FERMILAB BOOSTER TRANSITION CROSSING SIMULATIONS AND BEAM STUDIES *

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Abstract

The Fermilab Booster accelerates beam from 400 MeV to 8 GeV at 15 Hz. In the PIP (Proton Improvement Plan) era, it is required that Booster deliver 4.2×10^{12} protons per pulse to extraction. One of the obstacles for providing quality beam to the users is the longitudinal quadrupole oscillation that the beam suffers from right after transition. Although this oscillation is well taken care of with quadrupole dampers, it is important to understand the source of these oscillations in light of the PIP II requirements that require 6.5×10^{12} protons per pulse at extraction. This paper explores the results from machine studies, computer simulations and solutions to prevent the quadrupole oscillations after transition.

INTRODUCTION

The Fermilab Booster was built in the 1970s [1] and will remain the workhorse for the PIP (Proton Improvement Plan) II era for many years until it is replaced. From the start of its operational life to the present (2016), the beam flux per hour through it has increased by an order of magnitude. See Fig. 1. The goal of PIP is to provide 4.2×10^{12} protons per pulse at extraction. And in the PIP II era, Booster is required to provide 6.5×10^{12} protons per pulse at extraction. There can be many show stoppers that prevent us from achieving the PIP II goals. [2] One obstacle that we have identified is transition crossing.

The traditional belief at Fermilab is that transition crossing in Booster is dominated by space charge effects or other beam intensity effects. [3–5] Many simulations have been done to reproduce measurements and to suggest methods to help the beam cross transition properly. However, from what we can see, these simulations only use a select few Booster beam pulses for comparison which we have found to be very naïve. In our experience, there is sufficient pulse to pulse variation in any measurement that we need to have a large enough sample set to actually be able to have any insight into the problem.

Therefore, in order to avoid the pitfall of using too few data sets, we have collected sufficient Booster transition crossing data for our analysis. We will use this data to generate a hypothesis as to what causes the beam to suffer from quadrupole oscillations after it crosses transition. We will then test our hypothesis with computer simulations. And finally, we will suggest methods for mitigating this problem.

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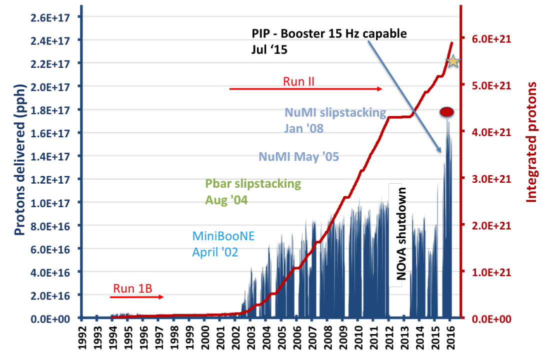

Figure 1: The proton flux per hour in Booster increased from $< 10^{16}$ to $> 10^{17}$ over a decade.

MOTIVATION

One of the recent striking observations that led to suspect the traditional lore mentioned earlier was that the amplitude of the longitudinal quadrupole oscillations measured with a wall current monitor (Fig. 2) did not scale at least as a quadratic w.r.t. beam current, I_b. (Note: it is quadratic because we are using a wall current monitor to measure the quadrupole oscillations and thus the measured amplitude contains a factor of I_b. For example, the emittance growth from space charge effects has another factor of I_b. [6]). In fact, it looked like the amplitude of the quadrupole oscillations was independent of I_b after normalizing the measured amplitude w.r.t. I_b. An example of what we saw is shown in Fig. 3 for 4.5×10^{12} and 2.5×10^{12} protons per Booster batch where the quadrupole dampers have been set to a very low gain value (0.1 units). These plots trace the evolution of the I_b normalized $2\times$ synchrotron peak during the ramp. We noticed that the maximum amplitude of the quadrupole peak is ~0.5 units in both cases and is independent of I_b.

These observations motivated us to investigate whether the source of quadrupole oscillations is, in fact, a bucket mismatch rather than from space charge or other beam intensity effects.

DATA COLLECTION AND ANALYSIS

The wall current data clearly exhibits quadrupole oscillations after transition. In order to clearly see these oscillations, the data has to be processed to reveal the amplitude modulation. This is easily done by peak detecting the data. Two examples of the wall current data after peak detection and filtering is shown in Fig. 4.

