

Observation of Ion-induced Instabilities at NSLS2 Storage Ring*

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Abstract

NSLS2 storage ring has been commissioned and is open for user operations. At relatively low beam current ($\sim 25\text{mA}$) multi-bunch fills, ion-induced instabilities have been observed. For the present user operations, 150mA of total beam current is filled in ~ 1000 bunches, fast ion is the dominant instability at the NSLS2 storage ring. Although the ion-induced dipole motions can be suppressed using bunch by bunch (BxB) feedback system and it is expected to decrease in severity as the vacuum conditioning progresses further, a thorough understanding and characterization of this effect is still important, especially in preparation to the future 500mA operations. A number of ion instability related studies, mostly parasitic to other machine activities, have been carried out at various fill patterns and beam currents. Preliminary measurement results are reported in this paper.

INTRODUCTION

Residual gas in the vacuum chamber will be ionized by high energy beam. Ions will be trapped by the beam potential and cause ion related instabilities. Conventional ion trapping can be easily cured with empty buckets. However fast-ion instability during the single pass of bunch train will be strong in the low-emittance high current ring like NSLS2. NSLS2 is an advanced third generation light source recently constructed at Brookhaven National Laboratory. Weak dipoles and three damping wigglers are used to decrease the horizontal emittance from $2\text{nm}\cdot\text{rad}$ (bare lattice, no insertion devices) to $< 1\text{nm}\cdot\text{rad}$ (with 3 DWs). Vertical emittance has been measured to be less than $8\text{pm}\cdot\text{rad}$ [1].

Even with ion-clean gap, another kind of ion instabilities could happen in small emittance high current storage rings, called “Fast” ion instability. Fast ion instability has been considered to be important for the NSLS2 storage ring and was investigated at design stage of the machine [2]. Transverse BxB feedback has been designed, constructed and commissioned to cure the fast ion and other coupled bunch instabilities [3].

Theory of fast-ion instability and early observations were reported almost 20-years ago [4-6]. As the recent machine development push to lower emittance and high current, fast-ion instability is getting severe for modern light sources and colliders. More recent observations on newly constructed light sources can be found, for example [7-9].

Fast ion instability will be affected by vacuum pressure, chromaticity and coupling. As vertical beam sizes are smaller than horizontal sizes, ion instability is usual dominant in vertical plane and it’s expected to be worse at improved coupling. With three DWs, NSLS2 storage ring

horizontal emittance is half of bare lattice, this may change the fast ion growth rate. Close the IVUs may have elevated localized vacuum pressure which will in turn makes the fast ion easier to accumulate. Unfortunately, there was not much machine study time allocated to investigate fast ion behaviors at various machine conditions. Most of the observations reported here were parasitic to other studies, not insertion devices were closed and chromaticity was at nominal value of $+2/+2$ if not specified. We would like to have further systematic study of the issue in the future, to understand the fast ion behavior with different vacuum condition, chromaticity, coupling and insertion devices.

FAST ION INSTABILITY OBSERVATION

During early commissioning stage of NSLS2 storage ring, fast ion instability was first observed at about 10mA filled in 500 bunches during BxB feedback commissioning. Preliminary observations have been reported in [3].

More recently a study was done at fixed, 1000-bunch and approximately uniform fill pattern while varying the total beam current. Specifically, there were 17mA , 31mA , 46mA , 100mA and higher total beam current evenly distributed in ~ 1000 bunches. Fill patterns of the first three data sets (17mA , 31mA and 46mA) were well controlled to minimize the bunch to bunch current variation. Rising/falling edges of the bunch train were trimmed to have a uniform bunch train. Figure 1 gives the measured bunch to bunch current at 46mA . Details on how to measure the bunch to bunch fill pattern can be found in [10]. 100mA and other higher current fill patterns had somewhat larger bunch to bunch current variation, edge bunches were not trimmed as these observations were parasitic to other studies.

