PIP-II

Fermilab

U.S. DEPARTMENT OF ENERGY | Office of Science

LLRF system for the Fermilab PIP-II Superconducting LINAC

P. Varghese, B. Chase, S. Raman, Syed. A, P. Hanlet, D. Nicklaus, FNAL

L. Doolittle, S. Murthy, K. Penney, LBNL

C. Hovater, J. Latshaw, JLAB

23 October 2023

PIP-II is a partnership of:

- US-DOE
- India-DAE
- Italy-INFN
- UK-STFC-UKRI
- France-CEA, CNRS/IN2P3
- Poland-WUST, WUT, TUL

LLRF2023

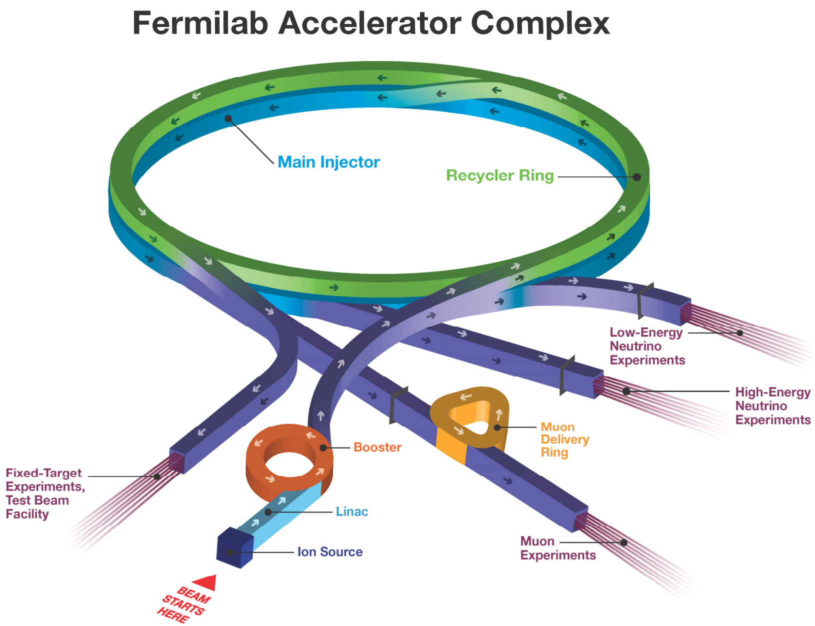
LOW LEVEL RADIO FREQUENCY WORKSHOP 2023

OCTOBER 22-27, 2023 IN GYEONGJU, REPUBLIC OF KOREA

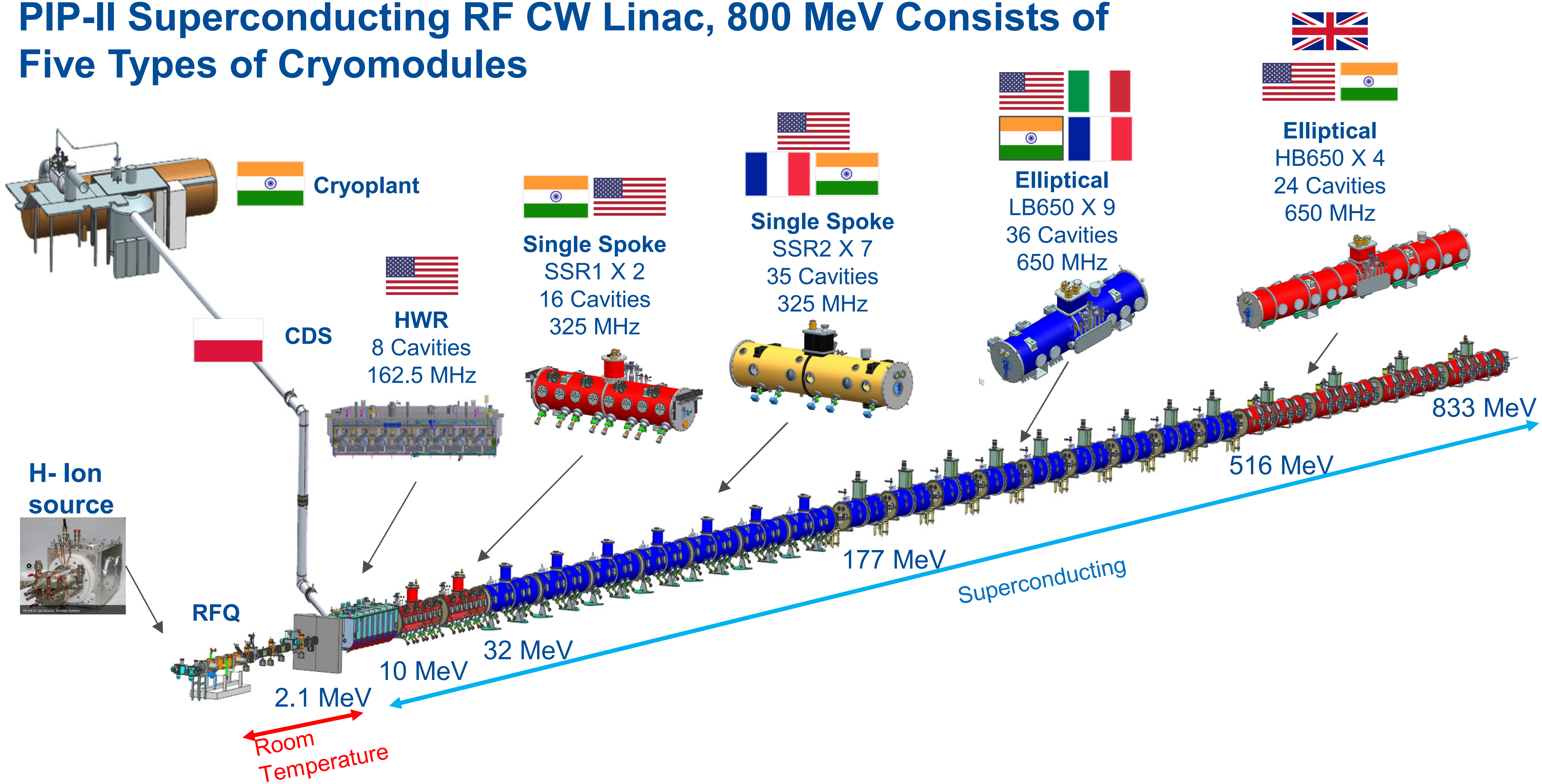
Outline

1. PIP2-LINAC Accelerator Components
2. Physics Requirements – LLRF Specifications
3. LLRF Systems
    a) RFQ
    b) Bunchers 1-4
    c) HWR Cryomodule
    d) SSR1 Cryomodule
    e) HB650 Cryomodule
3. LLRF Testing at CMTF and STC
4. EPICS User Interface
5. Results and system performance

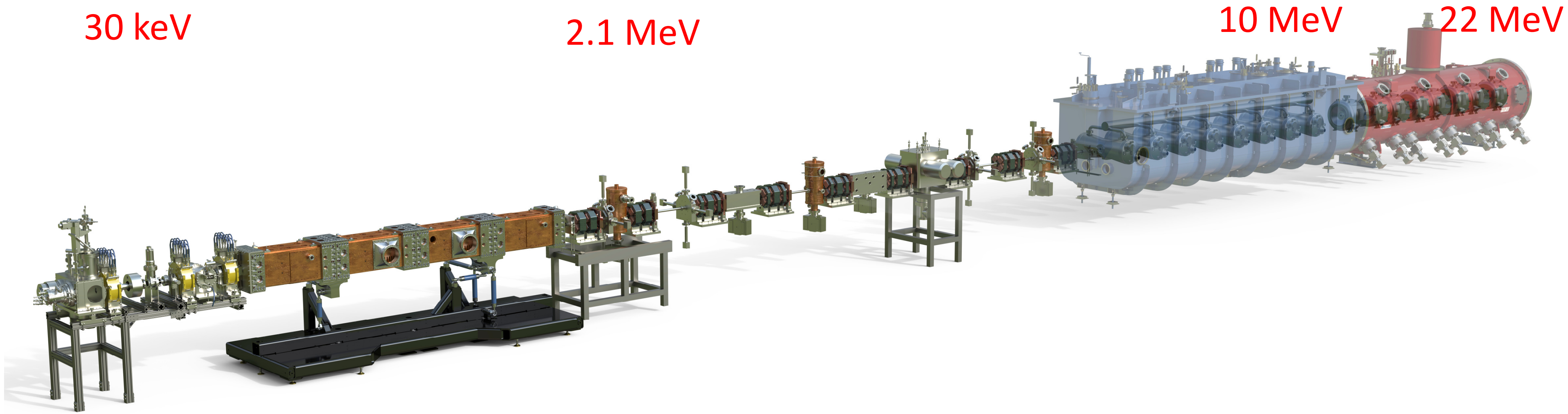
Fermilab Accelerator Complex



PIP-II Superconducting RF CW Linac, 800 MeV Consists of Five Types of Cryomodules



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

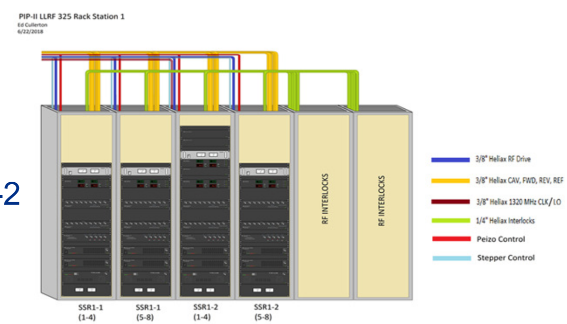
SSR1
4 SOCMFC Chassis
2 Resonance Control Chassis

PIP2 LLRF Systems

CM type	Cavities per CM	Number of CMs	CM configuration^{+}	CM length (m)	Q_0 at 2K (10^{10})	Surface resistance, (nΩ)	Loaded Q$^{\Delta}$ (10^6)
HWR	8	1	8×(sc)	5.93	0.5	9.6 (2.75†)	2.32
SSR1	8	2	4×(csc)	5.53	0.6	14 (10‡)	3.02
SSR2	5	7	sccsccsc	6.3*	0.8	14.4	5.05
LB650	4	9	cccc	5.52*	2.15	9.0	10.36
HB650	6	4	cccccc	9.92*	3	8.7	9.92

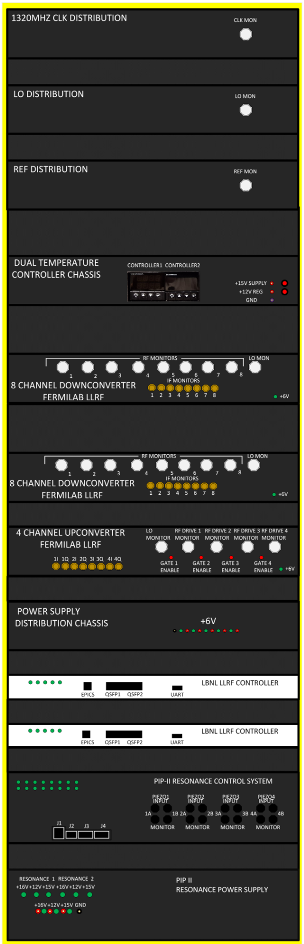
	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6	Station 7	Station 8	Station 9	Station 10	Station 11	Total
	RFQ, B1-4	HWR	SSR1-1,2	SSR2-1,2,3	SSR2-4,5	SSR2-6,7	LB650-1,2,3	LB650-4,5,6	LB650-7,8,9	HB650-1,2	HB650-3,4	
Number of cavities	6	8	16	15	10	10	12	12	12	12	12	125
RF Freq (MHz)	162.5	162.5	325	325	325	325	650	650	650	650	650	

