TOP OFF ALGORITHM DEVELOPMENT AND COMMISSIONING AT NSLS-II*

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Abstract

Recently, NSLS-II introduced top off as the standard mode of beam delivery for the users. During top off, we are required to maintain the beam current within ±0.5% of nominal, and the bunch to bunch variation over the train less than 20% for all operating conditions. In this paper, we discuss the algorithm used for top off, simulations of various operating conditions and performance of the algorithm during operations.

INTRODUCTION

On September 22, 2015, Top Off operation was successfully demonstrated for the first time at NSLS-II. [1] Operations with top off started on October 1, 2015 after testing the controls over the summer and in studies leading to operations. [2] It is now the standard operating mode for NSLS-II. In order to meet user requirements, the beam current must remain within ±0.5% of the nominal, and the bunch to bunch variation over the train must remain less than 20% for all operating conditions. In this paper, we discuss the algorithm used for top off with simulations, and the performance of the algorithm during user operations.

TOP OFF REQUIREMENTS

The specifications for top off operation are given in Table 1.

Table 1: Top Off Specifications

Parameter	Value
Current	500 mA
Charge	1.3 µC
RF buckets	1320
Number of Bunches	1000
Lifetime	3 hrs
Beam Current Stability	±0.5%
Bunch to Bunch Charge Variation	<20%
Min time between top off injections	1 min
Required Charge per Injection	7.3 nC

These requirements can be quantified in the following way. Assuming that the beam lifetime is dominated by Touschek scattering with a lifetime of τ at the nominal current, the change in the stored charge after some time Δt_{inj} is:

$$\frac{\Delta Q_{ring}}{Q_{ring}} = 1 - \left[1 + \frac{\Delta t_{inj}}{\tau}\right]^{-1} \leq 0.005 \quad (1)$$

This equation indicates how much charge must be injected every top off shot, and the maximum time between injections. For NSLS-II design parameters of a 3 hour lifetime at 500 mA, this requires 6.6 nC every 54 seconds.

The next consideration is the total amount of time allowed to top off all bunches in the ring. Consider any bunch in the storage ring immediately after it has received charge in a top off injection. This bunch will be injected into again a time Δt_p later, and by that time the charge in that bunch will decay.

$$\frac{\Delta Q_{bunch}}{Q_{bunch}} = 1 - \left[1 + \frac{\Delta t_p}{\tau}\right]^{-1} \leq 0.1 \quad (2)$$

Equation 2 states the pass time Δt_p is the maximum amount of time one has to inject into all of the bunches in the ring, and defines the lower limit on the bunch to bunch charge variation. This is 16 minutes for 500 mA and a 3 hour lifetime.

The pass time and injection period can be used to determine the minimum number of bunches to inject each shot. The ratio of the total number of bunches in the ring N_b to the the number of bunches injected each shot N_{bi} is the ratio of the pass time to the injection period.

$$\frac{\Delta t_p}{\Delta t_{inj}} = \frac{N_b}{N_{bi}} \quad (3)$$

For 1000 bunches in the ring, this means at least 57 bunches must be injected every top off injection. Increasing N_{bi} will lead to a reduction in the pass time, and a subsequent improvement to the bunch to bunch charge stability

We note that these equations are generic and independent of the actual bunch pattern in the ring or the method used to govern top off injection.

TOP OFF ALGORITHM

The simplest way to implement top off is to use equations 1-3 to specify the charge, number of bunches, and injection period for the injector, and then step through the bunch train in the storage ring. Presumably, the number of injected bunches is a divisor of number of bunches. This approach does not account for several issues which may arise, for example:

- Beam losses through the injector chain
- Storage ring injection efficiency
- Uneven fill pattern at the start of the fill
- Changes in lifetime
- Bunch train shape from the injector

The NSLS-II top off algorithm uses a fixed injection period determined via the beam lifetime, or an expert selected override value.

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There are two feedback loops to determine the charge to request from the injector each shot. The first loop is a proportional/integral loop on the total ring charge. This loop has the largest gain and is sufficient to maintain the ring current stability. However, it makes no compensation for irregularities in the bunch pattern. Therefore, the second loop is a proportional loop on the charge in the target bunches. This second loop reduces the time necessary to even out irregularities in the bunch train, and has a gain of less than 1.

The remaining parameter to set is the number of bunches to inject. One could set N_{bi} to a convenient divisor of N_b, as long as Equation 3 is satisfied. Then all one needs to do is starting at the front of the train inject N_{bi} bunches, choose $N_{bi}+1$ as the next target bunch, and continue every injection period until the entire train has been topped off.

However, if the bunch train delivered from the injector is not uniform, as is the case for NSLS-II, then this pattern gets written on the fill pattern in the storage ring. Figure 1 shows the bunch train delivered from the injector measured at the electron gun, both transport lines, and upon injection into the storage ring. Clearly, no matter what the loop gains are, it is not possible to produce a uniform fill pattern with this train.

