ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-MOPA19

THE EFFECT OF THE MAIN INJECTOR RAMP ON THE RECYCLER

N. Chelidze*, R. Ainsworth, K.J. Hazelwood
Fermi National Accelerator Laboratory†, Batavia, IL, USA

Abstract

The Recycler and Main Injector are part of the Fermilab Accelerator complex used to deliver a high power proton beam. Both machines share the same enclosure with the Recycler mounted 6 ft above the Main Injector. The Main Injector accelerates beam from 8 GeV to 120 GeV. While the majority of the Recycler has high permeability metal shielding, the effect of the Main Injector ramp is still significant and can affect both the tunes and the orbit. In this paper, we describe the size of these effects.

OPERATIONS

The Main Injector (MI) and Recycler (RR) are part of the Fermilab accelerator complex which are used to deliver beam to various experiments [1]. For the high intensity Neutrino experiments, the Recycler performs slip-stacking at 8 GeV and sends beam to the Main Injector, which accelerates this beam to 120 GeV. The Recycler is also used to rebunch beam from 53 MHz to 2.5 MHz for the Muon campus experiments. The Main Injector can ramp every 1.2 s however, when Muon campus is requesting beam, the time between pulses increases to 1.4 s. Figure 1 shows this in more detail. Depending on the operational mode i.e. if the MI is ramping at 1.2 s vs 1.4 s, the Recycler beam will be injected in the machine at different points with respect to the MI ramp. Due to the Recycler's limited aperture, the machine at high intensity is very sensitive to small orbit or tune changes. As both machines share the same tunnel, stray magnetic fields originate from both the quadrupole and the dipole bus (supply and return) excitations during the MI ramp (8 to 120 GeV). An example schematic of the tunnel is shown in Fig. 2.

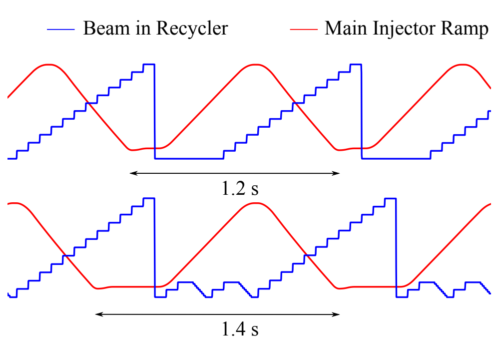

Figure 1: The position of the Recycler beam with respect to the MI ramp. When Muon campus is requesting beam, the MI ramp sits at 8 GeV for extra 0.2 s.

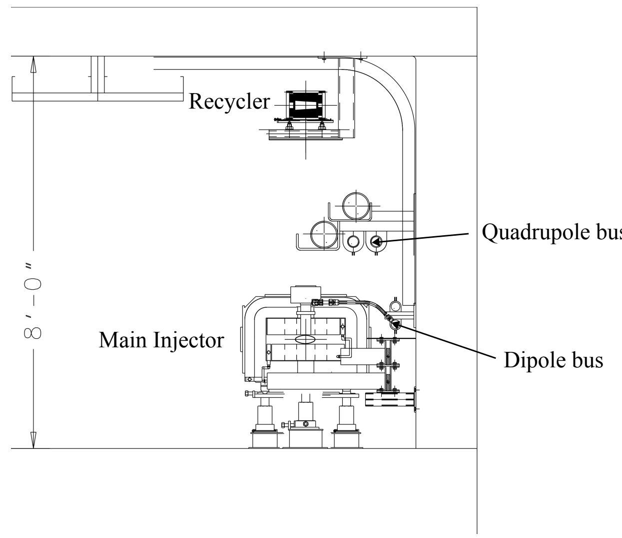

Figure 2: A schematic of the Main Injector enclosure which holds both the Main Injector and Recycler accelerators.

At the top of the ramp the current in the quad and dipole buses are close to 3 kA and 7 kA respectively. Both buses contribute about equally to the transverse magnetic field at the Recycler beam location [2]. In order to compensate for these effects, high-permeability shielding was added to the Recycler however, there is still a measurable effect on both the Recycler's orbit and tunes.

