

RF COGGING IN THE FNAL BOOSTER ACCELERATOR

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Abstract

The Fermilab Booster operates at a Radio Frequency (RF) harmonic number of 84 with beam in all buckets. One or two bunches of beam are systematically lost in the 8 GeV extraction process as beam is swept across a magnetic septum during the extraction kicker rise time. The prompt radiation and component activation resulting from this localized high energy beam loss become serious concerns as Booster beam throughput must be increased more than tenfold to meet the requirements of RUN II, NUMI, and MiniBooNE experiments. Synchronizing a gap in the beam to the firing of the extraction kickers, a relatively easy and standard practice in many machines, can eliminate the problem. This seemingly simple operation is greatly complicated in the Booster by the need to synchronize extraction to beam already circulating in the Main Injector. Coupled with the inflexibility of the Booster resonant magnetic cycle, cycle to cycle variations, and constraints inherent in the accelerator physics, that requirement forces active control of the gap's azimuthal position throughout the acceleration process as the revolution frequency sweeps rapidly. Until recently, the complexities of actually implementing and demonstrating this process in the Booster had not been worked out. This paper describes a successful demonstration of gap coggling in the Booster.

1. INTRODUCTION

The Booster accelerates protons from 400MeV to 8GeV for injection into the Main Injector accelerator. The Main Injector, seven times the Booster circumference, has numerous operating modes requiring 1 to 7 batches of Booster beam per cycle. The method of synchronous transfer between the Booster and the Main Ring was historically done by extracting Booster beam upon receipt of a marker signal corresponding to the desired Main Ring bucket [1]. The extraction pulse was tuned by changing the marker delay in units of RF cycles. The risetime of the extraction kicker is approximately twice the Booster bunch spacing, resulting in 8GeV Booster beam loss. A solution to the loss would be to put a gap in Booster beam at the injection energy and then cog the gap to be synchronous with the desired Main Injector bucket marker at extraction. An analysis of Booster's acceleration process is needed to understand some of the difficulties in accomplishing a gap synchronous transfer.

2. TYPICAL BOOSTER CYCLE

Injected beam is adiabatically captured in Booster using a RF paraphasing process that takes approximately 600 us. Acceleration phase and position feedback is turned on after the beam is bunched. The Booster's time dependent radial position curve, radial gain curve, a frequency curve, and associated high level curves are triggered by clock events delivered by a 10Mhz clock distribution system. The Booster magnets are powered as part of a 15 Hz resonant circuit. The beam momentum will therefore ideally be a sinusoidal function of time:

$$p(t) = p_i + 0.5(p_f - p_i)(1 - \cos(30\pi t))$$

where p_i is the Booster injection momentum and p_f is the final Booster momentum

The magnet circuit is driven at one-fourth the power line frequency, not identically 15 Hz. The clock system has feedback to track the line frequency for slow variations. However, the clock and magnet current exhibit pulse timing variations due, at least in part, to changes in power line frequency drift that occurs on a short time scale. At about 18ms in the cycle the Booster beam goes through transition. At the end of the acceleration cycle, approximately 3 ms prior to extraction, position feedback is shut off and phase lock between Booster and Main Injector is enabled. Hardware design requires the phase lock on time to be set to the time when Booster RF is 8 kHz below Main Injector RF. The acceleration frequency changes rapidly early in the cycle with very little change occurring after transition. The synchrotron frequency also changes rapidly early in the cycle, goes to zero at transition, then levels off at about 2.5Khz for the remainder of the cycle. Booster's revolution period changes from 2.22us to 1.69us in 33ms. During the Booster cycle, the Main Injector rests at a fixed injection frequency of 52.811 MHz; its revolution marker period is fixed at seven times 1.69us. Figure 1 shows some useful RF curves plotted verses time in the Booster cycle.

