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MITIGATING TRANSITION IN THE FERMILAB BOOSTER USING A TRIPLE PHASE JUMP *

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Abstract

The PIP-II project will significantly enhance neutrino production for DUNE, Fermilab's flagship long-baseline neutrino oscillation experiment, by doubling the beam power delivered by the accelerator complex. To achieve this, the total charge injected from the new PIP-II linac into the Booster rapid cycling synchrotron (RCS) will increase from 4.5×10^{12} to 6.5×10^{12} protons per pulse. Simultaneously, the Booster's ramp rate will rise from 15 to 20 Hz, while the injection energy will go from 400 MeV to 800 MeV.

The Booster accelerates the beam to 8 GeV and crosses transition at $\gamma_t = 5.45$. In current operations, no dedicated γ_t jump system is employed; instead, longitudinal emittance growth is controlled via an active quadrupole-mode feedback system. Downstream, the Recycler Ring uses slip-stacking to accumulate beam and increase bunch intensity. However, this process imposes a constraint on the longitudinal emittance at Booster extraction, limiting it to 0.1 eV·s (95%) to avoid excessive particle loss.

Because collective effects scale with intensity, additional measures to mitigate transition crossing may be required to stay below this limit. One potential approach is the so-called triple phase-jump technique. While the method has known limitations, it offers some advantages: it can be implemented using the existing digital low-level RF (LLRF) system, requires no additional magnets or pulsed power supplies, and remains compatible with quadrupole-mode feedback.

INTRODUCTION

The PIP-II project currently under construction at Fermilab will replace the existing 400 MeV warm linac with a new 800 MeV superconducting machine. The total charge injected from the new PIP-II linac into the Booster rapid cycling synchrotron (RCS) will represent an increase from 4.5×10^{12} to 6.5×10^{12} protons per pulse. Simultaneously, the Booster resonant power supply system will be modified to increase the ramp rate from 15 to 20 Hz.

The Booster accelerates the beam to 8 GeV and crosses transition at $\gamma_t = 5.45$. In current operations, no dedicated γ_t jump system is employed; instead, longitudinal emittance growth is controlled via an active quadrupole-mode feedback system. To further increase intensity, the extracted beam is slip-stacked at fixed energy in the downstream Recycler ring. It is subsequently transferred to the main Injector synchrotron and accelerated to 120 GeV. The slip-stacking process imposes a constraint on the longitudinal emittance at Booster extraction. To prevent excessive particle loss, this limit is set 0.1 eV-s (95%).

A distinctive feature of the Fermilab Booster is that the bending magnets entire aperture is under vacuum and the beam is directly exposed to the magnet laminated poles. This arrangement side steps issues with eddy currents induced in a metallic beam chamber by the rapidly changing bending field. A downside of the design is that both the resistive and the reactive parts of the longitudinal impedance are substantial and exhibit a complicated frequency dependence [1].

TRANSITION

In general, deviations in both synchronous orbit size L_s and particle velocity v_s are proportional to momentum deviation. The force experienced by a particle depends on the rf phase when it arrives at a cavity; particles which deviates from the synchronous momentum experience phase slippage due to slightly different revolution frequencies. The phase slip factor η is defined as the relative change in frequency per unit of change in relative momentum deviation:

$$\eta = \frac{\Delta\omega/\omega_s}{\Delta p/p_s} = \left[\frac{\Delta v}{v_s} - \frac{\Delta L}{L_s}\right] . \tag{1}$$

Transition takes place when η changes sign. To preserve stability, the rf restoring force must also change sign. For a single particle crossing transition is accomplished in a transparent way, by simply jumping the rf phase from ϕ_s to $\pi - \phi_s$ at the precise instant where the energy reaches $\gamma = \gamma_t$.

In the presence of collective effects, while the rf force changes sign, the collective forces do not. The net focusing mismatch across transition causes phase space filamentation and emittance increase. Other phenomena also contribute and may also be significant; they are not addressed here. The magnitude of the mismatch scales with intensity, making it likely that additional special measures will be needed to limit the emittance blowup in the PIP-II era. By far the most effective is the so-called gamma-t jump which involves very rapidly changing the slip factor by pulsing a set of dedicated quadrupoles at transition. While it is not excluded, cost considerations aside, a gamma-t jump system presents special technical difficulties in a machine like the Fermilab Booster where combined function magnets are used to achieve a high packing fraction and available space is at a premium.

In this context, we have been exploring less effective mitigation techniques that may nevertheless be useful, more economical and possibly usable in combination with oth-

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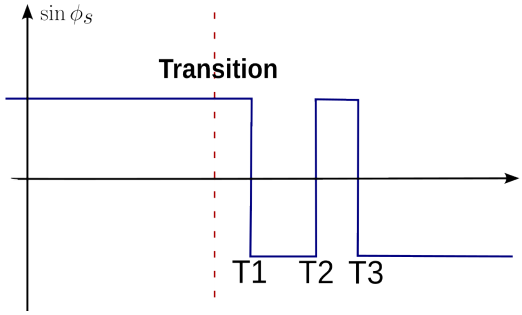

Figure 1: The triple phase jump. The phase is jumped at times T_1 T_2 and T_3. Note that T_1 does not have to coincide with the transition time. $\Delta T_{21} = T_2 - T_1$ and $\Delta T_{32} = T_3 - T_2$ are respectively the stable and unstable intervals.