S3 – SSR1-1,SSR1-2



S4-S11 – SSR2 (7), LB650 (9), HB650 (4)

4-cavity LLRF Station Rack – Components 1



1320 MHz Clock Distribution

LO Distribution

Reference Distribution

Dual Temperature Controller

8-Channel Downconverter

8-Channel Downconverter

4-Channel Upconverter

UC/DC Power Supply

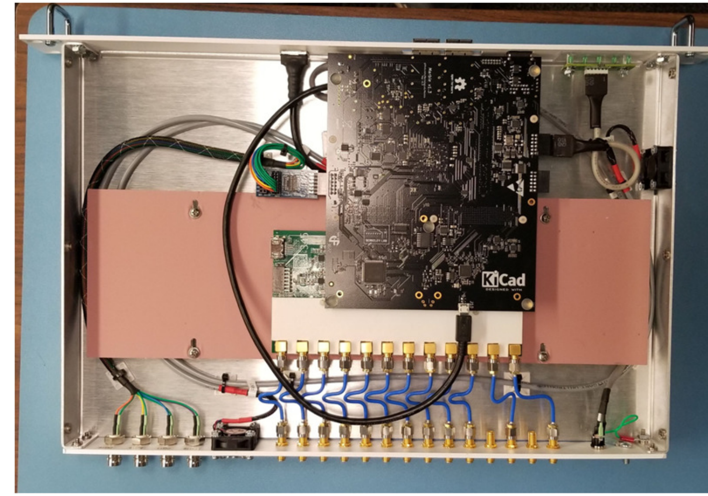
LLRF Controller

LLRF Controller

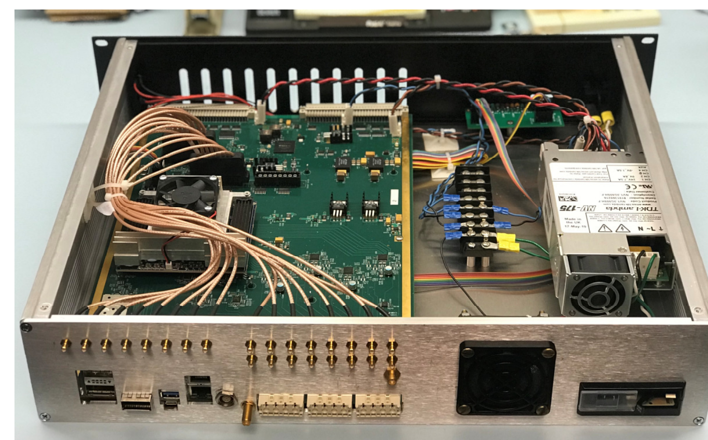
Resonance Controller

RCC Power Supply

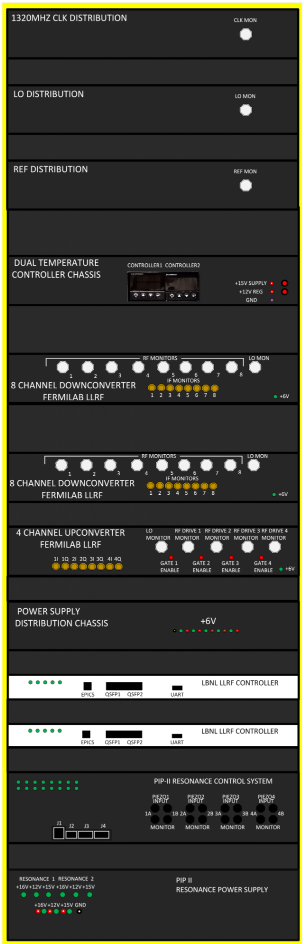
LBL-Marble RFS
Xilinx – Kintex



FNAL- LLRF Controller
Intel – Arria10 SOC



4-cavity LLRF Station Rack – Components 2



