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DEVELOPMENTS OF BUNCH BY BUNCH FEEDBACK SYSTEM AT NSLS-II STORAGE RING*

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Abstract

Transverse bunch-by-bunch (BxB) feedback system has been constructed and in operation since the very beginning of NSLS-II storage ring commissioning. As the total beam current continues increasing in the past years, the system has been operating stable and reliable. Advanced BxB diagnostic functions have been developed using the system. Continuous tune measurement is realized with a diagnostic single bunch. Coupled bunch instability growth rate is able to be measured with the transient excitation. The BxB feedback system is also capable to excite a small fraction of total bunches for lattice measurement during high current operations. We present the most recent developments and operation experience on the BxB feedback system at NSLS-II.

FEEDBACK PERFORMANCE

The transverse bunch-by-bunch (BxB) feedback system has been constructed and in operation since 2014 at NSLS-II storage ring [1-3]. The system includes button BPM pickups at large beta-function locations, low loss and sensitive analog electronics, commercially available digitizers [4] and broadband high power amplifiers/kickers. Stored beam current has been continuously increasing since 2014, making the feedback system critical for both high current operations and studies. With maximum current of 400mA achieved in the ring so far, the system performs well. We expect no problem at full current of 500mA.

The transverse feedback system is able to suppress the TMCI single bunch instability. At nominal chromaticity of +2/+2, TMCI threshold current was measured to be ~0.8mA per bunch. With feedback, more than 6mA single bunch current was able to be stored [5].

Typical fill pattern during normal NSLS-II operations has 1000 bunches with 2ns bunch separation, followed by 320 empty buckets. Fast ion and resistive wall (RW) have been measured as the dominant instabilities. Typical storage ring average vacuum pressure is around 5 nTorr during 375mA top off now. Transient grow/damp measurement reveal the ion-driven unstable modes have fast growth rate (<1ms). RW is stronger compared to earlier, as there are ~20 insertion devices (ID) installed.

At relatively low current of 38mA/1000bunches (0.8 nTorr average vacuum pressure), beam was unstable without BxB feedback although beam survived. Figure 1 compares the pinhole images with vertical feedback ON/OFF. Vertical emittance was about 5.8 pm.rad with feedback ON and varied significantly without feedback. The image saved had ~248 pm.rad effective vertical emittance. Note that the pinhole camera had 10ms exposure time and image update rate was ~10Hz.

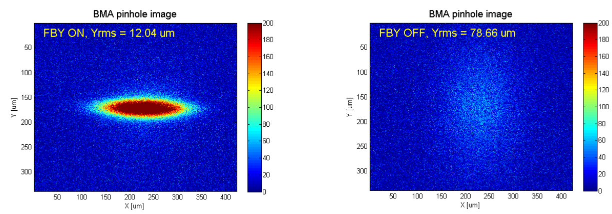

Figure 1: X-ray pinhole images with 38mA beam stored in 1000 bunches, vertical BxB feedback was ON (left) and OFF (right).

At high current operation of 375mA, less than 8pm.rad vertical emittance can be achieved with ~2 hours lifetime (horizontal emittance ~0.98 nm.rad, RF voltage 2.375 MV). During normal operation, the vertical emittance was increased to 20-30 pm.rad to have better lifetime, in favor of longer top off injection intervals.

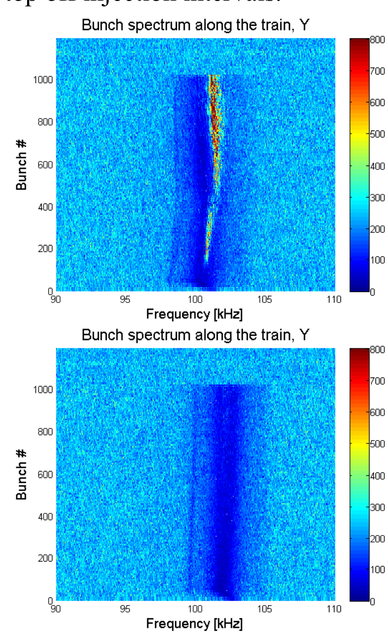

Figure 2: Bunch to bunch spectrum in vertical plane with 375mA/1000bunch fill with relative poor vacuum (top) and improved vacuum (bottom).

During a recent work to remove one problematic insertion device, storage ring vacuum was exposed near the area. Machine start up right after the vacuum work had large vertical emittance. Beam sizes increase along the bunch train was able to be measured using the gated

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camera [6]. BxB spectrum was measured at different vacuum conditions. Figure 2 gives results with relative poor vacuum (average pressure 10.4nTorr@375mA near the worked section) and better vacuum after 10 hours of high current conditioning (4.2nTorr). The dark blue band ~100kHz is the notch near betatron frequency due to feedback. When the vacuum conditions are poor, peaks above the vertical tune appear towards the tail of the bunch train, similar to earlier observation reported in [7]. The peaks are believed to be due to fast ion trapping along the bunch train, disappearing as the vacuum improves. It is also clear from the plot that tail bunches have slightly higher betatron frequency.

