OPTIMIZATION OF THE NOTCH SYSTEM IN FERMILAB BOOSTER*

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Abstract

The Booster Beam Notch is a beam gap needed to allow extraction kickers to reach full field strength for a single turn extraction scheme. The Notch is created at injection energy by kicking 3 out of the 84 bunches to a dedicated absorber. The kicker voltage, pulse length and geometry of the absorber must be optimized to minimize the beam loss due to the notch creation. Beam studies, simulation and implementation as well as the optimization and improvement of the notch system will be discussed in this paper.

PROTON IMPROVEMENT PLAN (PIP)

The notch system task was one of 35 PIP tasks identified for the Proton Source to address the need to increase proton beam flux. A more than doubling of proton per hour rate is required to meet the Fermilab HEP program. A significant effort to increase the flux went to increase Booster beam cycles from 7Hz to 15 Hz. The doubling of Booster beam cycles consequently would incur increased integrated beam loss at various phases of beam operations, including notch formation and extraction time. Reduction in extraction losses and better managed notch formation losses need to be optimized [1].

THE SWITCH FROM VERTICAL TO HORIZONTAL NOTCH SYSTEMS

A dedicated absorber was designed and then installed in the Booster ring, in the 2012/13 upgrade maintenance period, to contain the notched beam (Fig. 1). The kicking plane was changed to the horizontal plane as there is more aperture to separate notched beam [2]. Previously, notching was achieved with 2 kicker magnets in two different regions of the Booster ring. The kick was in the vertical plane. The kicked beam was deposited into the collimation region and 2 small mask absorbing elements 6 cells away to clean up the tails of the notched bunches. Simulation is seen in Fig. 2a.

This change would reduce the activation levels in the circulating beam collimation region significantly (see on Fig. 2a.) and allow for a more controlled deposition of the removed bunches to create the three-bucket notch in the new absorber (Fig. 2b). Fig. 3 depicts this this new layout.

Initially, the same notching equipment was relocated to the new physical locations in the Booster ring and equipment galleries with the addition of a third old kicker system until the new equipment could be built. Simulations indicated that a third kicker would be needed for the horizontal kick scheme to work at 400-700MeV. The new consolidated power supply system and faster filling magnets where implemented in phases. This Fermilab RR/NOVA style pulser would drive 6 half meter long kickers with two CX2610 thyratrons [3]. This would provide faster fill time than the previous 1.08 meter long kickers and power supply. Our rise time improved by about 10 nsec, giving a flatter notch pulse.

Figure 1: Hor. Notching kickers and absorber.

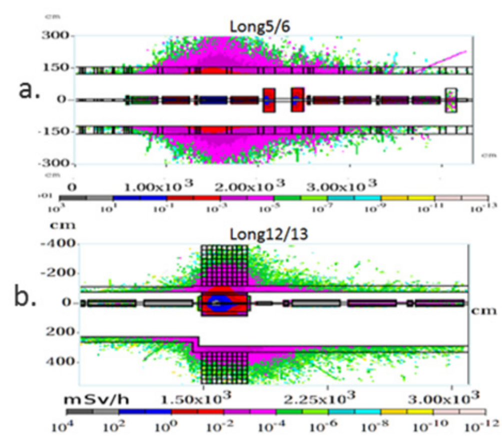

Figure 2: Loss sim. vert. (a) and hor. (b) notching.

Figure 3: Notched beam region.

700MEV TO 400MeV NOTCH

Beam notching was initially implemented in the horizontal plane at two energies, 400MeV (Booster injection) and 700MeV. The later energy was required to establish notch synchronization when utilizing the RF cogging method, required for MI/RR batches 2-12, which could not be initiated earlier than approximately 600-700MeV [4]. With the advent of a new magnetic cogging technique, horizontal dipole corrector magnets are used to achieve this goal thus enabling an earlier notch creation time for the cogged cycles to Fermilab's Main Injector and Recycler Ring [5]. The notch time has been optimized to occur just after recapture of the Linac beam via paraphrase method in Booster. Now all 12 notched beam events are fixed to 400MeV. For a 12 batch MI/ RR injection, this helped reduce the notch losses on the later cogged 11 batches.

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Notching beam early highlighted the fact that the separation between the circulating beam and notched beam was less, due to lower energy and larger emittance beam. There where losses due to broader tails on the bunches. Losses were still lower overall due to the reduced notch beam energy. This required more work on beam orbits to find an ideal operating point.

Beam size and orbit trajectories were simulated. Beam measurements were also made looking at beam position and losses through the notch region and ring wide. We took measurements looking at the kicked bunches using raw BPM data. We could see the effective aperture and relative beam positions of the two beams (Fig. 4).