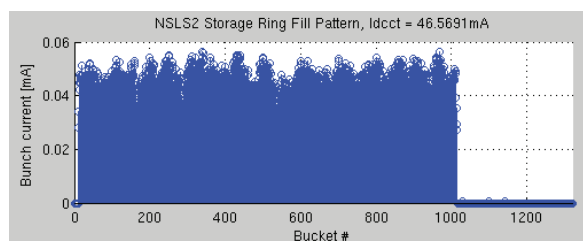


Figure 1: Bunch to bunch current measured at 46mA , machine was filled from bucket #1 to #1020. Rise/falling edge buckets were trimmed, only bunches #11 to #1005 were kept.

With injector set to multi-bunch fill with 20 bunch-train, storage ring was filled with 50% overlap (10 buckets) from shot to shot. After knocking out the head/tail bunches, bunch to bunch current variation shown in Fig 1 was $\sim 3.7\text{uA}$ RMS with mean bunch current at 46.4uA . Relative bunch to bunch current

*Work supported by DOE contract No: DE-AC02-98CH10886
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variation was ~8% which can be further improved at higher total beam current fill.

With the transverse BxB feedback switched ON, both horizontal and vertical instabilities were suppressed. There was no betatron motion sidebands observed on the button BPM spectrum. It was possible to switch OFF the feedback system at 46mA without losing the beam. Measured horizontal and vertical beam sizes from the x-ray pinhole camera were increased, as shown in Fig. 2. Top two x-ray pinhole camera images were captured with and w/o BxB feedback, camera exposure time was fixed at 2 seconds. As feedback switched OFF, x-ray pinhole profile saw spread out and fitted beam sizes were increased on both horizontal and vertical plane. Bottom plot in the figure shows history of horizontal and vertical beam sizes measured from the x-ray pinhole camera. When horizontal feedback was turned OFF, horizontal beam sizes jumped from ~102um to 160um. Vertical beam sizes increased from ~58um to 120um. Beam sizes were fitted to a one-dimensional Gaussian function. Note that even with BxB feedback ON, there was large coupling during the shift, that's why there x-ray profile was tilted. When horizontal feedback was turned OFF, vertical beam sizes saw small increases as well, this is another indication of x/y coupling.

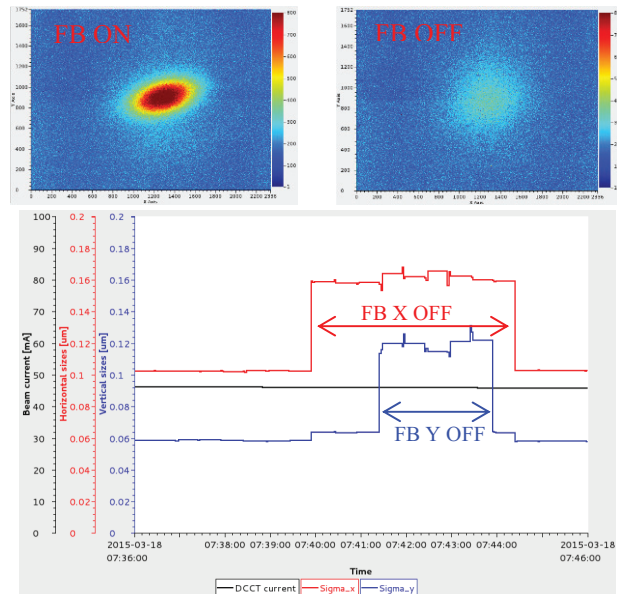


Figure 2: (Top) two x-ray pinhole camera images captured with and w/o BxB feedback separately. (Bottom) history plot of x-ray pinhole camera measured beam sizes.

