LOW LEVEL RF CONTROL FOR THE PIP-II INJECTOR TEST RFQ

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Abstract

The PIP-II injector test radio frequency quadrupole (RFQ) arrived at Fermilab in the fall of 2015. The RFQ is a 162.5MHz H- accelerator with a nominal drive power of 100kW, which produces a bunched H- beam at 2.1MeV. In this paper we discuss commissioning, operational performance, and improvements to the low level RF (LLRF) control system for the RFQ. We begin by describing the general system configuration and initial simulation results. We will then highlight temperature related issues in the high power RF system, which necessitate active control over the phase balance of the two amplifiers. Finally we demonstrate performance of the RF feedback and feed-forward compensation needed to meet specification during a 20-microsecond beam pulse.

INTRODUCTION

The PIP-II injector test radio frequency quadrupole (RFQ) was commissioned at Fermilab in January 2016. The RFQ operates at 162.5MHz with a nominal drive power of 100kW. The RFQ accelerates H- to an energy of 2.1MeV and can be operated in both pulsed and CW mode. In order to meet the machine requirements for PIP-II the LLRF system is required to achieve 10^{-3} regulation in the amplitude and 0.1 degrees in phase, and investigate areas for improvement.

The LLRF system is comprised of both analog and digital components. The analog RF components are used to translate the 162.5 MHz signals from the cavity and the directional coupler an intermediate frequency of 13MHz. The signals are then digitized and converted to base-band using the FPGA. The FPGA then performs control calculations on these signals to generate the output signal that is converted back to the intermediate frequency and then up to 162.5 MHz to drive RF amplifiers.

The controller can be operated in three modes: Feed-forward only, feedback (with feed-forward as needed), and frequency-tracking mode. In feed-forward only mode the LLRF system drives the amplifier with a fixed signal level. In feedback mode the LLRF system includes proportional and integral control calculations in order to regulate the cavity amplitude and phase to a desired set point. In the frequency-tracking mode, the LLRF system adjusts the drive frequency proportional to the error in the cavity phase. Additionally, due to the high average power of this RFQ, two solid-state amplifiers are used to power the cavity. To avoid two competing PI loops, the cavity is regulated with a single controller that has two drive outputs. These outputs have independent amplitude and phase calibrations to account for uneven RF distribution systems and unequal amplifier gains.

In this paper we discuss initial simulations of the feedback system and compare with measured data obtained during the system commissioning. Following this, we will discuss the necessary amplifier calibrations to ensure a proper match into the RFQ. Next we discuss temperature related issues in the RF system and an additional controller necessary to compensate for temperature drifts. Finally we demonstrate 10^{-3} performance of the RF system during a 20-microsecond beam pulse.

SYSTEM MODELING

The RFQ was modelled using Matlab's Simulink simulation environment [2]. By using a low-pass-filter model of the RF cavity and neglecting the RF distribution system, we can simulate the controller performance and compare with a measured RF envelope. Figure 1 shows a simplified block diagram of the LLRF system model created in Simulink [2].

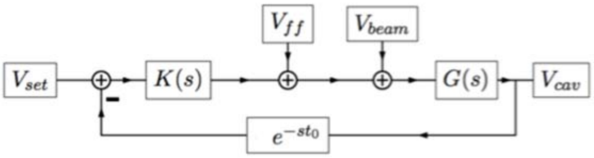

Figure 1: Block diagram of the LLRF simulation model.

Figure 2 shows the simulated RF pulse in the RFQ compared with the measured pulse obtained during RFQ commissioning.

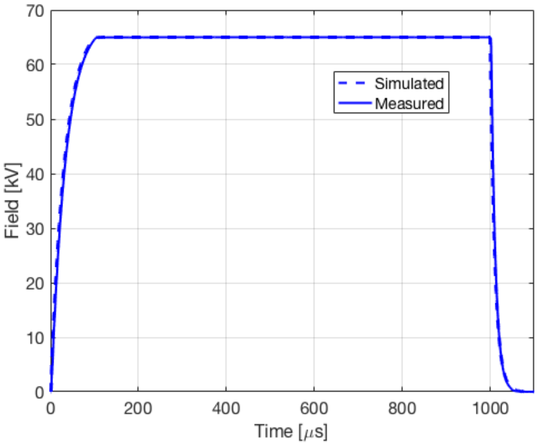

Figure 2: Comparison of measured RF pulse to simulated RF pulse in the RFQ. Proportional and integral gains were 9.0 and 8.0e5 respectively.

In Figure 1, $K(s) = K_p + K_i/s$, $G(s) = \frac{\omega_0}{2Q_L}/\left(s + \frac{\omega_0}{2Q_L}\right)$, and t_0 is the feedback delay of the system, 2 microseconds was used for our simulations in Figure 2.

