TOP OFF TESTS AND CONTROLS 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. As in many other light sources, top-off injection is considered as a standard operation mode resulting in more stable beam intensity to minimize heat load variation on the beamline optics. Top off injection specifications include maintaining the stored beam current within 0.5% and the bunch to bunch charge variation within 20% bands. To make the top off commissioning smooth and efficient, a virtual machine model based on the measured beam properties was developed. The model helped to study robustness of this application operating under different conditions and optimize the input parameters. Once tested the model was transitioned to beam commissioning. To make the beam tests more efficient, the beam lifetime was controlled by adjusting RF voltage and scrapers. In this paper, we'll share the experience from the test stage to machine implementation of the top-off controls.

INTRODUCTION

The National Synchrotron Light Source II [1] (NSLS-II) is a state of the art 3 GeV third generation light source at Brookhaven National Laboratory. Beam line operations started from February 2015 in decay mode. From October 2015, top-off operation became a standard operation mode to provide more stable beam intensity to minimize heat load variation on beamline optics. Currently, there are 10 beamlines operated at 250 mA and more beamlines are on the way of construction.

To meet top off injection requirements, different stage tests, including algorithm development [2], virtual machine test and beam commissioning with photon shutter close were conducted before implementation top off injection to normal operation mode. This is very helpful to minimize actual beam commissioning time. In this paper, we'll share the experience from the test stage to machine implementation of the top-off injection.

TOP OFF SPECIFICATIONS

Top off injection scenario includes:

1. >1 minute between injector cycles
2. Total beam current stability within +/- 0.5%
3. Bunch-to-bunch charge stability <20%
4. multi-bunch injection to storage ring with ~1000 bunches.

At 500 mA design beam current, the beam lifetime in NSLS II is Touschek-dominated, about 3 hours. To minimize top off injection disturbance on beamlines operation, the injection period is required to be longer than 1 minute. The beam current decays 0.5% and total charge to be filled is 6.6 nC. The linac gun can operate in two different modes, single bunch mode and multi bunch mode. In single bunch mode, it can deliver 0.5 nC charge per shot, which is far away from required fill charge. In multi-bunch mode, the gun can deliver up to 15 nC charge per shot with bunch train varying from 20 up to 150 bunches separated by 2 ns, but the bunch shape is hard to optimize as uniform distribution. To meet the beam current and bunch charge stability requirement, the injection bunch train length varies and SR target bucket number varies to compensate bunch to bunch charge difference.

The beam current changes with time t is

$$I(t) = I_0 e^{-t/\tau} \qquad (1)$$

Where I_0 is beam initial current and τ is beam lifetime. During a short time ($t \ll \tau$), beam current is approximate to be $I(t) \approx I_0(1-\frac{t}{\tau})$ or $\frac{dI}{I_0} \approx \frac{dt}{\tau}$. To maintain beam current change within 0.5%, the injection period should be

$$dt = 0.005 * \tau \qquad (2)$$

So the injection period is proportional to beam lifetime to get fixed beam current decay ratio. During normal operation, the beam lifetime varies in a small range for certain beam current and beamline prefer to do injection at fixed period, instead of varying injection cycle in seconds amplitude.

For the required injection charge, it includes the inputs from DCCT total beam current and Filling Pattern Monitor charge of the injected target bunches. The weight from DCCT current is large to maintain the ring beam current stability, while the weight for FPM charge is optimized to wash out bunch to bunch charge variation, refer [2] for more details. This requires DCCT and FPM charge reading to be reliable.

VIRTUAL MACHINE

To make the top off commissioning smooth and efficient, a virtual machine based on the measured beam properties was developed. The model helped to study robustness of the top off application operating under different conditions and optimize the input parameters. The program would allow to:

1. Develop and test the top off algorithm implementation without code affecting the live machine.
2. Have full control over simulated machine parameters with faster simulation rate to reduce algorithm adjustment time.
3. Optimize top off input parameters, such as gains and injection bunch train lengths and be compatible with the future algorithm implementation.

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4. Study the algorithm stability with various imperfect situations, e.g. charge variation from injection bunch train, injection efficiency or missed shots.

Top off interfaces with machine control system through a set of EPICS Process Variables (PVs) such as total beam current measurement, top off safety system enable signal. To allow seamless interfacing between model and algorithm parts, the virtual machine was implemented similar as the top off injection control.

Figure 1 shows virtual machine control interface. It allows fully control of simulation input, such as the machine simulation rate (from 1 to 100 Hz), injection pattern, lifetime, shot to shot injection efficiency variation, etc.

