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Observation of a Synchro-Betatron Instability in Fermilab Booster

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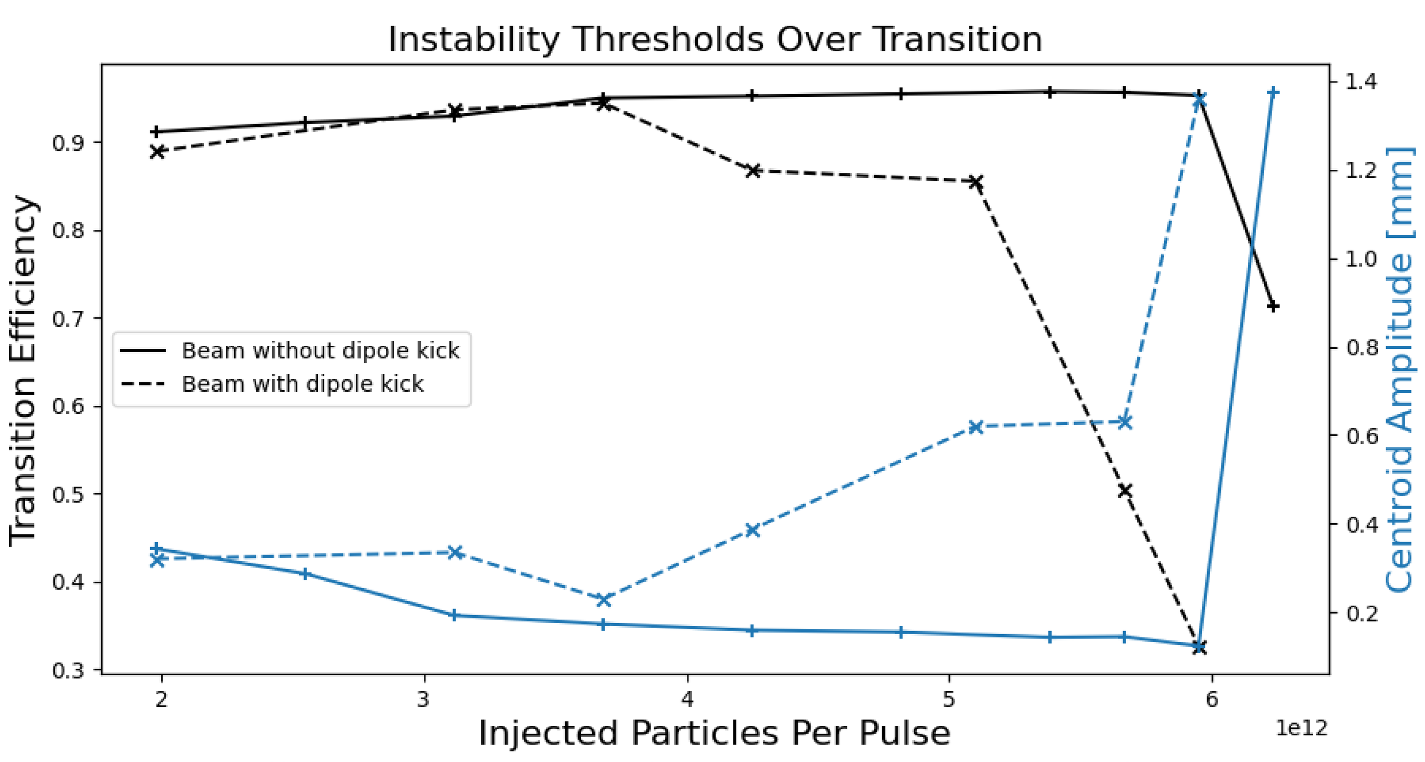
Abstract

In preparation for PIP-II, there has been interest in running the Fermilab Booster at a higher current more indicative of the PIP-II era operation. In July 2023, an experiment was performed to study collective instabilities over the transition crossing at the Fermilab Booster. Over the transition crossing, the synchrotron tune becomes small and synchro-betatron instabilities become possible. During the experiment, an intensity threshold was observed, above which a dipole instability with losses concentrated in the tail of the bunch. These losses are consistent with the Convective Instability.



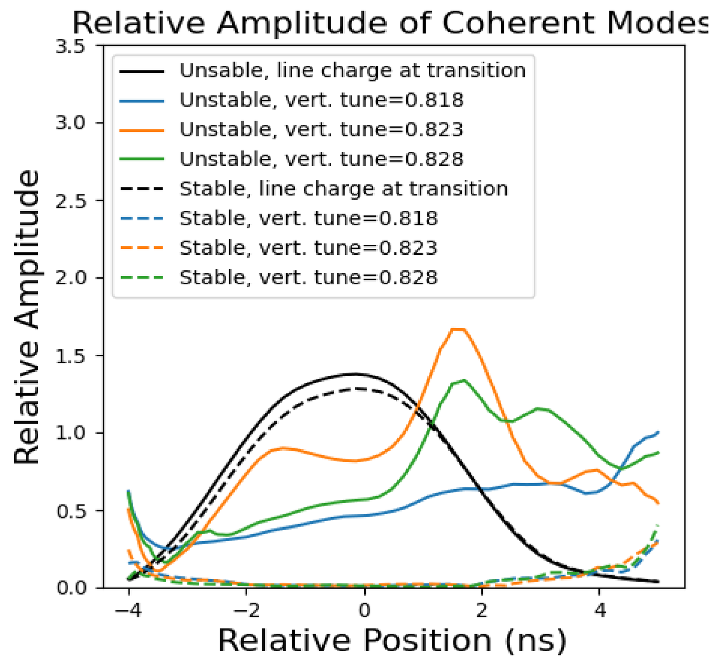
Transition efficiency (proportion of particle lost over transition) and the dipole amplitude of the bunch centroid. Although the centroid amplitude is small, it not homogeneous, with a larger amplitude at the tail of the bunch.

