EXPERIMENTAL STUDY OF SINGLE BUNCH INSTABILITIES AT NSLS-II STORAGE RING*

Weixing Cheng#, Belkacem Bacha, Gabriele Bassi, Alexei Blednykh, Boris Podobedov, Om Singh, Victor Smalyuk
NSLS-II, Brookhaven National Laboratory, Upton, NY 11973, USA

Abstract

Single bunch instabilities have been observed since the early stage of NSLS-II storage ring commissioning when normal conducting 7-cell cavity was used. After installing the super-conducting cavity, the transverse single bunch instability threshold current was still at around 0.7mA. The instability was determined to be due to transverse mode coupling(TMCI) when vertical betatron sideband meets the negative synchrotron frequency sideband (-fs). Microwave instability has been characterized using streak camera bunch lengthening, horizontal beam sizes at dispersion location and beam spectra. Microwave instability threshold current dependency on bunch lengths and IVU gaps has been studied. Most recent experimental results will be presented in this paper.

INTRODUCTION

NSLS2 is a newly constructed synchrotron light source with electron energy of 3GeV, emittance of 1nm.rad/8pmrad (H/V). The storage ring circumference is ~792m with 30 DBA cells. Three damping wigglers are available symmetrically to decrease the horizontal emittance below 1nm.rad. For the 30 straight sections, 3 of them are for injection and RF cavities, the rest 27 straight sections are available for various types of insertion devices. At present, there are 6 in-vacuum undulators (IVU), 3 damping wigglers (DW) and 2 elliptical polarized undulator (EPU) commissioned and in operation. More insertion devices are being installed and will come online in the coming years.

Table 1: NSLS2 Storage Ring Parameters

Energy	3.0 GeV
Circumference	792 m
Emittance (h,v)	< 1nm, 0.008 nm
Energy Spread	0.094 %
RF Frequency	499.68 MHz
Harmonic Number	1320
RF Bucket Height	> 2.5 %
RMS Bunch Length	10ps – 40ps (measured)
Average Current	500 mA (400mA reached)
Current per Bunch	0.5 mA
Charge per Bunch	1.3 nC
Touschek Lifetime	> 3 hrs
Top-Off Injection	1/min
Betatron tune (ν_x/ν_y)	0.22/0.26
Synchrotron tune (ν_s)	0.007

Table 1 shows the related NSLS-II storage ring parameters. Emittance and energy spread are the values with three damping wigglers. Bunch lengths have been measured with different RF voltages and insertion devices gaps [1]. Synchrotron tune of 0.007 is for the typical RF voltage of 2MV.

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#chengwx@bnl.gov

TMCI INSTABILITY

Single bunch vertical instability was observed when the single bunch current was around 0.7mA. This instability was observed with normal conducting 7-cell cavity at early stage of ring commissioning, as well as super conducting single cell cavity. Measurements of the transfer function at different single bunch current revealed that vertical instability happened when the vertical betatron sideband meet the low sideband (- fs sideband), details of the single bunch transfer function measurement have been reported in previous paper [2]. Similar measurements using BPM turn by turn spectrum after pulse kicker are available at [3,4].

With bunch by bunch feedback on, the vertical single bunch instability can be suppressed. Beam can be stored to more than 6mA per bunch with nominal chromaticity of +2/+2. Fig. 1 shows the single bunch spectrum at different bunch currents with feedback on. There are dips observed near the betatron frequency. As the single bunch current increases, the dip becomes broader and shallow due to chromaticity. Vertically the betatron tune (dip minimum) moving towards lower frequency with a slope around -0.007/mA. At around 0.8mA, vertical betatron sideband merges with the –fs sideband. Higher single bunch current can still be stored stably with feedback ON and the fy sideband continues moving to lower frequency. There are multiple small peaks observed in the dip which are likely –fs sideband and other synchrotron frequency harmonics.

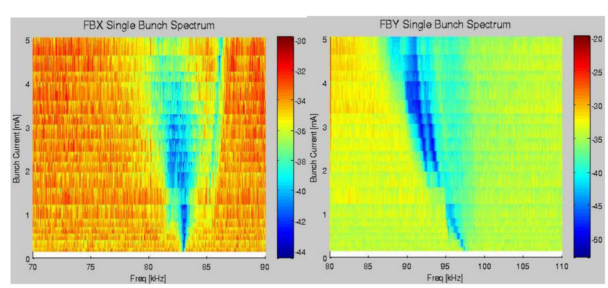

Figure 1: Single bunch spectrum measured at different bunch current, with bunch by bunch feedback ON. Dips observed near the betatron frequency shown as blue color.

Top two images in Fig. 2 are from the visible synchrotron light monitor (SLM) when single bunch current was at TMCI threshold current of 0.8mA. With feedback OFF, the image was blown up in vertical plane. As the feedback turns ON, vertical instability was cured and the SLM image was compressed vertically. SLM CCD camera exposure time was 2ms while acquiring the images. Vertical beam size was compressed from ~550um (no feedback, RMS size) down to ~90um (with feedback), which is close to the diffraction limit of the diagnostic beamline.

