



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

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13 October 2022

Low Level RF Workshop 2022



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

30 keV

2.1 MeV

10 MeV

22 MeV



Ion
Source

RFQ, B1
VXI Crate
2 MFC cards

Buncher2,3
1 SOCMFC
Chassis

HWR
4 SOCMFC
Chassis
1 Tuner
Signal Cond
Module

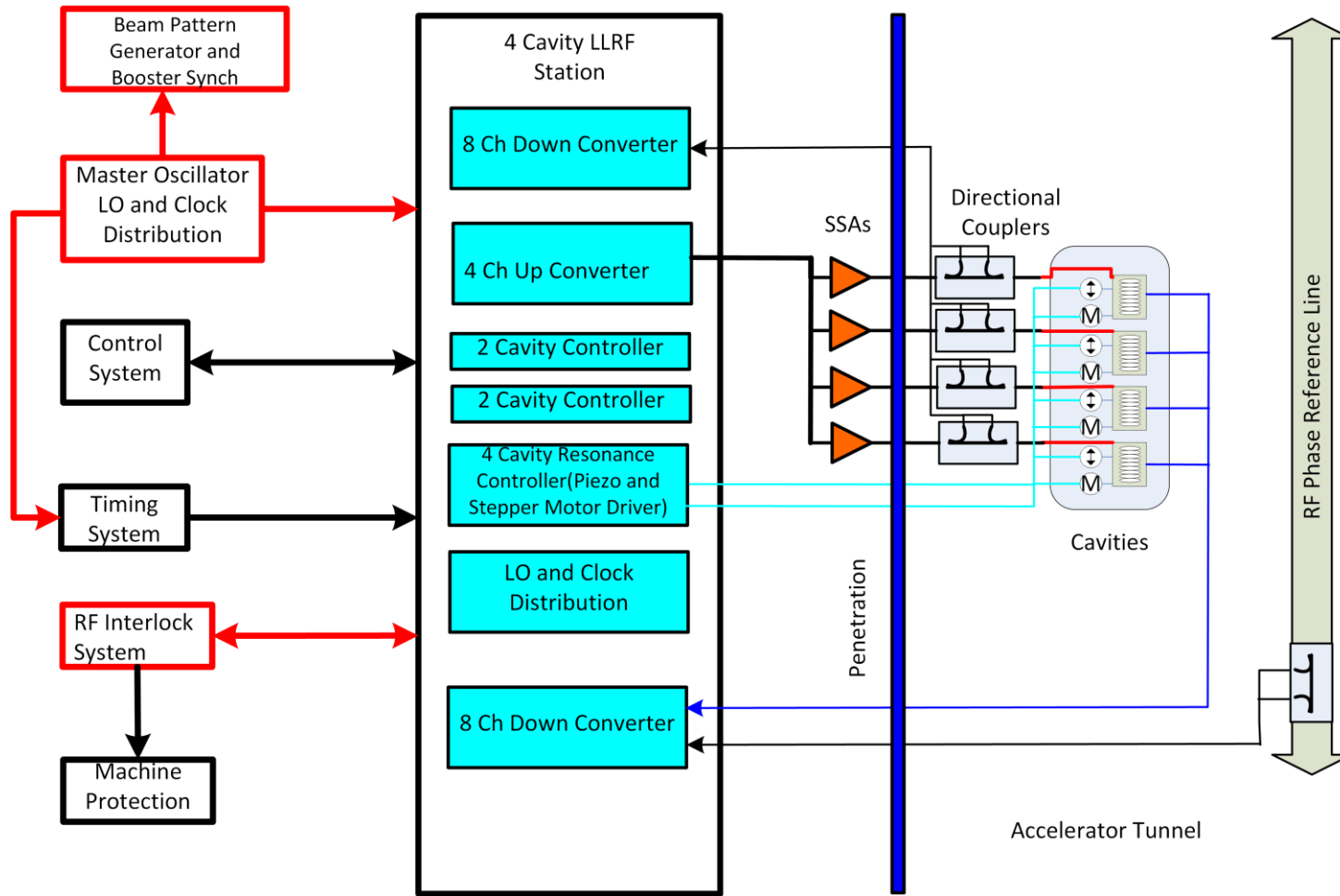
SSR1
4 SOCMFC
Chassis
2 Resonance
Control Chassis



