digitizer-based solution, due to the easy configuration and good linearity[5]. This helps to have a full knowledge of time domain structure of the beam, bunch-by-bunch with a sub-nanosecond time resolution.

2 System setup

2.1 Basic idea

As a common diagnostic component in an electron storage ring, a four-button BPM pickup carries the information of beam position and intensity. Assuming the bunch charge (Q_0) was in Gaussian distribution at a bunch length σ, the beam intensity is given by

$$I(t) = \frac{Q_0}{\sqrt{2\pi}\sigma}\exp(-\frac{t^2}{2\sigma^2}) \tag{1}$$

the peak value of the four-button sum signal is

$$V_{\text{peak}} = k(r,\theta)Z\sqrt{\frac{e}{2\pi}}\frac{Q_0}{\sigma^2} \tag{2}$$

where, $k(r,\theta)$ is a calibration factor determined by cross section structure of the vacuum chamber and beam position, Z is transfer impedance of the measurement system, r and θ are polar coordinates of the beam position. Treating $k(r,\theta)$ as a constant k_0[6] and defining a scaling factor (K_Q), V_{peak} can be obtained by Eq.(3),

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$$V_{\text{peak}} = K_Q \cdot Q_0$$
$$K_Q = k_0 Z \sqrt{\frac{e}{2\pi}} \frac{1}{\sigma^2} \quad (3)$$

where, K_Q is calibrated with DCCT (DC current transducers) readings in single bunch operation, and Q_0 is derived by measuring peak value of the four-button pickup sum signal.

2.2 Hardware

The BCM hardware consists of the beam pickup, RF front-end, waveform digitizer, and a PXI IOC. Fig.1 shows its block diagram.

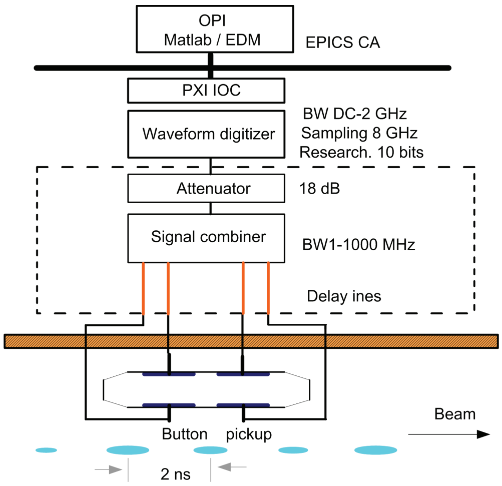

Fig.1 Hardware block diagram of the bunch charge monitor.

Beam bunches are sensed by standard Φ10 mm BPM buttons at SSRF, and the bunch signals are fed into a front-end chassis of filter/combiner/attenuator, which consists of four delay coaxial cables, a power combiner (4 to 1, BW 1-1000 MHz), and a fixed attenuator (18 dB). The coaxial cables were trimmed to eliminate time delay between signals. The power combiner produces the position independent of signal intensity, and the attenuator adjusts an output signal level to fit the ADC input range. An ultra-high speed ADC(DC252), which has 2 GHz analogue bandwidth, 8 GHz sampling rate, 10 bits resolution, and up to 1 M samples data buffer[7], is adopted as waveform digitizer, and triggered by 2-Hz injection event to take 576 k samples (50 turns, 72 μs) continuously. On running a Linux EPICS IOC core, the PXI CPU overlays the multi-turn digital data into a single turn waveform via equivalent sampling.

2.3 Signal processing

The 8-GHz sampling rate of real time ADC is not enough to determine the peak value from a single shot. A waveform rebuilding technique, that is, equivalent sampling, is used to improve time resolution, and record the beam signal of 50 turns. The samples are shifted by the bucket due to the frequency difference between the 8-GHz sampling clock and the 499.654-MHz accelerator RF. An effective sampling rate of about 400 GHz (roughly 8 GHz×50) was obtained by overlaying 50 successive revolutions. The real time value of accelerator RF was acquired by EPICS CA to calculate the precise time axes for each sample. Compared with 10-h lifetime, the beam intensity of 2-ppm drop can be ignored at 50 turns.

Fig.2 shows a typical signal reconstruction, which overlays data of 50 turns together. The raw data and rebuilt single turn data, and the distribution of bunch charges calculated by bunch signal waveform are shown in Fig.2(a–c), respectively. On time resolution increasing, the peak of each bunch can be easily located by searching the maximum value. To improve accuracy of measurement, the 100 samples averaging around the peak is applied.

