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HIGH INTENSITY PROTON STACKING AT FERMILAB: 700 kW RUNNING*

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Abstract

As part of the Nova upgrades in 2012, the Recycler was repurposed as proton stacker for the Main Injector with the aim to deliver 700 kW. Since January 2017, this design power has been run routinely. The steps taken to commission the Recycler and run at 700 kW operationally will be discussed as well as plans for future running.

INTRODUCTION

During the long shutdown from May 2012 until September 2013, the Recycler was repurposed from an antiproton storage ring to a proton stacker as part for the NOvA [1] project. The Recycler is a permanent magnet ring consisting of strontium ferrite gradient magnets and strontium ferrite quadrupoles in the straight sections.

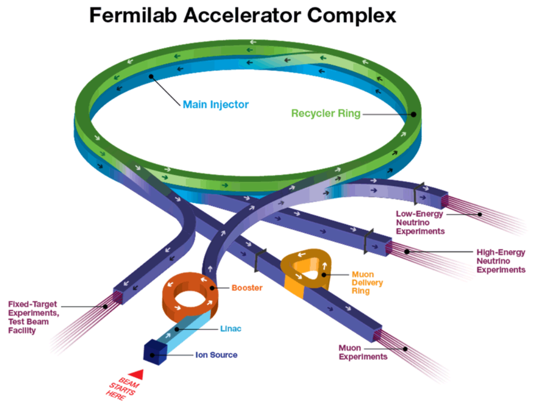

Figure 1: The Fermilab Accelerator complex.

The Recycler performs slip-stacking at 8 GeV which doubles the bunch intensity and then delivers beam to the Main Injector where it is accelerated to 120 GeV and sent to NuMI. The design goal for the NOvA project is for a 700 kW proton beam (48.6×10^{12} protons per pulse (ppp) every 1.333 s.) The recycler also stacks lower intensity beam which is sent to the MI for resonant extraction as well as rebunch protons from 53 MHz buckets to 2.5MHz buckets to be sent to the Muon campus [2].

Since January 2017, the Fermilab accelerator complex (Fig. 1) has been running at the design goal of 700 kW consistently. Some typical Recycler properties for beam sent to NuMI in 2018 are shown in Table 1. This paper will discuss the steps required to reach that goal and will focus on the changes since summer 2016. An outline of the commissioning period from 2013 until 2016 can be found in [3].

Table 1: Typical Recycler Properties for Beam Sent to NuMI

Parameter	RR	unit
Q_h	25.42	
Q_v	24.42	
ξ_h	-6	
ξ_v	-7	
$\varepsilon_{n,95\%}$	15	π mm mrad
$\varepsilon_{L,95\%}$	0.08	eV s
Intensity	51×10^{12}	ppp
V_{RF}	80	kV
Max Beam Power	730	kW (1 hr average)

PERFORMANCE

Figure 2 shows the the evolution of the NuMI beam power since end of the long shutdown in 2013 until April 1st 2018. The power is initially limited to 240 kW in which only the Main Injector is used. Slip-stacking in the Recycler was commissioned in multiple phases as "2+6", "4+6" and "6+6" in which the first number represents that the number of batches that are slipped. "6+6" slip stacking was established just prior to the 2016 Summer shutdown in which twelve batches from the booster are injected into the recycler which are slip-stacked to make six double intensity batches.

Slip-stacking works by injecting 6 batches at the design momentum of the Recycler ring. These 6 batches are then decelerated by Δf = 1260 Hz which is given by the product of the booster harmonic number (84) with the booster cycle rate (15 Hz). Six more batches are then injected on-momentum. The decelerated batches will then slip with respect to these on-momentum batches and when the two sets of six batches are overlapped, they are extracted to the Main Injector. A full Recycler ring contains seven batches, however a gap is needed for injection. The slip-stacking procedure results in beam lost from the bucket due to deceleration and the beating of the two RF systems running at different frequencies. Gap clearing kickers [4] are fired just before each injection in order to abort any out of bucket beam in the gap. In order to damp the resistive wall instability, a bunch by bunch damper system is used which damps the two sets of six batches individually. However, when the batches begin to overlap, this system no longer works as it is unable to resolve the individual bunches position. Therefore with no damper during this time (around the seventh injection),

