

## NSLS-II STORAGE RING INJECTION OPTIMIZATION\*

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### Abstract

The National Synchrotron Light Source II (NSLS-II) is a state of the art 3 GeV third generation light source at Brookhaven National Laboratory. The SR is designed to work in top-off injection mode. The injection straight includes a septum and four fast kicker magnets with independent amplitude and timing control. The beam injection is designed as 9.5 mm off-axis in x plane and on-axis injection in y plane. To capture the injected beam within the SR acceptance for high injection efficiency, it requires 6-D phase space match. Besides that, the fast kickers formed local bump is also required to be locally to minimize the injected beam extra betatron oscillation and keep the stored beam disturbance within the specification, 10 % beam size to minimize the injection transient. This paper will present our injection commissioning experience.

### INTRODUCTION

The National Synchrotron Light Source II (NSLS-II) is a 3 GeV, ultra-small emittance (H: 1 nm-rad and V: 8 pm-rad), high brightness third generation light source [1].

The Storage Ring phase I commissioning started in Mar. 2014 and finished in one and a half months later to achieve 25 mA stored beam current with >90% injection efficiency.

The designed beam injection is 9.5 mm horizontal off-axis injection and vertical on axis injection. The commissioning strategy is to circulate beam first by doing on-axis injection [2] with sextupoles and RF off, then get the stored beam with sextupoles and RF on and finally move to nominal off-axis injection [3] to accumulate high beam current with good injection efficiency. In this paper, we describe our experience.

### SR INJECTION OVERVIEW

The NSLS II storage ring injection system is located in one 9.3 m long straight section. As shown in Fig. 1, it consists of four kickers, a DC septum and a pulsed septum for beam injection. The four kicker magnets, producing a closed bump in x plane for stored beam, are placed symmetrically in the straight section. Their bending angles are the same but in different bend direction. The stored beam gets the maximum bump amplitude at the middle of injection straight line. There are one injection straight flag, 4 BPMs and two neutron beam loss monitor are dedicated for injection related beam monitor and study. BPMs P1 and P4 are centered on the SR stored beam orbit, P2 is shifted by  $X = -5.8$  mm off center and P3 is shifted by  $X = -15$  mm from SR stored beam center. These four BPMs are inside the local

fast bump and can be used for the bump amplitude study. 180 BPMs along the ring were used for the bump leakage study.

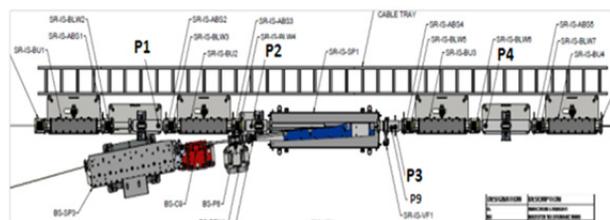


Figure 1: Top view of the SR injection straight section.

When the injected beam arrives, kickers K1 and K2 kick the stored beam towards the septum knife by 15 mm. The stored beam and the injected beam merge at the exit of the AC septum. Kickers K3 and K4 will kick both beam, so that the stored beam returns to its designed orbit, and the injected beam is off-axis oscillation. These kickers angle are 7.5 mrad with 5.2  $\mu$ s kicker pulse length, two times long of storage ring revolution. The stored beam bump amplitude is 15 mm. The injected beam and stored beam relative position at the exit of septum is shown in Fig. 2. The designed stored beam equilibrium orbit is 17.5 mm away from septum knife with 2.5 mm safe region away from septum knife. At the end of bump, injection beam is 9.5 mm away from stored beam close orbit, which requires  $\sim 11$  mm SR acceptance, comparing with the SR designed acceptance 15 mm [4].

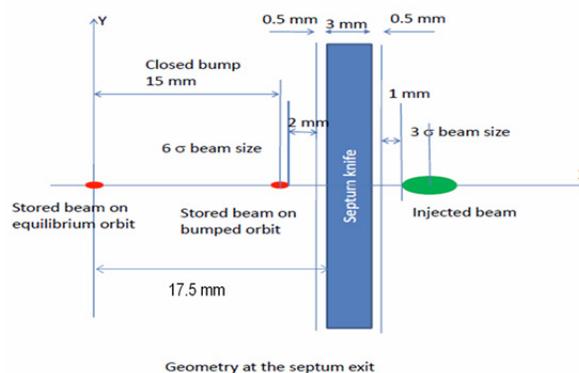


Figure 2: Injected beam and stored beam relative position at the exit of septum.

### FAST KICKERS STUDY

Each kicker has independent voltage and timing control. The kicker voltage to the kick strength conversion is not very precise from the lab measurement. The timing delay is separated into two control parts. One is for four kickers' common delay relative to the injection time, and the other is for each kicker precise delay to compensate the cable length or beam arrival time difference. The initial timing trigger for all kickers is

aligned with the beam signal from BPMs raw data and monitored with oscilloscope, as shown in Fig. 3.

