

LONGITUDINAL BUNCH PROFILE MEASUREMENT AT NSLS2 STORAGE RING*

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Abstract

Longitudinal bunch profile has been measured at NSLS2 storage ring using streak camera. From the measured profile, bunch lengthening and synchronous phase information can be derived to study the single bunch collective effect. Single bunch lengthening effect has been measured for bare lattice and for other lattices with different insertion devices. The streak camera can also be setup for other beam physics studies, for example to measure the injection beam dynamics and fast ion effects. Y-z imaging was measured using cylindrical lenses. Single bunch y-z profile was measured at threshold current.

INTRODUCTION

Visible synchrotron light monitor (SLM) diagnostic beamline has been constructed and commissioned at NSLS2 storage ring. The diagnostic beamline utilizes the radiation from Cell 30 bending magnet B (BM-B), which is the second dipole magnet after injection straight section. The nominal source point is $\sim 2.75\text{mrad}$ into the dipole. The beamline has acceptance of $\pm 1.5\text{mrad}$ horizontal and $\pm 3.5\text{mrad}$ vertical. Visible light from the dipole synchrotron radiation is reflected by in-vacuum mirror through a vacuum window. The visible light is guided into SLM hutch located on the C30 experimental floor. There are various optics setups on the $4' \times 10'$ optical table, currently there are four setups: 1) CCD camera for continuous beam profile monitoring, spatial resolution of the CCD camera was analyzed to be around $60\text{ }\mu\text{m}$, which makes the direct imaging method possible to measure horizontal beam sizes ($\sim 100\text{ }\mu\text{m}$). Vertical beam size at SLM source point is $\sim 10\text{ }\mu\text{m}$ which is not possible to measure with direct x-y imaging. There are methods that can be tested using the CCD camera, such as double slit interferometer and π -mode beam size measurement. Preliminary test of double slit interferometer has been carried out during user operations. 2) Fast gated camera for transient x-y profile measurements. The camera has minimum gate width of 3ns which makes it suitable to measure turn to turn profile of individual bunches. 3) Test branch which is used for Time Correlated Single Photon Counting (TCSPC) system to measure the single bunch purity and fill pattern. 4) Streak camera for various longitudinal beam dynamics studies. Visible light can be directed to different cameras/detectors through beam splitter and flip mirrors. More information on the diagnostic beamline design and the commissioning results can be found at [1, 2].

Streak camera has been used for longitudinal bunch profile measurements. The camera is Hamamatsu C5680 with 2ps resolution and it includes synchroscan module M5675, slow sweep module M5677 and dual sweep module M5679. Synchroscan frequency was chose to be 125MHz, which is 1/4 of the NSLS2 storage ring RF frequency. The sweeping clock signal is getting from master oscillator through long Heliac cables. Phase jitter of the clock signal was measured to be less than 1ps. Small jitter is important for precise bunch length measurements. The long Heliac cable runs inside the NSLS2 buildings where the temperature is well regulated. Phase drift of the streak camera 125MHz synchroscan signal should be small, this is helpful to measure the relative synchronous phase from streak camera profiles.

Depends on the applications, optics setup for streak camera measurement can be different. There is different optical density (OD) filters ($\text{OD} = 0.5, 1, 2, 3, 4$) mounted on a rotation wheel so that different filters can be easily selected according to the beam current. A band-pass filter with center wavelength of 500nm and bandwidth of 10nm is typically used to limit the chromatic aberrations. For a typical bunch length measurement setup, 20x objective lens mounted on a 6-dimesional stage ($x/y/z/x'/y'/z'$) right in front of the streak camera slit. The lens forms a very tight image on the camera slit which is then relayed to photocathode through streak camera input optics.

There are cases to observe the vertical and longitudinal (y-z) profile to understand the single bunch and coupled bunch instabilities. Dove prism was used to rotate the image by 90 deg and cylindrical lenses are used to image on the streak camera slit. Vertical lens has focal distance of 500mm and horizontal lens has focal distance of 50mm to make the beam image tight in horizontal plane and with reasonable magnification vertically. This setup is suitable to detecting the head-tail coupling motions. Fast ion has been observed as the most dominant instability since beginning of NSLS2 commissioning. Using the slow sweep module and y-z imaging setups, streak camera can monitor the bunch motions in vertical plane along the bunch train.

