Full-Cycle 6D Simulations of the FNAL Booster

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OUTLINE

As part of an effort to better understand potential losses and emittance blow-up in the Booster, we have been conducting full cycle 6D simulations using the code `PyOrbit`. The simulation include space charge, wall impedance and transition crossing. We discuss our experience with the code and present representative results for possible operational scenarios. We focus on longitudinal emittance blowup.

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 π	14-16 π	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**	

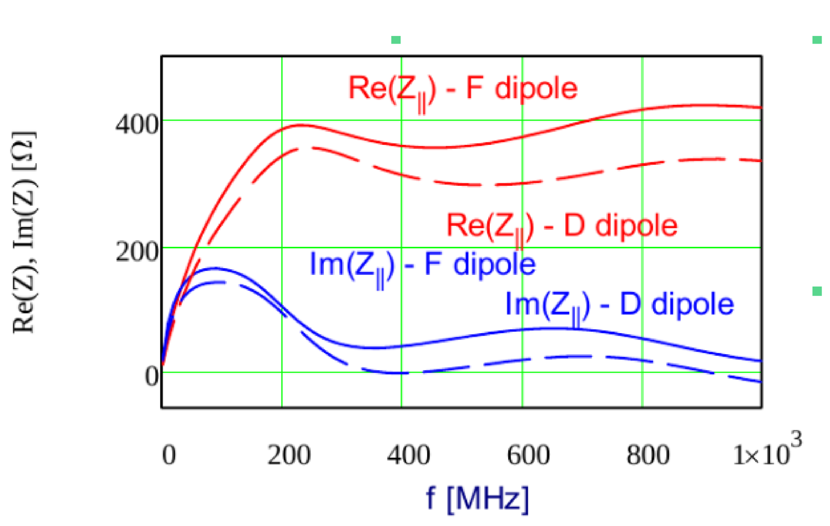

Figure 1: Longitudinal impedance of a single Booster bending magnet (there is a total of 96). The Booster does not have a beam pipe; the entire magnet aperture is evacuated. This sidesteps issues with eddy currents; a downside is that the impedance is unusually lossy.

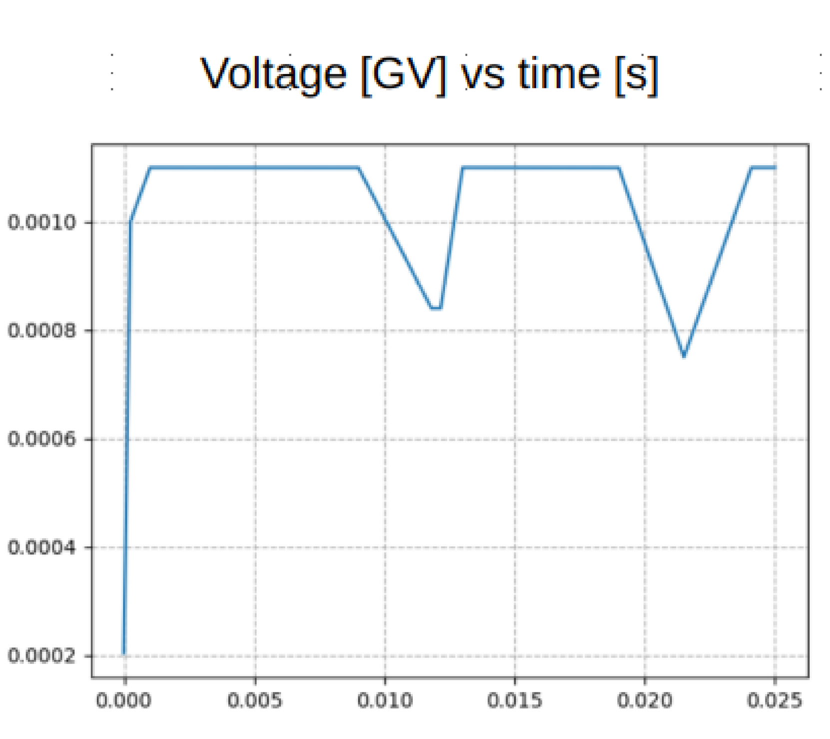

Figure 2: A typical rf curve used in simulation.

