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‡ Current address: KEK/J-PARC, 2–4 Shirakata, Tokai, Ibaraki 319-1195, Japan.

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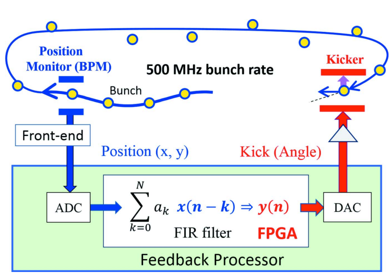


Transverse bunch-by-bunch feedback system for time-resolved experiments at PLS-II

Jaeyu Lee,[a] T. Nakamura,[b]‡ K. Kobayashi,[b] D.-T. Kim,[a] T. Ha,[a] G.-R. Hahn,[a] K.-J. Kim[a] and S. Shin[a]*

[a]Pohang Accelerator Laboratory, POSTECH, Pohang, Kyungbuk 37673, Republic of Korea, and [b]SPring-8, Kouto, Sayo-cho, Sayo-gun, Hyogo 679-5198, Japan. *Correspondence e-mail: tlssh@postech.ac.kr

A description of the upgraded bunch-by-bunch feedback system for time-resolved experiments at Pohang Light Source II (PLS-II) is provided. The bunch-by-bunch feedback system has been upgraded to increase the single-bunch current in the hybrid fill pattern of the PLS-II facility. The project is part of the SPring-8 and PLS-II collaboration. The main features of the upgrade are to employ a single 500 MHz analog-to-digital converter (ADC) instead of the previous four 125 MHz interleaved ADCs for 500 MHz rate, to replace a single-loop two-dimensional feedback with two independent one-dimensional feedback loops, to implement the tune measurement function with a single bunch, and mainly to implement single-bunch and stretcher control. The realization of a 400 mA hybrid fill pattern including a 10 mA single bunch demonstrates the precision of the upgraded bunch-by-bunch feedback system.

1. Introduction

Currently, the second-generation Pohang Light Source (PLS-II) (Shin *et al.*, 2013; Hwang *et al.*, 2014) operates 35 beamlines including 18 insertion-device beamlines for user service. Two multipole-wiggler beamlines, three elliptically polarizing undulator beamlines, one planar-undulator beamline, 12 in-vacuum undulator beamlines and bending-magnet beamlines have been operated for surface science, magnetic spectroscopy, material science, X-ray scattering, X-ray absorption fine structure, macromolecular crystallography, small-angle X-ray scattering, imaging and lithography (see http://pal.postech.ac.kr/paleng/Menu.pal?method=menuView&pageMode=paleng&top=2&sub=3&sub2=1&sub3=0 for more information on the PLS-II beamline). The change of research paradigm from PLS to PLS-II has involved an increase in the proportion of the real time and *in situ* experiment for dynamic science, including time-resolved X-ray absorption spectroscopy.

Three superconducting radiofrequency (RF) cavities and the bunch-by-bunch feedback system are essential for stable 400 mA beam operation with 12 in-vacuum undulators at minimum gap settings. The bunch-by-bunch feedback system consists of a button-type pick-up, a digital processor (Nakamura & Kobayashi, 2005) and a strip-line kicker for horizontal and vertical planes. The digital processor is operated as a single-loop two-dimensional feedback with a finite impulse response (FIR) filter optimized for both horizontal and vertical tunes.

User demand for time-resolved experiments is increasing, so hybrid mode with a high-current single bunch is strongly required. To satisfy user requirements, the bunch-by-bunch feedback system had to be upgraded. The main features of that upgrade are to use a 500 MHz analog-to-digital converter

(ADC) instead of the previous four interleaved 125 MHz ADCs for 500 MHz rate, to replace a single-loop two-dimensional feedback with two independent one-dimensional feedback loops for flexible tuning, to implement the tune measurement function with a single bunch, and mainly to implement single-bunch and stretcher control. As a result of the upgrade, a 400 mA beam current with a hybrid fill pattern (330 bunches + 12 mA single-bunch current) could be stored.

The scheme and precision of the upgraded PLS-II bunch-by-bunch feedback system will be described in this article. Section 2 reviews the instability during PLS-II operation and the previous bunch-by-bunch feedback system. Section 3 describes the process of digitizing signal processing in the bunch-by-bunch feedback system. Section 4 shows the precision of the digital processor in operation. Section 5 summarizes and gives concluding remarks.

