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PXIE Low Level RF Vector and Resonance Frequency Control

Brian Chase

PIP-II Collaboration Meeting

9-10 November 2015

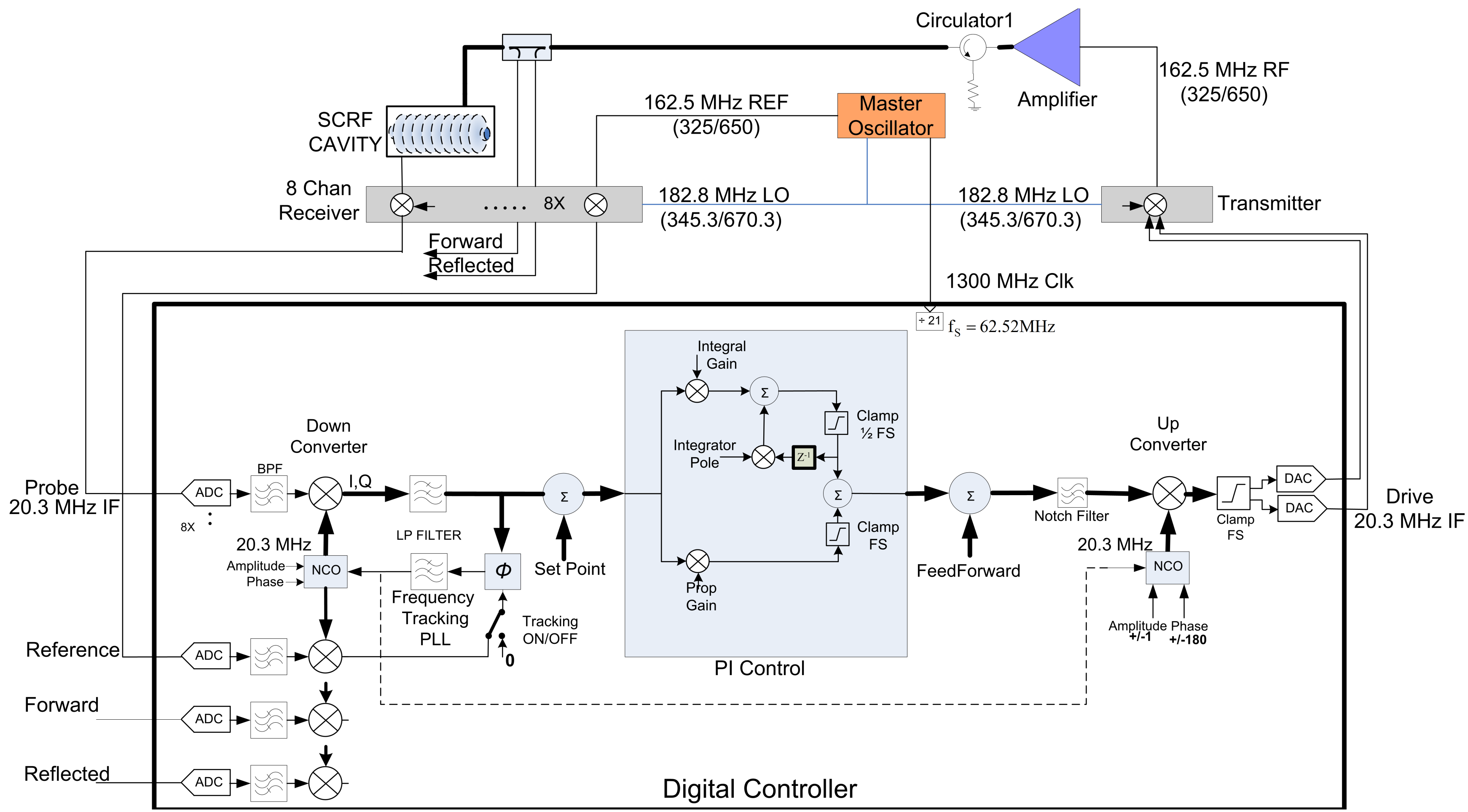
Outline

- Collaboration
- Current design and installation for 162.5 MHz systems (RFQ Bunchers and HWRs)
  - RF processing, digital controller, modeling, resonance control
- India collaboration design for 325 MHz SSR1 cavities
- Summary

The Collaboration Team

- Accelerator Division
  - LLRF - Brian Chase, Ed Cullerton, Jonathan Edelen, Joshua Einstein, Philip Varghese, Dan Klepec
  - RFQ resonance control – Daniel Bowring, Auralee Edelen-CSU, Jim Steimel, Dennis Nicklaus
- Technical Division
  - SRF resonance control – Yuriy Pischalnikov, Warren Schappert, Jeremiah Holzbauer
- IIFC (BARC, RRCAT)
  - LLRF Gopal Joshi, Shailesh Khole, Paresh Motiwala, Dheeraj Sharma, and many others
- LBNL – informal now, but would have great leverage from LCLS-II design

