

Booster Main Injector Phase Lock Divide-By-16 Phase Error Trajectory Method

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I. Introduction

The Main Injector phase lock controls are designed to phase lock the Booster LLRF, and in turn the Booster beam bunches to be delivered to the Main Injector, to the MI RF reference. Phase lock is to be accomplished within a 3 milli-second interval just before beam extraction from the Booster to the Main Injector. There are significant limits on how we can manipulate the Booster LLRF without inducing synchrotron oscillations in the beam. The AC Damper feedback to the Phase Controller (radial position control loop) provides some dampening of these oscillations; however the induced oscillations must remain sufficiently weak so they can be damped to sufficiently low amplitude before beam leaves the Booster.

This note discusses a variation of the current MI phase lock controls. The basic controller layout is presented. There is a discussion on how the phase error reference trajectory curve was chosen and how it was made to be adjustable online. One source of variation in the system response is discussed and a method of dealing with the variation is proposed. This note also documents details on how the bench testing was carried out.

II. Background and System Specification

The system of electronics that currently implements the MI phase lock was designed and installed in the early 1980's. There are obsolescence issues with the circuit components and some lack of information on the various calibrations and fine compensations that make the system work. There is also a desire to be able to have more access to the systems configuration, to make the phase lock interval shorter, and to reduce the intermittent instabilities that have been observed.

During March and April of 2012 studies with the actual operating Booster were performed to test prototype replacements for the MI phase lock system. Many of the details on triggering and integrating the prototype system in alongside the normal, operating system were worked out. A couple different approaches to phase locking the Booster RF to the MI RF were attempted in order to shorten the phase lock interval. It was found, however, that the Booster beam was very sensitive to changes in the RF frequency and would begin to oscillate if the phase error feedback slew rate exceeded a rather low threshold.

From these tests and observations made with the Booster we have some reasonable limits on the acceptable frequency/phase feedback control voltage for the phase lock to avoid inducing excessive oscillations in the beam. The limits on the feedback control voltage were determined to be

Control Voltage Peak < 30 milli-Volts (1.5 kHz)

Control Voltage Slew Rate < 50 milli-Volts/milli-second (2.5 kHz / milli-second)

The existing MI phase lock control electronics uses a "divide-by-32" scheme along with a reference phase error trajectory that guides the phase error to zero. The system uses two phase detectors. The first one monitors the wrapping phase between the MI RF and the Booster LLRF. Figure I.1 below shows the typical phase detector output signal.

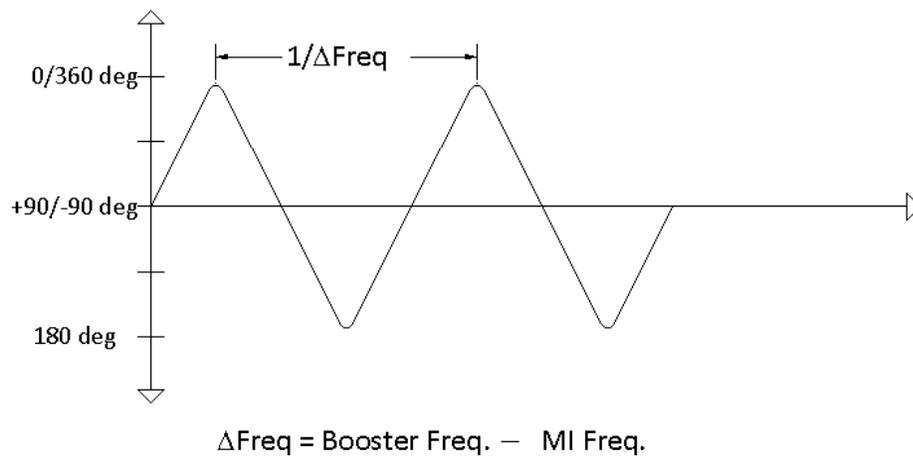


Figure II.1 Typical phase detector output

As the Booster LLRF frequency ramps towards the MI frequency the period of the triangle-wave output of the phase detector increases. The first phase detector notes when the slope of this signal switches from positive to negative and resets the divide by 32 high speed ECL counters that divide the Booster RF and the MI RF. The lower frequency outputs of the two counters are then compared using a second phase detector. The frequency difference between these two signals is 32 times smaller and hence the triangle-wave output of this second phase detector has a period that is 32 times longer.

Figure II.2 below shows the phase detector output when the Booster LLRF frequency is 8000 Hz different from the MI RF frequency 4 milli-seconds before extraction and then ramps to become equal to the MI RF frequency after the 4 milli-seconds.

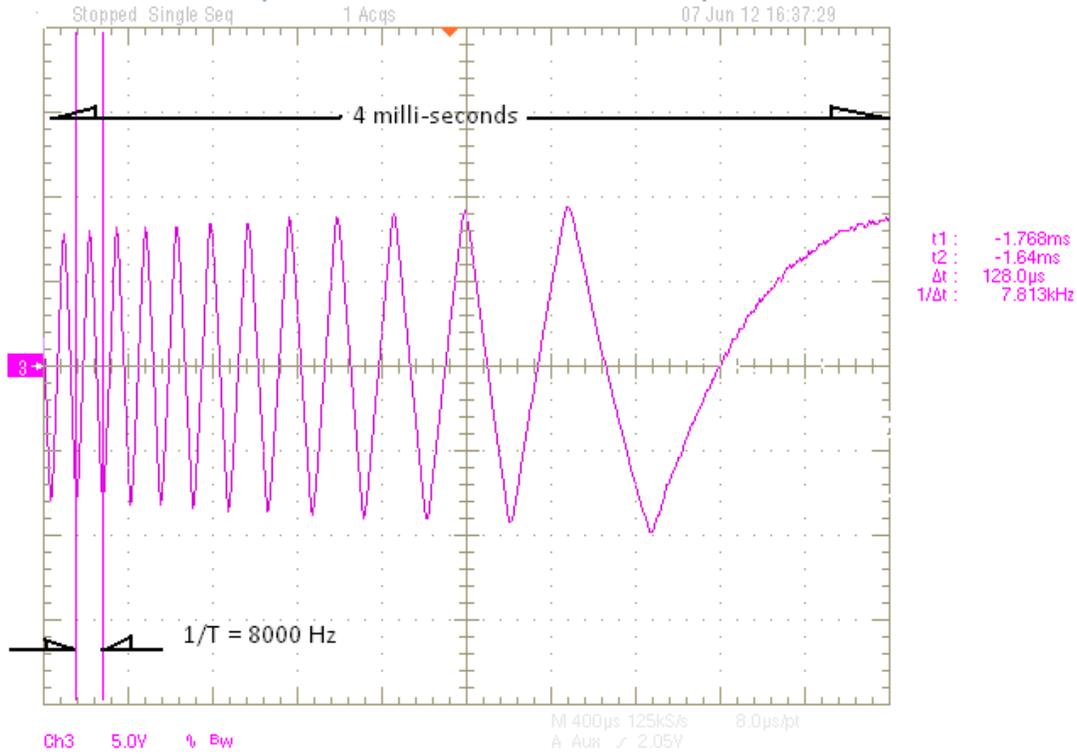


Figure II.2 Phase detector output just before beam extraction

Figure II.3 shows the output of the phase detector whose inputs are the divide-by-32 versions of our RF signals. You can see from the traces that, if we reset the divide-by counters and start the phase lock process at the appropriate frequency offset between the Booster RF and the MI RF, the phase approaches zero in a desirable manner in the normal course of the acceleration. However many factors will cause the phase to deviate from this desired course and hence we provide a reference trajectory, similar to the expected natural trajectory, to drive the phase error to follow the desired path.

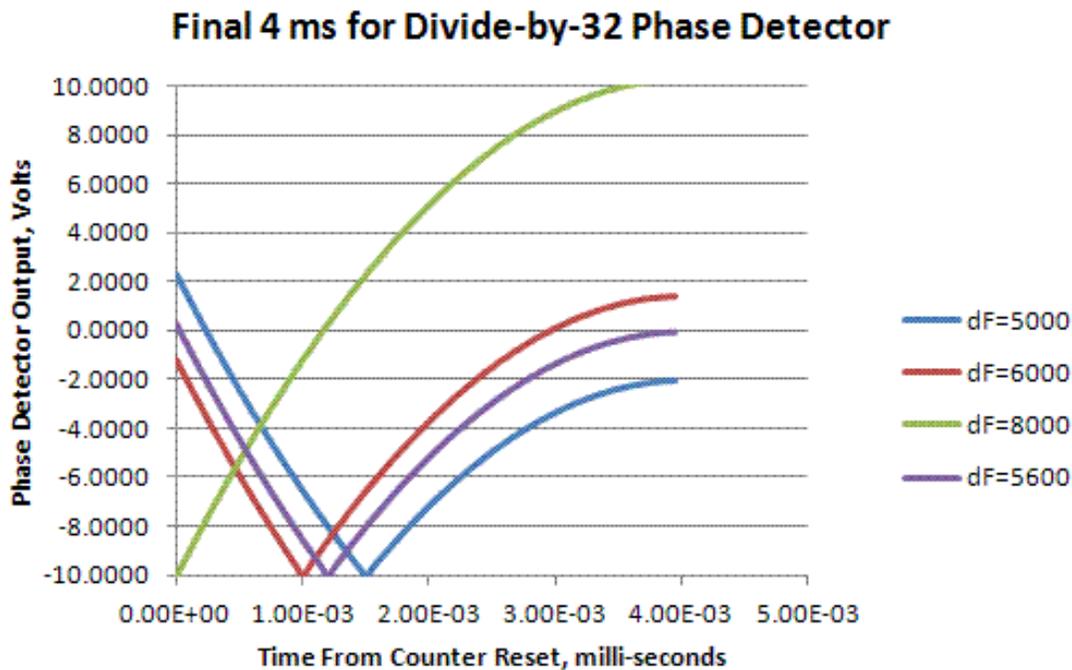


Figure II.3 Phase error trajectories for the divide-by-32 phase detector

III. The Proposed Main Injector Phase Lock Controller

The new version of the MI phase lock controls uses a divide-by -16 scheme instead of 32 to try to shorten the duration of the phase lock interval. With this approach the trigger frequency that starts the process is 4 kHz away from the MI RF frequency instead of 8 kHz. In testing so far there is only a slight decrease in the interval needed for phase lock.