Beam motion spectrum was measured with BxB feedback gated OFF for a short period of time (growth damp measurement). Most unstable mode(s) will appear during the period without feedback. Figure. 3 is an example of such kind of measurement using Tektonic FFT spectrum analyzer, vertical BxB feedback was OFF for 20ms, spectrum analyzer was external trigger on the same signal to gate OFF the feedback. Center frequency of the spectrum analyzer was at $F_{rf} + 6 * F_{rev}$ to see the most unstable mode (-6). As can be seen, vertical betatron sidebands (~100kHz away

from the center) started to grow before it was suppressed as feedback switched back ON. Spectrum around F_{rf} was checked and no apparent betatron sidebands appear during the period w/o feedback. This means the instability with fastest growth rate was not due to resistive wall. Most unstable mode(s) vary at different storage current which is another evidence of ion induced instabilities, as ion frequency increases at higher current, described in Eq. (1).

$$\omega_{ion} = 2\pi f_{ion} = \left[\frac{2N_b r_p c}{A \sigma_{x,y} (\sigma_x + \sigma_y) T_b} \right]^{1/2} \quad (1)$$

Where N_b the number of electrons per bunch, T_b the bunch separation period, r_p the classical proton radius, A the atomic mass number of the ion and $\sigma_{x,y}$ the horizontal and vertical beam sizes.

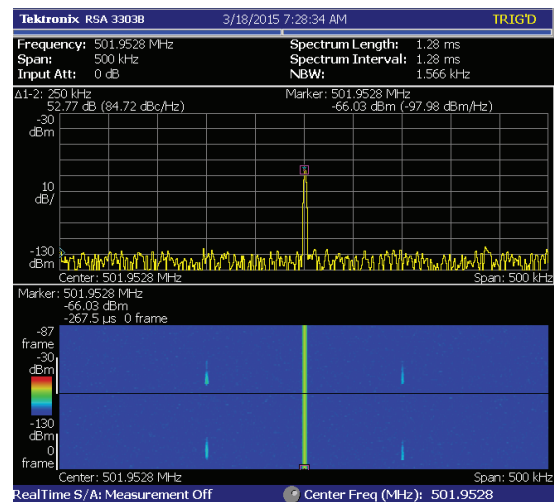


Figure 3: FFT spectrum while vertical BxB feedback was gated OFF for 20ms. Center frequency of the SA was set to be at $F_{rf} + 6 * F_{rev}$. Vertical betatron sidebands grew at around 100kHz and suppressed once the feedback was switched back ON.

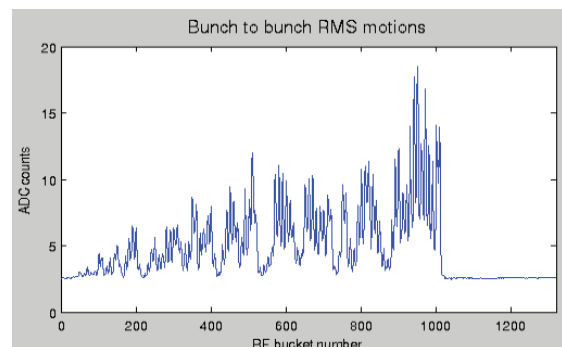


Figure 4: Bunch to bunch RMS motions along the 1000-bunch train with vertical feedback gated OFF for 20ms. Beam was filled to 46mA with all insertion devices gap closed.

Bunch by bunch position data from the feedback system is useful to determine how the bunch oscillation was developed with feedback OFF and ON transient. Fig. 4 gives an example of bunch to bunch motions collecting at 46mA filled in 1000 bunches, all insertion devices gap

closed. Vertical feedback was turned OFF for 20ms while horizontal feedback was ON all the time. From turn by turn position information, RMS motion of individual bunches along the bunch train can be calculated. As can be seen in the figure, starting from bunch #100, vertical position oscillations were growing along the bunch train, which is a typical behavior of a fast ion-instability. Therefore even with four IVUs gap closed the fast ion is still the most unstable instability presently dominates over the resistive wall. However, as more IVUs are installed in the ring, resistive wall instability may get stronger, while ion-related effects are expected to get weaker with further vacuum conditioning.

