NSLS-II COMMISSIONING WITH 500 MHZ 7-CELL PETRA-III CAVITY*

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Abstract

The NSLS-II storage ring has been commissioned during Phase 1 with 500 MHz 7-cell PETRA-III RF cavity. In this paper we present our first beam-measured data on instabilities and collective effects with a normal conducting RF system.

INTRODUCTION

The first phase of the NSLS-II storage ring (SR) commissioning has been successfully completed in May 12, 2014. The average current of $I_{av} = 25\,mA$ was achieved in the storage ring w/o ID's and Landau cavities in accordance to the project milestone. In about 5 weeks we delivered a 3 GeV beam to the ring injection straight section, made the 1st turn around the ring, achieved hundreds of turns optimizing injection, stored beam having sextupoles and RF turned ON. Injection efficiency was achieved 95%, close orbit rms value is ~100 um, tune and chromaticity were measured and adjusted as desired, and beam lifetime was a few hours depending on the stored beam current.

Prior to the storage ring commissioning our NSLS-II team tested and started operations of the NSLS-II injector. During Booster commissioning (Dec. 2013 to Feb. 2014) we gained experience with 7-cell PETRA-III cavity. This cavity, together with an IOT-driven (85 kW) transmitter runs at 1.2 MV ramping the beam energy from 200 MeV to 3 GeV. Just before completing the booster commissioning we tested accumulation of nearly 20 mA of average beam current.

Next we run an equivalent spare PETRA-III cavity as the RF system for the storage ring. During commissioning we tested both 25 mA of average current (which corresponds to a significant portion of current per bunch in our design goal of 500 mA) and up to 1 mA of current in a single bunch (with transverse feedback system OFF). We describe our first experience with instabilities observed during first tests and project on questions we will resolve in the next phase of the commissioning with the superconducting CESR-B 500 MHz RF cavity operation.

LINEAR CHROMATICITY

Linear chromaticity measurements are performed by changing the master oscillator frequency within $\pm 1\,kHz$ and the measuring tunes, $\nu_{x,y}$, variation $\xi = \frac{\Delta\nu}{\Delta E/E} = -\alpha_c \frac{\Delta\nu}{\Delta f/f}$, where $\alpha_c = 3.63 \times 10^{-4}$ is the momentum compaction. We use all three families of chromatic sextupoles for the chromaticity adjustment. The chromaticity responses to sextupole strengths/power supplies currents are calculated based on the designed model and written as a matrix format $M_{x/y,j} = \frac{\Delta\xi_{x/y}}{\Delta I_j}$, where $\Delta\xi_{x/y}$ is the chromaticity shift due to the j^{th} sextupole's power supplier current change ΔI_j. Thus the needed ΔI_j to adjust $\Delta\xi_{x/y}$ are obtained by solving a linear equation $\Delta\xi_{x/y} = M_{x/y,j}\Delta I_j$.

HORIZONTAL PLANE

The horizontal tune ν_x was measured by several methods but here only use an FFT calculation of Turn-by-Turn (TBT) beam position data. The betatron oscillation was driven by a horizontal kick using a lower voltage on the last of the four injection kickers ~0.1 kV (0.1 mrad). The horizontal TBT data have been measured in single bunch mode at different currents. To estimate the resolution on ν_x, we used two methods. The first was using a 4K point FFT which should have statistical resolution of 2×10^{-4} on the peak frequency, but could be sensitive to decoherence and other systematic effect. This method was used for the ν_x shown in Fig. 1a for data from one BPM versus the single bunch current I_o for $\xi_{x,y} = 0$, $+1/+1$ and $+2/+2$. Tune ν_x remains quite constant versus I_o with no indication of an impedance driven tune shift, as seen in the vertical plane. To insure this isn't the result of systematic effects, the TBT data was analysed over only 1K turns with an interpolated FFT [1]. The statistical resolution for this method for ν_x is shown in Fig. 1b by plotting the values obtained with this method for each of 180 BPMs in the ring versus current.

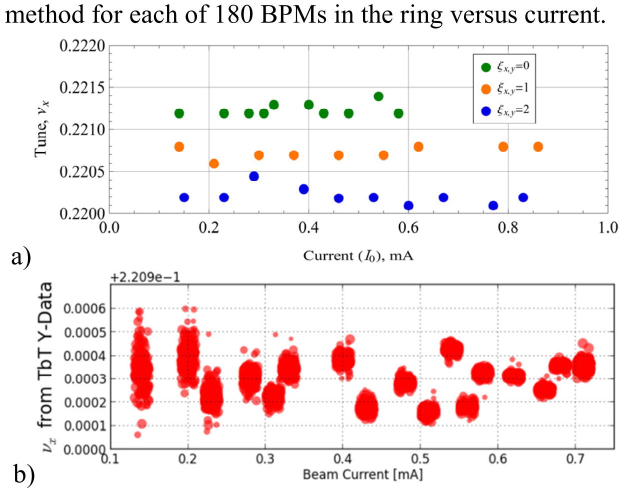

Figure 1: Horizontal tune versus current for a) high resolution FFT method and b) interpolated FFT method for all 180 BPMs.