2. Instability in the PLS-II

PLS-II uses lattice functions (Fig. 1) that have appropriate parameters (Table 1). The lattice of the PLS-II has an additional straight section between two 15° gradient bending magnets in each cell. Therefore, compared with a storage ring of similar circumference, the number of insertion devices is doubled. As a result, 12 in-vacuum undulators are operating with a minimum 6 mm full gap to provide a high-brightness X-ray photon beam. However, these devices that have narrow gap apertures cause high impedance which reduces the stability of high-current operation. In practice, many components in addition to the narrow-gap in-vacuum undulators contribute to the ring impedance; these components produce coupled bunch instabilities by resistive wall impedance and thereby limit the stored beam current.

Beam-loss processes from resistive wall impedance have been observed and investigated using bunch-by-bunch measurements (Lee *et al.*, 2017). Bunches in the tail part are lost as a consequence of the large vertical betatron oscillation. The measured growth time was 0.5 ms, whereas the expected growth time calculated using the impedance of the narrow-gap in-vacuum undulators is 2 ms, because in practice many components in addition to the narrow-gap in-vacuum undulators contribute to the ring impedance. However, the previous bunch-by-bunch feedback system in PLS-II attained a damping time <0.2 ms and supported stable 400 mA beam operation (Lee *et al.*, 2014).

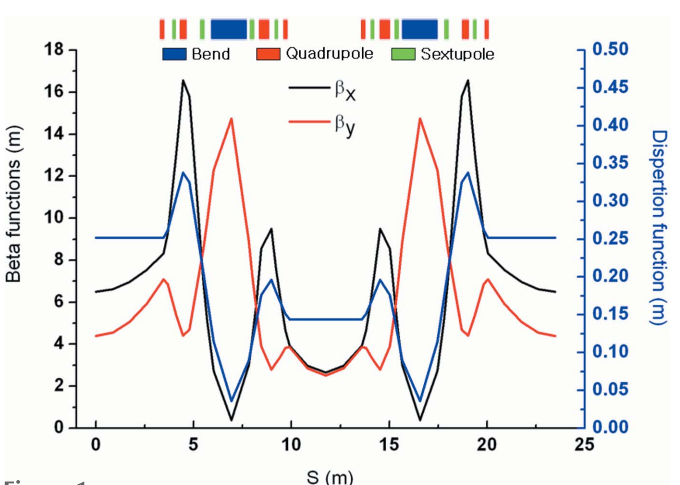


Figure 1
Superperiods in the PLS-II lattice for the 3.0 GeV ring and its optical functions.

Table 1
Major parameters of the PLS-II storage ring.

Parameter	Value	Unit
Beam energy	3	GeV
Beam current	400	mA
Lattice structure	Double-bend achromat	
Superperiods	12	
Emittance	5.8	nm rad
Tune (*x*/*y*)	15.375/9.145	
RF	499.97	MHz
Energy spread	0.1	%
Revolution frequency	1.06	MHz
Bunch length	20	ps

Some users of synchrotron radiation from the storage ring want to exploit the time structure of radiation, in particular to study the dynamic properties of materials by means of time-resolved pump–probe experiments. At PLS-II, the time-resolved X-ray science beamline (1C BL) is in the commissioning stage. To simultaneously meet the needs for both high-flux high-brilliance experiments and temporal-structure experiments, the most common filling pattern in the storage ring is the use of so-called hybrid modes, in which most of the intensity is given by a large number of small contiguous bunches, followed by a window in the middle in which a single bunch with high current is located. The previous bunch-by-bunch feedback system was enabled to realize stable 400 mA operation but the upgrade of the feedback system is strongly required to maximize the bunch charge in the hybrid bunch.

3. Bunch-by-bunch feedback system with wide acceptance of bunch current

The transverse bunch-by-bunch feedback system (TFS) (Fig. 2) consists of a position pick-up, a feedback processor and a kicker with power amplifiers. For hybrid filling with a high-current single bunch, mainly the feedback processor and the pick-up were upgraded. The power amplifiers and kicker were reused (Lee *et al.*, 2014). The upgraded feedback processor (Nakamura *et al.*, 2018; Nakamura, 2018) was developed with recent advances in the digital technology of field-programmable gate arrays (FPGAs), ADCs and digital-to-analog converters (DACs) by SPring-8 in Japan, in collaboration with SOLEIL in France, and the Pohang Accelerator Laboratory (PAL) in Korea. The upgraded feedback processor (Fig. 3) includes multiple 500 MHz ADCs. [One ADC can sample all the bunch signals from the beam-position monitor (BPM).] Each ADC has its own front-end circuit with different amplifier gain, optimized for a range of bunch current. The processor has another ADC to measure the bunch current by analysing the BPM sum signal.