In the following sections, measurement results with different optics setups and streak camera modules will be presented, starts with single bunch profile measurement at different bunch current and RF voltage. Injecting beam longitudinal dynamics has been checked to optimize the phase and energy mis-match of injecting beam. Y-z imaging to study the head-tail coupling due to chromaticity and Transverse Mode Coupling Instability (TMCI) will be followed. Direct observation of fast-ion motions along the bunch train using slow sweep module will be discussed as well.

*Work supported by DOE contract No: DE-AC02-98CH10886

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SINGLE BUNCH PROFILE

Single bunch profile has been typically measured in synchroscan mode. Beam was stored in the ring with different single bunch current and RF voltage. Proper OD filters are used to minimize the space charge effect of cathode generated electron pulse. Measurement resolution can be checked with streak camera operated in focus mode, where smallest focused image gave ~ 6 pixels FWHM. This is corresponding to measurement resolution of 1.74ps RMS in the most used synchroscan range. Adding 1ps jitter of 125MHz signal, total measurement resolution should be around 2ps RMS. A typical measured longitudinal profile is shown in Fig. 1. Single bunch with current of 0.11mA was stored in the ring with three damping wigglers (DWs) gap closed to 15mm. As the single bunch current increase, bunch lengthen is expected to increase due to imaginary broadband impedances, in the meantime, real part impedance will cause synchronous phase move towards the bunch head.

As detailed in Ref [1], longitudinal bunch profile was fitted to a skewed Gaussian function. Figure 1 lower plot shows the raw profile data and its fitting results. Bunch lengths and centroids are available from the fitting. This sets of profile were measured with three DWs closed at different single bunch current up to 3.5mA. RF voltage was fixed at 1.78MV. Blue dots are the raw data from the streak camera image, red lines are fitted curves. When

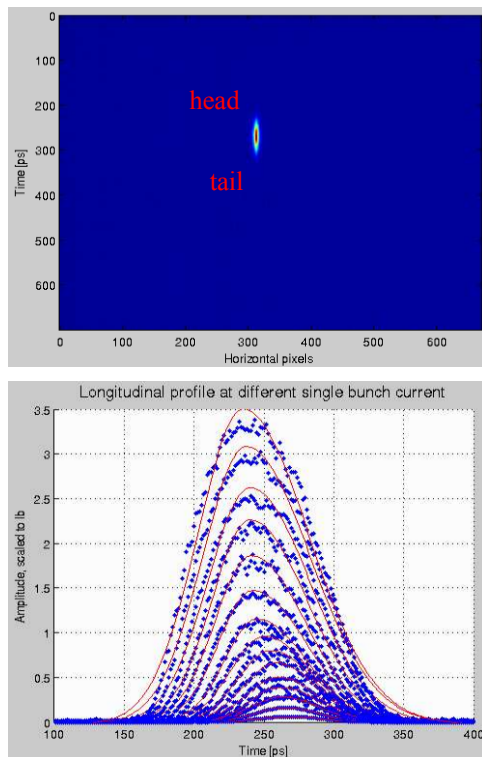


Figure 1: (Upper) Streak camera measured longitudinal profile in synchroscan mode, single bunch was stored in the ring at 0.11mA with all three DWs gap closed to 15mm. (Lower) Measured profile at different single bunch current (blue dots) and its fitting results (red line), vertical peak amplitude scaled to the bunch current.

bunch current was below 2mA, fitted curve is quite close to the raw data. When bunch current is above 2mA, fitting is not that well, probably due to more complicated longitudinal distributions.

NSLS2 has three DWs to further decrease the horizontal emittance below 1nm.rad. With bare lattice (dipole radiation only, no DWs), horizontal emittance is about 2nm.rad, energy spread is $\sim 0.05\%$. Energy spread will be increased when DWs are closed hence 0-current bunch lengths will be longer. Bunch lengths have been measured during early commissioning stage with bare lattice and lower RF voltage. Recent developments at NSLS2 include commissioning of DWs and In-Vacuum Undulators (IVUs), RF voltage was increased to 1.78MV for normal operation, we measured bunches with different configuration of insertion devices and RF voltages. Results of recent measurements are summarized in Fig. 2. All data were collected at 1.78MV RF voltage. Single bunch instability appears at around 0.7mA [3] with nominal chromaticity $+2/+2$, bunch by bunch transverse feedback was switched ON to accumulate single bunch with higher current. Single bunch lengthening effect was measured twice in April and August, 2015. Those data are plotted with blue circles and red stars in Fig. 2. The results agree well. With one DW gap closed to 15mm, bunch length at different single bunch current results are shown as green diamonds. Magenta triangles are results with all three DWs gap closed. Lattice was well characterized and corrected to the model before collecting the bunch length data. As more DWs close, bunch length at 0-current increases, bunch lengthening effect is not as strong as bare lattice. Bunch length was measured with all commissioned insertion devices (three DWs, two EPUs and four IVUs) gap closed, the results are shown as cyan triangles (feedback OFF) or cyan diamonds (feedback ON). IVUs gap close doesn't change bunch lengthening much.

