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Fermilab PIP-II Injector Test - LLRF System Design and Performance

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Outline

1. PIP2-IT Accelerator Components
2. LLRF Systems
   a) RFQ and Buncher 1
   b) Buncher 2 and 3
   c) HWR Cryomodule
   d) SSR1 Cryomodule
3. LLRF Testing and Calibration
4. Labview, ACNET and EPICS interfaces
5. Results and system performance

PIP2-IT Accelerator Components

Ion Source

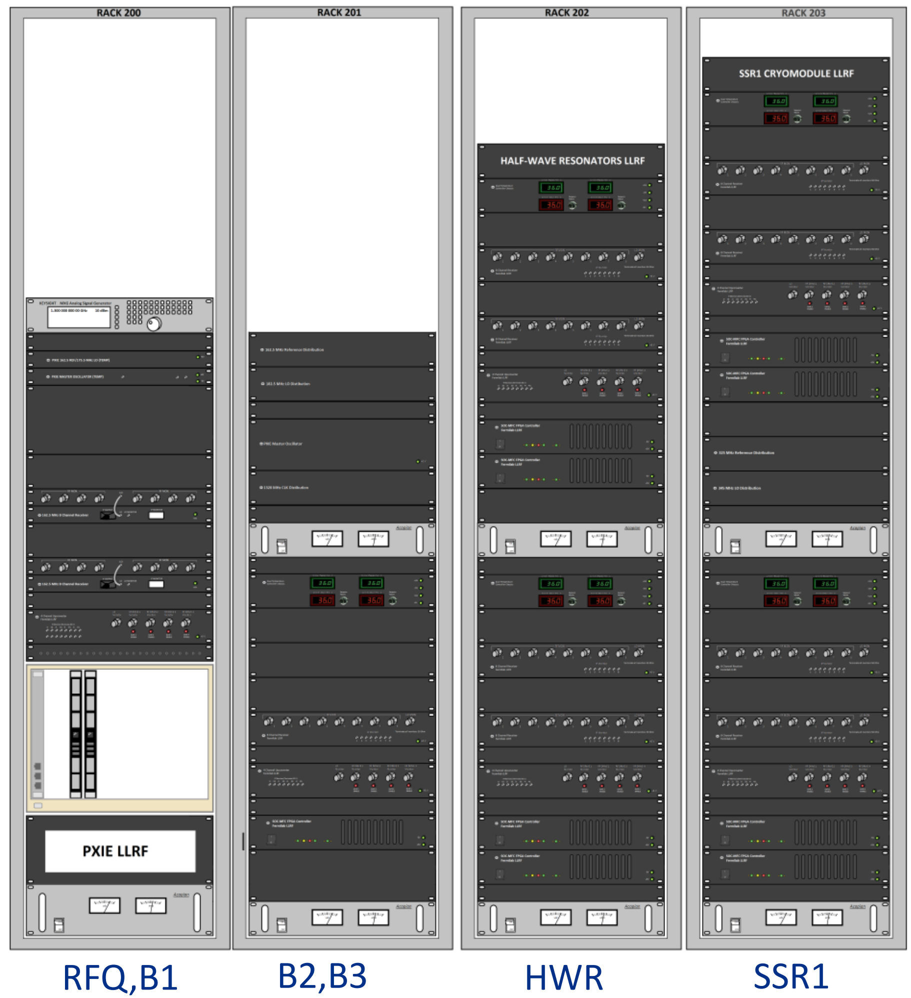
RFQ, B1
VXI Crate
2 MFC cards

Buncher2,3
1 SOCMFC Chassis

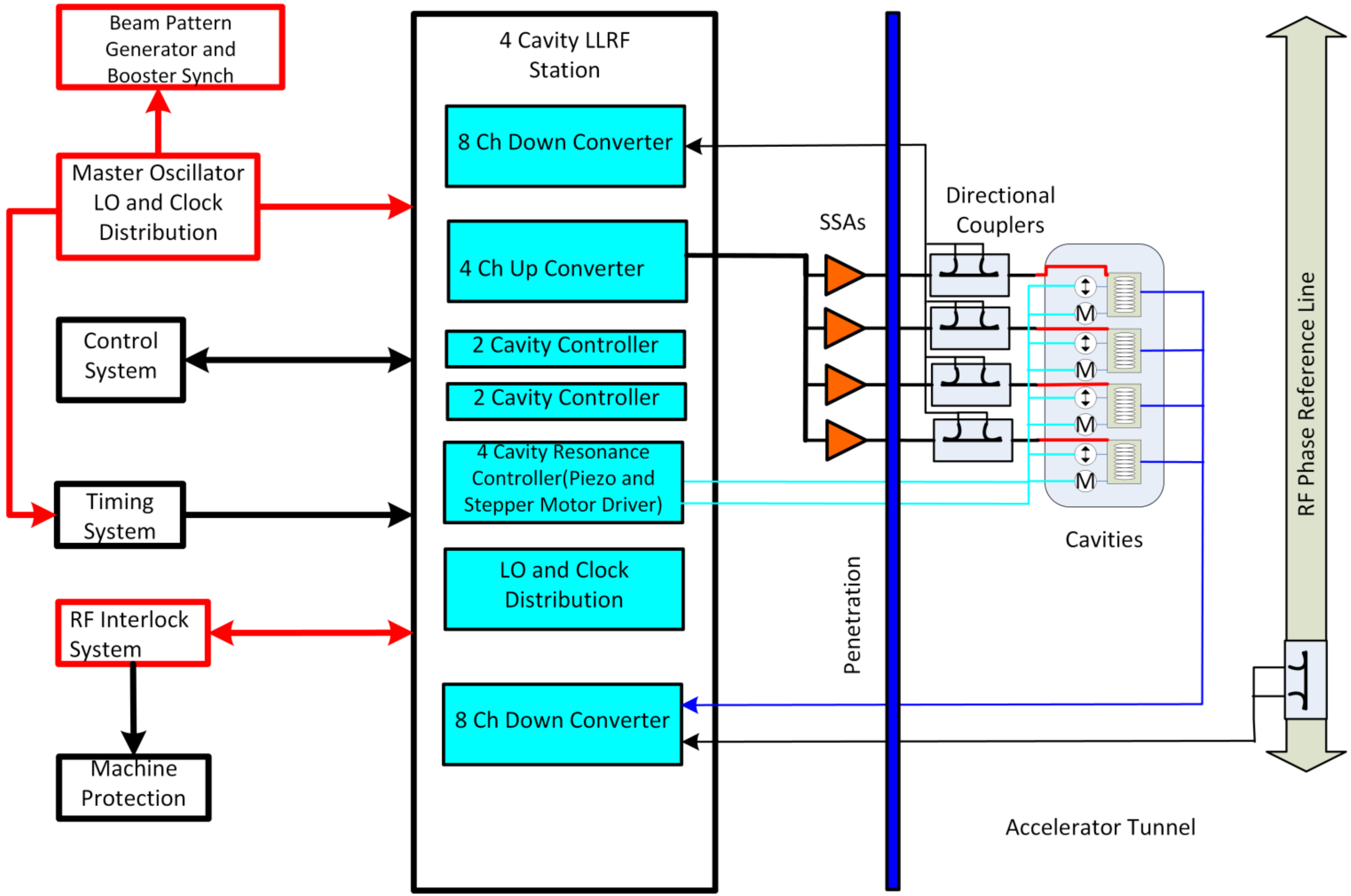
HWR
4 SOCMFC Chassis
1 Tuner Signal Cond Module