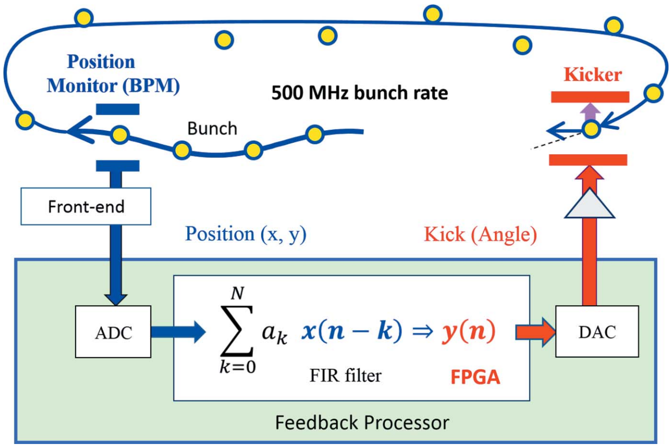


Figure 2
A schematic overview of the TFS.

With the upgraded processor, the feedback system for hybrid filling is simplified and the signal-to-noise ratio (SNR) for high-current bunches is improved, compared with the previous variable attenuator system (Kobayash & Nakamura, 2009). The strength of the feedback for high-current bunches can be increased without emittance increase by feedback noise, and, because of the high SNR, the signal of the bunch motion is distinct from noise. The FPGA program can process two independent feedback loops, one for the horizontal plane and one for the vertical plane (Fig. 3). The feedback processor has several functions. (i) Selector: performs bunch-by-bunch selection of sets of ADCs and digital front-ends that correspond to the bunch current with anti-chattering function, to compensate for the bunch-current dependence of the BPM signal at hybrid filling. (ii) Stretcher: extends the pulse length of a kick signal for selected ADCs of specific bunch-current ranges. The nominal pulse length is 2 ns and the length of a stretched pulse is ∼8 ns. The gap around those bunches is 100 ns, so kick-pulse length for isolated bunches like singlets can be increased to several clock lengths in the processor to obtain the kicker's full efficiency. (iii) FIR filters of 500 MHz RF bucket/bunch rate for compensation of the response of kickers and power amplifiers. (iv) Signal switchyard: to convert the horizontal and vertical signals to the signals for skewed position kickers. (v) Bunch-by-bunch switching between the feedback signal and the signal from an internal signal source for tuned measurement during user operation by exciting only one bunch in a ring.

The FIR filter for the one-dimensional feedback has the form

$$y(n) = \sum_{k=0}^{N} a_k\, x_{n-k}\,, \tag{1}$$

where a_k is a coefficient and $N + 1$ is the number of taps. Furthermore, x and y are the history of turn-by-turn position data as the input and the feedback kick as the output of the filter, respectively. To obtain the coefficients of the FIR filter, the time-domain least-squares fitting (TDLSF) method (Nakamura, 2018; Nakamura *et al.*, 2004) is used with an arbitrary number of taps. TDLSF fits the measured beam-position data x_n with the assumed sinusoidal betatron beam motion $x[n]$ as

$$x[n] = A\cos(2\pi\nu n + \psi) + B = p_0 + p_1\cos n\phi + p_2\sin n\phi, \tag{2}$$

where A is the oscillation amplitude, ν is the betatron tune, $\phi = 2\pi\nu$, B is a position offset and ψ is the phase offset. Here p_l can be fitted to measured position data from the turn-by-turn BPM as

