CHARACTERIZATION OF NSLS2 STORAGE RING BEAM ORBIT STABILITY*

Weixing Cheng#, Kiman Ha, Joe Mead, Boris Podobedov, Om Singh, Yuke Tian, Li-hua Yu
NSLS-II, Brookhaven National Laboratory, Upton, NY 11973

Abstract

Similar to other advanced third generation light sources, NSLS2 storage ring has stringent requirements on beam orbit stability. NSLS2 BPMs can be synchronously triggered to record turn by turn or fast acquisition 10kHz data. Spectrum of these data reveals various beam motion frequencies and it has been characterized at various machine conditions. Compared to the ground motion and utility system vibration spectra, beam motion introduced by the vibrations can be identified. An algorithm to locate possible noise sources from the measured spectrum has been developed. Preliminary results of locating orbit sources will be discussed in this paper as well.

INTRODUCTION

NSLS2 is an advanced third generation light source recently constructed at Brookhaven National Laboratory. The 3GeV storage ring generates ultra-low emittance of less than 1nm.rad horizontally and 8pm.rad vertically. Machine commissioning has been finished with six beamlines early this year and it's open for user experiments. With one super-conducting cavity, average beam current of 300mA has been achieved. Typical user operation current has been increased in steps, now it operates at 150mA and refills at every three hours. Top off operation will start soon.

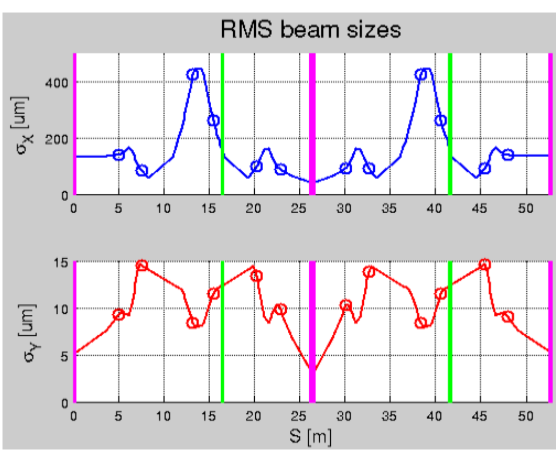

Figure 1: Horizontal and vertical RMS beam sizes in one super cell, calculated using emittance of $\varepsilon_x/\varepsilon_y$ = 0.9/0.008 nm.rad and energy spread of 0.09%.

NSLS2 storage ring has 30 DBA cells. 15 high beta (long) and 15 low beta (short) straight sections are available for insertion devices. Three damping wigglers are installed at long straight sections in C08,C18 and C28. These damping wigglers decrease the bare lattice horizontal emittance of 2nm.rad down to 0.9nm.rad. Figure 1 plots the RMS beam sizes in one super cell (high beta cell + low beta cell). Beam sizes at various beamline source points are marked with vertical lines. Smallest beam sizes of 3 μm are found to be at the center of short straight sections. With 10% beam stability requirement, the orbit needs to be controlled within 300nm at these source points. There are 6 BPMs in each cell to monitor the beam trajectory/orbit. BPM locations are marked as circles in Fig. 1. These BPM readings are used for orbit correction and fast orbit feedback control. There are 6 slow correctors and 3 fast correctors per cell to maintain the beam in desired reference orbit. In addition to the normal BPMs in the cell, there are 2 (or 3 for canted ID straights) ID BPMs on both end of the insertion devices. These BPMs are typically mounted on high stability stands and configured to have better vertical sensitivity. ID BPMs are used to monitor the orbit at the insertion devices. This information is used to ensure that the beam stays within the pre-defined active interlock envelope, as required for machine protection. More information of the NSLS2 button BPM design and performance can be found at [1,2].