SSR1
4 SOCMFC Chassis
2 Resonance Control Chassis

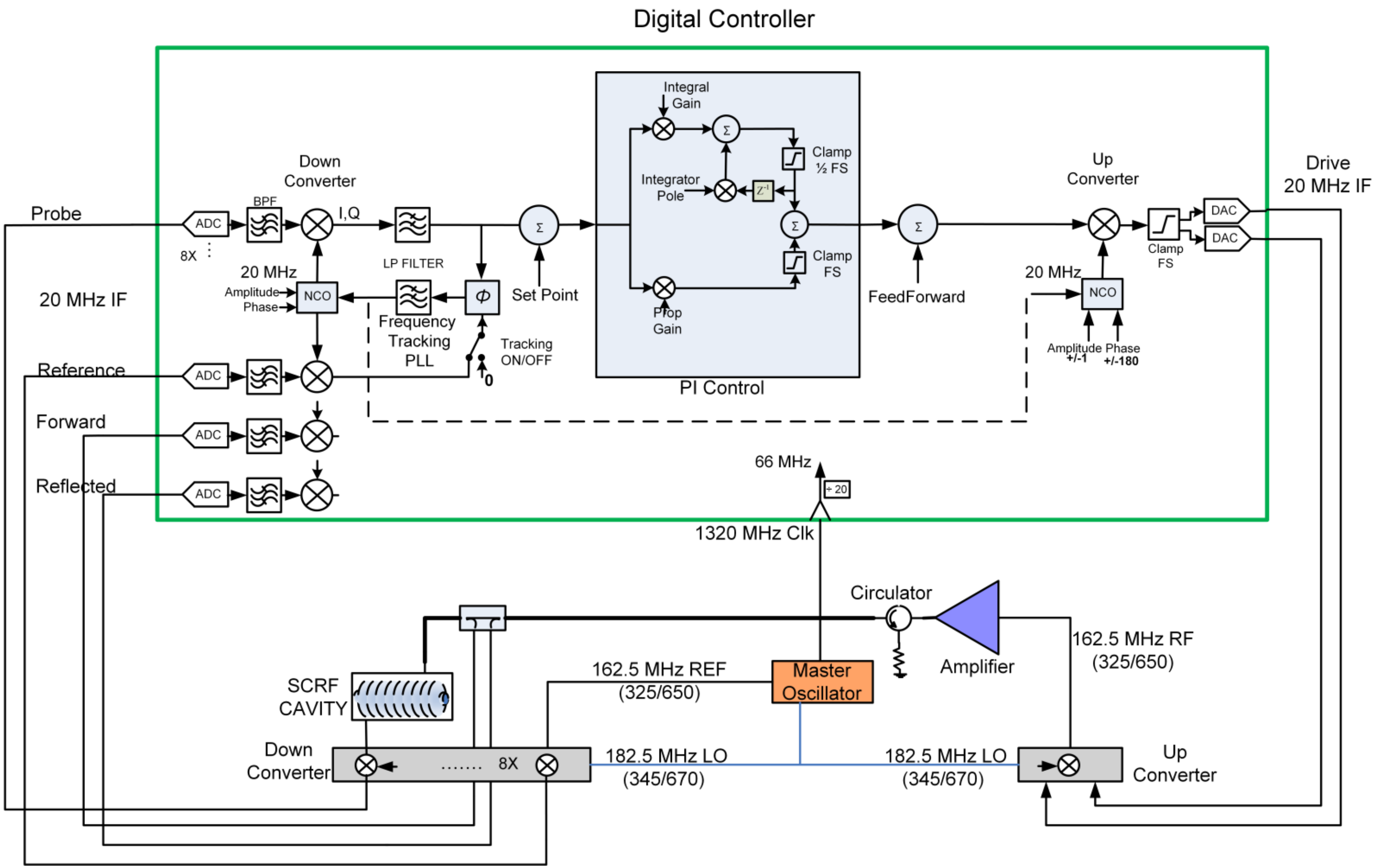
PIP2-IT LLRF Systems



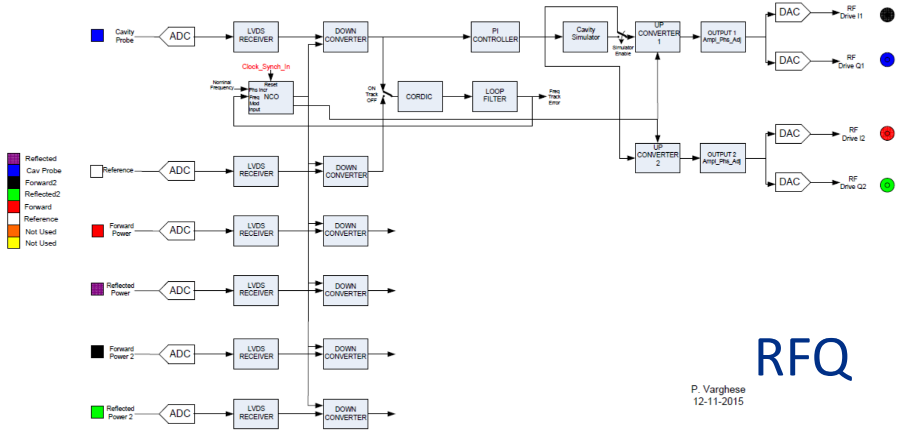
PIP2 4-Cavity RF Station



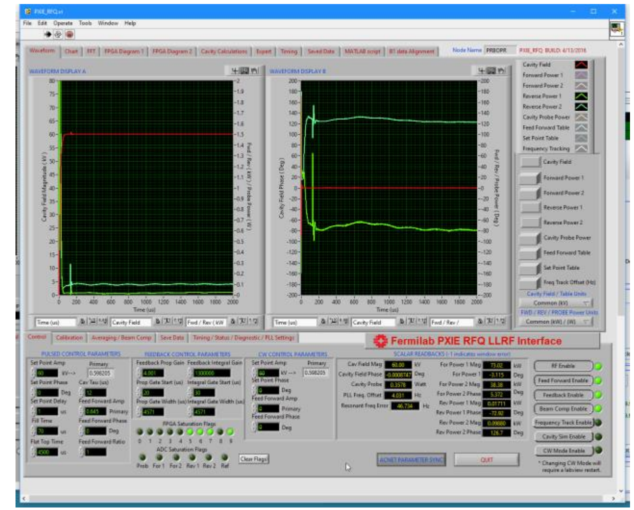
