LONGITUDINAL EMITTANCE GROWTH IN THE FERMILAB BOOSTER SYNCHROTRON

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Abstract

In order to shorten the proton bunches in the Fermilab Tevatron Collider, it would be quite helpful to reduce the longitudinal emittance for proton bunches generated by the Booster Synchrotron. A study was undertaken to re-evaluate the sources of longitudinal instability and resultant longitudinal emittance growth as a function of Booster beam and bunch currents. Employing a novel technique for generating partially populated circumferences of protons, the Booster was tested to understand whether increased longitudinal emittance growth was correlated with total current in the synchrotron, consistent with coupled-bunch instability, or with the number of protons per individual bunch. This paper will present findings that indicate that the instability responsible for poor Booster emittance performance is consistent with single bunch (or low cavity-Q) instabilities.

MOTIVATION

The formation of the 36 proton bunches required for Fermi National Accelerator Laboratory (Fermilab) Tevatron Collider operations [1] requires that several proton bunches spaced at 53 MHz are coalesced [2] into a single high intensity bunch with correspondingly large longitudinal emittance. It was proposed to reduce the longitudinal emittance of the Collider proton bunches by performing an alternative coalescing scheme at injection of the Main Injector [3]. Because of large coherent longitudinal oscillations in the bunches from the Booster ring [4], it was necessary to step back into the Booster to understand the origin of these oscillations and to find methods of reducing them.

BOOSTER BACKGROUND

Negatively charged atomic hydrogen is injected from the Fermilab Linac into the Booster at a kinetic energy of 400 MeV. The Linac pulse length is equal to an integer number of Booster revolution periods, or "turns". By stripping the electrons during the injection process, multiturn injection of protons is accomplished without significant emittance dilution.

The Booster ramps to a peak kinetic energy of 8 GeV in 33 msec due to the resonant 15 Hz power supplies driving the magnet system. The RF frequency that accelerates the beam swings from 37.6 MHz to 52.8 MHz. The beam feedback loops that control the RF frequency and synchronous phase ramps rely on the fact that all 84 RF buckets are filled with beam (with the recent upgrade that a few bunches can be empty to accommodate an extraction kicker risetime gap to minimize beam losses and reduce tunnel losses. Transition crossing occurs at roughly halfway through the ramp.

FULL BATCH OPERATIONS

It was found in the Main Injector [3] that the bunch length and coherent longitudinal oscillations increase little as the ring intensity increases from one to four turns, but after that, they grow quickly to the operational maximum of 12 Booster turns.

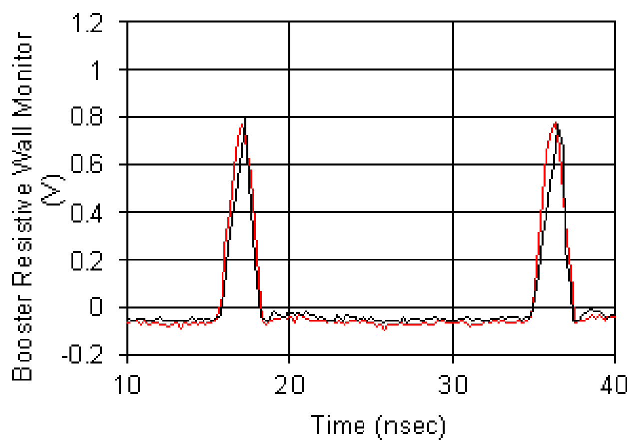

Figure 1: Two bunches on a single revolution before transition crossing. The black trace corresponds to two Booster turns. The red trace corresponds to twelve Booster turns, with the bunch area scaled down to that of two turns. Note that the 95% bunch lengths are identical.

