REUSE RECYCLER: HIGH INTENSITY PROTON STACKING AT FERMILAB*

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Abstract

After a successful career as an antiproton storage and cooling ring, Recycler has been converted to a high intensity proton stacker for the Main Injector. We discuss the commissioning and operation of the Recycler in this new role, and the progress towards the 700 kW design goal.

INTRODUCTION

Fermilab's Recycler is a 3319.4 m circumference permanent magnet ring, installed in the Main Injector tunnel at Fermilab. It consists of strontium ferrite gradient magnets and in the straight sections strontium ferrite quadrupoles. It was designed as a storage ring for antiprotons, and with the use of electron cooling it was a key factor in the delivery of increased luminosity during the later years of the Tevatron operation.

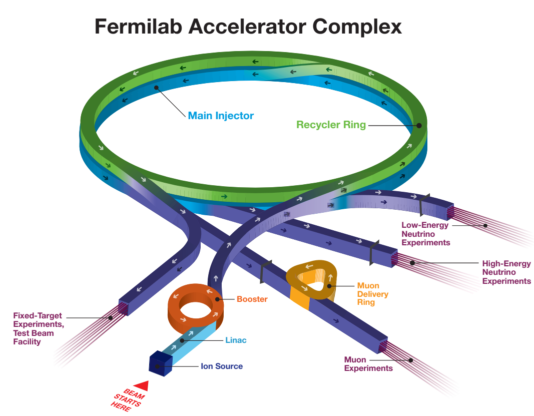

Figure 1: The Fermilab Accelerator complex in the NOνA era.

In a 16 month long shutdown, between May 2012 and September 2013, Recycler was converted for use as a proton stacker as part of the NOνA project [1]. The stochastic and electron cooling systems were removed, the section of ring used for electron cooling was rebuilt with a standard FODO lattice to match the rest of the ring, and the transfer lines used for antiproton transfer between Recycler and Main Injector were replaced with a new transfer line with larger acceptance. A new injection line to accept protons from the Booster was built, a 53 MHz rf system was installed, and new BPM cables and electronics capable of supporting 53 MHz operation was added. The Main Injector loss monitor system was modified to enable it to be continuously active (with Recycler used as a pre-stacker for Main Injector, high-intensity protons will be continuously present in the Main Injector tunnel.)

Recycler's most challenging task is the slip-stacking and delivery of high intensity beam to the Main Injector for NuMI. The NOνA project [2] design goal is for a 700 kW proton beam (48.6×10^{12} protons every 1.333 s.) In addition, Recycler stacks lower-intensity beam for transfer to Main Injector for resonant extraction to Switchyard 120 (the SeaQuest experiment, and the Fermilab Testbeam Facility), and beginning in 2017, it will rebunch protons into 2.5 MHz buckets for delivery to the Muon Campus (first Muon g-2, then μ2e.) In normal operation, roughly 10% of the time is devoted to Switchyard 120, so 630 kW would be delivered to the NuMI target at the design intensity.

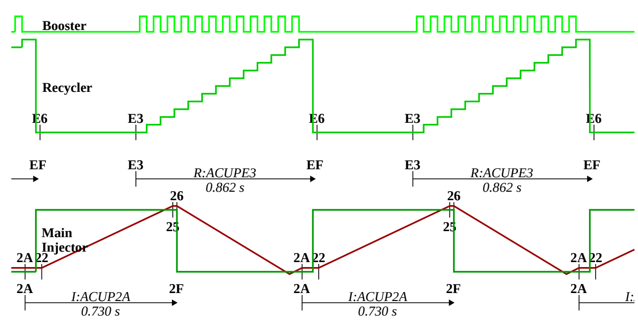

Figure 2: Relative timing of Booster, Recycler and Main Injector cycles for NOνA-era NuMI operation. Beam in each machine is shown in green, and Main Injector momentum in red. The start and end of cycle clock events for MI and Recycler are also shown.

The NOνA upgrade increases the beam power available at 120 GeV principally by reducing the cycle length. By moving the slip-stacking process from the Main Injector to the Recycler, the long front porch is eliminated, and the Main Injector can be kept ramping up and down at its maximum rate. As shown in Fig. 2, the Recycler starts stacking for the next NuMI pulse before the previous pulse has left the Main Injector.