LLRF System Architecture

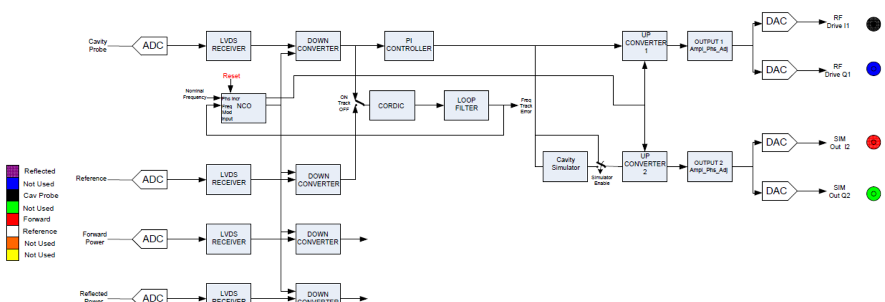


RFQ and B1 LLRF System

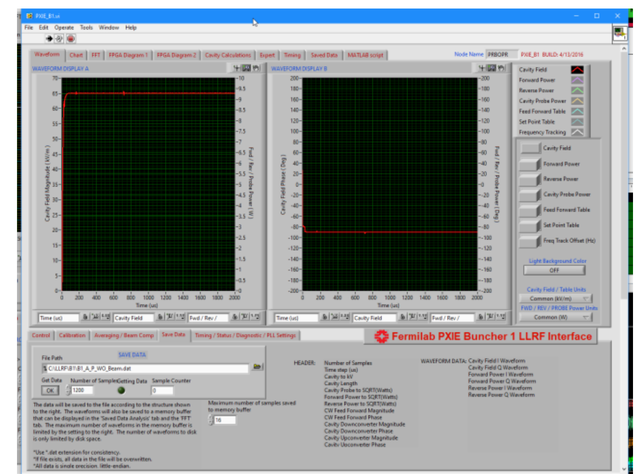


RFQ

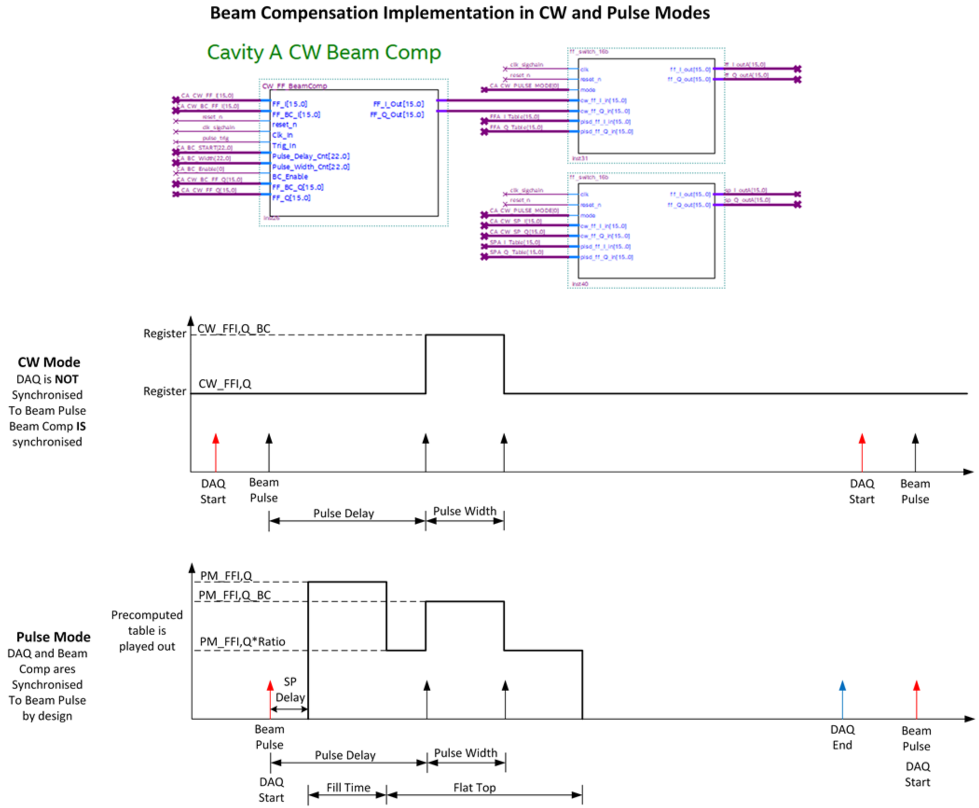


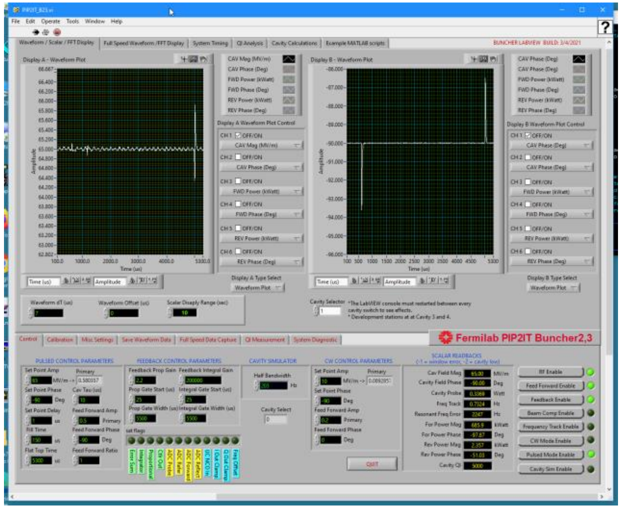


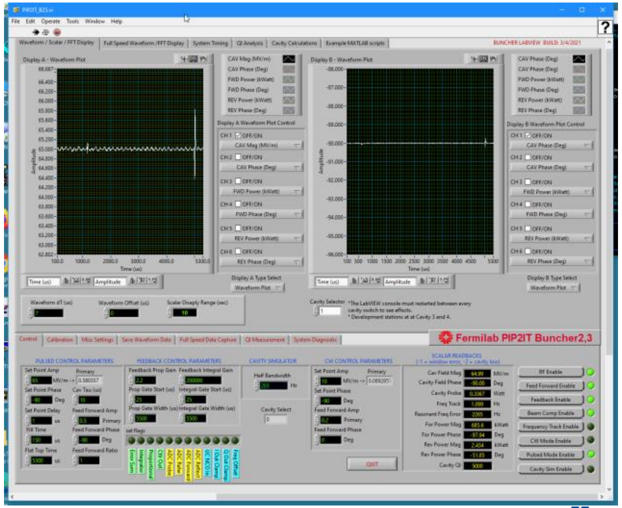