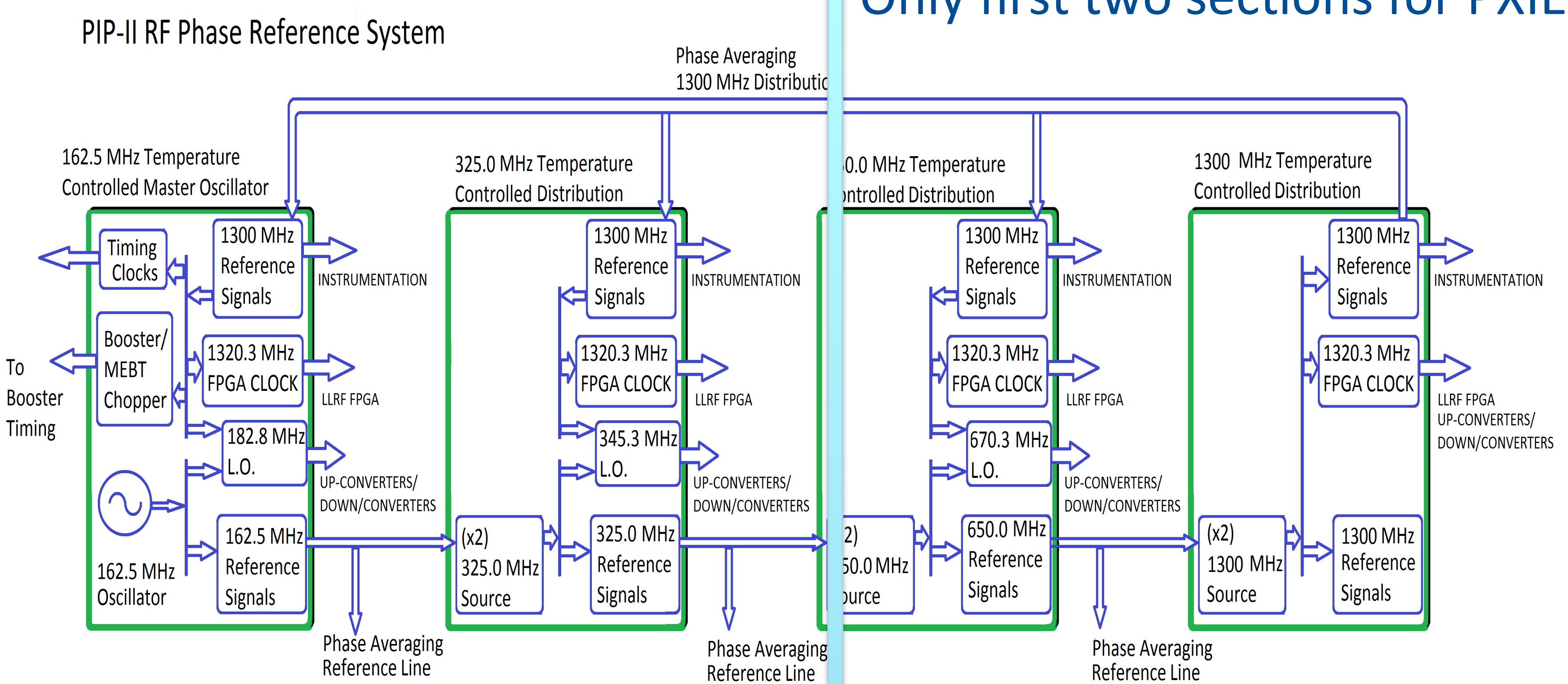
PXIE RF Station Controller



Fermilab PIP-II

162.5 MHz and 325 MHz Reference Generation

Only first two sections for PXIE



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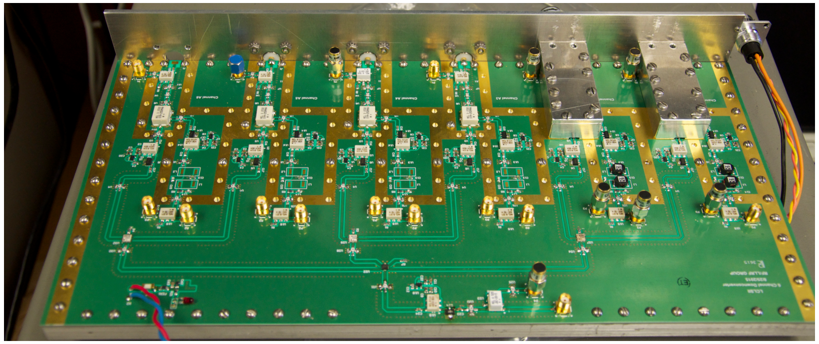
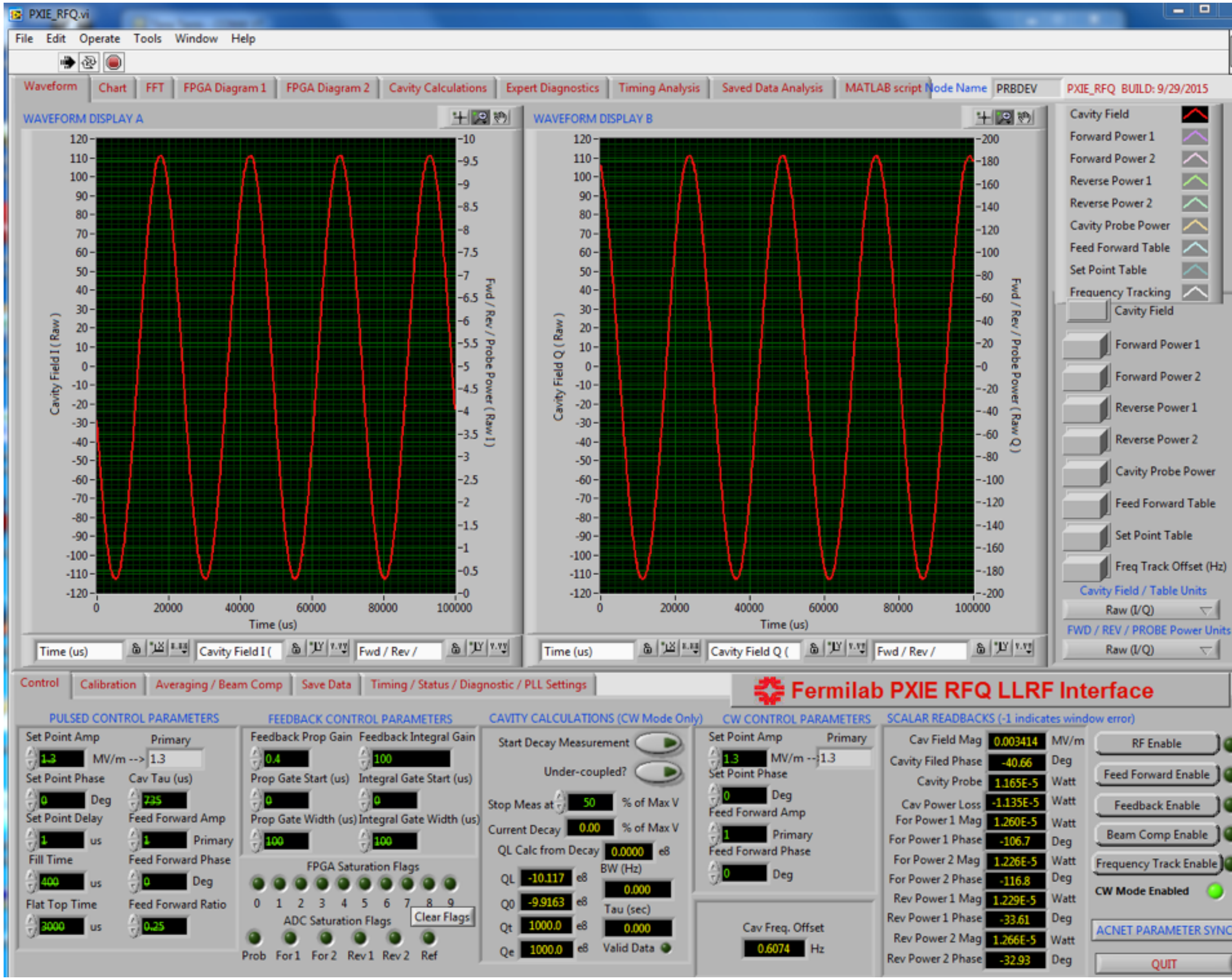
PXIE LLRF Rack Layout and Modules

Down-converter and chassis



Controller Labview Interface

- User and expert pages
- Calibration
- Calculation
- Diagnostics
- Long record to disk



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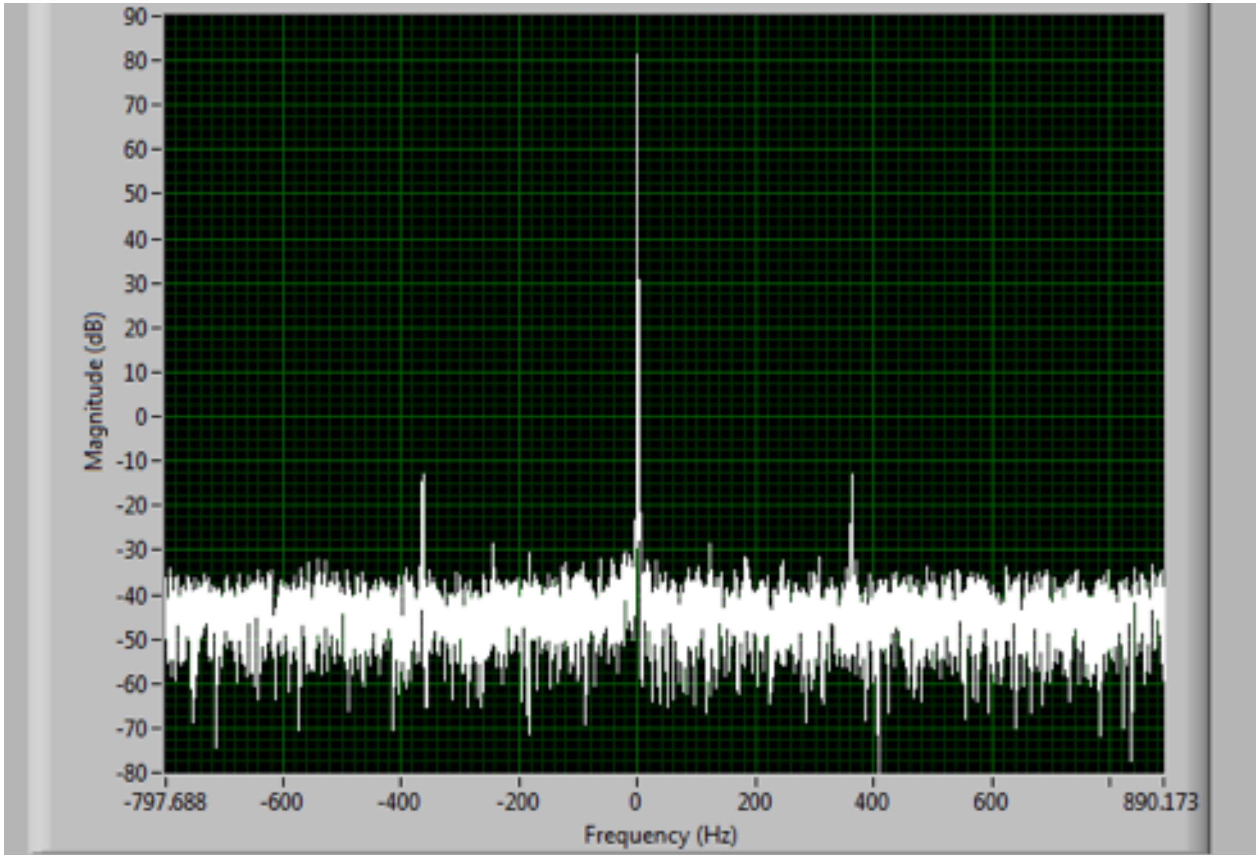
FFT available in real-time or from long records

