SPACE CHARGE SIMULATIONS IN THE FERMILAB RECYCLER FOR PIP-II [*]

R. Ainsworth[†], P. Adamson, I. Kourbanis, E. Stern, Fermilab, Batavia, USA

Abstract

Proton Improvement Plan-II (PIP-II) is Fermilab's plan for providing powerful, high-intensity proton beams to the laboratory's experiments. Upgrades are foreseen for the Recycler which will cope with bunches containing fifty percent more beam. Of particular concern is large space charge tune shifts caused by the intensity increase. Simulations performed using Synergia are detailed focusing on the space charge footprint.

INTRODUCTION

Proton Improvement Plan-II (PIP-II) [1] is Fermilab's plan for providing powerful, high-intensity proton beams to the laboratory's experiments. The increased beam power will position Fermilab as the leading laboratory in the world for accelerator-based neutrino experiments.

The heart of PIP-II is a 800-MeV superconducting linear accelerator, which capitalizes on the lab's expertise in superconducting radio-frequency technologies. Along with modest improvements to Fermilab's existing Main Injector and Recycler accelerators, the superconducting linac, called SCL, will provide the megawatt proton beam that is needed for the Long-Baseline Neutrino Facility.

This paper will focus on the Recycler which will need to slip-stack [2] 50% more beam than in than it does currently for PIP. Increased intensity will result in larger space charge effects. This size of these effects are simulated using Synergia. In the simulations, the key parameter differences between PIP and PIPII are shown in Table 1.

Table 1: The Parameter Differences between PIP and PIPII

Parameter	PIP	PIPII
V_{rf} [kV]	80	140
Intensity [ppb]	5e10	8e10
Booster Frequency [Hz]	15	20
f_{rev} [kHz]	89.6	89.6
h [kHz]	588	588
η	-8.6×10^{-3}	-8.6×10^{-3}

Slip-stacking will be used in the Recycler in which a batch of 84 bunches is decelerated and then slipped with another batch that remains on-momentum. Once the two batches are aligned, they are combined into a single batch in the Main Injector. For this process, two RF cavities are required. The cavities will operate at different frequencies due to the deceleration. The size of this separation is given by the booster harmonic number h_b and the booster cycle rate f_b.

$$\Delta f = h_b f_b \tag{1}$$

Thus, for 15 Hz operation, $\Delta f = 1260$ Hz and for 20 Hz operation, $\Delta f = 1680$ Hz. The momentum separation is related to this frequency separation by

$$\Delta\delta = \frac{\Delta f}{f_{\mathrm{rev}} h \eta} \tag{2}$$

where f_{rev} is the revolution frequency, h is the harmonic number of the recycler and η is the slip factor. Thus, for PIP, the momentum separation is -0.0027 and for PIPII -0.0037.

The importance of the momentum separation is that the Recycler will operate with non-zero chromaticity ξ causing a tune shift ΔQ given by

$$\Delta Q = \xi \Delta\delta \tag{3}$$

This means that the on-momentum beam and off-momentum beam will be separated by ΔQ for a given set machine tune.

SIMULATIONS

This section will discuss the Synergia [3] simulations for PIP and PIPII cases focusing on the space charge footprint. More information about the simulations can be found in [4]. Before looking at the PIPII cases, the PIP case is simulated. The default simulation parameters are shown in Table 2.

Table 2: 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
$\varepsilon_{n,95\%}$ [π mm mrad]	15
$\varepsilon_{L,95\%}$ [eV s]	0.08

Each simulation is run for 500 turns. Only two bunches are simulated. An on-momentum bunch and an off-momentum bunch which slips with respect to the on-momentum bunch. Periodic boundary conditions are use such that the off-momentum bunch continually slips with the same bunch. Figure 1 shows the space charge footprint for the two bunches during when they overlap and when they don't overlap. The left plot shows the longitudinal phase space. The right plots shows the space charge footprint along with resonance lines

---

[*] Operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy.

