

# NSLS2 FILL PATTERN MONITOR AND CONTROL\*

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## Abstract

NSLS2 storage ring has harmonic number of 1320. Possible fill patterns include multi bunch train(s) followed by ion cleaning gap(s), hybrid fill with single bunch in the ion gap. Storage ring filling pattern can be measured using button BPM sum signal together with high speed digitizer or oscilloscope. Button BPM sum signal typically has dynamic range of  $10^{-2}$  to  $10^{-3}$ . Nonlinearity of BPM sum signal dependence on beam position has been characterized. In preparation for high dynamic single bunch current measurement, a filling pattern monitor system using synchrotron radiation is under development. Besides, the storage ring filling pattern can be controlled using the bunch cleaning function integrated in the bunch-by-bunch feedback system. Results of these two filling pattern monitors and bunch cleaning will be presented.

## INTRODUCTION

NSLS2 storage ring has been commissioned recently and it's open for user operation. The ring is using super conducting 500MHz single cell cavity. There are maximum of 1320 bunches that can be filled in the ring. There is one cavity available with RF voltage at 1.78MV. 300mA total beam current were able to be stored with this cavity. Once the second super-conducting cavity is available in the coming months, high storage current can be achieved. NSLS2 storage ring was designed to have weak dipoles and damping wigglers (DW) to further decrease the horizontal emittance to sub-nm level. Depending on RF gap voltage, number of DWs used and bunch lengthening due to broadband impedance, typical bunch lengths at NSLS2 storage ring are between 15-

Arbitrary fill pattern can be generated in the NSLS2 storage ring. Typical fill pattern includes a long bunch train of about 1000 bunches (80% fill) followed by an ion-clearing gap. Bunches are separated by 2ns in the bunch train. Camshaft single bunch can be added in the ion gap for future time correlated experiments. At the current user operation, a single bunch is filled with similar bunch current to the main train bunches. The single bunch is used to monitoring betatron tune continuously. Even with the ion gap, fast ion instabilities have been observed [1,2] along the long bunch train. With bunch by bunch feedback, ion instabilities can be suppressed well up to 300mA, bare lattice at nominal chromaticity of +2/+2. As the total beam current increasing and machine emittance (especially vertical plane) decreasing like coupling correction, fast-ion effect will be more severe. There is possibility to fill the ring with 4 (or 6) bunch trains. Each train will have ~250

bunch filled followed by a short ion gap of 80 buckets. Camshaft single bunches can be populated in the ion gaps as well.

During top-off operation at 500mA, beam lifetime is expected to be around 3 hours. To keep the total beam current variation within 1% and top off injection period > 1 minute, 7nC charge per shot are required to be delivered to the storage ring. Relative bunch to bunch current variation is specified to be within 20%. It's desired to measure the bunch to bunch current with better than 1% resolution. Fill pattern monitor and control is also important to various machine studies.

Button BPM SUM signal is not only determined by the bunch current, it may depend on the button size and BPM chamber geometry, cable attenuation, electronics attenuations, beam position and bunch lengths. For the fill pattern monitor BPM SUM signal, button geometry, cable and electronics attenuations are fixed once the system is installed. SUM signal nonlinearity dependence on the beam position has been analyzed in [3]. Figure 1 plots the two diagonal buttons SUM signal nonlinearity of the FPM BPM pickup. As can be seen, if the beam orbit is controlled within +/-6mm horizontally and +/- 3mm vertically, BPM SUM signal dependency on beam position is within 1%. With stored beam and orbit corrected, beam position at the FPM pickup is well within 1mm from the BPM geometric center, typically the SUM signal dependency on beam position can be neglected.

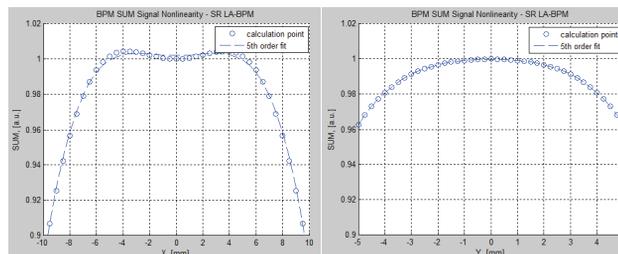


Figure 1: BPM SUM signal nonlinearity of two diagonal buttons. Two diagonal buttons SUM signal is used to measure the NSLS2 storage ring fill pattern.