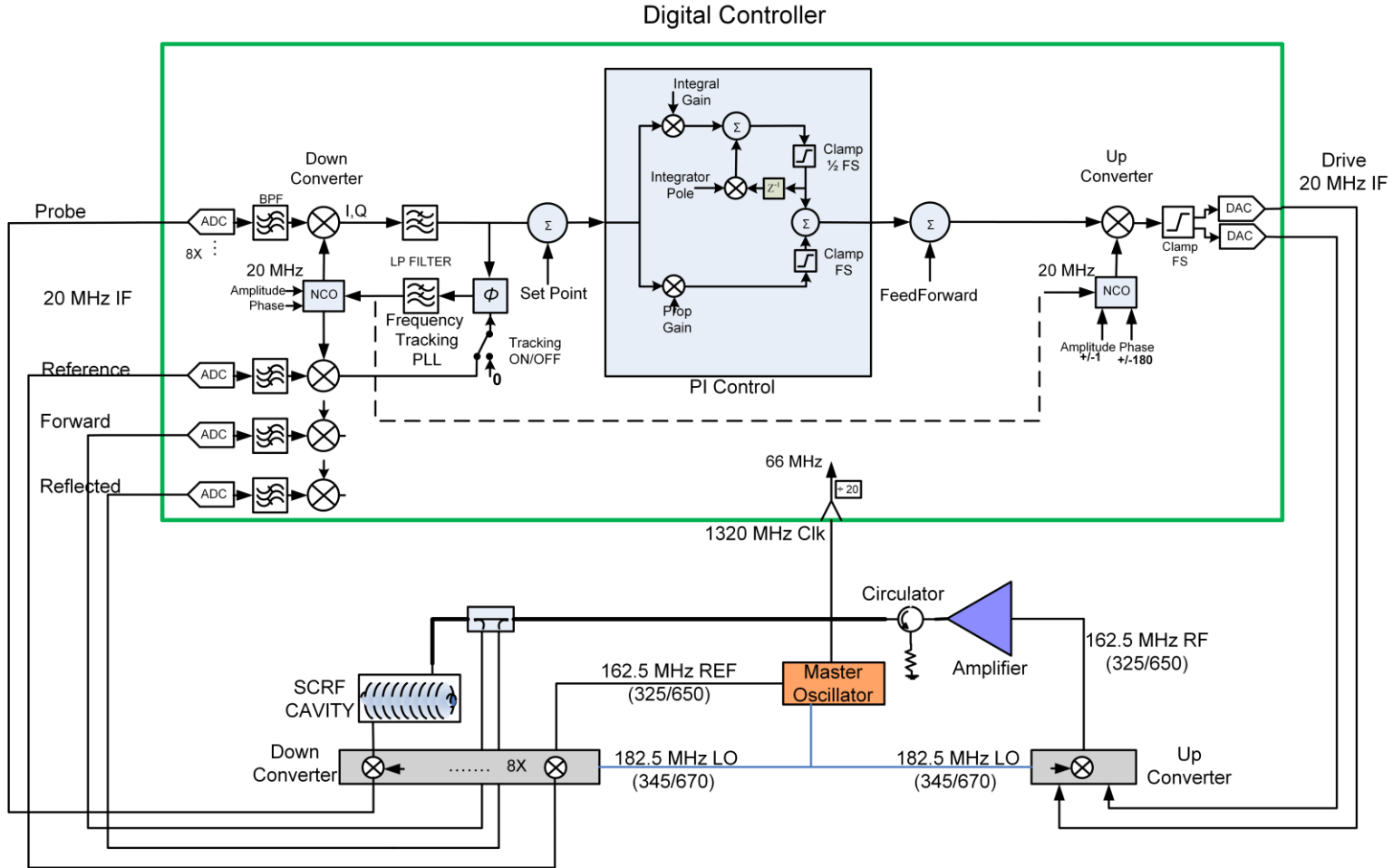
PIP2-IT LLRF Systems



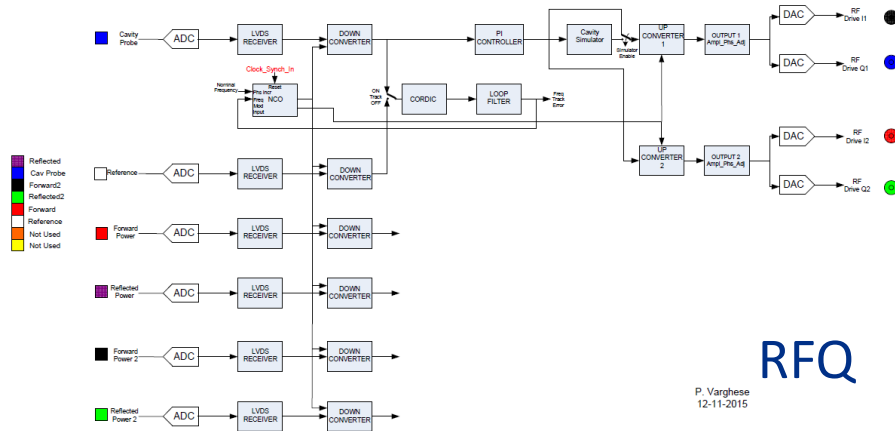
PIP2 4-Cavity RF Station



LLRF System Architecture

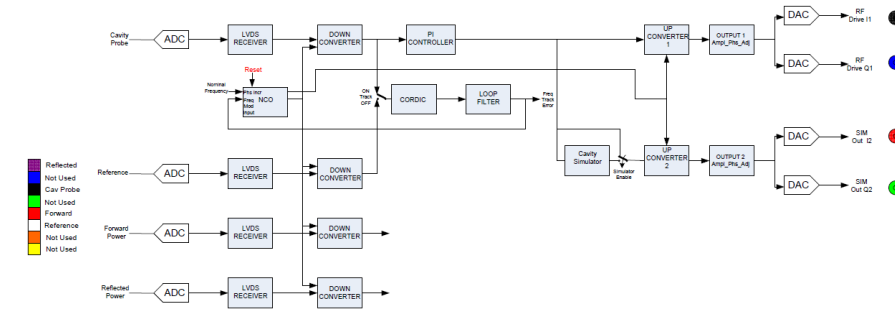


RFQ and B1 LLRF System

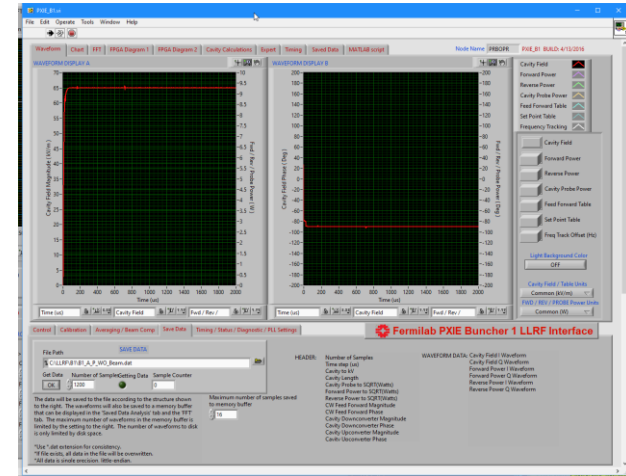


RFQ

P. Varghese
12-11-2015



Buncher1



Low Level RF Workshop 2022

Fermilab

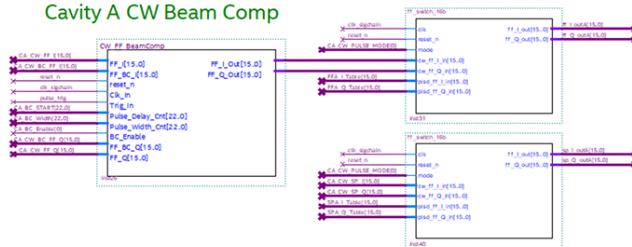
9-13 Oct 2022, Brugg-Windisch, Switzerland



