ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-WEYE3

IMPROVEMENTS TO THE RECYCLER/MAIN INJECTOR TO DELIVER 850 kW+

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Abstract

The Main Injector is used to deliver a 120 GeV high power proton beam for neutrino experiments. The design power of 700 kW was reached in early 2017 but further improvements have seen a new sustained peak power of 895 kW. Two of the main improvements include the shortening of the Main Injector ramp length as well optimising the slip-stacking procedure performed in the Recycler to reduce the amount of un-captured beam produce and eventually making its way into the Main Injector. These improvements will be discussed in this paper as well as future upgrades to reach higher beam powers.

INTRODUCTION

The Recycler (RR) and Main Injector (MI) are part of the Fermilab acclerator complex, as shown in Fig. 1, used to deliver high intensity beams for Neutrino experiments. The Recycler is a 8 GeV permanent magnet machine while the Main Injector can ramp from 8 GeV to 120 GeV. Both machines share the same enclosure. The Recycler also sends beam to the muon campus and the Main Injector also performs slow extraction for test beam experiments. These modes will not be discussed further in this paper.

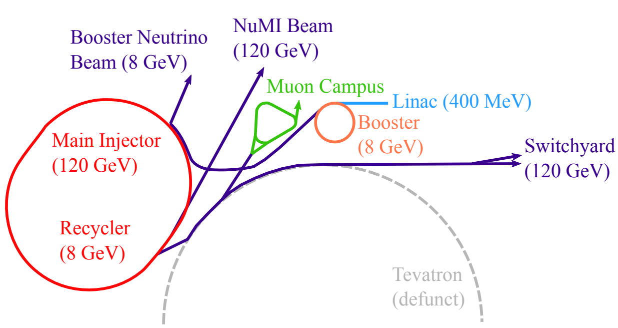

Figure 1: The Fermilab Accelerator complex.

For the high intensity neutrino beams the source produces H^- ions which are accelerated to 400 MeV in a normal conducting linac. Upon injection into the Booster, foil stripping is used to convert the H^- ions to protons. Here they are accelerated to 8 GeV and then sent to the Recycler ring. The slip-stacking procedure (which will be discussed in more detail in a later section) is used to double the bunch intensity. The protons are then extracted to the Main Injector which accelerates them to 120 GeV and are finally sent down the NuMI line to the experiments.

Figure 2 shows the beam power per hour since the Recycler was first used as a proton stacker in 2013. The steps to achieve the design power of 700 kW have already been described in [1]. Following further improvements, a record beam power of 895 kW was achieved at the end of the FY22 year run. It should be noted that the record beam powers are achieved when beam is only sent to the high energy neutrino experiments. If muon campus or test beam are requesting beam, the hourly power will drop by 5-15%. A large period of no beam is seen during 2020, this was caused partly due to the covid-19 pandemic as well as a longer shutdown planned for LBNF construction work. In the following sections, the improvements that led to the record beam power are described. While increasing beam intensity, losses around the rings are continually monitored to keep activation of the accelerator components to a minimum. Radiation surveys [2] are performed to compare with online beam loss monitoring.

FASTER RAMP

During long shutdown in 2013 the Main Injector ramp time was reduced to 1.33 s. For PIP-II, the ramp time needed to be reduced further to 1.2 s. Efforts to demonstrate this started in late 2018 and was implemented operationally in late 2019. Figure 3 shows a comparison of the two up ramps as well as the acceleration rate $\dot{P}$. While the maximum acceleration rate remained at 240 GeV/s for both ramps, the speedup came from by going much faster during the early parabola.

The reduction in MI cycle times leads to a 10% in beam power. However, it's important to note that in the case when muon campus is requesting beam, the Main Injector ramp must include an extra 0.2 s so the power increase cannot be taken advantage of.

RADIAL OFF-CENTER SLIP-STACKING

The Recycler has harmonic number h of 588 meaning it can accept 588 bunches. Each batch from the booster consists of 84 bunches so the Recycler can in principle accept 7 batches however this is limited to 6 batches to allow space for kicker rise times. In order to surpass the intensity limit that the booster can provide, slip-stacking is used allow the injection of 12 batches into the Recycler which are then combined into 6 double intensity batches.

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† Operated by Fermi Research Alliance, LLC under Contract No.De-AC02-07CH11359.