Reflection of the button signal could lead to inaccurate measurement of the fill pattern, especially when there are high current bunches filled in the ring. As the capacitive button is not 50 Ohm matched to the detection electronics, reflection signal is unavoidable. 3 dB attenuators have been added right after the button feedthrough which helped to suppress the reflection signal but not able to eliminate it. Reflection signal can come from the HOM of the vacuum chamber structure where BPM pickup is mounted on. Figure 2 shows an example of 0.2mA single bunch filled in the ring, the signal peak amplitude was about 800mV (out of scale), there were

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reflection peaks observed at  $\sim 40\text{ns}$  and  $200\text{ns}$  away from the main peak. The reflection peaks had amplitude about  $5\text{mV}$ , which is  $\sim 0.6\%$  of the main peak signal.

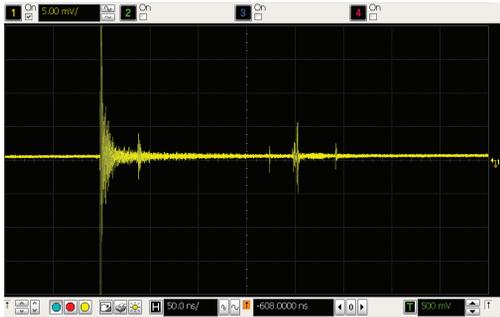


Figure 2: Reflection signals observed when a high current signal bunch was filled.

A time correlated single photon counting system (TCSPC) has been tested using visible light in the SLM diagnostic beamline. The setup is similar to other 3<sup>rd</sup> generation light sources [4,5], it has large dynamics range to measure the single bunch purity. The system can be used to measure the bunch to bunch fill pattern with better dynamics range and reasonable measurement time. As synchrotron light is used, TCSPC system has no position dependency or reflection issue.

### FPM FROM BPM SUM SIGNAL

Storage ring filling pattern was measured from a dedicated BPM. Broadband hybrid SUM signal from diagonal buttons was sent to high speed digitizer or 20GHz oscilloscope. Bunch filling pattern was calculated from pulse area or peak amplitude. Meanwhile bunch centroid can be used to measure beam synchronous phase, if the digitizer jitter is small. This could be a useful tool to detect the transient beam loading effect with long bunch train and ion gap fill. Shown in Fig. 3 is a typical bunch pulse observed on storage ring filling pattern monitor, using 20GHz oscilloscope. Red diamonds are the raw sampled data with 50ps separation.

To retrieve the peak amplitude and location with better resolution, 10 times interpolation was applied to the raw data. Interpolated data points are plotted as blue circles. Searched peak of interpolated point gives the green square in the figure, its amplitude was considered to be proportional to bunch current and its position as measured bunch arrival time (synchronous phase). Interpolated points have 5ps separation, the measured synchronous phase shall have accuracy better than 5ps, not including the trigger jitter. Storage ring revolution fiducial clock 378kHz was used for the 20GHz scope trigger, the fiducial signal from event timing system has jitter typically around 17ps relative to the beam signal. A lower jitter fiducial clock divided from the RF reference signal has been tested with jitter less than 3ps.

### Synchronous Phase Measurement

To validate the synchronous phase measurement

method, preliminary study was done by varying RF cavity voltage and recording the synchronous phase. From the synchronous phase vs. cavity voltage curve, energy loss per turn can be estimated. Assume bunch synchronous phase:

$$\phi_s = \phi_m + \phi_0 \quad (1)$$

Where  $\phi_m$  is the measured synchronous phase and  $\phi_0$  is the constant due to delays.