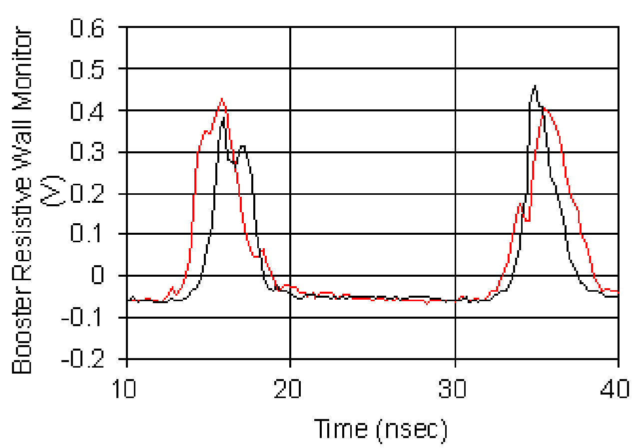

Figure 2: Two bunches on a single revolution after transition crossing. The black trace corresponds to two Booster turns. The red trace corresponds to twelve Booster turns, with the bunch area scaled down to that of two turns. Note that the 95% bunch lengths are now quite different, with the higher intensity bunches being wider.

Figures 1 and 2 show the difference in bunch length with beam intensity before and after transition. Clearly the problem of increasing longitudinal emittance with beam intensity occurs near transition crossing.

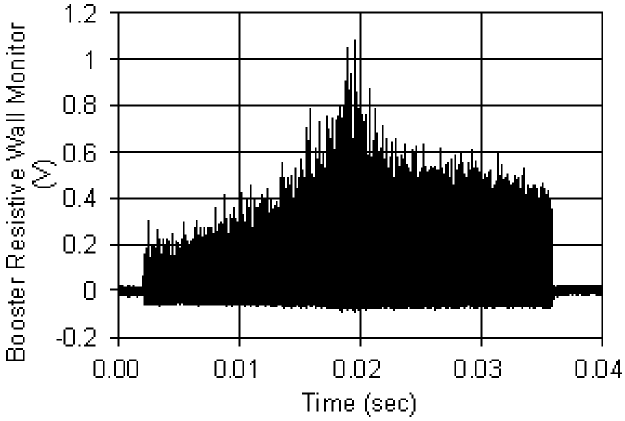

Figure 3: Peak current throughout the Booster acceleration cycle for two Booster turns. The noisiness of the data is not instrumental.

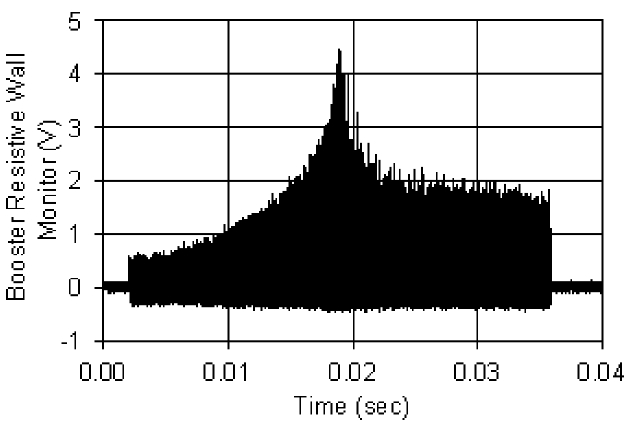

Figure 4: Peak current throughout the Booster acceleration cycle for twelve Booster turns.

Figures 3 and 4 are measurements of the peak bunch current throughout the Booster acceleration cycle. From this resolution, the difference in bunch length is not apparent. On the other hand, note that the ratio of final to initial peak current is nearly 2x for both two and twelve Booster turns of intensity.

Figures 5 and 6 show the variation of peak current with time after transition. Note that these oscillations are caused by bunch length oscillations, and violent ones at that. There are two conclusions that can be gleaned from these figures. First, the relative amplitudes of these oscillations is quite similar between two and twelve Booster turns, suggesting that it is not an intensity dependent effect. Second, the existence of such large low-intensity mismatches through transition should be a key priority in any future effort to minimize the longitudinal emittance of proton bunches injected into the Main Injector. Unfortunately, these investigations were terminated by Fermilab before the cause of this effect was fully understood.

