

Figure 2: PIP-II Linac Components

versity of Technology(TUL) for the Master Oscillator and Precision Reference Line (MO/PRL).

The first control system architecture, used in the warm front-end is the I/Q control loop shown in Fig.1. The I/Q control architecture has the advantage of low latency and therefore higher feedback gain for better amplitude and phase regulation. This is the control structure implemented in the FNAL controller which also supports both CW and Pulse Mode operations. The RFQ requires pulse mode for stable field control.

The second architecture used in the Marble controller is the Amplitude/Phase control loop that requires two CORDIC blocks at the input and output of the controller as shown in Fig.3. While this control scheme increases the latency in the feedback loop, it has several advantages that make it suitable for superconducting cavity control. The SEL architecture, with its independent amplitude and phase limiting permits the smooth transition between the various operating modes of operation for the cavity(SEL/SELA/SELAP) with lower transients. It is also very effective in addressing ponderomotive oscillations as will be seen with the LB650 cavity testing discussed later. Both architectures were tested interchangeably during the PIP2IT run and were found to perform well to meet the cavity field and phase regulation requirements.

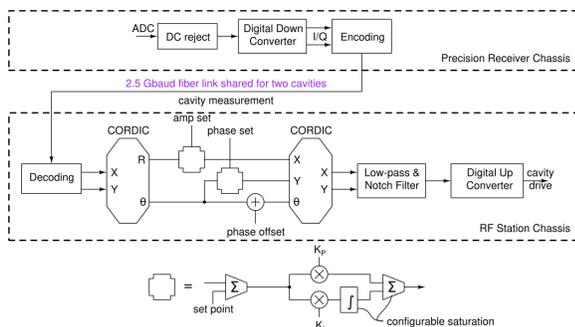


Figure 3: LLRF System Architecture - Amp/Phase Control

## LINAC REQUIREMENTS

The PIP-II project goal is to deliver 1 MW of proton beam power from the Fermilab Main Injector, over the energy range of 60 - 120 GeV, at the start of operations of the LBNF/DUNE program. It is also a platform for eventual extension of beam power to greater than 2 MW. The requirements for Linac beam energy stabilization are determined by the Booster RF bucket height and requirements related to static longitudinal painting in the course of multi-turn beam injection. The latter requires a Linac beam energy stability of 0.01 % rms. This is achieved with the field amplitude and phase regulation requirements of 0.06 % rms and 0.06 ° rms[7]. The LLRF feedback controller should be capable of regulating this level over a duration of less than one second. For durations greater than one second, an adaptive feed-forward algorithm corrects for drift in the cavity phase and amplitude calibrations by utilizing beam-based diagnostics along the Linac and in the Booster as well as RF diagnostics to provide feed-forward corrections and slow adjustments to LLRF calibrations.

Beam current, cavity field gradients, and worst-case microphonics detuning determine loaded cavity  $Q_L$ , bandwidths and RF power requirements. Dynamic correction of microphonic disturbances by resonance frequency control are required for gradient regulation without exceeding available RF power overhead. Total RF power specifications are based on cavity specifications with 2 mA of CW beam current and 20 Hz peak amplitude microphonics. Power loss through the HWR and SSR RF distribution is assumed to be 10% and power loss through the 650 MHz distribution is assumed to be 6%. Final power specifications include a 25% overhead in addition to distribution loss that allows for RF control margin.

## TESTING AT CMTF AND STC

PIP2IT was a test run at CMTF for the PIP-II project where the injector, warm front-end and the first two superconducting cryomodules were tested. The warm front-

end 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 were based on a FPGA/DSP LLRF controller in a VXI mainframe and are being upgraded to an Arria10 SoCFPGA based controller for PIP-II. The LLRF controllers for buncher 2,3 and for both cryomodules were based on a CycloneV SOC FPGA based hardware platform -these will also be upgraded to the newer Arria10 controller.

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. 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 included EPICS, Labview and ACNET - they will be replaced by an entirely EPICS based user interface and control system for PIP-II. Testing of the RF system with 2 mA beam accelerated to 20 MeV has been completed in May 2021. Some of the results from the testing are shown here[2].

### RFQ and Buncher

Both the RFQ and buncher 1 LLRF systems support 20 Hz pulsed and CW mode operation. During the PIP-II-IT run only pulsed mode operation was used due to stability issues with the RFQ. 2mA beam at 550 us pulse width was accelerated through the RF components by the end of the testing. Beam loading compensation synchronized with a beam arrival trigger was used effectively with both the RFQ and buncher cavities. The compensation is applied as an addition to the feedforward control input and supports both manual and automatic adaptive control schemes [8]. The resonance control system for the RFQ is regulated with a temperature control feedback loop and the static tuning of the bunchers was accomplished by manual stepper motor control. The RF system is turned on in self-excited loop(SEL) mode and switched to generator driven mode(GDR) with the cavities on resonance. A labview interface provides a display of all waveforms and allows for operator control of all parameters. All parameters are also available in ACNET which allows the control of the system with automated sequencers which simplifies the operator interface and also allows for data logging and monitoring.