To further investigate the bunch unstable motions, one turn profile was measured using a streak camera. Dove prism was used to rotate the synchrotron light by 90 deg, followed with cylindrical lens optics setup to measure the y-z bunch profile. Streak camera was operating in dual sweep mode. Horizontal sweep time was at 2μs to see one turn profile. Without bunch by bunch feedback, single bunch vertical beam sizes were blown up. Longitudinal and vertical coupling motion was observed with tilted y-z profile. With BxB feedback turned ON, single bunch was kept stable up to 6mA single bunch current. Bottom-right image shows the stable beam profiles. The streak camera y-z profile was measured at different chromaticity (0, +1, +2, +5). The profile behavior was similar even though TMCI threshold current was increased at higher chromaticity.

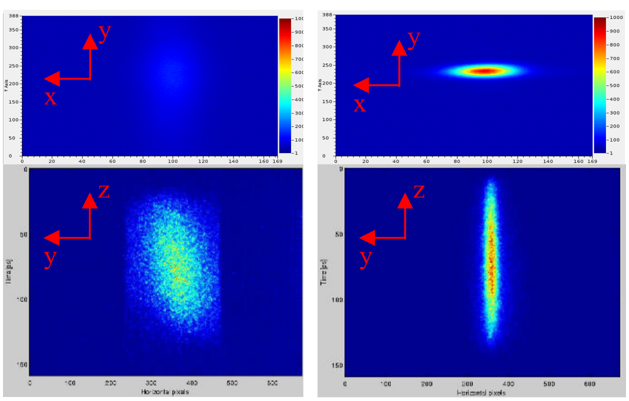

Figure 2: (top) SLM CCD camera images with single bunch current stored at TMCI threshold current of 0.8mA. x-y profile was measured on the CCD images. (bottom) y-z streak camera image at the same single bunch current. Without BxB feedback, beam was blown up vertically as shown in two left images. Longitudinal 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.

MICROWAVE INSTABILITY

There is no direct measurement of the energy spread (momentum spread), however, the energy spread can be estimated from the bunch length, horizontal beam sizes at dispersion location or beam spectrum.

$$\sigma_t = \frac{\alpha}{2\pi f_s}\left(\frac{\sigma_E}{E}\right) = \sqrt{-\frac{\alpha E_0 T_0}{e\omega_{rf} V_c \cos(\phi_s)}}\cdot\left(\frac{\sigma_E}{E}\right) \qquad (1)$$

Bunch lengths have been measured at different RF voltages and ID gaps. '0-current' bunch length is given by Eq. (1), where α is momentum compaction factor; f_s is the synchrotron frequency; σ_E/E is the energy spread; E_0 is the electron beam energy; T_0 is the revolution period; $f_{rf} = \omega_{rf}/(2\pi)$ is the RF frequency; V_c is the RF cavity voltage and ϕ_s the synchrotron phase.

Due to longitudinal broadband impedance, the bunch synchronous phase, synchrotron frequency and bunch lengths will be affected (potential well distortion). At NSLS-II storage ring, bunch centroid drift was measured with a slope ~10ps/mA. Bunch-lengthening curves measured with bare lattice, one DW and three DWs are shown in Fig. 3. There is no clear threshold seen on the bunch lengthening curves. Independent of the initial bunch lengths, all three curves merge to the same slope shown as blue dash line. Similar observations at other facilities [5,6] indicate bursting instability when bunch length is approaching the scaling line.

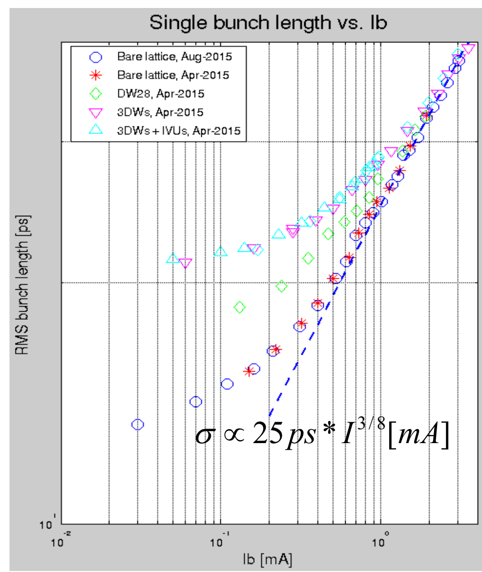

Figure 3: Bunch lengthening curves measured with bare lattice, 1DW and 3DWs. Four installed IVUs gap close didn't affect the bunch lengthening as expected. RF voltage was at 1.78MV.