$$p_l = \sum_{k=0}^{N} C_{l,k}\, x_{-k}. \tag{3}$$

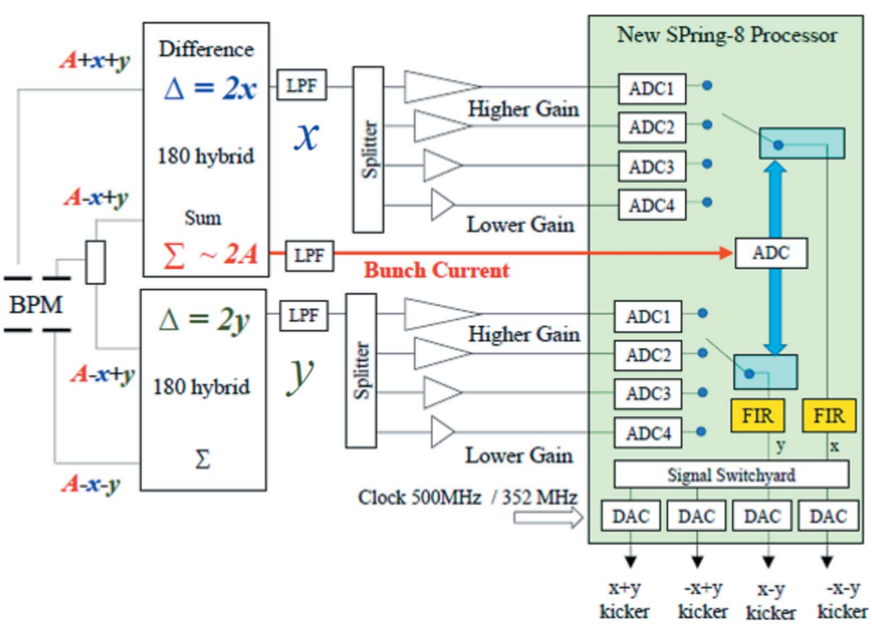


Figure 3
Two-dimensional signal processing by the upgraded processor for hybrid filling at PLS-II.

Equation (3) can be also expressed in matrix form as

$$\begin{pmatrix} p_0 \\ p_1 \\ p_2 \end{pmatrix} = \begin{pmatrix} C_{0,0} & \dots & C_{0,N} \\ C_{1,0} & \dots & C_{1,N} \\ C_{2,0} & \dots & C_{2,N} \end{pmatrix} \begin{pmatrix} x_0 \\ \vdots \\ x_{-N} \end{pmatrix}. \tag{4}$$

To estimate the coefficient $C_{l,\,k}$, we apply a least-squares fitting method to x_n as

$$S = \frac{1}{2}\sum_{n=0}^{-N} \left(x[n] - x_n\right)^2, \tag{5}$$

and then

$$\frac{\partial S}{\partial p_\mu} = \sum_{n=0}^{-N} \left(x[n] - x_n\right)\frac{\partial x[n]}{\partial p_\mu} = 0. \tag{6}$$

From equation (6),

$$\sum_{n=0}^{-N} x[n]\frac{\partial x[n]}{\partial p_\mu} = \sum_{n=0}^{-N} x_n \frac{\partial x[n]}{\partial p_\mu}, \qquad (7)$$

and, from equation (2),

$$\frac{\partial x[n]}{\partial p_1} = \cos n\phi, \qquad \frac{\partial x[n]}{\partial p_2} = \sin n\phi. \qquad (8)$$

Using equations (2) and (8), equation (7) becomes

$$FF^T \begin{pmatrix} p_0 \\ p_1 \\ p_2 \end{pmatrix} = F \begin{pmatrix} x_0 \\ x_{-1} \\ x_{-2} \\ \vdots \\ x_{-N} \end{pmatrix}, \qquad (9)$$

where

$$F = \begin{bmatrix} 1 & 1 & 1 & \dots & 1 \\ \cos(0) & \cos(-\phi) & \cos(-2\phi) & \dots & \cos(-N\phi) \\ \sin(0) & \sin(-\phi) & \sin(-2\phi) & \dots & \sin(-N\phi) \end{bmatrix}. \qquad (10)$$

Solving equation (9) yields the matrix C in equation (4) as

$$\begin{pmatrix} p_0 \\ p_1 \\ p_2 \end{pmatrix} = C \begin{pmatrix} x_0 \\ x_{-1} \\ x_{-2} \\ \vdots \\ x_{-N} \end{pmatrix}, \qquad (11)$$

where

$$C = \left[FF^T\right]^{-1} F. \qquad (12)$$

The feedback kick signal at current turn $n = 0$ that corresponds to the position motion in equation (2) is

$$y[0] = GA\cos(\psi + \zeta), \qquad (13)$$

where G is the gain and ζ is the phase required for feedback; both are produced by the FIR filter. The kick and position at the kicker should have -90° phase difference, so ζ should be $\zeta = -90^\circ + \phi$, where ϕ is the phase advance from the BPM to the kicker. From equations (2) and (3), equation (13) can be expressed as

$$\begin{aligned} y[0] &= p_1 G\cos\zeta + p_2 G\sin\zeta \\ &= \sum_{k=0}^{N} \left(C_{1,k} G\cos\zeta + C_{2,k} G\sin\zeta\right) x_{-k}. \end{aligned} \qquad (14)$$