Below are a series of figures showing the line charge, dipole moment, and transverse distribution along the length of a bunch as it crosses transition.

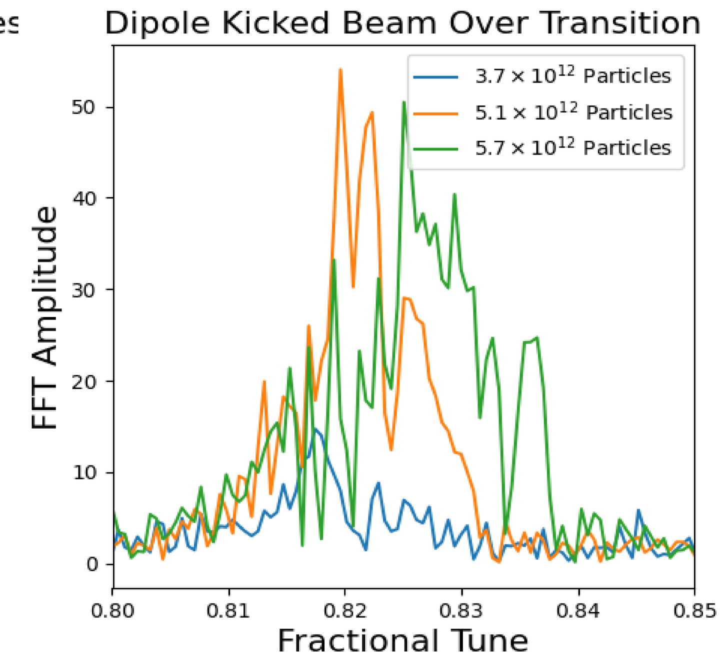
I. Prior to transition the intensity and dipole moment are well behaved and vary little.
II. After transition (~800 turns into oscilloscope window), the dipole moment increases and has maxima near the tail of the bunch. Particle losses are highest in tail and bunch deforms.
III. Particle losses continue. Although losses occurred in tail, synchrotron motion shuffles losses around bunch.
IV. Beam loss concludes. Dipole motion of bunch is larger than before transition. Uneven losses along bunch drive longitudinal dipole signal in bucket.

Head-Tail Amplification

Beyond an intensity threshold, beam losses and transverse dipole oscillations spike. Loss is focused around the bunch tail which has a larger oscillation amplitude than the head. This same head tail amplification can be seen for bunches at high intensity (but below threshold) beams have a similar structure when given a dipole kick. Dipole excited drives the normally suppressed modes making head-tail amplification visible.



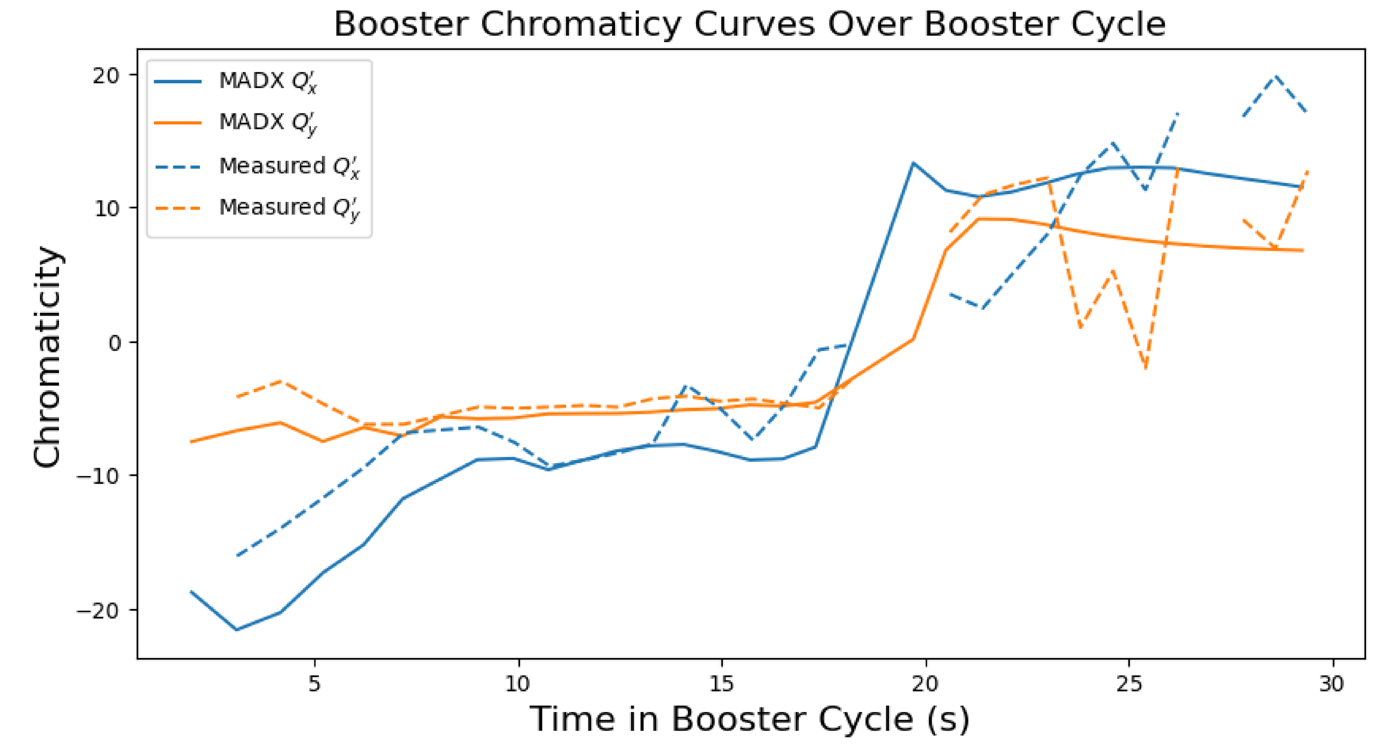
Relative Amplitudes of coherent modes above and below instability threshold. Note that tail amplitude significantly larger than at the head.