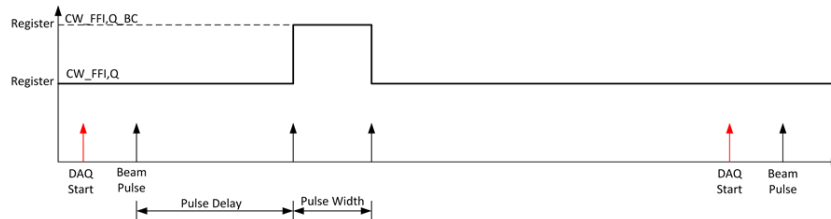
Beam Loading Compensation – B2

Beam Compensation Implementation in CW and Pulse Modes

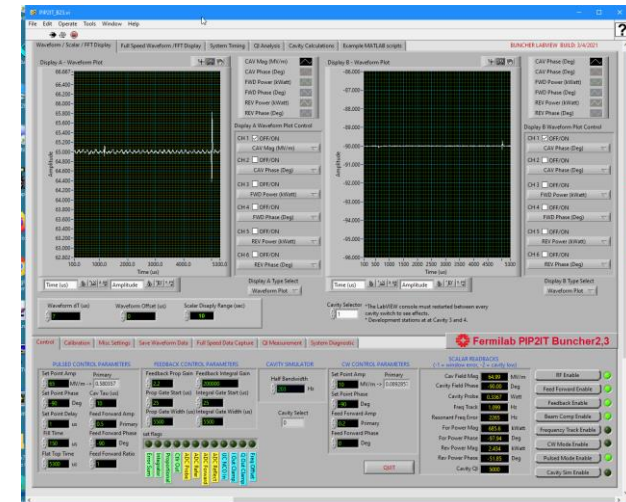
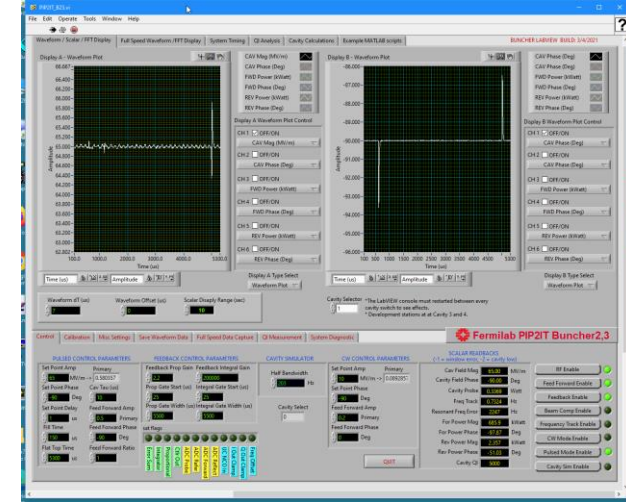
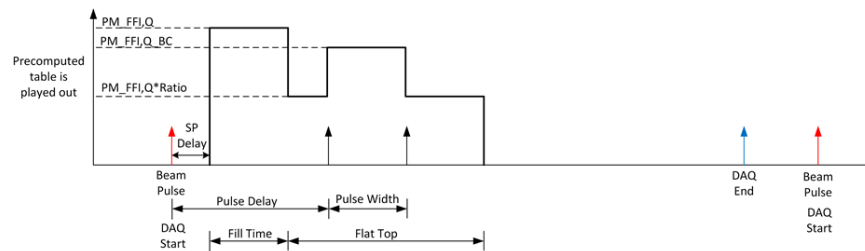
Cavity A CW Beam Comp



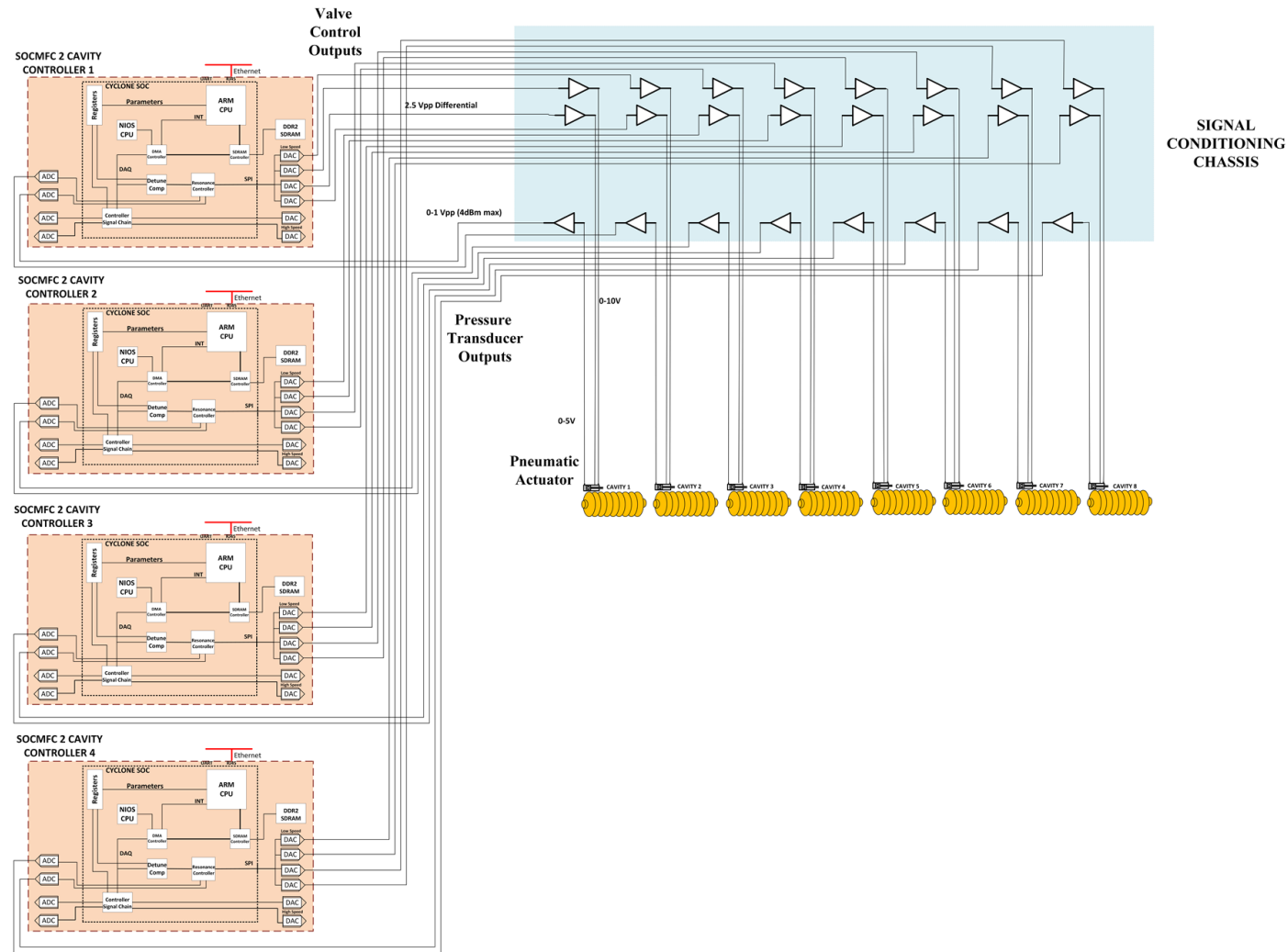
CW Mode
DAQ is **NOT**
Synchronised
To Beam Pulse
Beam Comp IS
synchronised



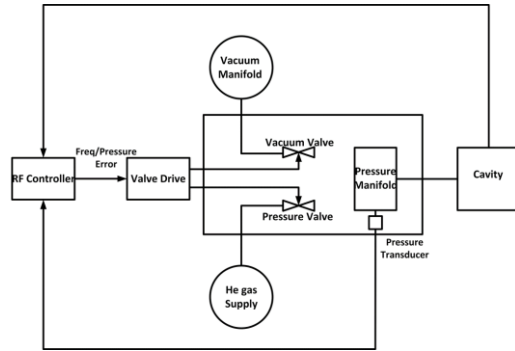
Pulse Mode
DAQ and Beam
Compares
Synchronised
To Beam Pulse
by design