RFQ LLRF in SEL
Mode locked to
external source

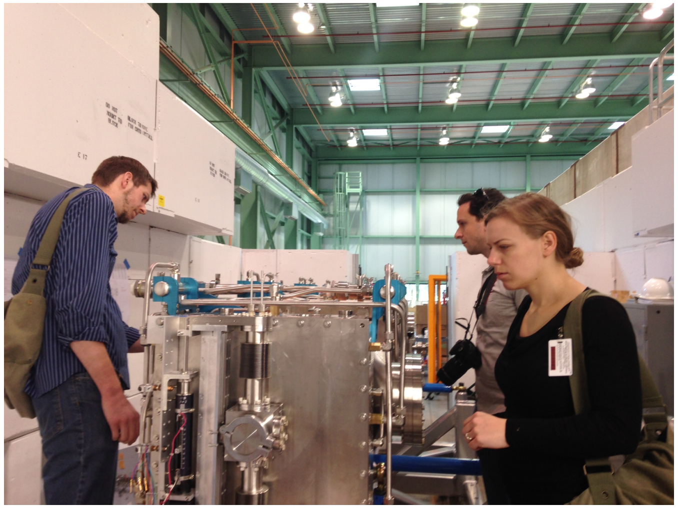
High dynamic range



1700 Hz, 0.3 Hz bin

RFQ Water Cooling System

Manifolds for vanes and body



Pumps outside cave

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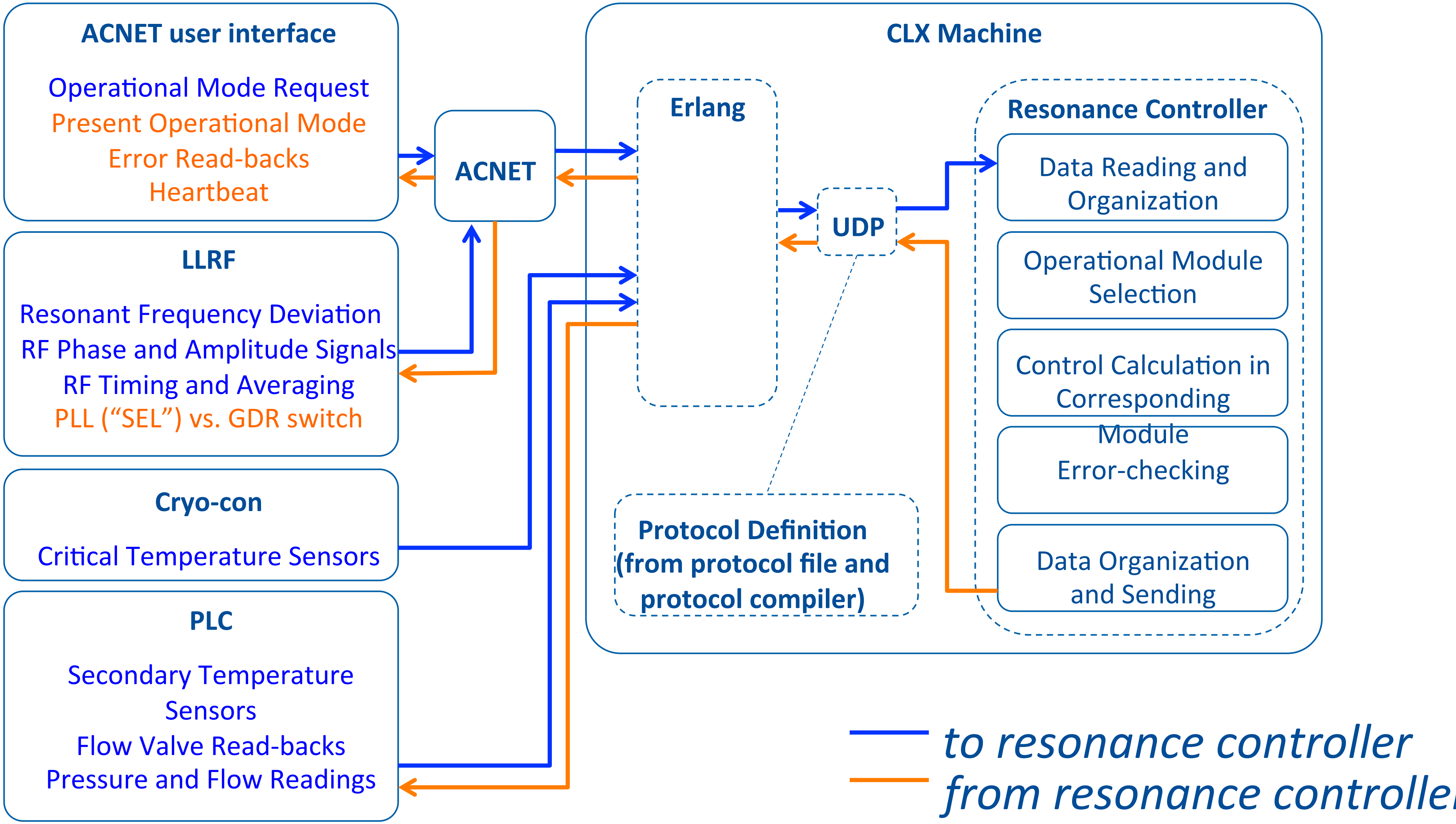
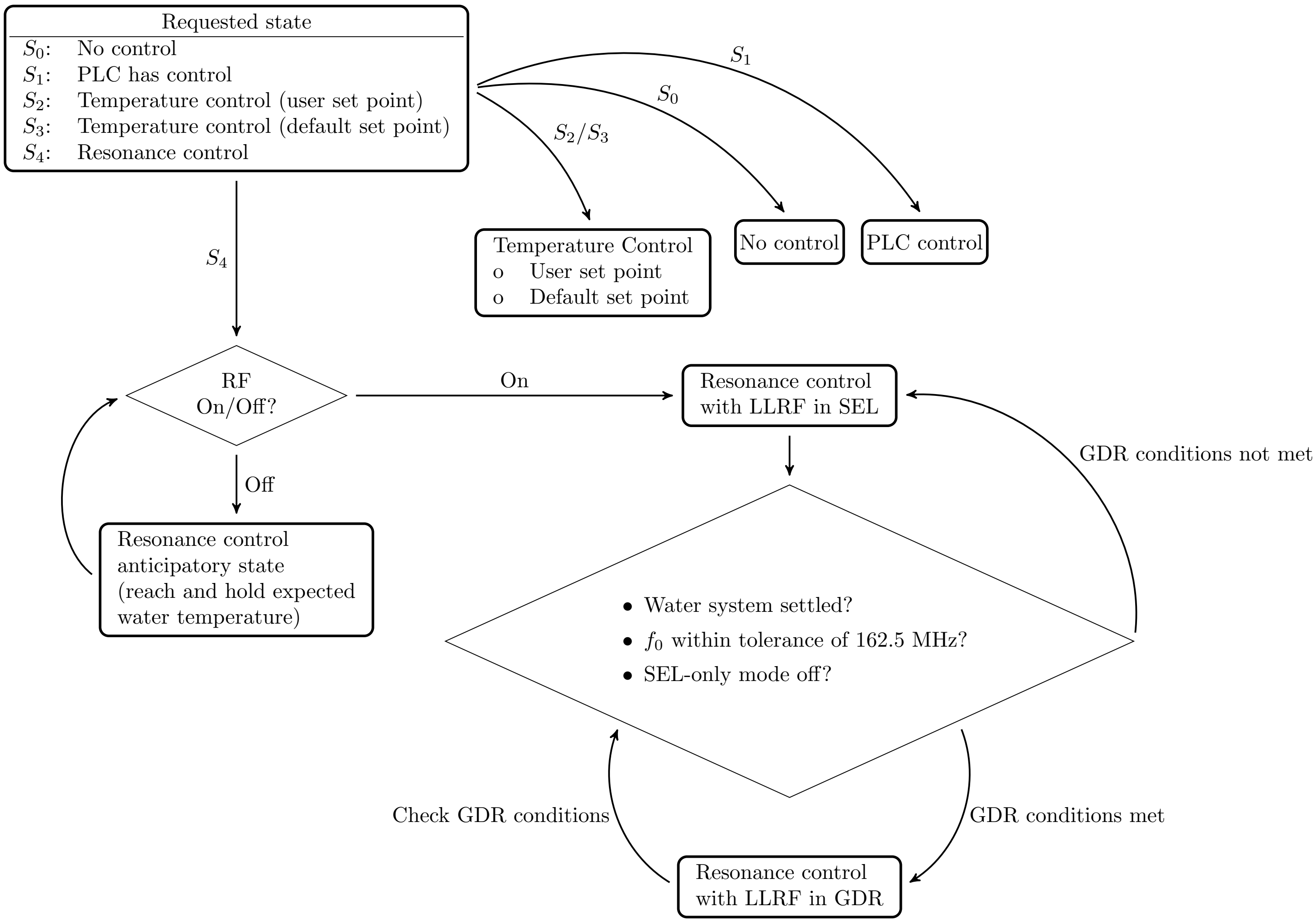
RFQ Resonance Control System Architecture and Component Interfaces