PYORBIT

- Developed at ORNL originally to simulate SNS ring
- python and C++ extensions for efficiency
- Various space charge solvers. Using 2.5 D solver.
- impedance, apertures
- MADX sequence parser
- parallelism via MPI
- established user community

Some Issues:

- dp/p increases at transition. Transverse tunes and chromaticities must be set carefully a-priori.
- γ_t implicitly defined by lattice; must be known very precisely a-priori. Precise value can be sensitive to magnet slicing (integration scheme).
- inflexible mechanism to handle rfcurve and phase jump timing.
- In presence of a very lossy impedance, the beam phase no longer coincide with the single particle synchronous phase and is not known a-priori. Modifications needed to dynamically redefine the phase reference.
- no built-in support for feedback

SIMPLE PHASE JUMP

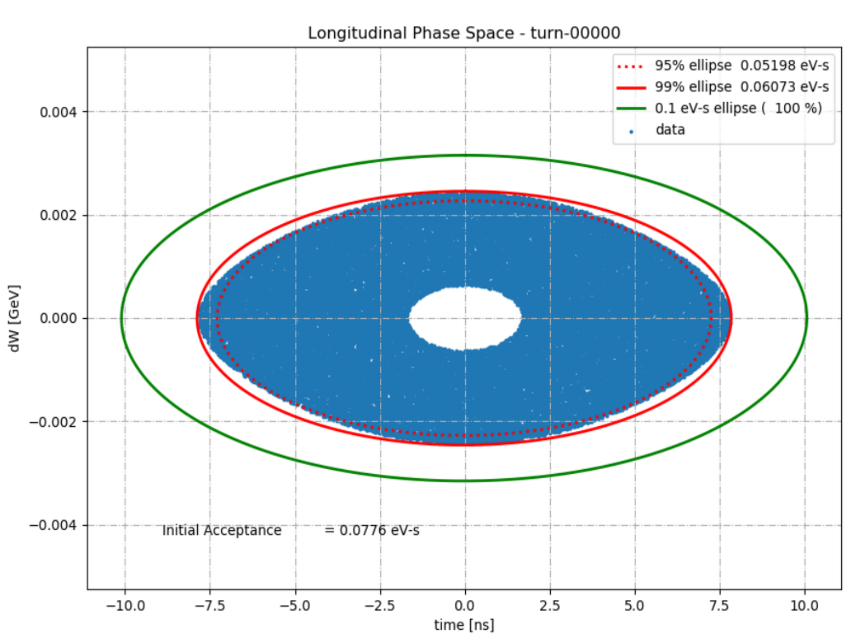

Figure 3: Initial longitudinal phase space. The hollow region is obtained by painting so as to reduce the peak line density.

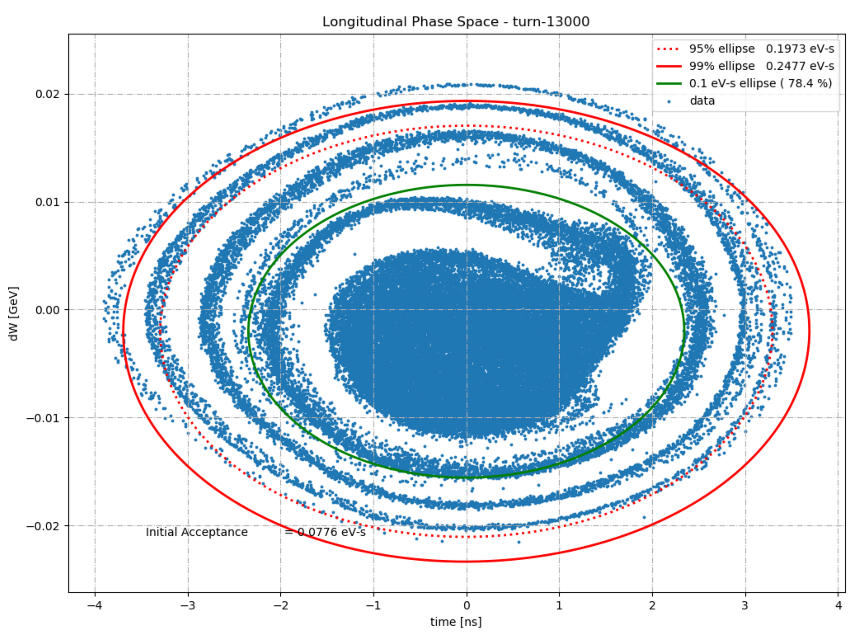

Figure 4: Longitudinal phase space near the end of a cycle assuming a simple phase jump at transition. The 95% emittance increases from 0.06 to 0.197 eV-s. The PIP-II requirement is 0.1 eV-s.