1320 MHz Clock Distribution

LO Distribution

Reference Distribution

Dual Temperature Controller

8-Channel Downconverter

8-Channel Downconverter

4-Channel Upconverter

UC/DC Power Supply

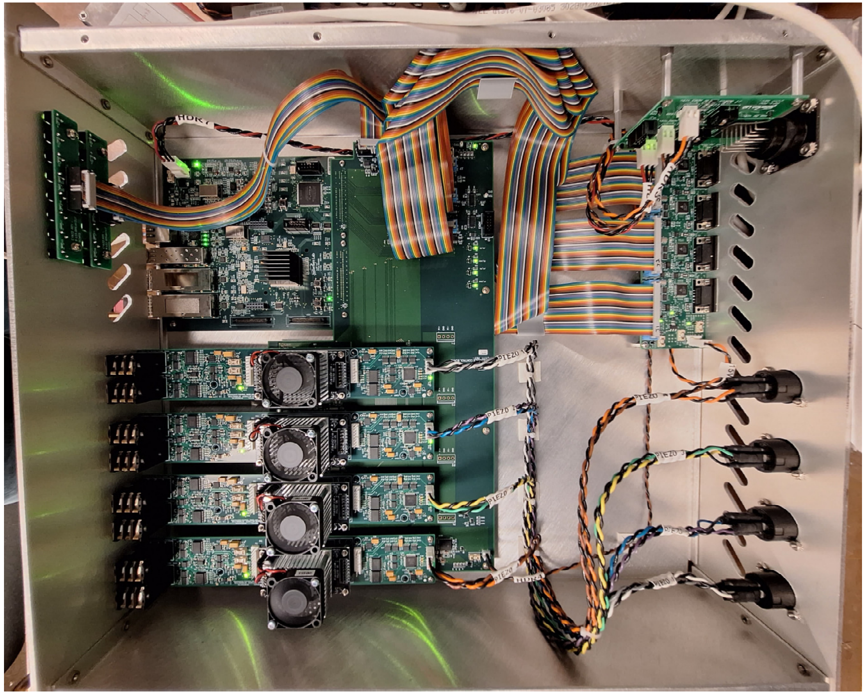
LLRF Controller

LLRF Controller

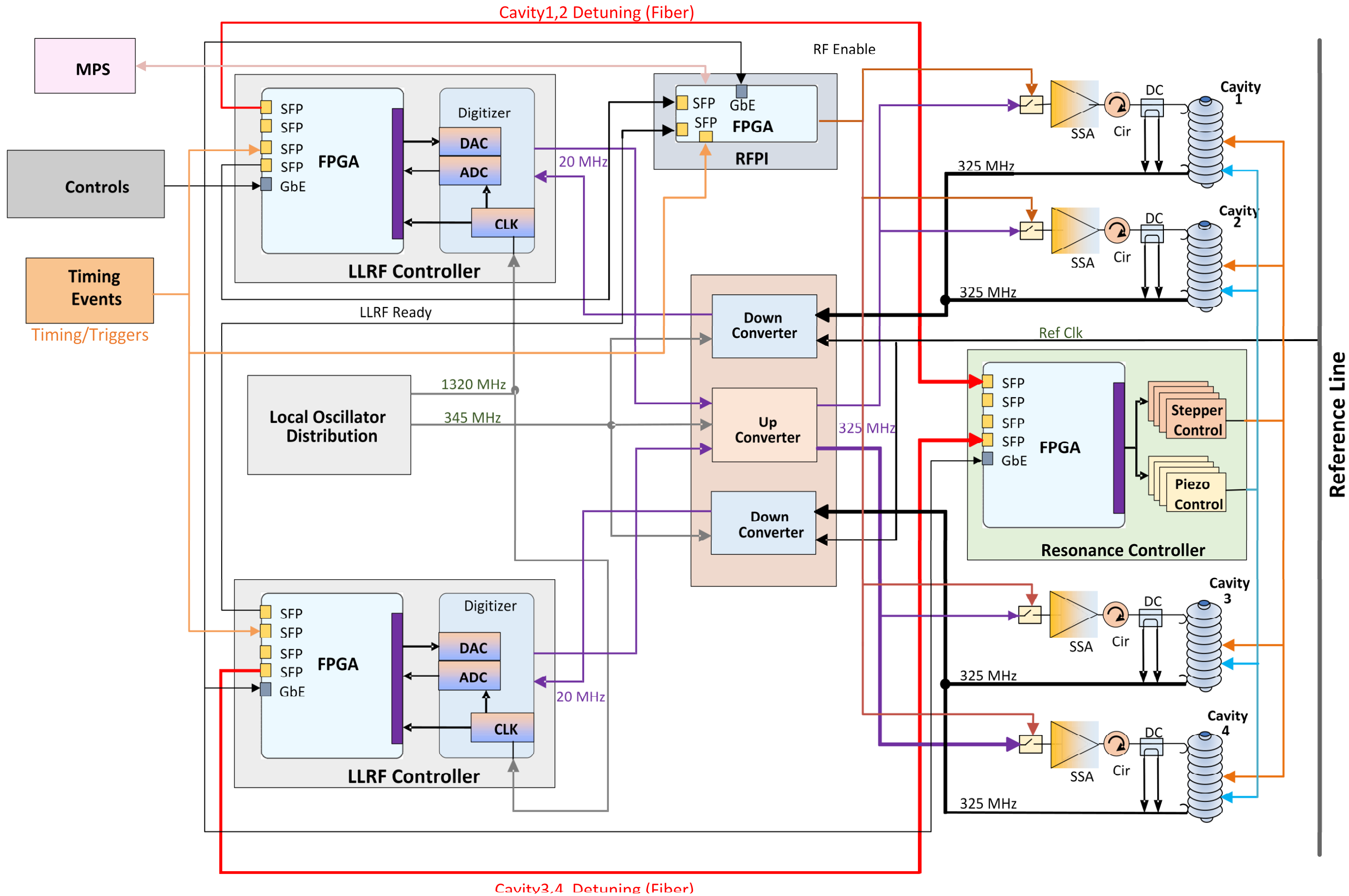
Resonance Controller

RCC Power Supply

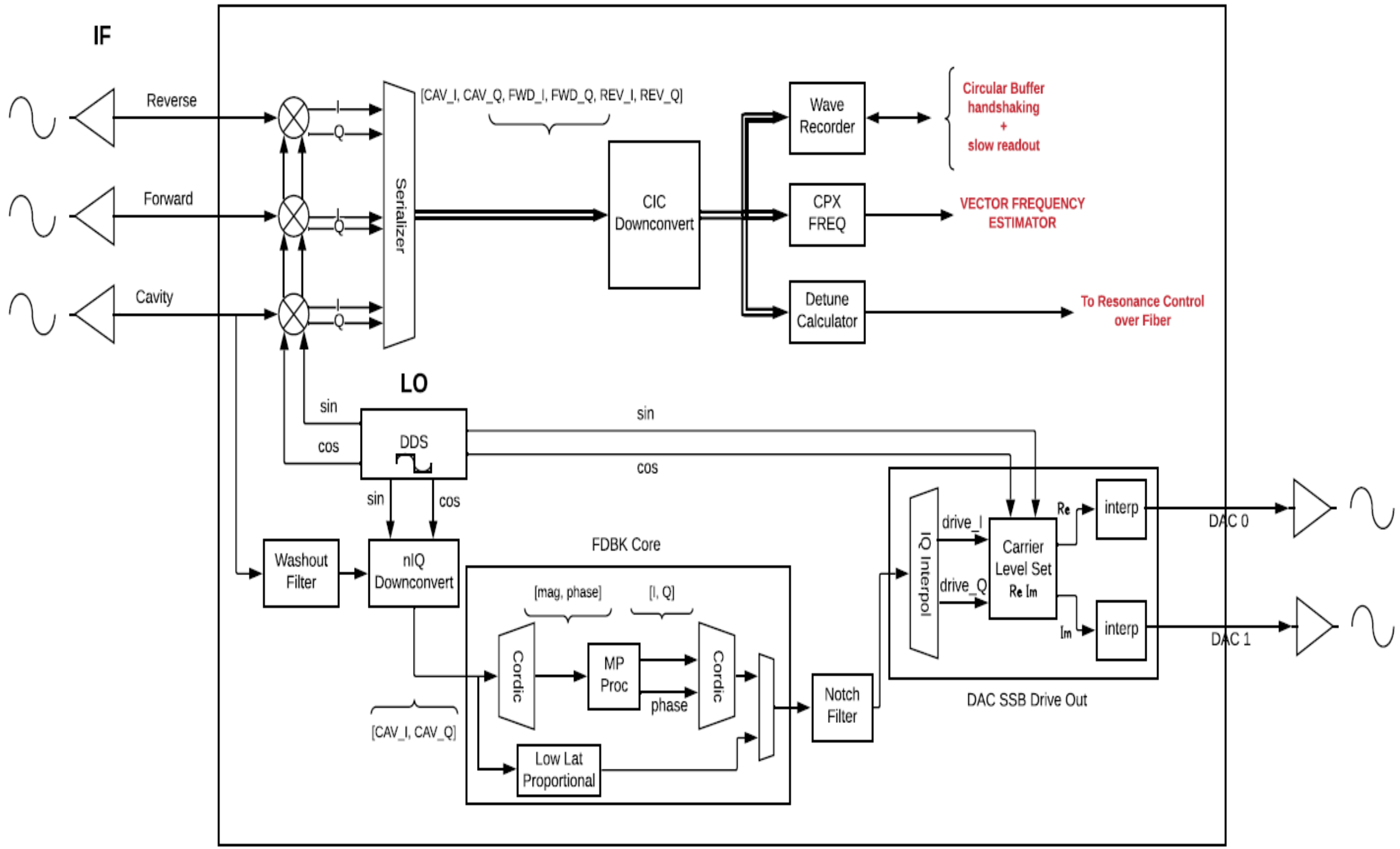
JLAB/FNAL
Resonance Controller
(Marble FPGA)
Xilinx – Kintex



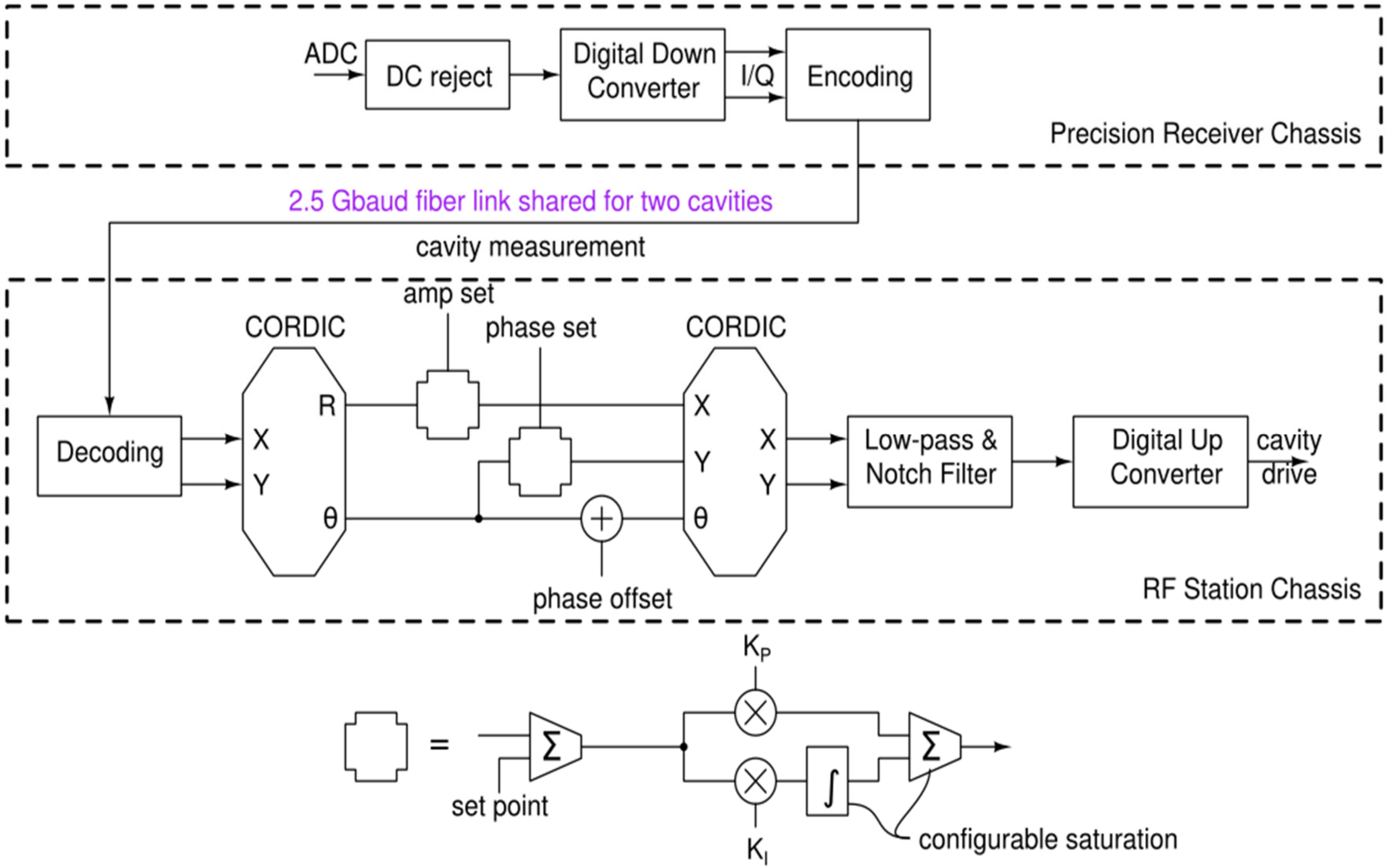
PIP2 4-Cavity RF Station



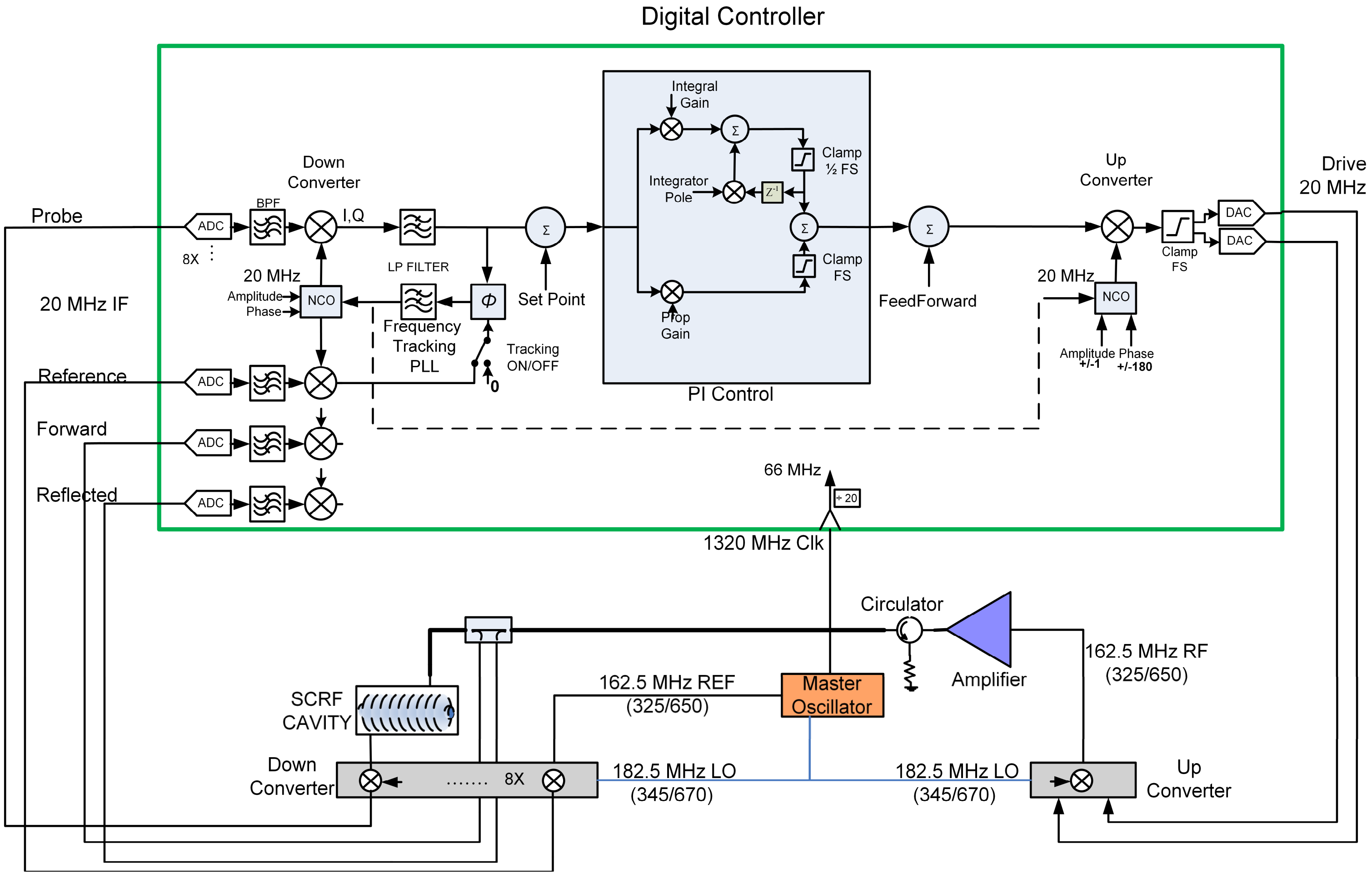
LLRF System Architecture 1 - Amp/Phs Control



