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PERFORMANCE OF THE LLRF SYSTEM FOR THE FERMILAB PIP-II INJECTOR TEST*

P. Varghese†, B. Chase, S. Raman, H. Maniar, D. Nicklaus, P. Hanlet
Fermi National Accelerator Laboratory (FNAL), Batavia, IL, USA
L. Doolittle, C. Serrano, S. Paigua
Lawrence Berkeley National Laboratory (LBNL), Berkeley, CA, USA

Abstract

PIP-II IT is a test facility for the PIP-II project where the injector, warm front-end and the first two superconducting cryomodules are being tested. The 8-cavity half-wave-resonator (HWR) cryomodule operating at 162.5 MHz is followed by the 8-cavity single-spoke resonator (SSR1) cryomodule operating at 325 MHz. The LLRF systems for both cryomodules are based on a common SOC FPGA based hardware platform. The resonance control systems for the two cryomodules are quite different, the first being a pneumatic system based on helium pressure and the latter a piezo/stepper motor type control. The data acquisition and control system can support both CW and Pulsed mode operation. Beam loading compensation is available which can be used for both manual/automatic control in the LLRF system. The user interfaces include EPICS, Labview and ACNET. Testing of the RF system has progressed to the point of being ready for 2 mA beam to be accelerated to 20 MeV. The design and performance of the field control and resonance control system operation with beam are presented in this paper.

INTRODUCTION

PIP-II IT is a test facility for the PIP-II project where the injector, warm front-end and the first two superconducting cryomodules are being tested. The warm frontend consists of an Ion source an RFQ and three buncher cavities.The superconducting RF section consists of the 8-cavity half-wave-resonator(HWR) cryomodule operating at 162.5 MHz which is followed by the 8-cavity single-spoke resonator (SSR1) cryomodule operating at 325 MHz. The LLRF systems for the RFQ and buncher 1 are based on a FPGA/DSP LLRF controller in a VXI mainframe. The LLRF controllers for buncher 2, 3 and for both cryomodules are based on a common SOC FPGA based hardware platform. The resonance control system for the HWR cryomodule uses a pneumatic tuner that changes the cavity resonant frequency by regulating the helium pressure on the cavity manifold. The SSR1 cavities use a piezo/stepper motor type control. The RFQ uses a cooling temperature regulation system for resonance control while the bunchers have static resonance control using stepper motors. This paper will focus more on the superconducting RF performance as the details of the warm frontend has been reported earlier [1]. The data acquisition and control system can support both CW and Pulsed mode operation. Beam loading compensation is available which can be used for both manual/automatic control in the LLRF system [2]. The user interfaces include EPICS, Labview and ACNET. Testing of the RF system with 2 mA beam accelerated to 20 MeV has been completed. The design and performance of the field control and resonance control system operation with beam are presented in this paper.

LLRF SYSTEM

The RF components of the PIP-II-IT test stand are shown in Fig. 1. With the exception of the RFQ and buncher 1, the LLRF systems are all based on the Fermilab SOCFPGA controller which combines an ARM CPU with an FPGA on the same silicon. This architecture combines the features of a microprocessor and FPGA allowing the development of standalone NAD (network attached device) systems that can be adapted to a variety of applications. The current hardware uses an Intel CycloneV SOC FPGA with sufficient resources to provide field control and resonance control independently for 2 cavities. Four controller chassis can provide the LLRF system control for an 8-cavity cryomodule. The architecture of one half of the 8-cavity LLRF sysyem for SSR1 is shown in Fig. 2. The resonance control chassis (RCC) used here was developed for the LCLS-II project. Cavity detuning data for 4 cavities is sent to the RCC over optical fiber and is used to drive the piezo tuners. In the case of the HWR, the tuner controls and the valve drives are integrated into the LLRF controller with an external analog signal conditioning module [3].

The user interfaces in Labview, EPICS and ACNET utilize automated scripts for cavity turn on/off and for switching the cavity from SEL (self excited loop) to GDR (generator driven) mode. While the SRF cavities were run primarily in CW mode, both pulse mode and CW mode are supported by the software. Cavity detuning computation is performed in the FPGA from the probe and forward power signals [4].

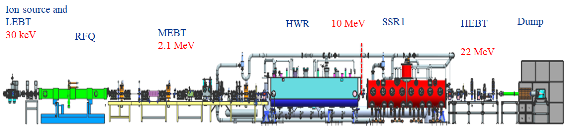

Figure 1: PIP-II-IT RF Components.