At low bunch current, parasitic energy loss due to wakefield can be neglected, bunch synchronous phase and energy loss per turn due to synchrotron radiation has the relation:

$$eV_{rf} \sin \phi_s = U_{sr} \quad (2)$$

Where  $V_{rf}$  is RF gap voltage;  $U_{sr}$  is energy loss due to synchrotron radiations. Substitute Eq. 1 in to Eq. 2, we get:

$$eV_{rf} \sin \phi_m \cos \phi_0 + eV_{rf} \cos \phi_m \sin \phi_0 = U_{sr} \quad (3)$$

Let's define:

$$x = eV_{rf} \cos \phi_m \quad (4)$$

$$y = eV_{rf} \sin \phi_m$$

Eq. 3 can be written as:

$$y \cos \phi_0 + x \sin \phi_0 = U_{sr} \quad (5)$$

From Eq. 4 and Eq. 5, one can see that by measuring the synchronous phase  $\phi_m$  at different  $V_{rf}$  and fitting the  $x, y$  variables, energy loss per turn can be calculated from the fitting slope.

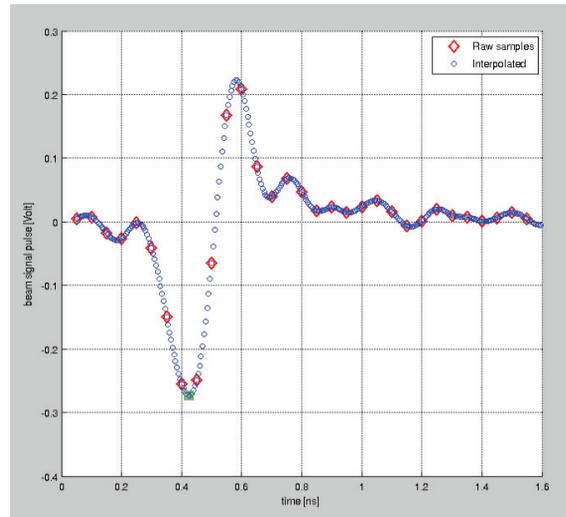


Figure 3: Storage ring filling pattern monitor signal from 20GHz real time sampling scope. Red diamonds were raw sample data points while blue circles were interpolated points by a factor of 10. Green Square is the searched peak of interpolated point, its amplitude was considered to be bunch current and its position was measured synchronous phase.

Figure 4 is the FPM measured synchronous phase at different RF gap voltage, with bare lattice (no DWs). 20 bunches were filled to 0.7mA, averaged synchronous phase from these 20 bunches was considered as measured results. Fitting the  $x, y$  values as defined in Eq. 4 yields the energy loss per turn for bare lattice to be 286.6 keV, this agrees well with the theoretical value of 287 keV. Three DWs in C08, C18 and C28 can be open/close at different gaps. Figure 4 (c) gives the measured energy loss per turn results with DW28 at different gaps.

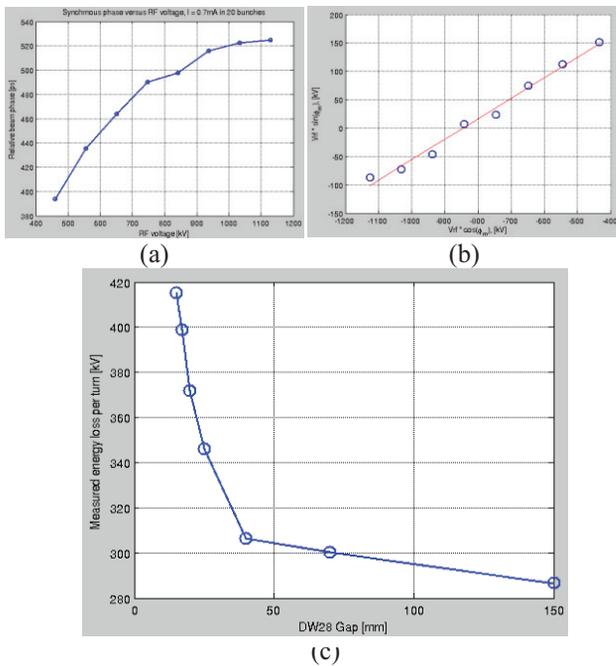


Figure 4: (a) measured synchronous phase at different Vrf; (b) Fitting the  $x, y$  values as defined in Eq. 4, blue points are the measured points, red line is the linear fit. Energy loss per turn is measured from the fitted line; (c) Measured energy loss per turn with DW28 closed at different gaps. The other two DWs were fully open.

*FPM Calibration*

As the bunch to bunch current varies a lot, it's important to check linearity of measured bunch peak voltage with different stored bunch current. With single bunch filled in the ring at 0.1mA to 0.6mA with 0.1mA steps, Fig. 5 plots the interpolated peak voltage at different single bunch current. FPM scope had fixed vertical scale of 500mV per division.