Betatron spectra of beams at varying intensities. Due to synchrotron motion, transverse dipole oscillations are sum of coherent modes and shift with intensity

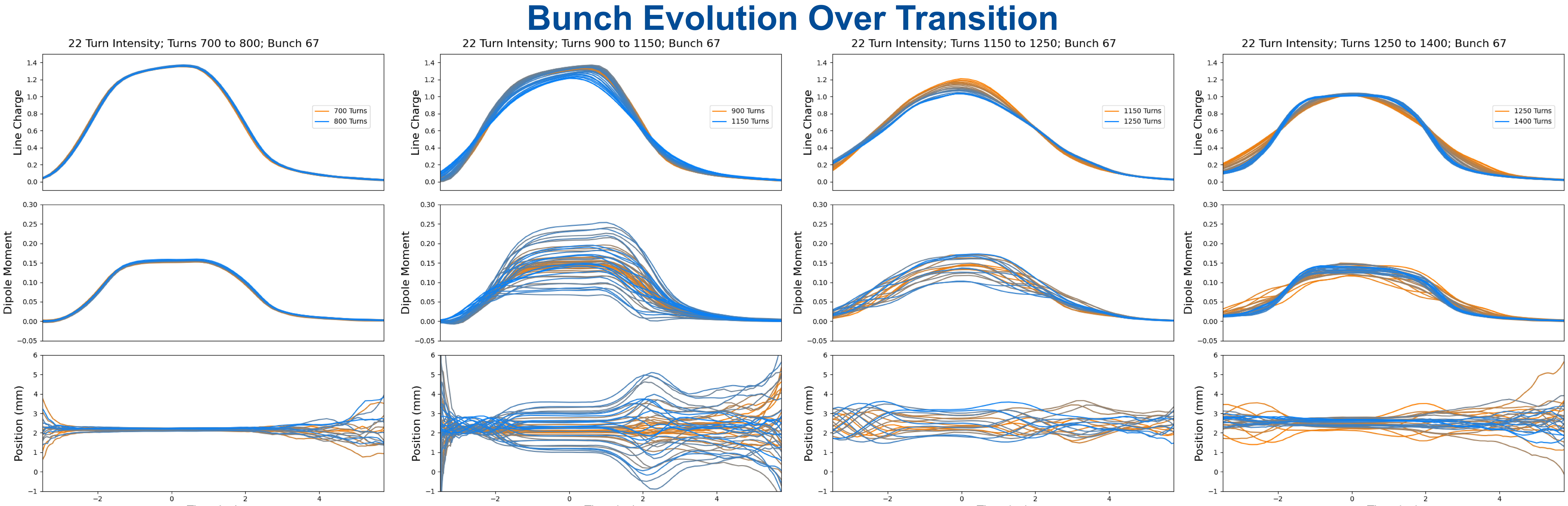
Measurements were taken with dipole stripline pickup. The dipole signal was sampled at 0.2 ns samples and in a 4m window around beam transition where losses are observed.

The corrector ramps are hand-optimized with chromaticity crossing zero near transition. Adjusting chromaticity to be nonzero near transition may weaken the observed instability but may also drive others. Systematic experiments needed to characterize chromaticity tuning at high-intensity.



Chromaticity over a booster cycle. For beam stability, chromaticity crosses zero near transition.

Bunch Evolution Over Transition



I. Stable Motion

II. Transverse Exponential Growth

III. Particle Loss

IV. Instability Stabilization