Beam loading compensation was implemented and tested with the buncher cavities towards the end of the run. The test was performed with 5 mA of beam with a 550 us pulse width. Manual tuning of the beam loading compensation parameters enabled the reduction of the phase disturbance at the leading edge of the beam from 3.5 degrees

Table 1: Cavity Maximum Feedback Gain Range

Cavity Type	$Q_L$	$f_0$ (MHz)	$f_H$ (Hz)	$K_P$
Warm	3000	53	$8.83 \times 10^3$	15
RFQ	15000	162.5	$5.542 \times 10^3$	23
Buncher	10000	162.5	$8.125 \times 10^3$	16
HWR	$2.32 \times 10^6$	162.5	35	3548
SSR1	$3.02 \times 10^6$	325	53.8	2317
SSR2	$5.05 \times 10^6$	325	32.2	3846
LB650	$10.36 \times 10^6$	650	31.4	3935
HB650	$9.92 \times 10^6$	650	32.76	3801
LCLSII	$4 \times 10^7$	1300	16.25	7600

to < 0.2 degrees. The relatively low Q values for the RFQ and buncher cavities do not allow large feedback gains. Table 2 shows the feedback gain limits for stable operation for the various types of cavities in the PIP-II-IT accelerator[2]. The feedback gains used were  $\approx 4$  and 3 for the RFQ and the bunchers respectively. Loop gain measurements were performed to confirm the actual gains in the feedback operation. Testing at PIP-II-IT showed that feedback is not sufficient to compensate for beam loading and an effective BLC scheme is essential for all components in the warm front-end. The feedback regulation performance for the warm frontend is indicated in Table 2.

Table 2: Warm Frontend Amplitude and Phase Regulation

Cavity	Amplitude (% rms)	Phase (° rms)
RFQ	0.0115	0.0228
Buncher 1	0.0106	0.0065
Buncher 2	0.0101	0.0056
Buncher 3	0.0081	0.0055

### HWR Cryomodule

The HWR cryomodule is the first one in the superconducting section of the PIP-II LINAC. The cryomodule is comprised of 8 cavities operating at a frequency of 162.5 MHz and accelerating beam upto 10 MeV. Resonance control of the cavities is performed with a pneumatically operated slow tuner which compresses the cavity at the beam ports. Helium gas pressure in a bellows mounted to an end wall of the cavity is controlled by two solenoid valves, one on the pressure side and one on the vacuum side. Each tuner has two actuators for the Pressure and Vacuum valves which are driven by two DAC channels through a signal conditioning unit. Each tuner also has a pressure transducer signal that is digitized using a DC coupled ADC channel whose output represents the pressure in the cavity manifold which is the primary physical parameter that is controlled[10].

The resonant frequency of the cavity can be controlled

in one of two modes. A pressure feedback control loop can hold the cavity tuner pressure at a fixed value for the desired resonant frequency - this is referred to as the 'Pressure Mode' operation. Alternately, the feedback loop can regulate the cavity tuner pressure to bring the RF detuning error to zero which is referred to as the 'RF Mode'. In the latter case, the tuner can compensate for slow drifts in resonant frequency. In the GDR (generator driven) mode of operation, all cavities are run at the same reference frequency. The RF Mode is necessary for the GDR mode. A state machine based system controller can provide an automatic transition between the modes of operation according to the machine state. The tuner implementation is done with a signal conditioning module and the same LLRF SoCFPGA controller is used for cavity field control. Table 3 shows the field regulation performance of the HWR cavities.

Table 3: 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

### SSR1 Cryomodule

The SSR1 cryomodule consists of 8 single spoke resonator type superconducting cavities operating at 325 MHz. They are equipped with piezo tuners and stepper motors for dynamic and static resonance control. Each cavity is driven by a 7kW solid state amplifier(SSA) with a maximum operating field of 10 MV/m. The LLRF system for all eight cavities is implemented with 4 SoCMFC controller chassis and 2 resonance control chassis(RCC). The RCC is the same hardware used in the LCLS-II project with controls for the stepper motors and piezo tuners for 4 cavities per chassis. The RCC uses an EPICS user interface and has a Xilinx FPGA for the digital control and communication. The LLRF controllers are implemented with Intel SoCFPGA's with a Labview and ACNET user interface for operator control. Cavity detuning data is transmitted from each LLRF controller to its corresponding RCC over an optical fiber and high speed transceivers on both ends. This cryomodule was unique in its mixed hardware/software and user interface diversity but was integrated and made fully operational without too much difficulty.

Table 4 shows the measured amplitude and phase regulation of the SSR1 cavities. All cavities meet the specifications for PIP-II. These measurements were all taken without beam. During the short period when the full 550 us width pulse of 2 mA beam was tested, no beam loading effects were seen due to the high feedback gains adequately suppressing the disturbances due to beam. The microphon-

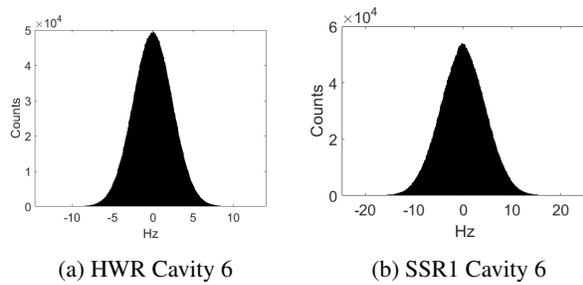


Figure 4: Cavity Detuning Histograms

ics detuning histograms for the HWR and SSR cavities are shown in Fig. 4.