Auralee Edelen - CSU

RFQ Resonance Control System States



Auralee Edelen - CSU

RFQ Resonance Control Project Status

- Interfaces and overall architecture being implemented and tested
- Communication with front-end, ACNET already tested
- Resonance control program framework is well-defined and being implemented.
- ACNET variable names and devices being established
- Plan to start characterizing water system and non-powered RFQ behavior as soon as instrumentation is in place
- Cryo-con, associated RTDs, and other instrumentation to be installed imminently
- Once the system is characterized, we can begin to refine the control algorithms

Auralee Edelen - CSU

Buncher Control Study

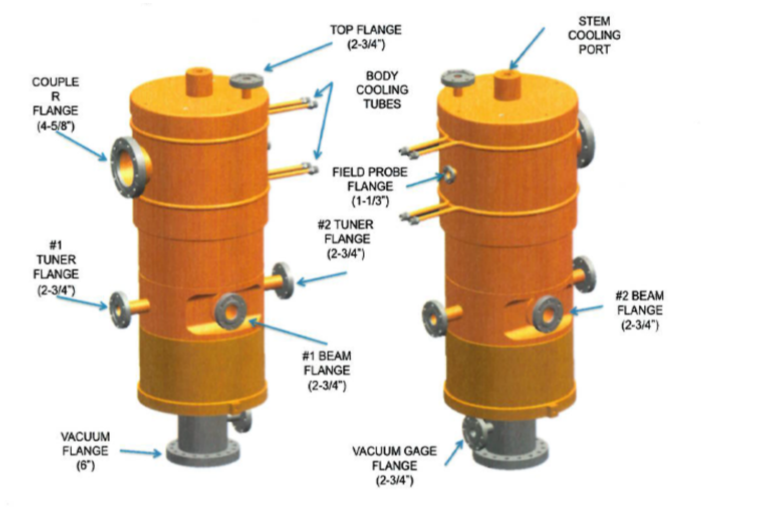


Figure: Front and back views of the solid model of the PXIE bunching cavities used in the medium energy beam transport line

Table: Figures of merit for the PXIE bunching cavities. Note that Q_0 is derived from Q_l and β

Figure of merit	Value
f_0	162.5 [MHz]
Q_0	$\approx$10000
Q_l	5240
β	0.904
$\Delta f_0/\Delta T_{H_2O}$	-1.65 [kHz/^{o}F]
$\Delta f_0/\Delta P_{rf}$	-9.5 kHz/kW
ΔT_{H_2O}	$\pm 2^o$F
R_s	7MΩ
C	19 [kJ/^{o}C]
t_0	1.5×10^{-6}
L_{gap}	$\approx$ 46 mm

Jonathan Edelen

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Buncher resonance analysis

- The cavity is on an open loop water cooling system that is only regulated to $\pm 2^o F$
- There is a stepper motor controlled tuner, there will not be active control over this tuner
- Large power amplifier overhead can be used to maintain the amplitude and phase response of the cavity
- Drift in the resonance of the cavity will impact the phase transient due to beam loading

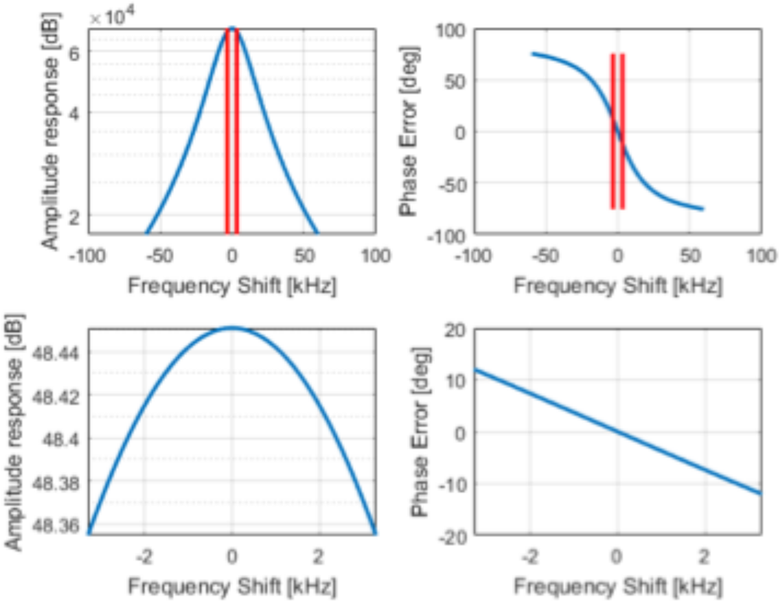


Figure: Amplitude and phase response of the bunching cavity with the temperature fluctuation boundaries shown in red. Note this assumes that the cavity is tuned to be on resonance in the middle of the temperature fluctuation band