The plots shown in Fig. 4 were taken with the quadrupole dampers on and with $\sim4.5\times10^{12}$ protons. Under these

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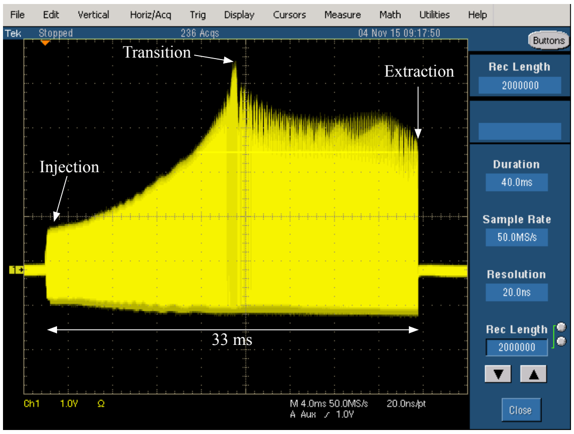

Figure 2: The wall current signal for the entire ramp as seen on an oscilloscope. There is clearly a quadrupole oscillation after transition.

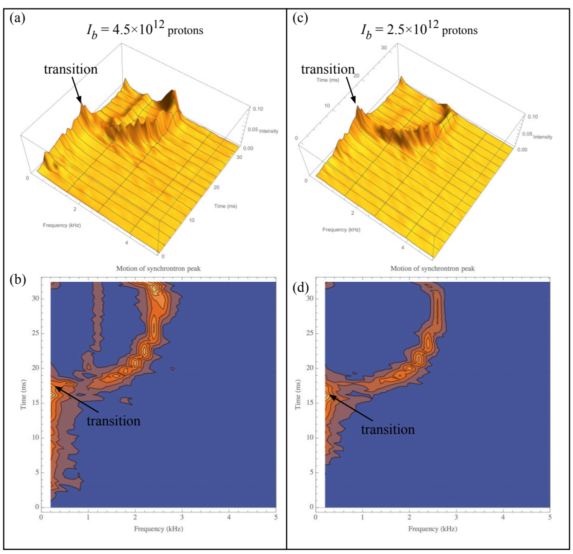

Figure 3: The motion of the intensity normalized 2× synchrotron peak during the ramp. The quadrupole dampers have been set to a very low gain value (0.1) in these plots.

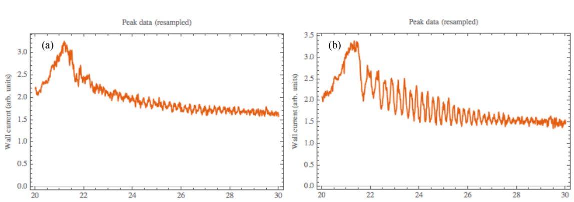

Figure 4: These plots show the envelope of the beam current after processing. Both (a) and (b) were taken with the quadrupole dampers on and beam current $\sim 4.5 \times 10^{12}$ protons.

supposed same conditions, it is obvious, that their behaviors are quite different at transition crossing. These two plots demonstrate that it is important to take multiple data sets rather than just rely on a few. The variations in their behavior can be traced back to the capture process and to the jitter of the Booster dipole ramp. The former is less likely because we have made the capture more adiabatic recently [7].

Jitter in the Booster Dipole Ramp

The Booster dipole ramp comes from a 15 Hz resonant circuit. The Booster RF is not a function of the dipole ramp. Instead its frequency ramp is triggered with an event called `TCLK`. Since these two systems are not tied together, there is a difference between the true transition time, which is determined by the energy of the ramp, and where the RF thinks it should execute its transition phase jump. Thus, there is a jitter between `TCLK` and the zero crossing of the Booster ramp. Its distribution is shown in Fig. 5.

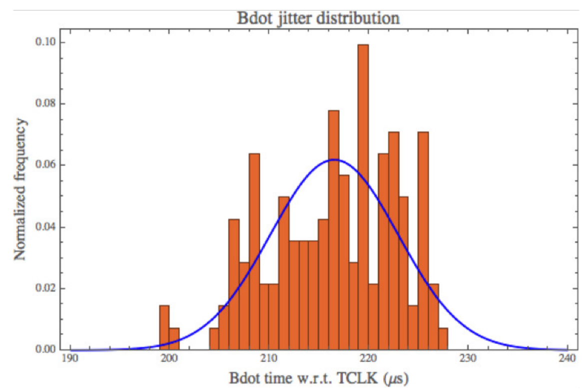

Figure 5: This shows the jitter between the zero crossing of the magnet ramp (Bdot) and the `TCLK` event.