The new Dual Phase Detector NIM modules were designed and fabricated to be used in this application. This module uses LVDS receivers to square up the Booster and Main Injector RF signals and converts the signals to LVTTTL for input to an FPGA programmable logic chip. The timing logic that starts the MI phase lock process generates a “load counters” signal that holds the counters at zero until the desired time to start. The release of the load signal is synchronized to the RF signals to provide more consistent initial conditions.

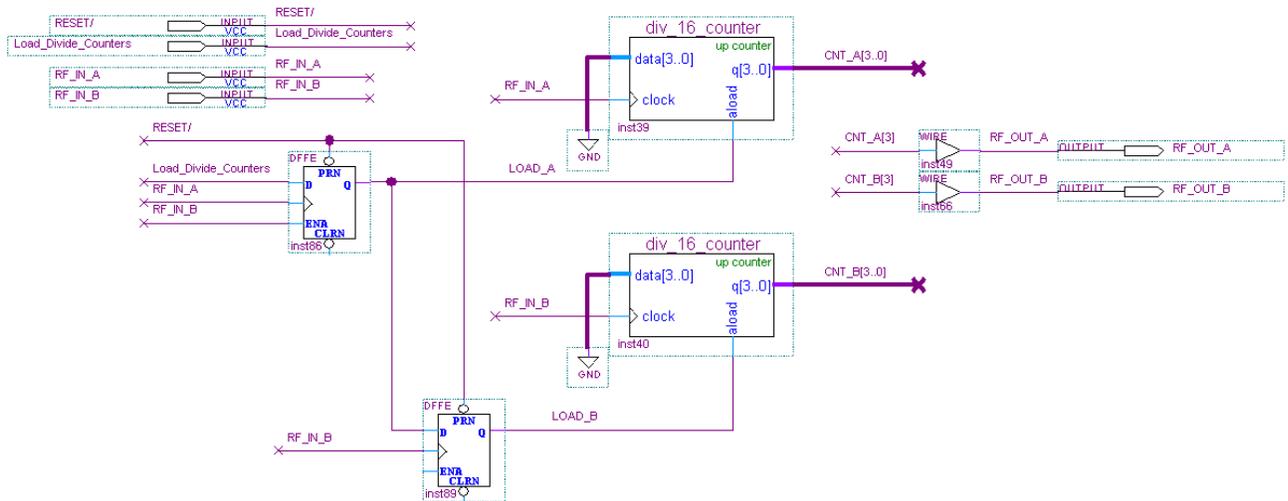


Figure III.1 The divide by 16 counters in the FPGA logic

The RF outputs of the divide by counters are transmitted back out the front panel to be taken back into the module at the phase detector inputs (phase detector B). The phase detector output signal for the divide by 16 RF signals contains both the difference frequency component, $f_{out} = |f_{in} - f_{ref}|$, and also the sum of frequencies term, $f_{out} = f_{in} + f_{ref}$, as is common with mixers. At input frequencies of 52MHz the sum of frequencies term was well out of the bandwidth of the following signal conditioning circuits. At the divide by 16 frequencies, around 3.25 MHz, the sum of frequencies term must be deliberately filtered out. This was done by adjusting the value of the filter capacitor on the AD8302 phase detector chip.

There is a transient interval in the divide by phase detector response following the release of the divide by counters. MI phase lock interval timing is setup to begin the reference trajectory and the phase lock feedback after the divide-by counters are started and then at the rising edge of the phase detector output.

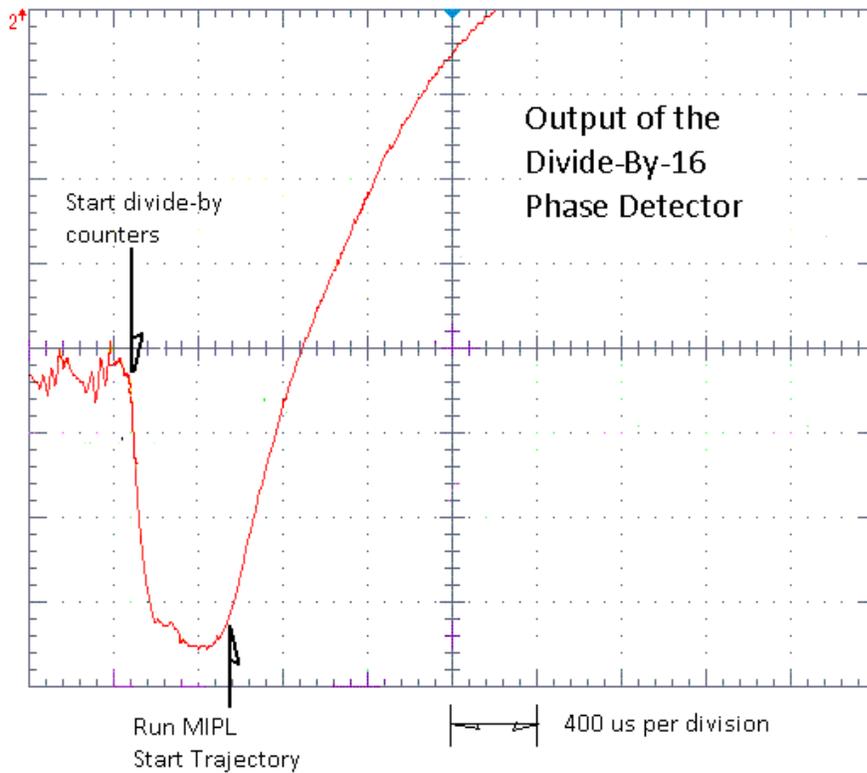


Figure III.2 Output of the divide-by-16 phase detector

The timing sequence that starts the MI phase lock interval is

1. Detect that the LLRF frequency has reach the target starting frequency.
2. Detect the next rising slope of the normal RF phase detector, , and start the divide-by-16 counters.
3. Detect the rising edge of the divide-by-16 phase detector and start the trajectory curve and phase lock feedback.

The reference trajectory curve the phase error follows is created using a trajectory gain curve, from 1.0 to zero, that is applied to the initial phase error value at the start of the MI phase lock interval. An initial phase error value is latched at the start of the interval and this trajectory gain curve drives this value to zero. Throughout the phase lock interval the measured phase error is subtracted from this reference trajectory and this difference is applied to a proportional gain term and an integral gain term. The two products are summed to become the control feedback value. Both the proportional and integral gain values are user adjustable through an MS Windows and USB interface.

The signal Run_MIPL triggers the MI phase lock interval. Note this signal in the controller block diagram, Figure III.3.