In-house developed BPM electronics are used in NSLS2 complex, including the LINAC, transport lines, Booster and Storage ring. Button signals feed to the pilot tone combiner (PTC) box inside the tunnel, where beam signal is filtered. PTC includes a coupler to allow the pilot tone signal be injected into the signal processing chain. This pilot tone signal was designed to dynamically calibrate the BPM electronics drift. It turned out that this kind of dynamic pilot tone calibration is not needed as BPM electronics reside in temperature stabilized racks (+/- 0.1 degC). BPM processing electronics are assembled in a 1-U chassis, analog front end (AFE) first conditions the button signal with band pass filter, variable attenuators and amplifiers. Button signal is sampled by 16-bit ADC sampling rate of 117MHz. Sampled data is then processed in the digital front end (DFE) board, in which ADC/TbT/FA/SA data are available. NSLS2 storage ring BPMs can provide to the user in 4 switchable modes, ADC, TbT (Turn-by-Turn, up to 1M samples, on-demand), FA (Fast Acquisition, 10 kHz, up to 1M samples, on-demand) , and SA (Slow Acquisition, 10 Hz, continuous). 10kHz FA data is shared around the ring through SDI fiber link network, these data are used for fast orbit feedback and active interlock system. Details of the BPM electronics development are reported in previous conferences [3-6]. We report the measured beam orbit stability using these advanced BPMs.

*Work supported by DOE contract No: DE-AC02-98CH10886
#chengwx@bnl.gov

ISBN 978-3-95450-176-2

BPM ELECTRONICS PERFORMANCE

To characterize the beam orbit stability, it's important to know the measurement resolution and accuracy. BPM electronics resolution is mainly determined by the beam current, electronics gain and measurement bandwidth. BPM resolution has been measured with beam at three different fills: single bunch, 20-bunches short train and ~1000 multi-bunch train. Total beam current was increased in steps till BPM electronics saturate. BPM ADC, TbT and FA waveform data was recorded to calculate the resolution of different types of data. During maintenance when there was no beam, pilot tone signal with the same frequency as of RF was injected to the electronics to characterize the BPM resolution in fine steps. BPM attenuator was varied to simulate different signal strength. Measured results are shown in Fig. 2. The figure plots the measured resolution at different averaged ADC counts, which is basically BPM SUM signal. At high current (>10mA) with long bunch train, BPM resolution in TbT mode is better than 1µm when ADC counts is more than 4000. FA data had about 200nm resolution at these current. It's also noticed that with single bunch measurement, at 0.7 mA bunch current, beam was unstable due to TMCI instability, that's the reason there is one point didn't follow the curve in the TbT resolution plot. During 20 bunch fill, horizontal measured resolution with beam was slightly higher compared to the pilot tone results, which could be due to some orbit instabilities.

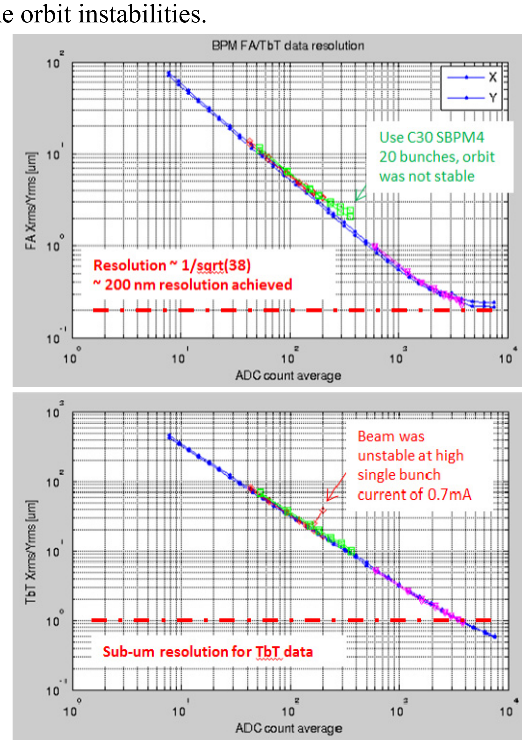

Figure 2: BPM TbT and 10kHz FA data resolution measured using pilot tone beam. Blue dots – test with pilot tone while varying the attenuators. Red diamonds – single bunch beam; Green square – 20 bunches beam; Magenta triangle – 1000 bunches beam. BPM attenuators were fixed at 0dB for beam test.