PERFORMANCE OF RECYCLER TO DATE

The NOνA ANU upgrades only provided the capability to transform the Recycler into a high intensity stacking ring. Significant work was required to realize this capability.

Figure 3 shows the NuMI beam power as a function of time since the end of the NOνA shutdown. During the 240 kW period at the start of the plot, the operational beam was

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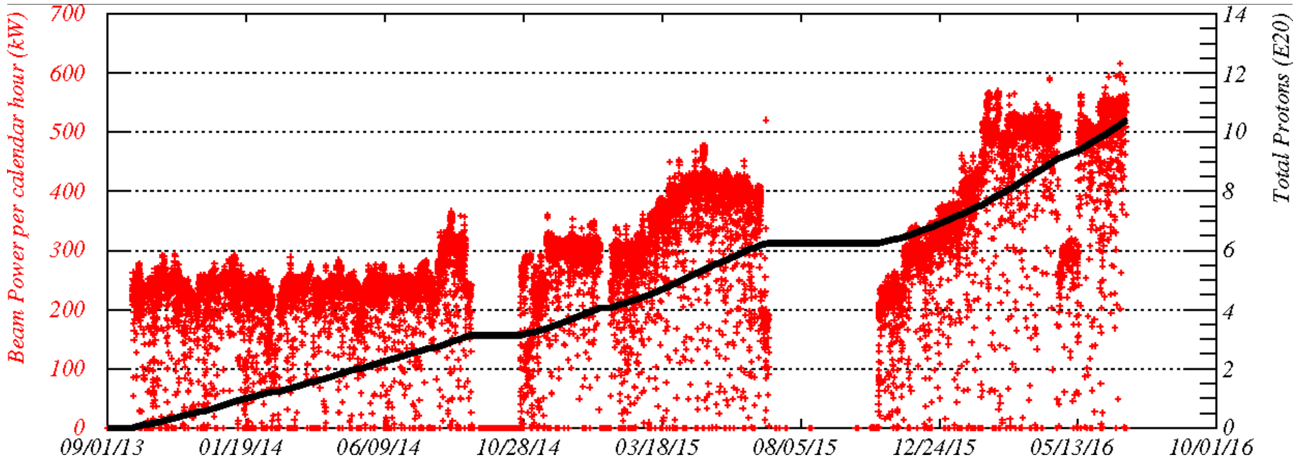

Figure 3: Hourly average beam power to NuMI and total protons delivered. The plot begins with the Main Injector only, at around 240 kW, while the initial commissioning of the Recycler was taking place. The increase to 300 kWbefore the 2014 summer shutdown is provided by the Recycler in 6-batch boxcar mode; subsequent steps to around 400 kW, 500 kW, and finally 550 kW in June 2016 are due to "2+6", "4+6" and "6+6" slip-stacking respectively. The best calendar hour averaged 615 kW, achieved while Switchyard 120 was not operating.

using only the Main Injector. This period contained all the initial commissioning of the Recycler: correction of gross aperture errors, commissioning of rf systems, transverse dampers, and instrumentation, and an initial period of "beam scrubbing". Once it was possible, running 6-batch "boxcar" stacking in the Recycler allowed us to decrease the cycle spacing from 1.66 s to 1.33 s, and increase the power to 300 kW.

Once this was possible, the process of commissioning slip-stacking [3] could begin. We describe the various modes of slip-stacking as "2+6", "4+6", or "6+6": in 2+6 slip-stacking, we inject two batches from the Booster, decelerate them, and allow them to slip against six further batches, producing at the time of recapture (on transfer into the Main Injector) two double-intensity batches and four singles. The initial 2+6 mode allowed us to deliver 400 kW; this was the largest number of batches usable for slip-stacking without an increase in the Booster beam pulse rate.

In order to deliver the design 700 kW beam, it was necessary to upgrade the Linac and Booster to increase the possible proton throughput. These upgrades were performed under the umbrella of the Proton Improvement Plan (PIP) [4–6]. Shortly before the 2015 summer shutdown, Booster became capable of delivering beam at 15 Hz, and so supporting the 4+6 and 6+6 slip-stacking modes.