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† varghese@fnal.gov

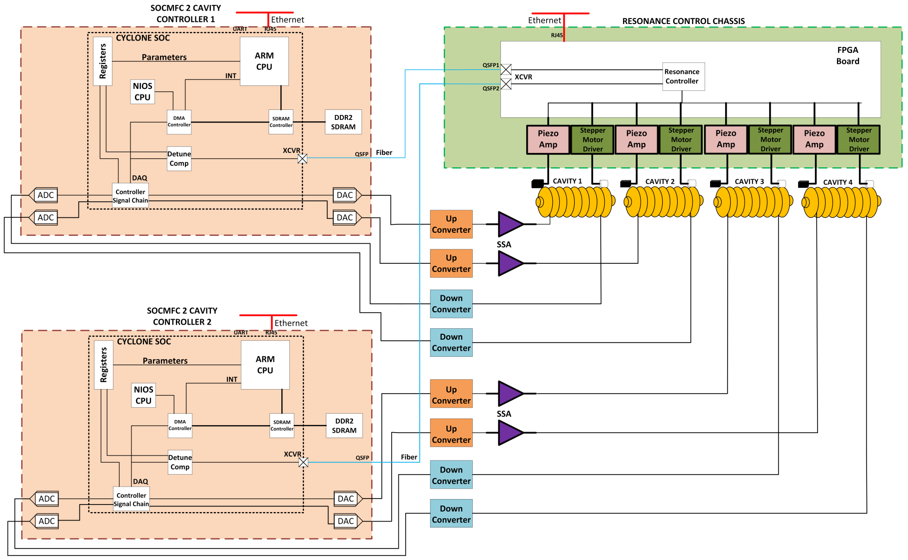

Figure 2: SSR1 LLRF System.

CAVITY FIELD REGULATION

The amplitude and phase feedback regulation for HWR cavities 4- 8 and for SSR1 cavities 1-8 are shown in Tables 1 and 2. The feedback proportional gains of the PI controller used were 1000 and 1600 for the HWR and SSR1 cavities. The integral gains were 3.0e6 radians/sec [5]. HWR Cavity 1 and 2 had a resonant frequency tuning range outside the RF reference frequency of 162.5 MHz and HWR cavity 3 became inoperable due to a coupler bias system failure and were therefore excluded from the RF testing.

Table 1: HWR Amplitude and Phase Regulation

Cavity	Amplitude (% rms)	Phase (°rms)
4	0.0115	0.0228
5	0.0106	0.0065
6	0.0101	0.0056
7	0.0081	0.0055
8	0.0103	0.0062

Table 2: SSR1 Amplitude and Phase Regulation

Cavity	Amplitude (% rms)	Phase (°rms)
1	0.0194	0.0116
2	0.0289	0.0164
3	0.0219	0.0118
4	0.0157	0.0091
5	0.0140	0.0088
6	0.0158	0.0093
7	0.0147	0.0092
8	0.0124	0.0076

The PIP-II specifications for the field regulation are 0.065 % rms for amplitude and 0.065 degrees rms for phase [6]. All the cavities are well within the specifications.

RESONANCE CONTROL

The pneumatic tuner performance for the HWR cavities is described in a separate paper in these proceedings (THPAB337). The piezo tuner for the SSR1 cavities uses an EPICS interface with manual and automatic controls. Various automated tests including piezo capacitance measurement and piezo drive to cavity detuning transfer function measurement are available. A frequency chirp signal input is provided to the piezos with some RF in the cavity and the resultant detuning is recorded. Spectral analysis of the data provides a transfer function for the piezo that can be used for system identification and control of the tuner.

The histogram of the HWR cavity 8 detuning is shown in Fig. 3. The histogram of the SSR1 cavity 8 detuning is shown in Fig. 4. The piezo transfer function for SSR1 cavity 4 is shown in Fig. 5.

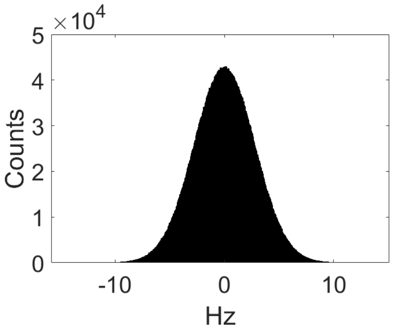

Figure 3: HWR Caviy 8 Detuning - Histogram.

The detuning fluctuations are seen to be within a +/- 10 Hz range which is well within the +/-20 Hz specification for PIP-II.