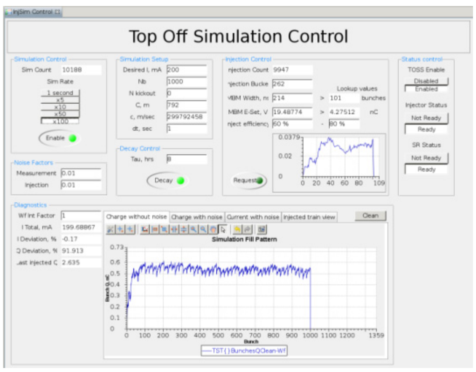

Figure 1: Virtual machine control interface.

The machine simulator is an essential tool for top off injection development, so that algorithm's new features can be tested and optimized without the beam study time, such as injections bucket overlap, injected bunch length vary, bunch train weights. This is very helpful to minimize actual beam commissioning time, saving the beam study only for final commissioning.

TOP OFF INJECTION COMMISSIONING AND OPERATION

Once top off injection application was tested in virtual machine, various parameters were optimized and the model was transitioned to beam commissioning from simulation inputs to hardware control system inputs. Besides all the PVs connection properly, it also verify hardware function, beam quality, top off injection application reliability and how to handle extreme condition, such as very high or low required injection charge since the injector optimized working charge range is limited, injection fail, etc. This part will show injection charge control, FPM and DCCT signal noise, lifetime limiter to make beam test efficient, booster main power supplies in sleep mode, injection transition and top off operation.

Injection Charge Control

Top off desired injection charge depends on DCCT current change and FPM bunch charge. The injection bunch length also varies, depending target bucket number. To get the actual injection charge following the desired charge, the gun charge change with voltage and bunch train length was studied in details. It was implemented as a lookup table, following the insertion device lookup ideal. With different desired charge and bunch train length, the gun voltage was adjusted by top off injection application. The injector was also optimized for good transfer efficiency. In Figure 2, it shows the desired charge from top off injection, actual charge in LTB and BTS transfer line. It can see that the charge at the end of linac follows desired charge well and the transfer efficiency from LTB to BTS is ~80%.

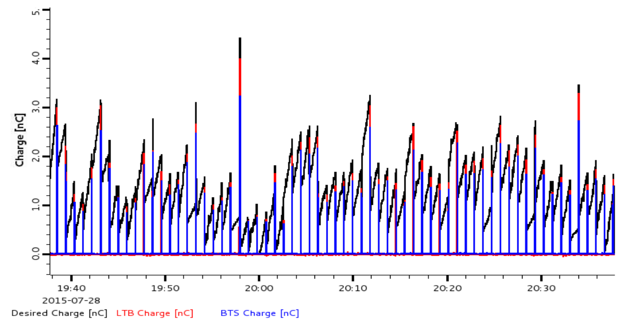

Figure 2: Desired charge and actual charge transfer.

FPM and DCCT Noise

As the required injection charge depends on FPM and DCCT reading, top off injection requires them to have stable charge reading to get feedback loop stable.

FPM sampling rate is 8 GHz with 1 M sampling length, which is 47 turns. Each bucket (2 ns), includes 16 sampling points. The initial filling pattern monitor processes raw voltage data to bunch charge by finding the peak value to separate different bucket. It has the disadvantage that single point value is noisy and bucket charge reading jumps with time. To improve this, each bucket was selected from peak value, then the same bucket from different turn raw data was average over 47 turns with their absolute sum value to get bucket relative charge reading. The absolute charge reading from FPM is dynamically calibrated with DCCT charge reading. FPM charge reading is improved from 10% down to 1%.

DCCT has two current ranges, 200 mA and 2 A. DCCT system was calibrated with no beam for all ranges using a DC current source in lab test. During top off injection study, it was observed that in 2A range DCCT accuracy is highly dependence on fill pattern, which reflected that the injection efficiency depends on target bucket number in SR. This was confirmed with BPMs sum signal and fixed by replacing electronics part.

Lifetime Limiter

During initial top off injection beam test, the stored beam current was set to 130 mA (it is about the machine allowed current), where the nominal beam lifetime is ~10 hrs. This means the injection period is 3 mins and there are 20 shots per hour, which only inject beam pass through SR two layers. It took a long beam study time for beam current, especially the bunch filling pattern converge and made the top off injection parameters optimization process hard, even they were optimized in the virtual

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machine. Lifetime limiter was introduced to speed up top off injection optimization by lowering the beam lifetime on purpose. First RF voltage was lowered than nominal to limit longitudinal aperture. Second, vertical scrapers were moved in to introduce transverse aperture limit, under the condition that it will not affect beam injection efficiency. The beam lifetime was still longer than 3 hrs. Then the bunch filling pattern was changed from 1000 buckets to 500 buckets to increase each bunch charge two times larger. The beam lifetime was lower to 3.6 hrs for top off injection, so that the injection period was close to once per minute.