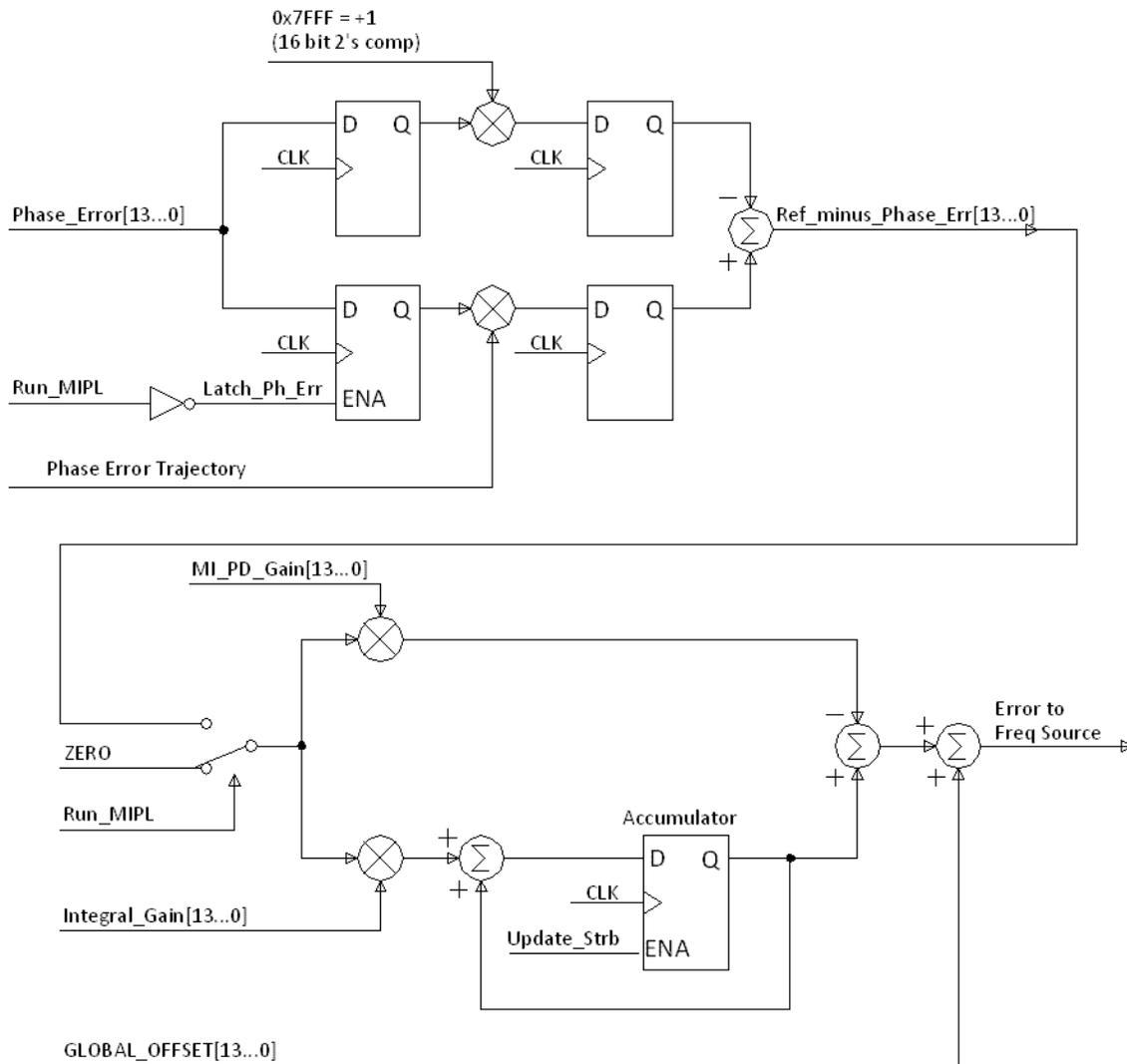


Figure III.3 The phase lock controller block diagram

IV. Generation of the Phase Error Reference Trajectory Curve

Presenting a phase error reference trajectory that guides the divide-by-32 phase error to zero in a short amount of time (< 3 milli-seconds) and results in keeping the control feedback within the tight limits mentioned previously is not a simple matter. The curve needs to be a “natural” exponential type of curve, for which it was found very convenient, if not essential to be able to adjust or flex this curve on-line.

The reference trajectory curve used in the MIPL module is derived from two other curves as a weighted average of the two curves.

The weighting term “ ” is a settable parameter through the USB interface. The Upper Curve and Lower Curve are initially exponential functions like $y = e^{-x/\tau}$, where τ is a time constant. Each curve is automatically scaled and offset so that the first value of the curve is always 1, and the 1024th value is always zero.

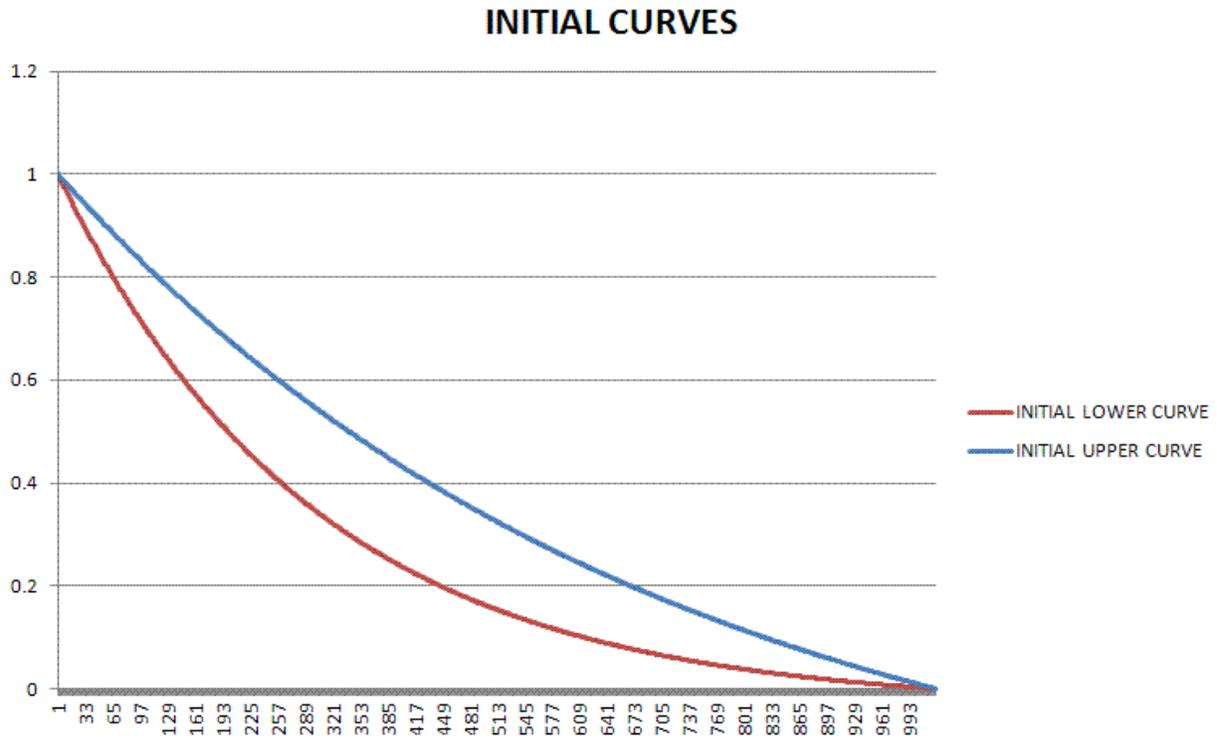


Figure IV.1 The initial upper and lower curves used to define the reference trajectory gain curve

Partly because of the scaling of the curves, the resulting upper and lower curves end fairly abruptly when they reach zero. There is a distinct discontinuity in the slope or d/dt of the curve at zero. This abrupt transition is difficult for the phase lock loop to follow and results in unnecessarily sharp changes in the control voltage at the end of the curve.

To smooth the transition to zero at the end of the curve we computed a weighted average between each curve, the Upper and Lower Curve, and a Warping Curve. The Warping Curve is also an exponential function with a very small time constant. Additionally the weighting term used for this average is not a scalar value but a curve. This “ ” curve is also derived from an exponential function, but has been flip about the axis that connects its endpoints. This weighting curve gives more weight to the warping curve near the end of the curve, where the Upper and Lower curves typically approach zero.