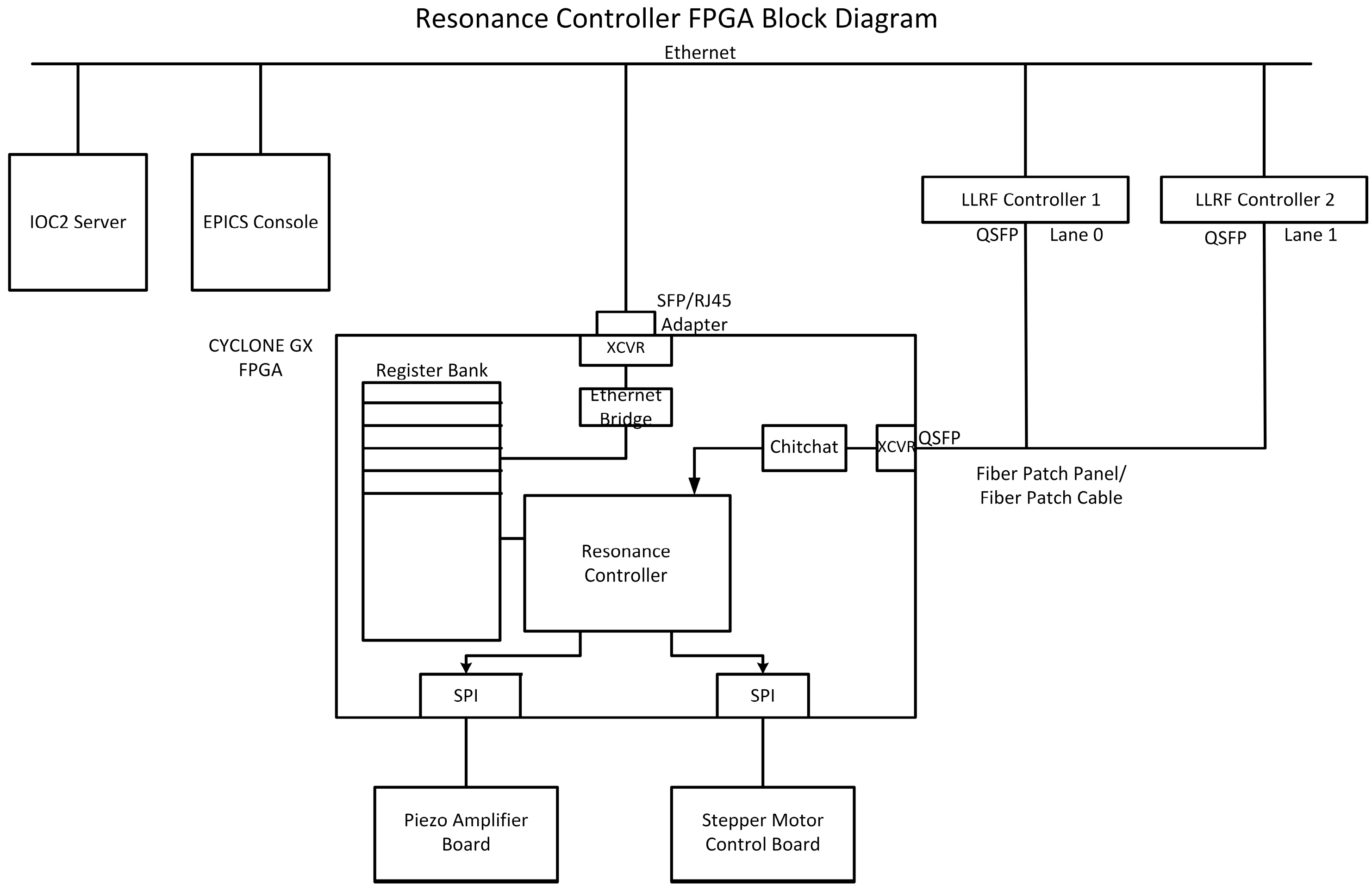
SEL System Architecture



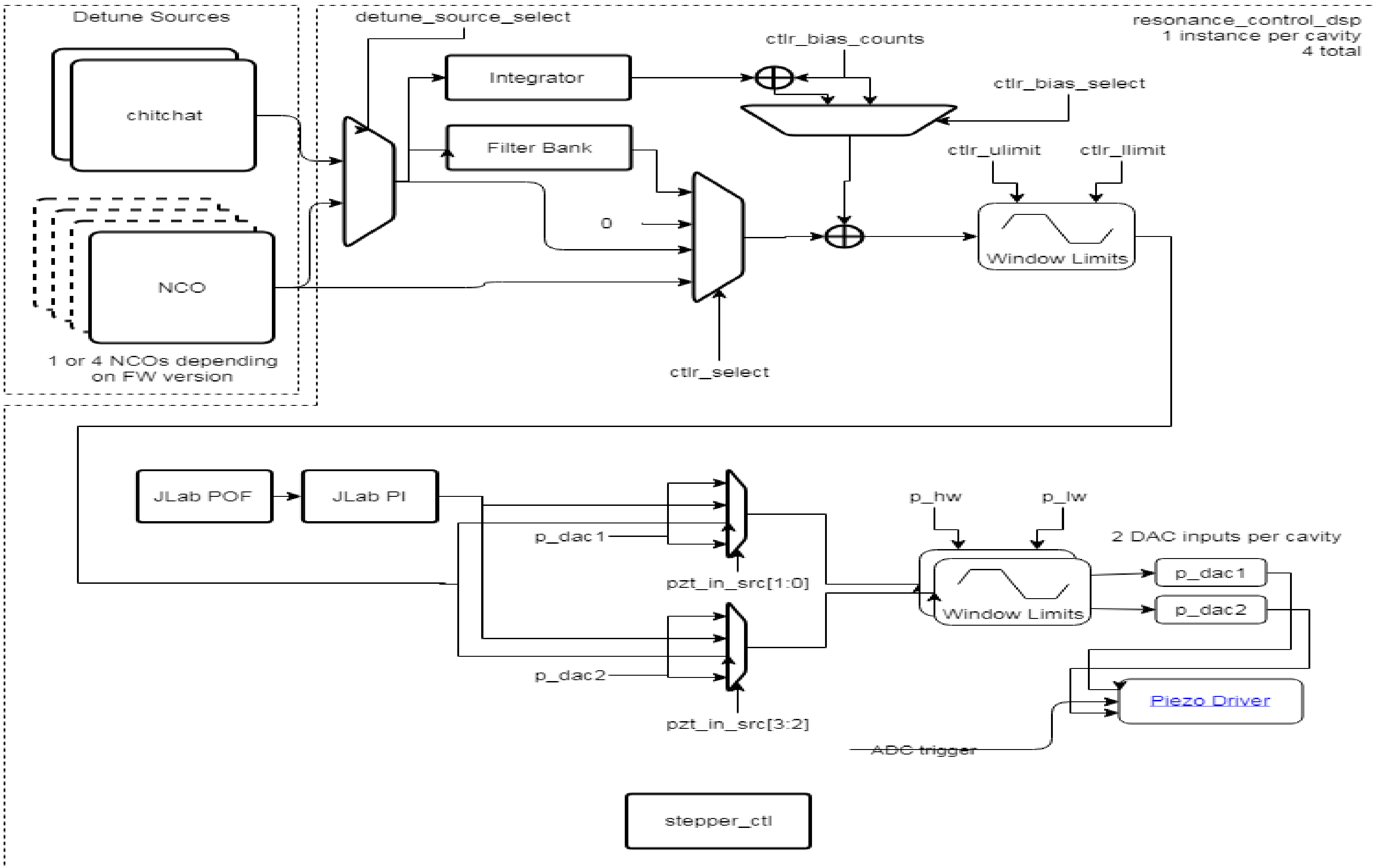
LLRF System Architecture 2 – I/Q Control



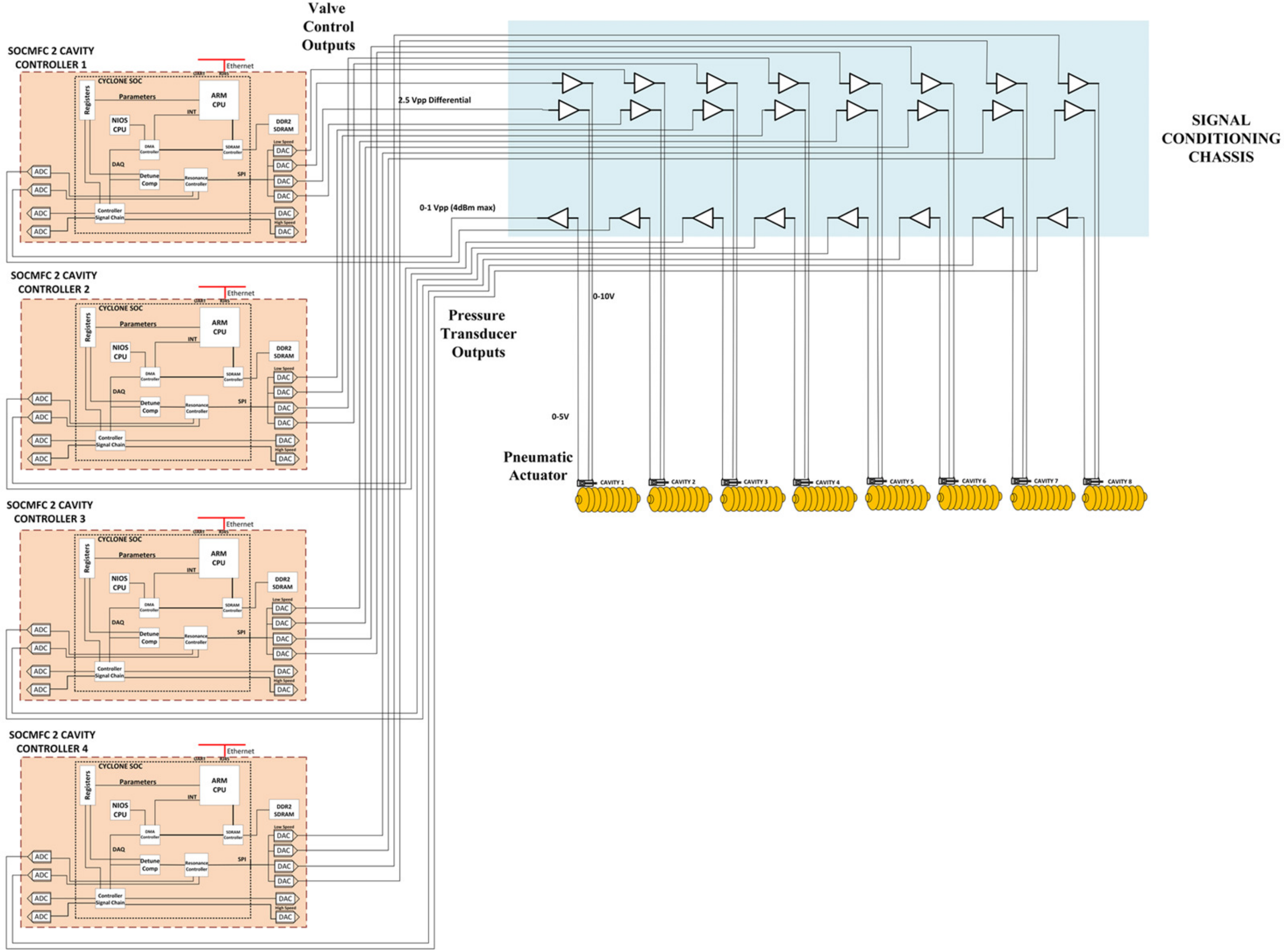
Resonance Controller Architecture



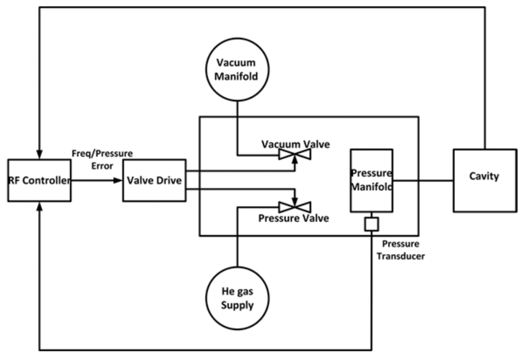
Resonance Control Processing



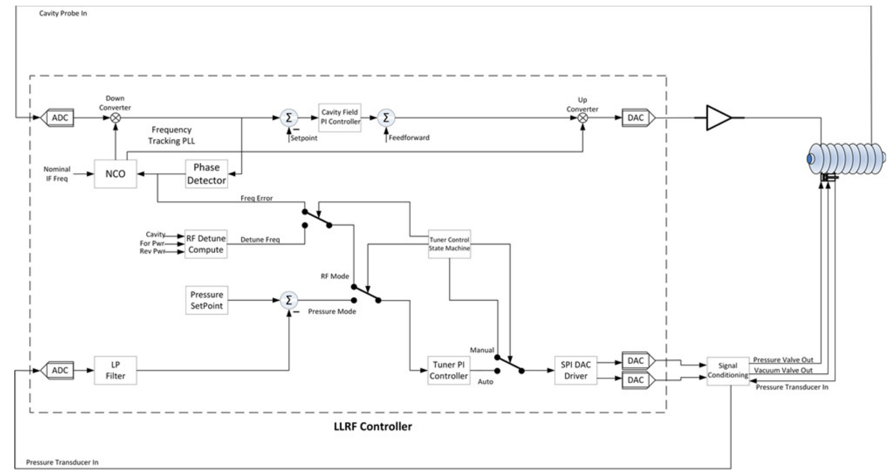
HWR LLRF System with Pneumatic Tuner Control