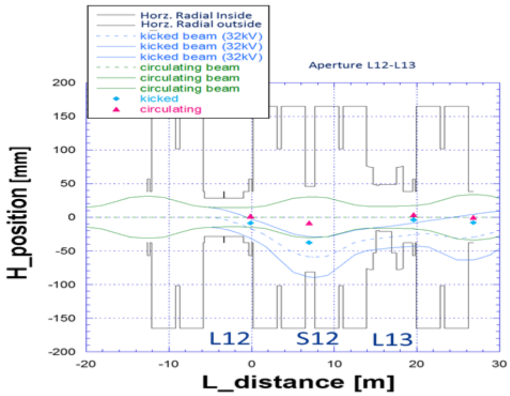

Figure 4 : Notched/circulating beam orbit.

MAXIMIZING APERTURE

The current Booster notching system consists of 6 kicker magnets and associated power supply system designed to remove desired bunches into an absorber jaw (Fig. 4). The betatron phase advance is 102 deg. between the kickers and absorber.

An overall layout of the kicker to absorber region is shown in Fig. 2. Beam is kicked at the Long 12 straight section with the six short kickers (.54m). Beam is directed to the radial outside orbit. Short 12 is where notched particles reach their maximum horizontal displacement (Fig. 5). Aperture is restricted by the maximum bore of the correction element at the Short 12 location. The beam tube aperture was increased in this element by removing the internal standard BPM strip-line plates, and using a wider aperture BPM mounted outside the correction element bore. This correction magnet assembly also was outfitted with 20mm offset spool flanges to allow for greater aperture to the radial outside of ring (Fig. 4). After reaching this element, beam then travels back towards the absorber jaw where it is intercepted at Long 13 (Fig. 4).

Beam data correlated well to the simulations showing most of the desired protons were removed in the first turn but more proton where left behind than desired. We measured the notched beam bunch displacement using BPM signals and scaled this information relative to the circulating beam (Fig. 4). BPM signals show larger amplitude on radial inside plate which is where the circulating beam has been tuned to allow separation for the kicked beam. The kicked bunches are closer to the radial outside plate and show a larger signal (Fig. 6). The next turn of beam shows bunches mostly removed. An envelope was created with measured beam values. We see, in Fig. 7, that for 5 sigma beam, particles were getting past the existing jaw design. A jaw extension was designed to be placed in to the absorber liner/jaw assembly to extend the jaw deeper into the beam path.

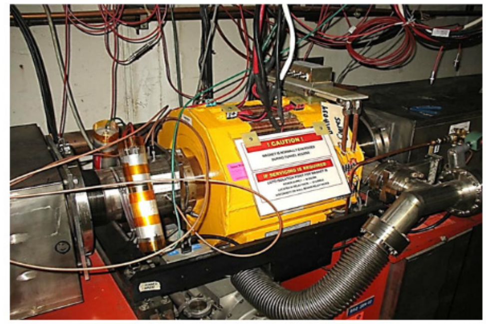

Figure 5 : Modified S12 Booster correction package.

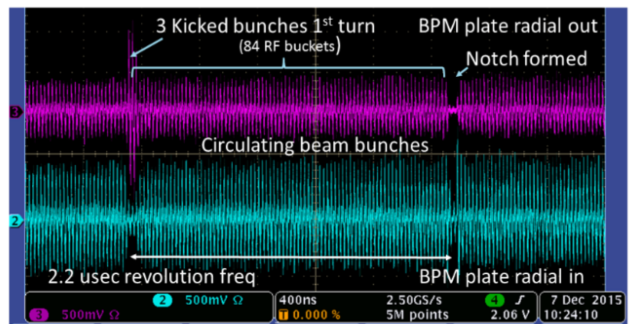

Figure 6: BPM plate signals notch forming.

ABSORBER INSERT EVOLUTION

Over a period of time, inserts were placed in the interaction region of the absorber jaw, with some reduction in notch formation losses. The first insert was placed to help reduce multi-turn losses. This modification included two inserts that created a curtain between the circulation beam and notched region, before the interaction region of the jaw was reached. This attempted to catch kicked bunch tails (Fig. 8). Thus, residual activation was higher than desired for the benefit achieved at the upstream end of the absorber.

In our next effort, we removed half of this curtain insert, and then all of it when the current jaw extension was installed. The current iteration at the jaw extension, Fig. 8, is in the circulating beam region. This would allow us to retract the jaw an additional 50-65mm to achieve more beam separation and better balanced losses at the absorber.

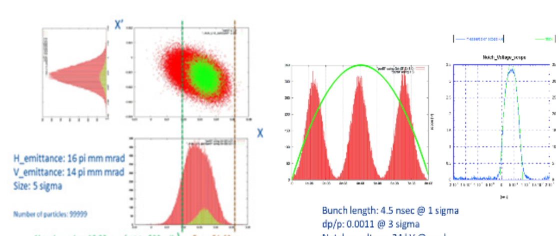

Figure 7: Notched beam particles at absorber.