QUADRUPOLE DAMPER

In current operations, the Booster relies on a quadrupole mode damper to control longitudinal blowup. `PyORBIT` does not readily provide support for dampers or feedback systems so we implemented a simple model of the existing system. By taking 2nd moments of the Vlasov equation, on can show that in the linear approximation the bunch length obeys the following differential equation

$$\frac{d^2}{dt^2}\Delta\sigma_\phi^2 + 4\omega_S\Delta\sigma_\phi^2 = -2\omega_S\sigma_0^2\epsilon(t)$$

where ω_S is the synchrotron frequency, σ_0^2 is the matched (equilibrium) bunch length, $\Delta\sigma_\phi^2 = \sigma_\phi^2 - \sigma_0^2$ and $\epsilon(t) = \frac{\Delta V}{V}$ is an rf voltage modulation. If one uses as modulation a signal proportional to the derivative of the second moment

$$\epsilon(t) = \frac{2\xi}{\sigma_0\omega_S}\frac{d}{dt}\Delta\sigma_\phi^2$$

where $0 < \xi < 1$, the differential equation becomes

$$\frac{d^2}{dt^2}\Delta\sigma_\phi^2 + 4\omega_S\frac{d}{dt}\Delta\sigma_\phi^2 + 4\omega_S\Delta\sigma_\phi^2 = 0$$

This is a standard second order ODE; its solution is a damped oscillation with damping time $\tau = \frac{1}{2\xi\omega_S}$. In the code the damper is implemented at the python level by taking a properly scaled and filtered version of the derivative of the envelope of the second moment signal to modulate the rf cavity voltage.

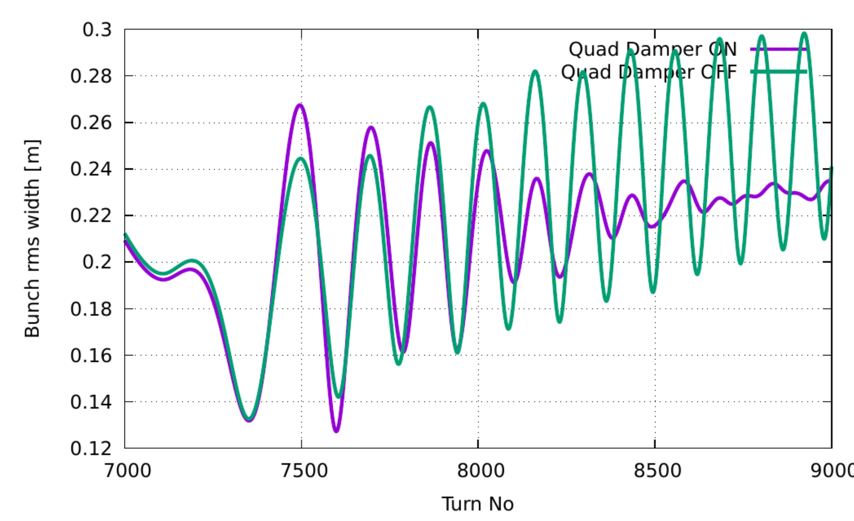

Figure 5: Quadrupole Bunch Length oscillations triggered by mismatch at transition. The damper quickly reduces the amplitude of these oscillations to reduce blowup due to phase space filamentation.

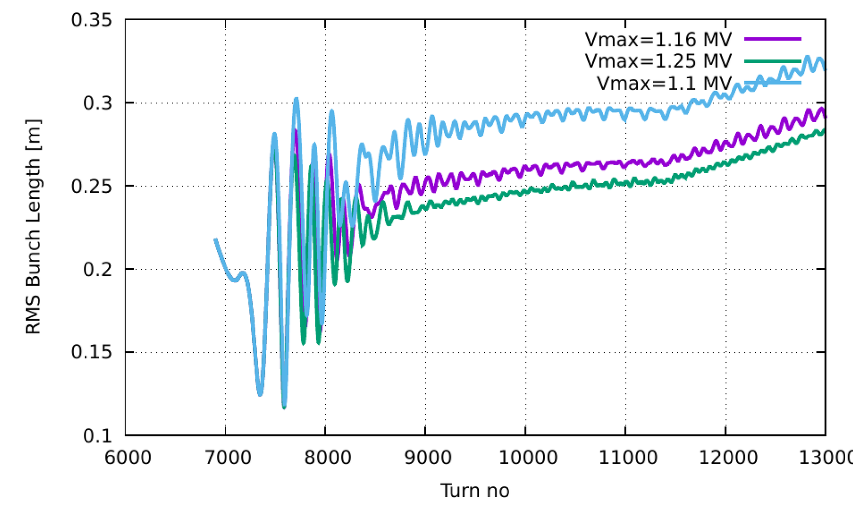

Figure 6: The damper effectiveness is improved when there rf cavities can provide sufficient modulation voltage. Assuming that the peak of the acceleration voltage curve is 1.1 MV, the curves show how the final bunch length is reduced when the max available voltage Vmax is increased.

