

BEAM DIAGNOSTICS USING BPM SIGNALS FROM INJECTED AND STORED BEAMS IN A STORAGE RING*

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Abstract

Many modern light sources are operating in top-off injection mode or are being upgraded to top-off injection mode. The storage ring always has the stored beam and injected beam for top-off injection mode. So the BPM data is the mixture of both beam positions and the injected beam position cannot be measured directly. We propose to use dedicated wide band BPM electronics in the NSLS II storage ring to retrieve the injected beam trajectory with the singular value decomposition (SVD) method. The beam position monitor (BPM) has the capability to measure bunch-by-bunch beam position. Similar electronics can be used to measure the bunch-by-bunch beam current which is necessary to get the injection beam position. The measurement precision of current needs to be evaluated since button BPM sum signal has position dependence. The injected beam trajectory can be measured and monitored all the time without dumping the stored beam. We can adjust and optimize the injected beam trajectory to maximize the injection efficiency. We can also measure the storage ring acceptance by mapping the injected beam trajectory.

INTRODUCTION

The NSLS-II [1] is a 3 GeV third generation synchrotron light source under construction at Brookhaven National Lab. Due to its short lifetime, NSLS-II storage ring requires the top-off injection (once per minute) to keep the storage ring current constant to 1%.

The performance of pulsed magnet power supply is more stable at lower voltage operation. We proposed to implement a DC local bump [2] in addition to the fast bump to reduce the kicker strength, and thus the kicker power supply voltage, by ~ 30%. On the other hand, the injected beam position and angle must be controlled very well to maintain the beam injection capture efficiency, as the injected beam oscillation range is pushed to the limit of storage ring acceptance range in the injection section.

The common way to optimize the beam injection is executed in an empty ring. The injected beam trajectory is deduced from the transport line BPMs. There are at least two BPMs closing to the injection point with well known optics between them to measure the injected beam angle. In NSLS II storage ring, the bunch-by-bunch feedback system [3] has 500MHz sampling rate digitizers, which can measure the beam position with stored beam and injected beam during top-off injection. This study was a

preliminary attempt to investigate the possibility to measure and monitor the inject beam trajectory without dumping the stored beam during the top-off injection with storage ring BPM.

We build a model to measure the injected beam trajectory with linear optics approximation. This is applied to the simulation result. The fitted result is compared with the input value. The BPM system requirements are discussed.

MEASUREMENT METHOD

The injected beam is off-axis injection in x plane and follows the betatron oscillation around the storage ring closed orbit for top off injection. Only the beam trajectory deviation from the closed orbit represents the oscillation source. The betatron oscillation from one turn to the next turn is

$$\overline{C}_x(k+1) = R_{11} * \overline{C}_x(k) + R_{12} * \overline{C}_{xp}(k) \quad (1)$$

where k is the number of turn, $R_{11} = \cos(2\pi\nu_x) + \alpha_x \cdot \sin(2\pi\nu_x)$, and $R_{12} = \beta_x \cdot \sin(2\pi\nu_x)$ are one turn map, $\overline{C}_x(k) = C_x(k) - \overline{C}_{xs}$, $\overline{C}_x(k+1) = C_x(k+1) - \overline{C}_{xs}$, $\overline{C}_{xp}(k) = C_{xp}(k) - \overline{C}_{xps}$, are the beam positive and angle relative to the closed orbit (\overline{C}_{xs} , \overline{C}_{xps}), which can be measured well with turn by turn BPM. $C_x(k)$ is the beam center relative to the ideal orbit. ν_x is the storage ring tune. It can also be written as the function of the beam position and angle in the first turn.

$$\overline{C}_x(k+1) = R_{11}^k * \overline{C}_x(1) + R_{12}^k * \overline{C}_{xp}(1) \quad (2)$$

where $R_{11}^k = \cos(2\pi k\nu_x) + \alpha_x \cdot \sin(2\pi k\nu_x)$ and $R_{12}^k = \beta_x \cdot \sin(2\pi k\nu_x)$ are the transfer map from the first turn to (k+1)'s turn. The stored beam follows the same rule to do betatron oscillation with perturbation.

Assuming the BPMs are linear, the BPM signal with injected beam and stored beam is

$$C_x = \frac{C_{xi}Q_i + C_{xs}Q_s}{Q_i + Q_s} \quad (3)$$

$$\text{or} \quad \overline{C}_x = C_x - \overline{C}_{xs} = \frac{(C_{xi} - \overline{C}_{xs})Q_i + (C_{xs} - \overline{C}_{xs})Q_s}{Q_i + Q_s}$$

where *i* indicates the injected beam and *s* indicates the stored beam and *Q* is the bunch charge.

Combining Eq. (2) and (3), the beam oscillation can be written as

$$\begin{bmatrix} C_x(1) - \overline{C}_{xs} \\ \vdots \\ C_x(N+1) - \overline{C}_{xs} \end{bmatrix} = \begin{bmatrix} R_{11}^1 & R_{12}^1 \\ \vdots & \vdots \\ R_{11}^k & R_{12}^k \end{bmatrix} \begin{bmatrix} \overline{C}_x(1) \\ \overline{C}_{xp}(1) \end{bmatrix}. \quad (4)$$

With the SVD method, the first turn "combined" beam position and angle can be fitted as

* This manuscript has been authored by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy.