Buncher1



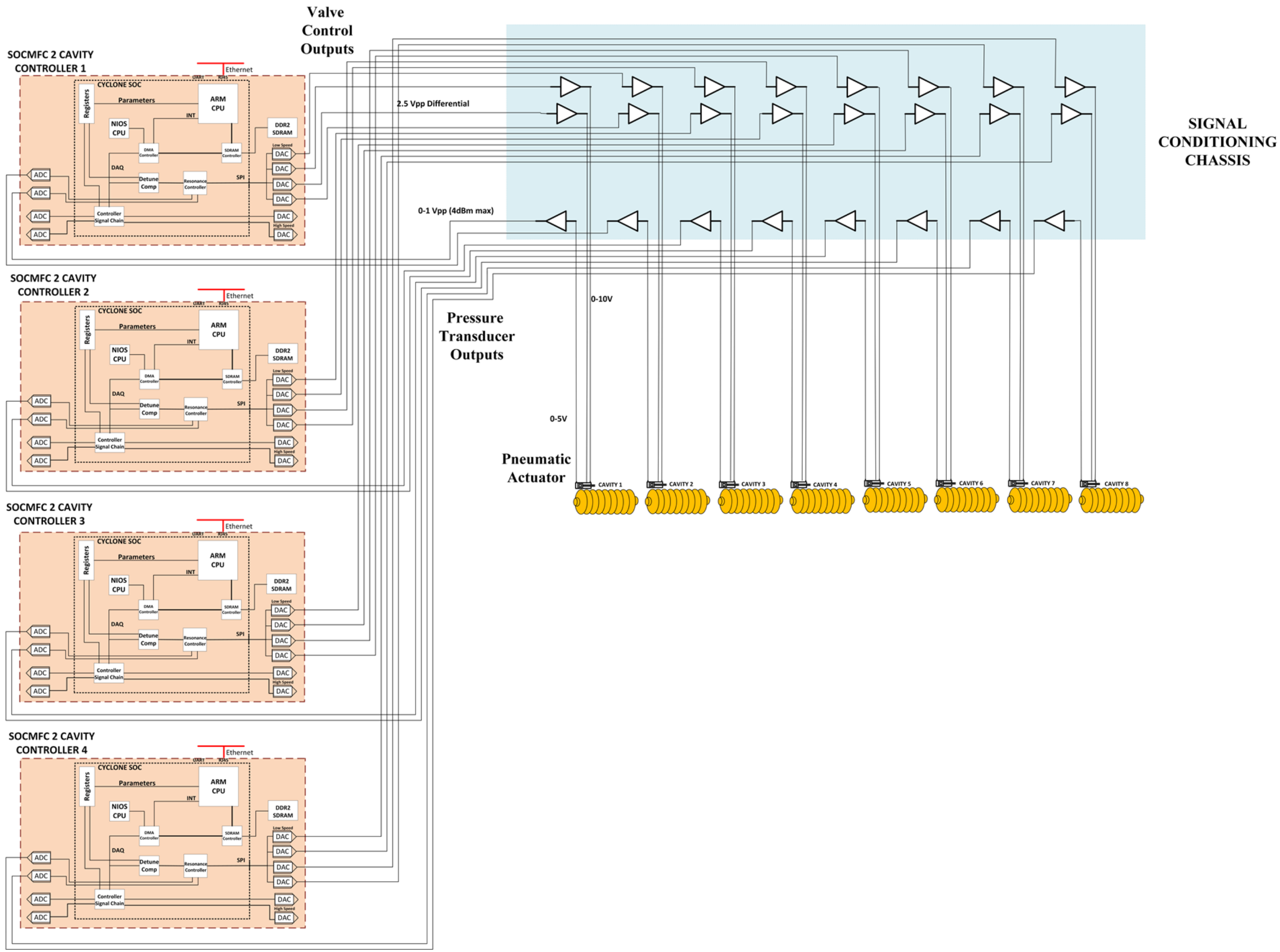
Beam Loading Compensation – B2



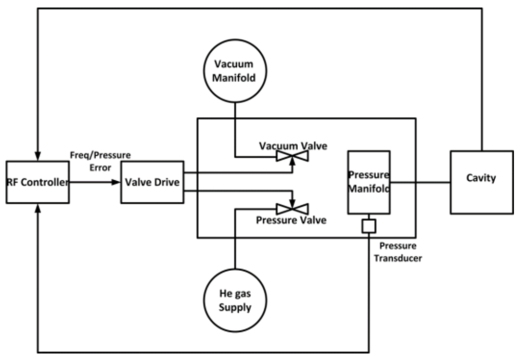




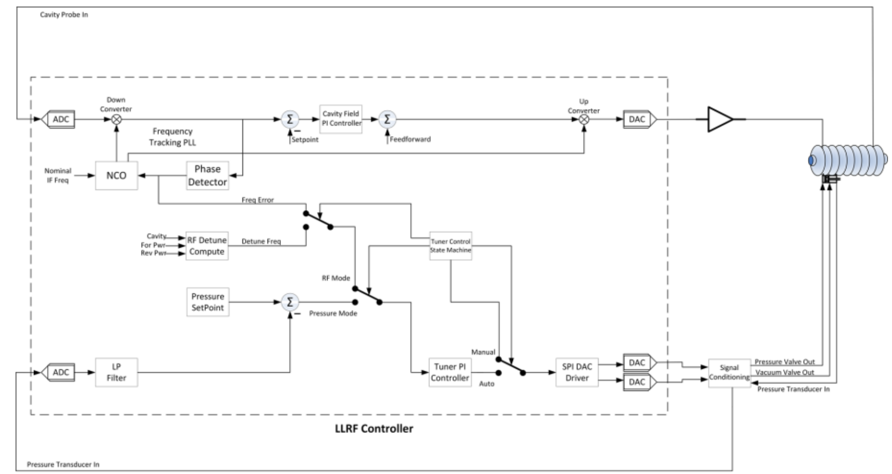
HWR LLRF System with Pneumatic Tuner Control