Buncher Baseband model

- Baseband cavity model is a low pass filter with a bandwidth determined by Q_l and ω_0: $T_{cav}(s) = \frac{\omega_0/Q_l}{s+\omega_0/Q_l}$
- In the simplest case the feed-forward component of the system is simply the set-point
- Initially assume that the I and Q loops are driven with the same PI parameters

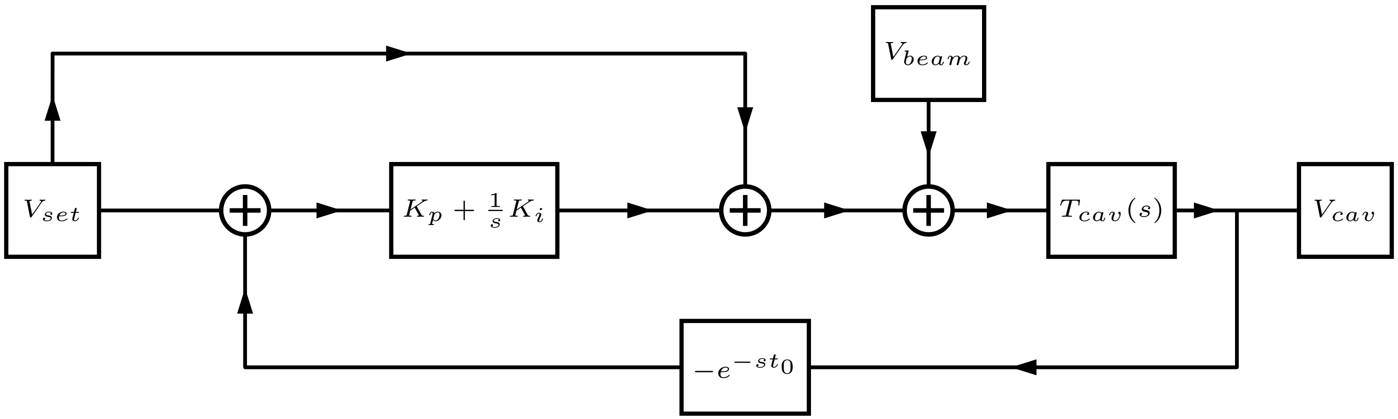


Figure: Baseband model of LLRF control system. Middle row (from left to right): Set-point, summing junction for feedback, PI controller, summing junction for feed-forward, summing junction for beam-loading, cavity transfer function, and cavity probe signal. Bottom row: group delay (negative for negative feedback). Top row: beam-loading

Feedforward Beam Loading Compensation

- Correct timing with a slight mismatch between the expected beam loading and the real beam loading leads to a disturbance
- An adaptive algorithm could actively adjust the beam loading compensation pulse to pulse and reduce this transient
- An optimization routine can be used to determine the beam loading compensation needed
- Simulations show a convergence in between 2-20 iterations depending on how close the initial guess is
- A large disadvantage is the algorithm does not learn, every time a change is made to the beam loading it will start over
- There are some stability issues that need to be worked out to make the controller more robust.

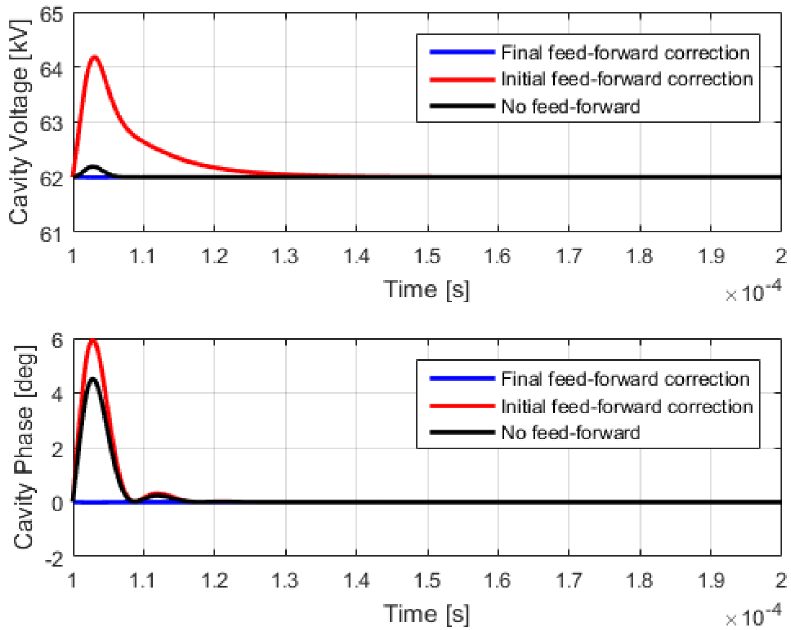
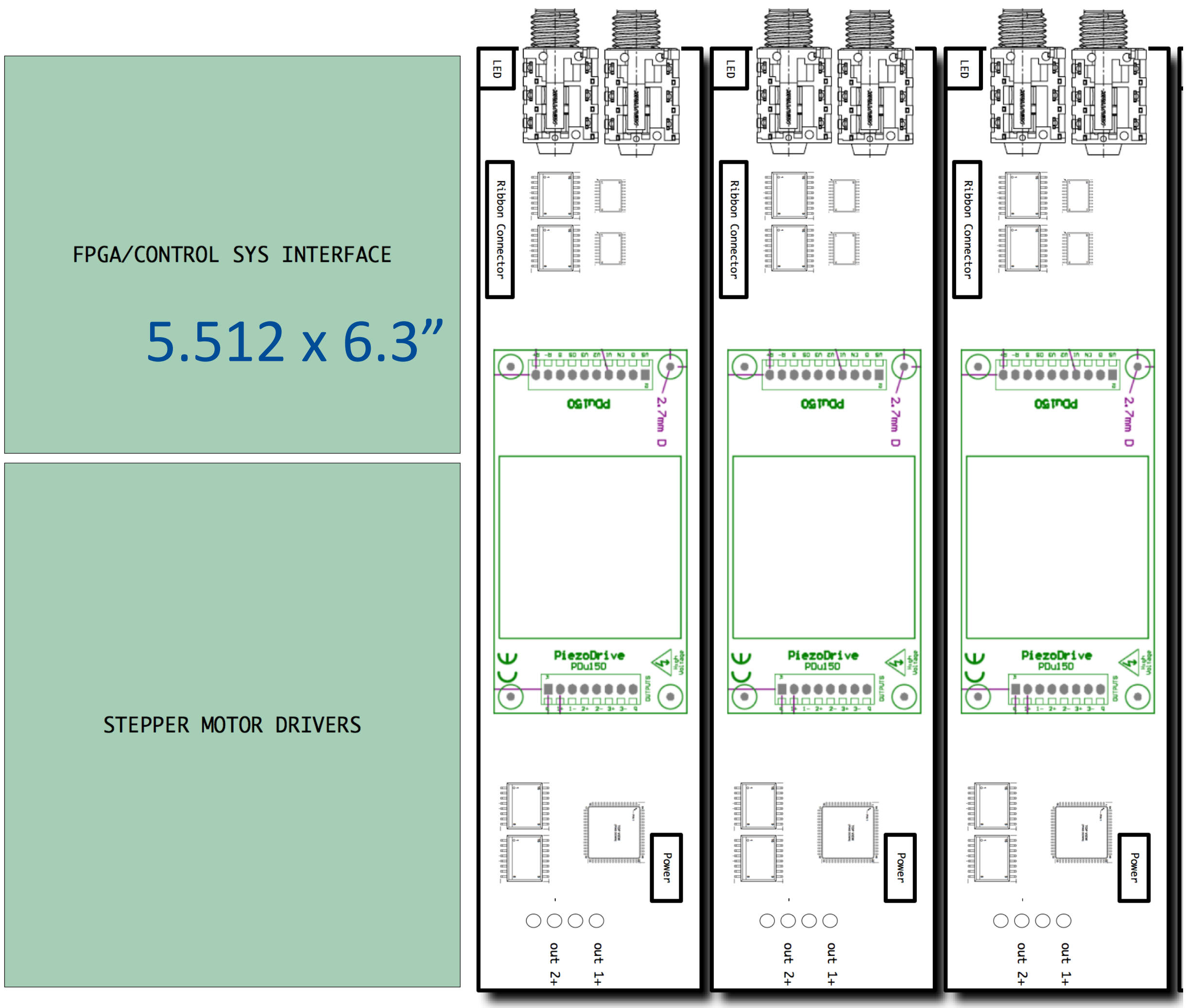
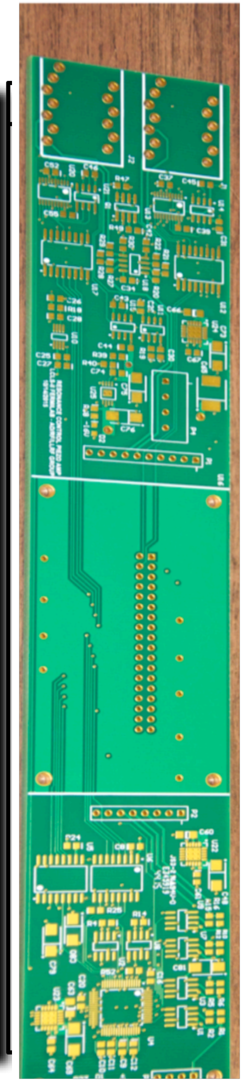