With bare lattice and  $V_{rf} = 1.78MV$ , measured bunch length changed from 15 ps to 22 ps with bunch current varied from 0.1mA to 0.6mA [6]. Peak voltage vs. bunch current had good linearity with this bunch lengthening effect.

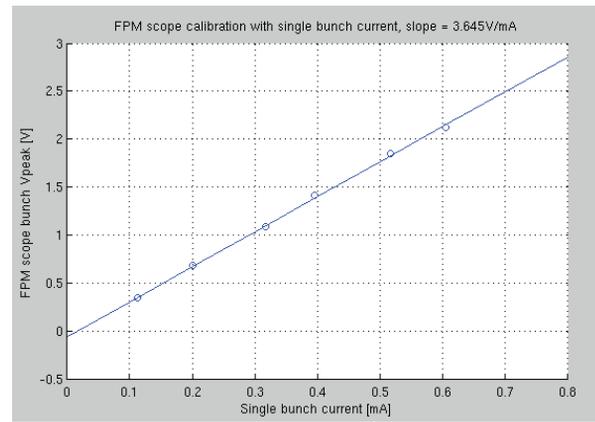


Figure 5: FPM scope measured peak voltage at different single bunch current. Scope vertical scale was fixed at 500mV per division.

*Uniform Fill Pattern*

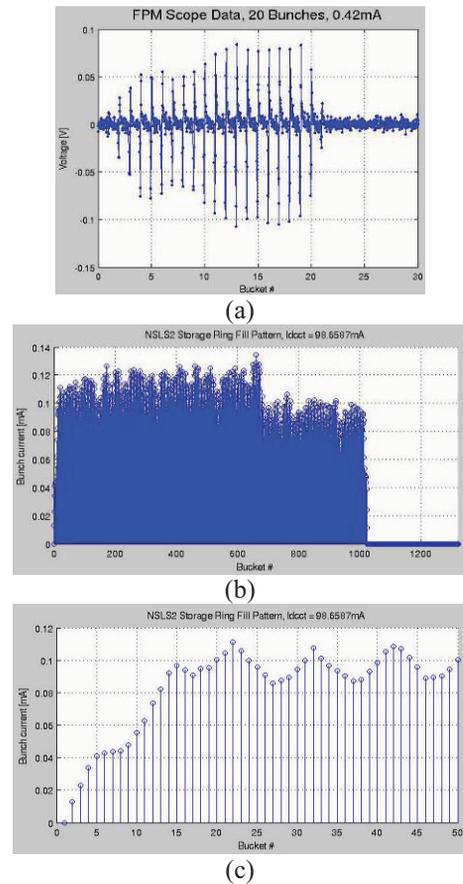


Figure 6: NSLS2 storage ring fill patterns. (a) Single shot injecting of 20 bunches stored in the ring, bunch to bunch current variation is mainly coming from the electron gun. (b) Typical fill pattern with 50% overlap fill, 20 bunches train was injected in the ring with target bucket increased by 10 between different shots of injections. Machine was filled to 99mA with 1000 bunches. (c) Zoom in the head bunches of the 1000-bunch train.

As discussed earlier, top-off injection requires  $\sim 7nC$  delivered to the storage ring per shot. Electron gun and injector are typically operated in multi-bunch mode to generate high charges. Gun pulse width can be adjusted to generate a pulse train of different bunches. At present 150mA user operation, typical bunch train from the injector includes 20 bunches with 2ns bunch to bunch separation. Bunch to bunch current variation is pretty big, as can be seen in Fig. 6 top plot. To have a more uniform fill pattern, overlap filling is typically used in between different injection pulses. With 20 bunches injection and 50% overlap fill, fill pattern at 100mA is typically like in Fig. 6 (b, c). RMS bunch to bunch current variation was able to be controlled within 10%, not including bunches in rise/falling edges.

As can be seen from Fig. 6 (c), even with the overlap fill, head/tail bunches in the long bunch train still have large bunch to bunch current variations, which is inherited from the un-even fill pattern of the injector. These head/tail bunches can be trimmed away using the bunch cleaning functions integrated in the bunch by bunch feedback system. After knock out the rise/falling edge bunches, rectangular shape bunch train can be generated. The best achieved fill pattern had 0.8% RMS bunch to bunch current variation, with 100mA stored in 1000 bunches.