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The slow head-tail effect provides damping at positive chromaticity (Fig. 2a) and can be used to estimate the real part of the effective impedance [2]

$$\tau^{-1} = -A\int_{-\infty}^{+\infty} dk\ \ Re\, Z_{\perp}(k)e^{-\left(k-\frac{\omega_0}{\eta c}\xi\right)^2\sigma^2}$$

$$= -A\sigma\chi\int_{-\infty}^{+\infty} dk\ k\ Re\, Z_{\perp}(k)e^{-k^2\sigma^2} \quad \text{for } \chi \ll 1,$$

where $A = \frac{eI\beta_x\omega_0 C}{8\pi^2 E\beta}$ and $\chi = 2\frac{\omega_0\sigma}{\eta c}\xi$ is the head-tail phase. For NSLS-II, $\chi = 0.13$ for $\xi = 1$. From the measurement of the growth rates τ_m^{-1} as a function of current at a given chromaticity (see Fig.2b) and assuming a broadband resonator impedance, the horizontal shunt impedance $R_{sh,x}$ can be estimated for a given resonator frequency ω_r and quality factor Q

$R_{sh,x} = \frac{\tau_m^{-1}}{\chi A\sigma F}$, where $F = F(k_r, Q, \sigma) = \int_{-\infty}^{+\infty} dk\ \frac{k}{k_r(1+B^2)}$, and $ReZ_x(k) = \frac{k}{k_r}\frac{R_{sh,x}}{1+B^2}, B = Q\left(\frac{k}{k_r} - \frac{k_r}{k}\right)$, and $k_r = \frac{\omega_r}{c}$.

From the growth rates of Fig. 2b and assuming $\omega_r = 2\pi \times 30$ GHz and $Q = 1$, we obtain $R_{sh,x} = 0.4\ M\Omega/m$.

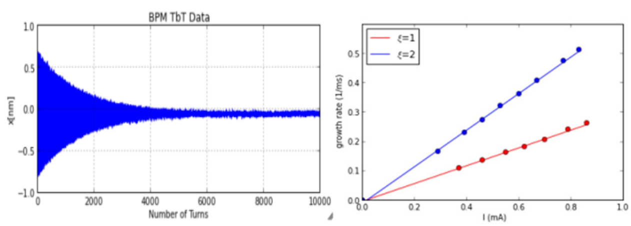


Figure 2: a) Measured horizontal TBT data at chromaticity $\xi_{x,y} = +1/+1$, BPM 6 ($I_0 = 0.85\ mA$). b) Absolute value of the measured horizontal growth rate as a function of current at chromaticity $\xi_{x,y} = +1/+1$ and $\xi_{x,y} = +2/+2$ with the fitted slope.

VERTICAL PLANE

Studies of the single bunch current accumulation during the first phase of the commissioning showed that we can store about $I_0 = 0.96\ mA$ in a single bunch at positive chromaticity $\xi_{x,y} = +2/+2$ in both planes and at nominal RF voltage $V_{RF} = 0.8815 \times A_{RF}$ of the PETRA-III RF cavity, where $A_{RF} = 2.14\ MV$. This is with the transverse feedback system OFF. The measured bunch length at low current is 11 ps. The intensity of the single bunch in the storage ring was accumulated by a small portion of the delivered charge from the booster (0.2 nC per shot, in a single bunch mode) due to safety requirements during the commissioning Phase 1. After storing $I_0 = 0.96\ mA$ no further accumulation was observed, but the single bunch continued to circulate with high enough beam life time, 13.5 hours (fitted sum signal from 2 BPMs). The beam started to increase its vertical size at $I_0 = 0.6\ mA$, when some first burst signal could be recognized from the vertical TBT data. The synchrotron light monitor images (Fig. 3) show how the beam blow-up vertically at high current. In Figure 3 we present two snapshots of the circulated single bunch in the storage ring from the synchrotron light monitor for two currents, 0.96 mA and 0.7 mA, keeping the same scale for both images.