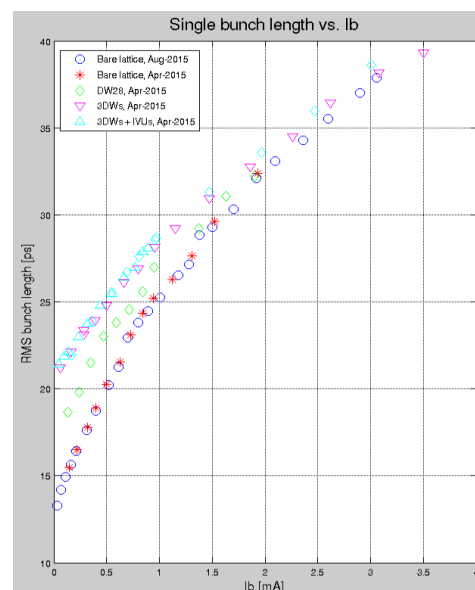


Figure 2: Single bunch lengthening effect with different insertion devices configurations.

As can be seen from the bunch lengthening curves, bare lattice, one DW and three DWs curves merged at higher bunch currents, which indicate microwave instability happens. Preliminary horizontal beam sizes measurement at different single bunch current shows energy spread increase from pretty low current. Further measurements and analysis will help us to understand the issue.

Assume 125MHz synchro scan signal has no drift during the streak camera measurement, bunch centroid (synchrotron phase) can be measured from the profile. There is concern that this assumption may not be true even though the long Heliax cable is housed in temperature regulated environment. Precise bunch synchronous phase can be measured with reference bunch(s) filled with low charge, as described in [4]. To have balanced image intensity of main bunch and reference bunch(s), multi buckets can be filled with very low bunch current. Precise bunch to bunch current measurement will be important to determine the main bunch currents. In the future, we plan to use the photon counting system to measure the bunch current with high dynamic range and precision [5], accurate synchrotron phase drift can be measured at different single bunch current. Combined the bunch lengthening and synchrotron phase information, real and imaginary longitudinal impedance of NSLS2 storage ring can be understood better.

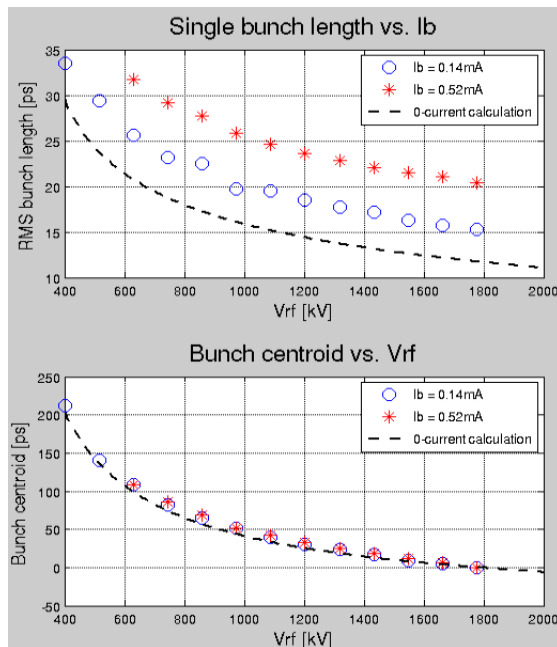


Figure 3: Measured bunch length and bunch centroid drift while scanning the RF voltage. (Upper) Single bunch length at different RF voltage, measured at single bunch current of 0.14mA and 0.52mA with bare lattice. Black dash line is the calculated bunch length. (Lower) Relative synchronous phase measured plot together with calculation result, while RF voltage varied.