When the front end BPM attenuators are changing, the four channels electronic gains may not change by exactly the same amount. This will cause artificial position jumps when the RF attenuator is varied. While this is not expected to be an issue during the planned top-off operations, when the beam current and fill pattern variations will be tightly constrained thus eliminating the need for attenuator change, this effect needs to be addressed for various machine physics studies as well initial user operations without top-off. This is why static gain calibration coefficients have been implemented to compensate this effect. Assuming the beam orbit didn't move during some short period of time (~30 minutes), beam based static gain calibration look up table was created at different attenuator settings. Fig. 3 shows one BPM's position drift before and after the calibration. While attenuators scanned from 0 to 20dB in 1dB steps, most of the BPMs saw position drift of several tens of microns, some BPMs had drifted more than 100 microns. With the new beam based calibration coefficients, all BPMs have position drifts less than +/-10µm in the same RF attenuator scan. Note that these coefficients were generated at fill of 20 bunches with total current ~1.2mA in Nov. 2014 and they are still working fine now, many months later, with different beam current and fill patterns. Notice the X/Y position scales are same in Fig. 3 which is 100µm full range. Absolute position readings are different because these two sets of data are separate by more than 6 months and reference orbits could be very different.

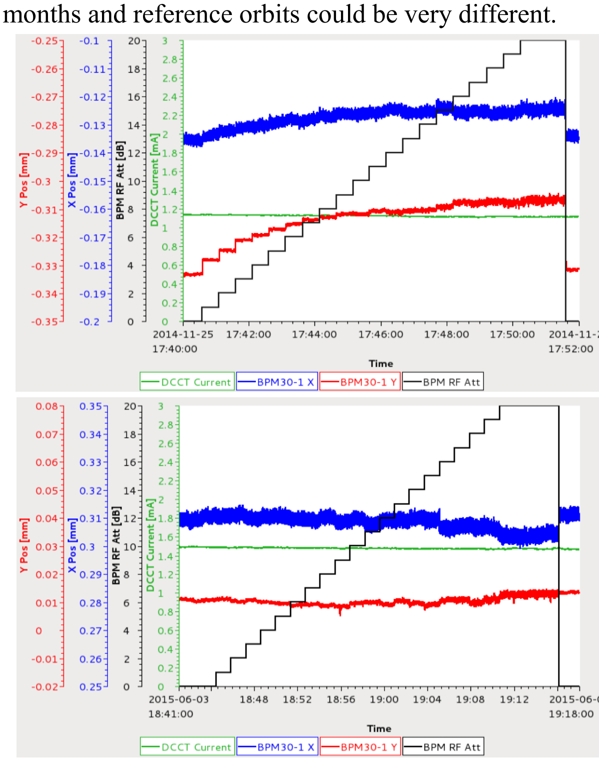

Figure 3: BPM RF attenuator dependency, C30 BPM1 horizontal/vertical position drift while attenuator scanned from 0 to 20dB in 1dB steps. Upper plot shows the position drifts before calibration, this particular BPM had vertical position drift about 30um; Lower plot gives the same scan with calibrated LUT.

To further check the BPMs current and fill pattern dependency, three consecutive fills were tried with 100 bunches, 200 bunches and 350 bunches, total beam current of all three fills were kept at 10mA. There was little difference on the BPM reported position readings. During the initial fill, especially when total beam current is low (<0.2mA, typically happened during single bunch studies), BPMs near RF cavity area saw large position drifts. This was investigated and found to be due to interference from RF system. Once beam signal is dominant (Ib > 0.2mA), BPM reported current dependency is negligible.

BPM ORBIT SPECTRUM

BPM 10kHz FA data are shared around ring through fiber network, there is one cell controller in each cell who communicate to the BPMs and power supplies in the cell. 30 cells in the ring are connected together with SDI interface. These synchronized 10kHz data are used for fast orbit feedback and active interlock. As the beam orbit motion typically appears in frequency range of several Hz to hundreds of Hz, 10kHz sampling rate FA data is well suitable to analyze the beam motion spectrum.