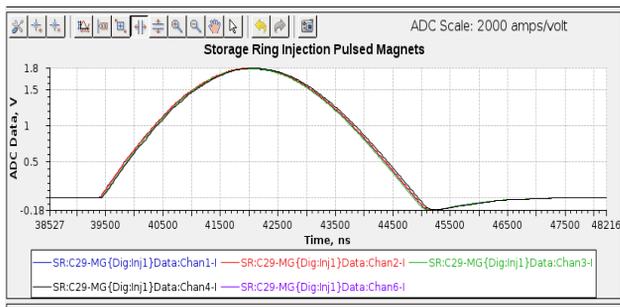


Figure 3: Fast kickers waveform.

The initial kicker strength is set based on the measurement calibration. After the off-axis injection was obtained, different filling pattern was required to achieve high current due to bucket current limit. At that time, it was found that when the injection bucket was changed, the capture efficiency was different and some filled buckets were lost. The kicker timing and amplitude were studied and optimized.

The timing and amplitude are related, as the kick strength on beam is  $A \cdot \sin(\omega t)$ . The common timing delay is optimized by moving the bucket number and comparing the capture efficiency (in fact, the capture efficiency for fresh injection does not change, but the stored beam is scratched at septum.) This process moves the beam relative to the pulse peak. It was found that the beam arrival timing was 520 ns away from the pulse peak and the kick voltage was ~5 % higher, which made the local fast bump too high and resulted in the stored beam loss in the septum knife. After fixing the common timing delay and kick amplitude, the beam could be captured well at every bucket.

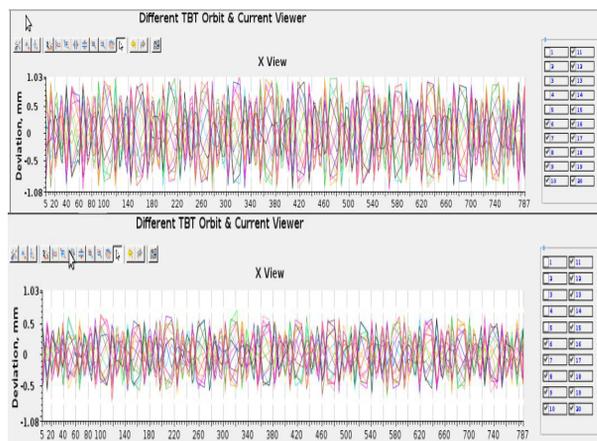


Figure 4: The local fast bump leakage before (upper) and after (lower) kicker strength optimization.

TBT data also show the local fast bump leakage when all four kickers are set to the same nominal amplitude. Figure 4 shows the amplitude of remaining betatron oscillations was about 1 mm (upper). To minimize the leakage, four kickers' response matrix to 180 BPMs TBT data was used. The kicker voltage changes by 0.05 kV

around its working point, so that the kicker calibration is in the working region and the BPMs reading is in linear region. After optimization, the leakage amplitude is lowered by half. Further studies, such as the precise timing alignment, kicker tilt correction, etc. should be conducted.

## SR CLOSE ORBIT CORRECTION TO MINIMIZE BETATRON OSCILLATIONS

The betatron oscillation was clearly seen from BPMs TBT data. It was also observed that the capture efficiency could not be further improved by matching the injection angle and position, since the injection angle and position control is limited by the BTS corrector strength and the aperture limit in AC septum and the y plane big betatron oscillation reached the SR dynamic aperture.

A method for matching the first and second turn trajectory with two correctors in the last cell before injection was proposed, so that the SR closed orbit was changed and the injection beam is on close orbit injection. Two correctors phase advance of ~ 90 degree was chosen for most effective control. By varying each corrector, we measured second turn trajectory change of 180 BPMs and get the response matrix (180\*2). Since the method depends on 180 BPMs reading, it is less sensitive to individual BPM accuracy. Figure 5 shows the y plane betatron oscillation and BPM sum signal before and after correction. Before correction, the beam lost 50% after 4<sup>th</sup> turn. After match SR new close orbit to injection, the BPMs shows ~80% survival after 20 turns.

This is proved to be a very quick way to establish the injection beam to the closed orbit and get the beam capture efficiently.

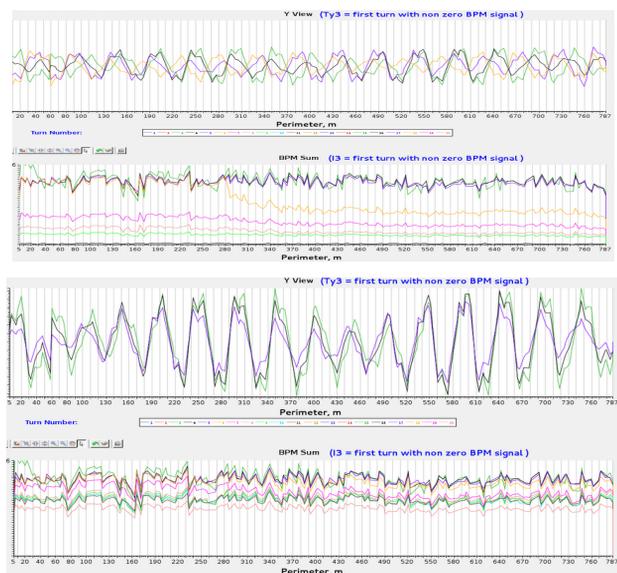


Figure 5: Beam capture before (upper) and after (lower) match SR new close orbit to injection.