HWR Resonance Control Design

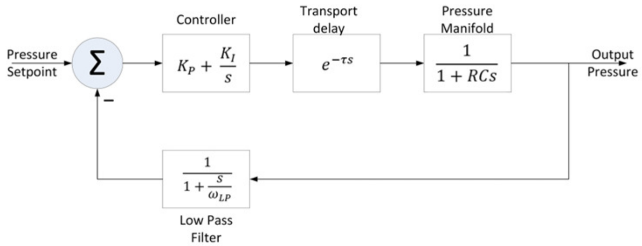


Physical Model

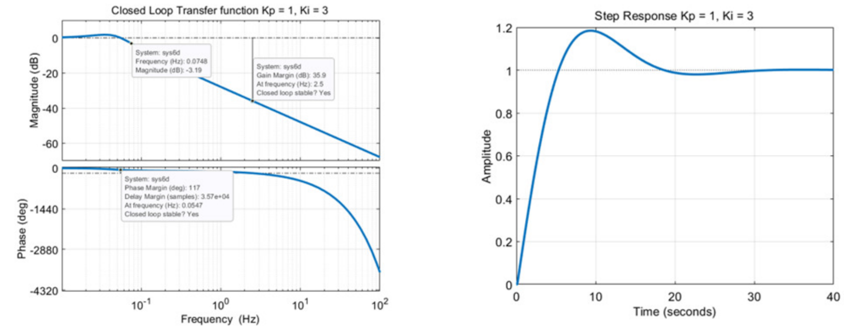


Controller Implementation

Control System Model



Control System Simulation



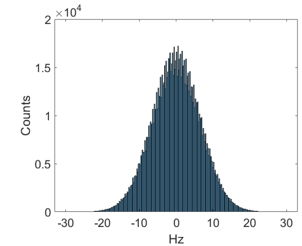
HWR Control Performance

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

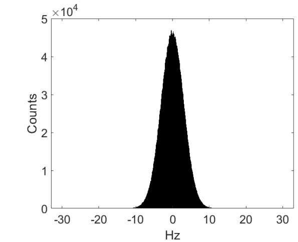
PIP-II Specifications

- Energy Stability(Linac) < 0.01%
- Amplitude Regulation(individual cavity) < 0.06 rms %
- Phase Regulation < 0.06 rms deg
- Maximum detuning < 20 Hz

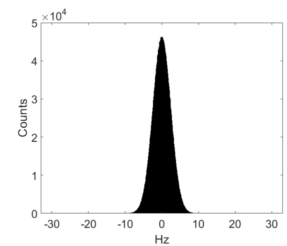
Detuning Histograms



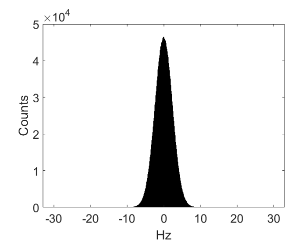
Cavity 4



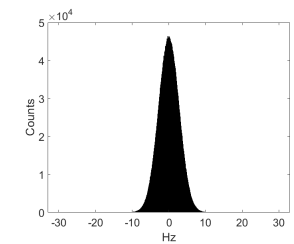
Cavity 5



Cavity 6



Cavity 7



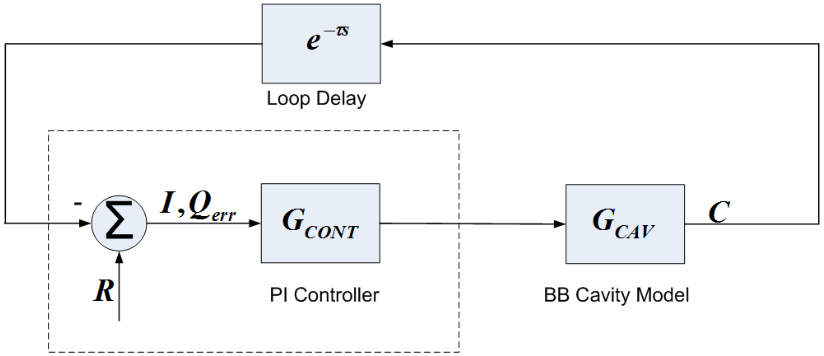
Cavity 8

RF Cavity Parameters and Feedback Gains

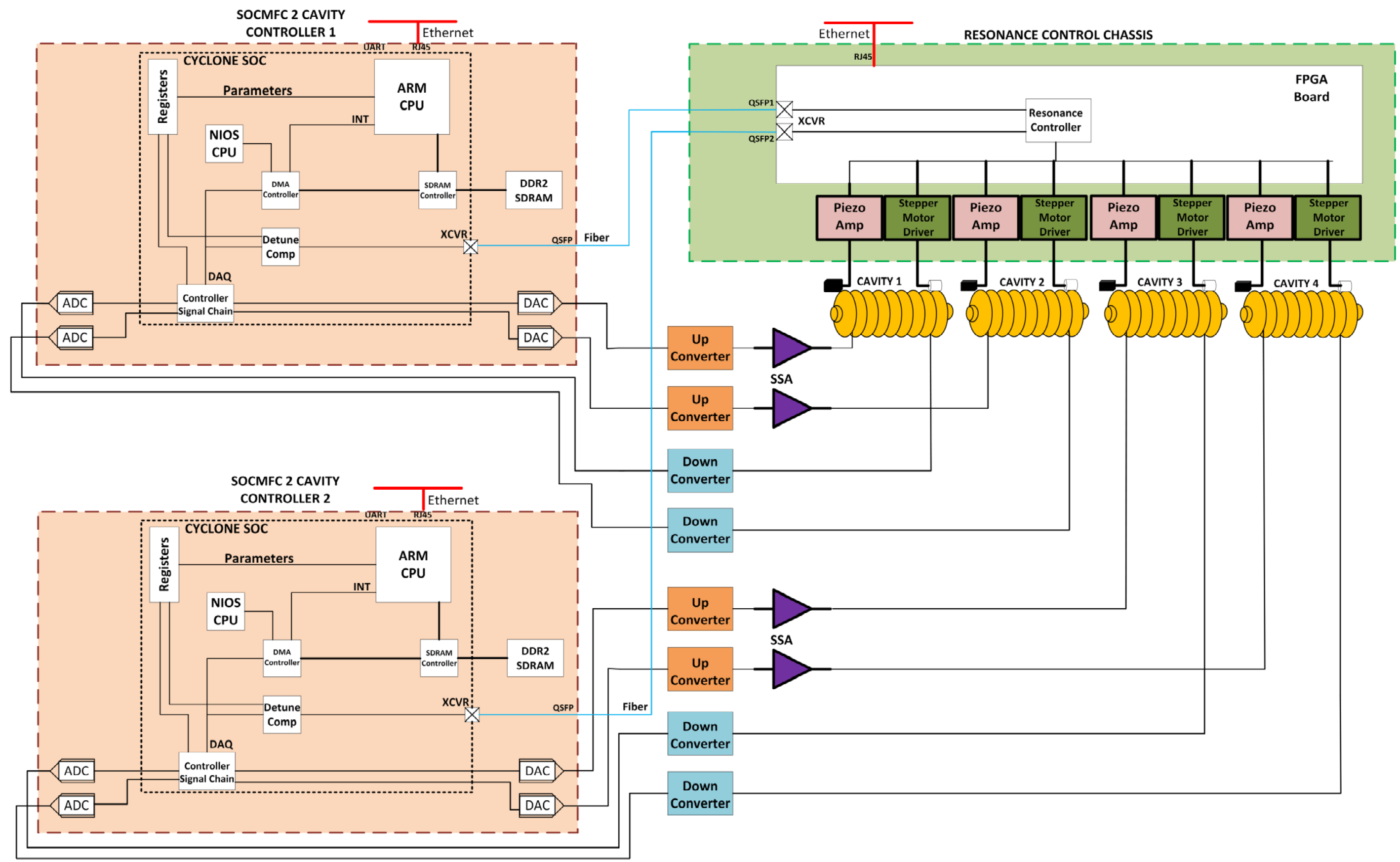
Cavity Type	Q_L	f_0 (MHz)	f_H (Hz)	K_P
Warm Cavity	3000	53	8.83×10^3	15
RFQ	15000	162.5	5.542×10^3	23
Buncher Cavity	10000	162.5	8.125×10^3	16
HWR Cavity	2.32×10^6	162.5	35	3548
SSR1 Cavity	3.02×10^6	325	53.8	2317
SSR2 Cavity	5.05×10^6	325	32.2	3846
LB650 Cavity	10.36×10^6	650	31.4	3935
HB650 Cavity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

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

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



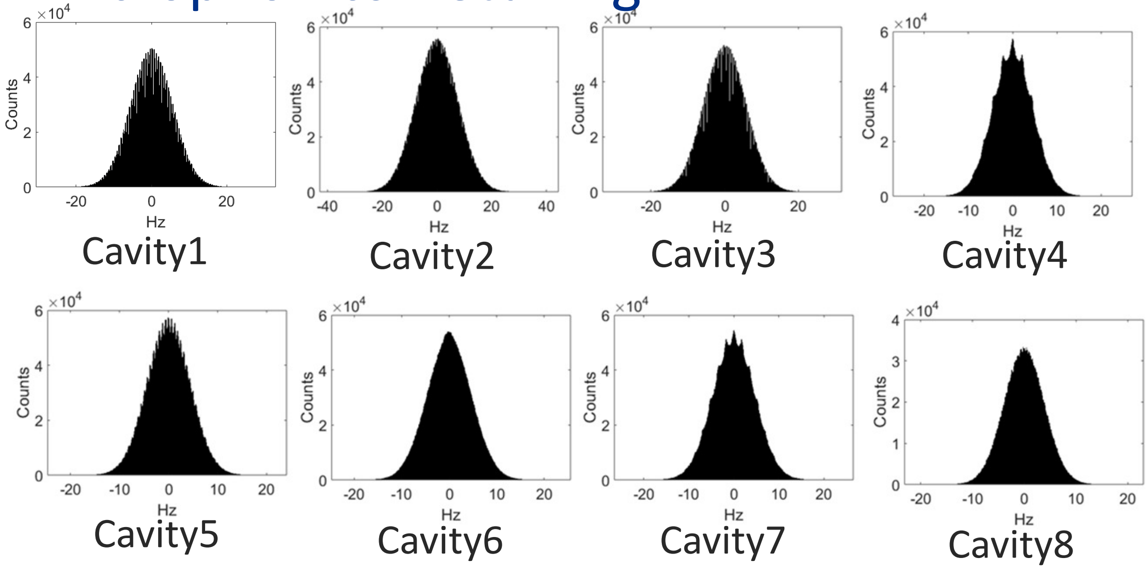
SSR1 LLRF System with Piezo Tuner Control