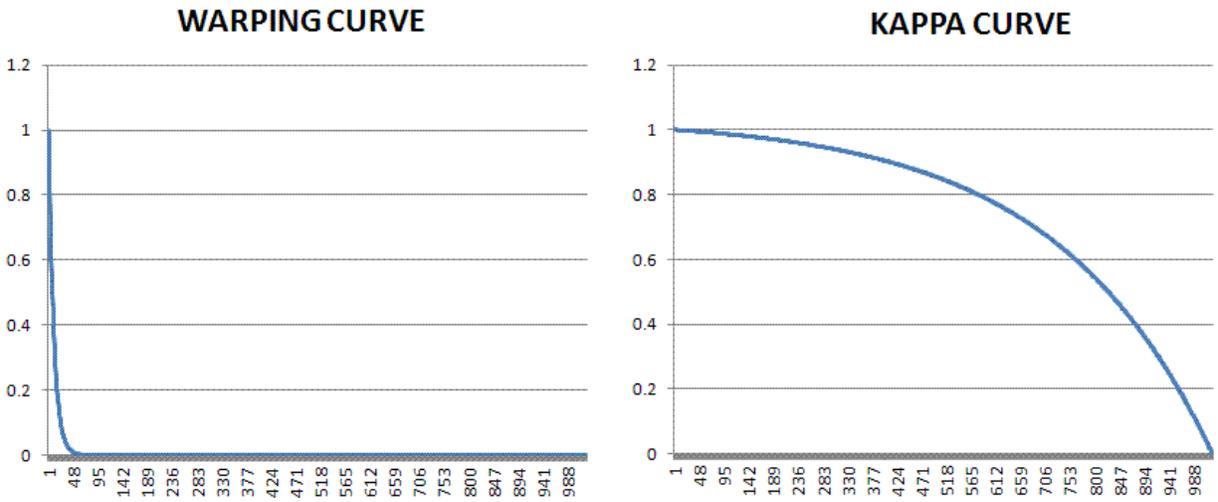


Figure IV.2 Plots of the warping curve and the weighting “kappa” curve

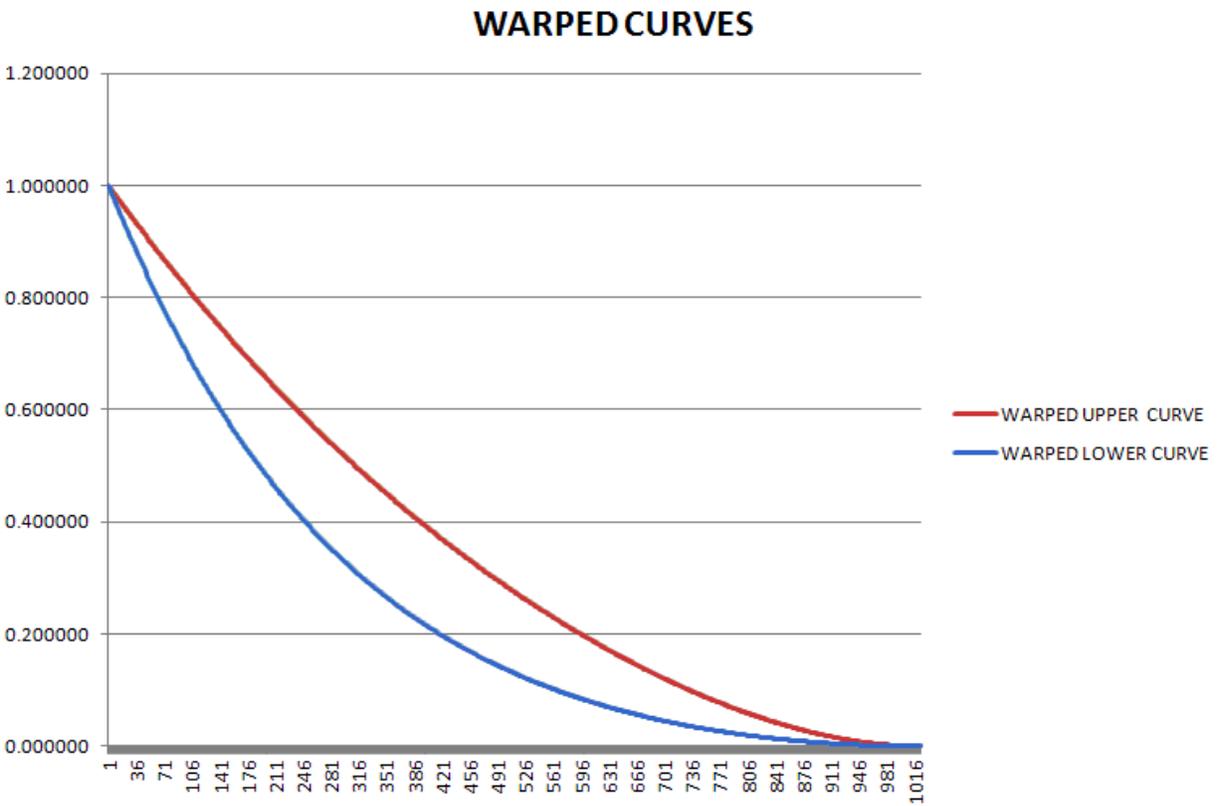


Figure IV.3 Plot of the final warped upper and lower curves that are installed into FPGA memory

The final reference trajectory curve is then the weighted average of the warped upper curve and the warped lower curve. The weighted average is done on-line in real time with the weighted upper and

lower curves read from ROM memory in the FPGA, and the weighting term “alpha” is a user settable parameter through the MS Windows / USB interface.

V. Jitter in the starting frequency at the start of MI phase lock

The frequency of the Booster at the start of the MI phase lock process can vary due to the need to synchronize the phase lock control process with up-slope and/or down-slope events. The wrapping phase error triangle wave is not entirely synchronous to the frequency curve. That is to say, for example, when the frequency curve reaches within 4k Hz of the MI RF frequency we begin looking for the next down-slope pulse before engaging the divide-by counters. When reaching this target frequency the down-slope pulse may follow immediately, or it may have just occurred and we will have to wait a full period of the 4k Hz triangle wave, 250 micro-seconds. A frequency curve that is changing 8k Hz in 4 milli-seconds can change as much as 500 Hz in this time. This variation in frequency will result in a variation in the initial slope of the phase error at the time we wish to begin following the phase error trajectory.

These variations in the slope of the phase error versus the fixed slope of the phase error trajectory can easily result in control feedback that exceeds the beam limitations of keeping slew rates less than 50 Volts/second.

The tracking error between the phase error and the reference trajectory is not as significant at the start of phase lock as it is at the end when the phase error is to converge to zero. A ramping gain term is applied to the trajectory minus phase error difference, starting at zero and rising to one within 1.2 milli-seconds. In doing this, tracking errors early in the cycle, and other initial transients do to the adjustments described below, have only a small impact on the control signal fed back to phase lock the frequency source.

By noting the slope of the error between the trajectory and phase error early in the cycle, corrections can be made early in the cycle to the slope of the trajectory we wish the phase error to follow. We extend or contract the trajectory to make it more “agreeable” for the phase error to follow resulting in smaller feedback control signals to the frequency source and less disturbance to the Booster beam. The phase error trajectory can be extended or contracted by increasing or decreasing the curve update rate.

Curve update refers to fetching the next gain curve point value from memory. Recall that the trajectory curve is generated by applying a changing gain to the initial phase error value latched at the start of the phase lock interval. A typical trajectory curve update interval is around 1.8 micro-seconds with adjustments applied in the range of +/- 0.3 micro-seconds. Figure V.1 shows a portion of a trajectory curve and the definition of the Update Interval. Figure V.2 is another block diagram of the computation of the difference between the phase error and the phase error trajectory which includes the error rate detection and the feedback adjustment to the trajectory curve update interval.

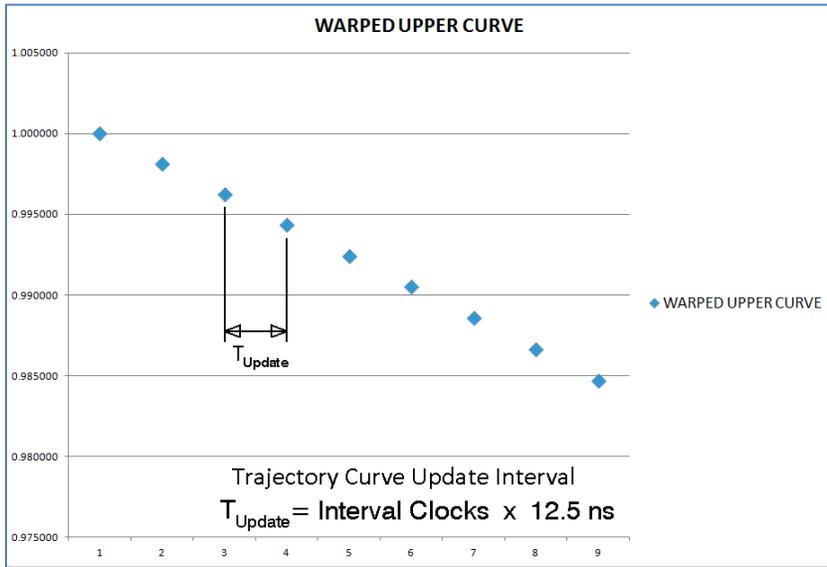


Figure V.1 Definition of the Update Interval

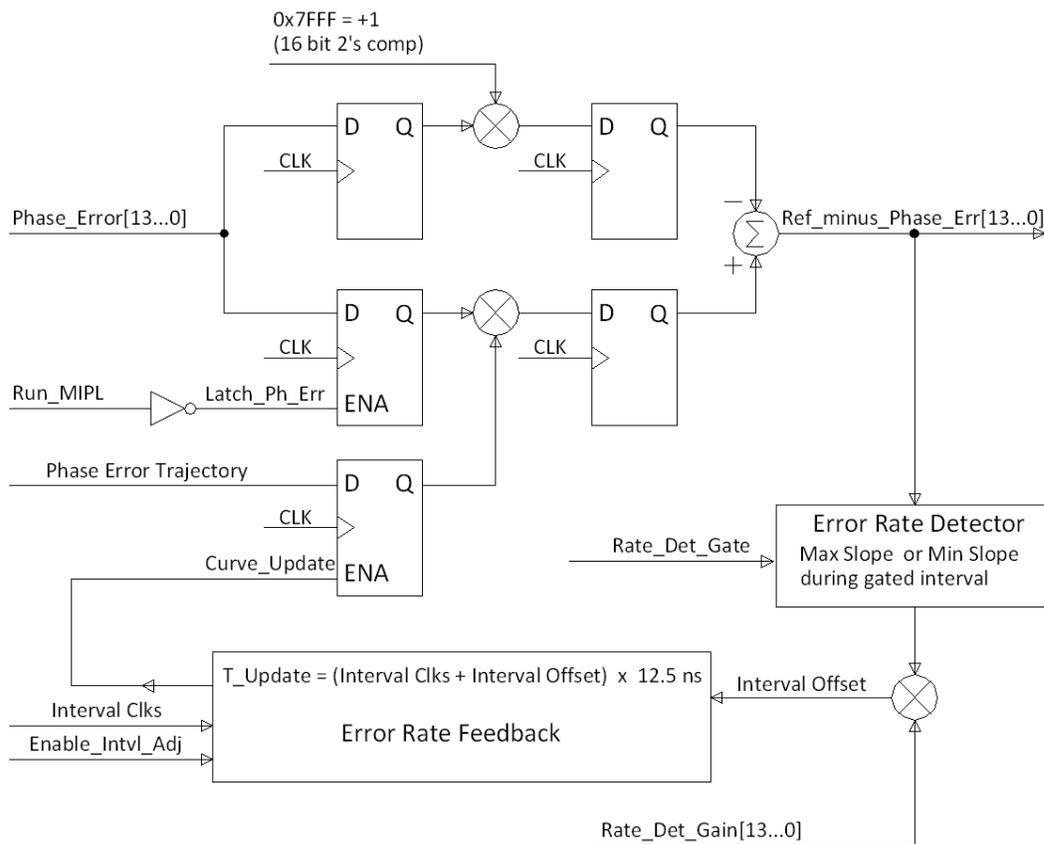
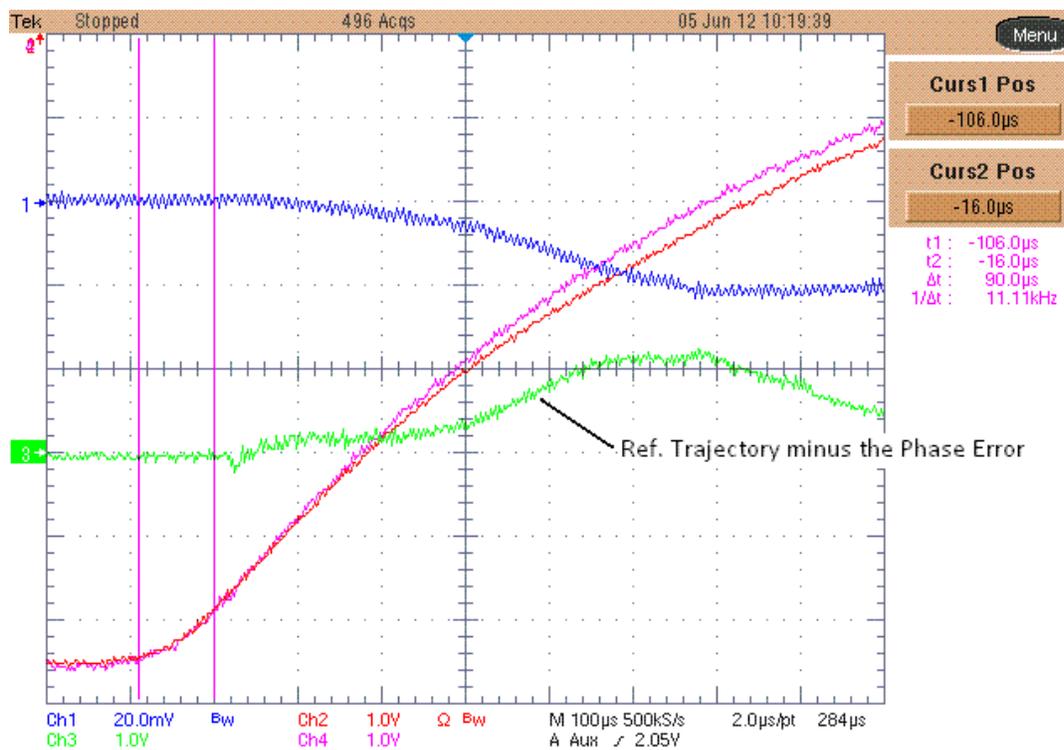