From the measured data, we found that the base spread of the zero crossing of the Booster ramp (Bdot) and the `TCLK` event is about 30 μs with a mean value $\pm 6.4\mu$s. However, this jitter can introduce an error as much as ±10 Booster turns at transition!

Quantifying the Mismatch

We will parameterize the mismatch by taking the ratio of the first quadrupole peak to the transition peak. The advantages of doing this are that the strength of the wall current signal is normalized and any later bunch evolution effects do not affect it. An example of how we get the ratio is shown in Fig. 6.

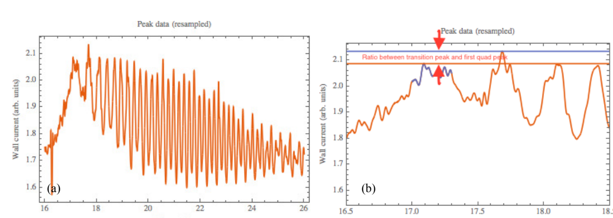

Figure 6: (a) This is an example of the envelope of the modulation with the quadrupole dampers turned off (b) The quantification of the mismatch is the ratio between the first quadrupole peak and the transition peak.

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Measurement Results

We took data at two different intensities 2.5×10^{12} protons (8 Booster turns) and 5.2×10^{12} protons (16 Booster turns) as a function of RF transition time setting. This time, we turned off the quad damper on all measurements to avoid any bias arising from the dampers. More than 10 data sets were collected for each RF transition time setting. All the data were then processed to get the ratio between the first quadrupole peak and the transition peak. The results are shown in Fig. 7. It is clear from this figure that both data sets have the same minimum value but shifted, irrespective of the beam intensities. We interpret that this shift comes from beam loading of the cavities. Next, we can also see that the spread of the data at each RF transition time setting tells us that we have to collect enough data before performing any analysis. Insufficient data can lead us to the wrong conclusions if we are not careful.

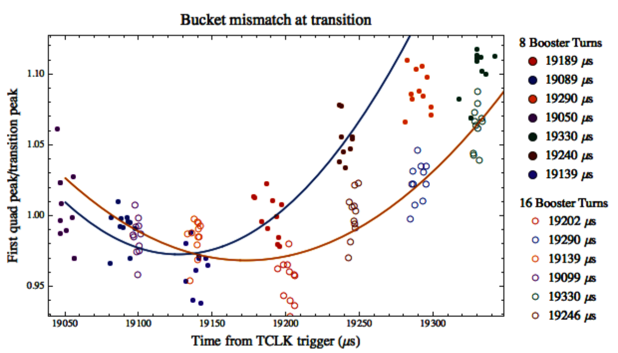

Figure 7: The ratio the transition peak to the first quadrupole peak of 8 BT and 16 BT are plotted here. The quadratic curves are used for guiding the eyes only.

Finally, we can form a hypothesis from the data. Our interpretation of these measurements is that space charge or beam intensity effects are not the dominant source of the quadrupole oscillations because there are no obvious I_b dependent effects. Therefore, our hypothesis is that bucket mismatch is the culprit.

SIMULATIONS

We have carried out 2D longitudinal beam dynamics simulations using ESME [8] to study the variation of peak current by taking into account the longitudinal space charge effects in our simulation model. The self-impedance per revolution harmonic n arising from space charge in a beam traveling in a perfectly conducting beam pipe is modeled as,

$$\frac{Z}{n} = -\frac{Z_0[1 + 2ln\left(\frac{b}{a}\right)]}{2\beta\gamma^2} \tag{1}$$

and by relating the Fourier coefficient of the space charge energy increment with that from the beam current. Where Z_0, a and b are impedance of free space (=377 Ω), beam pipe radius and average beam radius, respectively. We do not include any other impedances like impedances from resistive wall or RF cavities/bellows etc. It is important to notice that the Booster does not have any beampipes in the region of the dipoles. So, we have to take extra precautions when specifying the radius of the beampipe. We use $\gamma_T = 5.4782$ for the transition gamma for the Booster lattice. We assume that the beam and beam pipe radius to be 1.0 cm and 2.86 cm, respectively. The simulations were carried out as follows: (1) Inject LINAC beam pulses with 200 MHz structure. Each bunch is populated with parabolic distribution with $\Delta E \approx$ 1.4 MeV [9]. (2) Assume beam intensities of 3×10^{12} and 6×10^{12} protons/Booster batch. (3) Capture the beam iso-adiabatically. The observed emittance growth was about 20% during capture. (4) The beam is accelerated on a sinusoidal magnetic ramp up to about 6.8 GeV, which is well beyond the transition crossing. (5) Assumed one-turn RF phase jump near transition. These simulations were repeated at various values of slip factor, η, around the transition energy which are indicated in Fig. 8.