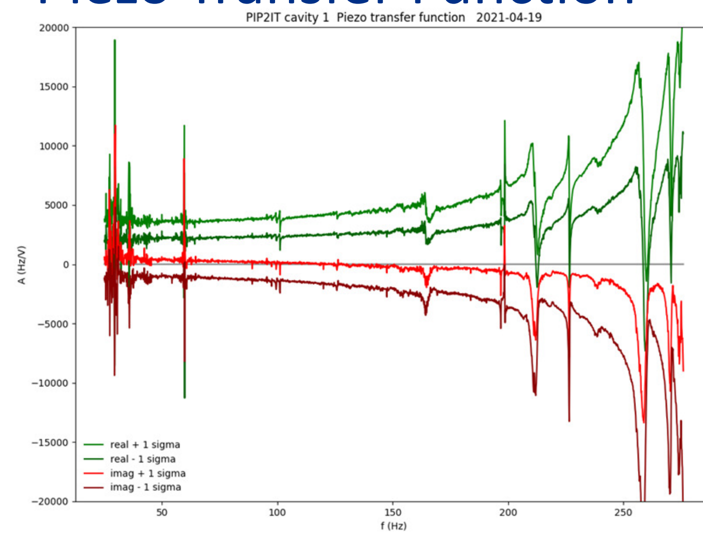
SSR1 Cryomodule Testing

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

Microphonics Detuning



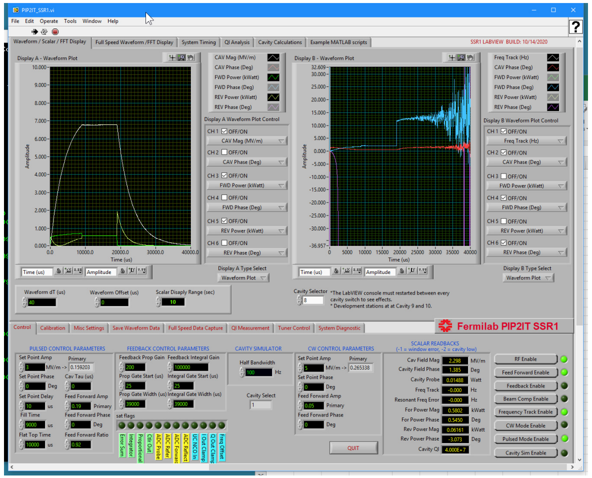
Piezo Transfer Function – C1



Fermilab

LLRF2023 LOW LEVEL RADIO FREQUENCY WORKSHOP 2023 OCTOBER 22-27, 2023 IN GYEONGJU, REPUBLIC OF KOREA

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

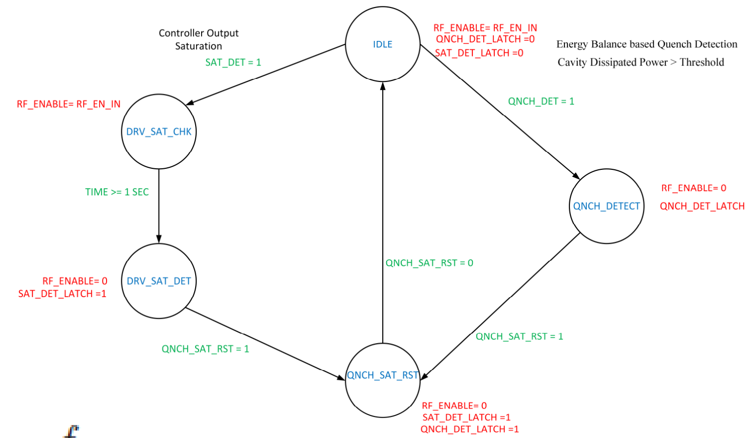
Cavity Quench Detection/ Overdrive Protection

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

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

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

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



- Quench Detection is based on computing the dissipated power in the cavity. The dissipated power is compared against a threshold for quench detection
- RF overdrive is detected when the controller output saturation persists beyond a specified time (~ 1 sec)

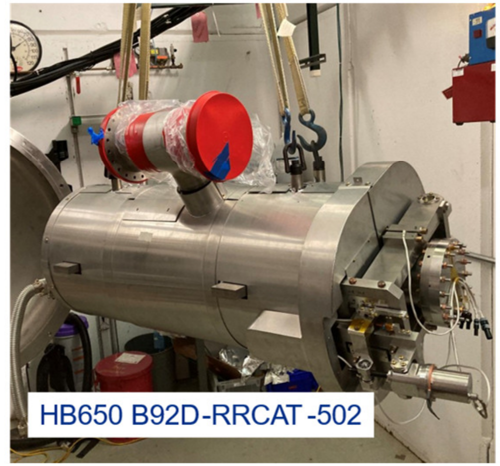
HB650 and LB650 Cavity Testing at STC

- HB650, beta=0.9, **B9A-AES-001**
- January-March 2020
- STC commissioning for 650 MHz operations
- Prototype coupler/tuner validation/testing
- Prototype cavity characterization

- HB650, beta=0.92, **B92D-RRCAT-502**
- October-November 2021
- Prototype coupler/tuner validation/testing
- Prototype cavity characterization, qualification for prototype HB650 cryomodule assembly

- LB650, beta=0.61, **B61-EZ-001**
- June-September 2022
- Preproduction coupler/tuner testing
- Prototype cavity characterization