Figure: Simulation of the adaptive feed-forward control for the PXIE bunching cavity. Here the initial conditions for the optimization of the feed-forward compensation for beam loading were poor. The I loop converged in 5 steps and the Q loop converged in 19 steps.

SRF Resonance control chassis layout





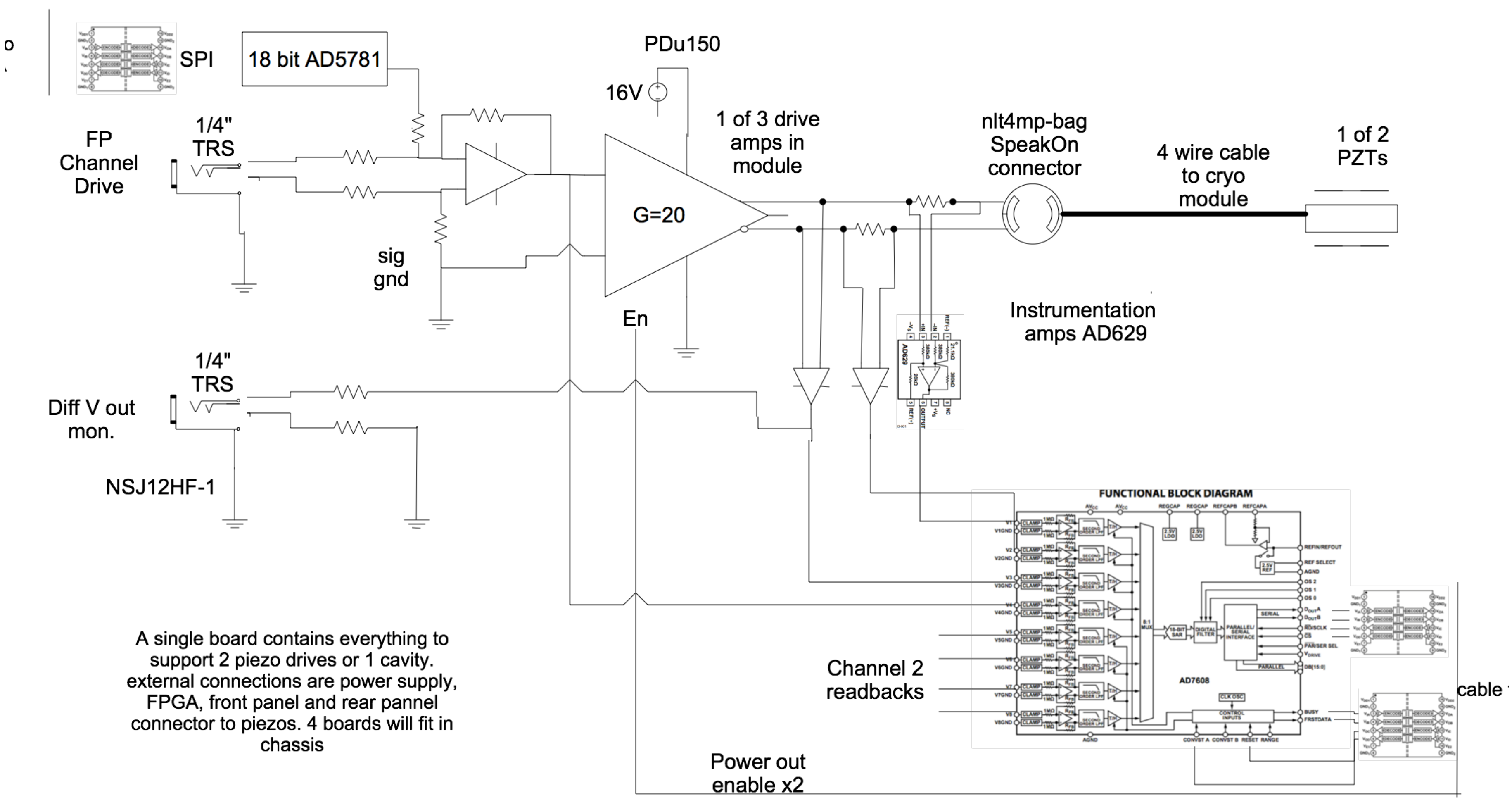
PCB is ready for assembly and test

Stepper motor driver will be available from Jlab

Fermilab PIP-II

Piezo Driver module

2 channel piezo drive circuits to support 1 cavity



A single board contains everything to support 2 piezo drives or 1 cavity. external connections are power supply, FPGA, front panel and rear pannel connector to piezos. 4 boards will fit in chassis