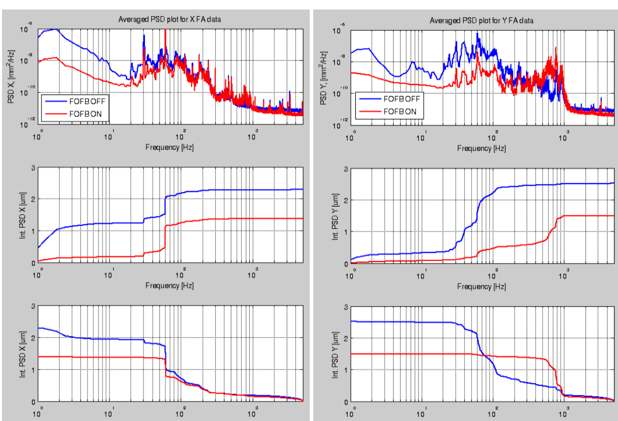

Figure 4: BPM 10kHz FA data spectrum and integrated RMS motions (from low to high frequency and vice versa), compared with FOFB ON and OFF.

Figure 4 gives an example of beam spectrum measured with FOFB ON and OFF. 10 seconds of synchronized data was acquired from all 180 BPMs, 16384 points of FFT spectrum was calculated with blocks of FA data. BPM at different locations will see different motion levels, the spectrum shown here is averaged from all non-dispersive BPMs in the ring. Blue lines are results without FOFB, most of the beam motions are in frequency range between 10Hz to 100Hz. There is a clear 60Hz peak coming from the AC line. A majority of this 60Hz noises is coming from pulse magnets. Around 30-40Hz peaks are believed to be utility system related. Mechanical motions of the girder and BPM chamber have been measured during operation. Girder motion is similar to what have been reported in [7], BPM chamber vibration spectrum saw peaks between 30-40Hz, which are likely induced by cooling water on the multipole vacuum chamber. Red lines are the PSD spectrum and integrated RMS motions with FOFB ON. Below 200Hz motions were able to be suppressed significantly in vertical plane. Horizontal FOFB is able to reduce the motions below several tens of Hz, which can be further optimized.

From the above mentioned PSD spectrum, RMS motions at each BPM can be calculated in some pre-defined frequency ranges. Figure 5 gives the 12 BPMs in C02 and C03 RMS motion integrated between 1-500Hz. Blue circles and red stars represent the RMS motions without and with FOFB. 1% of horizontal beam sizes and 10% of vertical beam sizes along the cells were plotted as dashed lines, to have a comparison of beam motions to the beam sizes. As can been seen, due to large horizontal beam sizes, X RMS motions is around 1% of the beam sizes which is well within the requirement. Vertical motions are typically ~ 20% of beam sizes without FOFB and they were able to be suppressed to ~ 5% of the beam sizes. In the middle waist locates C03 IVU, which supplies x-ray for the HXN (Hard X-ray Nano probe) beamline. This particular beamline has the tightest requirement on orbit stability. From two BPM readings on both ends of the insertion device, position and angle at the IVU center can be calculated. This virtual BPM position and angle spectrum were calculated and integrated motions in the same frequency range are 0.216 μm and 0.136 μrad, both meet the requirements of 10% beam sizes and 10% of beam divergence.