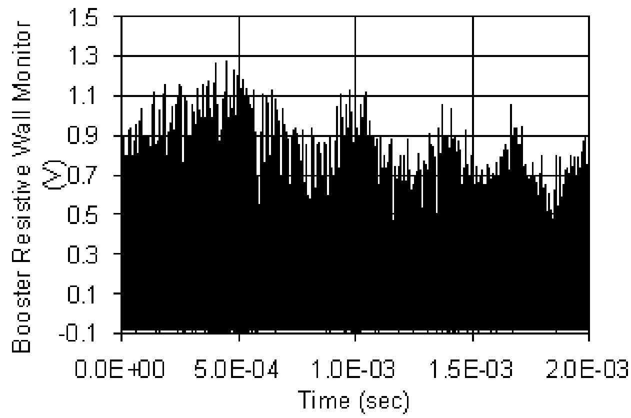

Figure 5: Peak bunch current after transition (which occurs at 0.5 msec in the figure) at a beam intensity of 2 Booster turns.

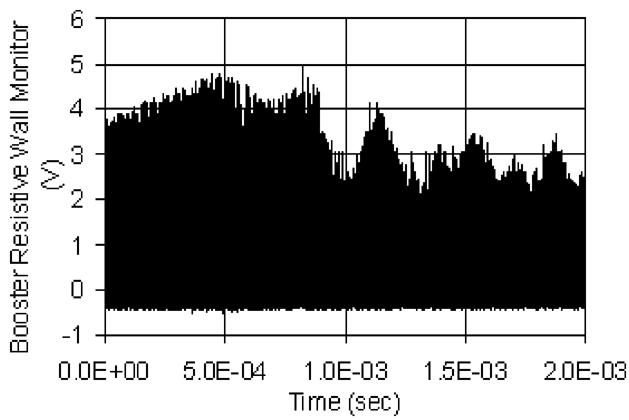

Figure 6: Peak bunch current after transition (which occurs at 0.5 msec in the figure) at a beam intensity of 12 Booster turns.

PARTIAL BATCH OBSERVATIONS

In order to diagnose the cause of the high intensity emittance dilution in figure 2, the author suggested a novel method for determining whether the intensity dependence was due to the total current in the Booster or the intensity per bunch.

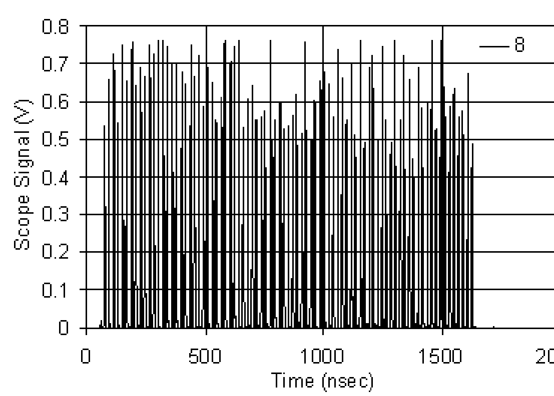

Figure 7: Full batch injection into the Main Injector at eight Booster turns of intensity. Note the variation of peak bunch current over the 82 (out of 84) bunches that are transferred by the extraction kickers.

It is known that the RF feedback loops can operate at one Booster turn of intensity, and that they have sufficient dynamic range to also accelerate twelve Booster turns. Therefore, with injection controls set for 12 Booster turns, one of the extraction kickers was fired just after turn 11. In comparison to full batch (a batch is a set of 84 bunches extracted from the Booster) injection into the Main Injector shown in figure 7, figure 8 shows the result of partial batch acceleration and extraction in the Booster.