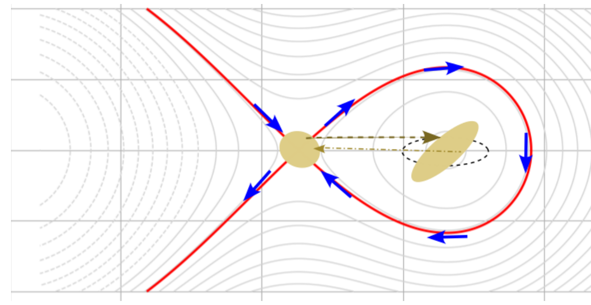

Figure 2: The triple phase jump principle. The bunch is first rotated and then moved to an unstable (saddle) fixed point. Particles are attracted along one of the the perpendicular separatrices and repelled along the other, modifying the bunch aspect ratio to achieve a better match.

ers. One such technique is the so-called triple phase-jump. While it has known limitations, it can be implemented with only minor tweaks to an existing digital low-level RF (LLRF) system; no additional hardware is needed.

TRIPLE JUMP

With a single phase jump, emittance blowup is known to be sensitive to precise timing. In the presence of collective effects, an early or delayed jump often proves beneficial. When the jump is mistimed, the bunch sits for a moment on an unstable fixed (saddle) point and this alters the bunch aspect ratio. By adjusting the duration of the unstable interval one can often achieve a better match to the stable phase space contours after transition.

The triple jump technique was first described by Sorenssen [2]. His insight was that one could achieve a match by using multiple jumps to make the bunch rotate in phase space to a more favorable orientation prior to being moved to an unstable fixed point. As shown in schematically in Fig. 1, the phase is jumped three times, usually starting at transition, to yield in succession a first time interval where the bunch rotates in phase space, followed by a second time interval where the motion is unstable and the aspect ratio is modified. A third jump restores normal stable motion once an improved match has been achieved.

For an elliptical bunch, provided the collective forces are linear, it is theoretically possible to achieve a near perfect match. In a more realistic scenario involving nonlinear forces and a complex phase space distribution, things become more complicated. Nevertheless, it is reasonable to speculate that the triple-jump can still be somewhat effective at reducing mismatch across transition.

SIMULATIONS

To conduct our simulations, we used the longitudinal dynamics code ESME [3]. This code has a long history and has been used successfully both at Fermilab and elsewhere. Despite a rudimentary user interface, problem specification is very compact and concise and requires no specialized programming. A wide array of flexible options to model magnetic ramps, RF Voltage, phase and frequency programs, etc, are provided. Accelerator models can include space charge and wall impedance as well as phase and voltage feedback systems.

Restriction to longitudinal dynamics make the calculations very efficient; however it also implies that transverse effects are accounted for in an approximate manner. Thus, the variation of the total orbit length with respect to a relative momentum deviation is modeled as a power series. In addition, since the program knows nothing of the local dispersion around the ring nor of the aperture geometry, particle losses are estimated using the change in average orbit radius. A particle is declared lost when the deviation $|\Delta R|$ from its average orbit radius is larger than an a-priori specified (global) aperture radius. On a typical desktop computer, tracking a few 100 K particles over a full 25 ms Booster acceleration cycle (about 15000 turns) may be performed in a few minutes.

Figure 2 shows the simulated phase space footprint of an accelerated bunch very shortly after transition and at the end of the Booster acceleration cycle in three cases: (1) no collective effects (2) with space charge only and (3) with both space charge and wall impedance. The filamentation due to the space charge and to the wall impedance are very visible. The final rms emittance in the single particle case is 0.015 eV-s. In the presence of space charge it increases to 0.019 eV-s and to 0.031 eV-s when the wall impedance is also included.

So far we have not found conditions under which a triple phase jump leads to a meaningful emittance blowup reduction in the presence of space charge and wall impedance. At this point, the jury is still out on how effective the technique might prove to be. Figures 3 and 4 present a sample preliminary simulation result. In this case, T_1 was chosen to coincide with the transition time and $\Delta T_{21} = 100\,\mu s$ and $\Delta T_{32} = 50\,\mu s$. The figure shows the phase space footprint