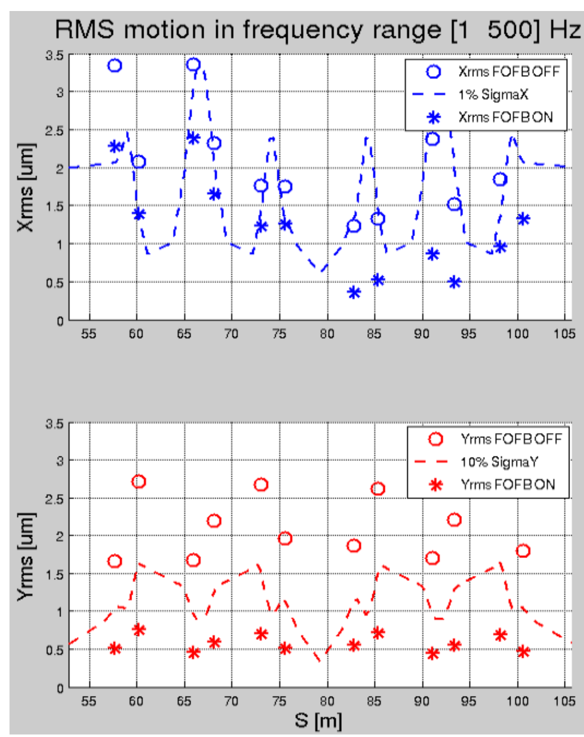

Figure 5: Integrated RMS motion in frequency range 1-500Hz, plotted for 12 BPMs in one super-cell (C02 and C03). C03 IVU locates in the center where beam sizes are smallest in both x/y planes.

In the HXN beamline, there is a photon BPM (xBPM) locates ~16 m from the source point. Using a similar digitizer, this photon BPM is capable to acquire long

ISBN 978-3-95450-176-2

buffer of 10 kHz data. X/Y position spectrums at the photon BPM location have been compared from direct measurement of xBPM and calculated from two ID BPMs in the straight section. The directly measured and calculated spectrums agree well, as shown in Fig. 6. Photon BPM directly measured spectrum better performance above 1kHz which indicated less electronics noises. For lower frequency range, beam motion is dominant.

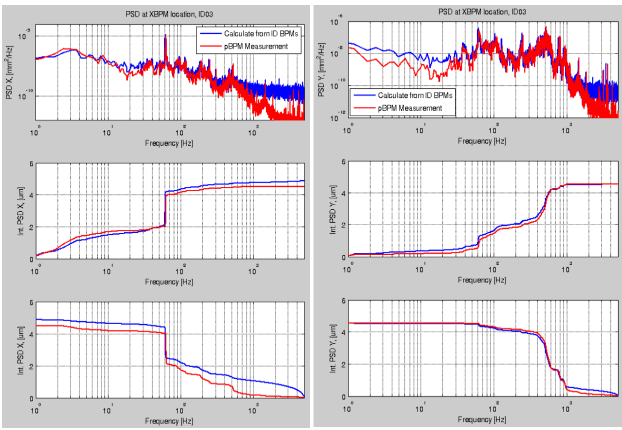

Figure 6: Photon beam spectrum at C03 xBPM location. Blue lines are the calculated spectrum and integrated RMS motions from two ID BPMs; Red lines are directly measurement spectrum from xBPM.

LONG TERM STABILITY

To check the long term stability of BPM electronics and beam orbit, 10Hz slow acquisition data was used. All BPMs 10Hz data was archived. There is a dedicated BPM pickup used to test the electronics noises, four buttons signal were combined together then splitting in to four digitizer channels. This configuration is to measure the electronics noises instead of beam motions.

NSLS2 user operation beam current has been increased in steps, at present user operation beam is initial filled to 150mA and refilled every three hours. Typical beam current is around 110mA at refills. BPM electronics long term stability has been checked during the 150mA operation, for ~8 hours period, BPM electronics drift has 450 nm peak to peak variations, RMS drift during the time is ~ 80nm. NSLS2 BPM electronics are housed in well regulated environment, experiment hall temperatures are controlled within +/- 1 degC; tunnel and rack temperatures are within +/- 0.1 degC.

With fast orbit feedback in operation, typical beam orbit drift measured at short ID center are within 0.5 μm vertically. Angle stability is the insertion device is within 0.2 μrad for the 8-hour period, see Fig. 7, which shows the data from July 04 0:00 to 8:00. The position and angle are calculated from synchronized 10Hz data of two ID BPMs on both ends of the insertion device. Horizontal plane has slightly worse long term stability performance and usually it's not a concern.

