SIMULATIONS AND MEASUREMENTS OF STOPBANDS IN THE FERMILAB RECYCLER *

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Abstract

Fermilab has recently completed an upgrade to the complex with the goal of delivering 700 kW of beam power as 120 GeV protons to the NuMI target. A major part of boosting beam power is to use the Fermilab Recycler to stack protons. Simulations focusing on the betatron resonance stopbands are presented taking into account different effects such as intensity and chromaticity. Simulations are compared with measurements.

SYNERGIA

Synergia [1] is developed and maintained at Fermilab by the Accelerator Simulations group within the Scientific Computing Division to provide detailed high fidelity simulations of particle accelerators or storage rings specializing in space charge and wakefield collective effects. Synergia is a Particle-in-Cell (PIC) based code that tracks macro-particles through the lumped elements of the accelerator. Synergia simulates the usual single particle optics produced by magnetic elements as well as RF cavities. Space charge and impedance kicks are applied at locations around the ring using the split-operator method. Space charge kicks are calculated with the Hockney [2] algorithm in 2.5 dimensions which is appropriate to the Recycler bunches which are much larger longitudinally than transversely. So that realistic particle losses can be simulated, apertures may be associated with each element. The Synergia aperture model includes rectangular and elliptical apertures of arbitrary size and transverse offset as well as arbitrary user defined polygonal apertures. To achieve statistically meaningful results in a reasonable time, Synergia has been designed from the beginning to take advantage of multiprocessing systems such as Linux clusters and supercomputers.

RECYCLER SIMULATION MACHINE MODEL

The Recycler machine lattice is described by a MAD file [3, 4] incorporating the measured multipoles for the magnet body and shim correctors. Synergia reads and interprets the same MAD description. The lattice functions for the Recycler calculated by Synergia are identical to those calculated by MAD. The apertures in the recycler are: 3" diameter pipe, 4" diameter pipe, Recycler elliptical pipe (3.75 × 1.75 in full width), a rounded rectangular kicker (90.5 × 39.4 mm) and an irregular Lambertson magnet as shown in Fig. 1. The Lambertson magnets are the usual limiting apertures. The simulation includes orbit correctors

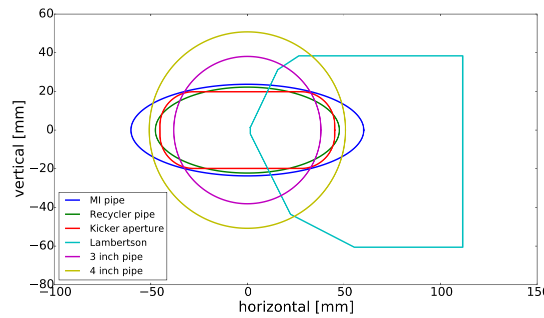

Figure 1: Apertures in the Recycler.

which steer the circulating beam through the Lambertson apertures which are displaced from the central orbit.

In order to help understand the effects of space charge and chromaticity on the tune space, a series of simulations are performed looking at the stopbands and how they shift. This note will discuss simulations performed using Synergia. The default parameters for the simulation are shown in Table 1.

Table 1: Default Parameters for Recycler Simulations

Parameter	RR
Macroparticles	131072
Q_h	0.39
Q_v	0.44
ξ_h	-5.8
ξ_v	-7.74
V_{RF} [MV]	0.09
$\varepsilon_{n,95\%}$ [π mm mrad]	15
$\varepsilon_{L,95\%}$ [eV s]	0.08

SPACE CHARGE

In order to study the stopbands, the set tune of the machine is varied and the corresponding transmission measured. By scanning the tune around resonances at different intensities, the shifts can be attributed to space charge.

Simulations were performed in the horizontal plane with and without space charge. At each tune value, the simulation was run for 500 turns. For the simulations involving space charge, a low intensity and a high intensity simulation were performed. At low intensity, the bunch contained 1e10 particles and for the high intensity run, 5e10 particles were simulated.