Figure V.2 Block diagram of the computation of the difference between the phase error and the phase error trajectory

When the phase error is changing with a different slope than the reference trajectory the difference between the two will have a slope, or rate of change. We are concerned with the rate of change of the error because it is a “tracking” control situation. This rate is measured by computing the difference between the current value of this difference and the value of this difference 112 samples previous. With a phase error update rate of 1.6 micro-seconds, 112 samples is 179.2 micro-seconds. A circular buffer is used to retain the previous samples.

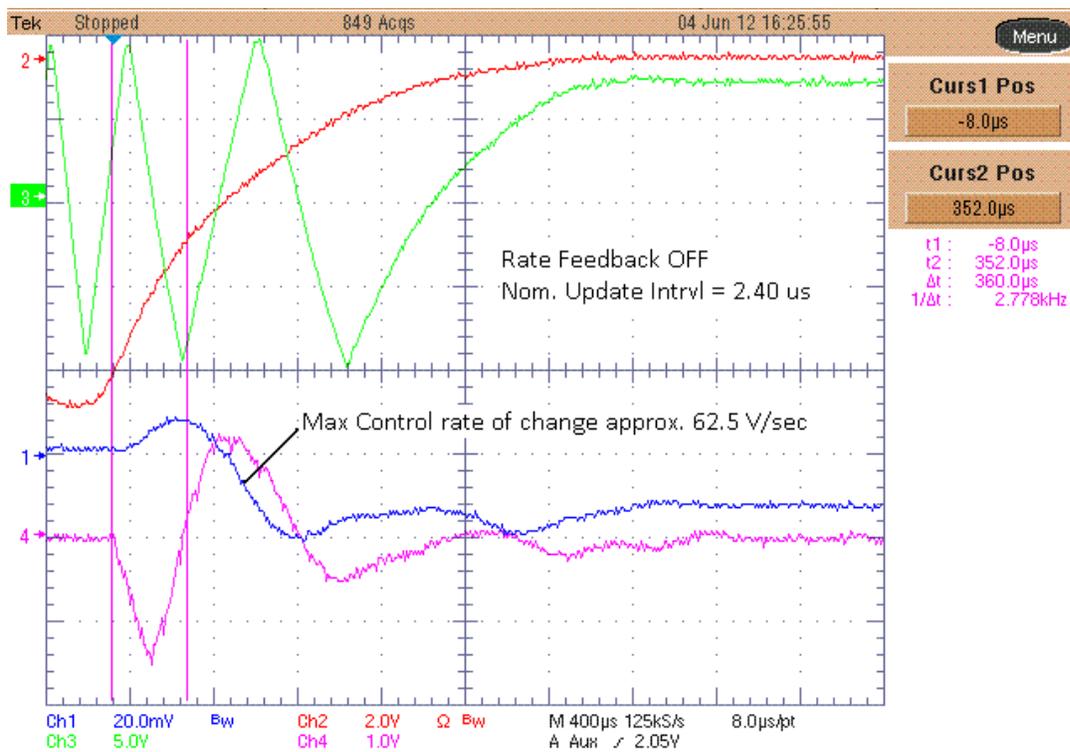
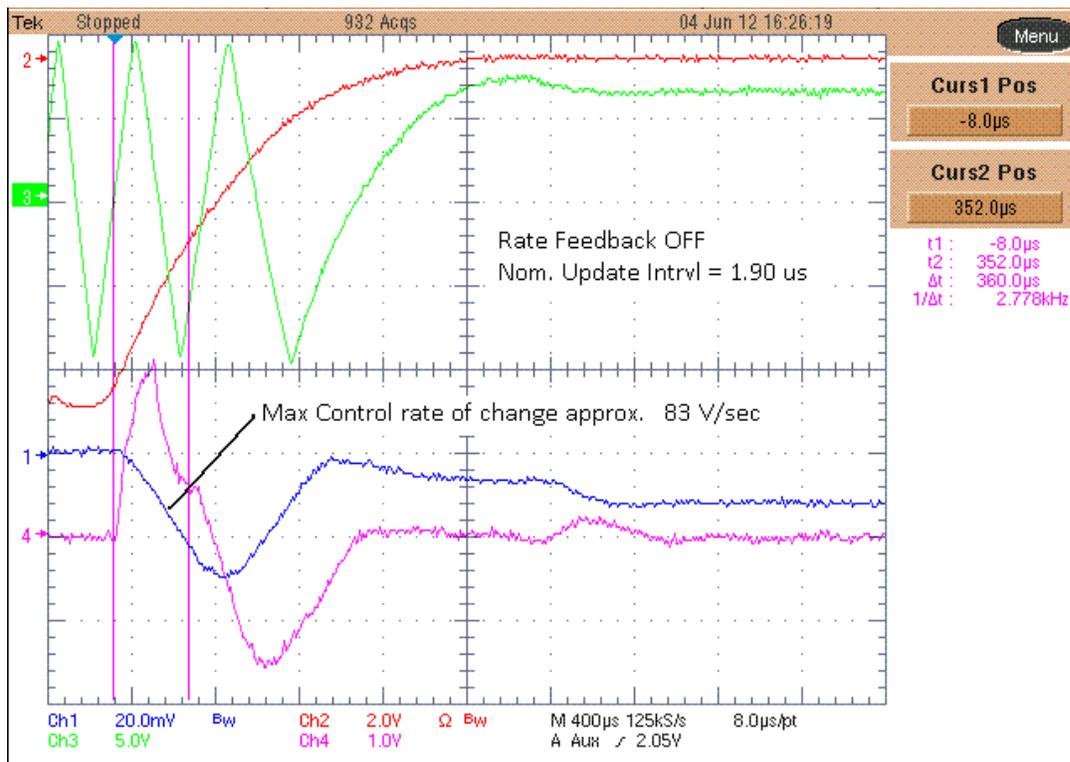
Curve update interval control is based on the maximum positive or the minimum negative peaks of this rate that occur during the first 360 micro-seconds of the phase lock cycle. The sign, or direction, of the update interval offset is determined by whether the magnitude of the positive peak or negative peak is the larger. The amplitude of the offset is computed using an adjustable gain applied to the magnitude of the positive or negative peak, as long as this magnitude exceeds a minimum threshold. Currently a threshold is applied only to positive peak rates. This was to avoid a small initial positive peak that was always present.

The set of scope screen captures on the following pages indicate the effect of different curve update interval settings and show the improvement achieved when enabling the rate feedback. The actual ideal interval setting changes with the frequency at the time the phase lock interval is triggered. The rate feedback compensates for the effect of starting at different frequencies.



