

Mitigating Transition in the Fermilab Booster Using a Triple Phase Jump

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BACKGROUND

The PIP-II project aims at increasing the beam power delivered by the accelerator complex to 1.2 MW. Fermilab will replace the existing 400 MeV warm linac with a new 800 MeV superconducting machine (currently under construction). The total charge injected from the new PIP-II linac into the Booster rapid cycling synchrotron (RCS) will increase from $4.5E12$ to $6.7E12$ protons per pulse. To further increase intensity, the beam extracted from the Booster is slip-stacked at fixed energy in the downstream Recycler ring before being subsequently transferred to the Main Injector synchrotron for acceleration to 120 GeV. Slip-stacking imposes a constraint on the longitudinal emittance at extraction from the Booster. To prevent excessive particle loss, it should not exceed 0.1 eV-s (95%).

A focusing mismatch at transition arises because contrary to the rf force, the collective forces do no change sign. This mismatch is responsible for a substantial amount of emittance blowup. It scales with intensity, making it likely that additional special measures will be needed 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. 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 other mitigation techniques which, although less effective, are more economical and possibly usable in combination. One such technique is the so-called triple phase-jump. It can be implemented with only minor tweaks to an existing digital low-level RF (LLRF) system; no additional hardware is needed.

SINGLE PHASE JUMP REFERENCE SIMULATIONS

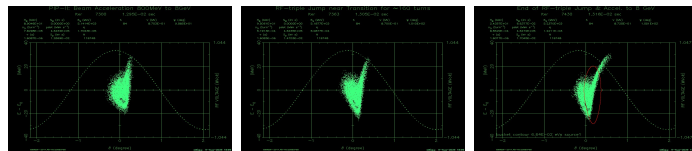
The figures on the right show the simulated phase space footprint of an accelerated bunch immediately after transition and at the end of the Booster acceleration cycle in three cases: (1) no collective effects (2) with space charge only and (3) with both space charge and wall impedance. The filamentation 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.

PRINCIPLE OF THE 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 Sorensen. His insight was that one could achieve a better 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 the figures on the right 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.

TRIPLE JUMP SIMULATIONS

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. The figures below are a sample preliminary simulation result. In this case, T1 was chosen to coincide with the transition time and T2=100 micro-sec and T3=50 micro-sec. The figure shows the phase space footprint at times T1, T2 and T3. In this specific instance a long tail is already visible at transition. The tail grow further during the unstable interval resulting in subsequent filamentation and emittance growth. A successful triple jump should suppress the formation of this tail.



SIMULATION TOOL: ESME

- Longitudinal dynamics code with a long history developed at Fermilab
 - written in Fortran 9X
 - rudimentary interface but concise and effective for problem specification
 - a wide variety of options to specify magnetic field ramps, rf voltage, frequency or phase programs, feedbacks etc...
 - Space charge
 - Longitudinal Impedance
 - Efficient
- A full acceleration cycle simulation 25 ms – (approx. 15000 turns) with 150 K particles runs in a few minutes

THE FERMILAB BOOSTER

Parameter	Present	PIP-II	
Circumference	474.2	474.2	m
Injection Energy	400	800	MeV
Extraction Energy	8	8	GeV
Cycle Frequency	15	20	Hz
Harmonic no	84	84	
Transition gamma	5.45	5.45	
Injection Frequency	37.77	44.70	MHz
Extraction Frequency	52.81	52.81	MHz
Max RF Voltage	0.86	1.16	MV
L emittance [95%]	0.25	0.1	eV-s
T emittance [95%, norm]	12 n	14-16 n	mm-mrad
Tunes	6.7/6.8	6.7/6.8	
Typical bunch intensity	4.5E12/82	6.7E12/82	
Injection scheme	Adiabatic capture	Phase space painting	

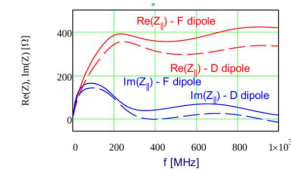
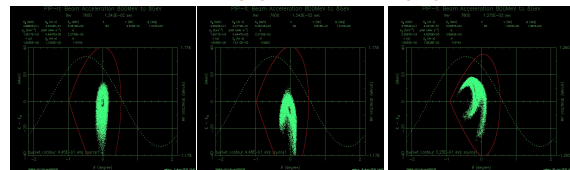


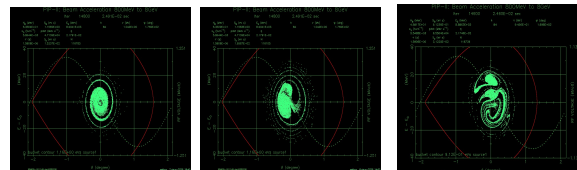
Figure 1: Longitudinal impedance of a single Booster bending magnet (there is a total of 96). The Booster does not have a beam pipe; the entire magnet aperture is evacuated. This side-steps issues with eddy currents; a downside is that the impedance is unusually lossy.

VERY SHORTLY AFTER TRANSITION

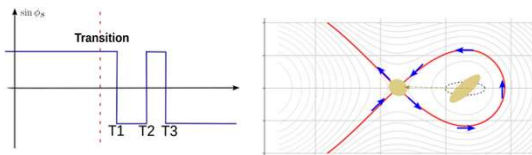


Single particle Space charge only Space charge and Wall Impedance

NEAR THE END OF THE ACCELERATION CYCLE



Single particle Space charge only Space charge and Wall Impedance



CONCLUSION AND OUTLOOK

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.

REFERENCES

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