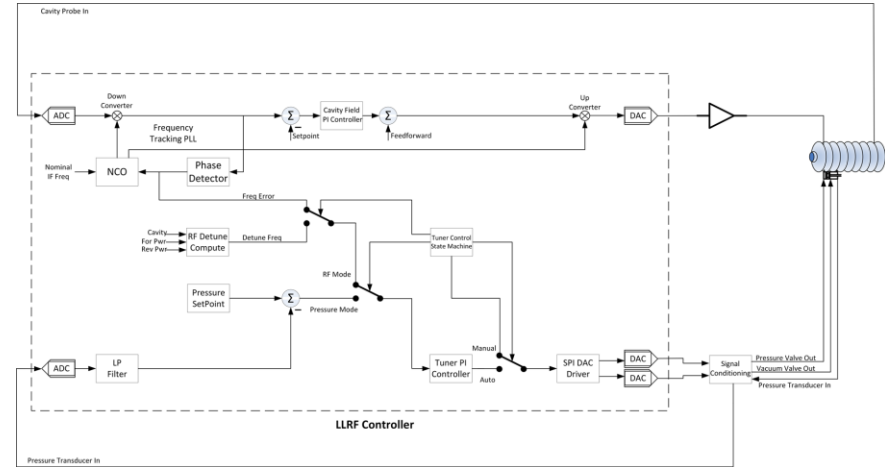
HWR LLRF System with Pneumatic Tuner Control



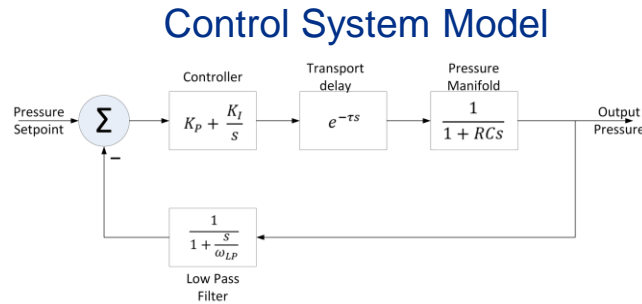
HWR Resonance Control Design



Physical Model

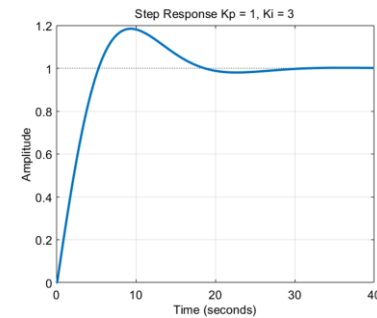
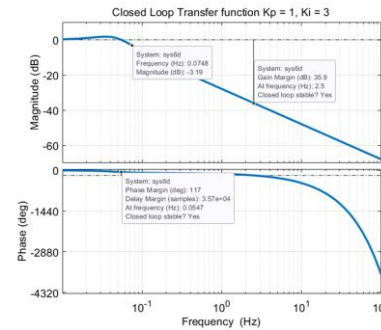


Controller Implementation

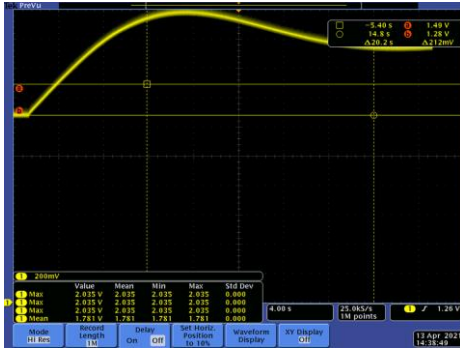


Control System Model

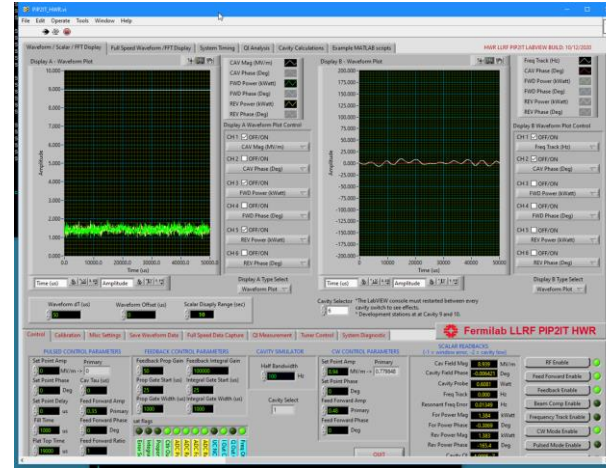
Control System Simulation



HWR Resonance Control Performance

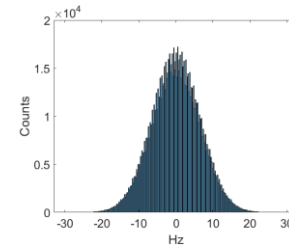
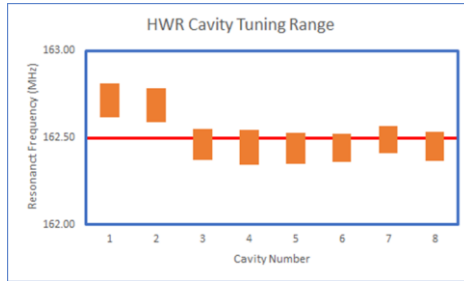