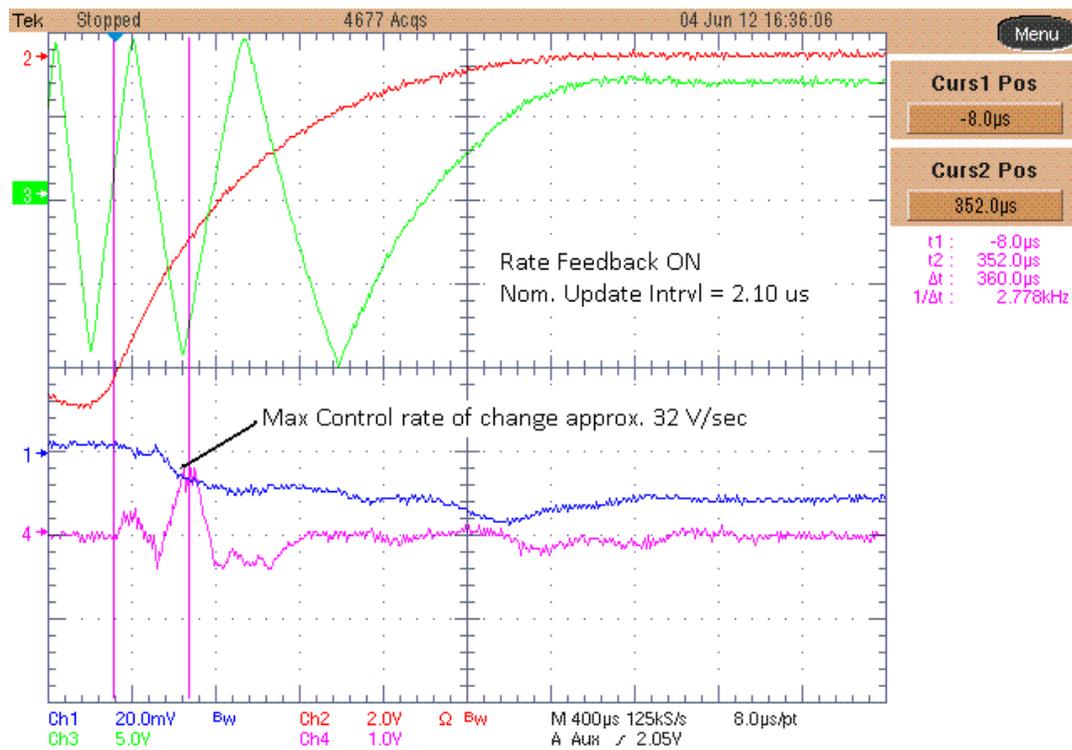
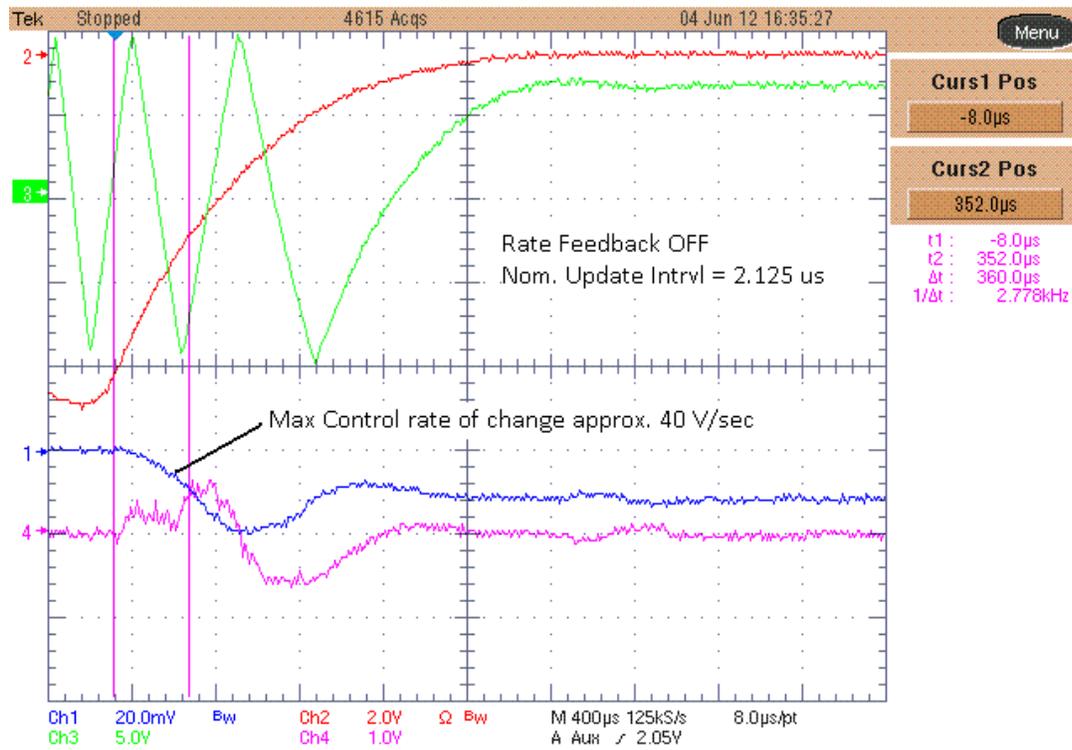
- Ch 1 (blue) Control Output to Frequency Source
- Ch 2 (red) Divide by 16 Phase Detector Output
- Ch 3 (grn) Ref. Trajectory minus the Phase Error
- Ch 4 (mag) Phase Error Reference Trajectory

Figure V.3 Scope screen shot indicating the Reference Trajectory minus the Phase Error signal



- Ch 1 (blue) Control Output to Frequency Source
- Ch 2 (red) Divide by 16 Phase Detector Output
- Ch 3 (grn) MIRF to Freq Source Phase Detector Output
- Ch 4 (mag) Computed phase error vs trajectory slope (rate)

Figure V.4 Scope plots with control feedback exceeding specification



- Ch 1 (blue) Control Output to Frequency Source
- Ch 2 (red) Divide by 16 Phase Detector Output
- Ch 3 (grn) MIRF to Freq Source Phase Detector Output
- Ch 4 (mag) Computed phase error vs trajectory slope (rate)

Figure V.5 Scope plots of adjusted reference trajectory update intervals and acceptable feedback rates

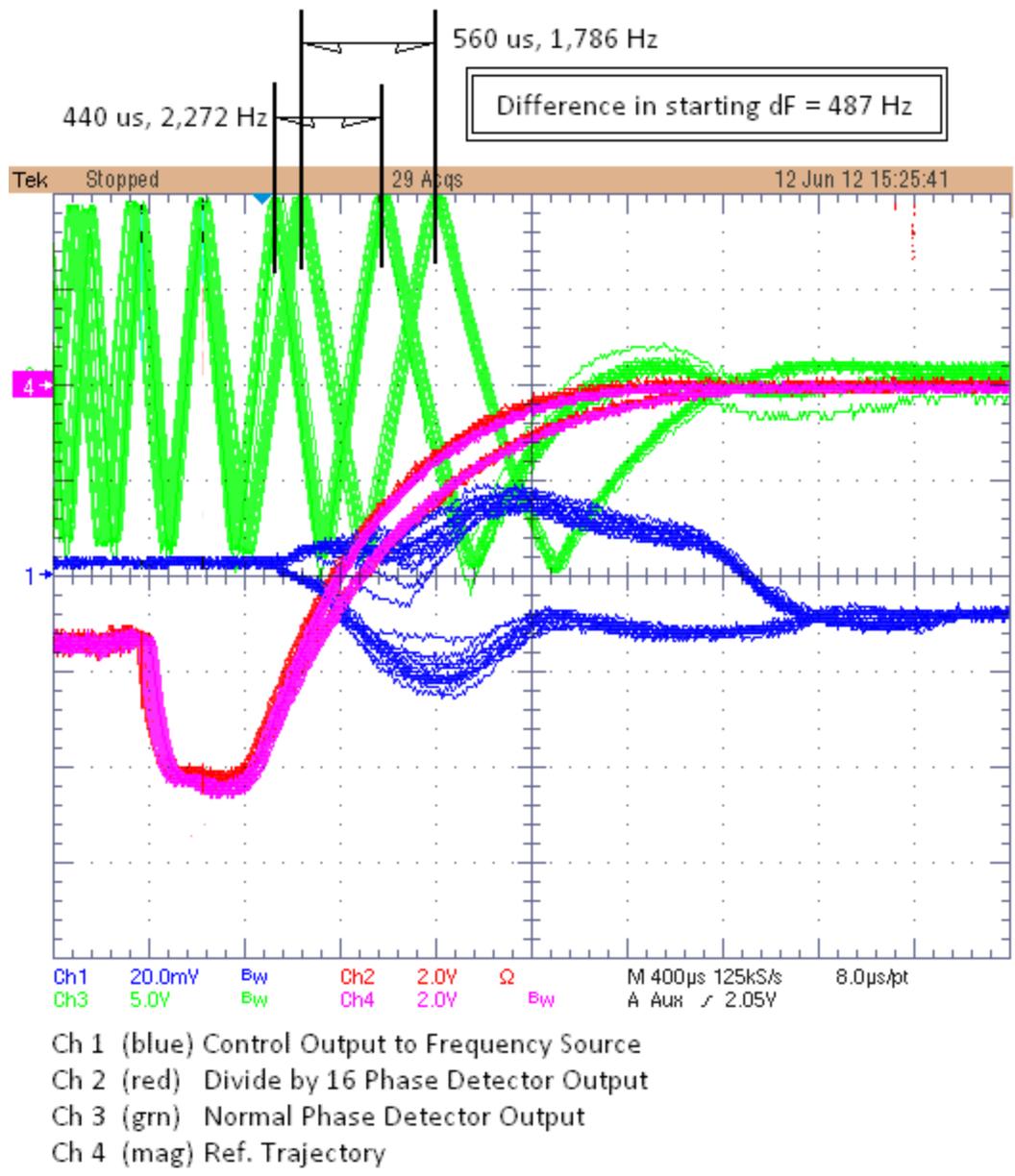


Figure V.6 Scope plots in persist mode showing effects of variation in starting difference frequencies.

VI. Setup for Bench Testing

For testing on the bench we use the HP 8657B RF Generator. We set it up as the Booster LLRF at approximately 50 MHz with FM modulation. The phase control feedback and a bias curve that acts as the frequency curve are summed to manipulate the sources frequency at 50 kHz/Volt (or 1 kHz / 20 milli-Volt).

The frequency curve signal is intended to sweep the RF generator 8 kHz in the last 4 milli-seconds of what would be the Booster acceleration cycle. This provides the essential “base” phase response between the Booster RF and the MI RF.

The frequency curve is generated by a specially programmed Dual Phase Detector Module. This module takes the control feedback from the phase controller module and sums it with a frequency curve it is playing out from memory in its FPGA. USB interface parameters for this special Frequency Curve Module can be set to control the Frequency Curve Scale (Parameter 9) and the time duration of the curve (Parameter 5). The Phase Controller feedback is applied into the External Input (front panel AUX) and is summed with the frequency curve at the output summing amplifier.