PiezoDrive PDu150 three channel Ultra-low noise

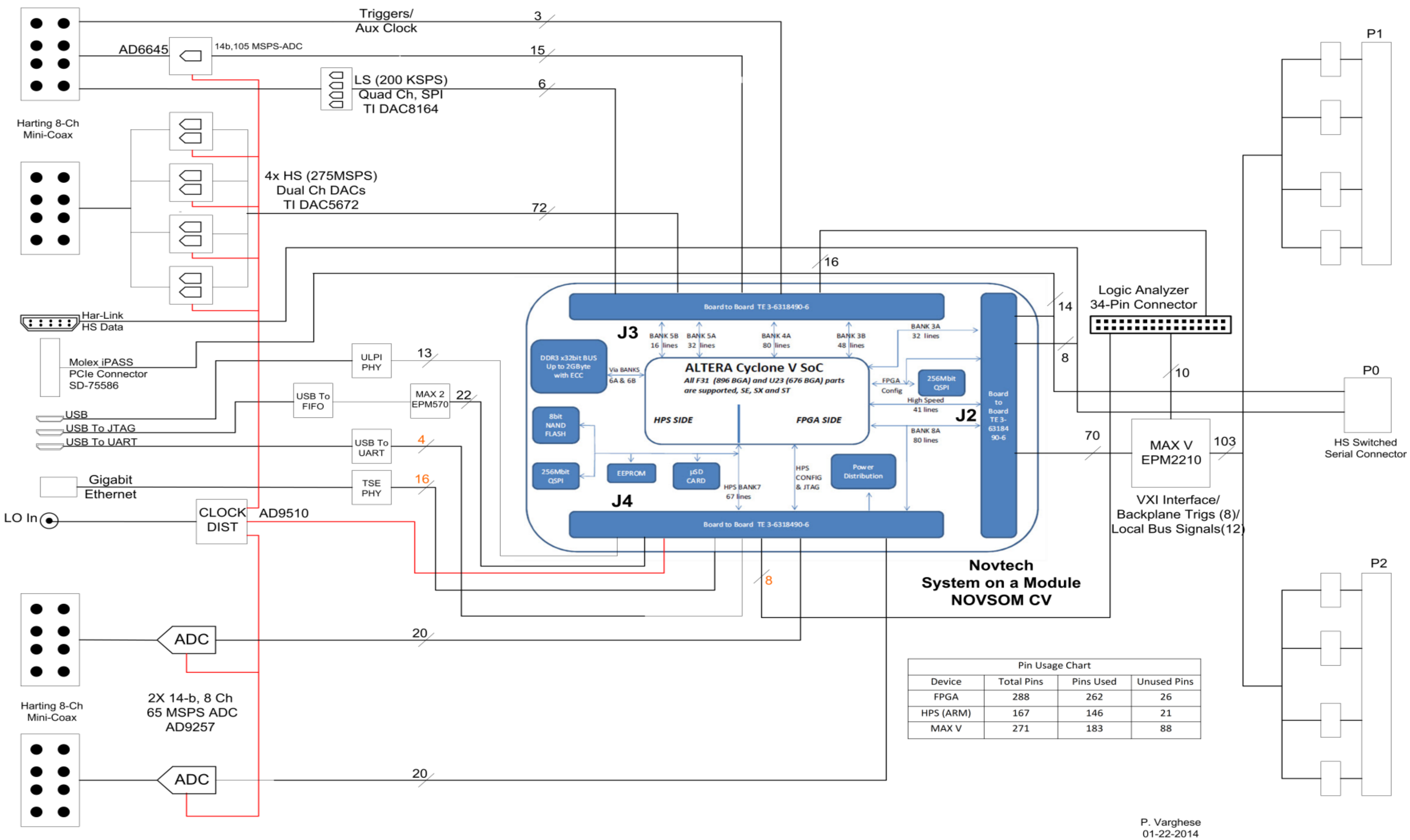
Specifications

Load Cap.	Bandwidth
No Load	180 kHz
10 nF	105 kHz
30 nF	40 kHz
100 nF	11 kHz
300 nF	3.8 kHz
1 uF	1.0 kHz
3 uF	320 Hz
10 uF	62 Hz
30 uF	24 Hz

Small signal bandwidth versus load capacitance (-3dB)

Specifications	
Power Supply	+24 V, Ground
Output Voltage	-30 V to +150 V
Peak Current	100 mA (300 mA single channel)
RMS Current	78 mA (235 mA single channel)
Power Bandwidth	80 kHz (150 Vp-p)
Signal Bandwidth	180 kHz
Slew Rate	38 V/us
Gain	20 V/V
Input Impedance	110 kOhm (Input), 3.3 kOhm (Offset)
Input Offset	+/- 5 mV
Load	Unlimited
Output Noise	26 uV RMS (1 uF load, 0.03 Hz to 1 MHz)
Protection	Short circuit, over-current, and temperature
Quiescent Current	100 mA (10 mA in shutdown)
Connectors	Screw terminals (AWG 20-30)
Dimensions	76 x 40 x 37 mm (L x W x H)
Environment	-40C to 60C (-40F to 140F)
Weight	80 gram

System on Chip LLRF Controller



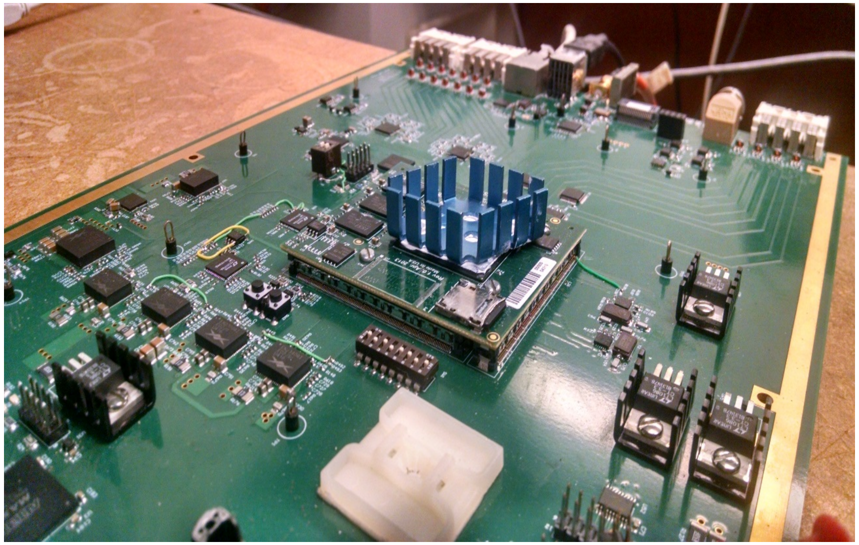
Pin Usage Chart			
Device	Total Pins	Pins Used	Unused Pins
FPGA	288	262	26
HPS (ARM)	167	146	21
MAX V	271	183	88

SoC-MFC Development Status

- Assembled Rev2 boards due here this week
- Currently developing:
  - Test procedures
  - Documentation
  - Version and source control procedure