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$$\begin{bmatrix} \overline{C_x}(1) \\ \overline{C_{xp}}(1) \end{bmatrix} = \text{pinv}(R) * \begin{bmatrix} C_x(1) - \overline{C_{xs}} \\ \vdots \\ C_x(N+1) - \overline{C_{xs}} \end{bmatrix} \quad (5)$$

Here, $\text{pinv}(R)$ is the R 's pseudoinverse matrix. $\overline{C_x}(1) = \frac{(C_{xi}(1) - \overline{C_{xs}})Q_i + (C_{xs}(1) - \overline{C_{xs}})Q_s}{Q_i + Q_s}$ and

$$\overline{C_{xp}}(1) = \frac{(C_{xpi}(1) - \overline{C_{xps}})Q_i + (C_{xps}(1) - \overline{C_{xps}})Q_s}{Q_i + Q_s}$$

Stored beam oscillation contribution $(C_{xs}(1) - \overline{C_{xs}})$ and $(C_{xps}(1) - \overline{C_{xps}})$ should be zero, if the top-off injection is ideally transparent to stored beam. Then the injected beam position and angle relative to closed orbit can be measured as

$$(C_{xi}(1) - \overline{C_{xs}}) = \frac{Q_i + Q_s}{Q_i} \overline{C_x}(1) \quad (6)$$

$$(C_{xpi}(1) - \overline{C_{xps}}) = \frac{Q_i + Q_s}{Q_i} \overline{C_{xp}}(1). \quad (7)$$

Here we assume that the bunch propagation is linear. The beam motion smears out in a few tens of turns due to nonlinear effect on a real machine. But this is not a big problem for the first few turns. With ~ 10 turns of good data, the betatron motion can be measured.

On a real machine, the closed pulsed bump for stored beam is not closed due to the pulse magnets error during the top-off injection. The tolerated stored beam oscillation amplitude δC_{xs} is $0.7\sigma_x$ beam size [4], which bring the injection measurement error as

$$\begin{aligned} \delta C_{xi} &= 0.7\sigma_x \frac{Q_s}{Q_i} \\ \delta C_{xpi} &= 0.7\sigma_{xp} \frac{Q_s}{Q_i}. \end{aligned} \quad (8)$$

The bunch charge accuracy also affects the measurement error. The induced measurement error is

$$\begin{aligned} \delta C_{xi} &\approx \frac{Q_s \delta Q}{Q_i^2} \overline{C_x}(1) \\ \delta C_{xpi} &\approx \frac{Q_s \delta Q}{Q_i^2} \overline{C_{xp}}(1). \end{aligned} \quad (9)$$

SIMULATION WITH ELEGANT

Elegant [5] is used to simulate the beam position change in the first 100 turns. Tracking takes into account the synchrotron radiation and turns on the RF system. The input beam includes the stored beam and injected beam. The stored beam is on the closed orbit and the injected beam center is 9.5 mm off-axis which is nominal injection offset. The ratio of stored beam bunch charge to the injected beam bunch charge in one RF bucket is 12.5, which is consistent with the nominal operation parameters. In NSLS II, the storage ring nominal beam current is 500 mA with 1300 nC total charge. The bunch charge is 1.3 nC. The injected bunch train includes 80~150 bunches with 7.3 nC total charge.

For 9.5 mm off-axis injection, the BPM signal is supposed to change by $\sim 50 \mu\text{m}$, but the tolerated stored beam oscillation is $\sim 100 \mu\text{m}$ during top-off injection. The turn by turn signal is too weak and is hard to distinguish

from the stored beam oscillation. We use bunch-by-bunch BPM data.

There are a few available positions in storage ring for the bunch-by-bunch BPM. We select the position at girder 28, two super periods before injection straight, in order to measure of closed orbit position and angle at this BPM.

We firstly study the beam propagation with injected beam only. Figure 1 shows the beam center change at different turn with single particle and multi-particle tracking. The storage ring chromaticity is 5 and the synchrotron period as the number of turn is 125. It shows that in the first 15 turns, they agree pretty well. After that, the multi particles beam quickly smears out due to the decoherence effect.

The single particle tracking includes the high-order effect, comparing with the model propagation. Simulation shows that up to 100 turns, they agree very well. We can have the conclusion that the model is good in first 15 turns from the simulation.

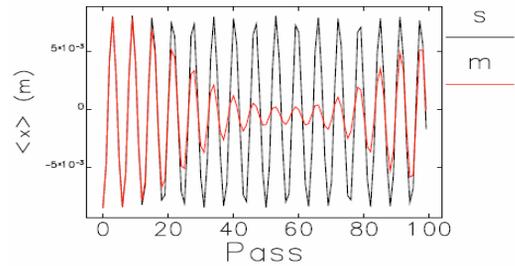


Figure 1: The beam center change with single and multi particles tracking.