[†] rainswor@fnal.gov

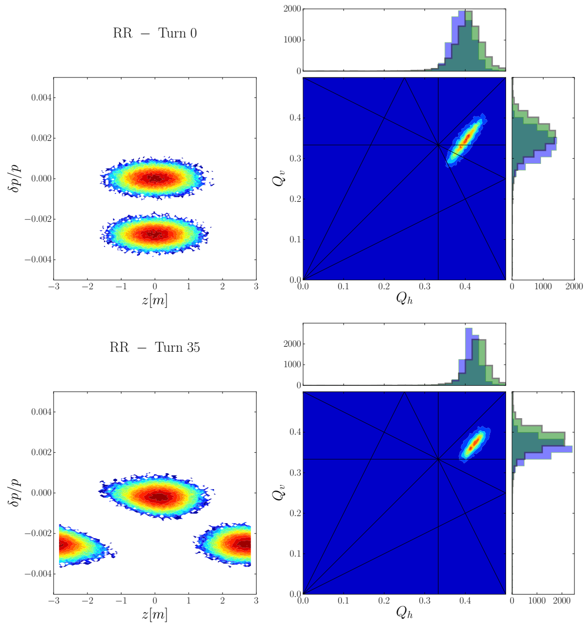

Figure 1: The longitudinal phase space and space charge footprint for the PIP case when the bunches overlap and when they are not overlapping.

up to third order. Projections along the horizontal and vertical axis are also shown. The blue histogram represents the on-momentum bunch and the green histogram corresponds to the off-momentum bunch.

One can see that the space charge tune shift grows when then bunches overlap. This growth is observed for approximately 5 turns centered around the overlap. It can also be seen that the off-momentum tune footprint has an offset with respect to the on-momentum bunch. This is caused by chromaticity as discussed in the previous section. For all following footprint plots, only the case when the bunches are overlapping i.e. maximum shift is shown.

Comparing the footprint between PIP and PIPII, the tune spread in the horizontal plane is ~ 30% larger and ~ 40% larger in the vertical plane.

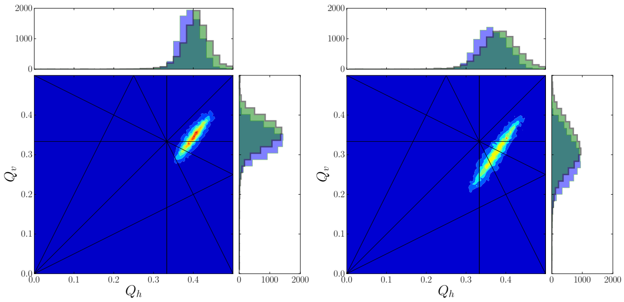

Figure 2: The space charge footprint for PIP (left) and PIPII (right) using the default simulation parameters.

HIGH CHROMATICITY

Operationally, high chromaticity is required to stablilize the resistive wall instability during slip-stacking as the transverse damper is unable to operate on two overlapping batches. For PIP, $\xi = -18$ is required. The simulations were repeated with the chromaticity increased to -18 in both planes. The results are shown in Figure 3.

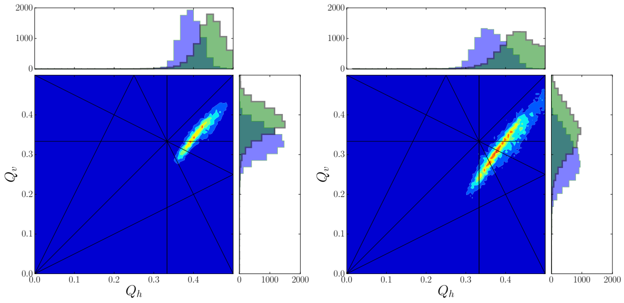

Figure 3: The space charge footprint for $\xi = -18$ for PIP (left) and PIPII (right).

One can see that the main difference is that the off-momentum bunches' tune footprint is shifted due to chromaticity. For PIP, the tune shift is 0.0486 and for PIPII, the shift is 0.066. High losses were observed particularly in the PIPII simulations as the large shift caused the off-momentum bunch to hit the half integer resonance in the horizontal plane. For PIPII, 10% of particles were lost within 500 turns compared to just 1.6% in the PIP case. The location of these losses are shown in Figure 4.

It can be seen that the losses occur at the Lambertson magnets where the beam is steered to pass through the aperture of the field-free region of the magnet. Due to the large shift from chromaticity, the simulations were run at a lower horizontal tune to verify that the loses were caused by half integer resonance rather than by another effect related to chromaticity. After the tune changes, losses for both cases with less than 0.01%. The size of the tune footprint showed no real increase due to high chromaticity. This probably means that space charge tune spread dominates.

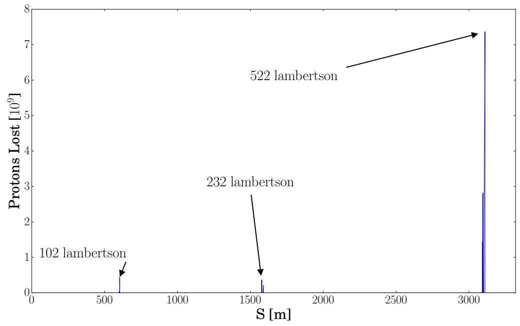

Figure 4: The locations of loss points around the Recycler. The major losses occur at the Lambertson magnets.