Table 4: 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

### HB650 and LB650 Cavity Testing at STC

Single cavity testing of various PIP-II cavities has been an ongoing effort at STC facility since 2019. HB650, LB650 and SSR2 cavities have been tested here. It has proved to be a good test bed for testing and validating various LLRF system hardware components for PIP-II. The Jlab provided Resonance Controller, LBNL's LLRF controller along with the FNAL designs of LLRF controllers have all been tested here.

The first LB650 cavity was tested last year with significant ponderomotive force effects that highlighted the advantages of the SEL architecture. The five cell cavity had significant excitation of the  $4/5\pi$  and  $3/5\pi$  passband modes as shown in Fig. 5. These modes had to be suppressed with notch filters before increasing the feedback



Figure 5: LB650 Cavity Resonant Modes

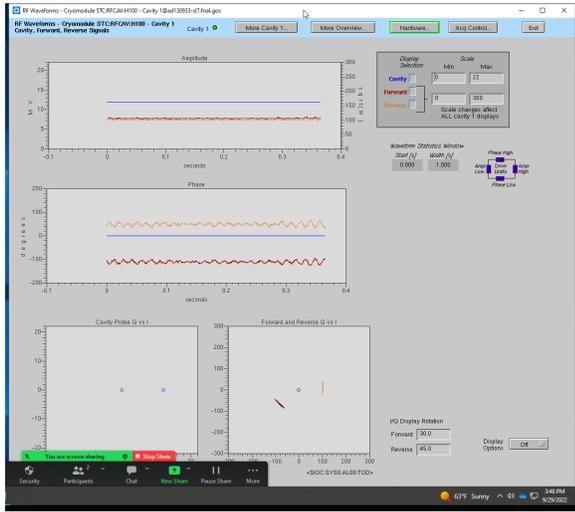


Figure 6: LB650 Cavity Waveforms in GDR Mode

gains and reaching the full gradient of 17 MV/m in GDR mode. The cavity waveforms are shown in Fig. 6.

### HB650 Test Stand at CMTF

A prototype HB650 cryomodule with 6 cavities has been under test at the CMTF facility since January 2023. A single 40 kW SSA provided by DAE, India has been used to test the cavities, one at a time. This facility will be used to test all the PIP-II cryomodules that have not been tested - HB650, LB650 and SSR2. This facility is also an important test bed to validate the performance of various subsystems for PIP-II such as SSA's, RFPI, MPS, Timing and Synchronization and the EPICS controls interface. Additional testing with the prototype HB650 cryomodule will resume when it returns from its transportation test to the UK at the end of this year. The amplifier non-linearities have been a challenge to run the cavity in GDR mode. SSA calibration pro-

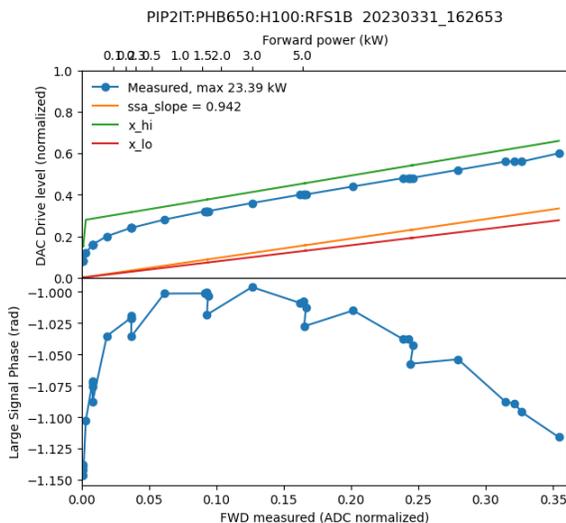


Figure 7: HB650 SSA Calibration- Affine Fit

cedures and computations were modified to compensate for the non-linearities of the SSA as shown in Fig. 7.

The PIP-II RFPI prototype hardware designed by TUL was successfully tested and has entered the final design prototype phase. New LLRF and Resonance control hardware based on the Marble FPGA board are being readied for testing at CMTF.

## CONCLUSION

The PIP-II LLRF system components are in the final design phase. Testing at the two teststands STC and CMTF over the past few years has provided the opportunity to test and validate both hardware and software/firmware components of the design with all cavity types with and without beam. These facilities will continue to serve as test areas where additional cryomodules and cavities will be tested until installation and commissioning starts at the end of 2026. The control system and user interfaces implemented with EPICS will also get tested in these test stands.

Resonance control with temperature control, helium pressure control and piezo tuners were tested in the PIP2IT phase. The project specifications for microphonics detuning were met by all the cavities tested so far. Field magnitude and phase regulation specifications for these LLRF systems for the project have also been met. The phase reference line components and timing and synchronization subsystems will also be tested here as they become finalized.

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