Measured Step Response

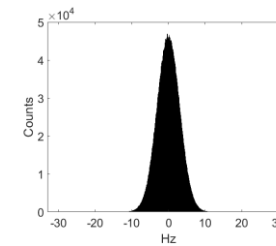


Cavity GDR Mode Waveforms

Cavity Tuning Range

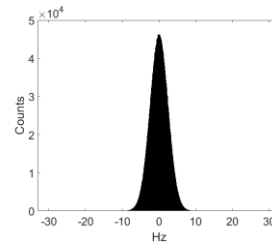


Cavity 4

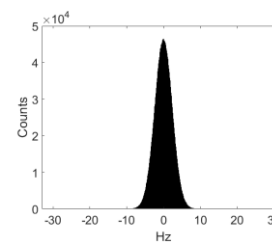


Cavity 5

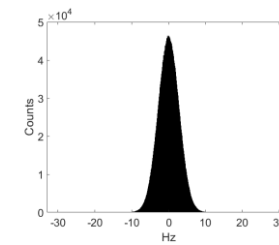
Detuning Histograms



Cavity 6



Cavity 7



Cavity 8

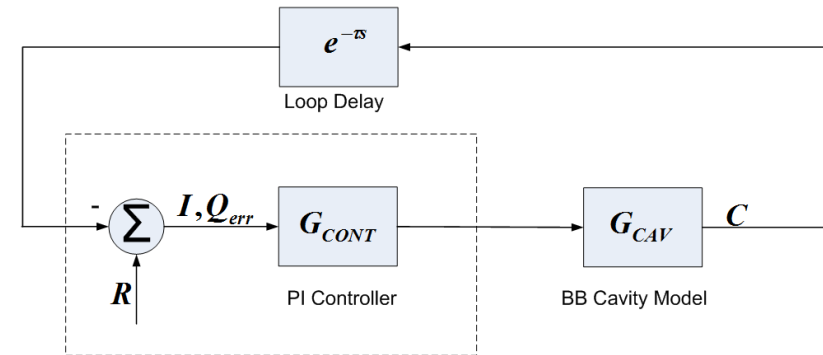


RF Cavity Parameters and Feedback Gains

| 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

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



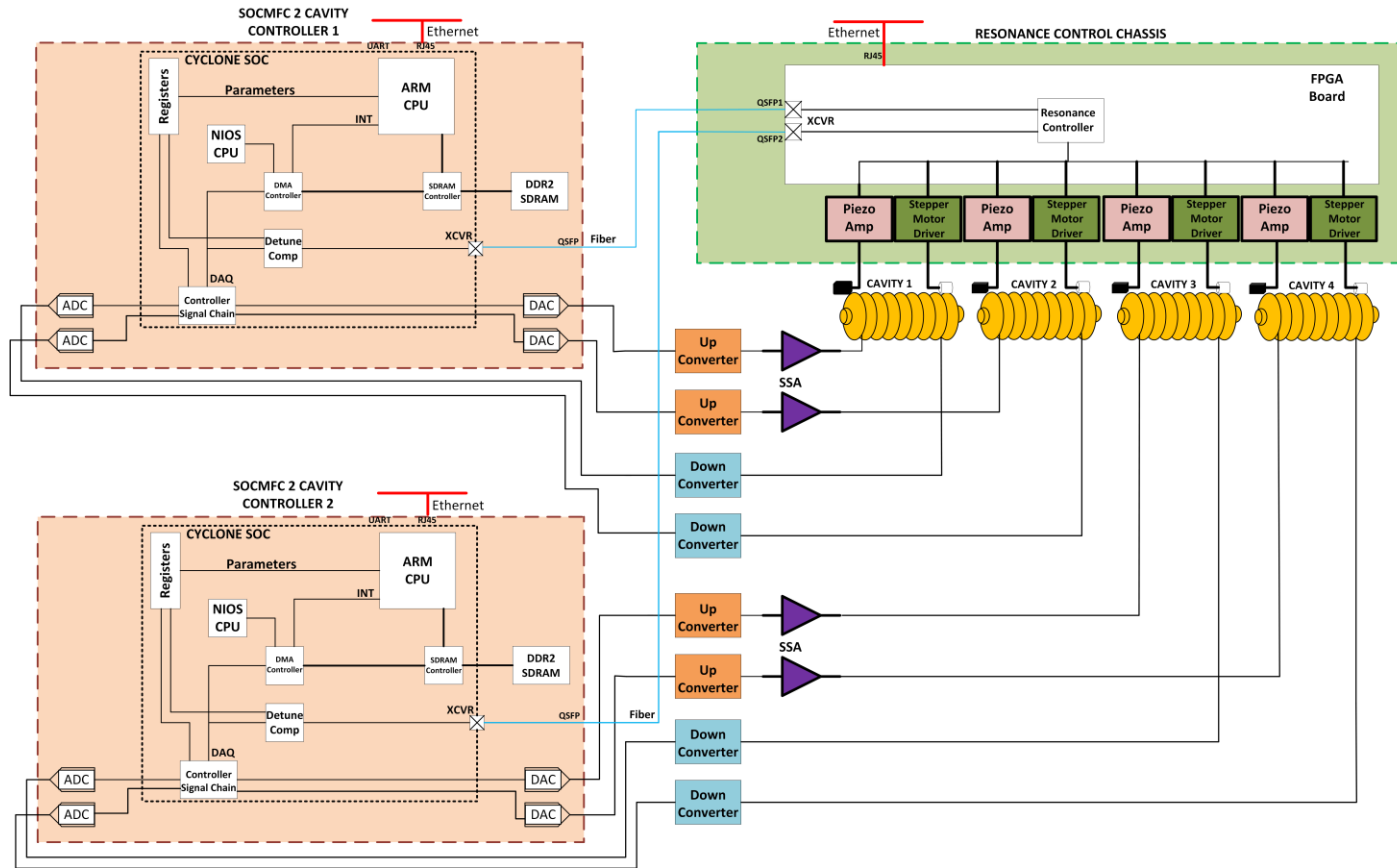
HWR Cavity Field Regulation

| 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

SRF Cavity
Cryomodule PIP2IT:L1B:H100 Cavity 5

Overview Characterization Detune **Tuners** Interlocks **RF Controller** Ampl/Phas Diag Pulsed Hardware Signal Calib

PIP2IT:L1B:H100 Resonance Control

Other Detune Measurements

RFS CavFwd 0.0 Hz
Cav and Fwd 0.0 Hz
Freq Counter 0.0 Hz
Chirp 0.0 Hz

Stepper Tuner

Move Size 0 steps max 1000000

ABORT

Last Message Await request

Control Word

Clear total steps count
Clear signed steps count
Mode (0 man, 1 auto)
Direction (0 pos, 1 neg)
Clear command
Abort command
Move command

Status Word

Abs Step Limit
Sgn Step Limit
Low Current(25%)
Inhibit
Any Limit
Limit A
Limit B
Motor Done
Last Direction (0 = pos)
Motor Moving

All 8 Cavities...

Expert

Mode Manual

Velocity 20000 usteps/s
Acceleration 4000 usteps/s
Motor Drive Current 11 raw 430.8 mA

If any of these readbacks are red → Set Motor Settings

Steps

Total 0 Reset Counter
Signed 0 Reset Counter
Current/bias request 0

Piezo Tuner

Enabled Enable Disable

Feedback Manual Feedback

Piezo Voltage (calculated) 7.8 V

Detune from RFS, used in feedback -21.3 Hz Valid Comm

DC Offset 0.0 V 0 100

Feedback Setpoint 0.0 Hz -39322 0.0 39321

Bias 0.0 V nominally 25V

ADC/Waveform Acquisition Enabled Enable Disable

Diagnostic Readback

Controller Select Integrator

Detune Source RFS

Integrator Enable Enable

Bias Enable 0

Active Channels A and B Expert

DC Offset Raw 0

Integrator 20574 7.8 V

Integrator Min -65535 Max 65535

Controller 0 262143

DAC 0 262143

DAC (signed) Power

Channel 0 -110478 counts 0.0 mW

Channel 1 -110478 counts 0.0 mW

Recommended workflow

1. Start with piezo disabled.
2. Set bias voltage to reasonable value, nominally 25 V.
3. Set piezo to Manual mode. Enable piezo.
4. Adjust steppers and piezo DC offset to zero detune frequency.
5. Set piezo to Feedback mode. Using the setting from 2. as a starting point, firmware will then continuously adjust piezo as needed to zero detune frequency.

