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 $4.2 \times 10^{12}$ 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 $6.5 \times 10^{12}$ 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 $4.2 \times 10^{12}$ protons per pulse at extraction. And in the PIP II era, Booster is required to provide $6.5 \times 10^{12}$ 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.

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 $4.5 \times 10^{12}$ and $2.5 \times 10^{12}$ 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 ~ $4.5 \times 10^{12}$ protons. Under these conditions...
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.

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 $\mu$s with a mean value $\pm 6.4\mu$s. However, this jitter can introduce an error as much as $\pm 10$ 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.
Measurement Results

We took data at two different intensities $2.5 \times 10^{12}$ protons (8 Booster turns) and $5.2 \times 10^{12}$ 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.

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 $I_n$ 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,

$$Z_n = \frac{Z_0[1 + 2ln\left(\frac{b}{a}\right)]}{2b^2\gamma^2}$$  (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 LINCAC 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 $3 \times 10^{12}$ and $6 \times 10^{12}$ protons/Booster batch. (3) Capture the beam isodiametrically. 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, $\eta$, around the transition energy which are indicated in Fig. 8.

Finally, we compare measurement data with predictions. 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 $3 \times 10^{12}$ protons/Booster batch to $6 \times 10^{12}$ 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.

Figure 8 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 $3 \times 10^{12}$ protons/Booster batch to $6 \times 10^{12}$ 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
Figure 9: Simulated peak currents as a function of acceleration time for various slip factors around the transition energy. The blue curve is $3 \times 10^{12}$ and the red curve is $6 \times 10^{12}$ protons per Booster batch.

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

The bunch length is minimum. Our comparisons for $2.7 \times 10^{12}$ protons/Booster batch and $5.2 \times 10^{12}$ 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 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 $\mu$sec in the minimum magnetic field, $B_{\text{min}}$, as well as at the maximum magnetic field, $B_{\text{max}}$, 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 $5.5 \times 10^{12}$ (supported by simulations), we have extended our simulations to higher beam intensities. From these simulations, we have found that we
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.

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REFERENCES