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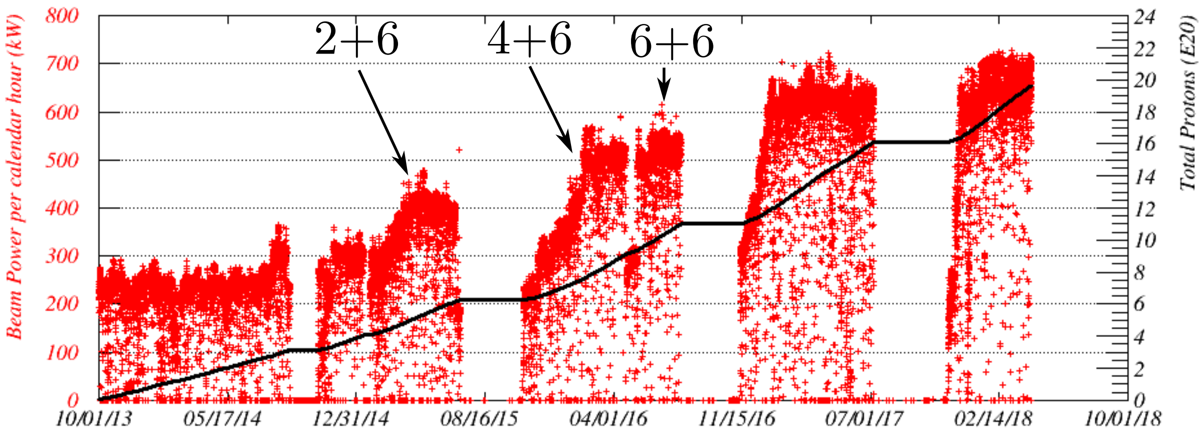

Figure 2: The hourly beam power to NuMI and the total protons delivered since the end of the long shutdown in 2013. The beam power is initially limited to 240 kW when only the Main Injector is used. As Slip-stacking in the Recycler is commissioned, the beam power is steadily increased until January 2017 when the beam power meets the design goal. If SY120 is in the timeline, NuMI will see a 10% decreases in beam power (630 kW).

the chromaticity is increased to stabilise the beam against the instability. At high intensities, large chromaticity is required at the end of the cycle which results in a new set of issues.

The first issue is running high chromaticity resulted in lifetime losses around this ring that were not controlled which were particularly high at lambertson locations. The second issue is a much more constrained tune space. The decelerated bunches during slip stacking have a tune offset compared to the set machine tune caused by chromaticity which to first order is $\sim \frac{\delta p}{p}\xi$. The the larger the chromaticity, the larger the tune offset. At -7 chromaticity, this offset is 0.018 compared to 0.054 for -20 chromaticity. This meant that as the chromaticity was increased, the set tune of the machine was lowered to prevent the off-momentum beam being pushed towards the half-integer resonance [5]. Figure 3 show how the losses increased exponentially as the chromaticity was increased during a "4+6" cycle. The black line shows the average of 100 pulses along a blue band showing one standard deviation from this mean. In order to reduce this problem, the tune was lowered as the chromaticity was increased

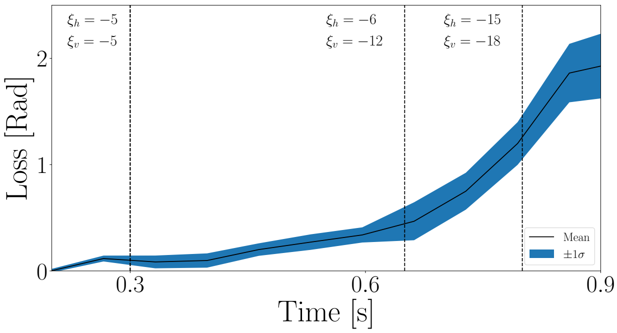

Figure 3: An example of how losses increase with chromaticity. The black line shows the average of 100 pulses along a blue band showing one standard deviation from this mean.

It was found that by introducing an injection phase offset on the first six injected batches, the final chromaticity could be reduced by 2 or 3 units. The injection offset resulted in more beam in the gap however this could be controlled cleanly with the gap clearing kickers rather than losing beam around the ring. Figure 4 shows the beam injected into the Recycler and how much survives. Around 1.2E12 is sent to the abort and ~ 2E11 is lost around the ring. The beam lost to the ring shows a non-linear increase towards the end of cycle caused by the high chromaticity running.