Notes

- DC Offset is used only in Manual mode. It is added to the bias voltage. Its value is overwritten during switch from Integrator to Manual mode.
- Feedback Setpoint can be used to compensate for an observed fixed frequency offset.
- Bias is used to operate the piezo away from the limit of its operating range. It changes rarely or never.
- Software currently sets the operating range to: Bias=25V to Bias+25V

Control Word

DAC Continuous
DACs Unsynced
Error Reset
Debug Mode
ADC Reset
DAC Enable
ADC Enable
Board Enable
All 8 Cavities...
Waveforms...

Status Word

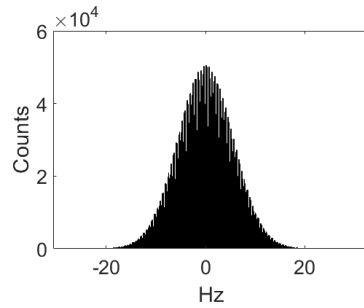
Ch1 power limit
Ch0 power limit
Ch1 current warning
Ch0 current warning
ADC States
ADC Errors
ADC Busy
DAC Busy

<SIOC-SVS0:AL00.M >

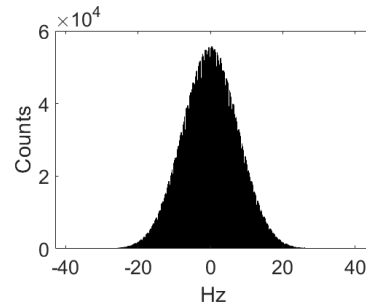
<SIOC-SVS0:AL00.TOD>



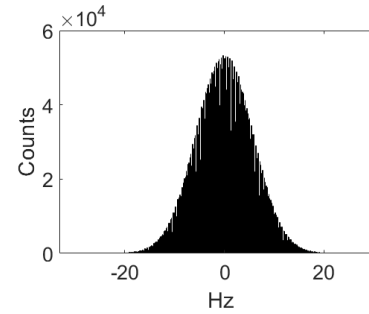
SSR1 Cavity Detuning Histograms



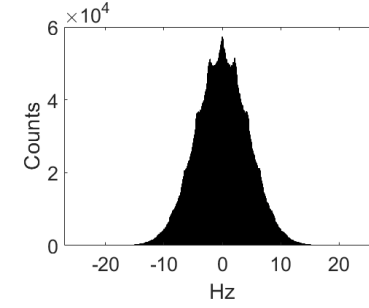
Cavity1



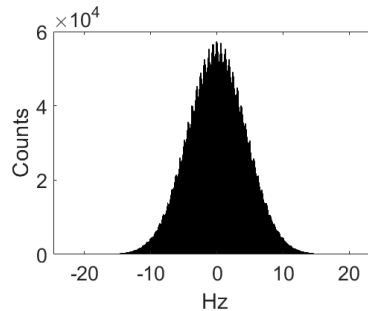
Cavity2



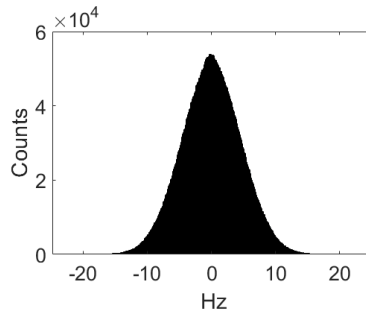
Cavity3



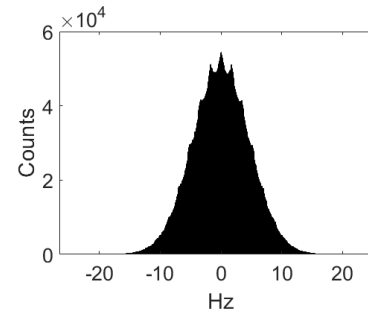
Cavity4



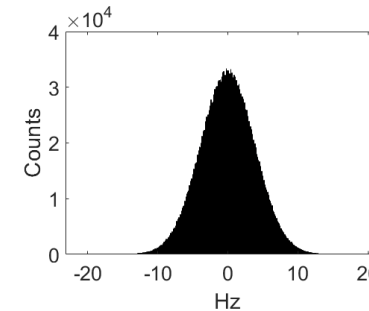
Cavity5



Cavity6

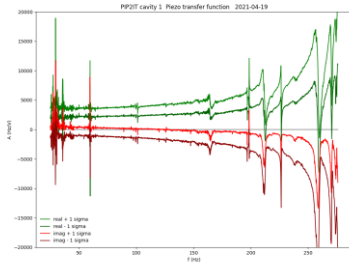


Cavity7

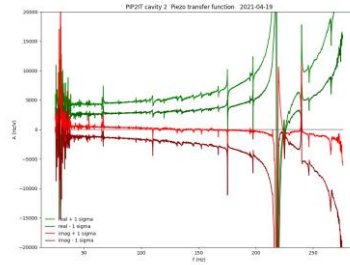


Cavity8

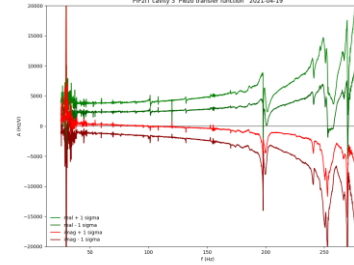
SSR1 Piezo Transfer Functions



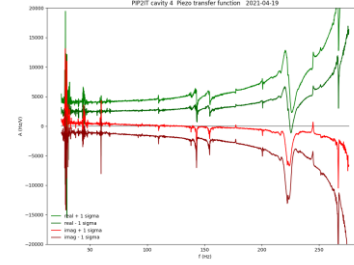