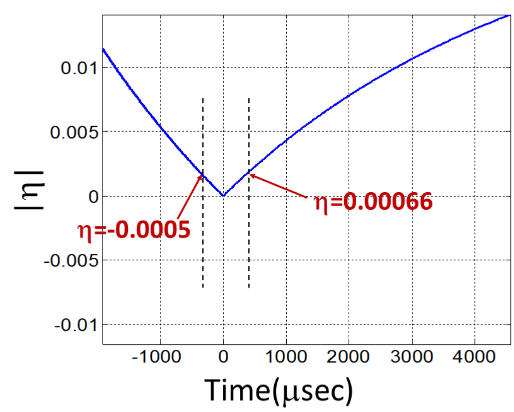

Figure 8: Absolute values of η versus time around transition. The minimum value on the curve corresponds to$|\eta| = 0$. The range of η used for the simulations are indicated by the dashed lines.

Figure 9 shows the simulated peak currents and its oscillations after transition crossing. The predicted oscillations of the peak current (which comes from bunch length oscillations) is certainly due to bucket mis-match. Simulations also show beam particle losses if the phase jump is forced to be far away from $\eta = 0.0$, this is consistent with measurements though we do not know exactly when $\eta = 0.0$. In any case, simulations show that if we go up in intensity from 3×10^{12} protons/Booster batch to 6×10^{12} protons/Booster batch we do not see the change in the amplitude of the oscillations which would scale with intensity if the space charge force plays a dominant role. This feature is very similar to the measurement that we have shown in Fig. 10.

Finally, we compare measurement data with predictions. The comparison shows oscillations that have similar features both in amplitude and phase despite our lack of knowledge about when $\eta = 0.0$ exactly occurs in our measurements. In this presentation, we have aligned the first two peaks where

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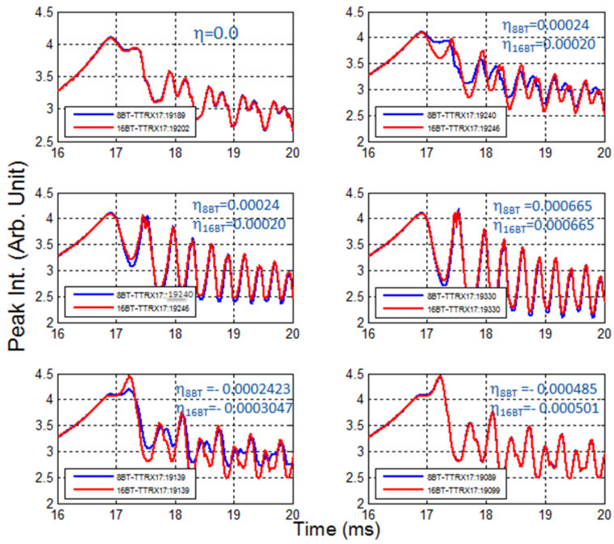

Figure 9: Simulated peak currents as a function of acceleration time for various slip factors around the transition energy. The blue curve is 3×10^{12} and the red curve is 6×10^{12} protons per Booster batch.

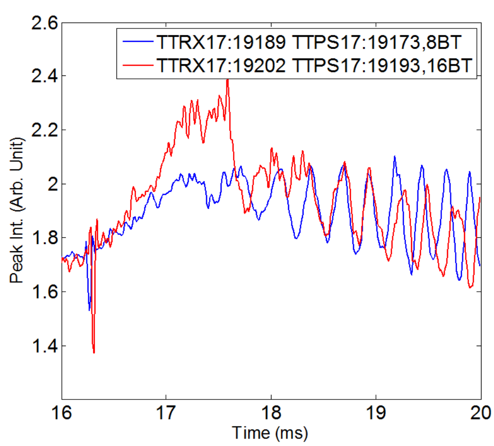

Figure 10: Measured peak intensity oscillations for the optimal settings of transition phase jumps with quad-dampers off for 2.7×10^{12} protons/Booster batch (blue) and 5.2×10^{12} protons/Booster batch (red).

the bunch length is minimum. Our comparisons for 2.7×10^{12} protons/Booster batch and 5.2×10^{12} protons/Booster batch are shown in Fig. 11. In both cases, the measured frequency of the oscillations are higher than what we have predicted. This needs further investigations.