3. MEASUREMENT SYSTEM LAYOUT

A measurement system was assembled to track the location of the Booster beam gap relative to the MI revolution marker throughout the Booster cycle. The measurement consists of counting the number of Booster RF cycles between each MI marker (occurring about every 10 usec) and the first Booster gap marker to follow. The measurement system was able to be tested online with

¹ Operated by the University Research Association, under contract with the U.S. Department of Energy.

actual beam signals or to be run off-line in a more controlled environment. The test setup adapted spare operational low level hardware to minimize the initial engineering setup time [2]. The system consists of a VXI crate with a Direct Digital Synthesizer (DDS), a

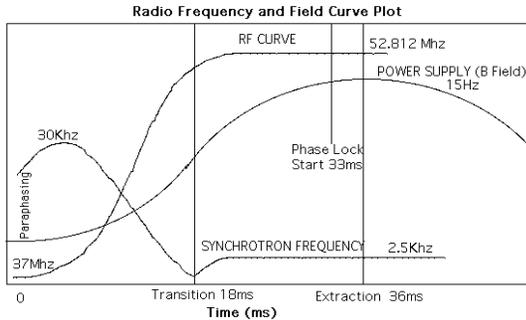


Figure 1: Booster RF and magnet field curves for a typical cycle.

Digital Synthesizer Processor (DSP), a programmable VLSI chip located on the DSP VXI card, and a personnel computer (PC). The DDS generates simulated beam RF when running off-line. The DSP reads and processes data and writes it to shared memory and to one of three on-board DACs. The programmable VLSI acts as a counter, buffer, and timer interface for the test setup. The PC provides a user interface for the necessary online control and a platform for off-line analysis. The interface between the PC and DSP was done using the VXI based CPU.

4. DESIRED BUCKET VERSE MAIN INJECTOR

In a typical Booster cycle the Booster gap marker wraps past the MI revolution marker many times [3]. The rate of wrap is greatest in the beginning of the cycle and slows as the RF frequency difference between the two machines diminishes. The initial offset between the MI marker and Booster gap marker can be made to be zero by starting the gap marker synchronously with the MI marker. The RF count measured throughout the cycle will be in the range of 0 to 84. The wrap in RF counts is the result of mixing two different frequencies, which will result in a sinusoidal term corresponding to the signal's frequency difference. Figure 2 shows a typical measurement data set during a Booster cycle. The plot size does not allow one to see the initial bucket offset or step size.

The DSP software can be set up to recognize the fact that the error count need not be greater than 42 (half a Booster turn) and give a count plot that wraps at 42 buckets.

Figure 2 has 3000 data points that were generated by the VLSI counter. Each data point, in units of Booster RF cycles, is obtained by starting the counter on a MI

marker and stopping it on the first Booster Gap marker to follow. The DSP is given an interrupt after each count to let it know there is new data to be read. The VXI CPU is used to collect the data from shared memory to be used for off-line analysis. The majority of phase wrap that occurs is expected and does not change pulse to pulse. A small fraction of the phase wrap is due to cycle to cycle

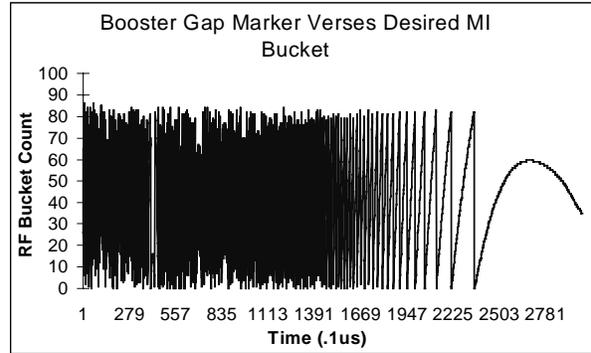


Figure 2: Plot of the RF bucket count between the MI revolution marker and the Booster Gap marker.

variations. The cycle dependent RF count difference can be filtered out of the bucket wrap error by defining a nominal cycle.

The result of comparing a nominal cycle to other Booster cycles is a slowly varying error count that is more easily managed. Figure 3 below shows a typical comparison between a nominal cycle and another Booster cycle. The DSP can also be made to integrate the error count. A comparison between the nominal cycle and one that is allowed to integrate the error will show the difference in the total number of revolutions. The variations in Booster

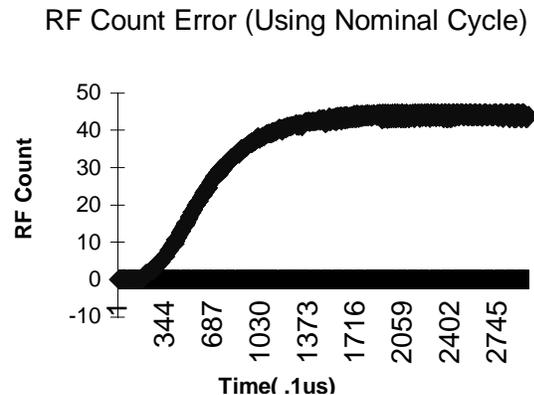


Figure 3: A typical cycle RF count slip when a nominal cycle count is subtracted.

cycles can be traced to several factors. The largest variance appears to come from the previously mentioned variation between timing of Booster triggers and the magnetic field cycle. When the radial position is held fixed, a bend field out of synch with the frequency curve will necessitate a frequency correction. Another contributor of pulse to pulse variations is incoming beam momentum fluctuations.