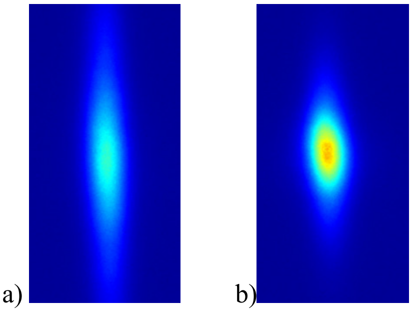
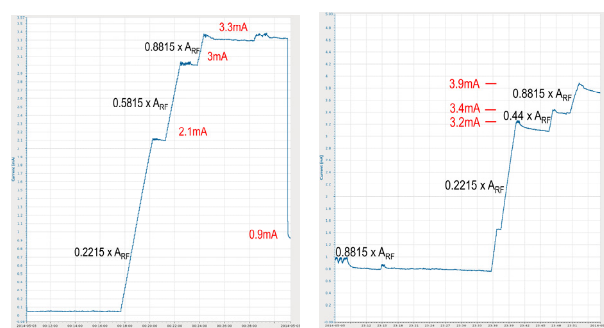


Figure 3: Synchrotron light monitor images of the single bunch for the currents a) $I_0 = 0.96\ mA$ and b) $I_0 = 0.7\ mA$ keeping the same scale for both images.

To understand the course of the instability and single bunch limitations we 1) varied the RF voltage, 2) changed the chromaticity and 3) switched ON the transverse bunch-by-bunch feedback system. Lowering the RF voltage down to $0.2215 \times V_{RF}$ from its nominal value $0.8815 \times V_{RF}$ helps to accumulate more current per bunch. As can be seen from Fig. 4a the single bunch current is stored up to 2.1mA ($\xi_{x,y} \approx +2/+2$). Raising the RF voltage up to nominal value $0.8815 \times V_{RF}$ helps to store $I_0 = 3.3\ mA$. In Fig. 4 we plot bunch accumulation history for two different chromaticities $\xi_{x,y} \approx +2/+2$ (Fig. 4a) and $\xi_{x,y} = +4.6/+4.6$ (Fig. 4b). The single bunch current $I_0 = 3.9\ mA$ has been stored at chromaticity $\xi_{x,y} = +4.6/+4.6$ by lowering and ramping up the RF voltage (Fig. 4b).



a) b)

Figure 4: Accumulation of the single bunch with high intensity due to lowering and ramping up the RF voltage with transverse bunch-by-bunch feedback system OFF.

It should be noted that we were able to accumulate more than 6 mA in a single bunch with the transverse feedback ON at nominal RF voltage $0.8815 \times V_{RF}$. Further intensity accumulation to the single bunch has been stopped due to the premature vacuum conditioning (1Ahr) of the surfaces inside the storage ring. Temperature rise of several vacuum components was carefully monitored including two special bellows with temperature sensors (6 RTDs per bellows) located under vacuum on the RF fingers. The result was an eventual temperature rise of ~3°C on RF Bellows fingers at $I_0 = 6\ mA$. More detailed studies of the temperature dependence as a function of current in single bunch and multi-bunch modes are planned.

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An approximate relation determining the threshold of the transverse coupled-mode instability (TMCI) at zero chromaticity is given by [3]

$$\frac{\Delta\nu_y}{\nu_s} = \frac{eI_o^{th}}{2E\nu_s\omega_0}\sum_j \beta_{y,j}k_{y,j} \cong 0.7 \qquad (1)$$

where I_o^{th} is the threshold bunch current, $\beta_{y,j}$ is the average value of the betatron function in the j^{th} component, and $k_{y,j}$ is its kick factor. $E = \gamma mc^2$ is the electron energy and ν_s is the synchrotron tune. Using the NSLS-II parameters presented in Table 1 and the measured coherent vertical tune shift versus single bunch current at zero chromaticity (Fig. 5a), we find that the global vertical kick factor of the NSLS-II storage ring is $k_y = 14\ kV/pC/m$ for the current ring configuration, where 6 straight section are occupied by the RF (Cell 24, PETRA-III), Injection (Cell 30), Diagnostic (Cell 16, Feedback and Tune Measurement Systems), DW's chambers (Cell, 8, 18 and 28). Other straight sections filled out with standard aperture Al chambers.

Table 1: Parameters for the Kick Factor Estimation

Energy, $E\ [GeV]$	3
Circumference, $C\ [m]$	791.9589
Revolution Period, $T_0\ [\mu s]$	2.64
RF Voltage, $V_{RF}\ [MV]$	1.86
Synchrotron Tune, ν_s	7 x 10^{-3}
Vertical/Horizontal Average beta-function: $\beta_y, \beta_x\ [m]$	7.7, 3.8
Damping Time: $\tau_x, \tau_s\ [ms]$	54, 27
Bunch Length, $\sigma_\tau\ [ps], \sigma_o\ [mm]$,	11, 3.3

The vertical tune variation as a function of current is plotted in Fig. 5 as well as the spectra of BPM41 vertical TBT data in Fig. 6 for different chromaticities at nominal RF voltage $V_{RF} = 0.8815 \times A_{RF}$. No TMCI effect appears at $\xi_{x,y} = 0$, since $I_o = 0.71\ mA$ was limited by a horizontal instability which needs further study.

