TRANSITION CROSSING IN THE MAIN INJECTOR FOR PIP-II *

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Abstract

Proton Improvement Plan-II (PIP-II) [1] is Fermilab's plan for providing powerful, high-intensity proton beams to the laboratory's experiments. PIP II will include upgrades to the Booster, Recycler and Main Injector which will be required to accelerate 50% more beam as well as increasing the Booster repetition rate from 15 to 20 Hz. To accommodate the faster rate, the momentum separation of the slip stacking beams in the Recycler must increase which will result in in larger longitudinal emittance bunches in MI. In order to cross transition without losses, it is expected a gamma-t jump will be needed. Gamma-t jump schemes for the MI are investigated.

INTRODUCTION

Transition occurs when the relative rate of change of speed β equals the relative increase in path length

$$\frac{1}{\beta}\frac{d\beta}{d\delta} = \frac{1}{\gamma_t} = \frac{2\pi}{C_0} < D_x > \tag{1}$$

Particles with different momenta in the Main Injector experience transition at different times, known as the Johnsen effect. Transition is delayed or advanced by the Johnsen time from a particle with $\delta p/p = \pm\delta p_{max}/p$.

This note will detail simulations performed to determine whether losses can be expected when crossing transition for PIP-II and different schemes that could be used to remedy this loss.

RECYCLER SIMULATIONS

This section will outline the procedure used to create the input for the Main Injector simulations by first performing simulations in the Recycler. Some important parameters for PIPII are shown in Table 1 a long with the current running parameters (PIP) for comparison. Also simulations were perfomed using Synergia [2].

Table 1: Default Parameters for Recycler Simulations

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 is used in the Recycler in which a batch of 84 bunches are 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. Two RF cavities, each locked to the different momentum are used. 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.

$$\Delta f = h_b f_b \tag{2}$$

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

$$\Delta\delta = \frac{\Delta f}{f_{\mathrm{rev}} h\eta} \tag{3}$$

where f_{rev} is the revolution frequency, h is the harmonic number of the recycler and η is the slip factor. Thus, for PIPII, the offset in $\delta p/p$ is -0.0037. This is important for transition crossing, as the larger separation will give a larger longitudinal emittance in the Main Injector.

The RR simulations were performed in two parts. For the first part, a real longitudinal distribution as measured using a tomography tool was used as an input for the longitudinal phase space. For the transverse distribution, a matched distribution was generated corresponding to a normalised 95 % emittance of 15π mm mrad. The simulation was then run for 50 ms allowing the bunch to filament in a 140 kV bucket.

For the second part, the filamented distribution was separated into 2 bunches in which every other particle was given a $\delta p/p$ offset corresponding to the frequency separation. The two bunches were allowed to slip past each other in the double RF cavity RR simulation for 500 turns. These final distributions were passed through a transfer line simulation to match the transverse phase space to the Main Injector simulation.

MAIN INJECTOR SIMULATIONS

Main Injector simulations were performed with the parameters shown in Table 2 and the input longitudinal phase space are shown in Figure 1. For each simulation, the bunch was accelerated from 8.9 GeV to 40 GeV.

Table 2: Default Parameters for Main Injector Simulations

Parameter	MI
Q_h	0.425
Q_v	0.415
ξ_h	-4.92
ξ_v	-5.00
γ_t	21.6

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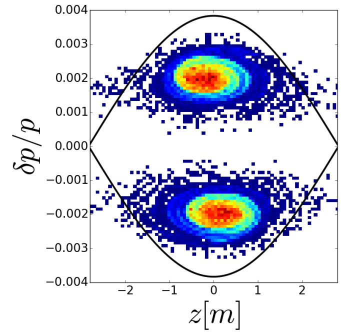

Figure 1: The longtudinal phase space distributions at the beginning of the simulation for PIP (left) and PIPII (right).