By using equation (1), a_k can be given by

$$a_k = C_{1,k} G\cos\zeta + C_{2,k} G\sin\zeta. \qquad (15)$$

Using this method with $G = 1$ yields $\zeta = -90^\circ$, assuming that $\phi = 0$. In actual cases, to calculate an effective FIR filter, ϕ should be considered. Two nine-taps for FIR filters are calculated with successive turn position data as their input. The tap number nine is chosen to generate the flat region of the gain and phase around the operation points by setting extra constraints $\mathrm{d}G/\mathrm{d}\nu = \mathrm{d}\psi/\mathrm{d}\nu = 0$ on the FIR filter at the operation tune, by extending the above procedure to the case with tune shift (Fig. 4).

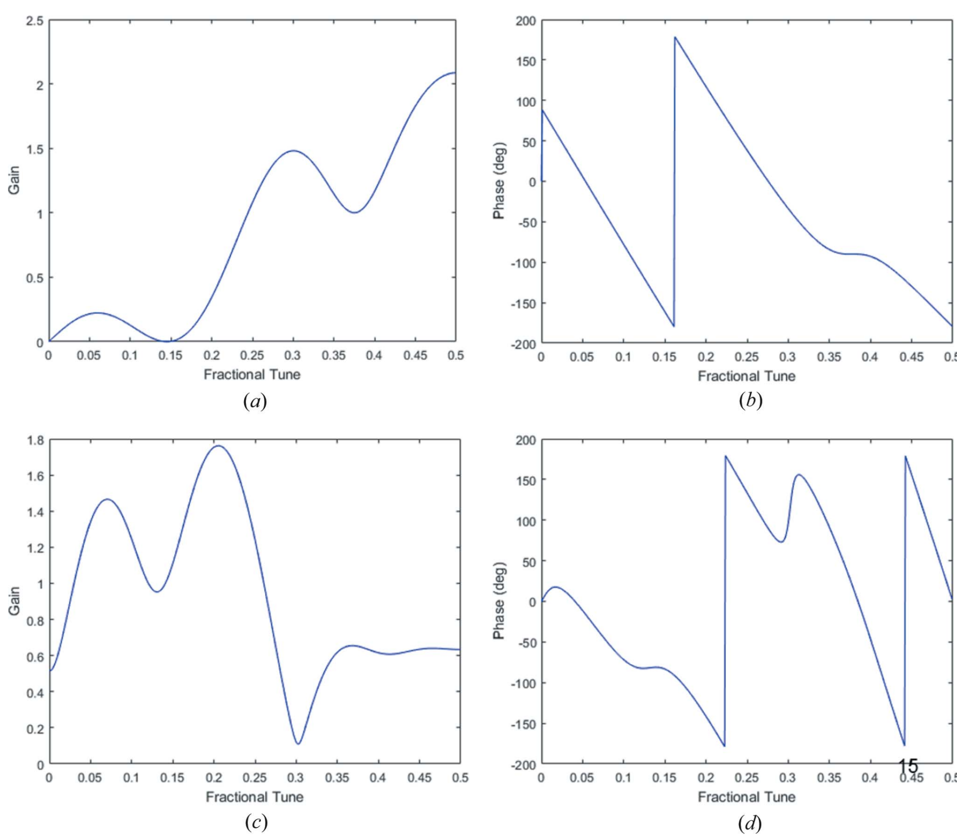


Figure 4
The responses of the nine-tap FIR filters. (*a*) x gain, (*b*) x phase, (*c*) y gain, (*d*) y phase. The betatron tunes of the PLS-II are 15.375 for x and 9.145 for y.

