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# TOP OFF OF NSLS-II WITH INEFFICIENT INJECTOR*

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*Abstract*

The NSLS-II is a 3 GeV storage with a full energy injector capable of top off injection. The injector consists of a 200 MeV linac injecting a 3 GeV booster. Recent operational events have caused us to investigate 100 MeV injection into the booster. As the booster was not designed for injection at this low energy, beam loss is observed with this low energy booster injection. This beam loss not only results of overall charge loss from the train, but a change in the overall charge distribution in the bunch train. In this paper we discuss the performance of injecting into the storage ring with the inefficient charge transfer through the injector. The changes to the top off method are discussed, as well as the achieved storage ring current stability and fill pattern.

## INTRODUCTION

The NSLS-II is a 3 GeV electron storage ring with a full energy injector consisting of a 200 MeV linac and 3 GeV booster. The linac is designed to operate powered by two klystrons with a third serving as a hot spare to ensure that the linac always has sufficient energy to inject into the booster. The booster was designed to have a minimum injection energy of 170 MeV to ensure that there was some margin at injection for lower linac energy.

Recent operational events required that the linac operate with two klystrons with no spares. In this scenario, the failure of one more klystron would leave the linac with insufficient energy to inject into the booster. Therefore we embarked on a program to see if the booster was capable of injecting with 100 MeV beam from the linac, an energy within the reach of the linac operating on one klystron. This is the subject of [1] in these proceedings. A result of this is that although it is possible to inject into the booster at 100 MeV, the injection efficiency is on the order of 40%, where 80% or more is typical. Additionally the bunch train that exits the booster is distorted from the injected train.

The next question to be answered is can the NSLS-II be filled and operated in top off mode with the injector operating in this state. This is the subject of this paper.

## PRESENT TOP OFF OPERATION

The NSLS-II has operated in top off since the fall of 2015. The general parameters and algorithm used can be found in [2]. In brief, the NSLS-II presently operates at 375 mA, with a design of 500 mA. The lifetime is approximately 6 hours. The beam current variation is required to stay less that ±0.5%, with the bunch to bunch variation less than 20%.

Injections should not be more than 1 per minute, as requested by users, though injection rates up to 1 per second are possible. The injected charge is limited to 30 nC per minute by two safety current transformers, one in the linac to booster transport line and one in the booster to storage ring transport line. [3]

To achieve this performance at 375 mA, the linac produces an average of 6.3 nC per 100 bunch train. The charge transfer efficiency from the linac exit to the storage ring is 77%. The storage ring injection efficiency is typically 90%. The actual charge and train length requested of the linac is subject to the top off algorithm.

Injections occur approximately every 140 s for a 6 hour lifetime. This injection frequency is determined by the time it takes the storage ring current to decrease 0.5%

When injecting into the ring, the top off algorithm moves along the bunch train. However, the bunch pattern generated by the linac gun is not uniform. This is due to limitations of the linac gun pulser. In order to meet the requirement that the ring fill pattern remain flat, the injection locations in the ring precess so as to smear out the nonuniformities in the train form the injector.

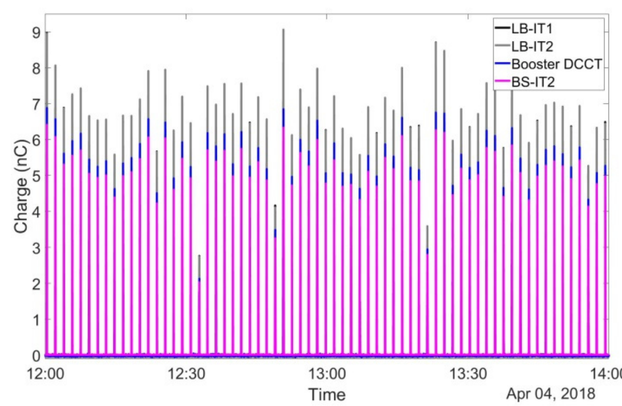


Figure 1: Typical injector performance during a 2 hour top off period. Explanation of the graph in the following text.

Figure 1 shows the typical injector performance during top off. The black trace shows the charge at the exit of the linac. The grey trace is the charge at the entrance to the booster, it almost covers the black trace. The blue trace is the charge at the booster injection porch. The magenta trace is the charge at the entrance to the storage ring.

The same logic that tops off the storage ring also does the filling of the ring. Typical filling times can be less than 4 minutes after the initial injections and corrections.

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## 100 MEV INJECTOR OPERATION

When the linac is operated at 100 MeV, the resulting beam emittance and energy spread are twice the usual value because there is less adiabatic damping in the linac. The booster was designed to accept a beam from the linac with an emittance or energy spread twice the linac design values of 70 nm and 0.5%. However, the addition of the two is such that the beam fills the booster physical aperture. Careful tuning is necessary to achieve the maximum amount of charge from the injector. As Reference 1 shows, when the linac produces 8 nC per shot, 1.6 nC per shot is achieved in the booster to storage ring transport line. Most of the losses are at booster injection.