At this point, we ran the 4+6 slip-stacking mode at 525 kW, producing the unacceptably high per-cycle losses shown in Fig. 4. The next few months were spent systematically improving locations with poor apertures, and conducting detailed measurements of stopbands [7] in the Recycler in order to find a better working point. After these improvements, we returned to 4+6 slip-stacking at 525 kW, achieving beam loss in the ring that was reduced by a factor of close to four, as shown in Fig. 5.

Figure 4: Loss around Recycler for 525 kW operation July 2015.

Following this successful effort, we began studies with the 6+6 mode, culminating in operating routinely at 550 kW during June 2016, with a peak hour at 615 kW and a demonstration of the design beam power of 700 kW (see Fig. 6.)

COLLIMATION

Following our experience in the Main Injector [8], we plan to control the remaining losses associated with beam lifetime with a collimation system. In the 2016 summer shutdown, we will install a two-stage collimator, with a primary scraping foil edge, and two large (20 ton) steel and marble secondary collimators. The system will be similar to that already installed in the Main Injector [9]. The intent is that this collimation system should contain the majority of the losses from Fig. 5. The exception is the loss at the 401-

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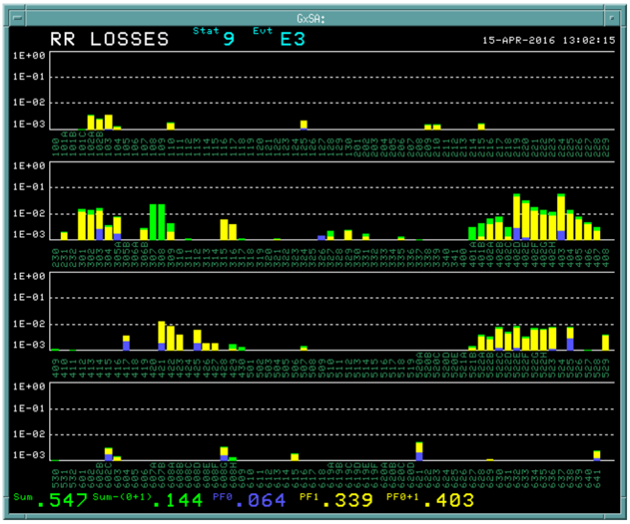

Figure 5: Loss around Recycler for 525 kW operation April 2016.

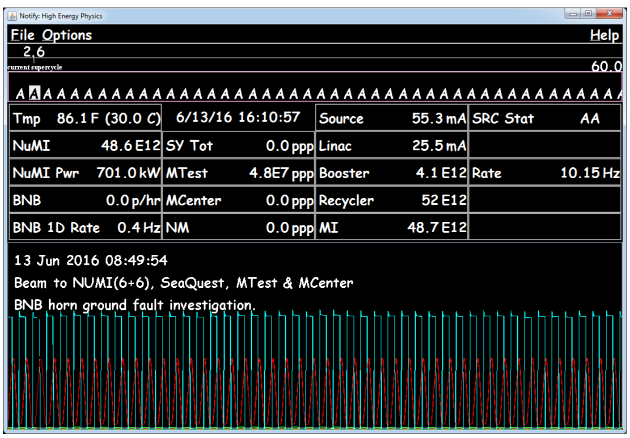

Figure 6: On June 13th, 2016, we demonstrated operation at the NOνA design 700 kW level. Some work remains to be done on loss control before we operate consistently at this level.

402 region: these are single-turn losses caused by tails from the operation of the gap clearing kicker [10] system removing beam from the injection gap, and is directly proportional to the amount of uncaptured (DC) beam present.

The installation of the collimation system is tightly constrained by available space. In order to contain the resultant hadronic shower, the secondary collimator must extend around two feet from the beam pipe in the transverse directions. In most parts of the ring, Recycler is only one foot from the ceiling. There are two locations with high ceilings in the tunnel—where the ring meets the old transfer lines to the Tevatron for protons (locations 523-529) and antiprotons (613-619). The former location is occupied by the new extraction line from Recycler to deliver 2.5 MHz protons to the Muon Campus, so we are led to select the latter.