HB650 B9A-AES-010

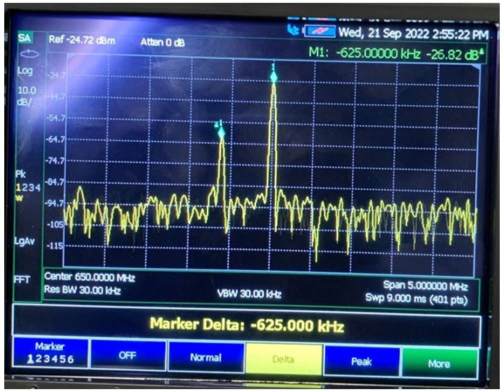

HB650 B92D-RRCAT-502


LB650 B61-EZ-001

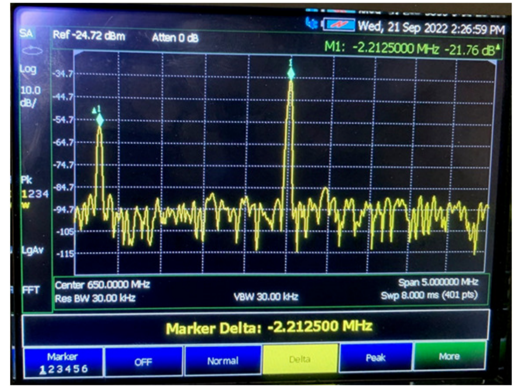

Bare HB650 Cavity


LB650 Cavity on ANL EP stand

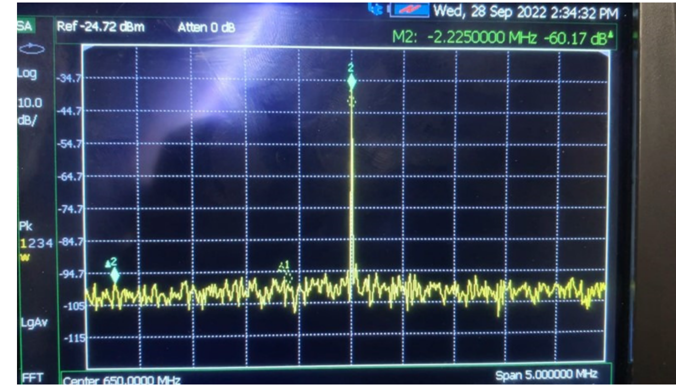
LB650 Cavity Measurements



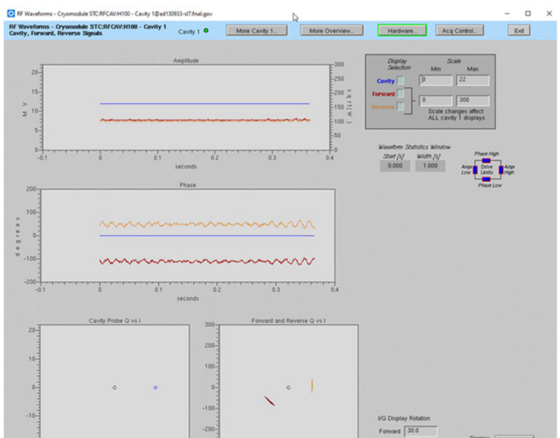
4/5π Mode, 625 kHz



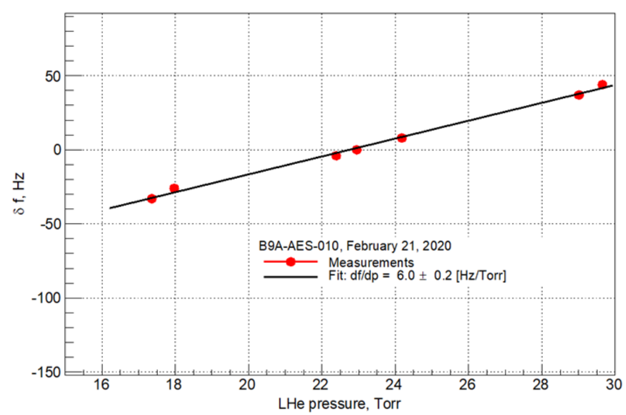
3/5π Mode, 2.125 MHz



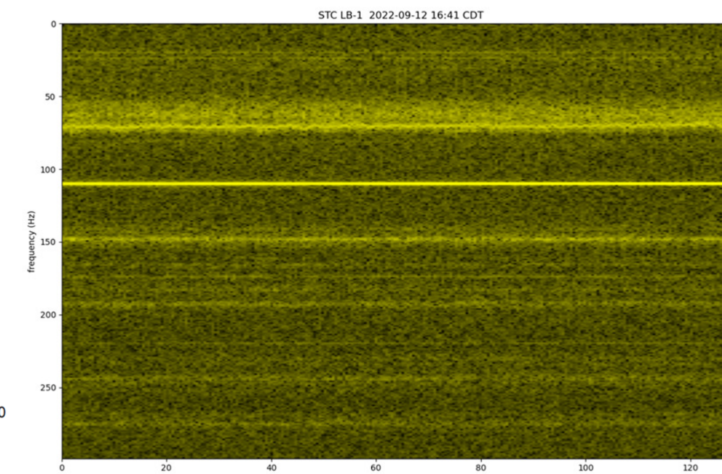
Suppression with notch filters



GDR Mode at 17 MV/m



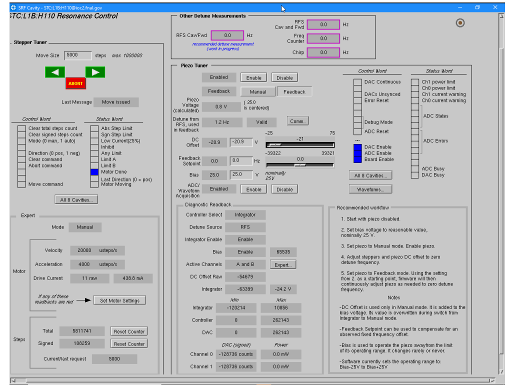
LFD Coefficient = 2.4



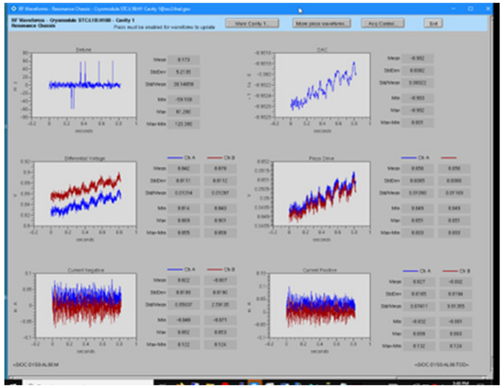
Detuning Spectrogram

HB650 Cavity Measurements

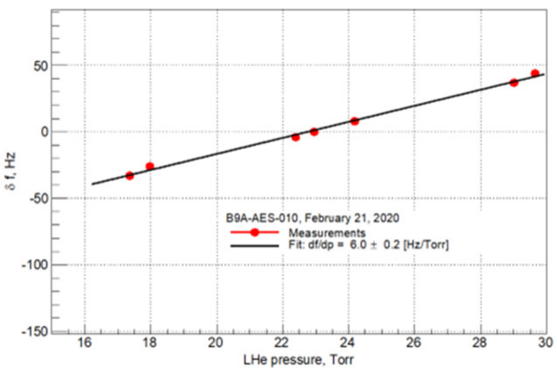
GDR Mode 15 MV/m



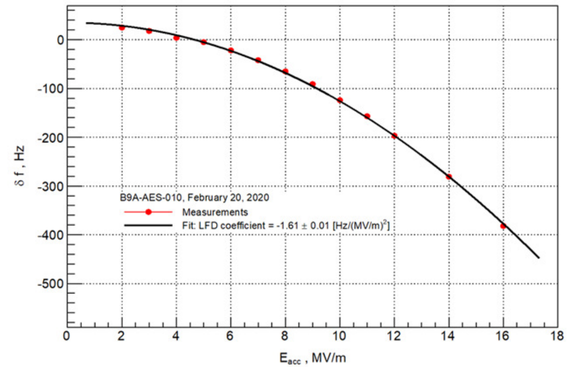
Piezo Tuner Controls



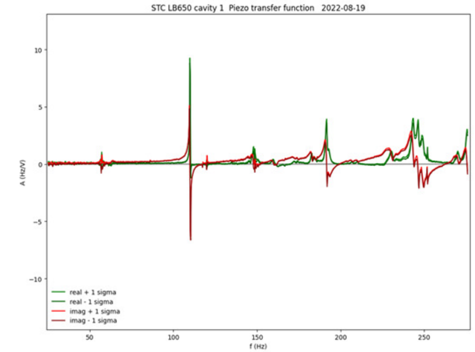
Tuner Waveforms



df/dp = 6.0 Hz/Torr



LFD Coefficient = 1.6

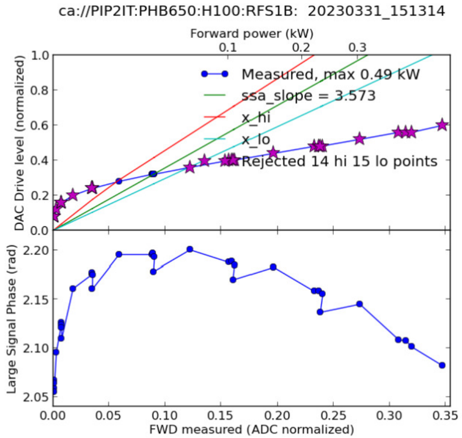


Piezo Transfer Function

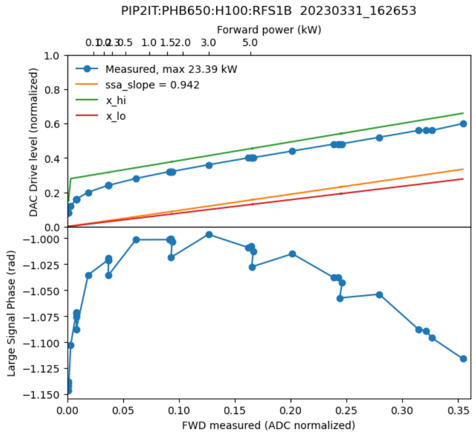
Prototype HB650 Cryomodule Testing at CMTF