In addition, and as importantly for filling and top off performance, the bunch pattern that exits the booster is not the same as what exits the linac. Figure 2 shows the bunch pattern measured with fast current transformers (FCT) in each transport line. The black trace is from the first FCT after the linac. It shows the nominal bunch pattern generated by the linac. Under standard operating conditions, this is the bunch pattern that is transmitted to the ring. The grey trace is the bunch pattern at the end of the linac to booster transport line with the energy slit inserted. The energy slit is inserted to the point that the total current successfully injected into the booster is not affected, yet some of the losses are captured prior to the booster. The magneta trace is the bunch pattern in the booster to storage ring transport line. This is what is injected into the ring. Approximately 40 bunches of 100 are completely lost.

This change in the overall bunch pattern has implications to how flat the resulting fill pattern in the storage ring is, and what modifications to the top off algorithm are needed to maintain a uniform fill in the

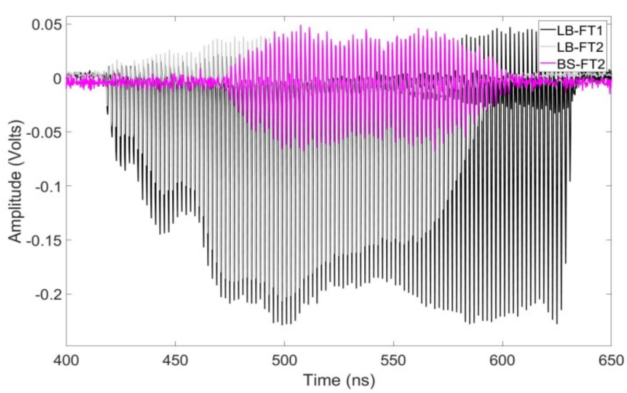


Figure 2: Bunch Pattern from injector during 100 MeV operation. The color code matches Figure 1. The horizontal position of the grey and magnet trains are aligned manually relative to the black.

storage ring.

## STORAGE RING FILLING

A typical storage ring fill to 375 mA (990 nC) under nominal operating conditions lasts approximately 3 minutes. The linac produces 7.5 nC per shot in 100 bunch trains at 1Hz. The booster delivers 5.6 nC per shot to the ring. The resulting fill pattern is 1000 bunches long and has a bunch to bunch variation of ~17%. This variation ignores the first 30 and last 10 bunches of the train which cannot be adequately flattened by injector train.

A fill with 100 MeV booster injection lasts approximately 13 minutes with the linac delivering 8 nC per 100 bunch shot at 1 Hz The booster delivers 1.6 nC per shot to the ring. The resulting fill pattern is 1000 bunches long and has a variation of ~52%, which ignores the first 30 and last 10 bunches. Figure 3 shows, the filling pattern has a slope over the first 80 bunches. If the first 80 bunches are ignored, the filling pattern has a uniformity of 18%. In order to achieve this pattern, it was necessary to tell the top off program not to fill bunches 1 through 40. If the top off program attempts to fill these bunches, it cannot as these bunches are lost, and the result is a huge hump at the start of the bunch train in bunches 40 through 80.

Figure 3 compares a filling pattern with 100 MeV top off to a filling pattern under nominal operating conditions, but lower current. Even though the uniformity is the same for the majority of the bunch train, the 100 MeV pattern has ripples with a longer period than the nominal conditions.

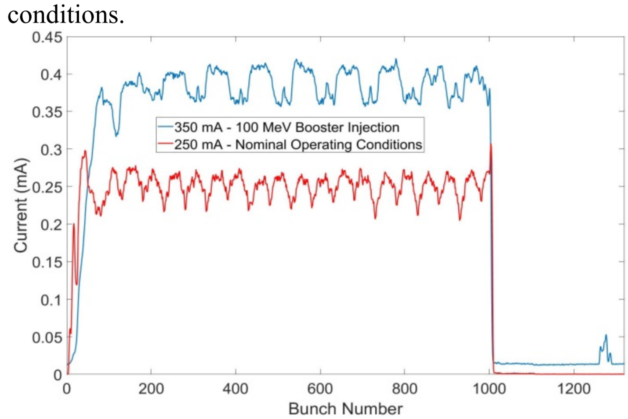


Figure 3: Filling pattern in the ring using 100 MeV booster injection vs nominal operating conditions.

## TOP OFF

As mentioned above, typical top off injections occur every 140 s with an average of 5 nC per shot delivered to the ring. Under nominal circumstances, the injection period is determined by the lifetime and the charge is determined from a proportional-integral loop on the ring current and a proportional loop on the fill pattern. In order to precess the injector bunch pattern around to smear out its structure on ring fill pattern, shorter trains are injected at the ends of the storage ring train. Because the injector is limited in charge, and the bunch pattern is significantly different, a number of questions arose about the feasibility of topping off in this mode.