MITIGATION

From our measurements, the cause of the oscillations after transition crossing in the Booster comes from multiple sources. The dominant sources are: (1) Bdot jitter. See for example Fig. 7 and (2) phase mismatch (see for Fig. 9). The source of the Bdot jitter can be traced to the variation in the magnetic ramp due to changes in the ComEd power line

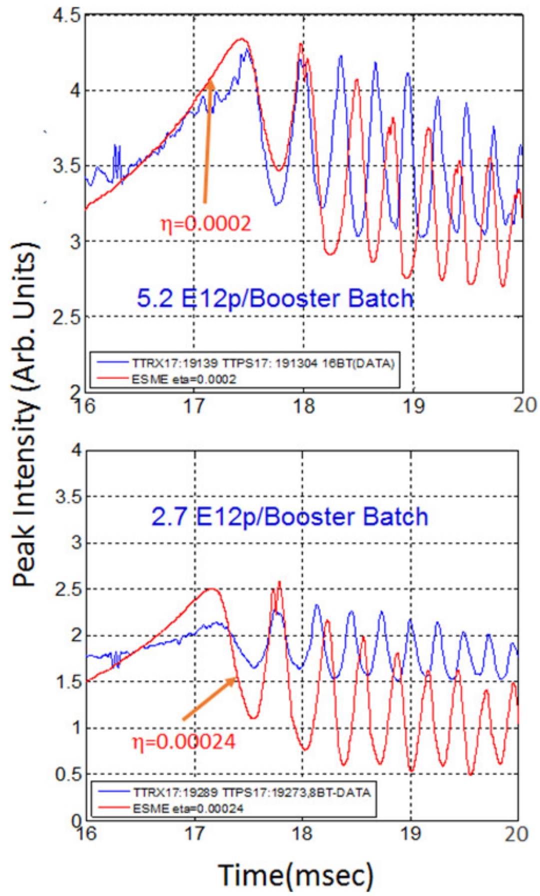

Figure 11: Measurement data compared with simulations. In the absence of information on measurement data on $\eta = 0.0$, we compare data with simulation in a rather random way based on similar features on oscillations. Exact comparison needs further information on measurements on timings of$\eta = 0.0$

frequency which is of the order of 100 mHz out of 60 Hz. Since the Booster magnets have a 15 Hz sinusoidal ramp that is derived from ComEd, the power line frequency errors introduce both time and amplitude jitters of the order of 50 μsec in the minimum magnetic field, $B_{\min}$, (as well as at the maximum magnetic field, $B_{\max}$) relative to the beam injection time. This in turn introduces time jitter to the transition RF phase jump leading to the oscillations. Our observations clearly show a cycle dependent factor in the bunch length oscillation amplitudes which is much larger than any other effects, in particular beam intensity. Currently, R&D for mitigating the Bdot jitter is being carried out. To correct for the phase mismatch, we are making improvements to the LLRF (low level RF) to incorporate transition phase jumps based on RF frequency rather than on the "start of cycle" event from the clock system (`TCLK`). Since our measurement data shows longitudinal space charge is not an issue at beam intensities of the order of 5.5×10^{12} (supported by simulations), we have extended our simulations to higher beam intensities. From these simulations, we have found that we

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can increase beam intensities by more than 50% from the current maximum operational beam intensities without any quadrupole oscillation problems due to space charge. The higher intensity simulations are above the baseline beam intensity limits set by the PIP-II design [2].

CONCLUSION

Our measurements and simulations show that the leading cause of the quadrupole oscillations after transition come from bucket mismatch and not from space charge or beam intensity effects. In addition, because of Bdot jitter there is significant variation in the bucket mismatch from cycle to cycle. To mitigate these oscillations we have proposed two solutions — not any one by itself can solve the problems; both of them need to be in place for better performance of the Booster and intensity upgrades.

ACKNOWLEDGMENTS

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