The loaded quality factor for the RFQ is approximately 5490. Figure 2 shows good agreement between the simulated and the measured RF waveform.

AMPLIFIER GAIN AND PHASE CALIBRATION

In order to ensure a proper phase and amplitude match of both amplifiers into the RFQ, the two drives from the LLRF controller need to be calibrated by adjusting the up converter amplitude and phase adjustments. To calibrate the phase and amplitude, we scanned the up-converter gains and phases while measuring the reflected power. Figures 3 and 4 show the reflected power as a function of the phase difference between the two up-converter settings, and the up converter gains respectively. Both Figures 3 and 4 are showing the sum of the reflected power in the left leg and the right leg.

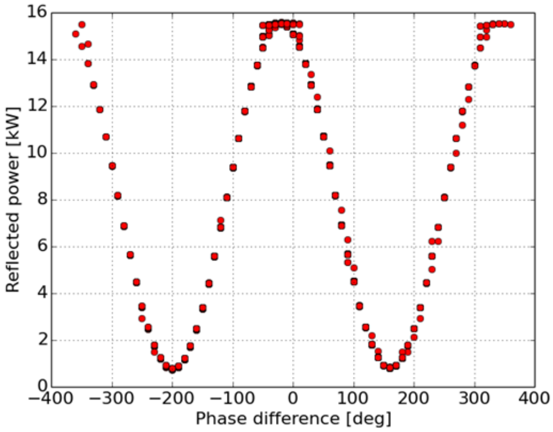

Figure 3: Phase difference between the LLRF drives vs. reflected power.

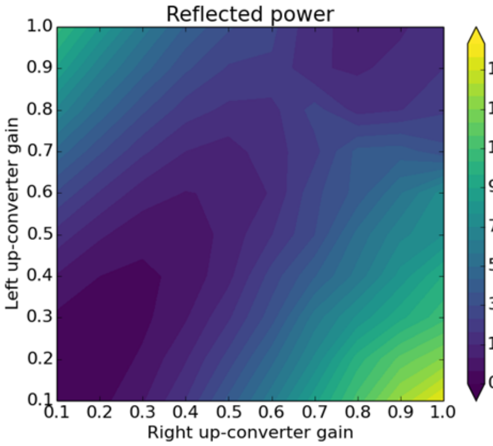

Figure 4: Gain of the LLRF drives vs. reflected power.

Figure 3 shows that in order to ensure a proper phase match, the phase difference between the two up-converter calibrations should be 160 degrees. Figure 4 shows that in order to maintain a proper amplitude match into the RFQ the right up converter should be slightly attenuated relative to the left. Therefore we attenuate our drive of the right up-converter by scaling the associated drive to 0.82.

PHASE TRACKING LOOP

The RF distribution system experiences significant phase drift due to temperature fluctuations, especially when operating in CW. If left unregulated, these drifts significantly degrade the ability to track the frequency of the RF cavity using only the cavity phase. While frequency of the cavity is determined by the difference between the forward and cavity phase, the frequency-tracking loop uses only the cavity phase in order to reduce complexity and resource usage in the FPGA. Figure 5 shows the drift in the forward phase at the directional coupler due heating during RF turn on.

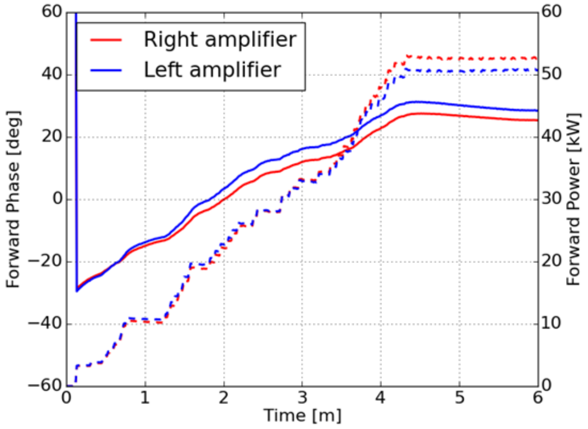

Figure 5: Phase drift due to RF heating, dotted lines for power solid lines for phase.

During turn-on, operators can adjust the feed-forward phase to compensate for the drift while tracking the frequency. This drift results in a relatively slow ramp in the RF power. This slow ramp can be significantly improved by active phase regulation of the RF system. To correct for this drift we implemented a slow feedback-loop on the drive phase in control software. The controller adjusts the two up converter phase calibrations simultaneously in order to match the drive phase from the FPGA to the forward phase measured at the directional coupler.