Booster Main Power Supplies in Sleep Mode

The injector should be in operation state during top off injection. From device long term lifetime view point, it is not preferred for Booster main PSs in 1Hz ramping mode. Besides, it is also observed that booster main PSs ramping 1 Hz affect SR beam motion, even it is mostly suppressed by fast orbit feedback system. To solve this issue, there is a choice to make booster in sleep mode through timing control system. The booster PSs will wake up a few seconds (adjustable) before injection, while in between, they are hold in low DC current.

Injection Transient

NSLS II injection straight [3] has four fast kicker magnets to form a local bump for stored beam during injection. The pulsed magnet errors, from amplitude, timing alignment and waveform mismatch will make local bump leak and excite residual betatron oscillation. The amplitude and timing delay was aligned with beam dynamically [4], but studies showed that the bottleneck of residual oscillation is limited by pulsed magnet waveform mismatch, which requires mechanical adjustment of pulser.

Figure 3 shows SR beam one BPM turn by turn residual oscillations due to injection bump distortion. The amplitude is ~ 2mm in X plane and ~ 0.4 mm in Y plane (coupling and pulse magnets tilt error). The oscillation amplitude decays to 10% after 250 turns and stabilizes to nominal level in 1000 turns. The total disturbance lasts ~ 1.8 ms.

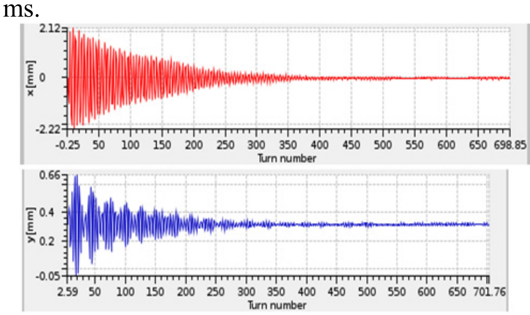

Figure 3: SR beam turn by turn residual oscillations due to injection bump distortion.

It is very difficult to have top off injection process fully transparent for beamlines. Besides the countdown signal for next injection, the precise injection timing trigger signal was also provided so that beamlines have the choice to gate the top-off injection process. The feedback from operation beamlines are that some beamlines can see the injection effect, but it is acceptable for their experiments while others do not care about the transition.

Operation

From top off injection demonstrated to top off operation, it took a few days to verify top off safety system [5]. Top off routine operations started on October 1, 2015 at 150 mA. Now the beamline operation beam current is 250 mA with 10 hrs beam lifetime, as shown in Figure 4. The beam current can maintain within 0.5% well except the injector down period. The top off injection reduces and maintains the bunch charge deviation to an average of 15%, except the a few buckets in head and tail of bunch train, which is determined by injection pattern and cannot be compensated with multi-bunch train injection.

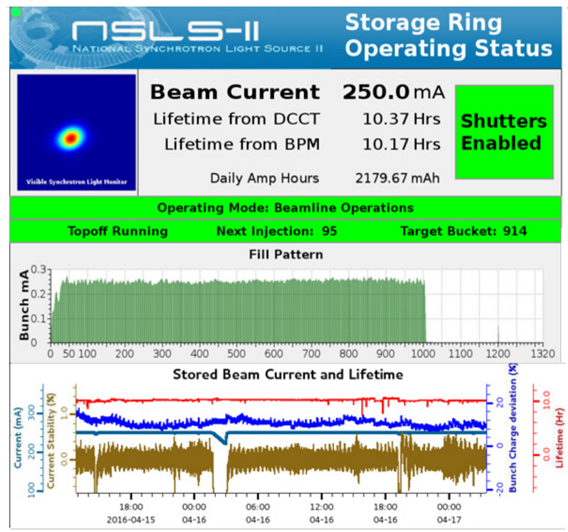

Figure 4: SR Top off operation status.

CONCLUSION

Top off injection has been commissioned successfully with various hardware issues solved. The beam current stability and bunch to bunch charge variation were well within specification. Routine top off operation for beamlines started in Oct. 2015 and operation beam current was upto 250 mA.

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