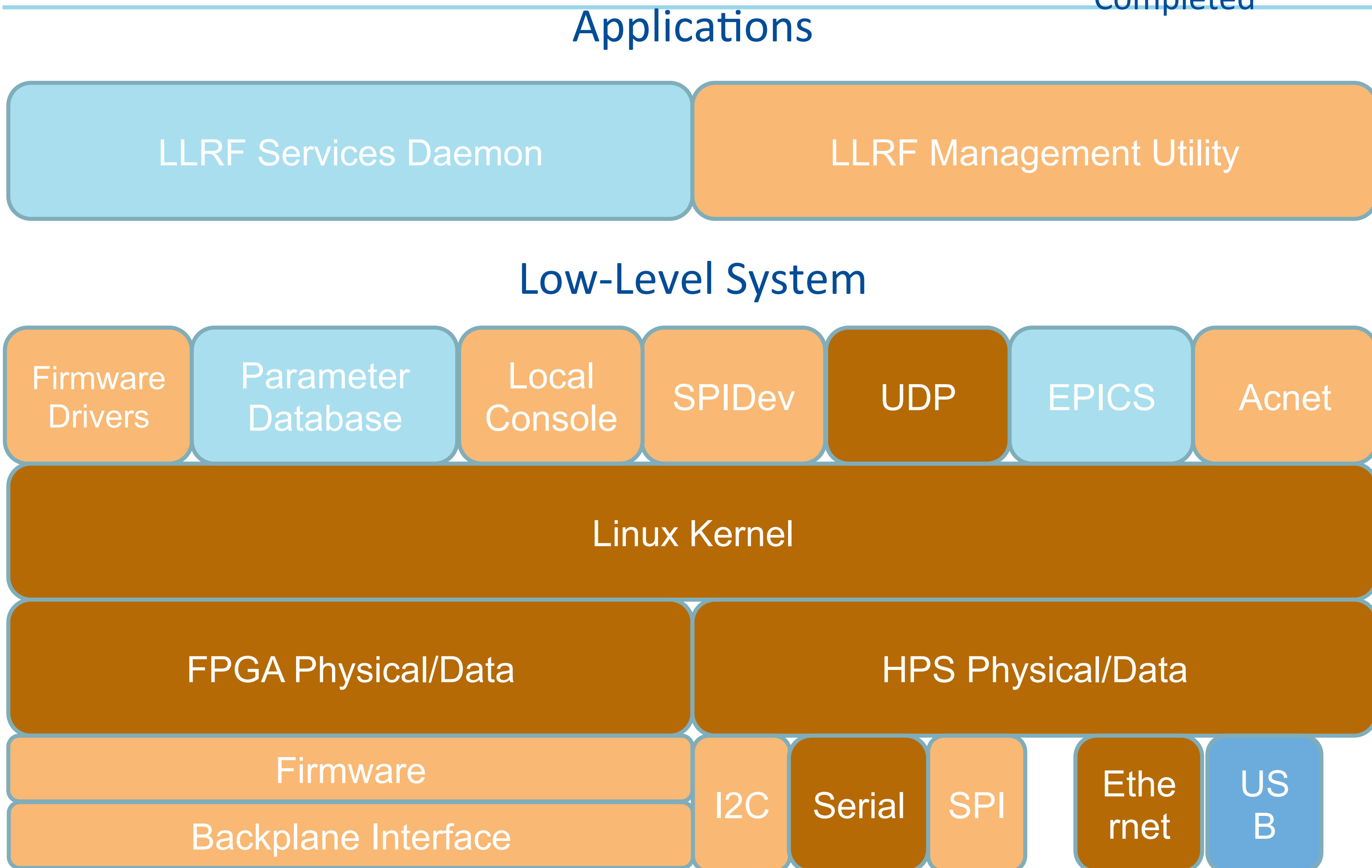
Use on Bunchers Q3FY16

2 cavities per card



SoCMFC Software Status

Not Started
In Development
Completed



SoCMFC Controls Status

Not Started
In Development
Completed

Labview

Local Data Logging

FFT and Data Statistics

Streaming and Control

Controls Systems

Controls Frontend

Systems Callbacks

Acnetd

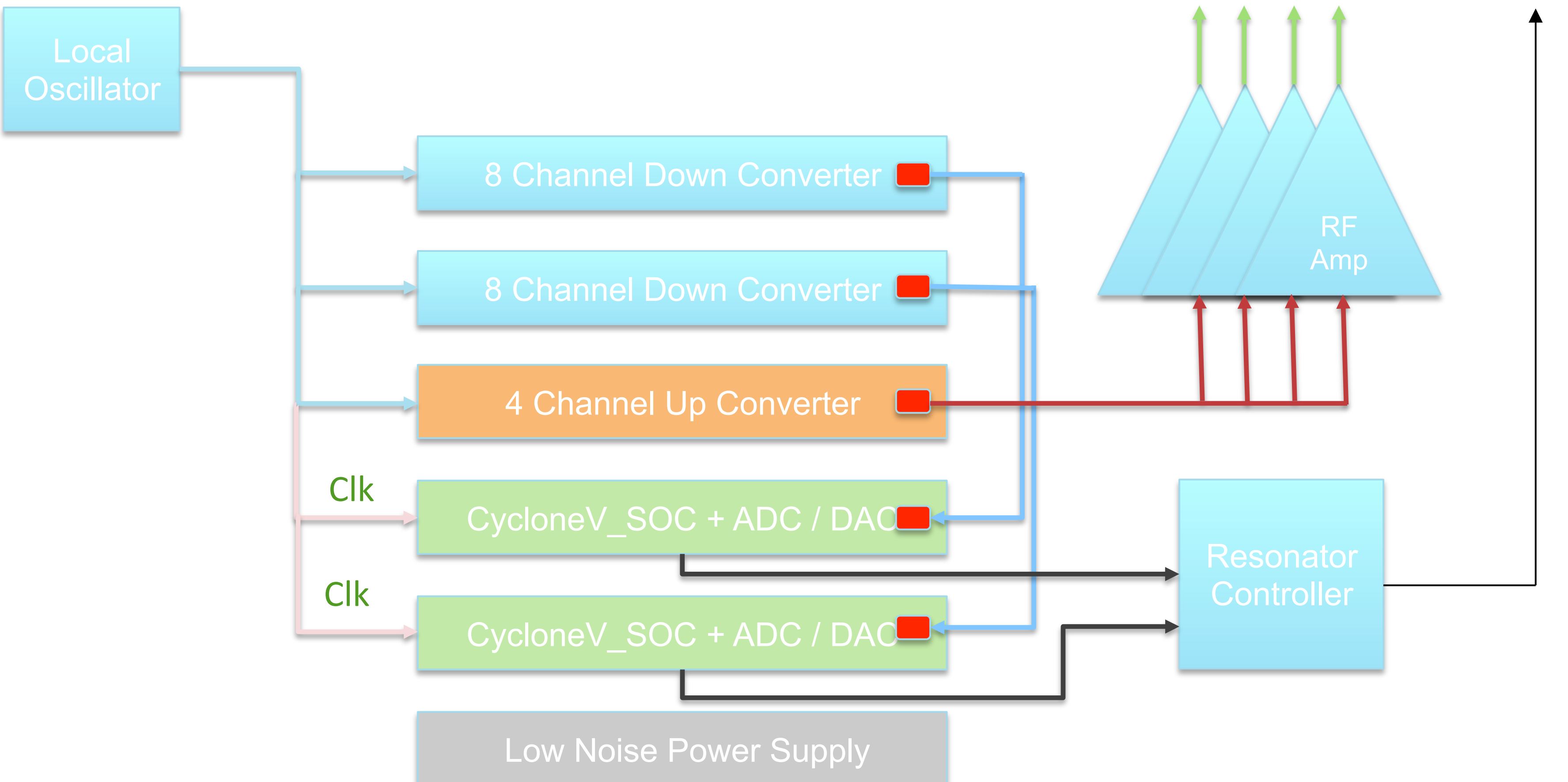
EPICS

Local Console

Collaboration Chassis Design Status

- 8 Channel down converters chassis
  - Modify 6 Ch LCLS-II receiver to 8 Ch - In progress
- 4 Channel up converter chassis
  - Modify existing up-converter – In progress
- Two Cavity Controller chassis
  - SOC-FPGA PCB and ADC/DAC PCB
  - Each PCB is mounted on a heat sink for uniform temperature distribution
- Resonant controller chassis
  - SOC-FPGA PCB, Stepper motor dirver, 4 Piezo Amplifiers
- Power Supply Chassis - low noise 6V and +- 16V
- Each rack has temperature controlled air flow

Rack Block Diagram



Summary

- The RFQ and first buncher LLRF will be ready for installation when the racks are installed in the next few weeks
  - Support for CW operation in SEL and GDR modes – 10 kHz DAQ
  - Support for Pulsed mode with up to 5 ms pulses at up to 10 Hz rep rate – 1 MHz DAQ
- RFQ Resonance control development is expected to keep pace with commissioning needs
- The Fermilab SOC-MFC controller will be likely used through the 162.5 MHz section including HWRs
- IIFC will produce LLRF and resonance control for the 325 MHz section and is on a good track for 2017