HWR Resonance Control Design

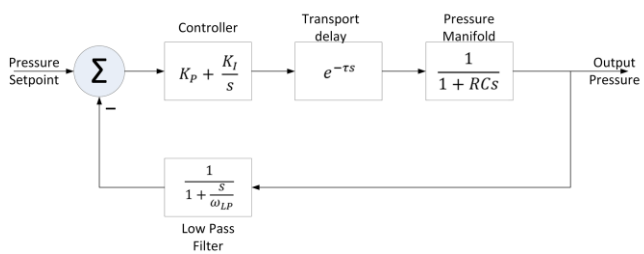


Physical Model

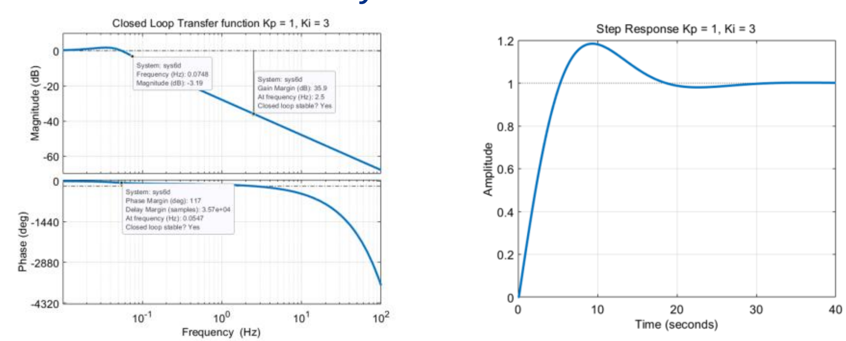


Controller Implementation

Control System Model

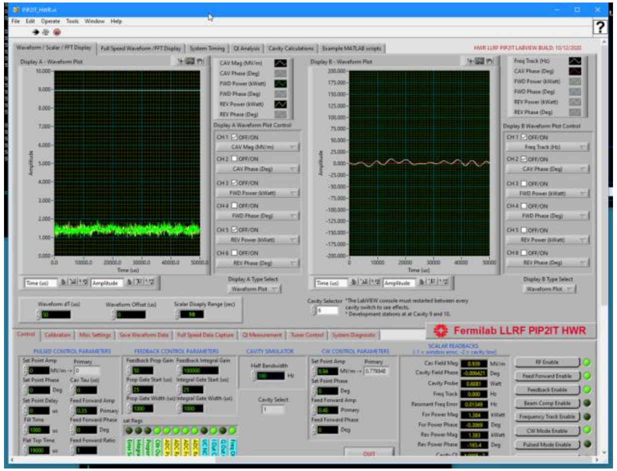


Control System Simulation



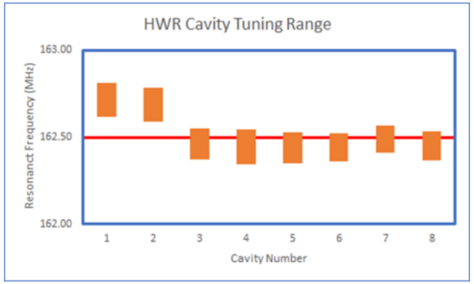
HWR Resonance Control Performance

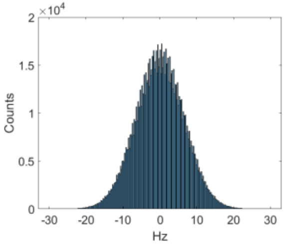
Measured Step Response



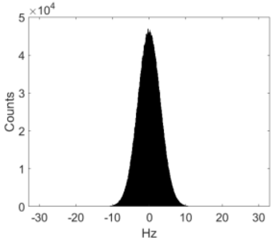
Cavity GDR Mode Waveforms

Cavity Tuning Range



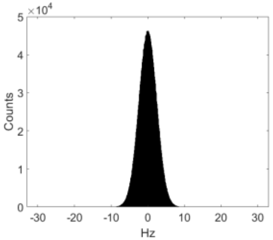


Cavity 4

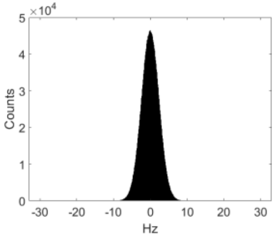


Cavity 5

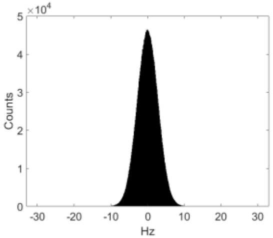
Detuning Histograms



Cavity 6



Cavity 7



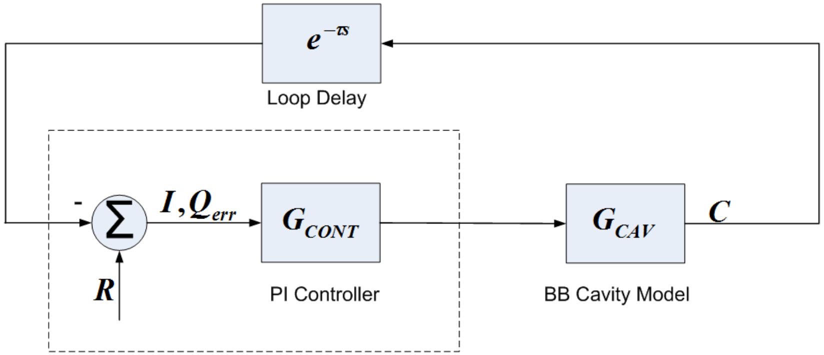
Cavity 8

RF Cavity Parameters and Feedback Gains

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

Maximum Feedback Gains computed for Stability with 45 degree phase Margin with 1 us Loop delay

$$\frac{C(s)}{R(s)} = \frac{K_P \omega_H (s + K_I/K_P)}{s^2 + s(K_P + 1)\omega_H + K_I \omega_H}$$



