COGGING IN THE FERMILAB BOOSTER*

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Abstract

The Fermilab Booster is a rapid-cycling synchrotron which accelerates 84 bunches of protons from 401 MeV to 8 GeV for injection into the Fermilab Main Injector. The entire circumference, ie., all RF buckets, of the Booster is filled. At extraction, a kicker deflects the beam into the extraction channel. The kicker risetime is long enough so that several of the bunches do not receive the full kick and are deflected instead into Booster magnets, creating radioactive components in the tunnel and radiation at ground level outside. At future Booster intensities and repetition rates, the radiation levels will be unacceptably high. One way of reducing these losses is to create a "notch" of several consecutive unfilled RF buckets. If the beam can be accelerated while tracking and controlling the position of the notch so that the unfilled buckets are aligned with the rising edge of the extraction kicker, losses will be eliminated. We have studied this process and developed an algorithm to count and control RF cycles during the Booster ramp and move ("cog") the notch longitudinally so that it is aligned with the kicker at extraction time. We will describe the relevant parts of the Booster hardware, measurements we have made to understand what controls the total number of RF cycles during a Booster ramp, and the algorithm we intend to use for cogging during the Booster cycle.

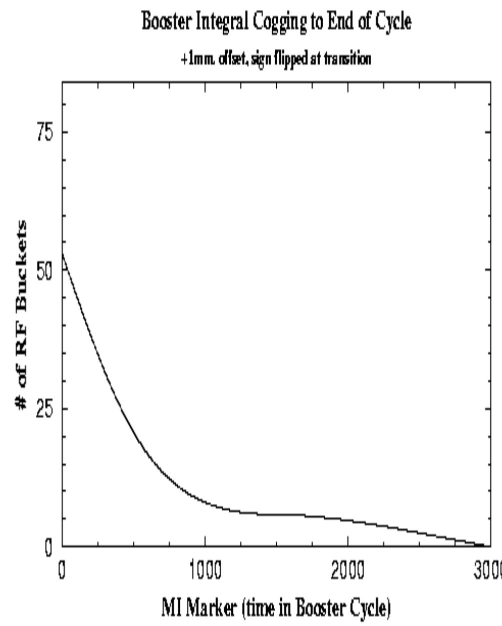

Figure 1: Integral cogging for a 1 mm. radial offset. The horizontal axis is in Main Injector marker units. There are roughly 3000 Main Injector revolutions in a single Booster pulse.

1 BOOSTER PARAMETERS

When the Fermilab Main Injector is in full operation, the Booster must deliver its batch of 84 bunches to a specified RF bucket in the Main Injector. In addition, the notch in the beam must be located at the Booster kickers when they fire. In order to move the notch to the proper location, we must be able to predict the total number of RF cycles in a Booster pulse to within a multiple of 84, the Booster harmonic number. Cogging is done by adding a radial offset to the beam, changing the revolution frequency, to add or subtract the necessary number of RF cycles. This technique has been used routinely at Fermilab in the Main Ring and Tevatron but in these accelerators cogging is done at flattop, ie., at a time when the RF frequency is constant. Cogging in the Booster is more complicated because there is no flattop. In addition, the shape of the Booster ramp (number of RF cycles) changes from pulse to pulse in ways which we do not completely understand.

The Booster design ramp is a 15 Hz. sinusoidal ramp in which the gradient magnets ramp at a "15 Hz." rate determined from the power line frequency. In principle, this enables us to calculate the RF ramp exactly. However, the power line frequency is not exactly 60 Hz. but fluctuates by ±30 mHz. A 30 mHz. difference in the line frequency causes a change of about 80 RF cycles from the ideal ramp. One could try to correct for variations in the line frequency by measuring the instantaneous frequency and calculating the change in the ramp, but it is not clear that the calculations could be done in real time. Changes in the radial position of a few mms. over the pulse also effect the number of RF cycles by roughly the same amount. Finally, there may be synchronization differences between the start of the magnet ramp and the start of the RF ramp, adding or subtracting hundreds of RF cycles to a pulse.

The Booster harmonic number is 84 so moving the notch to an arbitrary location at extraction requires cogging by ±42 RF buckets. Fig. 1 is a plot of the number or RF buckets cogged for a 1 mm. radial offset whose sign is reversed at transition. The horizontal axis is in Main Injector Marker units where 1 unit represents about 11 μsec., the Main Injector revolution time. Several important features are apparent from this plot. It is "easiest" to cog from about MI markers 200 to 800 (about 2 msec. to 8 msec. in time) in the cycle when the number of buckets cogged/radial offset is maximum. Conversely, the amount of cogging that can be done at the end of the cycle is very small. Of course, there is also

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a large period around transition (17 msec.) in which no cogging can occur. This information has already been applied [1] to do a simple form of cogging to try to align the notch with the kickers. In the rest of this paper I will describe a cogging algorithm which will attempt to do feedback during the cycle to align the gap with the kickers while minimizing the radial offset.