5. GAP BUCKET CONTROL

The Booster gap needs to be created early in the cycle in order to guarantee enough time to cog the worst case 42 buckets. Booster's large η before transition allows the radial position to have a greater lever arm in controlling the cogging during that portion of the cycle. A one-millimeter radial position offset from injection to the end of the cycle will result in a 55 bucket offset from that of a nominal cycle. That same one-millimeter position offset beginning at transition, about half way through the cycle, will result in only a 5 bucket offset at the end of the cycle. Clearly the control process needs to start shortly after injection.

With the gap created early in the cycle, there is the problem of integrating the cogging feedback with the required low level feedback systems. The different systems may fight, making the overall feedback unstable. The radial position feedback attempts to force the radial position to track a programmed curve. The cogging feedback may well require a different position offset. In the cogging test, the cogging error signal was used to modify the programmed radial position curve, but clipped in amplitude to limit resulting position excursions. The DSP controls the cogging error gain and correctly handles the sign flip required at transition.

The resulting system proved able to cog Booster beam to ± 3 RF cycles of the desired target (see Figure 4.) Initially, large position swings from overly aggressive cogging sometimes resulted in beam loss. A solution was to make the DSP smarter, calculating a predicted final bucket offset from a few milliseconds of observed bucket error at the start of the cycle. The prediction relied upon the fact that once the cycle begins the relative frequency curve/Booster momentum offset can be determined. This offset will manifest itself in terms of a bucket slip rate. (As mentioned

earlier, measurements have shown that the initial mismatch between the Booster's momentum cycle and frequency curve timing will be the major contributor to the final bucket offset.) This bucket prediction alleviated some over correction and allowed for most of the correction to be done early in the cycle. The DSP was also set up to have different gains before and after transition. The reason for different gains was to give flexibility and control the amount of position correction after transition. Other work is in progress to define an improved cogging prediction and control algorithm [4].

6. CONCLUSION

The ability to cog beam in a rapidly cycling machine with a large frequency swing has proven to be a difficult task. The successful outcome was made possible by using a system that could quickly gather and perform the necessary mathematical computations. The DSP software allows for flexibility in data collection and error calculation. This proved important since the required functions seemed to need to change during each step of the cogging development process. The software now does all the number crunching for the feed forward prediction, gain control, and data I/O. The VLSI hardware puts out a count, the number of Booster RF cycles between the MI revolution marker and the first Booster gap marker it sees, which is detected by the DSP. The DSP will then collect enough points to make a prediction of the gap and MI revolution marker's final separation. The error will translate into a position correction, which has both amplitude and time constraints. The ability to control both the horizontal position amplitude and duration will allow greater operational tuning.

A possible upgrade to the prediction code will be to incorporate the predicted error into the creation of the gap. This will alleviate the need to make any large initial corrections. The trade off between smaller positional corrections and creating a gap later in the cycle needs further analysis.

7. REFERENCES

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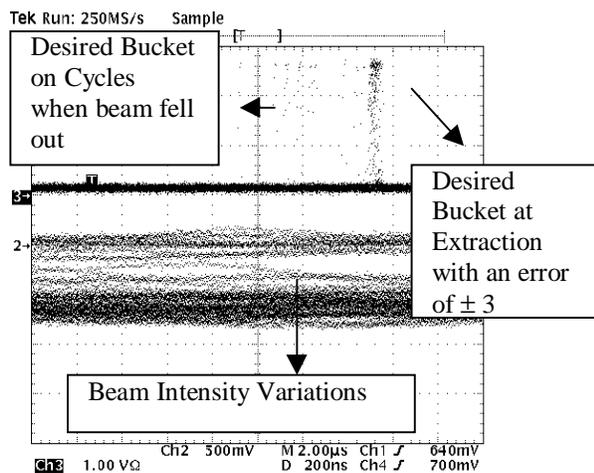


Figure 4: The clogged Booster Gap at extraction showing a small error. The top trace is the marker at extraction time on a 200ns/division time scale.