## INJECTION 6-D PHASE SPACE MATCH

If the injection beam transverse phase space (x, xp, y, yp) is mismatch with the SR close orbit at the injection

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point, the beam will do the betatron oscillation [5]. If the injection beam longitudinal (phase and energy) is mismatch with the SR synchrotron phase and energy, the beam will do the synchrotron oscillation. These oscillations have different behaviour as the betatron oscillation fraction tune for is  $\sim 0.2$  range (a few turns) and the synchrotron tune is  $\sim 0.007$  ( $\sim 100$  turns). Moreover, the synchrotron oscillation is only viewed from dispersion region BPMs. So it is easy to differentiate from the BPMs TBT data.

The transverse phase space control knob is from the BTS correctors. The longitudinal control knob is the injection energy and SR RF phase.

For the x plane, the beam is off-axis injection, which naturally introduces the betatron oscillation. Theoretically, this mismatch can be extracted from TBT data with designed oscillation value, but the oscillation is  $\sim 10$  mm range, which is the BPMs nonlinear region. The data does not show good result.

For the y plane, the beam is on-axis injection. The injection mismatch is fitted 180 BPMs TBT data. The response matrix is from the model, which gives very good fitting. The mismatch value is oscillation of the first turn position relative to closed orbit from several turns' data average. The knob in BTS is C8 and C9. Usually, after one correction, the betatron oscillation can easily suppress down to 1mm. Figure 6 shows the y plane turn by turn data before and after injection beam correction. Before correction, the y plane betatron oscillation amplitude is  $\sim 4.2$  mm, closer to the dynamic aperture and limit the injection capture efficiency. After correction, the betatron oscillation amplitude is  $< 1$  mm.

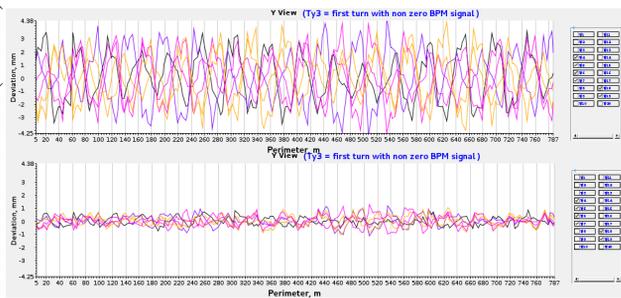


Figure 6: y plane TBT before and after injection beam correction.

For the longitudinal phase space, the dispersion regions BPMs were used. Figure 6 shows one dispersion region BPM TBT data. From the TBT x plot, it is clearly that the beam has  $\sim 200$  turns oscillation period, which due to phase or energy mismatch. The phase mismatch and energy mismatch evolve to each other. The oscillation due to energy mismatch starts from large amplitude. The oscillation due to phase mismatch starts from middle and moves to large amplitude, positive or negative depending on the offset. The energy and phase induced oscillation amplitude can be extrapolated by fitting data into sine

wave and cosine wave form.

Figure 7 shows the mismatch mainly from phase, induced dispersion BPMs residual synchrotron oscillation. After adjust RF phase, the oscillation from synchrotron oscillation was minimized from 2.3 mm to  $< 1$ mm.

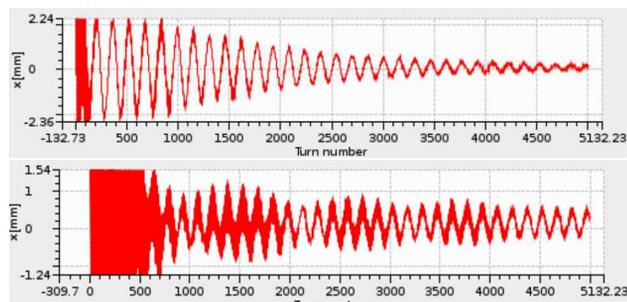


Figure 7: The injection beam energy mismatch monitor from dispersion BPM.

## CONCLUSION

The NSLS II storage ring commissioning went smoothly and successfully. The injection commissioning experience was discussed. The kicker timing delay and amplitude was aligned initially with oscilloscope, but BPMs turn by turn data were used for precise alignment. The y plane betatron oscillation was minimized with traditional way from transport line steering and SR two correctors. The latter one was proved to be very useful to get the beam on-axis injection and stored quickly. The injection induced synchrotron oscillation was monitor and optimized from dispersion BPMs horizontal oscillation. The injection efficiency is usually  $> 90\%$  after phase space match in vertical and longitudinal plane.

## ACKNOWLEDGEMENTS

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