SUMMARY

The average current 25 mA has been stored in SR with 7-cell PETRA-III cavity during Phase 1 commissioning. The measured single bunch threshold at zero chromaticity is $I_o = 0.71\ mA$, which is due to horizontal dipole instability. Possible candidates are HOM's of the PETRA-III RF cavity [4]. At positive chromaticity (Fig. 6b, c, d) we can accumulate more current per bunch, $I_0 = 0.9\ mA$. With transverse feedback ON and at positive chromaticity +2/+2 we stored more than 6 mA in a single bunch. This limit was due to the premature vacuum conditioning (1Ahr) of the surfaces inside the storage ring.

ACKNOWLEDGMENT

The NSLS-II team will always remember Samuel Krinsky for his remarkable accomplishments as an accelerator physicist, a supervisor and as NSLS-II team member.

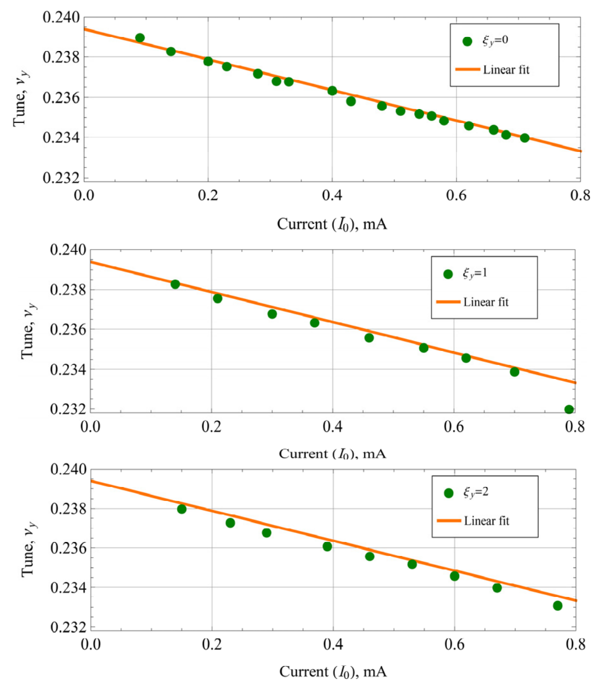
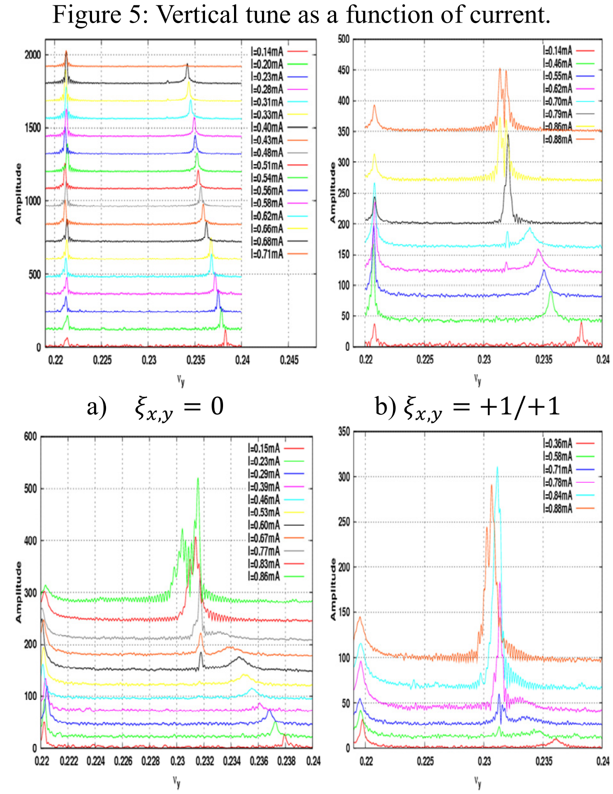


Figure 5: Vertical tune as a function of current.



a) $\xi_{x,y} = 0$ b) $\xi_{x,y} = +1/+1$

c) $\xi_{x,y} = +2/+2$ d) $\xi_{x,y} = +3/+3$

Figure 6: Spectra of BPM41 vertical TBT data.

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[2] A. W. Chao, Physics of Collective Beam Instabilities in High Energy Accelerators (Wiley, NY, 1993).
[3] See e.g., S. Krinsky, BNL-75019-2005-IR.
[4] G. Bassi et al., Paper TUPRI070, these Proceedings.