This simultaneous adjustment removes the effects of any phase advance that occurs from the LLRF output to the directional coupler on the RFQ. The feedback loop has a discrete time domain equation given by Equation 1.

$$\phi[n+1] = \phi[n] + k\phi_{error}[n] \qquad (1)$$

It is important to ensure stability of this controller because it will impact the fast feedback that occurs during the RF pulse. Taking the z-transform of Equation 1 and solving for the system transfer function gives Equation 2.

$$(\phi\hat{~}(z))/(\phi\hat{~}\_error\ (z)\ ) = \ k/(z-1) \qquad (2)$$

Equation 2 will be stable for a sample rate of 10Hz (control system update rate) and a gain, k, less than one. Figure 6 shows the improved turn on performance as well as fully compensated phase drift of the two amplifiers.

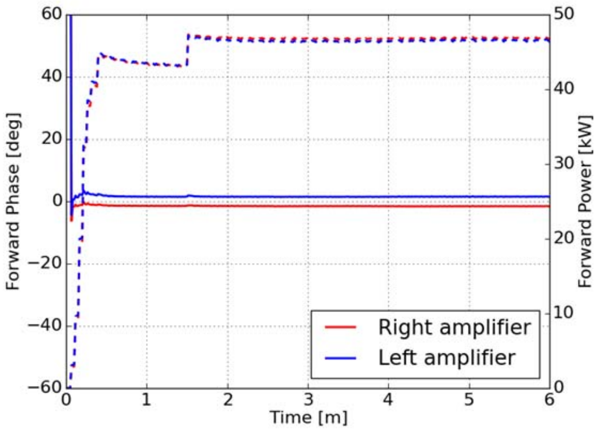

Figure 6: Compensated phase drift with slow feedback, dotted lines for power solid lines for phase.

Figure 6 shows that both the turn on speed is improved in addition to complete mitigation of the amplifier phase drift. Additionally, there is no required operator intervention to adjust the feed-forward phase and a fast ramp could therefore be programmed into a turn-on sequencer.

REGULATION PERFORMANCE

We have also demonstrated the regulation performance during a 20-microsecond beam pulse. For a long beam-pulse we would meet our requirements after the initial beam disturbance, however we are out of specification for the short pulse diagnostic beams. In order to minimize the beam-loading effects and ensure that the cavity is within specification for initial beam measurements, we implemented a simple feed-forward compensation for beam-loading. Figure 7 shows the performance of this feed-forward compensation. This feed-forward compensation was tuned manually. We are in the process of developing new adaptive beam-loading compensation algorithms.

Figure 7 shows that we can meet our regulation specification for these short pulses. Additional work is needed to meet the more stringent energy regulation requirements of 10^{-4} with beam-based feedback.

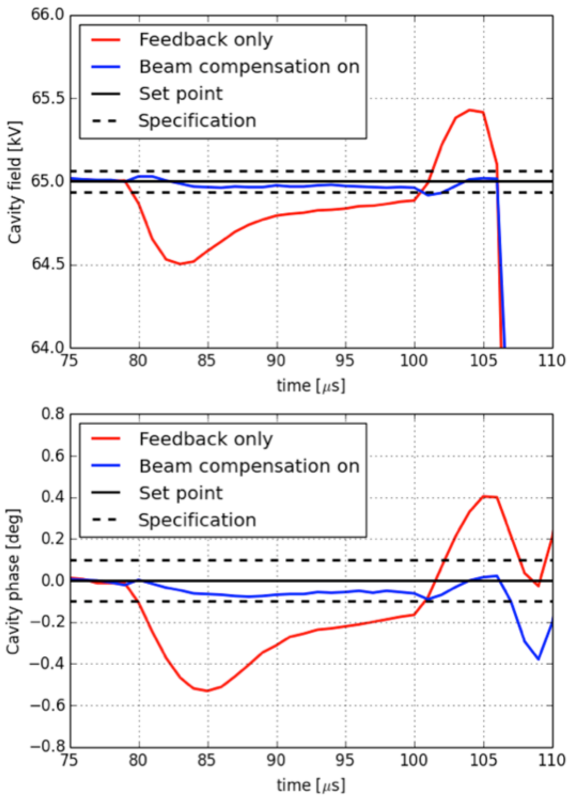

Figure 7: Demonstrated 10^{-3} regulation in amplitude and 0.1 degrees regulation in phase with feed-forward beam loading compensation

CONCLUSIONS

In this paper we have shown good comparison between simulations of the RF controller and measurements, provided phase and amplitude calibration results of the two amplifiers, shown improvements to the system's operational performance in CW mode through the use of slow phase control to compensate for temperature drifts in the high level RF system, and shown that through the use of feed-forward compensation we can meet our initial specifications during a short beam pulse.

ACKNOWLEDGMENTS

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REFERENCES

[1] V. Lebedev, Editor, "The PIP-II Reference Design Report," June 2015.

[2] MATLAB and Statistics Toolbox Release 2016a, The MathWorks, Inc., Natick, Massachusetts, United States.