C03 photon BPM long term stability has been checked during the same period of time. Using the calculated ID center position/angle from ID BPMs (as shown in Fig. 7), photon beam positions can be calculated similar to 10kHz FA data. Calculated 8-hour positions from ID BPMs have been compared with the direct measurement results from photon BPM, the results agree within the same 8-hour period of Fig. 7. At the xBPM location, photon beam drifted within +/- 10 μm horizontally and +/-2 μm vertically. This photon beam drift was mainly determined by the electron beam angular stability at ID source point.

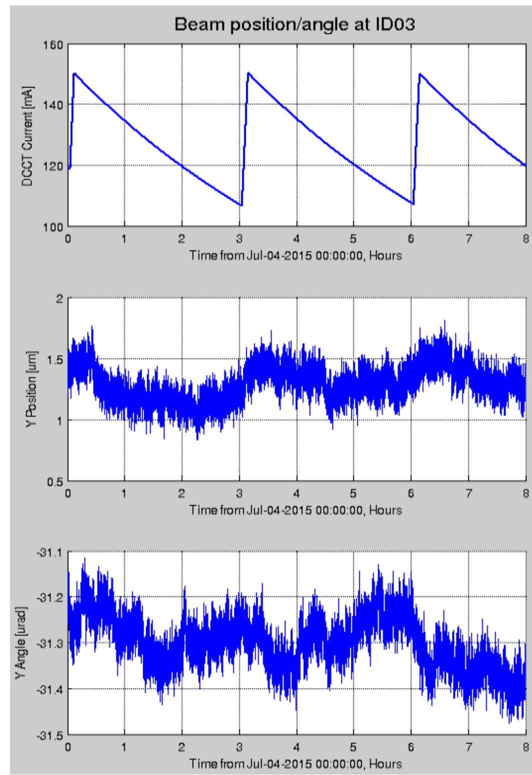

Figure 7: BPM long term stability at ID03 center. Position and angle at the location were calculated from two ID BPMs.

NSLS2 storage ring is measuring the betatron tunes using a pilot single bunch. It was first noticed that horizontal tune had a daily drift pattern when slow orbit feedback was operating. Once fast orbit feedback was commissioning and left ON for user operations, it's interesting to find out that the tune shift pattern disappeared but there is daily orbit drifts on dispersive BPMs, which are not included in the horizontal plan FOFB loop. With further investigation, it is believed that the tidal effect causes ring circumference change and energy mis-match. Plot in Fig. 8 are the six BPMs X/Y position histories in C30. During the two days period, beam was operated at 150mA for the first day and decayed from 150mA to ~20mA due to injector power supply failure. Positions are offset by 50 μm in between BPMs to have a better view of the drift. First two BPMs (red and blue) and last two BPMs (cyan and black) in the cell don't see much drifts, these BPMs are in the non-dispersion sections. However dispersive BPMs (green and magenta) have a clear daily drift pattern on the X position

ISBN 978-3-95450-176-2

readings. The position valleys are checked to appear at high tides of nearby harbors. It's not obvious though, only one valley was observed on the BPM position drifts while there should have two high tides daily, further investigation is needed.

One can see at the larger dispersive BPM (BPM #3 in the figure), X position drifted more than 50 µm. As the lattice has been well characterized and corrected, dispersive at the BPM should be close to the model of 0.424 m, which gives energy drift of $\Delta E/E$ = 1.18e-4. Assume the momentum compaction factor is known, we calculate the ring circumference changed by 34 µm. RF frequency should be adjusted by 21Hz to compensate this energy mis-match. Considering NSLS2 site is close to the ocean and the ring size is relatively big (~792m circumference), it's not surprise to observe these tidal effects on the beam orbit. RF frequency dynamic adjustment could be added to correct this effect, even though it doesn't have a direct effect on the orbit stability at the ID source points.