The results of these simulations are shown in Figure 2. As expected, space charge results in both a shifting and a broadening of the resonance. One can also see the coupling

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resonance ($2\nu_x + \nu_y = n$) at a slightly lower tune than the third. At high intensity, this resonance appears much less pronounced. Above fractional tunes of 0.36, there is no simulated loss until the half integer resonance.

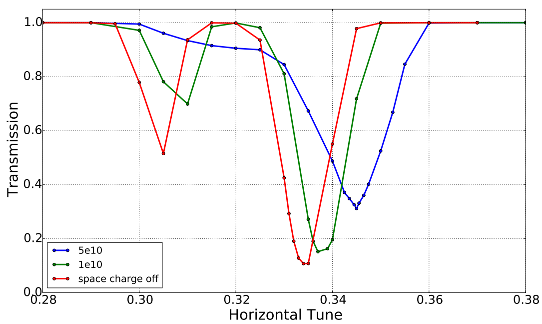

Figure 2: The effect of space charge on the third order resonance.

CHROMATICITY

The simulations for high intensity is repeated with the chromaticity increased in magnitude from the nominal value to -18. Figure 3 shows the results. It can be seen that high chromaticity results in a slight broadening but as expected, no shifting.

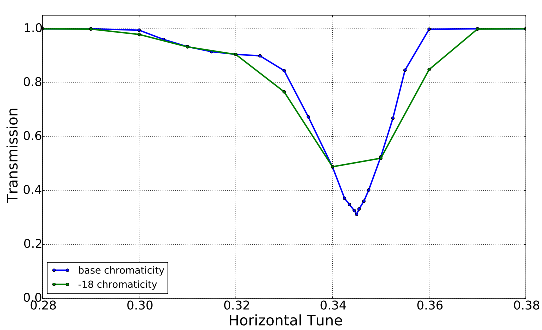

Figure 3: The effect of chromaticity on the third order resonance.

MEASUREMENTS

A measurement of the stopbands was also performed in which the set tune is gradually changed and the transmission measured at each set tune. Figure 4 shows the results for 3 turns (low intensity) and 12 turns (high intensity). One can see the same resonances as in the simulations. The coupling resonance appears lower as the measurements were performed with a different vertical tune setting. Looking at third in more detail, one can see the resonance broadening and slightly shift due to space charge. However, these are smaller than predicted from simulation. Also of interest is how at high intensity, two minima are observed. It was measured that the separation of the two minima is twice the synchrotron frequency and perhaps this is a synchro-betatron resonance however it is still not understood.

Possible reasons why the simulations show larger tune shifts could be that an ideal bunch distribution is used. In reality, the bunch is likely to filament and the bunch length increase resulting in a smaller shift. It's also possible that the transverse emittance of the bunch could be larger than 15 π mm mrad.

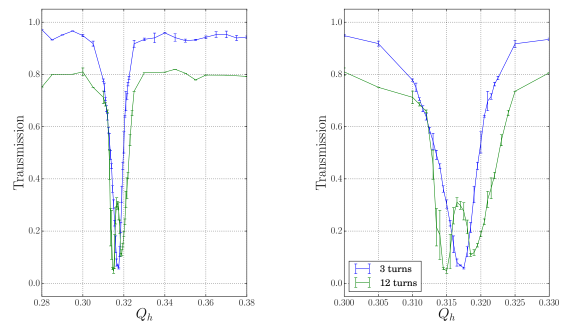

Figure 4: Measured stopbands in the Recycler for two different intensities. The transmission is measured as a function of horizontal set tune. The full scan is shown (left) and a zoomed in plot of the third is shown (right).