The filters that use nine-taps have gain only near the tune; this trait reduces noises during monitoring and eliminates the ambiguity in the choice of data points for the FIR tap. This reduction of noises is effective in reducing unwanted kick. The phase response of a nine-tap FIR filter is $-90°$ along a wide range of fractional tune (Fig. 4). Here the nine-tap components used for the x and y FIR filters were a_k = [0.3863, −0.7153, 0.6126, −0.00449, −0.0853, −0.2296, 0.2431, −0.0531, −0.1137] and a_k = [0.2750, 0.6716, 0.4057, −0.2462, −0.2767, 0.0418, 0.0145, 0.1068, −0.4778], respectively, where $1 \le k \le 9$, and we set $a_0 = 0$ because the required delay between the kick and the last position detection for it is one turn in PLS-II. The amount of delay depends on the revolution period of a ring and the latency of the feedback, and is an indispensable parameter to calculate/specify FIR filters.

4. Precision of the upgraded bunch-by-bunch feedback system

In PLS-II, the hybrid fill mode is the nominal operation mode to support time-resolved experiments. The hybrid fill mode consists of 330 bunch trains and one camshaft bunch. The harmonic number of PLS-II is 470, so bunch separation between the multi-bunch train and the camshaft bunch is 140 ns. For an efficient execution of time-resolved experiments, the charge of the camshaft bunch should be much higher than the charges in the train of bunches. In total, a beam current of 400 mA is stored in the PLS-II storage ring.

In a hybrid-fill-mode operation, a multi-bunch train suffers from multi-bunch instabilities and the camshaft bunch suffers from single-bunch instability. To increase the charge of the camshaft bunch, the bunch-by-bunch feedback system should provide good suppression of both instabilities. The analogue signal from the BPM button is proportional to both the bunch current and position. Therefore, a single front-end cannot process both the high-level signal of the high-current camshaft bunch and the low-level signal of the low-current bunches without causing saturation of circuits for high-current bunches or insufficient feedback gain for low-current bunches. One solution is the optimum adjustment of the ADC input signal level based on the measured bunch current in the RF front-end.

The kick pulse length for isolated bunches like singlets can be increased to several clock lengths in the processor to obtain the kicker's full efficiency, because isolated bunches in hybrid fill mode are generally led and followed by a 100 ns gap. By using this stretcher function in the upgraded processor, 15 mA single-bunch current was achieved in the nominal operation condition (Fig. 5). As shown in Fig. 6, under the nominal operation condition of 400 mA stored beam current in the hybrid fill mode, a maximum of 12 mA was achieved for the camshaft bunch. Both cases used the calibration by the beam-current monitor in the storage ring.

The upgraded processor can also measure the operating tune by exciting the specified bunch around the tune frequency without needing a feedback loop. In the tune measurement system [Fig. 7(*a*)], the single-bunch selector switch is located after the FIR filter so that the FIR filter can reject ADC direct-current offset data. Excited-signal data are updated on memory during 8.5 ms, and tune values are calculated by fast Fourier transform (FFT). The feedback system was turned off for 8.5 ms, and tune measurement data were updated every 5 s [Fig. 7(*b*)]. The tune measurement system by bunch-by-bunch feedback system was more precise than the old tune in both the horizontal [Fig. 8(*a*)] and vertical [Fig. 8(*b*)] directions.

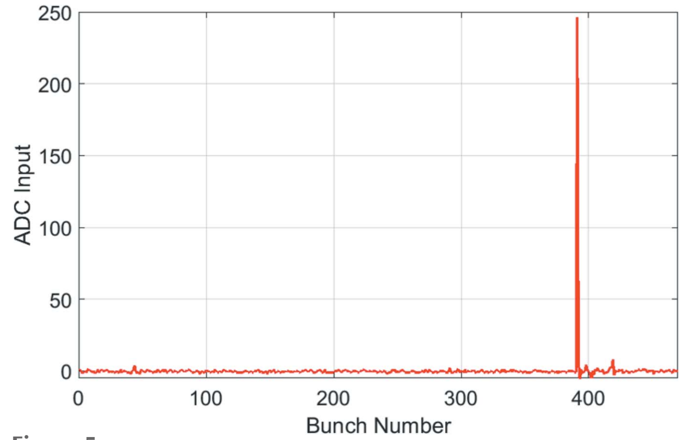


Figure 5
15 mA single-bunch current in the nominal operation condition.