### FPM FROM TCSPC

Button BPM SUM signal may suffer from the position dependency nonlinearity, reflections and bunch length dependency etc. To avoid these issues, synchrotron radiation detection with a photon diode looks to be a good solution. For the isolated single bunch in the ion gap, it is important that there are no (very little) diffused electrons in the nearby buckets so that experiments will see a clean isolated x-ray pulse. Due to dark current from the gun and scattering, there will always be electrons escape from the main single bunch and captured in the nearby buckets. Single bunch purity is defined as ratio of electrons in nearby bunches to the main bunch. It's of great interest to measure the single bunch purity for the potential time resolved users. NSLS2 bunch by bunch feedback system has the integrated function to knock out unwanted bunches, similar to trim the head/tail bunches in the long bunch train. This method is very helpful to create a 'pure' single bunch so that there will be no polluted electrons nearby. While cleaning the bunches, there is little disturbance to the main bunch.

Using the visible light in SLM hut, a time correlated single photon counting (TCSPC) system has been tested. Visible light was guided on to a test branch where a fast photo diode will generate a pulse whenever single photon was detected. The pulse was then amplified with an integrated broadband amplifier. PicoHarp300 [7] system was used to measure the photon arrival time relative to the ring revolution clock, which is 378kHz for NSLS2 storage ring. To avoid pile up, a pinhole and optical density filters are added before the photo diode to detect less than one photon per turn. Figure 7 shows the

preliminary single bunch purity measurement results. A single bunch was filled in the ring with current  $\sim 0.2mA$ , TCSPC system was counting photons for 2 minutes. Before bunch cleaning, one can see there are unwanted photons coming 2ns, 4ns and 6ns later from the main single bunch. After cleaning these buckets were not seeing photons within the measurement duration. The single bunch purity was better than  $1e-5$ . It's worth to note that with higher current in the single bunch, scattered electrons from the main bunch can be re-captured in the following buckets, depends on the bunch in-purity growth rate, periodical bunch cleaning may be necessary to guarantee a high purity single bunch.

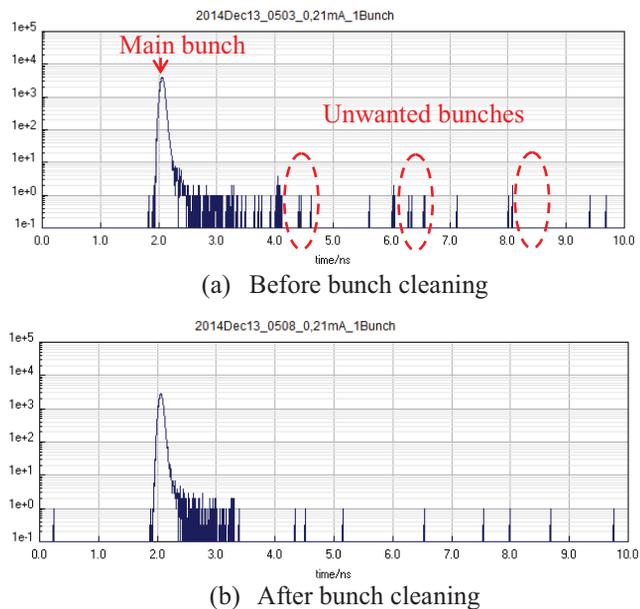
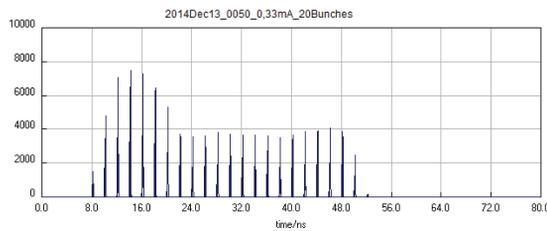