Figure 2 shows the injected beam and stored beam horizontal phase space in the first 15 turns. The number increase from left to right. The stored beam is stable at the closed orbit. The injected beam oscillates around the stored beam. Figure 3 extracts the beam center and compares the tracking center with the model. In the first 12 turns, they agree well with each other. With 12 turns data, the injected beam parameters is fitted as shown in Table 1. The fitted value agrees with the input value very well. If the fitted angle is converted to position oscillation, the equivalent fitted position is the same as the input value.

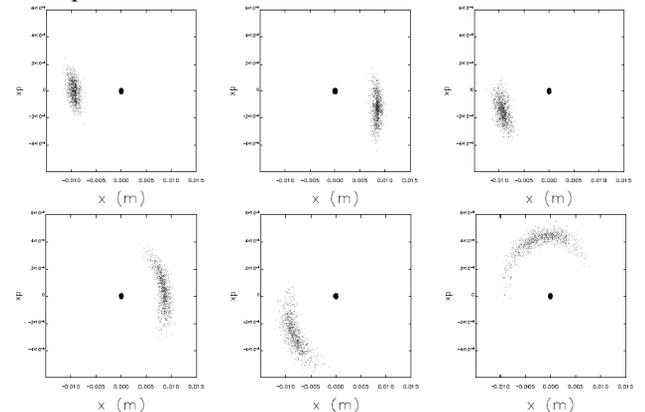


Figure 2: The injected beam and stored beam beam horizontal phase space in the first 15 turns (number increase from left to right for every 3 turns).

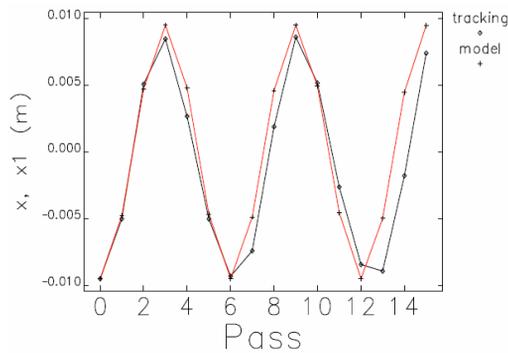


Figure 3: The beam center change with tracking and model propagation.

Table 1: Injected Beam Trajectory Fit

Parameters	Cx (mm)	Cxp (μrad)
Input value	-9.5	0
Fitted value	-9.34	1.3

BPM SYSTEM FOR BEAM POSITION AND CURRENT MEASUREMENT

The bunch by bunch BPM system has a RF front end and a 500MHz digitizer. The electronics have a good isolation of the neighbour bunches, separated by 2ns.

Figure 4 shows a schematic drawing of the broadband BPM electronics. Two button differential signals, including the betatron oscillation information of both horizontal and vertical plane, are mixed down to baseband. The digitizer has a 12-bit 500MHz ADC, the sampling clock is synchronized with the storage ring RF frequency. Sampled data can be saved to on-board memory with a maximum of 8 gigabyte samples, which is equivalent to more than 600k turns data. FPGA inside the digitizer can be programmed for advanced calculation like Fourier transform. The electronics is expected to have a measurement resolution better than 10 μm. If the beam offset is too big, such as 10mm injection beam oscillation, the button BPM delta signal is not linear. Nonlinear term due to BPM should be considered for a precise measurement.

The sum signal from the hybrid can send to the same 500MHz digitizer for beam current measurement. We know that the sum signal from button-BPM has position dependence. The sum signal could change more than 10% with the injecting beam oscillation amplitude as large as 10mm. This makes the precise bunch-to-bunch current measurement un-realistic during the top-off injection. An alternative way to measure the bunch current is using the visible synchrotron light in the diagnostic beamline. Light

emitted from stored beam and injected beam are focused onto the photon multiplier. Photon multiplier output signal does not depend on the beam position, thus gives a bunch current resolution of better than 1%.

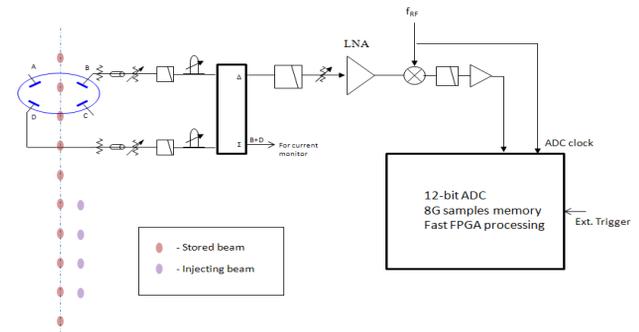


Figure 4: Block diagram of the broadband BPM detection system.

SUMMARY

One method to measure and monitor the injected beam position and angle is explored with storage ring BPM. It has the advantage that the injected beam trajectory can be measured and monitored all the time without dumping the stored beam. It is very useful to monitor and optimize the injected beam for top-off injection, especially for NSLS II. By adjusting the injected beam trajectory, we can optimize the injection efficiency. By mapping the injected beam trajectory, we can measure the storage ring acceptance.

Simulation shows that with the linear model, the fitted results agree with the input value. The measurement accuracy depends on the hardware.

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