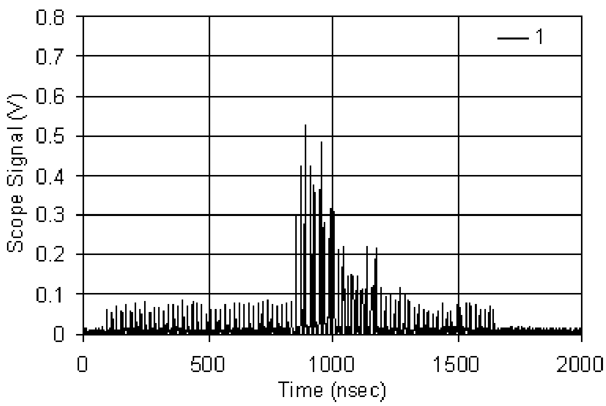

Figure 8: Partial Booster batch injection into the Main Injector. Booster injection was set to eight turns, and the extraction kicker allowed one turn to remain in the full circumference to allow the low level RF feedback loops to operate. Note that the peak current is lower than in the full batch case of figure 7.

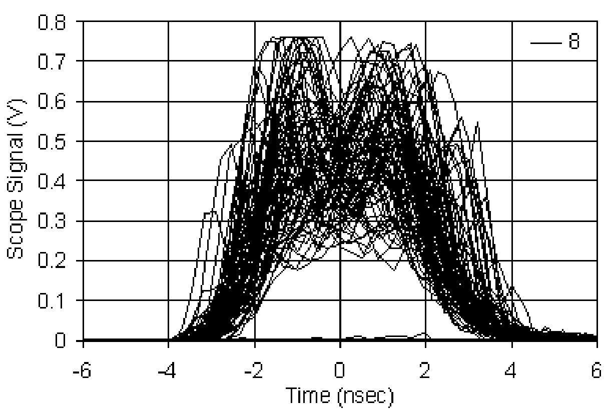

Figure 9: Overlap of 82 bunches injected into the Main Injector after normal full batch acceleration of eight Booster turns of intensity.

Individual bunches were resolved by recording the first turn in the Main Injector using a LeCroy digital scope connected to a resistive wall monitor. By knowing that the injection RF frequency is 52.811400 MHz, Microsoft Excel was used to overlap their profiles. For example, a full batch at eight Booster turn intensity is shown in figure 9. The number of intense bunches during partial batch operations is determined by the fact that the extraction kickers are shorter than a single revolution at the injection revolution frequency. The extraction kicker was fired on revolution 7 out of 8 during the Booster injection sequence. It was observed that the dozen intense bunches had the same bunch length and erratic shape as a full batch of beam at the same bunch intensities. This suggests that the cause of the longitudinal emittance problems above four Booster turns depends on the intensity per bunch, and not the total current in the Booster. This further suggests that the standard blame on longitudinal coupled bunch instabilities is incorrect. Because the bunch lengths are independent of intensity before transition, space charge at injection is clearly also not the culprit.

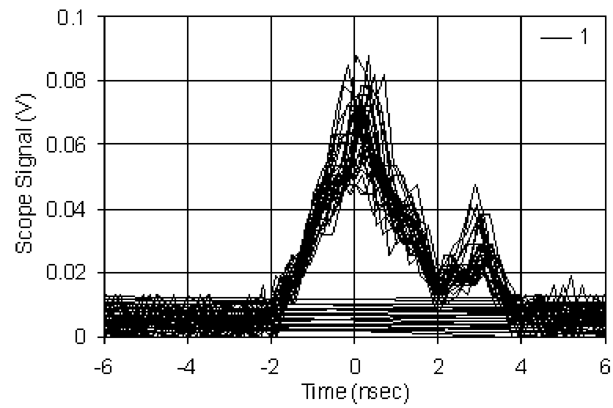

Figure 10: Low intensity stabilization bunches after the intense bunches during partial batch operations.

One outstanding mystery is the distortion of the low intensity stabilization bunches directly after the intense bunches. One unlikely explanation is a wakefield at the third harmonic of the RF frequency at half its amplitude.

ACKNOWLEDGEMENTS

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