Bunch profile while scanning the RF voltage has been measured as well. Figure 3 gives an example of such measurement for the bare lattice, RF voltage was varied from 1.78MV down to 400kV, at single bunch current of 0.14mA and 0.52mA. Calculated 0-current bunch length and synchronous phase drift are plotted as well. While scanning the RF voltage, measured synchronous phase drift agree well with the calculation. Other measurements using fill pattern monitor has shown synchrotron frequency drift at different RF voltage agrees with theoretical calculation. Based on this, it's fair to say that synchro-scan signal used for streak camera had no large phase drift during the period of data recording (~30 minutes).

INJECTION BEAM DYNAMICS

Streak camera dual sweep measurement is a powerful tool to observe the injection beam phase/energy mismatch. Two dual sweep images with 20 deg RF phase difference are presented in Fig. 4. Injection beam was captured and kept in the ring for 100ms before it was kicked out, this way there is no stored beam in the ring and only fresh injecting beam dynamics can be studied. 20-bunch trains were injected during the shift, that's the reason there are two strips on the image.

Left image shows injecting beam came in with phase mis-match, beam was doing synchrotron oscillation (fs ~2.5kHz, oscillating period ~ 0.4ms) start at 90 deg phase. After adjusting the storage ring RF phase by 20 deg, we achieved minimum synchrotron oscillation as shown in the right image. Injecting beam was still doing a smaller amplitude synchrotron oscillation start with 0 phase, which means there was slightly energy mis-match. This energy mis-match induced oscillation can be corrected by adjusting the Booster extraction energy or tune the storage ring RF frequency slightly.

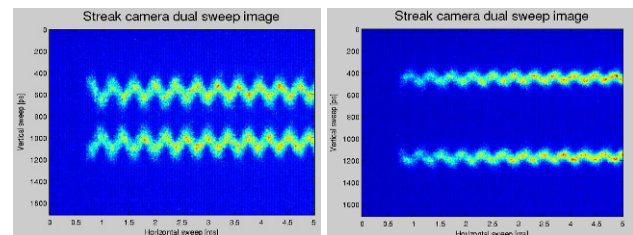


Figure 4: Injection beam phase and energy mis-match observation on the streak camera. (Left) Storage ring RF phase was 20 deg above the matched value. (Right) Storage ring RF phase best matched to the injector.

Synchrotron oscillation will be eventually damped down due to synchrotron radiation. Energy or phase mis-match will couple to horizontal motion due to dispersion. Turn by turn data from dispersive BPMs can be used to optimize the injection beam as well. Due to large horizontal betatron motion added on top of the synchrotron motion and filament in phase space, limited number of turns data is available and typically one needs to filter out the high frequency betatron motions to observe the clean synchrotron oscillations.

Y-Z IMAGING

It has been observed since early stage of NSLS2 storage ring commissioning, single bunch was getting unstable vertically at 0.7mA. This rather low single bunch threshold current has been studied carefully and it was determined due to TMCI when mode 0 and mode -1 of vertical tune sidebands collide [3,6]. CCD camera measured x-y profile saw blowup in vertical plane. To understand the bunch motions at single bunch threshold current, optics of the streak camera has been modified to monitor y-z profiles, dove prism and cylindrical lenses were added for the streak camera branch. Typical synchroscan and dual sweep images are shown in Fig. 5. Stable single bunch was stored in the ring while taking the images. In dual sweep, horizontal sweep time was set to 10 μ s to see four consecutive turns image.

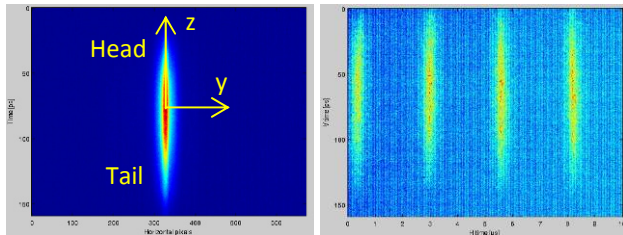


Figure 5: y-z image on the streak camera with stable single bunch stored in the ring. Left image is a synchroscan image while right side shows a dual sweep image with horizontal sweep time of 10 μ s.