Temperatures have been continuously monitored, at the stripline kicker feedthroughs, chambers, high power attenuators etc. Highest temperature observed at 400mA was 35 degC (10 degrees rise) at vacuum feedthrough. The feedthrough has cooling water channel available which is not used now.

Besides its major function to suppress the coupled bunch instabilities, the BxB feedback system integrates powerful diagnostic tools. The system has been used for continuous monitoring of the betatron tune from a single bunch; to do transit measurements of the bunch by bunch position data, revealing unstable modes and growth rates of individual modes; to study the emittance changes with feedback gains and chromaticity, etc. We present these developments in the next sections.

TUNE MEASUREMENT

As can be seen in Figure 2, the betatron frequency/tune can be measured from the notch of bunch spectra. The method is not as reliable in cases when there are external disturbances, like the peaks due to fast ion trapping for tail bunches, or injection transient during top-off. Another tune measurement approach is to use a dedicated single bunch in the ion gap. Feedback is disabled for that bunch and swept sinusoidal excitation at low amplitudes is applied. Betatron tune can be precisely measured from the single bunch spectrum. One concern for the single bunch tune measurement is that vertical tune depends on the bunch current (measured -0.007 per mA [5]), it is desired to have similar bunch charge of the single bunch to be same as other bunches. With knowledge of bunch current, the tune shift with single bunch current can also be corrected.

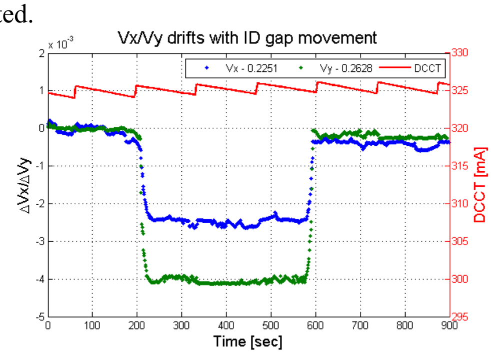

Figure 3: Tune variation measured during top off operation, affected by an IVU gap movement.

Betatron tune measurement from the single bunch has been implemented since 2015, allowing continuous tune measurement during operations. Figure 3 is an example showing an in-vacuum undulator (IVU) gap movement and its effect on the betatron tunes during 325mA top off operation. The gap (not shown in the plot) was changed from 6.1mm to 15mm at around 200 second and back to 6.1mm at ~600 second. Horizontal and vertical tunes changed ~0.0025/0.004 respectively. The ID gaps are frequently varied during normal operation. Sometime the betatron tune variation affects the injection efficiency. Tune feedback has been considered and tested, based on the continuous single bunch tune measurement.

In addition to the tune variation while moving the ID gaps, the storage ring coupling and lattice can be affected as well. A recent developed method uses gated BPM TBT data and transient excitation through BxB feedback system to characterize the lattice parameters and make corrections as needed [8,9].

During initial fill or beam scrape out, strong tune dependency with total beam current have been observed. The phenomenon is explained by the flat chamber and magnet poles [10,11]. Figure 4 presents a measurement of horizontal/vertical tune vs. total beam current. The tunes were measured from the single bunch filled in to ion gap with small charge variation, so that the tune dependency on the single bunch charge is negligible. With more damping wiggler (DW) or IVU gaps closed, the tune slopes increase. Table 1 summarizes the tune slopes measured at various ID gaps.

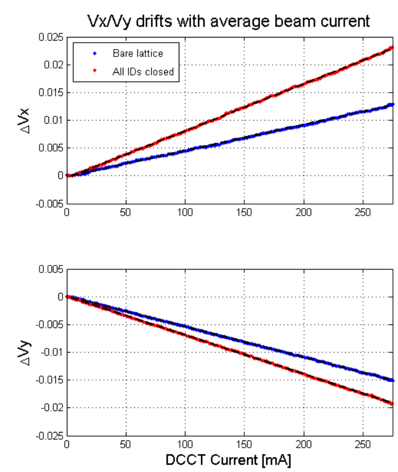

Figure 4: Tune shifts vs. average beam current, measured at different ID gaps. Blue lines are for bare lattice (no ID gaps closed), red lines are the results with all IDs closed.