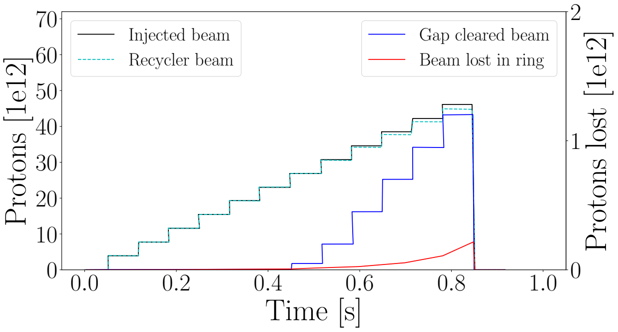

Figure 4: The beam injected into the Recycler during a "6+6" cycle along with the beam sent to the abort and beam lost in the ring in 2016.

Figure 5 shows a typical loss pattern in Rad around the Recycler before the 2016 summer shutdown. The different colours of the losses determine where the loss happened during the cycle. Blue is during the first 6 injections, yellow is the second six and green is during extraction. The worst losses occur at the lambertson locations used to extract beam to the Main Injector located at 232 and the abort lambertson located at 402. The majority of the loss at 402 is caused by the tails of the gap clearing kickers which are fired 13 times a cycle. In order to run 700 kW consistently, the transverse losses needed to be controlled better.

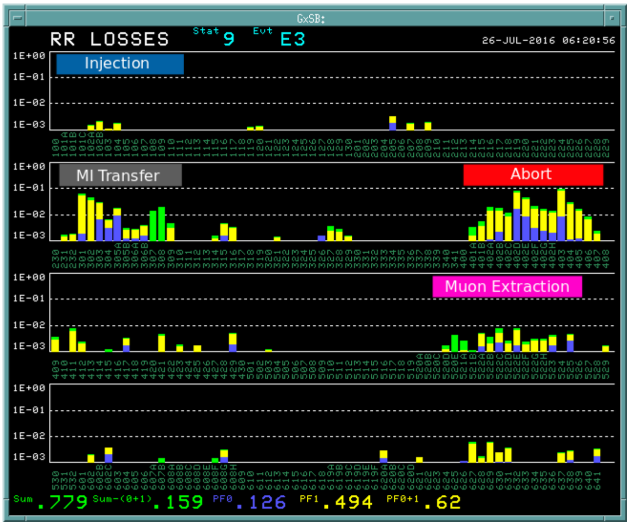

Figure 5: Typical loss pattern around the Recycler before the 2016 summer shutdown. Intensity is 42E12 ppp.

COLLIMATION

During the 2016 summer shutdown, a two-stage collimation system [6] was installed in the Recycler to take care of uncontrolled transverse losses. Longitudinal losses from slip-stacking are already controlled using gap clearing kickers. The system consists of a primary scraping foil edge, and two large, 20 ton secondary collimators made from steel and marble. After each injection, a vertical bump is used to move the beam edge towards the collimators in order to let the damper system remove any injection errors.

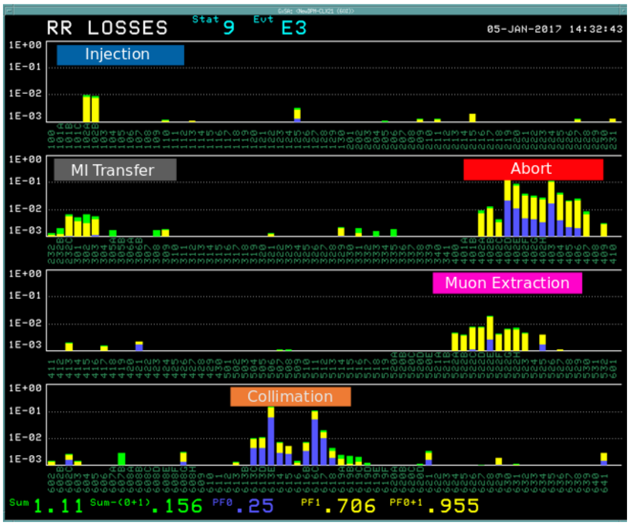

Figure 6: Typical loss pattern after installing the two stage collimation system. Intensity is around 45E12 ppp.

Figure 6 shows a typical loss pattern around the Recycler ring after the collimators were installed. It can be seen that the large losses at the MI transfer lambertson were reduced as well as many small losses around the ring caused by limited aperture. Note the intensity is higher compared to Fig. 5 hence why the loss sum is larger. While commissioning the collimators, tests were performed with just the secondary collimators and increased losses were observed at Lambertson locations confirming that a 2 stage system was the most efficient way to operate the collimators.

DIODE DAMPER

While the collimators were able to control a large amount of the transverse losses, there was still a loss associated with running very high chromaticity (-20) at the end of the cycle. During the slipping process the bunch by bunch damper system is turned off as it is unable to resolve the bunches position while they are overlapping. High Chromaticity is therefore needed to suppress the resistive wall instability.