Energy spread can be estimated from the horizontal beam size at dispersion locations, see Eq. (2).

$$\sigma_x^2 = \varepsilon_x \beta_x + \left(\eta_x \frac{\sigma_E}{E}\right)^2 \qquad (2)$$

where the first term is the betatron horizontal size and second term is the dispersive horizontal size. η_x is the dispersion function.

NSLS2 storage ring has an x-ray pinhole camera at non-dispersion location to measure the ring emittance. Visible SLM diagnostic beamline source point locates near the second dipole entrance of a DBA cell, where horizontal dispersion is ~0.13m. SLM horizontal beam sizes at different single bunch current have been measured, shown in Fig. 4. As can been seen that horizontal beam sizes increase when single bunch current was above 0.5mA. In the meantime, SLM measured

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vertical beam sizes were constant. Pinhole camera located at non-dispersion location was used to monitor the horizontal/vertical emittance. There was no emittance increase at single bunch current stored up to 6mA. Based on these observations, it's likely that energy spread starts to increase with threshold current ~0.5mA. It's worth to mention the measurement was carried out with bare lattice. For lattices with DWs, the threshold current is expected to be higher due to a longer bunch.

Attempt has been tried to measure the bunch longitudinal profile, in the hope to see phase space distortion when microwave instability happens. Streak camera optics was configured to measure the x-z profile. Due to dispersion, x direction on the streak camera is affected by dispersive beam size (Eq. 2). There was no clear longitudinal phase space distortion observed. Small horizontal emittance lattice (for example with 3DWs) may be helpful to see the phase space distortion better, as the dispersion and energy spread contribution to the horizontal beam sizes are dominant.

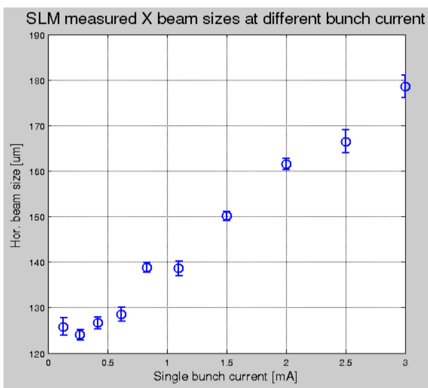

Figure 4: Horizontal beam sizes at different single bunch current, measured using visible synchrotron light monitor at dispersion location.

To further study the microwave instability threshold, beam synchrotron sideband spectrum were recorded at different single bunch current. Stripline signal feeds to a broadband spectrum analyzer through ~30m of low loss Heliax cable. Similar methods have been used to study the microwave instabilities at other machines, see for example [7,8]. Fig. 5 gives the synchrotron sideband spectrum at different single bunch current, measured with bare lattice at RF voltage of 1.8MV. Carrier frequency was chose to be ~11GHz (22*Frf) to have better sensitive for high mode synchrotron motions.

A clear threshold current was observed at 0.51mA when 3*fs sideband appeared. As the single bunch current keeps increasing, the sideband shifts to 4*fs and transits to multiple humps at current more than 1mA. The 0.51mA threshold current agrees well with the dispersive horizontal size increase in Fig. 4. It has also been confirmed that threshold current tends to be higher with lower RF voltage or with DW gap closed. After installation of second super-conducting cavity, similar measurement was carried out with threshold current ~0.34mA (bare lattice, RF voltage 2.1MV) when 2*fs sideband appeared.

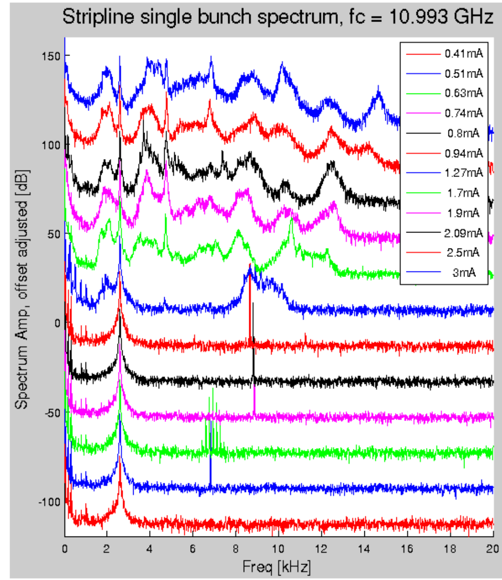

Figure 5: Synchrotron sideband spectrum at different single bunch current, measured with bare lattice, RF voltage 1.8MV.

CONCLUSION

Vertical single bunch instability has been observed since early storage ring commissioning. The instability was found to be transverse mode coupling when betatron frequency meets the –fs sideband. Streak camera y-z turn to turn profile measurement shows that the vertical beam sizes blow up when the instability happens. Longitudinal and vertical coupling motion was observed as well. With BxB feedback turned ON, single bunch can be kept stable up to 6mA.

Longitudinal microwave instability was studied by means of bunch lengthening, dispersive horizontal size and synchrotron sideband spectrum measurements. Threshold current ~0.5mA was observed with bare lattice.

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