Table 1: Tune Slopes at Different ID Gaps (unit: 1/A)

ID gaps	dVx/dI	dVy/dI	Note
Bare lattice	0.046762	-0.055156	All ID gaps open
1DW	0.048143	-0.056737	DW28
2DW	0.049024	-0.058885	DW28+DW08
3DW	0.050146	-0.061134	All three DWs
All IDs	0.084611	-0.070046	DWs + EPUs + IVUs*

* 3 damping wigglers, 10 IVUs and 4 EPUs gap closed

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TRANSIENT MEASUREMENT

BxB feedback system can be switched off for a short period of time (several ms) to allow the instabilities to grow and then turned back on to damp the motion. This kind of grow/damp measurement is useful to characterize the unstable modes in the storage ring. Typical unstable modes measured during top off operations are related to fast ion trapping and RW. Figure 5 is an example measured with 325mA/1000bunch fill. Vertical feedback is switched off for 5ms. As can be seen, ion instabilities (group of unstable modes near #1270) grow first, but the growth rates drop off with amplitude. Modes, driven by the resisitive wall impedance (mode #1318, 1319 or -2, -1 relative to the NSLS-II harmonic number of 1320) have slower growth rates that, however, stay constant, leading to larger oscillation amplitudes. Compared to earlier observations [7], RW instability is getting stronger as more IDs are installed.

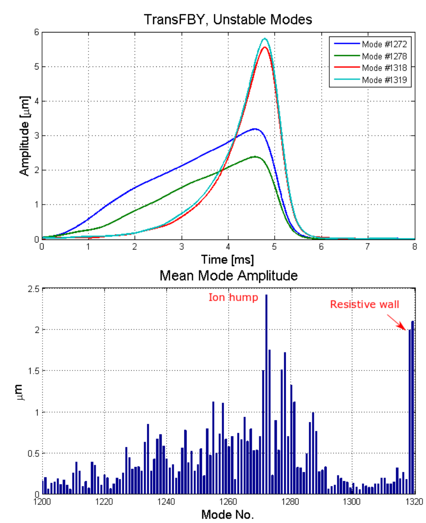

Figure 5: Unstable modes with vertical BxB feedback 5ms off time. (top) several unstable modes evolution during the grow/damp transient; (bottom) averaged mode amplitude from 2ms to 5ms.

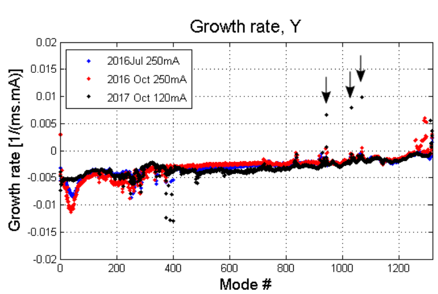

Figure 6: Measured growth rate of coupled bunch instability modes in vertical plane.

Measurement of stable modes is achieved by applying excitation to the mode of interest, then turning off both feedback and excitation and capturing open-loop evolution of beam oscillations. Captured data allows one to extract the modal growth or damping rate. Figure 6 shows the results measured at several different conditions.

The machine had operational condition with all gaps closed and 1000-bunch train filled. Three narrow unstable peaks (near #1000, marked with arrows) are noticed from the Oct 2017 data, compared to the 2016 results. The peaks are likely coming from the newly installed IDs. With the technique, ID impedance effects can be systematically studied, as previously reported by other facilities [12-14]. Also, with 120mA, the ion hump (near #1280) was not obvious.

The transient excitation has also been used for physics developments. Besides the lattice measurement using diagnostic bunches, we used the similar technique to excite individual bunches onto 3rd resonant islands.

EMITTANCE BLOWUP EFFECT

Increased vertical emittance (and lifetime [15]) has been observed with excess BxB feedback gain. This has been studied at various chromaticities, as shown in Figure 7. At higher chromaticity, the emittance blowup effect is more pronounced. Similar measurements were carried out for single bunch or high current 1000-bunch fills. Preliminary multi-particle tracking simulations agree with the experimental results. The feedback system has been optimized for normal operation of +2/+2 chromaticity.

Feedback sensitivity can be increased in the analog front end, with less dynamic range. This is helpful to minimize the noise kicking seen by beam and in turn reduces the emittance blowup. Transverse profiles measured within one turn confirm the sizes blowup at excess noise/gain, while residual dipole motion is not increased.

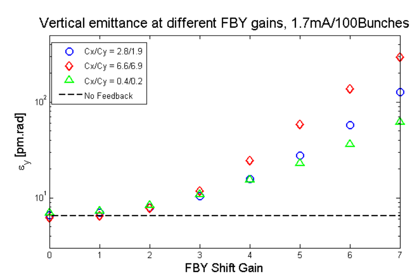

Figure 7: Vertical emittance measured with various feedback gains and chromaticity.

SUMMARY

The transverse BxB feedback system at NSLS-II storage ring has been operation well to 400mA. The system is not expected to be a limitation in achieving the designed beam current of 500mA. The feedback system is critical for the high current operation of the machine. During the past years, advanced beam diagnostic tools have been developed based on the system, including tune measurement from single bunch; transient excitation and measurements etc.

Feedback gain and its effect on the small vertical emittance have been studied. <8pm.rad was able to be achieved at 375mA stored in the ring. At higher chromaticity, high feedback noise/gain affects the emittance more.

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