Cavity1



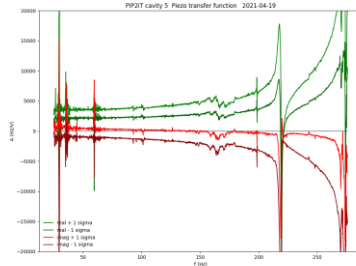
Cavity2



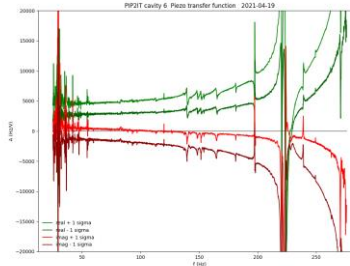
Cavity3



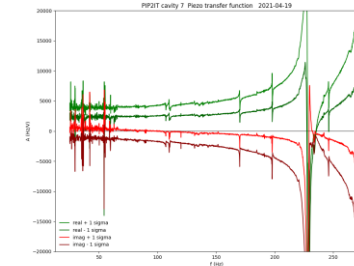
Cavity4



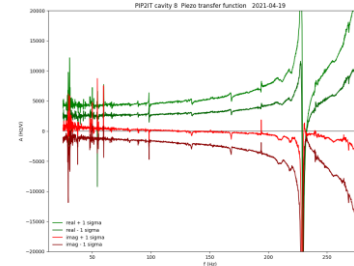
Cavity5



Cavity6



Cavity7



Cavity8

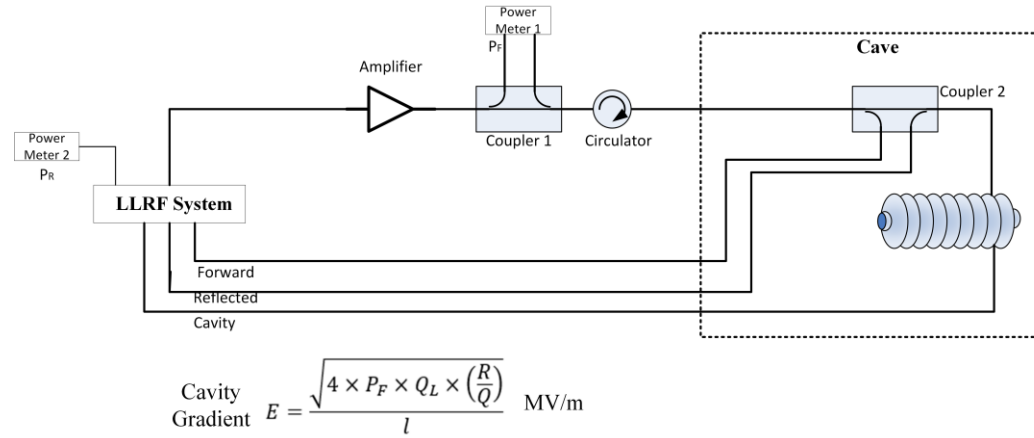
SSR1 Amplitude and Phase Regulation

| 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

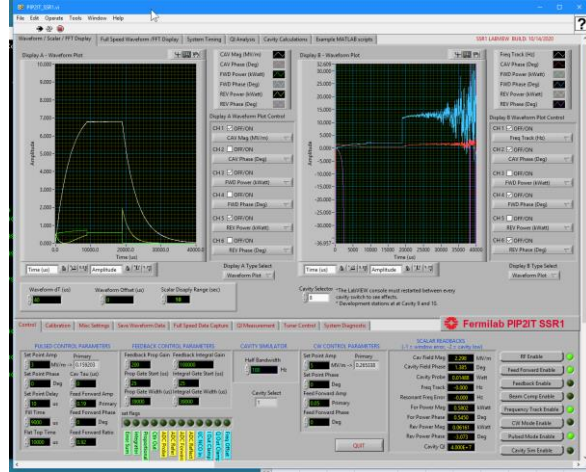
- Amplitude Regulation (individual cavity) < 0.06%
- Energy Stability (Linac) < 0.01%
- Phase Regulation < 0.06 deg

RF Power Calibration



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 P_F
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



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

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

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

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

- The cavity is operated in pulse mode with a cavity field $\sim 1/2$ 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



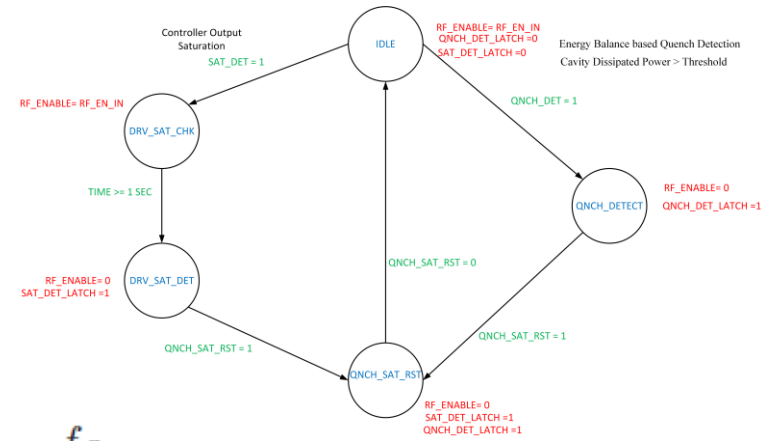
Cavity Quench Detection/ Overdrive Protection

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

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

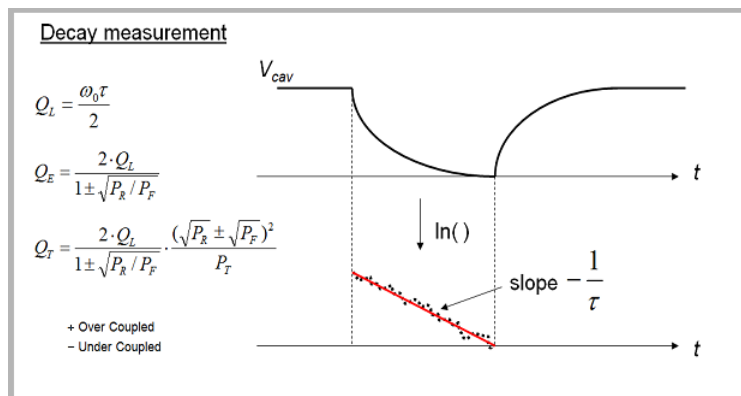
$$\frac{dU}{dt} = 2\Re \left(\vec{V} \frac{d\vec{V}}{dt} \right) \cdot \frac{1}{\omega_0(R/Q)}$$