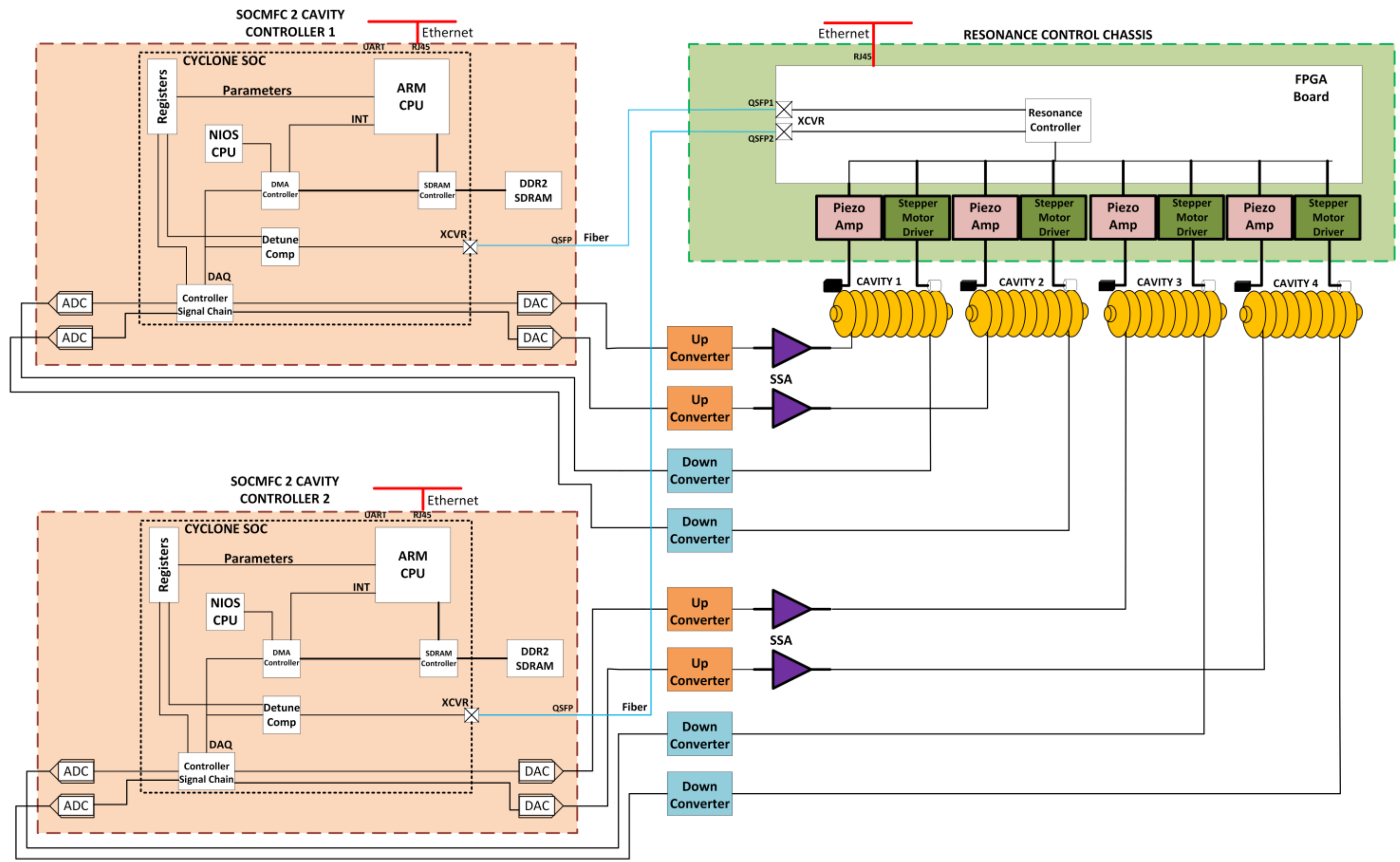
HWR Cavity Field Regulation

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

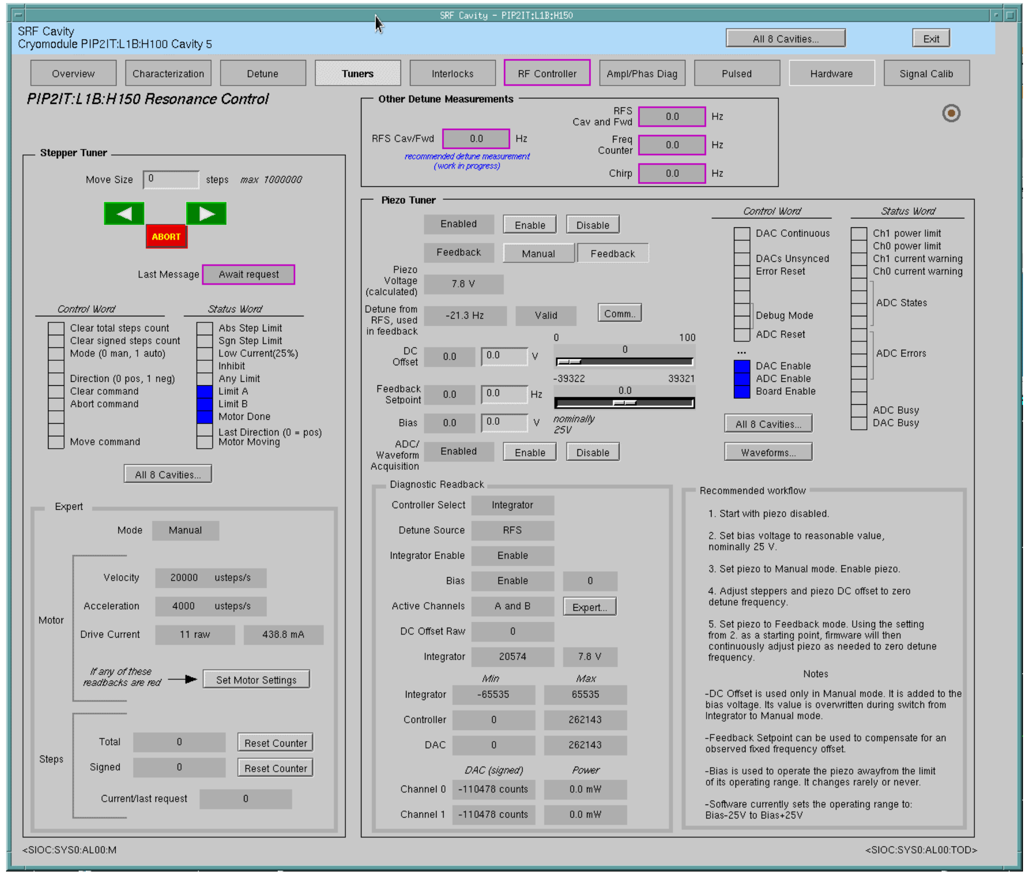
PIP-II Specifications

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

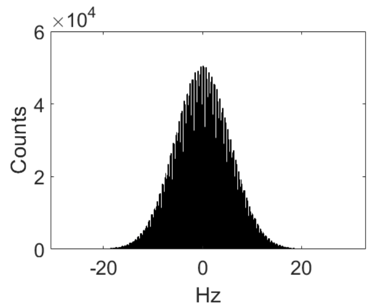
SSR1 LLRF System with Piezo Tuner Control



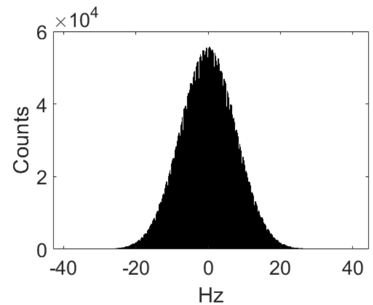
SSR1 Piezo Tuner Control – EPICS Interface