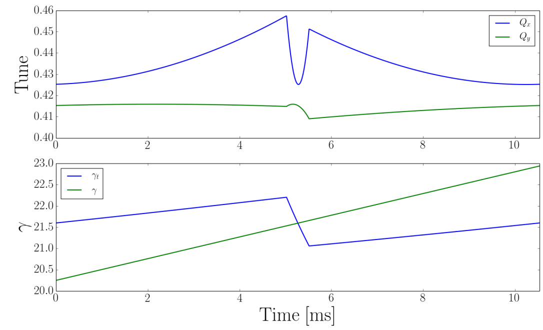

Figure 2: The effect on the tunes and the γ_t of the lattice during the jump scheme.

γ_t-JUMP

In an attempt to reduce the losses caused at transition and keep the longitudinal emittance under control, a γ_t-jump scheme had been previously developed for the Main Injector [3, 4]. The developed scheme was a so-called first-order system [5] making use of local dispersion inserts at the dispersion-free straight sections. The previous γ_t-jump aimed to provide a $\Delta\gamma_t$ from +1 to −1 in 0.5 ms. The system consisted of 8 sets of pulsed quadrupole triplets. Each triplet has two quads in the arc and one of twice the integrated strength in the straight section. The phase advance between each quad is π in order to minimize the β-beating caused by the inserts.

The quads in the arcs are set to have a integrated field of 0.85 T-m/m and a length of 0.508 m while the quad placed in the straight section is set to have twice the integrated field and double length and so is fact the just the two quads from the arc section placed next to each other.

Simulated γ_t Jump

Different γ_t scenarios were simulated using Synergia. Two cases were investigated based on the original scheme discussed above both using 4 triplets, looking at a +0.5 to −0.5 jump and a +0.75 to −0.75 jump. Even though a first order jump scheme is used, there are still large effects on the optics of the lattice that cannot be ignored. The lattice functions for the different schemes considered can be seen in Figure 3.

Figure 2 shows the effect of the γ_t jump on the horizontal and vertical tune during the jump for the 1/2 unit jump using 4 triplets. At the beginning of the jump, the pulsed quads are ramped linearly for 5 ms and then the polarity is swapped linearly over 0.5 ms and the ramped back down to zero over another 5 ms. Transition crossing occurs during the middle of the polarity swap. It can be seen that the dγ_t/dt is half of dγ/dt, this because a 1/2 unit jump is used but based on the full unit jump parameters. The effect on the horizontal tune is very large and needs to be compensated to avoid hitting any resonances.

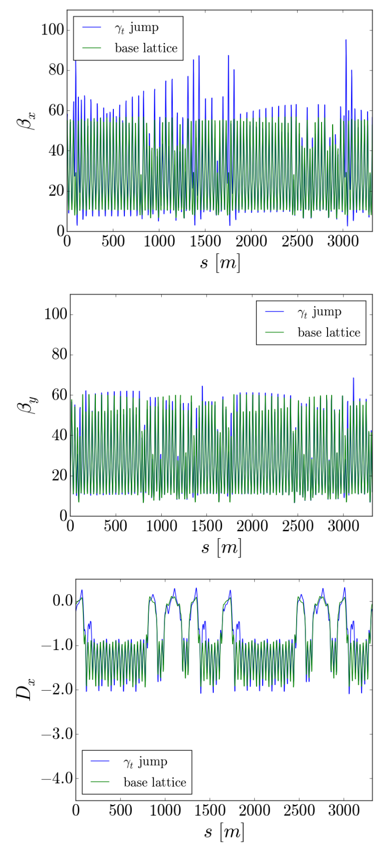

Figure 3: Lattice functions at the maximum γ_t of the jump for the 1/2 unit jump.

For the 1/2 unit jump the horizontal tune was reduced by 0.035. For the 3/4 unit jump, the horizontal tune was reduced by 0.06.