From bunch by bunch data acquired during the gated OFF period, unstable mode analysis reveals how the ion frequency varied at different storage current. Unstable mode amplitude is defined as sideband amplitude when it appears at $p \cdot F_{rf} + m \cdot F_{rev} + f_{x,y}$ appear, where m is called mode number ($m = 0, 1, \dots, 1319$, $p = 0, 1, 2, \dots$). Fig. 5 gives the averaged unstable modes amplitudes measured in March 2015, when a 1000-bunch train was filled with different amounts of total beam current. As can be seen, as total beam current increasing, unstable modes are shifting to higher frequencies which mean higher ion frequencies.

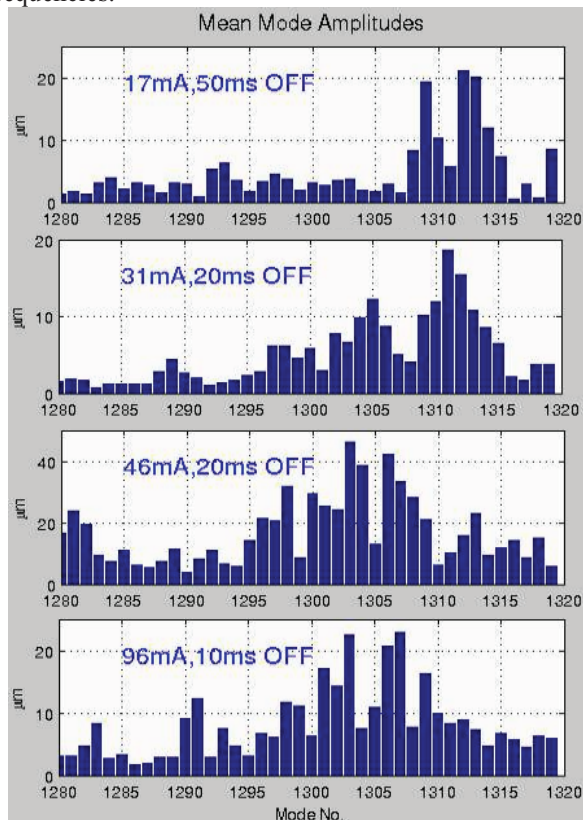


Figure 5: Averaged unstable mode amplitudes at different total beam current. Machine was filled with ~1000 bunches with small bunch to bunch current variations. BxB feedback was switched OFF for short period of time to allow most unstable modes grow.

96mA result in the figure was filled to 1000 bunch train as well, fill pattern was not well controlled as the first

three fills at 17mA, 31mA and 46mA. That’s probably the reason unstable modes didn’t continue to higher frequencies. After months of high current user operation, storage ring vacuum condition was improved. Fill the ring to similar 100mA 80% fill (~1000 bunches), averaged vacuum pressure was improved from 3 nTorr (Mar 2015) to 2.2 nTorr (Aug 2015). Similar analysis was applied to data collected in August, ion instability growth rate was not as fast but unstable mode hump around 1300 (-10) is still obvious.

CHROMATICITY EFFECT

During studies with high chromaticity of +7/+7, up to 100mA of beam current was stored in the ring with bunch-by-bunch feedback off. No apparent instabilities were observed from BPM turn-by-turn data. Using FFT spectrum analyzer measuring button BPM spectrum, there were unstable modes observed at 100mA 80% fill, most unstable modes were -8 horizontally (stronger sideband at $p \cdot F_{rf} + 8 \cdot F_{rev} - f_x$ which is the same sideband as $p \cdot F_{rf} + 1312 \cdot F_{rev} + f_x$) and -12 vertically (stronger sideband at $p \cdot F_{rf} + 12 \cdot F_{rev} - f_y$).