2 COGGING ALGORITHMS

The variations from Booster pulse to pulse mentioned earlier make it impossible to calculate the ramp from first principles. Instead, we must look for a set of measurements that can be performed during the cycle which will let us calculate the number of RF cycles. Two pieces of hardware are used to perform the measurements [1]: the Main Injector revolution marker and a module which will count the number of Booster RF cycles between consecutive Main Injector markers. These devices make it possible for us to calculate the number of RF cycles throughout the pulse in real time.

The algorithm I have found that seems to predict the location of the notch at extraction uses the RF cycles data acquired continuously throughout the pulse to make better and better predictions for the extraction location. We divide the Booster pulse into segments 100 Main Injector turns in length and count the number of RF cycles during each segment. Starting after receipt of the 500th Main Injector marker, we do a linear, 2 parameter fit of the form

$$TRF_i = a_i + b_i \sum_{j=0}^{j=i} RF_j$$

where TRF_i is the total number of RF cycles in the Booster pulse that one predicts based on measurements up to and including segment i. The slope (b_i) and offset (a_i) are different for each segment and have been determined from fits to complete Booster pulses. The 20 Booster pulses used for the comparison were chosen at random and are representative of the overall pulse to pulse variation in the total number of RF cycles. Application of this algorithm results in the data in Fig. 2 which shows the standard deviation between the predicted number of pulses at extraction and the measured number. By the midpoint of the cycle we can predict the extraction location to better than 2 RF buckets, and by the end of the cycle the standard deviation is less than 0.5 RF buckets.

I should make several comments about Fig. 2. We have found that there is very little predictive power contained in the information in the first 5 msec (500 MI markers) of the Bosoter cycle. This is the period during which the RF frequency changes most rapidly. Also, the radial loop turns on during this period, and we have observed large excursions in the horizontal closed orbit caused by the radial loop, and this certainly will effect the number of RF cycles at that instant without necessarily changing any other parts of the ramp. The plateau from segment 12 to 20 corresponds to transition, in which no cogging occurs. This is the same plateau that occurs in Fig. 2 between MI markers 1200 and 2000.

From these data, we can sketch a more detailed version of the cogging algorithm. No cogging is done until 5 msec. after injection. Betwen 5 and 12 msec, the predictions for the extraction location improve to under 1 RF bucket, and we can set the radial offset at the end of each 100 MI-marker segment to align the notch with the kickers to a precision of about 1 RF bucket. The maximum radial offset needed will be less than 3 mm., comfortably within the Booster aperture. For the rest of the cycle until extraction, we can continue this “feedback” process every 100 MI markers, but since the predicted extraction location is now accurate to within 1 RF bucket, only very small radial offsets will be needed.

This algorithm requires only a small number of calculations (summing RF cycles and performing the multiplications needed to predict the total number of RF cycles in a pulse) and can easily be done in the DSP which runs the low level RF system [1] and which can control the radial offset.

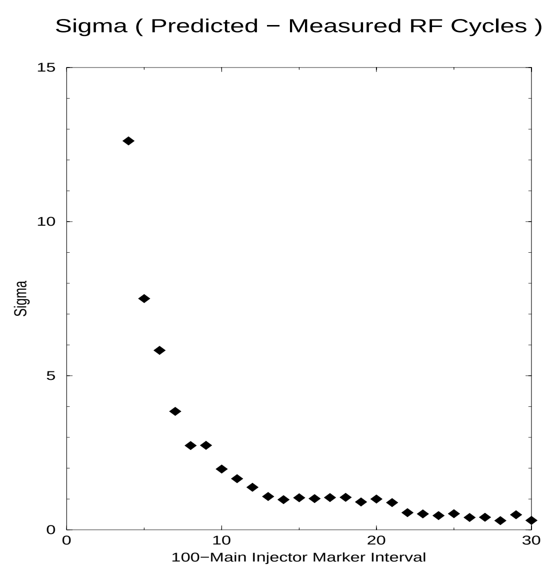

Figure 2: Integral cogging for a 1 mm. radial offset. The horizontal axis is in Main Injector marker units. There are roughly 3000 Main Injector revolutions in a single Booster pulse so extraction occurs at about MI marker 3000.

3 CONCLUSIONS

I have outlined an algorithm which I believe will allow the notch in the Booster beam to be aligned with the kickers at extraction, thereby eliminating extraction losses which occur in a completely filled ring. The algorithm develops a cogging trajectory which tries to use as small a radial offset as possible by improving the estimate of the extraction location of the notch throughout the pulse.

Considerably more work must be done before we shall have a working cogging system. There are, of course, the hardware issues associated with creating the notch and ensuring that instrumentation will work properly [1]. We shall repeat these measurements and try to refine the algorithm in small ways and to re-determine the constants. Finally, the algorithm must must be coded in the low level RF DSP and diagnostics developed.

4 ACKNOWLEDGEMENTS

Thanks to Bob Webber for suggesting this problem and Bill Pellico for developing the hardware.

5 REFERENCES

[1] William A. Pellico and Robert C. Webber, RF Cogging in the FNAL Booster Accelerator, proceedings of this conference.