Figure 4 compares the effect on the longitudinal phase space for PIPII with and without a γ_t-jump scheme. For the no jump case, large oscillations can initially be seen while the bunch filaments inside the bucket. Focusing on just the momentum spread, it can be seen that it slowly increases to a maximum at transition and then drops down again undergoing oscillations on the way.. The number of particles lost

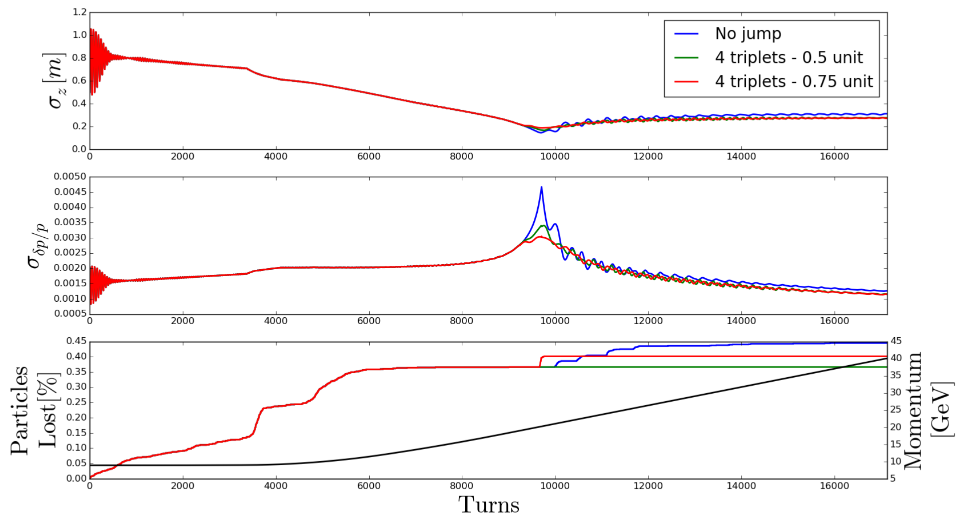

Figure 4: The evolution of the bunch length momentum spread throughout the simulation.

is also shown with the biggest loss occuring around 9 GeV in which the out of bucket beam hits an aperture restriction. After that point, losses occur multiple times after transition is crossed.

The maximum $\delta p/p$ is much reduced for the γ_t-jump schemes compared to the no jump case. For the 1/2 unit jump case, no losses are seen during the jump or after it. For the 3/4 unit jump, some losses are seen near transition crossing. This is a transverse loss caused by the large tune shift when the pulsed quads are close to maximum. An 8 triplet case was also explored but it was found very difficult to keep losses low due to the large disturbances on the lattice from having 8 inserts.

Figure 5 shows the longitudinal phase space distribution for the 1/2 jump simulations after the same number of turns as where the first $\delta p/p$ maximum occurs for the PIPII case. The much smaller emittance explains why losses don't occur for the γ_t-jump case.

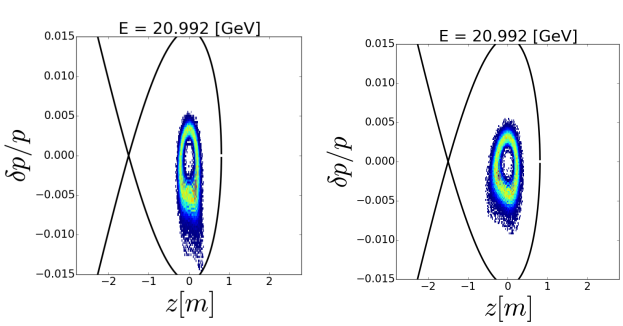

Figure 5: The longitudinal phase space distribution at the first maximum after transition of PIPII (left) and for the 1/2 unit jump (right) simulations as the same time .

SUMMARY

Simulations were performed using the 3D PIC code Synergia to investigate transition crossing in the Main Injector in the case of PIPII. The regular crossing was compared with two different γ_t-jump schemes. For the PIPII case, losses were observed after crossing transition. γ_t-jump schemes were then simulated in attempt to reduce these losses. By adding quad triplets that could ramped to alter γ_t near transition, the rate at which transition was crossed was increased. It was important to take into account the transverse effects of these jumps. Although, the longitudinal effects were improved, it was important to minimise the effects on the lattice as much as possible. It was found that use just 4 triplets, altering γ_t from +0.5 to −0.5 resulted in the best performance as long as tune offset was introduced to avoid hitting a resonance.

REFERENCES

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