Performance of the LLRF System for the Fermilab PIP-II Injector Test

P. Varghese*, B. Chase, S. Raman, H. Maniar, D. Klepec, D. Nicklaus, P. Hanlet, Fermilab, Batavia, IL, USA L. Doolittle, C. Serrano, S. Paiagua, LBNL, Berkeley, CA, USA ID2277

Introduction

- PIP-II IT is a test facility for the PIP-II project where the \bullet injector, warm front-end and the first two superconducting cryomodules were tested.
- The RF system consists of an RFQ, 3 Buncher cavities, an 8ulletcavity half-wave-resonator(HWR) cryomodule, and an 8-cavity single-spoke resonator(SSR1) cryomodule.

PIP-II IT Components



Beam Loading Compensation in Buncher 2

- The LLRF systems for both cryomodules and Bunchers 2 and 3 use an SOC FPGA based controller whereas the RFQ and Buncher 1 use an FPGA/DSP board in a VXI crate.
- For resonance control, the HWR cavities use a pneumatic \bullet tuner and the SSR1 cavities use a stepper motor/piezo tuner. The resonance controller chassis used is the one from LCLS-II.
- The user interfaces include EPICS, Labview and ACNET.
- Testing of the RF system has been completed with 2 mA beam accelerated to 20 MeV.
- Performance of the system was shown to meet PIP-II requirements

Amplitude and Phase Regulation

HWR Amplitude and Phase Regulation								
	Cavity4	Cavity5	Cavity6	Cavity7	Cavity8			
Cavity Field Setpoint (MV/m)	2.89	6.04	8.94	8.5	8			
Amplitude Regulation (rms) %	0.0135	0.0106	0.0101	0.0081	0.0103			
Phase Regulation (rms) deg	0.0228	0.0065	0.0056	0.0055	0.0062			
Feedback Proportional Gain	1000	1000	1000	1000	1000			
Feedback Integral Gain (rad/sec)	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000			

SSR1 Amplitude and Phase Regulation									
	Cavity1	Cavity2	Cavity3	Cavity4	Cavity5	Cavity6	Cavity7	Cavity8	
Cavity Field Setpoint (MV/m)	4.88	4.63	4.78	7.32	7.8	7.56	7.32	10	
Amplitude Regulation (rms) %	0.0194	0.0289	0.0219	0.0157	0.014	0.0158	0.0147	0.0124	
Phase Regulation (rms) deg	0.0116	0.0164	0.0118	0.0091	0.0088	0.0093	0.0092	0.0076	
Feedback Proportional Gain	1600	1600	1600	1600	1600	1600	1600	1600	
Feedback Integral Gain (rad/sec)	3,000,000	3,000,000	3,000,000	3,000,000	3,000,000	3,000,000	3,000,000	3,000,000	

PIP-II Specifications

- < 0.01% Energy Stability (Linac) < 0.06 deg Phase Regulation
- Amplitude Regulation (individual cavity) < 0.06%





Compensation ON Uncompensated BLC Tuning was focused on minimizing phase excursion at leading edge Phase disturbance reduced from -3.5 deg to < 0.2 deg

SSR1 Piezo Transfer Functions





Resonance Control – Cavity Detuning Histograms



Detune Calibration and DAQ Features

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8.000-	REV Phase (Deg)	12.500-	REV Phase (Deg)	
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Control Calibration Misc Settings Save Waveform Data Full S	peed Data Capture QI Measurement	Tuner Control System Diagnostic	Fermilab	LLRF PIP2IT HWR	
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Q_L Measurement



HWR Cavity 5, *Q*_{*L*} = 2.07e6







Summary



*varghese@fnal.gov

- The LLRF system for PIP-II IT used a diverse mix of hardware, software and user interfaces for the various RF components. Major requirements such as field/phase regulation, resonance control and beam loading compensation met the project specifications
- The experience with testing at PIP-II IT will guide the final design for the projects LLRF systems.