Since the injector is limited in charge, injections need to be more frequent than once per minute in order to maintain the total ring current. For a 6 hour lifetime, injections are required every 35 seconds if the injector is limited to 1.6 nC per shot. However, this leaves no

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headroom in case the lifetime is reduced, or more charge is needed to fill in a hole, the charge from the injector drops, etc.

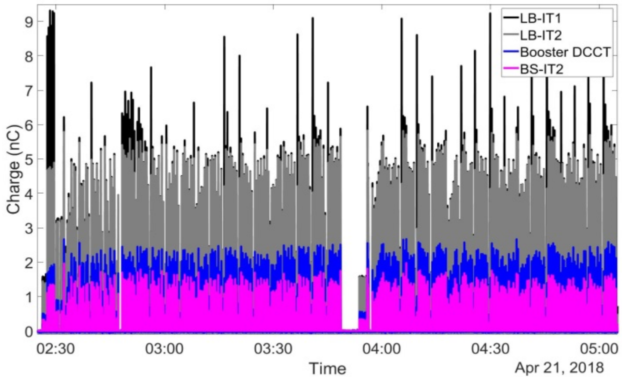


Figure 4 : Injector performance during top off with 100 MeV booster injection. The color code is the same as Figure 1.

Furthermore, the change in the bunch train from the injector is a concern. As the shape of the train is significantly different than the nominal one, the effect of the precession is different, and it may not be possible to flatten out the storage ring fill pattern, or even worse, it may make it less uniform.

Figure 4 shows the action of the injector during a two and a half hour period of top off operation with 100 MeV booster injection. Figure 5 shows the storage ring current in the same time interval. Initially the injection frequency was once per 16 seconds. This was too frequent given the amount of charge coming from the injector and at 02:48, the injection frequency was decreased to once per 22 seconds. At 03:48, injections stop. In fact, top off is attempting to inject a train with 4 bunches, which is not possible in any event. This was traced a parameter that was not properly set. The ring was filled back to 375 mA and top off resumed.

During the time when top off was operating, the current stability was better than 0.25%. This is a function of the increased injection frequency. If the injector was operating normally, the current stability would be similar.


Figure 5 : Storage Ring Current during top off with 100 MeV booster injection. The horizontal lines show ±0.5% of the nominal current.

As mentioned above, the variation of the bunch train current was 18% at the start of the fill for bunches 80 through 970. At the end of 3.5 hours of top off the variation was 14%. More time would be needed to see what that variation settles to, however, it is not anticipated that the periodicity of the ripples on the train decreases because of the way the injector bunch train is moved along the storage ring.

We note that other than not injecting into the first 40 bunches, and increasing the injection frequency, no other adjustments were made to top off settings. We also note that if the injector charge was reduced another factor of two, it may be difficult to maintain top off. This is because the amount of charge produced by the linac would start to be too much for the injection rate limit, even though that charge is lost before it is injected into the ring.

## FUTURE IMPROVEMENTS

There are some paths that may improve the performance of top off in this mode of operation. There is little more that can be done to improve the booster injection efficiency with 100 bunch trains. However, it may be possible to inject shorter trains of 50-60 bunches, as Fig 2 suggests. The shorter trains may be advantageous if they can be extracted from the booster without loosing bunches. This would also automatically change how the injected bunch train moves along the stored bunch train. Even if the overall efficiency is low, the shorter trains can be used to smooth the fill pattern in the storage ring. This would also reduce the losses in the linac to booster transport line and in the booster.

Even with the long trains, it may be possible to adjust how the injected bunch train moves through the stored train to even out the fill pattern. Another route is to reduce the charge that is generated by the linac, and optimize booster injection with a lower charge. This may lead to improvements in train extracted from the booster.

## CONCLUSION

We have demonstrated successful top off operation of the NSLS-II with the injector running in a non-standard emergency mode of operation. The bunch train exiting the injector in this mode is highly attenuated in total charge and number of bunches. We have shown that it is possible to maintain the ring current within specifications if the injection rate limit of once per minute removed. Further improvement may be made if operating in this mode is required.

## REFERENCES


[1] X. Yang, *et. al.* "Development of New Operational Mode for NSLS-II Injector: Low Energy 100 MeV Linac-to-Booster Injection," presented at the 9th Int. Particle Accelerator Conf. (IPAC'18), Vancouver, Canada, Apr.-May 2018, paper TUPMF037, this conference.

[2] R. Fliller, *et. al.* "Top Off Algorithm Development and Commissioning at NSLS-II", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2017, pp.2988-2990.

[3] R. Fliller, *et. al.* "The NSLS-II Top Off Safety System," in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2017, pp.2985-2987.