VACUUM

In its incarnation as an antiproton storage ring, the Recycler vacuum was maintained at ultra-high levels (1×10^{-10} torr or better) with Titanium Sublimation Pumps. This level of vacuum isn't necessary now the beam remains in the ring for less than a second, and the use of TSPs presents some difficulties. Primarily, the titanium in the TSPs is a consumable, and is nearing the end of its life—something must be done. The use of TSPs presents additional downsides: to use TSPs, it is necessary to first bake the beam pipe after breaking vacuum to remove any adsorbed water. The heater tape for the bake-out is also reaching the end of its life, and would need to be replaced wholesale were this capability to be required; the requirement to bake also adds an extra week or so to the overhead associated with breaking vaccum.

We choose instead to convert the Recycler to a fully ion-pumped design, adding two additional ion pumps per half-cell to match the vacuum design of the Main Injector. A total of 600 pumps mus be installed. To minimize the required cutting and welding, and subsequent alignment work, we cut into the TSP cans themselves and weld on vacuum ports. In the three-month 2015 summer shutdown, we were able to complete about a third of the ring. An additional third will be completed in each of the 2016 and 2017 shutdowns.

RECYCLER FAST HORIZONTAL INSTABILITY

As previously reported in [11], when we started operating the Recycler to deliver beam to NuMI, in August 2014, we observed at high intensities a fast horizontal instability in the few hundred machine turns after injection, with a growth rate of 10-15 machine turns. The instability, shown in figure 7, is only driven in the horizontal plane—at our normal operating point, there is some coupling of this motion to the vertical plane. It has a strong dependence on linear charge density (bunch length). With such a rapid growth rate, the transverse damper system is unable to control the instability.

This is a single-batch effect: the instability only affects the newly-injected batch, and does not transfer to other batches already in the machine. In fact, existing beam in the machine provides extra stability. In August 2014, the intensity threshold for the instability was observed to be around 25% higher when injecting into a machine which already contained one or more batches of beam than when injecting into an empty ring. The stabilizing effect depends only on the total number of protons already present in the machine—the distribution of those protons into a smaller number of high intensity bunches or a larger number of low intensity bunches is observed to have no effect.

Since the 2014 fall shutdown, the instability threshold was observed to have increased, and no longer occurred for normal operations—either boxcar stacking or slip-stacking at any intensity up to 700 kW. During 2015, it was possible to force the instability to occur by manipulating bunch rotation in the Booster to create shorter bunches, rendering it

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accessible to special machine studies. In 2016, after additional ion pumps had been installed in a third of the ring, and higher-intensity beam had caused additional "scrubbing" of the beam pipe and reduced the secondary electron yield (SEY) [12], we are no longer able to generate the instability.

We have identified the instability as caused by electron cloud. We have some evidence that suggests the presence of electrons [12,13], and measure tune shifts that are consistent with a model of electron cloud buildup [14]. We assume that a small fraction of the electrons produced in the gradient magnets are trapped in the magnetic bottle formed by the converging magnetic field lines, providing a seed for the electron cloud that persists until the beam passes again on the next turn. This cloud seed would be dispersed by below-threshold bunches, explaining why we were able to run in August 2014 with the second and subsequent batches over the instability threshold, but the first batch under it. We note that this instability seems to share some features with an instability at high field in the CERN PS, also a combined function machine, which has also been identified as due to electron cloud [15].

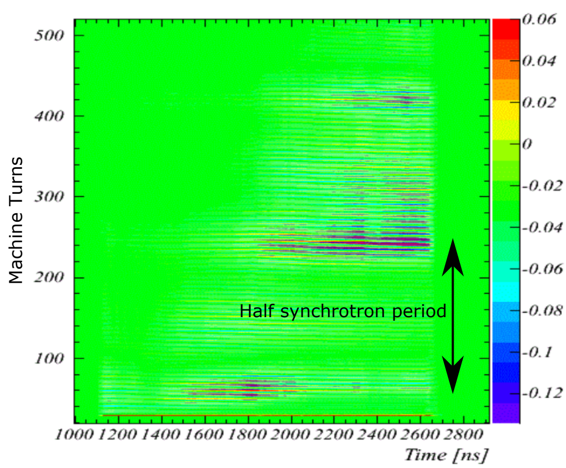

Figure 7: The fast recycler instability in the horizontal plane. The color scale represents horizontal motion, in arbitrary units. Shown is the first injected batch (1.6 μs) for about 500 turns after injection. The incoming beam is not perfectly matched to the rf bucket here, and the instability is seen to occur at bunch length minima, and in the center and the end of the batch.