At nominal chromaticity of +2/+2, single bunch instability threshold was around 0.76mA. Figure 6 shows the x-y (measured with SLM CCD camera) and y-z profiles captured at the threshold current, horizontal sweep time was at 2 μ s to see one turn profile. Without bunch by bunch feedback, single bunch vertical beam

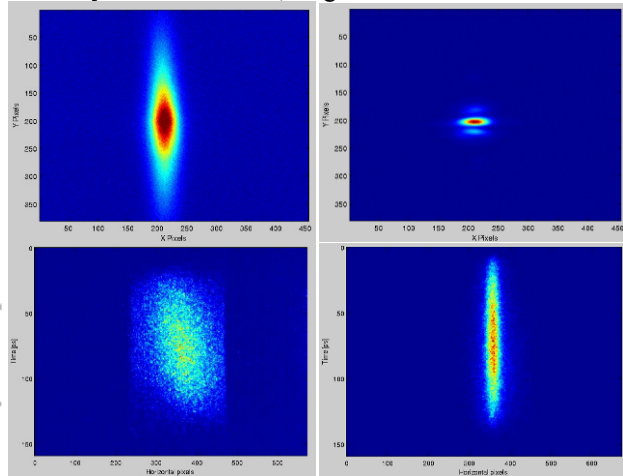


Figure 6: x-y CCD image and y-z streak camera image at single bunch current of 0.76mA. Without BxB feedback, beam was blow up vertically as shown in two left images. Longitudinal and vertical coupling motion was observed. With BxB feedback turned ON, single bunch was kept stable up to 6mA. Right side images show the stable beam profiles.

sizes were blown up. Longitudinal and vertical coupling motion was observed, y-z image was tilted. With BxB feedback turns ON, single bunch was kept stable up to 6mA single bunch current. Right side images show the stable beam profiles. Similar observations were noticed at different chromaticity (0, +1, +5), although threshold current was increased at higher chromaticity.

Using the same streak camera setup, chromatic head-tail motion (synchro-betatron coupling) has been observed as well, as shown in Fig. 7. Several single bunches separate by 8ns (4 RF buckets) were filled to get a better streak camera image, beam was kicked using vertical pinger at turn #0, streak camera trigger was adjusted to see the images at different turns after the kick. Single bunch current was measured to be ~ 0.28 mA per bunch and chromaticity was measured at +2.18/+1.94. Vertical pinger was set to 0.15kV kicker, from BPM turn by turn data, bunch centroid oscillation amplitude at SLM source point was measured to be around 0.8mm peak-to-peak, right after the pulse kick.

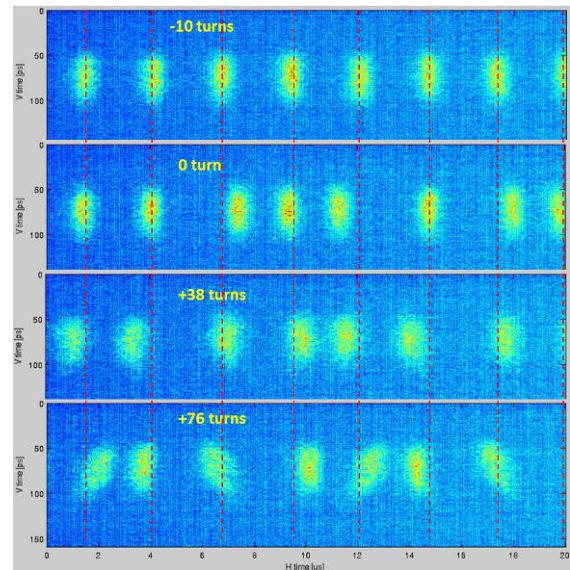


Figure 7: y-z profile at different turns after pulse kick of 0.15kV, oscillation amplitude was measured to be 0.8mm peak-to-peak from BPM TbT data.

Beam was kicked vertically at turn #0 and started betatron oscillation. Red dash lines are added in the figure to mark when the nominal vertical beam position should be when there is no pulse kick. Due to chromaticity, head and tail bunches will have slightly different betatron frequency, head and tail bunch betatron oscillation phase difference will be maximum at half synchrotron period T_s . Synchrotron oscillation frequency was ~ 2.5 kHz with RF voltage of, which is ~ 150 turns. As can be seen, tilted bunch profile was observed at $T_s/4$ and more apparent at $T_s/2$. Passing the tilted bunch through a slit at primary image plane, several pico-second short pulses can be generated. High repetition rate of short x-ray pulses generation of this method may have attractive application as it will have little impact on general high flux user. Short x-rays pulses had been demonstrated at APS [7],

NSLS2 is developing a plan for high repetition rate (\sim kHz) excitation using transverse feedback stripline kicker.