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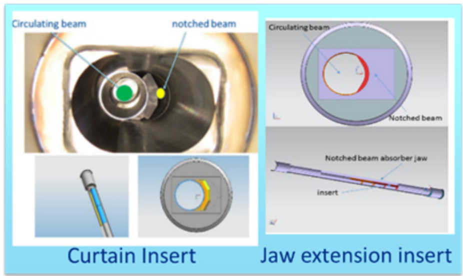

Figure 8: Absorber jaw and inserts.

MULTI-TURN LOSSES

Multi-turn losses are a continuing challenge. Depending on how high we set the notching kicker voltage, we can leave more or less of the three bunches (Fig. 9). We can only kick so hard as to not lose the beam prematurely on the way to the absorber at the S12 location.

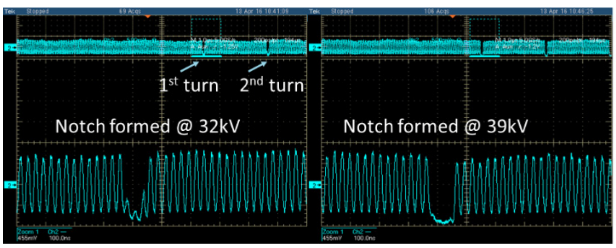

Figure 9: Wall current monitor.

Multi-turn losses can be seen in Fig. 10 as spikes that decay over time. These spikes match the revolution frequency and betatron motion of beam. Raising kicker voltage can reduce the duration and these losses but we are limited by aperture at the S12 corrector.

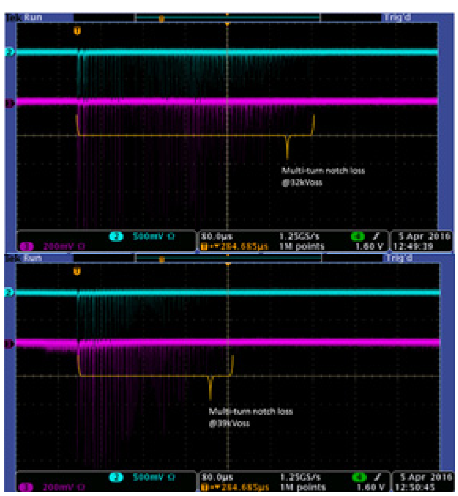

Figure 10: PMT signals near notch formation.

IMPROVEMENT IN PERFORMANCE

Over the various phases of upgrades, we see reasonable losses for the total flux in Booster (Fig.11 &12). Our activation levels around the absorber did increase for a period while we explored the curtain insert (Fig.11). We have since improved on the reduction of upstream absorber losses with the new jaw extension. We continue to strive to match the notched beam orbit with the jaw surface through daily tuning. Optimization for beam energy drift or other orbit variations is critical.

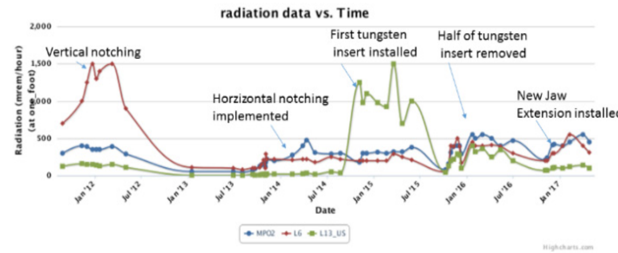

Figure 11: Notch region loss over time.

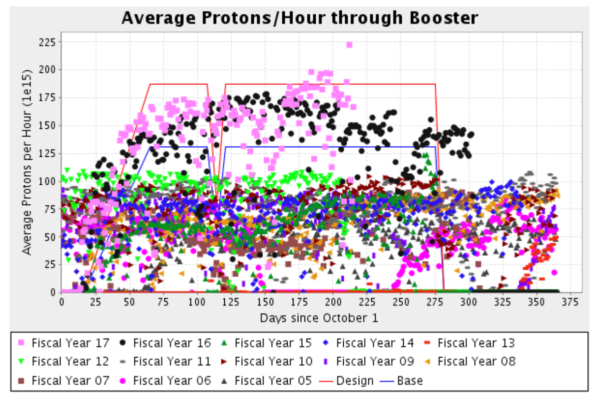

Figure 12: Booster proton flux.

CONCLUSION

Notching in the Booster has been improved over time through various upgrades. Our configuration optimization has continued to yield improvements but is still limited by factors that cannot be completely removed. Beam tube aperture for adequate beam separation is a significant issue that limits improvements of multi-turn losses. A possible option is a bumper magnet that can make a deflection just upstream of the absorber, but room is very limited. We will also soon have a Laser Notching system being commissioned that may remove about 90% of the three bunches before beam transfers to Booster. We will see how well the notch is preserved in the transfer between Linac and Booster. Laser Notching may demonstrate that our notching system will only need to perform a clean-up function and/or full notching function at times Laser notching is unavailable.

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