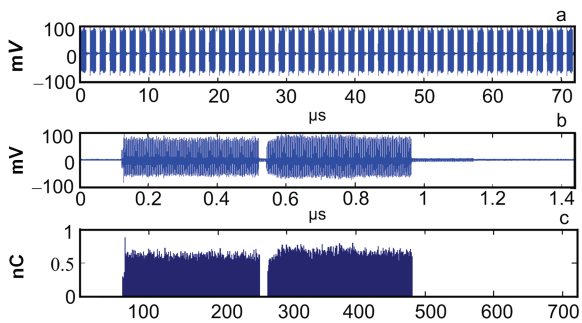

Fig.2 An example of equivalent sampling technique. (a) raw data of 50 turns, (b) rebuilt data of one turn, (c) filling pattern.

3 Calibration and performance evaluation

To calibrate the K_Q and evaluate the linearity of BCM system, several beam experiments were carried out on the storage ring. A Bergoz NPCT and NI4070 digital voltage meter-based DCCT was used as reference[8], as shown in Fig.3. At single bunch operation mode, the beam current was increased from 0.2 to 7 mA in 0.2-mA steps, and the average current of DCCT and bunch charge of BCM were synchronously recorded within 70 min. Fig.4 shows that the BCM linearity is better than 0.5% in the full range.

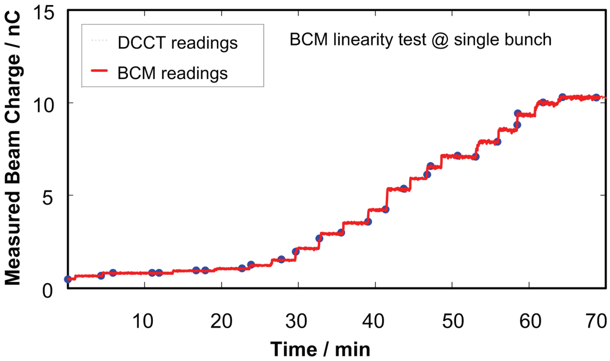

Fig.3 Beam experiments for K_Q calibration and performance evaluation.

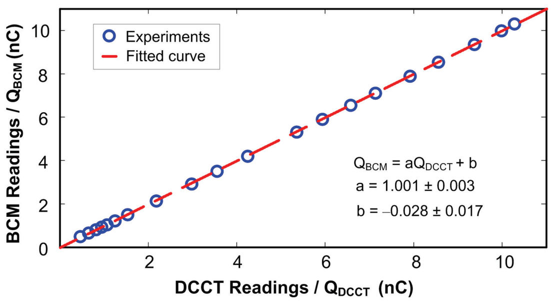

Fig. 4 Linearity of the BCM.

Fig.5 shows a dynamic range of charge input and its resolution of BCM. The charge input range was determined by the voltage input range of waveform digitizer. In our case, with the DC252 input voltage of 0.2, 0.5, 1, 2, and 5 V, the BCM charge input is selectable at 0.5, 1.3, 2.5, 5, and 12.5 nC. The evaluation result show that the relative uncertainty of measurement was better than 0.1% in the ranges of charge input, which can be extended by replacing the fixed attenuator with an adjustable attenuator.

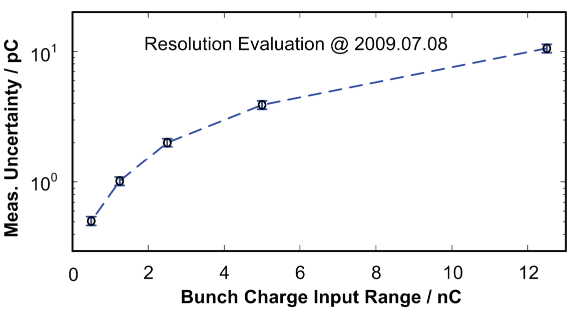

Fig.5 Input dynamic range and charge resolution.

Fig.6 shows that the DCCT uncertainty of measurement was almost the same with that of BCM at input of 2.5 nC, and the difference of readings between the DCCT and BCM was 0.5% less than the 2.5 nC input range. The resultant BCM performance for the linearity, resolution, charge input range, and accuracy of measurement fully satisfies the filling pattern monitoring in the SSRF storage ring. Besides, the good xlinearity makes the BCM qualified for measuring individual bunch life-time.

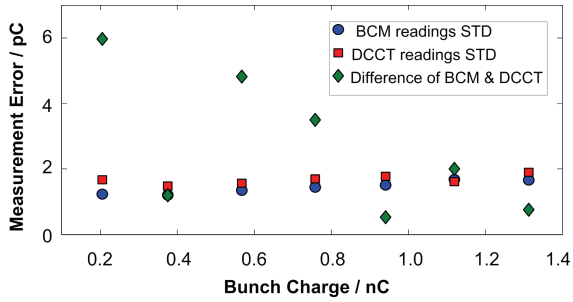

Fig.6 Evaluation of accuracy at 2.5 nC input range.