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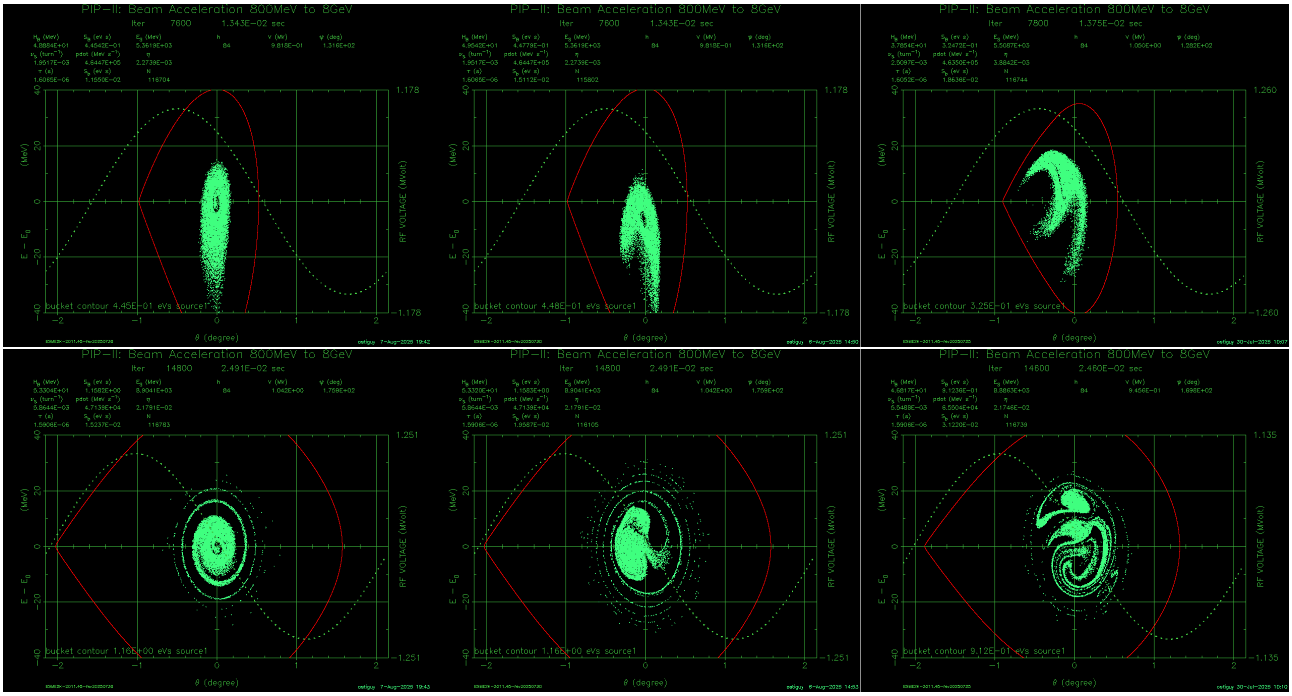

Single particle Space charge only Space charge and wall impedance

Figure 3: Effect of the space charge and wall impedance. Top: Phase space very shortly after crossing transition. Bottom: Phase space at the end of acceleration.

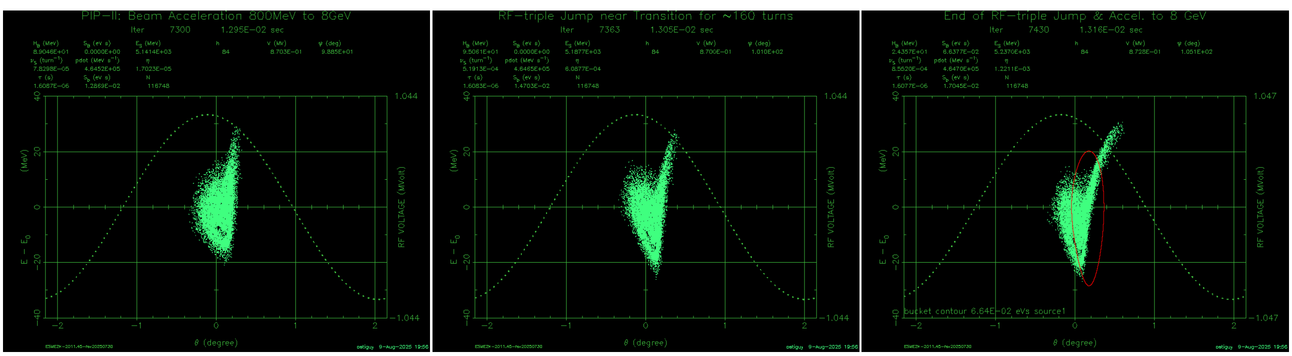

Figure 4: Phase space at $T_1 = T(\gamma_t)$, $T_2 = T_1 + \Delta T_{21}$ and $T3 = T_2 + \Delta T_{32}$. In this example, $\Delta T_{21} = 100$ µs and $\Delta T_{32} = 50$ µs.

at times T_1, T_2 and T_3. In this specific instance, a narrow tail already becomes visible at transition. The tail grows further during the unstable interval resulting in subsequent filamentation. A successful triple jump would suppress this tail.

CONCLUSION

We used ESME to model the longitudinal dynamics of the triple jump in presence of space charge and collective forces due to wall impedance. Although preliminary results have so far been inconclusive, further work and a systematic study of the parameter space will be necessary to reach definitive conclusions.

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