Figure 3 shows the horizontal beam position in the Recycler at different times with respect to the Main Injector ramp. The initial oscillation is caused by a kicker magnet used for tune measurements however, the orbit distortion visible at 9 GeV is caused by the Main Injector ramp.

ORBIT CORRECTION

In order to measure the effect of the MI ramp on the Recycler orbit, beam is injected into the Recycler and held for one full MI ramp. The Recycler closed orbit is measured and averaged at various MI ramp currents that correspond to commonly used MI momentum breakpoints. The orbit measured at the MI ramp current equivalent to 8.9 GeV is used for the ideal reference orbit. The orbit at 8.9 GeV is set each startup by scanning the Recycler beam apertures and finding the BPM position that causes the least loss and the least feed-down effects from higher order elements.

Compensating for the MI ramp in Recycler is a routine enough task that a specific sub-page has been created in the operational Recycler orbit correction and smoothing client application known as R50. The R50 client takes the difference of each averaged orbit and the reference orbit and calculates the required dipole trim corrector currents needed

* chelidze@fnal.gov
† Operated by Fermi Research Alliance, LLC under Contract No.De-AC02-07CH11359

5th North American Particle Accel. Conf. NAPAC2022, Albuquerque, NM, USA JACoW Publishing
ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-MOPA19

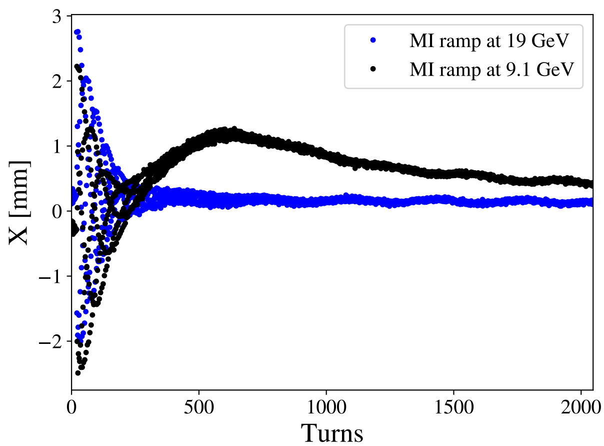

Figure 3: Example tbt data showing the effect of the MI ramp on the horizontal beam position at two different momentum during the MI ramp. The initial amplitude increase is from the ping for tune measurements.

to maintain the same orbit up (and down) the MI ramp. These currents are then sent to each corrector c453 CAMAC ramp card where a table exists specifically for MI ramp compensation. The ramp table contains the MI ramp currents that the orbits were measured at, for domain values vs requested corrector current. The c453 ramp card performs a linear interpolation between specified table points to provide a full MI ramp compensation waveform for each corrector.

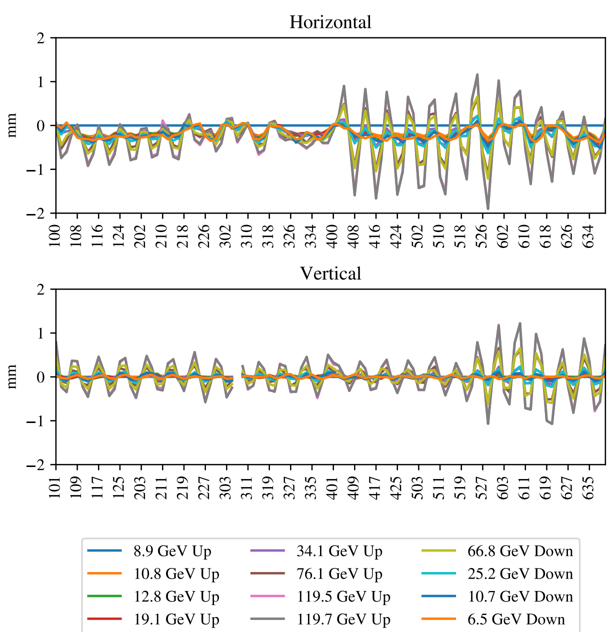

Figure 4: Recycler difference orbits taken at various MI ramp momentum breakpoints with no MI ramp compensation enabled.