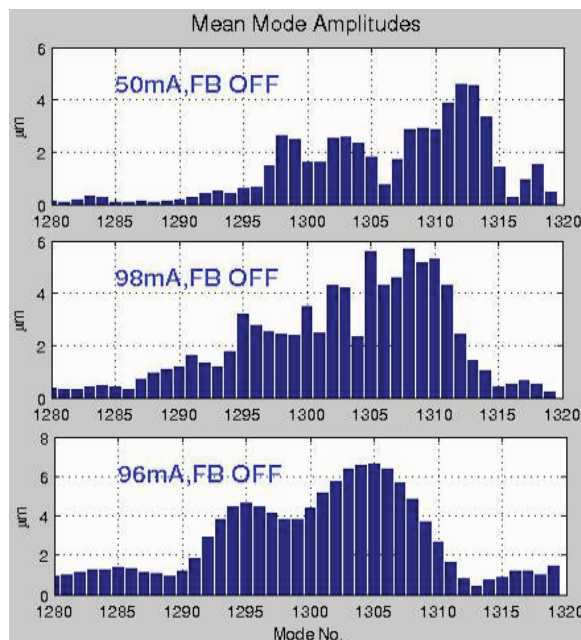


Figure 6: Average unstable mode amplitudes measured with high chromaticity +7/+7. BxB was OFF, there were unstable modes observed.

Similar to Fig. 5, mode analysis of bunch by bunch feedback data tells what the most unstable modes at high chromaticity were. Fig. 6 compares the unstable modes at different currents and filling patterns. The first two plots have the same 1000-bunch (80%) fill with total current at 50mA and 98mA. As the beam current roughly doubled, the most unstable mode shifts from -8 to -12 which agrees with Eq. (1). The third plot shows the 100mA 50% fill (660 bunches), and as compared to the middle plot with the same total current, the ion frequency is even shifted to higher values (the most unstable mode is at -15), which is expected as per-bunch intensity is 60% higher.

BETATRON TUNE SHIFT

Single bunch spectrum can be measured to determine the bunch betatron oscillation frequency and amplitude. BxB feedback was configured to have feedback OFF for the bunch under measurement while keeping the rest of bunches stable with feedback ON. By scanning the single bunch under measurement along the bunch train, betatron oscillation frequency/amplitude of bunch to bunch can be measured.

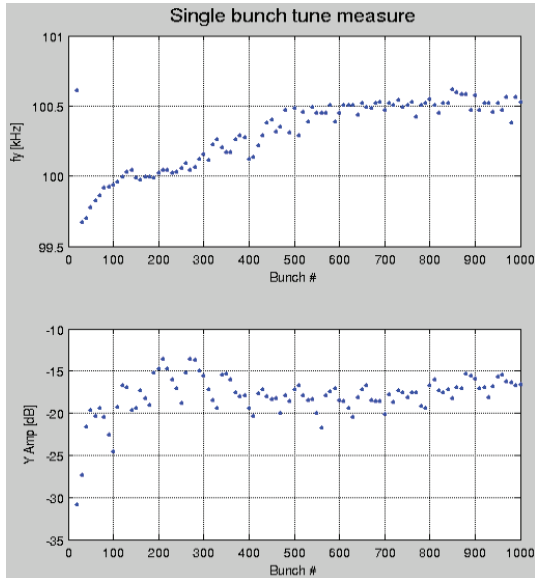


Figure 7: Single bunch vertical tune and amplitude measurement along a 1000-bunch train. BxB feedback was switched OFF one bunch at a time to see the betatron motion of that particular bunch.