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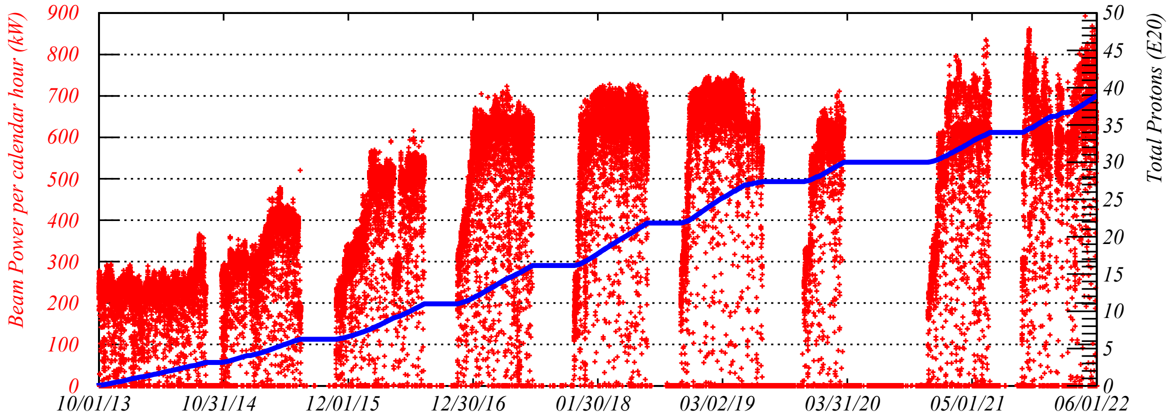

Figure 2: The hourly beam power to NuMI and the total protons delivered since the end of the long shutdown in 2013.

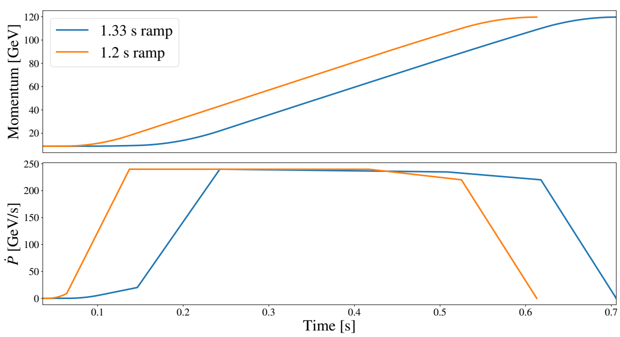

Figure 3: The 1.2 s ramp vs. the 1.33 s Main injector ramp. The rate of change of momentum $\dot{P}$ is also shown.

Slip-stacking works by injecting 6 batches at the design frequency of the machine i.e. in the radial center of the machine (R ON). These 6 batches are then decelerated by 1260 Hz (the product of the booster cycle rate and it's harmonic number i.e. 15 Hz × 84). A further 6 batches are then injected at the design frequency. Due to the momentum difference, the initial 6 batches will slip with respect the the second group of 6 batches until they are eventually overlapped and extracted to Main Injector. Just before extraction, both sets of beams are accelerated by 630 Hz such that the two different momentum beams are symmetric about the radial center.

For the PIP-II era, the booster will increases its cycle rate from 15 Hz to 20 Hz, this means the separation frequency between the two beams increases from 1260 Hz to 1680 Hz. This increase in required momentum aperture could lead to increased losses. In order to reduce the required amount of momentum aperture, Radial Off Center (R OFF) slip-stacking was implemented. In this case, the first group of 6 batches is now injected at +630 Hz from the design frequency i.e. intentionally off-center in the machine. A schematic of the frequency curves is shown in Fig. 4.

R OFF slip-stacking has been implemented operationally since the beginning of the FY22 run. This new scheme reduced the losses in MI by a factor of two as removing the last acceleration step dramatically reduced the amount of DC beam produced in Recycler which eventually makes it to MI.

LATTICE CORRECTION IN THE RECYCLER

The Recycler's aperture is limited, partly because it was not originally designed to be a proton stacker. Elliptical beam pipe is used (100×44 mm) which means the machine is particularly sensitive to β function errors in the vertical plane resulting in large losses. The Recycler is a permanent magnet machine and has two straight sections containing tune trombones which can be used to make a local phase advance change. The trombone at 60 is used to control the tune. An additional correction was applied to the trombone at 30 to bring the β functions closer to the design values. Figure 5 shows a comparisons of the β function error before and after correction. Significant improvement is observed in the vertical plane which reduced losses.

RESONANCE CORRECTION IN THE RECYCLER

Previous studies have shown that as the bunch intensity is increased, space charge tune shifts can lead to particles crossing resonance lines leading to emittance growth and eventually beam loss. Figure 6 shows a measured two dimensional tune scan at low intensity in which the colors correspond to beam transmission. Lines from resonances are clearly visible. The typical operating point for the RR is $Q_x = 25.43, Q_y = 24.42$ which is very close to the linear coupling resonance which is seen clearly.