4 Application

4.1 Filling pattern monitoring

The filling pattern of injected beam for user operation mode at SSRF storage ring has been defined as 210-mA average current with 500 equal charge bunches in the first stage run, which was conducted manually by machine operators tuning the injected bunch charge and controlling injection bucket index before filling pattern of automatic control system on-line. The BCM was used to deliver information of bunch charge to operators during injection and check filling pattern performance after injection.

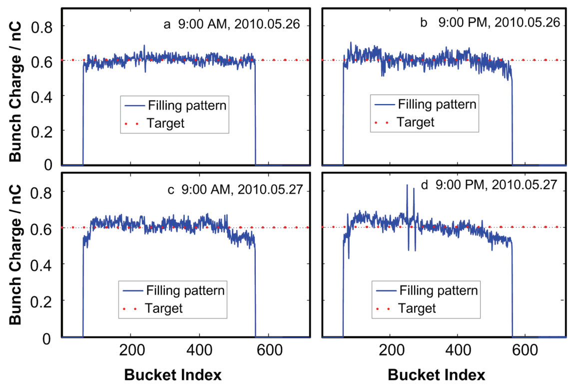

Fig.7 Measured filling patterns in the SSRF storage ring.

Fig.7 shows four measured filling patterns during user operation from 9:00 May 26 to 21:00 May 27, 2010. The bunch charges (solid line), and the 0.605-nC target charge for each bunch (dotted line) were taken after injections. The filling pattern between injections varied obviously due to manually operation. The software-timing mismatch (Fig.7d) made some buckets missing in a few injections, and some buckets over injected. The charge standard deviation of 500 bunches (Fig.7a) was 0.02 nC at 3% target value, and the peak-to-peak deviation was ±0.08 nC at 13% target value.

4.2 Measurement of individual bunch lifetime

The evaluation results show that the performance of BCM system satisfies requirement of top-up operation and measures well the individual bunch lifetime. This was demonstrated by a dedicated beam experiment of filling pattern, as shown in Fig.8, the six bunches were filled with 100-ns apart.

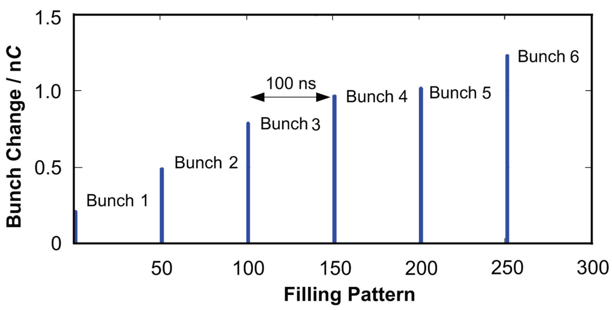

Fig.8 Beam experiment for measuring beam bunch lifetime.

The bunch charge decaying and corresponding lifetime are shown in Figs.9 and 10, respectively. A 0.08-h lifetime difference between Bunches 4 and 5 could be identified, and their relationship shall be described by a double exponential function.

5 Conclusions

The BPM button pickup and waveform digitizer-based bunch charge monitoring were implemented in the storage ring at SSRF. The resolution of bunch charge was better than 0.5%, and linearity of 0.2–12 nC was better than 0.5% using DCCT readings as reference. The accuracy of charge measurement was good enough to calculate individual bunch lifetime. All requirements of top-up operation and machine study have been met.

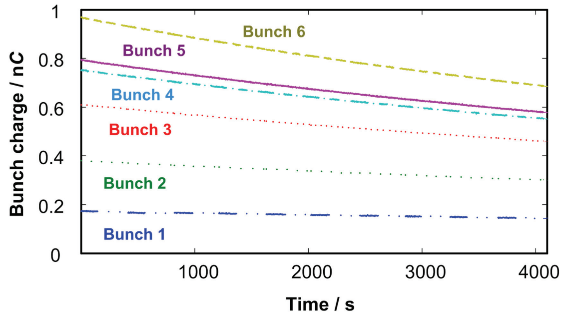

Fig.9 The decaying bunch charge.

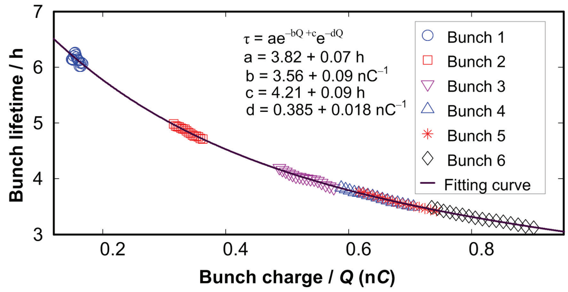

Fig.10 Bunch charge and lifetime for individual bunches.

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