HIGH CHROMATICITY OPERATION

To achieve high intensity operations, slip-stacking [5] is used in the Recycler. Slip-stacking involves decelerating a batch of 84 bunches and slipping against another batch injected on-momentum. When the two batches are aligned, they are combined into one batch in the Main Injector. When slipping beams occupy the same portion of the recycler circumference, the damper which stabilises the beam against the resistive wall instability cannot function effectively and so high chromaticity is required. To first order, chromaticity relates the tune spread to the momentum spread. In the case of slip-stacking, beam is decelerated resulting in a momentum shift which also results in a tune shift because of non-zero chromaticity. In the case of high chromaticity i.e. $\xi = -18$, the tune shift is of the order 0.05. This shift was seen in simulations using Synergia and measurements were performed to confirm.

A single batch of 84 bunches is injected into the recycler at a chromaticity of -6. By 120 ms the batch is decelerated by 1260 Hz shifting the fractional change of momentum $\delta p/p$ to ~ -0.0027. Four cases are investigated. For the first case, the chromaticity was left at -6. In the second case, the chromaticity was increased to -18 after 150 ms. For the third case, the chromaticity was increased to -18 in steps of 4 every 30 ms at 150 ms. Finally, the chromaticity is set to -18 at injection and left constant for the rest of the cycle. In all cases, the losses are sampled along the cycle so we can determine if they occur before or after the beam is decelerated.

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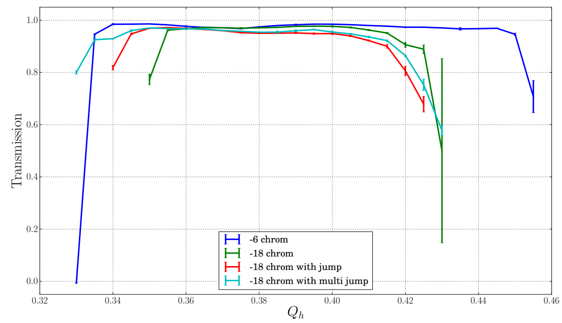

Figure 5: A stopband scan for different chromaticity settings.

For the ξ=-6 case, the on-momentum beam hits the third at around 0.33 and off-momentum beam hits the half at closer to 0.45. That half appears low probably due to measured tune not being identical to the set tune. At -18 chromaticity from injection, one can see the smallest tune space available. This is because the half is shifted down due to chromaticity and the third appears at high tunes due to increased tune spread. If the chromaticity is increased in steps one can see more space at lower tunes as the on-momentum beam will have a smaller tune spread. In this measurement, it is always the on-momentum beam that hits the third first as the chromaticity will cause the off-momentum beam to see the third order resonance at lower set tunes.

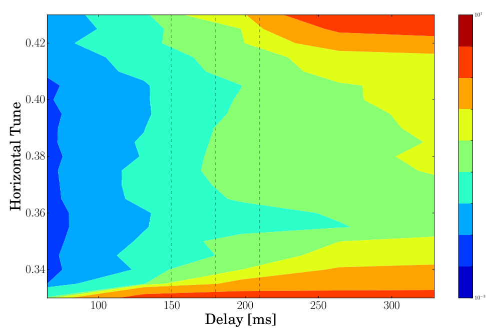

Figure 6: Losses as a function of time for different horizontal tunes.

Figure 6 shows the loss sum in the recycler during the cycle for the case when the chromaticty is increased in steps. The black dotted lines show when the chromaticity changes occur. It can be seen that the biggest losses occur at high tunes when the chromaticity reaches -18. At lower tunes, high losses are seen almost immediately due to the on-momentum beam hitting the third order resonance.

Following on from these results, the working point of the recycler was lowered to avoid hitting the half integer resonance at high chromaticity.

SUMMARY

Simulations and measurements were performed looking at stopbands in the Recycler. Currently, simulations predict large tune shifts and spreads than what is measured. Using simulations, it was predicted that at high chromaticity, the decelerated beam during slip-stacking will be shifted closed to half integer resonance. This was verified experimentally and led to an change in the recycler working point operationally.

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