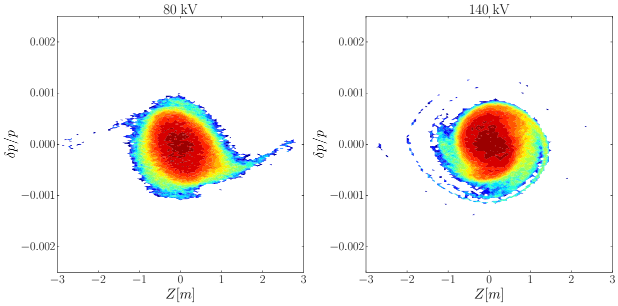

Figure 5: Input distributions for PIP and PIPII. The 80 kV distribution is extracted directly from a measured distribution. To create the 140 kV distribution the 80 kV distribution was filamented for 1000 turns in a 140 kV bucket.

Due to the increased intensity for PIPII, it is estimated that even higher chromaticity is required to stabilise the beam. Thus, further simulations were performed for the PIPII case using $\xi = -22$. The resulting tune shift is 0.0814. The tunes were lowered further and only 0.06% was lost. The footprint itself looks very similar to the $\xi = -18$ case except it is shifted to take into account the lowered tune and thus is not shown.

REAL DISTRIBUTION

So far all simulations were performed using an ideal distribution i.e. a matched bunch distribution. In reality that's not the case and therefore, measured distributions were used. Using TARDIS [5], a tomography tool, a longitudinal distribution at injection in the Recycler was measured. Currently, the RF cavities cannot produce 140 kV so a measured distribution is not possible. As an estimation, the measured distribution at 80 kV used as input to a single bunch Recycler simulation and allowed to filament for 1000 turns where the cavity voltage is set to 140 kV. This filamented distribution is then used as an input for PIPII simulations. Figure 5 shows the measured distribution for 80 kV and the simulated distribution after 1000 turns at 140 kV.

The matched case is compared with a real distribution for PIPII. The comparison is shown in Figure 6 for $\xi = -18$.

The space charge footprint was found to be $5-6\%$ smaller when real distributions were used. This likely cause is due to the increased bunching factor.

SUMMARY

Simulations comparing PIP and PIPII were compared focusing on the space charge footprint. It was found that the tune spread was 40% bigger in the vertical plane and 30% bigger in the horizontal plane.

Increasing the chromaticity did not appear to affect the size of footprint except shift the off-momentum footprint higher. To compensate this, a lower working point was chosen. Assuming a higher chromaticity of $\xi = -22$ is needed, a the tune shift caused by chromaticity will be 68% higher for PIPII compared to PIP with $\xi = -18$.

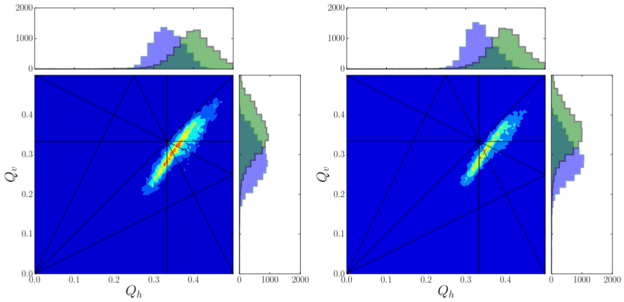

Figure 6: The space charge footprint for PIPII at $\xi = -18$ using a matched distribution (left) and a realistic distribution (right).

Read distributions were also simulated and found to reduced the space charge footprint on the order of 5%.

REFERENCES

[1] PIP2, `http://pip2.fnal.gov/`

[2] K. Seiya *et al.*, "Status of slip stacking at Fermilab main injector", in *Proc. of PAC'05*, Knoxville, Tennessee, USA, June 2005, paper MOPA004, pp. 347-9.

[3] Synergia, J. Amundson *et al.*, `http://web.fnal.gov/sites/synergia`

[4] R. Ainsworth *et al.*, "Simulations and measurements of stopbands in the Fermilab recycler", presented at IPAC'16, Busan, Korea, May 2016, paper MOPOY010, this conference.

[5] N. Evans, S. Kopp, P. Adamson and D. Scott, "A new tool for longitudinal tomography in Fermilab's main injector and recycler rings", in *Proc. of IPAC'13*, Shanghai, China, May 2013, paper MOPWA061, pp. 816-8.