As Fig. 4 shows, without MI ramp compensation, the orbit in Recycler deviates from ideal as much as 1.9 mm horizontally and 1.22 mm vertically. The effect is most pronounced at MI ramp flattop, 119.7 GeV. With MI ramp compensation enabled, the orbit deviation in Recycler is reduced during MI flattop to less than 0.77 mm horizontally and less than 0.29 mm vertically (Fig. 5).

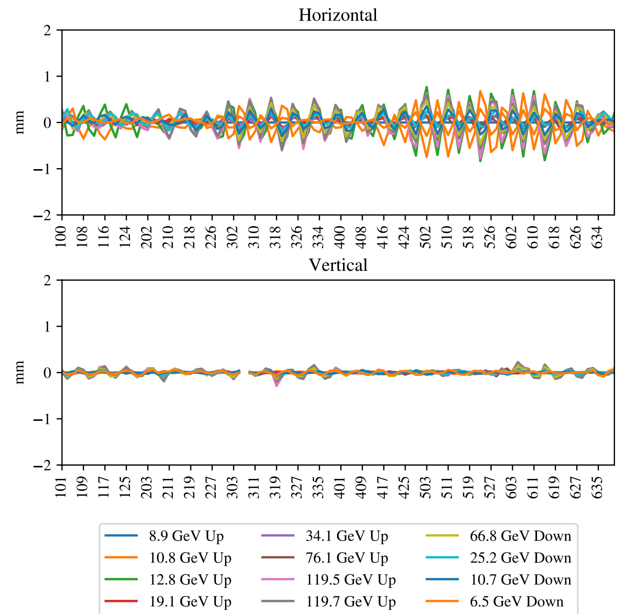

Figure 5: Recycler difference orbits taken at various MI ramp momentum breakpoints with MI ramp compensation enabled.

Possible future improvements to the Recycler MI ramp orbit compensation system may include adding additional breakpoints to the Recycler dipole corrector compensation ramps to better follow the MI bend bus ramp instead of relying on the c453 linear interpolation. Other improvements include additional compensation driven by the MI focusing and defocusing quad bus difference, possibly adding additional tune settings to the MI tune ramp to reduce the quad bus current difference after MI beam has left the machine but Recycler beam remains, and identifying locations where Recycler magnetic shielding is deficient or missing.

TUNE CORRECTION

In order to measure the effect of the MI ramp on the Recycler tunes, beam was injected into the Recycler for 1.85 s to overlap with at least one full MI ramp. The beam was then pinged both horizontally and vertically at the same time and the turn-by-turn BPM data was recorded, from which the tunes could be extracted. The tune was measured every 40 ms to fully see the effect of the MI ramp on the tunes.

Figure 6 shows the result of this measurement. A dependence on the Main injector ramp programmed momentum, P can be seen as well as a dependence on the $\dot{P}$ (up ramp vs down ramp).

In order to account for this dependence, a linear fit was made to the tunes vs the MI momentum. The difference be-

ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-MOPA19

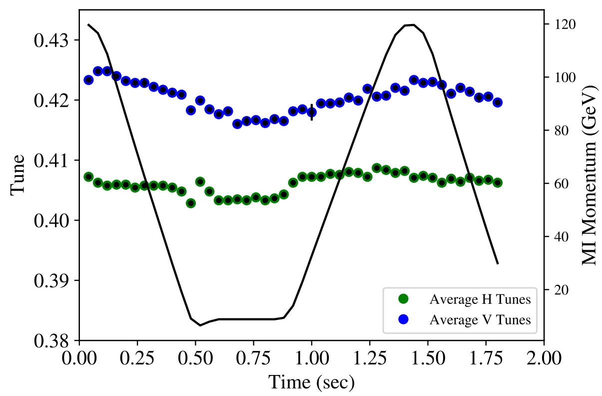

Figure 6: The horizontal and vertical tunes in the Recycler as measured at different points with respect to the MI ramp.

tween the horizontal tunes at 8 GeV vs 120 GeV was −0.0016 and −0.0059 vertically. Figure 7 shows the horizontal tunes measured vs the Main Injector $\dot{P}$ with and without corrections. Initially, three distinct clusters appear at -300, 0 and 250 Gev/s with the 0 GeV cluster having a lower measured tune than the other clusters. After applying corrections, all three clusters are at similar measured tunes. After applying the new P and $\dot{P}$ corrections, the tune vs MI ramp dependence was remeasured and is shown in Figure 8. It can be seen that the tunes are much flatter along the ramp.