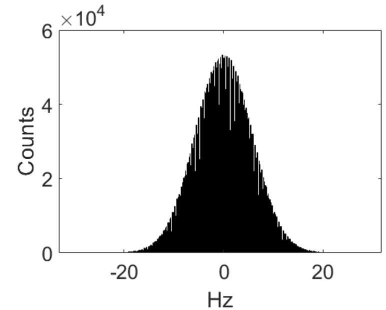
SSR1 Cavity Detuning Histograms



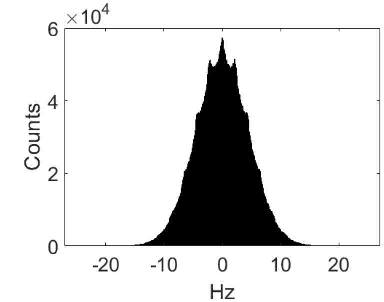
Cavity1



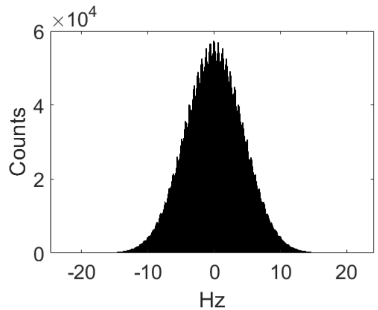
Cavity2



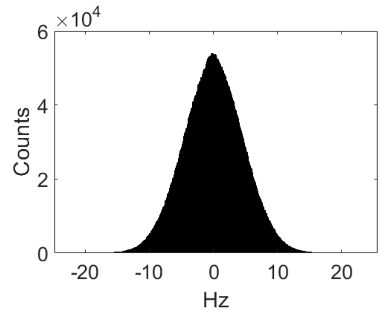
Cavity3



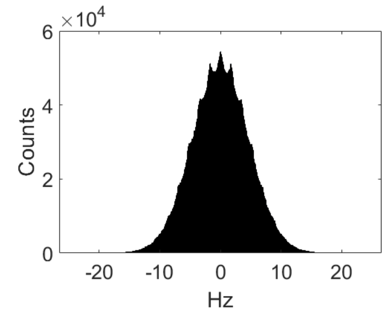
Cavity4



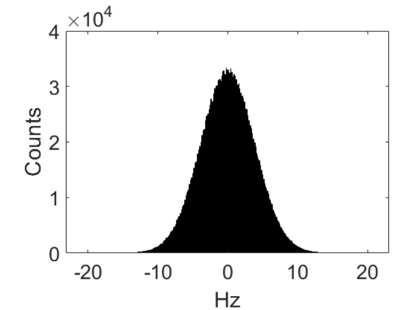
Cavity5



Cavity6



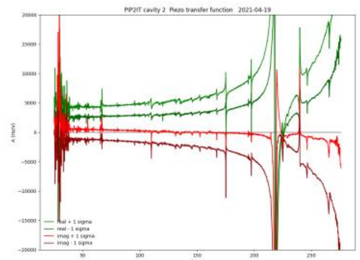
Cavity7



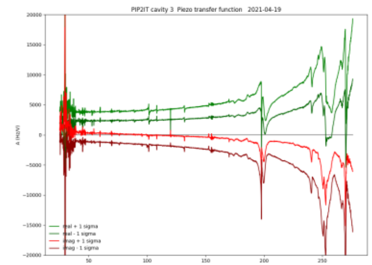
Cavity8

SSR1 Piezo Transfer Functions

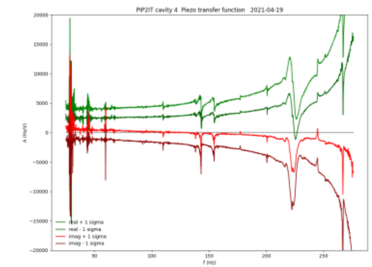
Cavity1



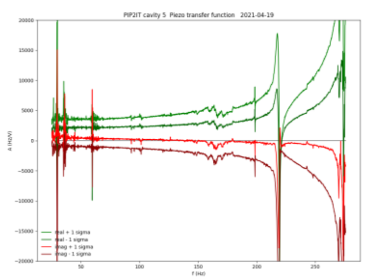
Cavity2



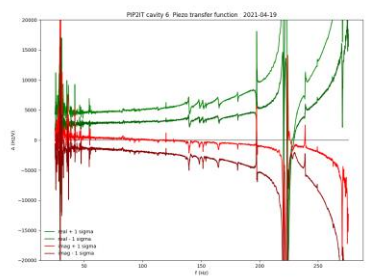
Cavity3



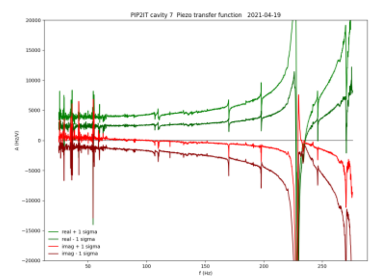
Cavity4



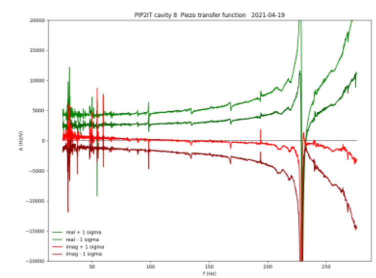
Cavity5



Cavity6



Cavity7



Cavity8

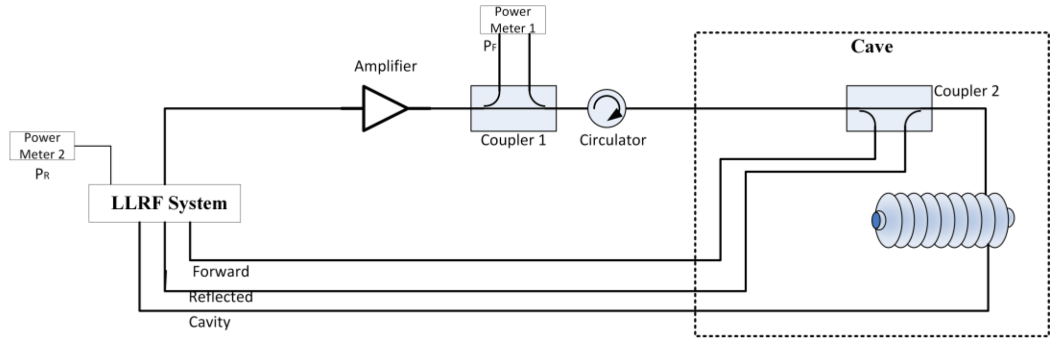
SSR1 Amplitude and Phase Regulation

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

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

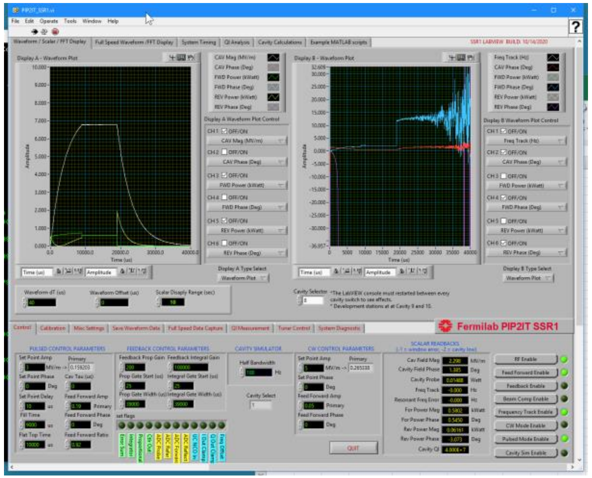
RF Power Calibration



Cavity Gradient $E = \frac{\sqrt{4 \times P_F \times Q_L \times \left(\frac{R}{Q}\right)}}{l}$ MV/m

1. Perform the calibration with the LLRF system in CW mode
2. Apply RF power using FF to desired forward power (Meter 1) for calibration (Start with 10 dB attenuator in the RF Drive for safety)
3. Allow for attenuation in cable to the cavity and for coupler 1 attenuation to get cavity forward power PF
4. Calculate cavity gradient from forward power and other parameters shown in equation
5. Adjust gradient and forward power calibration constants to match measured readings.
6. Adjust reflected power calibration constant to make the reflected power waveform the same as the forward power. (With no beam, at steady state, forward power = reflected power)
7. Monitor front panel reflected power (Meter 2) allowing for cable and internal coupler attenuation for checking calibration
8. Repeat calibration at different power levels

RF Detune Calibration



$$\ddot{\mathbf{V}}(t) + \frac{\omega_0}{Q_L}\dot{\mathbf{V}}(t) + \omega_0^2\mathbf{V}(t) = \frac{\omega_0 R_L}{Q_L}\dot{\mathbf{I}}(t)$$

$$\frac{d\vec{V}}{dt} = (-\omega_{1/2} + j\Delta\omega)\vec{V} + R_L\omega_{1/2}\vec{I}$$

$$\frac{d\vec{V}}{dt} = a\vec{V} + b\vec{K}_1$$

$$a = \frac{1}{\vec{M}_V} \cdot \left[\frac{d\vec{M}_V}{dt} - \beta\vec{M}_K\right]$$

- The cavity is operated in pulse mode with a cavity field ~ 1/2 FS magnitude and the cavity probe and forward waveforms are recorded.
- Numerical analysis of the acquired data provides cavity parameters such as half bandwidth and the detuning constants

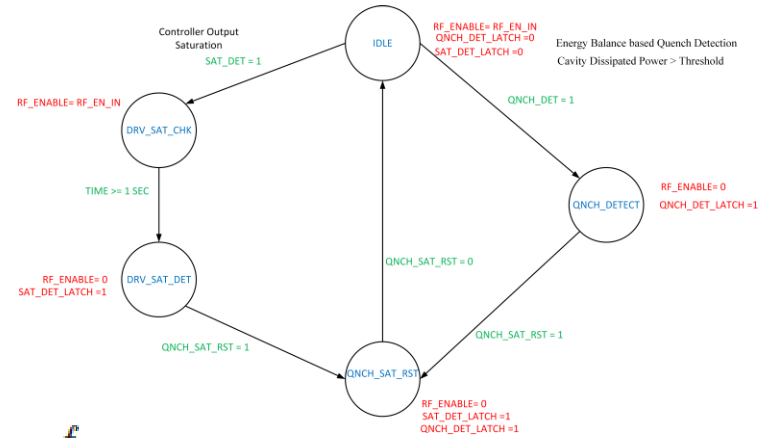
Cavity Quench Detection/ Overdrive Protection

$$P_{\text{diss}} = |\vec{K}|^2 - |\vec{R}|^2 - \frac{dU}{dt}$$

$$U = \frac{V^2}{\omega_0 (R/Q)}$$

$$\frac{dU}{dt} = 2\Re\left(\vec{V}\frac{d\vec{V}}{dt}\right) \cdot \frac{1}{\omega_0 (R/Q)}$$

$$f_K|\vec{M}_K|^2 - f_R|\vec{M}_R|^2 - f_V 2\Re\left(\vec{M}_V \cdot \frac{d\vec{M}_V}{dt}\right) - f_Q$$