The instability does not trouble 700 kW operation. We observe that as we increase the beam intensity, we continue to "scrub" the 316L stainless steel beam pipe and reduce its SEY, and so expect that we will be able to increase the per-pulse intensity by some further amount without encountering this instability.

CONCLUSION

Using the Recycler as a slip-stacker for the Main Injector, and running the ultimate 6+6 mode of slip-stacking, we have achieved a consistent sustained performance at the 615 kW level, and have demonstrated operation above 700 kW. A collimation system will be installed in Recycler this summer, which should control the losses at high intensity, and so permit sustained 700 kW operation. The Recycler vacuum system is in the process of being upgraded to be fully ion-pumped, providing a sustainable vacuum system for the future. As we continue to push the beam power beyond the design 700 kW, it will remain important to control the activation of the tunnel components in order to be able to perform maintenance effectively.

REFERENCES

[1] D. S. Ayres *et al.*, "The NOvA Technical Design Report," FERMILAB-DESIGN-2007-01.

[2] P. Derwent, "Accelerators for Intensity Frontier Research," Proceedings of IPAC2012, New Orleans, Louisiana, USA (2012), pp. 4185-4189.

[3] K. Seiya *et al.*, "Multi-batch Slip Stacking in the Main Injector at Fermilab," Proceedings of PAC07, Albuquerque, New Mexico, USA (2007), pp. 742-744.

[4] W. Pellico *et al.*, "FNAL—The Proton Improvement Plan (PIP)," Proceedings of HB2014, East Lansing, Michigan, USA (2012).

[5] K. Seiya, "Booster Upgrade for 700kW NOvA Operations," Proceedings of HB2014, East Lansing, Michigan, USA (2012).

[6] K. Seiya *et al.*, "Beam studies for the Proton Improvement Plan (PIP)—Reducing beam loss at the Fermilab Booster", THPF131, Proceedings of IPAC'15, Richmond, VA, USA (2015).

[7] R. Ainsworth *et al.*, "Simulations and Measurements of Stopbands in the Fermilab Recycler", in Proc. 7th International Particle Accelerator Conference (IPAC'16), Busan, Korea, paper MOPOY010, pp. 864-866, 2016.

[8] B. C. Brown *et al.*, "The Fermilab Main Injector: high intensity operation and beam loss control," Phys. Rev. ST Accel. Beams 16 (2013) 7, 071001.

[9] B. C. Brown *et al.*, "Fermilab Main Injector Collimation Systems: Design, Commissioning and Operation," Proceedings of PAC09, Vancouver, Canada (2009).

[10] I. Kourbanis *et al.*, "A gap clearing kicker for Main Injector," Proceedings of PAC11, New York, USA (2011).

[11] J. Eldred *et al.*, "Fast Transverse Instability and Electron Cloud Measurements in Fermilab Recycler," Proceedings of HB2014, East Lansing, Michigan, USA (2012).

[12] Y. Ji, L.K. Spentzouris, and R.M. Zwaska, "Secondary Electron Yield Measurement and Electron Cloud Simulation at Fermilab", Proc. 6th International Particle Accelerator Conference, Richmond, VA, USA, paper MOPMA039, pp. 629-632,2015.

[13] J. Eldred *et al.*, "Electron Cloud Measurements in Fermilab Main Injector and Recycler," Proc. 6th International Particle Accelerator Conference, Richmond, VA, USA, paper MOPMA026, pp. 604-607, 2015.

ISBN 978-3-95450-178-6

[14] S. A. Antipov, P. Adamson, S. Nagaitsev, and M.-J. Yang, "Study of Fast Instability in Fermilab Recycler," Proc. 7th International Particle Accelerator Conference (IPAC'16), Busan, Korea, paper TUPOR029, pp. 1728–1730, 2016.

[15] R. Steerenberg *et al.*, "Nominal LHC beam instability observations in the CERN proton synchrotron," Proceedings of PAC07, Albuquerque, New Mexico, USA (2007), pp. 4222-4224.

ISBN 978-3-95450-178-6