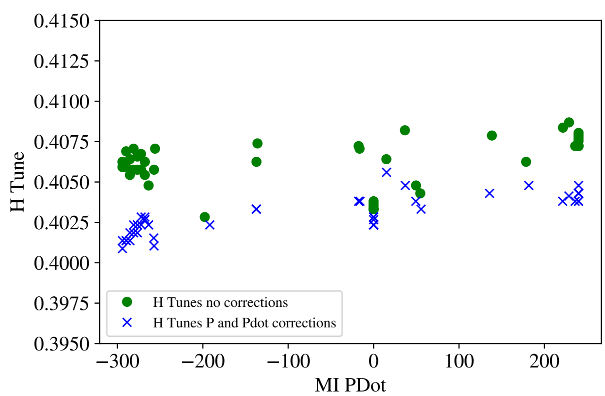

Figure 7: The horizontal and vertical tunes in the Recycler as measured at different points with respect to the MI ramp with P and $\dot{P}$ corrections.

QUAD COMPENSATION LOOP

The Main Injector has two sets of ramping quadrupoles. The focusing and defocusing quads each have their own bus in the tunnel. They are completely separate busses, with current flowing in one direction for the focusing bus, and the opposite direction for the defocusing bus. The MI horizontal tune is 26.425, and the vertical tune is 25.415. This difference in the integer number of the tunes means that the current through the defocusing bus is smaller than the focusing bus. Different currents mean different magnetic

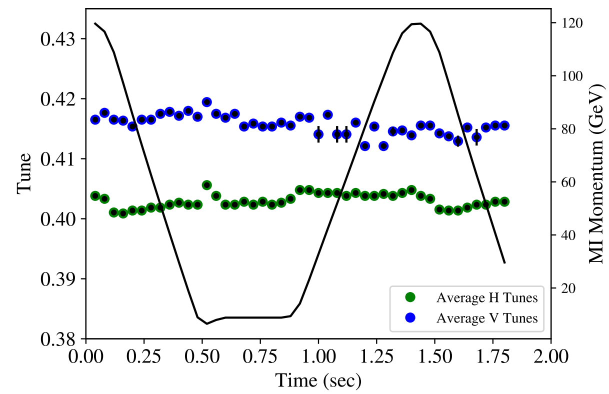

Figure 8: The horizontal and vertical tunes in the Recycler as measured at different points with respect to the MI ramp with P and $\dot{P}$ corrections.

field strengths, so they won't cancel for the Recycler. This is fixed by running a loop of cable around the ring, parallel to the quad busses. A power supply named R:QCLP housed at MI-60 drives current through the cable, compensating for the current difference in the quad busses of the MI.

SUMMARY

The ramping of the Main Injector leads to orbit distortion and tune shifts in the Recycler which mean the Recycler needed to be re-tuned depending on where beam was injected with respect to the MI ramp. The size of these effects were measured and series of corrections were implemented to correct for them. Since the changes were made, the Recycler no longer needs to be retuned when switching between the 1.4 s to 1.2 s modes.

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

REFERENCES

[1] R. Ainsworth *et al.*, "High intensity operation using proton stacking in the Fermilab Recycler to deliver 700 kW of 120 GeV proton beam", *Phys. Rev. Accel. Beams*, vol. 23, p. 121002, Dec. 2020. doi:10.1103/PhysRevAccelBeams.23.121002

[2] S. Nagaitsev, C. Gattuso, S. M. Pruss, and J. T. Volk, "Experience with Magnetic Shielding of a Large Scale Accelerator", in *Proc. PAC'01*, Chicago, IL, USA, Jun. 2001, paper RPPH062, pp. 3371–3373.