It was proposed by [7] that the slipping motion can be ignored i.e. bunches in both beams doing the same motion. Thus a damper system with a 5 MHz bandwidth looking at the envelope of all bunches motion rather than a bunch by bunch damper would be sufficient.

The damper system follows a similar idea to that of Direct Diode Detection [8]. The output of pickups are sent through a diode followed by a resistor and capacitor in parallel to form peak detectors which provide an envelope of the bunches motion. This is then given to a 3 turn filter with correct coefficients to provide a kick to damp the beam.

The system was successfully implemented in January 2017 and allowed the chromaticity during slipping to be reduced from -20 down to -7. Figure 7 shows the effect of the damper on the loss pattern for the same intensity as in Figure 6. The total loss sum has reduced by almost a factor of two with losses at the Abort and Muon Extraction Lambertsons reduced significantly. The ability to run with much lower chromaticity also provided much more freedom in choosing the working point and to remove the injection phase offsets.

APERTURE IMPROVEMENTS

Following this improvements, the next limiting loss location were at the abort and muon extraction lambertsons. In the 2017 summer shutdown, the permanent magnet lambertson in the abort region was replaced with a powered lambertson with improved aperture to help reduce losses in this area. Figure 8 shows aperture for the old permanent magnet Lambertson (left) and the new Main Injector style lambertson (right) along with solid lines for $\pm 3\sigma$ and dashed lines show $\pm 5\sigma$ for 25 π mm mrad beam. The $\pm 5\sigma$ beam fits comfortably with the lambertson aperture for the new MLAW. The beam pipe leading into the Muon extraction lambertson was also replaced with the larger style elliptical pipe used in the Main Injector. The beta wave in the machine was also modified slightly using quad trims in the 30 section phase trombone to help reduce the beta in the region on the Muon extraction lambertson. Figure 9 shows the loss pat-

Figure 7: Typical loss pattern after the implementation of the the slip stack damper which allowed chromaticity to dropped at the end of the cycle. Intensity is around 45E12 ppp.

terns after these changes for 700 kW operations. The losses seen at the abort lambertson are much reduced and now, almost no loss is seen at the Muon Extraction lambertson.

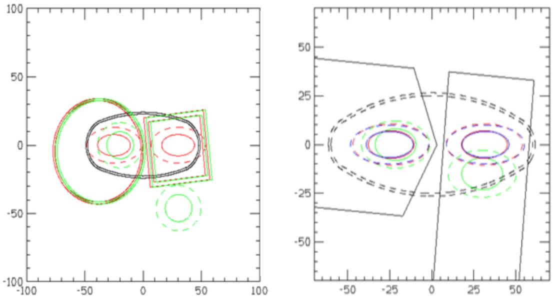

Figure 8: The aperture sizes for the old recycler permanent magnet lambertson (left) and the Main Injector MLAW lambertson (right). The solid line shows $\pm 3\sigma$ and the dashed line $\pm 5\sigma$ for 25 π mm mrad beam.

CURRENT RUNNING

In 2018, both the Recycler and Main Injector have an efficiency of around 98.5%. Figure 10 shows a similar plot to Figure 4. It can be seen that the aborted beam is now a factor of 3 smaller than what it was in 2016. This is partly due to the removal of the injection phase offsets and beam injected from the booster with smaller longitudinal emittance. The losses in the ring is a similar size to before except now more than 2/3 of this is going to the collimators.

INSTABILITIES

During commissioning of the Recycler, a fast instability [9] was previously observed in which attributed to electron cloud in which a small fraction of electrons were trapped in the magnetic field lines of the gradient magnets. This instability has not been observed for some time, most likely due to vacuum scrubbing from the high intensity beam or possibly from a change made to the vacuum system. Efforts to induce this instability for study purposes were also unsuccessful.

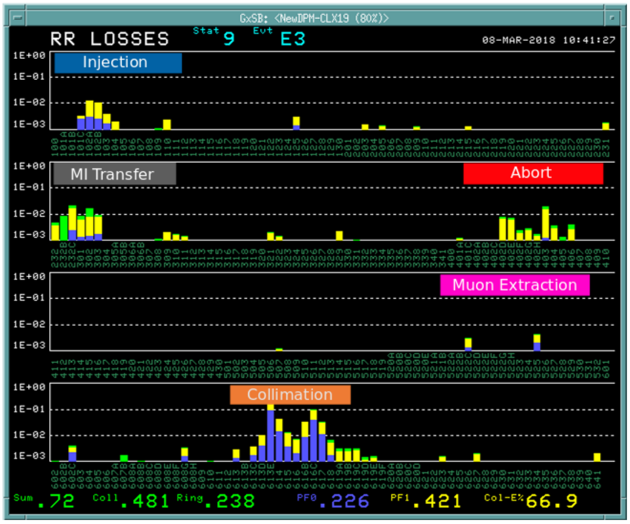

Figure 9: A typical loss pattern after the aperture improvements. Intensity is around 50E12 ppp.