Figure 7 gives the result of vertical plane single bunch spectrum with 100mA filled in ~ 1000 bunches, all insertion devices (3 DWs + 1 EPU + 4 IVUs) had gap closed. Switch OFF the feedback for one bunch at a time, from bucket 20 to 1000, with 10 buckets steps. No excitation was needed to see the betatron sideband of the bunch without feedback. During the data collection, total beam current was maintained at around 95mA, 1000 bunches had more or less even fill pattern. It's clear that the vertical betatron frequency increases along the bunch train and eventually reach to flat for tail bunches. There was ~ 800 Hz difference between the head and tail bunches. Bunch oscillation amplitude saturated at bunch #200. Notice the first data point was not accurate as the betatron oscillation amplitude was too low. Horizontally, there was no clear betatron sideband observed on the spectrum while turning OFF feedback for one particular bunch, which is consistent with our expectations for fast-ion instability.

At another time, the same measurement was performed at 150mA fill with all insertion device gaps open. Single bunch betatron frequency was increasing for the first ~ 200 bunch and reached equilibrium after that. This increase of vertical betatron oscillation frequency and amplitude is likely due to ion accumulation along the bunch train.

As a step for future study, a probe single bunch may be filled at different locations after the bunch train, measuring the probe bunch tune and amplitude will tell how the ions escape in the empty gap.

BUNCH TO BUNCH LIFETIME

Bunch to bunch current is measured using button BPM SUM signal in NSLS2 storage ring [10]. Lifetime of individual bunches can be measured from history of bunch to bunch current data.

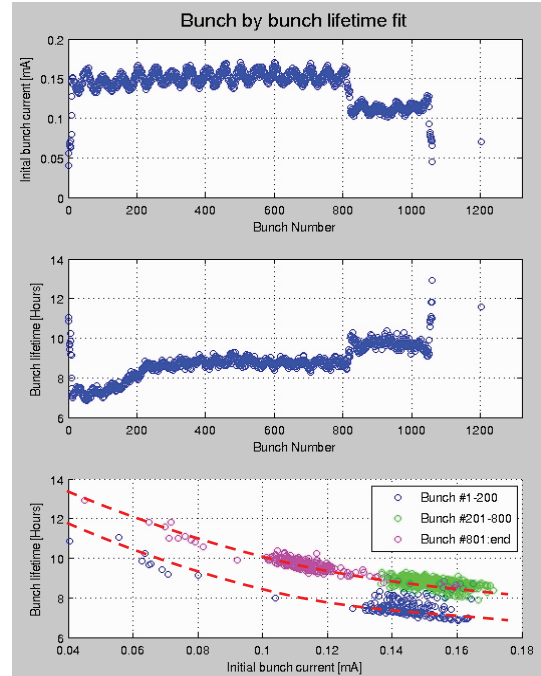


Figure 8: Bunch to bunch lifetime fitted from fill pattern monitor. First 200 bunches in the 1000-bunch train reside in a lower lifetime band.

It has been noticed that bunch to bunch lifetime varies, depends on the locations of the bunch. Fig. 8 is an example of measured bunch lifetime during 150mA user operation. An 80% fill long bunch train was filled, plus a camshaft single bunch at bucket 1200. Initial fill pattern is shown on the top, first 800 bunches had high bunch current as injection stopped there when 150mA total beam current reached. Bunch lifetime was fitted from 30 minutes of bunch to bunch current. As expected, bunches after 800 have longer lifetime due to smaller bunch charges. It's interesting to point out that first 200 bunches lifetime was gradually increased (middle plot), even though the first 800 bunches had more or less same bunch current. While plotting the bunch lifetime vs. bunch current, there were two clear bands, as shown in the bottom plot. Head bunches reside in the lower lifetime band (blue circles) and rest of bunches had longer lifetime.

Lifetime difference of head bunches seems correlated to the single bunch tune measurement and bunch RMS motion along the train. BxB feedback system was turned ON all the time during 150mA operation. There was no dipole motions observed with the feedback ON. As ions

are still accumulated along the bunch train, it is believed interaction of ion cloud with electron beam may cause beam sizes increase along the bunch train which in turn increases the Touschek lifetime. There is no direct observation of beam sizes with different length of bunch train which can be studied when the tools are prepared.