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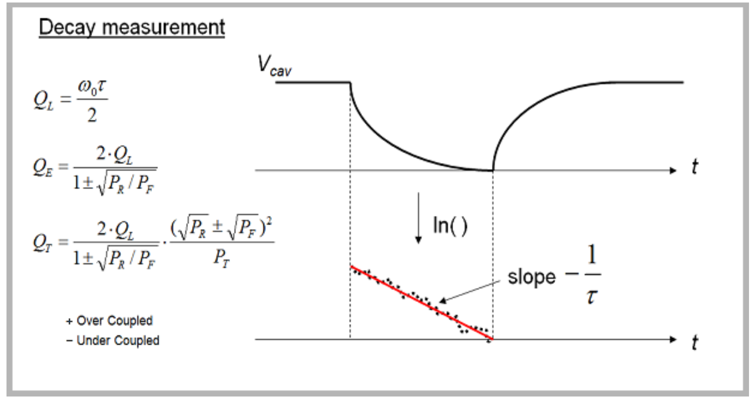
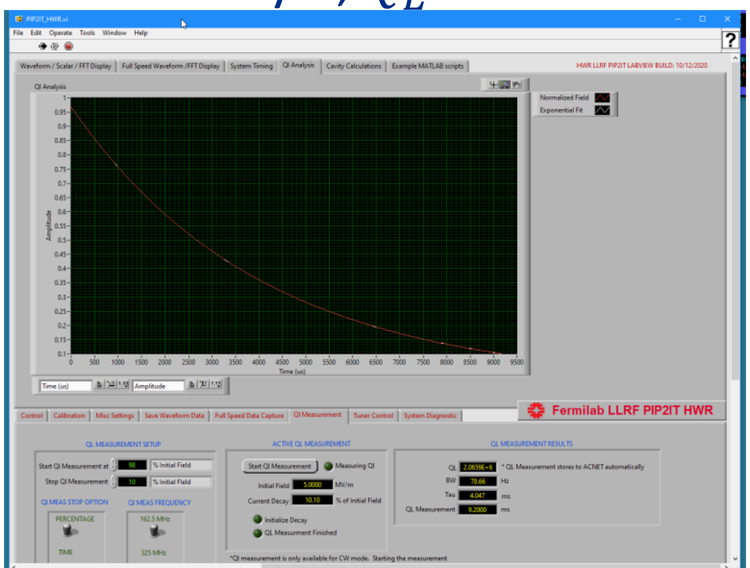
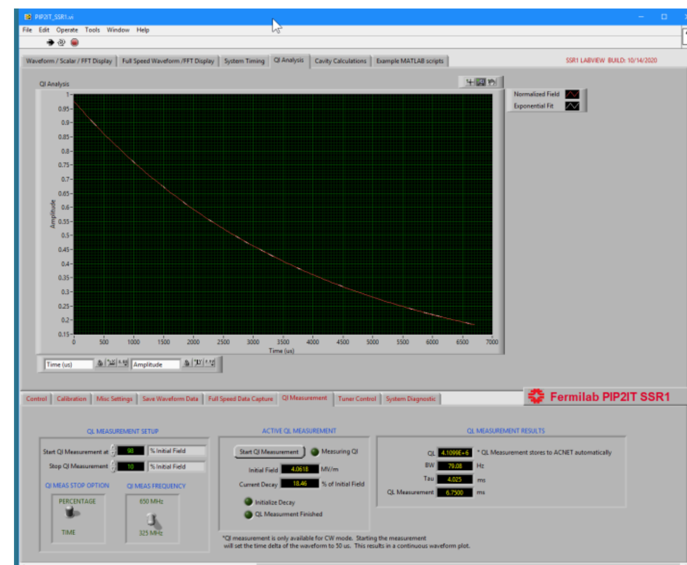
Q_L Measurement



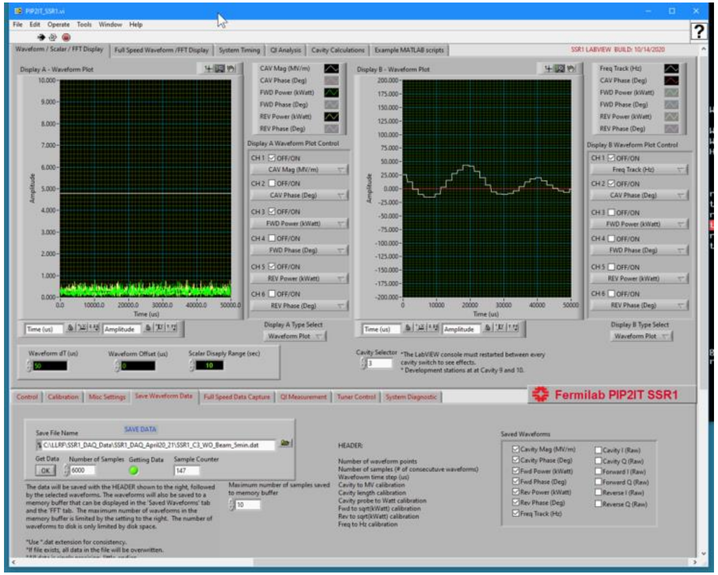
HWR Cavity 5, Q_L = 2.07e6



SSR1 Cavity 5, Q_L = 4.11e6

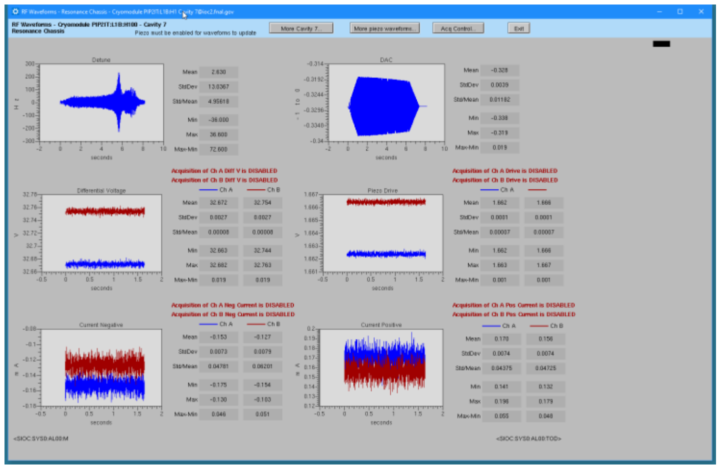


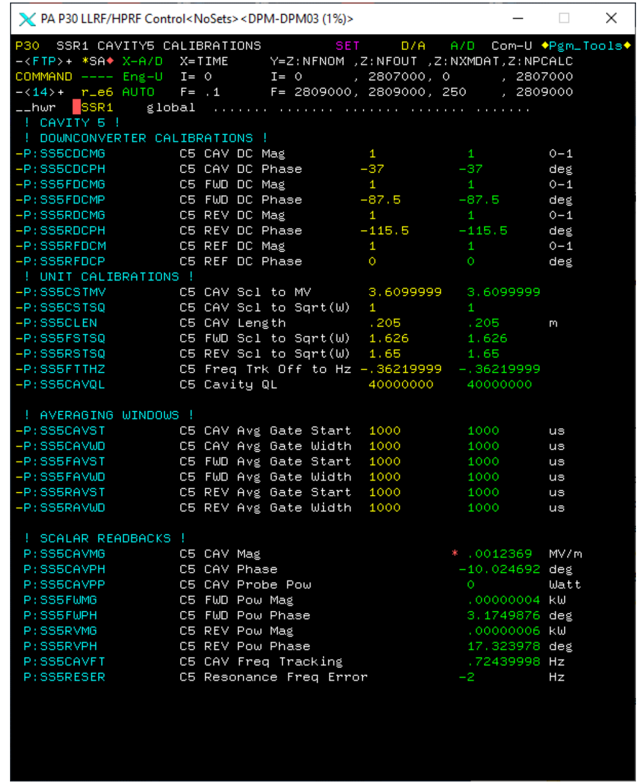
User Interfaces



Labview

EPICS





ACNET

Summary

- The LLRF systems at PIP2-IT met the project requirements
- A Resonance Control System for the HWR cryomodule was developed and integrated into the LLRF controller
- All LLRF systems had ACNET interfaces and the SSR1 LLRF system used an EPICS interface for the resonance control system
- Automated ACL sequencers were used to turn on the various LLRF systems and transition them into GDR mode at their operating gradients
- Operation at 2 mA beam with a 550 us pulse was limited to a short period due to some issues with the MPS system – 10 us pulses were used toward the end of the run
- Beam loading compensation was demonstrated in the warm front end. The SRF cryomodules were able to compensate for beam loading with their high feedback gains.
- A LBNL built LLRF controller based on the LCLS-II LLRF system was tested with the SSR1 cavities 7 and 8 and its various test features were exercised.

Thank You!