pHB650 Cryomodule

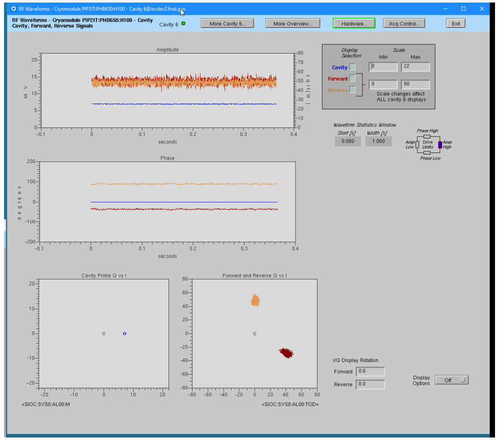
40 kW SSA



SSA Non-linearity

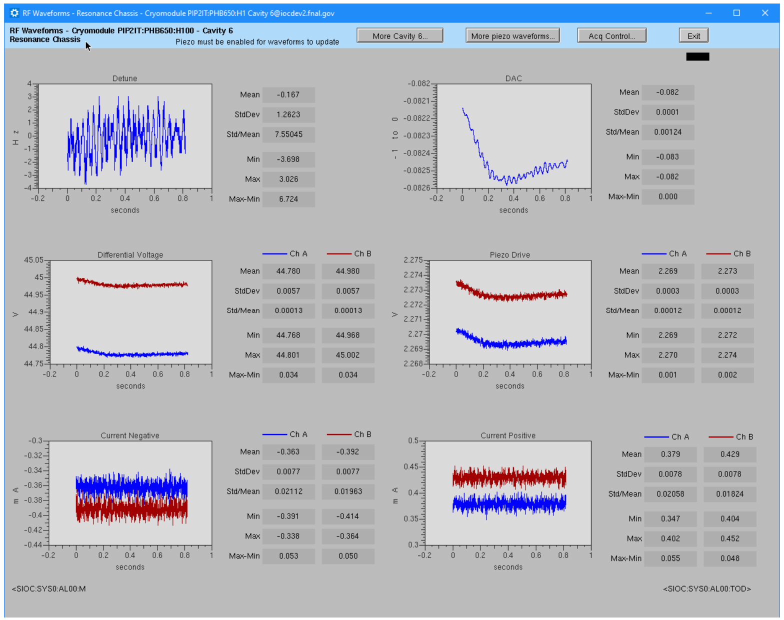


SSA Calibration

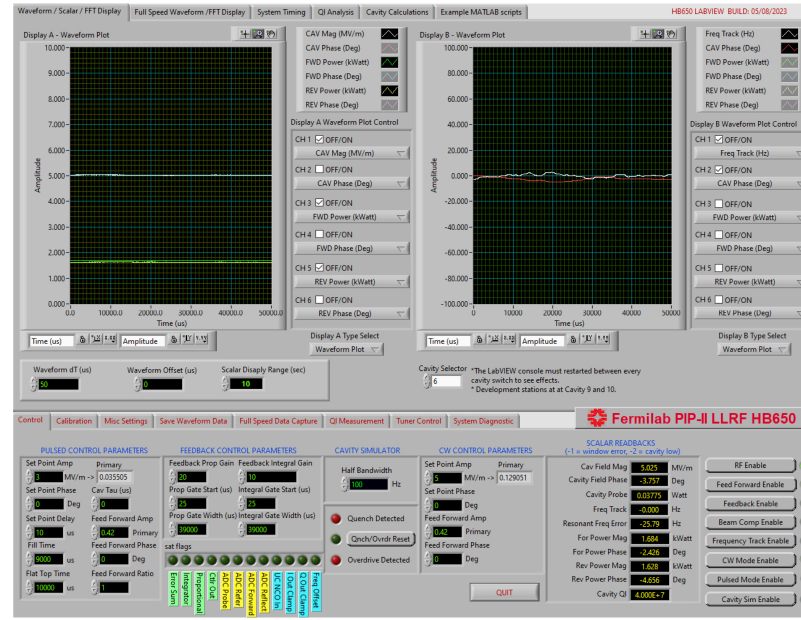


SELAP Mode at 7 MV/m

Prototype HB650 Cryomodule Testing at CMTF

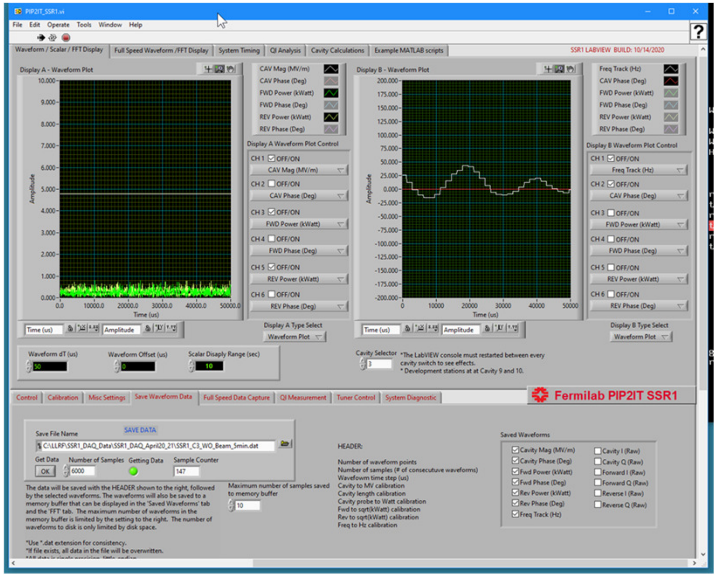


Piezo Waveforms



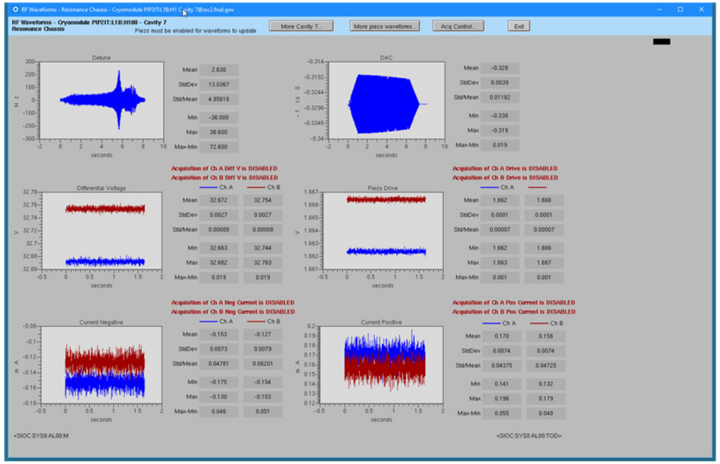
GDR Mode at 5MV/m

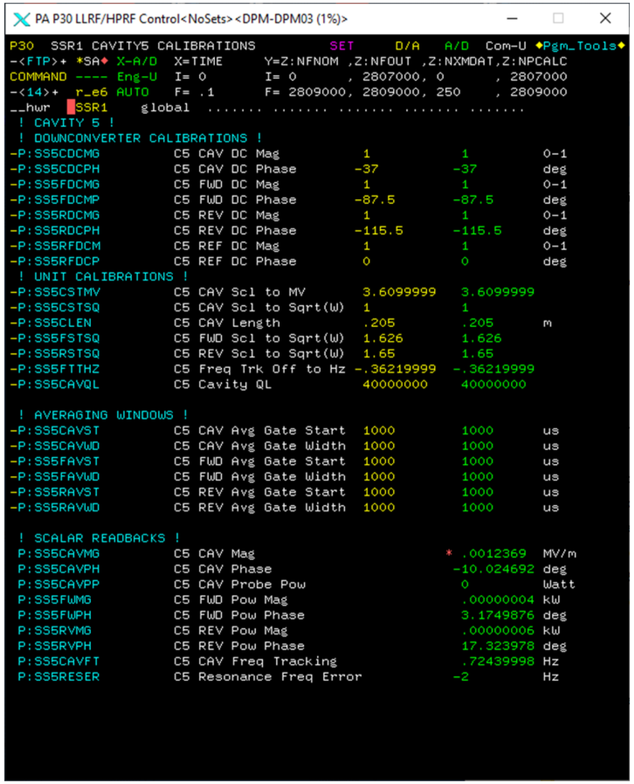
User Interfaces



Labview

EPICS





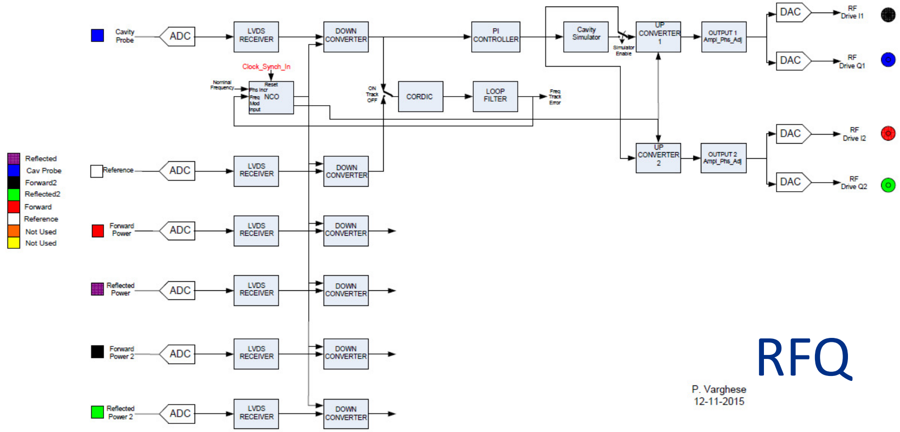
ACNET

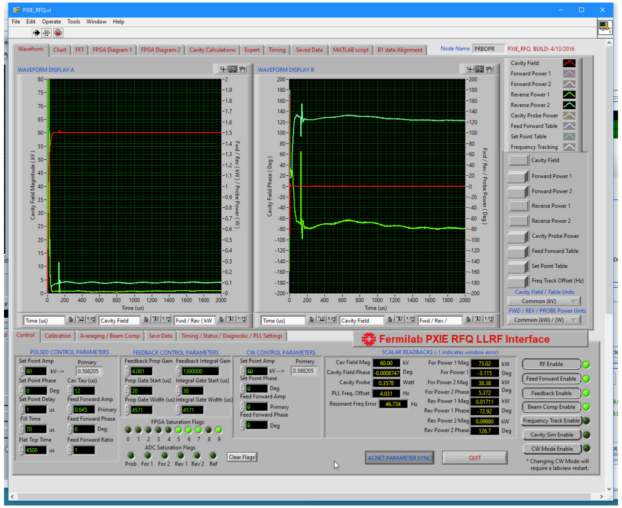
Summary

- PIP-II LLRF System is in the Final Design Review Stage
- The design is closely aligned with the LCLS-II LLRF system
- Various hardware/software components have been tested at PIP2-IT and STC
- The LLRF systems at PIP2-IT met the project requirements
- All the different cavity types(7) have been tested with the LLRF system
- Final design prototypes will continue to be tested at both facilities
- The EPICS user interface has been used in the test stands
- The Final Design Review is expected in early 2024

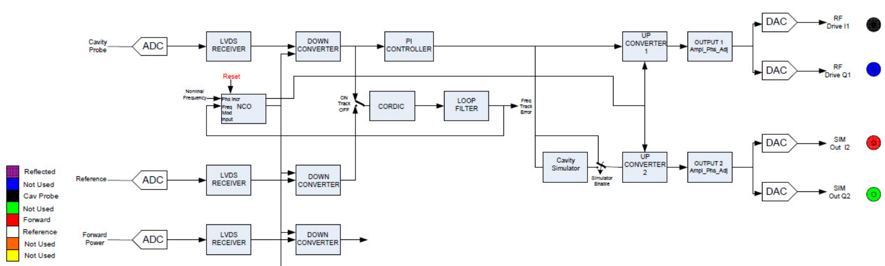
Thank You!

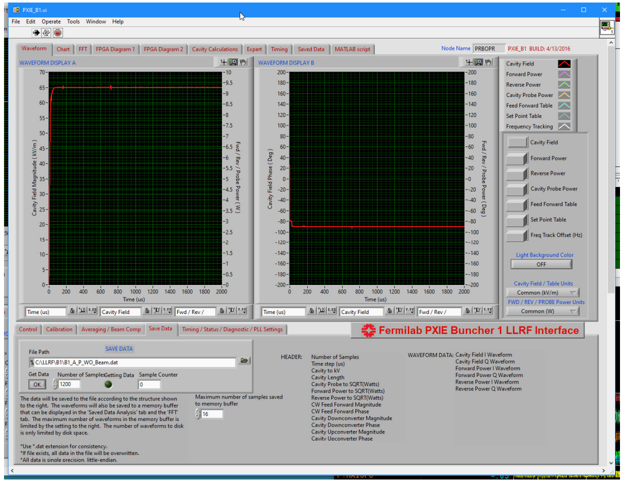
RFQ and B1 LLRF System





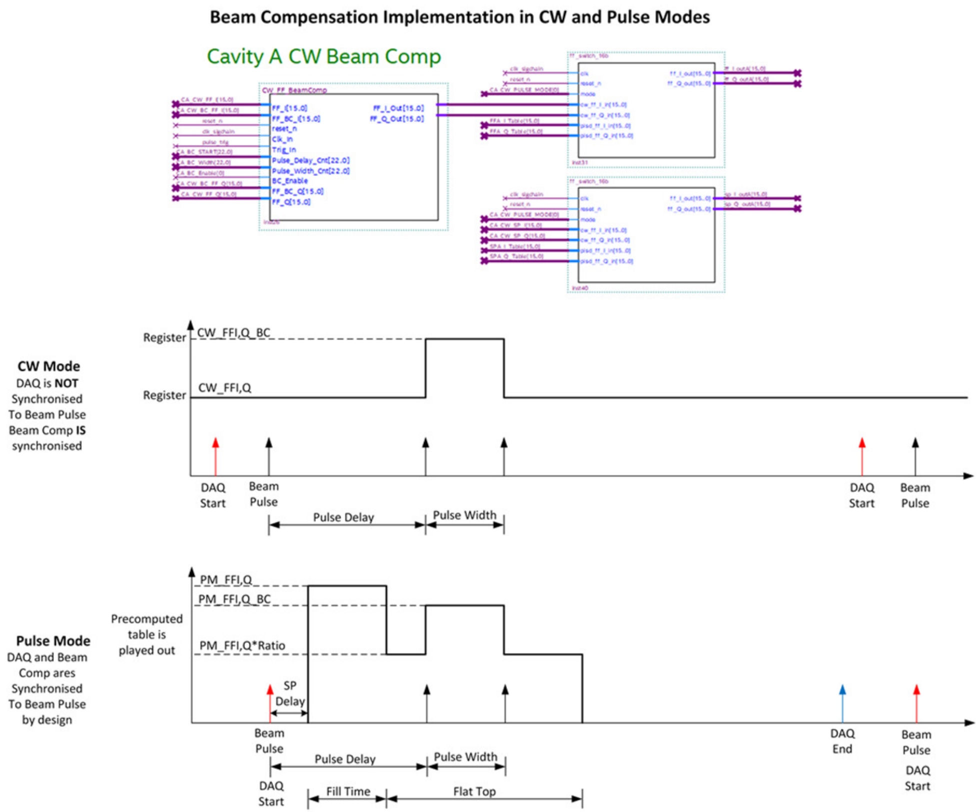
RFQ

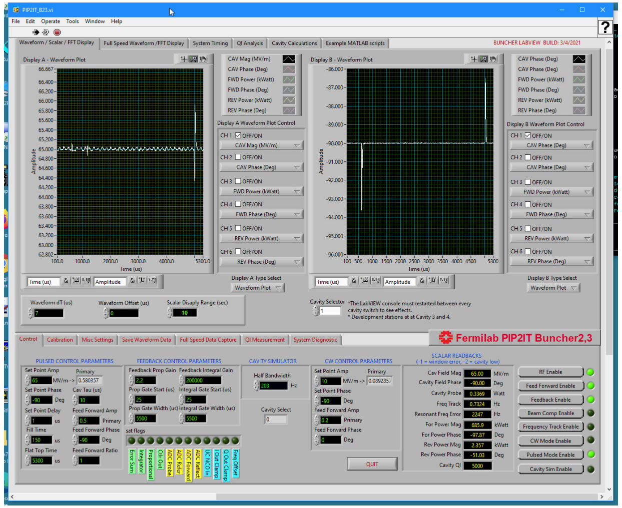


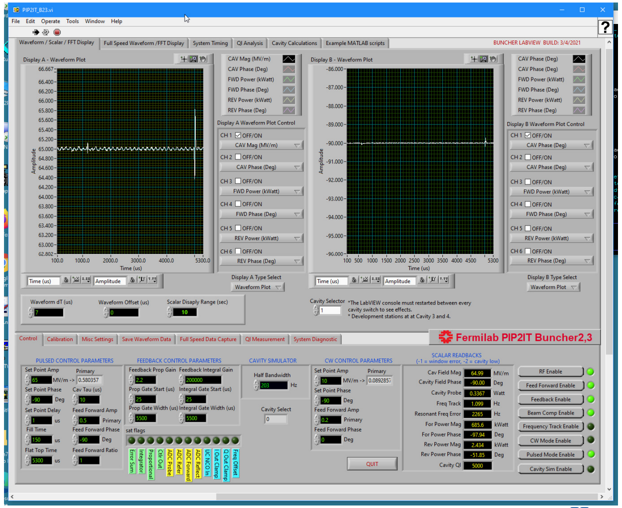


Buncher1

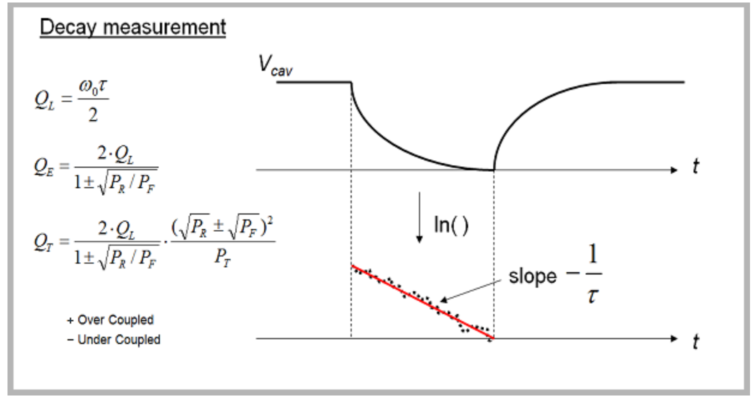
Beam Loading Compensation – B2



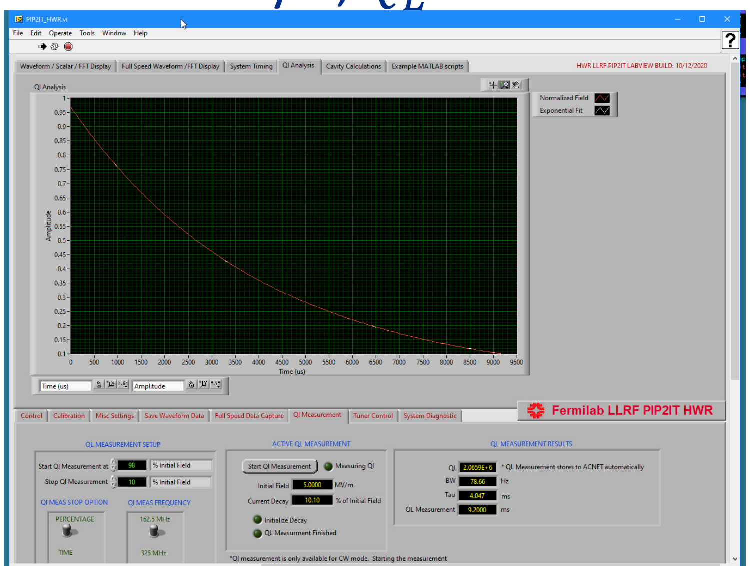




Q_L Measurement



HWR Cavity 5, Q_L = 2.07e6



SSR1 Cavity 5, Q_L = 4.11e6