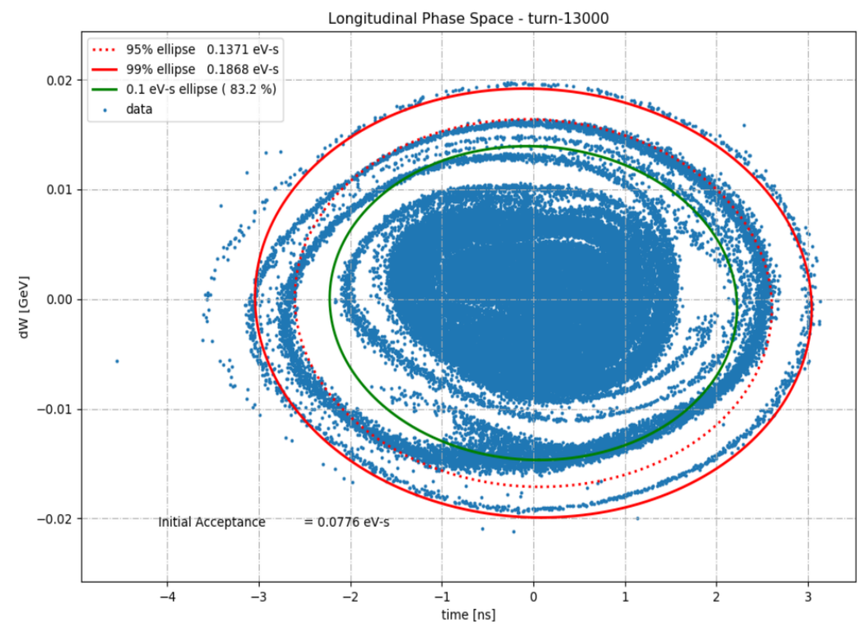

Figure 7: Longitudinal phase space shortly before the end of the acceleration cycle. The quadrupole damper is ON. Compared to a simple phase jump, the final 95% emittance has been reduced from 0.197 to 0.137 eV-s.

PSEUDO-γ_t JUMP

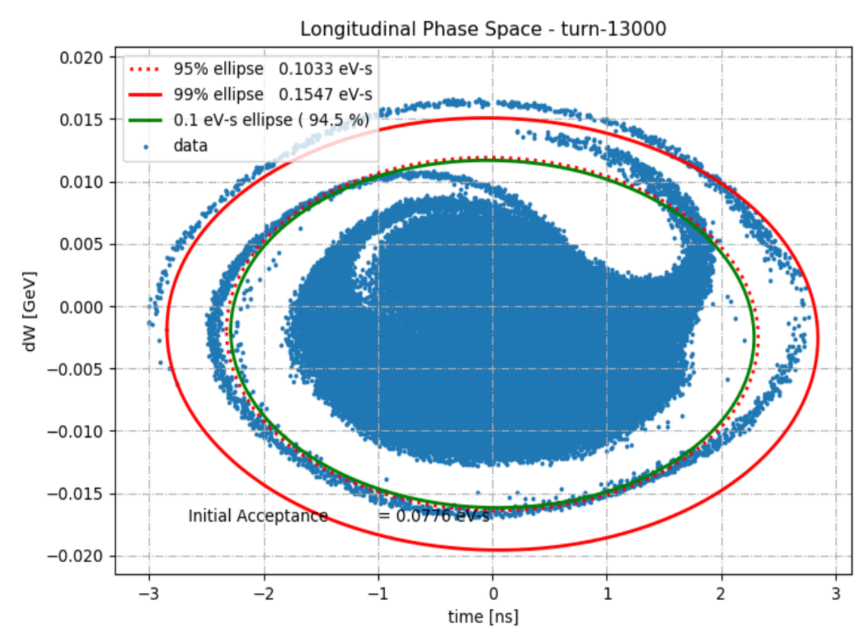

Figure 8: Longitudinal phase space shortly before the end of the acceleration cycle. In this example a ~ 0.6 unit "pseudo-gammat" obtained by pulsing existing quadrupole correctors has been employed to limit the emittance blowup. The quadrupole damper is OFF. Compared to a simple phase jump, the final 95% emittance has been reduced to 0.103 eV-s.

CONCLUSION

We demonstrated full cycle tracking simulations using the code `PyORBIT`. Albeit based on a simplified model, the simulation predicts that using the existing quadrupole damper, the Booster longitudinal emittance would come slig htly above the PIP-II requirement. To further reduce emittance blowup, a possible scenario would be to combine the quadrupole damper with a weak γ_t jump based on pulsing existing correctors. Both experimental and simulation work are on-going to determine the viability of this approach.

References

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[2] H. Klingbeil *et al.*, Modeling Longitudinal Oscillations of Bunched Beams in Synchrotrons, doi:10.48550/arXiv.1 01.3957

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