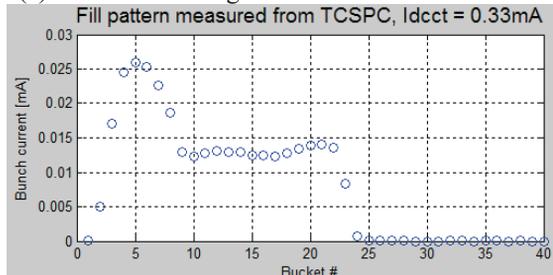
Figure 7: Single bunch purity measurement using timing correlated single photon counting (TCSPC) system. It counted photons for about 2 minutes with 0.2mA single bunch stored in the ring. Vertical scale is number of photons detected with the photo diode. (a) Before bunch cleaning, the single bunch purity was measured to be  $\sim 3e-4$ . (b) After bunch cleaning, single bunch purity is better than  $1e-5$ .

If there are more than one bunches filled in the ring, photon counting system can count the photons from different bunches and determine which bunch is the photon coming from, this can actually be used to precisely measure the electron bunch fill patterns. Usually for fill pattern measurement, it can count with shorter time to have loose dynamics range.

Figure 8 plots are the fill pattern measured with 20 bunches stored in the ring, machine was delivering beam to beamline commissioning with low average current of 0.33mA. Upper plot shows the raw photon counting data generated from these 20 bunches. Processed fill pattern is in the lower plot. Both plots have linear vertical scale. Compared to the fill pattern measured from BPM SUM signal, photon counting system has better dynamics range, for example, bunch # 24 in Fig. 8 had  $\sim 0.7uA$  which is not easy to detect with button signal.



(a) Photon counting with 20 bunches stored beam



(b) Measured fill pattern

Figure 8: Fill pattern monitor from TCSPC system. 20 bunches were fill in the ring with average beam current of 0.33mA.

## SUMMARY AND DISCUSSION

Two types of fill pattern monitors at NSLS2 storage ring have been used. Button BPM SUM signal digitized with high sampling rate scope (or digitizer) is the currently operational system. The system has dynamics range  $\sim 1\%$  which is sufficient to measure the bunch to bunch current variation of 20%. Button SUM signal dependency on beam position has been calculated to be small. For the future camshaft fill pattern for time resolved experiments, when a high current single bunch filled together with a long bunch train with low bunch current, reflection signal from the high current bunch may overlap with the low current bunch signal, which might cause inaccurate fill pattern measurement.

Bunch synchronous phase can be measured by interpolating the 20GHz sampled data. With low jitter revolution fiducial as trigger, bunch phase can be measured with resolution of 5ps. This method has been used to measure the energy loss per turn with bare lattice and different DW gaps. The measured energy loss per turn agrees well with the theoretical calculation. When the beam had longitudinal instability during several studies, scope measured synchronous phase saw  $\sim 50$  ps bunch to bunch motion. This had been cross checked on streak camera.

To generate a uniform fill pattern, overlap fill is implemented during the storage ring initial fill and top off. After trimming the rise/falling edges, typical bunch to bunch variation is within 10%.

A TCSPC system has been tested using visible light in the SLM diagnostic beamline. The photon counting system can measure the single bunch purity of the camshaft bunch. After bunch cleaning, single bunch purity was measured to be better than  $1e-5$ . The system can be used to precisely measure the storage ring fill pattern. Compared to the button BPM based fill pattern system, photon counting fill pattern monitor will have better dynamics range with reasonable measurement time

( $\sim 1$  min). However, TCSPC is not able to measure the bunch synchronous phase and other transient effect like bunch current at injection.

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## REFERENCES

- [1] W. Cheng, et. al., "Commissioning of Bunch-by-bunch Feedback System for NSLS2 Storage Ring", IBIC'2014
- [2] W. Cheng, et. al., "Observation of Ion-induced Instabilities at NSLS2 Storage Ring", this proceeding.
- [3] W. Cheng, et. al., "Performance of NSLS2 Button BPMs", IBIC'2013
- [4] C.A. Thomas, et. al., "Bunch purity measurement for Diamond", Nucl. Instr. Meth. A 566 (2), 762 (2006)
- [5] J. Corbett et. al., "Bunch Pattern Measurement via Single Photon Counting at SPEAR3", IBIC'2014
- [6] W. Cheng, et. al., "Longitudinal Bunch Profile Measurement at NSLS2 Storage Ring", this proceeding.
- [7] <https://www.picoquant.com/>