FAST ION DIRECT OBSERVATION

Fast ion instabilities have been observed when there was 25mA multi bunches stored in the ring in May 2014. Ion instability has been improved as the vacuum condition is getting better. At present average vacuum pressure of 3×10^{-9} Torr, fast ion is still observed as the major coupled bunch instability during 150mA user operation. At shorter bunch train and higher bunch current fill, fast ion instability is getting stronger.

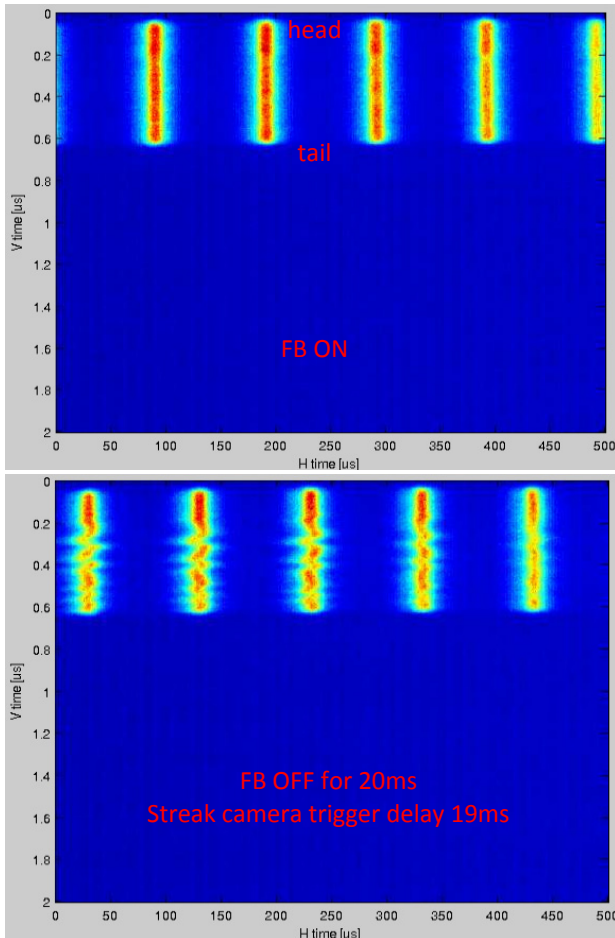


Figure 8: Dual sweep streak camera image using slow sweep module. (Upper) with bunch by bunch feedback ON, there was no instability observed on the streak camera y-z image. (Lower) with feedback turned OFF for 20ms, and streak camera trigger delay adjusted to see 19ms after the feedback OFF, bunches after #100 saw vertical motions on the streak camera image.

Use the same y-z imaging optics and streak camera slow sweep module, vertical motions along the bunch train can be directly observed. Fig. 8 gives the streak camera image taken with 300 bunches fill to total beam current of 63mA (~ 0.2 mA per bunch). Vertical sweep 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 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. With bunch by bunch feedback system, there was no instabilities observed hence head and tail bunches had no vertical motion. To see the fast ion instability build up, 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, head bunches were still stable while tail bunches ($>$ bunch #100) were doing vertical motions. Further information of fast ion instability observations can be found at [8].

SUMMARY AND DISCUSSION

Various measurements using streak camera have been carried at SLM diagnostic beamline, to characterize the single bunch and multi-bunch longitudinal motions.

Significant single bunch lengthening was observed at bare lattice and different insertion devices. Single bunch threshold current was noticed to be ~ 0.7 mA which is lower than expected. Y-Z imaging of single bunch profile at threshold current reveals how the longitudinal and vertical motions were coupled. Further analysis of measured longitudinal profile will help to understand the storage ring longitudinal impedances.

Streak camera has also been used to optimize injection beam energy/phase mis-matches. It is also a powerful tool for direct observation of synchro-betatron coupling and fast ion instabilities along the bunch train.

We thank NSLS2 operation group's help during machine studies. Continuous support from NSLS2 management is essential to make these measurements possible.

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