STREAK CAMERA OBSERVATIONS

Streak camera has been configured to observe the longitudinal and vertical (y - z) profile, when single bunch and multi-bunch instabilities appear [11]. Using slow sweep module, the streak camera can see y - z image of bunches along the bunch train.

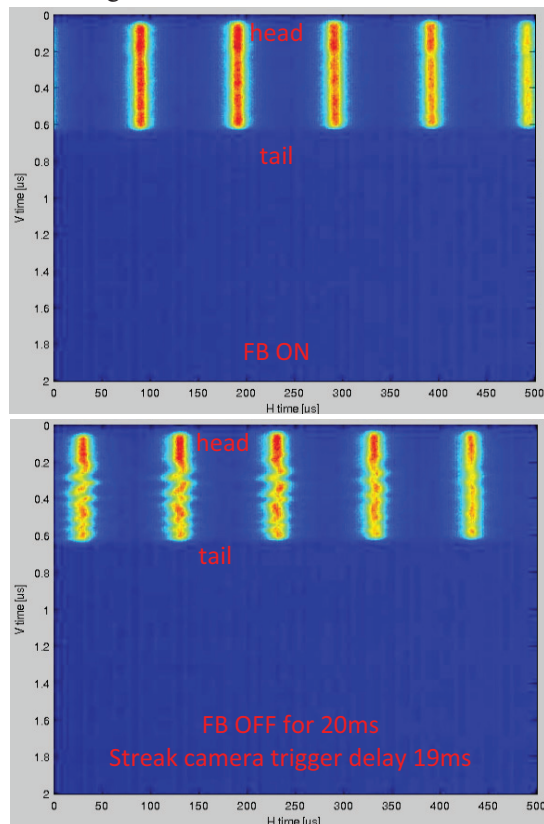


Figure 9: Dual sweep streak camera image using slow sweep module. (Top) with BxB feedback ON, there was no instability observed on the streak camera y - z image. (Bottom) with feedback turned OFF for 20ms, and streak camera trigger delay adjusted to see 19ms after the feedback OFF, bunches after #100 show vertical motions on the streak camera image.

Streak camera images have been saved with different length bunch train filled in the ring. When BxB feedback was kept ON, there were no vertical dipole instabilities. Turn to turn profile is like the image shown in Fig. 9 upper plot. There was 300 bunches filled in the ring with total current ~ 63 mA. Streak camera was operating in dual sweep mode, vertical sweep time was set to $2\mu\text{s}$ to see one turn profile of stored multi bunches, sweeping clock was adjusted to 10kHz period. Horizontal sweep time was at $500\mu\text{s}$ to see five turns of profile with $100\mu\text{s}$ separation. Each vertical strip in the figure is one turn

image, head bunches are at the top. It's worth to point out that diffraction limit of SLM direct image is limited to $\sim 60\mu\text{m}$. It's not possible to measure vertical beam sizes from the streak camera image.

To see the fast ion introduced dipole motions, vertical BxB feedback was gated OFF for 20ms and streak camera horizontal trigger delay was adjusted to see the turn to turn profiles at 19ms after feedback OFF. As shown in the bottom image, the head bunches were still stable while the tail bunches ($>$ bunch #100) were executing some dipole motions.

SUMMARY

Fast ion instability has been observed at NSLS2 storage ring at different vacuum conditions, beam current, filling pattern, chromaticity and insertion devices. Unstable modes tend to move to higher frequency at higher bunch current, due to increased ion frequencies. As beam sizes along the ring vary a lot, ion frequency and induced instabilities typically have a broadband hump. Further systematic studies at different emittance and coupling will help to understand the observations better. This will in turn help to operate the machine stably and reliably at high current and lower emittance.

Our measurements of single bunch tune, bunch to bunch tune shift and lifetime increase along the bunch train, as well as vertical oscillation developing along the train captured with the streak camera all show that the leading 100-200 bunches behave quite differently. Bunches after that are likely seeing ion effects.

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