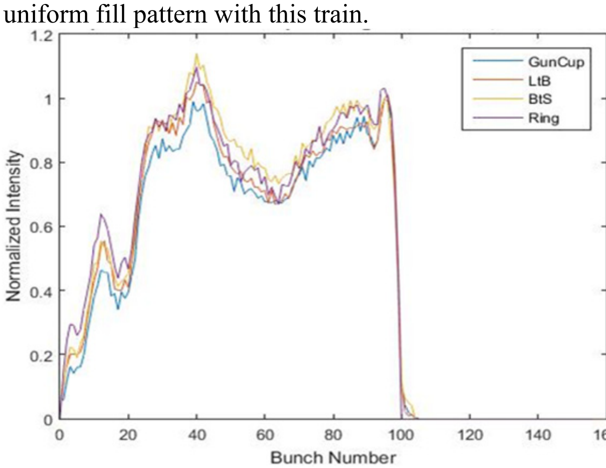

Figure 1: Injector bunch train envelope at various locations in the NSLS-II.

The solution to this problem is to ensure that the target bunches in the ring see high charge injector bunches as often as low charge injector bunches. The way this is done is to select N_{bi} to not be a divisor of N_b. This way, when the end of the ring bunch train is reached, all N_{bi} bunches will not be needed to finish the train. The Nbi bunches are split into 2 injections, one at the tail, and one at the head of the train, one machine cycle apart. For example, Nb=1000, we choose Nbi=102. Starting at the front of the train, after 9 injections the target bunch is 919. Only 81 bunches are needed. The next two injections are then 81 bunches, and then 21 bunches at the head of the storage ring train, three seconds apart. The next target bunch is then bunch 22. This effectively precesses the injector pulse through the ring bunch train. When the bunch train injected into target bunch 1 returns to Nbi, this is called a supercycle.

To further ensure that the train remains flat, the number of bunches injected varies between 101 and 109 each supercycle. This further ensures over the course of many hours or days that the same bunches are not targeted by the low charge injector bunches.

This is sufficient to make the ensure train flat, except for the first 30 bunches in the storage ring. These bunches will always receive low charge bunches from the injector. The feedback loops will attempt to compensate for this by increasing the amount of charge in these bunches. This lead to an increase in the charge per bunch in the bunches immediately after these 30 bunches, and in the tail of the train. Therefore, a system of weights was implemented that reduced the effect of these 30 bunches on the feedback. These bunches are also not counted in the bunch to bunch charge variation.

SIMULATIONS

A MATLAB simulation was written to show that this feedback scheme would work on the real machine. A series of simulations where performed to understand the optimal gain settings of the feedback, and show that the feedback loops work under a variety of conditions such as diagnostics noise, low injection efficiency, variation in the bunch train, missed shots from the injector, uneven fill patterns, low lifetime, etc.

Figure 2 shows the current stability for a 1000 bunch, 250 mA fill with a 6 hour lifetime. The current stability remains within +/-0.5% with short excursions caused by the head/tail shots described above. The initial dip in the current occurs as the integrator error builds to its equilibrium value. The average charge per shot is 3.5 nC, in agreement with equation 1, once injection efficiency is taken into account. Bunch to bunch deviation is 14%.

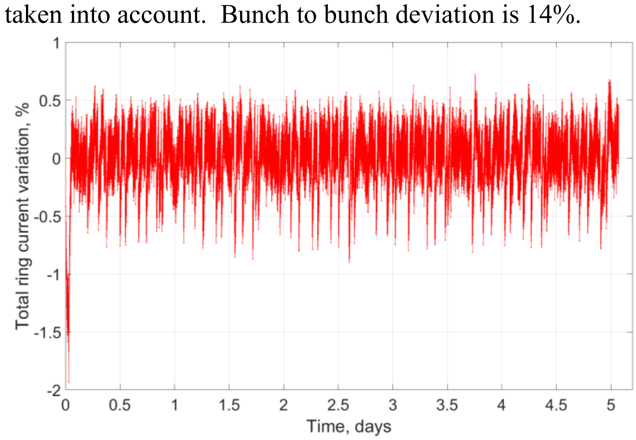

Figure 2: Simulation of beam current stability over 5 days of top off operation.

TOP OFF OPERATION

After an initial period of commissioning, tuning, and testing, top off entered operation on October 1, 2015. Since that time, top off has run for user operations with beam currents ranging from 150 mA to 250 mA, and for beam studies up to 400mA. Figure 3 shows the current stability in top off during a 5 day period which included a single beam dump. The deviation is high at the start of

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the fill due to the uneven filling pattern generated by the operators. The top off program reduces the charge deviation to an average of 15% and maintains it for the duration of the fill. The current was 150 mA during this period.