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

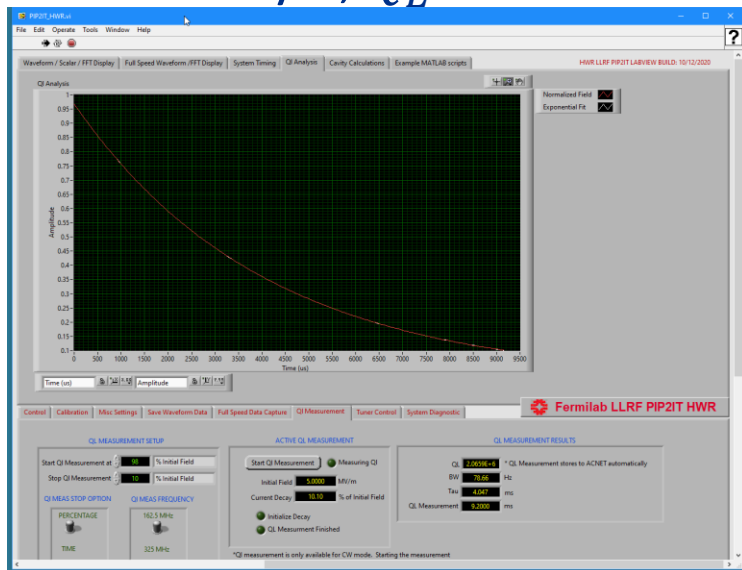


- The cavity is operated in pulse mode with a cavity field ~ 1/2 FS magnitude and the cavity probe and forward waveforms are recorded.
- Numerical analysis of the acquired data provides cavity parameters such as half bandwidth and the detuning constants

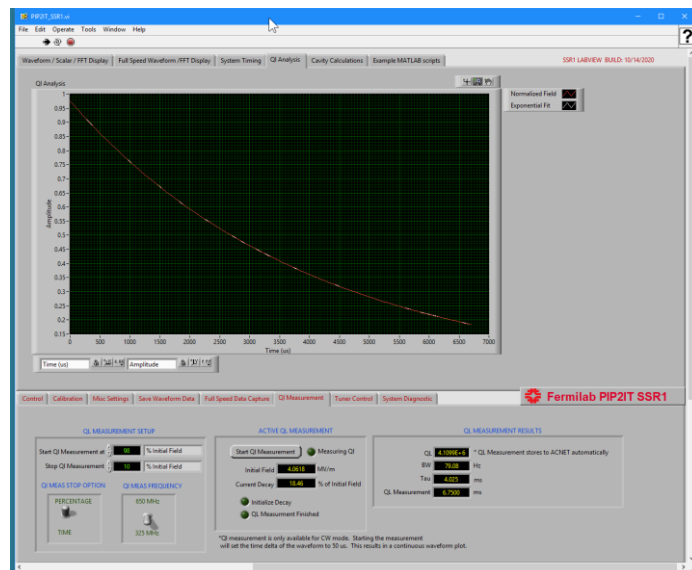
Q_L Measurement



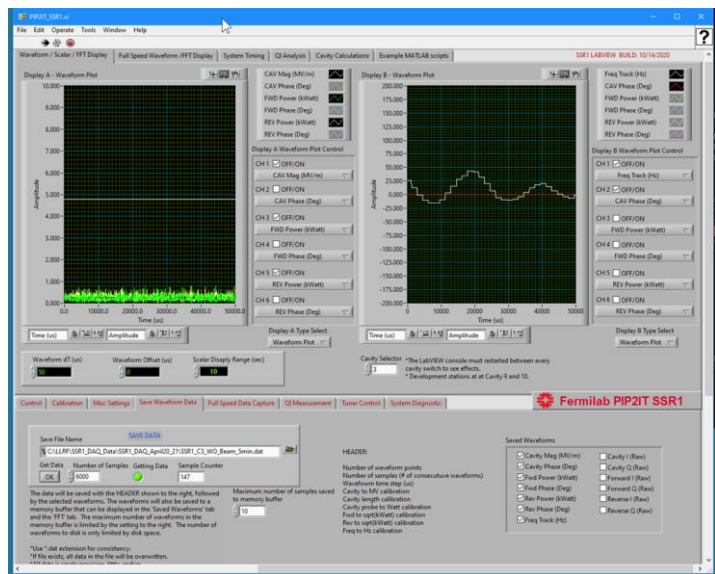
HWR Cavity 5, $Q_L = 2.07e6$



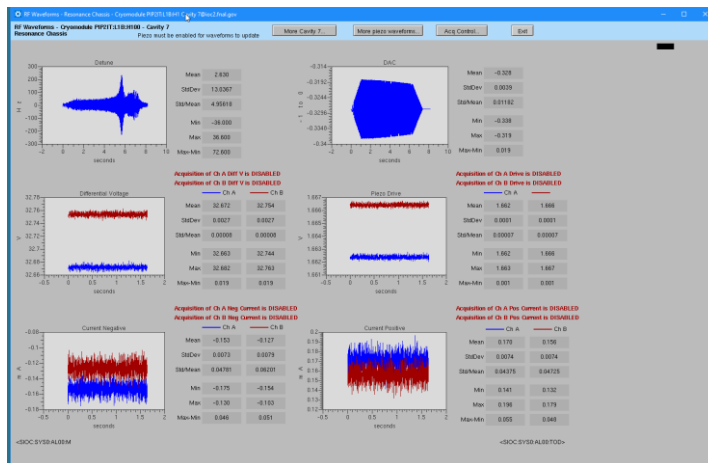
SSR1 Cavity 5, $Q_L = 4.11e6$



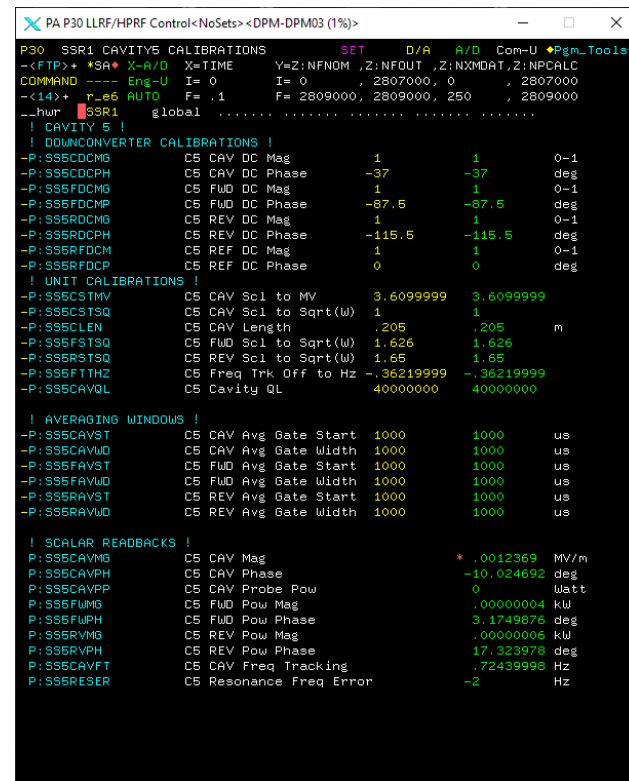
User Interfaces



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!