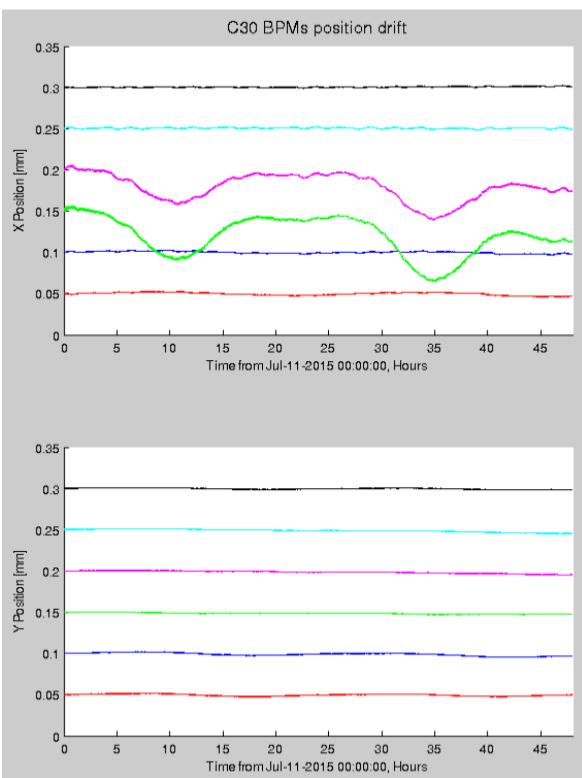

Figure 8: C30 six BPMs X/Y position drift during two days of period. BPM positions are offset by 50 µm. BPM #3, #4 (Blue, Magenta) located at dispersive section see the daily horizontal position drift pattern.

SUMMARY

NSLS2 BPMs system are designed, constructed and commissioned. BPM pickups sensitivity and nonlinear have been thoroughly investigated. Special ID BPMs are installed for better sensitivity and mechanical stability. Using the most advanced FPGA and digital processing technology, the in-hour developed BPM electronics are capable of suppling synchronized TbT/FA/SA data. Storage ring BPMs measurement resolution as well as attenuator dependency, current and fill pattern dependency have been characterized.

Long term and short term beam orbit stability has been measured with FOFB ON/OFF. With FOFB, RMS motions between 1-500Hz are well within the specification of 10% of beam sizes and divergences. Photon beam stability has been measured at one particular beamline using a dedicated photon BPM. Compare to the calculated values from two ID BPMs on both ends of the insertion devices, direct measured and calculated spectrum agree well. Even though the orbit stability meets the specification, tighter requirement may come up with particular beamlines. FOFB loop can be further optimized to improve the orbit stability in the future.

Long term stability was able to be analyzed with the archived 10Hz data. For a typical 8 hour period during 150mA user operation, position/angle stability has been checked to be within 0.5µm/0.2µrad at short ID straight center. A daily drift pattern has been observed on dispersive BPMs, this is likely due to the tidal effect. RF frequency feedback is under evaluation and can be implemented to compensate the energy mis-match due to ring circumference change.

Diagnostic group personnel gave various technical supports on the construction and operation of BPM system. Discussion with members from physics group, coordination group, control group, ID group and beamline groups are useful. Thanks for operation group for a reliable beam delivery during studies and operations. Special thanks to Ferdinand Willeke, Timur Shaftan and NSLS2 management for their continuous support.

REFERENCES

[1] W. Cheng et al., "NSLS2 Beam Position Calibration", BIW'2012

[2] W. Cheng et al., "Performance of NSLS2 Button BPMs", IBIC'2013

[3] K. Vetter et al., "NSLS-II RF Beam Position Monitor", PAC'2011

[4] K. Vetter et al., "NSLS-II RF Beam Position Monitor Update", BIW'2012

[5] O. Singh et al., "NSLS-II BPM and Fast Orbit Feedback System", IBIC'2013

[6] J. Mead "NSLS-II RF Beam Position Monitor Commissioning Update", IBIC'2014

[7] W. Cheng et al., "Vibration Measurement and Its Effect on Beam Stability at NSLS2", IBIC'2013

ISBN 978-3-95450-176-2