BEAM LOADING COMPENSATION

Beam loading compensation(BLC) synchronized to the beam arrival trigger pulse is available in all the LLRF systems. In CW operation data acquisition is continuous and

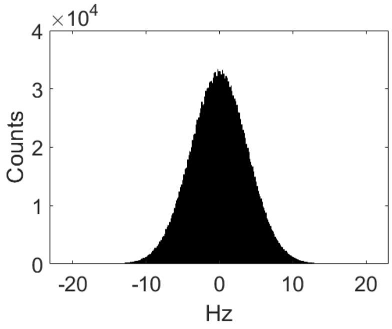

Figure 4: SSR1 Caviy 8 Detuning - Histogram.

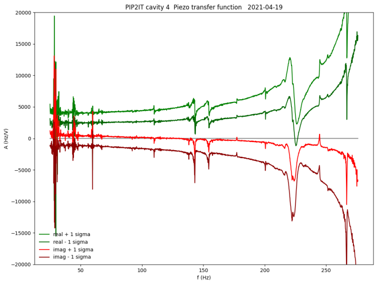

Figure 5: SSR1 Caviy 4 Piezo Transfer Function.

special attention must be paid to provide synchronized beam loading compensation. The RFQ and bunchers were operated in pulse mode due to stability considerations for the RFQ. In all systems BLC is provided as an addition to the feedforward with adjustments in phase amplitude and time of application. This feature can be used both for manual and automatic or adaptive compensation schemes. The results of the manual tuning in buncher 2, to minimize the phase disturbance at the leading edge of the beam are shown in Figs. 6 and 7. 5 mA beam with a 550 µs pulse width was applied to the cavity during this test. The phase disturbance was reduced from 3.5 degrees to < 0.2 degrees.

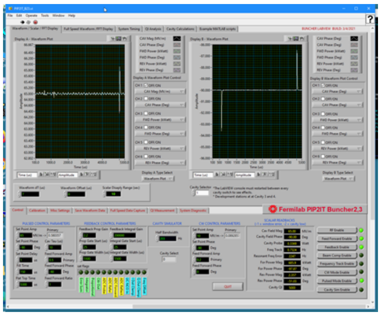

Figure 6: Buncher 2 BLC OFF.

Q_L MEASUREMENT

The Q_L measurement is a feature in the Labview inerface that measures the cavity Q_L in CW mode operation by turning RF OFF and recording the cavity field decay waveform. The measurement shown in Fig. 8 gave a Q_L of 2.07e6 for HWR cavity 5 and 4.11e6 for SSR1 cavity 5 which agrees with the other SRF measurements. There is a detuning calibration procedure when a short RF pulse is applied and the resultant cavity and forward waveforms recorded. Analysis of this data provides the calibration constants needed for the detuning computation as well as cavity bandwidth which is another way to confirm the Q_L measurement.

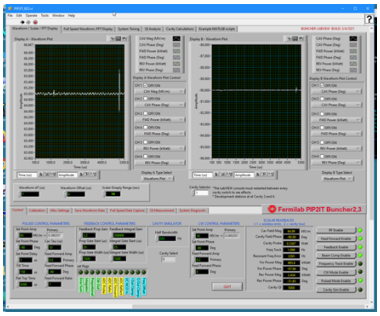

Figure 7: Buncher 2 BLC ON.

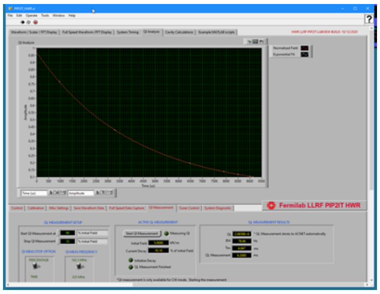

Figure 8: HWR cavity 5 Q_L measurement.

CONCLUSION

The performance of the LLRF systems of the PIP-II-IT test provided valuable experience with a variety of RF systems, hardware and user interfaces. The individual subsystems were very different for the various RF components. All systems were operated with and without beam over the approximately one year of the testing. The RF systems were shown to meet the project specifications for cavity field amplitude and phase regulation and the resonance control systems for HWR and SSR1 cavities were also shown to meet requirements. Operations with beam were limited to 10 us pulses towards the end of the run but data was taken with the full beam loading in parts of the accelerator. The high feedback gains of the SRF cavities proved to be adequate to compensate for beam loading. The buncher cavities operating at much lower fields and far lower feedback gains due their lower Q were more sensitive to beam loading. The results of the BLC tuning on buncher 2 showed that compensation can significantly mitigate the effects of the disturbance.

Experimental features such as RF overdrive protection and cavity quench protection were tried but not fully tested due to the end of the run. Resonance control of the SRF cavities requires the cavity detuning computation as its primary input. This computation was performed in the FPGA with an efficient logic block requiring minimal resources and proved to be critical for resonance control and GDR mode operation. The user interfaces in EPICS and Labview provided many features for data acquisition, detuning calibration piezo transfer function and Q_L measurements.

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