Of particular concern are 3rd order resonances. A dedicated set of sextupoles were installed in summer 2018 to correct the $3Q_x = 76$ resonance line. For current operations, the minimal losses are obtained with only partial corrections. Normal sextupoles can also drive the $Q_x + 2Q_y = 74$ line, and the settings, that work best for operations, reduce the

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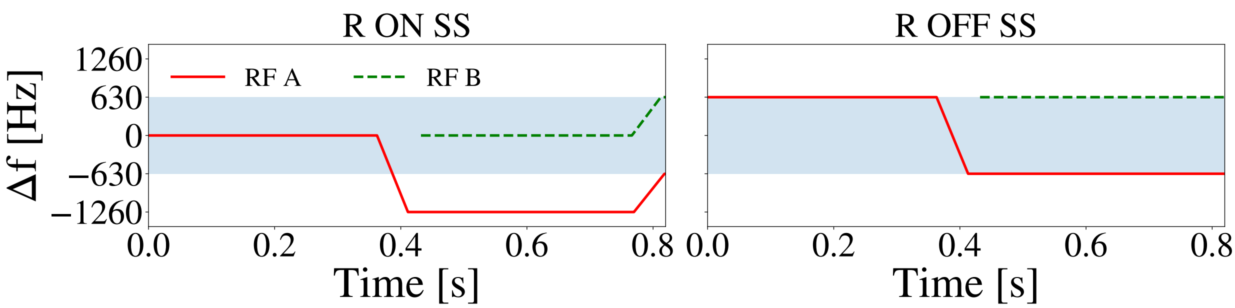

Figure 4: A comparison of the two slip-stacking schemes. Radial On-center (R ON) and Radial Off-Center (R OFF). The frequency of the two rf systems is shown.

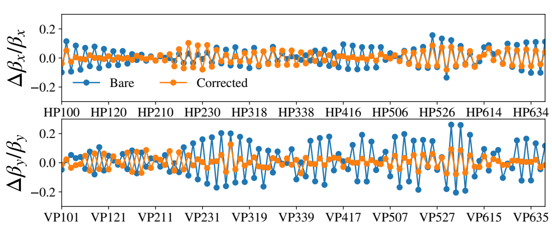

Figure 5: The difference between measured and design β functions before and after corrections.

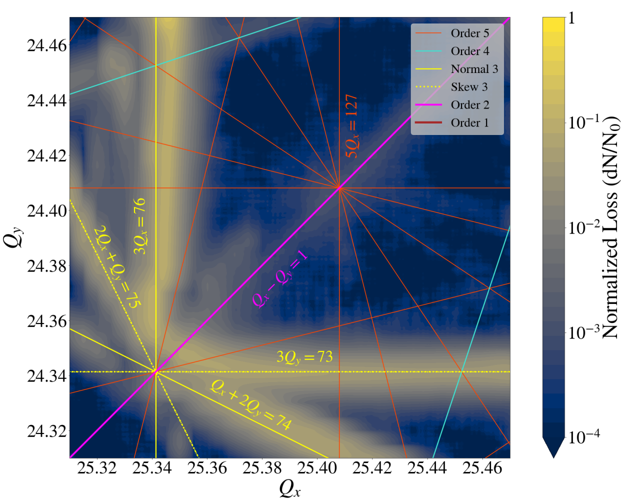

Figure 6: 2D tune scan in the Recycler. Third order resonance are particularly strong.

$3Q_x = 76$ resonance as much as possible without making the $Q_x + 2Q_y = 74$ resonance stronger. These effort is described in more detail in Ref. [3].

FUTURE UPGRADES

The aperture at the 232 location (just upstream of the lambertson used to extract beam from the Recycler to the Main Injector) has been highlighted as limited. Other lambertson locations have already been upgraded with larger beam pipe through the upstream quardrupole; the 232 location is unique in that there is a combined function magnet upstream of the lambertson through which larger beam pipe will not fit. During the summer 2022 shutdown, two combined function magnets at this location will be replaced with three quadrupoles and two dipoles with larger aperture.

The current collimators in the transfer line between the booster and the Recycler are insufficient for beam intensities and rates expected after the PIP-II upgrade. A project is underway to design a new set of collimators with the aim to install them during the summer 2023 shutdown [4].

SUMMARY

Following further improvements to the Recycler and Main Injector, a sustained record beam power of 895 kW has been achieved over 1 hour. The most significant improvement come from a faster Main Injector ramp and a modified slip-stacking procedure which dramatically reduced losses.

Further upgrades in the MI/RR are planned in order to prepare for the PIP-II era when both machines will be required to accelerate 50% more beam in order to deliver 1.2 MW.

ACKNOWLEDGEMENTS

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics

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