The frequency curve can be setup by removing the control feedback and monitoring the effect of the curve on the HP8657B RF generator output by looking at the output of the normal RF phase detector, , output. With the Frequency Curve Trigger as a time reference, the period of the phase detector triangle wave output at different time offsets from the trigger can be made. The magnitude of the final frequency change can be adjusted with USB Interface parameter 9, and the time between the Frequency Curve Trigger and the final frequency value can be adjusted with parameter 5. The range of frequencies generated also depends on the base frequency setting of the RF generator.

The Tektronix AWG520 is a two channel arbitrary waveform generator setup to produce two identical 50 MHz sine waves. By using one channel for the normal phase detector comparison and the other channel as input to the divide-by-16 counters and phase detector, we can adjust the phase between these two references as we could with cable length adjustments. The phase between these can be adjusted to produce a final phase difference between the Booster RF and MI RF near zero.

Figure V.1 shows the cabling of the signal generators and the two NIM modules. Additional trigger inputs are necessary for the Phase Controller Module at DI4, T1, T2, T3. These can all be the same as the Frequency Curve Trigger or a pulse that precedes it.

The FPGA code for the Phase controller fixes the input switches for the output summing amplifier so that only the FPGA DAC output is connected. All other switches are open. For the Frequency Curve Module the FPGA DAC and the External Input signals are connected and the other two switches are open.

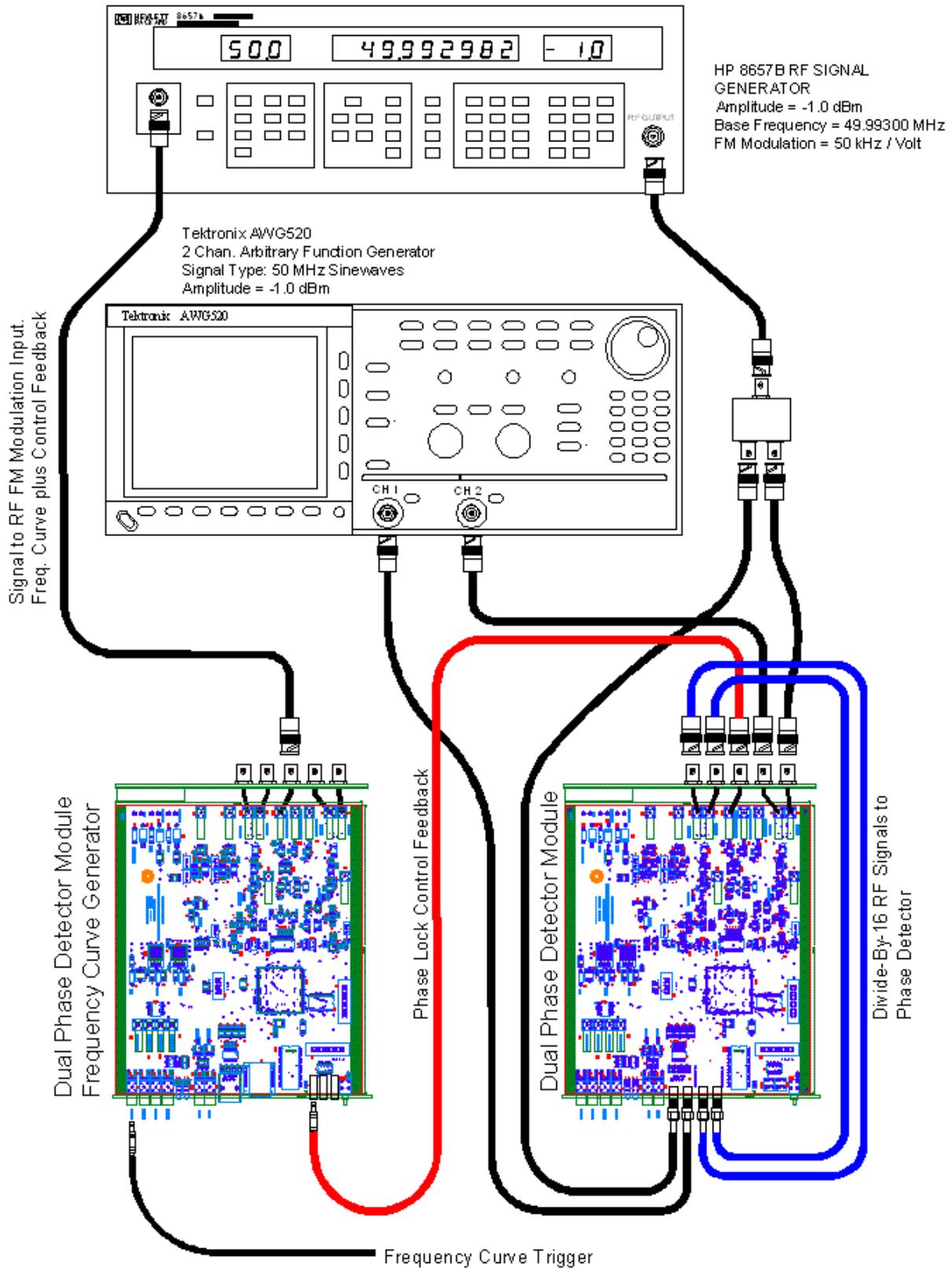


Figure VI.1 Test Bench Setup

Table VI.1 USB Interface Parameters as they apply to the Phase Controller module

Param#	Typical Value In Hex	Number Format	Description (Phase Controller Module)
0	0x0F00	12 Bit Offset Binary Value (0x0800 = zero)	Accel PD Gain (NOT USED)
1	0x0800	12 Bit Offset Binary Value (0x0800 = zero)	Accel PD Offset (NOT USED)
2	0x1E80	14 Bit Offset Binary Value (0x2000 = zero)	MI PD Controller Gain
3	0x0800	12 Bit Offset Binary Value (0x0800 = zero)	MI PD Offset
4	0x1E80	16 Bit Unsigned Integer	Internal Frequency Trigger Threshold. Number of clocks between zero crossings of the normal PD triangle wave output.
5	0x00A0	16 Bit Unsigned Integer	MIPL Transition Interval. Number of 12.5 ns clocks between memory curve updates.
6	0x1FF4	14 Bit Offset Binary Value (0x2000 = zero)	MI PD Controller Integral Gain
7	0xA000	16 Bit Unsigned Integer	MODE Control Word
8	0x2040	14 Bit Offset Binary Value (0x2000 = zero)	Rate Detector Gain
9	0x1FE8	14 Bit Offset Binary Value (0x2000 = zero)	Global FPGA DAC Output Offset
10	0x2802	Dual 8 Bit Unsigned Integers	<p>Bits [15..8] Filter delay term for the slope indication on the Divide-By PD. Value is the upper 8 bits of a 16 bit variable which is the number of 12.5 ns clocks. The slope state signal must be stable for this amount of time before a change of state (up, down) is registered.</p> <p>Bit[7..0] Integral controller gain stage rate adjustment. This divides the sample rate for updating the integral term accumulator.</p>
11	0x8000	16 Bit Offset Binary Value (0x8000 = zero)	Curve Weighting Factor, Alpha. Used to create the reference trajectory gain curve from the Upper and Lower curve memory values. Values below 0x8000 (zero) do not make sense.

Table VI.2 USB Interface Parameters as they apply to the Frequency Source module

Param#	Typical Value In Hex	Description (Phase Controller Module)	Description (Freq. Source Module)
0	0x0800	12 Bit Offset Binary Value (0x0800 = zero)	Accel PD Gain (NOT USED)
1	0x0800	12 Bit Offset Binary Value (0x0800 = zero)	Accel PD Offset (NOT USED)
2	0x2000	14 Bit Offset Binary Value (0x2000 = zero)	MI PD Controller Gain (Set to zero)
3	0x0800	12 Bit Offset Binary Value (0x0800 = zero)	MI PD Offset (Set to zero)
4	0x0000	16 Bit Unsigned Integer	Internal Frequency Trigger Threshold (NOT USED)
5	0x0500	16 Bit Unsigned Integer	Freq Curve Duration Setting. Number of 12.5 ns clocks between memory curve updates.
6	0x2000	14 Bit Offset Binary Value (0x2000 = zero)	MI PD Controller Integral Gain (Set to zero)
7	0xA000	16 Bit Unsigned Integer	MODE Control Word
8	0x0020	14 Bit Offset Binary Value (0x2000 = zero)	Frequency Curve Trigger Delay
9	0x2308	14 Bit Offset Binary Value (0x2000 = zero)	Frequency Curve Amplitude Adjustment.
10	0x0604	Dual 8 Bit Unsigned Integers	Bits [15..8] Filter delay term for the slope (NOT USED) Bit[7..0] Integral controller gain stage rate adjustment. (NOT USED)
11	0x3FFF	14 Bit Offset Binary Value (0x2000 = zero)	(NOT USED).