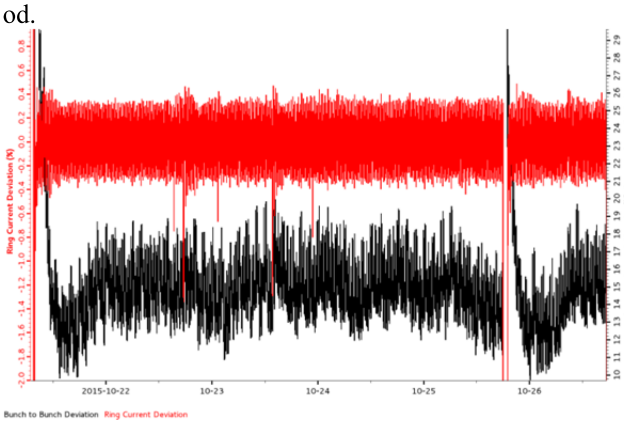

Figure 3: Beam Current stability and Bunch to Bunch deviation during 5 days of top off operation.

Figure 4 shows the injector performance during the same period. In the figure the black line are the charge form the linac, grey input to the booster, blue is booster injection, and magenta is the charge transported to the ring. The injection period is 144 seconds, which is adequate for the 9 hour lifetime. The required charge is 2 nC/shot to maintain conditions with 100% efficiency from the gun. One can see that top off is compensating for variations in the bunch train, injection efficiency, and transport effecieny through the injector chain.

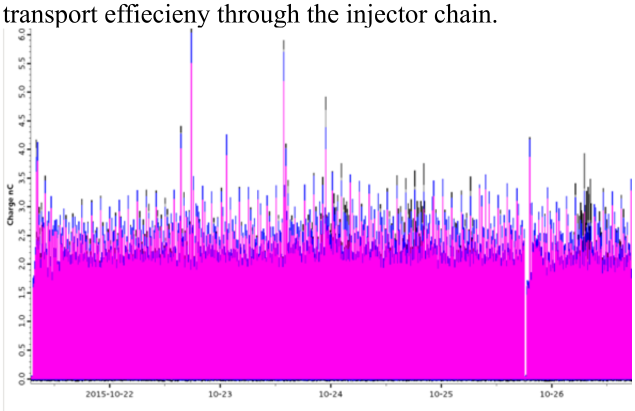

Figure 4: Injector Performance during top off operation. See text for color code.

ADDITIONAL USES

The implementation of the top off algorithm is such that it is easily extendable to additional modes of injection. Since the initial commissioning and use of top off, we have added two additional modes for the top off program, "prepare" and "fill".

As evidenced in Fig. 3, the initial fill pattern in the storage ring was not uniform and required a number of hours to improve the train uniformity. By changing a number of top off parameters, we can have a mode of operation which performs a rapid series of injections with short bunch trains, 20 bunches, to increase the charge in bunches below the required charge per bunch. The feedback loops on the total ring current have their gains set to zero, and the proportional loop on the target bunches has increased gain. This way, top off only looks to fill in any holes to even out the pattern. This mode is called "prepare" mode. It has also proved useful when increasing current during operations, or for restoring the beam current if the injector goes down temporarily.

The other new mode for the top off program is "fill". Originally fills were performed using a 20 bunch train from the injector. This was done so as not to imprint the bunch train from the injector onto the train in the ring. This limited the current from the injector to 3 nC/shot and required at least 15 minutes to fill the storage ring to beam currents over 200 mA. If the operators were not careful in choosing the charge from the gun, the fill pattern could have a large step in it. Again by modifying the top off parameters, we can use the top off program to fill the ring much faster with increased uniformity of the train. The precession scheme has proved it can even out the effect of the injector pulse, it is merely necessary to implement it for filling. Again the feedback loops on the total beam current have zero gain, and the target bunch feedback has increase gain. Using fill mode, presently it is possible to fill the ring in 8 minutes limited by the total charge that can be captured and the extracted from the booster. The bunch to bunch deviation is sufficient that a prepare cycle is generally not needed and normal top off cycles can begin. Additional improvements in fill mode will be implemented next run to reduce the fill time even further.

CONCLUSION

Top Off operation has been successfully implemented at the NSLS-II. We have shown the basic requirements that the algorithm needs to meet. A proportional/integral loop on the beam current and a proportional loop on the charge in the target bunches combined with a precession scheme to choose the injection location are used to select the bunch train charge and length from the injector. Simulations show the algorithm robust under a number of operating conditions. We have shown in normal operations that top off can successful maintain the required parameters at a variety of beam currents. The implementation's flexibility has been exploited to further improve operations with additional modes.

REFERENCES

[1] R. P. Fliller III, et al. "The NSLS-II Top Off Safety System" presented at the 7th Int. Particle Accelerator Conf. (IPAC'16), Busan, Korea, May 2016, paper WEPWO059.
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