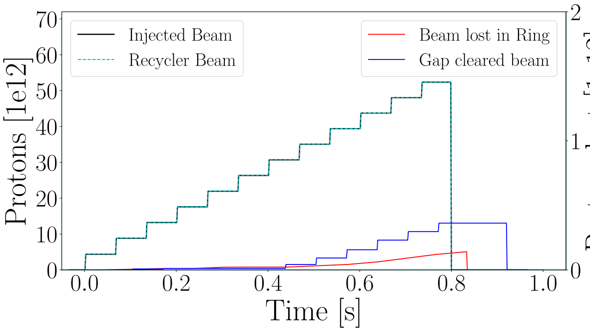

Figure 10: The beam injected into the Recycler during a "6+6" cycle along with the beam sent to the abort and beam lost in the ring in 2018.

Other instabilities that occur such as the resistive wall instability are controlled with dampers and do not affect operations.

RADIATION SURVEYS

While running 700 kW consistently, it is important to keep losses controlled and avoid irradiating the tunnel unnecessarily. Ring wide radiation surveys are performed whenever there is an opportunity to access the tunnel using DALE (Data Acquisition Logging Engine). DALE consists of a Geiger counter which has is position recorded by a wheel and attached to the back of cart. The radiation surveys are important to make sure that our beam loss system is not missing any locations. An example survey made on March 20th 2018 shows radiation hot spots around the tunnel measured on the aisle side (Fig. 11). The tunnel houses both the Main Injector and the Recycler so the resulting measurement shows the radiation dose in mRem/hr from both machines. DALE surveys underestimate loss locations where the reading is above 150 mRem/hr. Additional surveys are performed at these points with more accurate equipment.

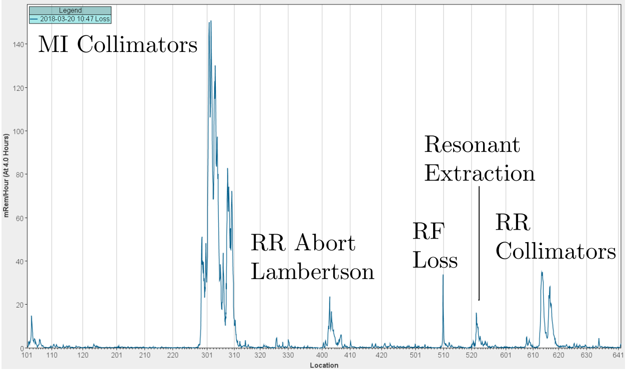

Figure 11: A DALE survey showing loss locations around the tunnel.

The largest spikes are between 301 and 310 which is the location of the Main Injector collimators. The other locations all match with locations shown in the Recycler loss plots with the exception of a large spike seen at 510. This is a Main Injector loss related to transition crossing when the RF voltage is limited due to tripped stations.

SUMMARY AND FUTURE RUNNING

Following a series of improvements with the most significant being the installation of collimators and a damper system for when beams are slipping, the Fermilab accelerator complex delivers 700 kW consistently to NuMI.

The current beam power that can be sent to NuMI is not limited by beam physics but by administrative limits. A new shielding assessment is required for the Main Injector to deliver more protons per hour. Also, there is currently a limit of 54E12 ppp on the NuMI target. Once these limits are removed, we will continue to push the intensity.

Studies are already under way looking at potential issues at higher intensity. In-depth simulations are already underway looking a potential problems from space charge. In the 2018 summer shutdown, there is a plan to install extra sextupoles to allow compensation of the third order resonance to open up the tune space. Lattice optimisation is underway to move the lattice functions as measured much closer to the design values.

There are plans to perform upgrades to the accelerator complex in the lead up to PIPII to allow 900 kW beam power for NOvA. For the Main Injector, it is planned to install a first order matched γ_t jump system in the future [10]. This will be important for the planned PIPII upgrades in which the frequency separation needed for slip stacking will be increased resulting in a larger $\delta p/p$ when crossing transition.

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