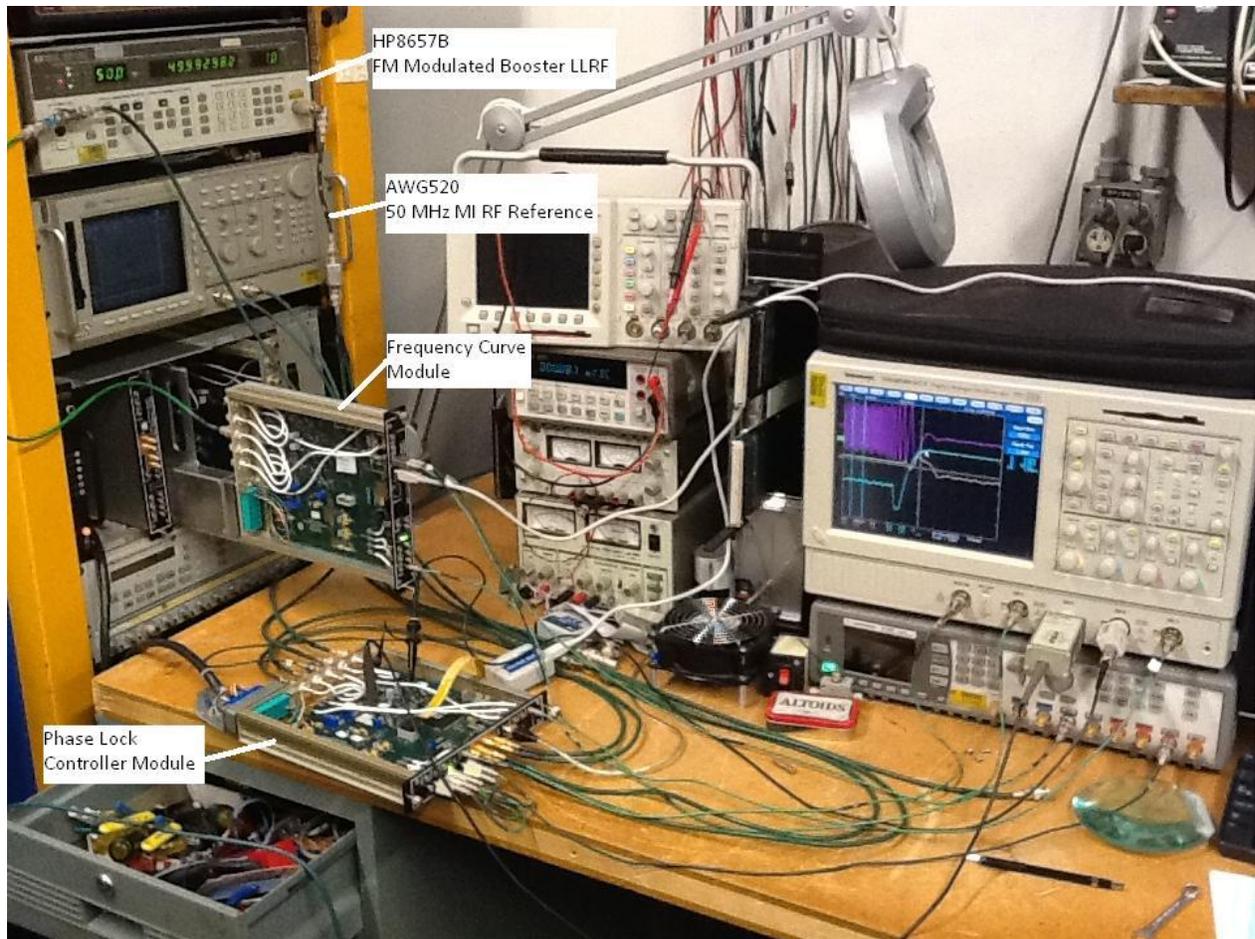


Figure VI.2 Photo of the test setup

VII. Proposal for Online System Testing

For testing the proposed MI phase lock method with the real system we will splice into the Phase Error feedback signal to the VXI DDS Frequency module at the output of the “Summing Box”. This signal has both the phase error applied during the acceleration phase lock interval, as well as the MI phase lock phase error. Analog switches are available on the Dual Phase Detector modules to switch between the “normal” phase error feedback signal and the “test” phase error feedback signal generated by the new electronics. Copies of the Booster RF, the Delayed VCO and the MI RF for the test system are available from RF splitters already in the system.

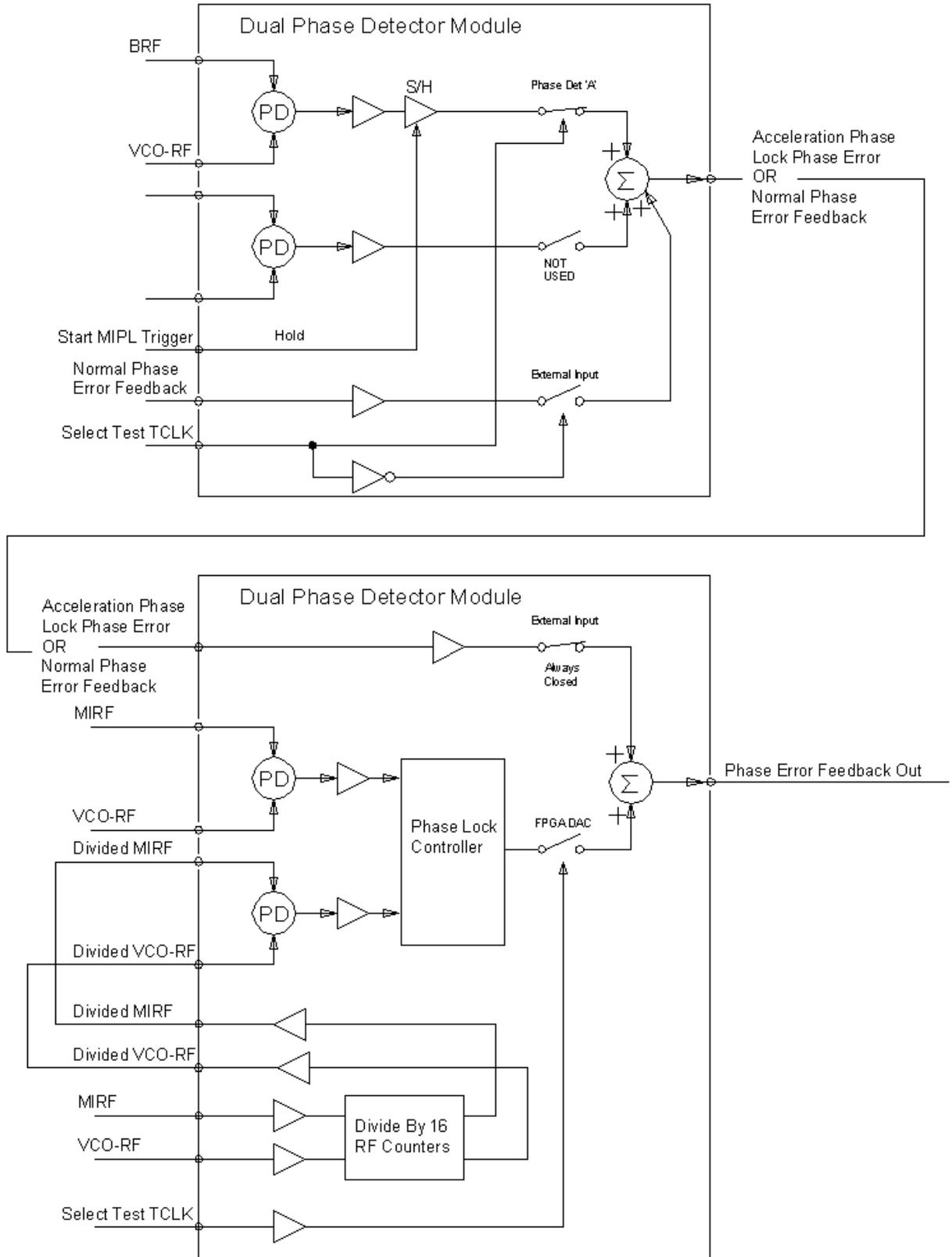


Figure VII.1 Simplified System Block Diagram

Figure VII.1 shows the use of two Dual Phase Detector modules. The upper one produces the acceleration phase lock phase error, and the lower is where the MI phase lock control is implemented. The output of each module is the switch selectable sum of four possible sources. The sources available are an analog phase error signal from each of the modules phase detectors, a DAC output connected to the FPGA and a buffered signal that is an external input to the module. Which signal is actually switched into the summing amplifier is controlled by the FPGA logic.

Unless the “Select Test TCLK” trigger pulses just before a Booster cycle begins, the External Input switches in each module remain closed and the other switches remain open. This selects the phase error feedback and MI phase lock control from the “normal” system. If the Select Test TCLK does pulse just before the Booster cycle the External Input switch in the upper block opens and the Phase Detector ‘A’ switch closes connecting the test phase error feedback to control the Booster acceleration, and the FPGA DAC switch closes in the lower block to prepare to control MI phase lock with the test system.

Table VII. Digital Input on the Dual Phase Detector Module

Front Panel Input	FPGA Signal Name	Description
DI3	Booster_Test_Event	This is a select Booster reset (TCLK) trigger that will generate a substitute “Test Beam Gate” out of the module to gate the LLRF Frequency Source when no beam is present. It does this by outputting the received ACCEL_PHLK_GATE as the Beam Gate. When this trigger does not pulse, the Test Beam Gate is a copy of the BEAM_GATE_IN. This function was created for testing phase lock with the Frequency Source without beam in the Booster.
DI4	Module_Select_Trigger	This is the Booster reset trigger that selects the test system to control acceleration phase lock and MI phase lock. When it does not pulse before a Booster cycle the normal LLRF system phase error signals are used.
T1	BEAM_GATE_IN	This gate is high when beam is in the Booster and gates output from the acceleration phase detector and is a requirement for the MI phase lock to run.
T2	ACCEL_PHLK_GATE	This gate is also required for acceleration phase lock and MI phase lock to be enabled. This signal turns on after an operator settable delay (B:VPLON) and turns off after another settable delay (B:VPLOFF).
T3	ARM_MI_PHASELOCK	This is a select Booster reset (TCLK) trigger that arms the MI phase lock “test” system to be triggered by MI_PHASELOCK_TRIGGER.
T4	MI_PHASELOCK_TRIGGER	This is the trigger from the LLRF Frequency Source that fires when the LLRF frequency reaches a specified value to start the MI phase lock process.

