Booster Main Injector Phase Lock Beam Studies Winter 2012

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I. Summary of attempted phase lock methods

In February, March and April several attempts at finding a new Booster to Main Injector phase lock method were made. The goal was to find a method that was quicker and more repeatable than the current method. The current method divides the two frequencies we want to match by 32 and provides a phase error trajectory to drive the phase difference between these lower frequency signals to zero.

After examining three different methods for doing the phase lock, none were found that improved on the current divide by 32 method. The essential issue was that the rate at which we can change the phase / frequency of the Booster beam at the end of the cycle is limited. When the rate of change of the LLRF phase was too high the beam would experience synchrotron oscillations that could not be sufficiently dampened before beam was to be extracted to the Main Injector.

The feedback control signal applied to the DDS LLRF frequency source needed to be slew rate limited. Direct feedback of the phase difference between the Booster RF and the Main Injector RF could not be adjusted in gain and or bandwidth to stay within the slew rate limit and still achieve phase lock within the 2-3 ms interval we desired. The divide by 32 method in current use managed to keep the slew rate of the control feedback below 25mV per 700us.

Three different methods for doing the phase lock were considered. Method 1 was similar to the current method in that it used a phase error trajectory to smoothly drive the phase difference between the two frequencies to zero and it relied on specific initial conditions for the magnitude and slope of phase error before initiating the phase lock and applying the trajectory error curve. The difference between the methods was that the new method started phase lock when the frequency difference between Booster and Main Injector was 1 - 2 kHz, where as the current method started at a frequency difference of 8 kHz and the phase difference output responding to the two frequencies divided by 32. The effective frequency difference at the start of phase lock between the two frequencies divided by 32 is 250 Hz.

The new phase error trajectory curve was able to be adjusted between 4 ms in duration to 0.4ms. The biggest catch was that no matter how much the curve was extended out in time the initial rise of the control feedback was nearly always the same. The rate could be varied a small amount with changes in gain and different trajectory curve shapes, but the smallest slew rate achievable was approximately 25mV per 200us. The initial step in the control feedback was mostly related to the initial change in the phase error slope (related to the difference in frequencies) to get on track with the set error trajectory.

This step was hard to avoid when changing the difference in frequencies from 1 – 2 kHz to zero, and the corresponding phase error slope, and avoiding the change in polarity of the phase error when the wrapping phase error triangle wave would crossed zero.

Method 2 involved modifying the LLRF DDS frequency curve so that the Booster frequency was driven up, approximately equal to the Main Injector frequency, within 2 ms of beam extraction time. Then phase lock was attempted with this smaller difference in frequency. The largest trade off with this method was that we could not choose an initial condition for the magnitude and slope of the phase error at the start of the phase lock cycle. In Method 1 the phase error slope and magnitude (polarity) determined the difference in degrees of phase we were from our target phase when we applied the error trajectory. Without being able to choose the phase difference allowed it to be anywhere between +/- 180 degrees. It was found that starting in one of the furthest phase quadrants from our target phase required too much time to reach phase lock when limiting the control feedback slew rates. Our best effort at controlling the feedback when starting in different phase quadrants involved setting up an additional phase detector in quadrature with the first in order to determine which phase quadrant we were in.

Method 2 was mainly developed and tested on the bench. Some work was done with the actual Booster LLRF control system to setup a frequency curve that ran up near the Main Injector frequency at the necessary time. Even with some software support with the frequency curve building tools, it was difficult to get the curve we needed without introducing discontinuities in matching the frequency to the requirements of the changing Booster magnetic field. Bench testing of Method 2 never produced phase lock times that met our requirements and was abandoned without further testing in the field.

With only two and a half weeks left before the shutdown a third approach was programmed into the phase detector modules and evaluated on the bench. Method 3, like Method 2, also involved bringing the Booster frequency very near the Main Injector frequency for the start of phase lock. One controller would attempt to reduce the slope of the phase error (the frequency difference) by feeding back a signal to the DDS LLRF source and a second controller would attempt to manipulate the phase difference to zero using the Phase Shifter module used typically for manipulating the radial position of the beam. Early on it was realized that the Phase Shifter could only shift the LLRF phase +/- 90 degrees, where we may need to shift the phase as much as +/- 180 degrees. Additionally, tests on the bench showed that this method would suffer the same time to phase lock issues as Method 2.

II. Where to go next

In the end, the virtues of the current divide by 32 method were made clearer. We were unable to attempt our own version of this method because we did not have sufficient time until the shutdown and electronic modules on hand. Future efforts will go into implementing this method with more current electronics hardware that will allow us to test variations of this method and smoothly integrate the tests into the normal Booster operations.

It is reasonable that simpler control methods were attempted first. Opportunities to test new hardware in the Booster LLRF controls while the Booster is delivering beam to the experiments is carefully metered out. We did gain an appreciation for the level of sensitivity of the parameters of the Booster and the LLRF controls. The gain between the phase error feedback to the DDS LLRF frequency source and the change in frequency out is approximately 1kHz per 20mV. With variations in the phase error feedback produced by the acceleration phase lock loop leading up to the Main Injector phase lock interval, there can be significant variation in the frequency and its derivative at the start of phase lock. It was also noted that small variations in the LLRF frequency curve from ideal values, dictated by the time profile of the beam energy and the Booster magnetic field can result in significant variations in the phase error and its derivative at the start of phase lock.

Variation in the initial conditions of system variables at the start of phase lock can occasionally result undesired effects. One specific case that is experienced with the current system is radial position variations occurring during phase lock that cause variation of the notch timing and the resulting position of the notch at extraction. Variations as small as 20 ns in the notch timing result in higher accumulated beams losses. During phase lock the radial position control is latched and the phase changes resulting from the phase lock process take the radial position where it will. It is sufficient if the phase lock process varies the radial position in nearly the same way from cycle to cycle, but occasionally initial conditions at the start of phase lock will drive the radial position differently. The integral of the difference between the radial position during an abnormal cycle and its typical position determines the amount of variation in the notch position at extraction. These recent attempts to find an alternate phase lock method were made in order to find a way to shorten the phase lock cycle and the magnitude of this integrated variation of the radial position.

Variations in the initial conditions can also result in disturbance to the beam causing more or less damping of oscillations appearing at the extraction of beam to Main Injector. To some degree variations cannot be avoided entirely, but further modeling of the beam/controls dynamics at the end of the cycle may aid in identification of which methods will and will not be sufficient to meet our requirements. In order to arrive at a phase lock method that is an improvement on the current system, I believe we will need a more detailed mathematical description than we are currently working with. Getting a better model may require involving another physicist or engineer, and would likely involve the need for some dedicated electronics to aid in model identification and verification with the Booster while it is trying to deliver beam to experiments.