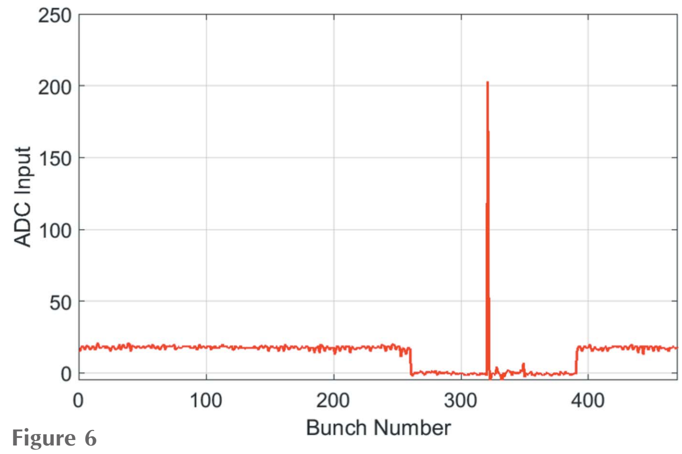
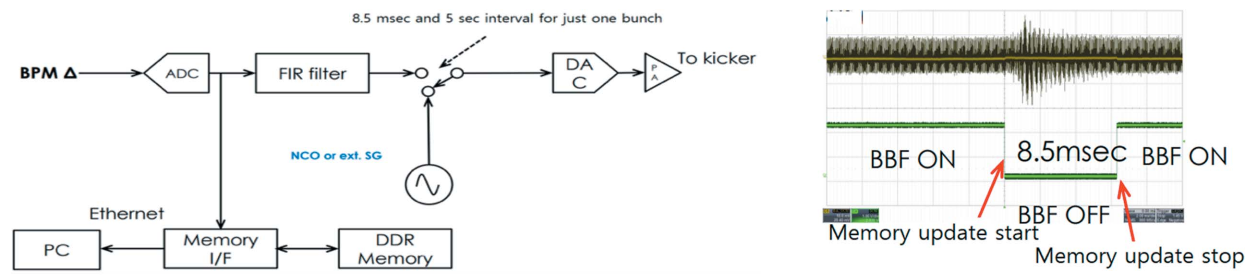


Figure 6
Current distribution of the 330 + 1 hybrid fill mode. The total beam current is 400 mA and the current of the camshaft bunch is 12.4 mA.

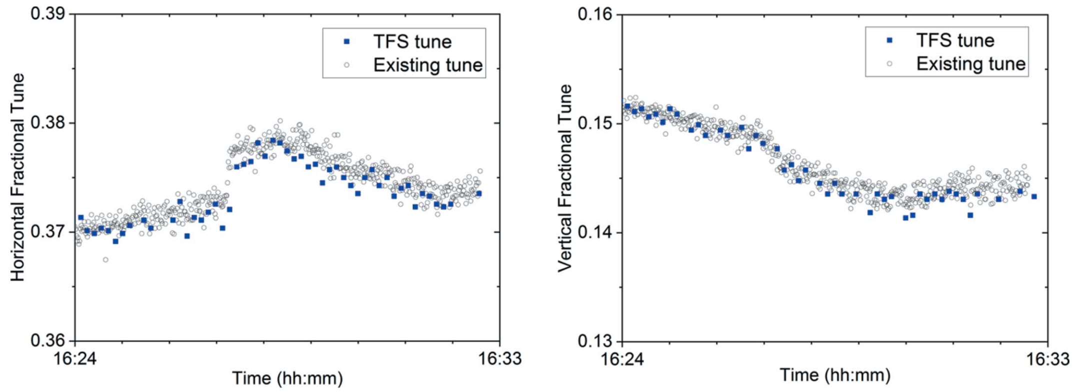
5. Conclusions

We have described the updated bunch-by-bunch feedback system at PLS-II. The main features of the upgrade are to use a single 500 MHz ADC instead of the previous four 125 MHz interleaved ADCs for 500 MHz rate, to replace a single-loop two-dimensional feedback with two independent one-dimensional feedback loops, to implement a tune measurement function with a single bunch, and mainly to implement single-bunch and stretcher control. The realization of a 400 mA hybrid fill pattern including a 10 mA single bunch demonstrates the precision of the upgraded bunch-by-bunch feedback system.



(*a*) (*b*)

Figure 7
(*a*) A schematic of the tune measurement system. (*b*) The beam oscillation signal from the ADC while the tune measurement system is turned on.



(*a*) (*b*)

Figure 8
Betatron tune measurements during beam injection by the upgraded TFS. The results are comparable with the values from the spectrum analyzer (the existing tune measurement system). (*a*) The horizontal tune. (*b*) The vertical tune.

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